The Status of the X17 Experiment at Jefferson Lab

(JLab experiment E12-21-003)

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for the PRad/X17 collaboration

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Outline

- physics goals
- experimental method
- experimental setup and resolutions
- estimated background and physics reach
- status of the experiment
- 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 ^{12}C decay spectrum (ATOMKI anomaly, → hypothetical X17 particle or 5th-force carrier).
  - ✓ **requires an urgent independent experimental validation.**

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

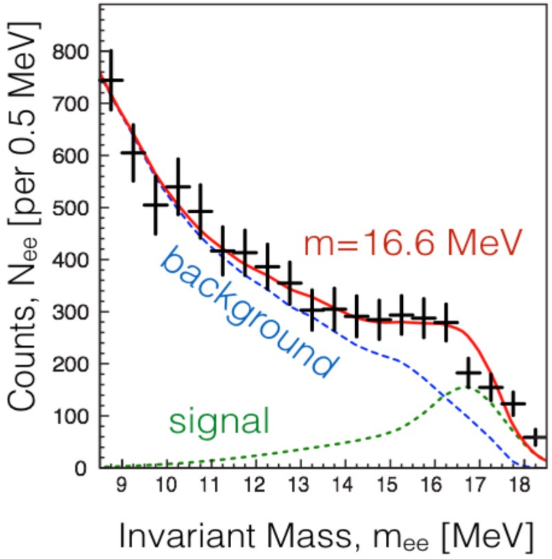
- ^{8}Be anomaly in nuclear transitions (*PRL 116(4):042501 (2016)*):
  - ✓ ^{8}Be excited states, decaying to ground state by E/M transitions.

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

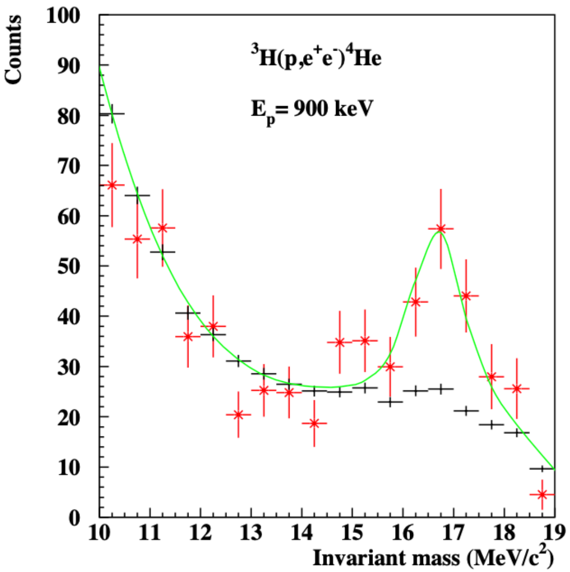


- Second experiment on ^{4}He with updated experimental setup and reduced background:

  $p + {}^3H \rightarrow {}^4He^* + \gamma \rightarrow {}^4He + \gamma^*,\ \gamma^* \rightarrow e^+e^-$ (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:

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

✓ 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±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 independent experimental confirmation so far!

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

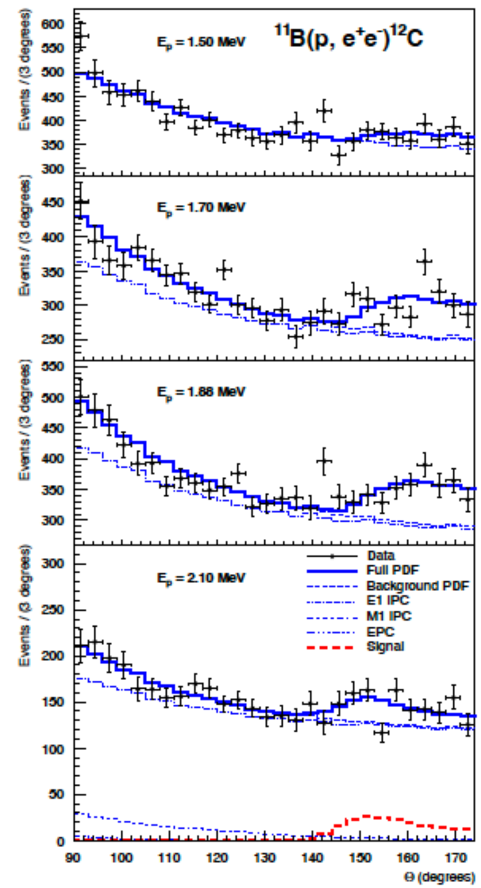


FIG. 4. Experimental angular correlations of the e^+e^- pairs measured at different proton energies. The full curves for each proton energy shows the results of the fit, using simulated angular distributions.

Objectives of this Experiment

- Our X17 experiment has two 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 $\gamma\gamma$) decay 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 $\gamma\gamma$) → 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)

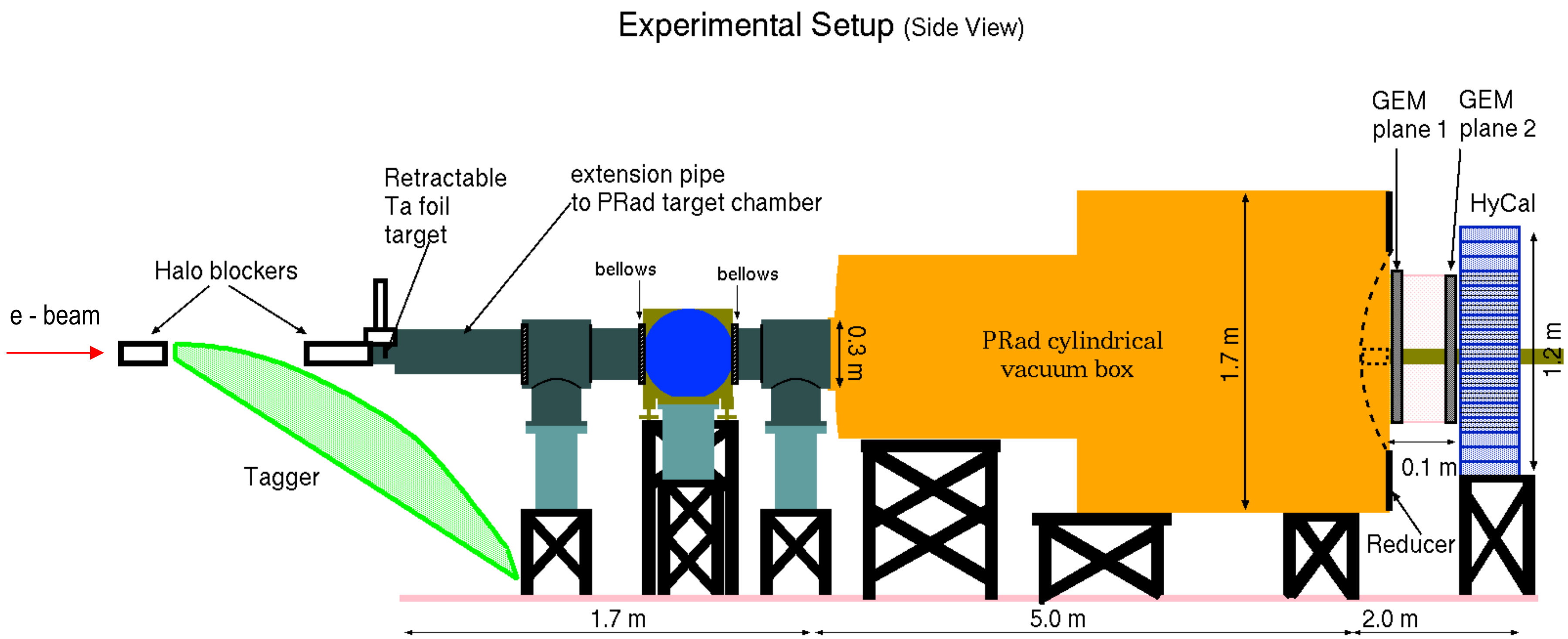
in mass range of: [3 - 60] MeV
target: Tantalum, ($_{73}Ta^{181}$), 1 μm (2.4×10^{-4} r.l.) thick foil.

- 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:
  - 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.

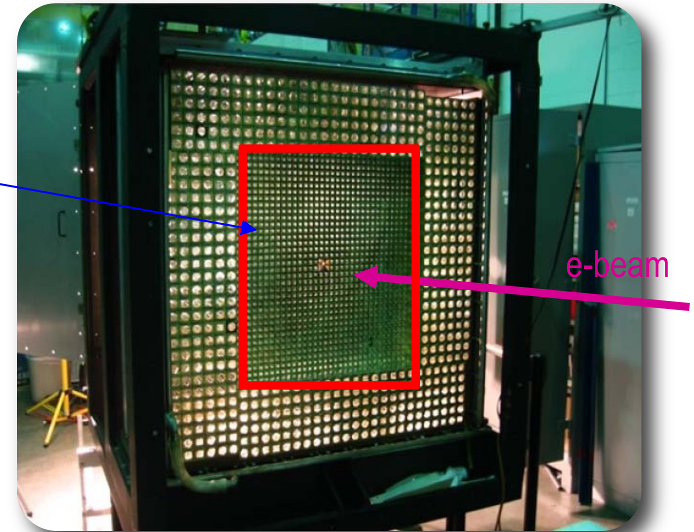


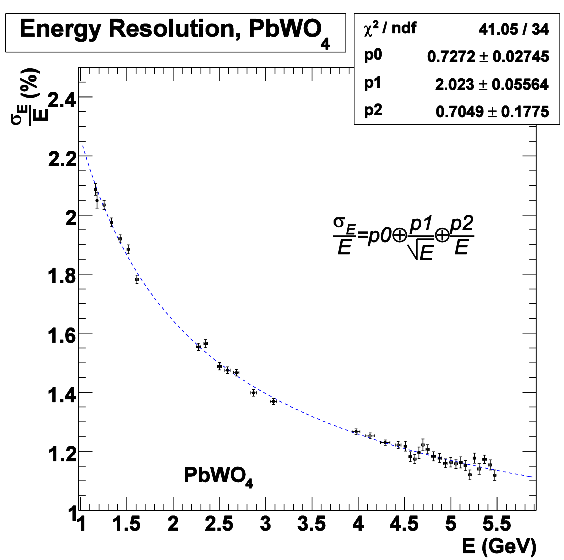
Experimental Apparatus: $PbWO_4$ Electromagnetic Calorimeter

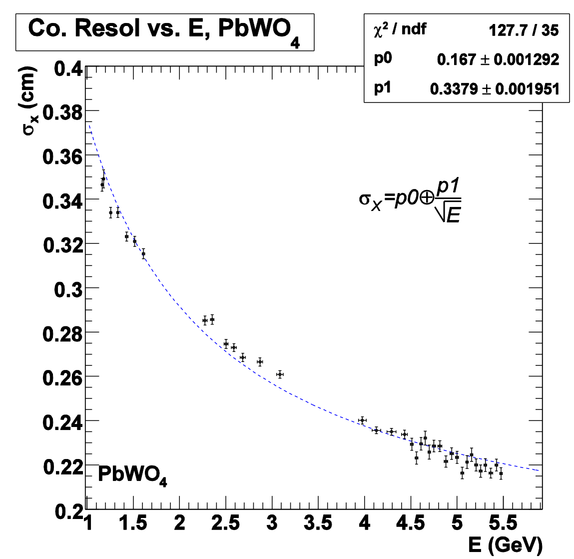
- Only the inner $PbWO_4$ part of HyCal will be used:
  - ✓ 34 x 34 =1156 crystal modules, each with 2x2x18 cm^3;
  - ✓ with 68 x 68 cm^2 total detection area;
  - ✓ 2x2 crystals are removed from center for beam passage

$\sigma_E/E = 2.6\%/\sqrt{E}$

$\sigma_{xy} = 2.5\text{mm}/\sqrt{E}$

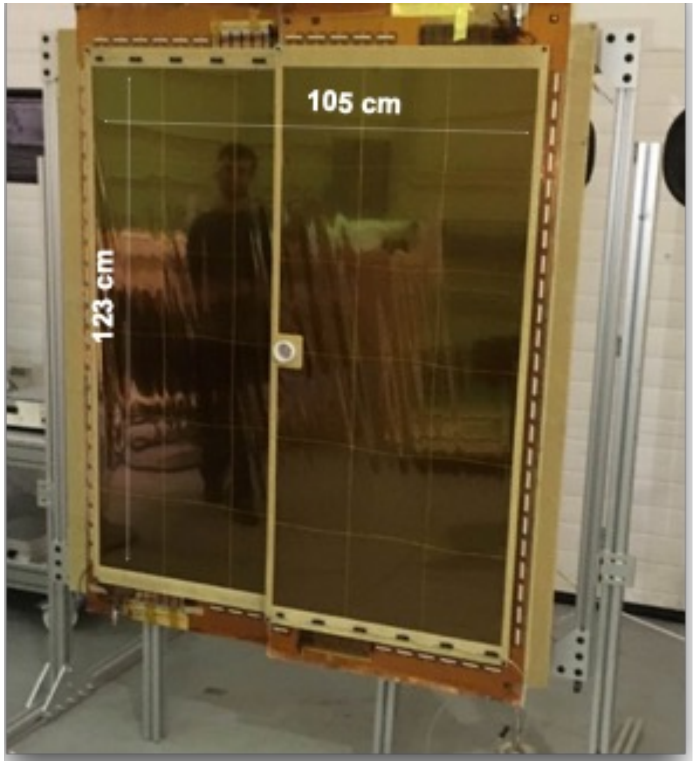






Experimental Apparatus: GEM Coordinate Detectors (Tracking)

- 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.

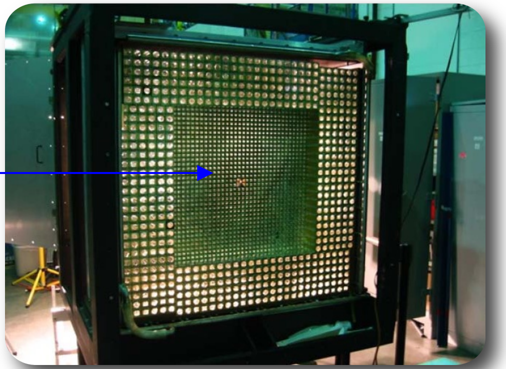


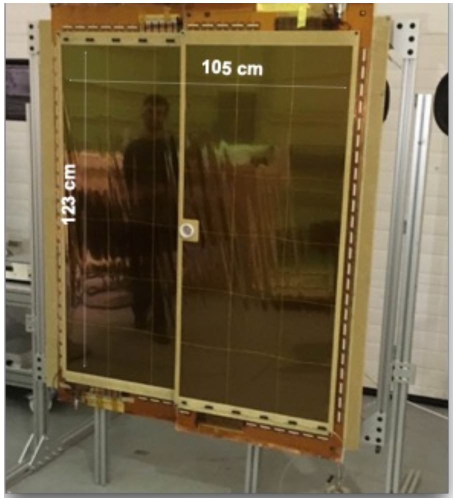
PRad GEMs

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

Experimental Resolutions

- This is a magnetic-spectrometer-free, calorimetric experiment using:
  - ✓ large acceptance high resolution $PbWO_4$ EM calorimeter;
  - ✓ two planes of GEM coordinate detectors providing tracking in the experiment.





- Advantages:
  a) detection of all 3 final state particles;
  b) more control on reaction kinematics.
  c) large detection acceptance (for both $X \rightarrow e^+e^-$ and $X \rightarrow \gamma\gamma$);

- Disadvantages:
  a) moderate resolutions, …

Experimental Resolutions: Invariant Mass

- Two ways to measure the invariant mass, M_{e+e-}

  a) with vertex, GEMs and $PbWO_4$ calorimeter,

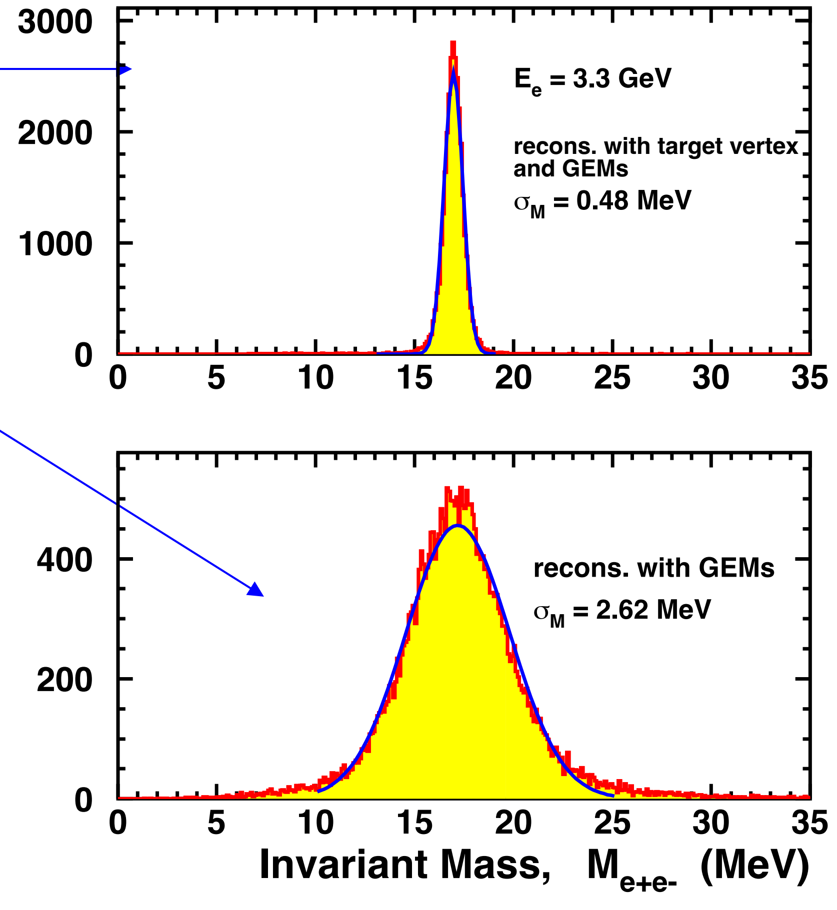
  σ_m = 0.48 MeV for X17 particle;

  b) with GEMs and $PbWO_4$ calorimeter (no vertex),

  σ_m = 2.6 MeV for X17 particle;

  This will be used to check if the “peak events” are coming from the target.

- For $M_{\gamma\gamma}$ only vertex and $PbWO_4$ will be used in this experiment, providing a factor of two lower resolutions.



Experimental Resolutions: Total Energy Conservation

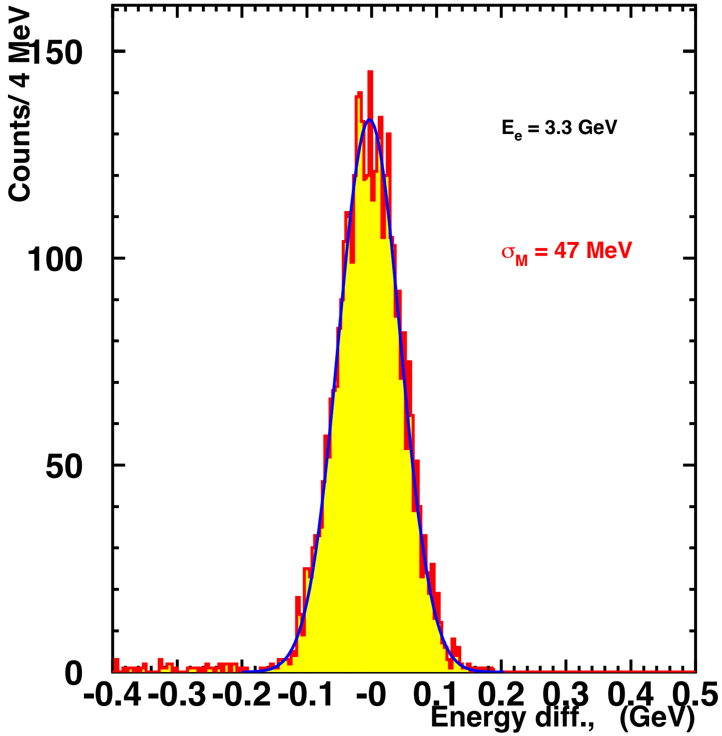
- Good CEBAF energy resolution (10^{-4}), the $PbWO_4$ calorimeter (2.6% @ E=1 GeV) and 1 μm thin target provide good energy selection criterion in this experiment:

ΔE = 47 MeV @ 3.3 GeV beam

Providing:

✓ important event selection criterion for multi-channel and accidental events;

✓ critical cut at low-mass range.



Experimental Resolutions: Reaction Coplanarity

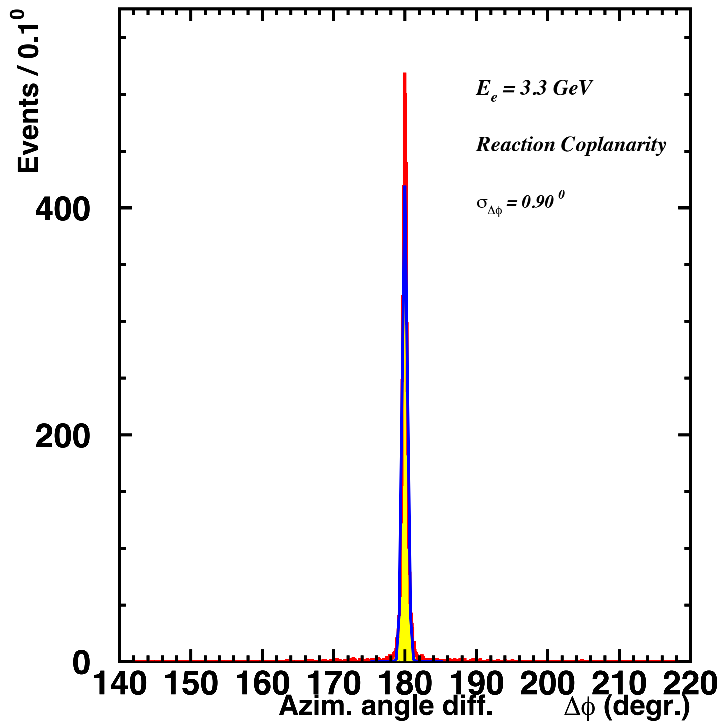
- Detection of all final states particles provides a Coplanarity cut:
  (between $\overrightarrow{P_{e'}}$ and ($\vec{P}_{e+} + \vec{P}_{e-}$) vectors):

  Good position resolution of GEMs (σ = 72 μm), together with very thin 1 μm target (2.4x10^{-4} r.l.) provide good resolution in reaction coplanarity:

  $\vartheta_{\Delta\varphi} = 0.9^0$

  Important for the background subtraction:

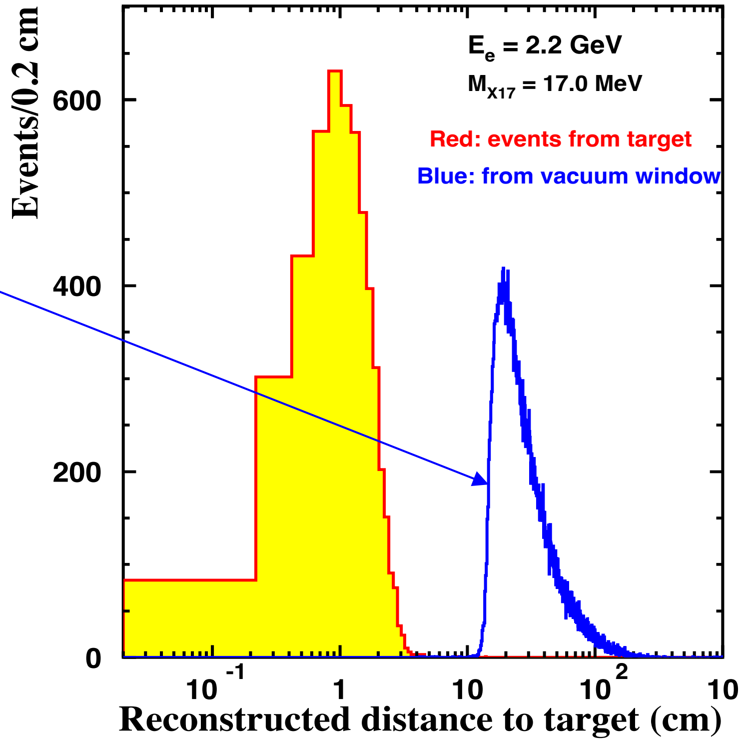
  - ✓ multi-particle and;
  - ✓ accidental coincidence events.



Experimental Resolutions: Vertex Reconstruction

- Two GEM planes and $PbWO_4$ will provide vertex determination effectively discriminating events not originated 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.

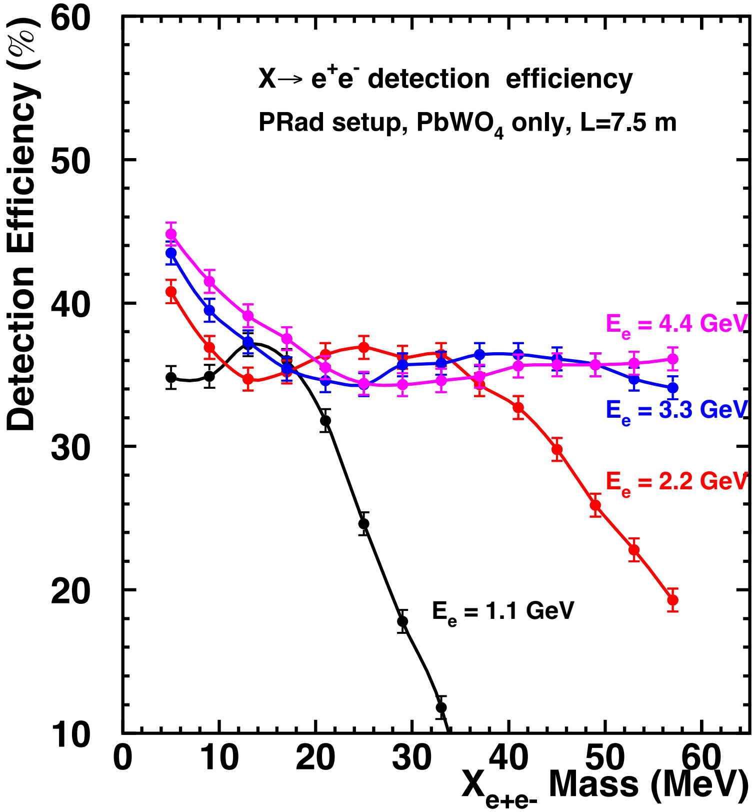
Geometrical Acceptance (or the Detection Efficiency)

- Two “resonance production” models have been applied to calculate the geometrical acceptance:

1) a simplified model (no reaction dynamics is included), assuming:
   a) the new “resonance” is produced from a virtual photon that is uniformly distributed within the energy and forward angles provided by the experiment trigger:
   b) the scattered electron is in the $PbWO_4$ crystal calorimeter ($\vartheta_{e'} \approx [0.4^0 -- 3.7^0]$

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)

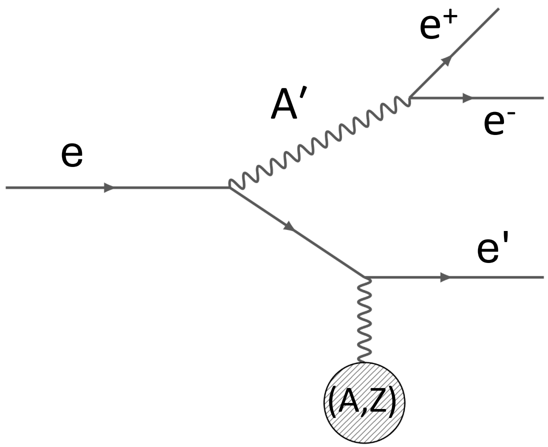


- Demonstrating good (integrated) detection efficiency in [3 - 60] MeV mass range for few GeV beams.

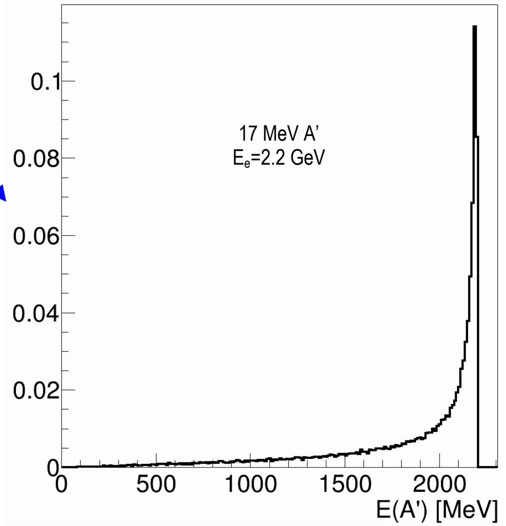
Geometrical Acceptance: with the MadGraph5 Generator

2) Assuming the X-particle is a dark photon type particle: use the MadGraph5 event generator

- Generates:
    a) very forward and close to beam energy A' ;
    b) soft scattered electrons with relatively larger angles.



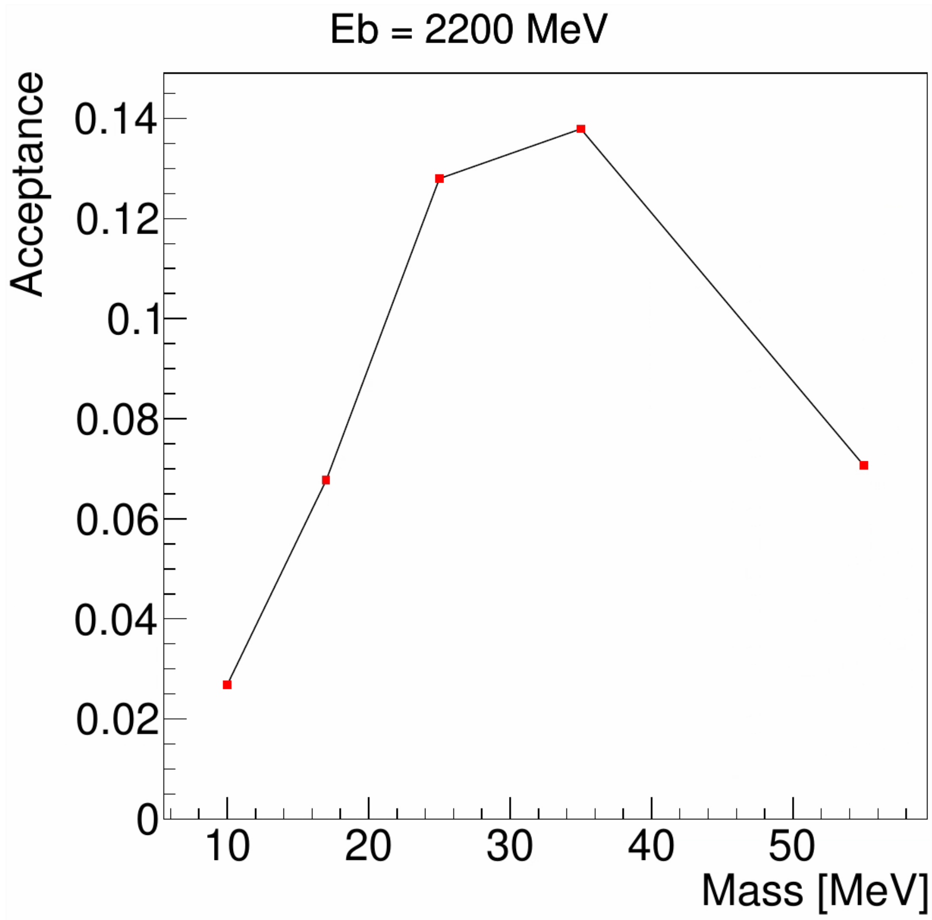
- Trigger configuration is the same:
    - ✓ total energy sum in calorimeter: $\Sigma E_{clust} > 0.7xE_{beam}$
    - ✓ 3 clusters in $PbWO_4$ calorimeter;
    - ✓ each cluster energy: 30 MeV $< E_{clust} < 0.8xE_{beam}$ (rejects the elastic scattered electrons)



- Hence, about order of magnitude smaller detection efficiency (see next slide).

Geometrical Acceptance: with the MadGraph5 Generator (Cont.)

2) Geometrical acceptance with MadGraph5 + GEANT4

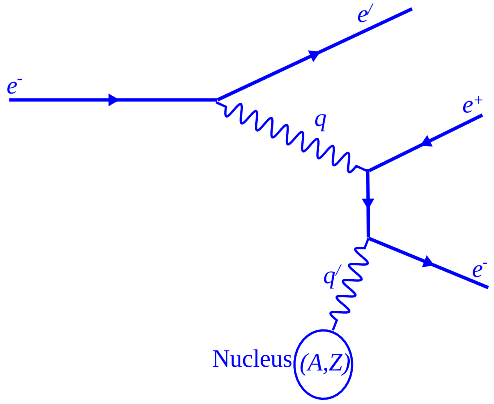


- This acceptance is used for the estimation of signal events (in slide # 21).

Physics Background Simulations

- Physics background was simulated in two different ways:

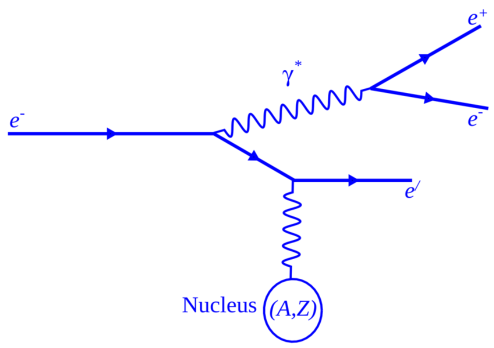
1) GEANT4 based Monte Carlo background simulations:
   - ✓ PRad experimental setup was adapted for these simulations;
   - ✓ all physics processes had been activated in GEANT;
   - ✓ large amount of beam electrons passed through the target;
   - ✓ events with $N_{cluster} \geq 3$ were analyzed in the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



Bethe-Heitler

2) MadGraph5 EM event generator with GEANT4 for secondary interaction and tracking including the following trident processes:
   a) Bethe-Heitler
   b) Radiative and
   c) Interference between them

   - ✓ large statistics (~2M) trident events;
   - ✓ these events were fed into the GEANT MC simulation package;
   - ✓ same analysis procedure was applied for these events.



Rad tridents

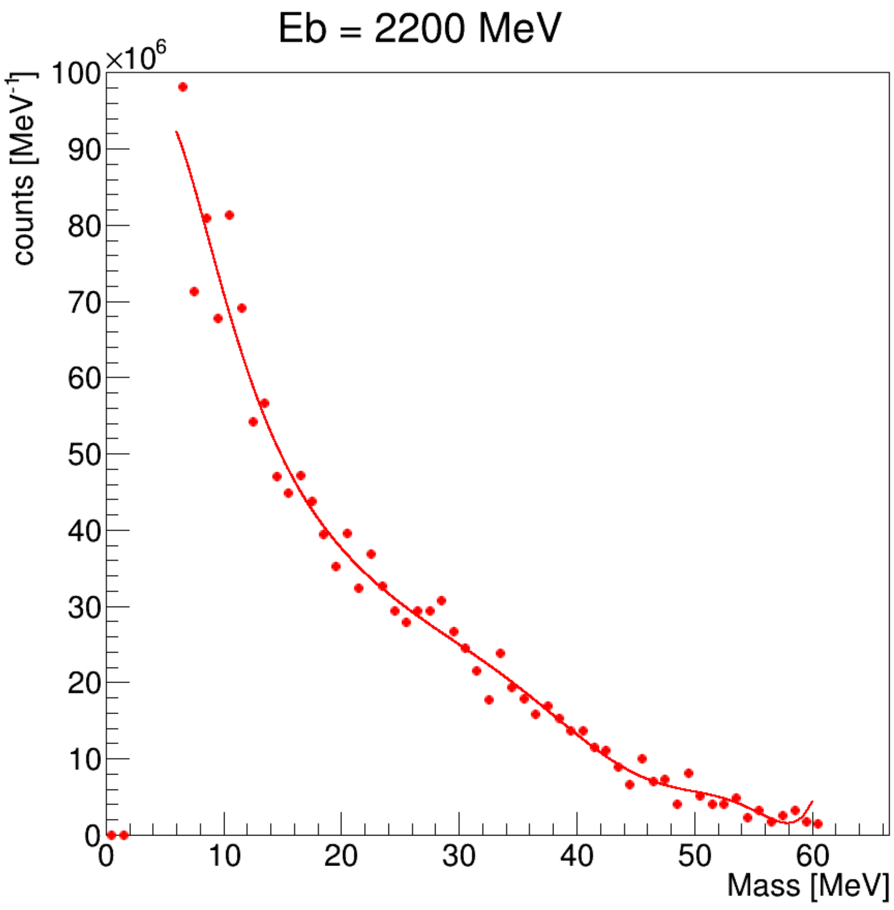
Physics Background Simulations (Cont.)

- The simulated background levels agreed for both methods within their uncertainties.

- Example,
  background simulated with
  MadGraph5+GEANT4

for:

- ✓ E_e = 2.2 GeV, I_e = 50 nA beam
- ✓ on 1 μm Ta target
- ✓ and for 40 days of running.



Rad tridents

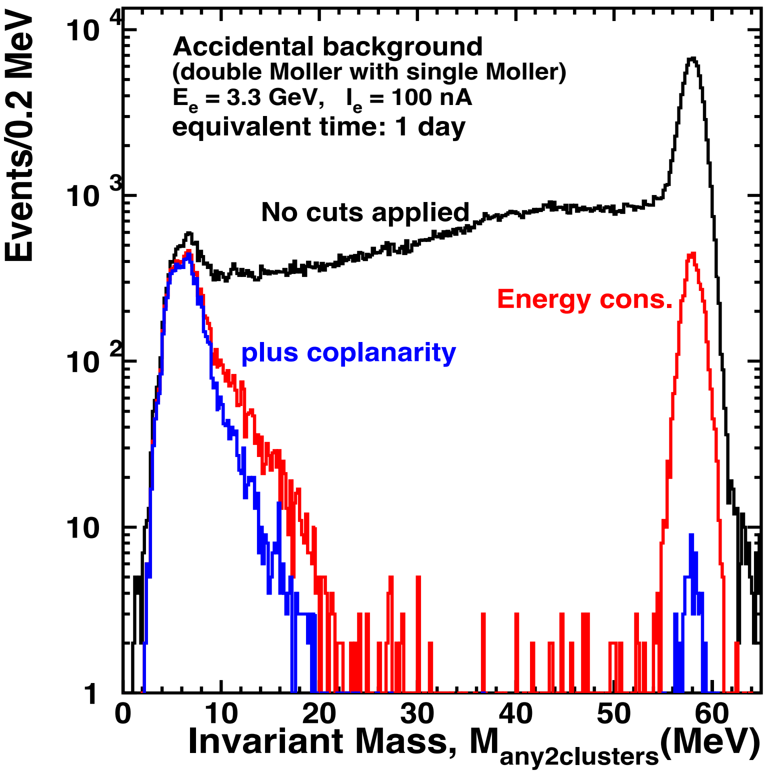
Accidental Background (Accidental Coincidence Rate)

- 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.



Estimation of Signal Events

- Target: ${}_{73}Ta^{181}$; thickness: 1 μm (T = 2.4×10^{-4} r.l.), $N_{tgt} = 0.56\times10^{19}$ atoms/cm^2
  for E_e = 2.2 GeV and I_e = 100 nA ($N_e = 6.25\times10^{11}$ e^-/s),

- Assuming the X17 is a "heavy photon" type of particle, following: J. D. Bjorken, et al. Phys. Rev. D, 80:075018. 2009):

$$N_X \sim N_C * N_e * T * \varepsilon^2 * (m_e/m_x)^2$$

with: $N_c = 5$,
N_e number of beam electrons
T target thickness in rad. length (2.4×10^{-4} r.l.)
ε coupling constant
A_{cc} geometrical acceptance

with accepted 5σ limits:

$$Nx = 5 * \sqrt{N_b * N_{sig}}$$

$$\epsilon^2 = \frac{\frac{N_X}{Acc}}{5 \times N_e T \frac{m_e^2}{m_X^2}}$$

The Expected Physics Reach: ε^2 vs. mass parameter space

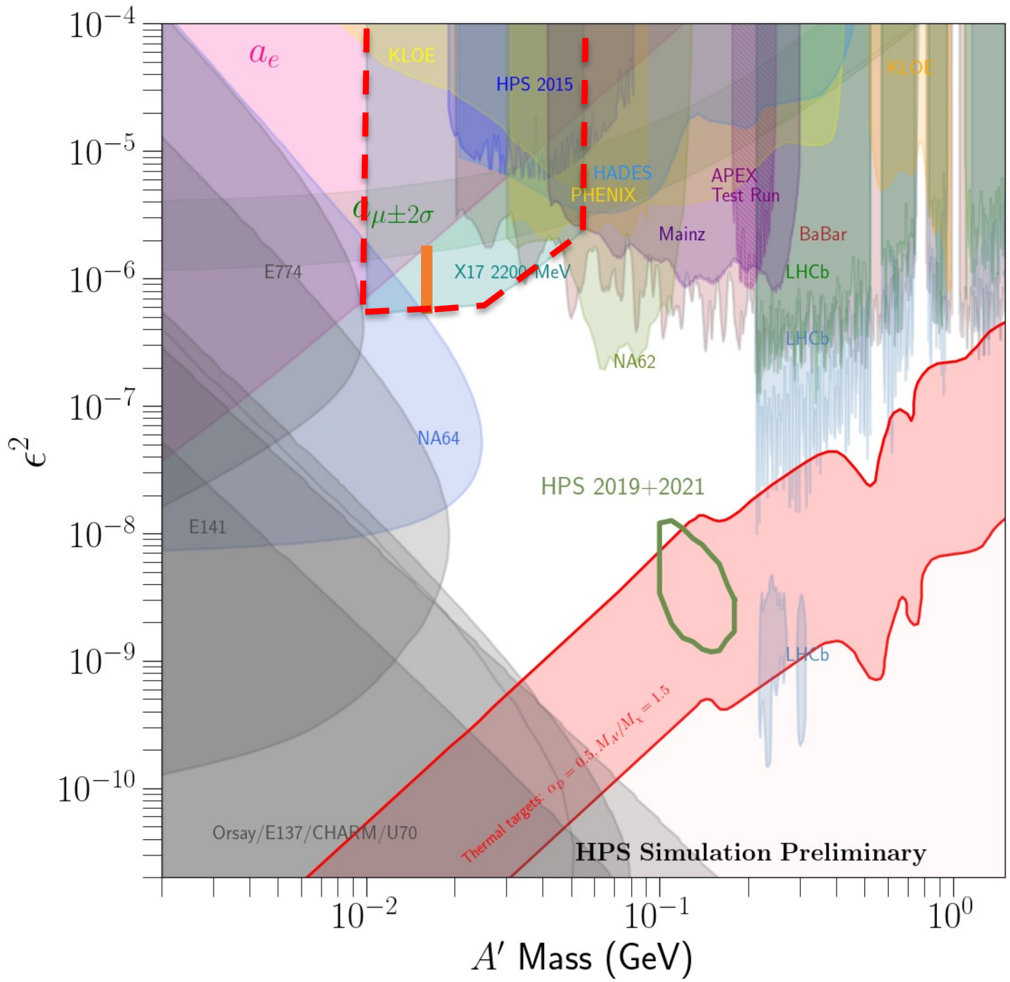
- For:

E_e = 2.2 GeV, I_e = 50 nA

40 days of run

- Invariant mass range: [3 -- 60] MeV
- Coupling constant range: $\varepsilon^2 \approx [10^{-7} - 10^{-6}]$
- with 5σ limits

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



Current Status of the Experiment Preparation

- ✓ All engineering design work (beam line elements, target and detector support system) is completed.
- ✓ Most of mechanical parts are on site and ready for the beam line installation.
- ✓ Refurbishment and testing of $PbWO_4$ is completed, ready for the experiment.
- ✓ Construction of 4 GEM detectors is on track (UVa group), ready in September.
- ✓ New DAQ electronics (based on fADC-250) are onsite, ready for the experiment.
- ✓ The first Experiment Readiness Review (ERR) passed in May, working on recommendations.
- ✓ Beamline installation is planned for September.
- ✓ Experiment is tentatively scheduled for run from February 2026

Summary and Outlook

1) 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 $\varepsilon^2 \approx 1.9 \times 10^{-8}$ sensitivity level);
   b) search for hidden sector new particles in the [3 ÷ 60] MeV mass range.

2) It is a non-magnetic electroproduction experiment, providing:
   a) large detection acceptances;
   b) detection of all 3 final state particles;
   c) tight control of background, reaching to a low range in coupling constant.

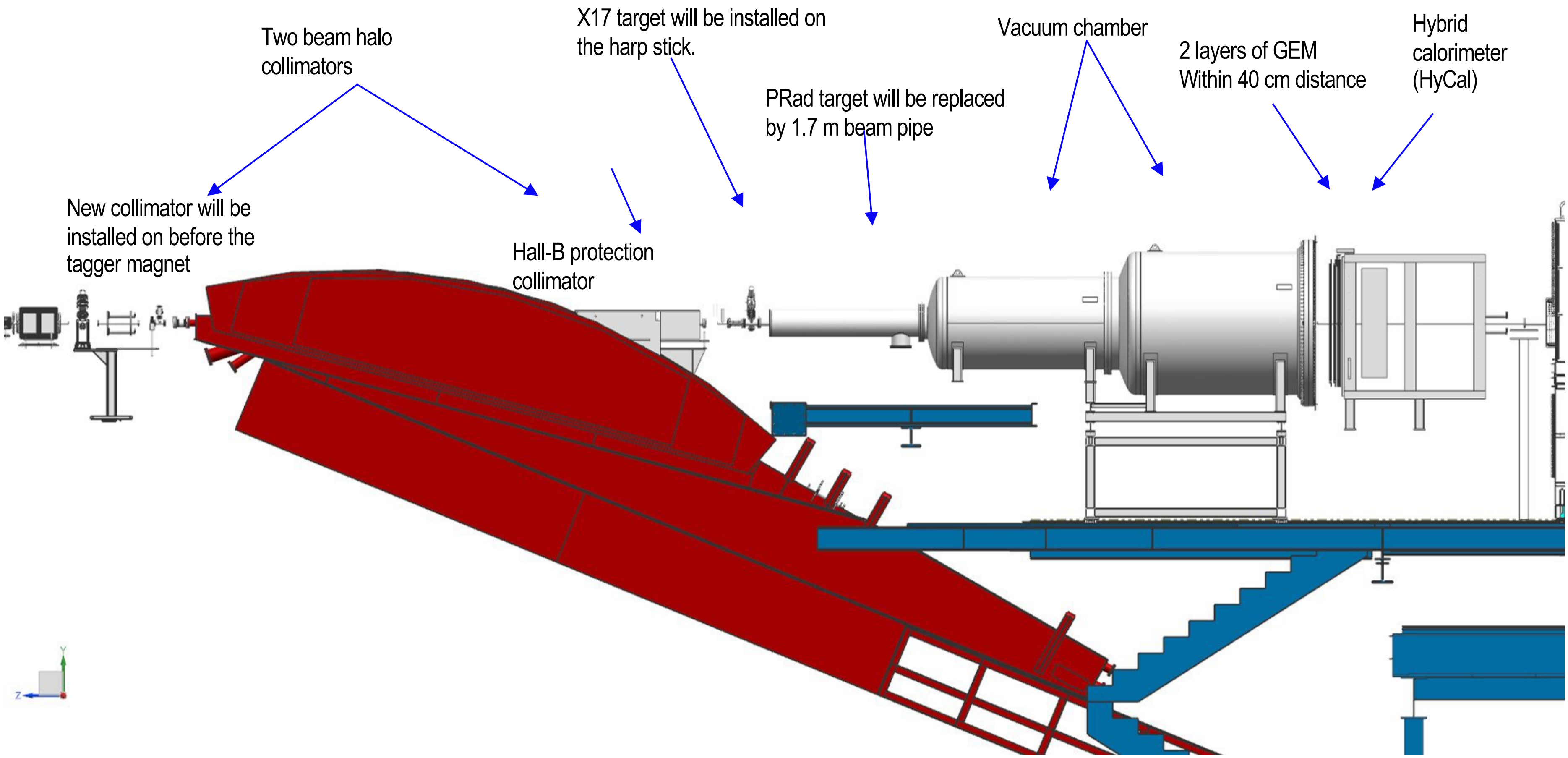
3) Sensitive to both charged ($X \rightarrow e^+e^-$) and neutral ($X \rightarrow \gamma\gamma$) decay channels.

4) The first ERR passed in May, experiment is scheduled for run from February 2026.

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

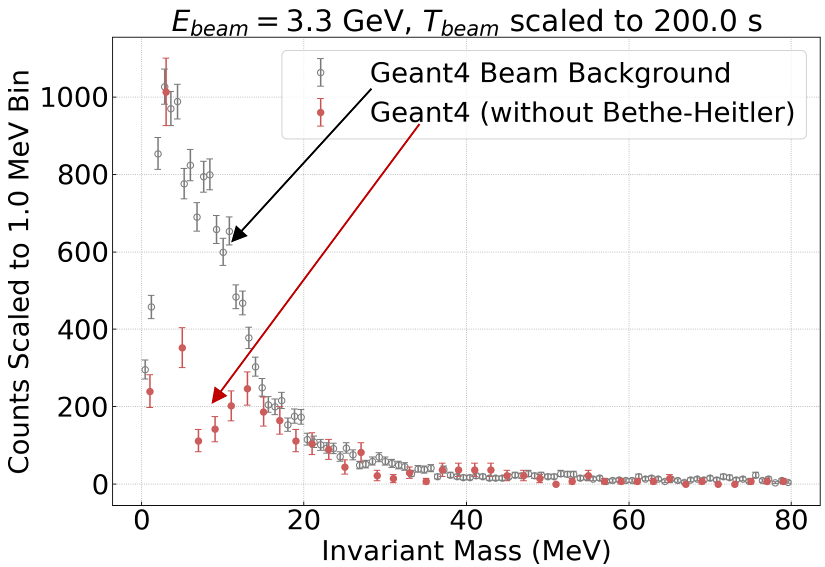
Backup Slides

X17 Experimental Setup



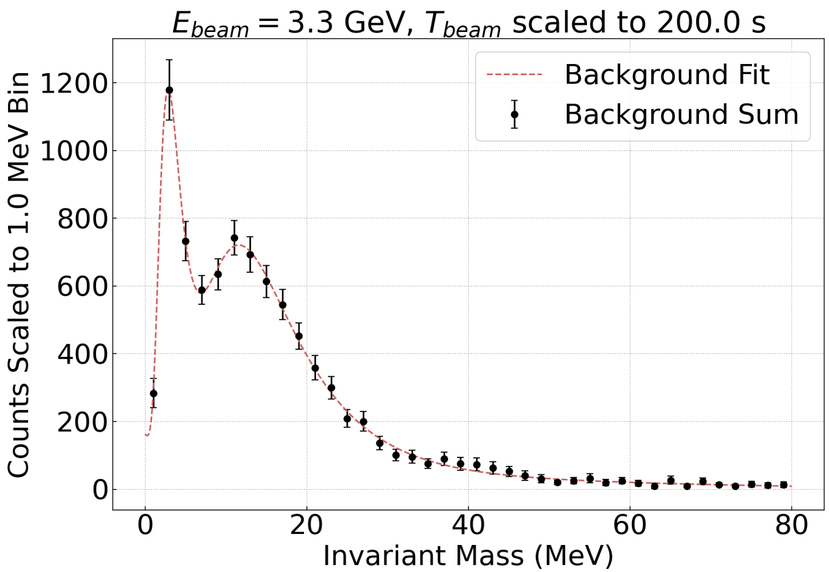
Physics Background Simulations (Hybrid Method) (GEANT4 without BH + MadGraph5)

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



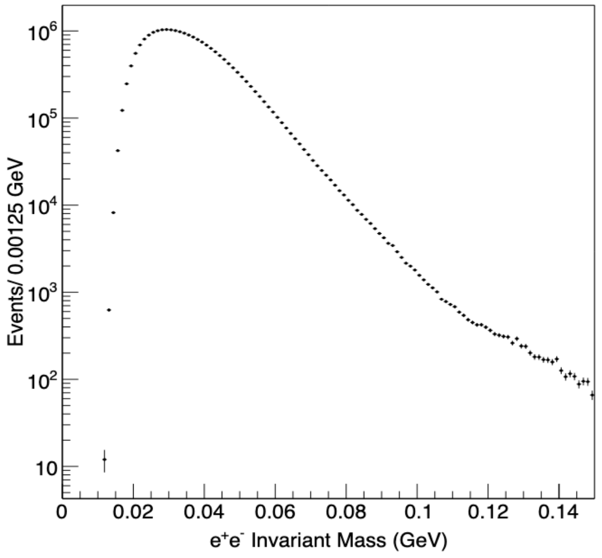
  - ✓ and summed with the results simulated with the full MadGraph5 event generator.

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



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

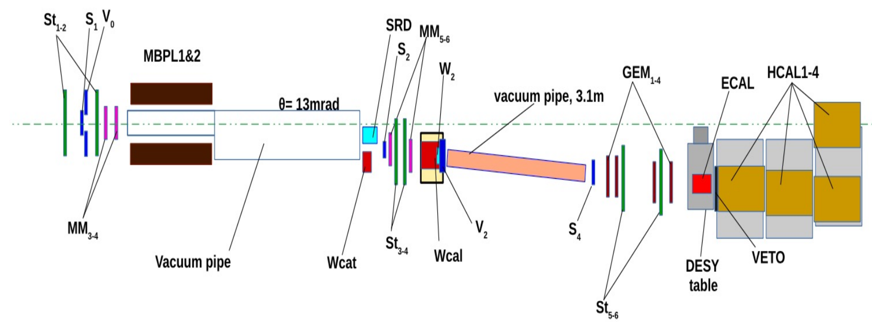
- APEX (at JLab)
  - ✓ search for A' → e^+e^- in $M_{A'}$ = [65−525] MeV;
  - ✓ magnetic spectrometer method;
  - ✓ only e^+e^- detected, $\varepsilon^2 > 9\times10^{-8}$;

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

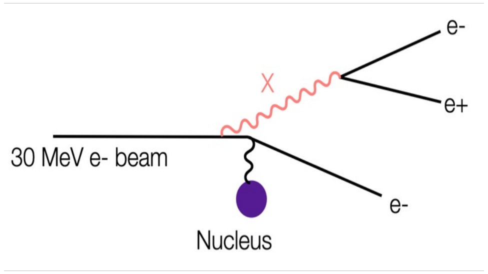
- NA64 (experiment and new proposal with SPS at CERN
  - ✓ combination of “beam dump” and direct e^+e- detection;
  - ✓ first EM calorimeter is an active “dump” (~40 r. l.), second EM detects e+e- pairs;
  - ✓ assumes relatively long decay length for A’ (or X);
  - ✓ total energy conservation;
  - ✓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

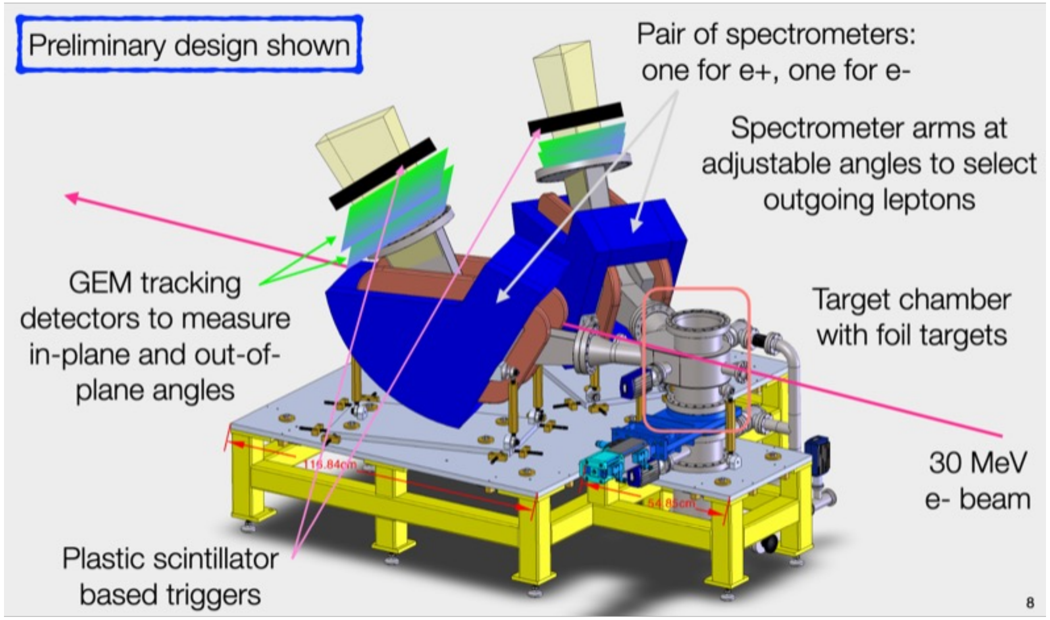


- MAGIX (proposed experiment with MESA at Mainz)
  - ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'} = [8 - 70]$ MeV;
  - ✓ magnetic spectrometer method;
  - ✓ only e^+e^- detected, $\varepsilon^2 \approx [2\text{x}10^{-7} - 8\text{x}10^{-9}]$

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

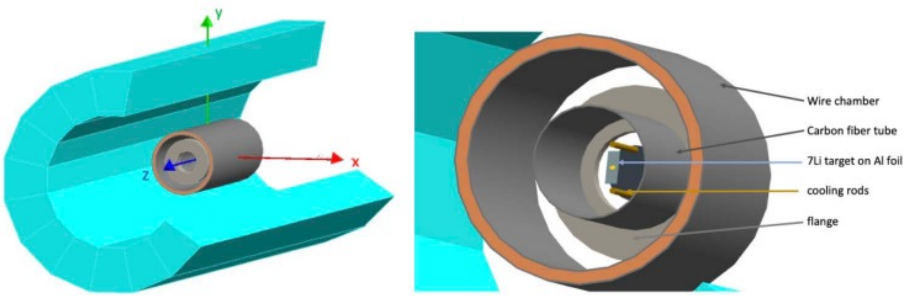


Figure 3. Geometry of the detector in Geant4 Monte Carlo.

- MAGIX (proposed experiment with MESA at Mainz)
  - ✓ search for $A' \to e^+e^-$ 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)