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We propose a search for photoproduction of leptophobic bosons that couple to quarks at the GlueX experiment at Jefferson Lab. We study in detail a new gauge boson that couples to baryon number B, and estimate that $\gamma p \to pB$ will provide the best sensitivity for B masses above 0.5 GeV. This search will also provide sensitivity to other proposed dark-sector states that couple to quarks. Finally, our results motivate a similar search for B boson electroproduction at the CLAS experiment.

I. INTRODUCTION

The possibility that dark matter may interact via as-yet-unknown forces has motivated a dedicated worldwide effort to search for dark forces (see Ref. [1] for a review). Most existing and planned searches for dark bosons rely on leptonic couplings; therefore, the constraints on dark forces that couple predominantly to quarks are significantly weaker than on those with substantial couplings to leptons [2]. A compelling – yet simple – dark-force scenario introduces a new $U(1)_B$ gauge symmetry that couples to baryon number [3–12]. Assuming the symmetry is broken gives rise to a massive vector boson referred to as the B boson. It is well known that $U(1)_B$ is anomalous, and that additional fermions with electroweak quantum numbers are required to cancel the anomalies [5]. Such massive fermions could be stable providing viable dark-matter candidates.

Beyond this specific model, searches for B bosons are sensitive to so-called dark ρ mesons and other proposed dark-sector states that mix with QCD vector mesons (see, *e.g.*, Ref. [13]). Since QCD vector mesons are photo-produced copiously and exclusively, such reactions may provide an ideal laboratory in which to search for leptophobic bosons that couple to quarks.

Searches for long-range nuclear forces and dark-photon decays to e^+e^- place strong constraints on B bosons with $m_B \lesssim m_\pi$ [2]. As we will show below, calculations for $m_B \gtrsim 0.9$ GeV are highly uncertain at the moment; therefore, we will focus here on the region $m_\pi \lesssim m_B \lesssim 0.9$ GeV. Within this region, Refs. [2, 14] showed that searches for $\eta \to B\gamma$ are the most sensitive for $m_B \lesssim 0.5$ GeV, while currently $\Upsilon \to$ hadrons provides the best limit at larger m_B.

In this article, we perform the first study of exclusive B boson photoproduction, *i.e.* $\sigma(\gamma p \to pB)$. We will show that the photoproduction data set to be collected by the GlueX experiment at Jefferson Lab – starting this year – will provide the most sensitive probe of B bosons with $m_B \gtrsim 0.5$ GeV. The electroproduction data collected by the CLAS experiment at Jefferson Lab is also expected to be highly sensitive to B bosons. Finally, while we

focus on the B boson, we stress that this search will provide sensitivity to other proposed dark-sector states that couple to quarks.

II. BARYONIC FORCE MODEL

Following Ref. [2], we consider the B boson interaction Lagrangian

$$\mathcal{L}_{\text{int}} = \left(\frac{g_B}{3} + \varepsilon e_q\right)\bar{q}\gamma^\mu q B_\mu - \varepsilon e \bar{\ell}\gamma^\mu \ell B_\mu, \qquad (1)$$

where B_μ is the new gauge field with universal gauge coupling to quarks g_B, q are quark fields, ℓ are charged-lepton fields, e is the electromagnetic coupling, and ε is the so-called kinetic mixing parameter between the B and the photon. Assuming that a non-zero value of ε arises at the one-loop level gives

$$\varepsilon = \mathcal{O}\left(\frac{eg_B}{(4\pi)^2}\right) \approx g_B \times 10^{-3}. \qquad (2)$$

The impact of the precise value of ε on B boson phenomenology in the mass region considered here is negligible, with the exception of the constraints derived from dark-photon searches.

We make the following important observations about the baryonic dark force based on $\mathcal{L}_{\text{int}}$:

- it preserves the low-energy symmetries of QCD;

- it preserves $SU(3)$ flavor symmetry due to its universal quark coupling;

- the B boson has quantum numbers $I^G(J^{PC}) = 0^-(1^{--})$.

Since the B boson has the same quantum numbers as the ω meson, in the m_B region considered in this paper one expects the dominant B decay modes to be $B \to \pi^+\pi^-\pi^0$ and $B \to \pi^0\gamma$. Indeed, as shown in Ref. [2], $B \to \pi^0\gamma$ is dominant for $m_\pi \lesssim m_B \lesssim 0.6$ GeV, while $B \to \pi^+\pi^-\pi^0$ is dominant for 0.6 GeV $\lesssim m_B \lesssim 0.9$ GeV. The only other decay mode with a branching fraction $\gtrsim 1\%$ in these m_B regions is $B \to \pi^+\pi^-$ which is $\lesssim 5\%$ for all m_B considered in this study. We note that for $m_B \gtrsim m_\phi$ the decay $B \to K^+K^-$ is expected to be important as well, since the B boson also has the same quantum numbers as the ϕ meson.

III. PHOTOPRODUCTION

We calculate exclusive photoproduction of B bosons within the hidden local symmetries (HLS) framework of vector meson dominance (VMD) [15–18]. This framework is highly successful at predicting low-energy SM observables, which motivates its use here. Within HLS-VMD, external gauge fields mix with the QCD vector mesons ($V = \rho, \omega, \phi, \dots$). For example, the decay $\omega \to \pi^0 \gamma$ is dominated by $\omega \to \pi^0 \rho$ followed by $\rho \to \gamma$ mixing in the HLS-VMD framework.

To calculate the photoproduction cross section of B bosons, we first consider the V meson photoproduction amplitude

$$\mathcal{A}(\gamma p \to pV)^\mu V_\mu^*, \tag{3}$$

where for simplicity we suppress the photon and proton spin states, and leave the kinematic dependence implicit. Next, we introduce $V \to B$ mixing assuming a narrow B boson, which is done in a similar way as $V \to \gamma$ mixing but making the substitution [2]

$$e \operatorname{Tr}[T_V Q] \to \frac{g_B}{3} \operatorname{Tr}[T_V], \tag{4}$$

where T_V are the $U(3)$ generators for V (discussed below) and

$$Q = \frac{1}{3} \begin{bmatrix} 2 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{5}$$

gives the coupling of the γ to quarks. Since the B has universal quark couplings, Q is replaced by the identity matrix for the B boson. The amplitude for $\gamma p \to p(V \to B)$ is then

$$\mathcal{A}(\gamma p \to pV)^\mu B_\mu^* \left[\frac{2g_B m_V^2 \operatorname{Tr}[T_V]}{3\sqrt{12\pi} D_V(m_B)} \right], \tag{6}$$

where B_μ is the physical B boson polarization vector with $p_B \cdot B = 0$, the VMD gauge coupling is extracted from $\Gamma(\rho \to \pi\pi)$ to be $\approx \sqrt{12\pi}$ [18],

$$D_V(m_B) = m_V^2 - m_B^2 - im_B \Gamma_V(m_B), \tag{7}$$

and $\Gamma_V(m)$ is the mass-dependent width of V taken from Ref. [19]. We note that $\mathcal{A}(\gamma p \to pV)$ should be evaluated for pB kinematics, which are different from pV since $m_B \neq m_V$; however, $|\vec{p}_B|_{\text{c.m.}}$, t, and u have little dependence on m_B in the mass range considered here for the GLUEX photon-beam energy (and s is approximately constant). Therefore, the m_B dependence of the

amplitude is expected to be small. Once the data are collected, the mass dependence of the strength of the $0^-(1^{--})$ partial wave can be used to confirm this, or to derive a correction factor if one is required.

We do not consider $B \to \rho$ mixing as this violates isospin conservation. The relevant $U(3)$ generators for the ω and ϕ mesons are

$$T_\omega = \frac{1}{2} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \qquad T_\phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{8}$$

assuming $\omega = (u\bar{u} + d\bar{d})/\sqrt{2}$ and $\phi = s\bar{s}$. We neglect both isospin and $SU(3)$ breaking effects since both are known to be small for the ρ, ω, and ϕ mesons. The B boson photoproduction amplitude is then

$$\mathcal{A}(\gamma p \to pB) \approx \left[\frac{2g_B}{3\sqrt{12\pi}} \right]$$
$$\times \left(\frac{m_\omega^2 \mathcal{A}(\gamma p \to p\omega)^\mu}{D_\omega(m_B)} + \frac{m_\phi^2 \mathcal{A}(\gamma p \to p\phi)^\mu}{\sqrt{2} D_\phi(m_B)} \right) B_\mu^*. \tag{9}$$

Therefore, if $\mathcal{A}(\gamma p \to pV)$ can be determined from the data for $V = (\omega, \phi)$, the B boson production rate can be inferred for a given g_B.

Our study targets the GLUEX experiment at Jefferson Lab which will employ a linearly polarized photon beam with $E_\gamma \approx 8 - 9$ GeV corresponding to

$$s = m_p^2 + 2m_p E_\gamma \approx (4 \text{ GeV})^2. \tag{10}$$

The most relevant Feynman diagrams for V photoproduction at this energy are shown in Fig. 1. Photoproduction processes that induce a spin flip of the target proton add incoherently with those that do not. For example, t-channel pion exchange amplitudes do not interfere with those for diffractive production. These processes are often referred to as *unnatural* and *natural* parity exchange, respectively, and we will adopt the notation of $-$ and $+$ to correspond with the parity of the pion and pomeron. We stress, however, that our results are not model dependent, since no assumption is made about the structure of the spin (non)flip amplitudes.

The total B boson photoproduction cross section is obtained from the sum of the natural and unnatural components

$$\sigma(\gamma p \to pB) = \sigma_+(\gamma p \to pB) + \sigma_-(\gamma p \to pB), \tag{11}$$

where the B boson cross sections are related to those of the ω and ϕ by

$$\sigma_\pm(\gamma p \to pB) \approx \frac{4\alpha_B}{27} \Phi(m_B) \left[\frac{m_\omega^4 \sigma_\pm(\gamma p \to p\omega)}{\Phi(m_\omega)|D_\omega(m_B)|^2} + \frac{m_\phi^4 \sigma_\pm(\gamma p \to p\phi)}{2\Phi(m_\phi)|D_\phi(m_B)|^2} + \frac{\sqrt{2}\cos(\varphi_\pm) m_\omega^2 m_\phi^2 \sqrt{\sigma_\pm(\gamma p \to p\omega)\sigma_\pm(\gamma p \to p\phi)}}{|D_\omega(m_B)||D_\phi(m_B)|\sqrt{\Phi(m_\omega)\Phi(m_\phi)}} \right].$$
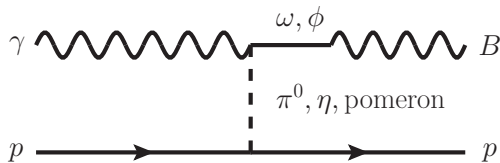
FIG. 1. Feynman diagrams for photoproduction of B bosons. At GLUEX energies, pion and pomeron exchange are expected to be dominant for ω photoproduction, while ϕ photoproduction is expected to be dominantly diffractive. These diagrams are shown for illustrative purposes only; no model of ω or ϕ photoproduction is assumed in this work.

Here $\alpha_B \equiv g_B^2/4\pi$, $\varphi_\pm$ is the phase difference between the ω and ϕ amplitudes (with implicit s, t, m_B dependence), and

$$\frac{\Phi(m_B)}{\Phi(m_V)} = \frac{\sqrt{(s-(m_p+m_B)^2)(s-(m_p-m_B)^2)}}{\sqrt{(s-(m_p+m_V)^2)(s-(m_p-m_V)^2)}} \quad (12)$$

are the usual phase-space factors. In the m_B range studied here and at GLUEX energies

$$\frac{\Phi(m_B)}{\Phi(m_V)} \approx 1. \quad (13)$$

The values of $\sigma(\gamma p \to pV)$ can be measured in the same data set in which the B boson is to be searched for. Furthermore, since GLUEX will employ a linearly polarized photon beam, $\sigma_\pm(\gamma p \to pV)$ can be obtained by measuring both $\sigma(\gamma p \to pV)$ and the V spin density matrix elements. We expect that such measurements will be made even in the absence of a B boson search, so the only missing input to infer the B boson signal in a data-driven manner is $\varphi_\pm$.

Existing ω and ϕ photoproduction measurements suggest the following for $s \approx (4\,\text{GeV})^2$ [20]:

$$\frac{\sigma_+(\gamma p \to p\omega)}{\sigma_+(\gamma p \to p\phi)} \approx 4,$$

$$\frac{\sigma_-(\gamma p \to p\omega)}{\sigma_+(\gamma p \to p\omega)} \approx 0.1, \quad (14)$$

$$\frac{\sigma_-(\gamma p \to p\phi)}{\sigma_+(\gamma p \to p\phi)} \approx 0.$$

Assuming the high-precision measurements that will be made at GLUEX confirm this hierarchy, the unnatural component is simply

$$\frac{\sigma_-(\gamma p \to pB)}{\sigma_-(\gamma p \to p\omega)} \approx \frac{4\alpha_B m_\omega^4}{27|D_\omega(m_B)|^2}, \quad (15)$$

while the natural term is

$$\frac{\sigma_+(\gamma p \to pB)}{\sigma_+(\gamma p \to p\omega)} \approx \frac{4\alpha_B}{27}\Big[\left|\frac{m_\omega^2}{D_\omega(m_B)}\right|^2 + \frac{1}{8}\left|\frac{m_\phi^2}{D_\phi(m_B)}\right|^2$$
$$+ \frac{\cos(\varphi_+)m_\omega^2 m_\phi^2}{\sqrt{2}|D_\omega(m_B)||D_\phi(m_B)|}\Big]. \quad (16)$$
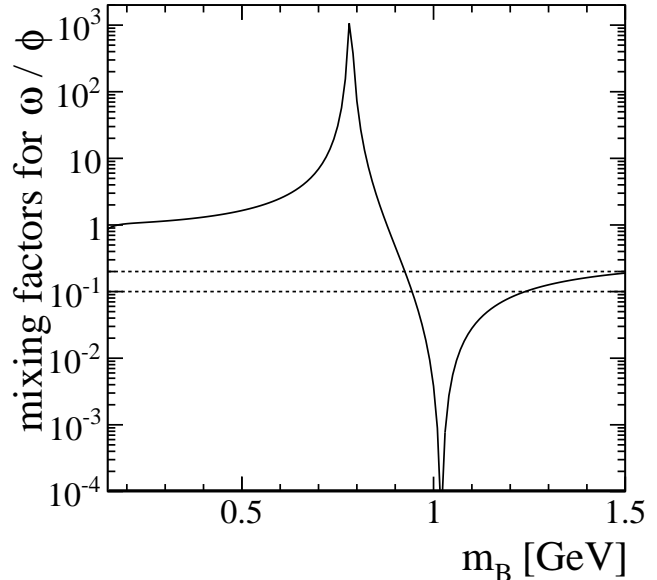
FIG. 2. When $\mathcal{R}_\phi^\omega \equiv |\frac{m_\omega^2}{D_\omega(m_B)}|^2/|\frac{m_\phi^2}{D_\phi(m_B)}|^2$ has a value that falls approximately between the horizontal dashed lines the natural ω and ϕ contributions to B boson photoproduction will cancel due to destructive interference if $\varphi_+ \approx \pi$.

Figure 2 shows the m_B dependence of the ratio of ω to ϕ mixing factors

$$\mathcal{R}_\phi^\omega \equiv \frac{\left|\frac{m_\omega^2}{D_\omega(m_B)}\right|^2}{\left|\frac{m_\phi^2}{D_\phi(m_B)}\right|^2}. \quad (17)$$

As expected, for $m_B \approx m_\omega$ we can ignore mixing with the ϕ, whereas for $m_B \lesssim 0.5$ GeV we find

$$\frac{\sigma_+(\gamma p \to pB)}{\sigma_+(\gamma p \to p\omega)} \approx \frac{\alpha_B}{6\left(1-\frac{m_B^2}{m_\omega^2}\right)^2}\left[1+0.5\cos(\varphi_+)\right]. \quad (18)$$

Therefore, without any constraints on φ_+ the uncertainty in the inferred B boson natural cross section is less than a factor of two for $m_B \lesssim 0.5$ GeV.

For $m_B \gtrsim 0.9$ GeV – and away from m_ϕ – the natural ω and ϕ contributions to B boson photoproduction could cancel due to destructive interference, $i.e.$ $\sigma_+(\gamma p \to pB) \approx 0$ if $\varphi_+ \approx \pi$. High-precision measurements of ω and ϕ photoproduction at GLUEX will determine:

- If $\sigma_-(\gamma p \to p\omega) \gg \sigma_-(\gamma p \to p\phi)$ as has been observed at lower E_γ, then φ_- does not need to be known and a conservative sensitivity can be determined by assuming maximal destructive interference at each m_B; $i.e.$, one can assume that $\sigma_+(\gamma p \to pB) = 0$ and that only $\sigma_-(\gamma p \to pB)$ contributes.

- If φ_+ can be determined in a data-driven manner, then inferring the sensitivity within HLS-VMD is straightforward. In Sec. V, we discuss the possibility of determining φ_+.

- Alternatively, if the kinematic dependence of the spin density matrix elements can be described well by a diffractive model of $\gamma p \to pV$ for both the ω and ϕ, then φ_+ could be calculated within the model.

Therefore, the situation will become much more clear once the data is collected. For this study, we choose to truncate our sensitivity predictions at $m_B = 0.9\,\mathrm{GeV}$, but stress that it is possible the sensitivity at higher masses can be inferred using HLS-VMD.

IV. SENSITIVITY

We estimate the sensitivity for the GLUEX experiment for its so-called Phase IV run period, which is expected to begin in 2017 and last for about two years [21]. We take the total number of photons with $8 \lesssim E_\gamma \lesssim 9\,\mathrm{GeV}$ on target to be

$$N_\gamma \approx 7 \times 10^{14}, \tag{19}$$

which takes the total Phase IV run time and assumes an 80% live time. GLUEX employs a 30-cm-thick liquid hydrogen target so

$$N_p/\mathrm{cm}^2 = 1.28 \times 10^{24}. \tag{20}$$

Finally, using previous measurements of ω photoproduction we estimate [20]

$$\sigma(\gamma p \to p\omega) \approx 2\mu\mathrm{b}, \tag{21}$$

which gives

$$N(\gamma p \to p\omega) \approx 2 \times 10^9, \tag{22}$$

excluding reconstruction and selection efficiencies.

Our nominal search involves the decays $B \to \pi^0\gamma$, $B \to \pi^+\pi^-\pi^0$, and $B \to \pi^+\pi^-$. We estimate the efficiency ϵ to reconstruct and select the reaction $\gamma p \to pB$ for these B decay modes using the official GLUEX GEANT-based simulation package. For concreteness, we assume the ω photoproduction model of Ref. [22] as it describes existing data at lower energies well [23]; however, due to the hermetic nature of the GLUEX detector the dependence of the acceptance on the ω photoproduction model chosen is small. We stress that in the actual B boson search, no model-dependent assumptions need to be made provided that both the search and normalization measurements are performed in the same fiducial region. For each mode, the efficiency is found to be $\epsilon \approx 20 - 30\%$ except
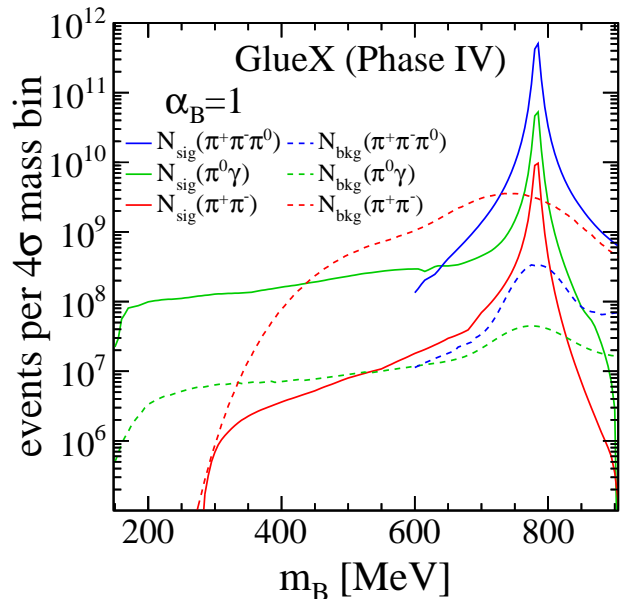

FIG. 3. Expected reconstructed and selected B boson yields versus m_B for $\alpha_B = 1$. Signal yields scale linearly with α_B. The expected background yields are also shown. *N.b.*, we do not consider the $\pi^+\pi^-\pi^0$ final state below 0.6 GeV to avoid the η mass peak.

near threshold. The expected B boson yield in the final state X is taken to be

$$N(\gamma p \to pB \to pX) \approx$$
$$\frac{4\alpha_B m_\omega^4}{27|D_\omega(m_B)|^2} N(\gamma p \to p\omega)\epsilon(pX)\mathcal{B}(B \to X). \tag{23}$$

Figure 3 shows the expected reconstructed and selected B boson yield for $\alpha_B = 1$ in each decay mode considered in our study.

The official GLUEX simulation package is also used to determine the expected m_B resolution:

$$\frac{\sigma(m_{\pi\gamma})}{m_{\pi\gamma}} \approx 2 - 3\%,$$
$$\frac{\sigma(m_{3\pi})}{m_{3\pi}} \approx 1 - 2\%, \tag{24}$$
$$\frac{\sigma(m_{2\pi})}{m_{2\pi}} \approx 3 - 4\%, \tag{25}$$

where we perform a kinematic fit that utilizes the well-known initial state 4-momentum to improve the resolution on the final-state kinematics.

Estimating the background yields is difficult since many photoproduction processes can result in either a $p\pi^0\gamma$, $p\pi^+\pi^-\pi^0$, or $p\pi^+\pi^-$ final state. For the 3π and 2π modes, we take the background spectra from a previous $\gamma p \to pV$ study at $E_\gamma = 9.3\,\mathrm{GeV}$ [20], and assume that any reducible mis-reconstructed contributions in those spectra are the same at GLUEX. For the $\gamma p \to p\pi^+\pi^-$ reaction, the background is dominantly from $\gamma p \to p\rho$. We

are not aware of any existing measurements of $\gamma p \to p\pi^0\gamma$ using high-energy photons. To estimate the $m(\pi\gamma)$ spectrum, we first note that the $m(3\pi)$ spectrum published by GLUEX using lower-energy $E_\gamma \approx 3$ GeV photons [24] is similar in shape and in size relative to the ω yield as that of Ref. [20]. Therefore, we take the shape and size relative to the ω peak of the $m(\pi\gamma)$ spectrum from Ref. [24], and simply rescale this to the expected ω yield for $E_\gamma = 8 - 9$ GeV.

While we have checked that PYTHIA [25] also suggests the background shapes at $E_\gamma = 3$ and 9.3 GeV are similar, and that the background yields relative to that of the ω are approximately constant with E_γ, one should view our backgrounds as approximate. In the actual B boson search, the background yields for each m_B can be estimated using the data sidebands. Therefore, while the uncertainty in predicting the background yields here results in an uncertainty on the potential sensitivity to B of a factor of ≈ 3, the impact on the actual sensitivity will be governed by the precision with which one can interpolate the background yield using the data sidebands which is expected to be a small effect.

To estimate the sensitivity at GLUEX to B boson photoproduction, we use as a rough criterion for the exclusion limits

$$\frac{N(\gamma p \to pB \to pX; m_B, \alpha_B)}{\sqrt{N(\gamma p \to pX; m_B)}} \approx 2, \qquad (26)$$

where the yields are in the region $m_B - 2\sigma(m) < m < m_B + 2\sigma(m)$. Figure 4 shows that using B boson photoproduction one can probe α_B values down to $\mathcal{O}(10^{-5})$, making this the most sensitive probe for $m_B \gtrsim 0.5$ GeV. Finally, we note that while we considered the full Phase IV data set, it is clear that GLUEX will be able to probe unexplored B boson parameter space with a much smaller data set, e.g., the data to be collected later this year.

The sensitivity of dark-photon searches to B bosons is model dependent in part because $\mathcal{B}(A' \to \ell^+\ell^-)$, where $\ell \equiv e$ or μ, depends on the kinetic-mixing parameter ε. Figure 4 shows the exclusion region obtained from a KLOE [27] dark-photon search for the decay $\phi \to \eta A'(e^+e^-)$, where here we assume $\varepsilon = eg_B/(4\pi)^2$. This decay has good sensitivity to B bosons due to the large predicted value of $\mathcal{B}(\phi \to \eta B)$[2]. Searches for $e^+e^- \to \gamma A'(\ell^+\ell^-)$ do not provide relevant constraints on α_B since both the production and decay of the B boson rely on its small leptonic coupling.

V. POTENTIAL IMPROVEMENTS

There are a number of potential improvements to this search. The non-V background may have a different angular distribution than a vector boson produced by a polarized photon beam and this could be exploited to improve the sensitivity. The proposed upgrade of the GLUEX forward calorimeter as part of the so-called
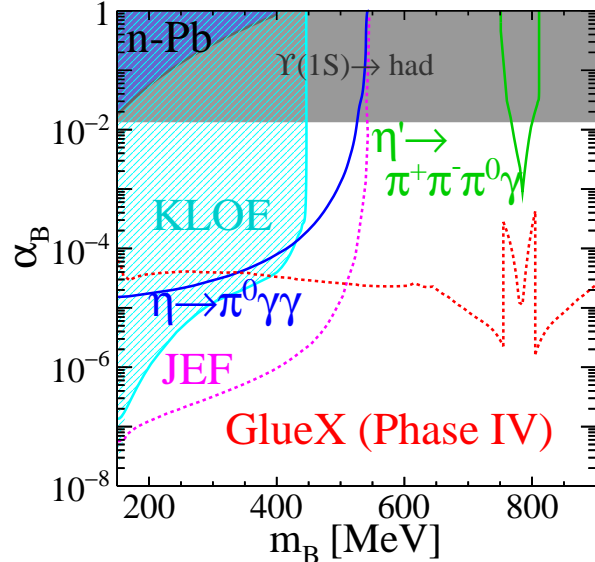

FIG. 4. Existing limits on B bosons [2] compared to the expected sensitivity obtained from η meson decays at JEF [14] and photoproduction (this work). Only the $B \to \pi^+\pi^-$ decay is used near m_ω in our study, since the large ω peak in $\pi^0\gamma$ and $\pi^+\pi^-\pi^0$ will complicate searching for a B boson with similar mass. The existing limits are derived from low-energy n-Pb scattering [26], the total rate of Υ decays into hadrons [10], and decays of η and η' mesons. The KLOE [27] sensitivity depends on the kinetic mixing parameter with the photon and is displayed here assuming $\varepsilon = eg_B/(4\pi)^2$.

JEF program would improve the invariant-mass resolution [14]. GLUEX may collect more integrated luminosity than we assumed here as it has been approved for additional running that will include an upgraded particle-identification system [28].

In principle, the $\omega - \phi$ phase differences $\varphi_\pm$ could be determined by studying the $J^P = 1^{--}$ partial wave strength versus $m(3\pi)$ in the $p\pi^+\pi^-\pi^0$ final state, or possibly versus $m(ee)$ in $\gamma p \to pe^+e^-$. This would greatly reduce the uncertainty in the normalization due to interference between the ω and ϕ amplitudes. Indeed, a dip consistent with $\omega - \phi$ interference is seen in $e^+e^- \to \pi^+\pi^-\pi^0$ which determines the phase difference to be near the expected value based on $SU(3)$ including a small $\omega - \phi$ mixing correction [19]. That said, if the natural and unnatural ω and ϕ cross sections are as predicted in Ref. [22, 29], then the normalization uncertainty for $m_B \lesssim 0.9$ GeV due to this unknown phase is at most $\approx 30\%$. At this level, one should view the use of the HLS-VMD framework itself with some degree of skepticism. For the purpose of setting exclusions, the use of HLS-VMD and ignoring the ϕ interference should be sufficient. As discussed previously, at higher masses φ_+ must be measured to determine the sensitivity using HLS-VMD, and the decay $B \to K^+K^-$ should be included in the search. Finally, in the case of a discovery,

we note that lattice QCD should be able to provide more precise results than HLS-VMD.

One could consider searching for displaced B boson decays which would have considerably less background contamination. The resolution on the B flight distance, *i.e.* the experimental resolution on the distance between the production and decay positions of the B boson, in the 2π and 3π decay modes is expected to be $\approx 1\,\text{cm}$. We do not expect GLUEX to collect sufficient luminosity to do a displaced search for B bosons in hadronic decay modes; however, we encourage pursuing a displaced search as it may be sensitive to unexplored parameter space of more general dark-sector models.

VI. ELECTROPRODUCTION

Our results also motivate looking for electroproduction of B bosons at the CLAS experiment at Jefferson Lab. Vector meson electroproduction dominantly proceeds via an off-shell photon γ^*. The γ^* kinematics vary event-by-event, making it possible for CLAS to include only regions of phase space where

$$\sigma(ep \to ep\omega) \gg \sigma(ep \to ep\phi), \qquad (27)$$

which includes most of the potential signal [30, 31]. This enables considering only $B \to \omega$ mixing, where the expected B boson electroproduction yield is given by Eq. 23 with photoproduction reactions replaced by the corresponding electroproduction ones.

VII. OTHER DARK-SECTOR THEORIES

More general models are also possible; *e.g.*, Eq. 1 could be modified to have non-universal quark couplings. In this case, the new boson B' need not be an isoscalar

and mixing with the ρ would also be possible. Without fully specifying the quark couplings $g_{B'}^q$ of the model, we cannot repeat the exercise of mapping B' yields directly to $g_{B'}^q$. Therefore, we suggest that GLUEX measure – or set upper limits on – each of the ratios

$$\frac{\sigma(\gamma p \to pB') \times \mathcal{B}(B' \to X)}{\sigma(\gamma p \to pV)}, \qquad (28)$$

where $X = (\pi^0\gamma, 2\pi, 3\pi, K^+K^-, K^*K, \ldots)$ and $V = (\rho, \omega, \phi)$, while scanning in $m_{B'}$ and B' lifetime. There is no reason to truncate the search at any m_B. The results of these measurements can subsequently be recast to determine the sensitivity to models that predict new bosons that couple to quarks. See Ref. [13] for an expanded discussion on such theories.

VIII. SUMMARY

In summary, we proposed a search for exclusive photoproduction of a gauge boson that couples to baryon number B at the GLUEX experiment at Jefferson Lab. We determined that $\gamma p \to pB$ will provide the best sensitivity for B boson masses above $0.5\,\text{GeV}$. This search will also provide sensitivity to other proposed dark-sector states that couple to quarks. Finally, our results motivate a similar search for B boson electroproduction at the CLAS experiment.

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