Search for Hidden Sector New Particles in the 3-60 MeV Mass Range: Focusing on the Hypothetical X17 Particle

(JLab Experiment E12-21-003)

A. Gasparian
NC A&T State University, NC USA

for the PRad/X17 collaboration

Co-spokespersons: A. Gasparian, D. Dutta, H. Gao, N. Liyanage, T. Hague, C. Peng, R. Paremuzyan

Outline

- physics goals
- experimental method
- experimental setup and sensitivities
- estimated background and physics reach
- current status
- summary and outlook

Physics Goals of the Experiment

- Most of cosmological observations suggest that:
  - ✓ ≈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 ^{8}Be and ^{4}He decay spectrum (ATOMKI anomaly, → 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 ^{8}Be and ^{4}He Experiments (Anomalies)

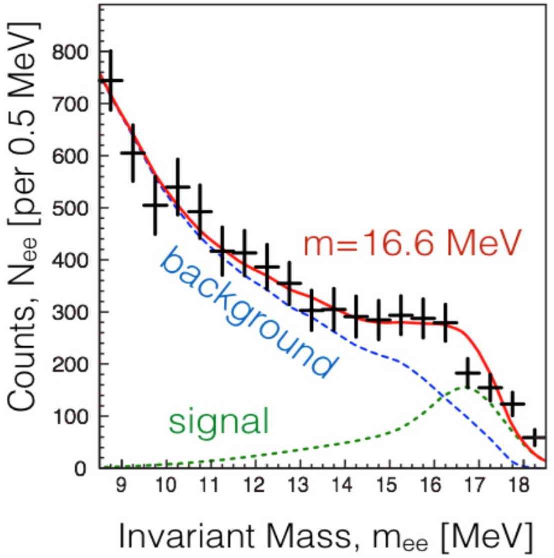
- ^{8}Be anomaly in nuclear transitions (*PRL 116(4):042501 (2016)*):
  - ✓ ^{8}Be excited states, decaying to ground state by E/M transitions.

  $p + {}^7Li \rightarrow {}^8Be^* \rightarrow 7Li + p$ (hadronic decay)

  $\rightarrow {}^8Be + \gamma$ (E/M decay)

  $\rightarrow {}^8Be + \gamma^*,\ \gamma^* \rightarrow e^+e^-$ (IPC)

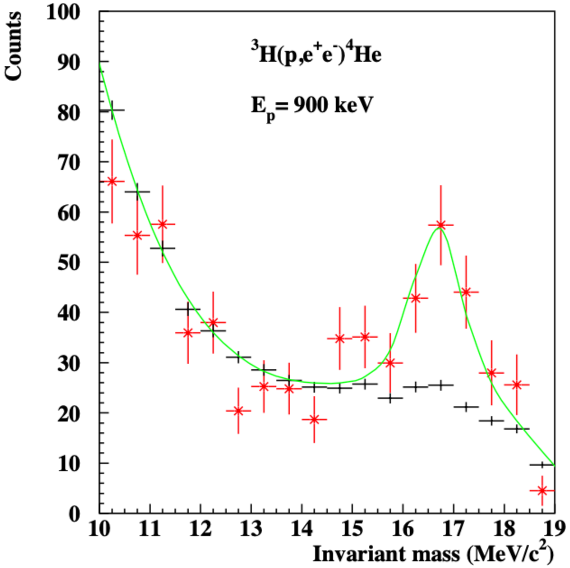
✓ excess of e^+e^- pairs in angular distributions (inv. mass) beyond the expectation of the Internal Pair Conversion (IPC).



- Second experiment on ^{4}He with updated experimental setup and reduced background:

  $p + {}^3H \rightarrow {}^4He^* + \gamma \rightarrow {}^4He + \gamma^*,\ \gamma^* \rightarrow e^+e^-$ (IPC)
  - ✓ e^+e^- peak at different angles but the same invariant mass.

  published in: Phys. Rev. C 104 (2021) 4, 044003



ATOMKI ^{12}C Experiment

- ^{12}C anomaly in nuclear transitions (J. Krasznahorkay et al., Phys. Rev. C. 106, L061601, (2022))
  - ✓ ^{12}C excited states, decaying to ground state by E/M transitions:

$$p + {}^{11}B \rightarrow {}^{12}C^{*} + \gamma^{*},\ \ \gamma^{*} \rightarrow e^{+}e^{-}\ \text{(IPC)}$$

✓ excess of e^+e^- pairs in angular distributions (inv. mass) beyond the expectation of the Internal Pair Conversion (IPC).

"… Our results suggest that the X17 particle was generated mainly in E1 radiation. The derived mass of the particle is $M_X = 17.03 \pm 0.11(\text{stat}) \pm 0.20(\text{syst})$ MeV. According to the mass, and to the derived branching ratio (Bx = 3.6(3)Å~10−6), this is likely the same X17 particle that we recently suggested for describing the anomaly observed in the decay of ^{8}Be and 4He.…"

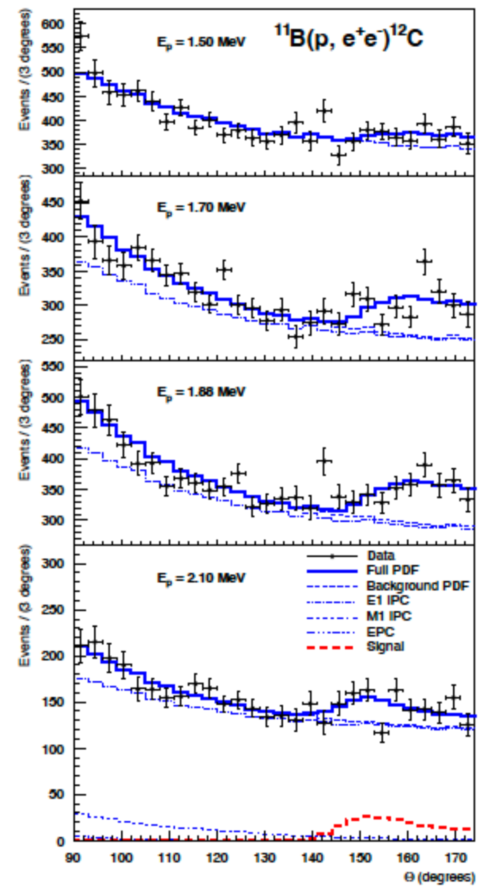


FIG. 4. Experimental angular correlations of the e^+e^- pairs measured at different proton energies. The full curves for each proton energy shows the results of the fit, using simulated angular distributions.

- No independent experimental confirmation so far!

- **Requires an urgent independent experimental validation.**

Objectives of this Experiment

- 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 the 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).

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

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:

$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta$, with $X \rightarrow e^+e^-$ (with tracking)
and $X \rightarrow \gamma\gamma$ (without tracking)

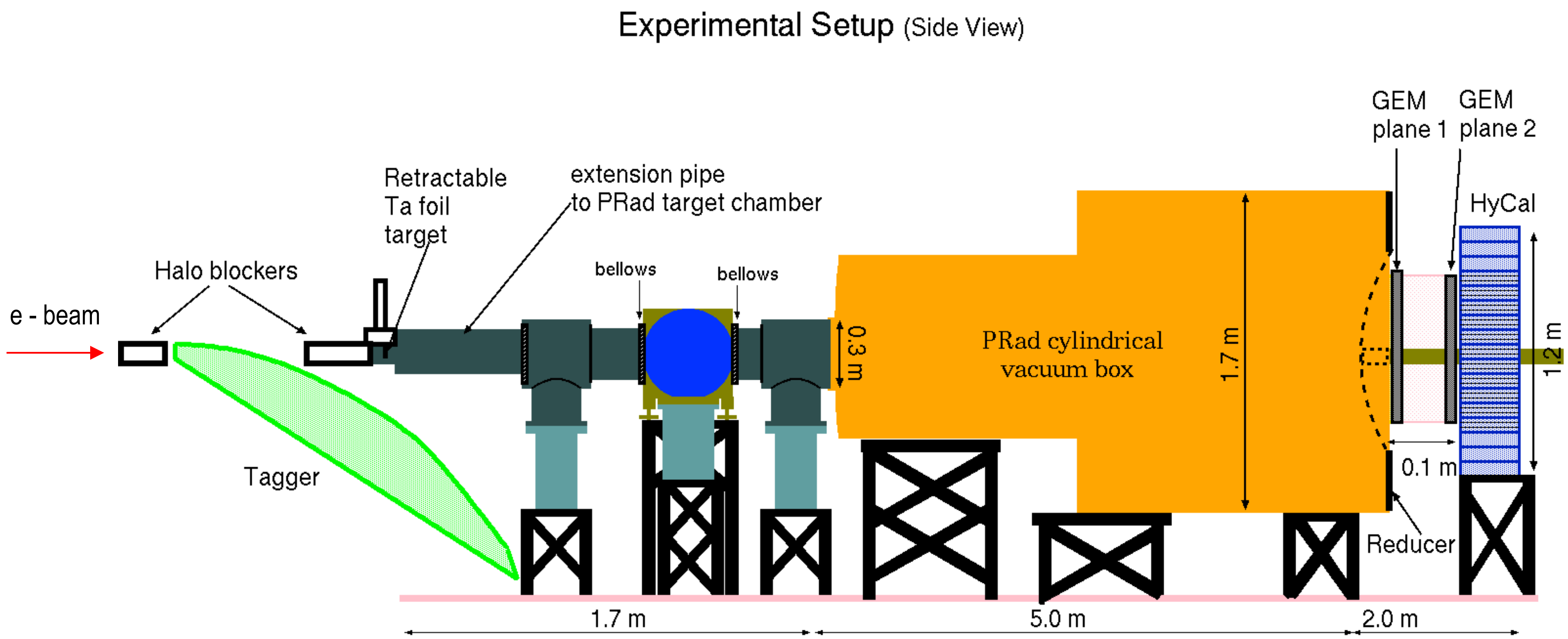
in mass range of: [3 - 60] MeV
target: Tantalum, $({}_{73}Ta^{181})$, 1 μm ($2.4\text{x}10^{-4}$ r.l.) thick foil.

- 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).

- That will provide a tight control of experimental background.

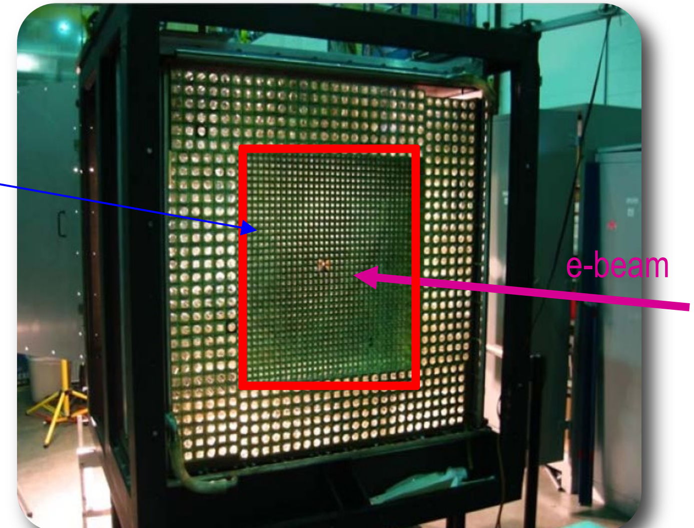
Experimental Setup in Hall B at JLab

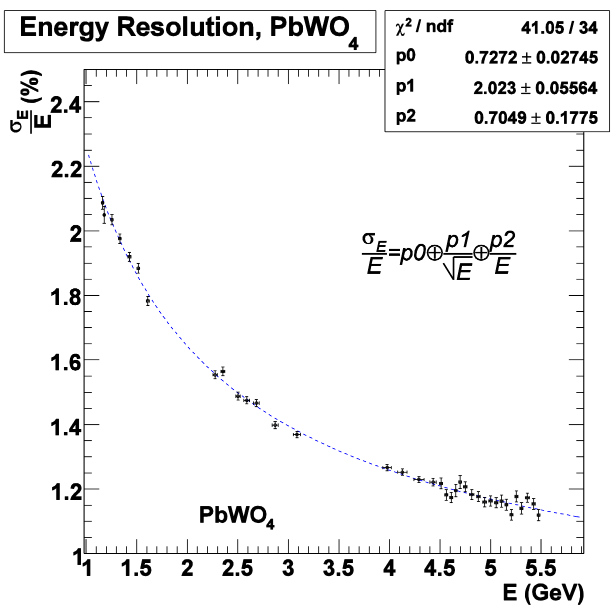
- Experimental setup is based on the PRad-II apparatus (see D. Dutta's presentation on PRad-II experiment)
  - Hall B Photon Tagger will be used for $PbWO_4$ calorimeter gain equalization and initial calibration
  - 1 μm $_{73}Ta^{181}$ solid targets (2.4×10^{-4} r.l.) will be placed on the target ladder (Harp);
  - 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.

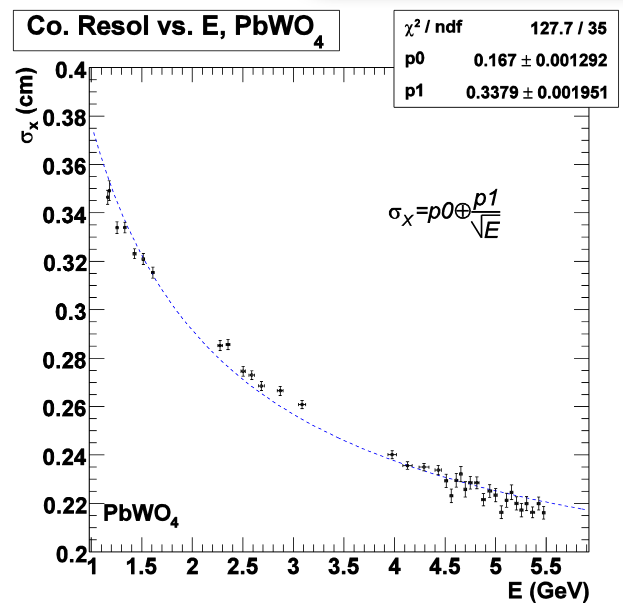


Experimental Apparatus: $PbWO_4$ Electromagnetic Calorimeter

- Only the inner $PbWO_4$ part of HyCal will be used:
  - ✓ 34 x 34 =1156 crystal modules, each with 2x2x18 cm^3;
  - ✓ with 68 x 68 cm^2 total detection area;
  - ✓ 2x2 crystals are removed from center for beam passage



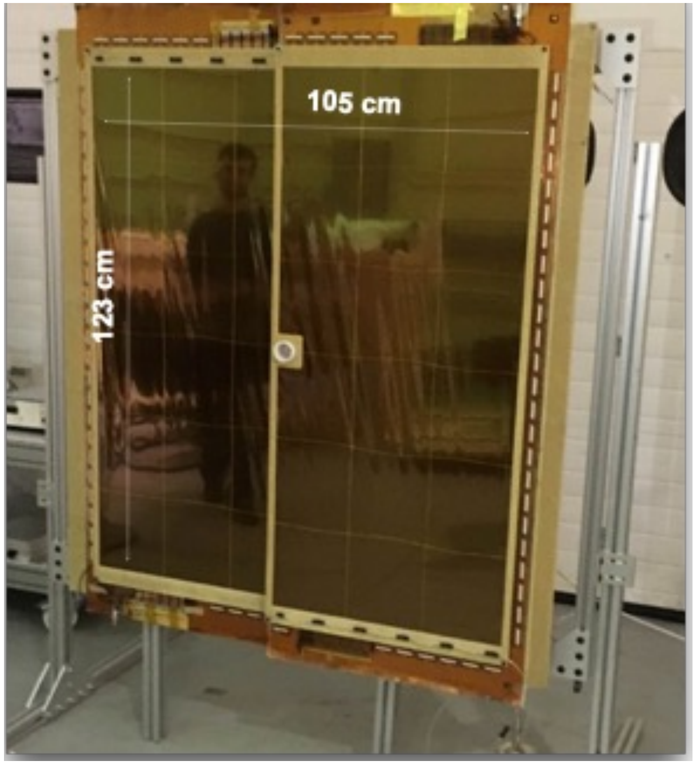




Experimental Apparatus: GEM Coordinate Detectors (Tracking)

- Two planes of GEM detectors for tracking:
  - ✓ similar to PRad-II GEMs but smaller size;
  - ✓ located on front of $PbWO_4$, after the vacuum window;
  - ✓ relative distance (40 cm), optimized between resolution and available material after the vacuum window;
  - ✓ good position resolution (σ=72 μm);
  - ✓ will veto neutral particles for $X \rightarrow e^+e^-$ channel and veto the charged particles for $X \rightarrow \gamma\gamma$ channels.

- Electronics: APV-25 based readout system.
  (UVA group is responsible for the GEMs)



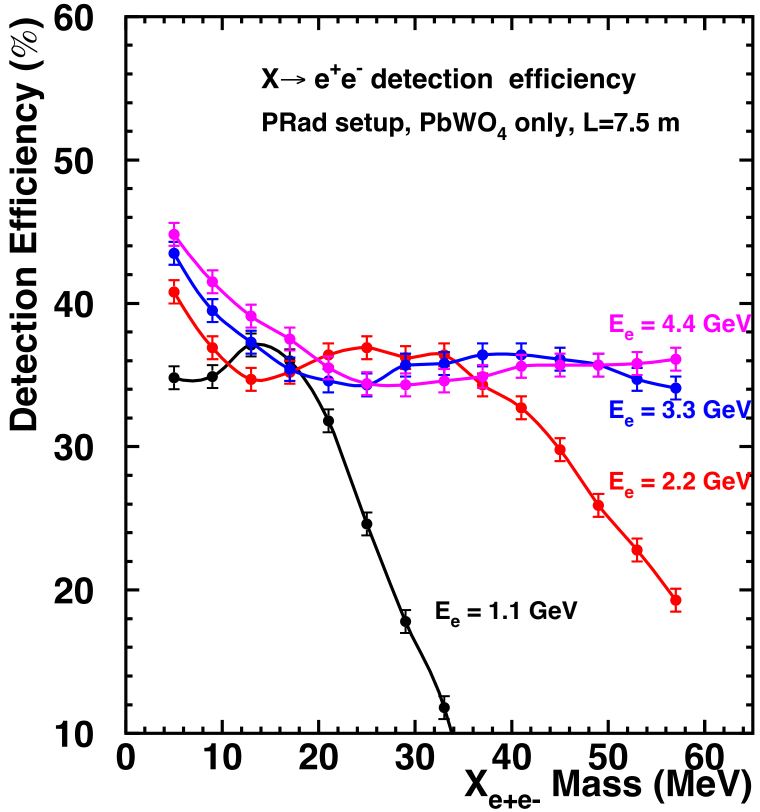
PRad GEMs

Geometrical Acceptance (Detection Efficiency)

- Trigger configuration:
  - ✓ total energy sum in calorimeter: $\Sigma E_{clust} > 0.7xE_{beam}$
  - ✓ 3 clusters in $PbWO_4$ calorimeter;
  - ✓ each cluster energy: 30 MeV $< E_{clust} < 0.8xE_{beam}$ (rejects the elastic scattered electrons)

- Large phase space for virtual photon, γ^*:
  - ✓ energy interval: $E_{\gamma^*} \approx [0.2 - 0.8]\ E_{beam}$;
  - ✓ $\vartheta_{e'} \approx [0.4^0 -- 3.7^0]$ angular range.
  - ✓ provides X-particle production in wide energy spectrum and in forward solid angle

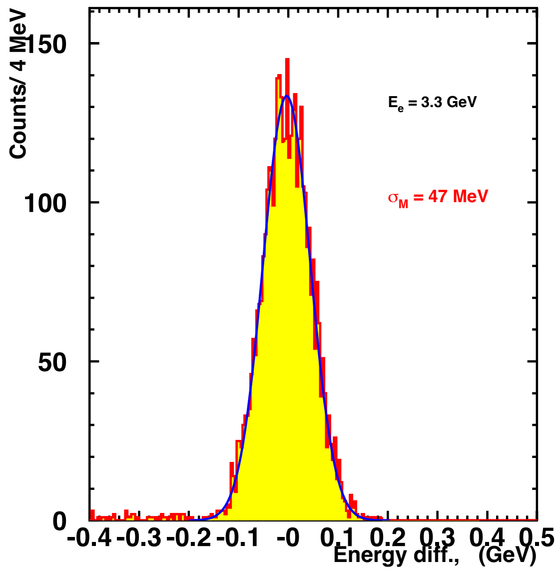
- Target to detector distance: L = 7.5 m provides good (integrated) detection efficiency in [3 - 60] MeV mass range.



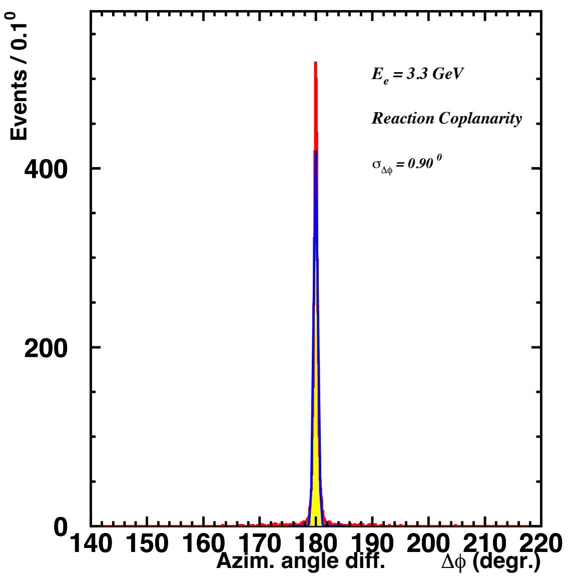
- E_e = 2.2 and 3.3 GeV were chosen for relative ease of scheduling during CEBAF low-energy runs.

Experimental Resolutions

- Good energy resolution of $PbWO_4$ calorimeter (2.6% @ E=1 GeV) and 1 μm thin target provide powerful energy selection cut in this experiment (ΔE = 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 $\overrightarrow{P_{e'}}$ and ($\vec{P}_{e+} + \vec{P}_{e-}$) vectors): ($\vartheta_{\Delta\varphi} = 0.9^0$)
  GEMs excellent position resolution (σ = 72 μm), together with very thin 1 μm target (2.4×10^{-4} r.l.) provides event selection criterion ($\vartheta_{\Delta\varphi} = 0.9^0$), important for:
  - ✓ multi-particle and;
  - ✓ accidental coincidence events.

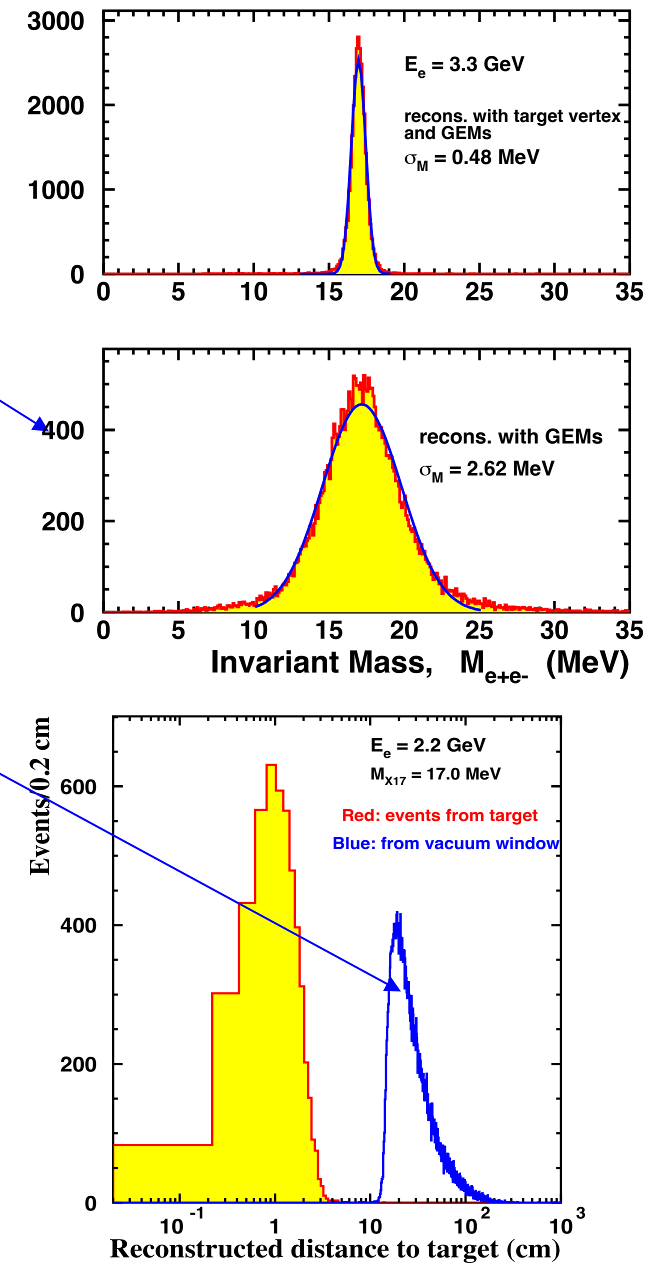


Experimental Resolutions (invariant mass and vertex plane)

- Invariant mass reconstruction (in two ways):
  - ✓ with vertex, GEMs and $PbWO_4$ calorimeter, σ_m =0.48 MeV for X17 particle;
  - ✓ with GEMs and $PbWO_4$ calorimeter (no vertex). This will be used to check if the "peak events" are coming from the target.

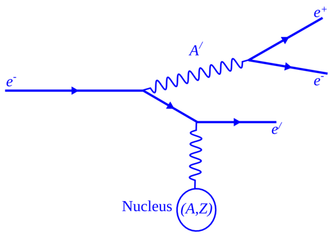
- Two GEM planes (with $PbWO_4$) will effectively discriminate events not originating from the target (for example, from the vacuum chamber exit window).

- However, in this experiment the GEMs are not designed to measure the "decay length". This is not a "displaced vertex" search experiment.



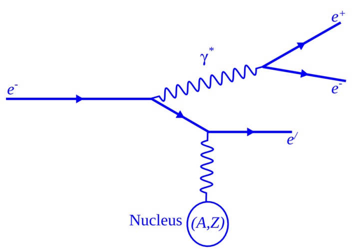
Physics Background Simulations

- 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



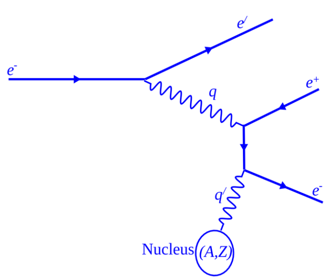
X production channel

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 $N_{cluster} \geq 3$ were analyzed in the same way as the signals.



Rad tridents

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.



Bethe-Heitler

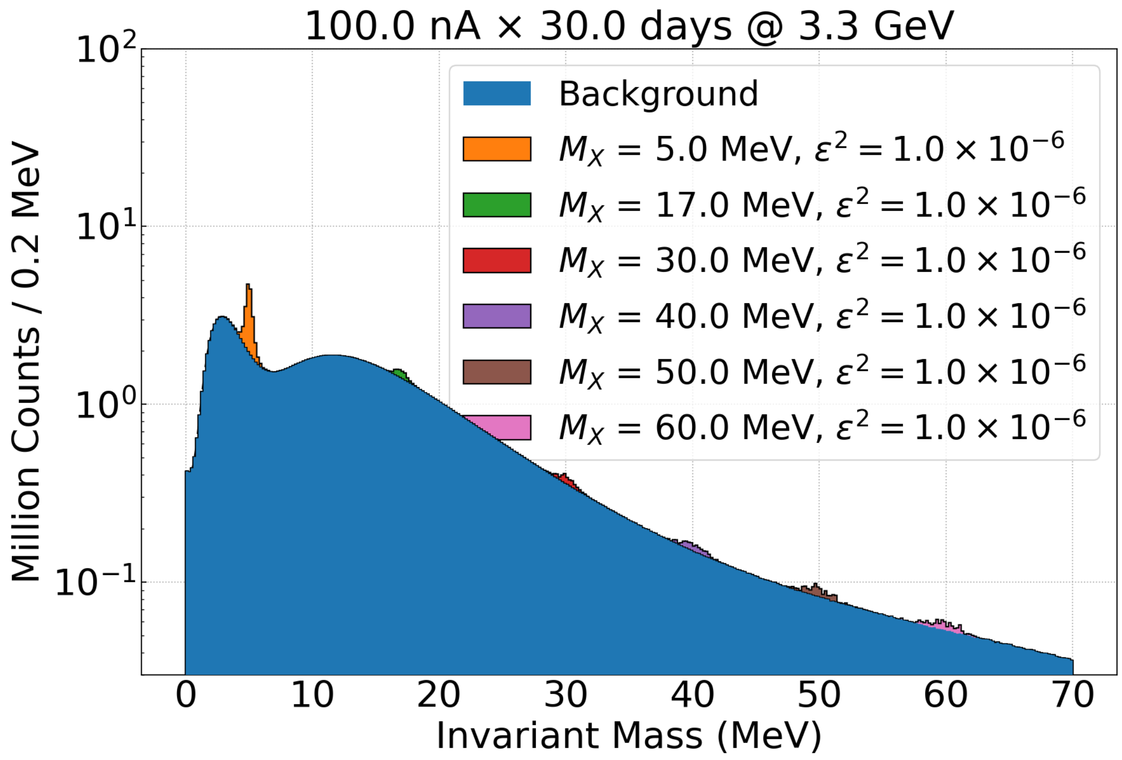
Physics Background Simulations

(fit and scaled to the beam time, with $\varepsilon^2 = 1.0\text{x}10^{-6}$)

(for illustration purposes only)

- The simulated hybrid background was scaled to 30 days of beam time, with I_e = 100 nA, 1 μm $_{73}Ta^{181}$ target

- projected signal events with $\varepsilon^2 = 1.0\text{x}10^{-6}$



Beam Time and Statistics

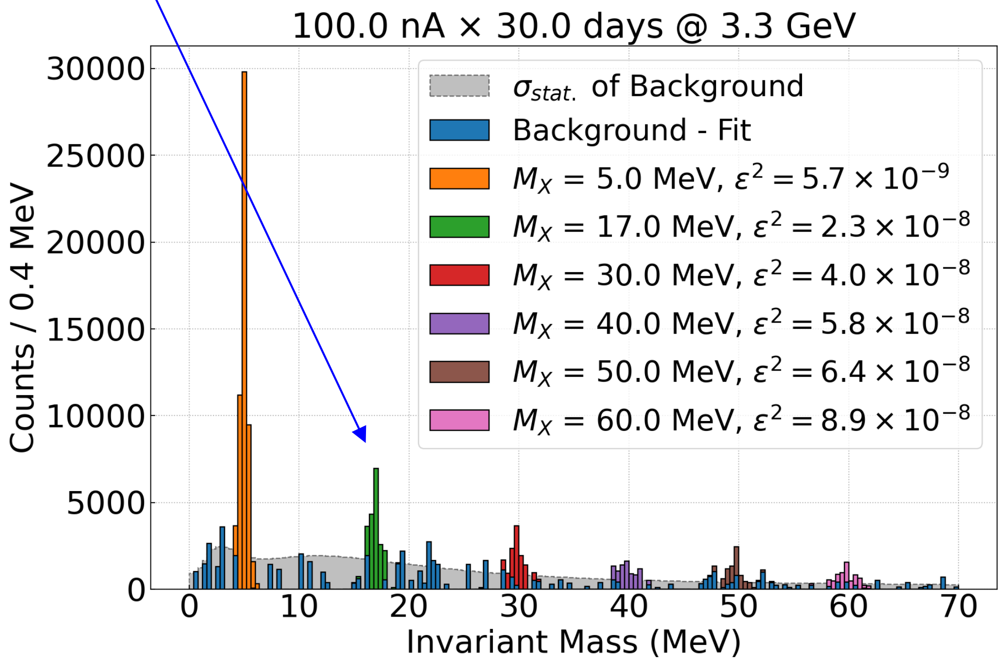
- Target: $_{73}Ta^{181}$; thickness: 1 μm (t = 2.4×10^{-4} r.l.), $N_{tgt} = 0.56 \times 10^{19}$ atoms/cm^2
  for E_e = 3.3 GeV and I_e = 100 nA ($N_e = 6.25 \times 10^{11}$ e$^-$/s),

  Example: the estimated X17 production rate (vs. 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



Physics Reach: Parameter Space (ε^2 vs. Mass)

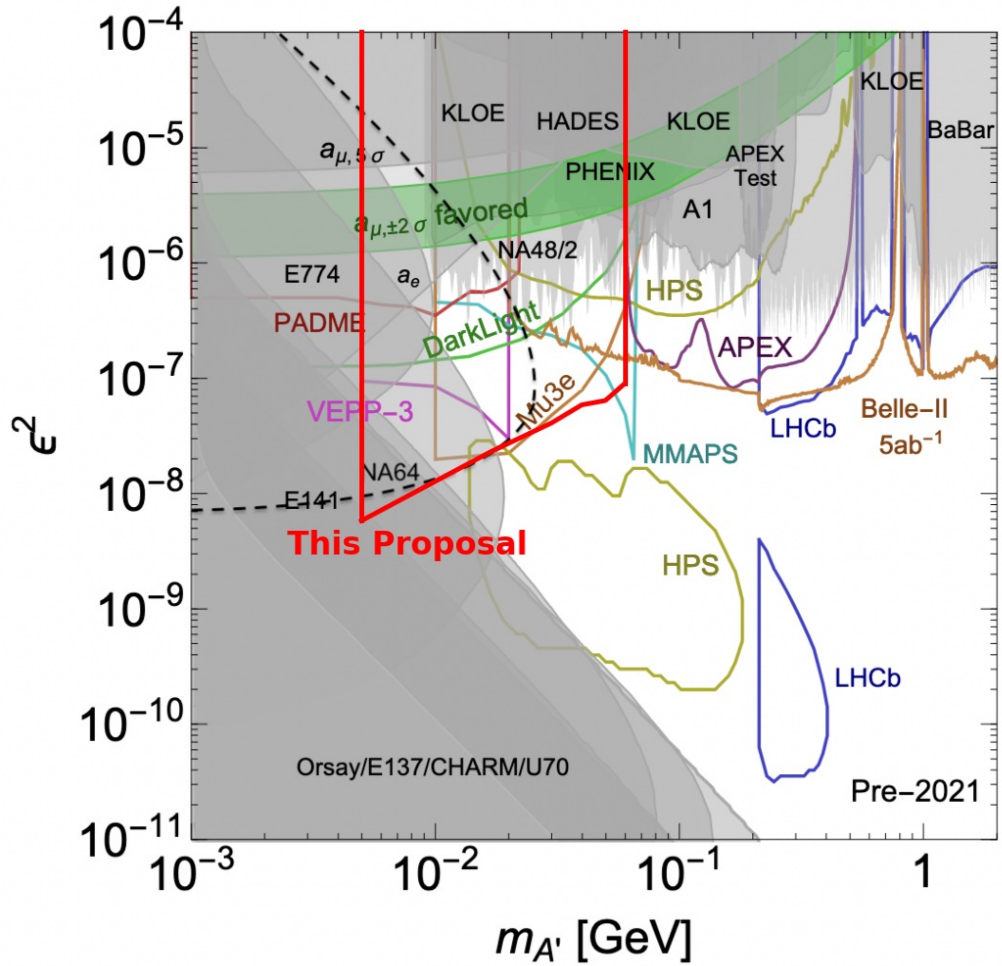
- Invariant mass range: [3 -- 60] MeV

- Coupling constant: $\varepsilon^2 \approx [10^{-8} — 10^{-7}]$

- This proposal uses 5σ limits (discovery criterion as per PDG),

while the 2 - 2.4 σ limit is commonly used in many other experiments.

$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{signal}} + N_{\text{bgd}}}} \geq 5$$



Current Status of the Experiment Preparation

- ✓ Conceptual design of all beamline elements (including the target) is finalized. Engineering design is in active progress.
- ✓ Refurbishment and testing of HyCal calorimeter started this summer.
- ✓ Construction of two GEM detectors is on track (UVa group):
  - construction, late 2024;
  - cosmic ray tests in JLab, starting from Spring of 2025.
- ✓ DAQ electronics is procured (based on new fADC-250 modules), ready in Spring 2025.
- ✓ Work on cables and other experimental parts is underway in Hall B at JLab.
- ✓ Experiment is (very) tentatively scheduled for the Fall 2025.

Summary and Outlook

- It is a cost-effective, mostly ready-to-run experiment based on the PRad-II apparatus, to:

  a) validate existence or set an experimental upper limit on a search for the hypothetical X17 particle (up to $\varepsilon^2 \approx 1.9\text{x}10^{-8}$ sensitivity level);
  b) search for hidden sector new particles in the [3 ÷ 60] MeV mass range.

- It is a non-magnetic electroproduction experiment with the detection of all 3 final state particles, providing a tight control of background, reaching a low range in coupling constant: $\varepsilon^2 \approx [10^{-8} - 10^{-7}]$ range.

- Sensitive to both charged ($X \rightarrow e^+e^-$) and neutral ($X \rightarrow \gamma\gamma$) decay channels.

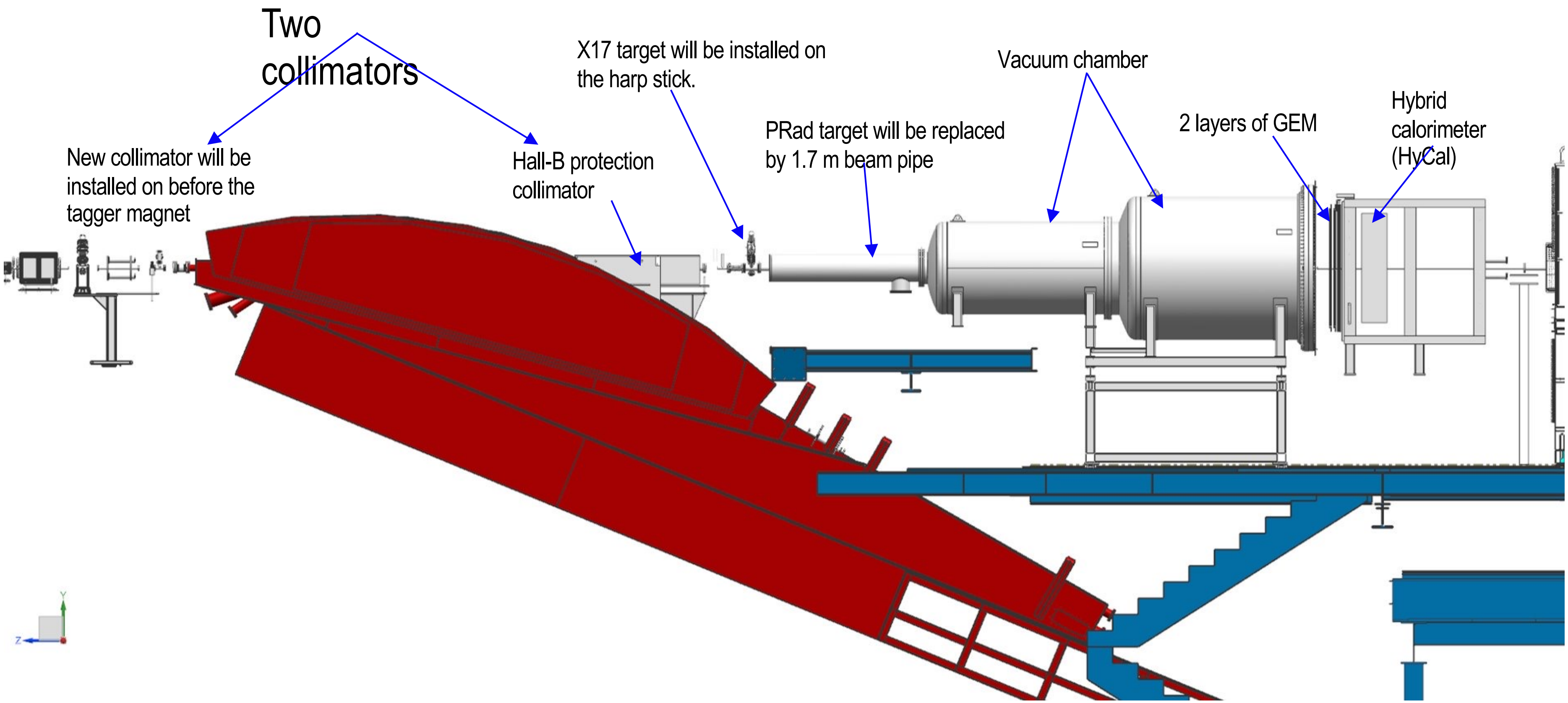
- Experimental preparations are actively underway, expected to be ready by Summer of 2025.

- We expect to run this experiment in Fall 2025.

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

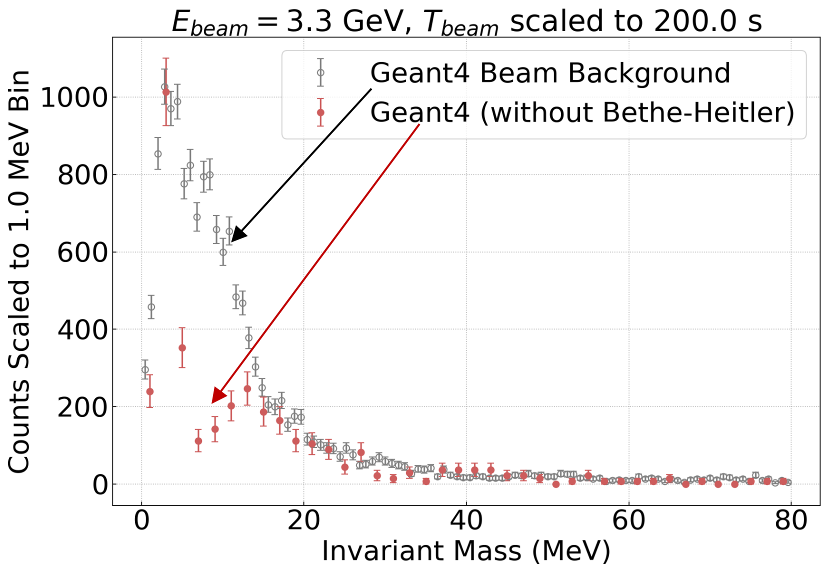
Backup Slides

X17 Experimental Setup



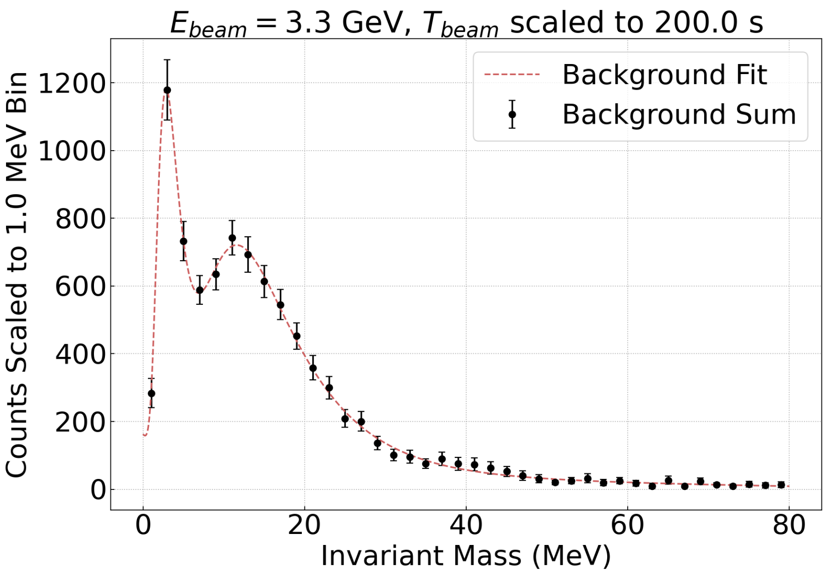
Physics Background Simulations (Hybrid Method) (GEANT4 without BH + MadGraph5)

- Therefore, we combined:
  - ✓ GEANT4 without the Bethe-Heitler process activated;



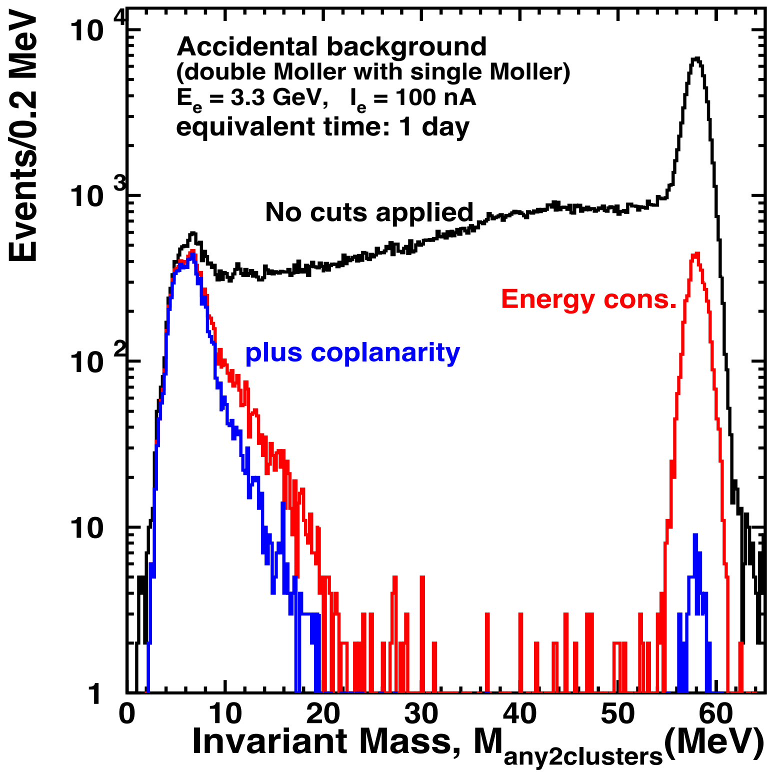
  - ✓ and summed with the results simulated with the full MadGraph5 event generator.

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



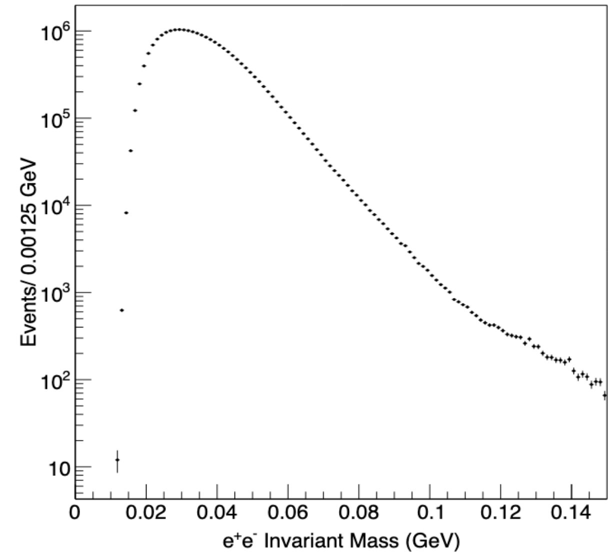
Accidental Background (Accidental Coincidence Rate)

- Hardware trigger requires 3-claster events:
  - ✓ $N_{cluster} \geq 3$
  - ✓ each one within: 30 MeV $< E_{cluster} < 0.8xE_{beam}$
  - ✓ $E_{total} > 0.7xE_{beam}$
- 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 ≈ 107 kHz
  - ✓ doubles from Moller: Rate ≈ 81.7 kHz
- Assuming 2 ns time resolution (bunch size):
  - ✓ accidental coincidence rate: ≈17 Hz
  - ✓ is not a significant background contribution.



Other Similar Experiments/Projects at JLab

- HPS (at JLab)
  - ✓ search for $A' \to e^+e^-$ 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

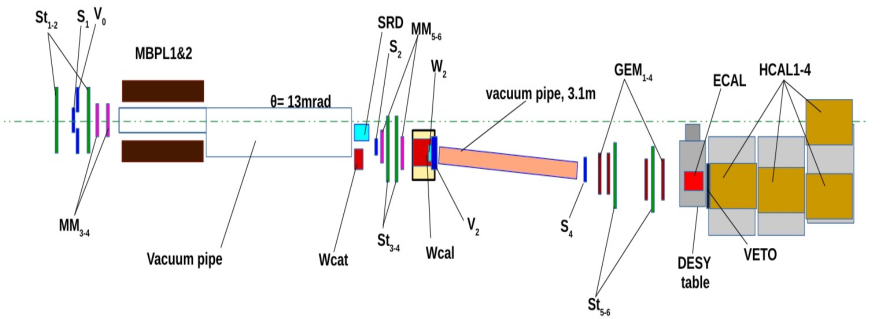
- APEX (at JLab)
  - ✓ search for $A' \to e^+e^-$ in $M_{A'}$ = [65 − 525] MeV;
  - ✓ magnetic spectrometer method;
  - ✓ only e^+e^- detected, $\varepsilon^2 > 9\times10^{-8}$;

- DarkLight (discontinued)
  - ✓ search for $A' \to e^+e^-$ in $M_{A'}$ = [10-90] MeV;
  - ✓ magnetic spectrometer method;
  - ✓ e^+e^- detected, $\varepsilon^2 > 3\times10^{-7}$;

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

Other Similar Experiments/Projects

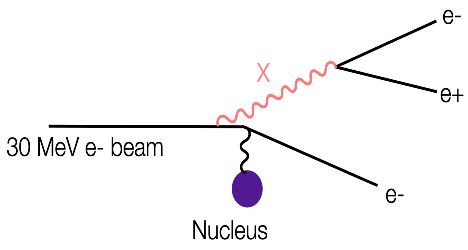
- NA64 (experiment and new proposal with SPS at CERN
  - ✓ combination of "beam dump" and direct e^+e- detection;
  - ✓ first EM calorimeter is an active "dump" (~40 r. l.), second EM detects e+e- pairs;
  - ✓ assumes relatively long decay length for A' (or X);
  - ✓ total energy conservation;
  - ✓ mass range: $\leq$ 23 MeV,
  - ✓ new proposal for 2021.

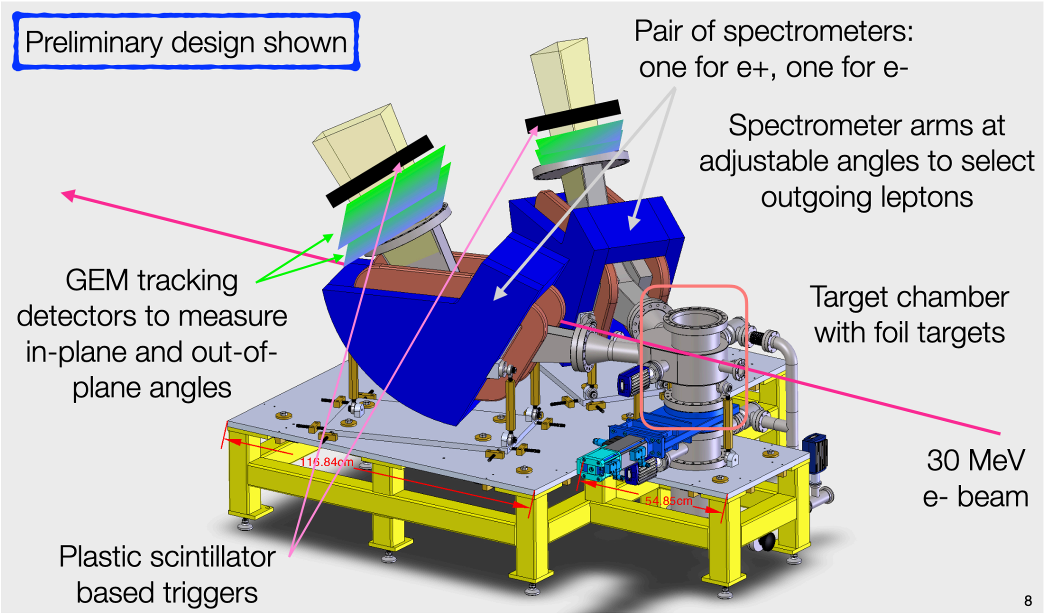


- MAGIX (proposed experiment with MESA at Mainz)
  - ✓ search for $A' \to e^+e^-$ in $M_{A'}$ = [$8 - 70$] MeV;
  - ✓ magnetic spectrometer method;
  - ✓ only e^+e^- detected, $\varepsilon^2 \approx [2\times10^{-7} - 8\times10^{-9}]$

Other Similar Experiments/Projects

- DarkLight X17 search at TRIUMF (2022-2026)
  - ✓ 30 MeV e^- beam





Other Similar Experiments/Projects (ATOMKI Type)

- Montreal Tandem Project (2022-2023)

  - ✓ Similar to ATOMKI ^{8}Be experiment

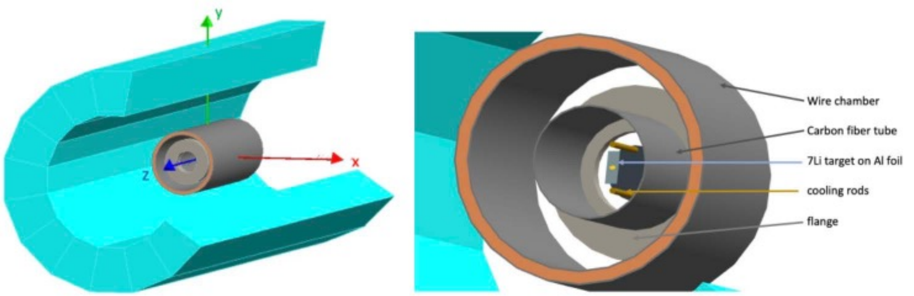


Figure 3. Geometry of the detector in Geant4 Monte Carlo.

- 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, $\varepsilon^2 \approx [2\text{x}10^{-7} - 8\text{x}10^{-9}]$

Other Similar Experiments/Projects (ATOMKI Type)

- EAR2 with Neutron Beam Project at Torino, Italy (2023)