

# *Probe axion-like particles at the electron-ion collider*

In collaboration with Reuven Balkin, Or Hen, Wenliang Li, Teng Ma,  
Christoph Paus, Yotam Soreq, Michael Williams

Hongkai Liu

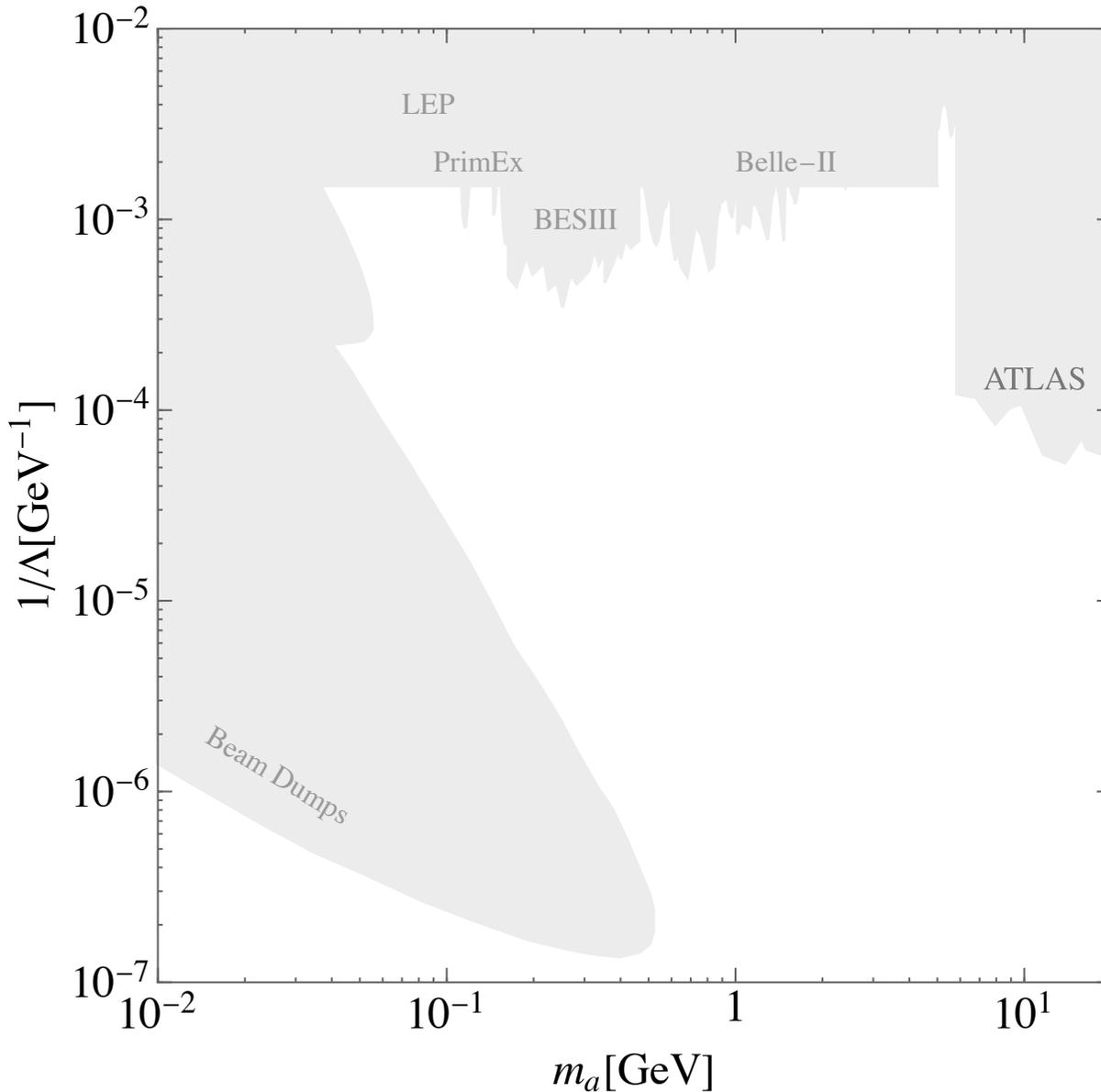
Technion

**Pheno 2023, Pittsburgh**  
**May 08, 2023**

# Motivation

- Shortcomings of the SM:
  - Dark matter, neutrino masses, baryon asymmetry, strong CP problem ...
- No strong deviation from the SM so far at the LHC motivates the searches for light and feebly-interacting particles.
- QCD axion is a solution to the strong CP problem.
- In the simplest model, the relation between the axion mass and coupling are in a narrow band. However, in less minimum UV models, the mass-coupling relations can be shifted.
- To be UV independent, we adopt EFT description and treat the coupling and mass as two independent parameters  $\longrightarrow$  axion-like particles (ALPs).
- Generally, ALPs are allowed to couple to both gauge bosons and fermions. Here, we only focus on investigating the ALP-photon coupling at the electron-ion collider (EIC).

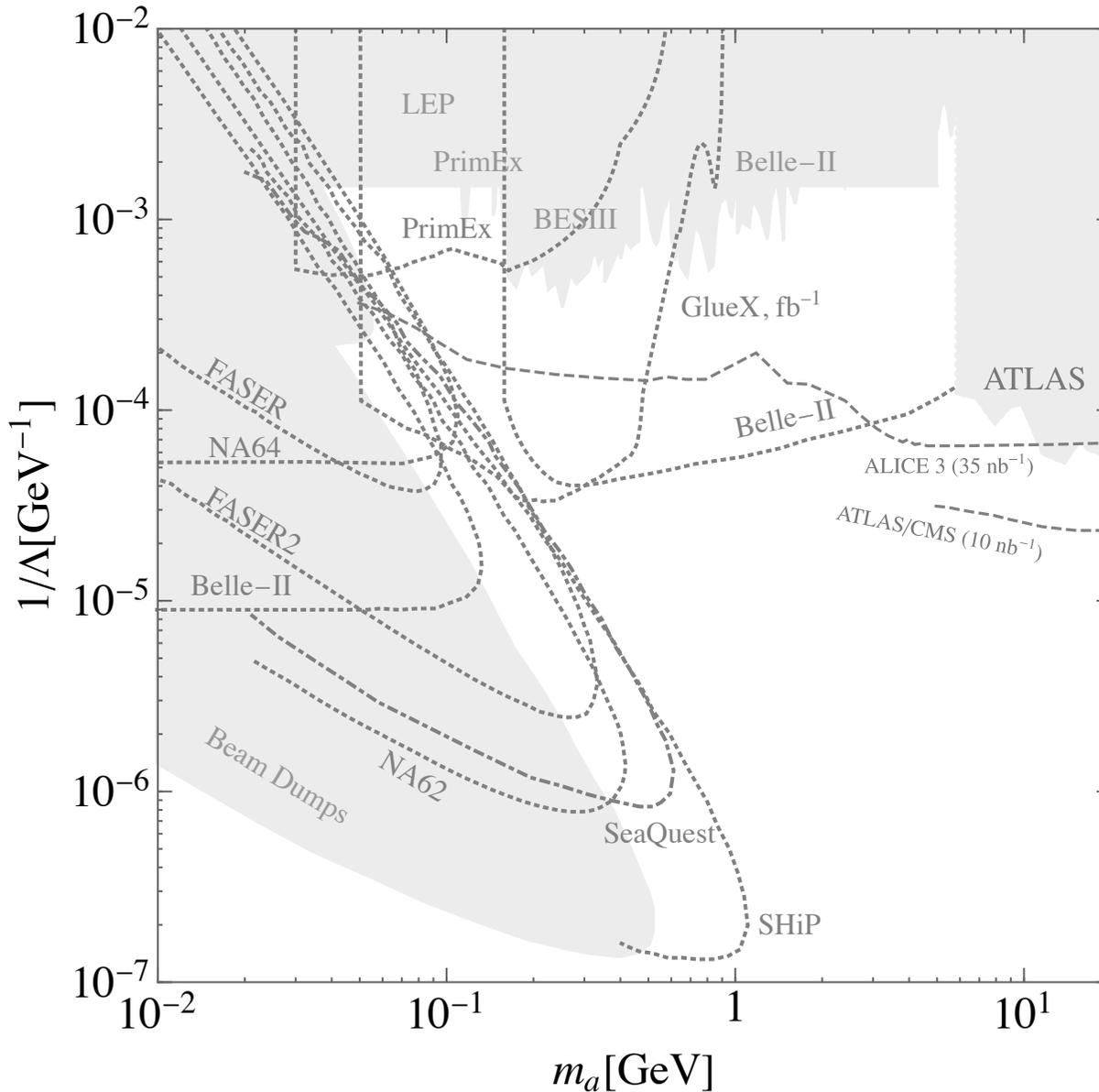
# Current bounds on ALP-photon coupling



## Current bounds:

- **Proton beam dump:**  
CHARM(Phys. Lett. B 157, 458 (1985), 1904.02091)  
NuCal(Z. Phys. C51 (1991) 341–350)
- **Electron beam dump:**  
E137(Phys.Rev.D 38 (1988) 3375)  
E141(Phys.Rev.Lett. 59 (1987) 755, 1708.05776)  
NA64(2005.02710)
- **Photon fixed target:**  
PrimEx(1903.03586)
- **Lepton collider:**  
OPAL(hep-ex/0210016)  
Belle II(2007.13071)  
BESIII(2211.12699)
- **Proton-proton collider:**  
ATLAS(1509.05051, 1407.6583)  
CMS(1209.1666)
- **Heavy-ion collider:**  
CMS(1810.04602)  
ATLAS(2008.05355)

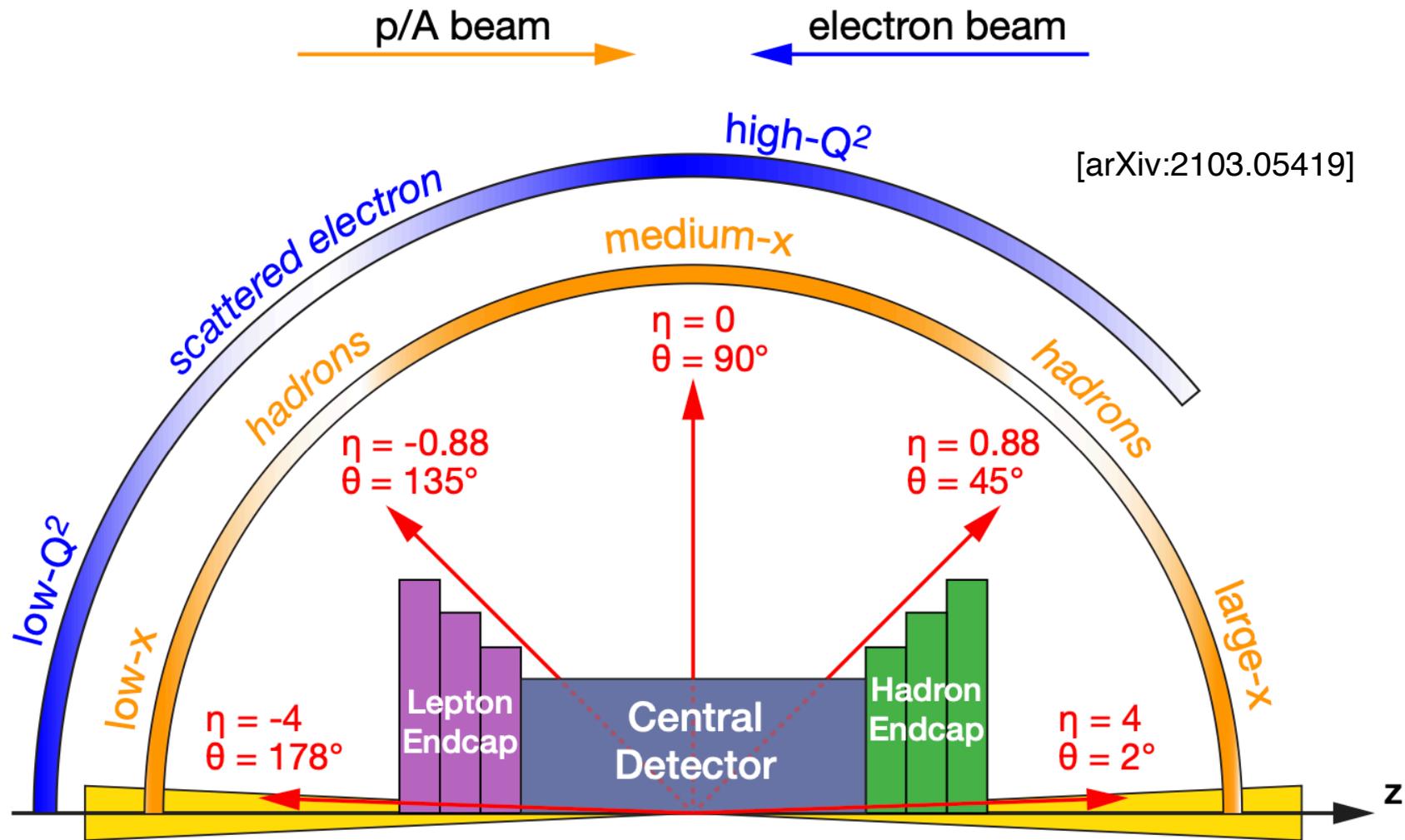
# Projections on ALP-photon coupling



## Projections:

- **Proton beam dump:**  
NA62 & SHiP (1512.03069)  
SeaQuest(1804.00661)
- **Electron beam dump:**  
NA64(2004.04469)
- **Photon fixed target:**  
FASER(1806.02348)  
GlueX(1903.03586)
- **Lepton collider:**  
Belle II(1709.00009)
- **Heavy-ion collider:**  
ATLAS/CMS(1607.06083)  
ALICE-3(2103.01862, 2203.05939)

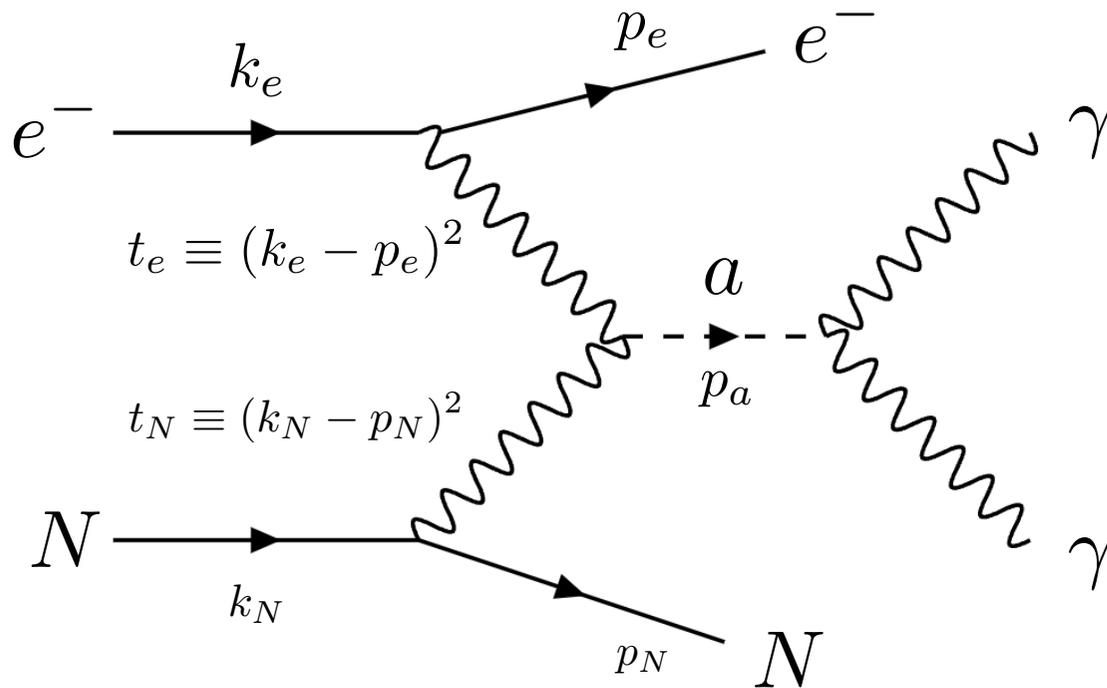
# Electron ion collider



- The different detector systems observe different particle distributions
- Precise identification of the scattered electron and extremely fine resolution in the measurement of its angle and energy are required by the its physics program.

# ALP coherent production at EIC

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



Electron beam:  $E_e = 18$  GeV,

Ion beam:  $E_{pb} = 20$  TeV.

- Weakly coupled but with an enhancement of  $Z^2$  in the ALP coherent production.

- The amplitude squared:

$$|\mathcal{M}_{2 \rightarrow 3}|^2 \propto (Z^2 e^4) / (t_e^2 t_N^2 \Lambda^2)$$

- Recoiled electron can be measured very precisely.

- The recoiled ion can be reconstructed:

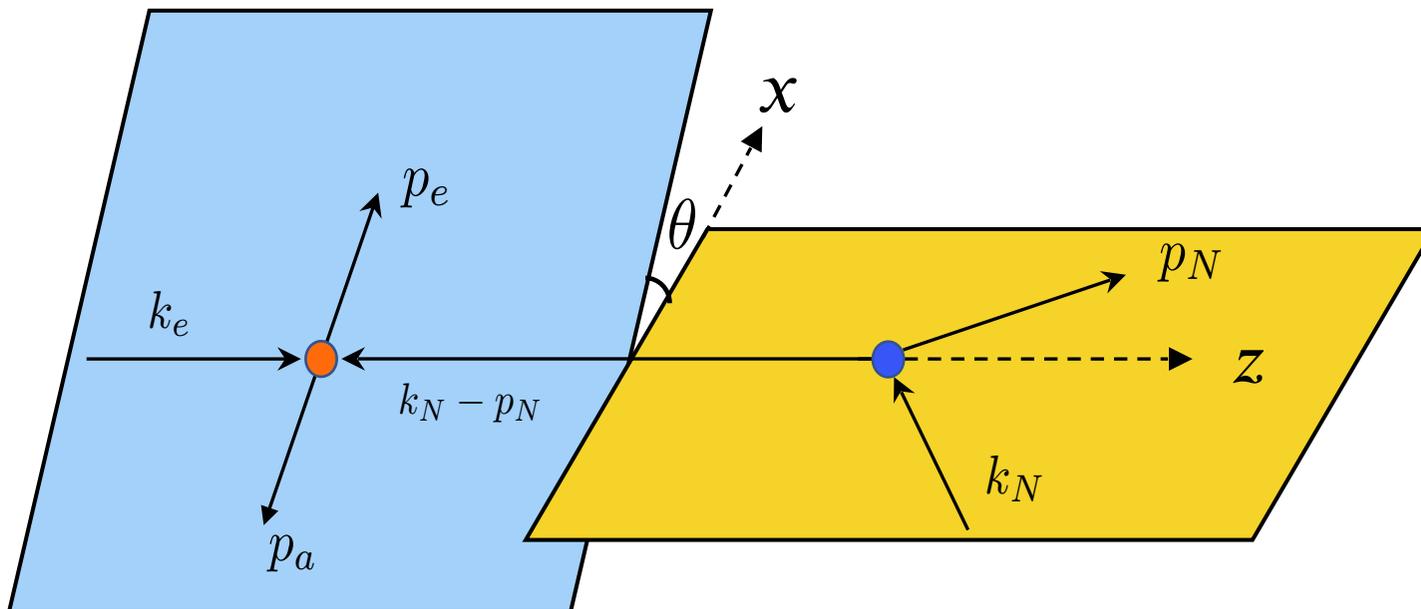
$$p_N^2 = (k_e + k_N - p_a - p_e)^2 = m_N^2$$

## 2-to-3 phase space

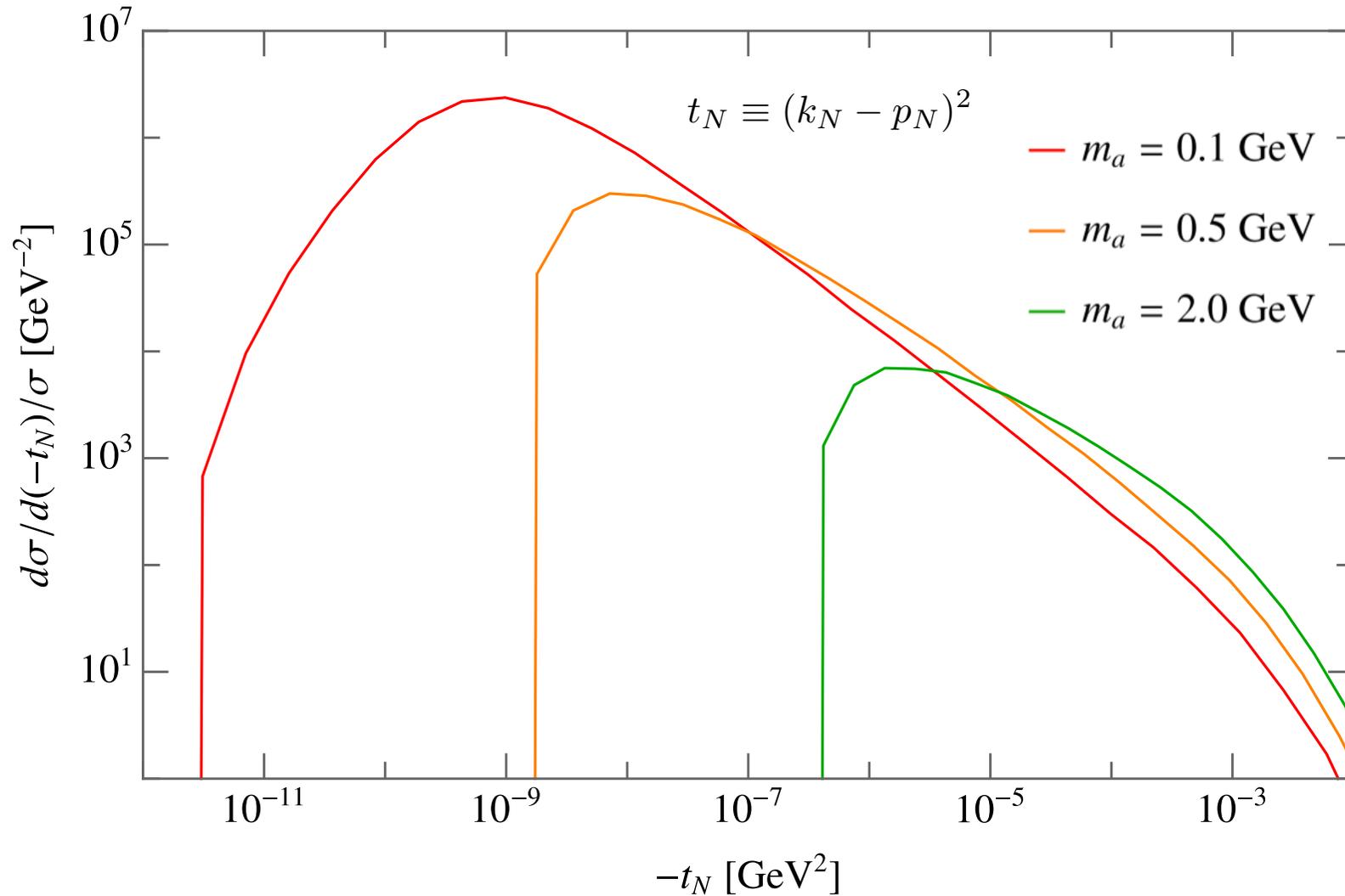
$$\Phi_3(s, m_e^2, m_N^2, m_a^2) = \int d^4 p_e d^4 p_N d^4 p_a \delta(p_e^2 - m_e^2) \delta(p_N^2 - m_N^2) \delta(p_a^2 - m_a^2) \\ \times \delta^4(k_e + k_N - p_e - p_N - p_a) \theta(p_e^0) \theta(p_N^0) \theta(p_a^0)$$

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

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



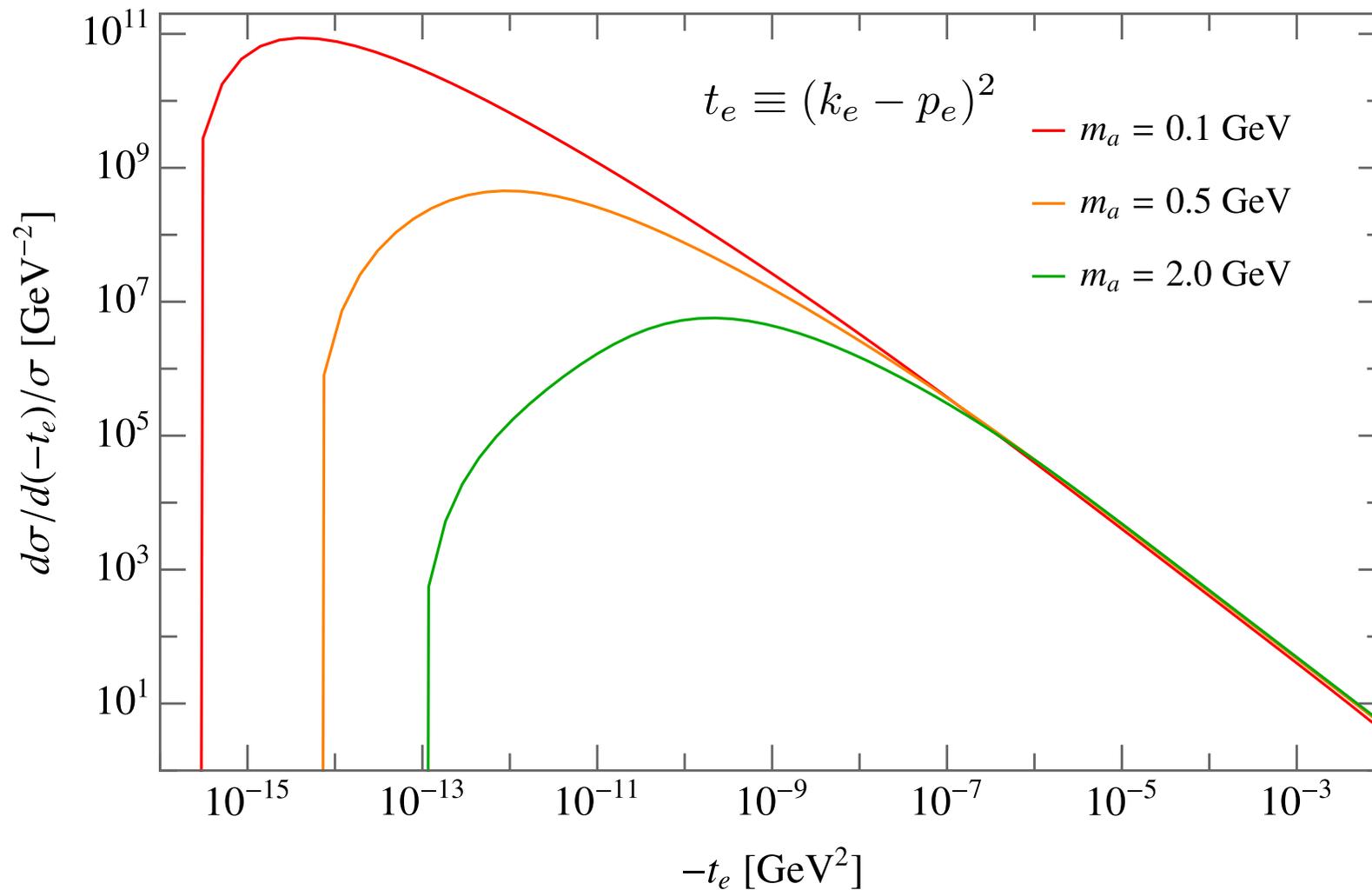
# Kinematics



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

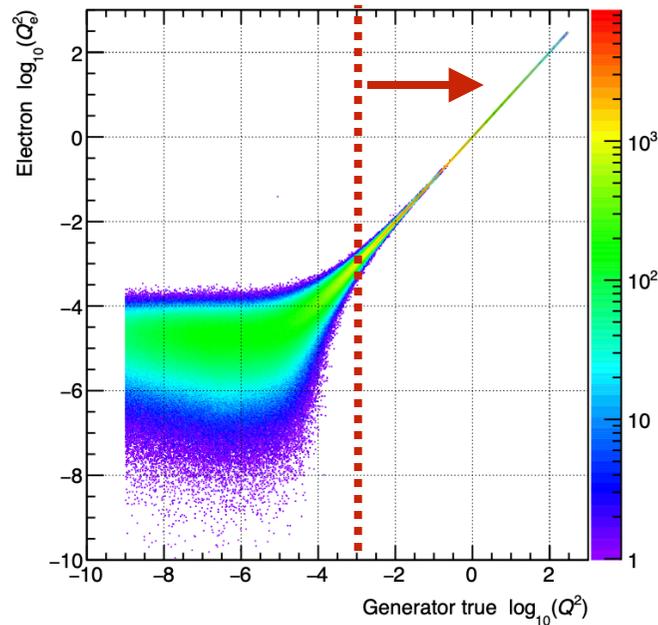
$$(-t_N)_{\min} \sim 0.164 A^{-2/3} \text{ GeV}^2 \longrightarrow [m_a]_{\max} \approx 23 \text{ GeV} \left( \frac{E_e}{18 \text{ GeV}} \frac{E_n}{100 \text{ GeV}} \right)^{1/2} \left( \frac{A}{207} \right)^{-1/6}$$

# Kinematics

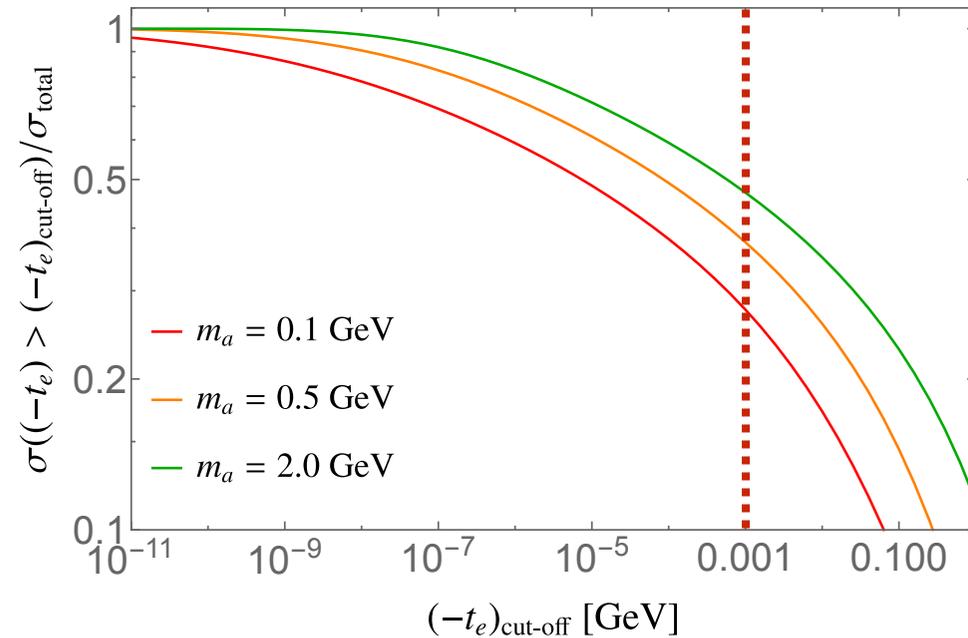


$$(-t_e)_{\min} \approx 1.9 \times 10^{-14} \text{ GeV}^2 \left( \frac{m_a}{1.0 \text{ GeV}} \right)^2 \left( \frac{m_N}{193 \text{ GeV}} \right)^2 \left( \frac{m_e}{0.51 \text{ MeV}} \right)^2 \left( \frac{\sqrt{s}}{1.2 \text{ TeV}} \right)^{-4}$$

# Tagging recoiled electrons



**Figure 11.121:** Comparison of generated and reconstructed electron  $Q_e^2$  with smearing for beam angular divergence.



[arXiv:2103.05419]

- Recoiled electrons with very low- $Q^2$  ( $10^{-9} \text{ GeV}^2$ ) can be tagged.
- We require  $-t_e > 10^{-3} \text{ GeV}^2$  to have reasonable good resolution.
- The efficiencies is around 30% (50%) for 0.1 (2.0) GeV ALP.

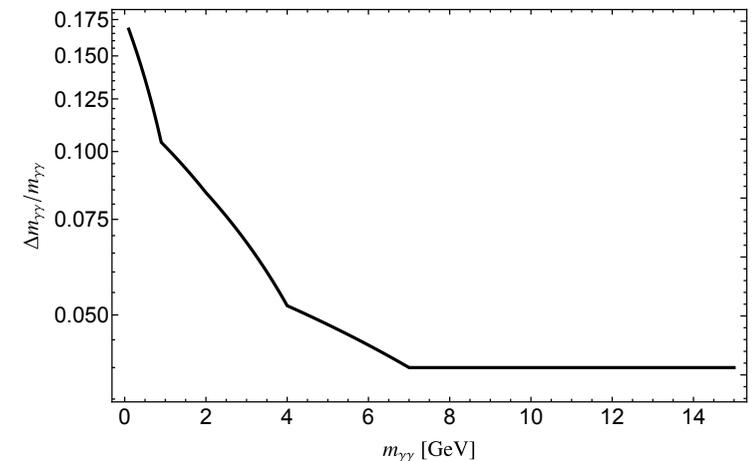
# Search strategies

## Prompt searches:

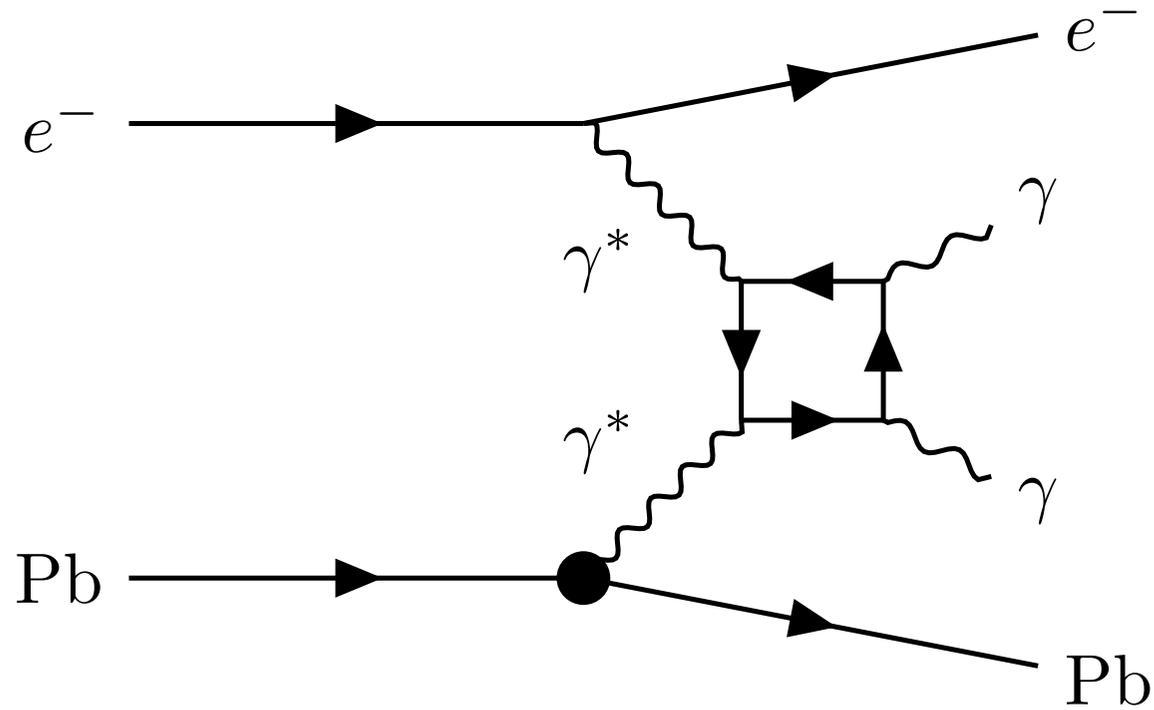
- The signal is very clean with only two photons and recoiled electrons
- Resonance search in the invariant mass of two photons
- Basic cuts:  $E_\gamma > 100$  MeV,  $|\eta_\gamma| < 3.5$ ,  $m_{\gamma\gamma} \in [m_a - \Delta m_{\gamma\gamma}/2, m_a + \Delta m_{\gamma\gamma}/2]$

## Displaced-vertex searches:

- The displaced vertex in the range of 10 - 100 cm
- Background free
- Require 3 signal events after applying the basic cuts



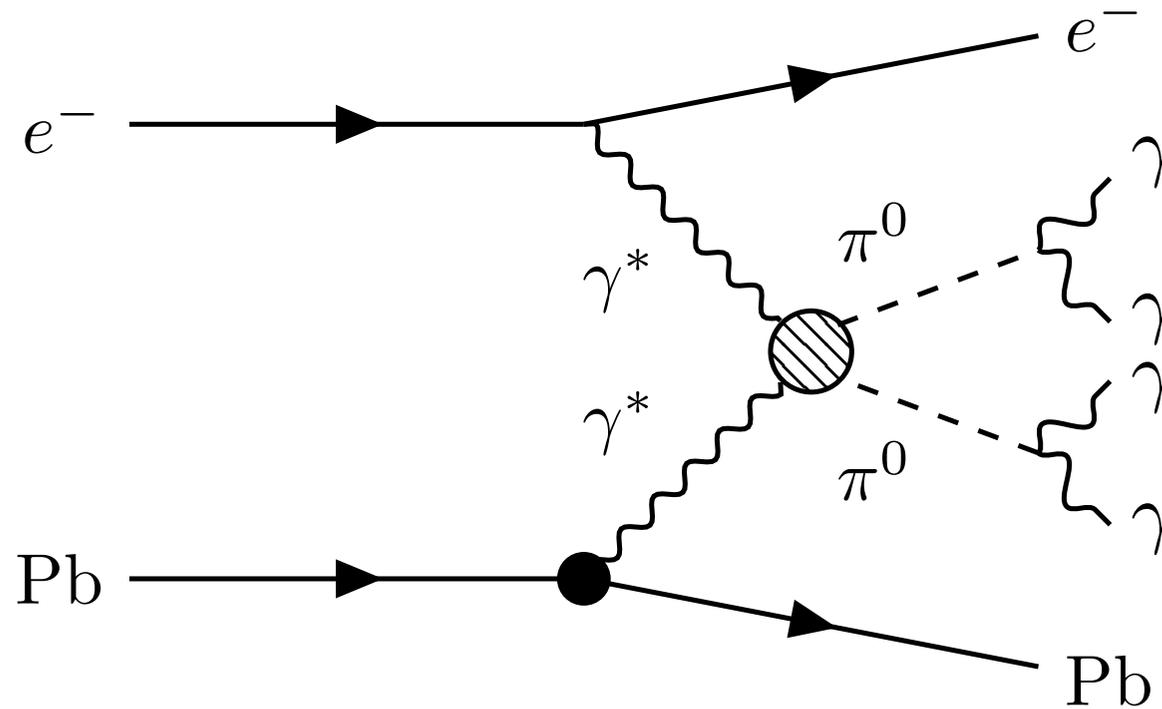
# Cuts and background in prompt searches



• **Irreducible** light-by-light (LBL) scattering:  $\gamma + \gamma \rightarrow \gamma + \gamma$

$$\frac{\sigma_{\text{sig}}}{\sigma_{\text{LBL}}} \Big|_{\sqrt{\hat{s}}=m_a} \simeq \left( \frac{m_a}{1.0 \text{ GeV}} \right)^3 \left( \frac{\text{TeV}}{\Lambda} \right)^2 \left( \frac{200 \text{ MeV}}{\Delta m_{\gamma\gamma}} \right)$$

# Cuts and background in prompt searches

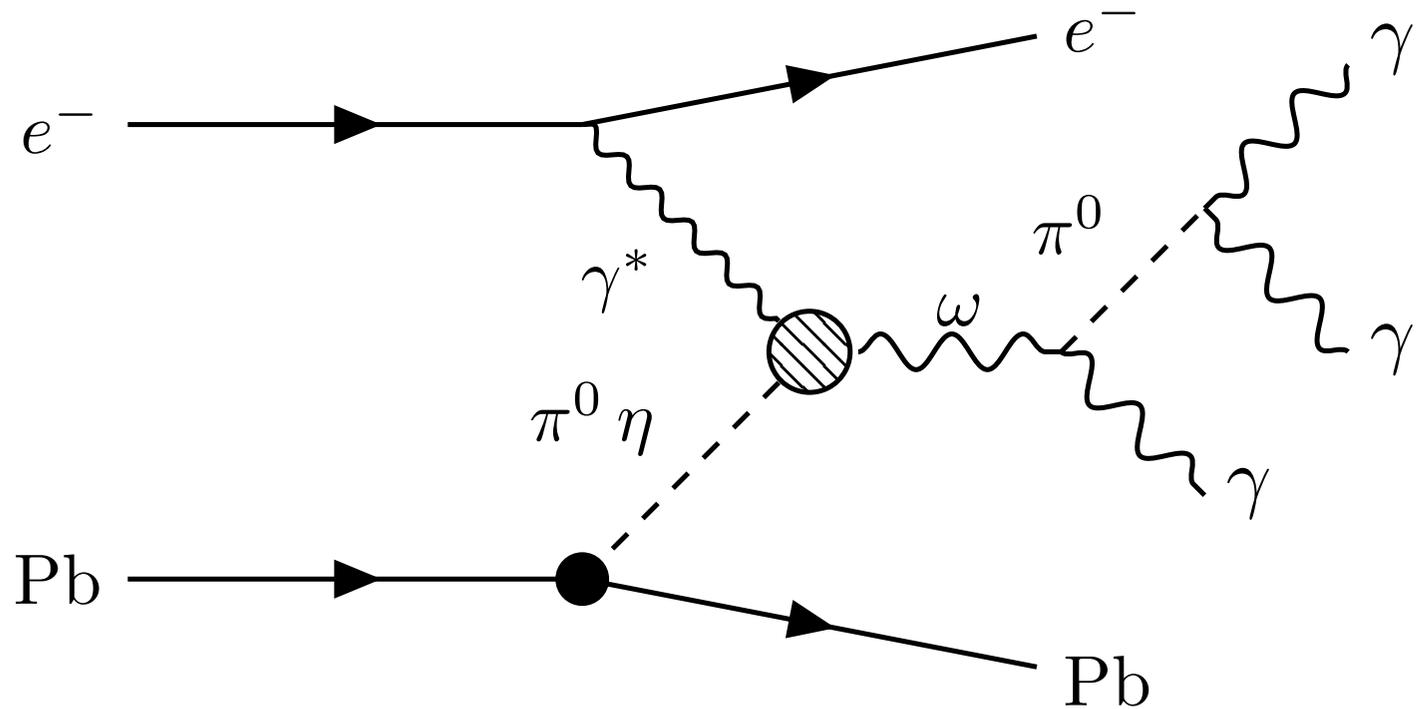


• **Reducible** Pion pair production:  $\gamma + \gamma \rightarrow \pi^0 + \pi^0 \rightarrow 4\gamma$

Require:  $-t_e > 10^{-3} \text{ GeV}^2$      $|\Delta\phi_{\gamma\gamma} - \pi| < 0.2$

$$p_N^2 \leq (1.1 m_N)^2$$

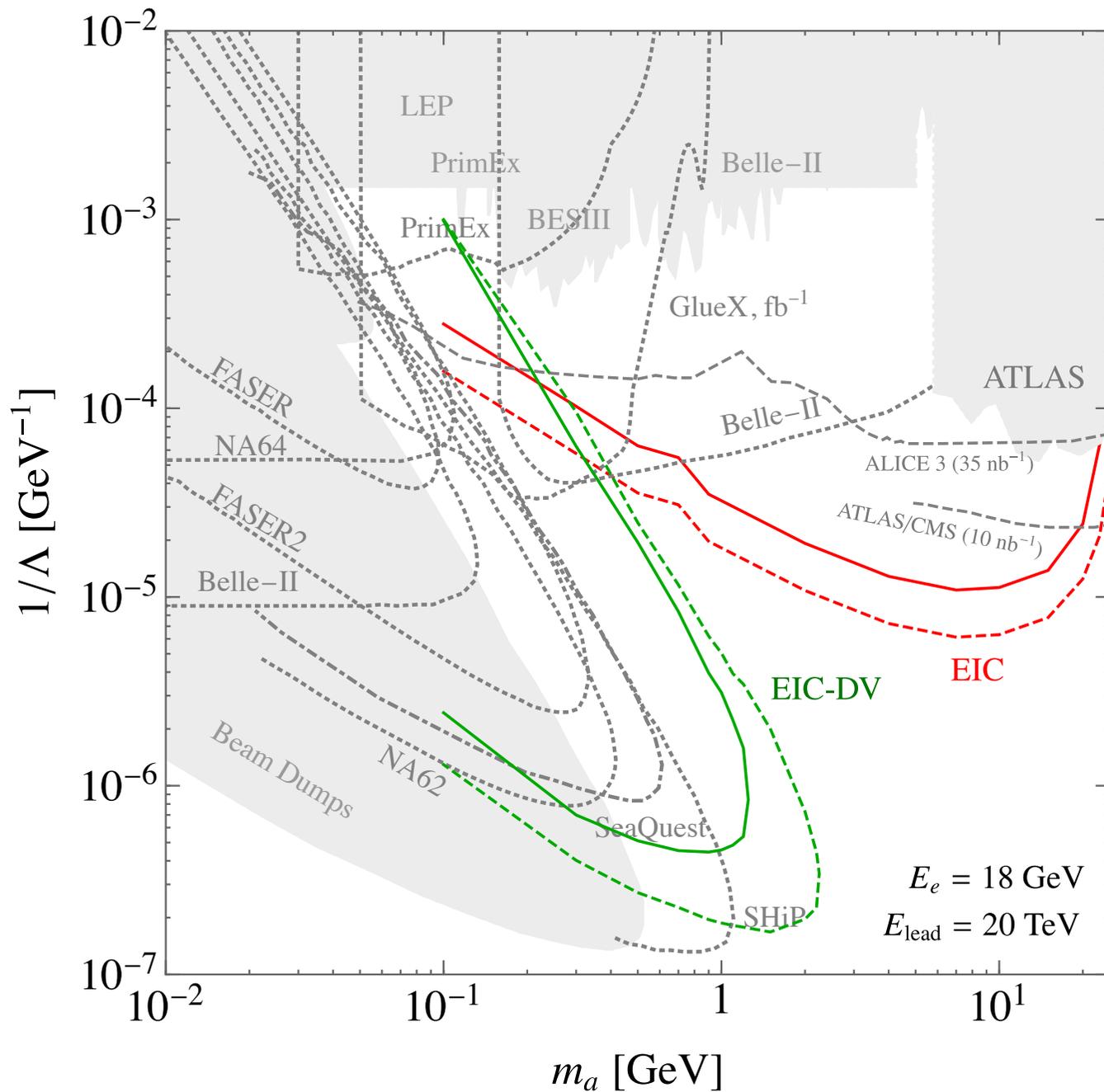
# Cuts and background in prompt searches



• **Reducible**  $\omega$  (782) :  $\gamma + N \rightarrow \omega + N, \omega \rightarrow \pi^0 + \gamma \rightarrow 3\gamma$

Further require:  $\eta_{\gamma_1,2} < 0$  if  $m_{\gamma\gamma} < m_\omega$

# EIC projections



# Summary

- ALPs with photon couplings can be produced by coherent elastic electron-ion scattering at EIC through photon fusion.
- ALPs coherent production cross section is enhanced by  $Z^2$ , which is  $\sim 6700$  for lead.
- To make use of the recoil information, we have performed the full 2-to-3 process calculations without using the traditional equivalent photon approximation.
- EIC can measure the recoiled electron with  $-t_e > 10^{-3} \text{ GeV}^2$  very precisely.
- Depending on the electron and ion energies, the mass of ALP produced by coherent scattering can be up to  $\sim 20 \text{ GeV}$  before breaking the ion.
- We have implemented two search strategies, namely, prompt-decay searches and displaced-vertex searches at the EIC.
- EIC can surpass the current lepton and hadron collider and future heavy-ion projection due to the large ALPs production cross section and high luminosity.
- EIC can reach  $\Lambda \sim 10^5 \text{ GeV}$  in the 2 to 20 GeV range in the prompt searches. For displaced-vertex search, it can reach  $\Lambda \sim 10^7 \text{ GeV}$  for GeV ALPs.

Thanks!

# Back-up slides

# Acceptance versus $Q^2$

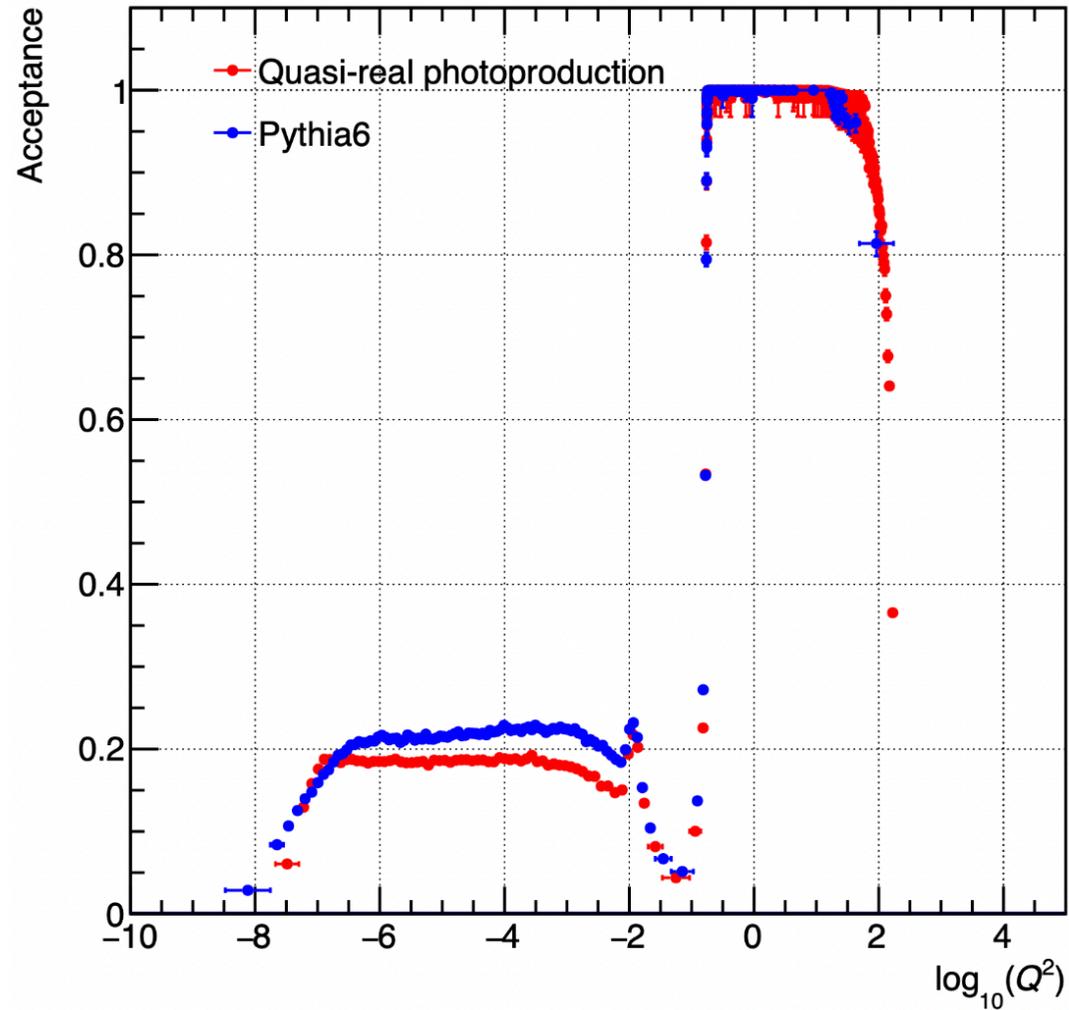


Figure 11.119: Acceptance versus  $Q^2$  for the tagger detectors and the ECAL.

# Cross section

