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

Yongsoo Jho (Yonsei U.)

Based on **arXiv:2012.04190 [hep-ph]**

Collaboration with
Kayoung Ban (Yonsei U.), Youngjoon Kwon (Yonsei U.),
Seong Chan Park (Yonsei U.),
Seokhee Park (KEK) and Po-Yan Tseng (Yonsei U.)

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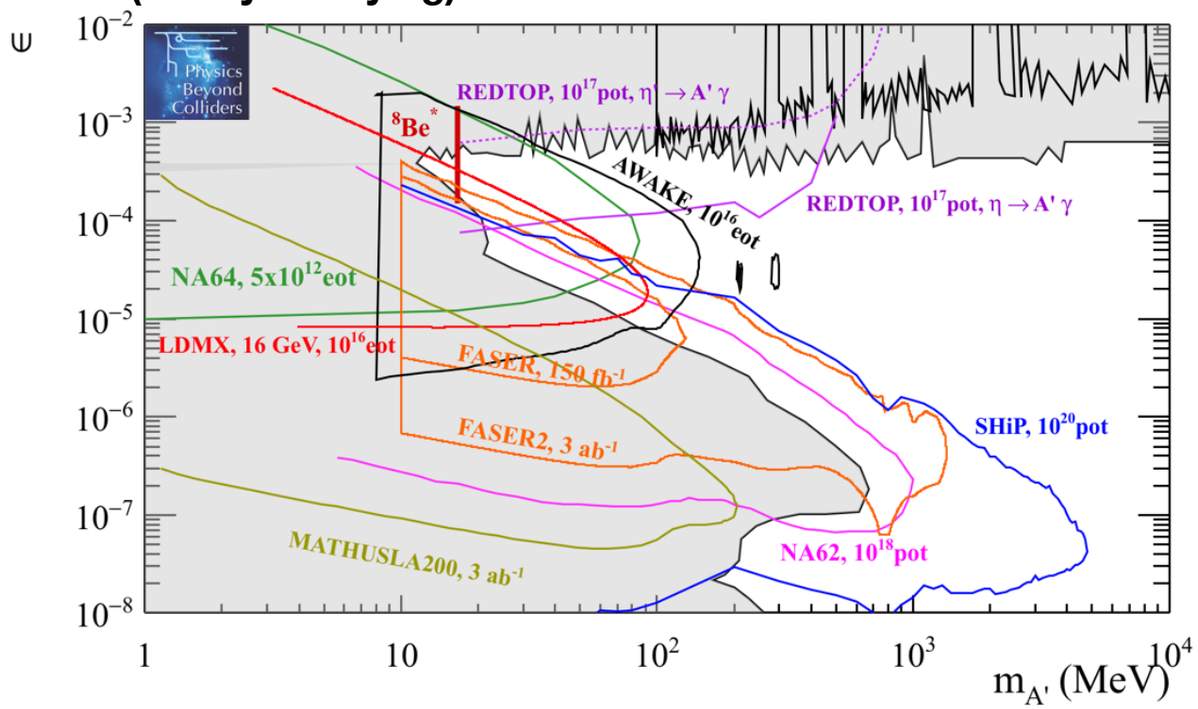
“Dark Matter as a Portal to New Physics”
APCTP, Pohang

Light (MeV-GeV) mediator (to dark sector) searches are recently very active (utilizing various current/future accelerator & fixed target experiments)

DP (visibly decaying)



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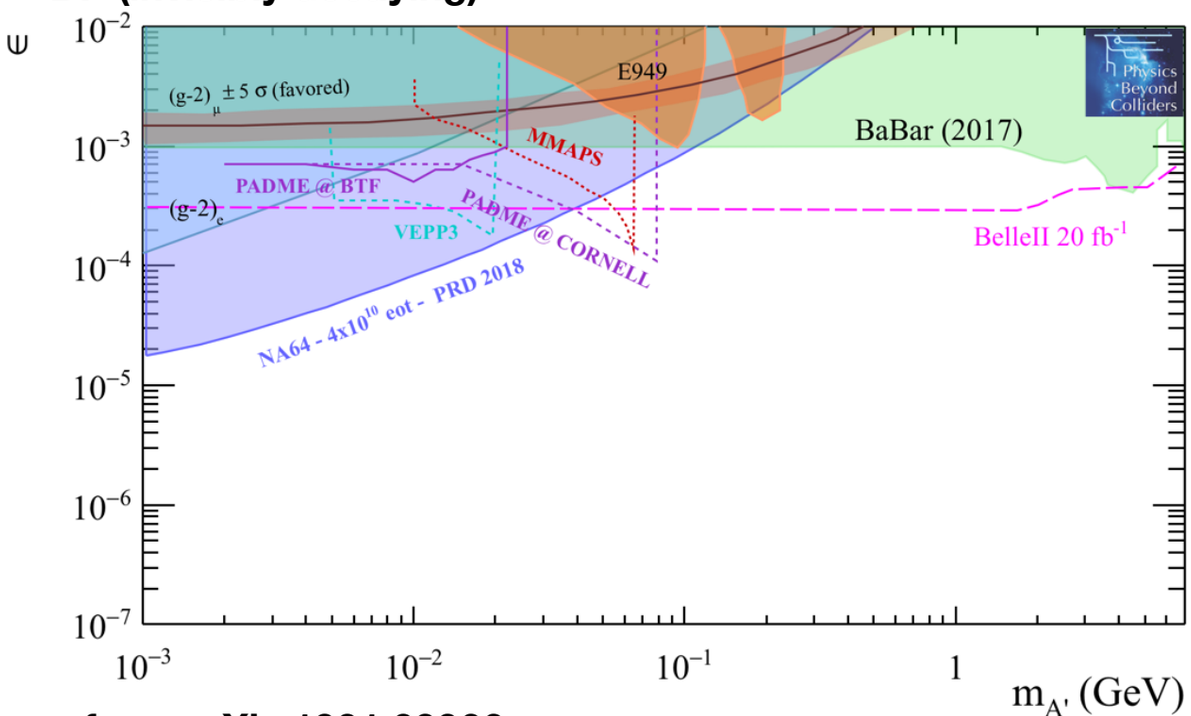

Figures from arXiv:1901.09966

- **Some Low energy discrepancies**
  - $(g-2)_{e,\mu}$
  - $K_L \to \pi^0 + (\text{invisible})$ **J-PARC KOTO**
  - $^8\text{Be}^*/^4\text{He}$ **ATOMKI**

  and so on..
- **Mediator to Sub-GeV dark sector**
- **For gauge interaction,**

$$U(1)_D, U(1)_{B-L}, U(1)_{L_i-L_j}, U(1)_{B-3L_i}, ..$$

- **In this study, We utilize J/Psi production and its decay process to probe light vector boson and its interactions**

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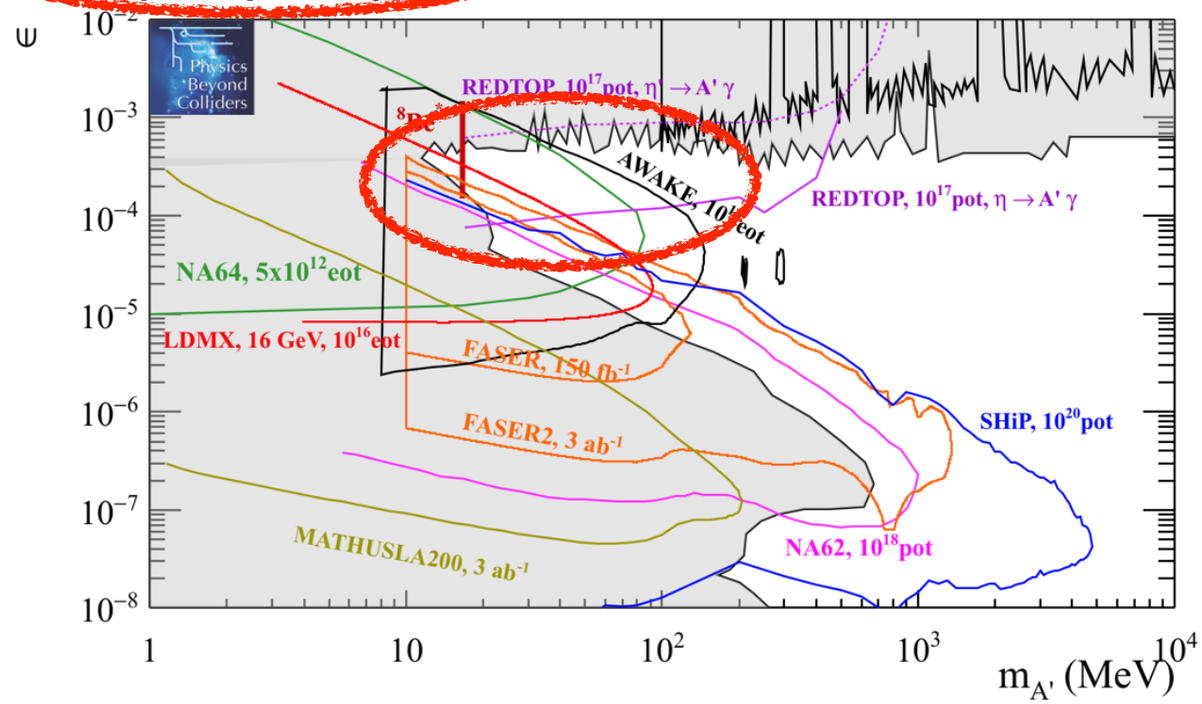

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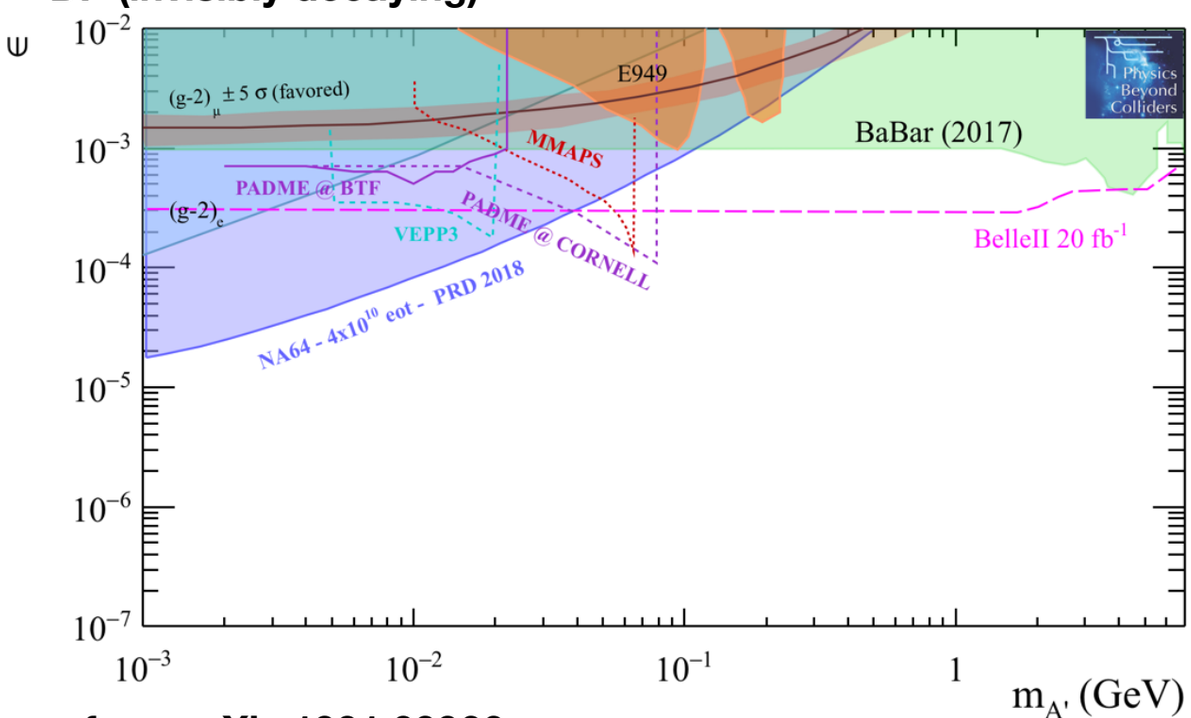

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Model & ballpark parameters

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

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

- For the one possible interpretation of ATOMKI anomaly in the transitions of $^8\mathrm{Be}^*/^4\mathrm{He}$ prefer: $|\varepsilon_u + \varepsilon_d| \simeq 3.7 \times 10^{-3}$

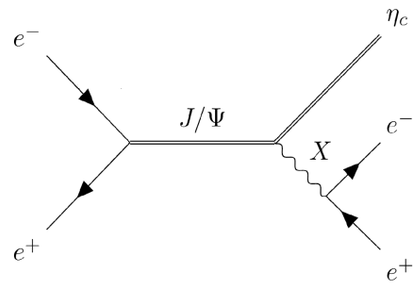
- For the couplings to first generation quarks, the constraint from NA48/2 for $\pi^0 \to X\gamma$ requires protophobic condition: $|2\varepsilon_u + \varepsilon_d| < 8 \times 10^{-4}$

- Taking both relations into account, we finally get the preferred value for up-type and down-type quark couplings: $\varepsilon_u \simeq \pm 3.7 \times 10^{-3}$, $\varepsilon_d \simeq \mp 7.4 \times 10^{-3}$

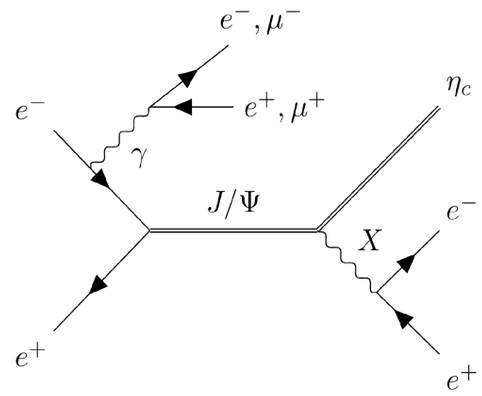
- The coupling to the leptons, especially to electron, are stringently constrained by the beam dump experiment SLAC E141, the anomalous magnetic moment of the electron $(g-2)$: $4.2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}$

Three options using J/Psi for search of light vector boson X

- Search for light vector boson at BESIII
  $J/\psi \to \eta_c X \to \eta_c e^+ e^-$ $\epsilon_e\ \epsilon_c$



- Search for light vector boson at Belle II (prompt)
  $e^- e^+ \to \ell^+ \ell^- J/\psi (\to \eta_c X \to \eta_c e^+ e^-) \quad (\ell = e, \mu)$ $\epsilon_e\ \epsilon_c$



- Search for light vector boson at Belle II (displaced)
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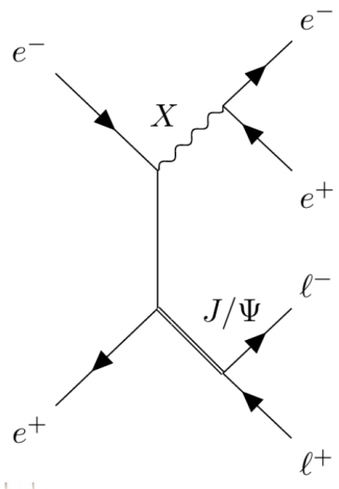
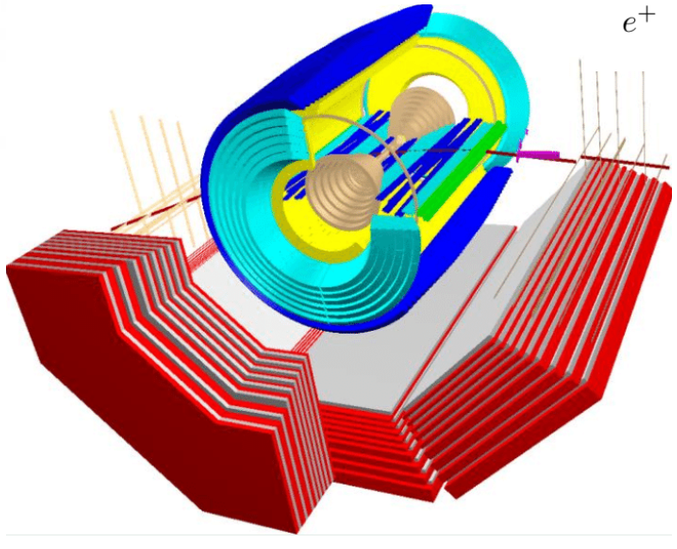
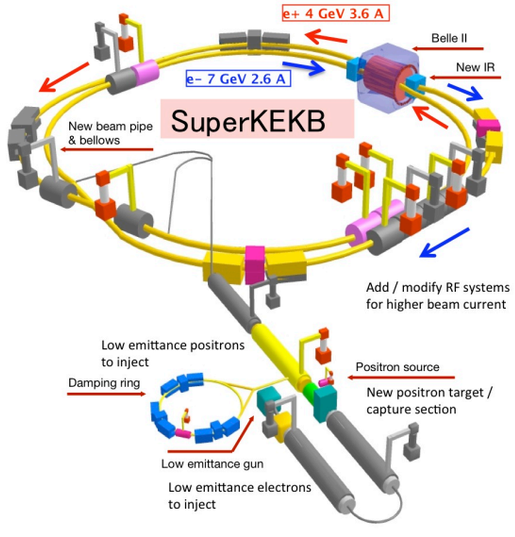
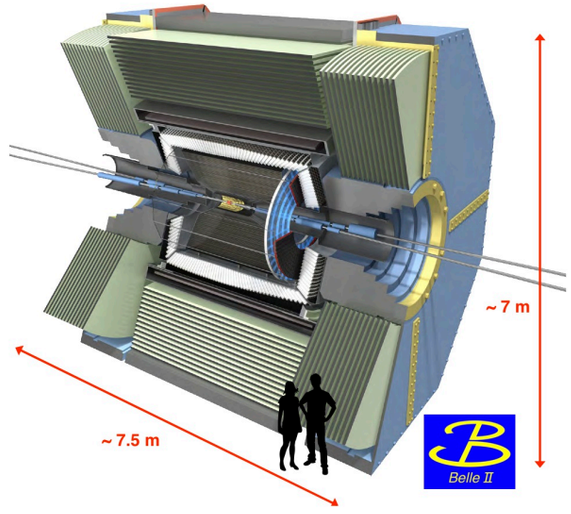


BESIII







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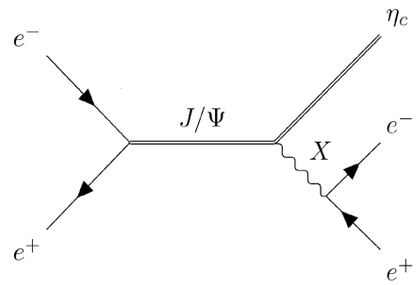

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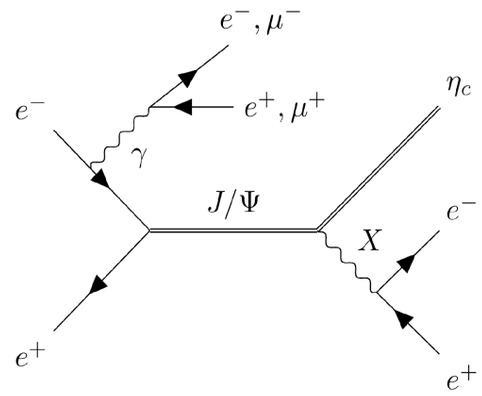

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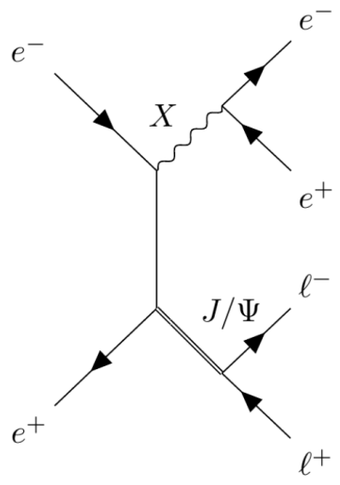

$V = J/\psi(c\bar{c})$

$P = \eta_c(c\bar{c})$

$$\mathcal{L} \supset f_{VP}(\underbrace{-2\sqrt{\pi\alpha_{\rm EM}}\partial_\mu P \partial_\nu V_\rho \epsilon^{\mu\nu\rho\sigma} A_\sigma}_{J/\psi \to \eta_c + \gamma/\gamma^*} \underbrace{- g_{Xc}\partial_\mu P \partial_\nu V_\rho \epsilon^{\mu\nu\rho\sigma} X_\sigma}_{J/\psi \to \eta_c + X}) \underbrace{- g_{eV}\bar{e}\gamma^\mu e V_\mu}_{e^+e^- \to J/\psi} \underbrace{- g_{Xe}\bar{e}\gamma^\mu e X_\mu}_{X \to e^+e^-}$$

$e\epsilon_c$ $e\epsilon_e$

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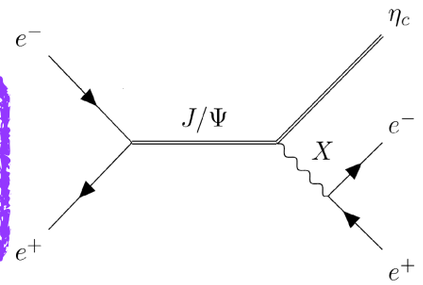

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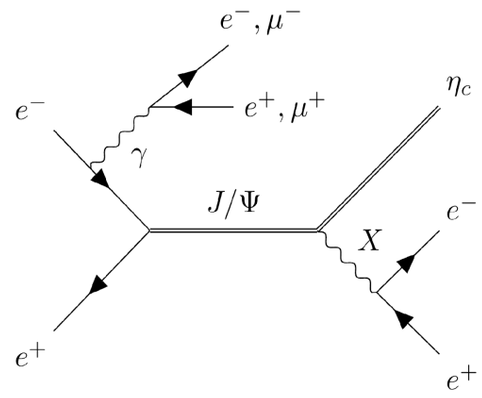

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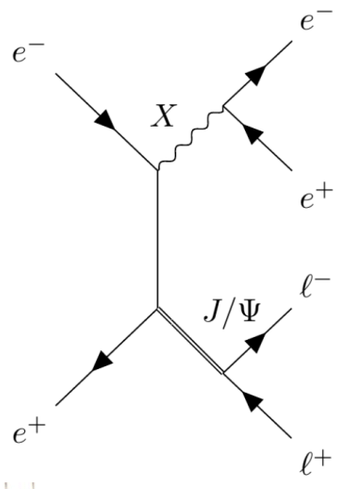
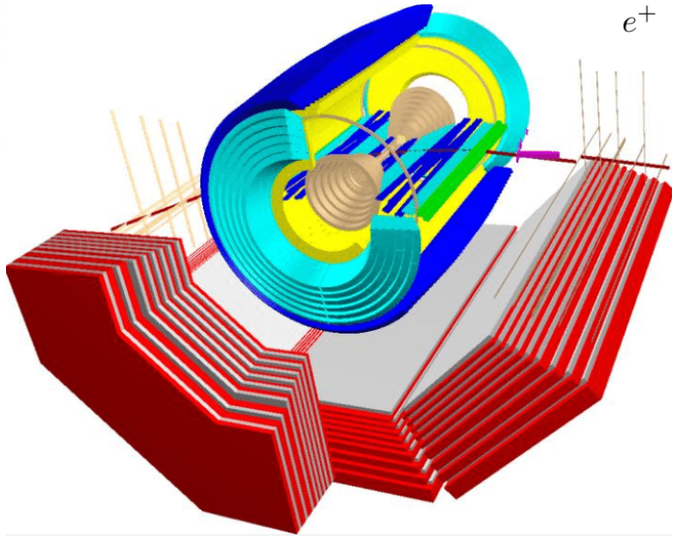
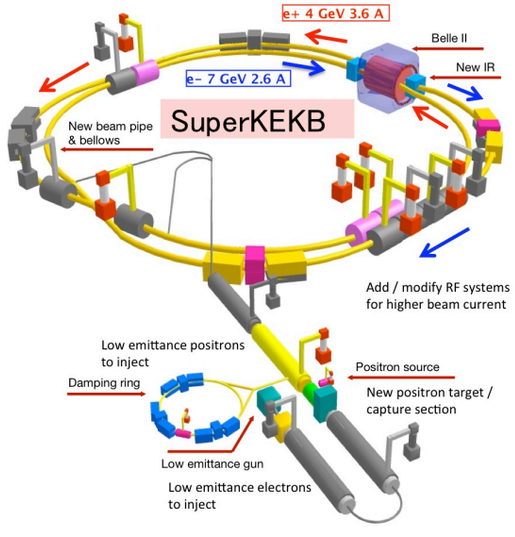
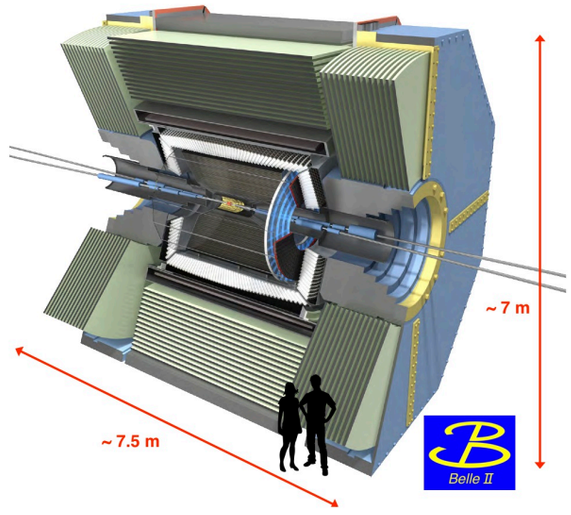


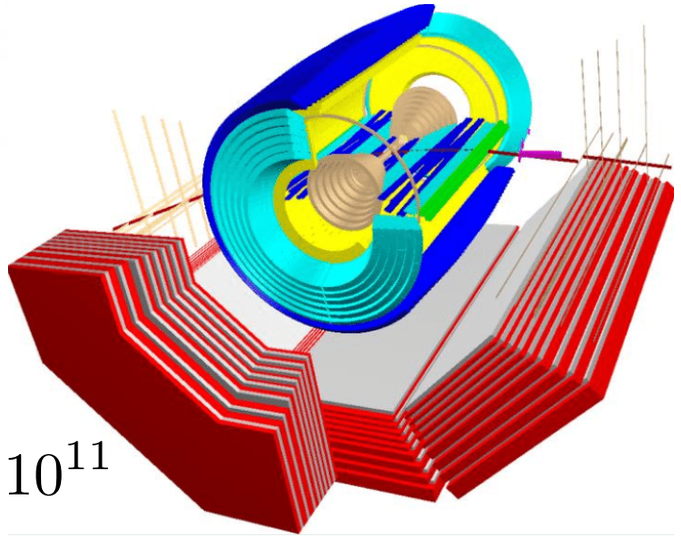






Search for X boson at BESIII

- BESIII is a resonant machine for J/Psi production
- BESIII have (currently) collected $N_{J/\psi} \sim 10^{10}$
- With the target integrated luminosity, The goal of BESIII is $N_{J/\psi} \sim 10^{11}$



- Form factor & Phase space factor

$$F_{VP}(q^2) \equiv f_{VP}(q^2)/f_{VP}(0) = 1/(1-\frac{q^2}{\Lambda^2})$$

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

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

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

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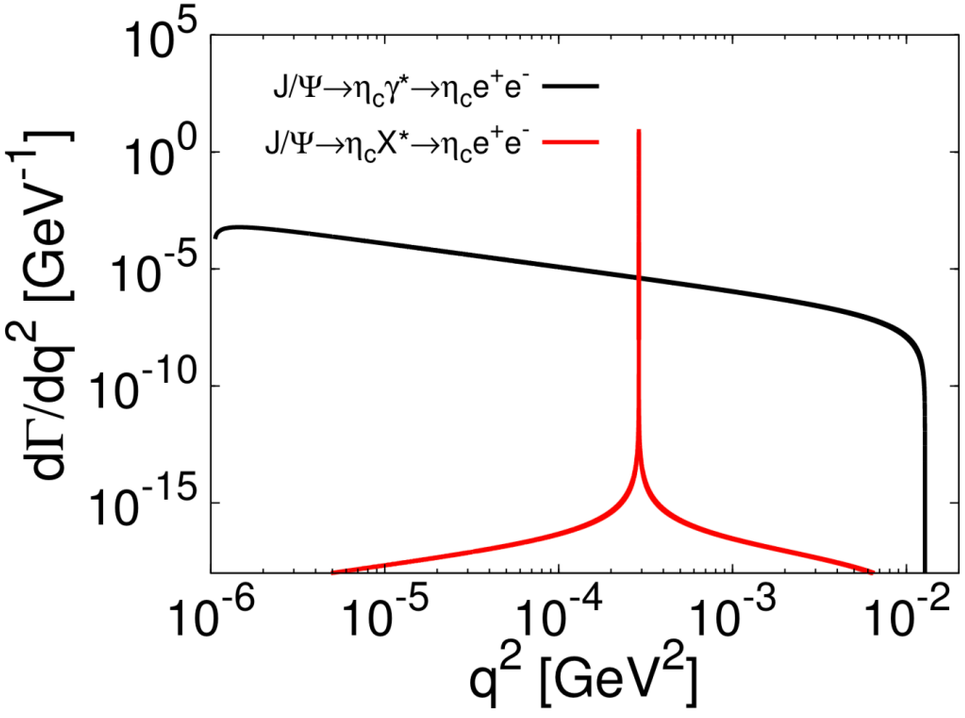
- Just increasing S/B using ee recoil mass cut



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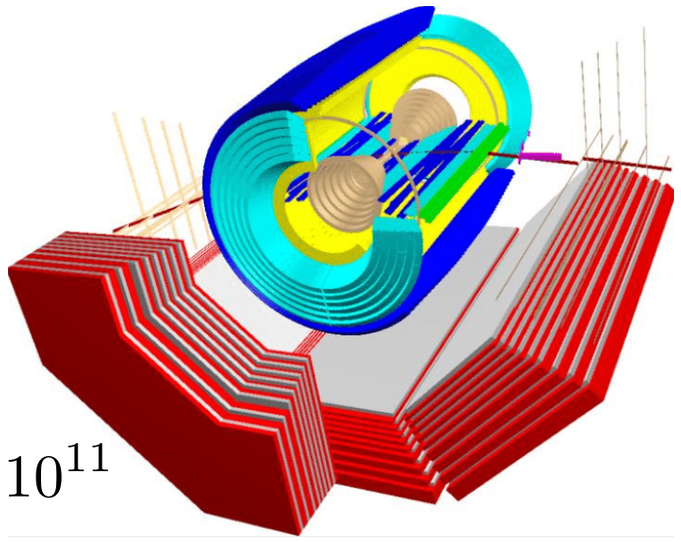
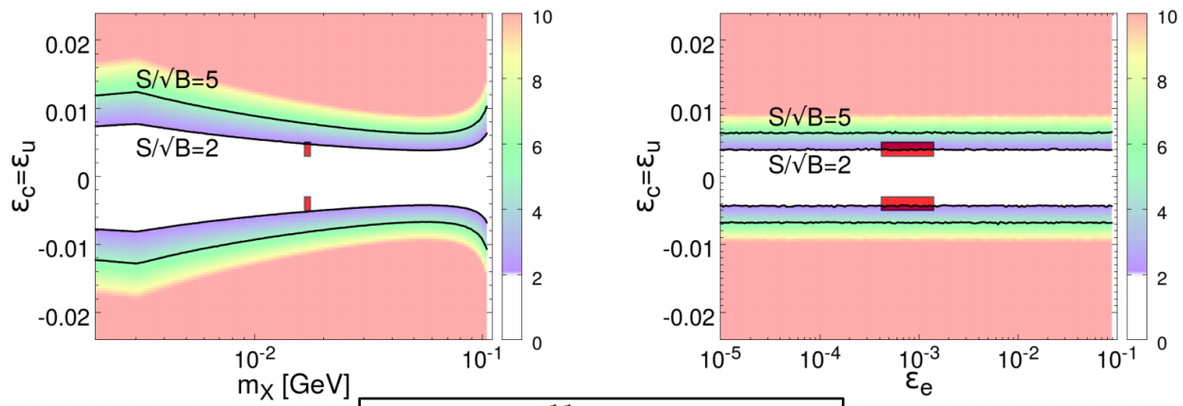


$|\varepsilon_c| \gtrsim 5 \times 10^{-3}$ at $m_X \simeq 17$ MeV

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

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



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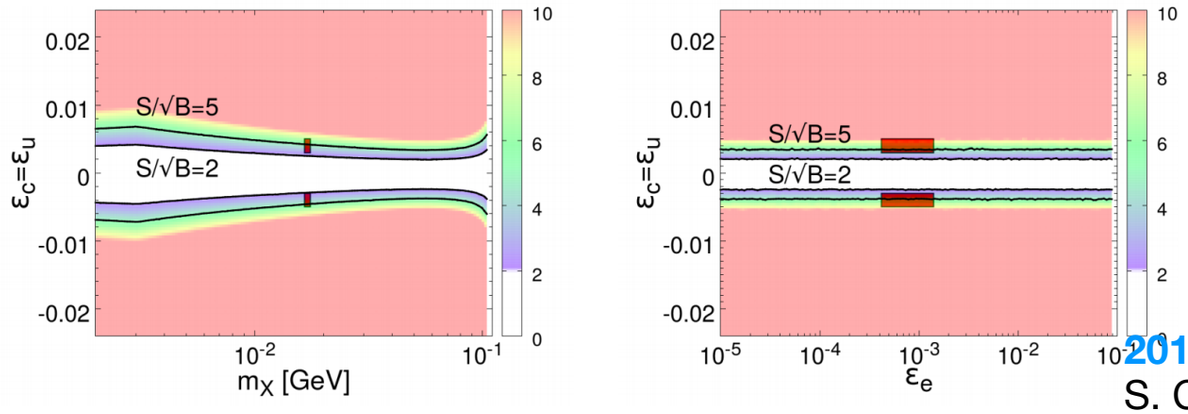
$N_{J/\Phi} = 10^{11}$(bottom panels)



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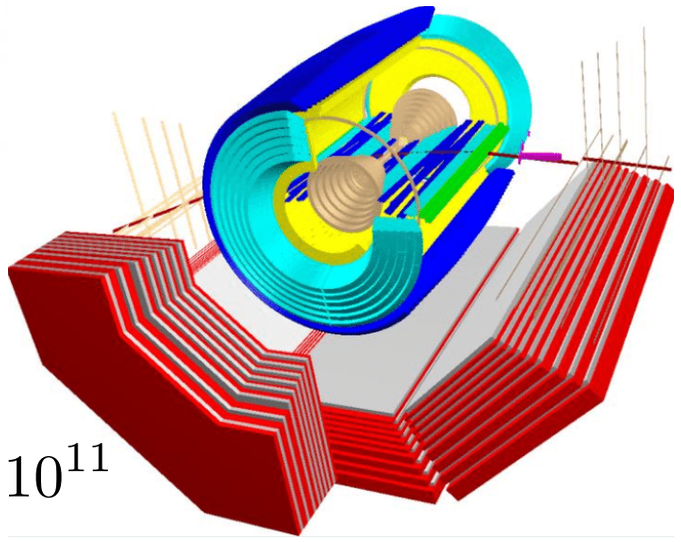

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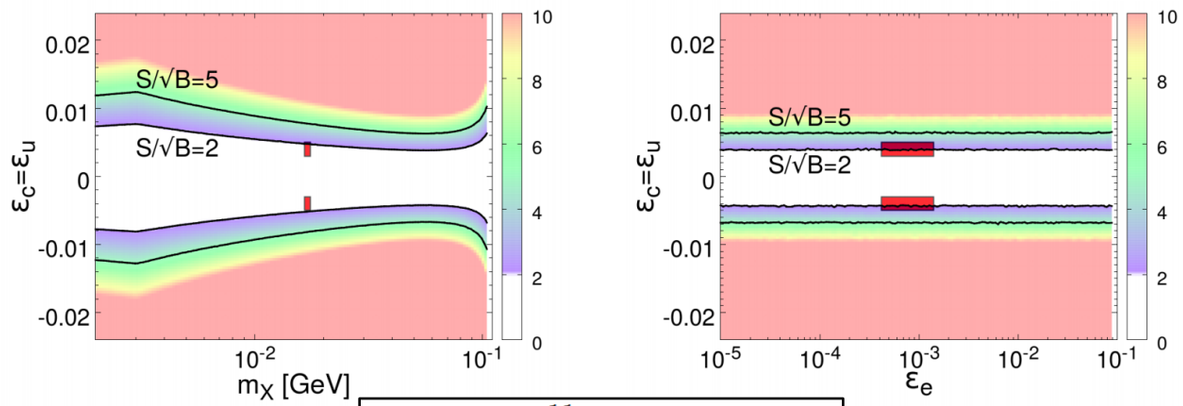

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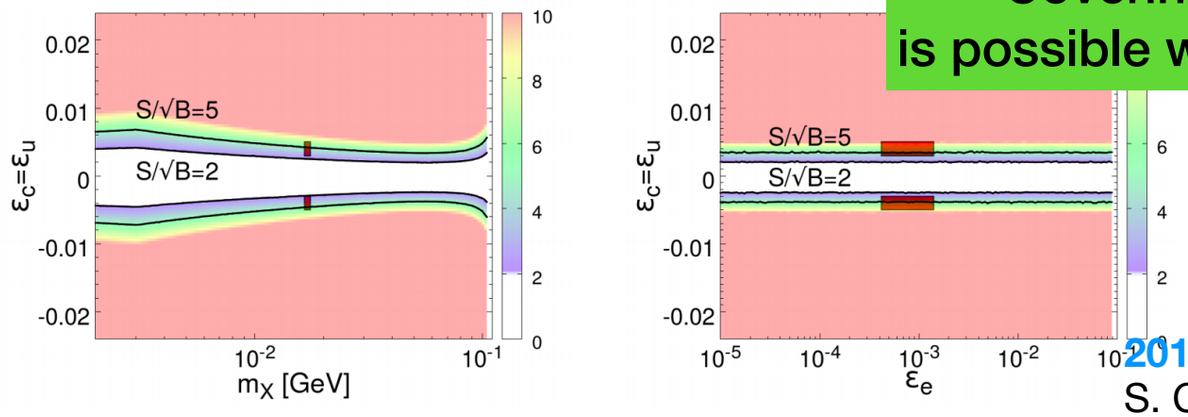

Covering ATOMKI desired region of ϵ_c is possible with the goal luminosity of BESIII

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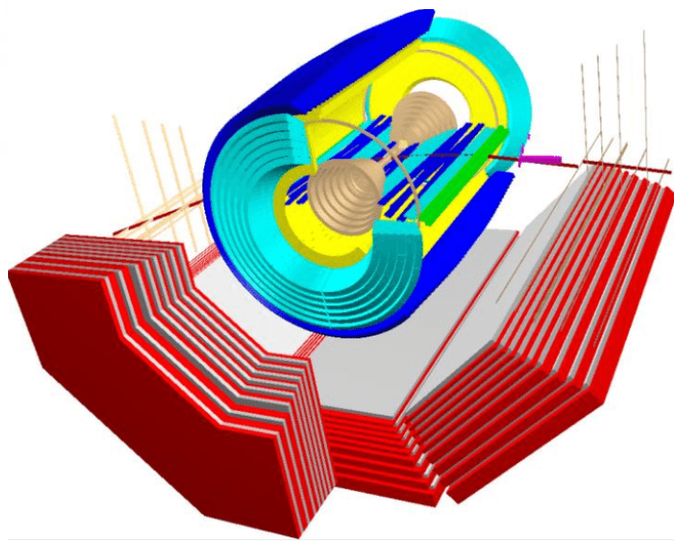
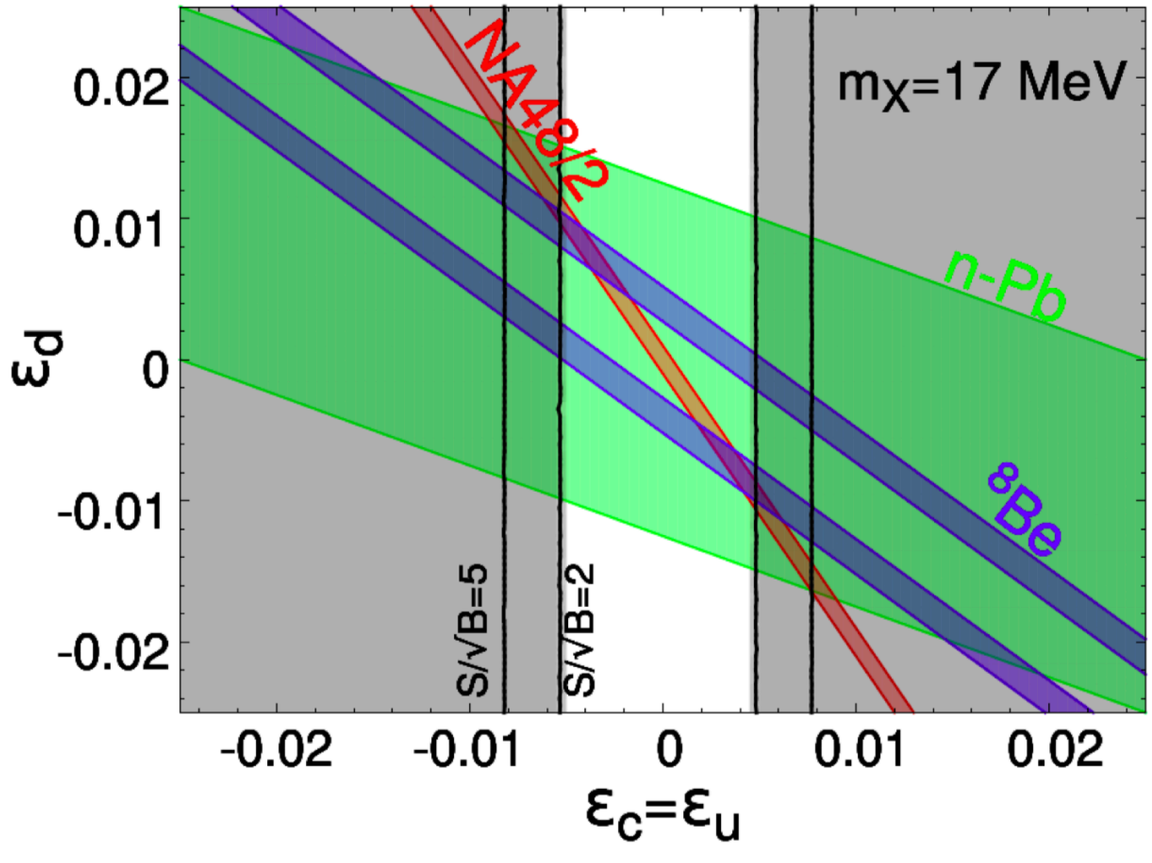
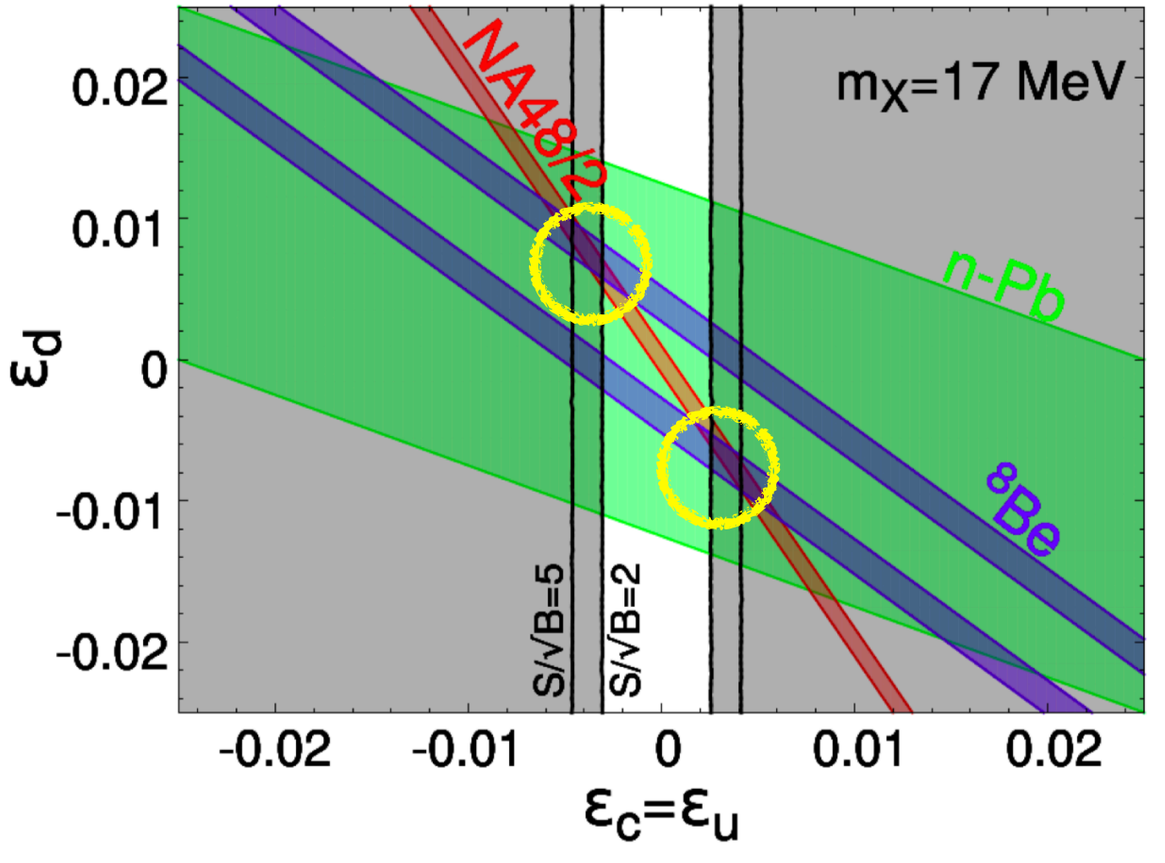


- Sensitivity limit in the protophobic scenario





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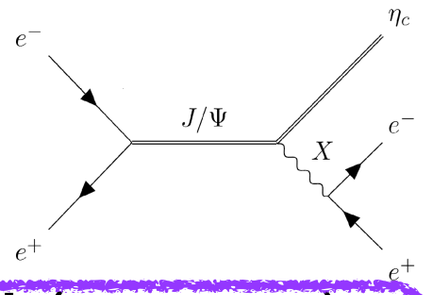

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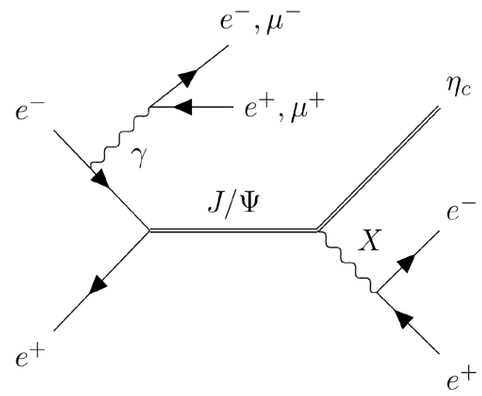

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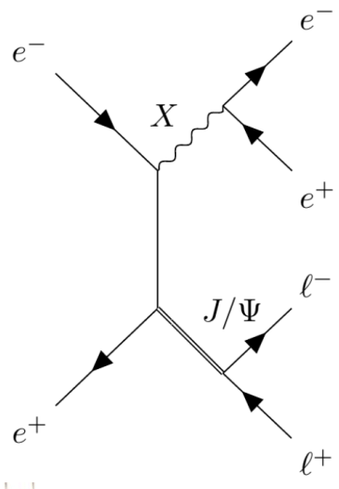

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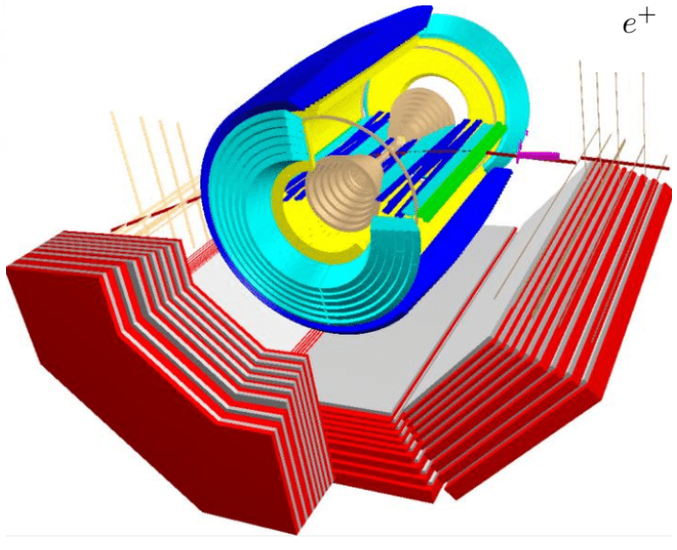
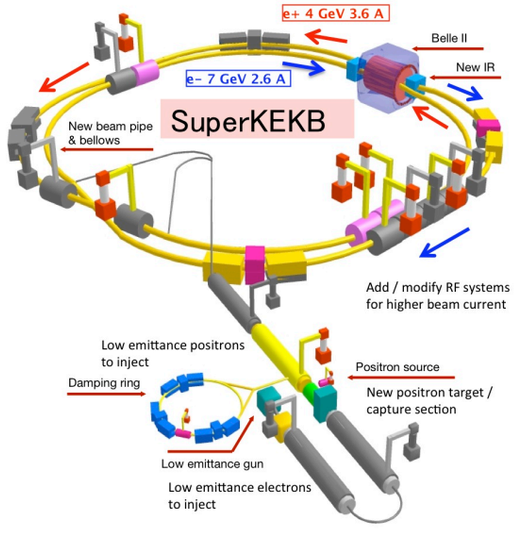
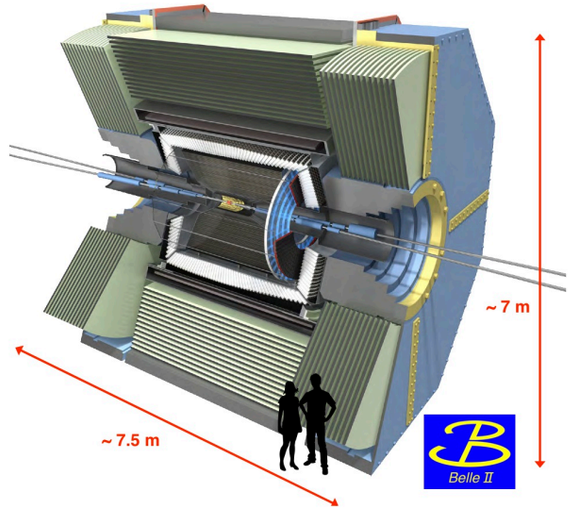
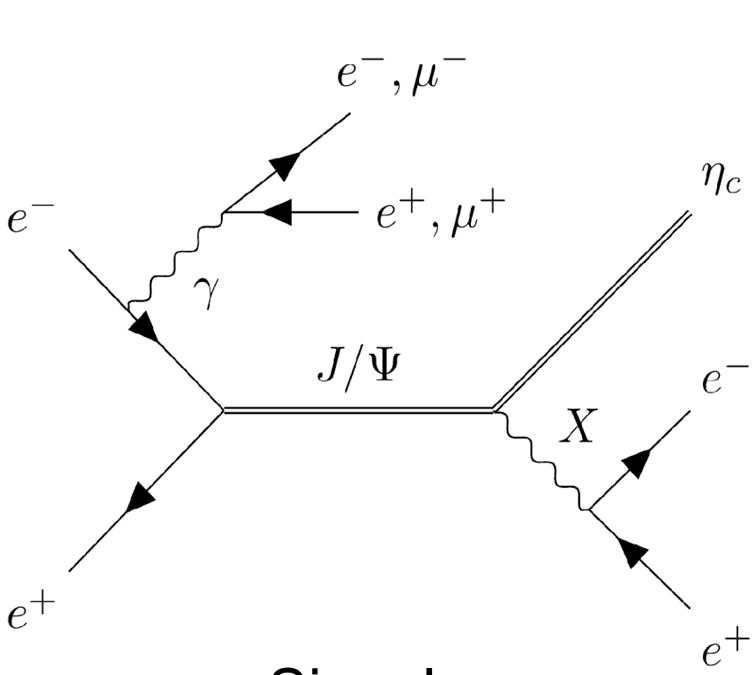


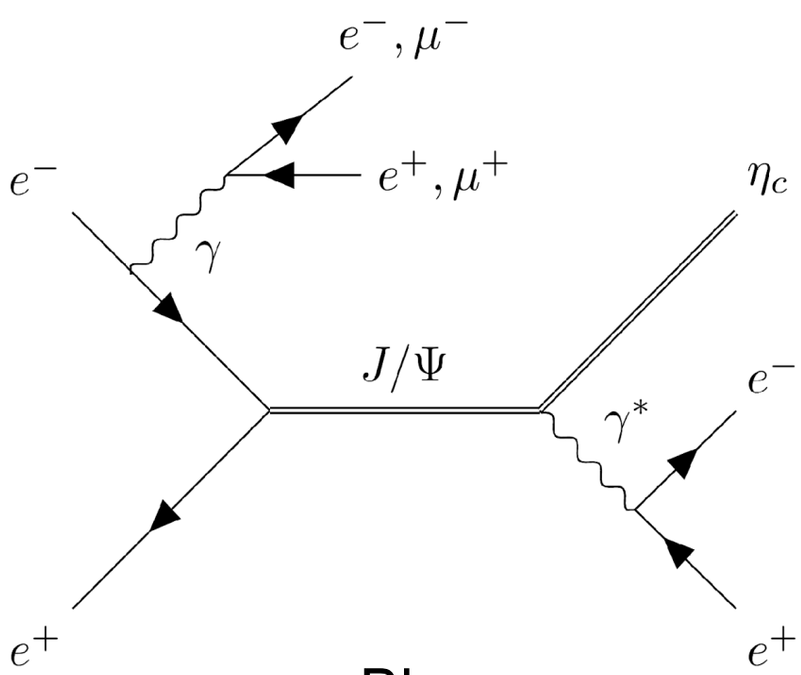




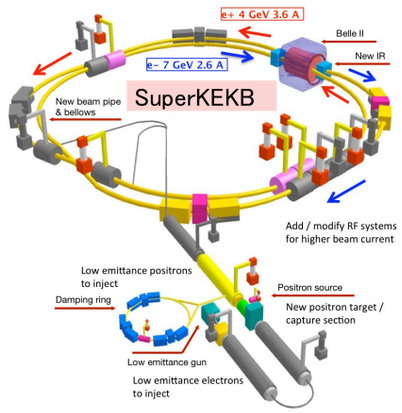
Search for X boson at Belle II (prompt search)

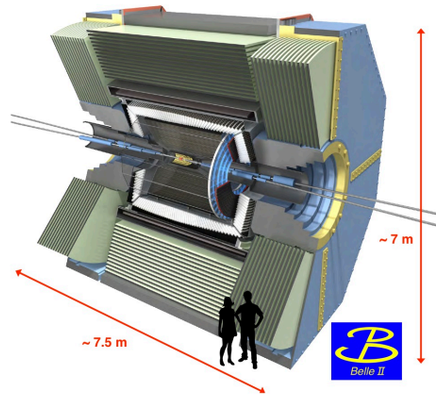


Signal



Bkg



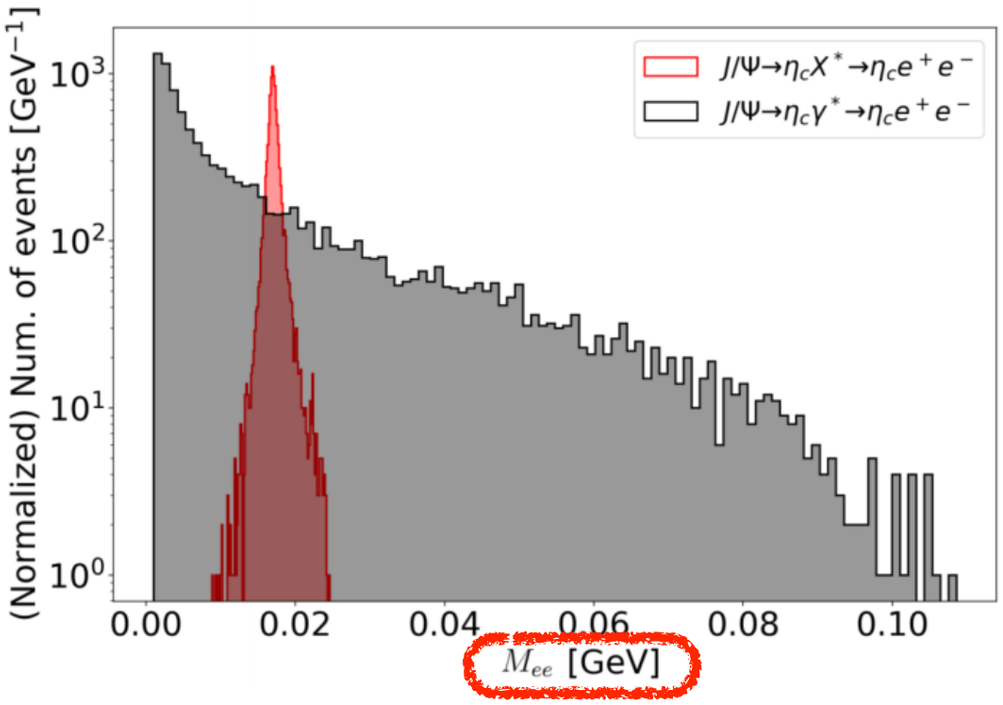


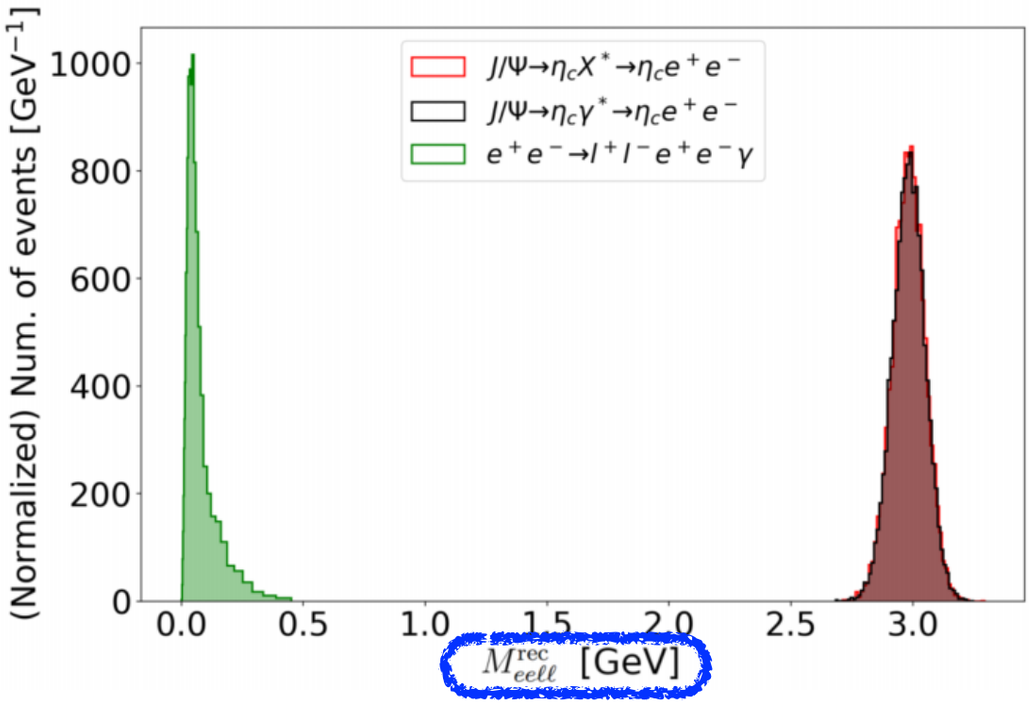
With the design integrated luminosity $L = 50\,\mathrm{ab}^{-1}$ we estimate $N_{J/\Psi} = 1.75 \times 10^7$ events for $e^+e^- \to \gamma^* + J/\Psi \to \ell^+\ell^- J/\Psi$

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

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

Search for X boson at Belle II (prompt search)





- Event generation
  MG5_aMC@NLO
  +
  FeynRules
- Energy resolution
  $\sigma_{p_{\ell^\pm}}/p_{\ell^\pm} = 0.005$

2012.04190 **[hep-ph],** K. Ban, Y. Jho, Y. Kwon, S. C. Park, S. Park and P.-Y. Tseng

Just required all final state leptons to be within ECL barrel region

$|E_{\mu^\pm}| \geq 0.6$ GeV
$|E_{e^\pm}| \geq 0.06$ GeV

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

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- Sensitivity Limit

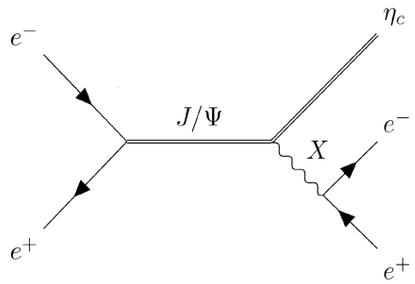
2012.04190 **[hep-ph],** K. Ban, Y. Jho, Y. Kwon, S. C. Park, S. Park and P.-Y. Tseng

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

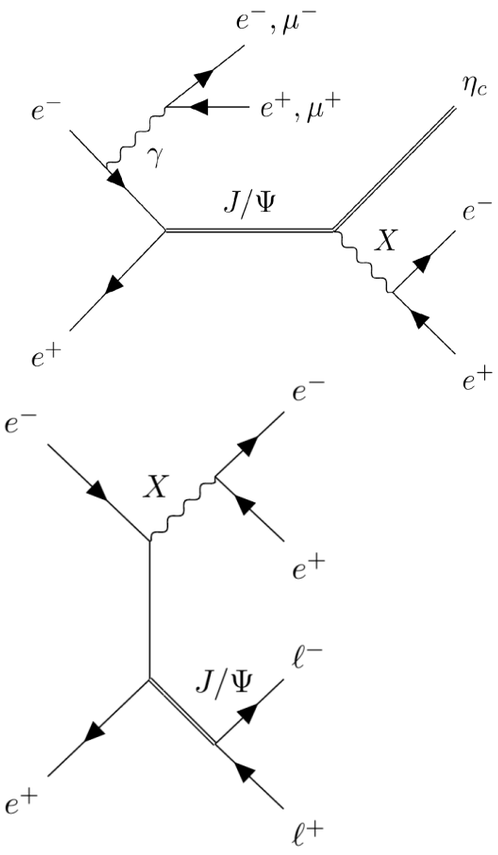
Covering ATOMKI desired region of ϵ_c -> Not easy to be achievable even with $L = 200$ ab^{-1} of J/psi data in the prompt search.

Three options using J/Psi for search of light vector boson X

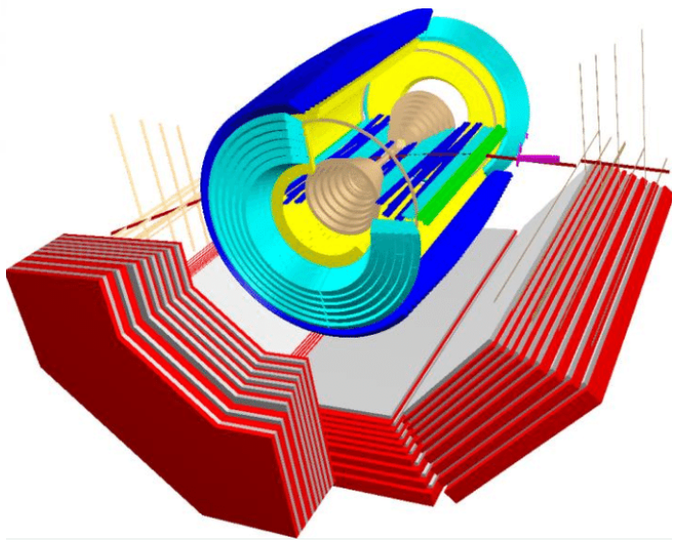
- Search for light vector boson at BESIII
  $J/\psi \to \eta_c X \to \eta_c e^+ e^-$ ϵ_e ϵ_c

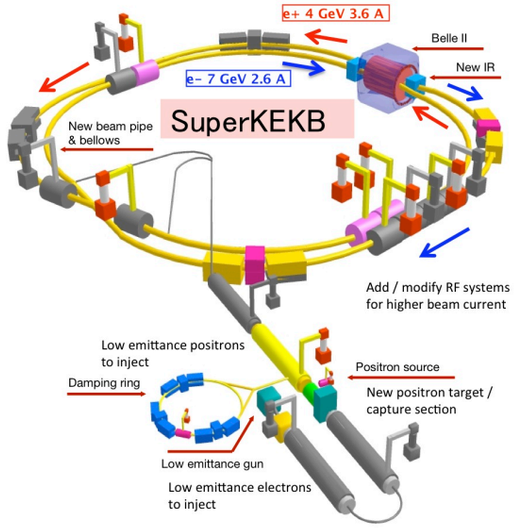


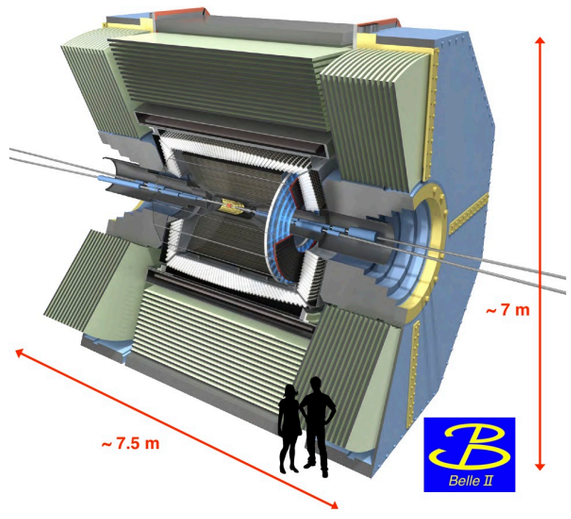
- Search for light vector boson at Belle II (prompt)
  $e^- e^+ \to \ell^+ \ell^- J/\psi (\to \eta_c X \to \eta_c e^+ e^-) \quad (\ell = e, \mu)$ ϵ_e ϵ_c



- Search for light vector boson at Belle II (displaced)
  $e^- e^+ \to J/\psi + X (\to e^+ e^-)$ ϵ_e



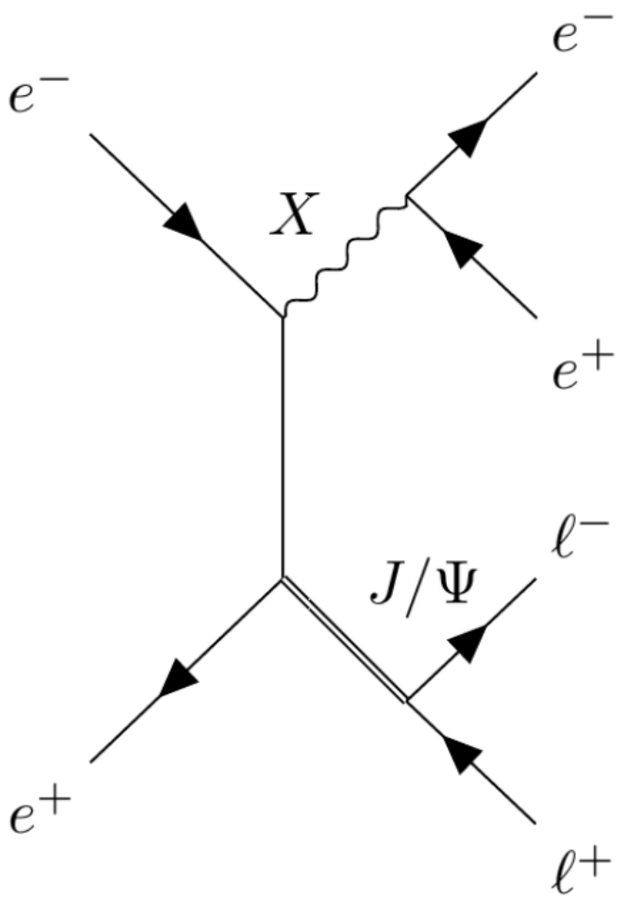


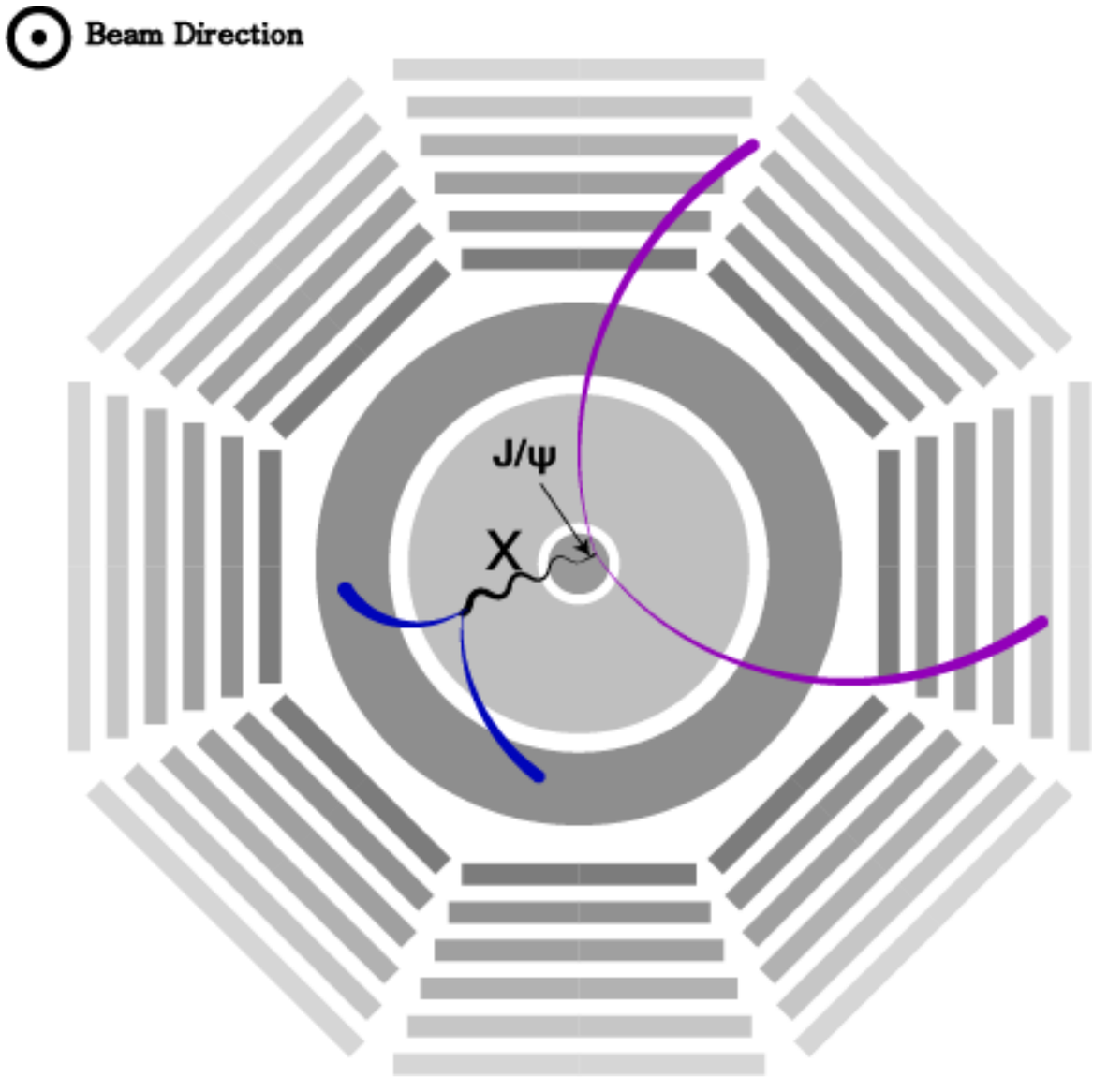


Search for X boson at Belle II (displaced vertex search)

- 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.

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





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

Search for X boson at Belle II (displaced vertex search)

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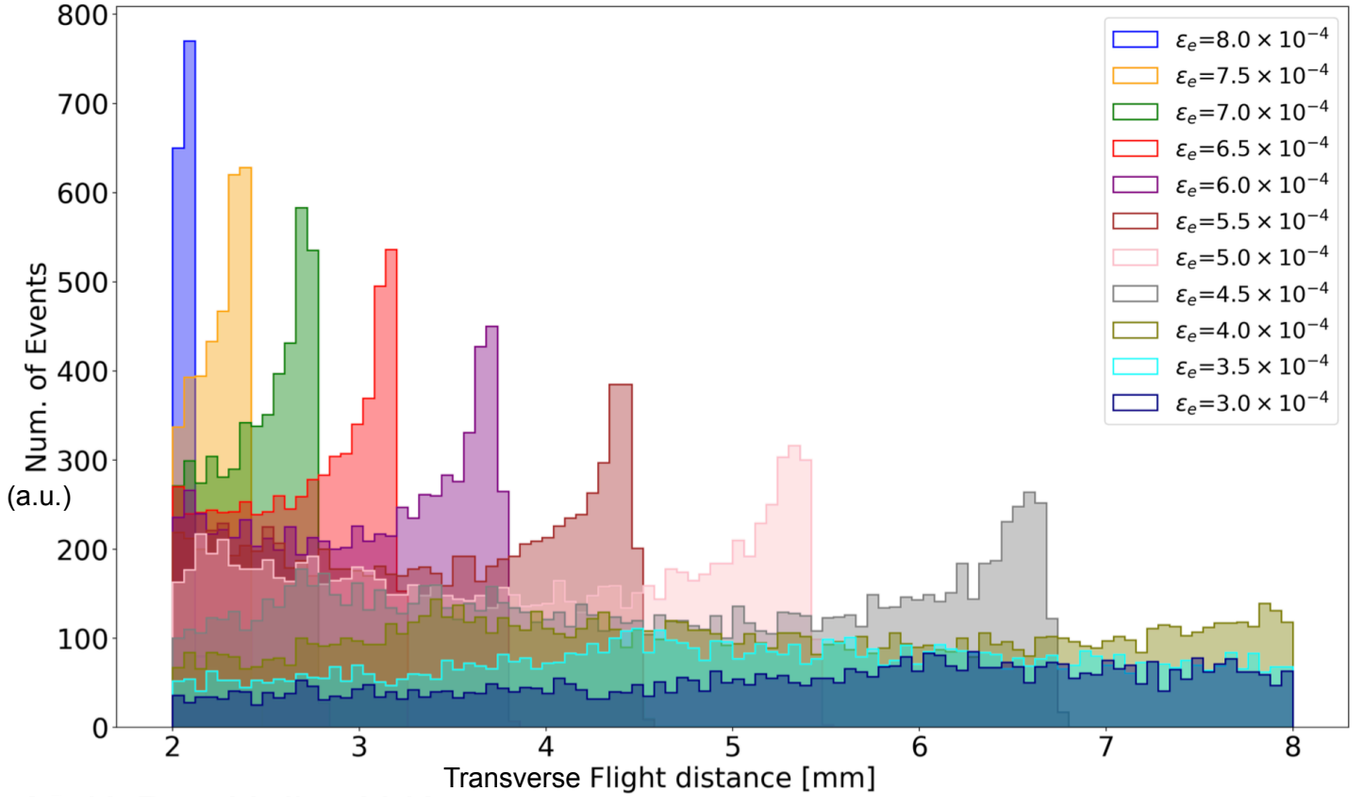
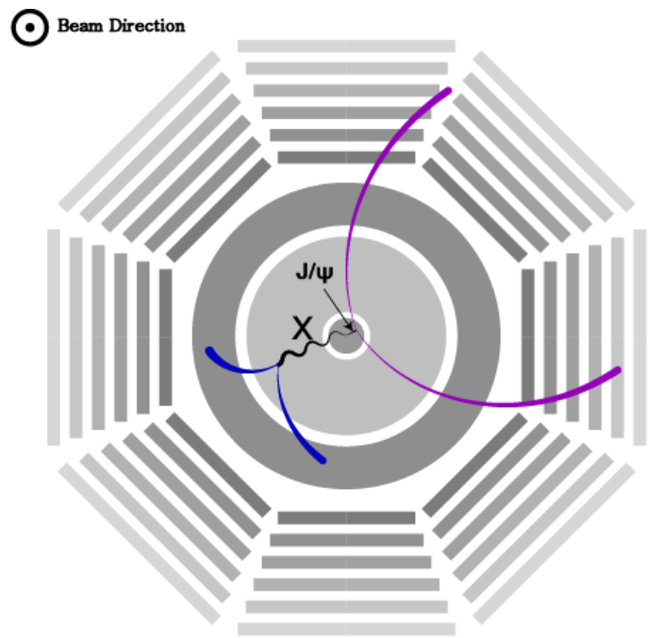
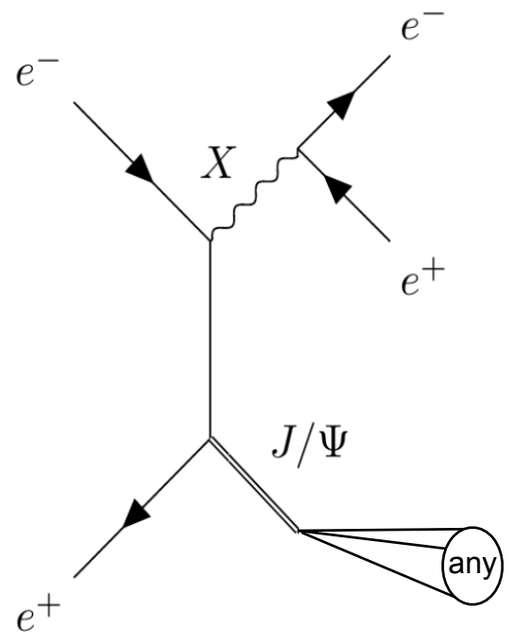




2012.04190 [hep-ph], K. Ban, Y. Jho, Y. Kwon, S. C. Park, S. Park and P.-Y. Tseng

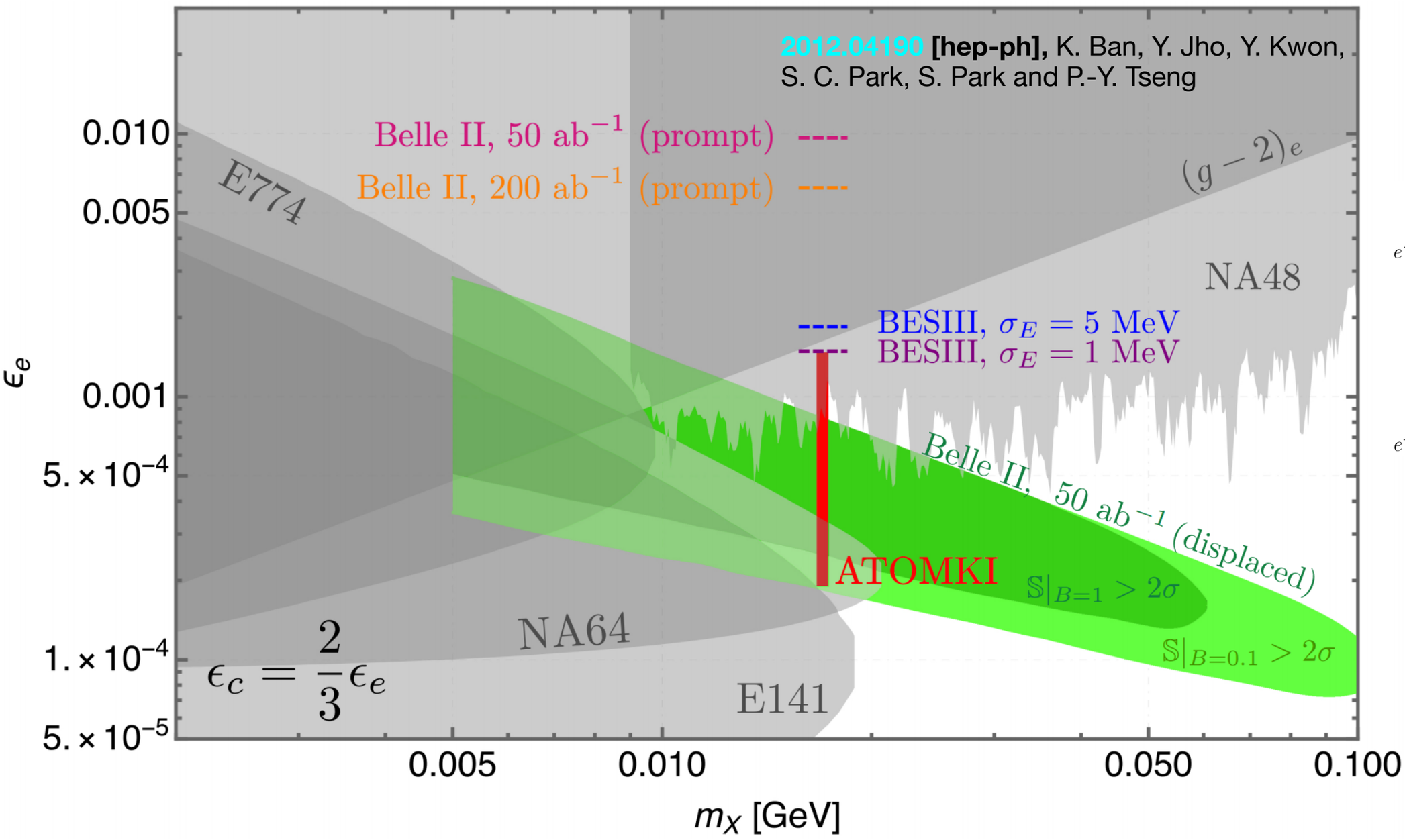
$L = 50\ \text{ab}^{-1}$

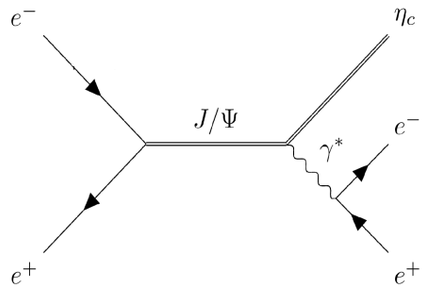
$\varepsilon_e/10^{-4}$	8.0	7.0	5.0	4.0	3.0	2.0	1.0
Baseline Cuts(%)	17.6	17.6	17.6	17.6	17.6	17.6	17.6
$2\text{mm} < d_{xy} < 8\text{mm}(\%)$	1.6	5.3	12.3	12.9	7.4	2.3	0.5
N_S	14.6	35.7	42.7	28.7	9.23	1.28	0.07
$\mathbb{S}_{B=0.1}$	$> 5\sigma$					2.2σ	0.4σ
$\mathbb{S}_{B=1}$	$> 5\sigma$					1.6σ	0.9σ



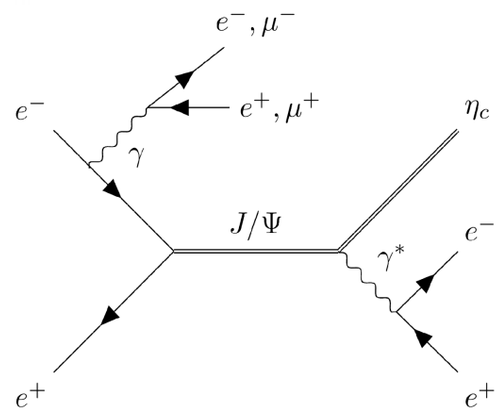
Constraint for minimal DP-type model

$$\epsilon_c = \epsilon_u = -\frac{2}{3}\epsilon_e$$

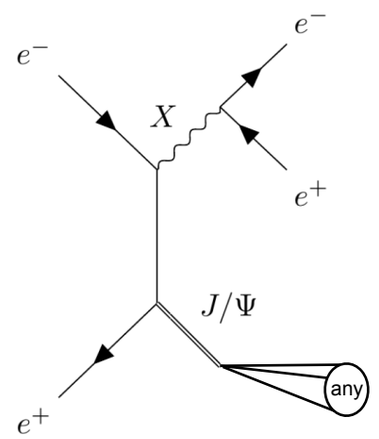




BESIII



Belle II, prompt



Belle II, displaced

Conclusion

- Search for light (MeV-GeV) gauge interaction is recently very active in both theoretical and phenomenological side.

- We study three options which are related to J/psi meson in BESIII and Belle II experiment.

- In BESIII, the expected data with the goal integrated luminosity can fully cover hadronic couplings suggested by X17 scenario and its protophobic constrained region.

- In Belle II, the prompt search can provide important information about light vector boson although it cannot beyond the current limits from previous searches.

- In Belle II, using the displaced vertex of the signal process, we expect the expected limit can cover a wide region of unexplored parameters, when we have a clear systematics in the 2-8mm of the transverse flight length of displaced vertex.

Thank you for your attention

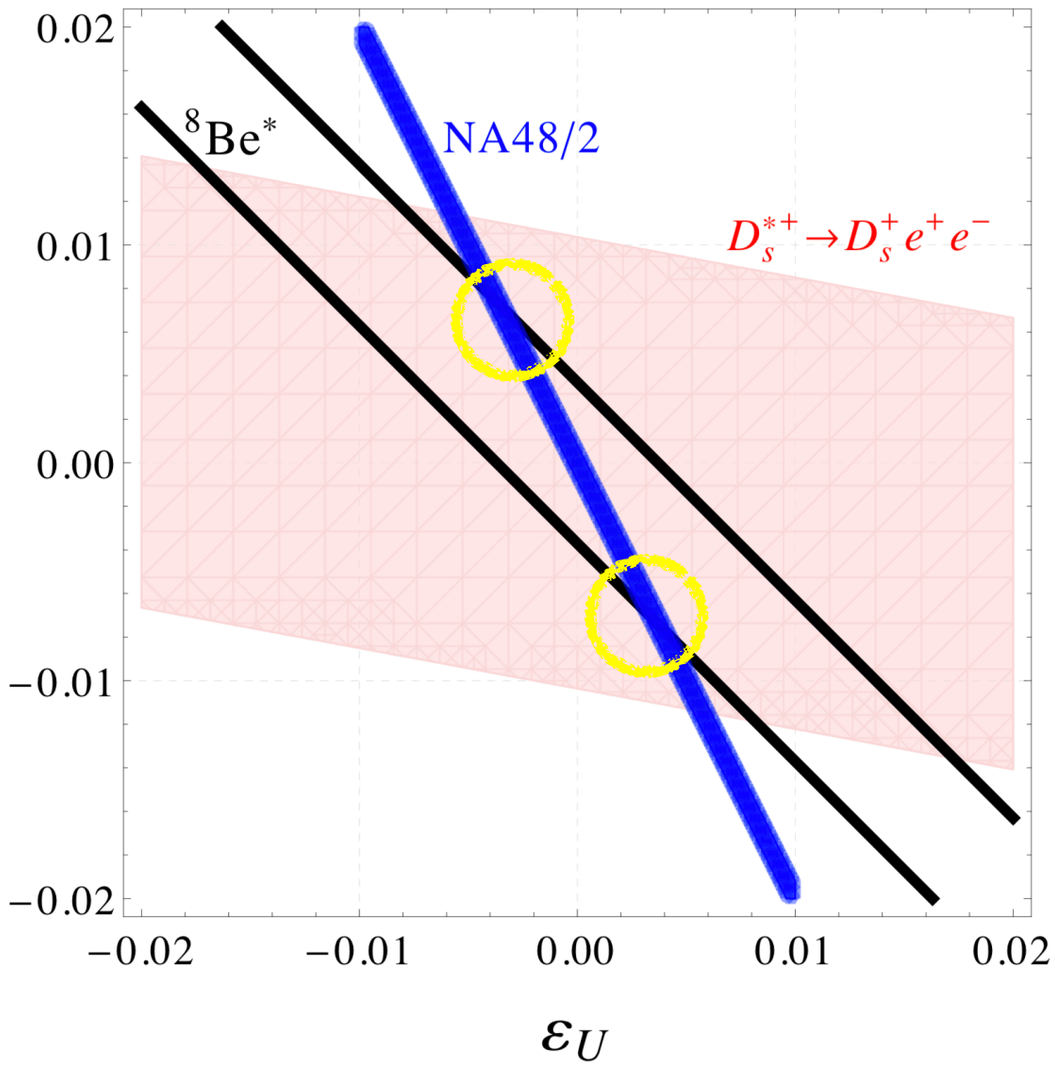
backup slides

cf) Constraints from D-meson decays

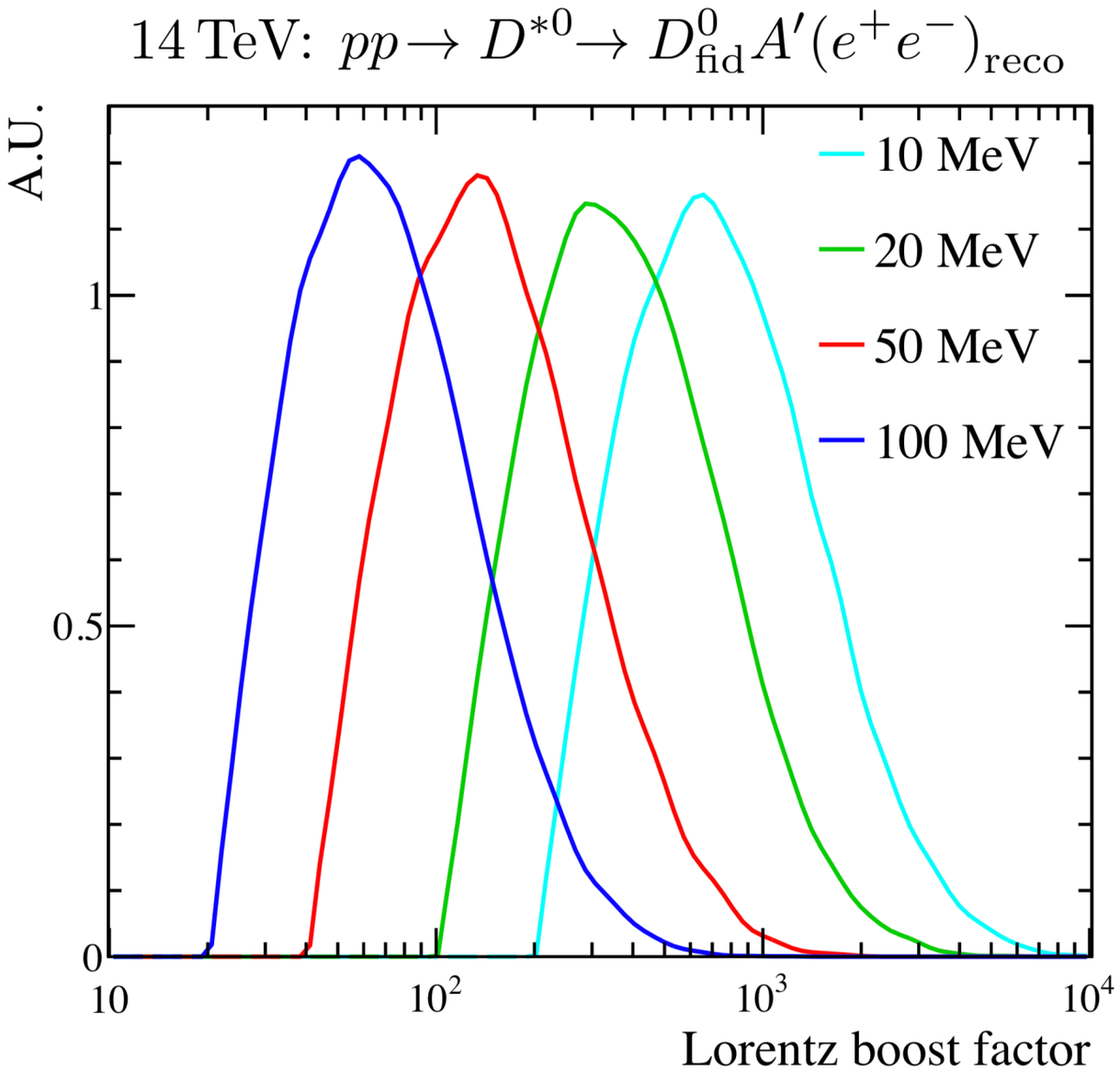
$$H^*(p_{H^*}, \epsilon_{H^*}) \to H(p_H) V(q) \qquad \mathcal{M}_\mu = ieF_{H^*HV}(q^2)\epsilon_{\mu\nu\alpha\beta}\epsilon^\nu_{H*} p^\alpha_H p^\beta_{H*}$$

Transition	photon	$X17$ boson	Total
$D^{*+} \to D^+ e^+ e^-$	$(6.7 \pm 0.3) \times 10^{-3}$	$(1.1 \pm 0.1) \times 10^{-3}$	$(7.7 \pm 0.3) \times 10^{-3}$
$D^{*0} \to D^0 e^+ e^-$	$(6.7 \pm 0.3) \times 10^{-3}$	$(3.0 \pm 0.1) \times 10^{-5}$	$(6.7 \pm 0.3) \times 10^{-3}$
$D_s^{*+} \to D_s^+ e^+ e^-$	$(6.8 \pm 0.6) \times 10^{-3}$	$(1.0 \pm 0.1) \times 10^{-3}$	$(7.8 \pm 0.6) \times 10^{-3}$
$B^{*+} \to B^+ e^+ e^-$	$(4.9 \pm 0.3) \times 10^{-3}$	$(1.9 \pm 0.1) \times 10^{-5}$	$(4.9 \pm 0.3) \times 10^{-3}$
$B^{*0} \to B^0 e^+ e^-$	$(4.9 \pm 0.2) \times 10^{-3}$	$(4.0 \pm 0.2) \times 10^{-4}$	$(5.3 \pm 0.2) \times 10^{-3}$
$B_s^{*0} \to B_s^0 e^+ e^-$	$(5.0 \pm 0.3) \times 10^{-3}$	$(4.1 \pm 0.2) \times 10^{-4}$	$(5.4 \pm 0.3) \times 10^{-3}$

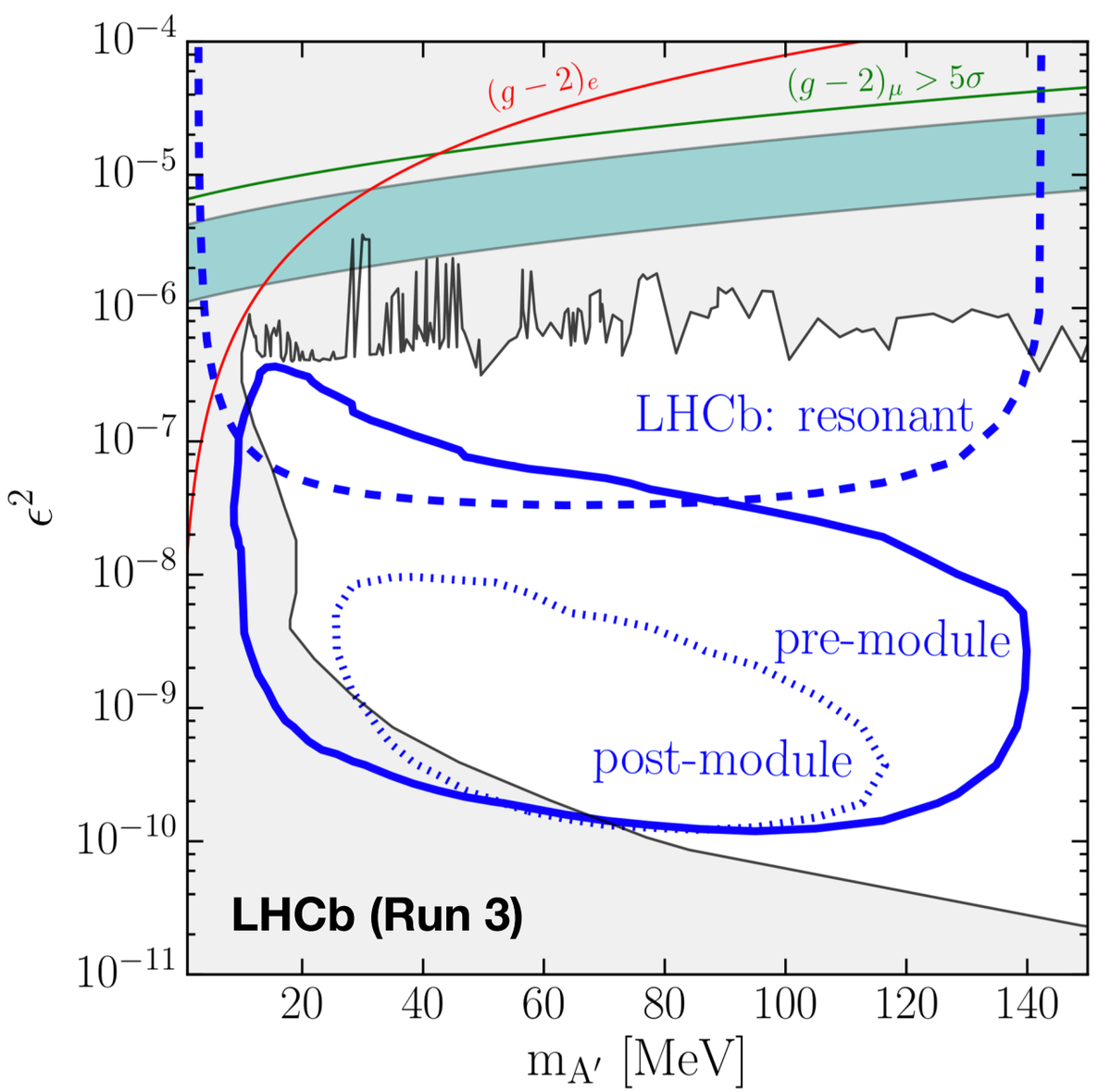
2101.01865 [hep-ph]



cf) DP search using D-meson decays at LHCb



1509.06765 [hep-ph]



Displaced vertex/possible bkgs at Belle II

1. *Direct* radiative lepton and meson pair production with two additional initial or final state radiation photons ($e^+e^- \to e^+e^-\gamma(\gamma)$, $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$, $e^+e^- \to \pi^+\pi^-\gamma(\gamma)$), where one of the photons is out of the detector acceptance,

2. *photon conversion* $\gamma \to e^+e^-$ from direct radiative electron pair production ($e^+e^- \to (e^+e^-)\gamma\gamma$) where both primary electrons are out of detector acceptance, or from radiative photon pair production ($e^+e^- \to \gamma\gamma(\gamma)$) where one photon is out of acceptance,

3. *meson decays*, e.g. $e^+e^- \to \phi\gamma, \phi \to K^0_S(K^0_L), K^0_S \to \pi^+\pi^-$.

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

Displaced vertex/possible bkgs at Belle II

1. $0\,\text{cm} \leq R_{xy} \leq 0.2\,\text{cm}$: The vertex location is very close to the nominal interaction point. We expect prohibitively large prompt SM backgrounds.

2. $0.2\,\text{cm} < R_{xy} \leq 0.9\,\text{cm}$: The vertex location is inside the beam pipe, but outside of the interaction region. We expect excellent vertex reconstruction efficiency and negligible SM backgrounds.

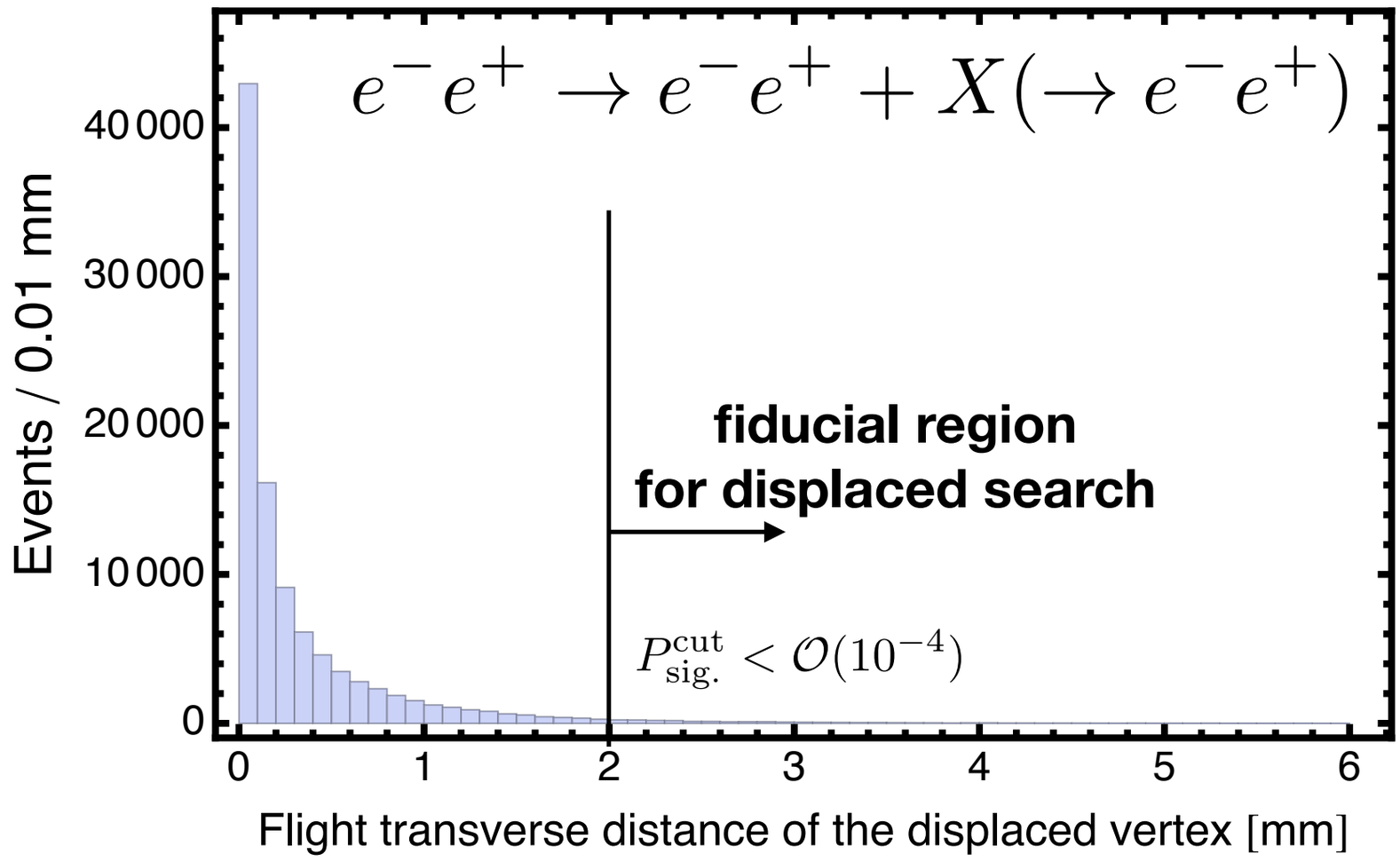
3. $0.9\,\text{cm} < R_{xy} \leq 17\,\text{cm}$: The vertex location is inside the region covered by the VXD. We expect very good vertex reconstruction efficiency, but a sizeable background from photon conversions due to the material in this detector region. The estimation of the background is beyond the scope of this paper. We expect that selections based on the invariant mass of the lepton pair, or opening angle requirements of the two leptons could reduce the background significantly and this region could be included in a future analysis also for electron/positron final states.

4. $17\,\text{cm} < R_{xy} \leq 60\,\text{cm}$: The vertex location is outside the VXD but inside the CDC. We expect that loose selections on the invariant mass of the lepton pair, or opening angle requirements of the two leptons, can reduce the background from photon conversion to a negligible level.

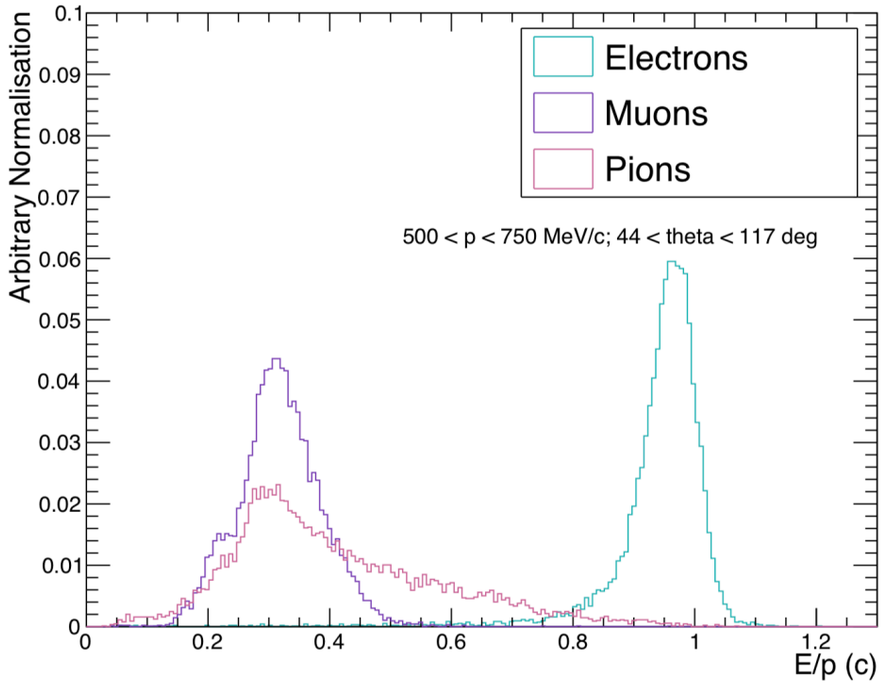
5. $60\,\text{cm} < R_{xy}$: The vertex location is inside the CDC but the tracking efficiency is too low, or the vertex location is outside of any tracking detector acceptance.

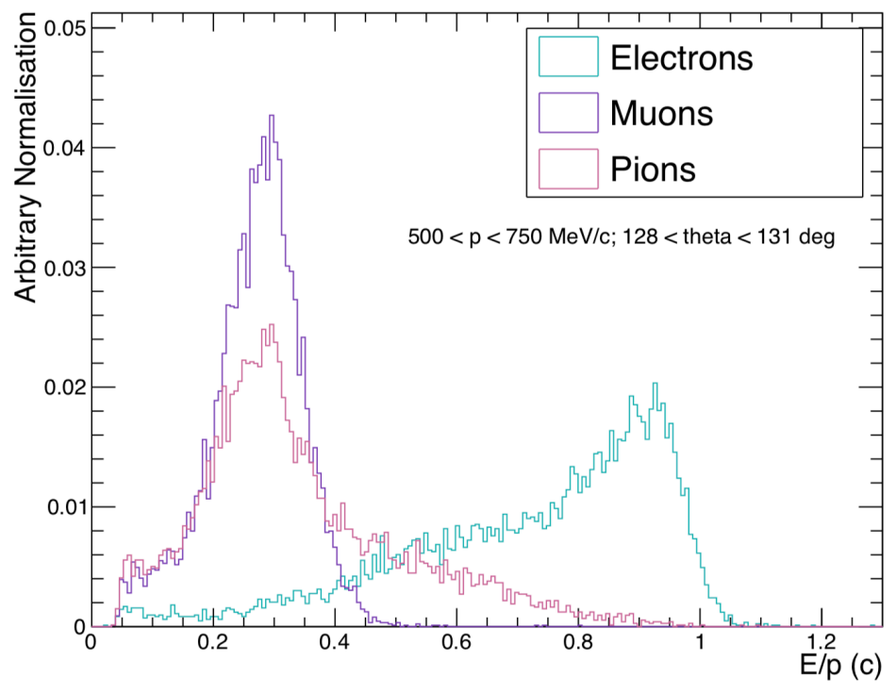
cf) M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg and P. Tunney, JHEP 304 2002, 039 (2020)

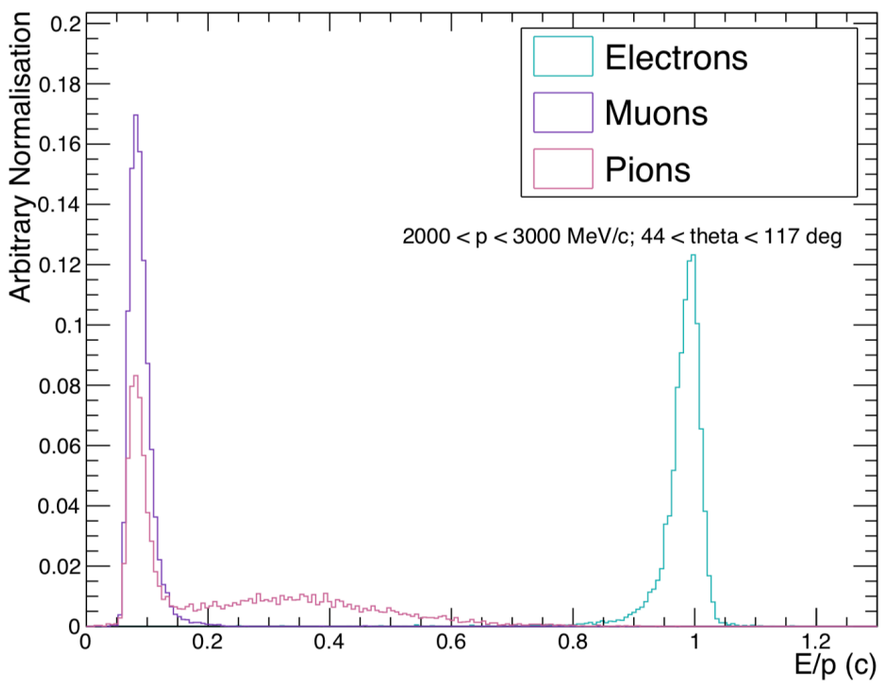
Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10^\circ < \theta^*_e < 170^\circ$, $E^*_e > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\mathrm{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10^\circ < \theta^*_\gamma < 170^\circ$, $E^*_\gamma > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\mathrm{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\mathrm{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\mathrm{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\mathrm{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH

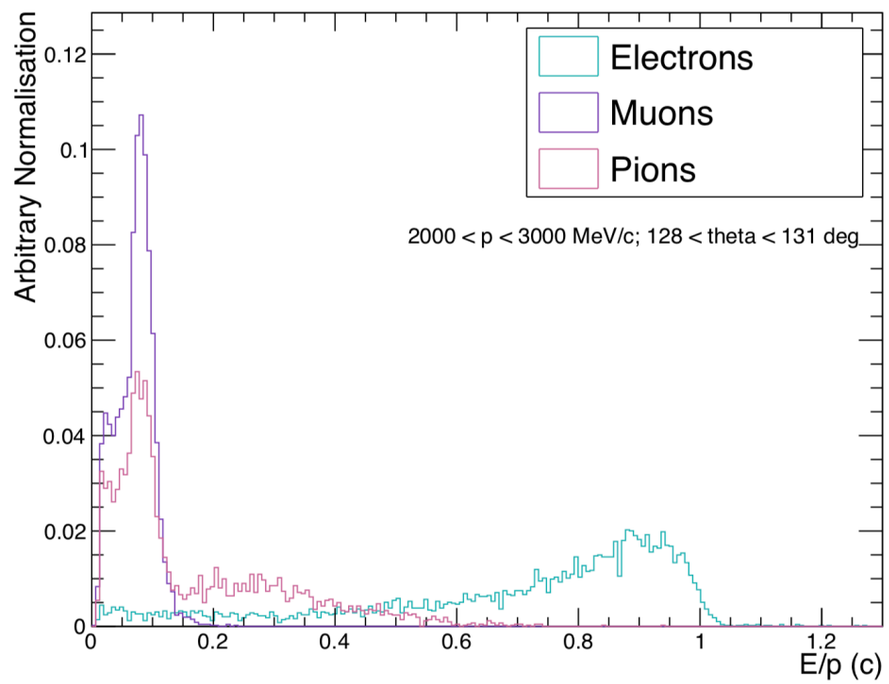

$e^-e^+ \to e^-e^+ + X(\to e^-e^+)$
Events / 0.01 mm
40 000
30 000
20 000
10 000
0
fiducial region
for displaced search
$P_{\text{sig.}}^{\text{cut}} < \mathcal{O}(10^{-4})$
0
1
2
3
4
5
6
Flight transverse distance of the displaced vertex [mm]

Pion misidentification bkg for low E (<0.6GeV) electrons









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