

Search for Hidden Sector New Particles in the 3 - 60 MeV Mass Range

(JLab Experiment E12-21-003)

A. Gasparian

NC A&T State University, NC USA

Co-spokespersons: D. Dutta, H. Gao, N. Liyanage, T. Hague, C. Peng, R. Paremuzyan
and the PRad collaboration

Outline

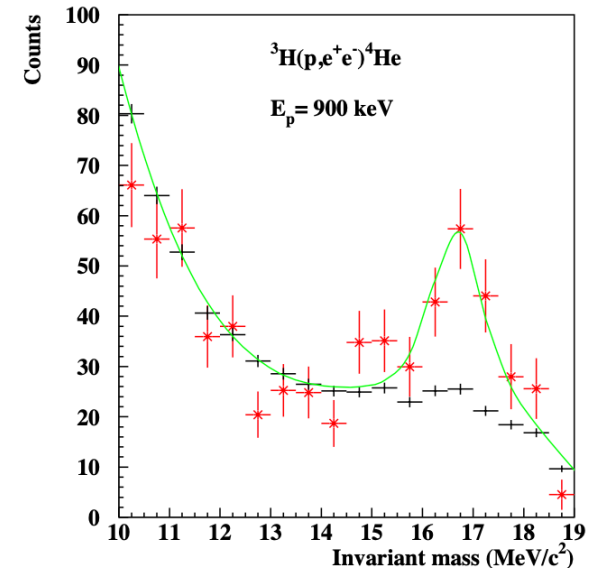
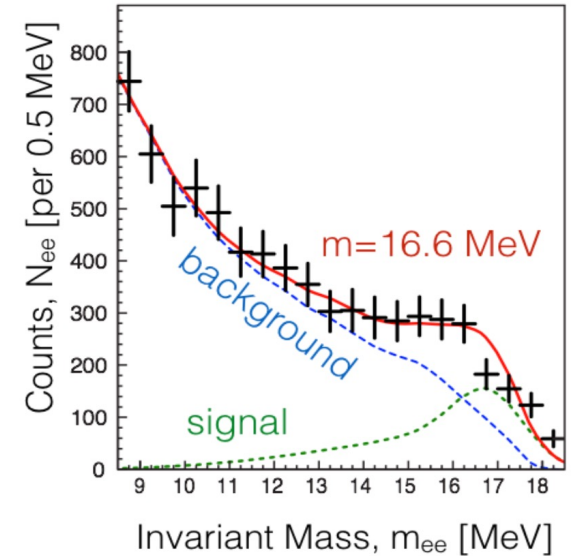
- physics goals
- experimental method
- experimental setup and resolutions
- estimated background and physics reach
- summary

Physics Goals of the Experiment

- Most of **cosmological observations** suggest that:
 - ✓ $\approx 85\%$ of Universe consist of matter with “unknown origin”, the so-called **Dark Matter (DM)**;
 - ✓ DM either does not interact with the known, ordinary matter (SM) or if interacts, then very weakly (**WIMPs**), weak enough we can not detect them so far;
 - ✓ many theoretical models, many search experiments ...
no experimental detection of DM so far.
- **DM** can be detected through their interactions with the **SM objects** (particles/fields).
- A viable theoretical model suggests:
 - ✓ existence of “**intermediate particles/fields**” (portals) between **DM** and **SM** objects;
 - ✓ providing interaction between DM and SM through the so-called “**kinetic mixing**” mechanism;
 - ✓ U(1) gauge boson (**dark photon** or **X-particle**);
 - ✓ the **[1 – 100] MeV** mass range is well motivated.
- **Recent experimental evidence**: excess of e^+e^- pairs in excited ^8Be and ^4He decay spectrum (ATOMKI anomaly, \rightarrow hypothetical **X17 particle** or 5th-force carrier).
 - ✓ **requires an urgent independent experimental validation.**
- We propose to **search for hidden sector intermediate particles** in low MeV-scale mass range through a direct detection method.

ATOMKI ^8Be and ^4He Experiments (Anomalies)

- ^8Be anomaly in nuclear transitions (*PRL 116(4):042501 (2016)*):
 - ✓ ^8Be excited states, decaying to ground state by E/M transitions.
 - $p + ^7\text{Li} \rightarrow ^8\text{Be}^* \rightarrow 7\text{Li} + p$ (hadronic decay)
 - $\rightarrow ^8\text{Be} + \gamma$ (E/M decay)
 - $\rightarrow ^8\text{Be} + \gamma^*, \gamma^* \rightarrow e^+e^-$ (IPC)
 - ✓ excess of e^+e^- pairs in angular distributions (inv. mass) beyond the expectation of the Internal Pair Conversion (IPC).
- Second experiment on ^4He with updated experimental setup and reduced background:
 - $p + ^3\text{H} \rightarrow ^4\text{He}^* + \gamma \rightarrow ^4\text{He} + \gamma^*, \gamma^* \rightarrow e^+e^-$ (IPC)
 - ✓ e^+e^- peak at different angles but the same invariant mass.
published in: *Phys. Rev. C 104 (2021) 4, 044003*
- Similar anomaly result with $^{11}\text{B}(p,\gamma)^{12}\text{C}$ by ATOMKI:
arXiv:2209.10795v2, Nov. 2022
- Over hundred theory papers, **no independent experimental confirmation**
- **Requires an urgent independent experimental validation.**



Experimental Objectives

- The experiment has two experimental objectives:
 - 1) Validate existence or establish an experimental upper limit on the electroproduction of the hypothetical **X17 particle** claimed in two **ATOMKI low-energy proton-nucleus experiments**.
 - 2) Search for “hidden sector” intermediate particles (or fields) in [3 – 60] MeV mass range produced in electron-nucleus collisions and detected in e^+e^- (or $\gamma\gamma$) channels.

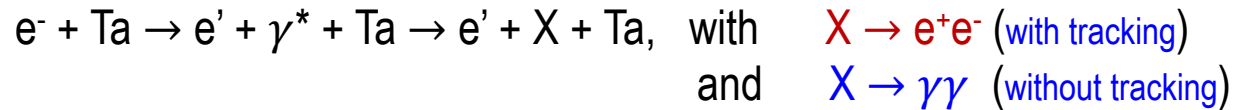
Many past and recent publications suggesting models predicting existence of **scalar or pseudoscalar** new particles in **low mass range, [1–50] MeV**, **decaying through $\gamma\gamma$** channel (Cheuk-Yin Wong, arXiv:2201.09764v1, QED bound state of quark-antiquark system).

This experiment is equally **sensitive to neutral decay channels ($X \rightarrow \gamma\gamma$)**.
(**significant advantage over many other proposals or running experiment**).

arXiv:1707.09749

Experimental Method

- The method:
 - ✓ “bump hunting” in the invariant mass spectrum over the beam background.
 - ✓ direct detection of all final state particles (e' , e^+e^- and/or $\gamma\gamma$) \rightarrow full control of kinematics
- Electroproduction on heavy nucleus in forward directions:



in mass range of: [3 - 60] MeV

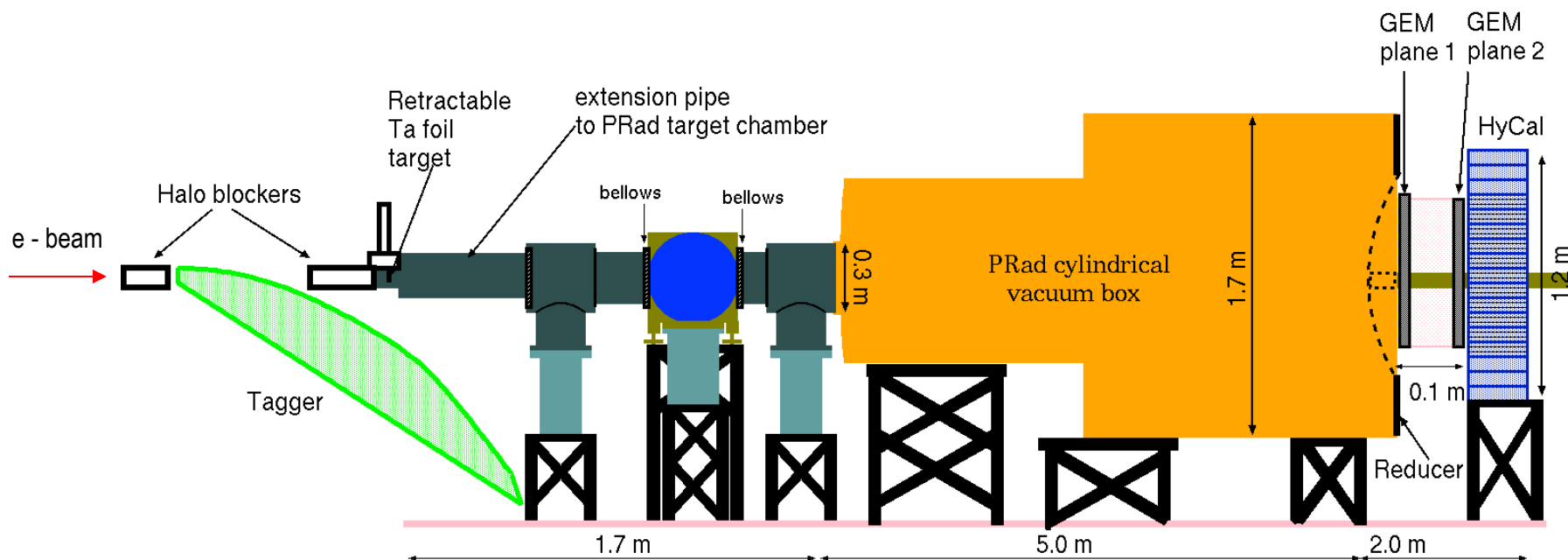
target: Tantalum, ($_{73}\text{Ta}^{181}$), 1 μm (2.4×10^{-4} r.l.) thick foil.

- All 3 final state particles will be detected in this experiment:
 - ✓ scattered electrons, e' , with 2 GEMs and PbWO_4 calorimeter;
 - ✓ decay e^+ and e^- particles, with 2 GEMs and PbWO_4 calorimeter;
 - ✓ or decay $\gamma\gamma$ pairs, with PbWO_4 calorimeter (and GEMs for veto).
- Will provide a tight control of experimental background.

Proposed Experimental Setup in Hall B at JLab

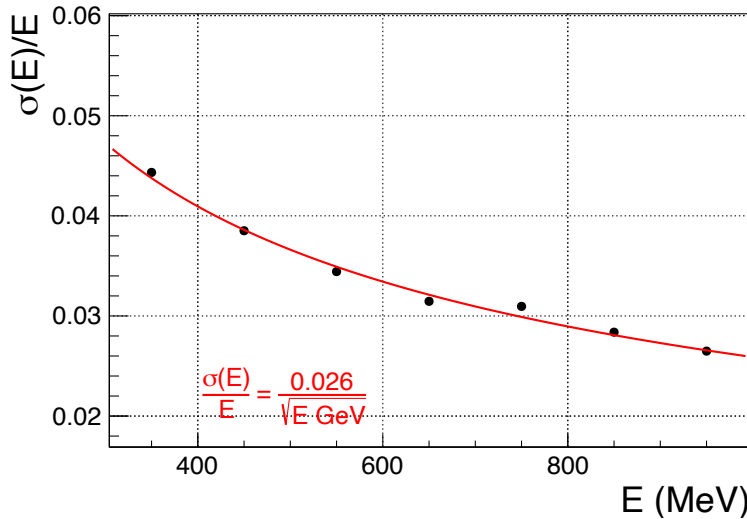
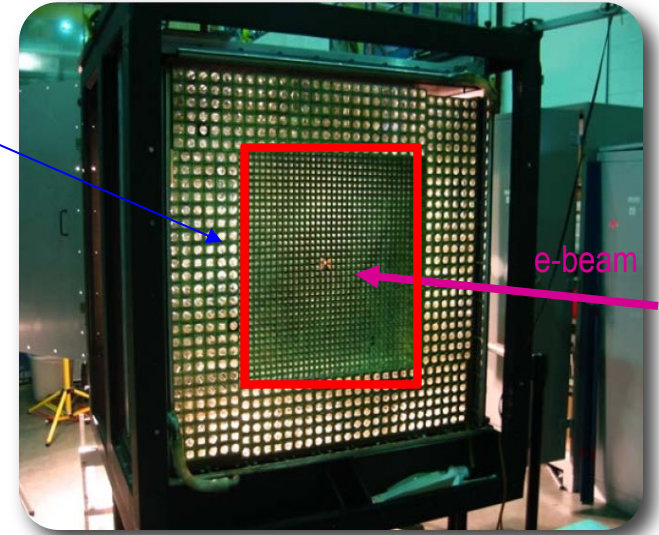
- Experimental setup is based on the **PRad-II apparatus**:
 - Hall B Photon Tagger will be used for PbWO_4 calorimeter gain equalization and initial calibration
 - $1 \mu\text{m}$ Ta solid targets (2.4×10^{-4} r.l.) will be placed on the target ladder (and Harp, **multiple foils**);
 - Two planes of GEM detectors on front of the PbWO_4 calorimeter, providing limited tracking;
 - Only the PbWO_4 part of HyCal will be used in this experiment.

Experimental Setup (Side View)



Experimental Apparatus: PbWO₄ Electromagnetic Calorimeter

- Only the inner PbWO₄ part of HyCal will be used:
 - ✓ 34 x 34 = 1156 crystal modules, each with 2x2x18 cm³;
 - ✓ with 68 x 68 cm² total detection area;
 - ✓ 2x2 crystals are removed from center for beam passage



Energy resolution (PrimEx measurement, limited by Hall B Photon Tagger).

- PbWO₄ crystals have excellent detection characteristics at MeV range energies too.
- example: recent Mainz measurements down to 30 MeV energies (crystals were not cooled): similarly good energy resolutions.

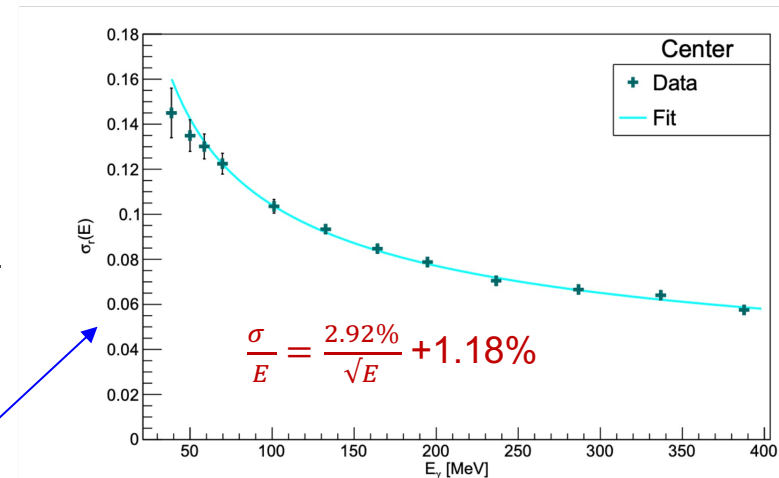
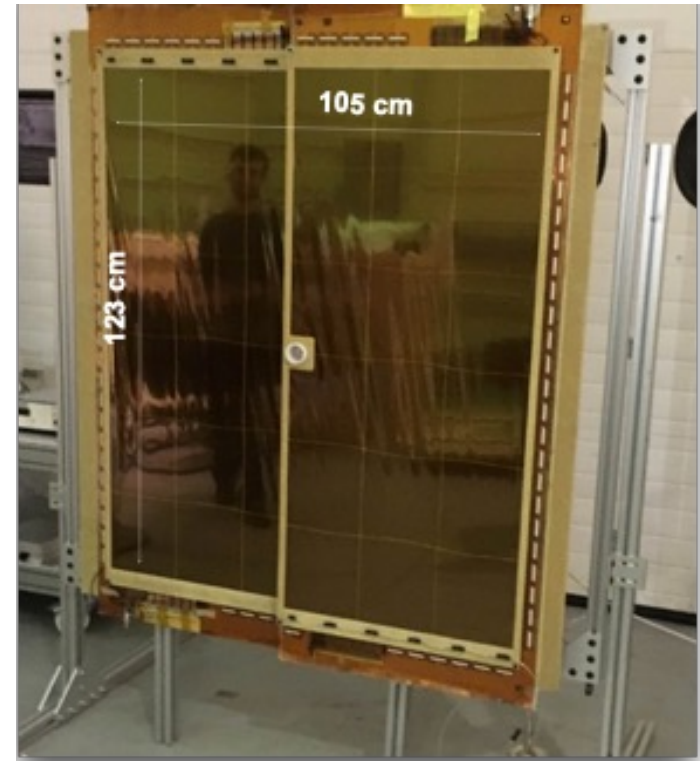


Figure 43: Measured relative resolution of the cluster energy response as a function of the incident photon energy E_γ for the center irradiation position in element 8. The errors are systematic.

Experimental Apparatus: GEM Coordinate Detectors (Tracking)

- Two planes of GEM detectors for tracking:
 - ✓ similar to PRad-II GEMs but smaller size: $68 \times 68 \text{ cm}^2$ each;
 - ✓ located on front of PbWO_4 , after the vacuum window;
 - ✓ relative distance (10 cm), optimized between resolution and available material after the vacuum window;
 - ✓ good position resolution ($\sigma = 72 \mu\text{m}$);
 - ✓ will veto neutral particles for $X \rightarrow e^+e^-$ channel and veto the charged particles for $X \rightarrow \gamma\gamma$ channels.

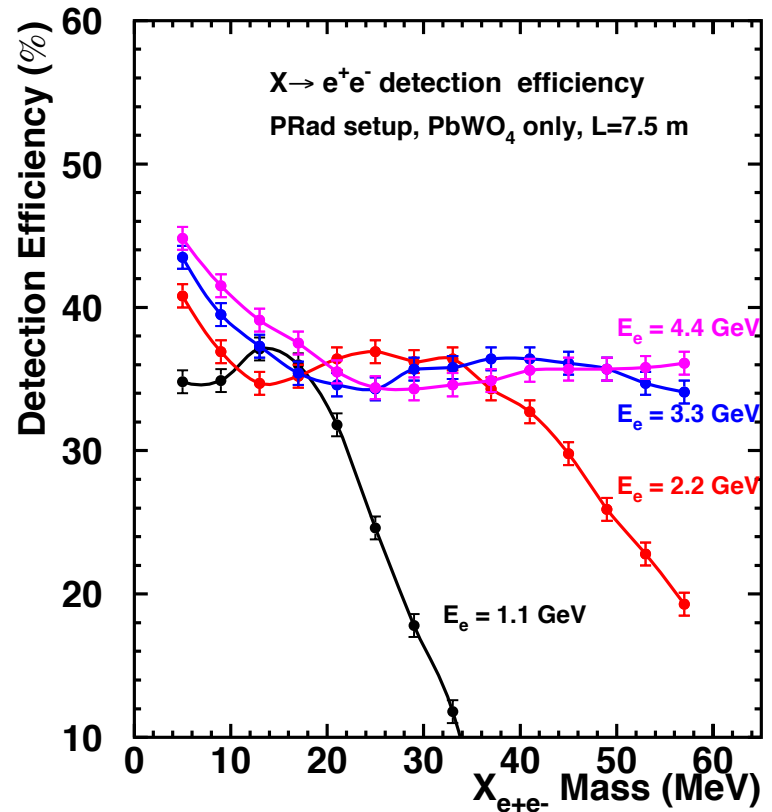


PRad GEMs
(larger size: $120 \times 120 \text{ cm}^2$)

- Electronics: APV-25 based readout system.

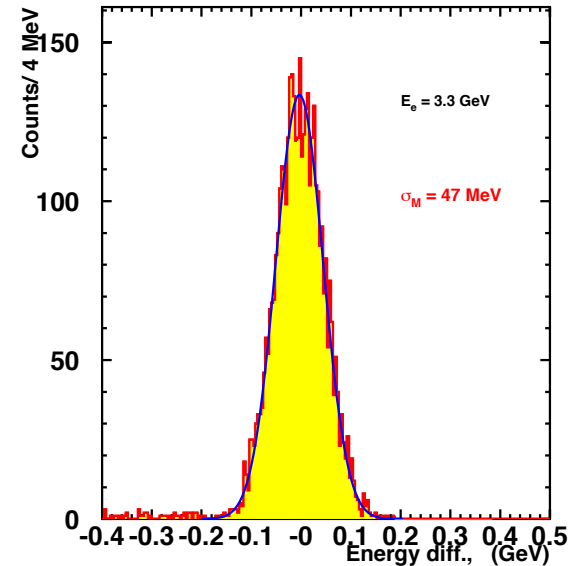
Detection Efficiency (Geometrical Acceptance)

- Trigger configuration:
 - ✓ total energy sum in calorimeter: $\Sigma E_{\text{clust}} > 0.7 \times E_{\text{beam}}$
 - ✓ 3 clusters in PbWO₄ calorimeter;
 - ✓ each cluster energy: $30 \text{ MeV} < E_{\text{clust}} < 0.8 \times E_{\text{beam}}$ (rejects the elastic scattered electrons)
- Large phase space for virtual photon, γ^* :
 - ✓ energy interval: $E_{\gamma^*} \approx [0.2 - 0.8] E_{\text{beam}}$;
 - ✓ $\vartheta_{e'}$ $\approx [0.4^\circ - 3.7^\circ]$ angular range.
 - ✓ provides X-particle production in wide energy spectrum and in forward solid angle
- Target to detector distance: $L = 7.5 \text{ m}$ provides good (integrated) detection efficiency in [3 - 60] MeV mass range for $E_e = 2.2, 3.3$ and 4.4 GeV .
- $E_e = 2.2$ and 3.3 GeV were chosen for relative ease of scheduling during CEBAF low-energy runs.



Experimental Resolutions

- Good energy resolution of PbWO_4 calorimeter (2.6% @ $E=1$ GeV) and $1 \mu\text{m}$ thin target provides powerful energy selection cut in this experiment ($\Delta E = 47$ MeV @ 3.3 GeV beam).



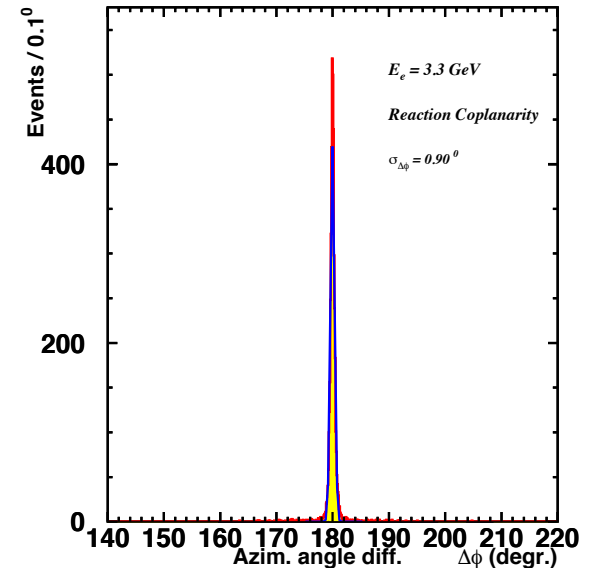
- ✓ important selection criterion for multi-channel and; accidental events;
- ✓ critical cut at low-mass range (see next slides).

- Coplanarity (between $\vec{P}_{e'}$ and $(\vec{P}_{e^+} + \vec{P}_{e^-})$ vectors): ($\vartheta_{\Delta\phi} = 0.90^\circ$)



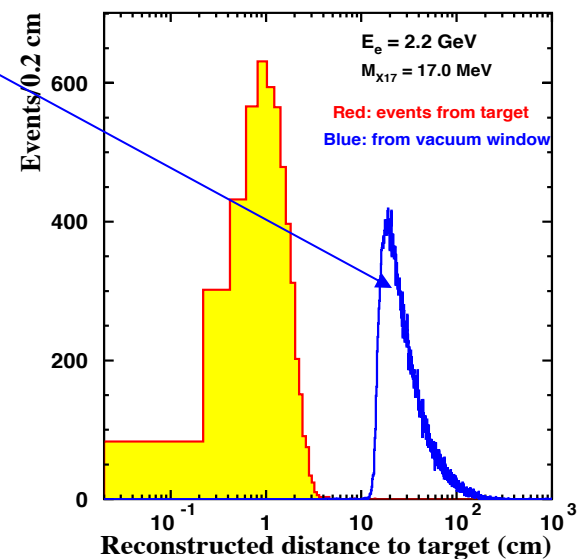
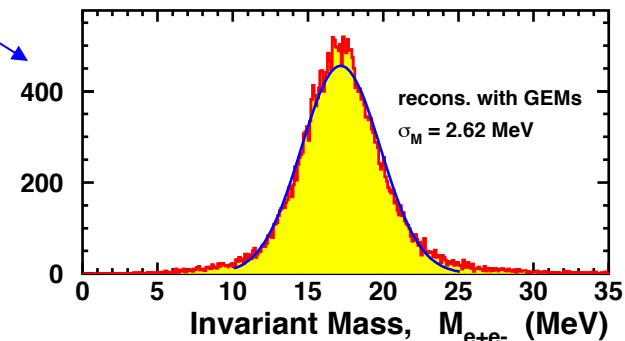
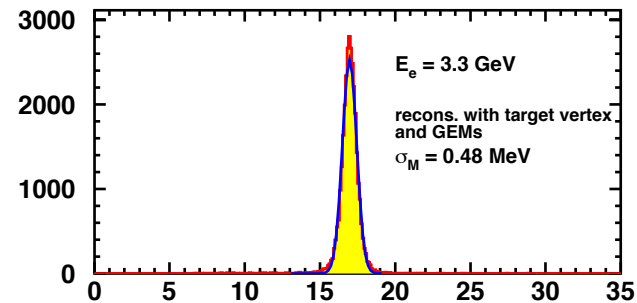
GEMs excellent position resolution ($\sigma = 72 \mu\text{m}$), together with very thin $1 \mu\text{m}$ target (2.4×10^{-4} r.l.) provides event selection criterion ($\vartheta_{\Delta\phi} = 0.90^\circ$), important for:

- ✓ multi-particle and;
- ✓ accidental coincidence events.



Experimental Resolutions (invariant mass and vertex reconstruction)

- Invariant mass reconstruction (in **two ways**):
 - ✓ with **vertex, GEMs and PbWO₄** calorimeter, $\sigma_m = 0.48$ MeV for X17 particle;
 - ✓ with **GEMs and PbWO₄** calorimeter (**no vertex**). This will be used to check if the “peak events” are coming from the target.
- Two GEM planes (with PbWO₄) will effectively discriminate events not originating from the target (for example, from the vacuum chamber exit window).
- However, in this experiment the GEMs are not designed to measure the “decay length”. This is not a “displaced vertex” search experiment.



Physics Background Simulations

- Physics background was simulated in **two different** ways:
 - 1) GEANT4 based MC simulation package.
 - 2) **MADGRAPH5 EM event generator** and GEANT4 for secondary interaction and tracking.
 - Including trident processes
 - a) **Bethe-Heitler**
 - b) **Radiative and**
 - c) **Interference between them**

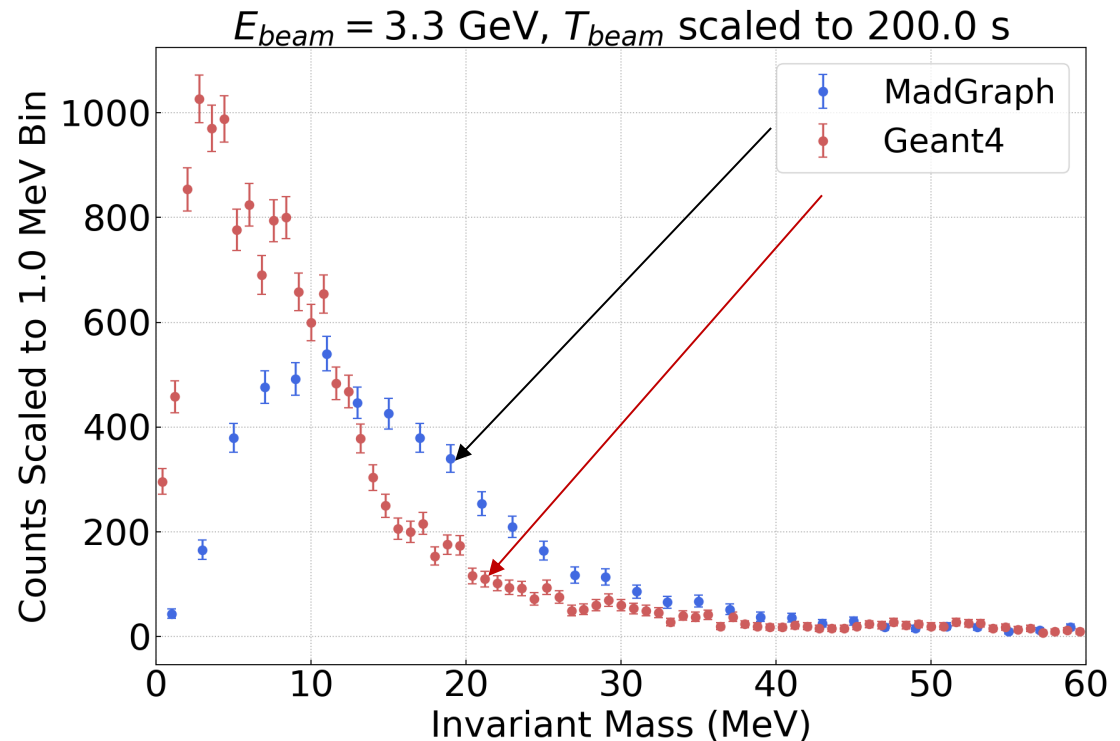
- 1) **GEANT4** based Monte Carlo background simulations:
 - ✓ PRad experimental setup was adapted for these simulations;
 - ✓ all physics processes had been activated in GEANT;
 - ✓ large amount of beam electrons passed through the target;
 - ✓ events with $N_{\text{cluster}} \geq 3$ were analyzed in the same way as the signals.

- 2) **MadGraph5** EM event generator-based background simulations:
 - ✓ large statistics (~2M) **trident events**;
 - ✓ these events were fed into the GEANT MC simulation package;
 - ✓ same analysis procedure was applied for these events.

Physics Background Simulations

(comparison between MadGraph5 and GEANT4 results)

- GEANT4 with full setup, with all physics processes included
- MadGraph5 + GEANT4 for tracking
 - ✓ consistent results at large mass range;
 - ✓ more GEANT4 events at very low mass range; (small angle scattering effects);
 - ✓ factor of 2 difference at middle masses, showing that:
 - the experiment is more sensitive to basic EM processes;
 - MadGraph5 is more advanced EM event generator than those used in GEANT.



Physics Background Simulations (Hybrid Method) (GEANT4 without BH + MadGraph5)

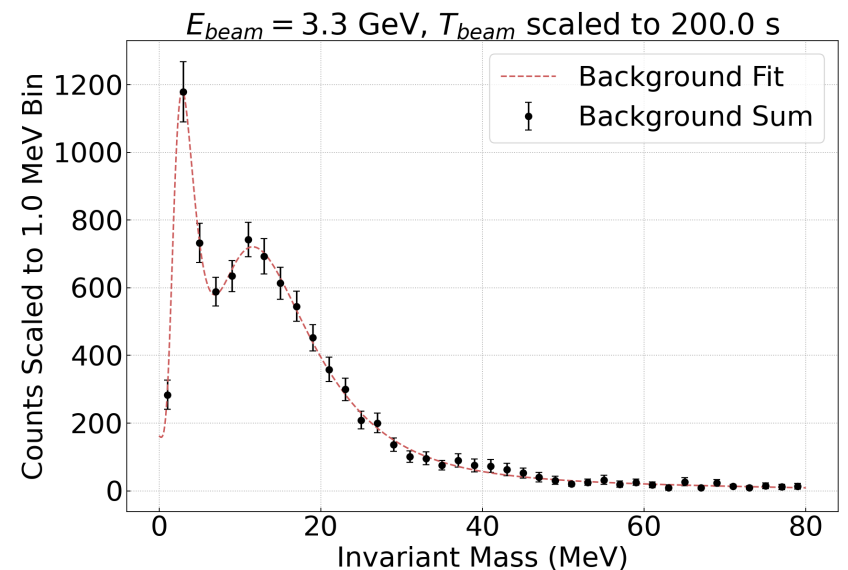
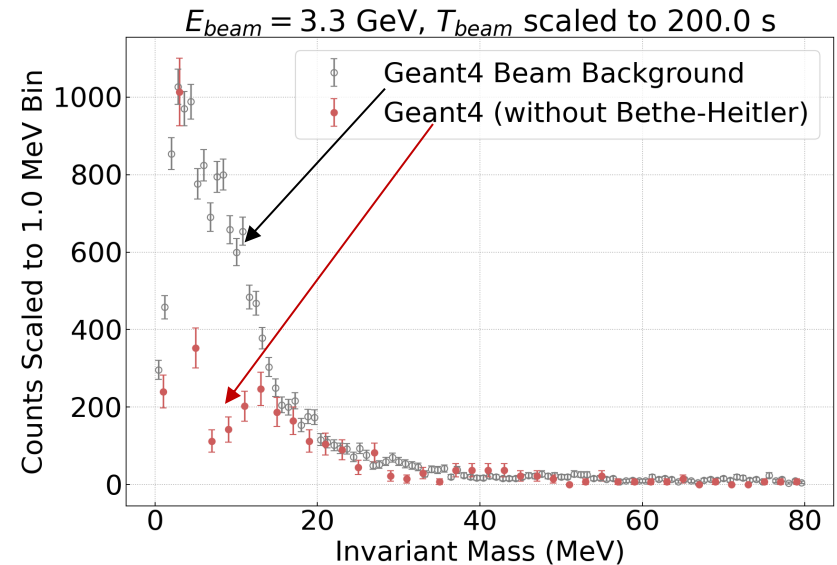
Therefore, we combined:

✓ GEANT4 without the Bethe-Heitler process activated;



✓ and summed with the results simulated with the full MadGraph5 event generator.

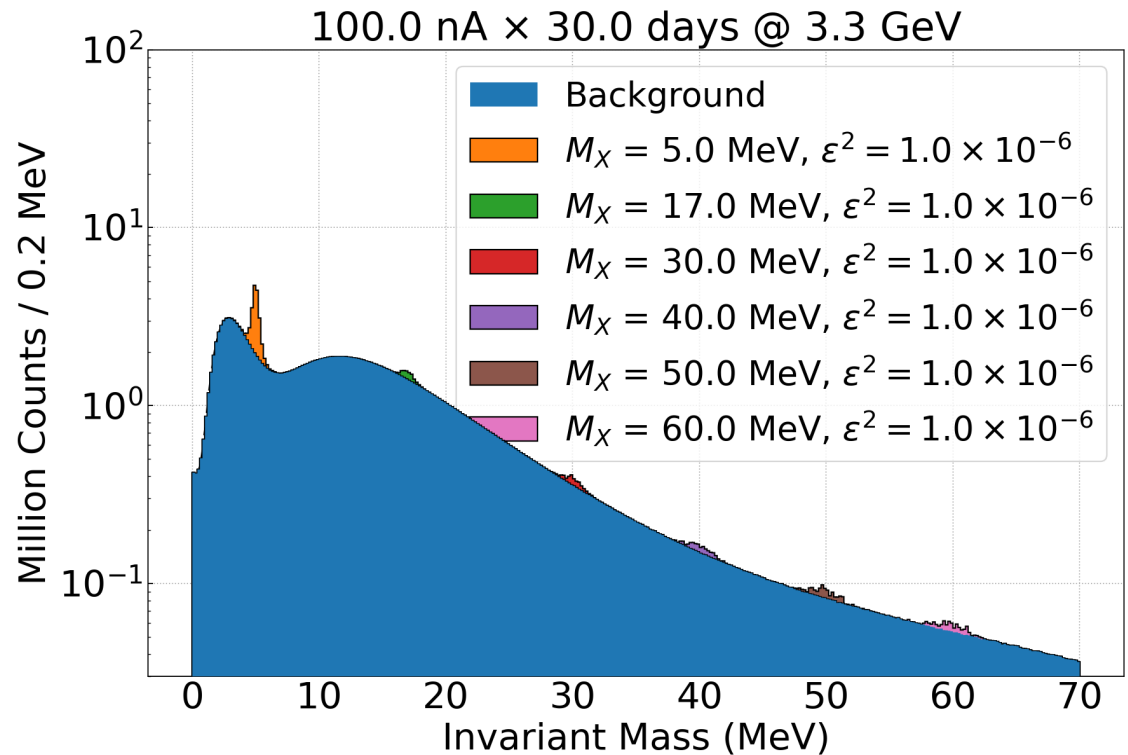
The resulting background shape was fit with:
Landau + Log + constant terms.



Physics Background Simulations (Hybrid Method)

(fit and scaled to the beam time)

- The simulated hybrid background was scaled to 30 days of beam time, with $I_e = 100 \text{ nA}$, $1 \mu\text{m Ta}$ target
- projected signal events with $\epsilon^2 = 1.0 \times 10^{-6}$ (for illustration purposes only)



Beam Time and Statistics

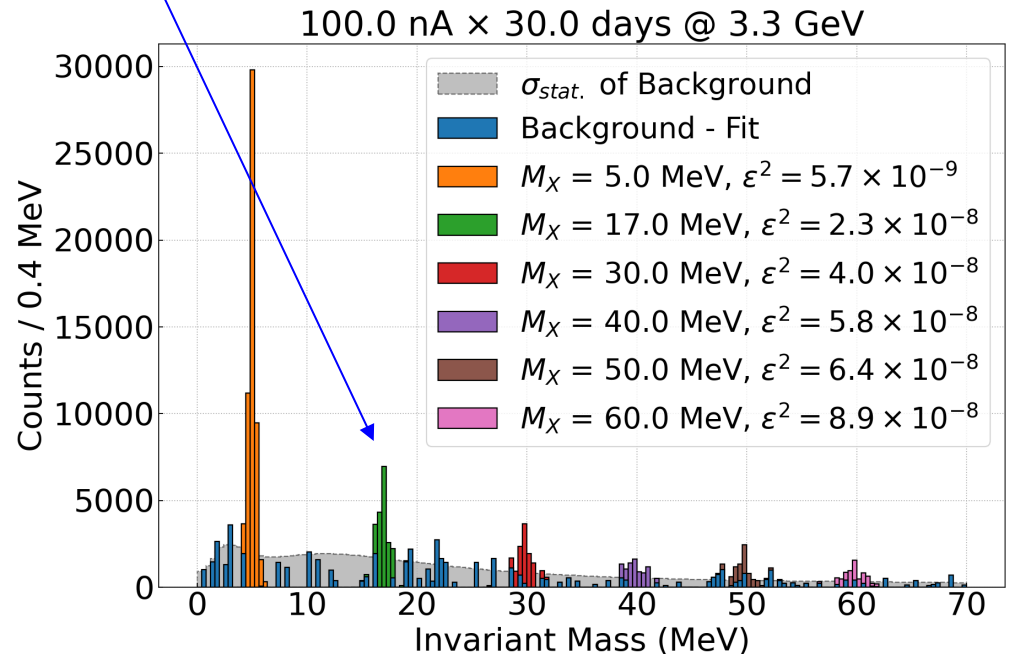
- Target: Ta; thickness: 1 μm ($t = 2.4 \times 10^{-4}$ r.l.), $N_{\text{tgt}} = 0.56 \times 10^{19}$ atoms/cm²
for $E_e = 3.3$ GeV and $I_e = 100$ nA ($N_e = 6.25 \times 10^{11}$ e⁻/s),

Example: the estimated X17 production rate (J. D. Bjorken, et al. Phys. Rev. D, 80:075018. 2009):

$$N_{X17} \sim N_C * N_e * t * \varepsilon^2 * (m_e/m_x)^2$$

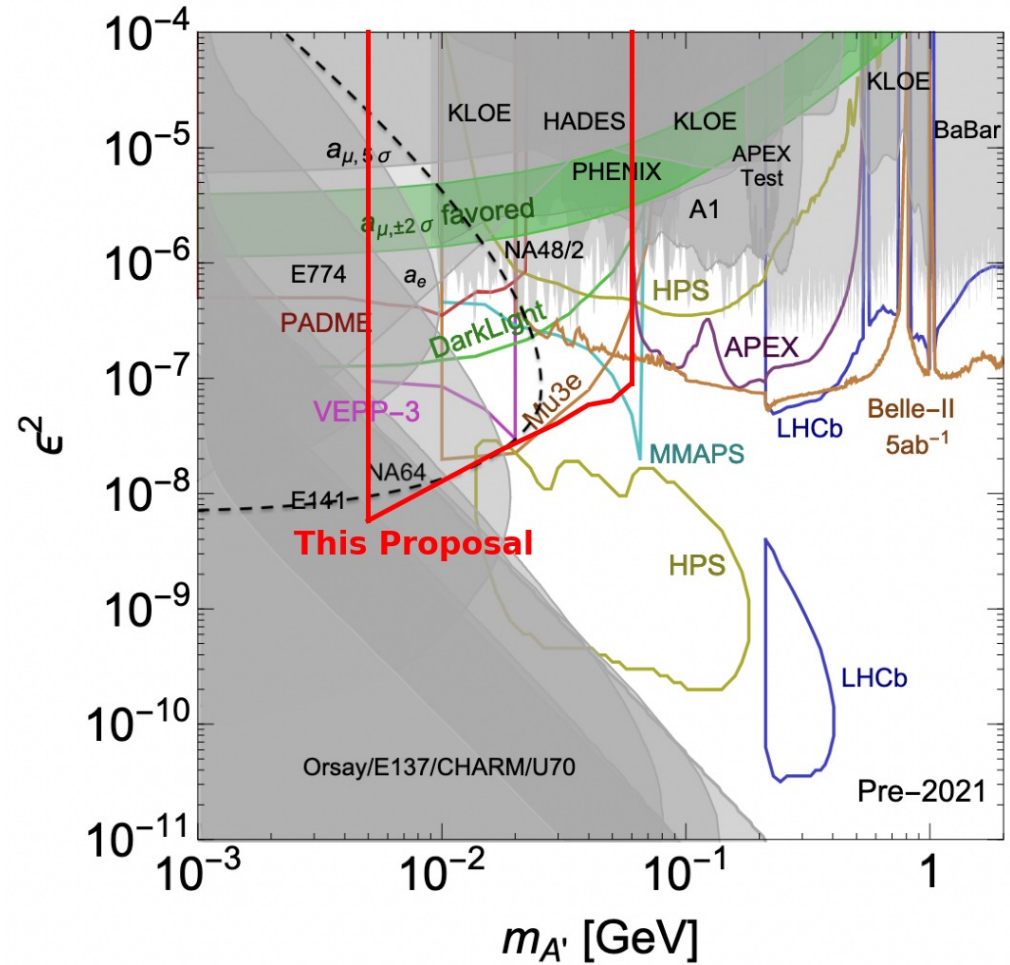
≈ 32 K produced events per 30 days for $\varepsilon^2 = 2.3 \times 10^{-8}$ ($N_C = 5$)

	Time (days)
Setup checkout, calibration	4.0
Production at 2.2 GeV, 50 nA	20.0
Production at 3.3 GeV, 100 nA	30.0
Energy change	0.5
Empty target runs	5.5
Total	60



ε^2 vs. Mass Parameter Space

- Invariant mass range: [3 -- 60] MeV
- Coupling constant: $\varepsilon^2 \approx [10^{-8} - 10^{-7}]$
- This proposal uses **5 σ limits** (discovery criterion as per PDG), while the **2 - 2.4 σ** limit is common used in many other experiments.



Summary

- We have designed a cost-effective, **ready-to-run experiment** to:
 - a) validate existence or set an experimental upper limit on a search for hypothetical X17 particle (up to $\varepsilon^2 \approx 1.9 \times 10^{-8}$ level);
 - b) search for hidden sector new particles in [3 ÷ 60] MeV mass range.
- It is a non-magnetic experiment with the **detection of all 3 final state particles**, providing a tight control of background, reaching to a low range in coupling constant:
 $\varepsilon^2 \approx [10^{-8} - 10^{-7}]$ range.
- It is sensitive to both charged ($X \rightarrow e^+e^-$) and neutral ($X \rightarrow \gamma\gamma$) decay channels.
- The experiment was approved by PAC50 in July, 2022, we expect to run in **2023-24**.

my research work is supported in part by NSF award: PHY-1812421

Backup Slides

$X \rightarrow \gamma\gamma$ Decay Channel

The **approach of this experiment**:

- The current design of the experiment is focused/optimized on the $X \rightarrow e^+e^-$ channel detection, providing a maximum resolution for e^+e^- invariant mass determination (**no converters on front of GEMs**).

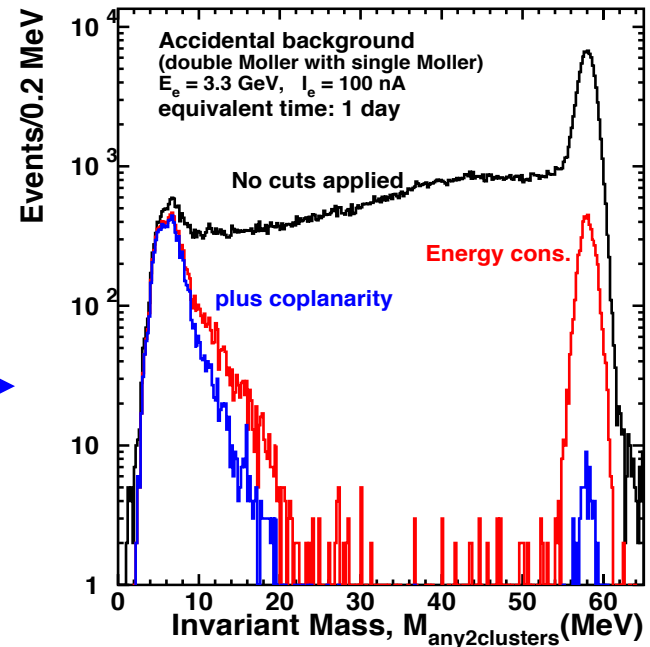
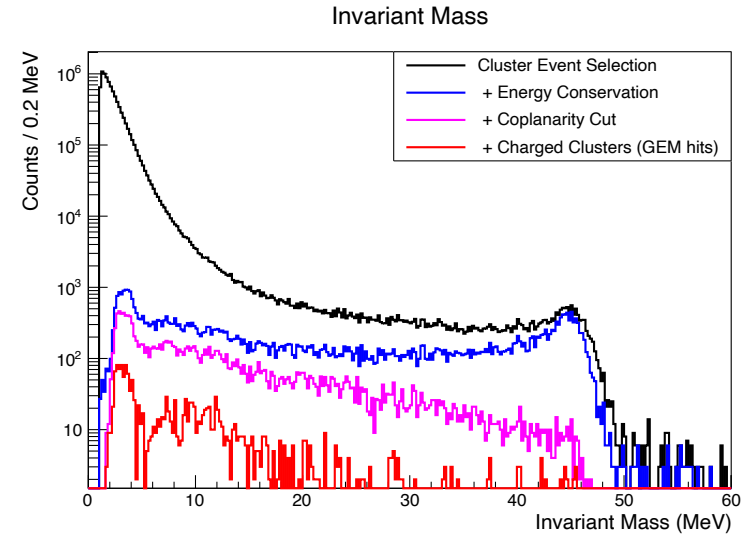
However, with this design:

- ✓ the $\gamma\gamma$ decay photons **will also be detected** by the PbWO_4 crystal part of HyCal (providing measurement of each photons **energy and position**).
 - ✓ both GEMs will act as veto detectors.
 - ✓ assuming the vertex origin (the target) that will provide reconstruction of the $\gamma\gamma$ invariant mass with $\approx 3 \text{ MeV}$ resolution.
 - ✓ **still providing an effective “bump hunting” search for the $X \rightarrow \gamma\gamma$ channel.**
- In case of any experimental indication of a “signal”, or for the second stage of this experiment **we will develop a new experimental proposal** focusing on the **neutral decay channels**:
 - ✓ add a converter on front of second GEM. The first GEM will still play as a veto detector.
 - ✓ the second GEM will effectively provide the positions and directions of the decay photons by detection the converted charged EM particles.
 - ✓ providing significantly approved $\gamma\gamma$ invariant mass determination (by a **factor of 2**).

Event Selection Criteria

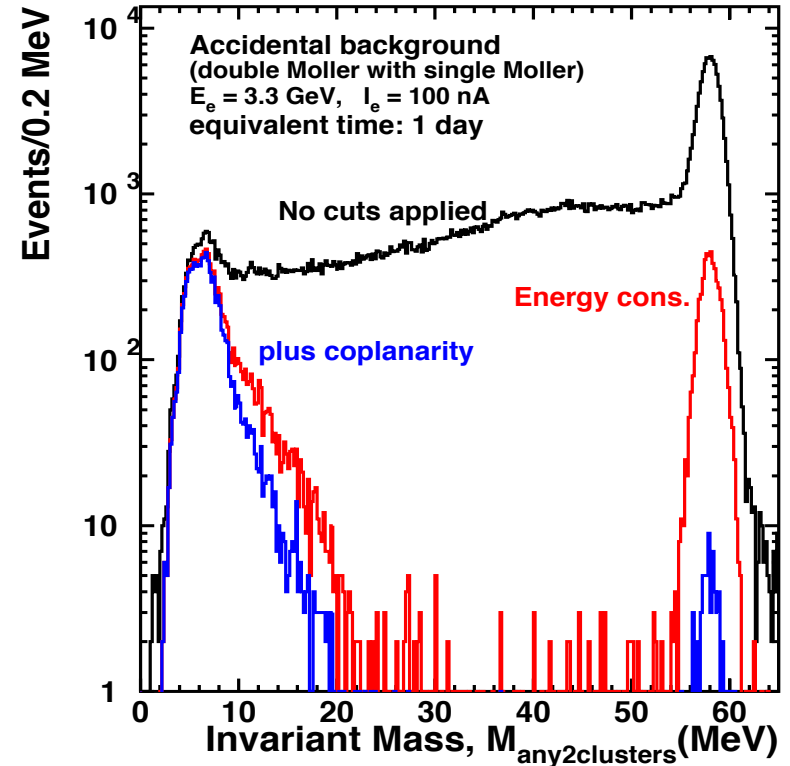
- Detection of all 3 final state particles provides following event selection criteria:
 - ✓ conservation of total energy;
 - ✓ reaction coplanarity;
 - ✓ invariant mass;
 - ✓ particles charge;
 - ✓ reconstructed position on target plane.
- Important feature of this experiment.
- Effects of these “cuts” are shown for PRad short test run on ^{12}C target.

... and for MC accidental events simulated for this experiment.



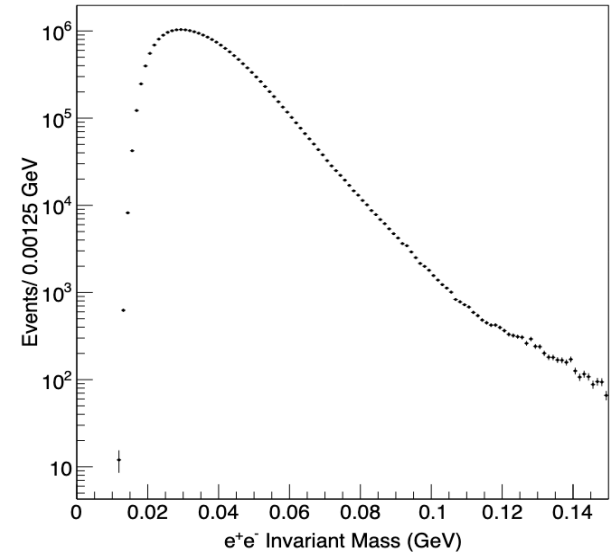
Accidental Background (Accidental Coincidence Rate)

- Hardware trigger requires **3-cluster events**:
 - ✓ $N_{\text{cluster}} \geq 3$
 - ✓ each one within: $30 \text{ MeV} < E_{\text{cluster}} < 0.8x E_{\text{beam}}$
 - ✓ $E_{\text{total}} > 0.7x E_{\text{beam}}$
- Two high-rate processes in this experiment are:
 - ✓ electron-nucleus (Rutherford) elastic scattering (trigger will effectively suppress these events).
 - ✓ Moller scattering (source of major accidentals).
- Estimated rates for two main sources are:
 - ✓ singles from Moller: Rate $\approx 107 \text{ kHz}$
 - ✓ doubles from Moller: Rate $\approx 81.7 \text{ kHz}$
- Assuming 2 ns time resolution (bunch size):
 - ✓ accidental coincidence rate: $\approx 17 \text{ Hz}$
 - ✓ is not significant background contribution.



Other Similar Experiments/Projects at JLab

- **HPS** (running experiment at JLab)
 - ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'} = [20-1000]$ MeV;
 - ✓ magnetic spectrometer method;
 - ✓ only e^+e^- detected, $\varepsilon^2 > 10^{-7}$;
 - ✓ with displaced vertex detection: $10^{-8} \leq \varepsilon^2 \leq 10^{-10}$



HPS: [hep-ex] arXiv:1807.11530, 2018

- **APEX** (running experiment at JLab)
 - ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'} = [65-525]$ MeV;
 - ✓ magnetic spectrometer method;
 - ✓ only e^+e^- detected, $\varepsilon^2 > 9 \times 10^{-8}$;

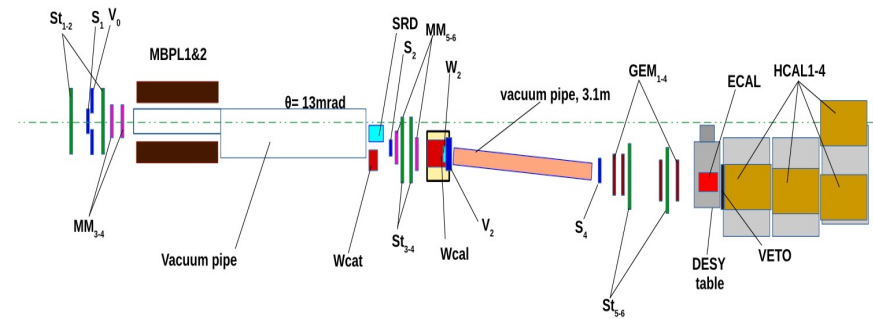
- **DarkLight** (approved JLab experiment)
 - ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'} = [10-90]$ MeV;
 - ✓ magnetic spectrometer method;
 - ✓ e^+e^- detected, $\varepsilon^2 > 3 \times 10^{-7}$;

- The proposed experiment:
 - ✓ non-magnetic, will detect all 3 particles, e', e^+, e^-
 - ✓ search for $X \rightarrow e^+e^- (\gamma\gamma)$ in $M_X = [3 - 60]$ MeV;
 - ✓ similar range: $10^{-7} \leq \varepsilon^2 \leq 10^{-9}$
 - ✓ sensitive to neutral channels.

Other Similar Experiments/Projects

- **NA64** (experiment and new proposal with SPS at CERN)

- ✓ combination of “beam dump” and direct e^+e^- detection;
- ✓ first EM calorimeter is an active “dump” (~40 r.l.), second EM detects e^+e^- pairs;
- ✓ assumes relatively long decay length for A' (or X);
- ✓ total energy conservation;
- ✓ mass range: ≤ 23 MeV,
- ✓ experiments in 2018 and 2020:
 $1.4 \times 10^{-8} \leq \varepsilon^2 \leq 4.6 \times 10^{-7}$ (90% confidence limit)
- ✓ new proposal for 2021.



- **MAGIX** (proposed experiment with MESA at Mainz)

- ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'} = [8 - 70]$ MeV;
- ✓ magnetic spectrometer method;
- ✓ only e^+e^- detected, $\varepsilon^2 \approx [2 \times 10^{-7} - 8 \times 10^{-9}]$