Search for a Leptophobic B-Boson via η Decay at Jlab

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A leptophobic B-boson couples predominantly to quarks and arises from a new $U(1)_B$ baryon number gauge symmetry. Its leading decay is $B \to \pi^0\gamma$ for the mass range of 140–620 MeV [1]. This offers a great experimental opportunity to search for such weakly-coupled gauge bosons in the sub-GeV mass range through the doubly-radiative decay $\eta \to B\gamma \to \pi^0\gamma\gamma$. The Jlab Eta Factory (JEF) experiment has been recently developed to search for B through this decay channel, with sensitivity to the baryonic fine structure constant as low as 10^{-7}. This sensitivity indirectly constrains the existence of anomaly cancelling fermions at the TeV-scale. The proposed search for B in the three-photon final state ($B \to \pi^0\gamma \to 3\gamma$) is complementary to a world-wide effort searching for a dark heavy photon A' at the high-intensity frontier.

1 Introduction

Dark Matter (DM) dominates the matter density in our universe, but very little is known about its nature. The existence and stability of DM provide a strong hint that there may be a dark sector consisting of rich symmetry structure with new forces and new particles that do not interact with the known strong, weak, and electromagnetic forces, except gravity. Discovery of any of these particles, new forces, and associated symmetries would redefine our worldview and have a profound impact. Additional $U(1)'$ gauge symmetries and associated vector gauge bosons are one of the best motivated extensions of the Standard Model (SM) [2]. A conserved charge can explain the stability of dark matter [3]-[7]. In addition, the conserved vector currents are uniquely positioned to avoid the violation of the Glashow-Iliopoulos-Maiani (GIM) mechanism for suppression of Flavor Changing Neutral Currents (FCNC) [8].

One model in the "Vector" portal from the SM sector into the dark sector that has been widely considered is a new force mediated by an abelian $U(1)'$ gauge boson A' (dark photon) that couples very weakly to electrically charged particles through "kinetic mixing" with the photon [9]. The mixing angle ϵ controls the coupling of the DM sector to the SM sector. Searching for a sub-GeV A' has drawn world-wide attention in recent years and has inspired broad experimental programs in different high-intensity frontier centers [10]. Most of experimental searches for the A' are through its decays to e^+e^- or $\mu^+\mu^-$, which rely on the leptonic coupling of this new force.

Another equally compelling model in the "Vector" portal not covered by the dark photon searches is a new force mediated by a leptophobic gauge B-boson that couples predominantly to quarks and arises from a new $U(1)_B$ baryon number gauge symmetry [1, 8]. The $U(1)_B$

symmetry was initially proposed by Lee and Yang back in 1955 [11] and subsequently discussed extensively in the literature [1, 7, 8, 12, 13]. Since quarks experience all known interactions, it is fitting to ask whether additional interactions of quarks exist [14]. A new $U(1)_B$ gauge symmetry provides a natural framework for the Peccei-Quinn mechanism in the quark sector for solving a long standing "strong CP problem" [12]. This model has also been motivated in part by the similar cosmological abundances of dark matter and baryonic matter in the Universe, which may point toward a unified baryogenesis mechanism for both types of matter [15]. Since $U(1)_B$ is spontaneously broken by a new Higgs field, the B-boson is massive. In addition, new baryonic fermions with electroweak quantum numbers are required to cancel the $SU(2)_L^2 \times U(1)_B$ and $U(1)_Y^2 \times U(1)_B$ anomalies. The new fermions acquire masses (Λ) via a $U(1)_B$-breaking Higgs field, with $m_B/\Lambda \geq g_B/(4\pi)$ [16], where m_B is the mass of B-boson and g_B is the $U(1)_B$ gauge coupling. As a result, a positive signal for sub-GeV B with a gauge coupling smaller than 10^{-3} will imply new fermions at the TeV-scale.

Experimental searches for leptophobic bosons at hadron colliders over the last few decades have set upper limits on their couplings for masses in the 50 GeV to 3 TeV range [14, 17, 18]. Masses smaller than the pion mass also have very strong constraints from searches for long-range nuclear forces [19]. However, masses around the QCD scale have been nearly "untouched" due to large SM backgrounds [14]. Nelson and Tetradis first proposed to search for a sub-GeV B-boson through the η decay in 1989 [8]. However, they assumed that $B \to \pi^+\pi^-$ would dominate for $m_B > 2m_\pi$. In that case, the signal of B would be mostly hidden under the ρ meson decay. Tulin demonstrated in his recent article [1] that $B \to \pi^+\pi^-$ is suppressed due to G parity conservation and the leading decay channel is $B \to \pi^0 + \gamma$ for $m_\pi \leq m_B \leq 620$ MeV. This offers a great experimental opportunity to search for B in this mass range through the doubly-radiative decay $\eta \to \pi^0\gamma\gamma$. The new physics decay $\eta \to B\gamma \to \pi^0\gamma\gamma$ would produce a resonance peak at m_B in the $\pi^0\gamma$ invariant mass distribution, while the SM-allowed $\eta \to \pi^0\gamma\gamma$ decay with a suppressed branching ratio of $\sim 2.7 \times 10^{-4}$ [17] would be present as the irreducible background in the signal window.

2 Jlab Eta Factory (JEF) Experiment

The Jlab Eta Factory (JEF) Experiment has been recently developed at Jefferson Lab (Jlab) using the newly developed GlueX apparatus in Hall D to measure η decays with emphasis on rare neutral modes [20]. One of the main physics goals for this experiment is to provide a stringent constraint on a leptophobic gauge boson (B) in the mass region 0.14–0.54 GeV through $\eta \to B\gamma \to \pi^0\gamma\gamma$. A 9.0–11.7 GeV tagged photon beam will be used to produce η mesons at small angles via the $\gamma + p \to \eta + p$ reaction. The majority of decay photons from the η's will be detected in an upgraded Forward Calorimeter (referred to as FCAL-II) in which the central lead glass blocks of the existing calorimeter will be replaced with smaller size, higher resolution $PbWO_4$ crystals. For not-too-small η production angles, the low energy recoil protons will be detected by the start counter and central drift chamber of the GlueX solenoid detector to help suppress backgrounds.

The measurement of rare η decay to 4γ final states has historically been limited by the background from $\eta \to 3\pi^0 \to 6\gamma$ (BR = 32.6%) with missing or merged photons. This problem is addressed in the JEF experiment by the fact that η's are significantly boosted so that the detector thresholds are low relative to the photon energies to reduce missing photons, the kinematics are over-determined (with recoil proton detection), and the decay photons are measured in an upgraded forward calorimeter (FCAL-II) with a central region of high-granularity, high-resolution lead tungstate crystals with flash ADC readout, to suppress merged photons. The Monte Carlo simulations demonstrate that the backgrounds can be reduced by about two orders of magnitude compared to the existing experiments and to experiments planned at other facilities, while maintaining a healthy η production rate.

3 Experimental Reach for B-Boson

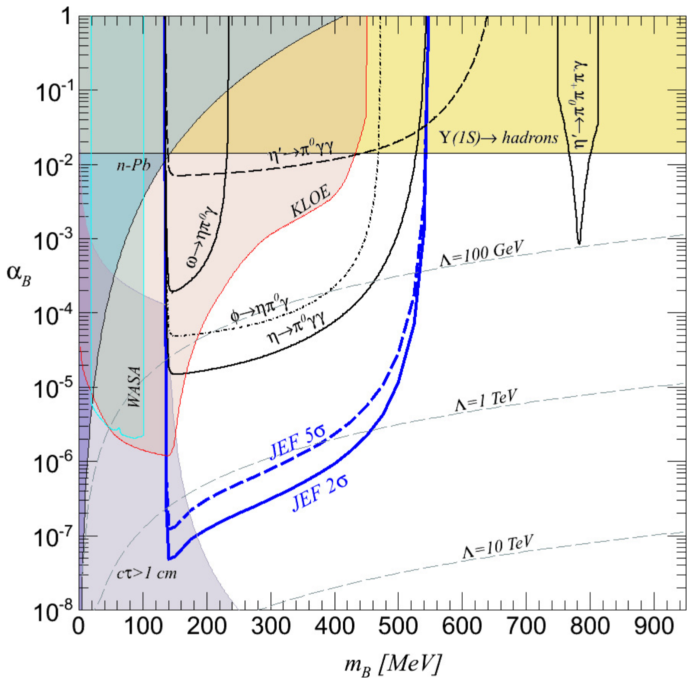

Figure 1: Current exclusion regions for a leptophobic gauge B-boson [1], with the projected JEF search region for the baryonic fine structure constant versus mass plane. Shaded regions are exclusion limits from hadronic $\Upsilon(1S)$ decay [18] and low energy n-Pb scattering [19]. The pink and blue shaded regions are from A' searches (KLOE [21] and WASA [22]). A' limits applied to B are model-dependent, constraining possible leptonic B couplings. Limits shown here are for $\epsilon = 0.1 \times e g_B/(4\pi)^2$. The black contours are current exclusion limits from radiative light meson decays based on their total rate (assuming the QCD contribution is zero). The light purple shaded region shows where the B has a macroscopic decay length $c\tau > 1$ cm. The solid blue curve shows the projected 2σ sensitivity and the dashed blue curve shows the projected 5σ sensitivity for the JEF experimental reach. Dashed gray contours denote the upper bound on the mass scale Λ for new electroweak fermions needed for anomaly cancellation.

The experimental limits on the baryonic fine structure constant $\alpha_B = g_B^2/(4\pi)$ and B-boson mass m_B are shown in Fig. 1 along with the projected JEF exclusion limits. As shown in the figure, the JEF experiment has the sensitivity to the baryonic fine structure constant α_B as low as 10^{-7}. The observation of a B-boson within the JEF limit would imply new fermions with masses around the TeV-scale or below. Although such new fermions may have escaped detection at colliders thus far, they are likely to be within the reach for discovery at the LHC or future high energy colliders.

4 Summary

A search for a GeV-scale leptophobic gauge boson (B) coupled to baryon number is complementary to ongoing searches for a dark photon. The JEF experiment at Jlab will search for B over the mass range of 0.14–0.54 GeV in the $\eta \to \gamma + B(\to \gamma + \pi^0)$ decay. This measurement will improve the existing bounds by two orders of magnitude, indirectly constraining the existence of anomaly cancelling fermions at the TeV-scale.

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