0.1 Update on JEF experiment

The $\eta^{(\prime)}$ meson, with the quantum numbers of the vacuum, 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). The JEF experiment [1, 2] was approved by JLab Program Advisory Committee (PAC) in 2017 to perform precision measurements of various $\eta^{(\prime)}$ decays with emphasis on rare neutral modes, running in parallel with the GlueX experiment using an upgraded Forward Calorimeter(FCAL-II). Significantly boosted $\eta^{(\prime)}$ will be produced through $\gamma + p \to \eta^{(\prime)} + p$ with an 8-12 GeV tagged photon beam. The $\eta^{(\prime)}$ decay photons (or leptons) will be measured in an upgraded forward calorimeter with high-granularity, high-resolution $PbWO_4$ core in the central region that minimizes shower overlaps and optimizes invariant mass reconstruction. Non-coplanar backgrounds will be suppressed by tagging $\eta^{(\prime)}$ with recoil proton detection. Compared to the previous or planned η/η' experiments, such as A2-MAMI [3, 4], WASA-at-COSY [5], KLOE-II [7], BESIII [6] and the proposed future REDTOP [8], 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 the upgraded calorimeter offers two orders of magnitude improvement in background suppression. JEF will simultaneously produce η and η' at the similar rate, $\sim 6 \times 10^7$ tagged η and $\sim 5 \times 10^7$ tagged η' (with detected recoil protons) per 100 days of beam time. These make JEF a unique η and η' factory in the world with no competition in rare neutral decay modes.

Though the JEF experiment will offer sensitive probes for a broad range of physics topics as described in [1, 2], its primary objectives will focus on the following:

1. Search for new sub-GeV gauge bosons.

   Vector:

   - A leptophobic vector boson (B') [9] coupled to baryon number.

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

   - A dark photon coupled to the Standard model photon via kinetic mixing [10, 11, 12, 13].

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

   Scalar: Search for hadrophilic [14, 15] scalar.

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

   Axion-Like Particle (ALP): Light pseudoscalars [16, 17, 18, 19] can be searched via

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

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 offer the best direct constraints on new C-violating, P-conserving reactions (CVPC). As pointed out by M. Ramsey-Musolf, the Electric Dipole Moment (EDM) searches may place no constraint on CVPC in the presence of a conspiracy or new symmetry; only the direct searches of CVPC are unambiguous [20].

3. Probing the low-energy QCD via precision measurements. A low-background measurement of the rare decay $\eta \to \pi^0 2\gamma$ provides a clean, rare window into $\mathcal{O}(p^6)$ in chiral perturbation theory [21]. This is the only known meson decay that proceeds via a polarizability-type mechanism. The precision in the Dalitz distribution will be sufficient for the first time to explore the role of scalar meson dynamics and its interplay with the vector meson dominance. This measurement will model-independently determine two Low Energy Constants (LEC) in the $\mathcal{O}(p^6)$ chiral Lagrangian and test the ability of models such as meson resonance saturation to calculate many other unknown $\mathcal{O}(p^6)$ LEC's. 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, offering important input to calculate hadronic light-by-light corrections to the muon $g-2$ [22].

4. $\eta \to 3\pi$ 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 $\mathcal{Q} = 22.1 \pm 0.7$ [23]. The statistical uncertainty due to fitting the Dalitz distribution of $\eta \to \pi^+\pi^-\pi^0$ (4.7M events) from KLOE-II [24] contributes ± 0.44 to the total error budget for the extracted $\mathcal{Q}$ [23], accounting for one of the biggest uncertainties. The A2-MAMI result for the neutral decay $\eta \to 3\pi^0$ with 7M events [25] was also considered in [23], 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 high statistical 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 than the KLOE-II and A2-MAMI results that have much lower energies of 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) [26] to normalize the $\eta \to 3\pi$ decay width, it will allow an independent cross-check on the systematic uncertainty of the extracted quark mass ratio $\mathcal{Q}$ for the first time.

Compared to the original JEF proposals [1, 2] submitted to the previous PACs, the scope of the JEF physics has been expanded mainly in two areas: (1) new physics searches have been broadened by not only searching for a leptophobic dark vector boson (B') [9] but also including dark photon [10, 11, 12, 13], hadrophilic scalar [14], and Axion-Like Particles (ALP) [27, 28, 29], probing two out of three dimension-4 portals to the dark sector; (2) production of η' simultaneously with η at the similar rate will extend the mass coverage of new mediator search to ~ 1 GeV.

About 85% of matter in the universe is Dark Matter (DM) whose constituents and interactions are unknown other than its gravitational properties. The stability of Dark Matter (DM) suggests that there may be a dark sector consisting of a rich symmetry structure with new forces and new particles. Dark sector may include one or more mediator particles coupled to the SM via a portal. The gauge and Lorentz symmetries of the Standard Model (SM) greatly restrict the ways in which the mediator can couple to the SM. There are three dimension-4 portals: the vector, scalar/pseudoscalar and fermion portals from the SM sector into the dark sector. Over the past decades, intensive efforts at the Large Hadron Collider (LHC) and underground laboratories have born no fruit for Weakly Interacting Massive Particles (WIMP), the simplest possible model for dark matter. There is a strong consensus among the physics community about the vital importance of broadening the scope of searches [30, 31, 32], both in the parameter space and in experimental approaches. The top-down models predict light mediators below GeV scale [33, 34]. These light states would have escaped detection thus far if they are very weakly coupled to the Standard Model. Recently, sub-GeV mediators have gained strong motivation, driven partly by several observed anomalies. Several reported excesses in high-energy cosmic rays could be explained by dark matter annihilation [35, 36]. The muon $g-2$ anomaly [15, 10, 37] and an anomalous e^+e^- resonance observed in ^{8}Be decay [38, 39] can be resolved by new gauge bosons. In addition, Scalar- or vector-mediated dark forces can also explain long-standing issues with galactic rotation curves and can solve small scale structure anomalies in dwarf galaxies and subhalos, while satisfying constraints on larger galaxy and cluster scales [40, 41, 42]. If these phenomena are interpreted in terms of new physics, all point toward mediator particles in the MeV–GeV mass range. Fig. 1 shows a map of the parameter landscape for the global efforts on the BSM searches. While LHC can realistically pick up new physics in the upper-right corner of the map for the coupling constant of $\alpha_X \sim \alpha_{SM}$ 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 bottom region for $\alpha_X \leq 10^{-6}$ and a broad range of m_X up to 1000 TeV. The JEF program will focus on the sub-GeV mediators for interactions that can be even "stronger than weak" as shown in Fig. 1. Even though LFV and EDM may stretch to the small mass range and overlap some of territory within JEF's interest, however, LFV requires flavor-changing and EDM is sensitive to CP-violating physics. Therefore, η/η' decays used in the JEF experiment offer a unique niche for new physics that are flavor-conserving, light quark-coupling, and CP-conserving. Fig. 2 gives an example for the sensitivity of the JEF experiment. With 100 day's beam time, a study of $\eta \to \gamma + B'(\to \gamma + \pi^0)$ will improve the existing 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.

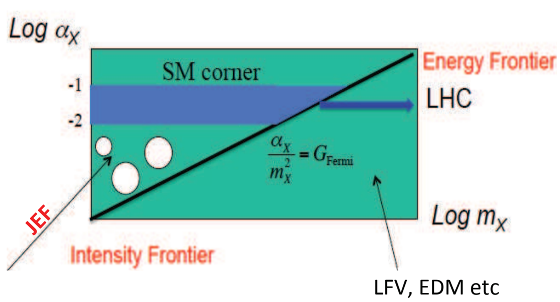

Figure 1: A sketch of the parameter landscape for BSM physics searches: the coupling constant α_X vs. the mass m_X [43].

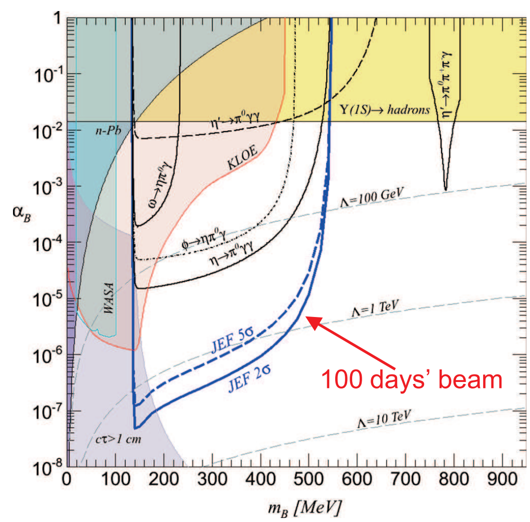

Figure 2: Current exclusion regions for a leptophobic gauge boson B' [9], with the proposed search region via $\eta \to \gamma + B'(\to \gamma + \pi^0)$ labelled "JEF" for the coupling vs mass plane. Dashed gray contours denote the upper bound on the mass scale Λ for new electroweak fermions needed for anomaly cancellation.

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