Searching for new light hidden particles with η and η' mesons

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We present an overview of the opportunities for η, η' meson factories to discover new light hidden particles beyond the Standard Model (SM). This is not part the traditional motivation for precision studies of the η, η' sector, which historically has been framed in the context of fundamental symmetry tests in and beyond the SM. The latter includes a testing ground for the dynamics of low-energy QCD (guided by chiral symmetries), as well as probes of discrete symmetries C, P, and CP from physics beyond the SM [1, 2]. On top of this, there is a potentially rich physics program to discover new hidden particles at the MeV–GeV mass scale [2, 3]. Possible states include spin-zero or spin-one bosons mediating new interactions beyond the Standard Model that can be produced on-shell in meson decays if kinematically allowed [4–6]. From a theoretical standpoint, there is strong motivation for such states in connection with dark matter [6–11], as well as experimental anomalies measured for $(g-2)_\mu$ [12, 13] and ^{8}Be decay [14] (see [15–18] for further references and reviews). Though a worldwide effort is underway to discover light hidden particles in many experimental facilities, η and η' mesons have not gained much attention in this context.

The original motivation for "beyond the SM" physics in η decays actually predates the SM itself. Following Ramsey and Purcell's proposal for P (and CP) violation in strong interactions [19], Kobzarev and Okun advocated $\eta \to 2\pi$ to search for this effect [20]. Soon after, it was hypothesized that CP violation discovered in K decays could arise as a second-order effect combining a CP-preserving $\Delta S = 1$ weak transition with a new CP-violating, flavor-conserving "semi-strong" force [21–24]. As an eigenstate of C and P, the η meson could be used to discover first-order effects of the latter type via decays such as $\eta \to 3\gamma$ or $\eta \to \pi^0 \ell^+\ell^-$. Kobayashi and Maskawa later famously realized that CP violation could arise within the weak interaction by itself (with a third quark generation) [25], which contributes to η and η' decays at a level many orders of magnitude below what is feasible to be measured [26]. Nonetheless, experiments have continued to search for C-, P-, and CP-violating η and η' decays in the context of new physics [27], though little work has been done on the theory side to identify models motivating such efforts [2].

There are two important points to make. First, hidden particle searches are synergistic with other physics goals for η, η' studies. Many target channels are also of prime interest for tests of QCD dynamics and/or discrete symmetries [2]. Second, while η, η' decays do have overlap with models being tested at other types of experiments, they have a somewhat unique sensitivity to hidden particles coupling only to light quarks and gluons (e.g., [28–30]) which is complementary, e.g., to probes from the flavor sector of couplings to heavier quarks.

Two new η, η' meson factories are on the horizon and it is worthwhile taking a broad look at what can be done to search for light hidden particles. First, there is the upcoming Jefferson Eta Factory (JEF) at Jefferson Lab, a fixed target experiment that will combine the GlueX experimental apparatus with an upgraded high-resolution forward electromagnetic calorimeter to measure rare neutral decay modes with unprecedented precision [31]. η, η' mesons will be produced synchronously via $\gamma p \to \eta^{(\prime)} p$ and are tagged by both tagging the incoming 8-12 GeV photon and detecting the recoiling proton. Second, there is the Rare Eta Decays with a TPC for Optical Photons (REDTOP) experiment, a proposed $\sim$few GeV proton beam fixed target experiment that anticipates a dramatic $\mathcal{O}(10^4)$ increase in statistics over present η, η' samples [32]. REDTOP will operate in stages, with different beam energies and targets, including both untagged (run I) and tagged (runs II and III) modes. In the latter runs, the four-momentum of the $\eta^{(\prime)}$ will be fully reconstructed, potentially allowing for searches for decays involving invisible final states. The REDTOP detector is also planned to have vertexing capability to detect displaced decays of long-lived hidden particles.

Let us summarize recent studies of light hidden sectors through the lens of η, η' physics. Naturally, search strategies depend on how the η, η' mesons decay (the hidden sector model) and whether samples are tagged or untagged. Several hadron colliders have large untagged samples that have been used to set limits on hidden particles (e.g., a dark photon A') inclusively produced by η and other meson decays. These include HADES [33], PHENIX [34], and LHCb [35, 36], which have searched for new dilepton resonances, i.e., arising via $A' \to \ell^+\ell^-$. Displaced vertices provide an additional signature if the decay is long-lived (but not too long-lived to escape the detector completely) [35, 36]. For these searches, η mesons in particular provide a leading production channel, $\eta \to \gamma A'$, when kinematically allowed [33–36]. Among experiments with sizable tagged η/η' samples, searches for hidden sector physics in η and η' decays remain limited. BESIII put upper limits on invisible η, η' decays, e.g., into light dark matter particles [37]. WASA-at-COSY put an upper limit on $\eta \to \pi^0 e^+ e^-$ [38]; this process is C-violating as a single-photon process and is highly suppressed in the Standard Model, but can arise from a light scalar boson [39]. Studies are in progress with KLOE/KLOE-2 data to constrain a leptophobic gauge boson in the rare decay $\eta \to \pi^0\gamma\gamma$ [40], while Belle has already made a search for this model in $\eta \to \pi^+\pi^-\gamma$ [41], although this channel is isospin-suppressed [28].

Many more channels can be studied to detect light hidden particles produced on-shell in η, η' decays. If they decay visibly into SM final states, there are three main search strategies: *(i) resonance searches*, i.e., bump-hunting, *(ii) displaced vertices* associated with long-lived decays, and *(iii) rare channels*, final states that are highly suppressed in the SM can be mimicked by new physics. Here we list various models and their signatures. We also emphasize how many of the channels overlap with SM physics or discrete symmetry tests.

- *Dark photon A':* Decays include $\eta^{(\prime)} \to A'\gamma \to \ell^+\ell^-\gamma, \pi^+\pi^-\gamma$. These final states are not rare, but can be searched for with *(i)* and *(ii)* and sensitivities projected for REDTOP will explore dark photon parameter space that is currently unexplored [42]. Other decays, e.g., $\eta^{(\prime)} \to \pi^+\pi^- A' \to \pi^+\pi^-\ell^+\ell^-$, are also possible but have not been studied. These final states are important in the SM context as well: they provide experimental extraction of η, η' transition form factors, used in turn as theoretical input for hadronic light-by-light contribution to $(g-2)_\mu$ [2].

- *Protophobic X boson:* Similar to the A', the 17 MeV X boson proposed in connection with the ^{8}Be anomaly [43, 44] can be discovered in $\eta^{(\prime)} \to X\gamma \to e^+e^-\gamma$. The predicted branching ratios are $\mathrm{BR}(\eta \to \mathrm{X}\gamma \to \mathrm{e}^+\mathrm{e}^-\gamma) \approx 10^{-5}$ and $\mathrm{BR}(\eta' \to \mathrm{X}\gamma \to \mathrm{e}^+\mathrm{e}^-\gamma) \approx 10^{-6}$ [2]. Published results for $\eta \to e^+e^-\gamma$ from A2 at MAMI only extend down to $m_{ee} = 30$ MeV [46] and smaller invariant masses are targeted for REDTOP [32]. While recent constraints from NA64 have constrained the X boson coupling to electrons [45], η, η' decays probe a combination of both quark and electron couplings that are more closely related to the purported ^{8}Be signal.

- *Leptophobic B boson:* A light gauge boson B coupled only to quarks yields distinct signals such as $\eta \to B\gamma \to \pi^0\gamma\gamma$ [4, 28]. A high priority for JEF, this all neutral final state is an uncommon decay that also has SM implications for scalar meson dynamics in QCD [2]. The total rate $\eta \to \pi^0\gamma\gamma$ already provides the strongest model-independent limit on B couplings over the range $m_{\pi^0} < m_B < m_\eta$ [28] and $\pi^0\gamma$ resonance searches in this channel will extend this reach by orders of magnitude [2]. JEF will also search for the B boson in the larger mass region via $\eta' \to B\gamma \to \pi^+\pi^-\pi^0\gamma$, with a background $\eta' \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$ that is also relevant for the η' isoscalar transition form factor in the SM [2].

- *Scalar bosons:* A light Higgs scalar S yields decays $\eta^{(\prime)} \to \pi^0 S \to \pi^0\ell^+\ell^-$, $\pi^0\gamma\gamma$, 3π and $\eta' \to \eta S \to \eta\ell^+\ell^-$, $\eta\gamma\gamma$, $\eta\pi\pi$. In the Higgs-mixing model, S couples preferentially to heavy quarks and flavor constraints already limit η, η' signals to be beyond REDTOP sensitivities [2, 42]. However, η, η' decays have a complementary and unique potential to probe scalar bosons coupled preferentially to light quarks [30, 47, 48]. The $\pi^0\ell^+\ell^-$, $\eta\ell^+\ell^-$ final states are experimentally clean and very rare in the SM: due to C-parity, the leading contribution is a two-photon loop process far below present sensitivities. Among photon channels, the total rate $\eta \to \pi^0\gamma\gamma$ provides the strongest limit on a "hadrophilic" scalar with prompt decays $S \to \gamma\gamma$ (displaced decays are subject to strong beam dump constraints) [30]. Further improvements in the prompt regime, beyond Ref. [30], can be made via $\gamma\gamma$ resonance searches in $\eta \to \pi^0\gamma\gamma$. Finally, the hadronic final states 3π, $\eta\pi\pi$ are not rare decays but S would appear as a resonance in their Dalitz distributions [30]. The absence of such a resonance in KLOE data for $\eta \to \pi^+\pi^-\pi^0$ places the strongest constraint over the mass range $2m_\pi < m_S < m_\eta - m_\pi$ [30], which could be improved at future facilities both with larger statistics and with the η' to extend the mass reach. The 3π and $\eta\pi\pi$ Dalitz distributions are interesting in their own right from the SM context as well (extraction of light quark masses, testing large-N_c chiral effective theory, etc.) [2].

- *Axion-like particles (ALPs):* Light ALPs are produced in $\eta, \eta' \to \pi\pi a$ decays through their minimal couplings to gluons, as well as direct couplings to light quarks [2, 29, 49, 50]. Minimally-coupled ALPs decay predominantly as $a \to \gamma\gamma$, $\pi^+\pi^-\gamma$, or 3π depending on mass [29]. It is also worthwhile to consider nonminimal couplings to leptons and decays $a \to \ell^+\ell^-$, which is motivated to solve the $(g-2)_\mu$ anomaly [51]. Hence, a myriad of 4- and 5-body decays are possible, many of which have never been measured [2]. These include $\eta^{(\prime)} \to \pi\pi a \to \pi\pi\ell^+\ell^-$, $\pi\pi\gamma\gamma$ and $\eta' \to \pi\pi a \to \pi\pi\pi^+\pi^-\gamma$, 5π. Several channels are rare decays highly suppressed in the SM: $\eta^{(\prime)} \to 2\pi^0\ell^+\ell^-$ (C-violating as a single-photon process) and $\eta' \to 5\pi$ (isospin-violating and phase-space suppressed); but these suppressions are absent for ALP processes. Even in the minimally-coupled model, considerable parameter space remains unexplored that can be accessed at future η, η' factories and presently a null result on the total rate for $\eta' \to 2(\pi^+\pi^-)\pi^0$ from CLEO [52] provides on one of the strongest limits [29]. Much parameter space is open as well for the nonminimally-coupled model with leptonic ALP decays [49], though further work is required to quantify η, η' predictions in the context of $(g-2)_\mu$.

In addition to visible decays, we briefly mention the exciting possibility that η, η' decays can produce light dark matter particles (or other long-lived hidden states). Any of the mediator particles discussed above could decay into dark matter if kinematically allowed, yielding partially-invisible channels, e.g., $\eta^{(\prime)} \to \gamma + \mathrm{inv}$, $\pi^0 + \mathrm{inv}$, $\pi\pi + \mathrm{inv}$. A related model with a dark photon and light inelastic dark matter was proposed to reopen the parameter space to explain the $(g-2)_\mu$ anomaly, which is otherwise excluded [53]. In this model, the A' decays into dark matter particle, one of which is produced in an excited state and then de-excites to yield an additional displaced $\ell^+\ell^-$ vertex: i.e., $\eta, \eta' \to A'\gamma \to \gamma + (\ell^+\ell^-)_{\mathrm{displaced}} + \mathrm{inv}$. Lastly, a fully invisible decay $\eta^{(\prime)} \to \mathrm{inv}$ is another possibility [54]. Further study is required to determine which among these invisible or partially-invisible decay channels is feasible experimentally.

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