

Probe axion-like particles at the electron-ion collider

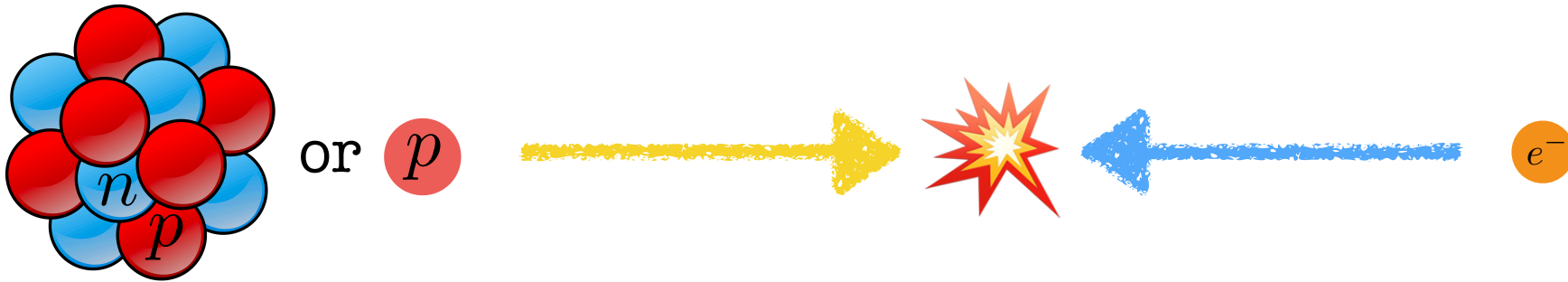
In collaboration with Reuven Balkin, Or Hen, Wenliang Li, Teng Ma, Christoph Paus, Yotam Soreq, Michael Williams

Hongkai Liu

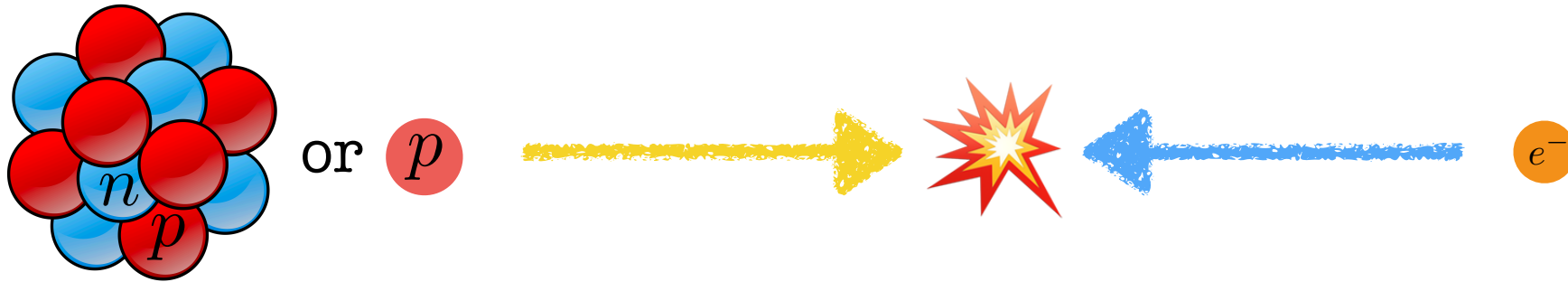


**17th TeV workshop, Nanjing
December 16, 2023**

The Electron ion collider (EIC)



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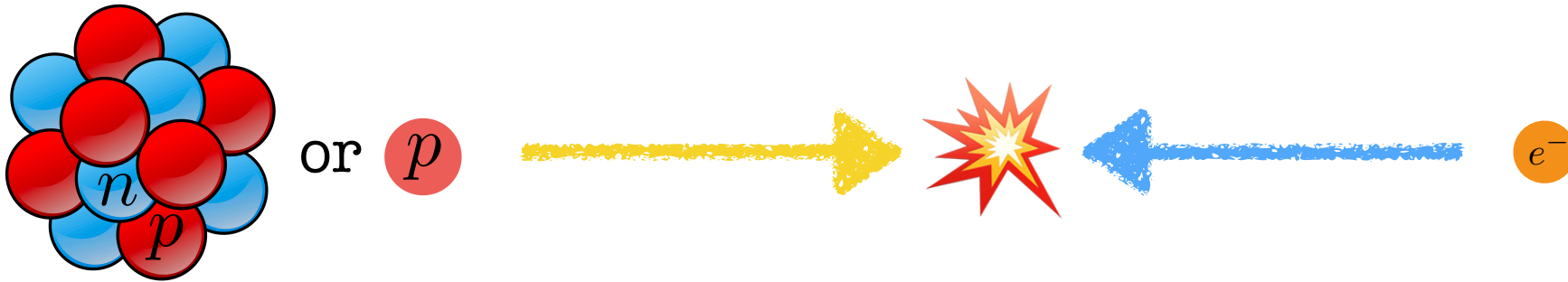


High energy:

$$E_e = 18 \text{ GeV}$$

$$E_p = 100 \text{ (275) GeV. For lead, } E_{\text{lead}} = 20 \text{ TeV}$$

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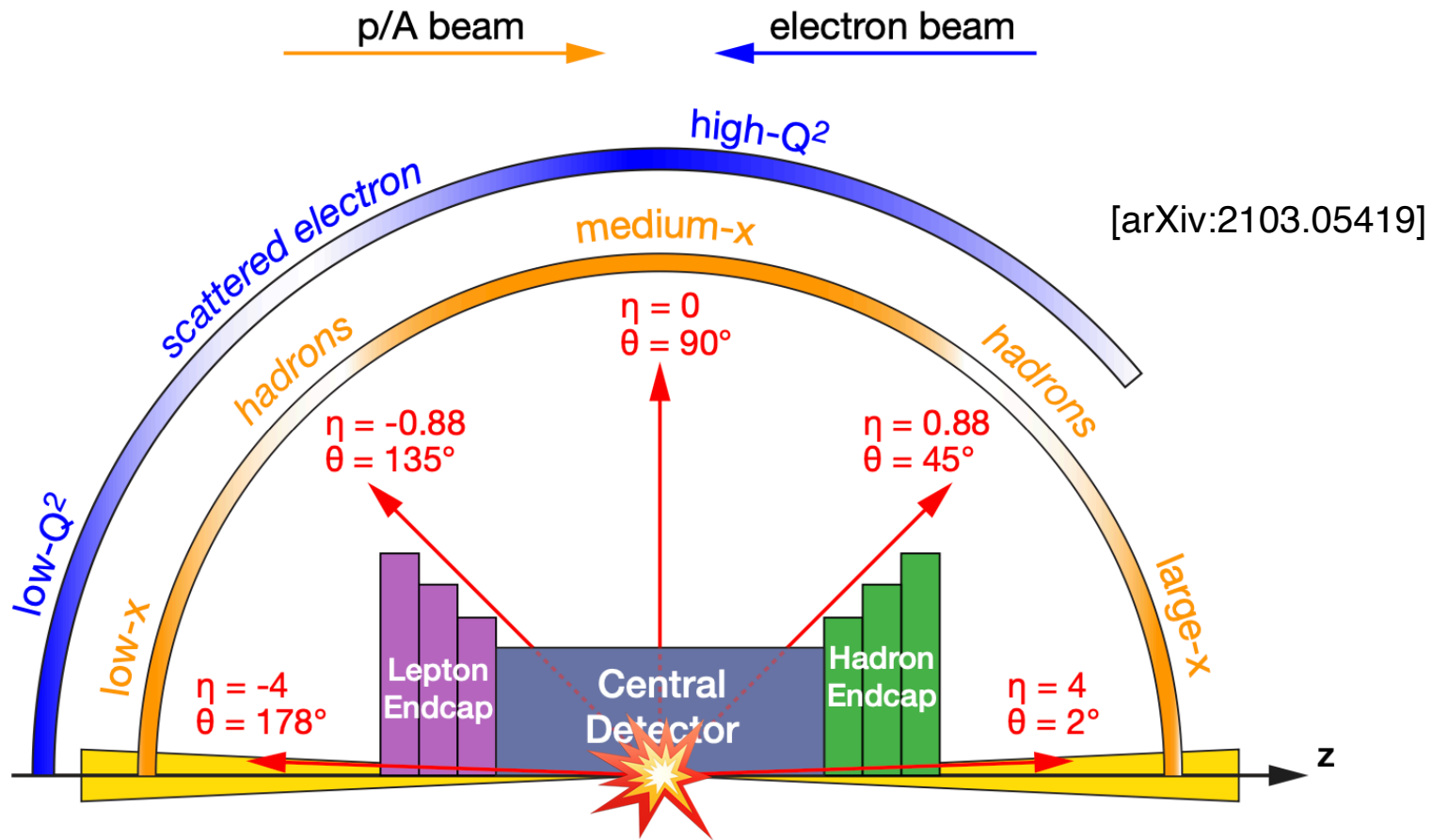
High luminosity:

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

- Most of its key physics topics are achievable with **10/fb**, corresponding to 30 weeks of running assuming 60% operation efficiency and $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ peak luminosities
- The study of the spatial distributions of quarks and gluons in the proton requires **100/fb**.

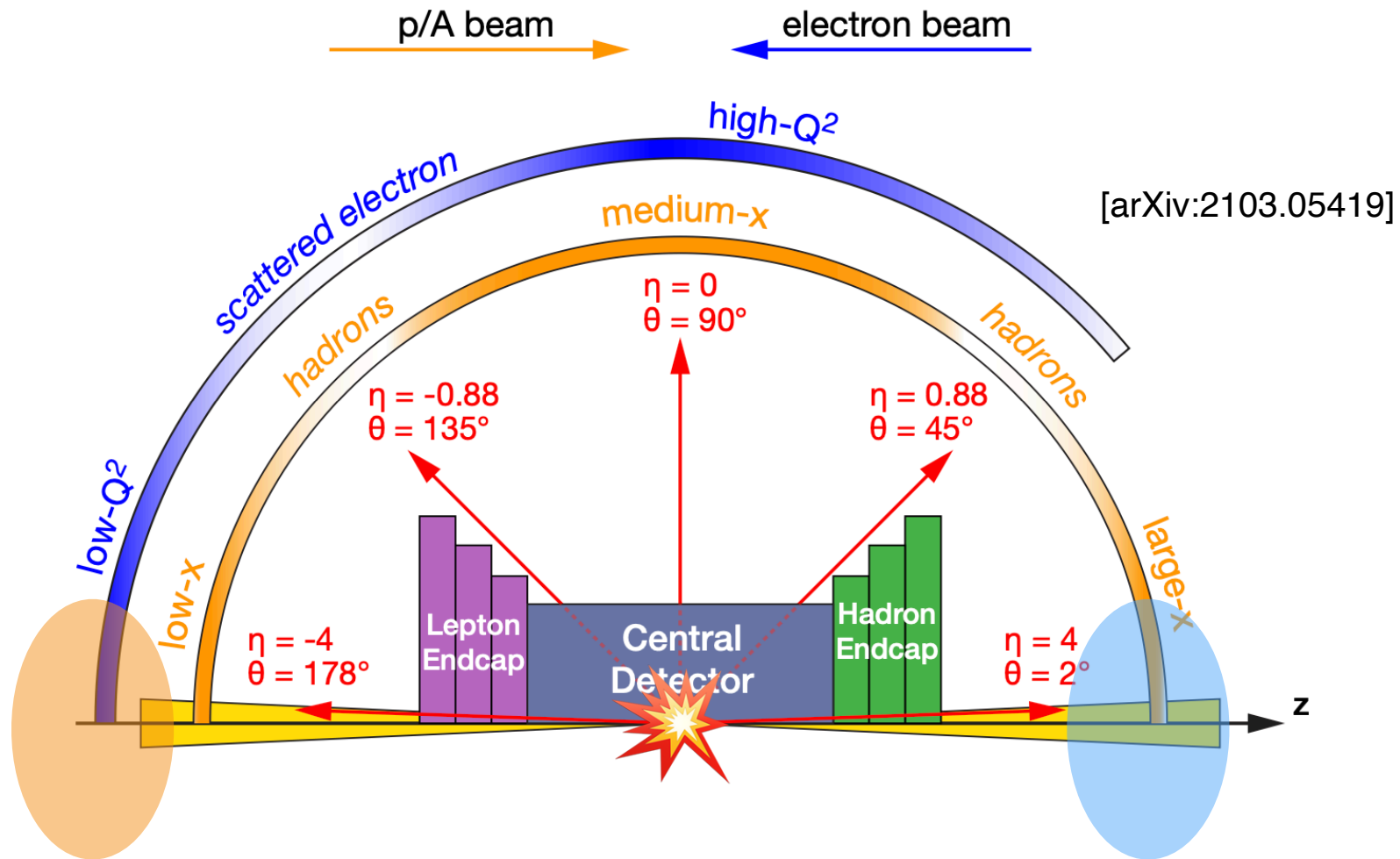
The Electron ion collider (EIC)

- 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 very low Q^2 and luminosity

Ideal for studying
coherent scattering

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

Motivation

$$\mathcal{L}_{\text{BSM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\nu \text{ mass}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_{\text{BA}} + \mathcal{L}_{\text{strong CP}} + \dots$$



Motivation

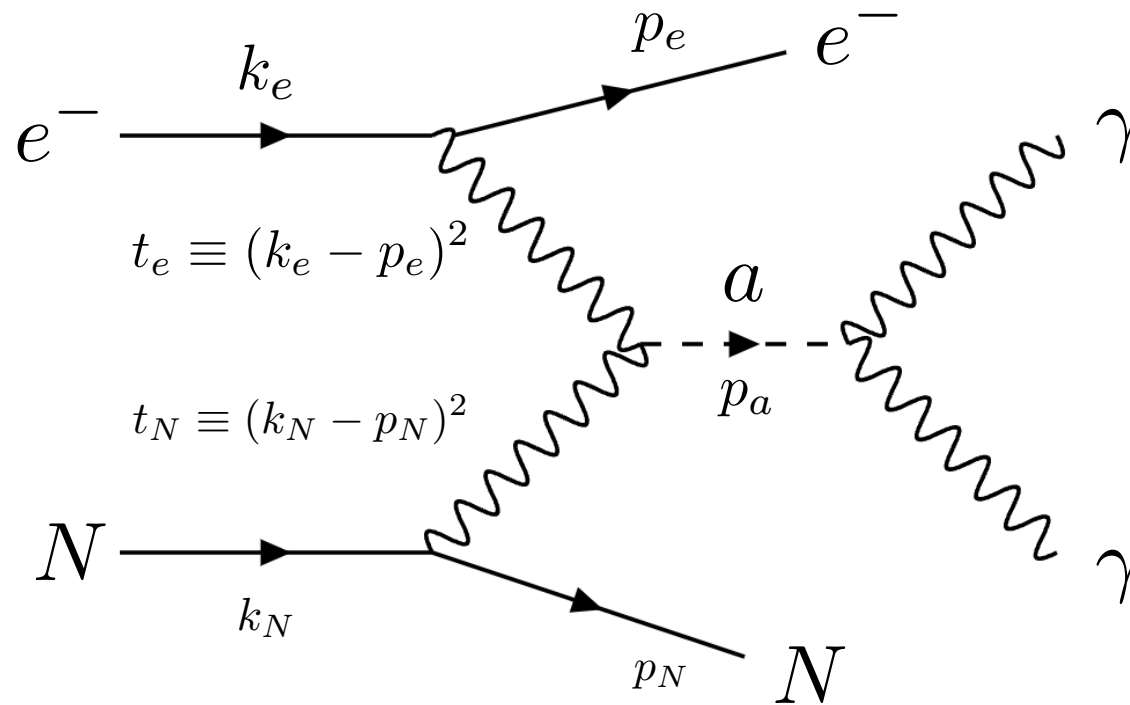
- QCD axion is a solution to the strong CP problem.

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a a^2 + \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G}$$

- 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)**.

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

ALP coherent production at EIC



- Weakly coupled but with an enhancement of Z^2 in the ALP coherent production.
- The amplitude squared:

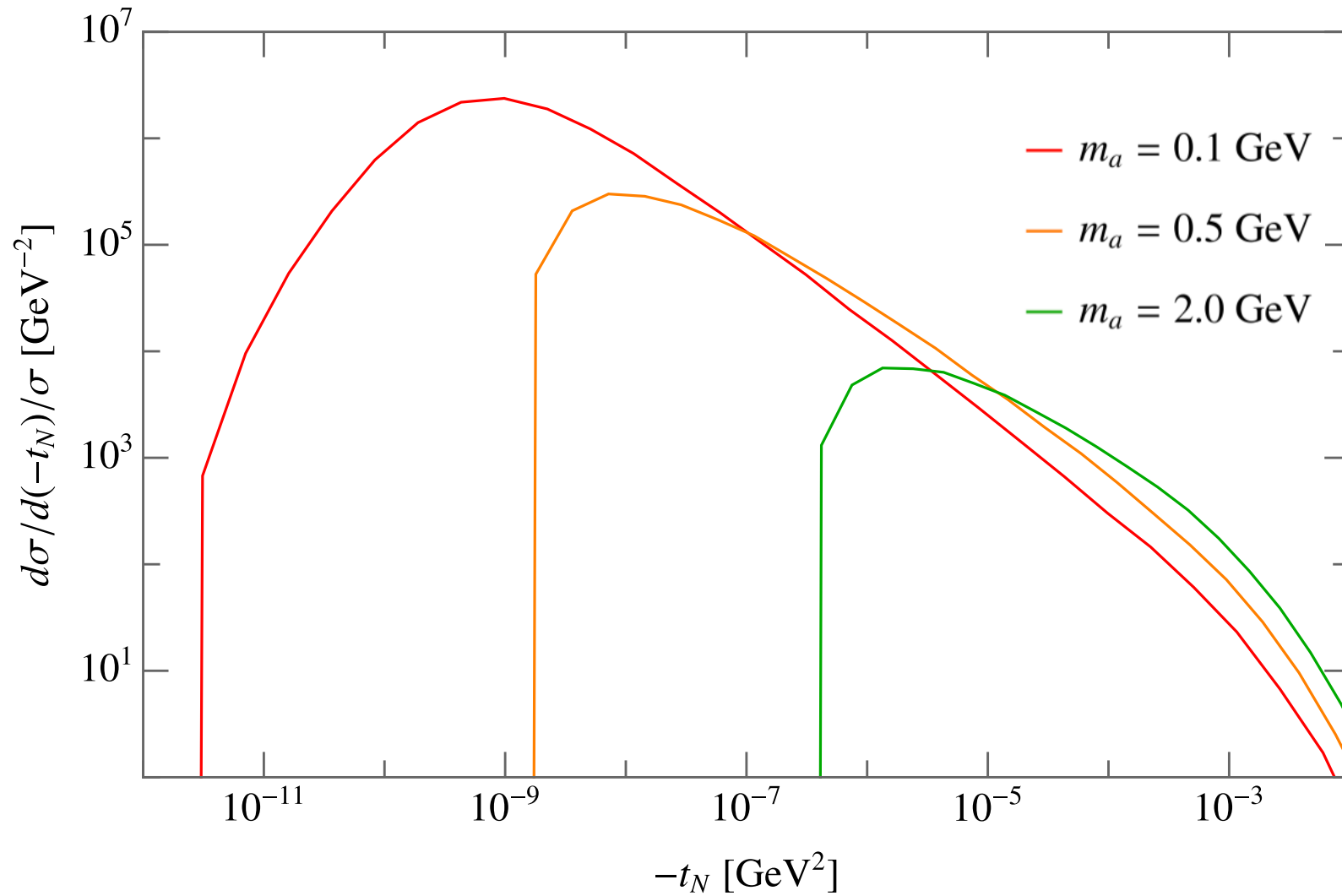
$$|\mathcal{M}_{2 \rightarrow 3}|^2 \propto (Z^2 e^4) / (t_e^2 t_N^2 \Lambda^2)$$

- As the recoiled electron can be measured very precisely, the recoiled ion can be reconstructed:

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

Kinematics

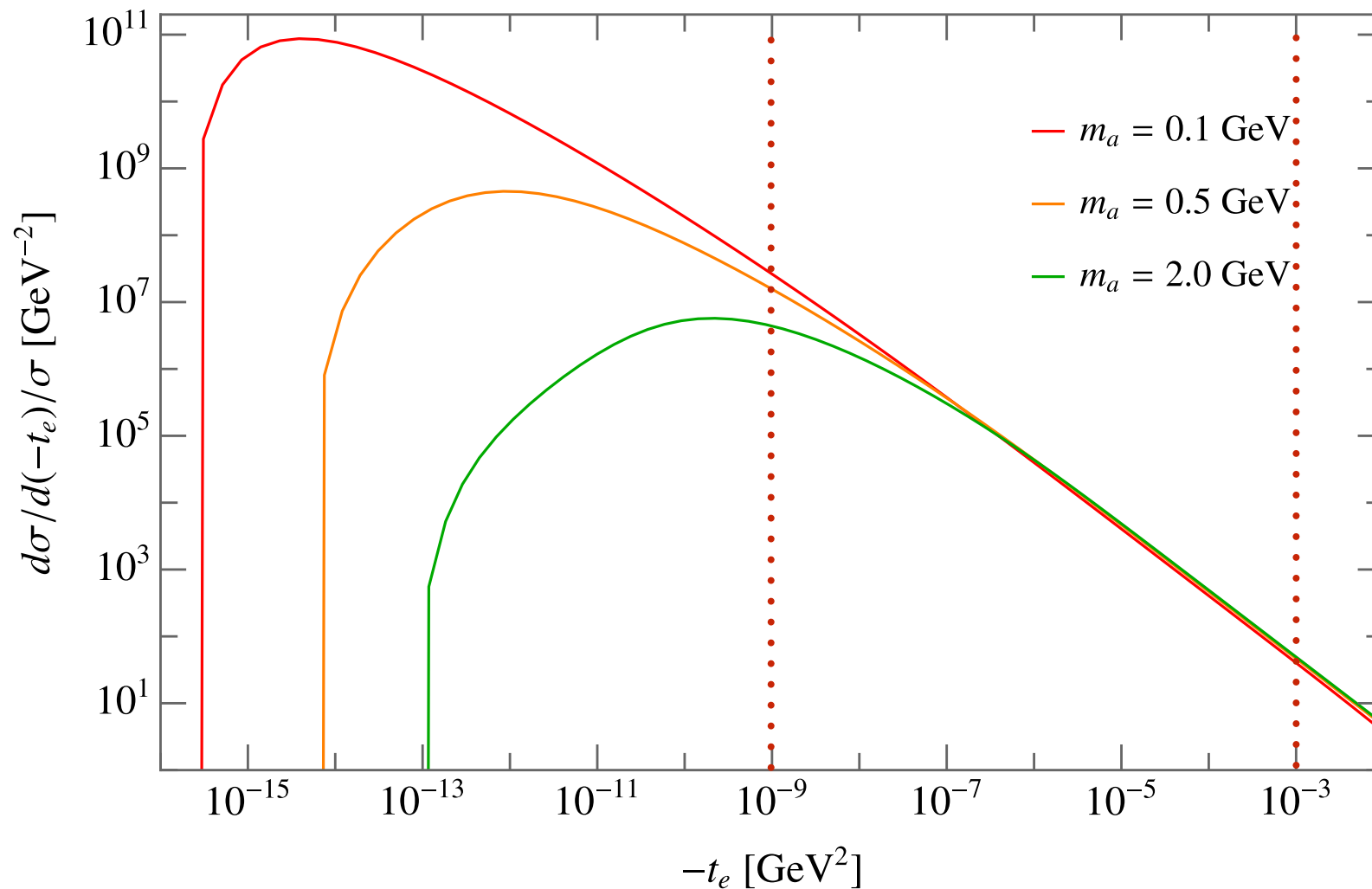
$$(-t_N)_{\min} \approx 1.8 \times 10^{-8} \text{ GeV}^2 \left(\frac{m_a}{1.0 \text{ GeV}} \right)^4 \left(\frac{m_N}{193 \text{ GeV}} \right)^2 \left(\frac{\sqrt{s}}{1.2 \text{ TeV}} \right)^{-4}$$



$$(-t_N)_{\min} \sim 0.164 A^{-2/3} \text{ GeV}^2 \longrightarrow [m_a]_{\max} \sim 20 \text{ GeV} \left(\frac{E_e}{18 \text{ GeV}} \right)^{1/2} \left(\frac{E_N/A}{100 \text{ GeV}} \right)^{1/2} \left(\frac{A}{207} \right)^{-1/6}$$

Kinematics

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



- The EIC can tag $-t_e > 10^{-9} \text{ GeV}^2$
- To obtain reasonable accuracy, we require $-t_e > 10^{-3} \text{ GeV}^2$

Prompt searches:

- The signal is clean:

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

- Basic cuts:

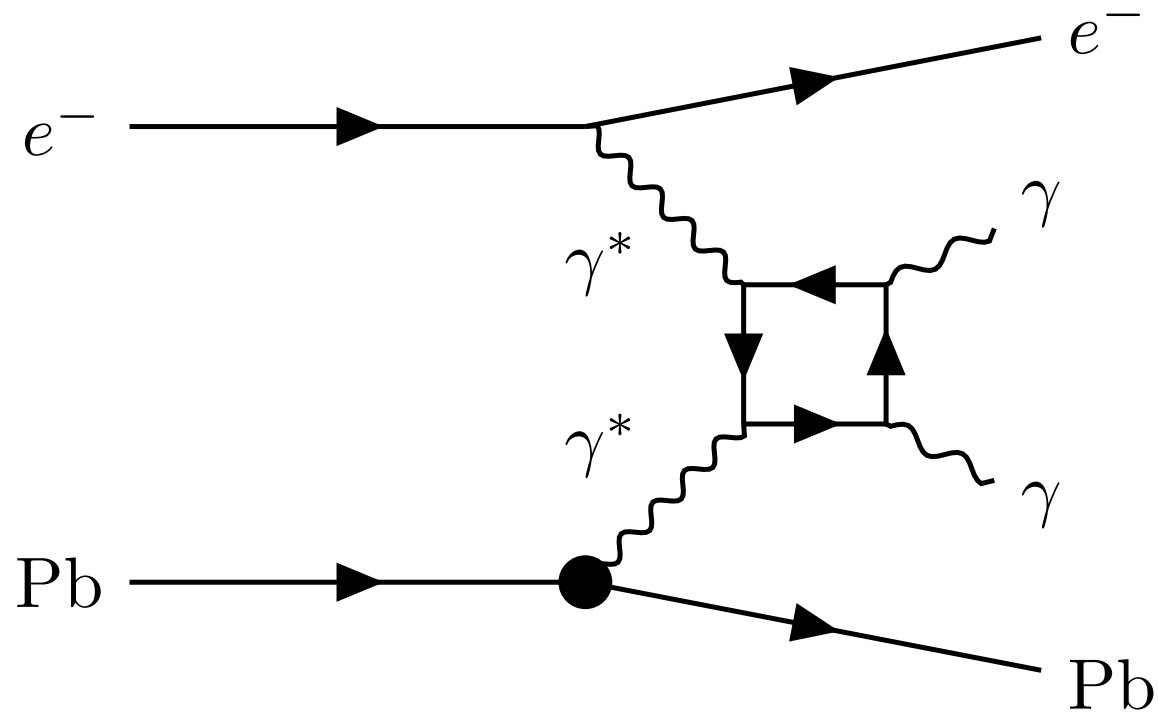
- Due to the angular acceptance, we require $|\eta_\gamma| < 3.5$
- To ensure an excellent photon resolution, we require $E_\gamma > 1 \text{ GeV}$
- Perform a resonance search in the invariant mass of two photons

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

- From a simulation:

$m_{\gamma\gamma} [\text{GeV}]$	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

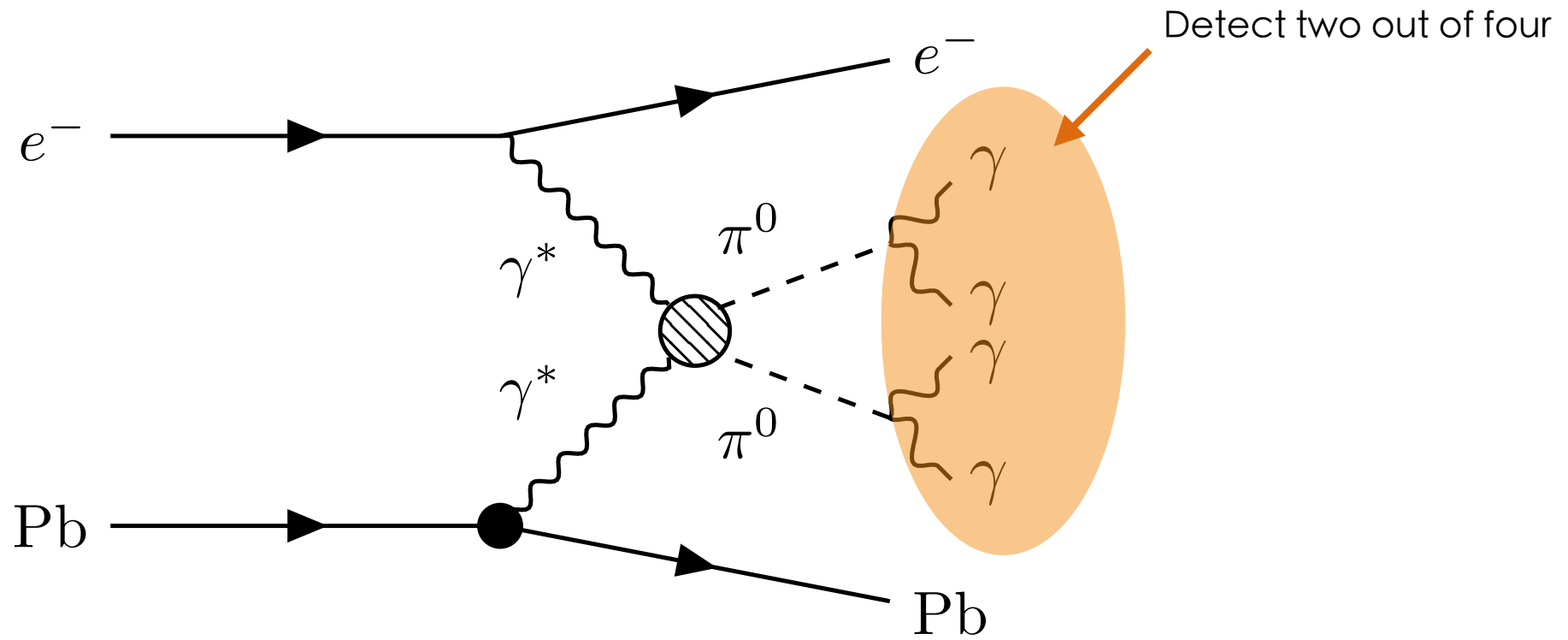
Backgrounds: light-by-light scattering



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

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

Backgrounds: pion-pair production

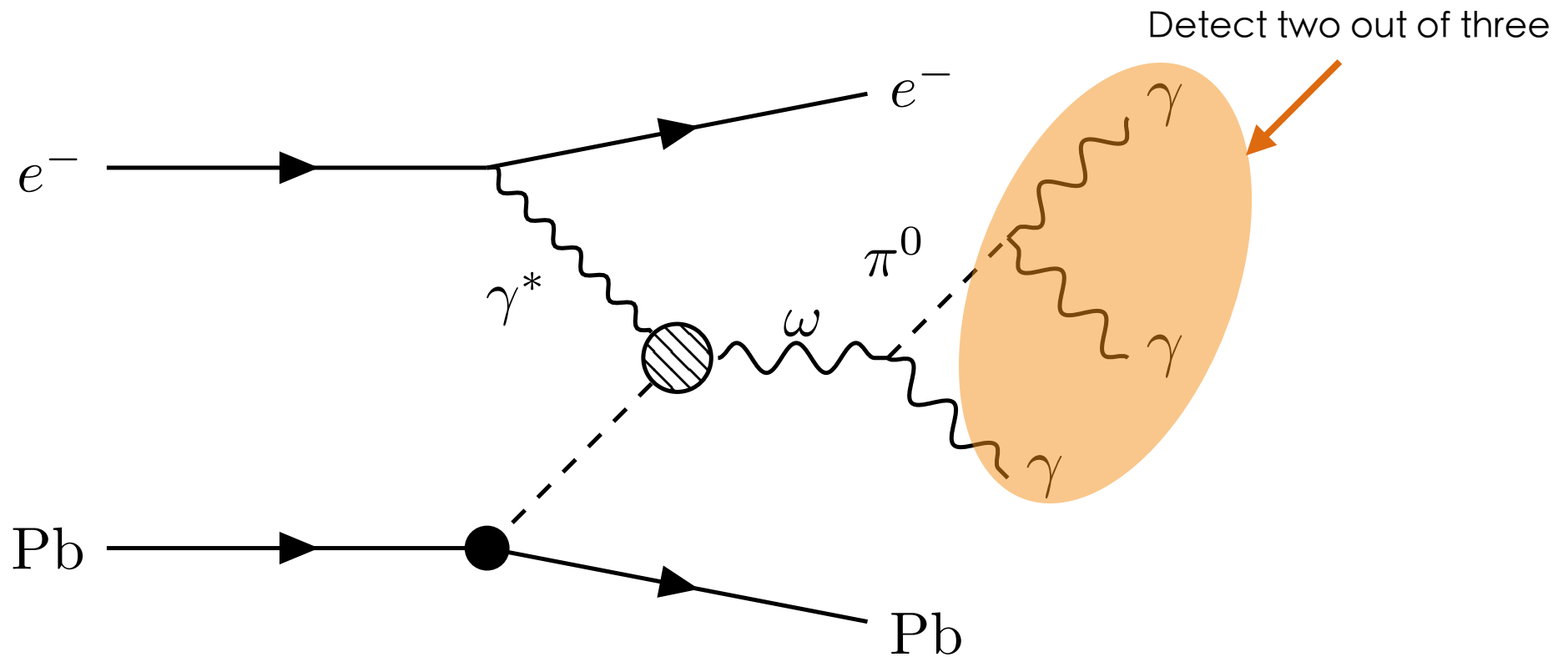


• **Reducible** Pion-pair production $\gamma + \gamma \rightarrow \pi^0 + \pi^0 \rightarrow 4\gamma$

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

Require: $p_N^{\text{rec},2} \leq (1.1 m_N)^2 \quad |\Delta\phi_{\gamma\gamma} - \pi| < 0.2$

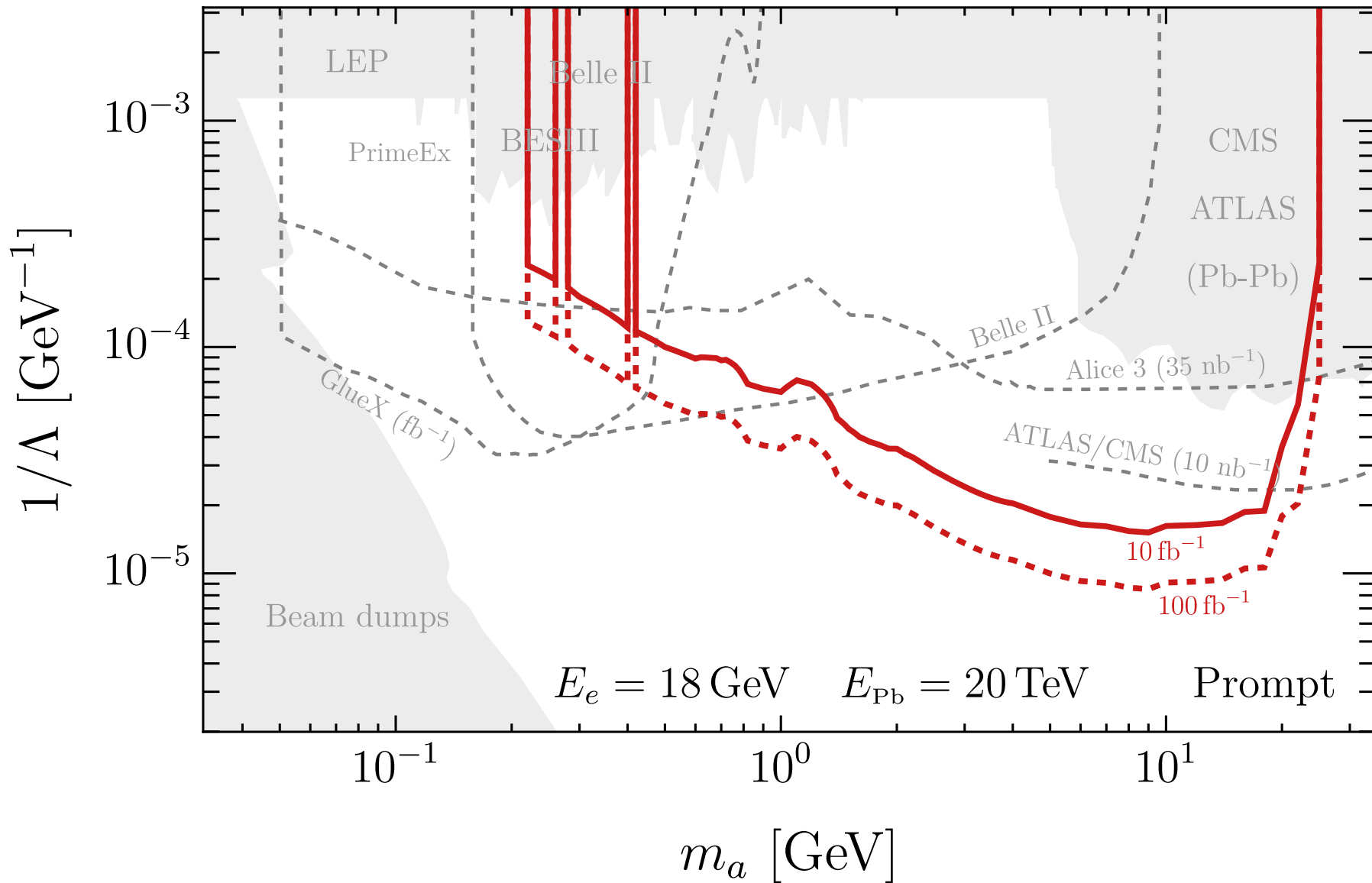
Backgrounds: omega production



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

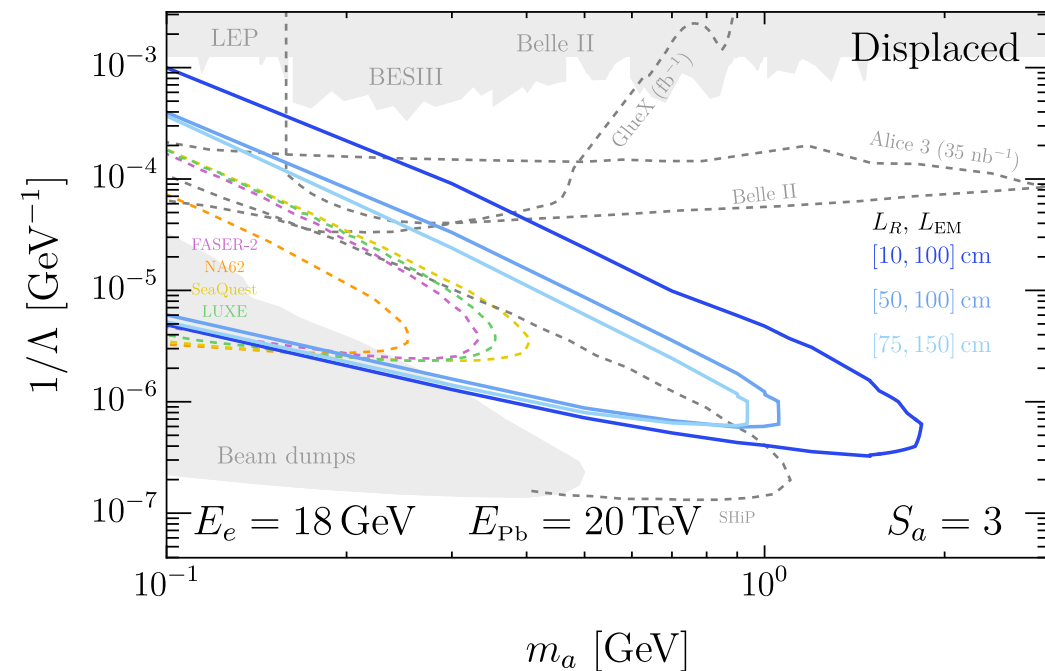
Further require: $\eta_{\gamma_1,2} < 0$ if $m_{\gamma\gamma} < m_\omega$

EIC projections: prompt searches

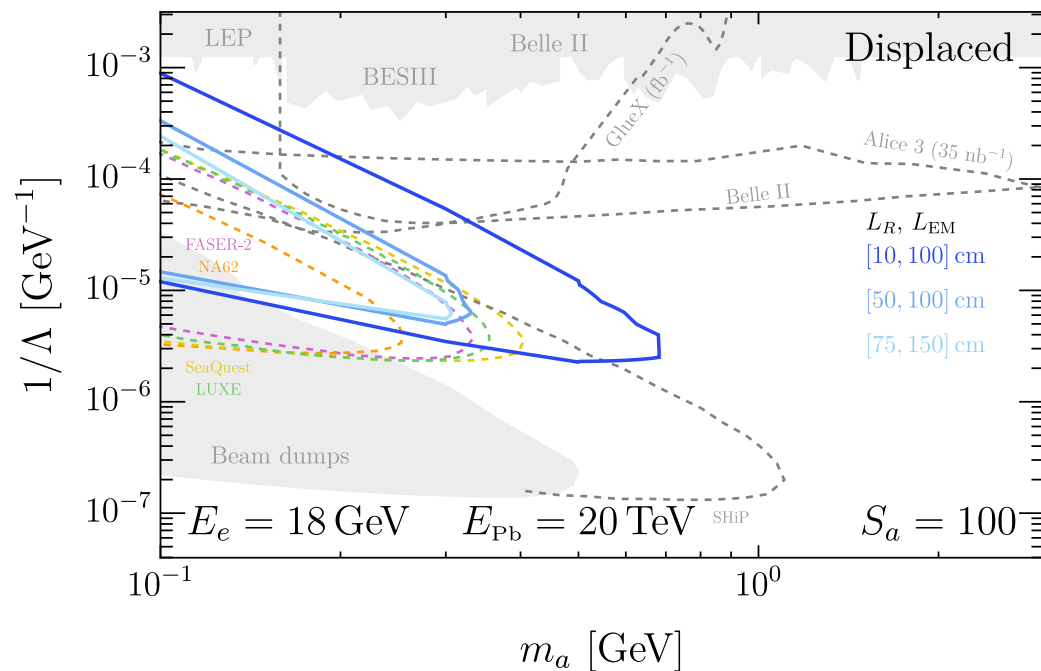


EIC projections: displaced-vertex searches

- Only basic cuts are applied
- $\mathcal{L} = 100 \text{ fb}^{-1}$

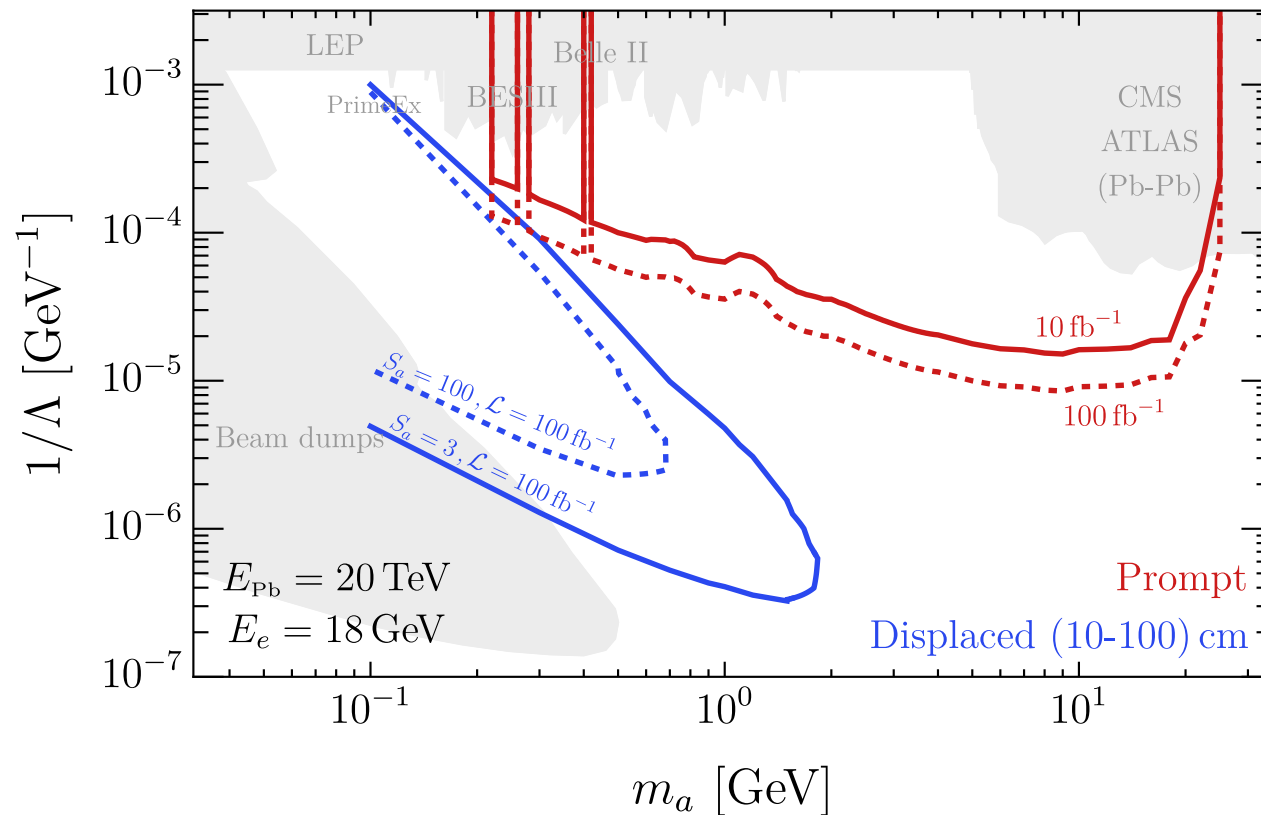


- Background free
- Bounds are set by $S_a = 3$



- Flat background 2500 ($\mathcal{L}/100 \text{ fb}^{-1}$)
- Bounds are set by $S_a/\sqrt{B} = 2$

Summary

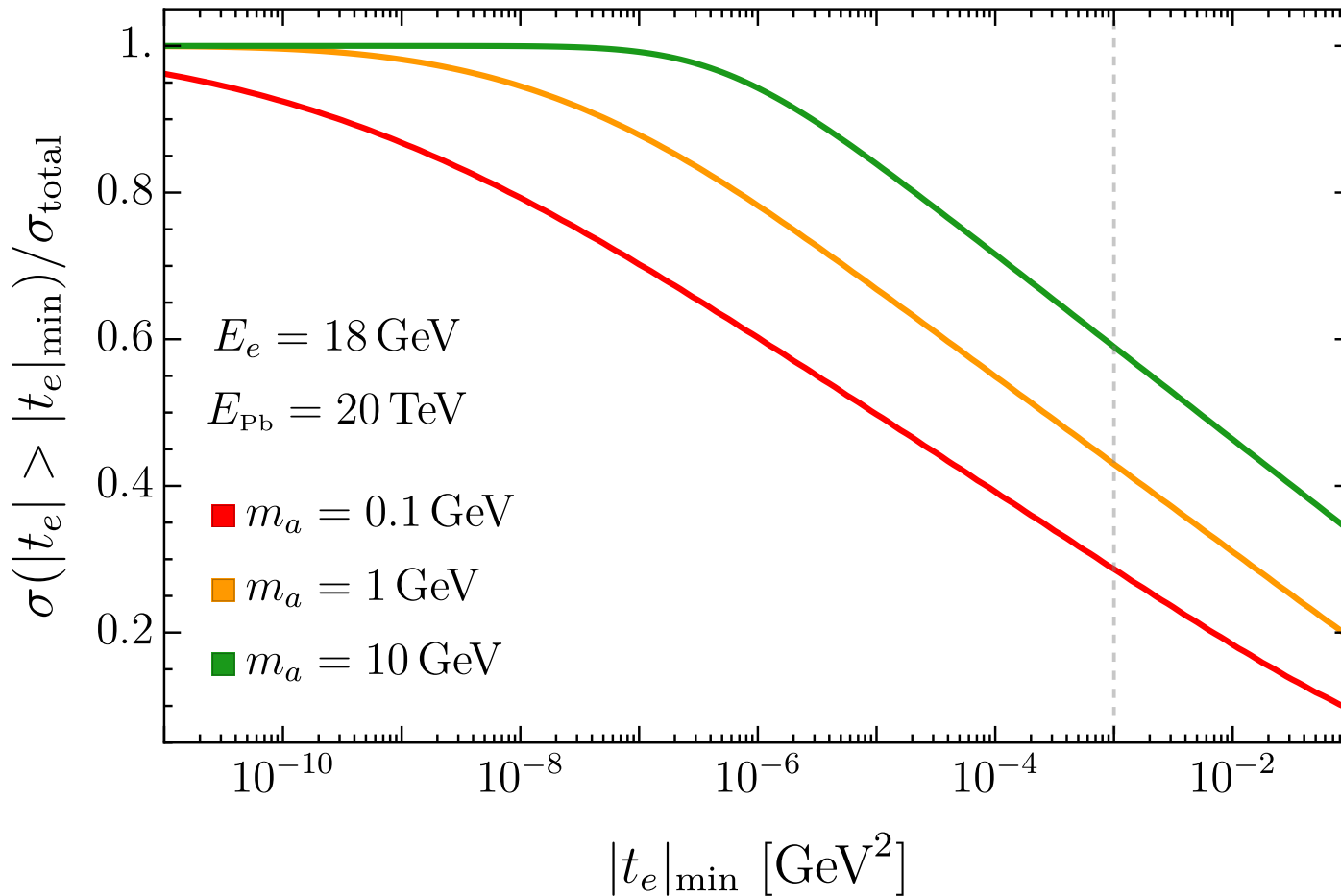


- EIC is good at detecting coherent process.
- EIC can surpass the current lepton and hadron collider and future heavy-ion projection due to the large ALPs production cross section and high luminosity.
- EIC can reach $\Lambda \sim 10^5 \text{ GeV}$ in the 2 to 20 GeV range in the prompt searches. For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

Thanks!

Back-up slides

Cut efficiencies on t_e



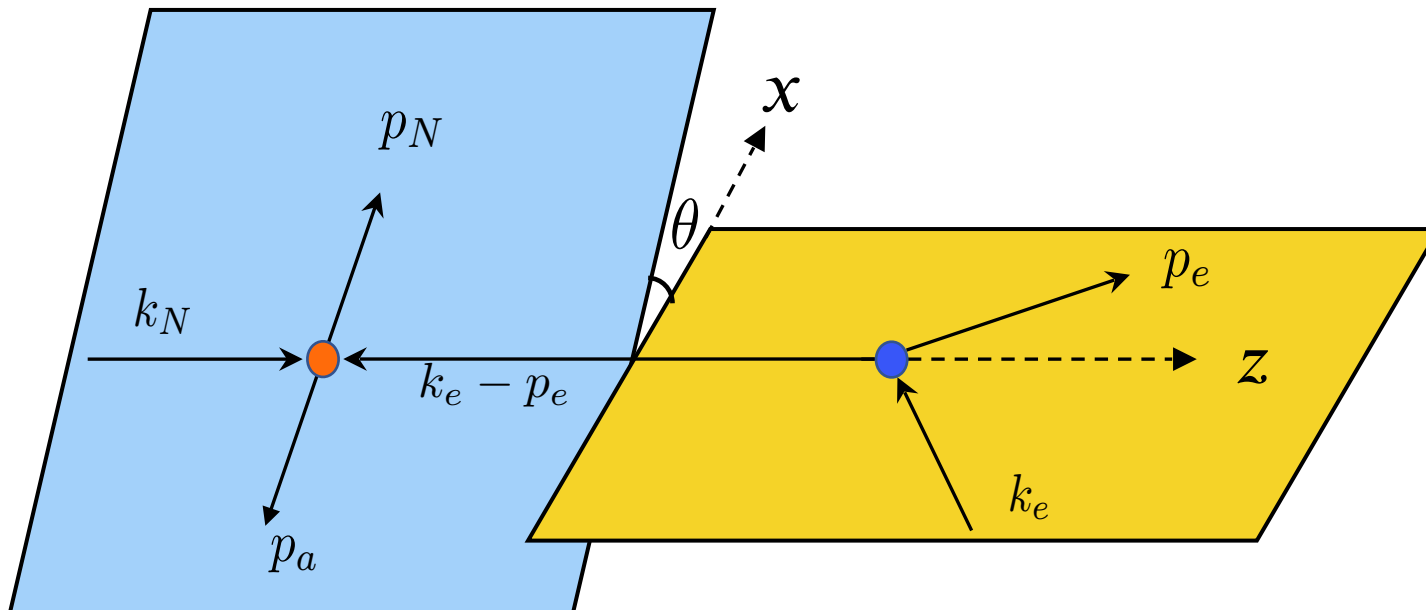
- We require $-t_e > 10^{-3} \text{ GeV}^2$ to have reasonable good resolution.
- The efficiencies is around 40% for 1 GeV ALP.

2-to-3 phase space

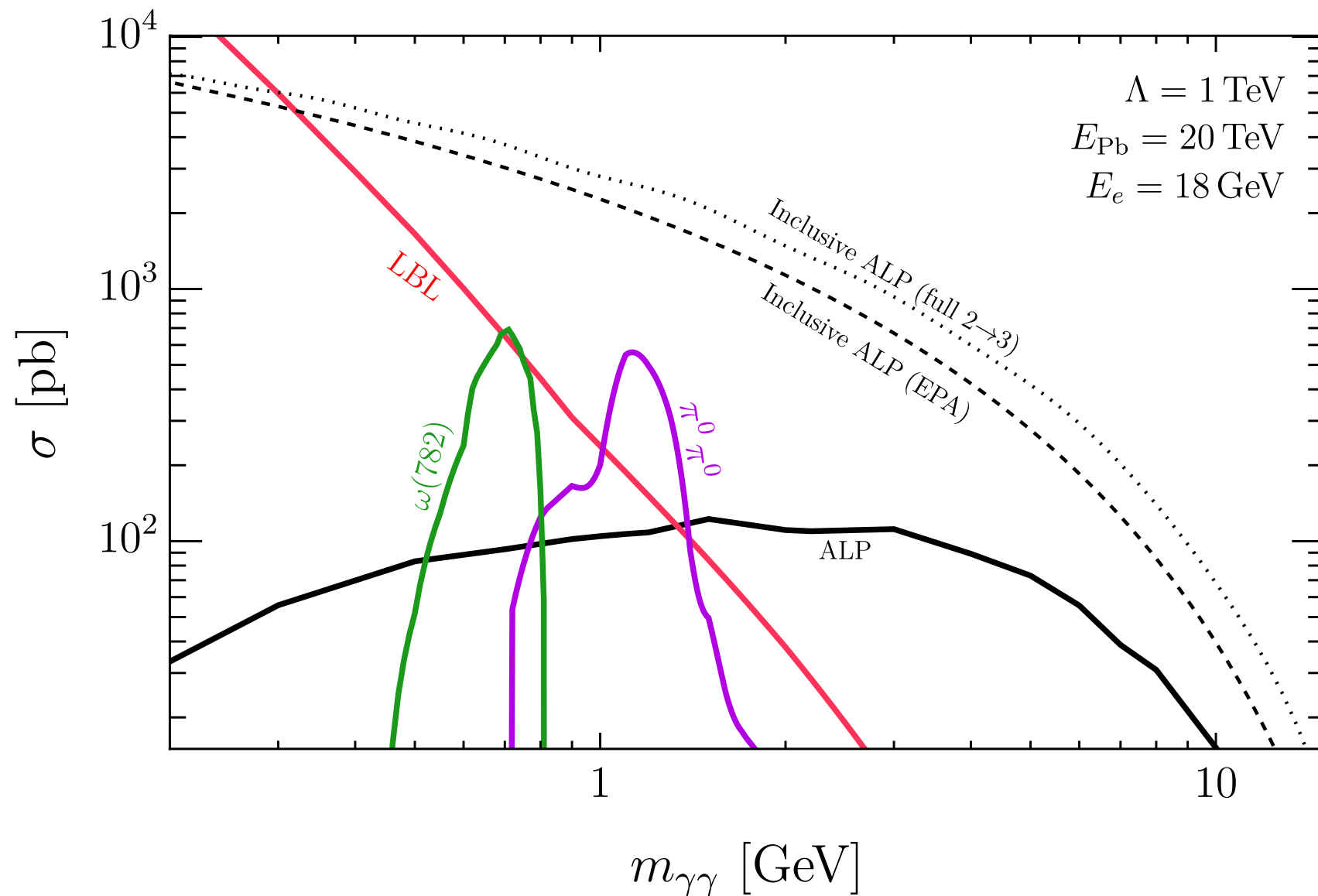
$$\Phi_3(s, m_e^2, m_N^2, m_a^2) = \int d^4 p_e d^4 p_N d^4 p_a \delta(p_e^2 - m_e^2) \delta(p_N^2 - m_N^2) \delta(p_a^2 - m_a^2) \\ \times \delta^4(k_e + k_N - p_e - p_N - p_a) \theta(p_e^0) \theta(p_N^0) \theta(p_a^0)$$

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

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



Cross sections after the cuts



Tagging recoiled electrons

[arXiv:2103.05419]

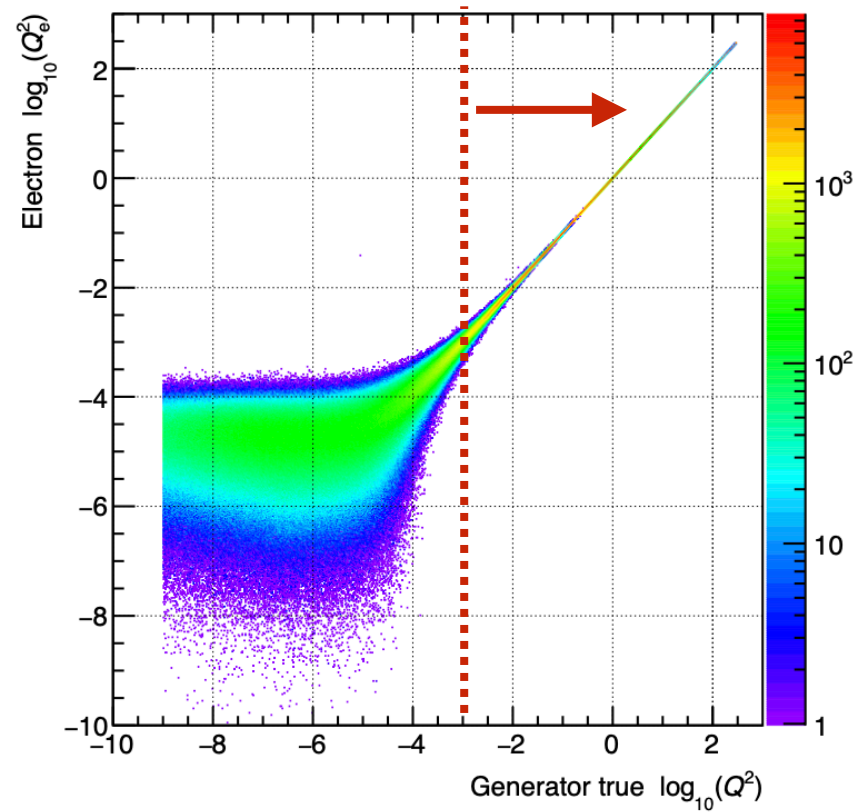


Figure 11.121: Comparison of generated and reconstructed electron Q_e^2 with smearing for beam angular divergence.

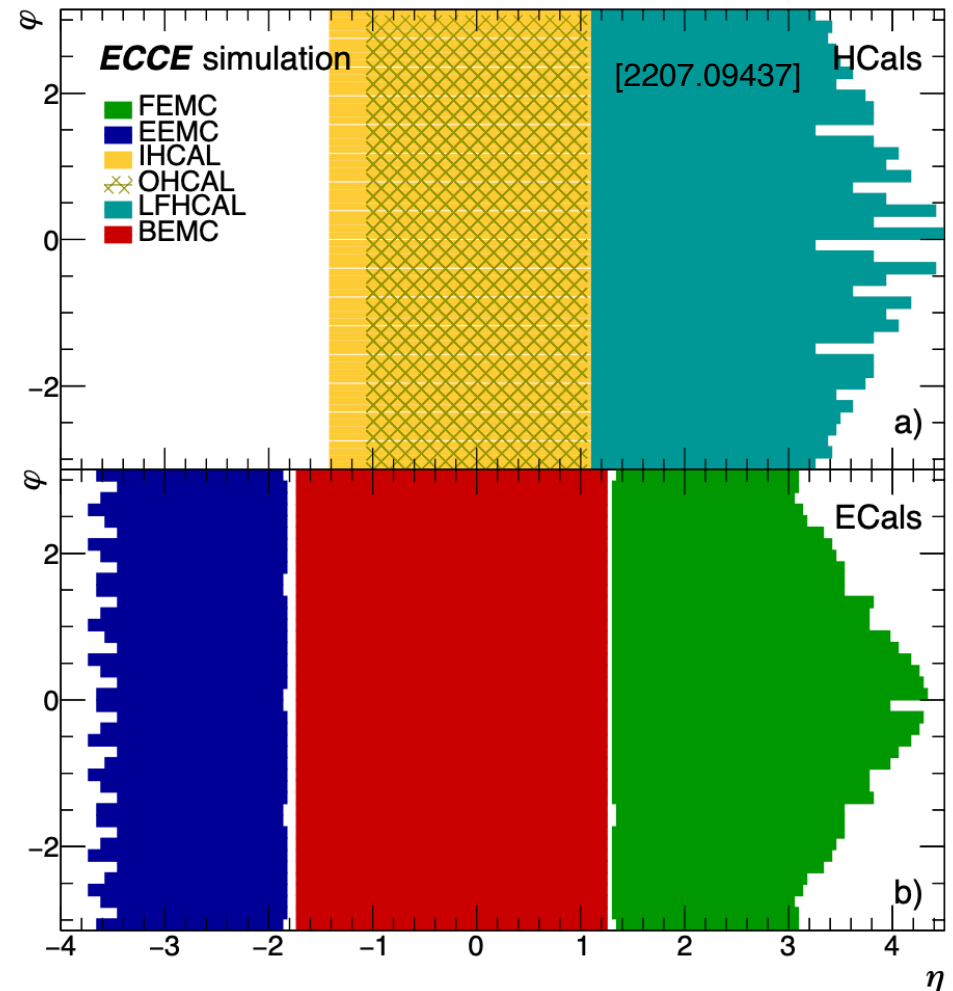
- Recoiled electrons with very low- Q^2 (10^{-9} GeV^2) can be tagged.
- But only when $Q^2 > 10^{-3} \text{ GeV}^2$ we can have reasonable good resolution.

Electron ion collider

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

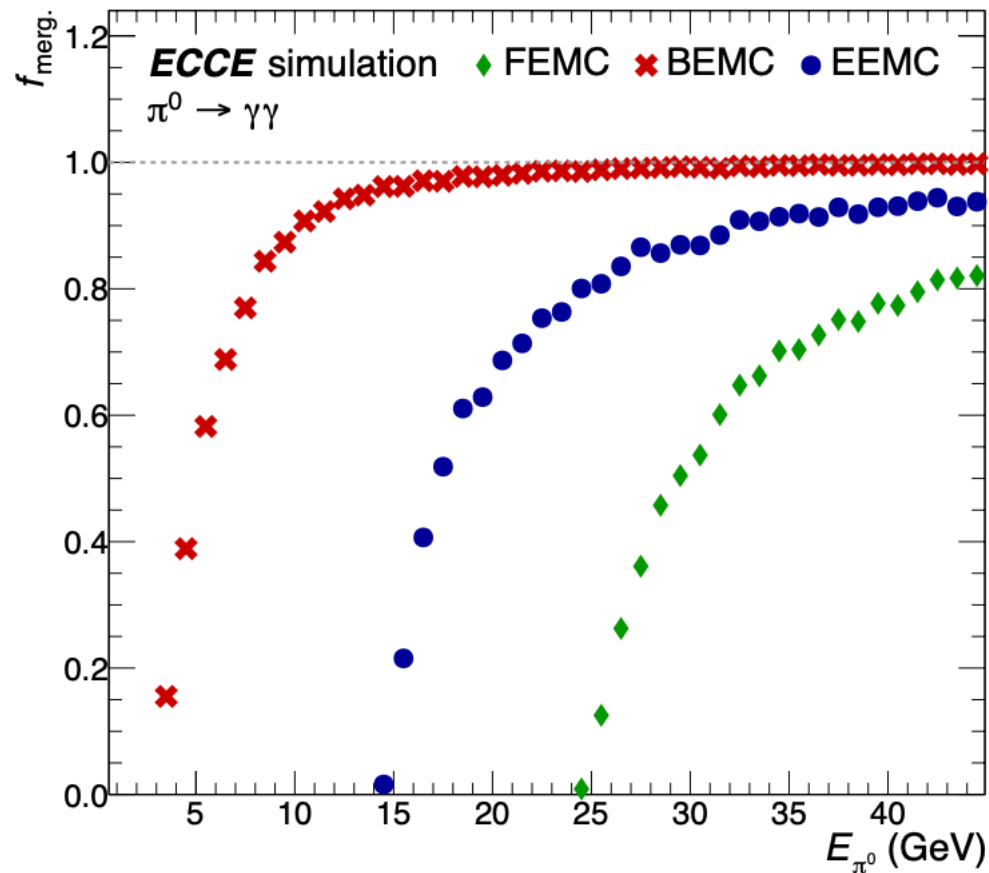
FEMC: Hadron/Forward-End-Cap Electromagnetic Calorimeter
 BEMC: Barrel Electromagnetic Calorimeter
 EEMC: Electron-End-Cap Electromagnetic Calorimeter

	EEMC	BEMC	FEMC
tower size	2x2x20 cm ³	4x4x45.5 cm ³	in: 1x1x37.5 cm ³ out: 1.6x1.6x37.5 cm ³
material	PbWO ₄	projective SciGlass	projective 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_0	~ 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 < η < -1.8	-1.7 < η < 1.3	1.3 < η < 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]

Merge efficiencies



[2207.09437]

Figure 19: Fraction of neutral pions for which the showers from their decay photons are merged into a single cluster and can not be reconstructed using an invariant-mass-based approach for the different ECals.