Dark Photon and ALP at EIcC

Teng Ma

United Nations
Educational, Scientific and
Cultural Organization

ICTP-AP
INTERNATIONAL CENTRE FOR
THEORETICAL PHYSICS ASIA-PACIFIC

CHINESE ACADEMY OF SCIENCES

Based on:

JHEP 06 (2025) 070 [2412.06301]

JHEP 02 (2024) 123 [2310.08827]

Collaborators: Dan Lin, Qiyuan Gao, Hongkai Liu

Strong CP problem

And

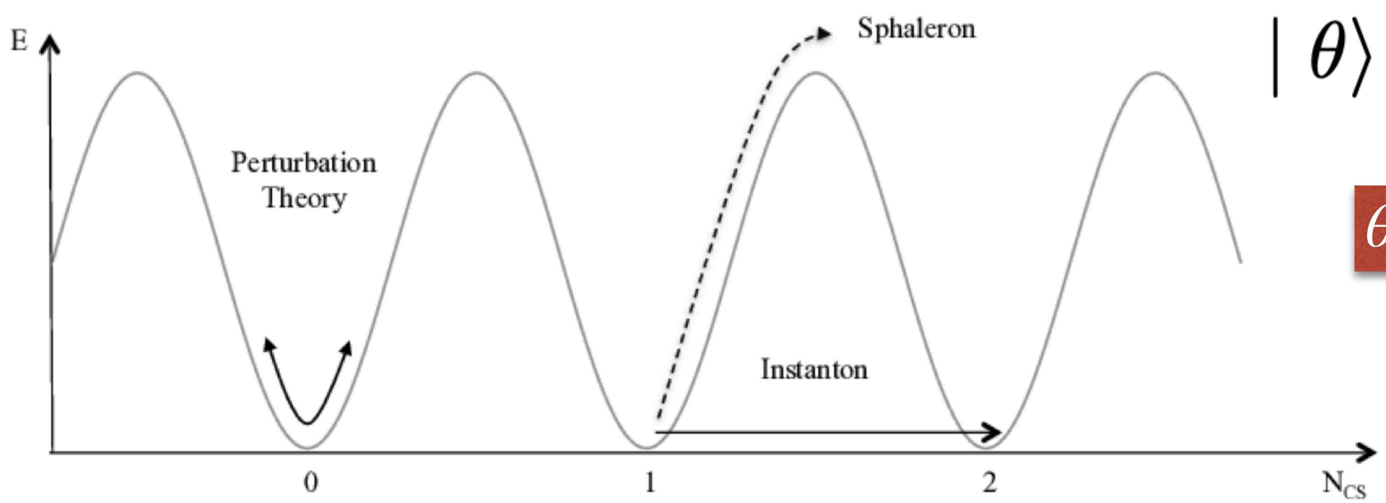
Axion like particle

Strong CP problem

- QCD vacuum

YM non-trivial field configurations :instanton

$$A_\mu = \frac{r^2}{r^2+\rho^2} g\partial_\mu g^{-1}, \qquad g = \frac{x_4 \mathbf{1} + i\vec{x}\cdot\vec{\tau}}{r}$$



$$|\,\theta\rangle = N \sum e^{i\theta n}\,|\,n\rangle$$

θ dependent vacuum

$$\longrightarrow \quad \mathcal{L} \supset -\frac{1}{4}G^2 + \frac{\theta g_s^2}{32\pi^2} G\tilde{G}$$

- Naturalness principle tells (if the quantity is not protected by symmetry, it should be order one

$$\theta \sim \mathcal{O}(1) \quad \longrightarrow$$

CP is violated in QCD sector

QCD Axion

- The Peccei-Quinn (PQ) mechanism

Introduce Goldstone a (axion)

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}.$$

Axion interaction is shifting symmetric

$$a \to a + \alpha f_a, \qquad \theta \to \theta - \alpha,$$

- Then this shift symmetry can remove the θ

$$a \to a + \theta f_a$$

- The axion VEV $\langle a \rangle = -f\theta$ preserves the CP

Neutron eDM

$$d_n \propto \frac{a}{f_a} + \bar{\theta} = 0$$

Axion like particle (ALP)

- The QCD axion

Couple to gluons

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}.$$

- Some UV completions of QCD axion also predict other couplings

Couple to Electroweak bosons

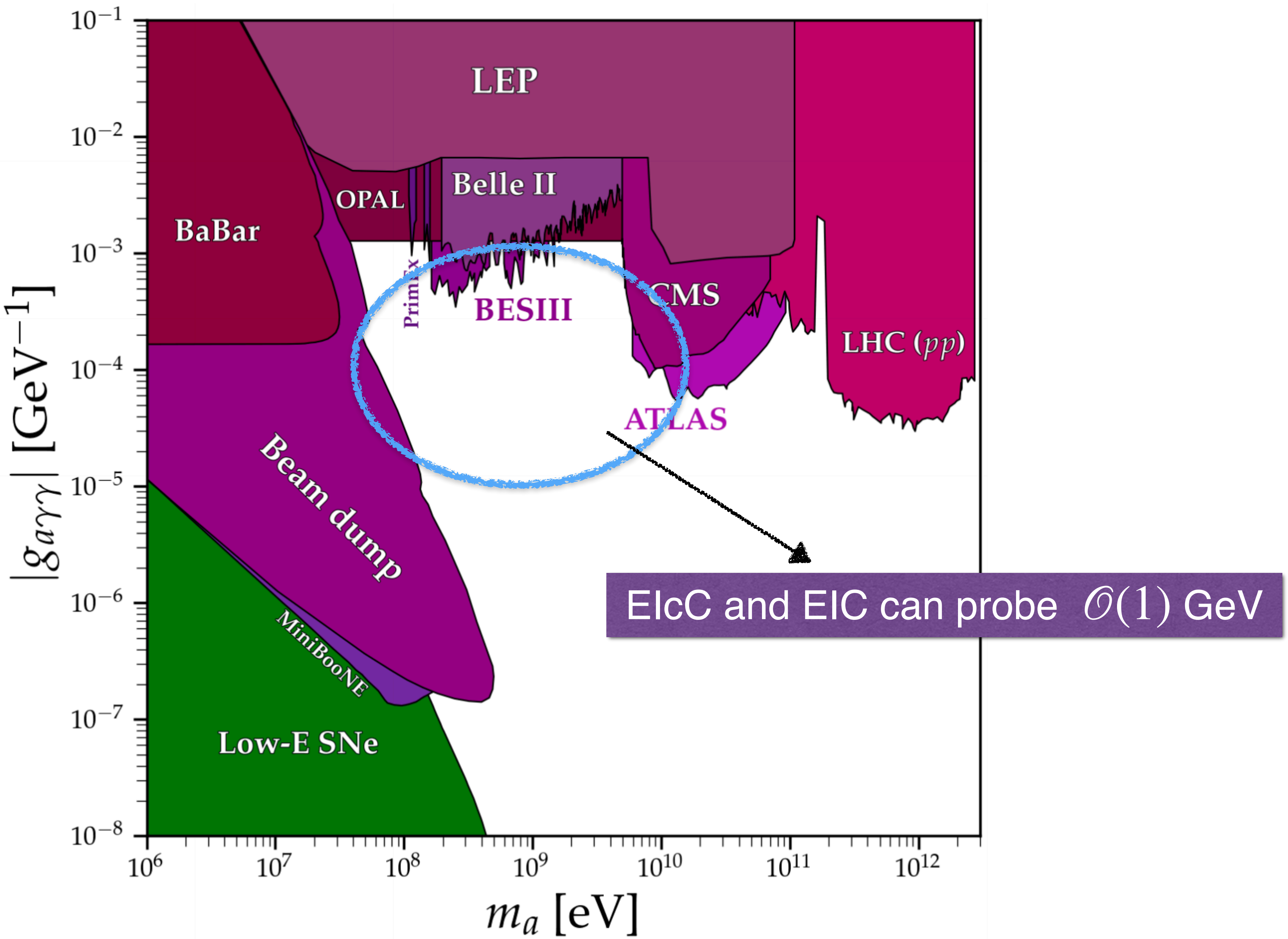
$$\mathcal{L} \supset \frac{a}{f_B} \frac{1}{32\pi^2} B\tilde{B} + \frac{a}{f_W} \frac{1}{32\pi^2} W\tilde{W}.$$

- Currently we only focus on the ALP only coupling to photons (simple)

$$\mathcal{L}_a = -\frac{1}{2} m_a^2 a^2 - \frac{a}{4\Lambda} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Axion like particle (ALP)

- The current bounds on ALP $\mathcal{L}_a = -\frac{1}{2} m_a^2 a^2 - \frac{a}{4\Lambda} F^{\mu\nu} \tilde{F}_{\mu\nu}$

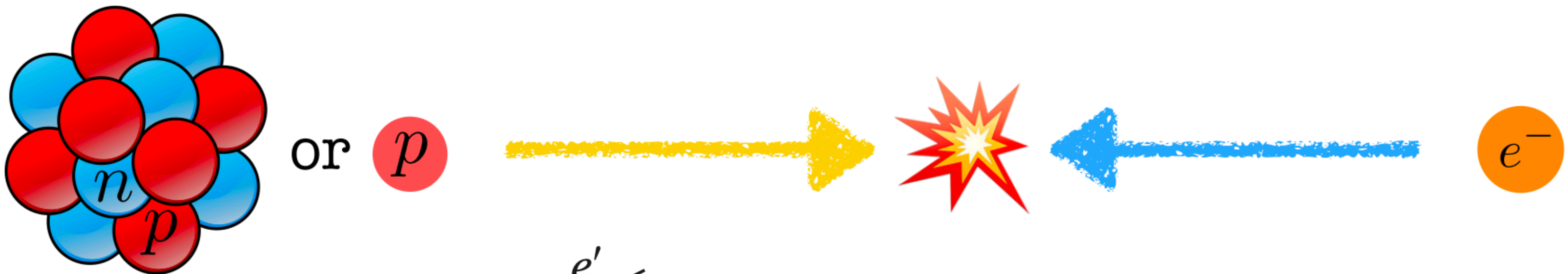


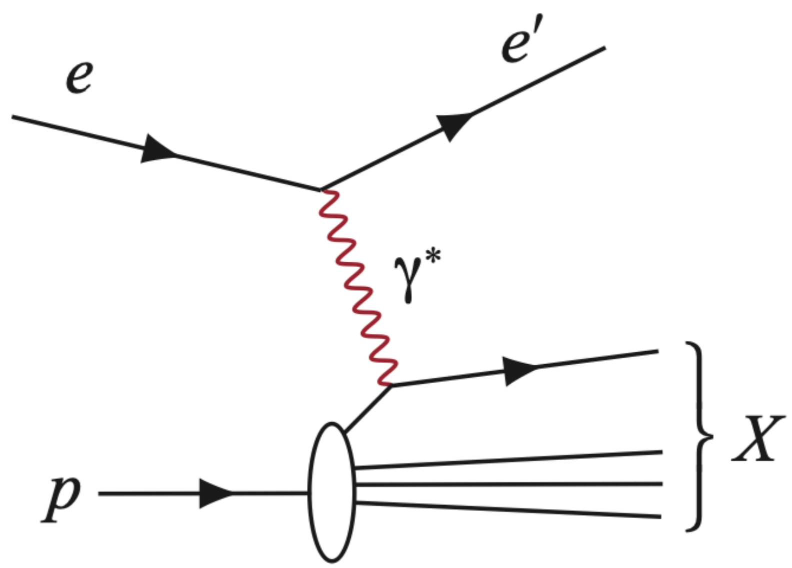
[https://github.com/cajohare/AxionLimits/blob/master/AxionPhoton_ColliderBounds.ipynb]

ALP
at
Electron-Ion Collider
in
China (EIcC)

EIcC

- The EIcC





Understand some QCD problems via DIS

- The EIcC has high enough energy to produce ALP at $\mathcal{O}(1)$ GeV

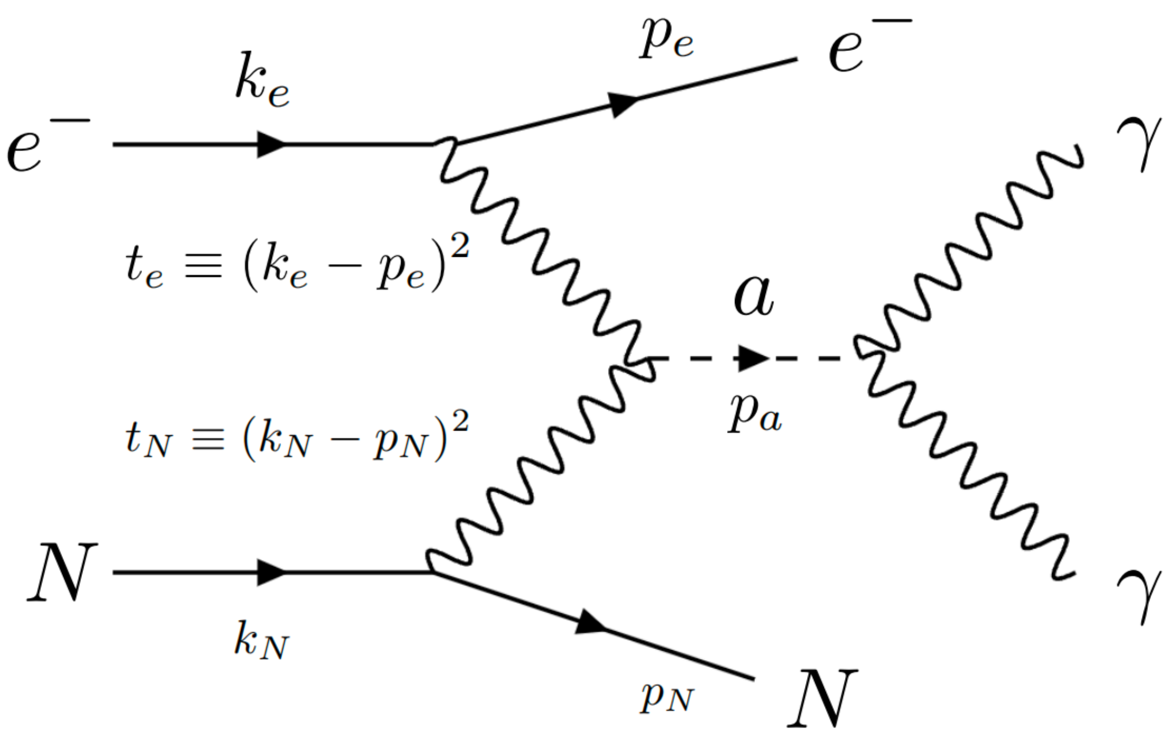
$E_p \sim 20$ GeV or $E_{pb} \sim 4$ TeV

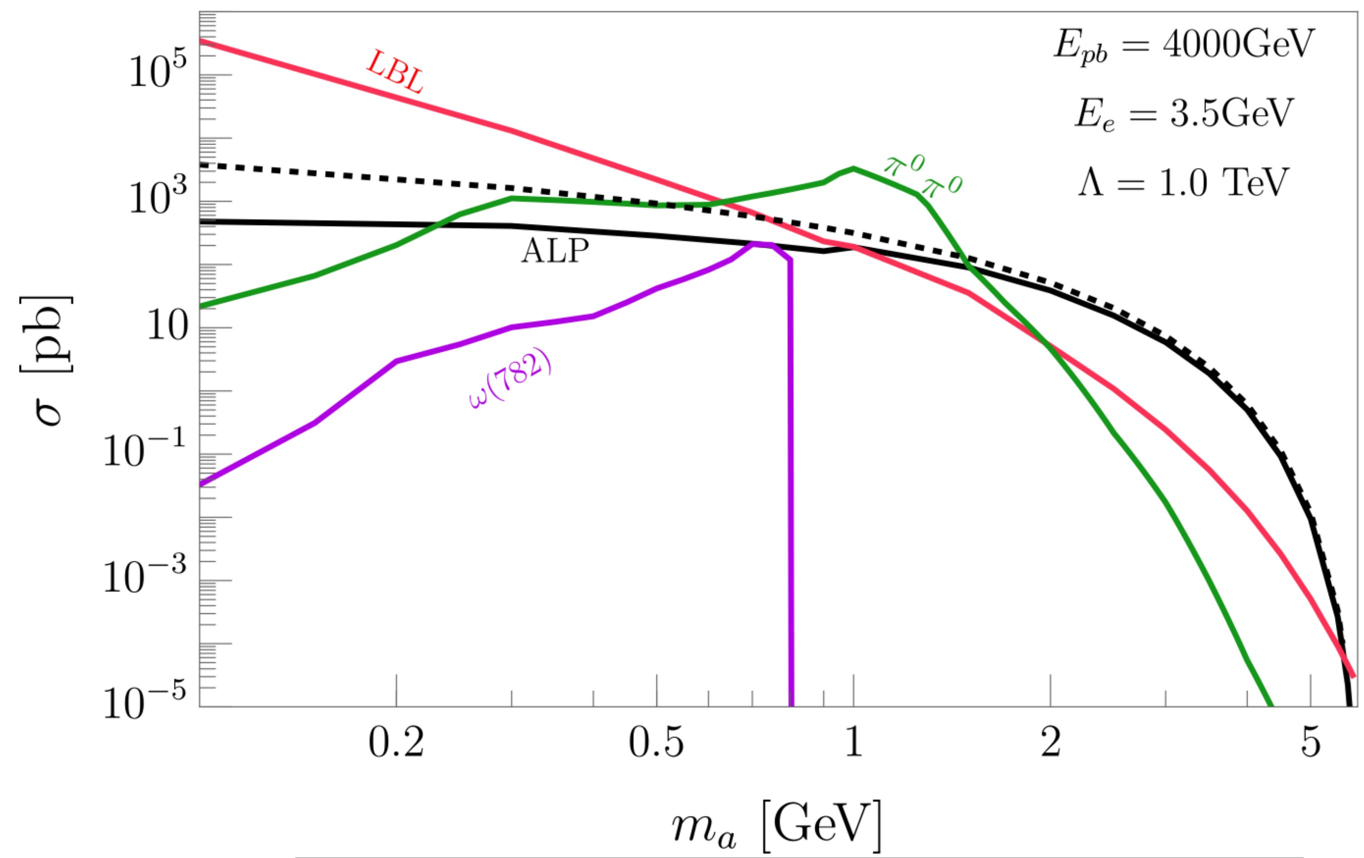
$E_e \sim 3.5$ GeV

- High luminosity $\mathscr{L} \sim 100\ \mathrm{fb}^{-1}$

ALP production at EIcC

- The ALP is coherently produced at EIcC





Black line is the ALP production cross section
Color lines are backgrounds

- The advantage of coherent production

  - The coherent production is enhanced by Z^2

$$|\mathcal{M}_a^{2\to 3}|^2 \propto (Z^2 e^4)/(t_e^2 t_N^2 \Lambda_a^2)$$

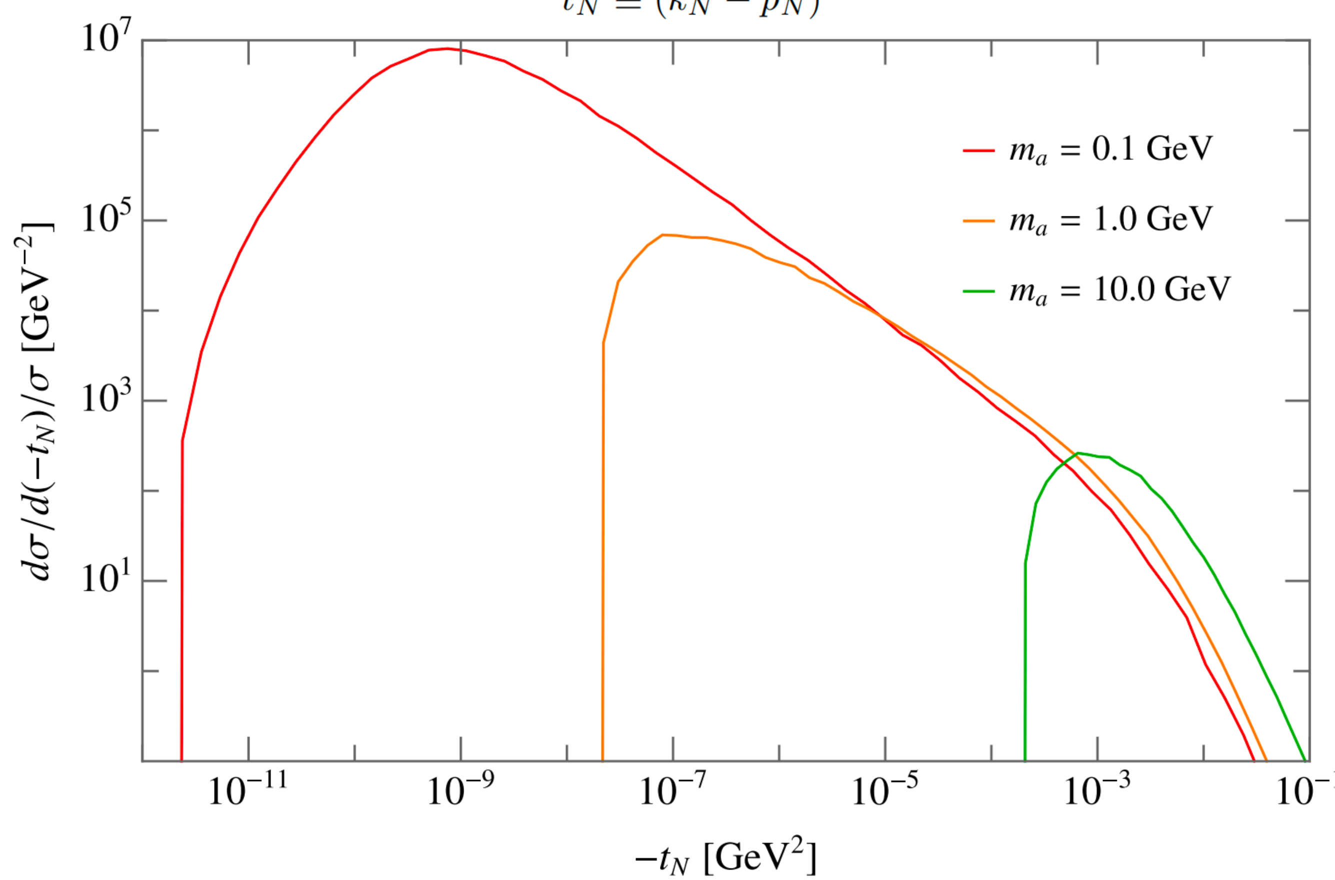
  - Coherent production can suppressed the background

Kinematics

- The production is dominated by the minimal values of t_e^2 and t_N^2

$$|\mathcal{M}_a^{2\to3}|^2 \propto (Z^2e^4)/(t_e^2 t_N^2 \Lambda_a^2)$$

$t_N \equiv (k_N - p_N)^2$



$$|t_N|_{\rm min} \approx 1.8\times10^{-8}\ {\rm GeV}^2 \left(\frac{m_a}{1.0\ {\rm GeV}}\right)^4 \left(\frac{m_N}{193\ {\rm GeV}}\right)^2 \left(\frac{\sqrt{s}}{1.2\ {\rm TeV}}\right)^{-4}$$

Coherent constraint

$$(-t_N)_{\rm min} \sim (1/r_N)^2 \sim 0.164 A^{-2/3}\ {\rm GeV}^2 \longrightarrow (m_a)_{\rm max} \sim 5\ {\rm GeV}\left(\frac{E_e}{3.5\ {\rm GeV}}\right)^{1/2}\left(\frac{E_N/A}{20\ {\rm GeV}}\right)^{1/2}\left(\frac{A}{207}\right)^{-1/6}$$

EIcC vs EIC

- The energy

EIcC	EIC
$E_p \sim 20$ GeV or $E_{pb} \sim 4$ TeV	$E_p \sim 300$ GeV or $E_{pb} \sim 20$ TeV
$E_e \sim 3.5$ GeV	$E_e \sim 18$ GeV

- Even the energy of ion at EIC is much higher than EIcC, coherent production suppress the energy of the ions transferred into ALP

$$(-t_N)_{\min} \sim (1/r_N)^2 \sim 0.164 A^{-2/3}\ \mathrm{GeV}^2$$

EIcC

$$(m_a)_{\max} \sim 5\ \mathrm{GeV} \left(\frac{E_e}{3.5\ \mathrm{GeV}}\right)^{1/2} \left(\frac{E_N/A}{20\ \mathrm{GeV}}\right)^{1/2} \left(\frac{A}{207}\right)^{-1/6}$$

EIC

$$(m_a)_{\max} \sim 20\,\mathrm{GeV} \left(\frac{E_e}{18\,\mathrm{GeV}}\right)^{1/2} \left(\frac{E_N/A}{100\,\mathrm{GeV}}\right)^{1/2} \left(\frac{207}{A}\right)^{1/6}$$

EIcC can have better ALP detect ability in lower mass range if has higher efficient detection of photons and electrons

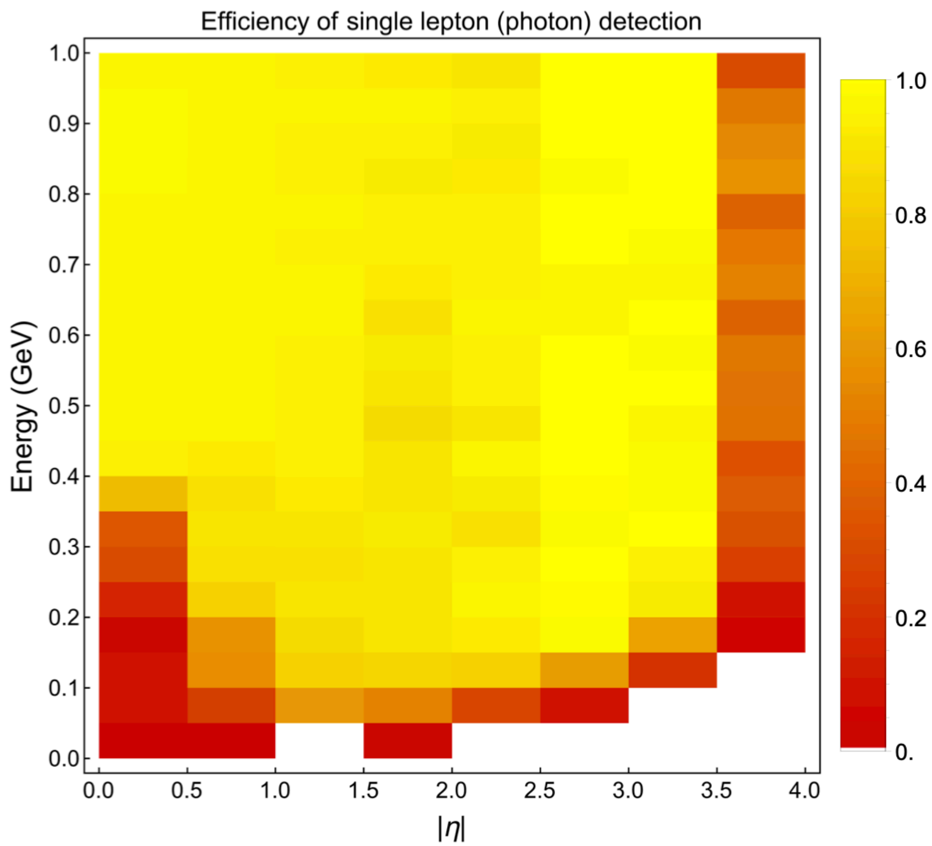
Basic Cuts

- For prompt searches, the signal is clean

$$2\gamma + \text{recoil } e^- + \text{intact lead ion}$$

- To ensure a good photon reconstruction efficiency, we apply some basic cuts on the final-state photons

$$E_\gamma > 0.05 \text{ GeV}, \quad |\eta_\gamma| < 4.0.$$



- The backgrounds at each m_a are estimated by integrating over the invariant mass in the window of

$$m_{\gamma\gamma} \in [m_a - 2\Delta m_{\gamma\gamma}, m_a + 2\Delta m_{\gamma\gamma}]$$

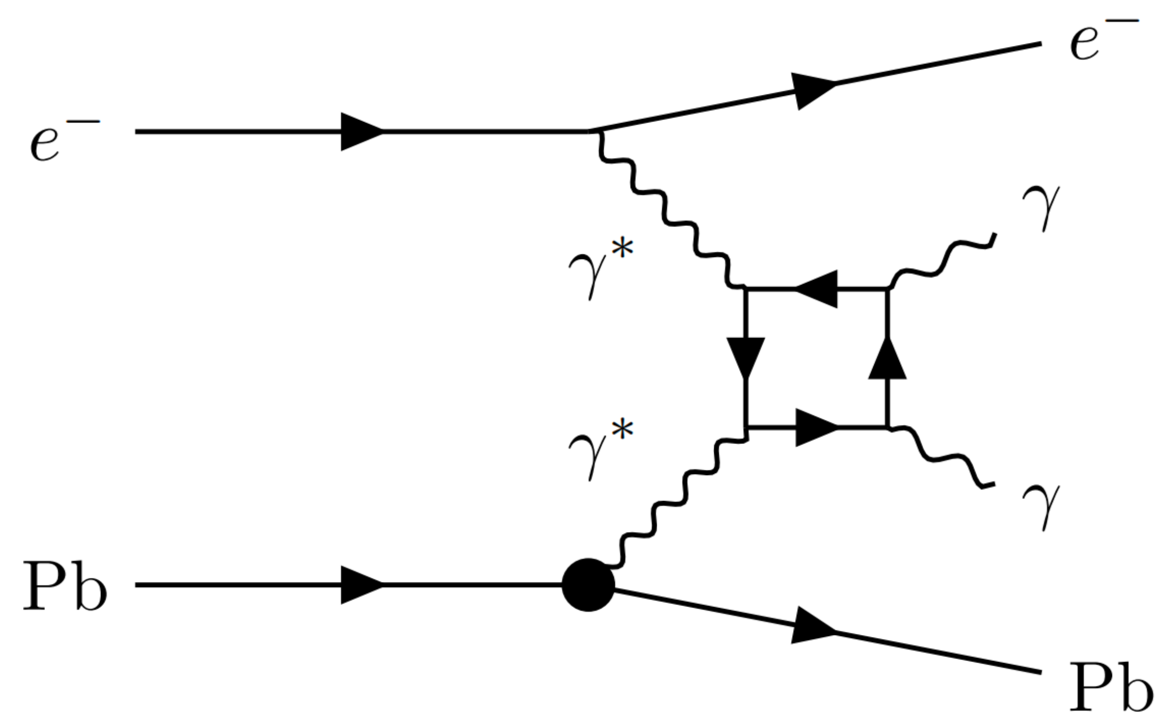
- The resolution of photons invariant mass

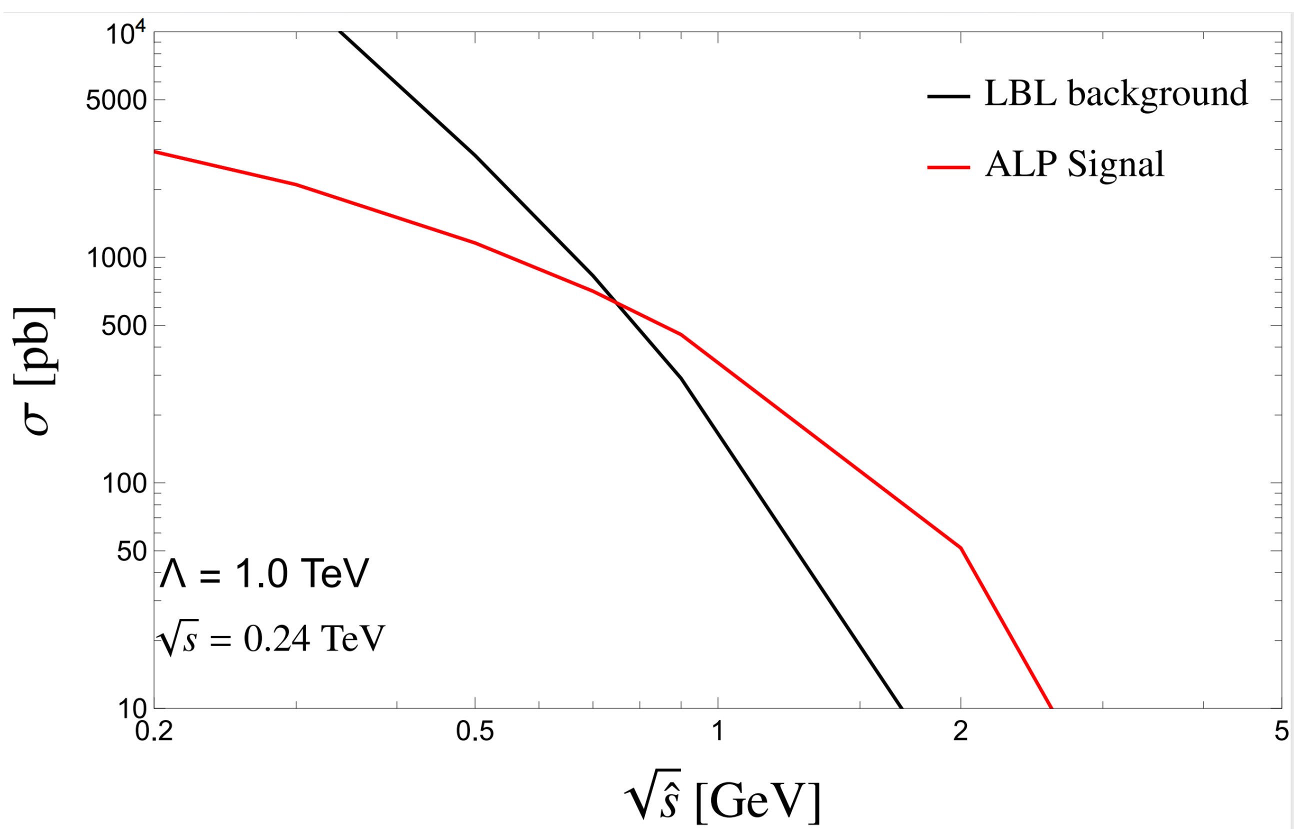
$m_{\gamma\gamma}$ [GeV]	0.3	0.5	0.7	0.9	2.0	4.0	7.0	15.0
$\Delta m_{\gamma\gamma}/m_{\gamma\gamma}$ (%)	3.5	3.3	3.1	2.8	1.7	1.2	0.97	0.72

Background

- The dominant BG is light-by-light scattering (irreducible BG)

$$eN \to eN\gamma\gamma$$



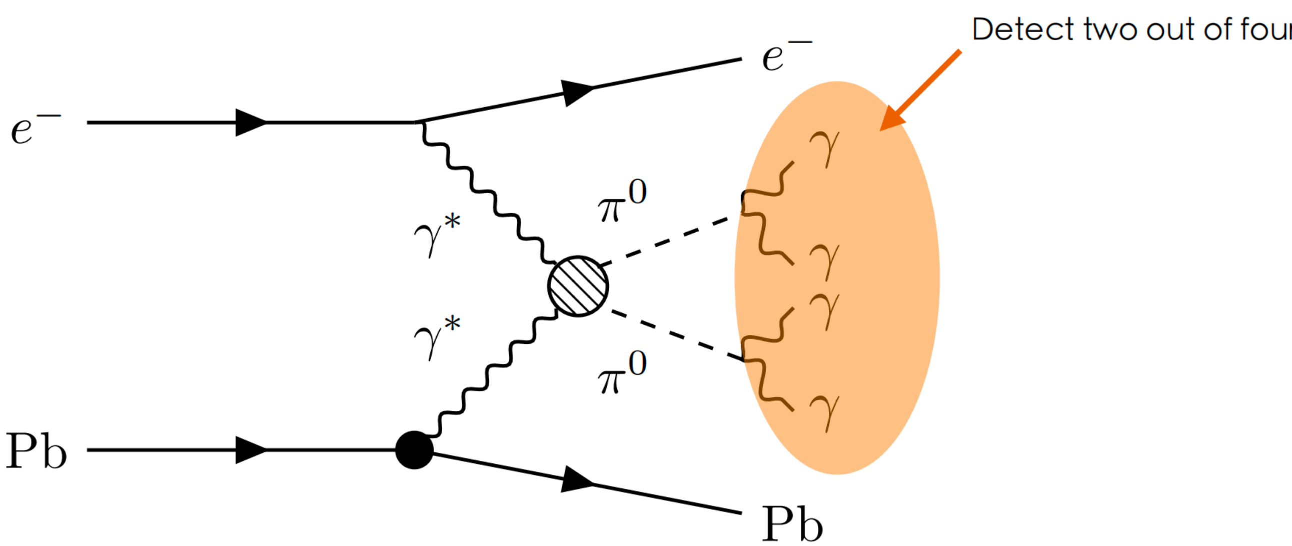


Background

- The other possible backgrounds from missing some photons

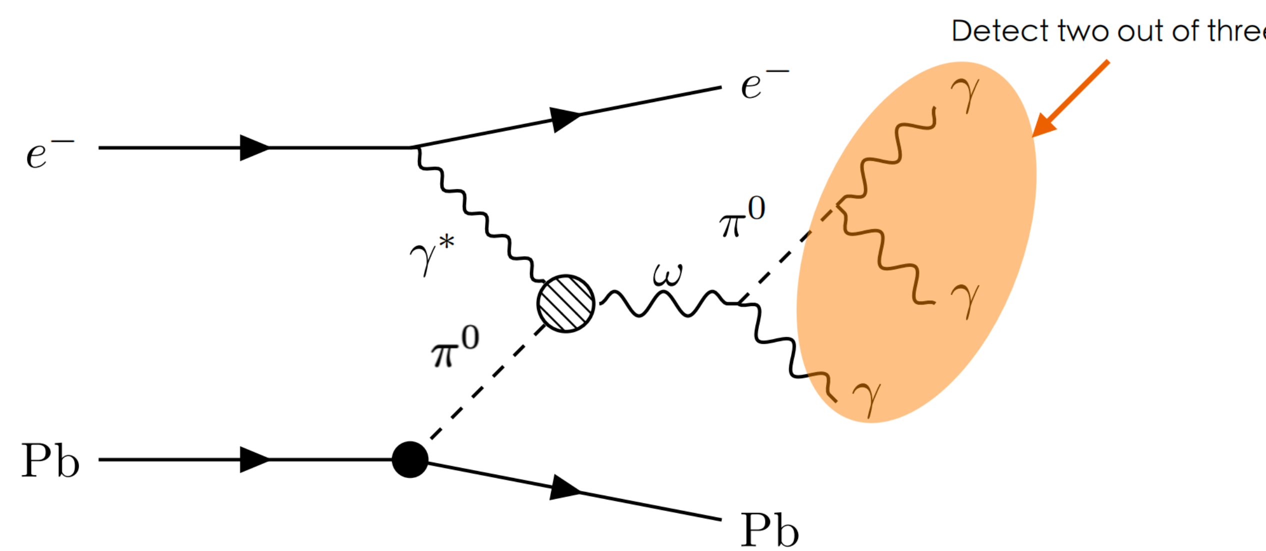
Pion-pair production

$$eN \to eN\pi^0\pi^0 \quad (\pi^0\pi^0 \to \gamma\gamma\gamma\gamma)$$



Omega production

$$eN \to eN\omega \quad (\omega \to \pi^0\gamma \to \gamma\gamma\gamma)$$



- Reducing BG, two photons should be back-to-back in transverse plane

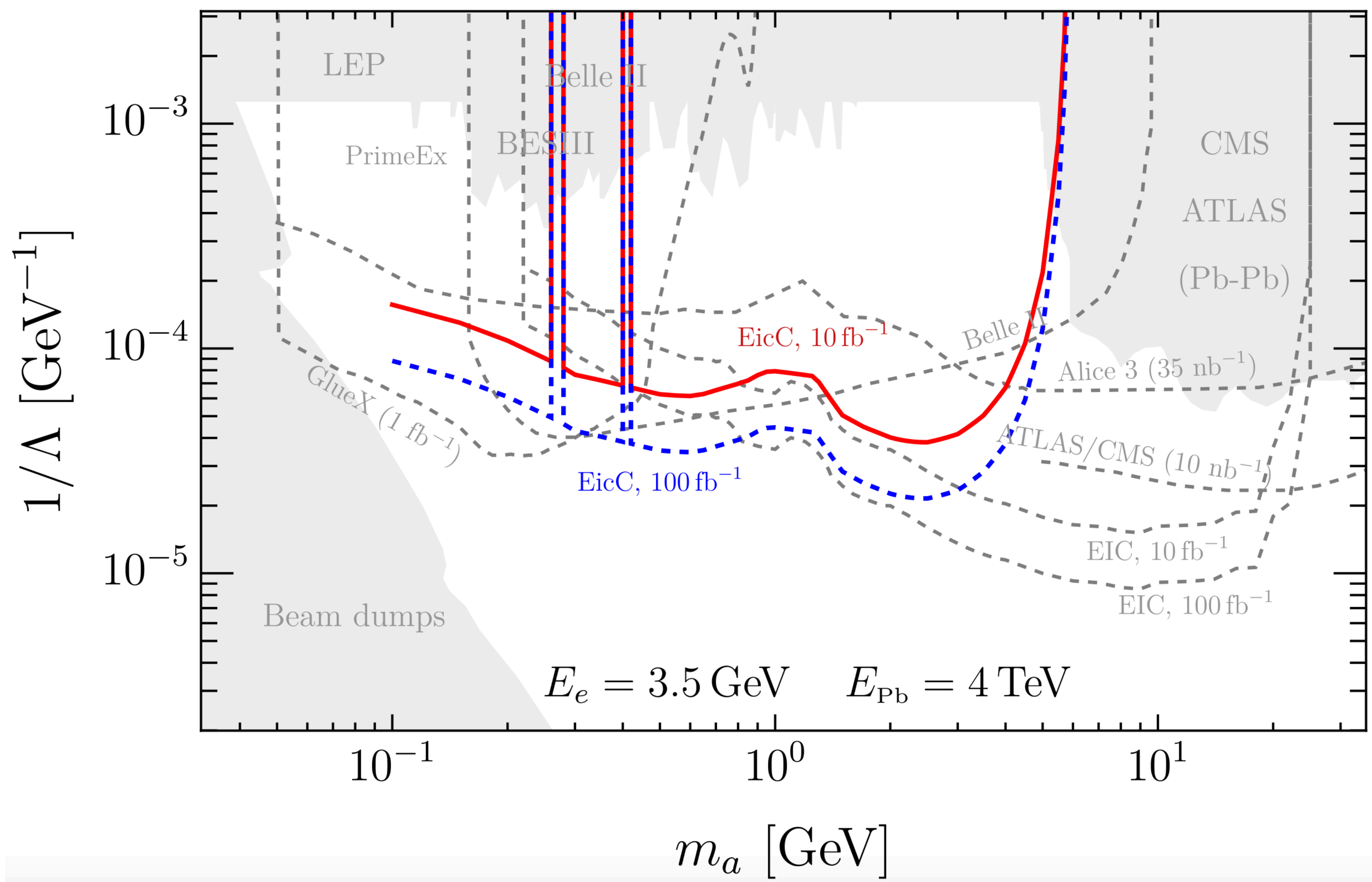
$$|\Delta\varphi_\gamma - \pi| < 0.2$$

Further suppress the second BG

$$m_{\gamma\gamma} < m_\omega : -4 < \eta_\gamma < 0$$

EIcC projections

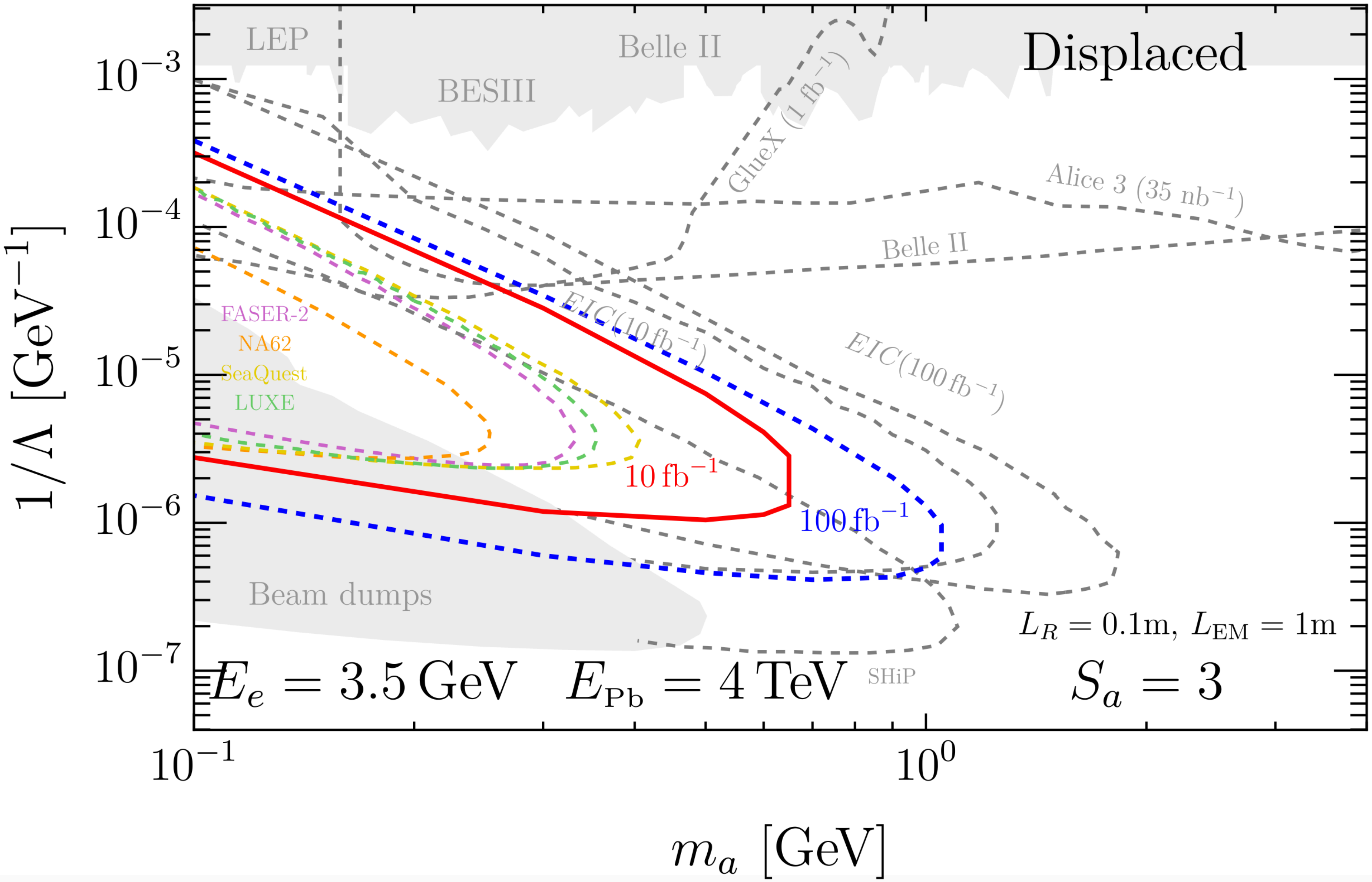
- The EicC projections on the ALP-photon coupling in prompt searches



The EIcC can have better ALP detection at lower mass

EIcC projections

- Displaced vertex search between [0.1, 1] meter



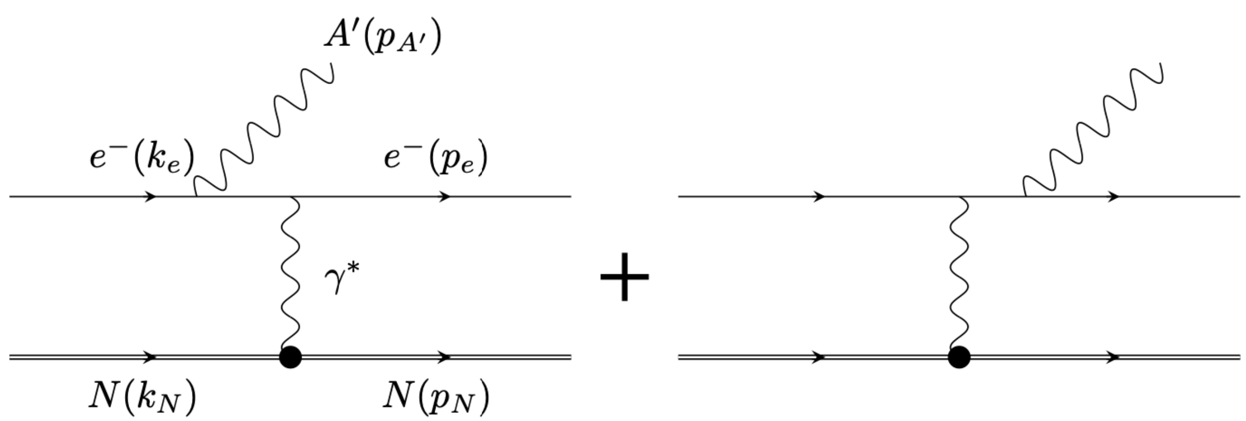
Dark Photon
at
Electron-Ion Collider
in
China (EIcC)

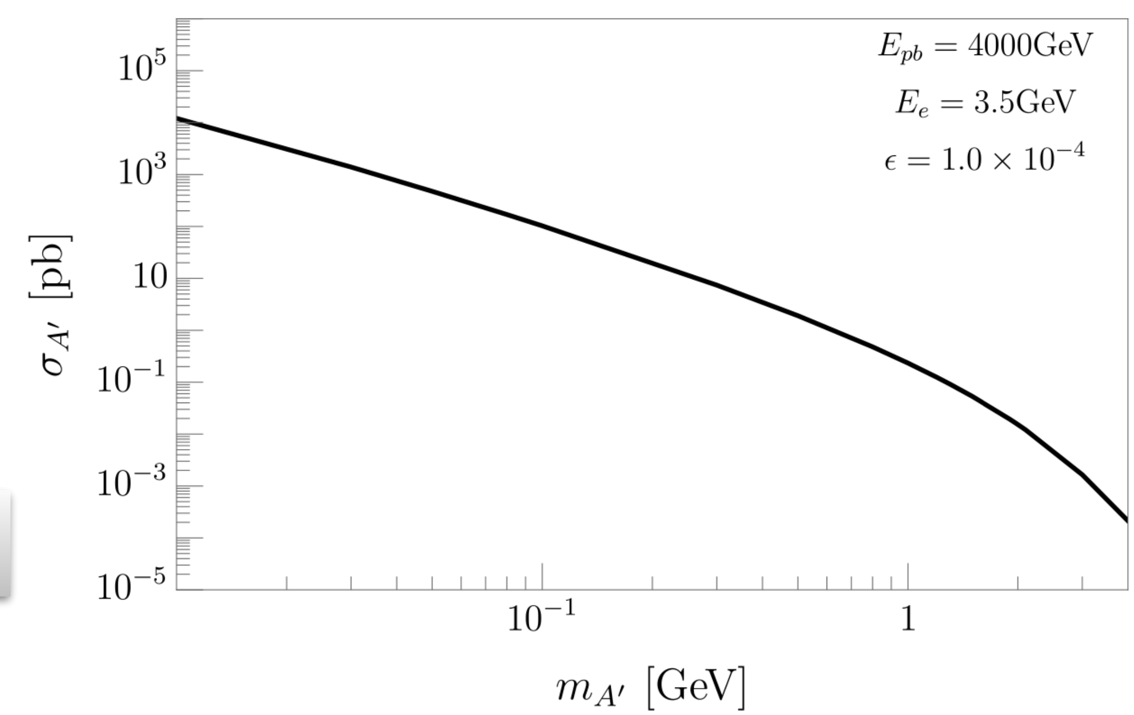
Dark Photon

- Focus on the kinetic mixing dark photon model (minimal)

$$\mathcal{L}_{A'} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 + eA_\mu J^\mu_{\rm em} \, ,$$

- Dark photon production via electron bremsstrahlung at EicC





- The coherent production is enhanced by Z^2

$$(m_{A'})_{\rm max} \sim 7.7 \text{ GeV} \left(\frac{m_N}{193\text{GeV}}\right)^{-\frac{1}{2}} \left(\frac{\sqrt{s - m_N^2}}{237\text{GeV}}\right) \left(\frac{A}{207}\right)^{-\frac{1}{6}}$$

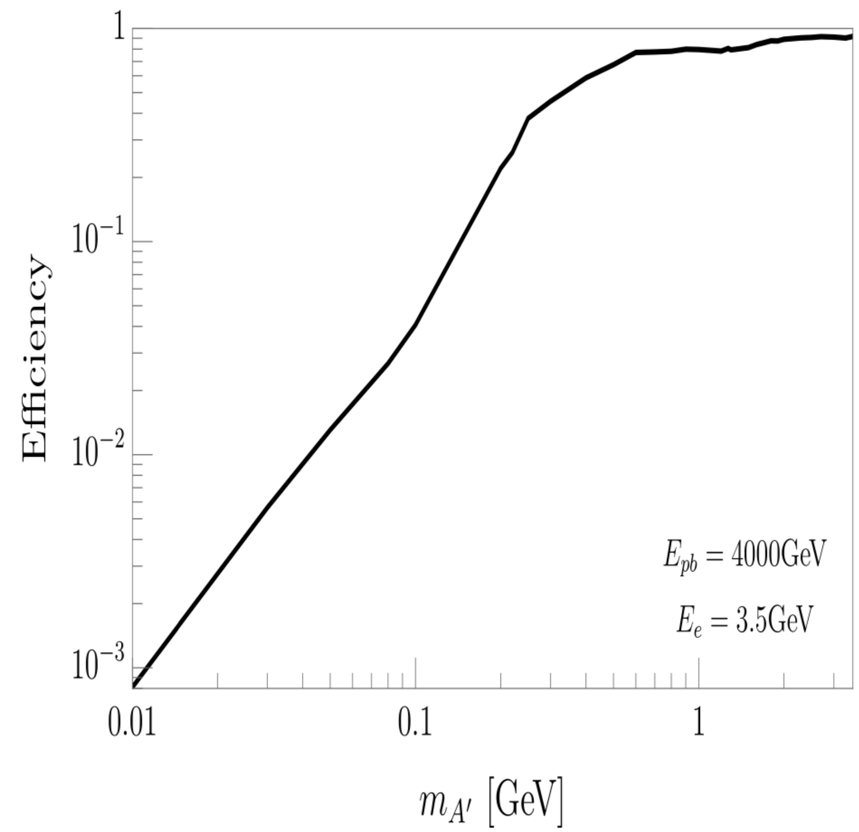
Dark Photon

- The signal: a pair of leptons from dark photon decay

$$\Gamma_{A'\to\ell^+\ell^-} = \frac{\epsilon^2\alpha}{3} m_{A'} \left(1 + 2\frac{m_\ell^2}{m_{A'}^2}\right)\sqrt{1 - 4\frac{m_\ell^2}{m_{A'}^2}}$$

- Impose the cuts on leptons for efficient detection

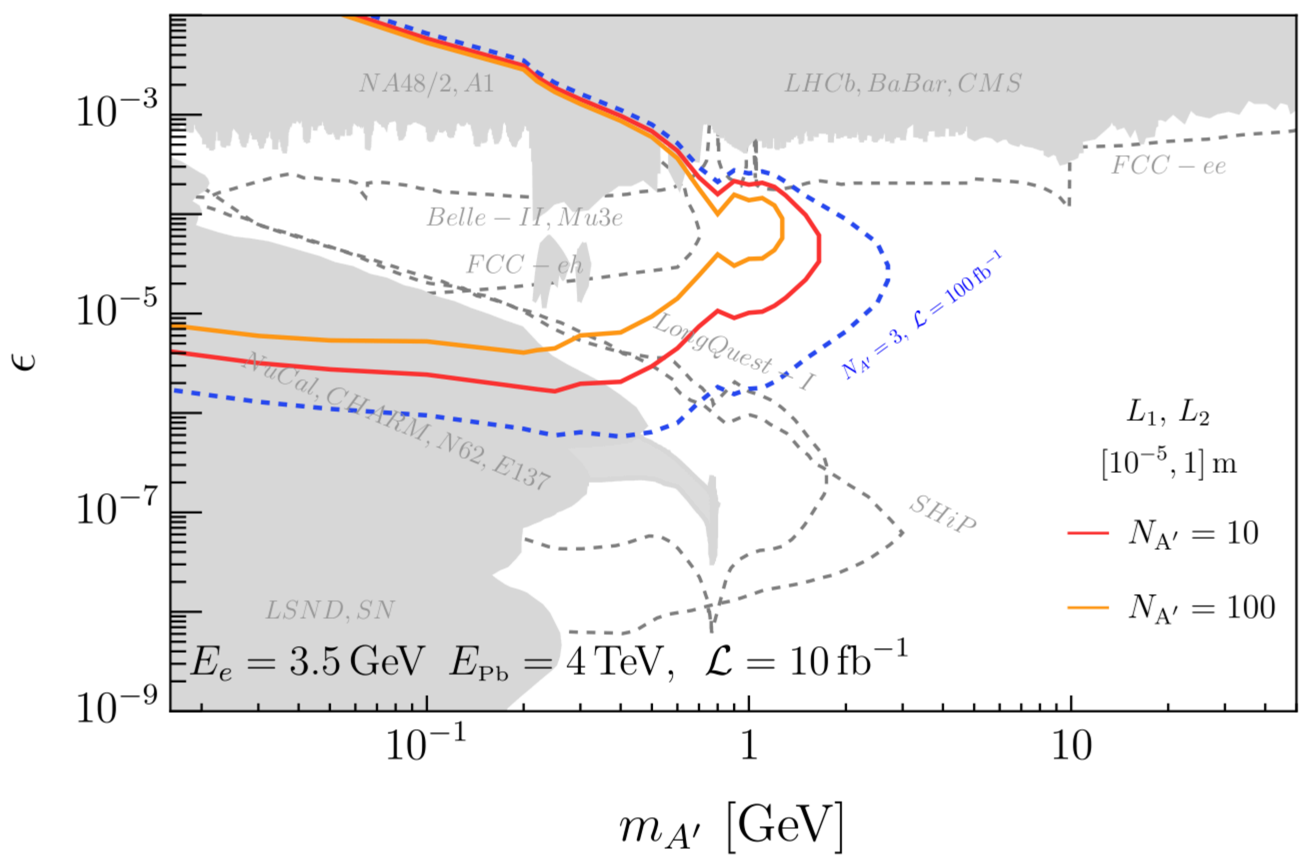
$$|\eta_\ell| < 4.0, \quad E_\ell > 0.05\ \text{GeV}$$

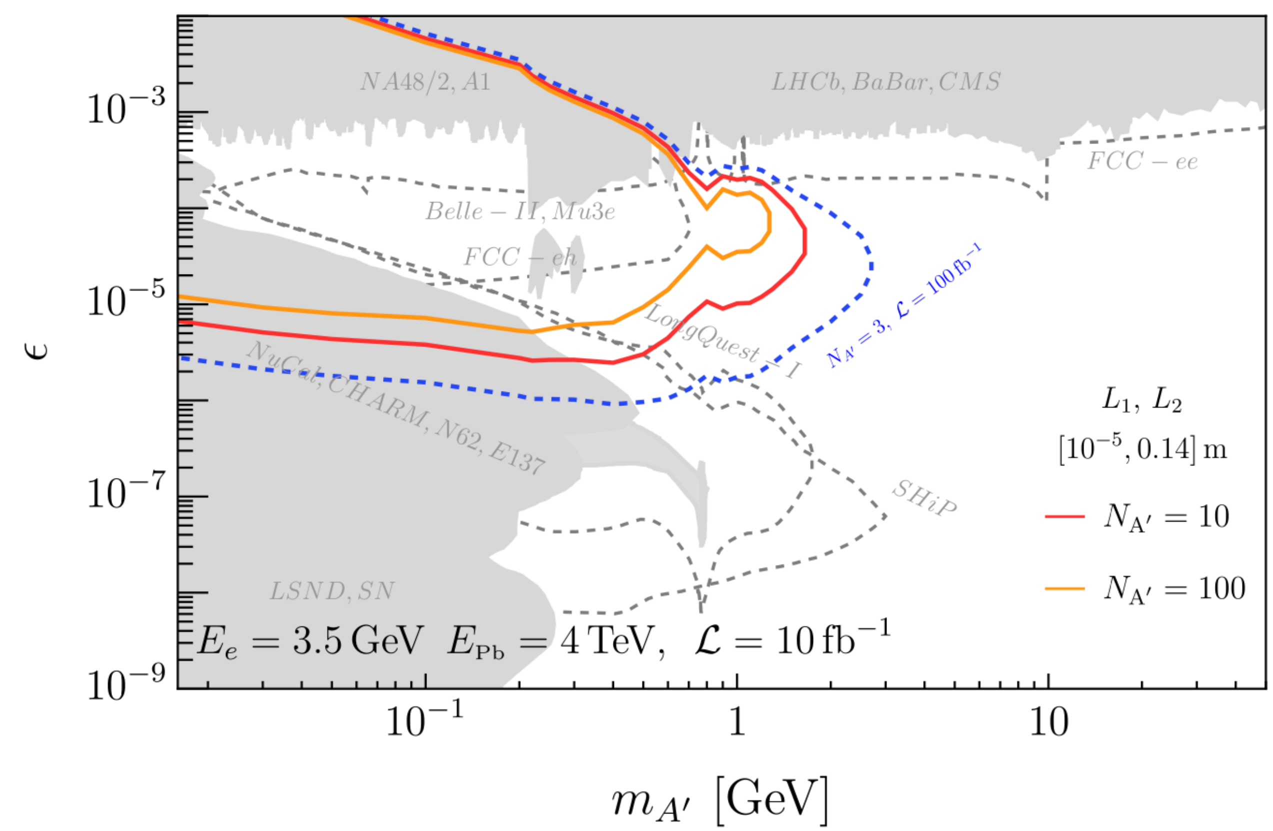


the detecting efficiency of the electrons

Dark Photon

- To suppress the BG, focus on the displaced-vertex search

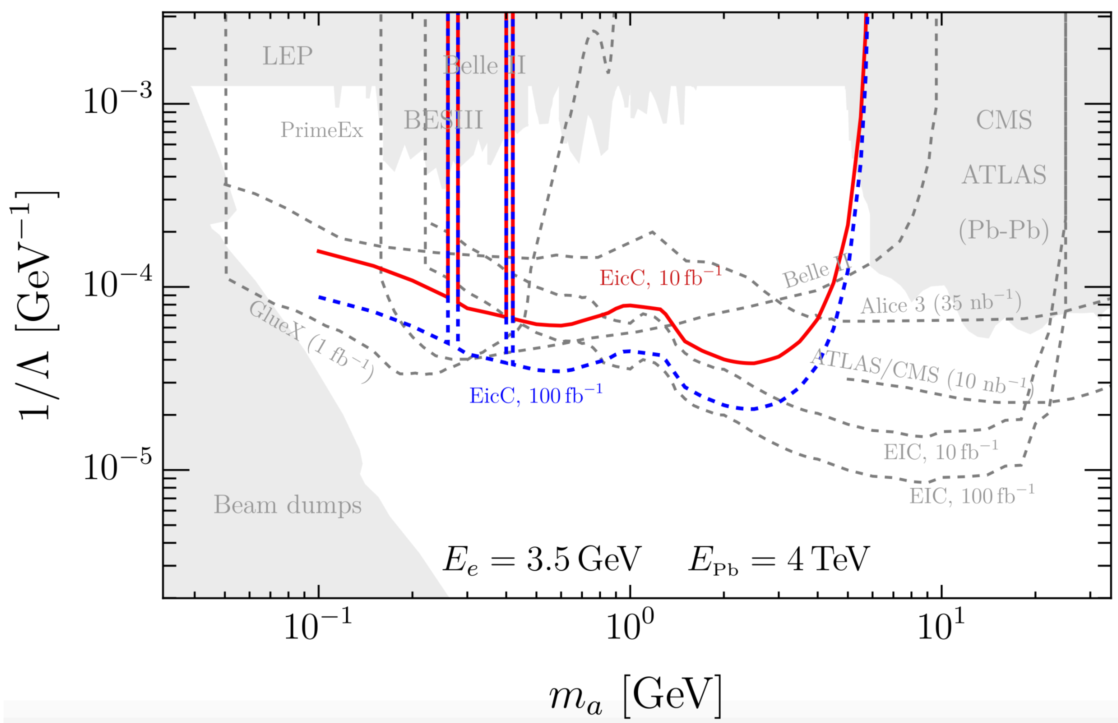


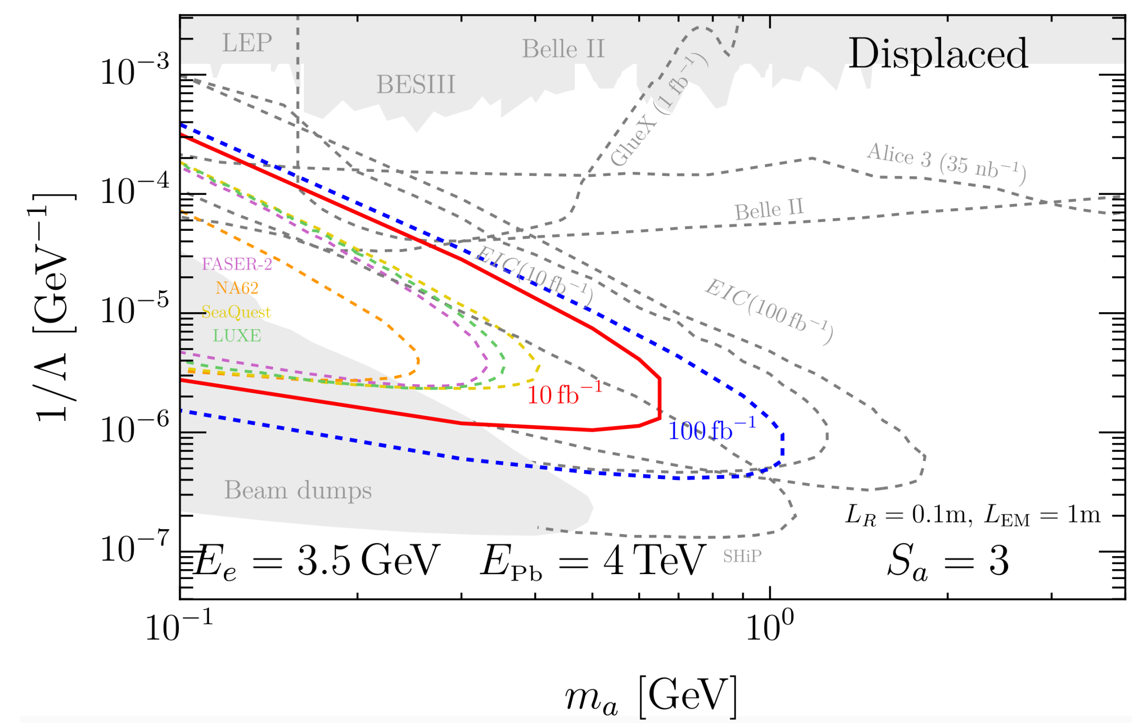


- displaced-vertex $[10^{-5}, 1]$ meter
- displaced-vertex $[10^{-5}, 0.14]$ meter

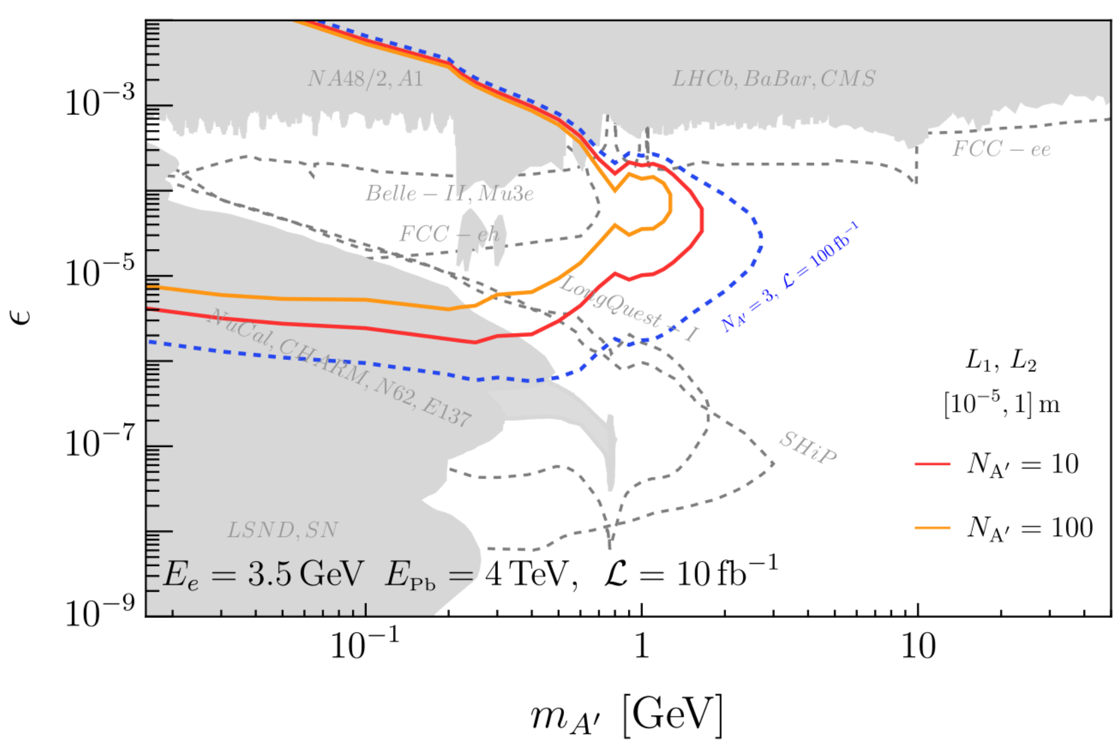
Summary

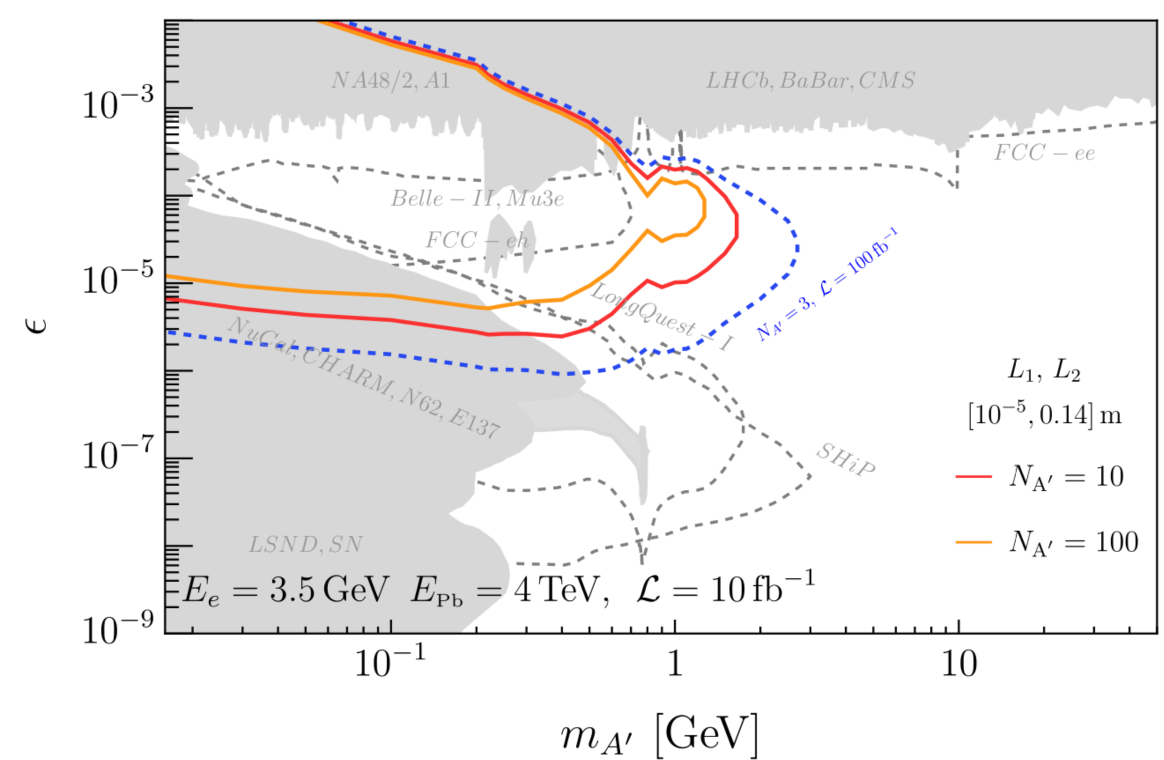
- EIcC can have world leading detection on ALP for $m_a \in [0.1\,, 5]$ GeV





- It also has world leading detection on dark photon for $m_A \in [0.1\,, 2]$ GeV





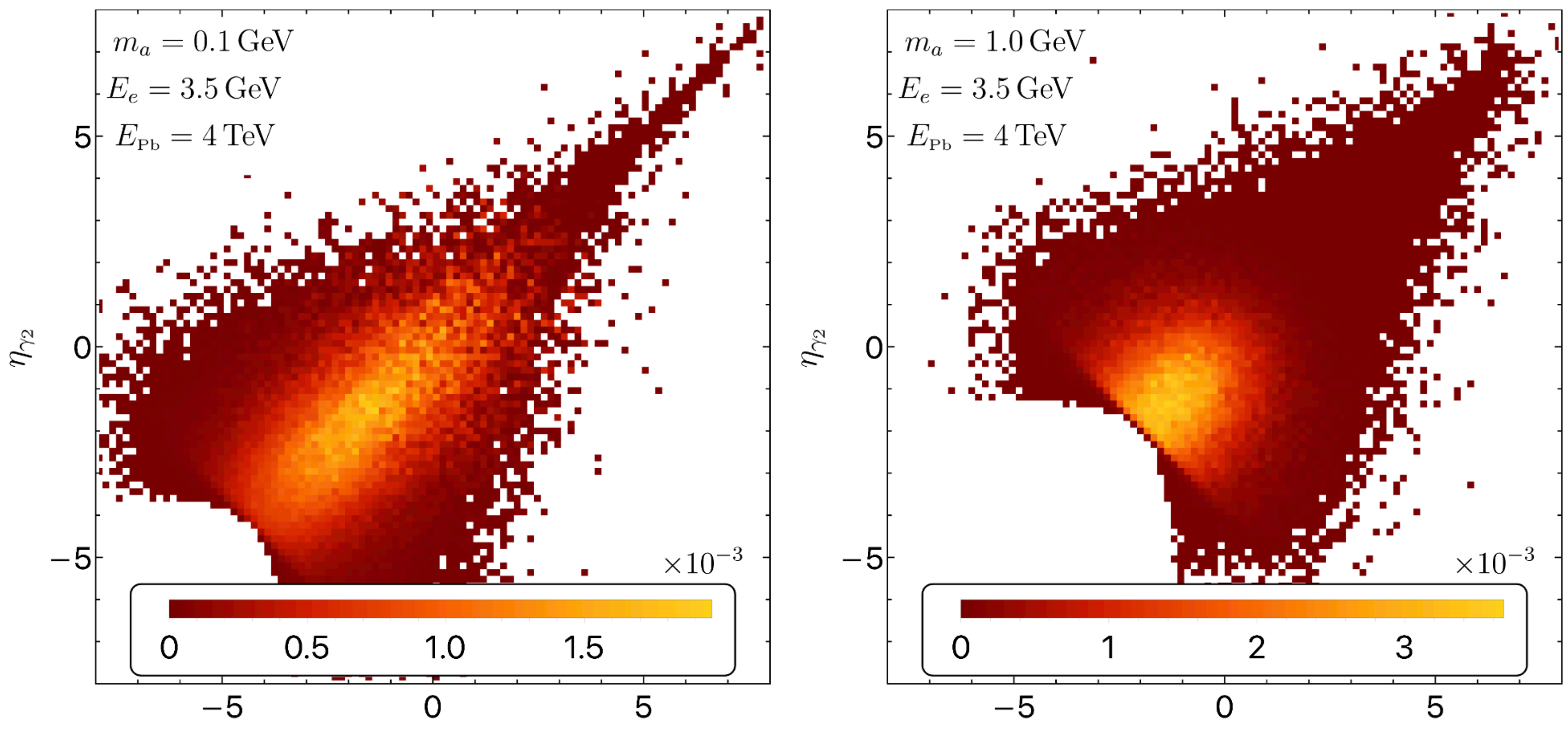
Thanks !!

Kinematics

- The signal: a pair of photons from ALP decay

$$a \to \gamma\gamma$$

- Pseudorapidity probability distribution for the two photons from ALP



Most the ALPs are boosted in the negative pseudorapidity so photons inherit this property

Heavier ALP is less boosted so the photons are separated at large angle