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

(JLab Experiment E12-21-003)

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Physics Goals of the Experiment

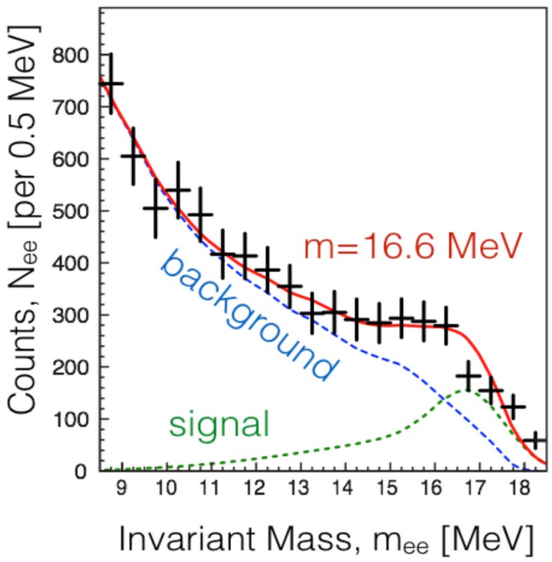
- Most of cosmological observations suggest that:
  - ✓ The Universe consist mostly of matter of "unknown origin" called Dark Matter (DM);
  - ✓ DM either does not interact with ordinary matter (SM) ***or*** it interacts weakly (WIMPs) and has not been detected to date;
  - ✓ many theoretical models have been generated, and many experimental searches proposed:
    - ✓ thus far no detection of DM.
- Assuming DM can be detected through interactions with SM particles and fields.
- Viable theoretical models suggest:
  - ✓ There exist "intermediate particles/fields" (portals) between DM & SM;
  - ✓ Possible interaction between DM and SM via "kinetic mixing" mechanism;
  - ✓ There might exist a U(1) gauge boson (dark photon or X-particle);
  - ✓ the [1 – 100] MeV mass range is a good place to look.
- Recent experimental evidence: excess e^+e^- pairs found in excited ^{8}Be and ^{4}He decay spectra, ***i.e.*** the ATOMKI anomaly → X17 particle or 5th-force carrier.
  - ✓ **requires independent experimental validation.**
- We propose a search for possible hidden-sector particles in low MeV mass range
- We propose using a direct detection method.

ATOMKI Anomalies in the ^{8}Be and ^{4}He Experiments

- ^{8}Be anomaly in nuclear transitions (*PRL 116(4):042501 (2016)*):
  - ✓ ^{8}Be* decaying to ground states.

$$p + {}^{7}Li \rightarrow {}^{8}Be^{*} \rightarrow 7Li + p \text{ (hadronic)}$$
$$\rightarrow {}^{8}Be + \gamma \text{ (E/M)}$$
$$\rightarrow {}^{8}Be + \gamma^{*},\ \gamma^{*} \rightarrow e^{+}e^{-} \text{ (IPC)}$$

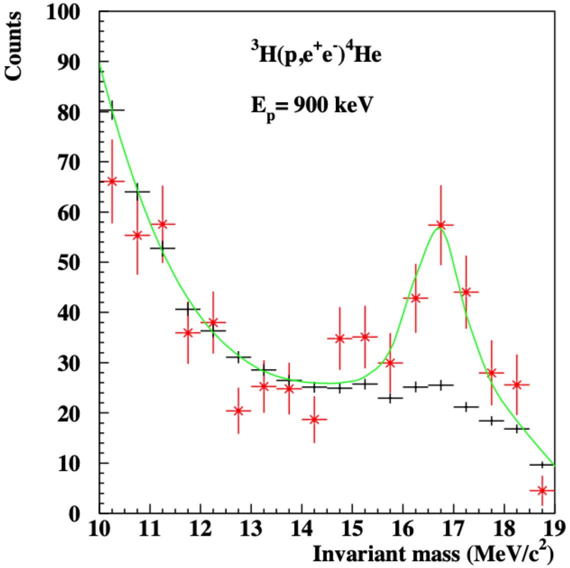
✓ excess $e^{+}e^{-}$ pairs in invariant mass in ***Internal Pair Conversion (IPC).***



- In second experiment on ^{4}He with updated setup and reduced background:

$$p + {}^{3}H \rightarrow {}^{4}He^{*} + \gamma \rightarrow {}^{4}He + \gamma^{*},\ \gamma^{*} \rightarrow e^{+}e^{-} \quad \text{(IPC)}$$

  - ✓ $e^{+}e^{-}$ peak at different angles, but same invariant mass. (Phys. Rev. C 104 (2021) 4, 044003)



ATOMKI ^{12}C Experiment also Found Anomaly

- ^{12}C Experiment
  (J. Krasznahorkay et al., Phys. Rev. C. 106, L061601, (2022))
  - ✓ ^{12}C excited states, decay to ground state:

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

✓ excess of e^+e^- pairs in angular distributions (inv. mass) of 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±0.11(stat) ±0.20(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…."

- No required independent confirmation thus far!

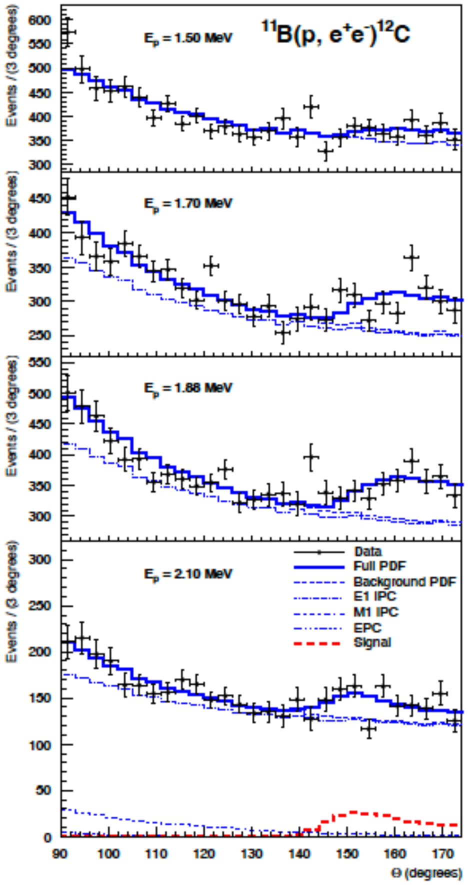


FIG. 4. Experimental angular correlations of the e^+e^- pairs measured at different proton energies. The full curves for each proton energy shows the results of the fit, using simulated angular distributions.

Objectives of this Proposed Experiment

- Our experiment has two experimental objectives:

  1) Validate existence ***or*** establish upper limit on electroproduction of hypothetical X17 particle claimed by ATOMKI low-energy hadroproduction experiments.
  2) Search for "hidden sector" intermediate particles/fields in [3 − 60] MeV mass range produced in electron-nucleus collision and detected in e^+e^- (or $\gamma\gamma$) channel.

- Several publications suggesting models predicting new scalar or pseudoscalar particles in the 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 approved experiment will be sensitive to the neutral decay channel ($X \rightarrow \gamma\gamma$).
  - A significant advantage over other proposals or running experiment

Experimental Method

- The method:
  - ✓ "bump hunting" in invariant mass spectrum over background.
  - ✓ direct detection of all final-state particles (e', e^+e^- and/or $\gamma\gamma$) → full control of kinematics

- Electroproduction off a heavy nucleus in forward directions:

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

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

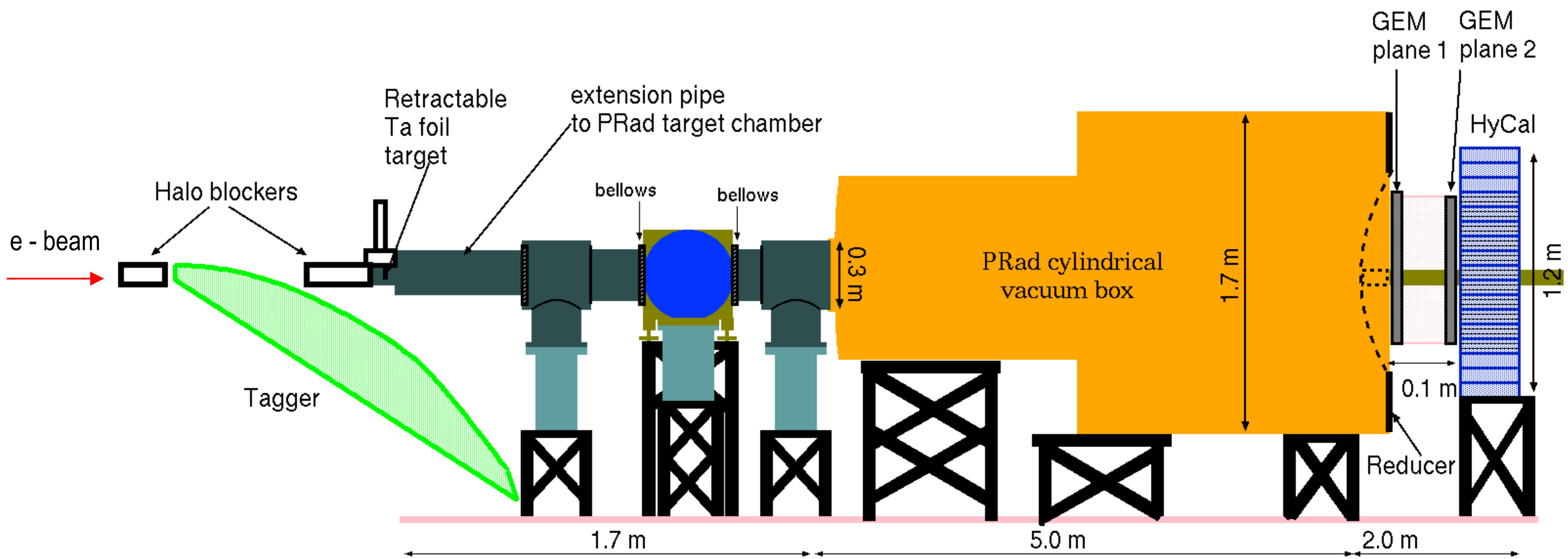
- All 3 final-state particles detected:
  - ✓ scattered electron (e') in 2 GEMs and $PbWO_4$ calorimeter;
  - ✓ e^+e^- particles, in 2 GEMs and $PbWO_4$ calorimeter;
  - ✓ $\gamma\gamma$ pairs, in $PbWO_4$ calorimeter (GEMs used for veto).

- Provides tight control of experimental background.

Experimental Setup in Hall B at JLab

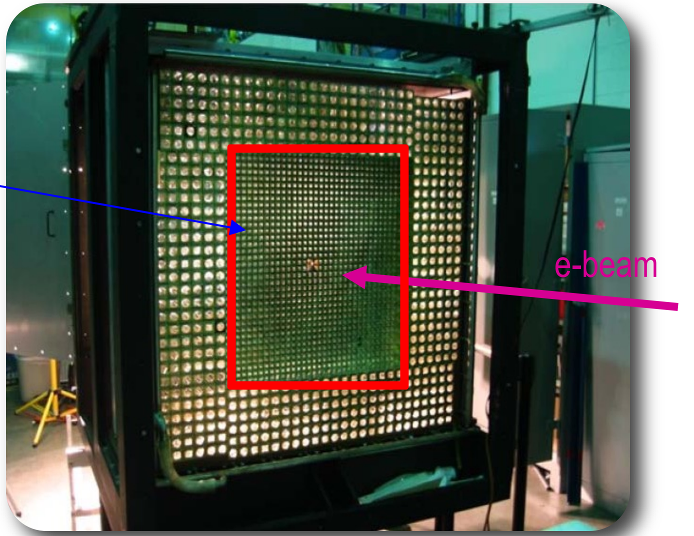
- Experimental setup is based on PRad-II apparatus: (https://indico.icc.ub.edu/event/180/contributions/2469/attachments/1237/2516/170_DDutta_new_PRad_II_expt.pdf)
  - We use the Hall B Photon Tagger for $PbWO_4$ calorimeter gain equalization and calibration
  - 1 μm $_{73}Ta^{181}$ solid targets (2.4x10^{-4} r.l.) placed on target ladder (Harp);
  - Two planes of GEM detectors on front of $PbWO_4$ calorimeter, providing limited tracking;
  - Only $PbWO_4$ portion of HyCal used in this experiment.

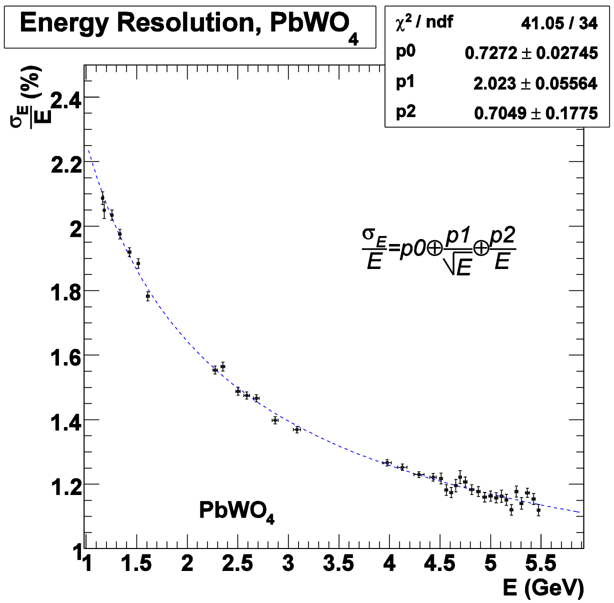
Experimental Setup (Side View)

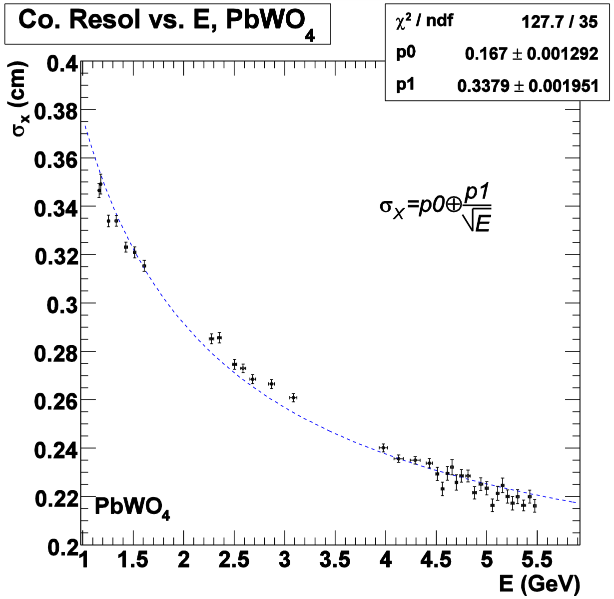


Experimental Apparatus: $PbWO_4$ Electromagnetic Calorimeter

- Only inner $PbWO_4$ portion of HyCal used:
  - ✓ 34 x 34 =1156 crystal modules, each 2x2x18 cm^3;
  - ✓ 68 x 68 cm^2 total detection area;
  - ✓ Central 2x2 crystals removed for beam passage

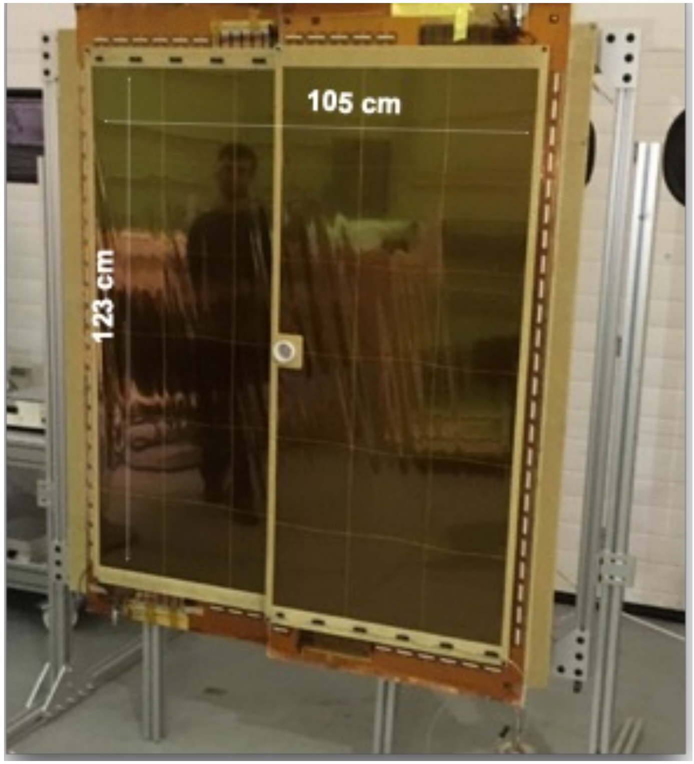






Experimental Apparatus: GEM Position Detectors (Tracking)

- Two planes of GEM detectors for tracking:
  - ✓ similar to PRad-II GEMs – smaller size;
  - ✓ located upstream of $PbWO_4$, downstream of vacuum window;
  - ✓ separation (40 cm), optimized between resolution and material downstream of vacuum window;
  - ✓ good position resolution (σ=72 μm) for charged particles;
  - ✓ vetoes charged particles for $X \to \gamma\gamma$ channels.



PRad GEMs

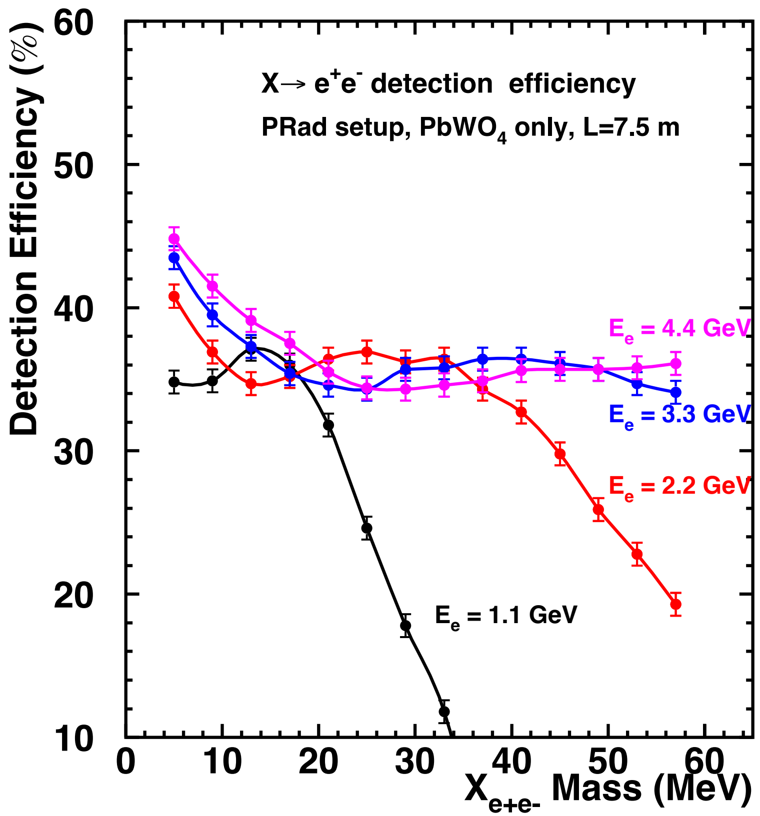
- Electronics: APV-25 based readout system. (UVA group)

Geometrical Acceptance and Detection Efficiency

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

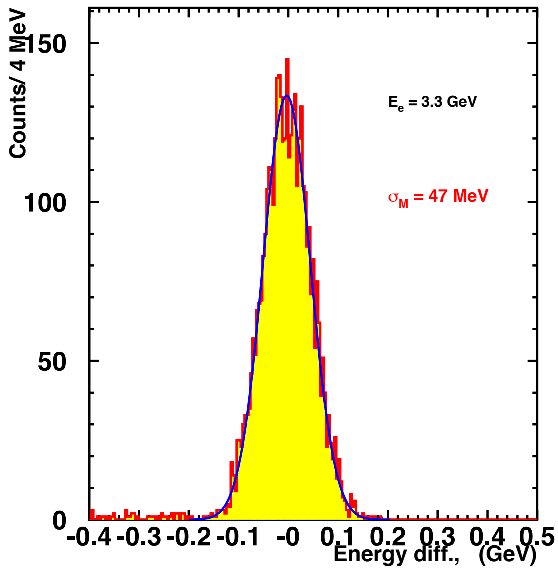
- Large phase space for virtual photons, γ^*:
  - ✓ energy range of $E_{\gamma^*} \approx [0.2 - 0.8]\ E_{beam}$;
  - ✓ angular range of $\vartheta_{e'} \approx [0.4^0 -- 3.7^0]$.
  - ✓ provides X-particle production with a wide energy spread in the forward solid angle

- Target to detector distance: L = 7.5 m provides a good (integrated) detection efficiency in the [3 - 60] MeV range.
- E_e = 2.2 and 3.3 GeV were chosen for relative ease of scheduling during CEBAF low-energy runs. (There are limits in energy to each experimental hall at JLAB.)

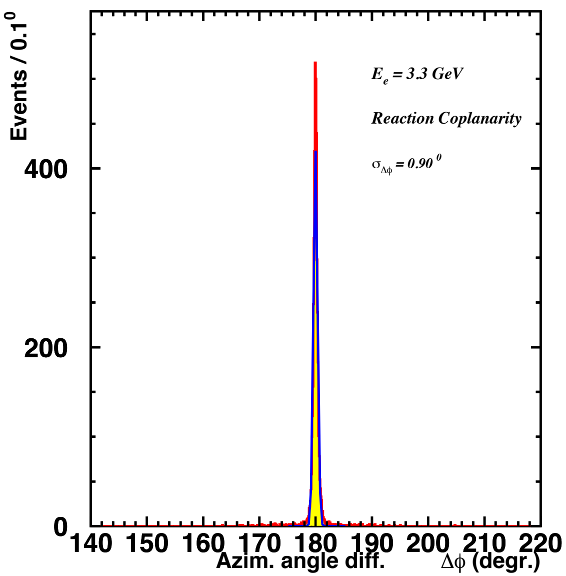


Experimental Resolutions

- Good energy resolution of $PbWO_4$ calorimeter (2.6% @ E=1 GeV) and 1 μm target provide powerful energy selection cut in this experiment (ΔE = 47 MeV @ 3.3 GeV beam).

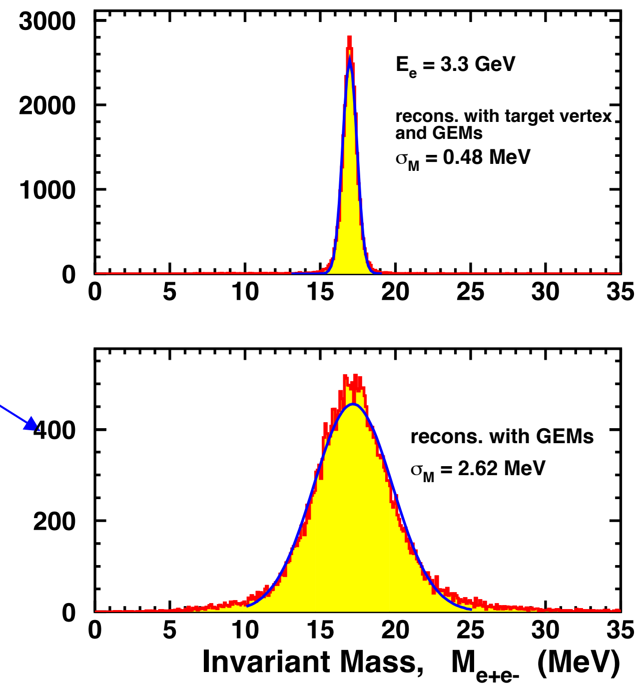


- Coplanarity (between $\overrightarrow{P_{e'}}$ and ($\vec{P}_{e+} + \vec{P}_{e-}$) vectors): ($\vartheta_{\Delta\varphi} = 0.9^0$)
  - ✓ important selection criterion for multi-channel and accidental events;
  - ✓ critical cut at low-mass range (see next slides).

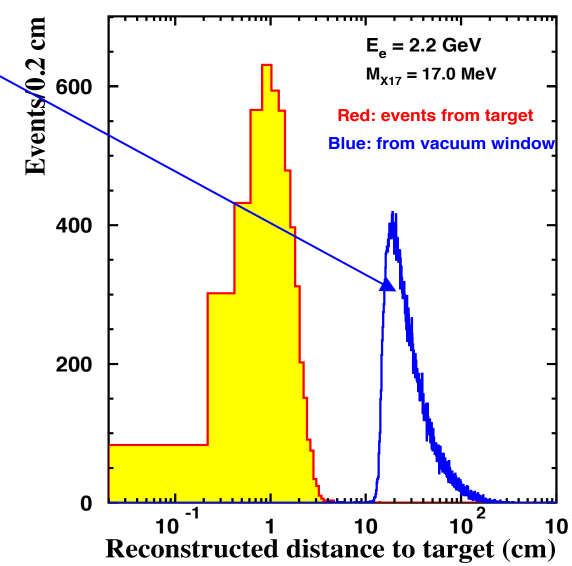


Experimental Resolutions (invariant mass and vertex plane)

- Invariant mass reconstruction (in two ways):
  - ✓ with vertex, GEMs and $PbWO_4$ calorimeter, $\sigma_m < 0.5$ MeV for X17 particle;
  - ✓ with GEMs and $PbWO_4$ calorimeter (no vertex). Used to check if the "peak events" are coming from the target.



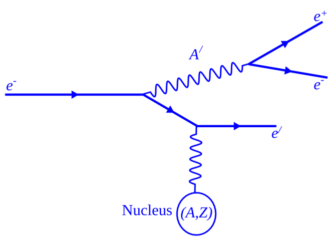
- The two GEM planes (with $PbWO_4$) will effectively discriminate events not originating from the target (*e.g.* from the vacuum chamber exit window).



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

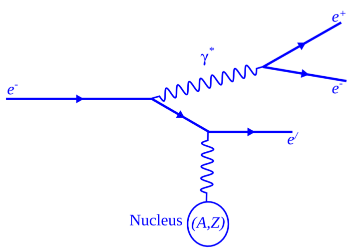
Physics Background Simulations

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



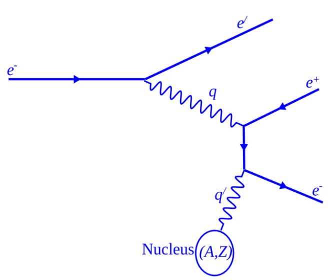
X production channel

1) GEANT4 based Monte Carlo background simulations:
   - ✓ PRad experimental setup was adapted for these simulations;
   - ✓ all physics processes activated in GEANT;
   - ✓ large number of beam electrons pass 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:
   - ✓ yield large statistics (~2M) for trident events;
   - ✓ these events were fed into the GEANT MC simulation package;
   - ✓ same analysis procedure was applied for these events as above.



Bethe-Heitler

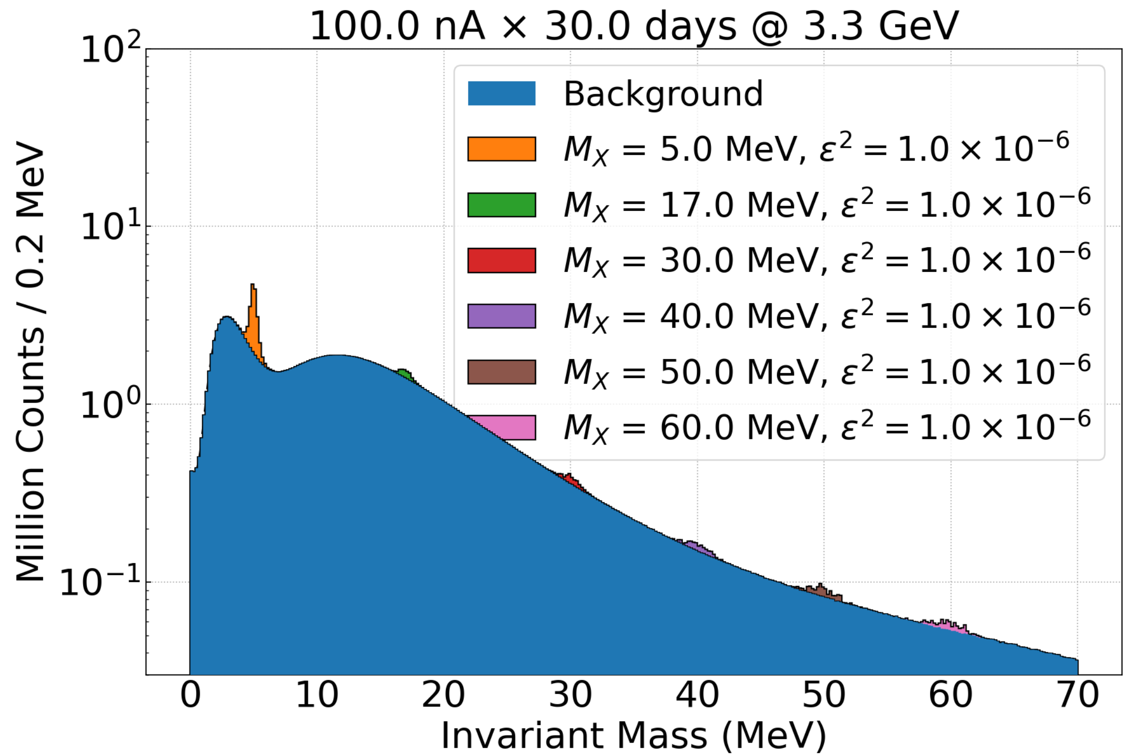
Physics Background Simulations

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

(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 coupling constant $\varepsilon^2 = 1.0\text{x}10^{-6}$



Estimated Beam Time and Statistics

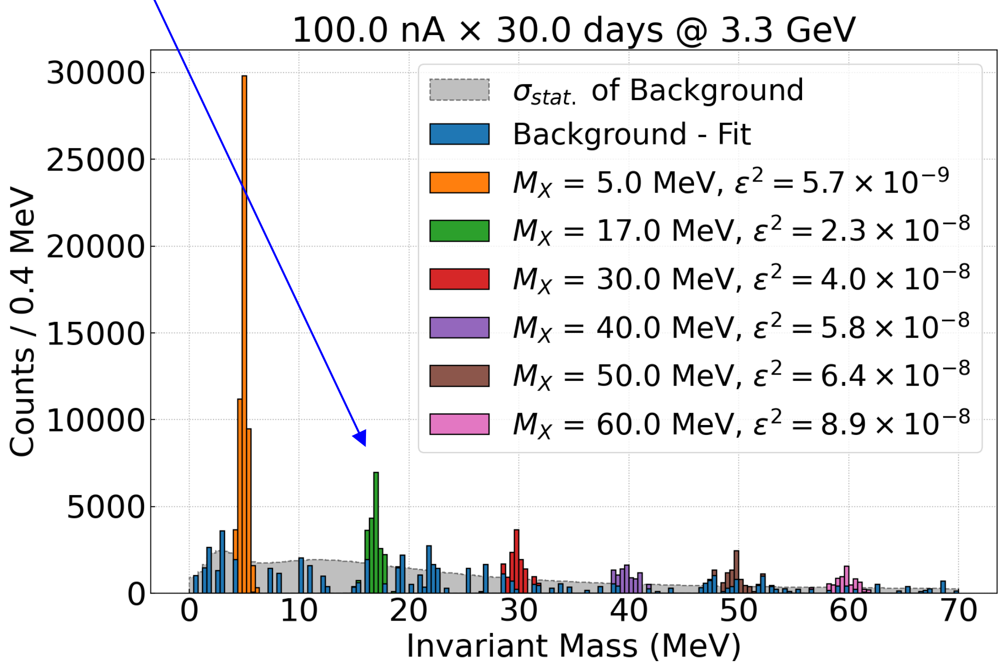
- Target: $_{73}Ta^{181}$; thickness: 1 μm ($t = 2.4 \times 10^{-4}$ r.l.), $N_{tgt} = 0.56 \times 10^{19}$ atoms/cm^2
  for $E_e = 3.3$ GeV and $I_e = 100$ nA ($N_e = 6.25 \times 10^{11}$ e^-/s),

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

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

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

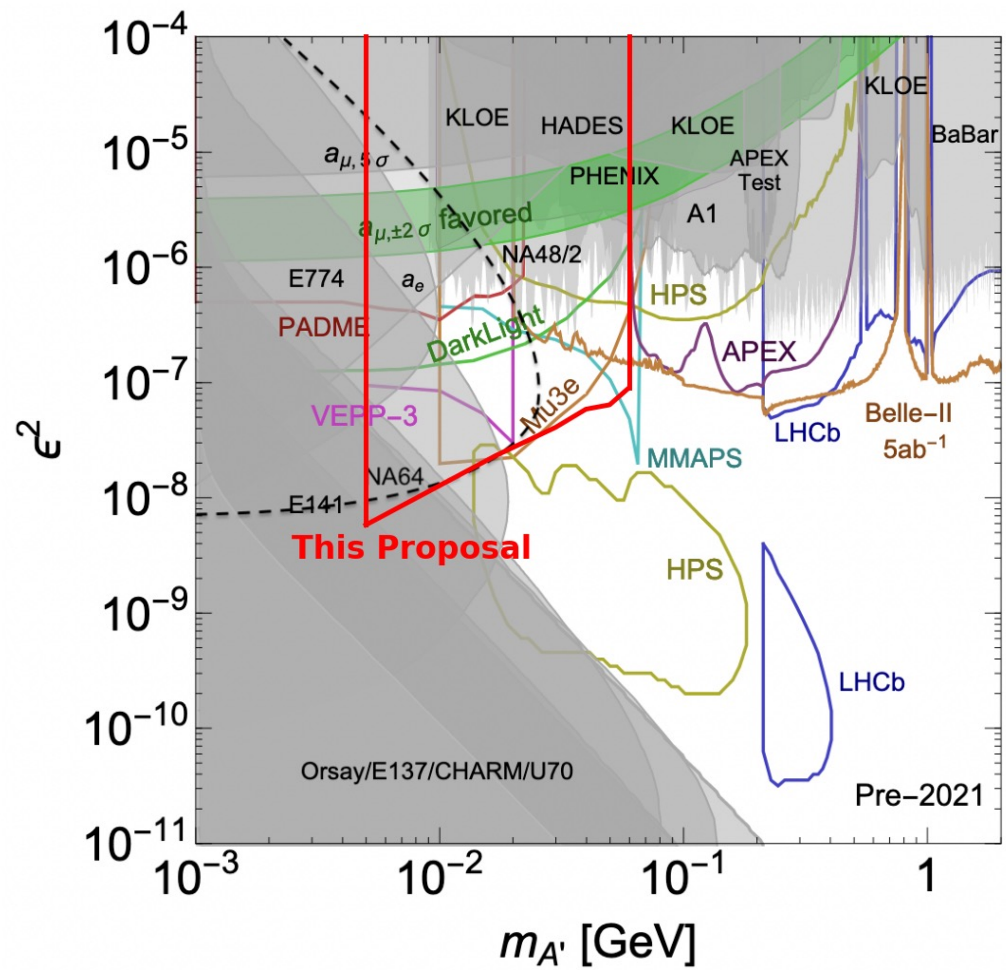
	Time (days)
Setup checkout, calibration	4.0
Production at 2.2 GeV, 50 nA	20.0
Production at 3.3 GeV, 100 nA	30.0
Energy change	0.5
Empty target runs	5.5
Total	60



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 per PDG), while 2σ limit is used in 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 target) is finalized.
- ✓ Engineering design is in active progress.
- ✓ Refurbishment and testing of HyCal calorimeter started summer 2024.
- ✓ Construction of two GEM detectors is on track at UVa:
  - construction, late 2024;
  - cosmic ray tests in JLab, starting Spring 2025.
- ✓ DAQ electronics procured (based on fADC-250 modules), ready Spring 2025.
- ✓ Work on cables and other experimental parts underway in Hall B at JLab.
- ✓ Experiment is (very) tentatively scheduled for the Fall 2025.

Summary and Outlook

- Cost-effective, mostly ready-to-run experiment based on current PRad-II apparatus:

  a) validate existence/set an upper limit on search for the hypothetical X17 particle ($\varepsilon^2 \approx 1.9 \times 10^{-8}$ sensitivity level);

  b) search for new hidden sector particles in the [3 ÷ 60] MeV mass range.

- Non-magnetic electroproduction experiment with detection of all final state particles, providing tight control of backgrounds, low range in coupling constant: $\varepsilon^2 \approx [10^{-8} - 10^{-7}]$.

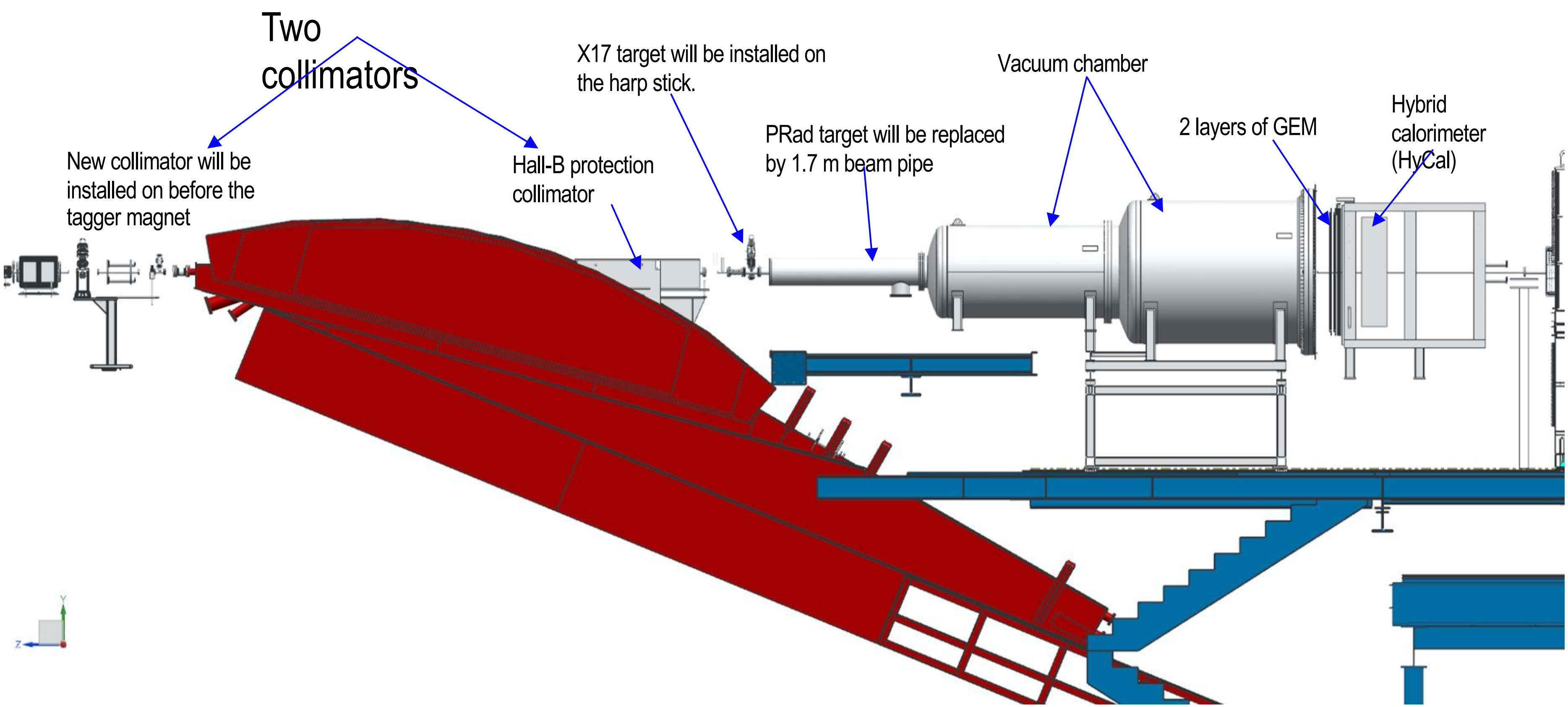
- Sensitive to both charged ($X \rightarrow e^+e^-$) and neutral ($X \rightarrow \gamma\gamma$) decay channels.

- Experimental preparations actively underway; complete by Summer of 2025.

- Ready to run Fall 2025.

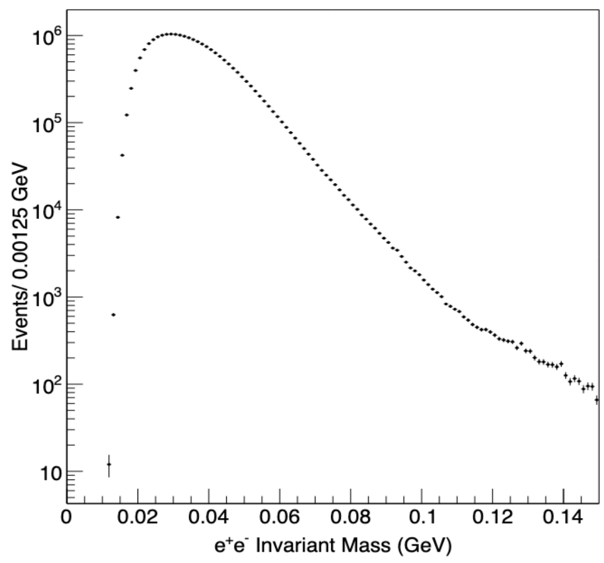
Backup Slides

X17 Experimental Setup



Other Similar Experiments/Projects at JLab

- HPS (at JLab)
  - ✓ search for A' → 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

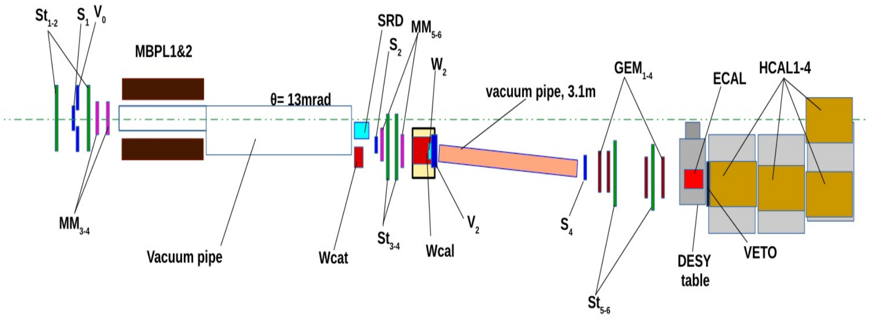
- APEX (at JLab)
  - ✓ search for A' → e^+e^- in $M_{A'}$ = [65−525] MeV;
  - ✓ magnetic spectrometer method;
  - ✓ only e^+e^- detected, $\varepsilon^2 > 9 \times 10^{-8}$;

- DarkLight (discontinued)
  - ✓ search for A' → 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 → 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

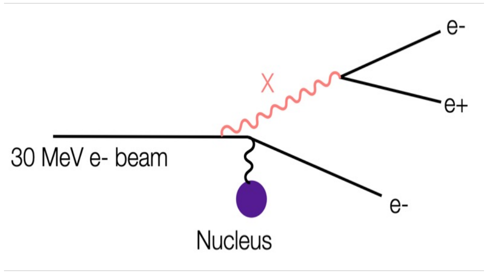
- NA64 (experiment and new proposal with SPS at CERN
  - ✓ combination of “beam dump” and direct e^+e- detection;
  - ✓ first EM calorimeter is an active “dump” (~40 r. l.), second EM detects e+e- pairs;
  - ✓ assumes relatively long decay length for A’ (or X);
  - ✓ total energy conservation;
  - ✓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

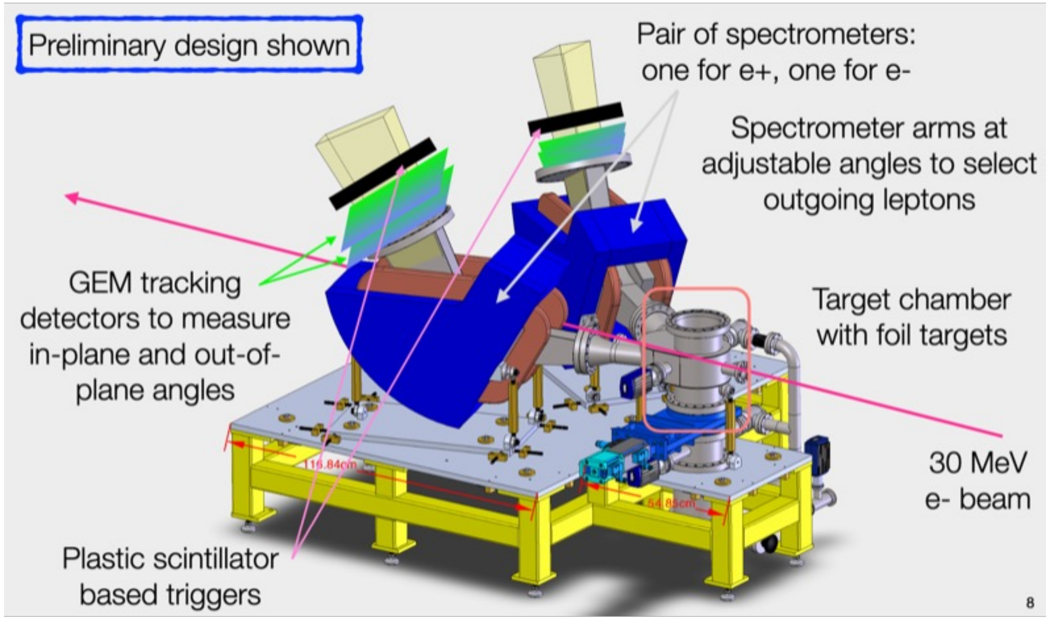


- MAGIX (proposed experiment with MESA at Mainz)
  - ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'}$ = [$8 - 70$] MeV;
  - ✓ magnetic spectrometer method;
  - ✓ only e^+e^- detected, $\varepsilon^2 \approx [2x10^{-7} - 8x10^{-9}]$

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

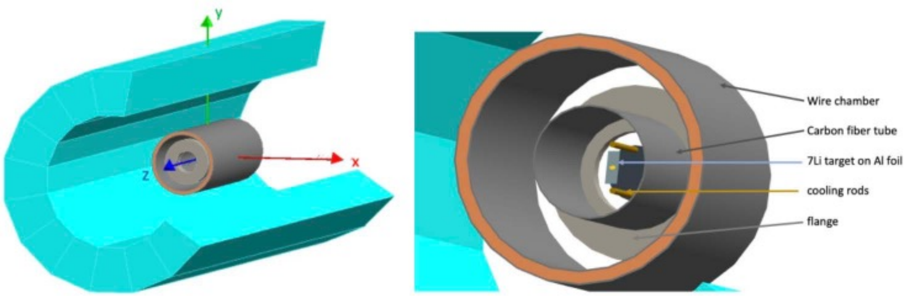


Figure 3. Geometry of the detector in Geant4 Monte Carlo.

- MAGIX (proposed experiment with MESA at Mainz)
  - ✓ search for A' → 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 (ATOMKI Type)

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