Search for new particles at JEF & JLab@22GeV

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for the GlueX Collaboration and the SRC-NT measurements

Precision tests of fundamental physics with light mesons
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Table of contents

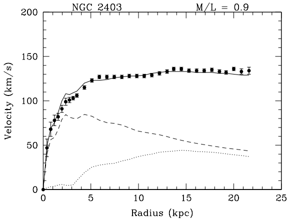
The Universe missing mass "problem"?

First observed by Fritz Zwicky in 1933 and reported in Helvetica physica acta, vol. 6, p. 110

- Missing mass problem, gravitational mass of galaxies in Coma galaxy cluster is much higher than expected
- Dunkle Materie or dark matter?

Validated by Vera Rubin and Kent Jr. W. Ford in 1970 and reported in Astrophysical Journal, vol. 159, p.379

- Measure rotation curves of spiral galaxies
- Observe: outermost components of the galaxy move as quickly as those close to the center



Rotation curve of NGC 2403. The points are the observed rotation curve, the dashed and dotted curves are the Newtonian rotation curves of the baryonic components (stars and gas respectively), and the solid curve is the MOND rotation curve, R. H. Sanders CJP 93 2 (2015).

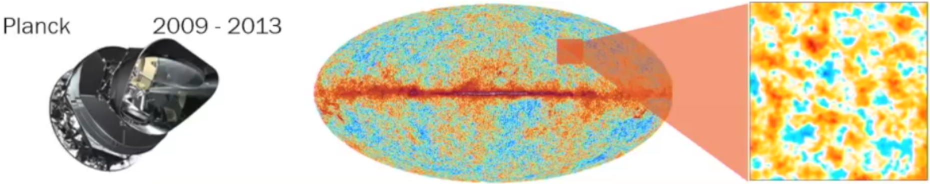
There are different ways to solve this relation problem between mass and gravity:

- Add an extra mass (most popular solution) which is not
  - Baryonic (Standard Model of Particles does not apply)
  - Interacting with known electromagnetic force (missing force(s))
- Modify the theories of gravity, eg MOdified Newton Dynamics (MOND) theories
- Combination of the above
- None of the above

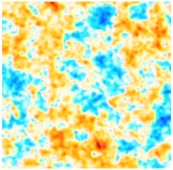
Mass and/or Gravity "problem"?

Universe missing mass "problem" at different ages

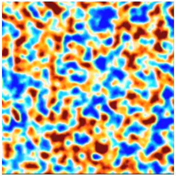
Cosmic Microwave Background (CMB), emitted by the Hydrogen spin flip at different Universe ages, observed by Planck (arXiv:1807.06205) cannot be explained by MOND (so far).



- CMB MC simulation with DM and visible matter



- CMB MC simulation with visible matter only



Difference between data and model is an indication of the proportion of:

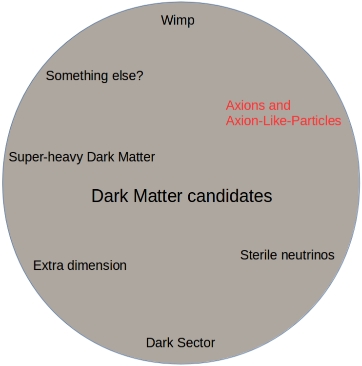
- Visible (luminous) matter (∼5 %)
- Non-luminous (dark) matter (∼25 %) to bind cosmic structures: Galaxies & clusters of Galaxies
- Dark energy (∼70 %) to drive cosmic acceleration: now and at primordial inflation

Criteria and list of candidates

Dark matter criteria:

- Slowly moving particle
- Does not emit light
- Produced during the Big Bang
- Does not decay

- Dark matter candidates



Robust evidence of new physics and many candidates

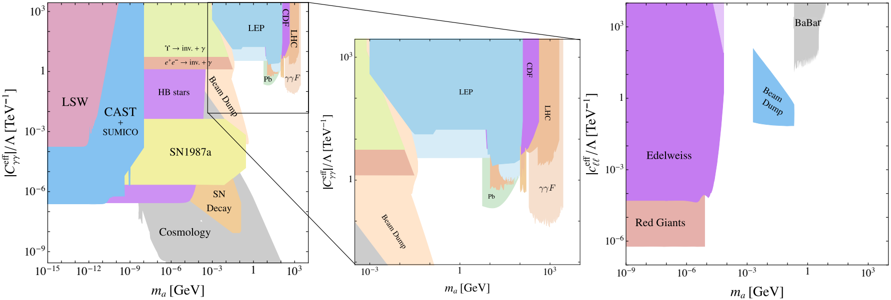
The (QCD) axion(-like)

To solve the neutron's electric spin or the strong-CP violation problem

- Peccei and Quinn proposed a pseudo-particle in 1977 ("CP Conservation in the Presence of Pseudoparticles") which
- Weinberg and Wilczek (the same year) formely introduced as the (QCD) axion ("A New Light Boson" and "Problem of Strong P and T Invariance in the Presence of Instantons")
- Sikivie in 1984 defined the experimental principals needed to observe this hypotetical ultra-light particle: (QCD) axion can convert into photon while crossing a magnetic field perpendicular to its direction

More generally, Axion-Like pseudo-scalar Particles (ALP) appear in any theory with a spontaneously broken global symmetry and possible ALP masses and couplings to SM particles range over many orders of magnitude.

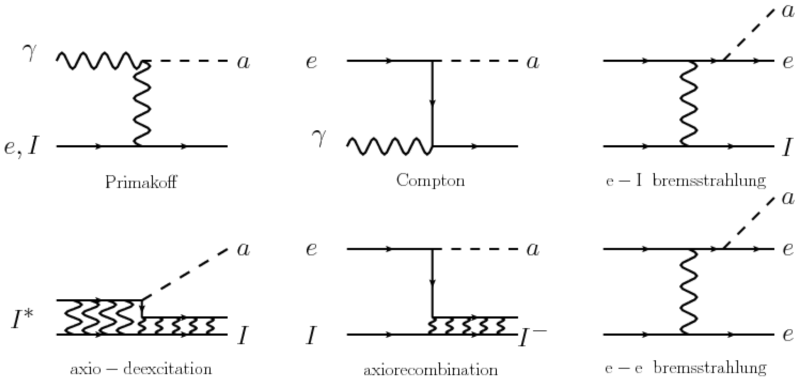
- (QCD) axion (below eV) could represent up to 30 % of dark matter
- MeV range ALPs could represent only a fraction of dark matter



$\Lambda/|C^{\rm eff}| = 32\pi^2 f_a$ where f_a and $C^{\rm eff}$ axion decay constant and effective coupling, respectively

ABC reactions

Atomic recombination and deexcitation, Bremsstrahlung and Compton responsible for the solar axion flux in axion models.

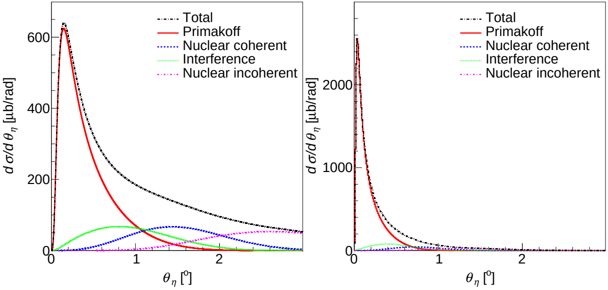


Focus on Primakoff photoproduction process

Analogy to Primakoff photoproduction of η-meson

$\gamma^{202}\mathrm{Pb} \to \eta^{202}\mathrm{Pb}$, theoretical differential cross-section known:

- $\frac{d\sigma_T}{d\Omega} = \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_{NC}}{d\Omega} + 2\sqrt{\frac{d\sigma_P}{d\Omega}\frac{d\sigma_{NC}}{d\Omega}} cos(\phi) + \frac{d\sigma_{NI}}{d\Omega}$
- Primakoff contribution is directly proportional to the $\Gamma_{\eta\to\gamma\gamma}$ decay width
  $\frac{d\sigma_P}{d\Omega} = \boxed{\Gamma_{\eta\to\gamma\gamma}} \frac{8\alpha Z^2}{m_\eta^3}\frac{\beta^3 E^4}{Q^4}\left|F_{e.m.}(Q)\right|^2 \sin^2\left(\theta_\eta^{\mathrm{lab}}\right)$
- Cross-section for $\mathrm{E}_\gamma = 10$ GeV (left) and $\mathrm{E}_\gamma = 20$ GeV (right):
  - $\Gamma_{\eta\to\gamma\gamma} = 510$ eV and $\phi = 57.5^o$



- Primakoff contribution increases with Z^2

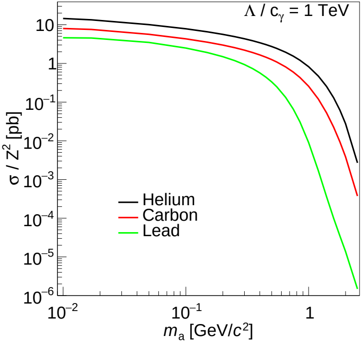
Atomic number impacts the measurements

Primakoff photoproduction of ALP

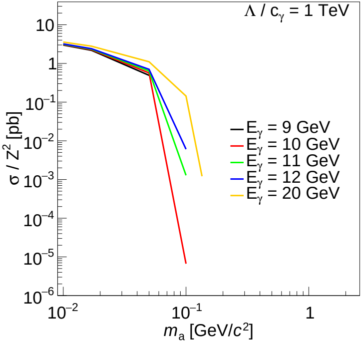
$\gamma A \rightarrow Aa$, theoretical cross-section:

- $\frac{d\sigma_P}{d\Omega} = \boxed{\Gamma_{a\to\gamma\gamma}} \frac{8\alpha Z^2}{m_a^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2(\theta_a^{\mathrm{lab}})$
- $\Gamma_{a\to\gamma\gamma} = \frac{c_\gamma^2 m_a^3}{64\pi\Lambda^2}$
- $\frac{c_\gamma}{\Lambda}$, axion coupling to photon, unit eV

- Off nuclei and $\mathrm{E}_\gamma = 20$ GeV



- Off Atomic electron



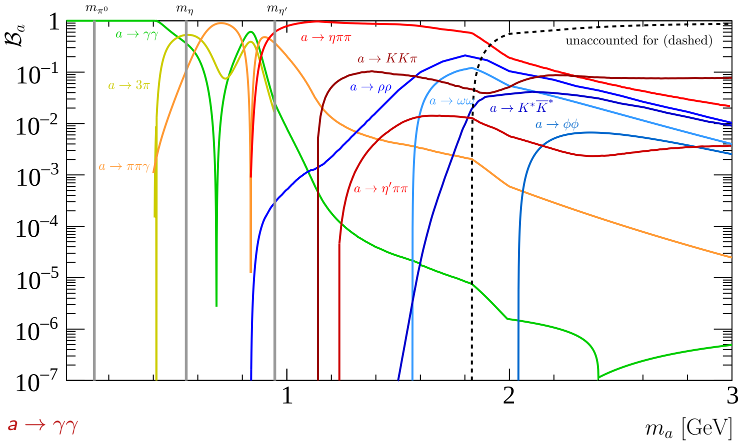
Atomic electron contribution below 50 MeV$/c^2$ non-negligible

ALP branching ratio

Golden modes for GlueX/JEF:

- $a \to \gamma\gamma$
- $a \to \pi^0\pi^+\pi^-$
- $a \to \gamma\pi^+\pi^-$
- $a \to \eta\pi^+\pi^-$

  D. Aloni et al. PRL 123 (2019), arXiv:1811.0347

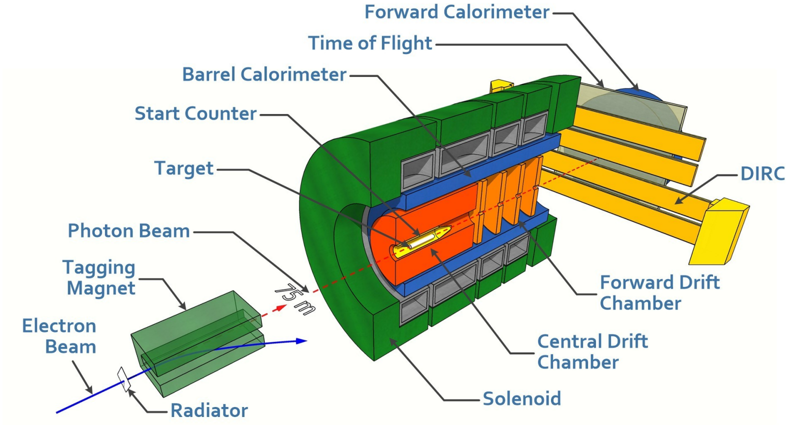


Focus on $a \to \gamma\gamma$

The GlueX setup

Photon-beam produced by (coherent) bremsstrahlung

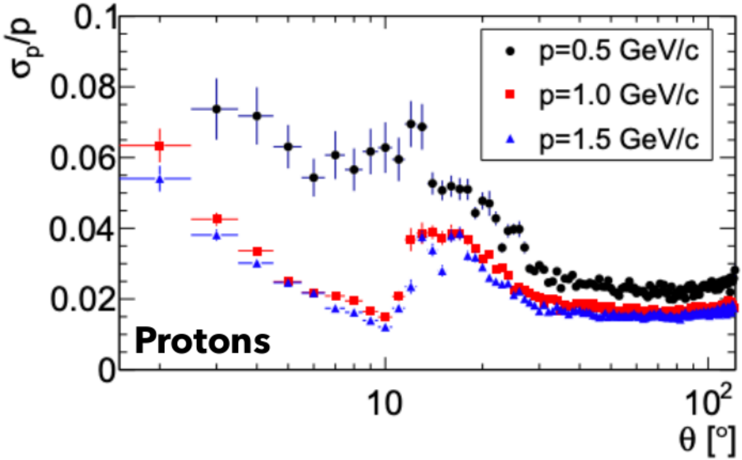
NIMA 987 164807 (2021) - arxiv:2005.14272



- Target: LH2, LHe, LD2, or solid (Be, C, Pb)
- Used by GlueX Collaboration, SRC-NT group, and in future KLF Collaboration

Typical integrated luminosity, $\mathcal{L} \sim 200\ \mathrm{pb}^{-1}$ per 100 days

Tracking capability

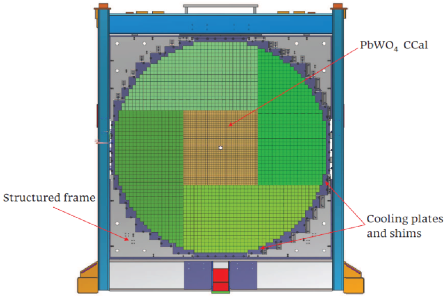


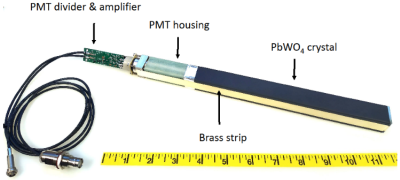
The JLab Eta Factory

Expected to produce $\sim 5 \times 10^7$ $\eta(')$ in 100 days between 8.4 and 11.7 GeV in E_γ

Experiment	total η	total η'
CB/AGS	10^7	-
CB/MAMI	2×10^7	-
CB/MAMIC	6×10^7	10^6
WASA/COSY	$\sim3\times10^7$ (p+d) $\sim5\times10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^6
BES-III	$\sim10^7$	$\sim5\times10^7$

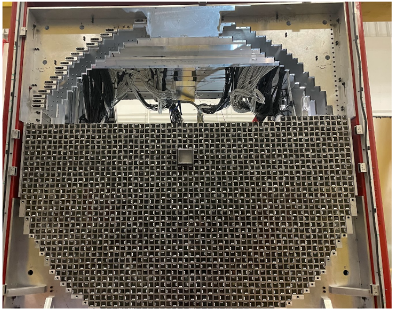
- Upgraded Forward Calorimeter covers angle between 0.3 and 8^o ($\sim$6 m from target center)
- 1600 PWO_2 modules placed in a 80 by 80 cm^2 matrix





Exclusive measurements and large solid angle coverage strongly reducing background

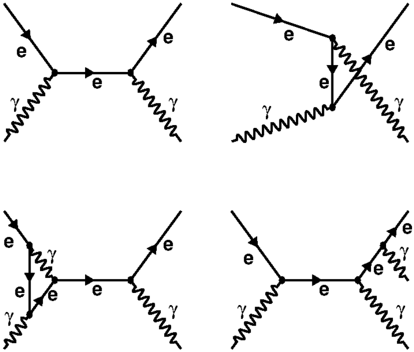
Unstacking

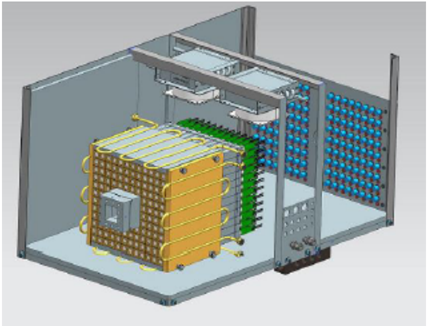


Malte Albrecht (JLab) 11 GlueX Collaboration Meeting 05/2023

Compton photoproduction off an atomic electron

- Compton cross-section is a known QED process and is used as a reference process:
  - Verify systematics
  - Monitor luminosity
  - MC simulation validation





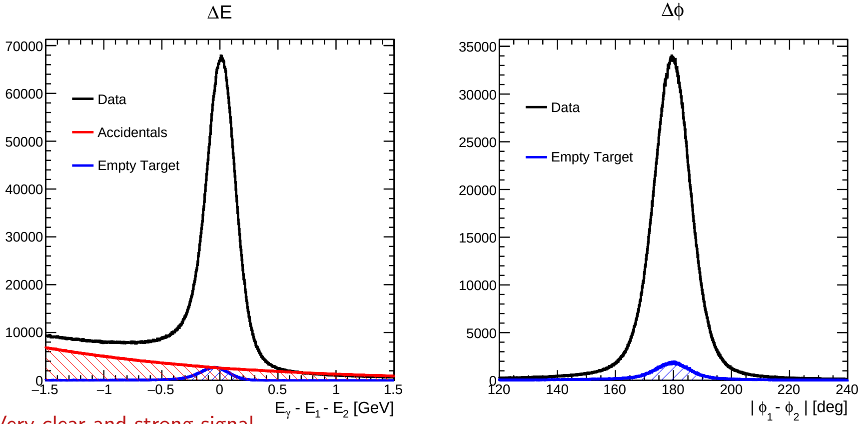
- Compton Calorimeter aka JEF prototype (right-figure) covers angle between 0.2 and 1^o (A. Assturyan and al. NIM, A 1013 (2021))

Compton detection efficiency varies between 12 and 5 % for E_γ between 6 and 11.3 GeV

Control channel: $\gamma e^- \rightarrow \gamma e^-$

Selection criteria: (Andrew Smith PhD)

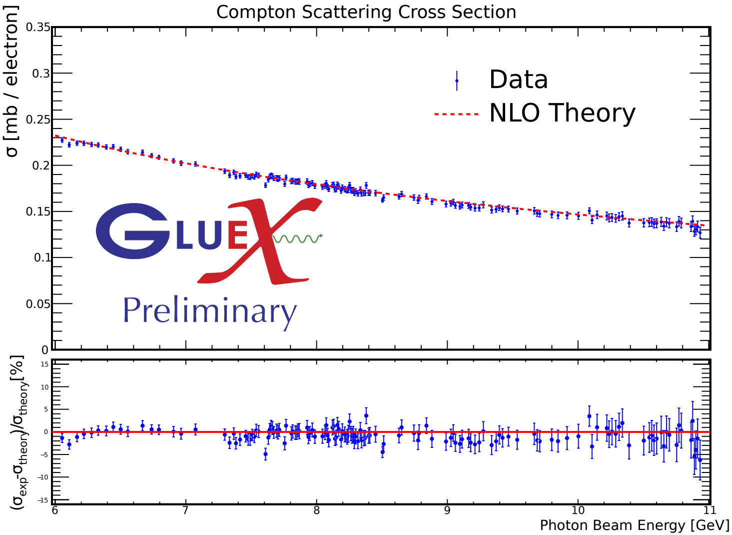
- At least two clusters with one in the Forward and one in the Compton Calorimeters
- Elasticity required
  (energy difference between incident photon-beam and two clusters)
- Coplanarity required



Very clear and strong signal

Preliminary Compton cross-section measurements

First cross-section measurements in this energy range: (Andrew Smith PhD)

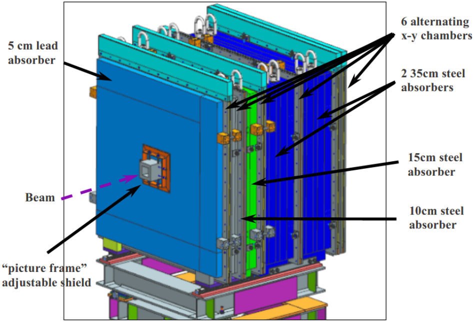


Within 5% from the theoretical cross-section

UMASS Muon detector

Used for the Charged and Neutral Pion Polarizability Experiments

Muon detector



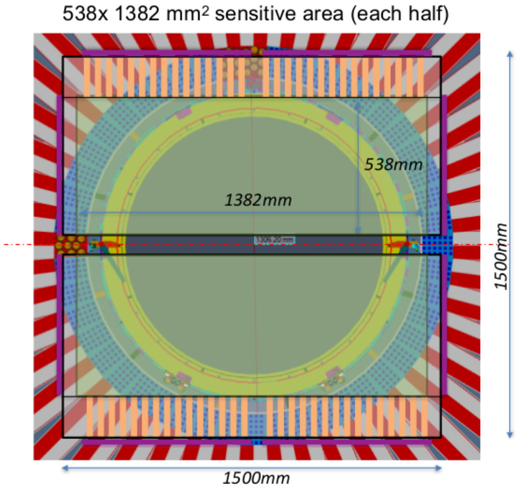
- Designed and assembled at UMASS, tested at JLAB and in beam
- Shielding thickness distribution has been optimized with AI
- First wall material has been changed to lead as we were tight in space for the deep e-m background tails after FCAL suppression
- 8 MWPC planes have been constructed, 6 of them were used during the run
- Each MWPC has 144 channels (i.e. sense wires, connected to fADC-125)
- Grounding has been improved in the Hall, suppressing high frequency noise
- 90% Ar + 10% CO_2 mixture has been chosen after beam tests for better timing
- Operated at ~1780V

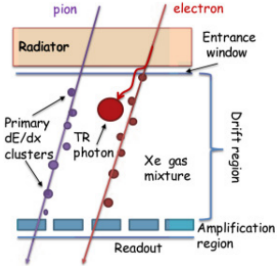
University of Massachusetts Amherst | Jefferson Lab | Andrew Schick | CPP/NPP Run Report GlueX Collaboration Meeting | May 24, 2023 | 10

Behind FCAL2, we can add UMASS Muon detector eg $\eta(') \to \pi^0 \mu^+ \mu^-$

GEMTRD

Currently being build, prototype tested at JLab and FermiLab, NIMA 942 (2019) 162356



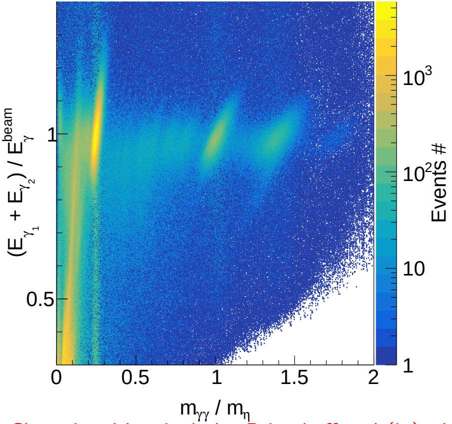


Can be added to improve separation power between pion and electron eg $\eta \to \pi^+\pi^- e^+ e^-$

Selection criteria

Two clusters in Forward Calorimeter:

- Barrel Calorimeter used to veto hadronic backgrounds
- Time-Of-Flight wall used to veto charged particles
- Elasticity required
- $\theta^{\mathrm{lab}}_{\gamma\gamma} \leq 0.5^0$



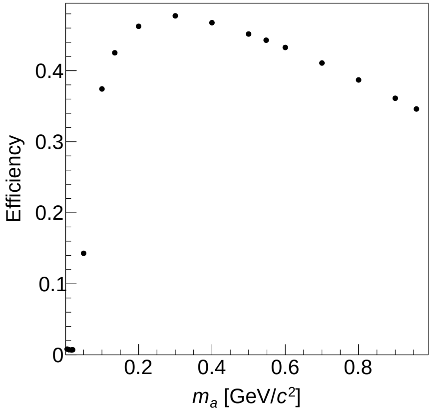
Example with Carbon target
$\gamma_{\mathrm{beam}}{}^{12}\mathrm{C} \rightarrow \eta/\pi^0{}^{12}\mathrm{C}$ and $\eta/\pi^0 \rightarrow \gamma_1\gamma_2$
In Primakoff process, most of the energy is transferred to η-meson
$=> \mathrm{E}^{\mathrm{beam}}_{\gamma} - \mathrm{E}^{\mathrm{cluster}}_{\gamma 1} - \mathrm{E}^{\mathrm{cluster}}_{\gamma 2} \sim$ 0 (elasticity)

Clear signal but includes Primakoff and (in)coherent events, and non-negligible backgrounds mainly target (hadronic) and beamline

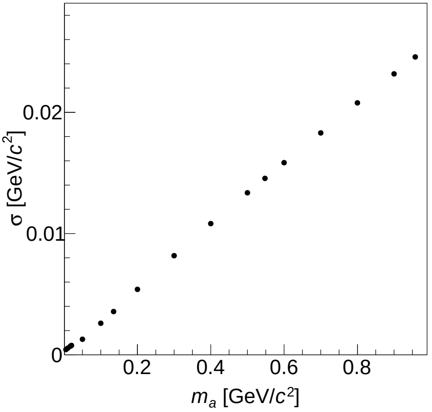
Signal detection efficiency and resolution

Very preliminary

- Efficiency



- Resolution

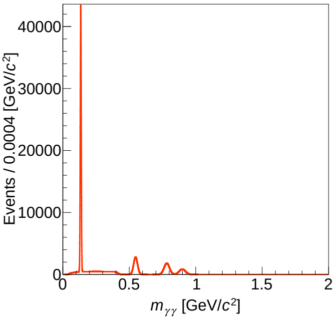


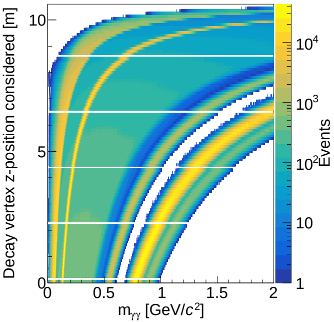
- Detection efficiency above 100 MeV/c^2 is improved with $\mathrm{E}_\gamma \nearrow$
- Resolution for all masses is improved with $\mathrm{E}_\gamma \nearrow$

Background coming from the target and beamline estimated for each mass scanned $\pm 3\sigma$

Very preliminary expected background

No bump search possible at π^0, η, ω, and η' masses

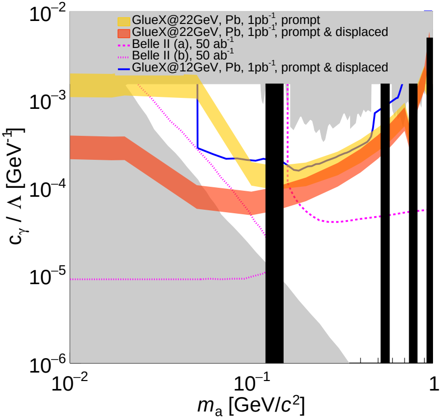




Background sources: π^0, η, ω, and η' produced in the target and downstream from the target via Primakoff and Coherent processes

Very preliminary expected sensitivity

No bump search possible at π^0, η, ω, and η' masses



- Expected $\pm 1\sigma$ for 1 pb^{-1}, Lead target, 30% systematic error, and decaying in the target and downstream from target
- GlueX/JEF vs Belle II or 100 days vs 10 years

JLab@22GeV is competitive

Conclusion

JEF (and JLab@22GeV) will open new opportunities to probe New Physics Beyond Standard Model

- Many different models can be tested
- Preliminary study for $a \to \gamma\gamma$ is presented
- Other ALP decays can be studied
- A 22GeV beam is naturally increasing Primakoff cross-section
  - White paper put on arxiv this week
  - Decision in 2030
  - First beam expected in 2039
- A heavy target is also naturally increasing Primakoff cross-section

For 1 pb^{-1} collected:

- A competitive sensitivity is expected
- If beamline is optimized for this measurements i.e. Helium bag is used
- Large sample of empty target