The JLab Eta Factory (JEF) Experiment

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The $\eta^{(\prime)}$ meson, with the quantum numbers of the vacuum (except the parity), provides a unique, flavor-conserving laboratory to probe the isospin-violating sector of low-energy QCD and to search for new physics Beyond the Standard Model (BSM) [1]. The JLab Eta Factory (JEF) experiment [2, 3] will perform precision measurements of various $\eta^{(\prime)}$ decays with emphasis on rare neutral modes, using the GlueX apparatus [4] and an upgraded Forward electromagnetic Calorimeter (FCAL-II). Significantly boosted $\eta^{(\prime)}$ mesons will be produced through $\gamma+p \to \eta^{(\prime)}+p$ with an 8-12 GeV tagged photon beam. Non-coplanar backgrounds will be suppressed by tagging $\eta^{(\prime)}$ with recoil proton detection. The $\eta^{(\prime)}$ decay photons (and leptons) will be measured by FCAL-II with a high-granularity, high-resolution $PbWO_4$ crystal core in the central region that minimizes shower overlaps and optimizes the resolutions of energy and position. Compared to previous or planned $\eta^{(\prime)}$ experiments, such as A2-MAMI [5, 6], WASA-at-COSY [7], KLOE-II [8], BESIII [9] and the proposed future REDTOP [10], JEF is the only one producing highly-boosted $\eta^{(\prime)}$ so that its detection efficiency is insensitive to the detector thresholds, thus less prone to the experimental systematics. The capability of tagging every $\eta^{(\prime)}$ in combination with a state-of-the-art FCAL-II offers two orders of magnitude improvement in background suppression (relative to the existing GlueX FCAL calorimeter). JEF will simultaneously produce η and η' at similar rates ($\sim 6\times10^7$ tagged η and $\sim 5\times10^7$ tagged η' per 100 days of beam time). The data collection for JEF can be performed in parallel with other experiments in Hall D, such as the GlueX meson spectroscopy experiment [11] and any future experiments using a hydrogen target. A high-statistics dataset will be accumulated continuously throughout the JLab 12 GeV era. These make JEF a unique η and η' factory with no competition in rare neutral decay modes. The data for nonrare $\eta^{(\prime)}$ decays has been accumulating since fall 2016 with the standard GlueX detector. The development of FCAL-II is currently in progress. The second phase of JEF with an upgraded calorimeter will start in 2024.

The primary objectives of the JEF experiment are:

1. A search for new sub-GeV gauge bosons, probing three out of four the most motivated portals coupling the SM sector to the dark sector.

   Vector: a leptophobic vector boson (B') [12] coupling to baryon number can be searched for via

$$\eta,\eta' \to B'\gamma \to \pi^0\gamma\gamma,\ (0.14 < m_{B'} < 0.62 \text{ GeV});$$
$$\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma,\ (0.62 < m_{B'} < 1 \text{ GeV}).$$

   A dark photon or leptophilic vector bosons [13–16] can be searched for using

$$\eta,\eta' \to A'\gamma \to e^+e^-\gamma.$$

   Scalar: a hadrophilic [17, 18] scalar will be searched for using

$$\eta \to \pi^0 S \to \pi^0\gamma\gamma,\ \pi^0 e^+e^-,\ (10 \text{ MeV} < m_S < 2m_\pi);$$
$$\eta,\eta' \to \pi^0 S \to 3\pi,\ \eta' \to \eta S \to \eta\pi\pi,\ (m_S > 2m_\pi).$$

   Axion-Like Particle: light pseudoscalars [19–22] can be searched for via

$$\eta,\eta' \to \pi\pi a \to \pi\pi\gamma\gamma,\ \pi\pi e^+e^-.$$

   In parallel to $\eta^{(\prime)}$ decays, these gauge bosons will also be explored in the direct photo-production, $\gamma+p \to X+p$, where X represents a vector, scalar and Axion-Like scalar.

2. A search for C-violating $\eta^{(\prime)}$ decays (such as $\eta^{(\prime)} \to 3\gamma$ and $\eta^{(\prime)} \to 2\pi^0\gamma$) and a mirror asymmetry in the Dalitz distribution of $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$ will provide the best direct constraints on new C-violating, P-conserving reactions (CVPC).

3. Precision tests of low-energy QCD. A low-background measurement of the rare decay $\eta \to \pi^0\gamma\gamma$ provides a clean, rare window into $\mathcal{O}(p^6)$ in chiral perturbation theory [23]. This is the only known meson decay that proceeds via a polarizability-type mechanism. The Dalitz distribution measured by JEF will offer sufficient precision for the first time to explore the role of scalar meson dynamics and its interplay with the vector meson dominance. The measurements of the transition form factor of η and η' via the $\eta^{(\prime)} \to e^+e^-\gamma$ decays will reveal the dynamic properties of those mesons, providing important input to calculate hadronic light-by-light corrections to the anomalous magnetic moment of muon [24].

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4. The $\eta \to 3\pi$ decay promises an accurate determination of the quark mass ratio, $\mathcal{Q} = (m_s^2 - \hat{m}^2)/(m_d^2 - m_u^2)$ with $\hat{m} = (m_u + m_d)/2$. A recent dispersive analysis result yields $\mathcal{Q} = 22.1 \pm 0.7$ [25]. The statistical uncertainty due to fitting the Dalitz distribution of $\eta \to \pi^+\pi^-\pi^0$ (4.7M events) from KLOE-II [26] contributes ± 0.44 to the total error budget for the extracted $\mathcal{Q}$ [25], accounting for one of the biggest uncertainties. The A2-MAMI result for the neutral decay $\eta \to 3\pi^0$ with 7M events [27] was also considered in [25], however, it imposes less constraint on $\mathcal{Q}$ because of identical final state pions. JEF will be able to reduce this uncertainty by a factor of two with data accumulated for the Dalitz distribution of $\eta \to 3\pi$ (both charged and neutral decays). More importantly, highly-boosted η production in JEF will offer improved systematics over the KLOE-II and A2-MAMI results that have much lower energies for η's. In combination with a new Primakoff measurement of $\Gamma(\eta \to \gamma\gamma)$ from the on-going PrimEx-eta experiment (E-10-011) [28] to normalize the $\eta \to 3\pi$ decay width, this will allow an independent cross-check on the systematic uncertainty of the extracted quark mass ratio $\mathcal{Q}$ for the first time.

There is a strong consensus among the physics community about the vital importance of broadening the scope of new physics searches [29–31], both in parameter space and in experimental approaches. Recently, sub-GeV mediators have gained strong motivation, driven partly by several observed anomalies. The reported excesses in high-energy cosmic rays could be explained by dark matter annihilation [34, 35]. The muonic anomaly [13, 18, 36] and an anomalous e^+e^- resonance observed in ^{8}Be decay [37, 38] can be resolved with new gauge bosons. In addition, scalar- or vector-mediated dark forces can solve small scale structure anomalies in dwarf galaxies and subhalos, while satisfying constraints on larger galaxy and cluster scales [39–41]. If these phenomena are interpreted in terms of new physics, all point toward mediator particles in the MeV–GeV mass range.

In the parameter landscape of the global efforts on the BSM searches, the Large Hadron Collider (LHC) can realistically pick up new physics for the coupling constant scale of Standard Model $\alpha_X \sim \alpha_{SM}$ and the mass scale of $m_X \sim 1$ TeV, and the Lepton Flavor Violation (LFV) and sub-atomic Electric Dipole Moment (EDM) searches can explore the region for $\alpha_X \leq 10^{-6}$ and a broad range of m_X up to 1000 TeV. Complementing to those efforts, the JEF program will focus on the sub-GeV mediators for interactions that can be even stronger than "weak". Even though LFV and EDM searches may extend to the small mass range and overlap some of the territory within JEF's interest, LFV requires flavor-changing processes and EDM is sensitive to CP-violating physics. Therefore, η/η' decays used in the JEF experiment offer a niche for new physics that are flavor-conserving, light quark-coupling, and CP-conserving. Figure 1 gives an example for the sensitivity of the JEF experiment. With 100 days of beam time, a study of $\eta \to \gamma + B'(\to \gamma + \pi^0)$ will improve the existing model-independent bounds by two orders of magnitude, with sensitivity to the baryonic fine structure constant α_B as small as 10^{-7}, indirectly constraining the existence of anomaly cancelling fermions at the TeV-scale.

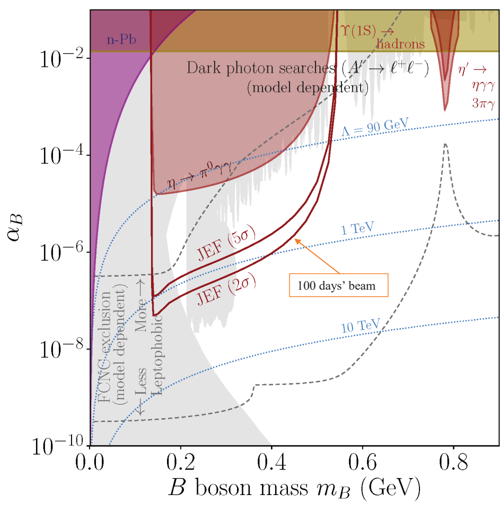

FIG. 1: Current exclusion regions for a leptophobic gauge boson B' [1, 12], with the projected $2\sigma/5\sigma$ sensitivity reach for the JEF experiment via $\eta \to \gamma + B'(\to \gamma + \pi^0)$. Color-shaded regions and curves are model-independent. These include constraints from rare η, η' decays (red), hadronic $\Upsilon(1S)$ decays [46] (yellow), and low-energy n-Pb scattering [47] (purple). The gray shaded regions and dashed contours are model-dependent and involve leptonic couplings via kinetic mixing $\varepsilon_x = x\frac{eg_B}{(4\pi)^2}$: these regions are excluded by dark photon searches for dilepton resonances [48–59], $A' \to \ell^+\ell^-$, for $\varepsilon_{0.1}$; and dashed contours are upper limits on α_B from FCNC $b \to s\ell^+\ell^-$ and $s \to d\ell^+\ell$ [60, 61], for $\varepsilon_{0.001}$ (upper line) and ε_1 (lower line). The blue dashed contours denote the upper bound on the mass scale Λ for new electroweak fermions needed for anomaly cancellation.

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