RECEIVED: December 24, 2020

REVISED: March 4, 2021

ACCEPTED: March 8, 2021

PUBLISHED: April 12, 2021

Search for new light vector boson using J/Ψ at BESIII and Belle II

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ABSTRACT: We investigate various search strategies for light vector boson X in $\mathcal{O}(10)$ MeV mass range using J/Ψ associated channels at BESIII and Belle II: (i) $J/\Psi \rightarrow \eta_c X$ with $10^{10} J/\Psi$ s at BESIII, (ii) $J/\Psi(\eta_c + X) + \ell\bar{\ell}$ production at Belle II, and (iii) $J/\Psi + X$ with the displaced vertex in $X \rightarrow e^+e^-$ decay are analyzed and the future sensitivities at Belle II with 50 ab^{-1} luminosity are comprehensively studied. By requiring the displaced vertex to be within the beam pipe, the third method results in nearly background-free analysis, and the vector boson-electron coupling and the vector boson mass can be probed in the unprecedented range, $10^{-4} \leq |\varepsilon_e| \leq 10^{-3}$ and $9 \text{ MeV} \leq m_X \leq 100 \text{ MeV}$ with 50 ab^{-1} at Belle II. This covers the favored signal region of ${}^8\text{Be}^*$ anomaly recently reported by Atomki experiment with $m_X \simeq 17 \text{ MeV}$.

KEYWORDS: Beyond Standard Model, Gauge Symmetry

ARXIV EPRINT: [2012.04190](https://arxiv.org/abs/2012.04190)

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1 Introduction

The Standard Model (SM) is a successful theory describing physics at least up to the electroweak scale, having survived more than 40 years of various experimental tests. However, there still remain a handful number of experimental and observational claims that indicate discrepancies from the SM predictions and consequently request extension of the SM: non-zero mass of neutrinos [1], anomalous magnetic moment of muon, $(g-2)_\mu$ [2, 3], existence of dark matter (DM) [4],¹ and baryon vs. antibaryon asymmetry of the universe [6, 7]. There have been discussions of extending the SM by gauging the lepton number, e.g. $L_\mu - L_\tau$ or $L_e - L_\tau$ [8], intending to explain DM [9, 10], the muon anomalous magnetic moment $(g-2)_\mu$ [11–14], and more recently EDGES 21cm anomaly [15]. The extension gives rise to a leptophilic light vector boson, dubbed as X in this paper. We note that the X boson may couple to the quarks via interactions with unknown heavy fermions that mix with SM quarks [16]. It may then be responsible for the recent anomaly from the KOTO experiment in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ [17–20] and also the anomaly from the Atomki experiment in both $^8\text{Be}^*$ and $^4\text{He}^*$. The preferred mass of X for these cases is in sub-GeV range; in particular $m_X \simeq 17$ MeV for Atomki [21, 22].

High luminosity lepton colliders provide ideal environments to test for such light X boson. Thanks to less severe QCD backgrounds, the lepton colliders have definite advantages over hadron colliders even when the X boson has feeble couplings with the SM particles. In this paper, we take the lepton colliders, BESIII and Belle II, and study the search strategies of X . In particular, we focus on the channels in association with a J/Ψ meson, which will be enormously produced at BESIII and also at Belle II, thereby leaving the signals of X in various channels:

- At BESIII, up to now, 10^{10} J/Ψ events are collected, thus provide an excellent probe to study the J/Ψ rare decays to the X boson.

¹Primordial black holes may explain the whole DM. See, e.g., [5].

- At Belle II, even though less number of J/Ψ are expected, we use the process $e^+e^- \rightarrow \ell^+\ell^- J/\Psi \rightarrow \ell^+\ell^-\eta_c X \rightarrow \ell^+\ell^-\eta_c e^+e^-$ ($\ell = e$ or μ), in which J/Ψ and η_c are inferred by the recoil masses of $\ell^+\ell^-$ and $\ell^+\ell^-e^+e^-$, respectively.
- At Belle II, we also use the channel $e^+e^- \rightarrow X + J/\Psi$ where the X bosons will leave signals with displaced vertices. Due to higher center-of-mass (CM) energy at Belle II, the X boson will be boosted and travel several millimeters before it decays into e^+e^- .

The rest of this paper is dedicated to studying the sensitivity reach of finding X boson taking realistic experimental situations into account under the effective field theory framework.

This paper is organized as follows: we first set up our theoretical framework and introduce the effective interactions in section 2. The analysis for BESIII is carried out in section 3. In section 4 and 5, $e^+e^- \rightarrow \ell^+\ell^- J/\Psi$ and $e^+e^- \rightarrow X + J/\Psi$ with displaced vertex signal are analyzed, respectively for Belle II. Finally, our results are summarized in section 6.

2 Effective Lagrangian

The vectorlike interactions of the X boson with the SM fermions, f , are introduced by the effective Lagrangian:

$$\mathcal{L} \supset -eX_\mu \sum_f \varepsilon_f \bar{f} \gamma^\mu f, \quad (2.1)$$

where we regard the couplings ε_f as free parameters without knowing the origin. In particular, we will assume four universal couplings, $\varepsilon_u, \varepsilon_d, \varepsilon_e$, and ε_ν , for up-type quarks, down-type quarks, charged leptons, and neutrinos, respectively, in our analysis below. We also note that the new interactions do not induce any axial anomaly by construction.

If the new boson X is responsible for the recent Atomki anomaly [22] via the process ${}^8\text{Be} + X \rightarrow {}^8\text{Be} + e^+e^-$, its mass should be $m_X \simeq 17$ MeV and the couplings with the first generation quarks should be in a particular window [23–25]:

$$|\varepsilon_u + \varepsilon_d| \simeq 3.7 \times 10^{-3}. \quad (2.2)$$

From the NA48/2 experiment for $\pi^0 \rightarrow X\gamma$, we require a *protophobic* condition [26]:

$$|2\varepsilon_u + \varepsilon_d| < 8 \times 10^{-4}. \quad (2.3)$$

Taking both relations in eq. 2.2 and eq. 2.3 into account, we finally get the preferred value for up-type and down-type quark couplings:

$$\varepsilon_u \simeq \pm 3.7 \times 10^{-3}, \quad \varepsilon_d \simeq \mp 7.4 \times 10^{-3}, \quad (2.4)$$

which we will rely on below.

The coupling to the leptons, especially to electron and electron-neutrino, are stringently constrained by the beam dump experiment SLAC E141 [27], the anomalous magnetic moment of the electron $g - 2$ [28], and neutrino-electron scattering experiment [29]:

$$4.2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}, \quad (2.5)$$

$$\sqrt{\varepsilon_e \varepsilon_\nu} \lesssim 7 \times 10^{-5}. \quad (2.6)$$

When a small coupling for neutrino $\varepsilon_\nu \ll 10^{-6}$ is assumed, we do not worry about constraints from neutrinos.

3 Signal and background from $J/\Psi \rightarrow \eta_c e^+ e^-$

In the SM, the decay $J/\Psi \rightarrow \eta_c \gamma^* \rightarrow \eta_c e^+ e^-$ is radiatively allowed [30]. Its partial width is expressed with the form factor $f_{VP}(0)$ for on-shell photon at the vanishing momentum transfer limit $q^2 = 0$ [31]

$$\Gamma(J/\Psi \rightarrow \eta_c \gamma) = \frac{1}{3} \frac{\alpha_{\text{EM}}(m_{J/\Psi}^2 - m_{\eta_c}^2)^3}{8m_{J/\Psi}^3} |f_{VP}(0)|^2, \quad (3.1)$$

from which the form factor $|f_{VP}(0)| = 0.68949 \text{ GeV}^{-1}$ is determined with the fine structure constant $\alpha_{\text{EW}} \simeq 1/137$, the masses of J/Ψ and η_c , $m_{J/\Psi} = 3.0969 \text{ GeV}$, and $m_{\eta_c} = 2.9839 \text{ GeV}$, respectively, and the measured width $\Gamma(J/\Psi \rightarrow \eta_c \gamma) = 1.5793 \text{ keV}$ [7, 32–34]. The form factor $f_{VP}(q^2)$ for general $q^2 \neq 0$ is obtained by $F_{VP}(q^2) \equiv f_{VP}(q^2)/f_{VP}(0) = 1/(1 - \frac{q^2}{\Lambda^2})$ from the pole approximation with pole mass $\Lambda = m_{\psi'} = 3.686097 \text{ GeV}$ for J/Ψ .

The normalized differential widths for partial decay widths of $J/\Psi \rightarrow \eta_c \gamma^* \rightarrow \eta_c e^+ e^-$ and $J/\Psi \rightarrow \eta_c X^* \rightarrow \eta_c e^+ e^-$, respectively for off-shell photon and X boson are obtained using a common factor $F_{VP}(q^2)$ [30]:

$$\begin{aligned} \frac{d\Gamma_{\eta_c \gamma^*}}{dq^2 \Gamma_{J/\Psi \rightarrow \eta_c \gamma}} &= |F_{VP}(q^2)|^2 \times F_{\text{QED}}(q^2) \\ \frac{d\Gamma_{\eta_c X^*}}{dq^2 \Gamma_{J/\Psi \rightarrow \eta_c \gamma}} &= |F_{VP}(q^2)|^2 \times F_X(q^2), \end{aligned} \quad (3.2)$$

where the kinematic window is given as $(2m_e)^2 \leq q^2 = m_{e^+e^-}^2 \leq (m_{J/\Psi} - m_{\eta_c})^2$. Since the mass difference between J/Ψ and η_c is only 113 MeV, it is hard to significantly boost X boson in this channel and produce displaced-vertex signal in a collider detector.

The precise expression for the factor F_{QED} is shown in ref. [30] where the factor is found to include the amplitude square and phase space factor for off-shell photon. Analogous expression for F_X is obtained:

$$\begin{aligned} F_X(q^2) &= \frac{\alpha_{\text{EM}}(\varepsilon_c \cdot \varepsilon_e)^2}{3\pi} \left(\frac{q^2}{[(q^2 - m_X^2)^2 + m_X^2 \Gamma_X^2]} \right) \\ &\times \left(1 - \frac{4m_e^2}{q^2} \right)^{1/2} \left(1 + \frac{2m_e^2}{q^2} \right) \left[\left(1 + \frac{q^2}{m_{J/\Psi}^2 - m_{\eta_c}^2} \right)^2 - \frac{4m_{J/\Psi}^2 q^2}{(m_{J/\Psi}^2 - m_{\eta_c}^2)^2} \right]^{3/2} \end{aligned} \quad (3.3)$$

by replacing the couplings and propagator from F_{QED} .

Assuming that $\varepsilon_\nu \ll 10^{-6}$ and $\varepsilon_e \simeq 10^{-3}$, and the quark channels are kinematically forbidden with $m_X \leq 2m_\pi$, the X boson dominantly decay to electrons with the width

$$\Gamma_{X \rightarrow e^+ e^-} = \frac{\varepsilon_e^2 \alpha_{\text{EM}} m_X}{3} \left(1 + \frac{2m_e^2}{m_X^2} \right) \sqrt{1 - \frac{4m_e^2}{m_X^2}}, \quad (3.4)$$

which is narrow $\Gamma_X \ll m_X$.

Figure 1. The e^+e^- invariant mass distributions of signal $J/\Psi \rightarrow \eta_c X^* \rightarrow \eta_c e^+ e^-$ (red) and background $J/\Psi \rightarrow \eta_c \gamma^* \rightarrow \eta_c e^+ e^-$ (black), where $q^2 \equiv m_{e^+e^-}^2$. Input parameters are $m_X = 17$ MeV, $\varepsilon_c = 3.7 \times 10^{-3}$, and $\varepsilon_e = 10^{-3}$.

After performing the integration of q^2 , we can obtain the partial decay width $\Gamma_{\eta_c X^*}$. By inserting favoured coupling values $\varepsilon_c = \varepsilon_u = 3.7 \times 10^{-3}$, $\varepsilon_e = 10^{-3}$ and fixing $m_X = 17$ MeV for ${}^8\text{Be}^*$ anomaly, it gives $\Gamma_{\eta_c \gamma^*} = 2.09 \times 10^{-5}$ keV and implies

$$\text{Br}(J/\Psi \rightarrow \eta_c X^* \rightarrow \eta_c e^+ e^-) = 1.64 \times 10^{-6} \left(\frac{\varepsilon_c}{10^{-2}} \right)^2,$$

which is about three orders of magnitude smaller than that of the $\eta_c \gamma^*$ background, $\text{Br}(J/\Psi \rightarrow \eta_c \gamma^* \rightarrow \eta_c e^+ e^-) = 1.03 \times 10^{-4}$.²

The e^+e^- invariant-mass-squared distributions for signal ($\eta_c X^*$) and background ($\eta_c \gamma^*$) are compared in figure 1. The different features are clearly displayed: the signal has a peak at $q^2 = m_X^2$ and the background is broadly distributed. Therefore our task now is to efficiently extract the signal near the peak and suppress the background.

We first impose a kinematic condition for signal: $M_{e^+e^-} \subset [(m_X - \sigma_m), (m_X + \sigma_m)]$, where σ_m is the e^+e^- mass resolution which is roughly of the same order of magnitude as the energy resolution σ_E . The signal yield S and background yield B are now obtained as

$$\begin{aligned} S &= N_{J/\Psi} \times \frac{\int_{(m_X - \sigma_m)^2}^{(m_X + \sigma_m)^2} dq^2 \frac{d\Gamma_{\eta_c X^*}}{dq^2}}{\Gamma_{J/\Psi}}, \\ B &= N_{J/\Psi} \times \frac{\int_{(m_X - \sigma_m)^2}^{(m_X + \sigma_m)^2} dq^2 \frac{d\Gamma_{\eta_c \gamma^*}}{dq^2}}{\Gamma_{J/\Psi}}, \end{aligned} \quad (3.5)$$

where $N_{J/\Psi}$ is the total number of J/Ψ produced in the collision, and $\Gamma_{J/\Psi} = 92.9$ keV is the total decay width of J/Ψ [7].

²In the background estimation, the other background sources are not considered. For instance, $\gamma \rightarrow e^+e^-$ conversion near the detector materials is contributed with $J/\Psi \rightarrow \eta_c \gamma$ decay as a background source. The process is suppressed by examining the vertex position of the resulting e^+e^- . For the vertexing performance of Belle II, the reader is directed to ref. [35].

Branching Ratio	Detection efficiency
$\text{Br}(\eta_c \rightarrow K^+ K^- \pi^0) = (1.15 \pm 0.12)\%$	18.82%
$\text{Br}(\eta_c \rightarrow K_S^0 K^\pm \pi^\mp) = (2.60 \pm 0.21)\%$	21.22%
$\text{Br}(\eta_c \rightarrow 2(\pi^+ \pi^- \pi^0)) = (15.2 \pm 1.8)\%$	3.07%

Table 1. The branching fractions of η_c decay modes with corresponding efficiencies.

	$\sigma_m=1$ MeV	$\sigma_m=2$ MeV	$\sigma_m=5$ MeV	$\sigma_m=10$ MeV	$\sigma_m=15$ MeV
S	188	263	277	277	277
B	3686	7399	18989	42436	87640
$S/\sqrt{B}$	3.10	3.06	2.01	1.34	0.94

Table 2. For $N_{J/\Psi} = 10^{11}$ and favoured parameters $\varepsilon_c = \varepsilon_u = 3.7 \times 10^{-3}$, $\varepsilon_e = 10^{-3}$, $m_X = 17$ MeV for ${}^8\text{Be}^*$ anomaly, the significances of signal to background from $J/\Psi \rightarrow \eta_c e^+ e^-$ with various energy resolutions of detector and 1.23% η_c reconstruction efficiency.

The BESIII experiment, which has collected 10^{10} J/Ψ events in the resonance process $e^+ e^- \rightarrow J/\Psi$ [30], plans to increase the size of J/Ψ sample to 10^{11} events in the near future. The energy resolution of BESIII is $\sigma_E/E \simeq 0.005$ for the final-state electron, which smears the invariant mass distribution of $e^+ e^-$ by $\sigma_m \simeq 1$ MeV.

In order to exclusively reconstruct the $J/\Psi \rightarrow \eta_c e^+ e^-$ decays, we have to consider η_c decay modes that can be fully reconstructed with reasonable background contamination. Table 1 lists the branching fractions of a few such η_c decay modes along with the corresponding efficiencies [36].

The overall efficiency ϵ of the above three η_c modes is obtained by adding the individual efficiencies weighted by their corresponding branching fractions: $\epsilon = 1.23\%$. Given these, and taking 17 MeV X boson for ${}^8\text{Be}^*$ anomaly to be real, we list, in table 2, the expected significances of $J/\Psi \rightarrow \eta_c X \rightarrow \eta_c e^+ e^-$ with $N_{J/\Psi} = 10^{11}$ at BESIII under the assumption of $\varepsilon_c = \varepsilon_u$, for various σ_m values.

For general light vector boson searches through $J/\Psi \rightarrow \eta_c e^+ e^-$, the variation of the expected significance over $(m_X, \varepsilon_c, \varepsilon_e)$ are shown in figure 2. With the present value of $N_{J/\Psi} = 10^{10}$ at BESIII, the region of sensitivity is $|\varepsilon_c| \gtrsim 5 \times 10^{-3}$ at $m_X \simeq 17$ MeV as shown in the upper left panel of figure 2 and left panel of figure 3. The sensitivity slightly improves as m_X increases, because of the reduction of background (see figure 1), and reaches the maximal sensitivity $|\varepsilon_c| \gtrsim 3 \times 10^{-3}$ at $m_X \simeq 60$ MeV. But as m_X approaches $m_{J/\Psi} - m_{\eta_c}$, the sensitivity becomes weaker due to the phase space suppression. The two right panels of figure 2 show that the significance is independent of the ε_e as we expect from the narrow width approximation. For $N_{J/\Psi} = 10^{11}$ which is expected in the near future, the projected sensitivity becomes $|\varepsilon_c| \gtrsim 3 \times 10^{-3}$ at $m_X \simeq 17$ MeV as shown in the bottom-left panel of figure 2 and the right panel of figure 3, whereby the entire favored region of ${}^8\text{Be}^*$ anomaly can be probed.

An alternative way to explicitly reconstructing η_c in $J/\Psi \rightarrow \eta_c e^+ e^-$ at BESIII is to use the recoil of $e^+ e^-$. As the $e^\pm$ carries low energy around 50 MeV, it gets difficult

Figure 2. The significance $S/\sqrt{B}$ on (m_X, ϵ_c) and (ϵ_c, ϵ_e) planes from $J/\Psi \rightarrow \eta_c e^+ e^-$ light X vector boson searches at BESIII. Adopt $N_{J/\Psi} = 10^{10}$ (upper panels) and $N_{J/\Psi} = 10^{11}$ (bottom panels), reconstructed efficiency of η_c from table 1, and the invariant mass cut $|M_{ee} - m_X| \leq \sigma_m = 2$ MeV. The red boxes indicate the preferred regions for ${}^8\text{Be}^*$ anomaly.

Figure 3. The current (left-panel: $N_{J/\Psi} = 10^{10}$) and future (right-panel: $N_{J/\Psi} = 10^{11}$) BESIII sensitivities by assuming the reconstruction efficiencies from table 1 and taking the invariant mass cut $|M_{ee} - m_X| \leq \sigma_m = 2$ MeV. Compare with the allowed regions for ${}^8\text{Be}^*$ anomaly, NA48/2 for π^0 decay [26] and neutron-nucleus scattering [37].

Figure 4. The Feynman diagrams of the signal (left) and background (right).

to distinguish $e^\pm$ tracks from $\pi^\pm$ background. With an improvement of low-energy electron identification in the future, the BESIII with $N_{J/\Psi} = 10^{11}$ can reach the sensitivity of $|\varepsilon_c| \simeq 10^{-3}$.

4 The $e^+e^- \rightarrow \ell^+\ell^- + J/\Psi \rightarrow \ell^+\ell^- e^+e^- \eta_c$ at Belle II

For vector meson J/Ψ , the partial width to e^+e^- is given by

$$\Gamma_{J/\Psi \rightarrow e^+e^-} = \frac{g_{J/\Psi ee}^2}{12\pi} m_{J/\Psi} \left(1 + \frac{2m_e^2}{m_{J/\Psi}^2} \right) \sqrt{1 - \frac{4m_e^2}{m_{J/\Psi}^2}}, \quad (4.1)$$

where $g_{J/\Psi ee} = 8.2048 \times 10^{-3}$ [7] is the coupling strength in the effective interaction $g_{J/\Psi ee} [\bar{e}\gamma^\mu e](J/\Psi)_\mu$ that matches the measured value $\Gamma_{J/\Psi \rightarrow e^+e^-} = 5.53$ keV [7].

Then the cross sections to $\ell^+\ell^- J/\Psi$ where $\ell = e$, or μ at Belle II are obtained via $e^+e^- \rightarrow \gamma^* J/\Psi$:

$$\begin{aligned} \sigma(e^+e^- \rightarrow \gamma^* + J/\Psi \rightarrow e^+e^- J/\Psi) &= 286 \text{ fb}, \\ \sigma(e^+e^- \rightarrow \gamma^* + J/\Psi \rightarrow \mu^+\mu^- J/\Psi) &= 58.4 \text{ fb}. \end{aligned} \quad (4.2)$$

With the design integrated luminosity $\mathcal{L} = 50 \text{ ab}^{-1}$, we estimate $N_{J/\Psi} = 1.75 \times 10^7$ events for $e^+e^- \rightarrow \gamma^* + J/\Psi \rightarrow \ell^+\ell^- J/\Psi$ at Belle II. This $N_{J/\Psi}$ is applied to eq. 3.5, along with eq. 4.1, to give estimates of S and B :

$$\begin{aligned} S &= \mathcal{L} \times \sigma(e^+e^- \rightarrow \ell^+\ell^- J/\Psi) \times \text{Br}(J/\Psi \rightarrow \eta_c X^* \rightarrow \eta_c e^+e^-) \simeq 28.2 \left(\frac{\varepsilon_c}{10^{-2}} \right)^2, \\ B &= \mathcal{L} \times \sigma(e^+e^- \rightarrow \ell^+\ell^- J/\Psi) \times \text{Br}(J/\Psi \rightarrow \eta_c \gamma^* \rightarrow \eta_c e^+e^-) \simeq 1772. \end{aligned} \quad (4.3)$$

Therefore, the estimated $S/\sqrt{B}$ is too small at this level so that we will improve the analysis by a more realistic MC study below.

For event generation, we use MG5_AMC@NLO [38] for both signal and background with FEYNRULES v2.0 [39] model for J/Ψ , η_c mesons and X boson couplings and X couples to the leptons. We generate with the $E_{\text{beam}1,2} = 5.2941$ GeV in the CM frame, which is

Figure 5. The $e^+e^-\ell^+\ell^-$ recoil mass (left) and e^+e^- invariant mass (right) distributions for the parton level Monte-Carlo simulation data with the smearing effect. Input parameter is $m_X = 17$ MeV. Here, we normalized to 10^5 events for each channel.

boosted by $\beta = 0.2732$ with respect to the lab frame. The amplitude of the electromagnetic Dalitz decay, $V \rightarrow Pe^+e^-$ can be written in a Lorentz-invariant form [30],

$$T(V \rightarrow Pe^+e^-) = 4\pi\alpha_{\text{EM}}f_{\text{VP}}\epsilon^{\mu\nu\rho\sigma}p_\mu q_\nu \epsilon_\rho \frac{1}{q^2}\bar{u}_1\gamma_\sigma\nu_2 \quad (4.4)$$

and we can obtain the interaction Lagrangian as,

$$\begin{aligned} \mathcal{L} \supset & f_{\text{VP}}(-2\sqrt{\pi\alpha_{\text{EM}}}\partial_\mu P\partial_\nu V_\rho\epsilon^{\mu\nu\rho\sigma}A_\sigma - g_{Xc}\partial_\mu P\partial_\nu V_\rho\epsilon^{\mu\nu\rho\sigma}X_\sigma) \\ & - g_{eV}\bar{e}\gamma^\mu eV_\mu - g_{Xe}\bar{e}\gamma^\mu eX_\mu, \end{aligned} \quad (4.5)$$

where g_{Xc} , g_{Xe} , and g_{eV} are the effective coupling constants, whose numerical values are to be obtained by experiments.

Similar to the BESIII, photon conversion process where the photon from $J/\Psi \rightarrow \eta_c\gamma$ hits the beam pipe or vertex detector layers and converts to e^+e^- can be a background source, but they are controlled by examining the e^+e^- vertex position. Another possible background is $e^+e^- \rightarrow \ell^+\ell^- + (\text{anything})$ where (anything) may contain a number of low-momentum charged particles that are misidentified as electrons. However, this process does not show peak in the $M_{\ell^+\ell^-}^{\text{recoil}} \simeq M_{J/\Psi}$ variable, and can be suppressed by inspecting the $M_{\ell^+\ell^-}^{\text{recoil}}$ distribution. In the figure 5, the recoil mass of $e^+e^-\ell^+\ell^-$ and invariant mass distributions of e^+e^- are plotted for the signal (shown in red), and the $\ell^+\ell^-e^+e^-(\gamma)$ (green) and $J/\Psi \rightarrow \eta_c\gamma^*$ (gray) backgrounds, where we produce equal number of events ($= 10^5$) for each sample at the parton level before applying any selection cuts. We give a Gaussian smearing effect with the momentum resolution $\sigma_{p_{\ell^\pm}}/p_{\ell^\pm} = 0.005$ on the parton level data for our analysis. To simulate the effects of the Belle II detector, we apply the following baseline cuts: $|\eta_{\ell^\pm}^*| \leq 1.60$ in the CM frame [14, 40], $|E_{\mu^\pm}| \geq 0.6$ GeV, and $|E_{e^\pm}| \geq 0.06$ GeV in the lab frame [35]. Note that we require very low energy threshold for electrons so as to keep most of the signals, because the e^+e^- from $J/\Psi \rightarrow \eta_c e^+e^-$ are very soft. This inevitably would cause large background from pion tracks being misidentified as electrons.³

³Currently, the most powerful observable for electron identification (e -ID) at Belle II is the E/p where

Cuts	B	S
Processes	$\eta_c \gamma^* \rightarrow \eta_c ee$	$\eta_c X \rightarrow \eta_c ee$
	100000	100000
Baseline Cuts	7170	6290
$ M_{e\ell\ell}^{\text{rec}} - m_{\eta_c} \leq 200 \text{ MeV}$	7071	6219
$ M_{ee} - m_X \leq 2 \text{ MeV}$	377	5880

Table 3. Signal and background events of $e^+e^- \rightarrow \ell^+\ell^-e^+e^-\eta_c$ after cuts at Belle II.

Luminosity	50 ab^{-1}	100 ab^{-1}	200 ab^{-1}
$ \varepsilon_c $	$\gtrsim 1.76 \times 10^{-2}$	$\gtrsim 1.48 \times 10^{-2}$	$\gtrsim 1.24 \times 10^{-2}$

Table 4. Sensitivities on ε_c of 17 MeV X boson from $\ell^+\ell^-J/\Psi \rightarrow \ell^+\ell^-e^+e^-\eta_c$ search at Belle II with luminosities 50, 100, and 200 ab^{-1} . Here we require $S/\sqrt{B} = 2$.

And we give two kinematic requirements: for the energy-momentum 4-vector of η_c , we use the energy and momentum recoiling against $e^+e^-\ell^+\ell^-$. The signal and background distributions of the recoil mass $M_{e\ell\ell}^{\text{rec}}$, smeared by the charged-track momentum resolution, are displayed in the left panel of figure 5. The $J/\Psi \rightarrow \eta_c e^+e^-$ events clearly show a peak at $M_{e\ell\ell}^{\text{rec}} \simeq m_{\eta_c}$, while the $\ell^+\ell^-e^+e^-(\gamma)$ background is mostly populated at $M_{e\ell\ell}^{\text{rec}} \simeq 0$, therefore we require $|M_{e\ell\ell}^{\text{rec}} - m_{\eta_c}| \leq 200 \text{ MeV}$ to eliminate the $\ell^+\ell^-e^+e^-(\gamma)$ background. In addition, we apply $|M_{ee} - m_X| \leq 2 \text{ MeV}$, whereby the $\eta_c \gamma^*$ background from the process shown in the right panel of figure 4 are suppressed. In table 3, we summarize the cumulative effects of the baseline cuts and the kinematic requirements.

The sensitivities of $\ell^+\ell^-e^+e^-$ search at Belle II are derived from the requirement of $S/\sqrt{B} = 2$. Combining eq. (4.3) and table 3, we obtain the corresponding values of ε_c with respect to luminosities of 50, 100, and 200 ab^{-1} in table 4. They are about 5 times larger than the estimates from current BESIII sensitivity $|\varepsilon_c| \gtrsim 5 \times 10^{-3}$ in section 3.

5 The $e^+e^- \rightarrow X + J/\Psi \rightarrow e^+e^- + J/\Psi$ displaced vertex at Belle II

The X boson produced in the process $e^+e^- \rightarrow X + J/\Psi$ travels several millimeters before decaying into e^+e^- in the Belle II detector and leaves displaced vertex. In particular, when the distance of the flight is between 2 mm and 8 mm, which is inside the beam pipe, and outside the interaction region, Belle II has excellent power to reconstruct the displaced vertex and makes the signal almost free from the SM background [43]. Therefore, we propose to use the clean displaced e^+e^- vertex from the X boson decay (along with prompt $\ell^+\ell^-$ from J/Ψ).

The leading-order Feynman diagram of the relevant process is shown in the left panel of figure 6. A typical event with displaced vertex at Belle II detector with the $\ell^+\ell^-$ from J/Ψ decay is schematically shown in the right panel of figure 6.

E is the energy measured in the electromagnetic calorimeter and p is the magnitude of 3-momentum measured in the drift chamber. [41] With low-momentum tracks that cannot reach the calorimeter [42], the performance of e -ID will thus degrade. For the actual data analysis, we encourage the Belle II collaboration to improve e -ID for low-momentum tracks along with systematic uncertainties.

Figure 6. (Left panel) The Feynman diagram of the $e^+e^- \rightarrow X + J/\Psi \rightarrow e^+e^-\ell^+\ell^-$ signal. (Right panel) The schematic picture of the decay process of the long-lived X boson in the Belle II detector.

Figure 7. (Left panel) The transverse flight distance d_{xy} of 17 MeV X boson for ϵ_e in 0.5×10^{-4} steps from 3×10^{-4} to 8×10^{-4} ; (Right panel) The number of events that pass the baseline cuts and satisfy $2 \text{ mm} \leq d_{xy} \leq 8 \text{ mm}$ from the sample of 10^5 generated signal events.

We note that compared with other lighter vector mesons, the heavier mass of J/Ψ helps to induce larger scattering angle in such a way that more events from $X \rightarrow e^+e^-$ will satisfy the cut $|\eta_{\ell^\pm}^*| \leq 1.60$. Furthermore, the electron and positron from $X \rightarrow e^+e^-$ carry energy above GeV, which make them easier to be distinguished from charged-pion backgrounds.

The other advantage of this channel is that the signal strength only depends on the ϵ_e coupling since only X - e^+e^- vertices are involved at tree level. For $0.3 \times 10^{-3} \leq \epsilon_e \leq 0.8 \times 10^{-3}$, it yields a few mm transverse flight distance d_{xy} which is defined as the distance between the beam axis and the X decay vertex. The left-panel of figure 7 shows the distribution of d_{xy} corresponding to several values of ϵ_e .

With the baseline cuts and $2 \text{ mm} \leq d_{xy} \leq 8 \text{ mm}$, we estimate the signal sensitivity by considering two cases: (i) explicitly reconstructing $J/\Psi \rightarrow \ell^+\ell^-$ ($e^+e^-\ell^+\ell^-$ channel), and (ii) using the recoil mass of $X \rightarrow e^+e^-$ to infer J/Ψ (e^+e^- channel). Tables 5 and 6 show, respectively for the $e^+e^-\ell^+\ell^-$ and e^+e^- channels, the signal efficiencies and expected significances for various assumed values of ϵ_e , according to the 50 ab^{-1} luminosity

$\varepsilon_e/10^{-4}$	8.0	7.0	6.0	5.0	4.5	4.0	3.0
Baseline Cuts(%)	13.8	13.8	13.8	13.8	13.8	13.8	13.8
$2\text{mm} < d_{xy} < 8\text{mm}$ (%)	1.5	4.7	7.4	10.1	11.0	10.1	5.2
N_S	1.60	3.85	4.42	4.18	3.69	2.69	0.78
Significance ($B = 0.1$)	2.4σ	4.6σ	5.0σ	4.8σ	4.5σ	3.6σ	1.5σ
Significance ($B = 1$)	1.6σ	2.9σ	3.2σ	3.1σ	2.8σ	2.3σ	1.2σ

Table 5. (From top rows to bottom) The fraction of events (in %) that survive the baseline cuts mentioned in section 4, and the flight distance $2\text{ mm} \leq d_{xy} \leq 8\text{ mm}$ cuts, for several values of ε_e of 17 MeV X boson; the number of signal events N_S in the $e^+e^-\ell^+\ell^-$ channel at Belle II with 50 ab^{-1} luminosity; and the expected significances assuming 1 event, and 0.1 event of the SM background in the analysis channel after all cuts.

$\varepsilon_e/10^{-4}$	8.0	7.0	5.0	4.0	3.0	2.0	1.0
Baseline Cuts(%)	17.6	17.6	17.6	17.6	17.6	17.6	17.6
$2\text{mm} < d_{xy} < 8\text{mm}$ (%)	1.6	5.3	12.3	12.9	7.4	2.3	0.5
N_S	14.6	35.7	42.7	28.7	9.23	1.28	0.07
Significance ($B = 0.1$)	$> 5\sigma$					2.2σ	0.4σ
Significance ($B = 1$)	$> 5\sigma$					1.6σ	0.9σ

Table 6. The same as table 5, but using the e^+e^- channel.

at Belle II and the $e^+e^- \rightarrow X + J/\Psi$ cross section

$$\sigma(e^+e^- \rightarrow X + J/\Psi) = 2.77 \times 10^{-2} \times \left(\frac{\varepsilon_e}{10^{-3}} \right)^2 \text{ fb}. \quad (5.1)$$

The significances are calculated from the expected p -value of background-only hypothesis for each case.

The final result of expected sensitivity with Belle II at 50 ab^{-1} luminosity is shown in figure 8. Also displayed in figure 8 are the expected results with the η_c -related studies at Belle II and BESIII as discussed in sections III and IV. The displaced e^+e^- vertex searches can probe the 17 MeV X boson in the region

$$2.5 \times 10^{-4} \leq \varepsilon_e \leq 8.0 \times 10^{-4}$$

with significance larger than 2 by assuming near-zero background, and it covers the ε_e region preferred by Atomki. While we expect less than one signal event with the currently available Belle data sample of 1 ab^{-1} , we can start exploring the Atomki preferred region within a few years once Belle II accumulates data sample of 10 ab^{-1} or more.

Our study with the displaced vertex is extended for wider mass range of X -like boson, whereby we determine the region of sensitivity with Belle II at 50 ab^{-1} , as displayed in figure 8. Two cases are considered: $B = 0.1$ and $B = 1$, where B is the expected number of background events from the SM processes. We then use the Poisson probability of the expected background to fluctuate upward, to calculate the p -values and the corresponding

Figure 8. The yellow (green) contour corresponds $\geq 2\sigma$ significance assuming SM background $B = 0.1$ ($B = 1$) from e^+e^- channel at Belle II with 50 ab^{-1} luminosity, which probes rest of the favour parameter region of Atomki (red vertical band). The gray-shaded regions are excluded by current experiments relate to Xee coupling. Compare to the sensitivities of $e^+e^- \rightarrow \ell^+\ell^- + J/\Psi \rightarrow \ell^+\ell^-e^+e^-\eta_c$ channel at Belle II and $e^+e^- \rightarrow J/\Psi \rightarrow e^+e^-\eta_c$ channel at BESIII by assuming the kinematic mixing between X boson and photon, bringing the relation $\epsilon_c = \frac{2}{3}\epsilon_e$. For the future Belle II experiments 50, 200 ab^{-1} in the 17 MeV mass region, the significance bounds are denoted by magenta, orange dotted lines, respectively. In the case of BESIII for the energy resolutions $\sigma_E = 1 \text{ MeV}$ and 5 MeV , corresponding to section 3, they are denoted in purple and blue, respectively.

significances. The 2σ significance region with $B = 0.1$ ($B = 1$) is shown as the yellow (green) contour in figure 8, which yields signal event $N_S \simeq 1$ ($N_S \simeq 2$).⁴ This study can probe the parameter region of $5 \text{ MeV} \leq m_X \leq 100 \text{ MeV}$ and $1.0 \times 10^{-4} \leq \epsilon_e \leq 3 \times 10^{-3}$, which have not been constrained by any existing experiments. The upper edge of this region is determined by the condition $2 \text{ mm} \leq d_{xy}$, while the lower edge is limited by the statistics. Therefore, with even higher luminosity of Belle II exceeding the target 50 ab^{-1} , the lower edge of the sensitivity region can be extended further.

6 Summary and conclusion

In summary, we propose several studies using J/Ψ at lepton colliders such as Belle II and BESIII, to search for light vector boson around the mass range suggested by the $^8\text{Be}^*$ anomaly of the ATOMKI experiment. At BESIII, the $J/\Psi \rightarrow \eta_c X \rightarrow \eta_c e^+e^-$ channel can be used to constrain the vector boson and charm quark coupling, ϵ_c . With the currently

⁴In this case, the p -value is obtained as $\sum_{n \geq N_S+B} P(n|B)$ which is the probability of upward fluctuation based on the SM-only hypothesis with $P(n|B)$ being the Poisson probability of observing n events given B events of expected background. Then the confidence level (CL) is $\text{CL} = 1 - p$. The 2σ significance corresponds to 95.4% CL. For $B = 1$ (0.1) events, we need $N_S \simeq 2$ (1) signal events to attain 2σ significance.

available sample of $N_{J/\Psi} = 10^{10}$ and effective η_c reconstruction efficiency of 1.23%, we can exclude the region $|\varepsilon_c| \gtrsim 5 \times 10^{-3}$ for $m_X = 17$ MeV. If $N_{J/\Psi} = 10^{11}$ is produced at BESIII in the near future, exclusion of the region $|\varepsilon_c| \simeq 3 \times 10^{-3}$ might be achieved. If universal coupling to up-type quarks is assumed, we expect that the entire favored signal region from the ${}^8\text{Be}^*$ anomaly could be covered.

On the other hand at Belle II, with higher CM energy of 10.59 GeV, we propose to study the process $e^+e^- \rightarrow \ell^+\ell^- J/\Psi$ followed by $J/\Psi \rightarrow \eta_c X \rightarrow \eta_c e^+e^-$. Using the recoil mass against $\ell^+\ell^- e^+e^-$, we perform MC study and find that the expected production of J/Ψ events is about three orders of magnitude smaller than that of BESIII, thus yielding the sensitivity of $|\varepsilon_c| \gtrsim 1.8 \times 10^{-2}$ at $m_X = 17$ MeV.

Alternatively, we can study the process $e^+e^- \rightarrow X + J/\Psi \rightarrow e^+e^- \ell^+\ell^-$ at Belle II and directly constrain the X boson-electron coupling. The X boson is boosted by the higher CM energy and heavy mass of J/Ψ , producing displaced vertex of $X \rightarrow e^+e^-$ which is longer than several millimeters. Particularly, it is almost background free when the transverse flight distance is $2 \text{ mm} \leq d_{xy} \leq 8 \text{ mm}$. Selecting this window and requiring $> 2\sigma$ significance, it gives the sensitivity $2.0 \times 10^{-4} \leq |\varepsilon_e| \leq 8.0 \times 10^{-4}$ at $m_X = 17$ MeV for 50 ab^{-1} luminosity and covers most of the favored signal region from the claimed ${}^8\text{Be}^*$ anomaly. Extending the range of the X boson mass, this method can cover the unprecedented parameter space of $9 \text{ MeV} \leq m_X \leq 100 \text{ MeV}$ and $1.0 \times 10^{-4} \leq |\varepsilon_e| \leq 10^{-3}$.

Acknowledgments

The work is supported in part by the National Research Foundation of Korea [NRF-2021R1A4A2001897 (SCP, YJK), NRF-2019R1A2C1089334 (SCP), and NRF-2020R1I1A1A01066413 (PYT)].

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