Search for new light vector boson using J/ψ at e^+e^- colliders

Youngjoon Kwon

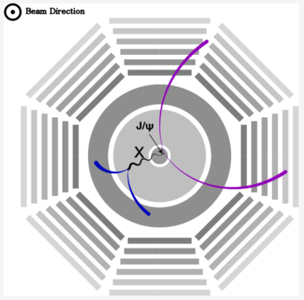
yjkwon63@yonsei.ac.kr

Yonsei University
Seoul, Korea

Mar. 16, 2021 @ QWG 2021

Outline

- Introduction & motivations
- Modeling of the interaction
- Using $J/\psi \to \eta_c\, e^+ e^-$
  - * method for BESIII
  - * method for Belle II
- Using $e^+ e^- \to X + J/\psi$ (with *displaced vertex*)
- Summary



(Note 1) *based on* `arXiv:2012.04190`, *to appear in JHEP* (K. Ban, Y. Jho, YJK, S.C. Park, S.H. Park, P.Y. Tseng).

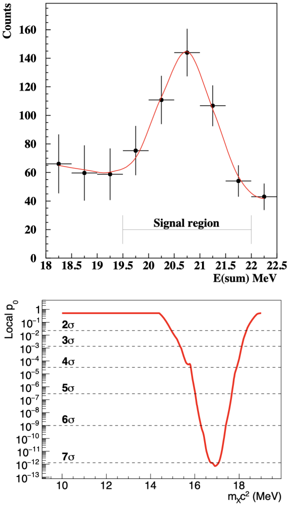
(Note 2) *This is a phenomenological work. Any mention of BESIII or Belle II is only for conceptual discussions.*

Motivations

- $\exists$ experimental and observational claims for discrepancies from the SM
- calling for extension of the SM
  - e.g. by adding a new sector gauging the lepton number, $L_\mu - L_\tau$
  - proposed for $(g-2)_\mu$, DM, EDGES 21 cm anomaly, etc.
- $X17$ 'anomaly' from ATOMKI
  - $^8\mathrm{Be}^*(1^+) \to {}^8\mathrm{Be}(0^+) + e^+e^-$
  - is it a new particle with $m_X \sim 17$ MeV?
- High-$\mathcal{L}$ e^+e^- colliders – ideal place to test $X17$

Motivations

- $\exists$ experimental and observational claims for discrepancies from the SM
- calling for extension of the SM
  - * e.g. by adding a new sector gauging the lepton number, $L_\mu - L_\tau$
  - * proposed for $(g-2)_\mu$, DM, EDGES 21 cm anomaly, etc.
- $X17$ 'anomaly' from ATOMKI
  - * $^8\text{Be}^*(1^+) \to {}^8\text{Be}(0^+) + e^+e^-$
  - * is it a new particle with $m_X \sim 17$ MeV?
- High-$\mathcal{L}$ e^+e^- colliders – ideal place to test $X17$



ATOMKI, arXiv:1910.10459

Modeling $\mathcal{L}_{\text{eff}}$

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

- X – a new vector boson interacting with an SM fermion f via $\mathcal{L}_{\text{eff}}$
- ε_f – a free (effective) parameter for the $Xf\bar{f}$ coupling
- (Note) the new interactions do not induce any gauge anomaly by construction

- ATOMKI $\Rightarrow m_X \simeq 17$ MeV, $|\varepsilon_u + \varepsilon_d| \simeq 3.7 \times 10^{-3}$
- NA48/2 ($\pi^0 \to X\gamma$) $\Rightarrow |2\varepsilon_u + \varepsilon_d| < 8 \times 10^{-4}$ (*protophobic*)
  combining the two, $\varepsilon_u \simeq \pm 3.7 \times 10^{-3}$, $\varepsilon_d \simeq \mp 7.4 \times 10^{-3}$
- for coupling to leptons, use beam dump (SLAC E141), $(g-2)_\mu$, νe scattering

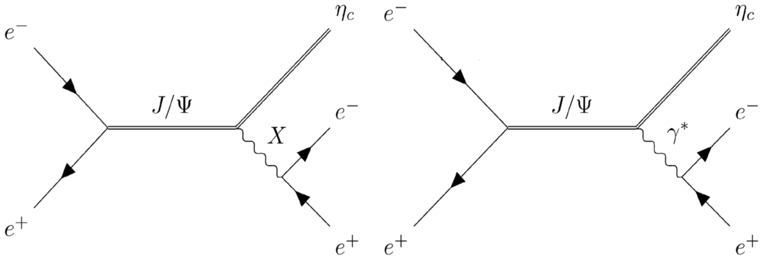
$$4.2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}$$

$$\sqrt{\varepsilon_e \varepsilon_\nu} \lesssim 7 \times 10^{-5}$$

Method for BESIII

- Use $e^+e^- \to J/\psi \to \eta_c X(\to e^+e^-)$ at $\sqrt{s} = m_{J/\psi}$ for the signal process
- $e^+e^- \to J/\psi \to \eta_c\, \gamma^*(\to e^+e^-)$
  - an SM background; same final state as the signal

decay width



Method for BESIII

- Use $e^+e^- \to J/\psi \to \eta_c X(\to e^+e^-)$ at $\sqrt{s} = m_{J/\psi}$ for the signal process
- $e^+e^- \to J/\psi \to \eta_c\, \gamma^*(\to e^+e^-)$
  - * an SM background; same final state as the signal
- decay width

$$\Gamma(J/\psi \to \eta_c\gamma) = \frac{1}{3}\frac{\alpha_{\rm EM}(m_{J/\psi}^2 - m_{\eta_c}^2)^3}{8m_{J/\psi}^3}|f_{\rm VP}(0)|^2$$

$$\frac{d\Gamma_{\eta_c\gamma^*}}{dq^2\Gamma_{J/\psi\to\eta_c\gamma}} = |F_{\rm VP}(q^2)|^2 \times F_{\rm QED}(q^2)$$

$$\frac{d\Gamma_{\eta_c X^*}}{dq^2\Gamma_{J/\psi\to\eta_c\gamma}} = |F_{\rm VP}(q^2)|^2 \times F_X(q^2)$$

- * $F_{\rm VP}(q^2) \equiv f_{\rm VP}(q^2)/f_{\rm VP}(0) = 1/(1 - \frac{q^2}{\Lambda^2})$, with $\Lambda = m_{\psi'} \approx 3.69$ GeV for J/ψ
- * kinematic window : $(2m_e)^2 \le q^2 = m_{e^+e^-}^2 \le (m_{J/\psi} - m_{\eta_c})^2$

Method for BESIII

$$\Gamma(J/\psi \to \eta_c\gamma) = \frac{1}{3}\frac{\alpha_{\rm EM}(m_{J/\psi}^2 - m_{\eta_c}^2)^3}{8m_{J/\psi}^3}|f_{\rm VP}(0)|^2$$

$$\frac{d\Gamma_{\eta_c\gamma^*}}{dq^2\Gamma_{J/\psi\to\eta_c\gamma}} = |F_{\rm VP}(q^2)|^2 \times F_{\rm QED}(q^2)$$

$$\frac{d\Gamma_{\eta_c X^*}}{dq^2\Gamma_{J/\psi\to\eta_c\gamma}} = |F_{\rm VP}(q^2)|^2 \times F_X(q^2)$$

$$\mathrm{QED}(q^2) = \frac{\alpha}{3\pi}\frac{1}{q^2}\left(1-\frac{4m_l^2}{q^2}\right)^{\frac{1}{2}}\left(1+\frac{2m_l^2}{q^2}\right) \times \left[\left(1+\frac{q^2}{m_V^2-m_P^2}\right)^2 - \frac{4m_V^2q^2}{(m_V^2-m_P^2)^2}\right]^{\frac{3}{2}}.$$

from L.-M. Gu *et al.*, PRD 100, 016018 (2019)

$$F_X(q^2) = \frac{\alpha_{\rm EM}(\varepsilon_c\cdot\varepsilon_e)^2}{3\pi}\left(\frac{q^2}{\left[(q^2-m_X^2)^2+m_X^2\Gamma_X^2\right]}\right) \times\left(1-\frac{4m_e^2}{q^2}\right)^{1/2}\left(1+\frac{2m_e^2}{q^2}\right)\left[\left(1+\frac{q^2}{m_{J/\psi}^2-m_{\eta_c}^2}\right)^2-\frac{4m_{J/\psi}^2q^2}{(m_{J/\psi}^2-m_{\eta_c}^2)^2}\right]^{3/2}$$

$$\Gamma_{X\to e^+e^-} = \frac{\varepsilon_e^2\alpha_{\rm EM}m_X}{3}\left(1+\frac{2m_e^2}{m_X^2}\right)\sqrt{1-\frac{4m_e^2}{m_X^2}}$$

$\Gamma_{X\to e^+e^-}$ dominates the width as we assume very small ε_ν and $m_X < 2m_\pi$

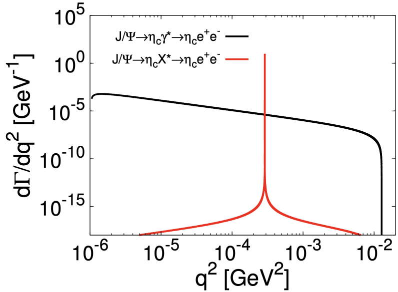
Method for BESIII

Collecting the above information, we have

$$\mathcal{B}(J/\psi \to \eta_c X^* \to \eta_c\, e^+ e^-) = 1.64 \times 10^{-6} \left(\frac{\varepsilon_c}{10^{-2}}\right)^2$$

$$\mathcal{B}(J/\psi \to \eta_c \gamma^* \to \eta_c\, e^+ e^-) = 1.03 \times 10^{-4}$$

and the q^2 dependence becomes



$\eta_c X^*$ and $\eta_c \gamma^*$ are clearly separated

Expected sensitivity for BESIII

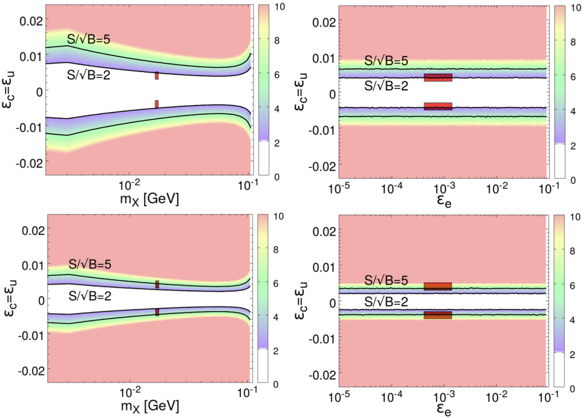
$$S = N_{J/\psi} \times \frac{\int_{(m_X-\sigma_m)^2}^{(m_X+\sigma_m)^2} dq^2 \frac{d\Gamma_{\eta_c X^*}}{dq^2}}{\Gamma_{J/\psi}}, \quad B = N_{J/\psi} \times \frac{\int_{(m_X-\sigma_m)^2}^{(m_X+\sigma_m)^2} dq^2 \frac{d\Gamma_{\eta_c \gamma^*}}{dq^2}}{\Gamma_{J/\psi}}$$

TABLE II. 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 $J/\Psi \to \eta_c e^+ e^-$ with various energy resolutions of detector and 1.23% η_c reconstruction efficiency.

	σ_m=1 MeV	σ_m=2 MeV	σ_m=5 MeV	σ_m=10 MeV	σ_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

$$1.23\% = \sum_i \mathcal{B}_i \epsilon_i$$

Expected sensitivity for BESIII



(Top) $N_{J/\psi} = 10^{10}$

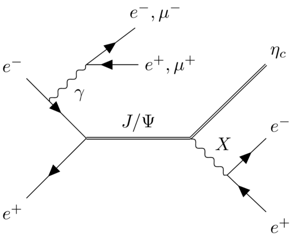
(Bottom) $N_{J/\psi} = 10^{11}$

■ ATOMKI allowed

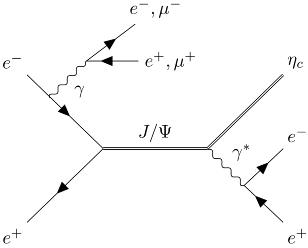
- Instead of explicitly reconstructing η_c, one may use the recoil mass against e^+e^- to check η_c thus avoiding the 1.23% scale. Due to small mass gap ($J/\psi - \eta_c$), identification of e^+e^- might be an issue experimentally.

Method (1) for Belle II

- Use $e^+e^- \to \ell^+\ell^- + J/\psi(\to \eta_c\, e^+e^-)$



signal $J/\psi \to X\eta_c$

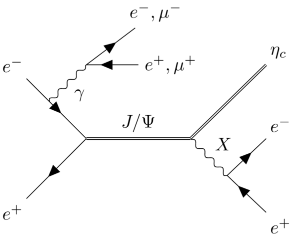


background $J/\psi \to \gamma^*\eta_c$

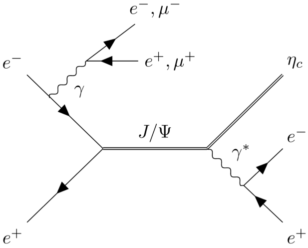
$\sigma(e^+e^- \to \gamma^* + J/\psi \to e^+e^- J/\psi) = 286$ fb, $\sigma(e^+e^- \to \gamma^* + J/\psi \to \mu^+\mu^- J/\psi) = 58.4$ fb

Method (1) for Belle II

- Use $e^+e^- \to \ell^+\ell^- + J/\psi(\to \eta_c\, e^+e^-)$



signal $J/\psi \to X\eta_c$



background $J/\psi \to \gamma^*\eta_c$

$$\sigma(e^+e^- \to \gamma^* + J/\psi \to e^+e^- J/\psi) = 286\text{ fb}, \quad \sigma(e^+e^- \to \gamma^* + J/\psi \to \mu^+\mu^- J/\psi) = 58.4\text{ fb}$$

- S and B to estimate the expected sensitivity

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

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

Method (1) for Belle II – MC study

- Use MadGraph & FeynRules for simulation with EM decay amplitude[1]

$$T(V \to P\, e^+ e^-) = 4\pi\alpha_{\rm EM}\, f_{\rm VP}\; \epsilon^{\mu\nu\rho\sigma} p_\mu q_\nu \epsilon_\rho \frac{1}{q^2} \bar{u}_1 \gamma_\sigma v_2$$

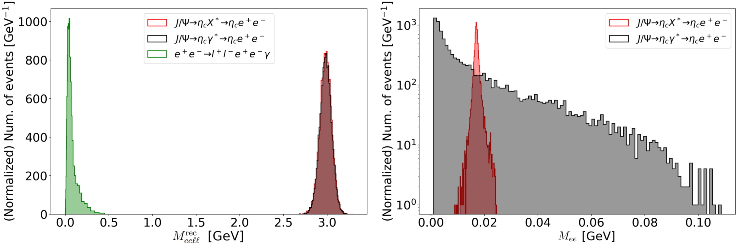
and interaction $\mathcal{L}$

$$\mathcal{L} \supset f_{\rm VP}(-2\sqrt{\pi\alpha_{\rm EM}}\partial_\mu P \partial_\nu V_\rho \epsilon^{\mu\nu\rho\sigma} A_\sigma - g_{Xc}\partial_\mu P \partial_\nu V_\rho \epsilon^{\mu\nu\rho\sigma} X_\sigma) - g_{eV}\bar{e}\gamma^\mu e V_\mu - g_{Xe}\bar{e}\gamma^\mu e X_\mu$$

- Background control
  - baseline cuts
    $|\eta^*_{\ell^\pm}| \le 1.60$ (CM frame); $|E_{\mu^\pm}| \ge 0.6$ GeV, and $|E_{e^\pm}| \ge 0.06$ GeV (lab frame)
  - photon conversion in the beam pipe or vertex detector – use e^+e^- vertex position
  - $e^+e^- \to \ell^+\ell^-$ +(anything) – low-momentum charged particles in the "anything" may fake the e-ID, but it does not peak in $M^{\rm recoil}_{\ell^+\ell^-} \simeq m_{J/\psi}$

[1] L.-M. Gu *et al.*, PRD **100**, 016018 (2019)

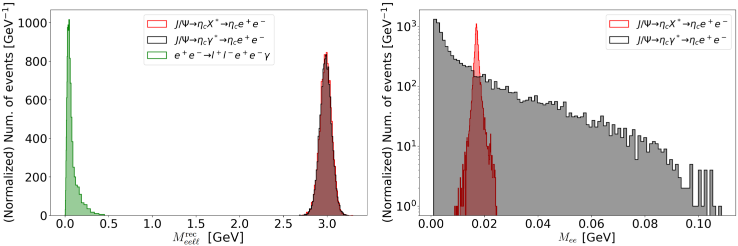
Method (1) for Belle II – MC study



[Left] Recoil mass against $e^+e^-\ell^+\ell^-$, whereby non-J/ψ, non-η_c events can be suppressed; [Right] Invariant mass of e^+e^-, looking for any peaking structure

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

Method (1) for Belle II – MC study



[Left] Recoil mass against $e^+e^-\ell^+\ell^-$, whereby non-J/ψ, non-η_c events can be suppressed; [Right] Invariant mass of e^+e^-, looking for any peaking structure

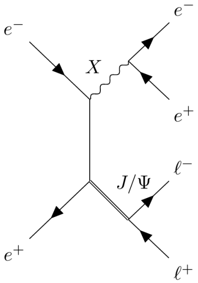
Processes	(B) $\eta_c\gamma^* \to \eta_c ee$	(S) $\eta_c X \to \eta_c ee$
N(generated)	100000	100000
Baseline Cuts	7170	6290
$\lvert M_{ee\ell\ell}^{\rm rec} - m_{\eta_c}\rvert \le 200$ MeV	7071	6219
$\lvert M_{ee} - m_X\rvert \le 2$ MeV	**377**	**5880**

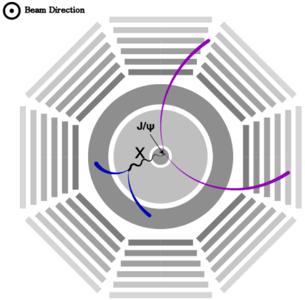
Luminosity	50 ab^{-1}	100 ab^{-1}	200 ab^{-1}
$\lvert\varepsilon_c\rvert$	$\gtrsim 1.76\times10^{-2}$	$\gtrsim 1.48\times10^{-2}$	$\gtrsim 1.24\times10^{-2}$

Sensitivity on ε_c, by requiring $S/\sqrt{B} = 2$

Method (2) for Belle II – displaced vertex

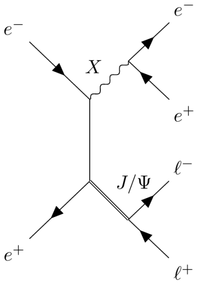
- $e^+e^- \to X(\to e^+e^-) + J/\psi(\to \ell^+\ell^-)$
  - * Xee vertex at tree level $\Rightarrow$ signal strength depends on ε_e only

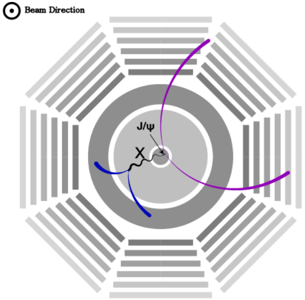




Method (2) for Belle II – displaced vertex

- $e^+e^- \to X(\to e^+e^-) + J/\psi(\to \ell^+\ell^-)$
  - * Xee vertex at tree level $\Rightarrow$ signal strength depends on ε_e only



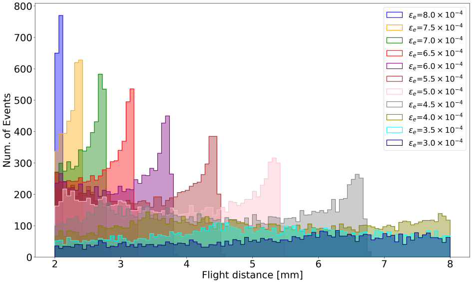


  - * γ conversion (as main SM bkgd.) at the beampipe ($r_\perp \sim 1.0$ cm) and vertex detector layers ($r_\perp \gtrsim 1.4$ cm)
  - * exploit the Belle II vertexing capability
  - * $e^\pm$ from X tend to have high-p_T ($\gtrsim \mathcal{O}(1)$ GeV), enabling clean e-ID

Method (2) for Belle II – displaced vertex

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

- transverse flight distance of X
  - * Figure (below) for $0.3 \times 10^{-3} \leq \varepsilon_e \leq 0.8 \times 10^{-3}$



  - * '$r_\perp$ sweet spot' (cut) $\Rightarrow$ 2 mm $\leq r_\perp \leq$ 8 mm

Method (2) for Belle II – sensitivity estimation

- (Case 1) Explicitly reconstruct $J/\psi \to \ell^+\ell^-$ ('$e^+e^-\ell^+\ell^-$ channel')

$\varepsilon_e/10^{-4}$	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
2mm < $r_\perp$ < 8mm (%)	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

Method (2) for Belle II – sensitivity estimation

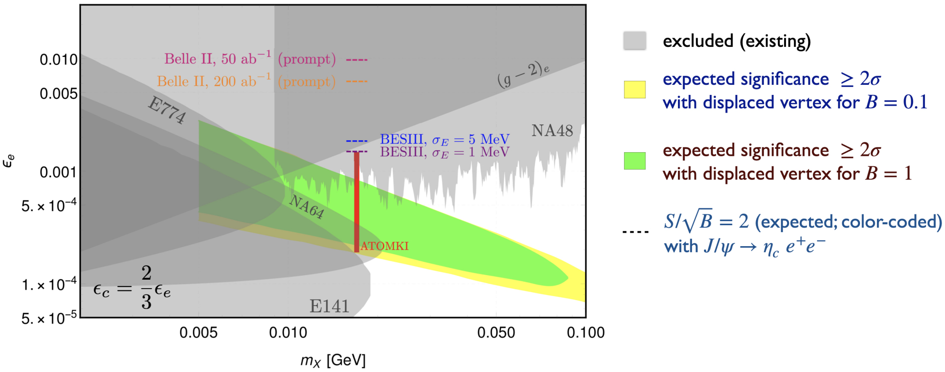
- (Case 1) Explicitly reconstruct $J/\psi \to \ell^+\ell^-$ ('$e^+e^-\ell^+\ell^-$ channel')

$\varepsilon_e/10^{-4}$	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
2mm < $r_\perp$ < 8mm (%)	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

- (Case 2) Use recoil against $X \to e^+e^-$ to infer J/ψ ('e^+e^- channel')

$\varepsilon_e/10^{-4}$	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

Summary



- Motivated by ATOMKI, we investigate strategies to search for X in $\mathcal{O}(10)$ MeV using J/ψ at the intensity-frontier e^+e^- colliders (BESIII & Belle II).
- With displaced-vertex signature at Belle II, $10^{-4} \lesssim |\varepsilon_e| \lesssim 10^{-3}$ can be explored for 9 MeV $\lesssim m_X \lesssim 100$ MeV with 50 ab^{-1} at Belle II.

Thank you!