Probing axion-like particles at the Electron-Ion Collider

In collaboration with Reuven Balkin, Or Hen, Wenliang Li,
Teng Ma, Yotam Soreq, Michael Williams
[2310.08827]

Hongkai Liu

Brookhaven National Laboratory

Uncovering New Laws of Nature at the EIC
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Introduction

- Axion-like particles (ALPs) are very well motivated hypothetical particles.

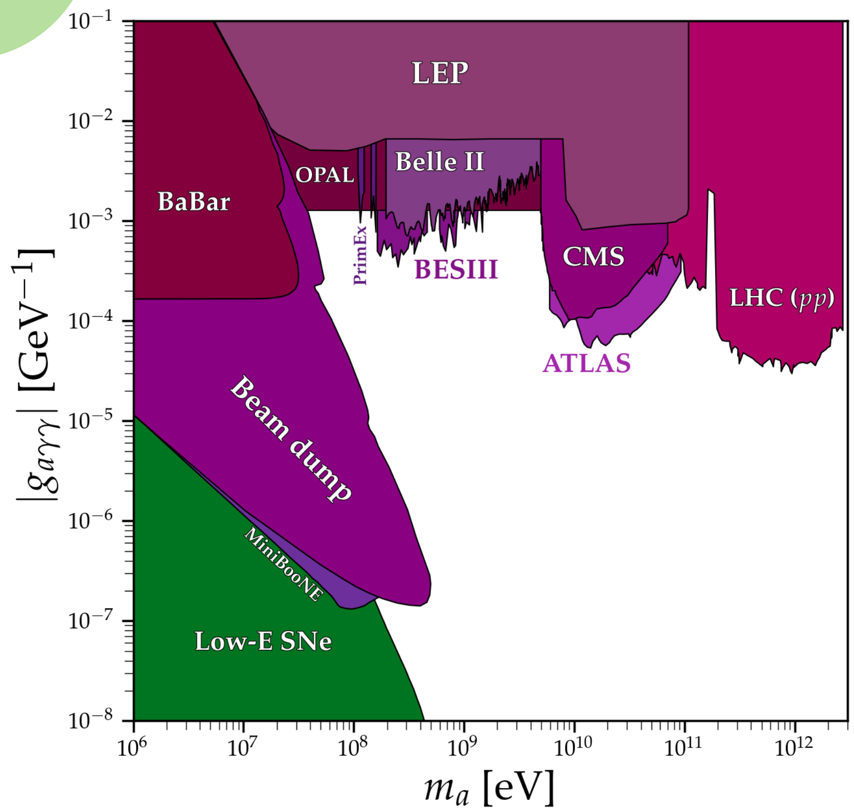
- Their interactions with the SM particles are described by EFT operators.

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a a^2 + \frac{a}{4\Lambda}F\tilde{F} + \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \ldots$$

Ongoing works

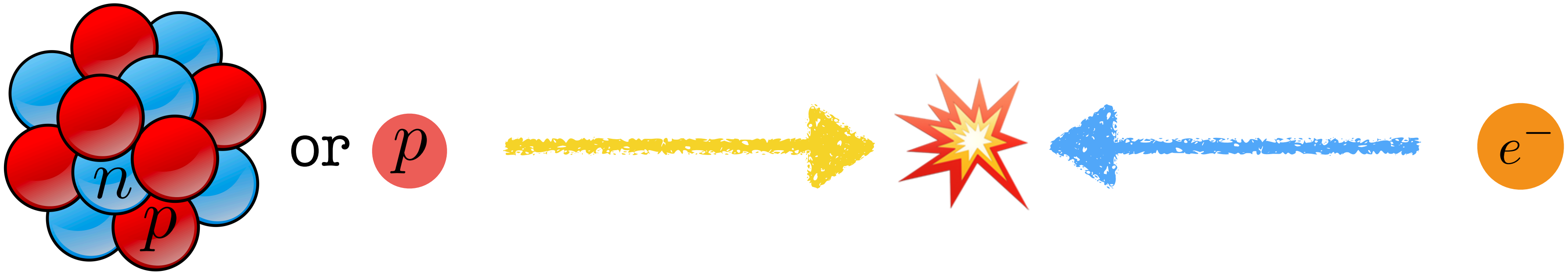
Focus in this talk

- We consider the searches of ALPs at the muon-ion collider (see Sokratis's talk this afternoon).



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

The Electron ion collider (EIC)



Understand quark-gluon structure of matter

- Understand the full three-dimensional momentum and spatial structure of nucleons and nuclei
- Understand the origin of nucleon mass and spin
- Study Nuclear PDFs
- …

$E_e:$ up to 18 GeV

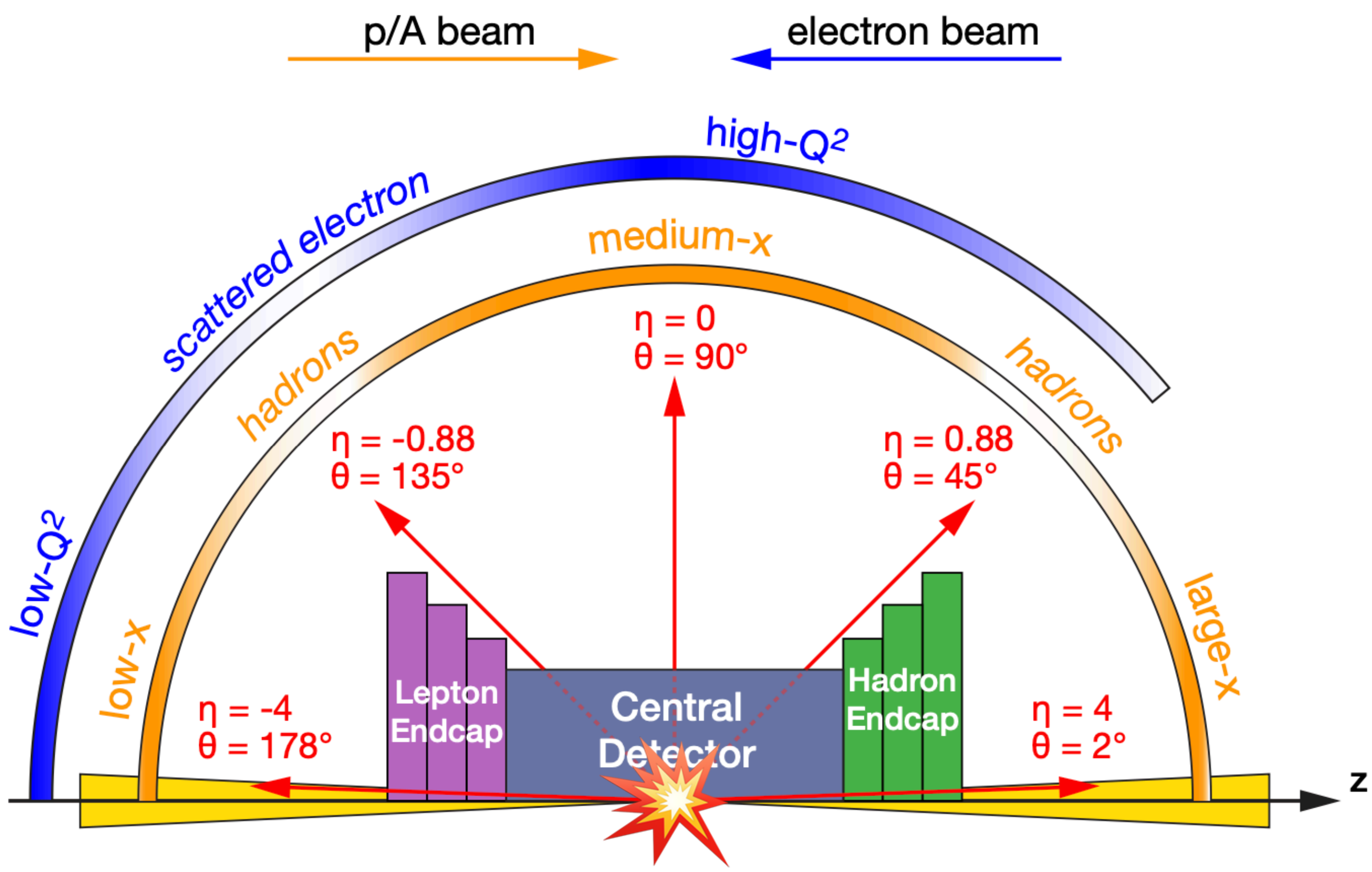
$L_{\text{peak}} = 10^{33} - 10^{34}\text{cm}^{-2}\text{s}^{-1}$

$E_p:$ up to 275 GeV. For lead, $E_{\text{lead}} = 20$ TeV

10 - 100 / fb / year

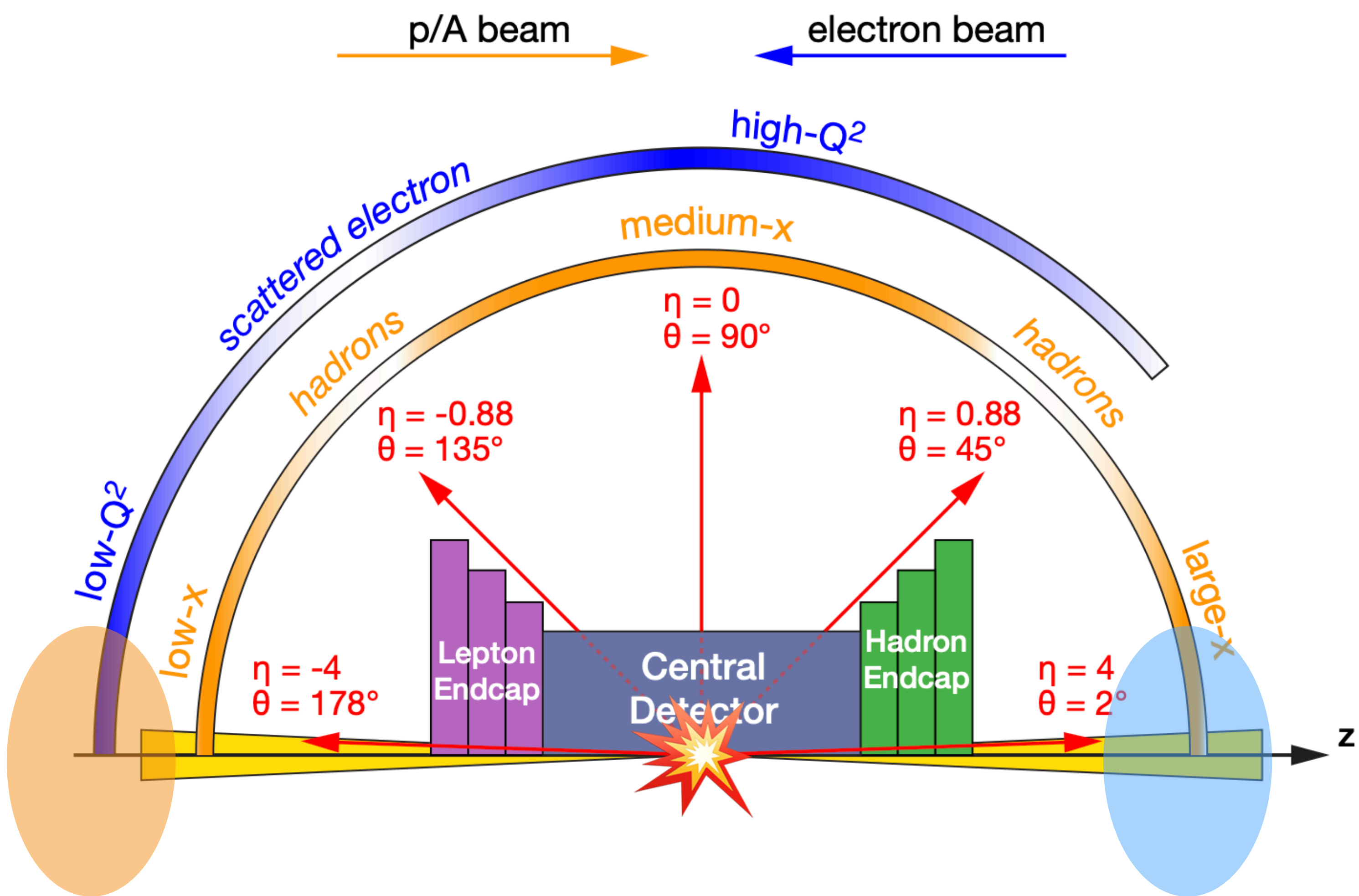
The Electron ion collider (EIC)

- The different detector systems observe different particle distributions.



The Electron ion collider (EIC)

- The different detector systems observe different particle distributions.



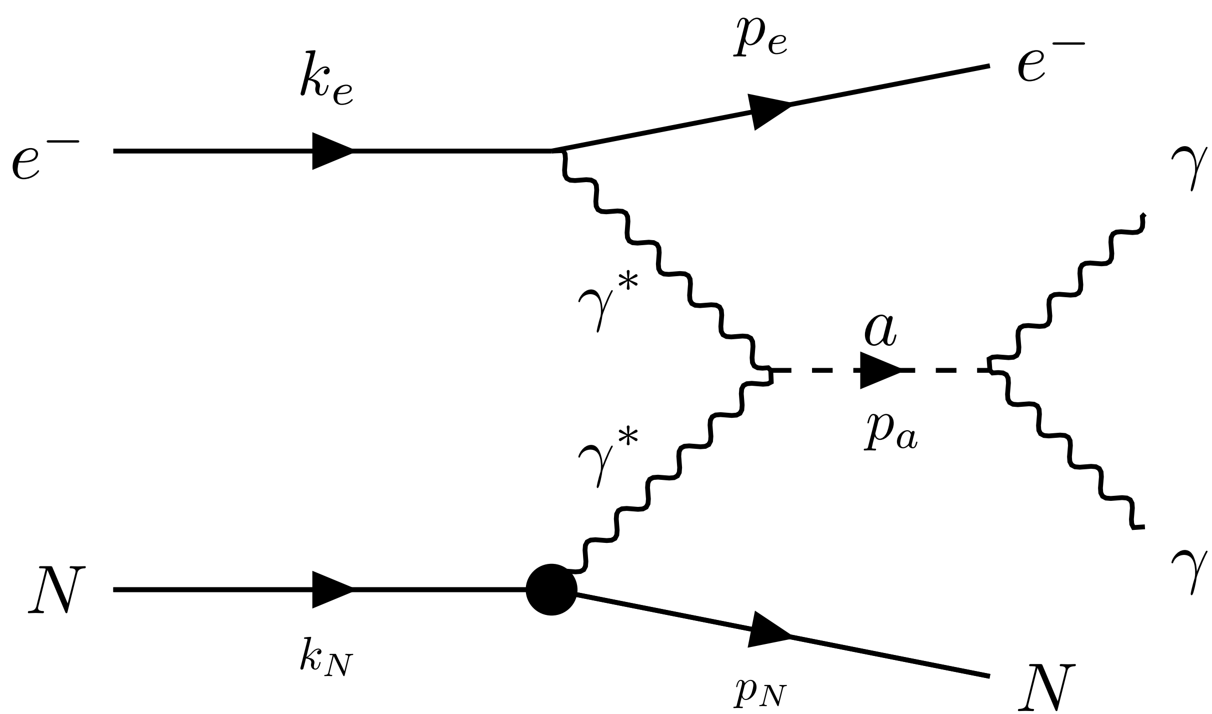
Far-backward detector:
Measure scattered electrons with extremely low Q^2

Ideal for studying coherent scattering

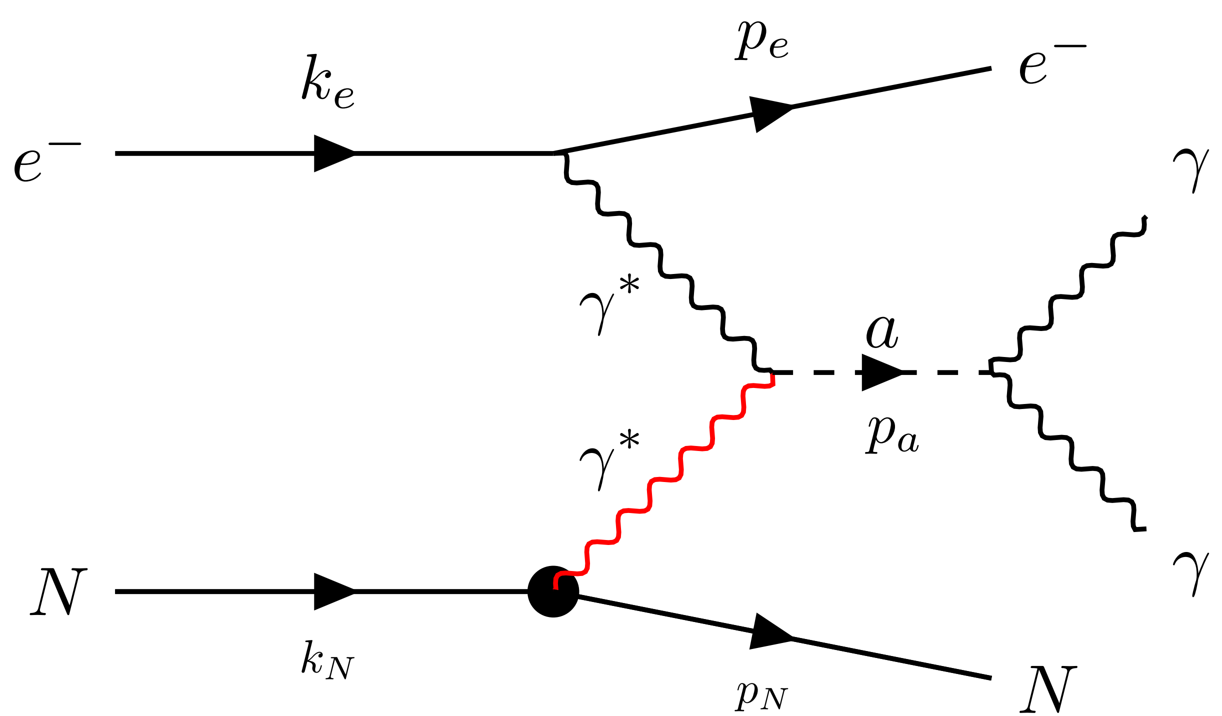
Far-forward detector:
Can select the coherent collision vetoing spectator neutrons from nuclear breakup

ALP production at EIC

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a a^2 + \frac{a}{4\Lambda}F\tilde{F}$$



ALP coherent production at EIC



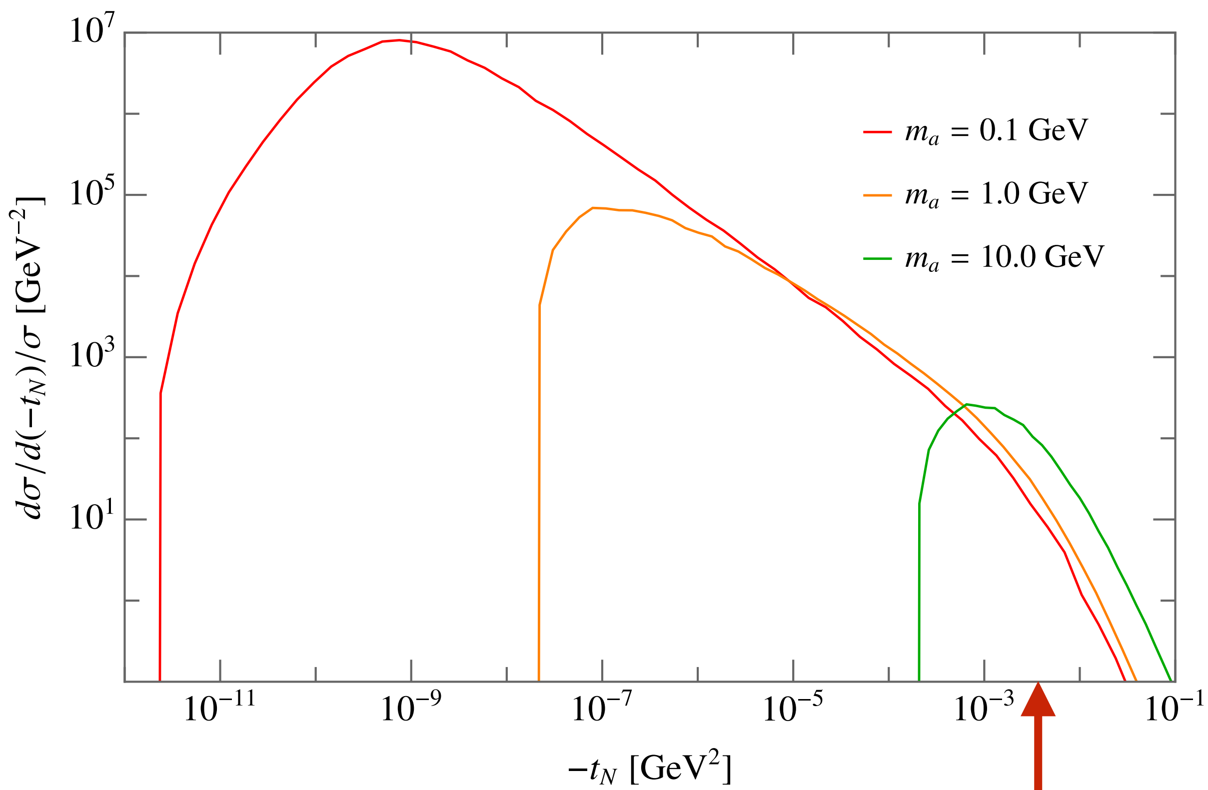
Ion-transferred momentum: $t_N \equiv (k_N - p_N)^2$

Amplitude square peaks at $|\, t_N \,|_{\min}$: $\quad |\mathcal{M}|^2 \propto \dfrac{1}{t_N^2}$

Coherent regime: $\sqrt{|\, t_N \,|} < 1/r_N, \quad r_N \sim A^{1/3}\ (1\ \mathrm{fm})$

Lead to an enhancement of Z^2 in the ALP production!

Kinematics: tN



Coherent production is suppressed beyond this point

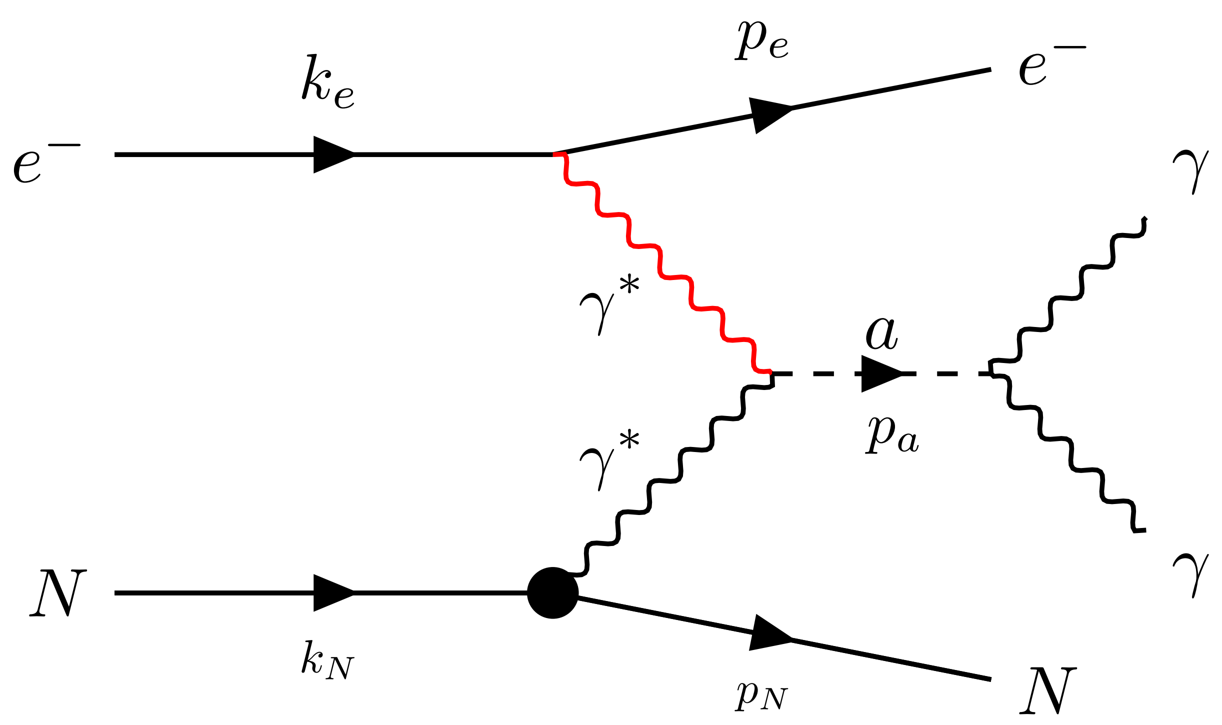
In the limit: $m_e, m_a \ll m_N \ll \sqrt{s}$

$$(-t_N)_{\min} \approx 1.8 \times 10^{-8}\ \mathrm{GeV}^2 \left(\frac{m_a}{1.0\ \mathrm{GeV}}\right)^4 \left(\frac{m_N}{193\ \mathrm{GeV}}\right)^2 \left(\frac{\sqrt{s}}{1.2\ \mathrm{TeV}}\right)^{-4}$$

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

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

ALP coherent production at EIC



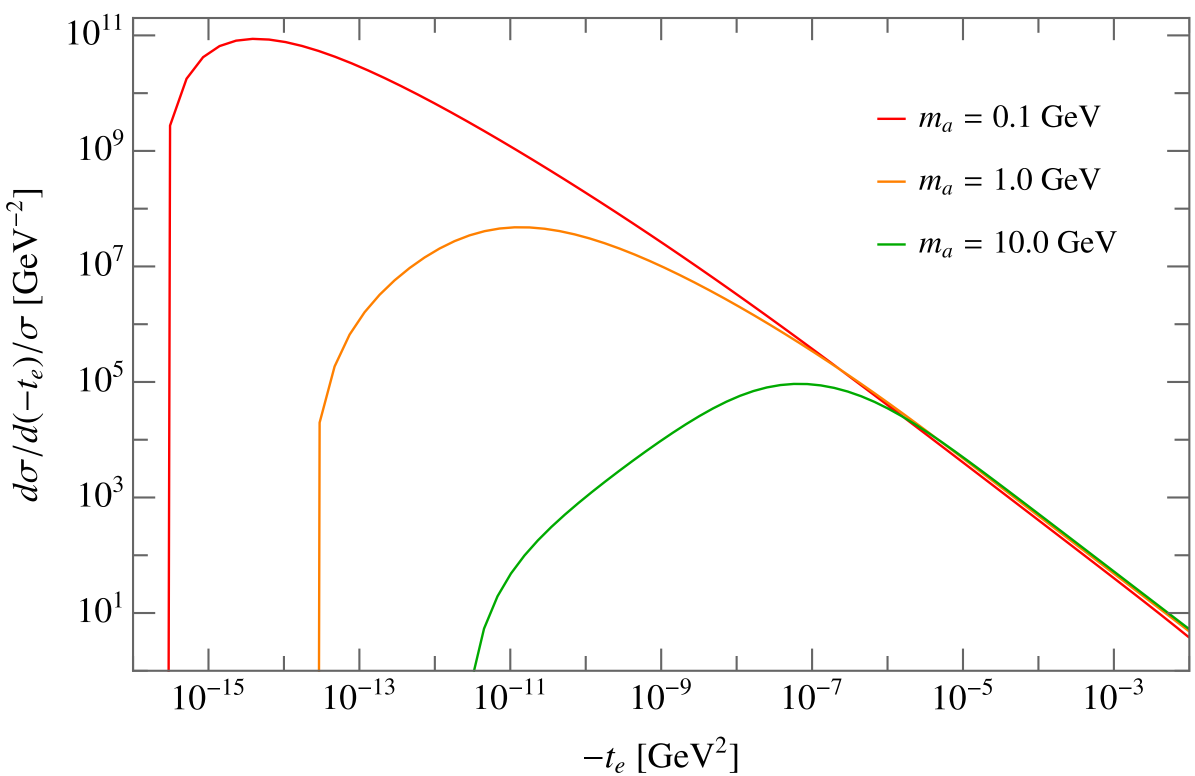
Electron-transferred momentum: $t_e \equiv (k_e - p_e)^2$

Amplitude square peaks at $|\ t_e\ |_{\min}$: $\quad |\mathcal{M}|^2 \propto \dfrac{1}{t_e^2}$

Once the recoil electron is measured very precisely, the outgoing ion can be reconstructed

$$p_N^2 = (k_e + k_N - p_{\gamma_1} - p_{\gamma_2} - p_e)^2 = m_N^2$$

Kinematics



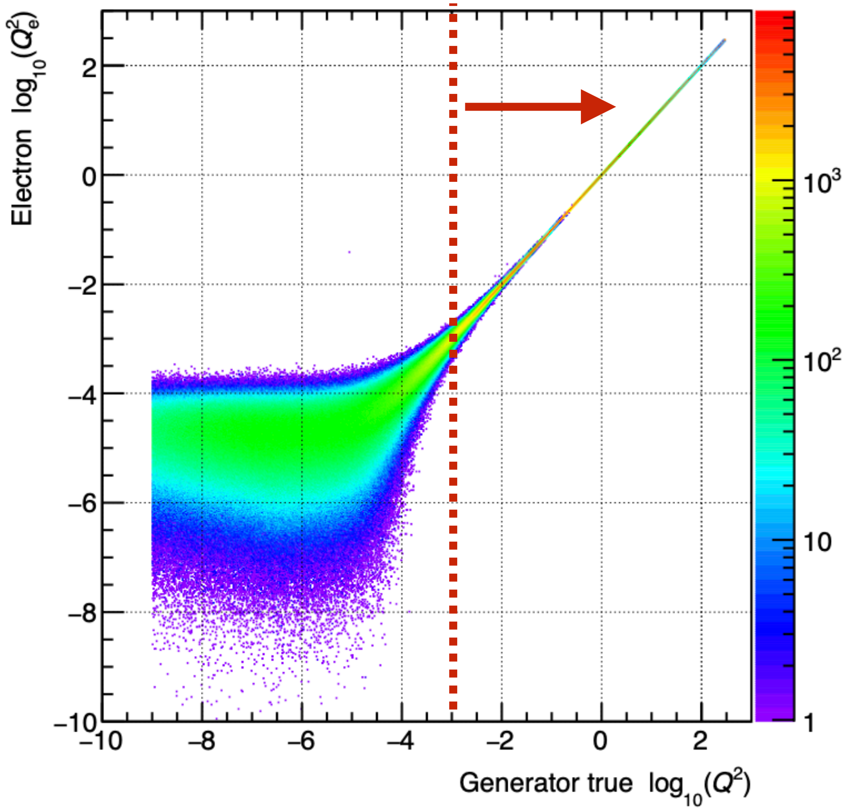
In the limit: $m_e, m_a \ll m_N \ll \sqrt{s}$

$$(-t_e)_{\min} \approx 1.9 \times 10^{-14}\ \text{GeV}^2 \left(\frac{m_a}{1.0\ \text{GeV}}\right)^2 \left(\frac{m_N}{193\ \text{GeV}}\right)^2 \left(\frac{\sqrt{s}}{1.2\ \text{TeV}}\right)^{-4}$$

Far-backward detector is extremely important for this search

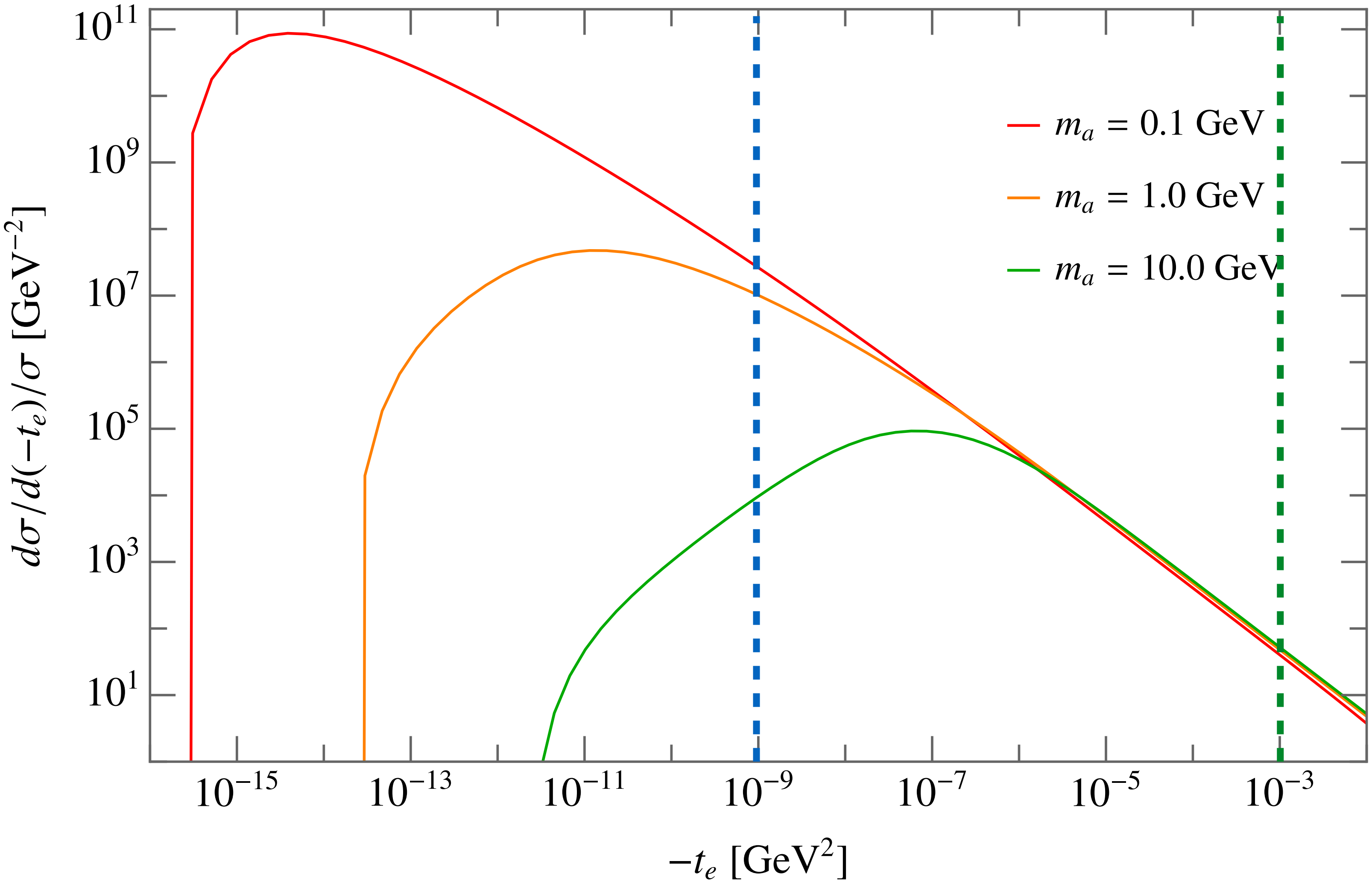
Tagging scattered electrons

[The EIC Yellow Report, arXiv:2103.05419]

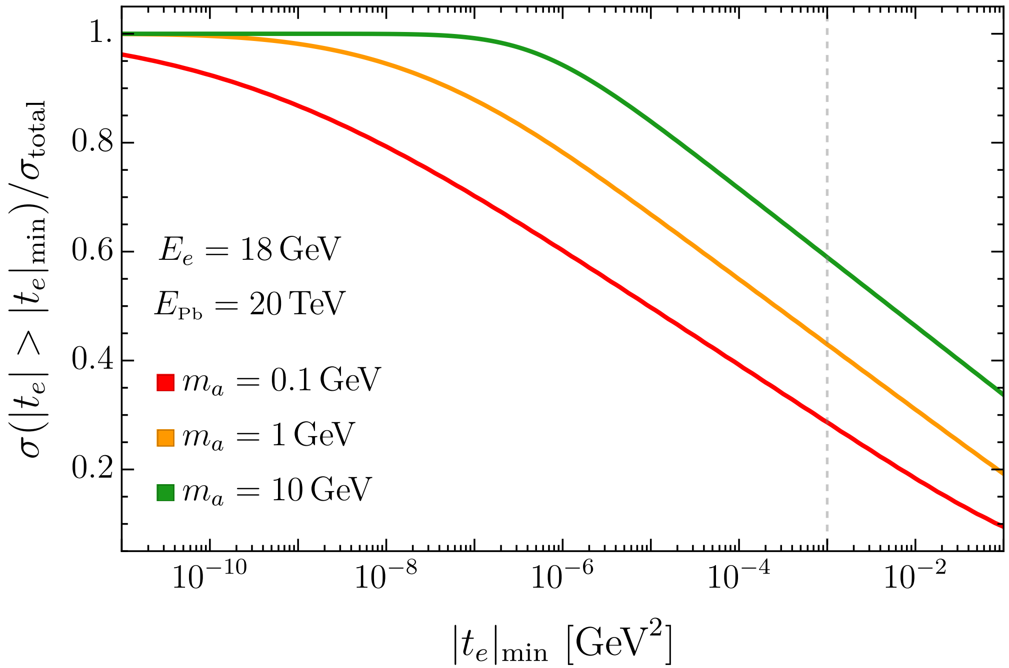


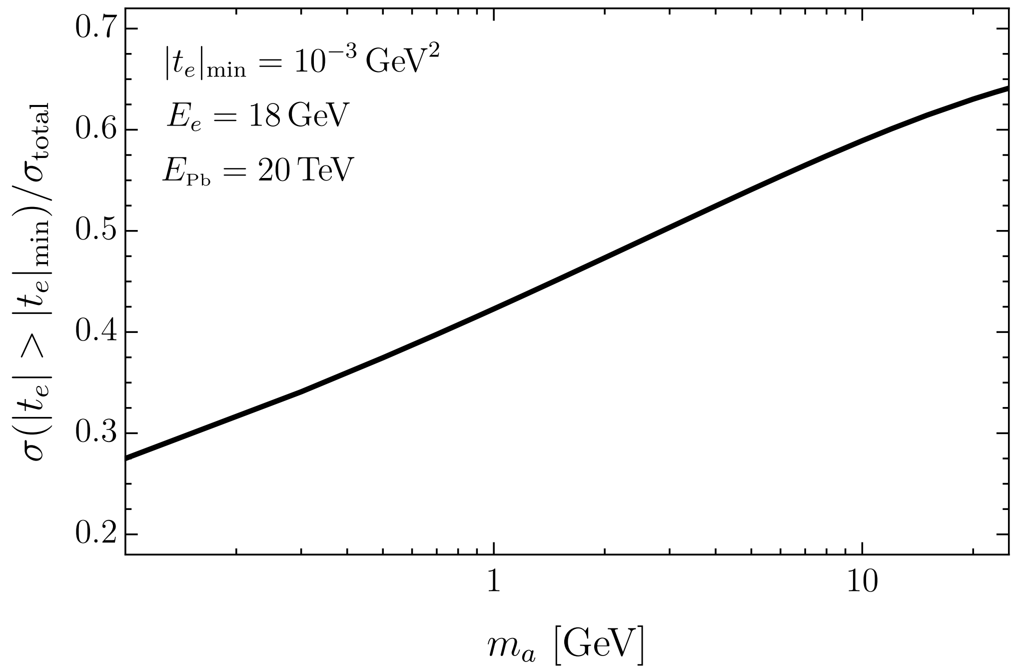
- Recoil electrons with very low-Q^2 ($10^{-9}\ \mathrm{GeV}^2$) can be tagged.
- But only when $Q^2 > 10^{-3}\ \mathrm{GeV}^2$ we can have reasonable good resolution.

Kinematics: te



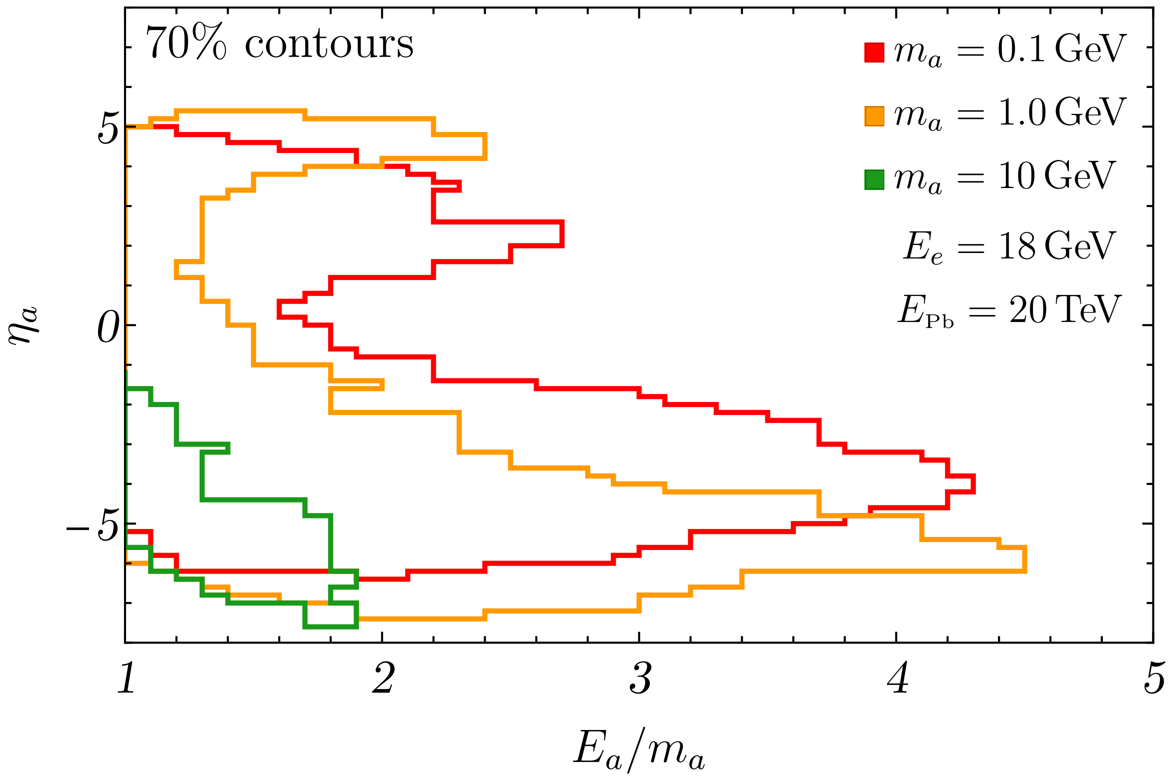
Cut efficiencies





- We require $-t_e > 10^{-3}\ \mathrm{GeV}^2$ to have reasonable good resolution.
- The efficiencies is around 40% for 1 GeV ALP.

Kinematics: ALP



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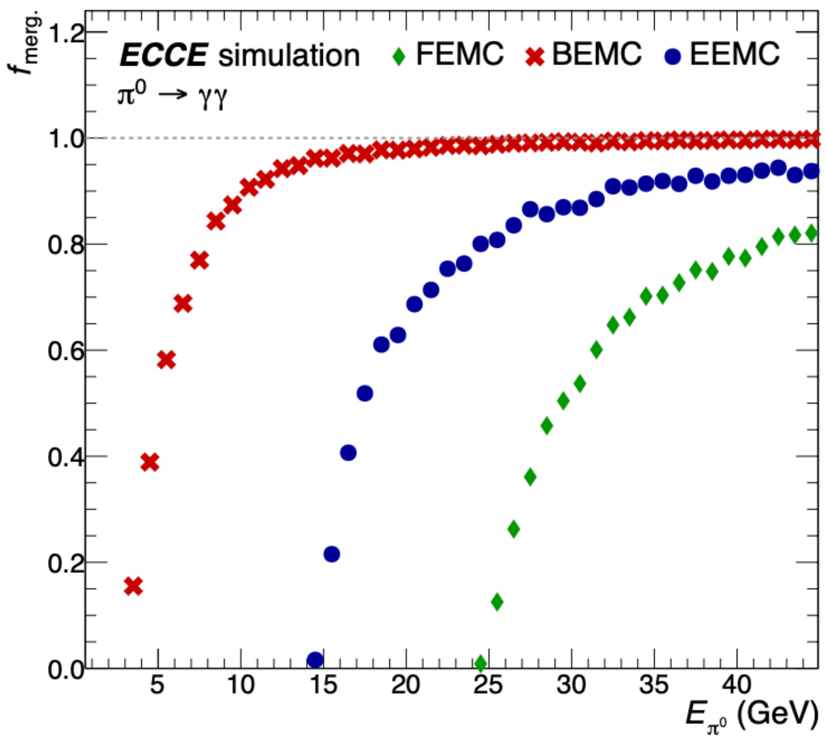
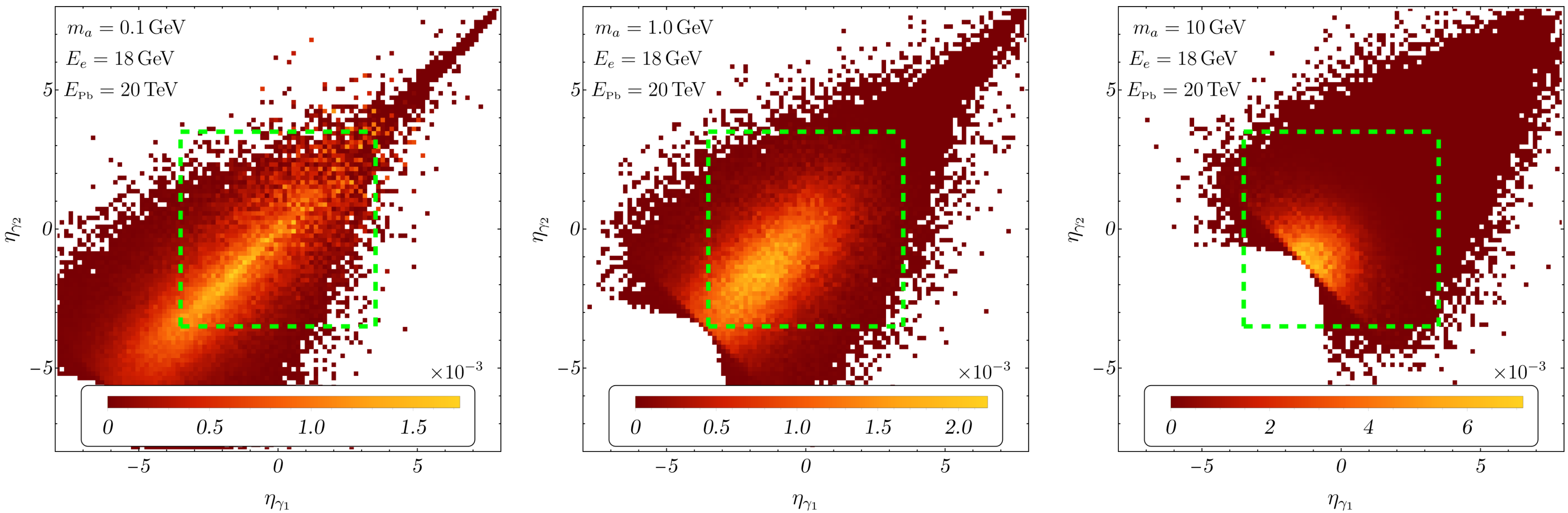


- No need to worry about the merge of two photons from ALPs decay.
- Heavier ALPs tend to be produced at more backward direction.

Kinematics: photon



- Heavier ALP has a smaller boost factor, the opening angle of the photon is larger. So, more events are closer to eta=0
- For heavier ALPs, there are more photons in the backward region.

Prompt searches:

- The signal is clean:

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

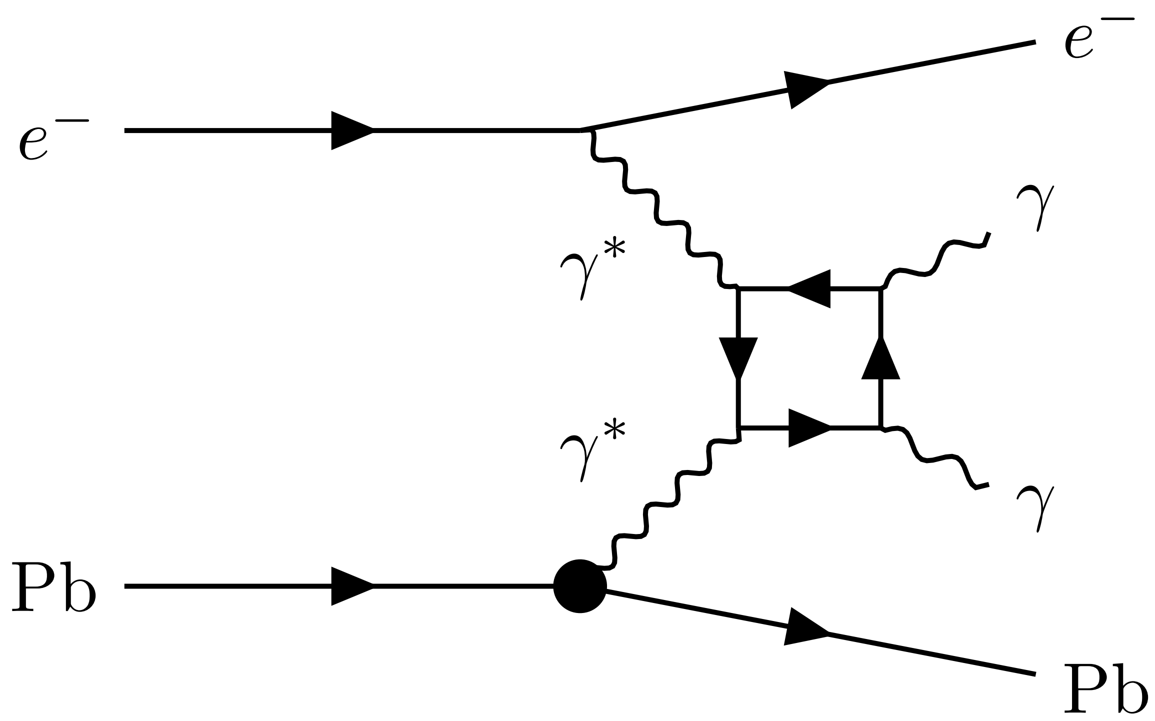
- Basic cuts:
  - Due to the angular acceptance, we require $|\eta_\gamma| < 3.5$
  - To ensure an excellent photon resolution and suppress beam related background , we require $E_\gamma > 1$ GeV
  - Perform a resonance search in the invariant mass of two photons

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

  - From a simulation:

$m_{\gamma\gamma}$ [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

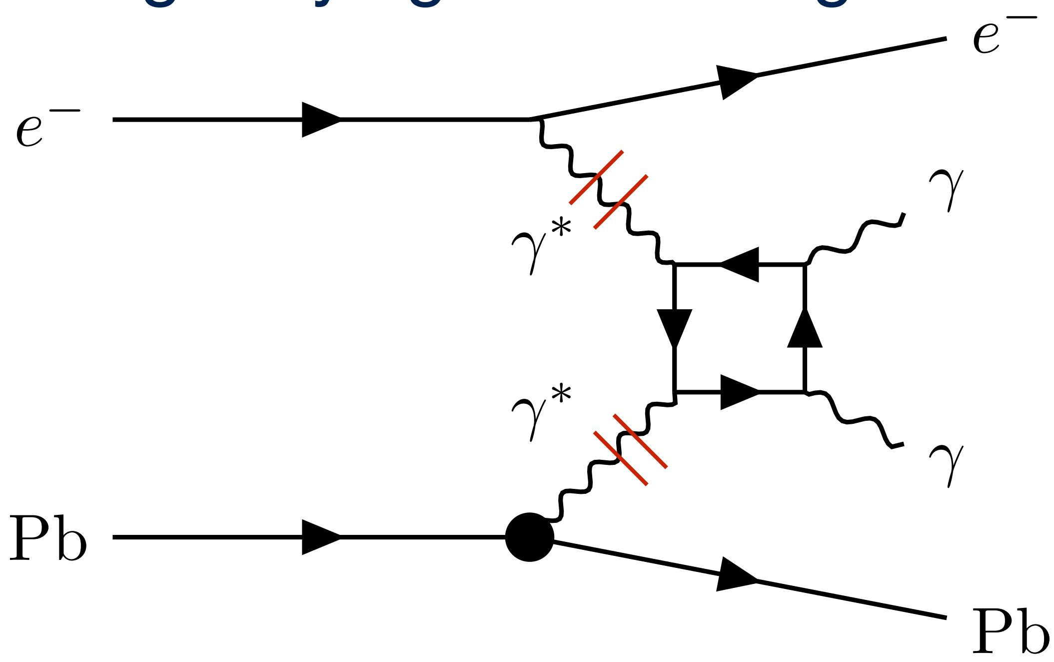
Backgrounds: light-by-light scattering



- Irreducible light-by-light (LBL) scattering: $\gamma + \gamma \to \gamma + \gamma$

- We use the equivalent photon approximation (EPA) to estimate the backgrounds

Backgrounds: light-by-light scattering



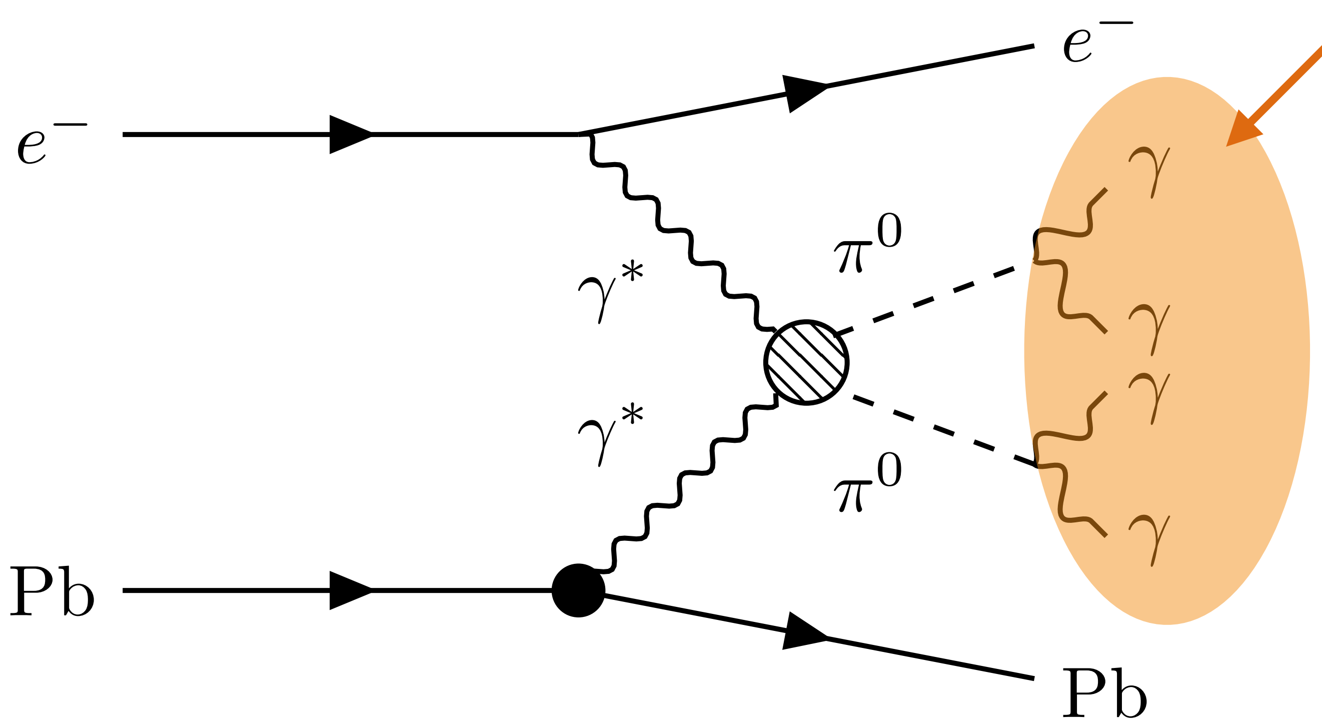
$$\frac{d\sigma_{eN\to eNX}}{d\hat{s}}(\hat{s}) = \frac{1}{\hat{s}}\int_{\frac{\hat{s}}{4E_{pb}}}^{E_e} \frac{d\omega_1}{\omega_1} f_{\gamma/e}(\omega_1)\, f_{\gamma/N}(\omega_2)\, \hat{\sigma}_{\gamma\gamma\to X}(\hat{s})$$

- LBL scattering: $\hat{\sigma}_{\gamma\gamma\to\gamma\gamma}(\hat{s}) \sim \frac{10^{-6}}{\hat{s}}$ [Bern, Freitas, Dixon, Ghinculov, Wong, hep-ph/0109079]

- Signal: $\hat{\sigma}_{\gamma\gamma\to a\to\gamma\gamma}(\hat{s}) = \frac{\pi m_a^2}{8\Lambda^2}\delta(\hat{s} - m_a^2)$

$$\frac{\sigma_a}{\sigma_{\rm LBL}} \approx 20\left(\frac{\rm TeV}{\Lambda}\right)^2\left(\frac{m_{\gamma\gamma}}{2\,\rm GeV}\right)^2\left(\frac{0.01}{\Delta m_{\gamma\gamma}/m_{\gamma\gamma}}\right)$$

Backgrounds: pion-pair production



Detect two out of four

The photon detection efficiency is assumed to be 70%

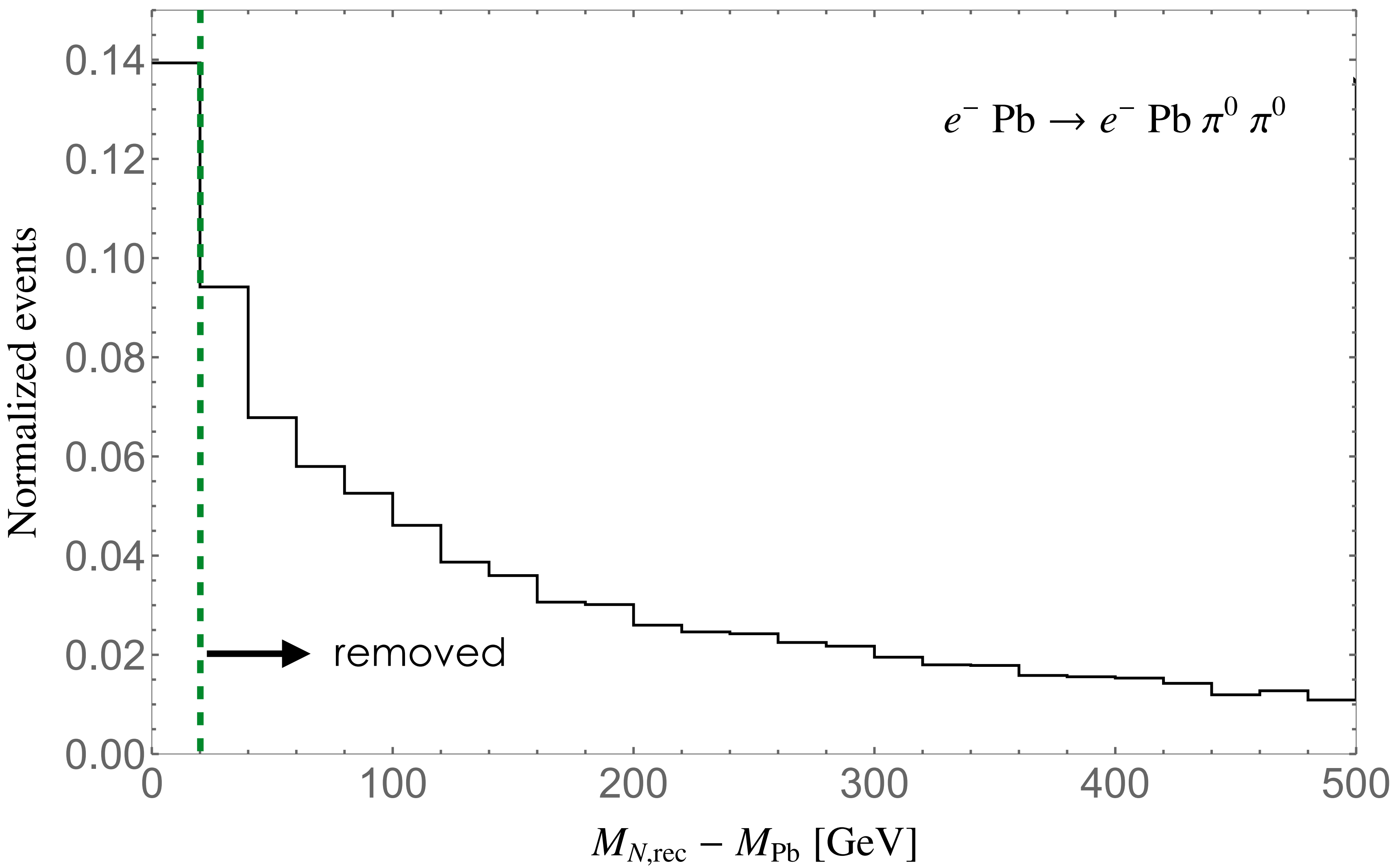
- Reducible Pion-pair production $\gamma + \gamma \to \pi^0 + \pi^0 \to 4\gamma$

Several processes contribute to the neutral pion pair production

[Klusek-Gawenda, Szczurek, arXiv:1302.4204]

Miss two photons: $p_N^{\mathrm{rec},2} = (p_N^{\mathrm{true}} + p_{\gamma_1}^{\mathrm{miss}} + p_{\gamma_2}^{\mathrm{miss}}) > m_N^2$

Backgrounds: pion-pair production

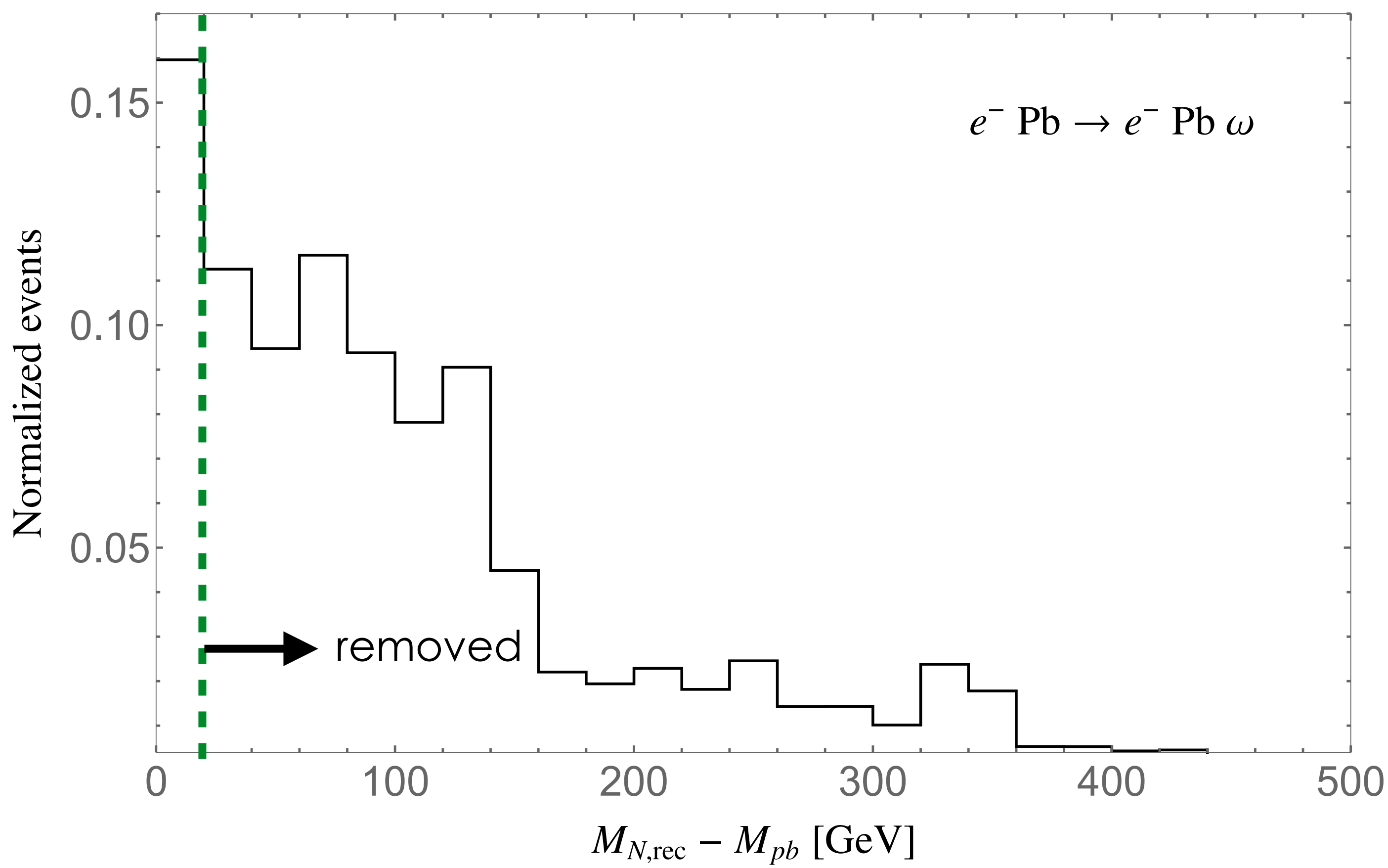


Require: $M_{\mathrm{Pb,rec}} - M_{\mathrm{pb}} \leq 10\% \; M_{\mathrm{Pb}}$ $\qquad |\Delta\phi_{\gamma\gamma} - \pi| < 0.2$

Backgrounds: omega production

Detect two out of three

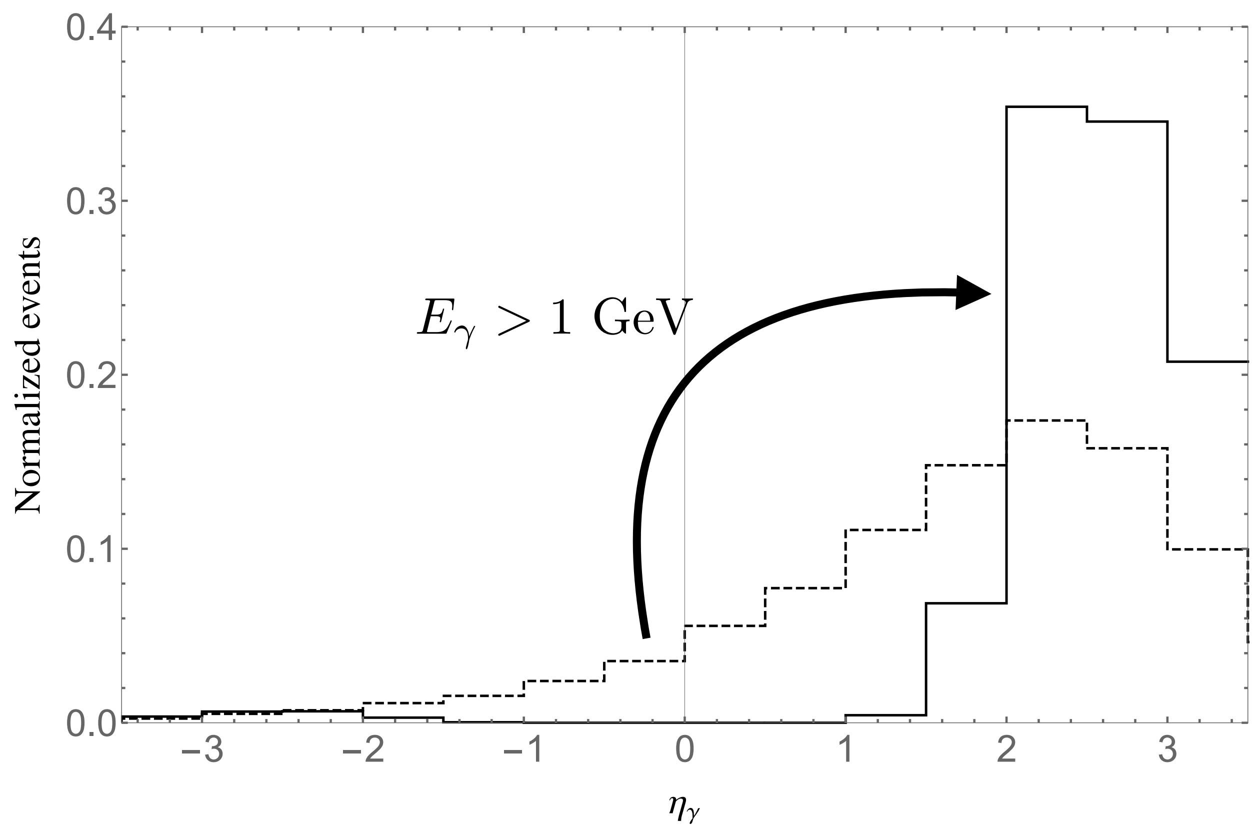
- Reducible $\omega\,(782) : \gamma + N \to \omega + N, \omega \to \pi^0 + \gamma \to 3\gamma$
- Only contribute at $m_{\gamma\gamma} < m_\omega$
- We take the photoproduction of omega resonance from [Ballam, etc, PRD 7 (1973) 3150]



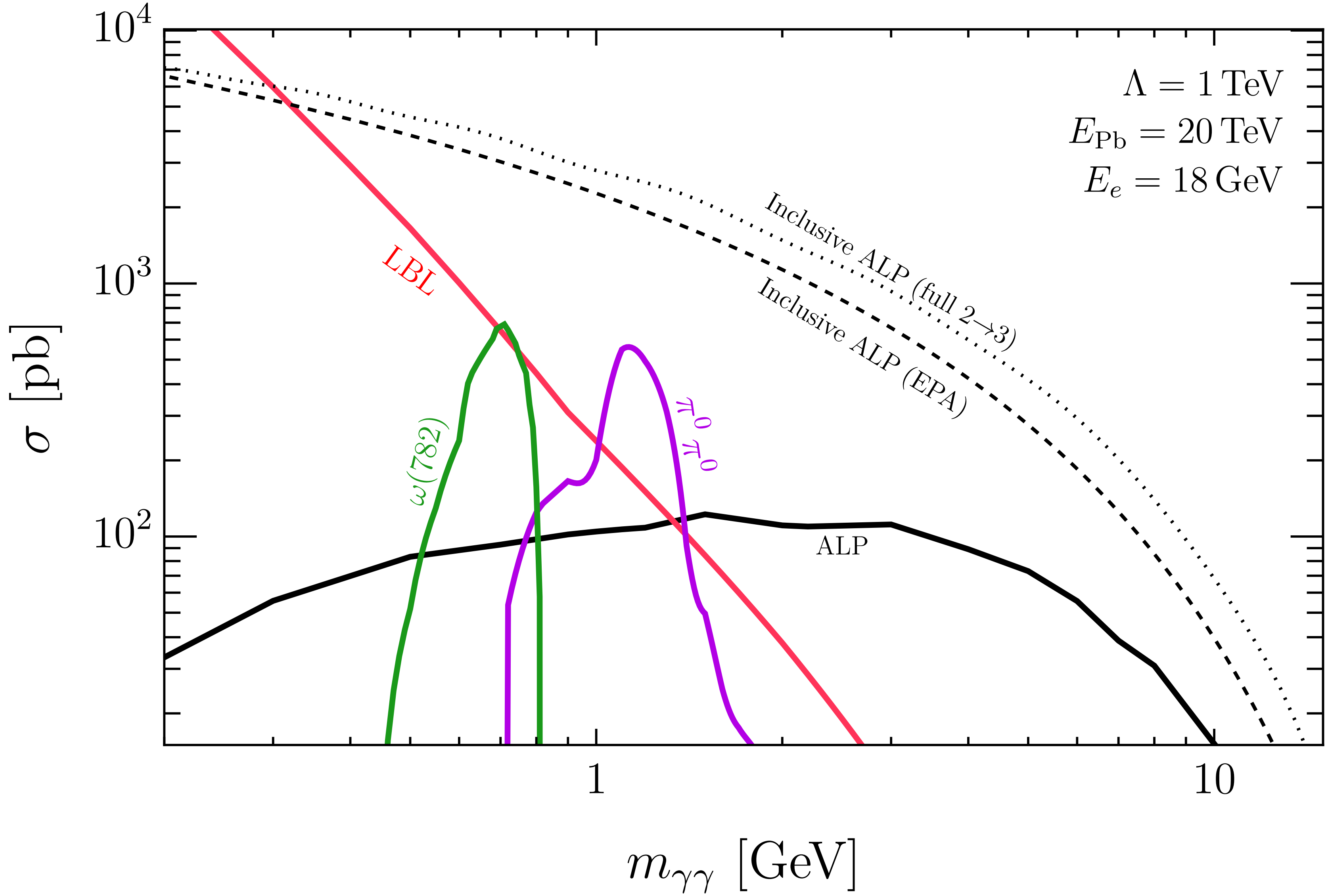
Backgrounds: omega production

Detect two out of three

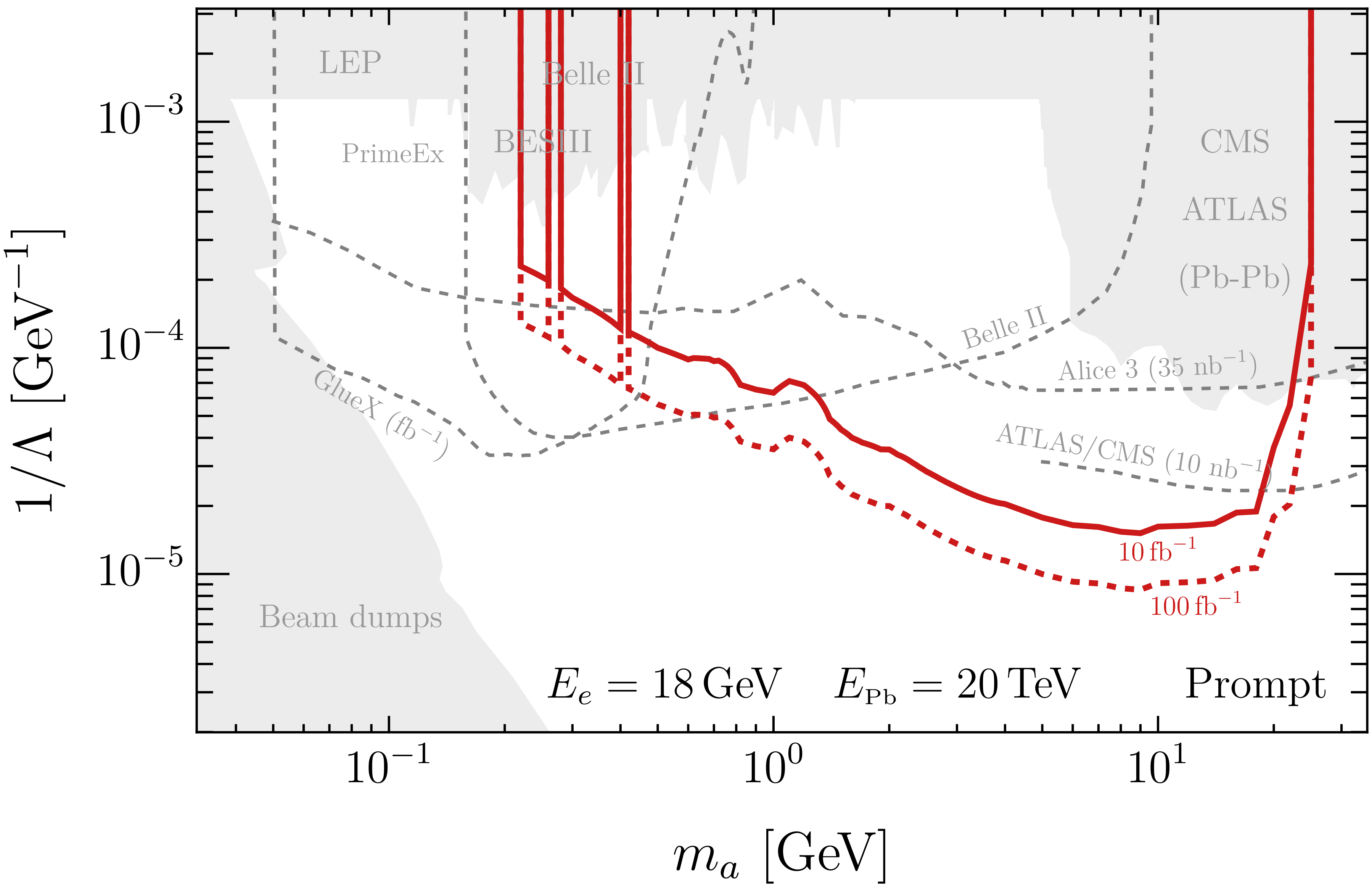
- Reducible $\omega(782): \gamma + N \to \omega + N, \omega \to \pi^0 + \gamma \to 3\gamma$
- Only contribute at $m_{\gamma\gamma} < m_\omega$
- We take the photoproduction of omega resonance from [Ballam, etc, PRD 7 (1973) 3150]
- We further require $\eta_{\gamma_{1,2}} < 0$ at $m_{\gamma\gamma} < m_\omega$



Cross sections after the cuts



EIC projections: prompt searches



EIC projections: displaced-vertex searches

ALP decay width $\Gamma_a = \dfrac{m_a^3}{64\pi\Lambda^2}$

ALP decay length at the lab frame $L_a \equiv \dfrac{\beta\gamma}{\Gamma_a}$ $\beta\gamma = p_a/m_a$

ALP decay probability between distance L_R and $L_{\rm EM}$ is

$$\mathcal{P}(L_R, L_{\rm EM}) = \exp\left(-\frac{L_R}{L_a}\right) - \exp\left(-\frac{L_{\rm EM}}{L_a}\right)$$

L_R is the spatial resolution of di-photon vertex

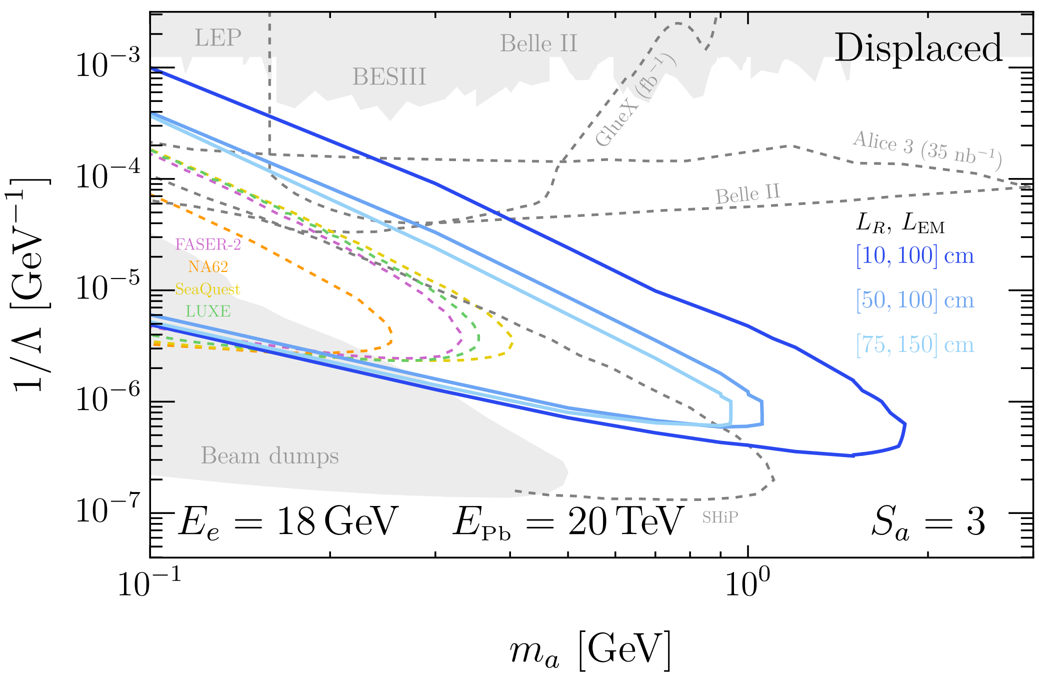
$L_{\rm EM}$ is the size of the EM calorimeter

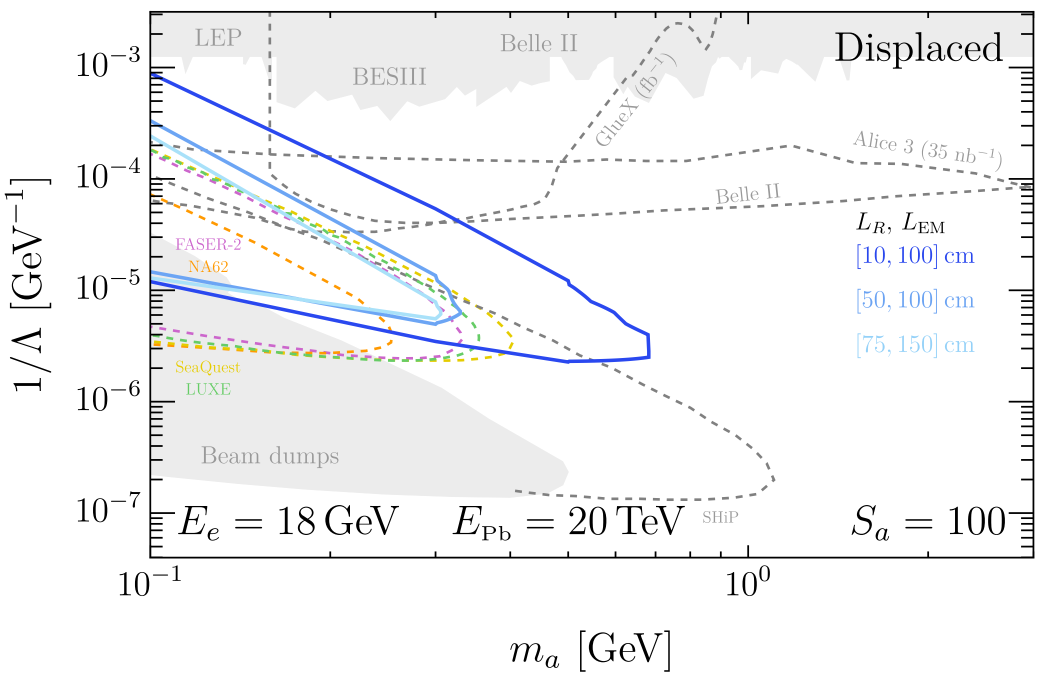
Consider 3 scenarios: $(L_R, L_{\rm EM}) = (10, 100),\ (50, 100),\ (75, 150)\ \text{cm}$

EIC projections: displaced-vertex searches

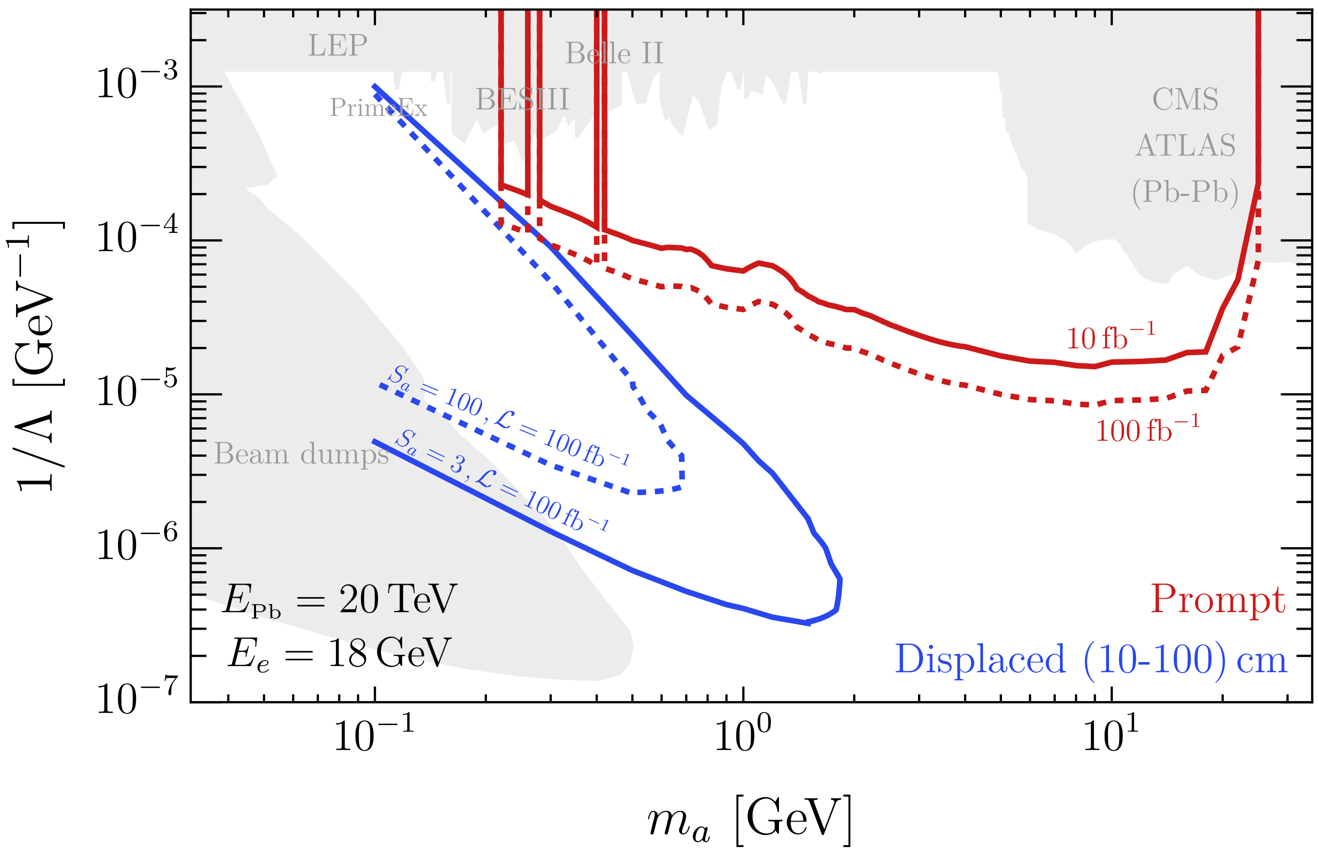
- Background free
- Bounds are set by $S_a = 3$

- Flat background
- Bounds are set by $S_a = 100$





Summary



- EIC is good at detecting coherent process.
- EIC can surpass the current lepton and hadron collider and future heavy-ion projection due to the large ALPs production cross section and the far-backward detector.
- EIC can reach $\Lambda \sim 10^5$ GeV in the 2 to 20 GeV range in the prompt searches. For displaced-vertex search, it can reach $\Lambda \sim 10^7$ GeV for GeV ALPs.

Thanks!

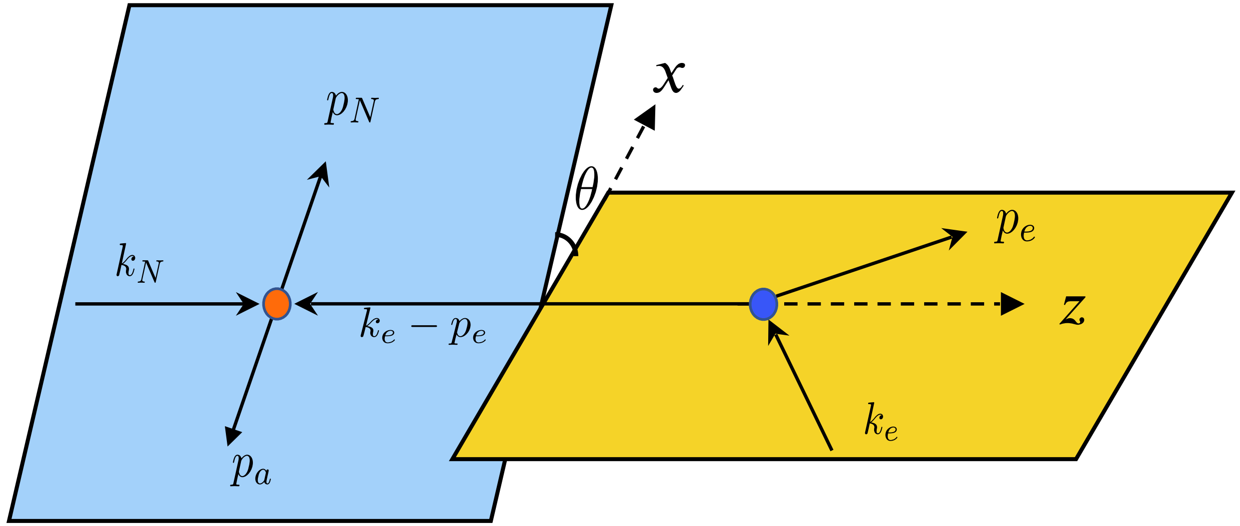
Back-up slides

2-to-3 phase space

$$\Phi_3(s, m_e^2, m_N^2, m_a^2) = \int d^4p_e d^4p_N d^4p_a \delta(p_e^2 - m_e^2)\delta(p_N^2 - m_N^2)\delta(p_a^2 - m_a^2)$$
$$\times \delta^4(k_e + k_N - p_e - p_N - p_a)\theta(p_e^0)\theta(p_N^0)\theta(p_a^0)$$

There are five independent kinematical variables. However, the integration over the azimuthal angle is trivial.

$$t_e \equiv (k_e - p_e)^2 \qquad t_N \equiv (k_N - p_N)^2 \qquad m_{aN}^2 \equiv (p_a + p_N)^2 \qquad \cos\theta \equiv \frac{(\vec{k}_N \times \vec{p}_N)\cdot(\vec{k}_e \times \vec{p}_e)}{|\vec{k}_N \times \vec{p}_N||\vec{k}_e \times \vec{p}_e|}$$



$$\frac{d\sigma_a^{2\to3}}{dt_e dt_N dm_{aN}^2 d\theta} = \frac{1}{(2\pi)^4}\frac{1}{4\sqrt{\lambda(s, m_e^2, m_N^2)}}\frac{1}{4\sqrt{\lambda(m_{aN}^2, m_N^2, t_e)}}\frac{|\mathcal{M}_a^{2\to3}|^2}{4[(k_e\cdot k_N)^2 - m_e^2 m_N^2]^{1/2}}$$

Electron ion collider

Calorimeter	Pseudorapidity acceptance	Projected energy resolution ($\Delta E/E$) [%]
FEMC	$[+1.3\,,\ +3.5]$	$7.1/\sqrt{E/\mathrm{GeV}}$
BEMC	$[-1.7\,,\ +1.3]$	$1.6/\sqrt{E/\mathrm{GeV}} \oplus 0.7$
EEMC	$[-3.5\,,\ -1.7]$	$1.8/\sqrt{E/\mathrm{GeV}} \oplus 0.8$

FEMC: Hadron/Forward-End-Cap Electromagnetic Calorimeter
BEMC: Barrel Electromagnetic Calorimeter
EEMC: Electron-End-Cap Electromagnetic Calorimeter

	EEMC	BEMC	FEMC
tower size	2x2x20 cm^3	4x4x45.5 cm^3	in: 1x1x37.5 cm^3
		projective	out: 1.6x1.6x37.5 c
		projective	out: 1.6x1.6x37.5 c
material	$PbWO_4$	SciGlass	Pb/Scintillator
d_{abs}	-	-	1.6 mm
d_{act}	20 cm	45.5 cm	4 mm
N_{layers}	1	1	66
$N_{towers(channel)}$	2876	8960	19200/34416
X/X_O	~ 20	~ 16	~ 19
R_M	2.73 cm	3.58 cm	5.18 cm
f_{sampl}	0.914	0.970	0.220
λ/λ_0	~ 0.9	~ 1.6	~ 0.9
η acceptance	$-3.7 < \eta < -1.8$	$-1.7 < \eta < 1.3$	$1.3 < \eta < 4$
resolution			
- energy	$2/\sqrt{E} \oplus 1$	$2.5/\sqrt{E} \oplus 1.6$	$7.1/\sqrt{E} \oplus 0.3$
- φ	~ 0.03	~ 0.05	~ 0.04
- η	~ 0.015	~ 0.018	~ 0.02

[2209.02580]