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

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Introduction

- The Standard Model (SM) is a successful theory describing the physics at particle level and their interactions.

- There have been discussions of extending the SM by gauging the lepton number, e.g. $L_\mu - L_\tau$ or $L_e - L_\tau$, mainly intending to explain the muon anomalous magnetic moments $(g-2)_\mu$.

- This gives rise to a **leptophilic light vector boson X.**

- The X boson may couple to the SM quark sector via interactions with heavy vector-like fermions mixing with SM quark.

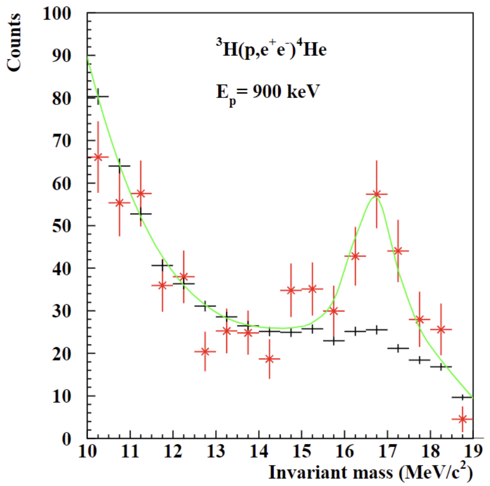


FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in* ^{4}*He.*

- Recent result of $^8\mathrm{Be}^*$ anomaly from Atomki experiment prefers a 17 MeV vector boson that couples to the electrons, u- and d- quarks.

- High luminosity lepton colliders, such as BESIII and Belle II, provide less QCD background than hadron colliders, making them ideal environments to search for sub-GeV particles with feeble couplings to SM particles.

Introduction

- In this work, we focus on the light vector boson search in association with J/Ψ at **BESIII** and Belle II
- At **BESIII**, if the vector boson is lighter than about 110 MeV, it can be produced through $J/\Psi \to \eta_c + X$ followed by the $X \to e^+e^-$ or $X \to \nu\bar{\nu}$ decays.
- At Belle II, the process $e^+e^- \to \ell^+\ell^- J/\Psi \to \ell^+\ell^-\eta_c X \to \ell^+\ell^-\eta_c e^+e^-$, in which J/Ψ and η_c are inferred by the recoil masses of $\ell^+\ell^-$ and $\ell^+\ell^- e^+e^-$, respectively

J/Ψ decay channel

- The alternative channel at Belle II is $e^+e^- \to X + J/\Psi$, which is only relevant to the X boson-electron coupling.
- Due to higher center-of-mass (CM) energy and J/Ψ mass, the boosted X could travel several millimeters before it decays into e^+e^-, thereby resulting in effective suppression of background.

J/Ψ associated channel

Model

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

$$\mathcal{L} \supset -eX_\mu \sum_f \varepsilon_f \bar{f} \gamma^\mu f$$

- If the new boson X is responsible for the recent Atomki anomaly via the process ${}^8\mathrm{Be} + X \to {}^8\mathrm{Be} + e^+e^-$, its mass should be $m_X \simeq 17\ \mathrm{MeV}$ and couples to the first generation quarks with the coupling strengths:

$$|\varepsilon_u + \varepsilon_d| \simeq 3.7 \times 10^{-3}\,,$$

- For the couplings to first generation quarks, the strong constraint from NA48/2 for $\pi^0 \to X\gamma$ requires protophobic condition

$$|2\varepsilon_u + \varepsilon_d| < 8 \times 10^{-4}$$

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

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

- The coupling to the leptons, especially to electron, are stringently constrained by the beam dump experiment SLAC E141, the anomalous magnetic moment of the electron $(g-2)$

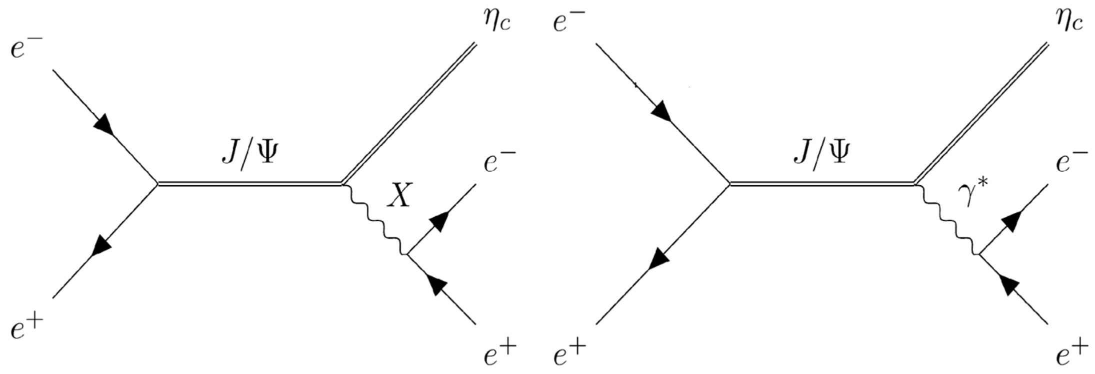
$$4.2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}$$

Model $\boxed{J/\Psi \text{ decay channel}}$

- Here, we assume the X boson has universal coupling to each quark generation, so that if $2m_e \lesssim m_X \lesssim m_{J/\Phi} - m_{\eta_c} \simeq 113\ \mathrm{MeV}$, the decay process $J/\Psi \to \eta_c + X \to \eta_c + e^+e^-$ is kinematic allowed and can be used to search for the 17 MeV or other light vector bosons.

- Lepton colliders such as **BESIII** and Belle II can copiously produce J/Ψ and therefore are sensitive to the J/Ψ rare decay channels.

- The dominating background comes from the off-shell photon contribution, $J/\Psi \to \eta_c + \gamma^* \to \eta_c + e^+e^-$



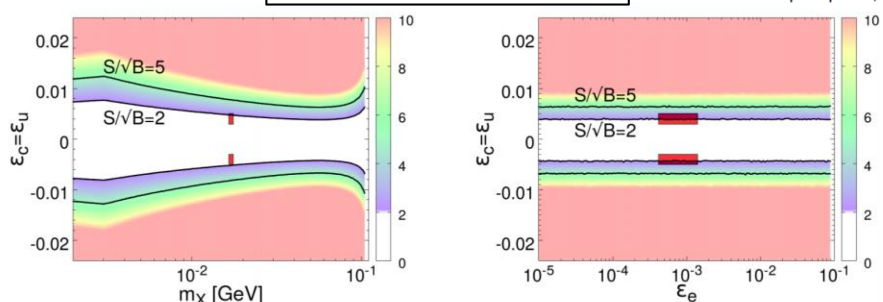
Model J/Ψ decay channel BESIII

- For general light vector boson searches through $J/\Psi \to \eta_c e^+ e^-$, we show the variation of the expected significance over $(m_X, \varepsilon_c, \varepsilon_e)$
- The red boxes indicate the preferred regions for $^8\mathrm{Be}^*$ anomaly.

$|\varepsilon_c| \gtrsim 5 \times 10^{-3}$ at $m_X \simeq 17$ MeV

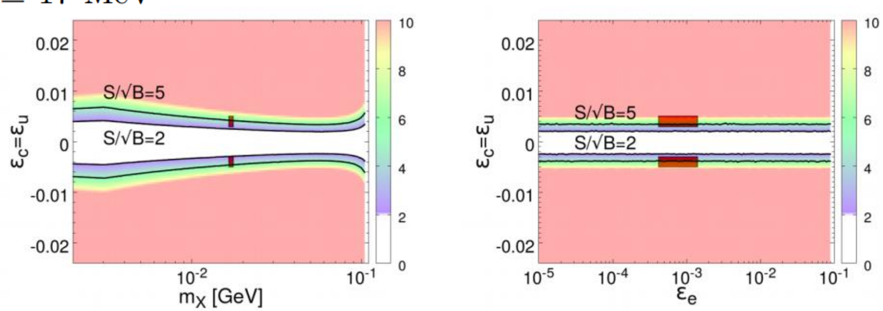
$N_{J/\Phi} = 10^{10}$(upper panels)

$|\varepsilon_c| \gtrsim 3 \times 10^{-3}$ at $m_X \simeq 60$ MeV



$N_{J/\Phi} = 10^{11}$(bottom panels)

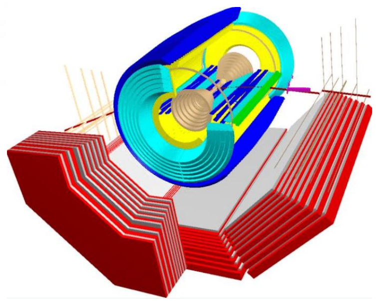
$|\varepsilon_c| \gtrsim 3 \times 10^{-3}$ at $m_X \simeq 17$ MeV

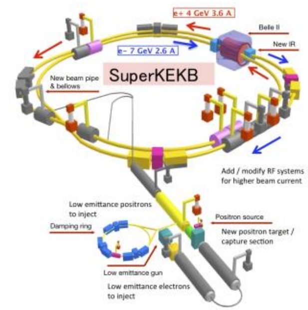


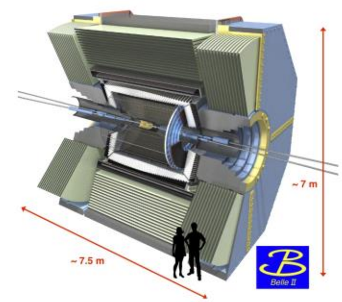
- The alternative way to reconstruct η_c from $J/\Psi \to \eta_c e^+ e^-$ at BESIII is using the recoil of $e^+ e^-$.
- With an improvement of low-energy electron identification in the future, the **BESIII** with $N_{J/\Psi} = 10^{11}$ can reach the sensitivity of $|\varepsilon_c| \simeq 10^{-3}$.

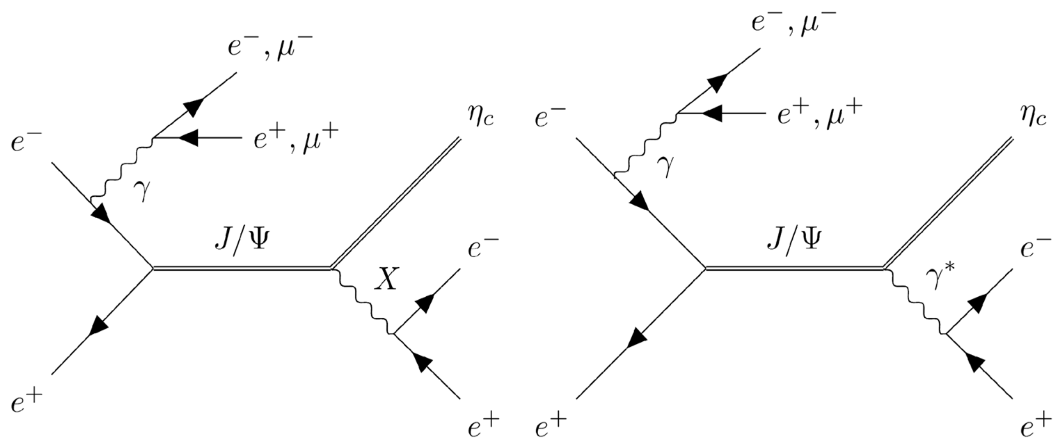
Model J/Ψ decay channel Belle II

Cross section estimation









For vector meson J/Ψ, the partial width is given by the formula

$$\Gamma_{J/\Psi \to e^+e^-} = \frac{g^2_{J/\Psi ee}}{12\pi} m_{J/\Psi} \left(1 + \frac{2m_e^2}{m^2_{J/\Psi}}\right) \sqrt{1 - \frac{4m_e^2}{m^2_{J/\Psi}}}$$

$$\Gamma_{J/\Psi \to e^+e^-} = 5.53 \text{ keV} \Longrightarrow g_{J/\Psi ee} = 8.2048 \times 10^{-3}$$

Model

J/Ψ decay channel

Belle II

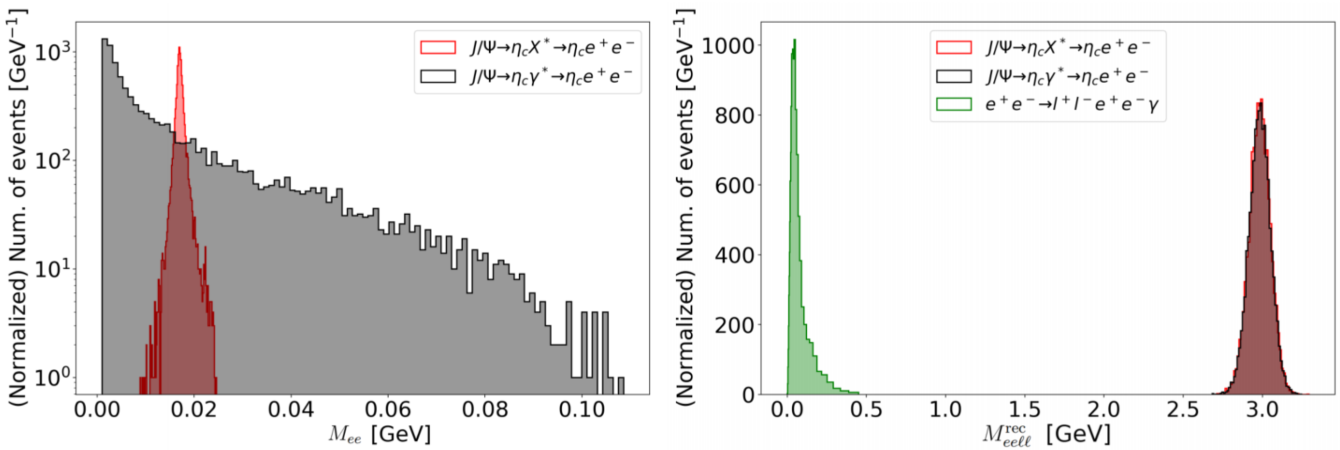
Cross section estimation

Event generation and detector Simulation

With the design integrated luminosity $L = 50\,\mathrm{ab}^{-1}$, we estimate $N_{J/\Psi} = 1.75 \times 10^7$ events for $e^+e^- \to \gamma^* + J/\Psi \to \ell^+\ell^- J/\Psi$ at Belle II.

$$S = L \times \sigma(e^+e^- \to \ell^+\ell^- J/\Psi) \times \mathrm{Br}(J/\Psi \to \eta_c X* \to \eta_c e^+e^-) \simeq 28.2 \left(\frac{\varepsilon_c}{10^{-2}}\right)^2$$

$$B = L \times \sigma(e^+e^- \to \ell^+\ell^- J/\Psi) \times \mathrm{Br}(J/\Psi \to \eta_c \gamma* \to \eta_c e^+e^-) \simeq 1772$$



MG5_aMC@NLO
+
FeynRules

- The e^+e^- invariant mass (left) and $e^+e^-\ell^+\ell^-$ recoil mass (right) distributions for the parton level Monte-Carlo simulation data with the smearing effect.

- We give the Gaussian smearing effect with the momentum resolution

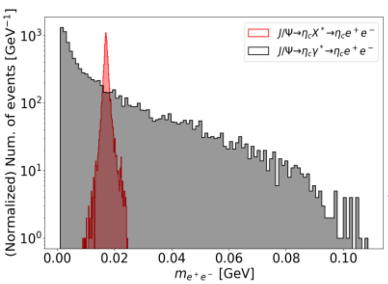
$$\sigma_{p_{\ell^\pm}}/p_{\ell^\pm} = 0.005$$

on the parton level data for our event analysis.

Model J/Ψ decay channel Belle II

[Baseline Cuts]

- To simulate the effects of the Belle II detector, we apply the following baseline cuts: $|\eta^*_{l^\pm}| \le 1.60$ in the CM frame, $|E_{\mu^\pm}| \ge 0.6$ GeV, and $|E_{e^\pm}| \ge 0.06$ GeV in the lab frame.



Cuts	B	S
Processes	$\eta_c\gamma^* \to \eta_c ee$	$\eta_c X \to \eta_c ee$
	100000	100000
Baseline Cuts	7170	6290
$\lvert M^{\rm rec}_{ee\ell\ell} - m_{\eta_c}\rvert \le 200$ MeV	7071	6219
$\lvert M_{ee} - m_X\rvert \le 2$ MeV	**377**	**5880**

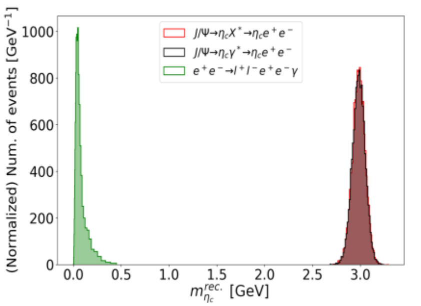


Table 3. Signal and background events of $e^+e^- \to \ell^+\ell^-e^+e^-\eta_c$ after cuts at Belle II.

- Sensitivity

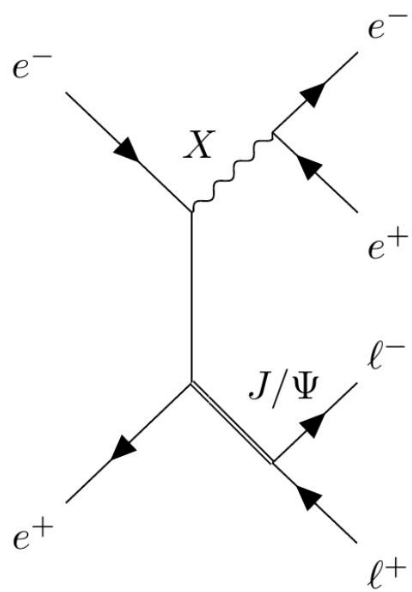
Luminosity	50 ab^{-1}	100 ab^{-1}	200 ab^{-1}
$\lvert\varepsilon_c\rvert$	$\gtrsim 1.76 \times 10^{-2}$	$\gtrsim 1.48 \times 10^{-2}$	$\gtrsim 1.24 \times 10^{-2}$

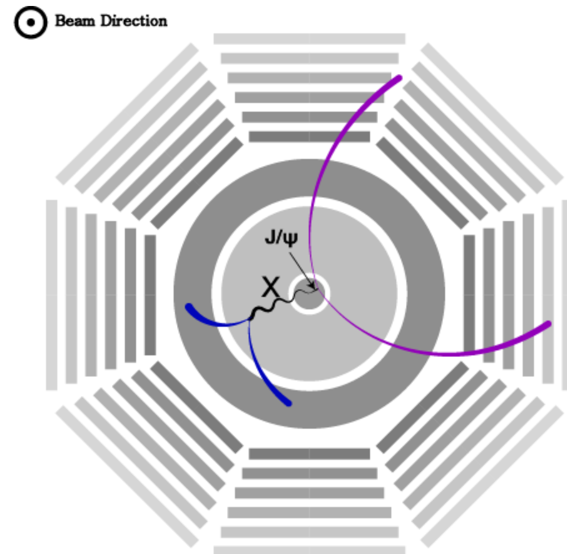
Table 4. Sensitivities on ε_c of 17 MeV X boson from $\ell^+\ell^-J/\Psi \to \ell^+\ell^-e^+e^-\eta_c$ search at Belle II with luminosities 50, 100, and 200 ab^{-1}. Here we require $S/\sqrt{B} = 2$.

Model J/Ψ associated channel Belle II

$$e^+e^- \to X + J/\Psi \to e^+e^- + J/\Psi$$

- The X boson can be boosted from the process $e^+e^- \to X + J/\Psi$ and travels several millimeters before decaying into e^+e^- in the Belle II detector.





- If the displaced vertex is between $2\ \mathrm{mm} \le d_{xy} \le 8\ \mathrm{mm}^*$, which is inside the beam pipe, and outside the interaction region, it provides excellent vertex reconstruction and almost free from SM backgrounds.

* M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg and P. Tunney, JHEP 304 2002, 039 (2020)

Model J/Ψ associated channel Belle II

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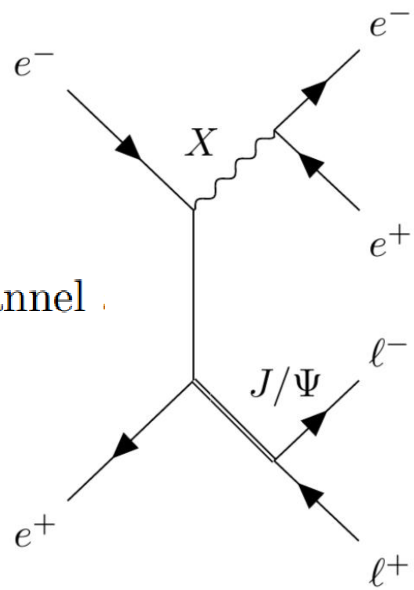
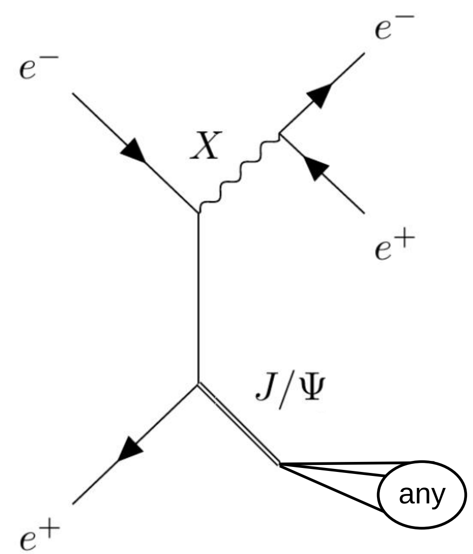
- With the baseline cuts and $2\ \mathrm{mm} \leq d_{xy} \leq 8\ \mathrm{mm}$, we estimate the signal sensitivity by considering two cases:
  (i) explicitly reconstructing $J/\Psi \to \ell^+\ell^-$ ($e^+e^-\ell^+\ell^-$ channel)
  (ii) using the recoil mass of $X \to e^+e^-$ to infer J/Ψ (e^+e^- channel)

$e^+e^-\ell^+\ell^-$ channel

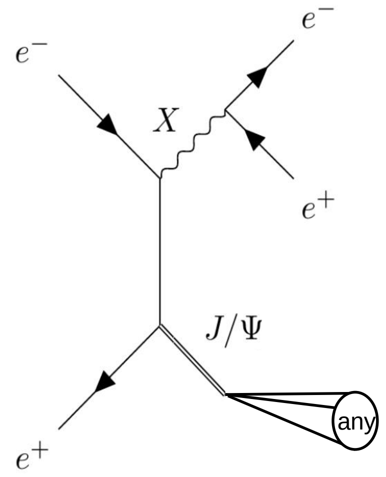




e^+e^- channel

$$\sigma(e^+e^- \to X + J/\Psi) = 2.77 \times 10^{-2} \times \left(\frac{\varepsilon_e}{10^{-3}}\right)^2\ \mathrm{fb}$$

Model J/Ψ associated channel Belle II



e^+e^- channel

- 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.

$\varepsilon_e/10^{-4}$	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
2mm $< d_{xy} <$ 8mm(%)	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.

- While we expect less than one signal event with the currently available Belle data sample of $1\ \mathrm{ab}^{-1}$, we can start exploring the Atomki preferred region within a few years once Belle II accumulates data sample of $10\ \mathrm{ab}^{-1}$ or more.

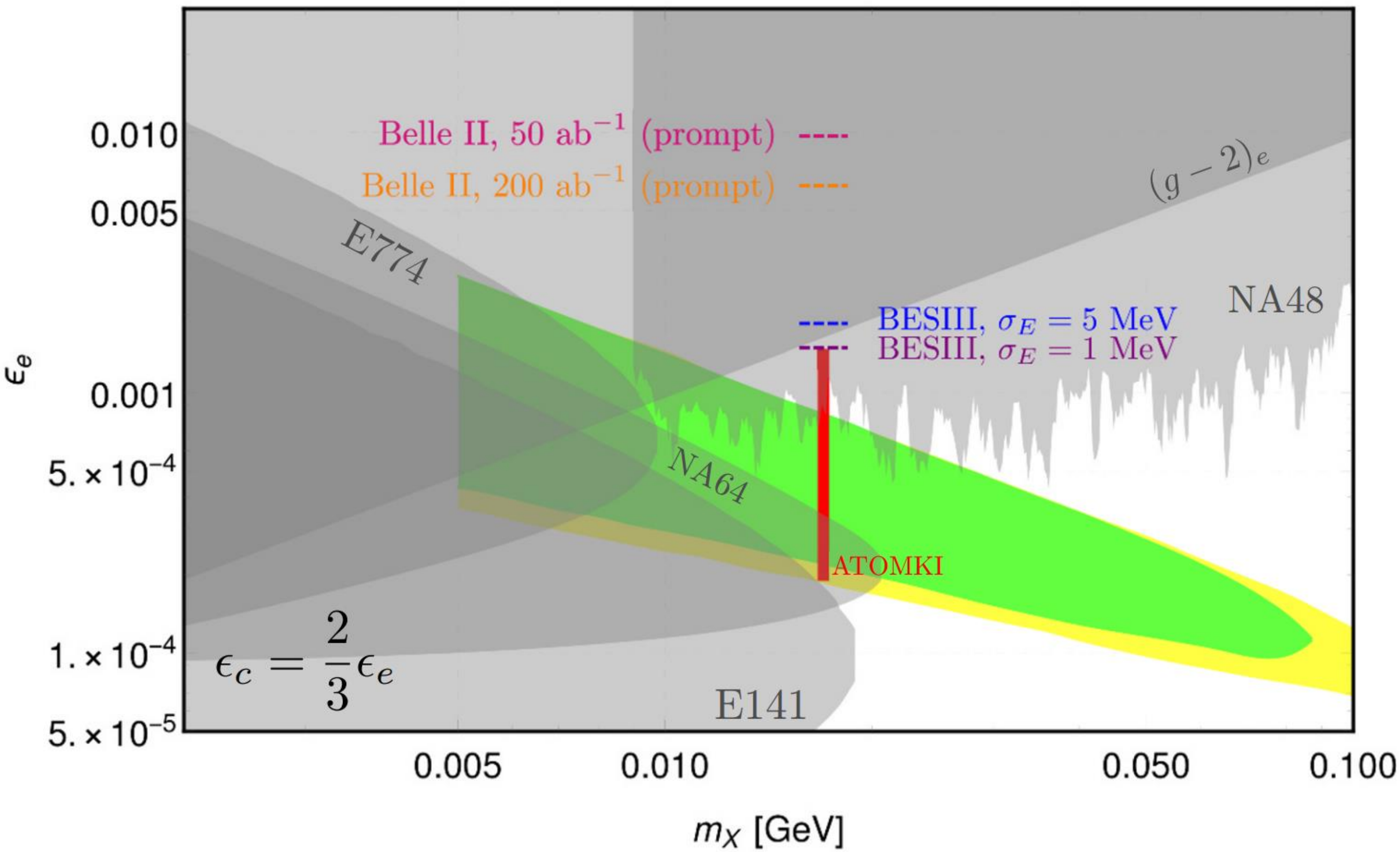
Model

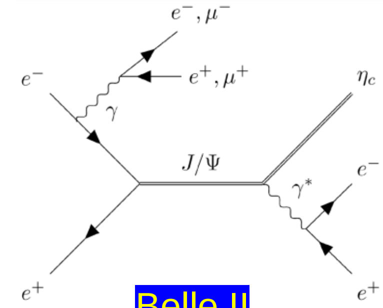
J/Ψ decay channel

J/Ψ associated channel

- The yellow (green) contour corresponds ≥ 2σ 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 favor parameter region of Atomki (red vertical band).

e^+e^- channel

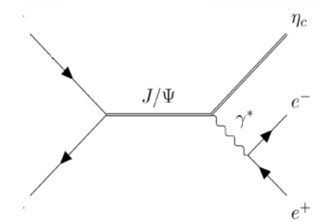


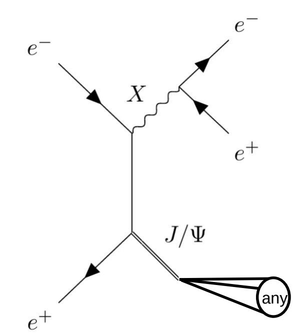


Belle II

J/Ψ decay channel

BESIII





Belle II

J/Ψ associated channel

- This study can probe the parameter region of $5\ \mathrm{MeV} \leq m_X \leq 100\ \mathrm{MeV}$ and $1.0\times 10^{-4} \leq \varepsilon_e \leq 3\times 10^{-3}$, which have not been constrained by any existing experiments.

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 $^8\mathrm{Be}^*$ anomaly of the ATOMKI experiment.

- At BESIII, the $J/\Psi \to \eta_c X \to \eta_c e^+ e^-$ channel with the currently 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.

- On the other hand at Belle II with higher CM energy, we propose to study the process $e^+e^- \to \ell^+\ell^- J/\Psi$ followed by $J/\Psi \to \eta_c X \to \eta_c e^+ e^-$ and this channel can yield the sensitivity of $|\varepsilon_c| \gtrsim 1.8 \times 10^{-2}$ at $m_X = 17$ MeV.

- Alternatively, we can study the process $e^+e^- \to X + J/\Psi \to e^+e^-\ell^+\ell^-$ at Belle II and the X boson is boosted and produce displaced vertex of $X \to e^+e^-$ which is longer than several millimeters.

- Selecting the $2\ \mathrm{mm} \le d_{xy} \le 8\ \mathrm{mm}$ window and requiring $> 2\sigma$ significance, it gives the sensitivity $2.0 \times 10^{-4} \le |\varepsilon_e| \le 8.0 \times 10^{-4}$ at $m_X = 17$ MeV for $50\ \mathrm{ab}^{-1}$ luminosity and covers most of the favored signal region from the claimed $^8\mathrm{Be}^*$ anomaly.

- Extending the range of the X boson mass, this method can cover the unprecedented parameter space of $9\ \mathrm{MeV} \le m_X \le 100\ \mathrm{MeV}$ and $1.0 \times 10^{-4} \le |\varepsilon_e| \le 10^{-3}$.

Thank you for your attention