Searching for X17 at JLab
(JLab PR12-21-003)

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for the PRad collaboration

Outline

- Physics objectives (very short)
- the method
- experimental setup
- resolutions
- background, statistics and sensitivity
- 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, in particular.

- 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).

ATOMKI ^{8}Be Experiment

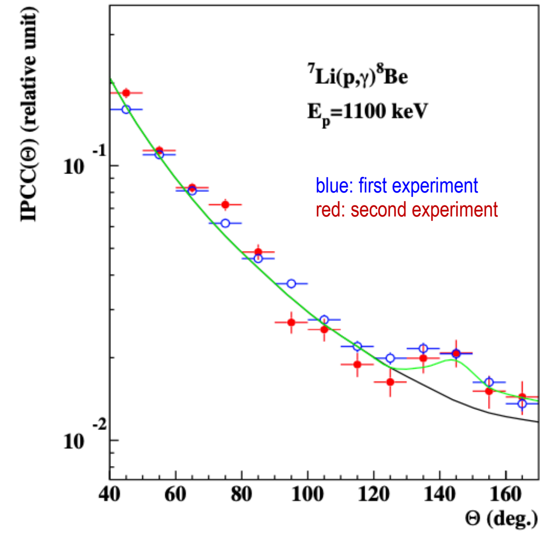
- ^{8}Be anomaly in nuclear transitions (*PRL 116(4):042501 (2016)*):
  - ✓ ^{8}Be excited states, decaying to ground state by E/M transitions.

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

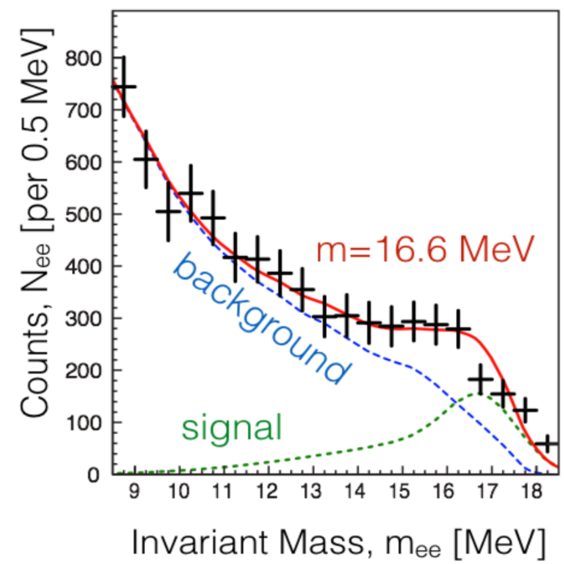
  $\rightarrow {}^{8}Be + \gamma$ (E/M decay)

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

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



- Over hundred theory papers:
  - ✓ Feng *et al*. *PRL 1 17, 071803 (2016):*
    X17 vector boson, 5th force mediator with SM;
  - ✓ Ellwanger *et al*. *JHEP 11, 039 (2016):*
    possible light pseudoscalar particle;
  - ✓ Kozaczuk *et al*., *PR D 95 115024 (2017):*
    possible axial vector boson;
  - ✓ Zhang and Miller, *PL B773:159-165, (2017):*
    … nuclear physics cannot explain the signal!
  - ✓ Zhang and Miller, *PL B 813:136061 (2021):*
    … protophobic X17 requires smooth energy spectrum over threshold…
  - ✓ ATOMKI group presented new data proving that requirement.

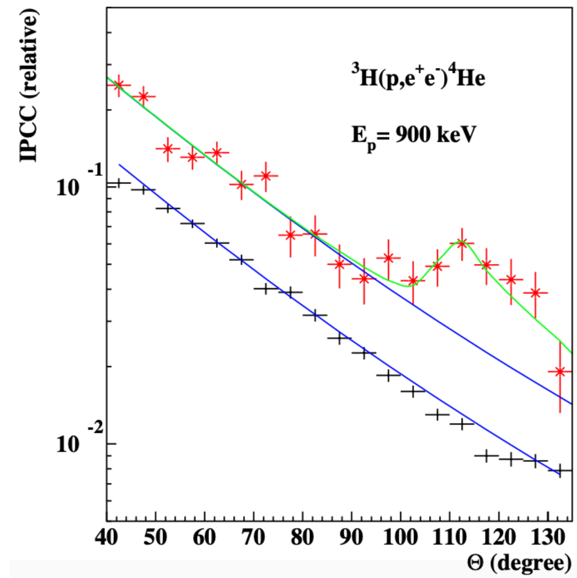


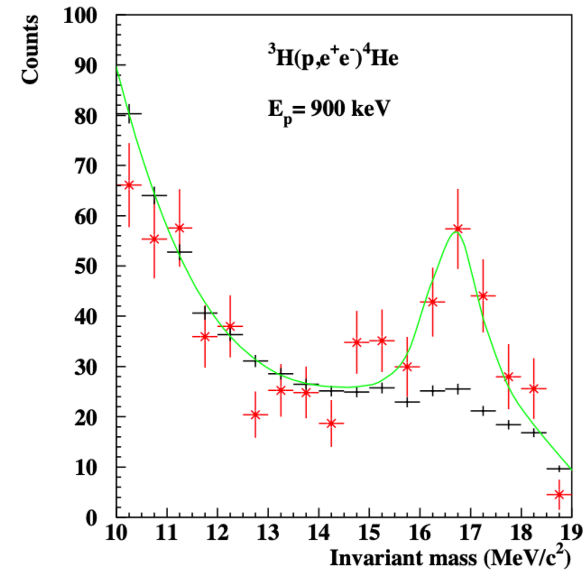
ATOMKI ^{4}He Experiment

- New results on ^{4}He with updated experimental setup and reduced background, *J. Phys.: Conf. Ser. 1643, 012001 (2020)* :

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

  - ✓ e^+e^- peak at different angles but the same invariant mass.
  - ✓ recently approved for publication.





- Requires an urgent independent experimental validation.

Objectives of this Experiment
(PR12-21-003)

- Two experimental objectives:

  1) Discover 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 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.

- This 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^- or $\gamma\gamma$) → full control of kinematics

- Electroproduction on heavy nucleus in forward directions:

$$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta, \quad \text{with} \quad X \rightarrow e^+e^- \text{ (with tracking)}$$
$$\text{and/or } X \rightarrow \gamma\gamma \text{ (without tracking)}$$

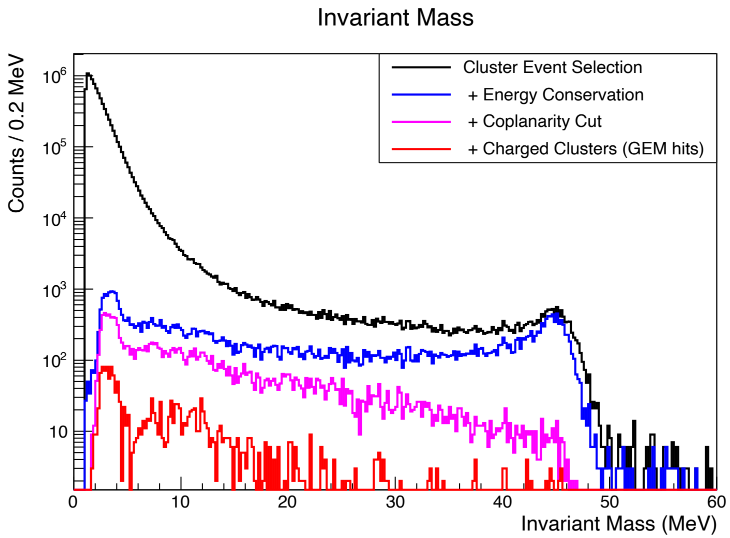
in mass range: [3 - 60] MeV
target: Tantalum, ($_{73}Ta^{181}$), 1 μm (2.4x10^{-4} r.l.) thick foil.

- All 3 final state particles will be detected in this experiment:
  - ✓ scattered electron, 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.

- Will provide a tight control of experimental background.

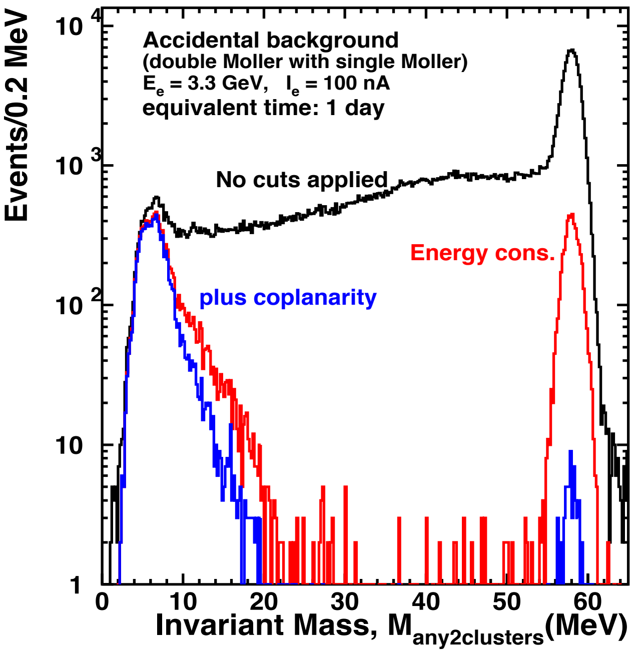
Event Selection Criteria

- Detection of all 3 final state particles will provide following event selection criteria:
  - ✓ conservation of total energy;
  - ✓ reaction coplanarity;
  - ✓ invariant mass;
  - ✓ particle charge;
  - ✓ reconstructed position on target plane.



- Critical feature of this experiment.
- Effects of these "cuts" are shown for PRad short test run on ^{12}C target.

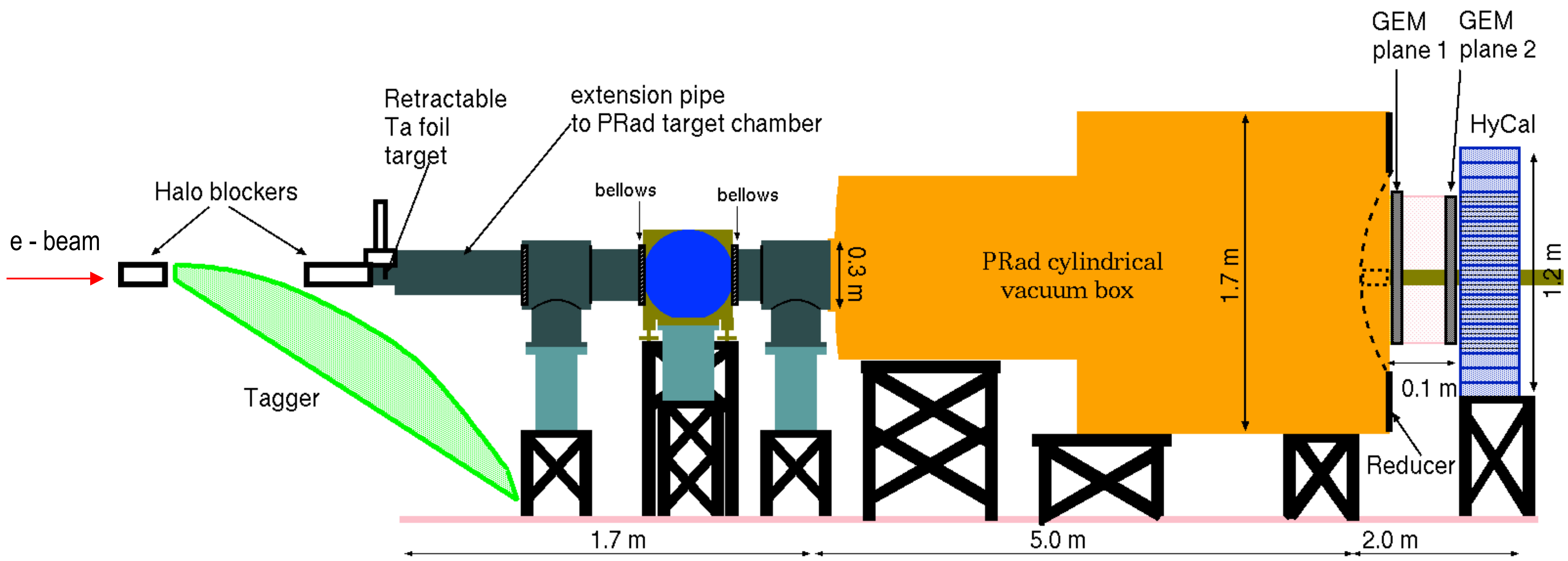
… and for MC accidental events simulated for this experiment.



Proposed Experimental Setup in Hall B at JLab

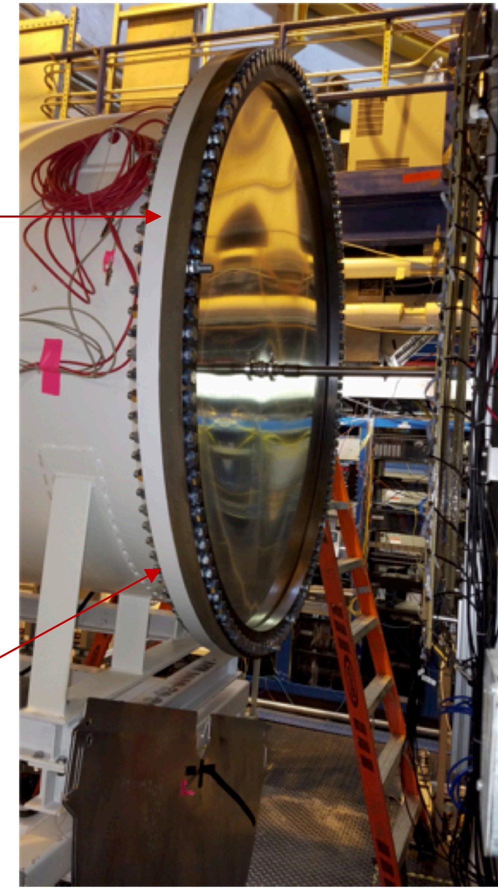
- Experimental setup is based on the PRad apparatus:
  - Hall B Photon Tagger will be used for $PbWO_4$ calorimeter calibration;
  - 1 μm Ta solid targets (2.4×10^{-4} r.l.) will be placed on a target ladder;
  - Two planes of GEM detectors on front of the $PbWO_4$ calorimeter, providing limited tracking;
  - Only the $PbWO_4$ part of the HyCal calorimeter will be used in this experiment.

Experimental Setup (Side View)

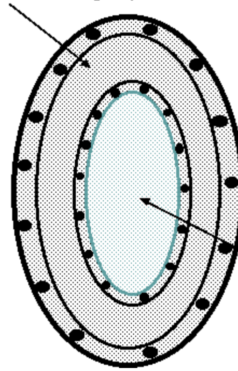


Scattering Chamber with Vacuum Window

- The PRad scattering chamber will be used.



Reducer flange (1.7 m dia.)

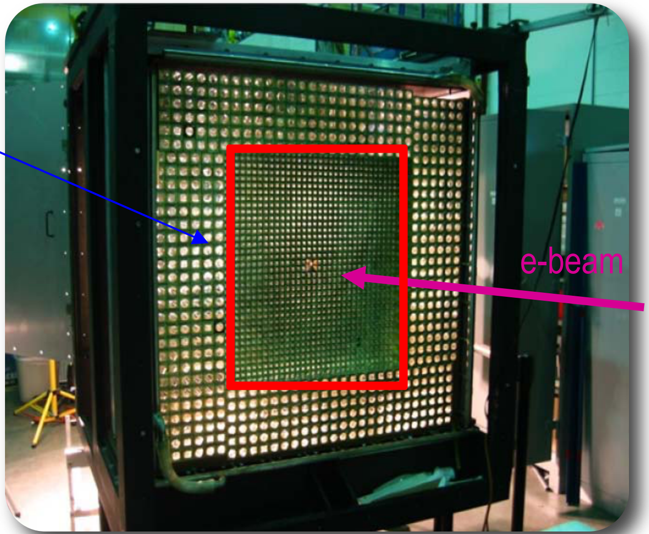


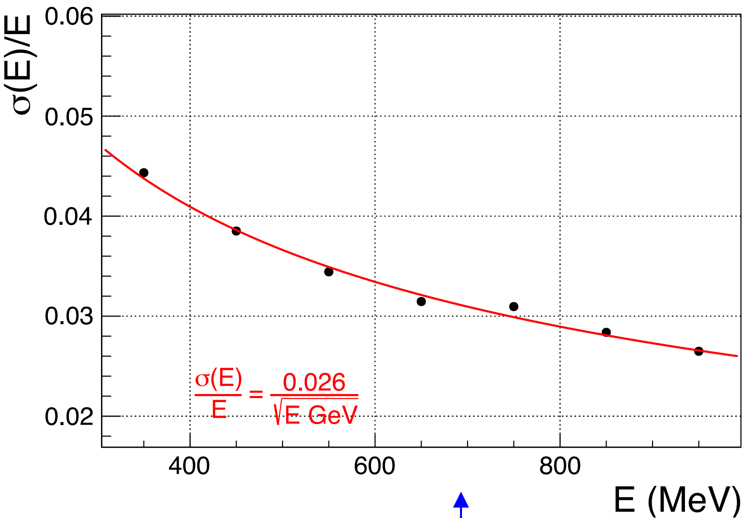
Thin Al. window
(1 m dia., 37 mil thick)

- with twice reduced vacuum window size:
  - ✓ 1m diameter and 1mm Al foil

Experimental Apparatus: $PbWO_4$ Electromagnetic Calorimeter

- The inner $PbWO_4$ part of HyCal only 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





Energy resolution (PrimEx measurement).

$PbWO_4$ crystals have excellent detection characteristics at MeV range energies too.

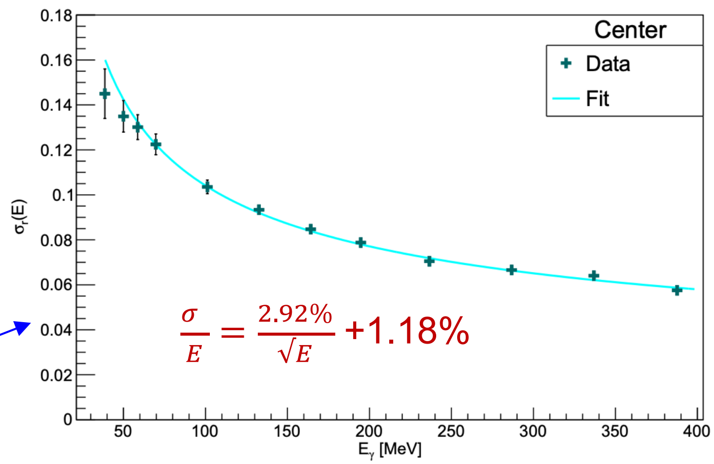
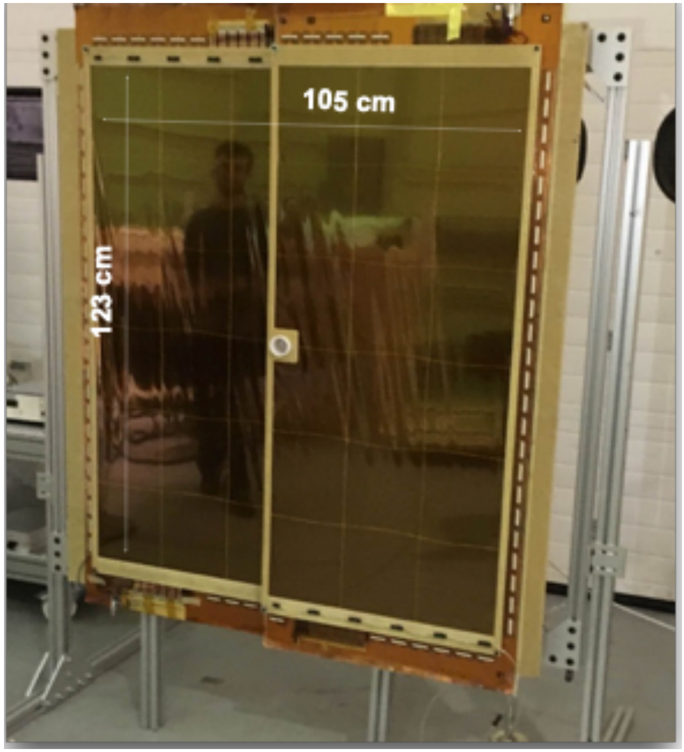


Figure 43: Measured relative resolution of the cluster energy response as a function of the incident photon energy E_γ for the center irradiation position in element 8. The errors are systematic.

M. Erzer, Masters Thesis, Mainz, 2020

Experimental Apparatus: GEM Coordinate Detectors (Tracking)

- Two planes of GEM detectors for tracking (limited tracking):
  - ✓ similar to PRad-II GEMs but smaller size: 68x68 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 (σ=72 μm);
  - ✓ will also be used to veto/select neutral clusters (like γ).
- Electronics: APV-25 based readout:



PRad GEMs (large size) before installation in Hall B.

Detection Efficiency (Geometrical Acceptance)

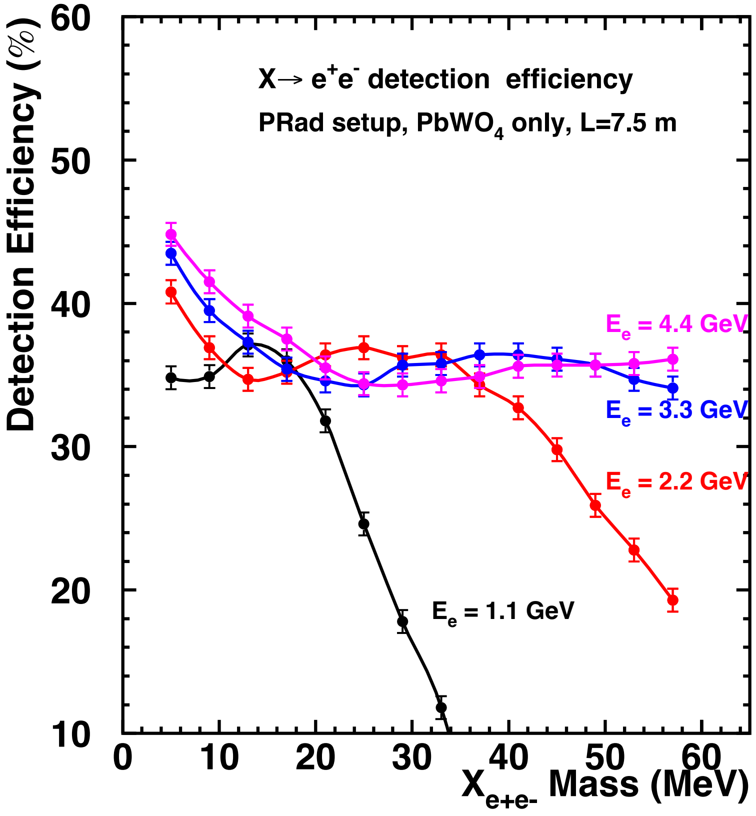
- Hardware trigger:
  - ✓ 3 clusters in $PbWO_4$ calorimeter;
  - ✓ each cluster energy: 30 MeV $< E_{clust} < 0.8xE_{beam}$ (rejects the elastic scattered electrons)
  - ✓ total energy sum in calorimeter: $\Sigma E_{clust} > 0.7xE_{beam}$

- Large phase space for virtual photon, γ^*:
  - ✓ energy interval: $E_{\gamma^*} \approx [0.2 - 1]\ E_{beam}$;
  - ✓ $\vartheta_{e'} \approx [0.4^0$ -- $3.7^0]$ angular range.

    provides X-particle production in wide energy spectrum in forward angles.

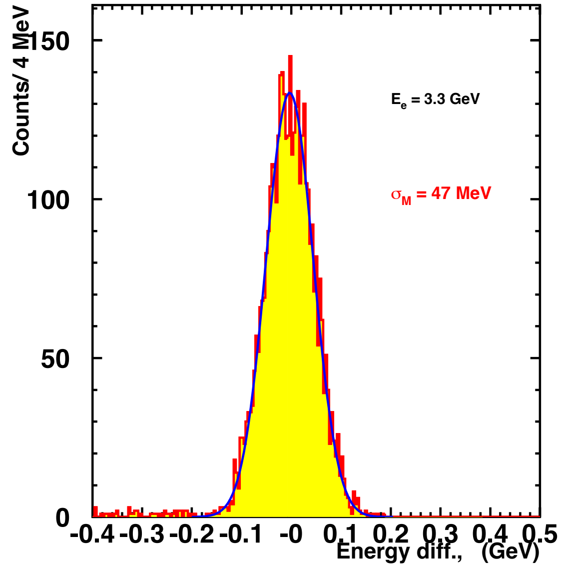
- Target to detector distance: L = 7.5 m provides good (integrated) detection efficiency in [3-60] MeV mass range for E_e = 2.2, 3.3 and 4.4 GeV.

- We plan to run with E_e = 2.2 and 3.3 GeV beams



Experimental Resolutions

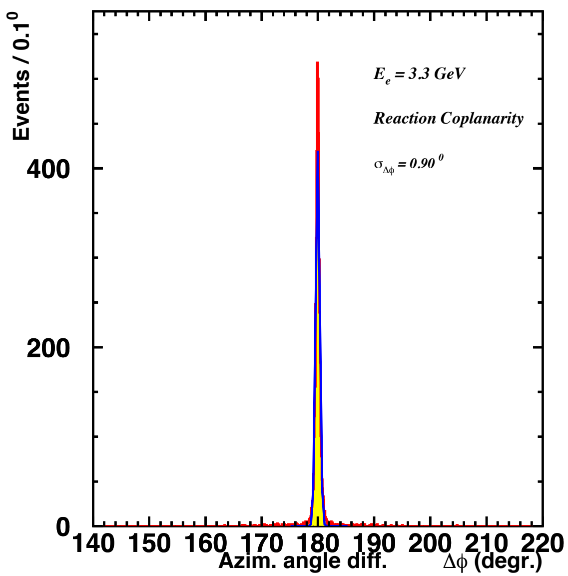
- Good energy resolution of $PbWO_4$ calorimeter (2.6% @ E=1 GeV) and 1 μm thin target provides powerful energy cut in this experiment (ΔE = 47 MeV @ 3.3 GeV beam).
  - ✓ important selection criterion for multi-channel and accidental events;
  - ✓ critical cut at low-mass range (see next slides).



- Coplanarity (between $\overrightarrow{P_{e'}}$ and ($\vec{P}_{e+} + \vec{P}_{e-}$) vectors):

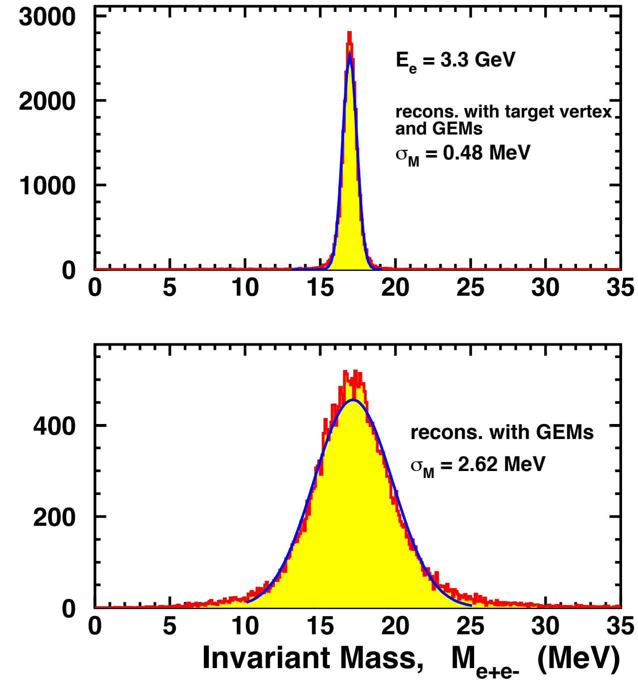
GEMs excellent position resolution (σ=72 μm), together with very thin 1 μm target (2.4×10^{-4} r.l.) provides an event selection criterion, important for:

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

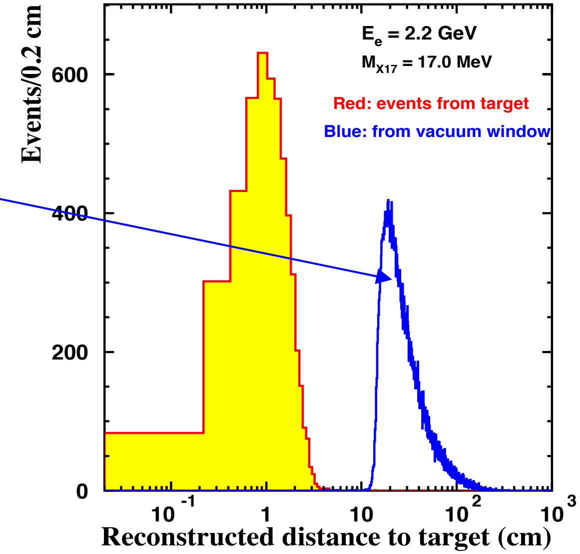


Experimental Resolutions (cont.)

- Invariant mass reconstruction (in two ways):
  - 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).
    - ✓ this will be used to check if "peak events" are originated from the target.



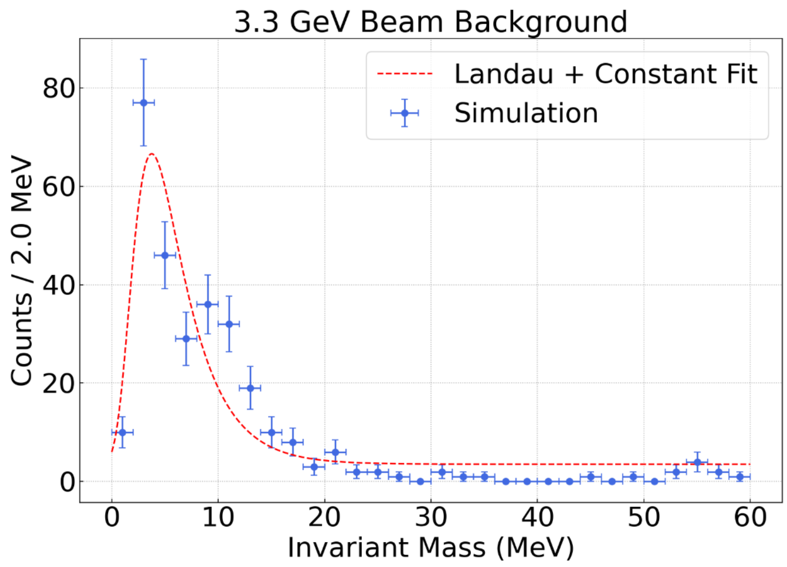
- Two GEM planes (with $PbWO_4$) will effectively discriminate events not originated from the target (example, from the vacuum chamber exit window).

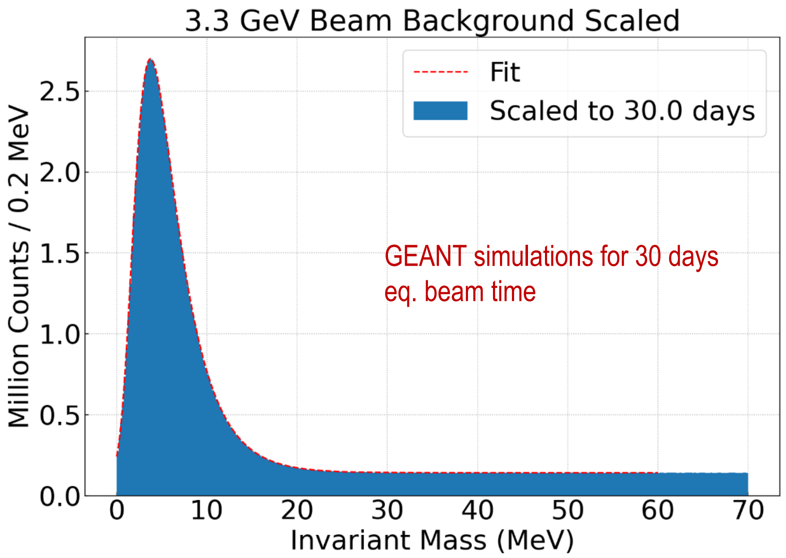


Physics Background Simulations

- Physics background was simulated in two different ways:
  1) with GEANT based MC simulation package;
  2) with MADGRAPH5 event generator and GEANT for tracing and detecting.

1) GEANT based Monte Carlo simulations
  - ✓ PRad-II GEANT based simulation package was adapted to this experimental setup;
  - ✓ all physics processes have been activated in GEANT;
  - ✓ large amount of beam electrons (N_e=3.5x10^{12}, equivalent to 5.6 s of beam time) passed through the target during MC simulations;
  - ✓ events with $N_{cluster} \geq 3$ were analyzed in the same way as the signals.

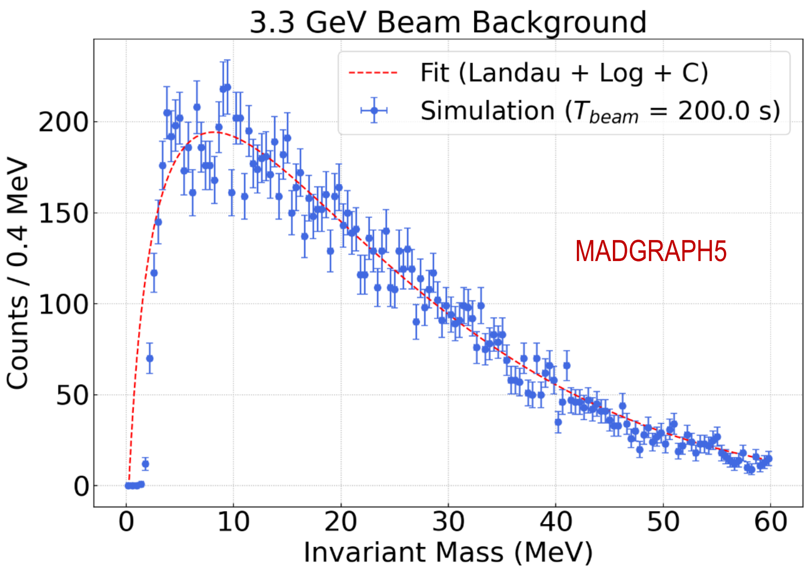


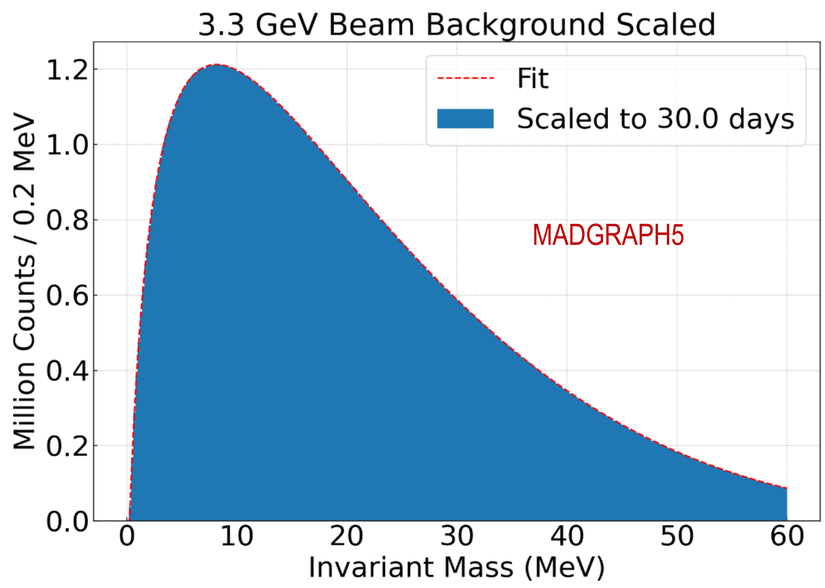


Physics Background Simulations (Method #2)

2) MADGRAPH5 based Monte Carlo simulations

- ✓ MADGRAPH5 was used to generate large statistics (2M) trident events (Bethe-Heitler, Radiative trident, and interference);
- ✓ these events were fed into the GEANT MC simulation package;
- ✓ events with $N_{cluster} \geq 3$ were analyzed as the signals.

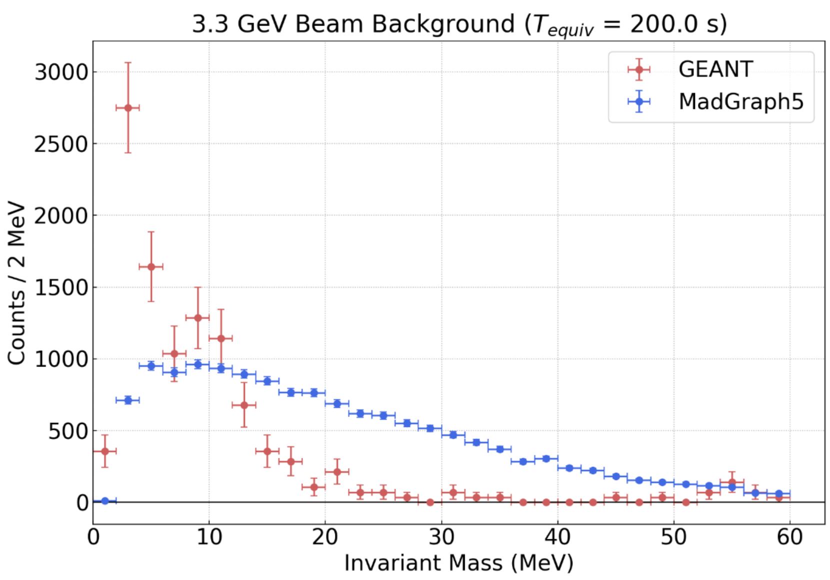


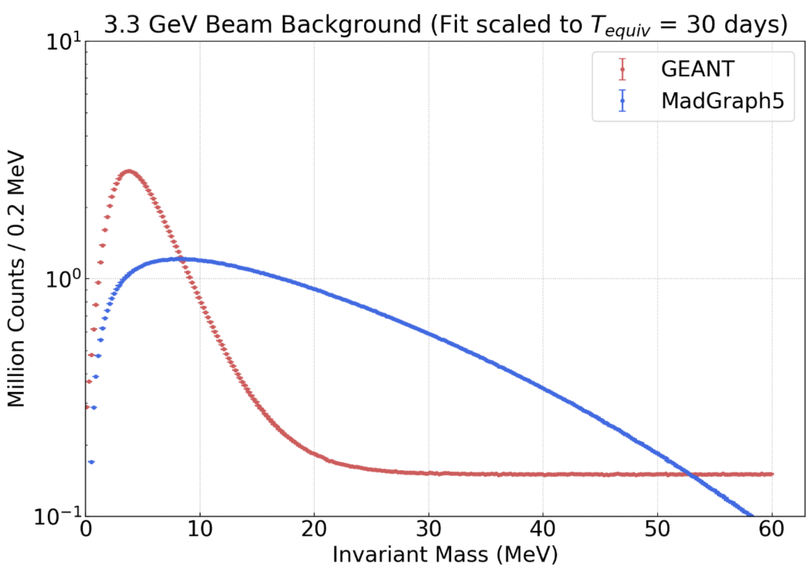


Physics Background Simulations (Comparison of Two Methods)

- Background simulation results were scaled to 200 seconds of beam time for comparison (left plot)
  - ✓ General agreement between two simulation methods;
  - ✓ slight shape difference (GEANT samples more small angle scattering events);
  - ✓ difference in total numbers is ≈37% (14016 vs. 10571, integrated over the mass)

- Both simulated backgrounds were scaled to 30 days of beam time (right plot)
  - ✓ they are used to estimate the 5σ sensitivity in the coupling constant $(\varepsilon)\ vs.mass$ phase space.





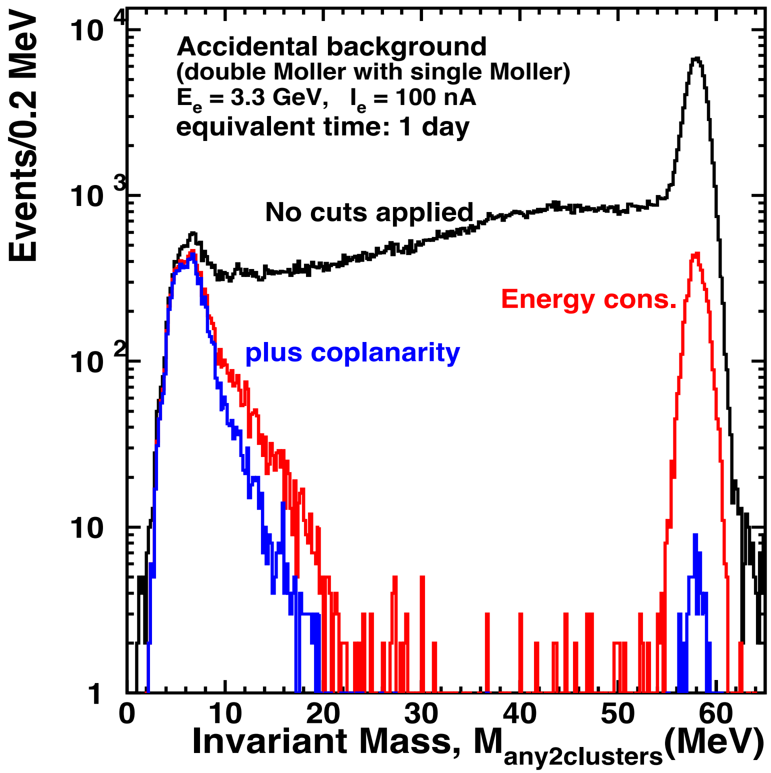
Accidental Background (Accidental Coincidence Rate)

- 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.



Statistics and Sensitivity Range

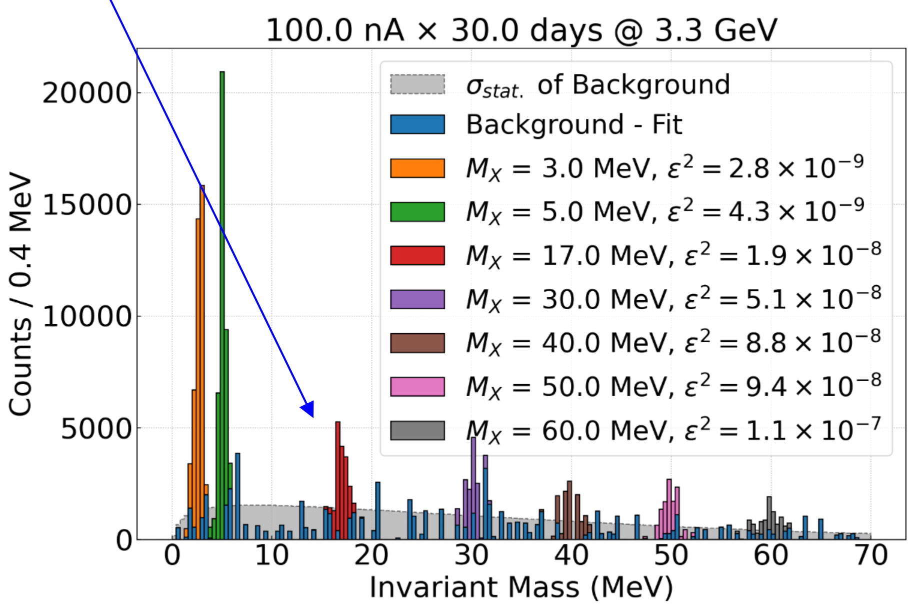
- Target: Ta; thickness: 1 μm ($t = 2.4\times10^{-4}$ r.l.), $N_{tgt} = 0.56\times10^{19}$ atoms/cm^2
  for $E_e = 3.3$ GeV and $I_e = 100$ nA ($N_e = 6.25\times10^{11}$ e$^-$/s),

  Example: the estimated X17 production rate:

  $N_{X17} \sim N_C * N_e * t * \varepsilon^2 * (m_e/m_x)^2$ (J. D. Bjorken et al. Phys. Rev. D, 80:075018, 2009)

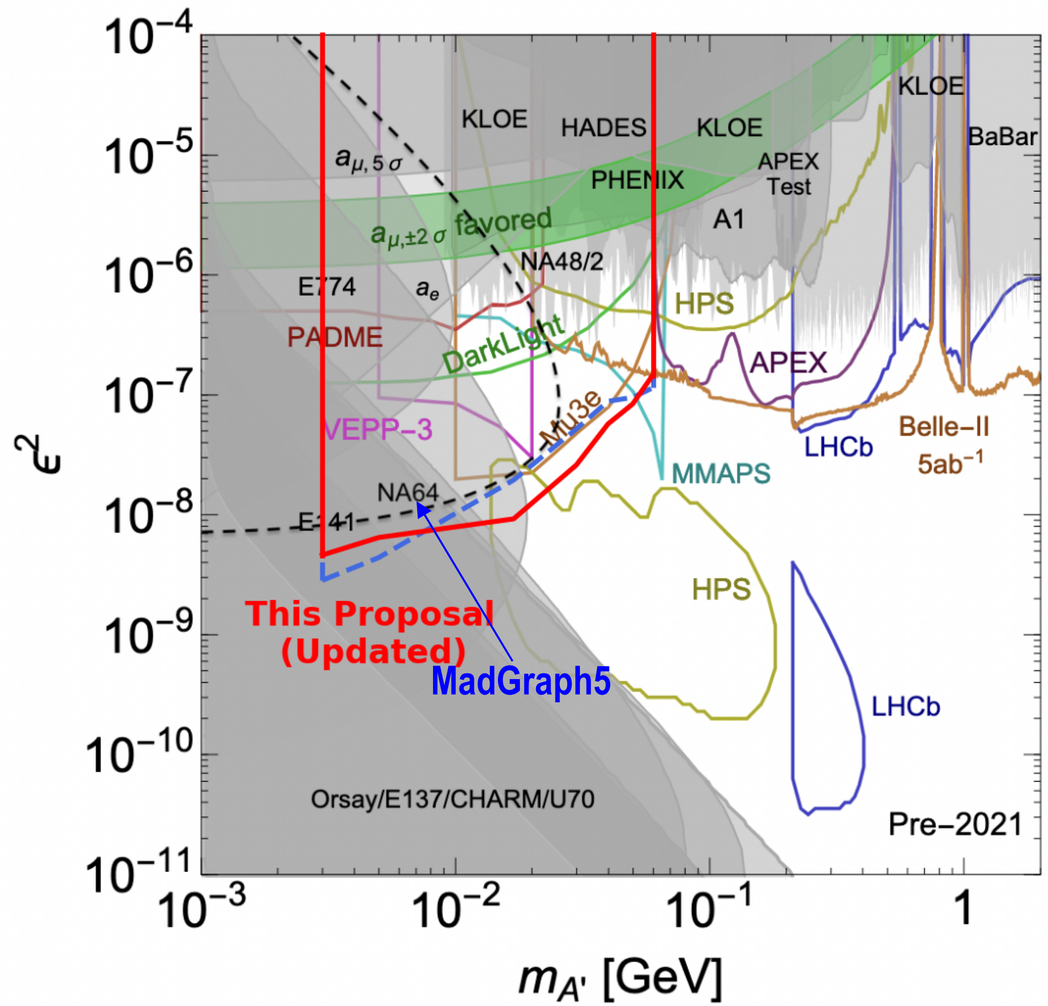
  $\approx$ 32,000 produced events per 30 days for $\varepsilon^2 = 1.9\times10^{-8}$ ($N_C \approx 5$)

	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: $\varepsilon^2 \approx [10^{-9} - 10^{-7}]$
- This proposal uses 5σ limits (discovery criterion as per PDG), while the common practice is to use from 2 to 2.4 σ.
- Example, NA64 results have 90% confidence limits.



Summary and Outlook

- We developed a cost-effective, ready-to-run experiment based on the PRad apparatus to:

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

- Detection of all 3 final state particles will provide a tight control of experimental background, reaching to a low range in coupling constant ($\varepsilon^2 \approx [10^{-9} - 10^{-7}]$) .
  (a unique feature of this experiment).

- The experiment is equally sensitive to charged (e^+e^-) or neutral $(\gamma\gamma)$ decay channels.
  (a unique feature of this experiment).

- Experiment was approved by PAC49 in past July with a C2 condition, requiring one more discussion (the background part) in next year's PAC50.

- We are preparing the experimental setup to be ready for a full approval.

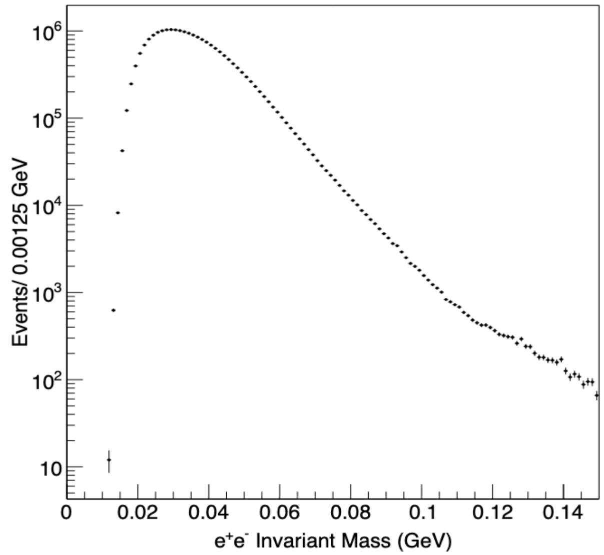
arXiv:2108.13276 [nucl-ex]

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

Backup Slides

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, $\varepsilon^2 > 9\times10^{-8}$;

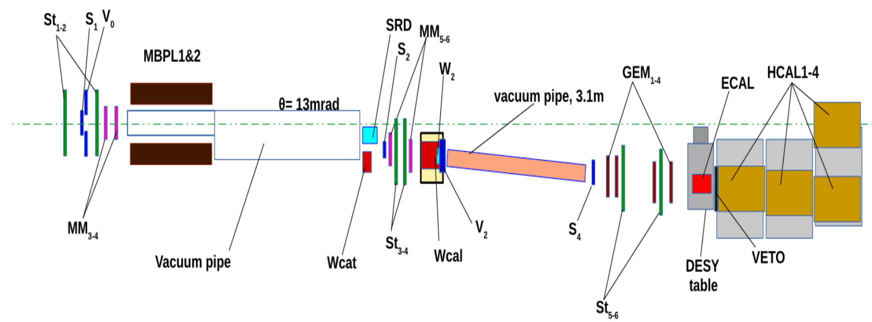
- DarkLight (approved JLab experiment)
  - ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'}$ = [10-90] MeV;
  - ✓ magnetic spectrometer method;
  - ✓ e^+e^- detected, $\varepsilon^2 > 3\times10^{-7}$;

- 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: $\leq$ 23 MeV,
  - ✓ experiments in 2018 and 2020:

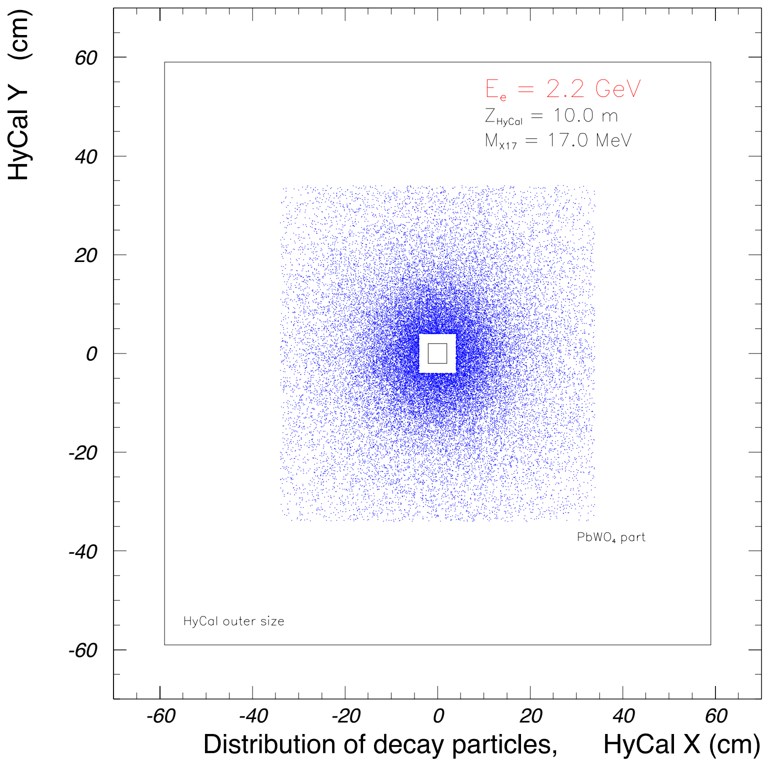
    $1.4x10^{-8} \leq \varepsilon^2 \leq 4.6x10^{-7}$ (90% confidence limit)
  - ✓ new proposal for 2021.



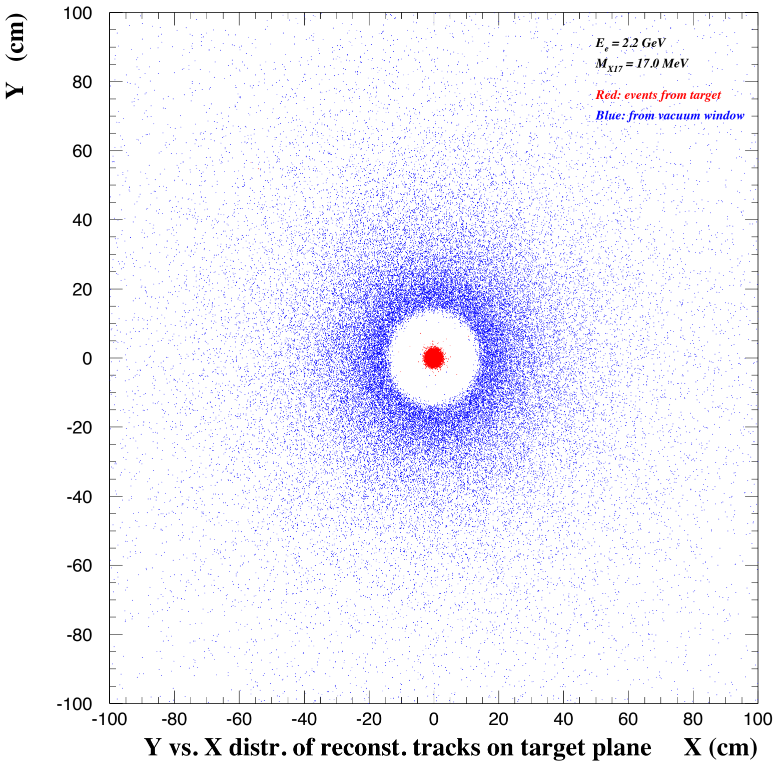
- MAGIX (proposed experiment with MESA at Mainz)
  - ✓ search for $A' \rightarrow e^+e^-$ in $M_{A'} = [8 - 70]$ MeV;
  - ✓ magnetic spectrometer method;
  - ✓ only e^+e^- detected, $\varepsilon^2 \approx [2x10^{-7} - 8x10^{-9}]$

Reaction Kinematics

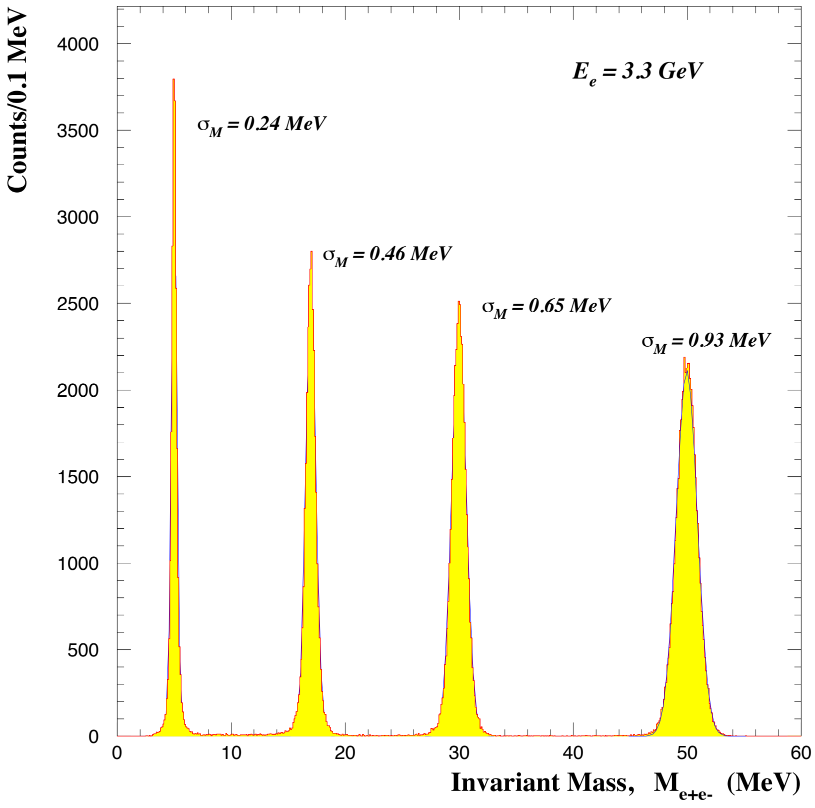
- X-Y distribution of all 3 particles on HyCal



- Reconstructed positions on target plane

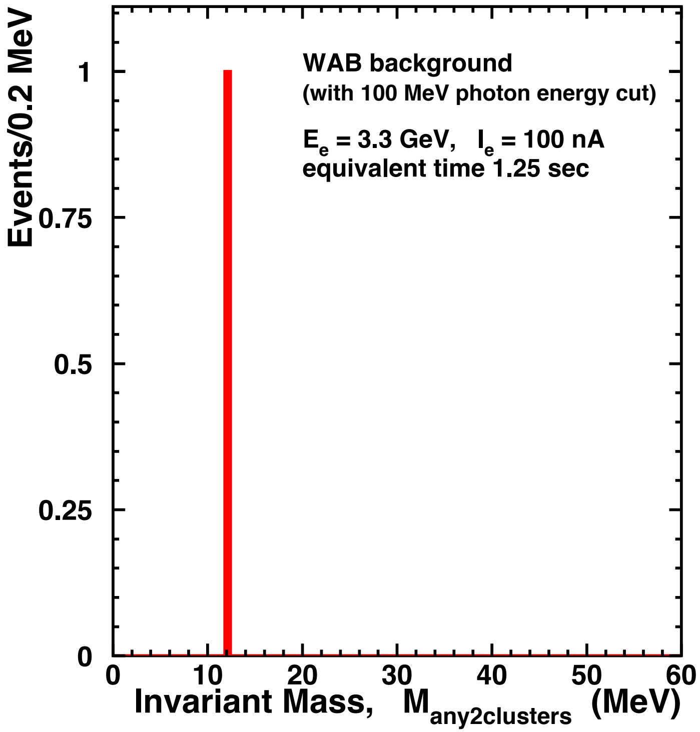


Kinematics (invariant mass resolutions)



Physics Background Simulations (WAB Generator)

- Wide Angle Bremsstrahlung (WAB) generator was also used to estimate the background (suggested by HPS people).
  - ✓ 1 M events were generated for E_e = 3.3 GeV beam, equivalent to 1.25 sec of I_e = 100 nA beam;
  - ✓ generator thresholds: $E\gamma$ = 100 MeV, $\vartheta_{x,y}$ = 0.003 rad;
  - ✓ these events also fed to the GEANT MC code,
  - ✓ detected events with $N_{cluster} \geq 3$ were analyzed same way as the signals.



- Estimated rate for this process is: ~1 Hz
  - ✓ not significant contribution to the background