X17 Search Experiment in Hall B

“A Direct Detection Search for Hidden Sector New Particles in the 3-60 MeV Mass Range”

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For the PRad-II/X17 collaboration

HPS collaboration meeting, June 3-5, 2024, Jefferson Lab, Newport News.

Outline

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

Physics Goals of the X17 Search Experiment

(Approved by PAC50 in 2022, E12-21-003)

- Two experimental objectives:

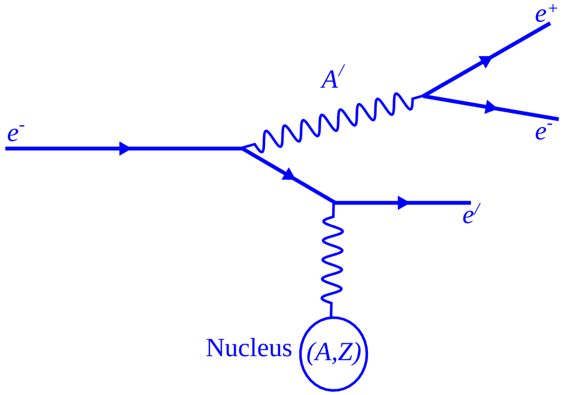
  1) Validate existence or establish an experimental upper limit on the electroproduction of the hypothetical X17 particle claimed in several ATOMKI low-energy proton-nucleus experiments.

  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.

The Reaction of the Interest

$$e^- + Ta \longrightarrow e^-\ \ e^-\ e^+$$

A' production



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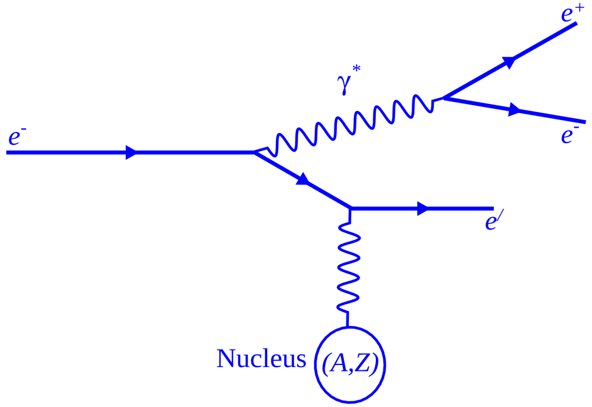
Rad tridents



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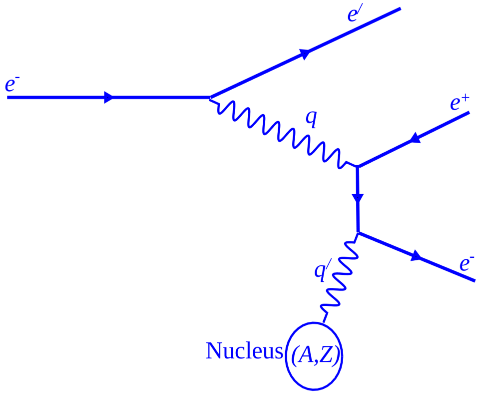
BH



Experimental Method

- The method:
  - ✓ "bump hunting" in the invariant mass spectrum over the beam background.
  - ✓ 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 → e' + γ^* + Ta → e' + X + Ta, with X → e^+e^- (with tracking)
  and X → $\gamma\gamma$ (without tracking)

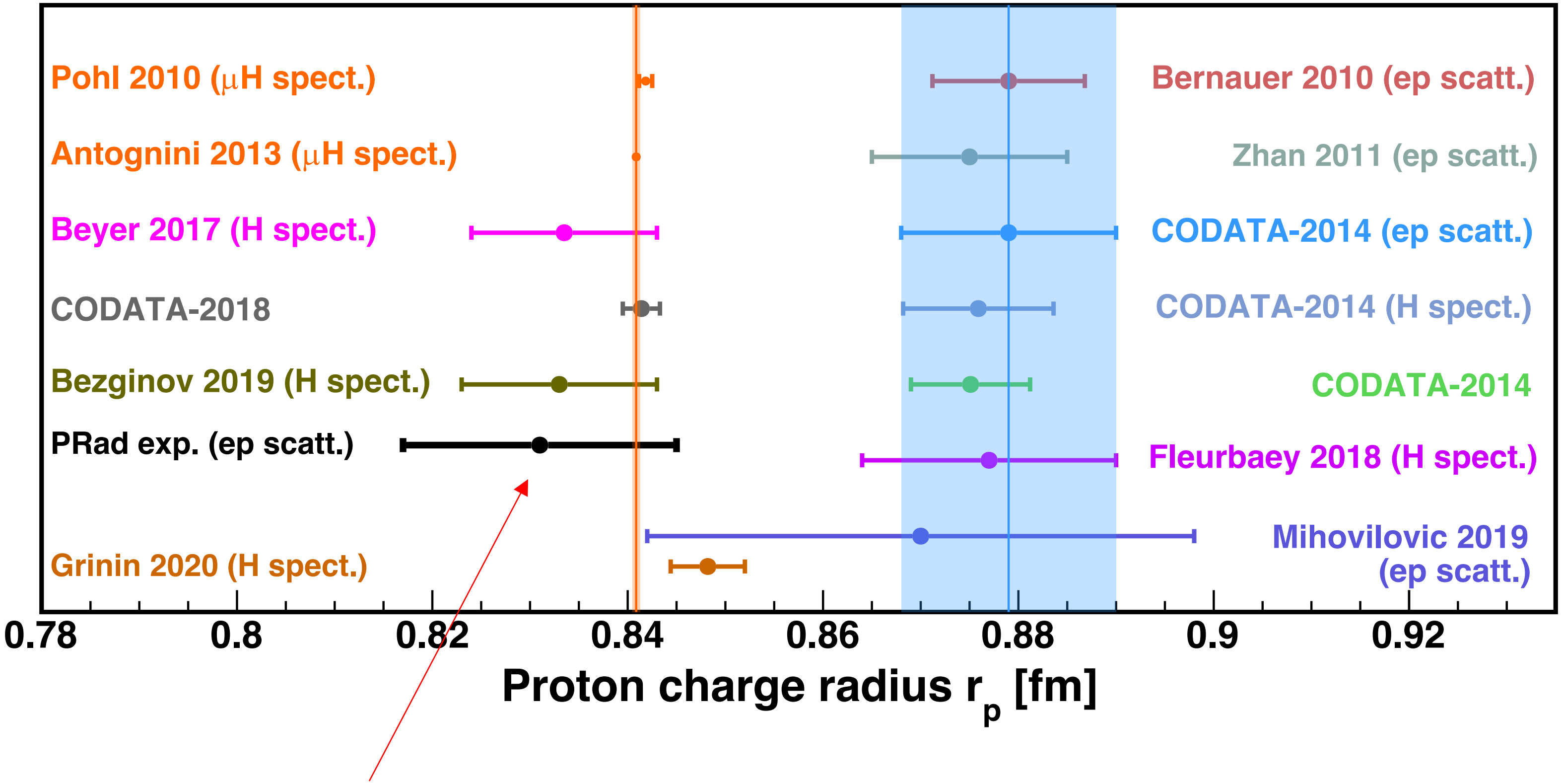
  in mass range of: [3 - 60] MeV
  Target: Tantalum, ($_{73}Ta^{181}$), 1 μm (2.4x10^{-4} r.l.) thick foil.

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

The PRad Experiment and its Result on the Proton Radius

(performed in 2016 in Hall B)



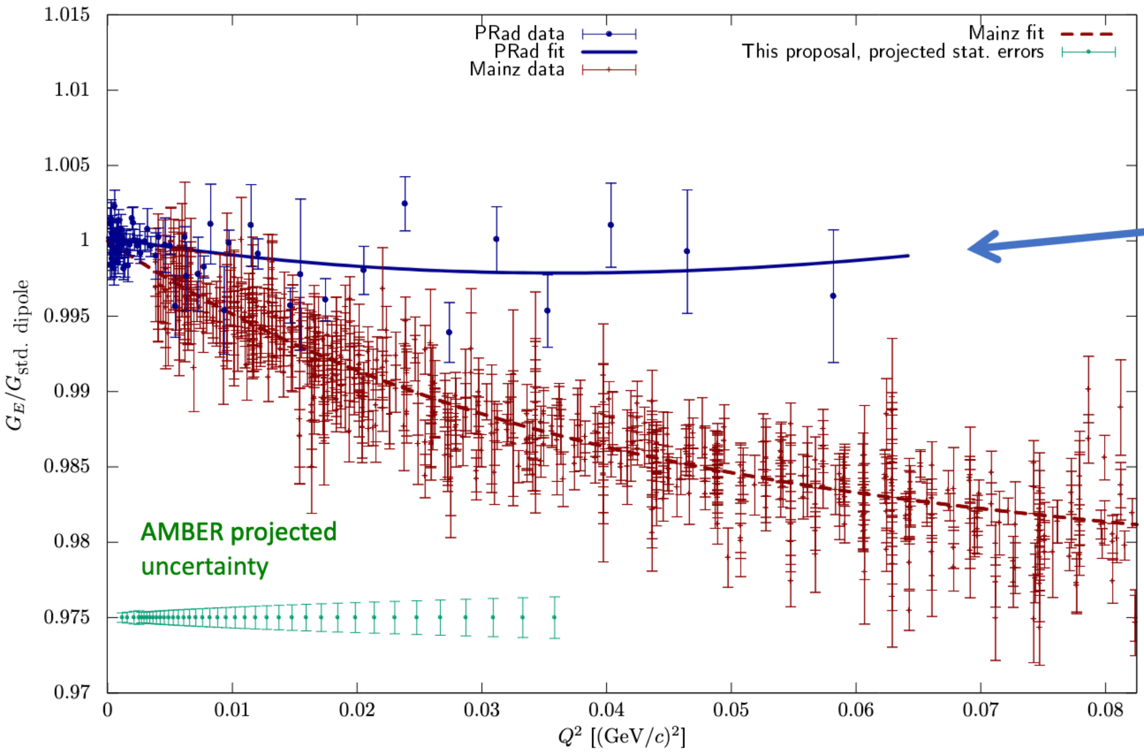
PRad final result: R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

published in: Nature 575, 145–150 (2019)

Major Objectives of the PRad-II Experiment

(approved by PAC48, 2020, E12-20-004)

- The “Puzzle” is still not fully resolved!
- PRad-II will improve the radius measurement by a factor of 4
- There is a certain discrepancy between the very recent two FF measurements (JLab and Mainz).



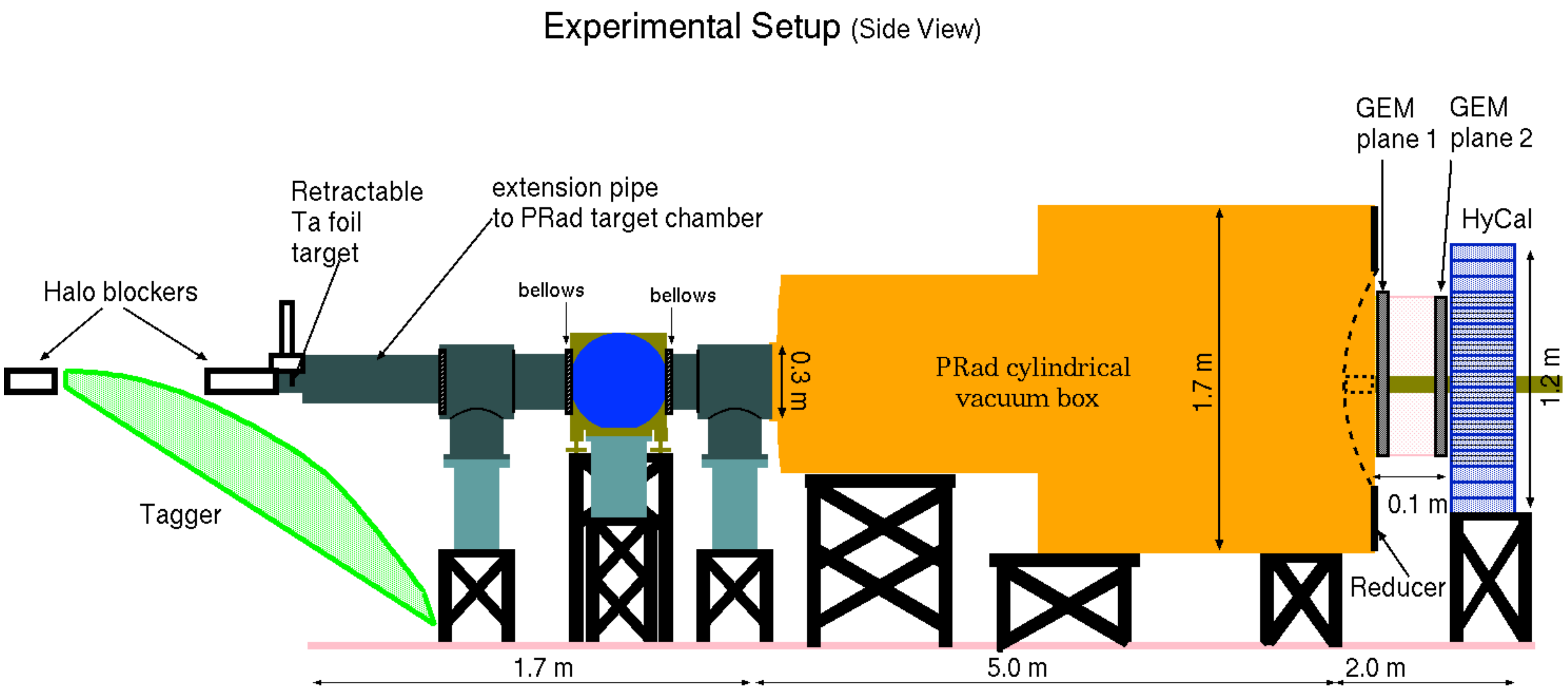
Proton Radius Experiment at Jefferson Lab

MAINZER MIKROTRON

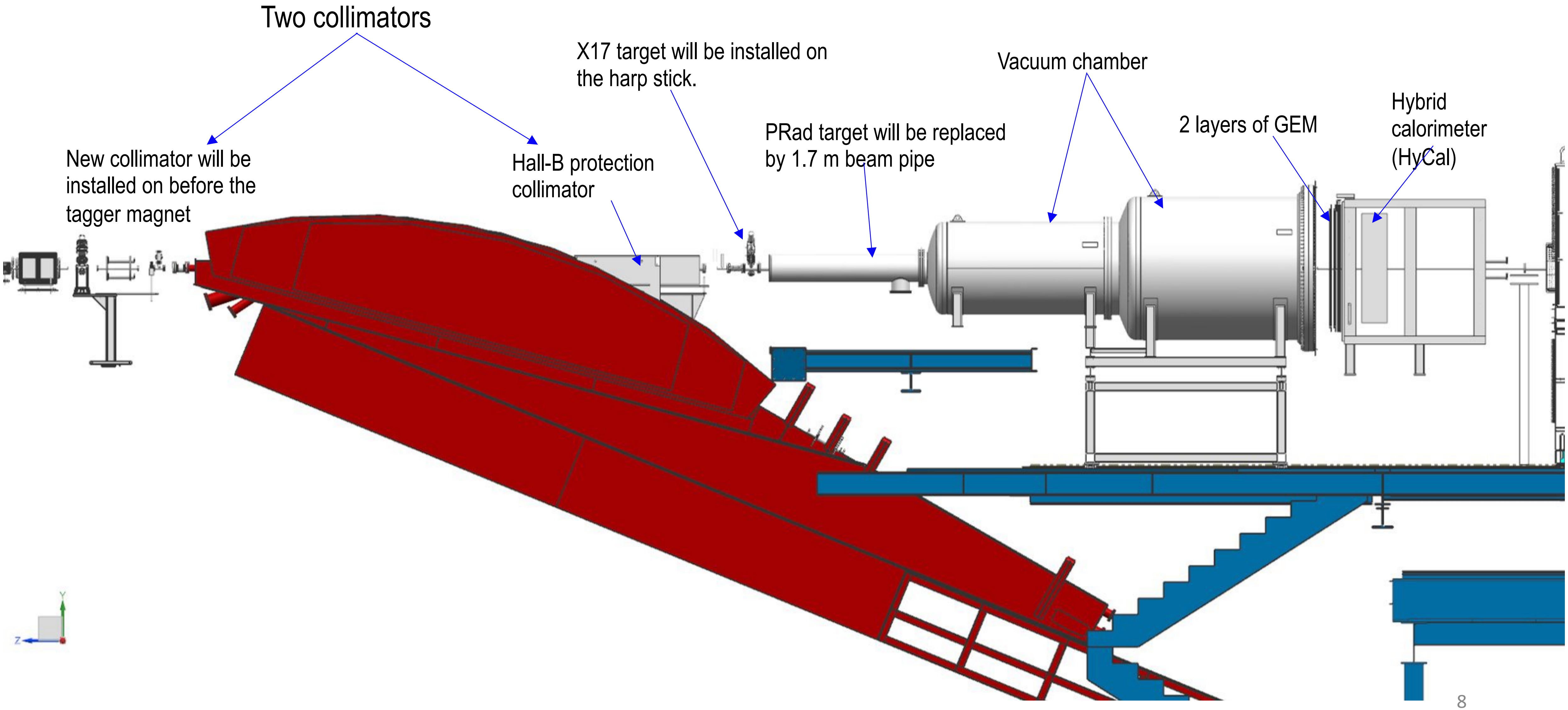
figure: J. Bernauer

PRad-II Experimental Setup Adjusted for the X17 Experiment

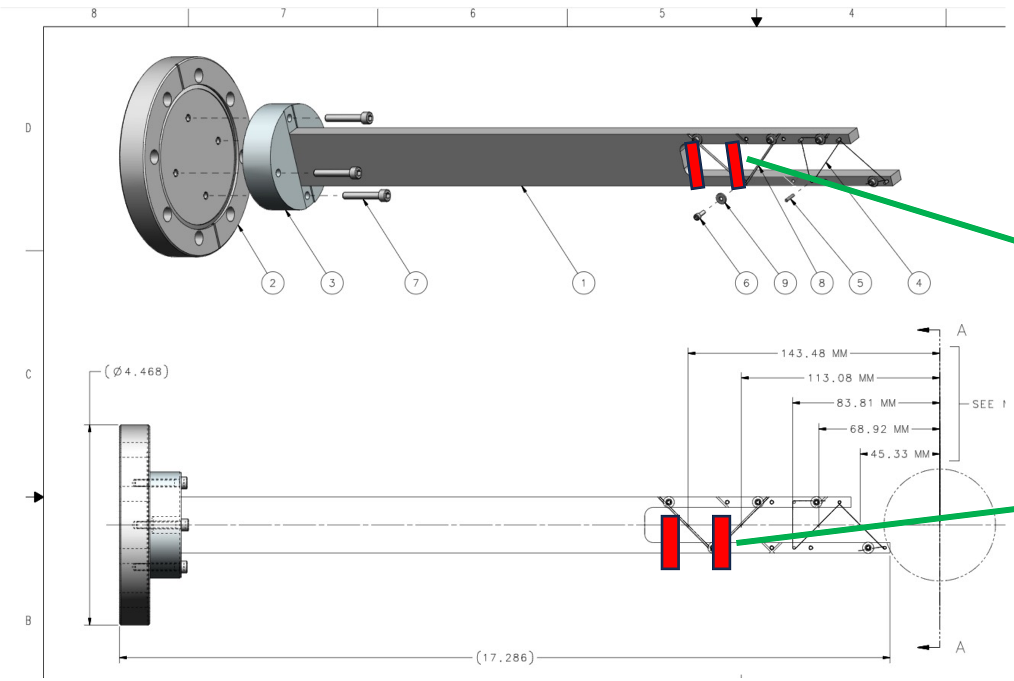
The experimental setup is based on the PRad-II experiment, which had run on May–June of 2016.
Located on the space frame in between the tagger magnet and the CLAS12 detector.
The most significant change is the replacement of the windowless hydrogen gas target with a d=30 cm, l= 1.7 m beam pipe.



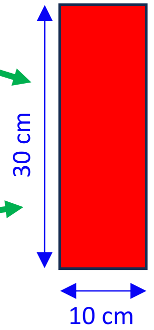
X17 Experimental Setup



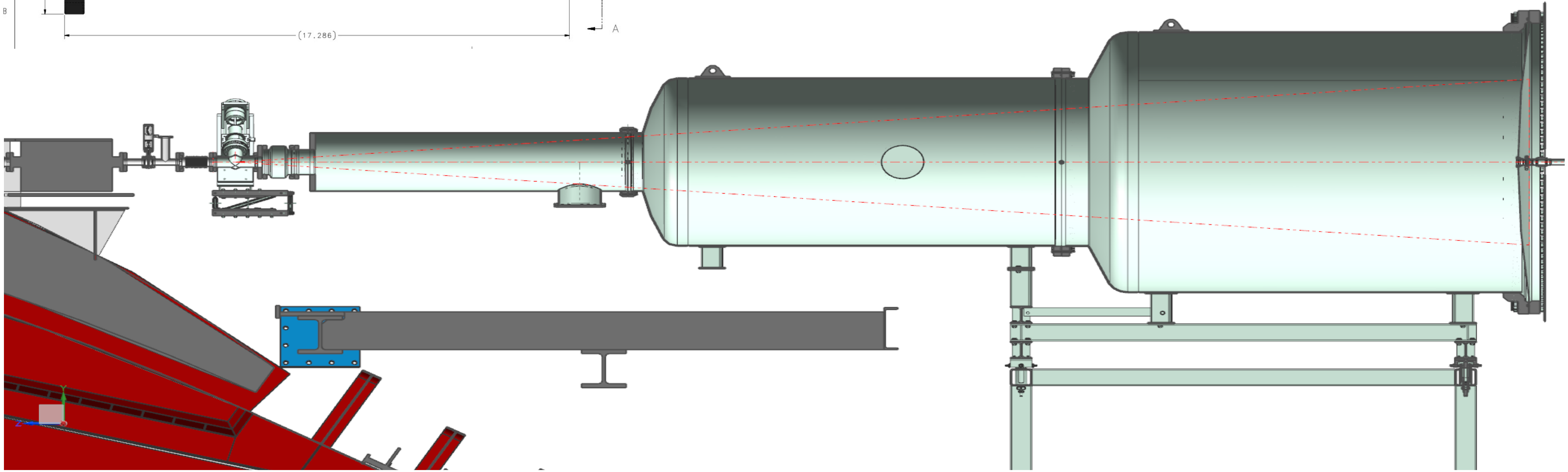
New Target Ladder



The target will be placed on the 2H02A harp stick.



Two 1 μm “Ta” target foils will be placed in the place of thick wires of the harp.
“Ta” foils are commercially available.

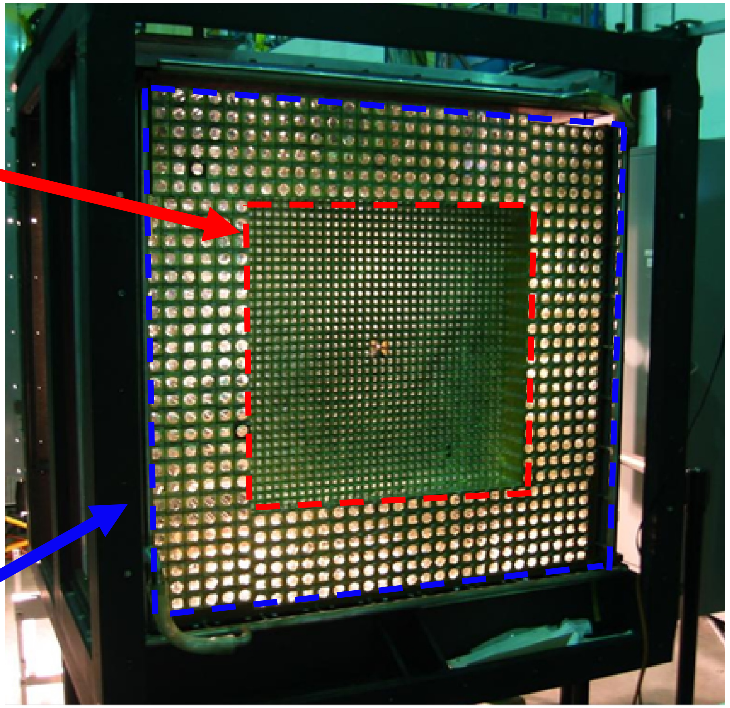


HyCal Hybrid Electromagnetic Calorimeter

(large acceptance, high position and energy resolutions)

$PbWO_4$ shower detectors (inner part):

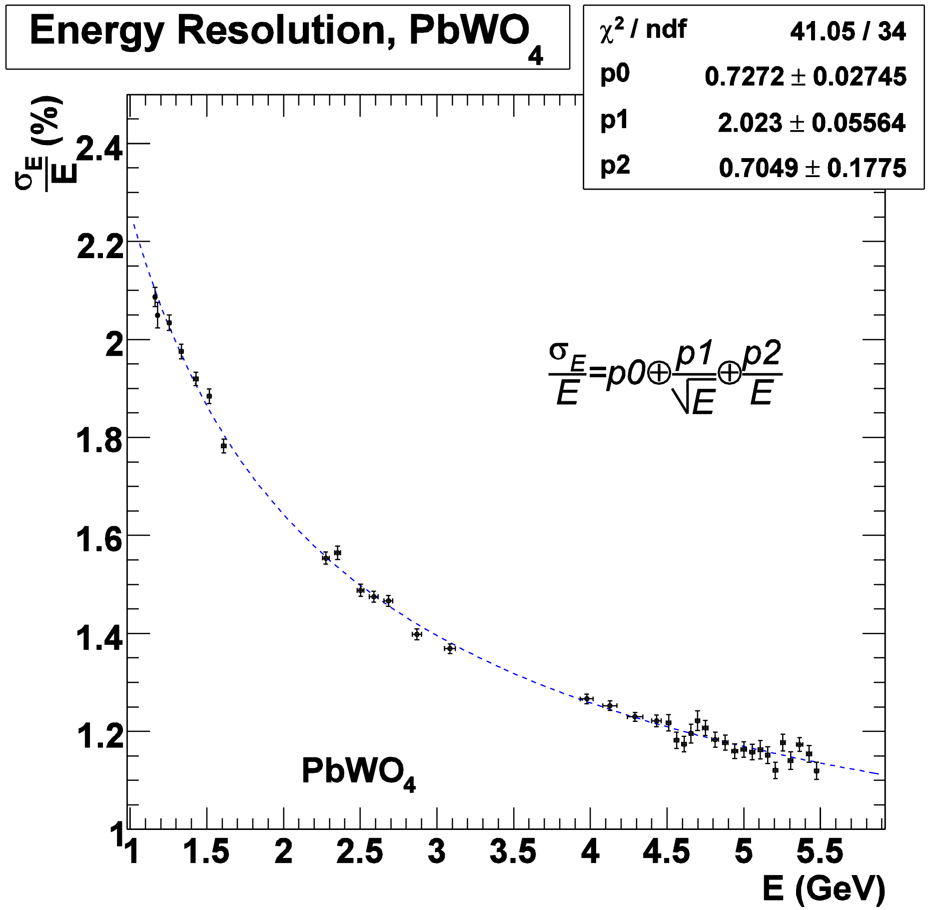
- 2.05 × 2.05 cm^2 x 18 cm (20 Rad. Length)
- 34 × 34 square matrix assembly
- inner 2x2 crystals are removed
- 70 x 70 cm^2 inner part
- full azimuthal coverage (1152 detectors)
- covers very forward angles (0.47° - 3.78°)

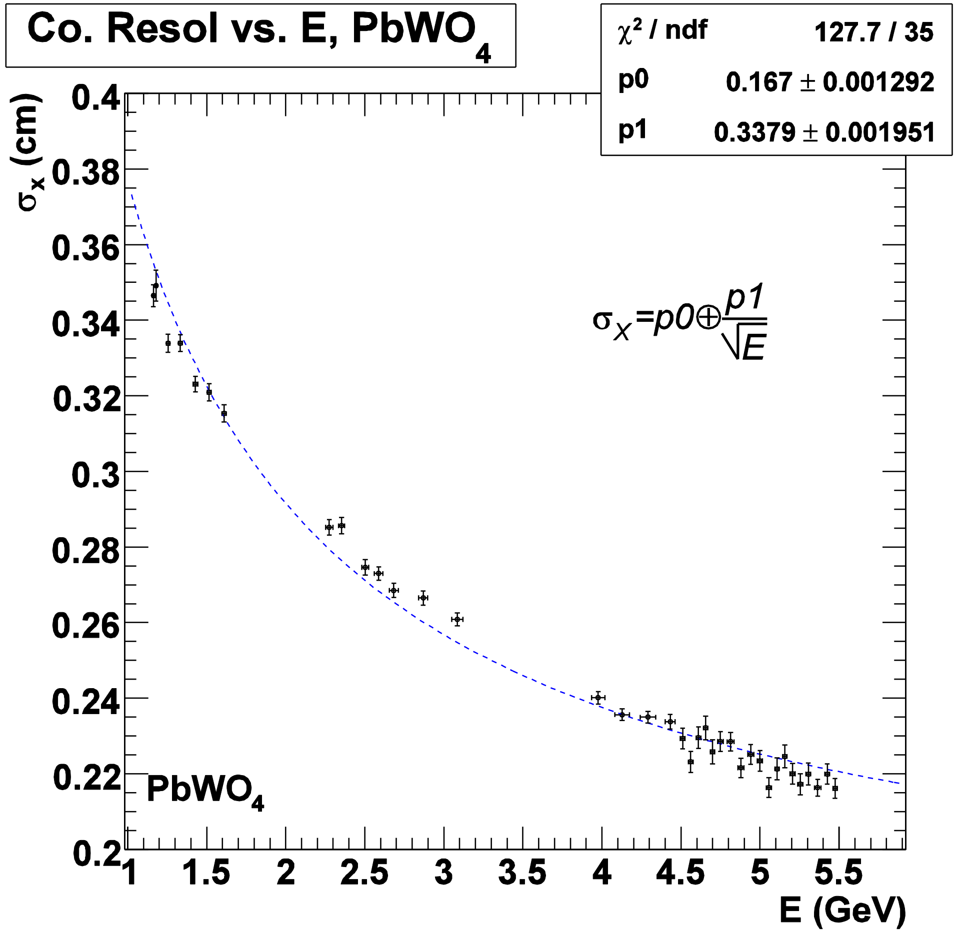


Pb-glass detectors (outer part):

- 3.82 x 3.82 cm^2 x 45 cm Pb-glass
- 576 Cherenkov shower counters
- will not be used in X17 experiment

$PbWO_4$ Energy and Position Resolutions





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

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

Experimental Apparatus: GEM Coordinate Detectors (Tracking)

- Two planes of GEM detectors for tracking:
  - ✓ 123 cm x 123 cm each (matching all 3 experiments)
  - ✓ 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 veto neutral particles for $X \to e^+e^-$ channel and select the charged particles for $X \to \gamma\gamma$ channels.

- Electronics: APV-25 based readout system.
- UVA group is responsible for this part.

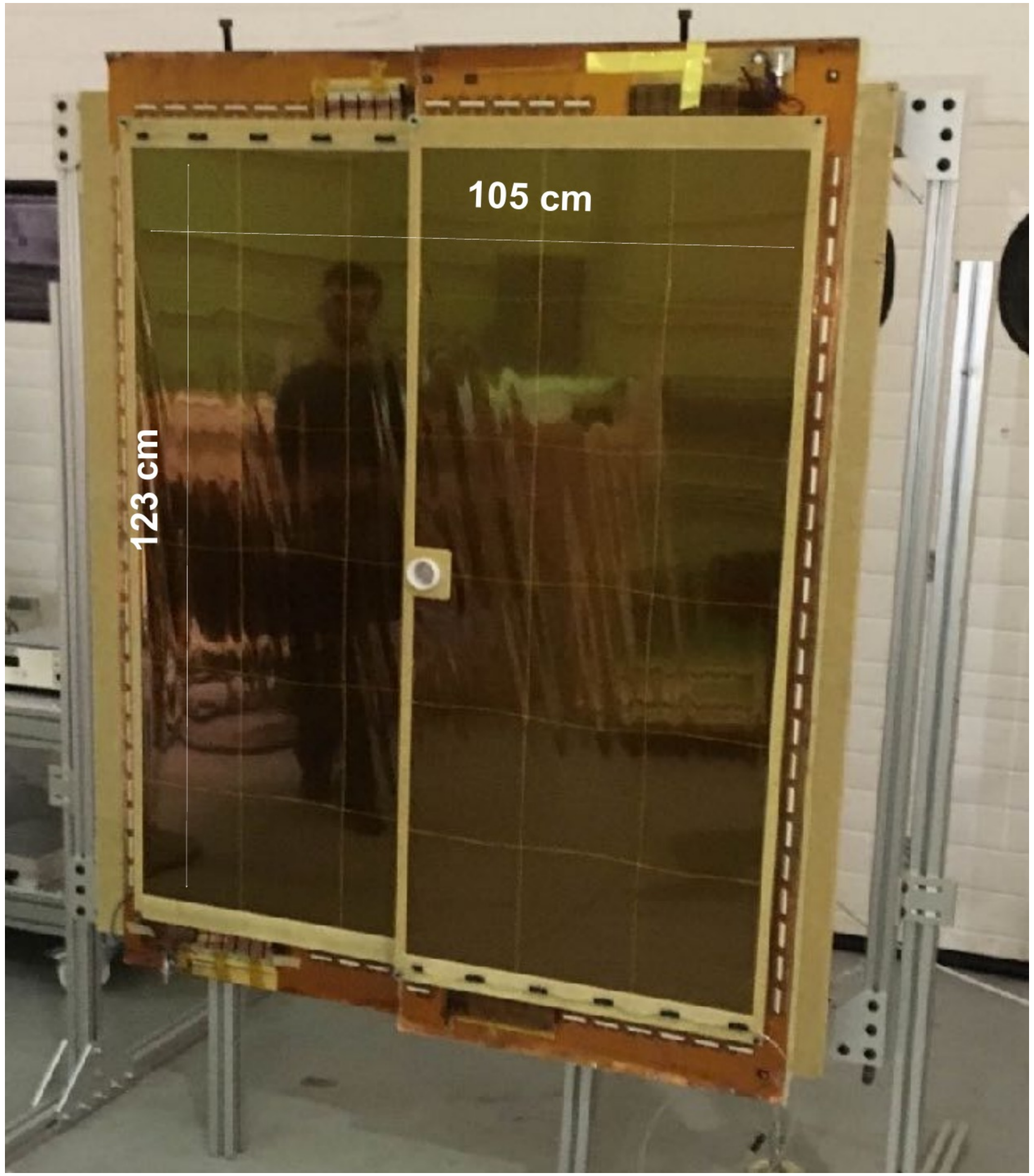


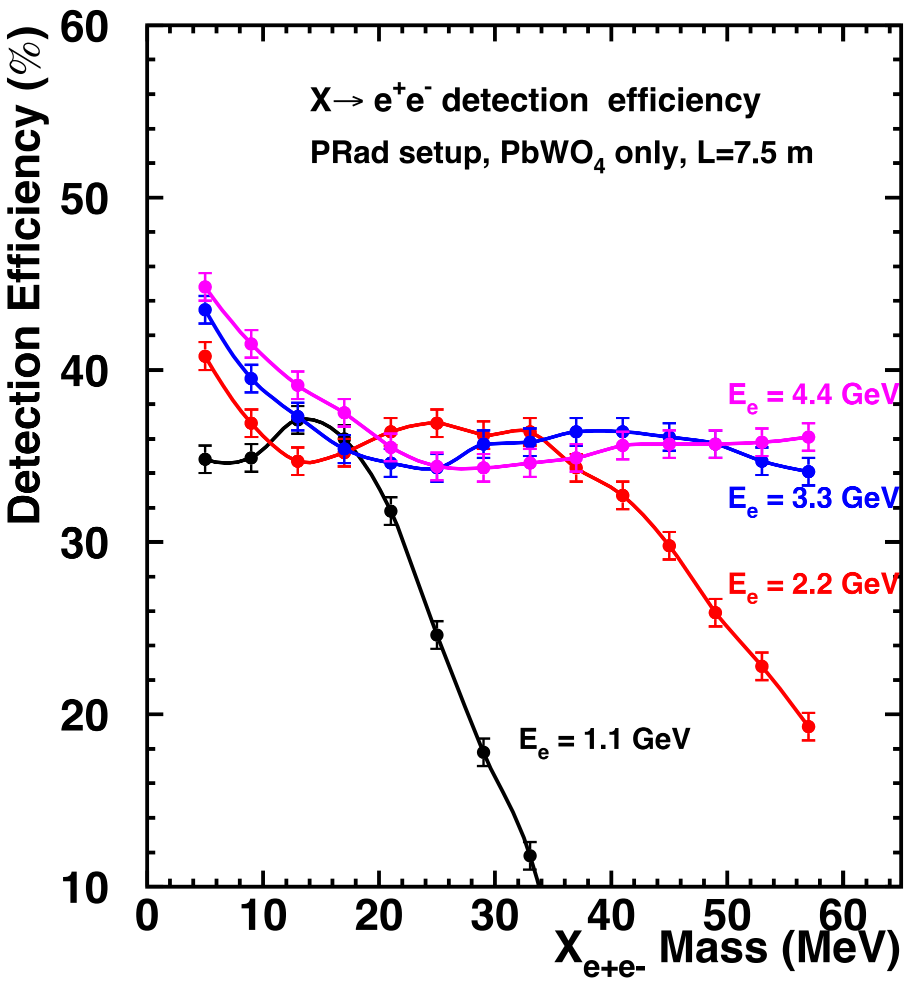
Photo from PRad GEM

Detection Efficiency (Geometrical Acceptance)

- 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: $E_{\gamma^*} \approx [0.2 - 0.8]\ E_{beam}$;
  - ✓ $\vartheta_{e'} \approx [0.4^0 \text{ -- } 3.7^0]$ angular range.
  - ✓ provides X-particle production in wide energy spectrum and in forward solid angle

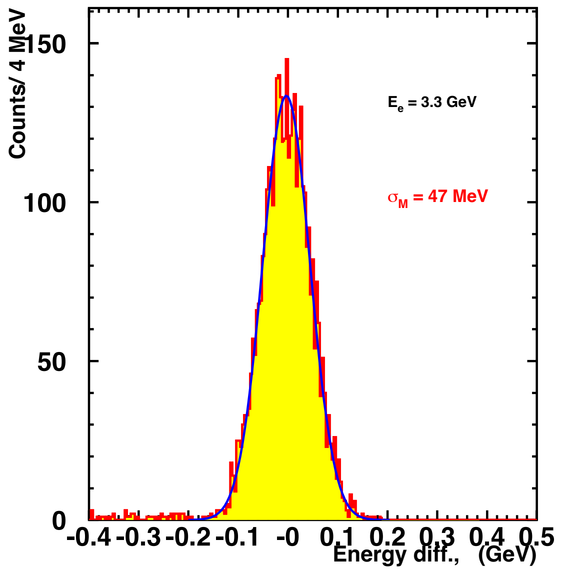
- Target to detector distance: L = 7.5 m provides good (integrated) detection efficiency in [3 - 60] MeV mass range for E_e = 2.2, 3.3 and 4.4 GeV.

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

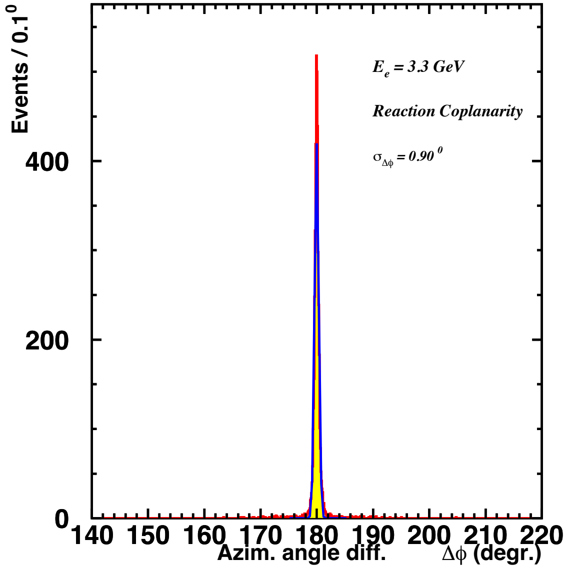


Experimental Resolutions

- Good energy resolution of $PbWO_4$ calorimeter (2.6% @ E=1 GeV) and 1 μm thin target provides 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).

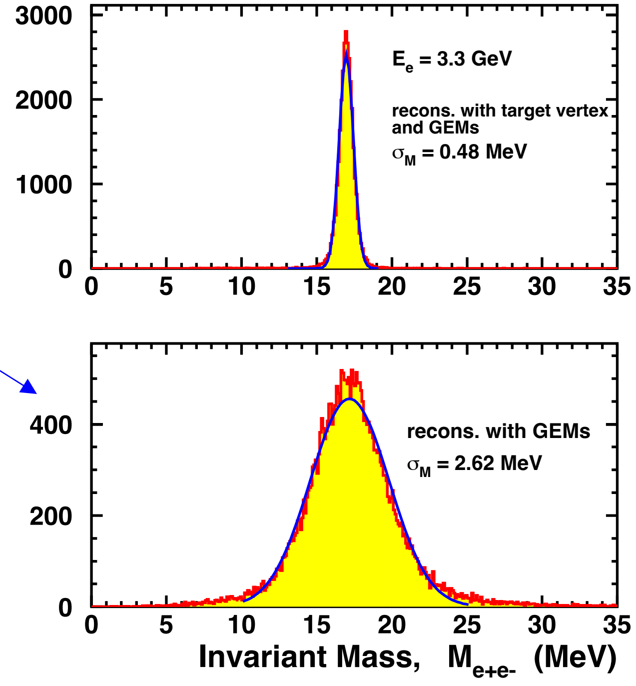


- Coplanarity (between $\overrightarrow{P_{e'}}$ and ($\vec{P}_{e+} + \vec{P}_{e-}$) vectors): ($\vartheta_{\Delta\varphi} = 0.9^0$)
  GEMs' excellent position resolution (σ = 72 μm), together with very thin 1 μm target ($2.4x10^{-4}$ r.l.) provides event selection criterion ($\vartheta_{\Delta\varphi} = 0.9^0$), important for:
  - ✓ multi-particle and;
  - ✓ accidental coincidence events.

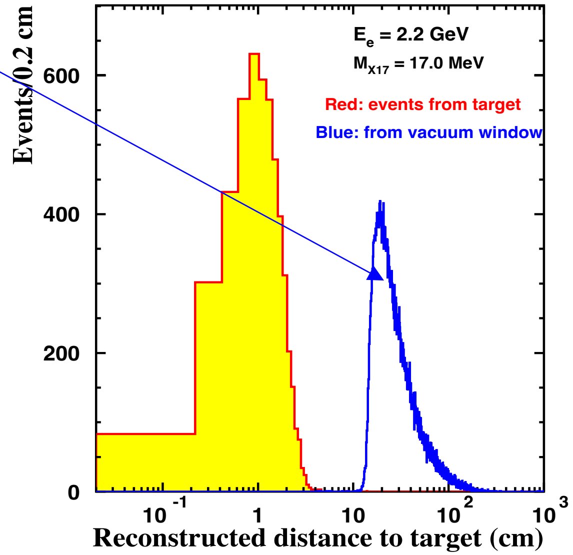


Experimental Resolutions (invariant mass and vertex plane)

- 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.

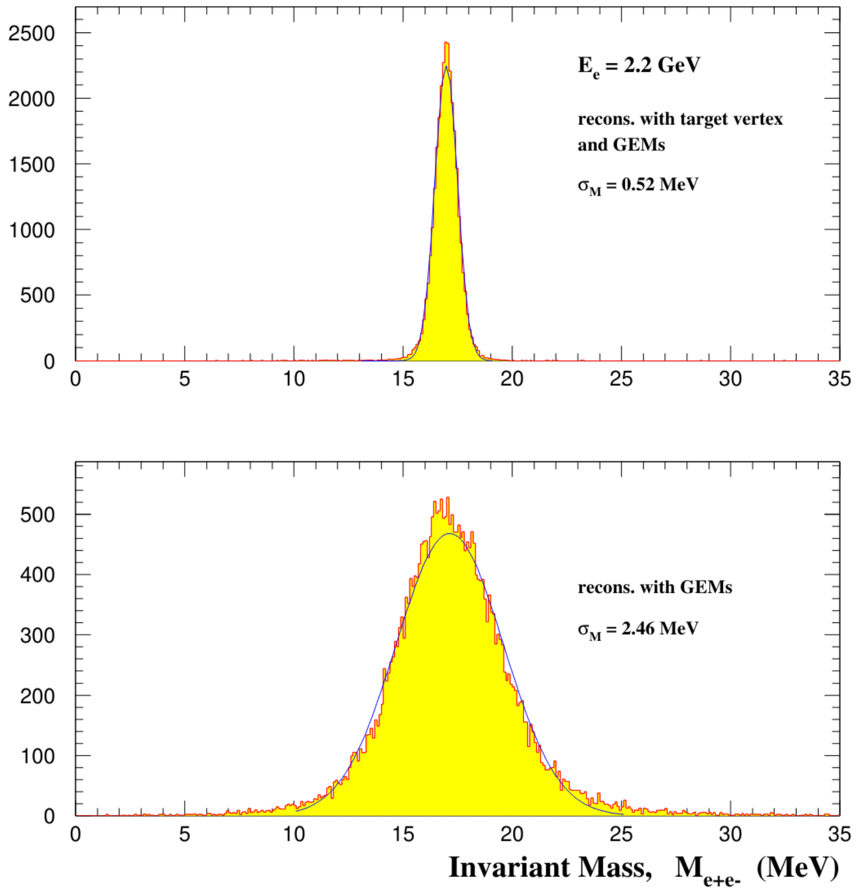


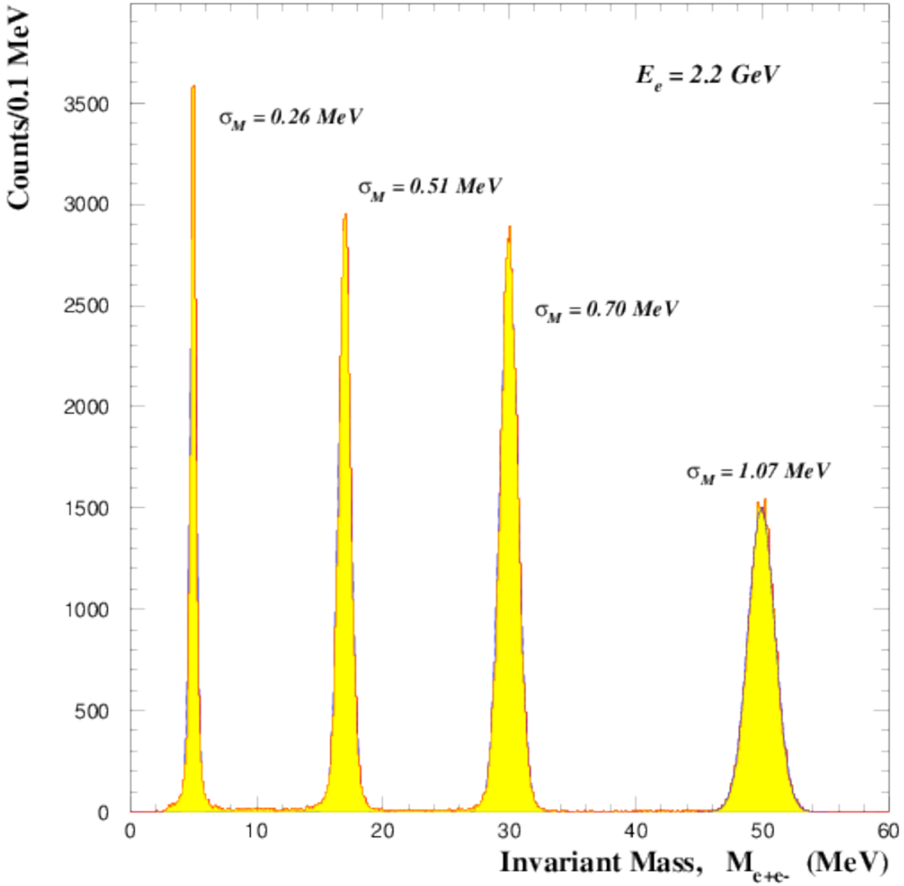
- Two GEM planes (with $PbWO_4$) will effectively discriminate events not originating from the target (for example, from the vacuum chamber exit window).



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

Invariant Mass resolution (more plots)





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.

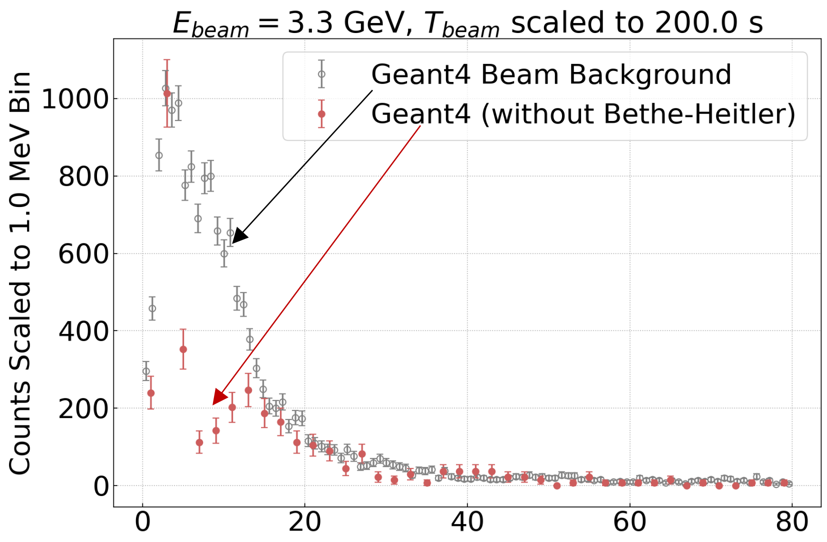
     Including trident processes
     a) Bethe-Heitler
     b) Radiative and
     c) Interference between them

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

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

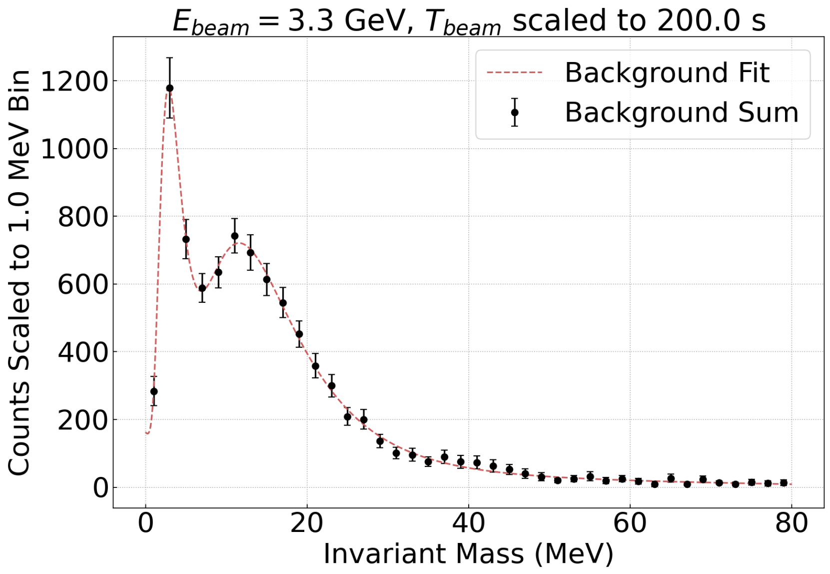
Physics Background Simulations (Hybrid Method)
(GEANT4 without BH + MadGraph5)

- We combined:
  - ✓ GEANT4 without the Bethe-Heitler process activated;



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

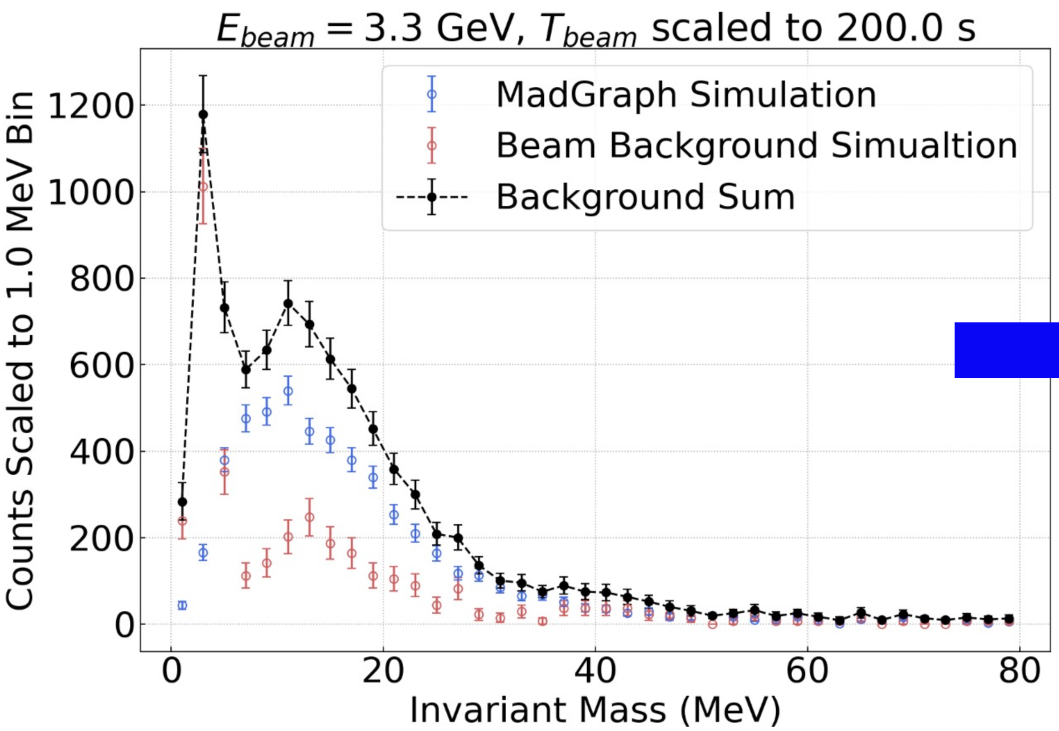
- The resulting background shape was fit with: Landau + Log + constant terms.

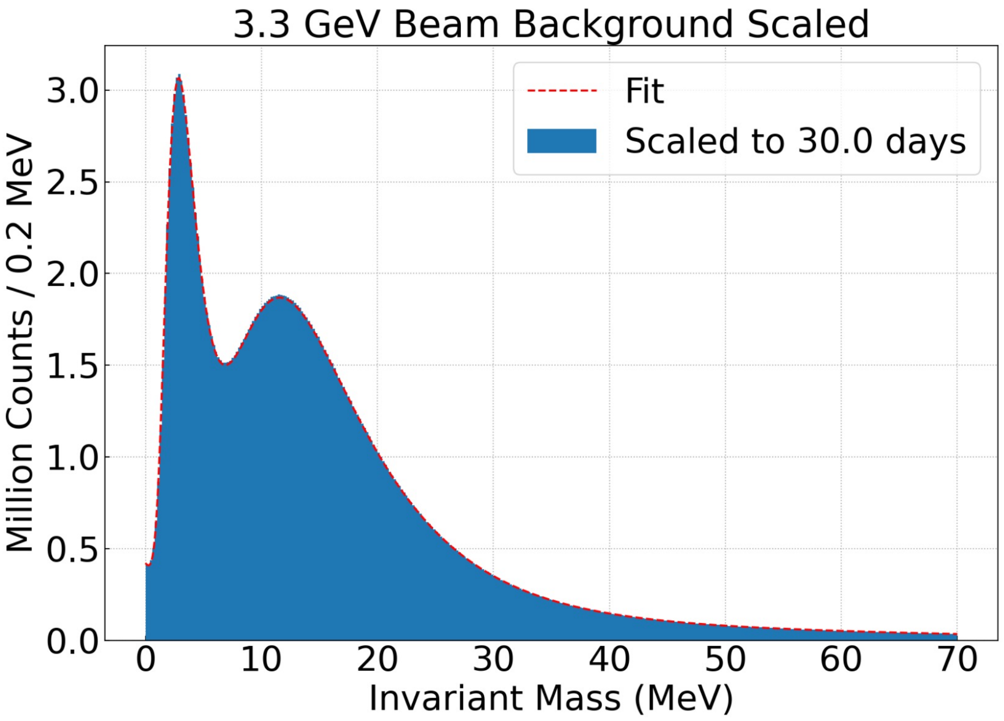


Background Monte Carlo Simulations (scaled to 30 days)

PRad GEANT4 and GEANT3 (for cross-check) detector models were used for simulations, with slight modifications to get the X17 geometry.

- Geant4 beam background (BH disabled)
- Madgraph5: Trig = Rad Trident + BH + Int.   (Performed by Tong Tong Cao and Chao Peng)



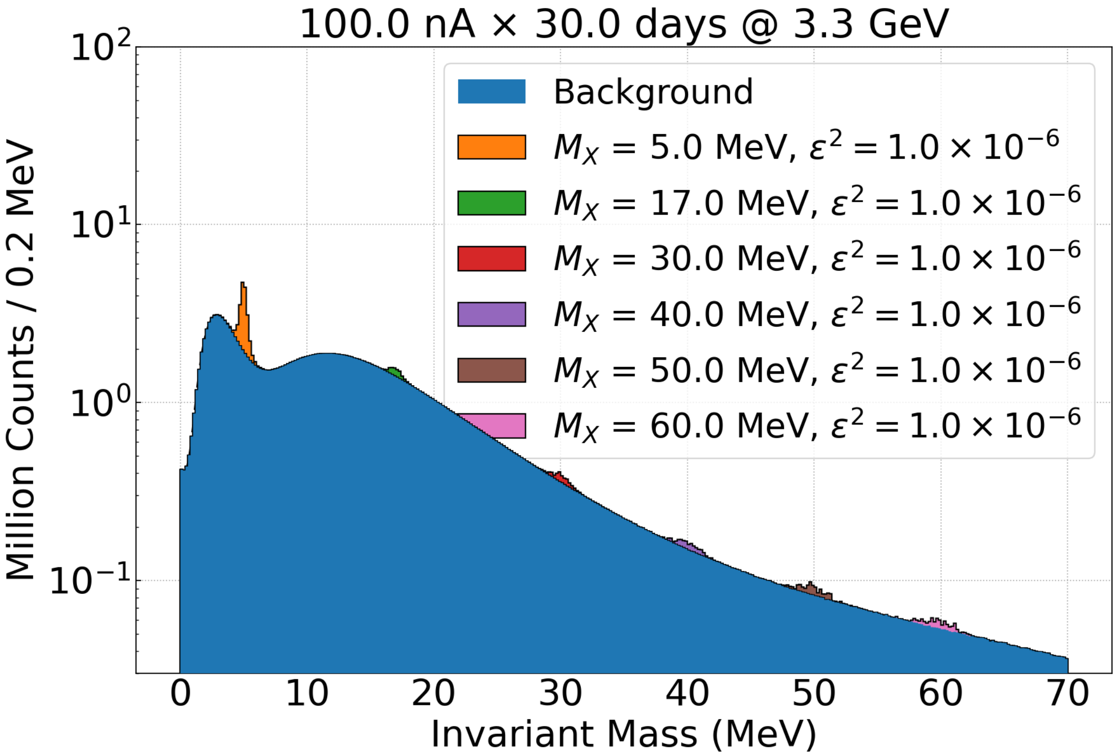


- Physics Background Simulations (Hybrid Method) (fit and scaled to the beam time with $\varepsilon^2 = 1.0\text{x}10^{-6}$)

- The simulated hybrid background was scaled to 30 days of beam time, with I_e = 100 nA, 1 μm Ta target

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

  (**for illustration purposes only**)



Beam Time and Statistics

- Target: Ta; 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),

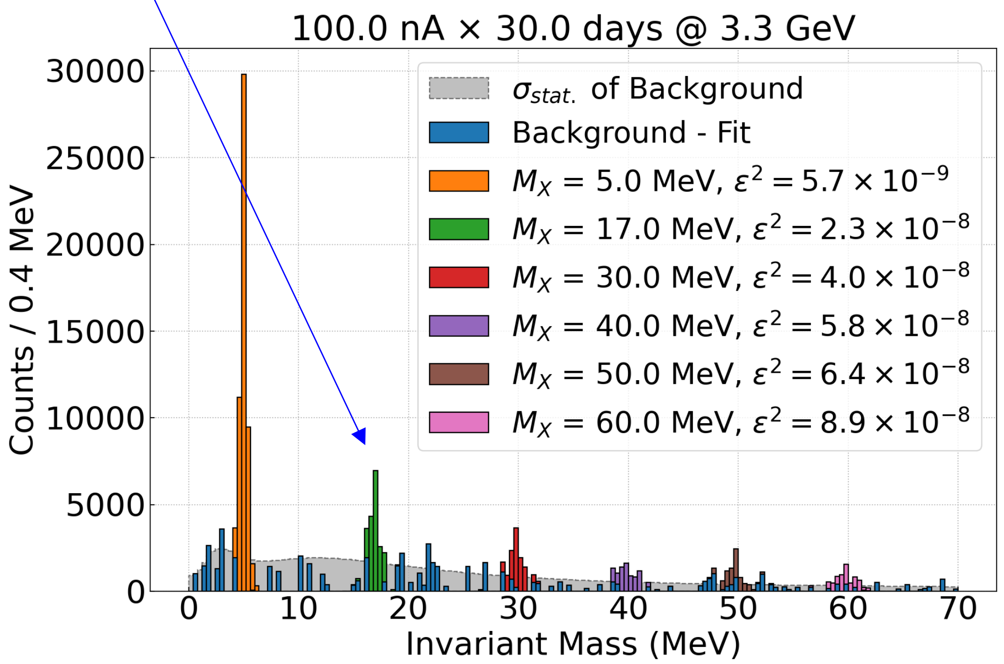
  Example: the estimated X17 production rate (Eq. 14, J. D. Bjorken, et al. Phys. Rev. D, 80:075018. 2009):

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

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

  $\approx$ 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

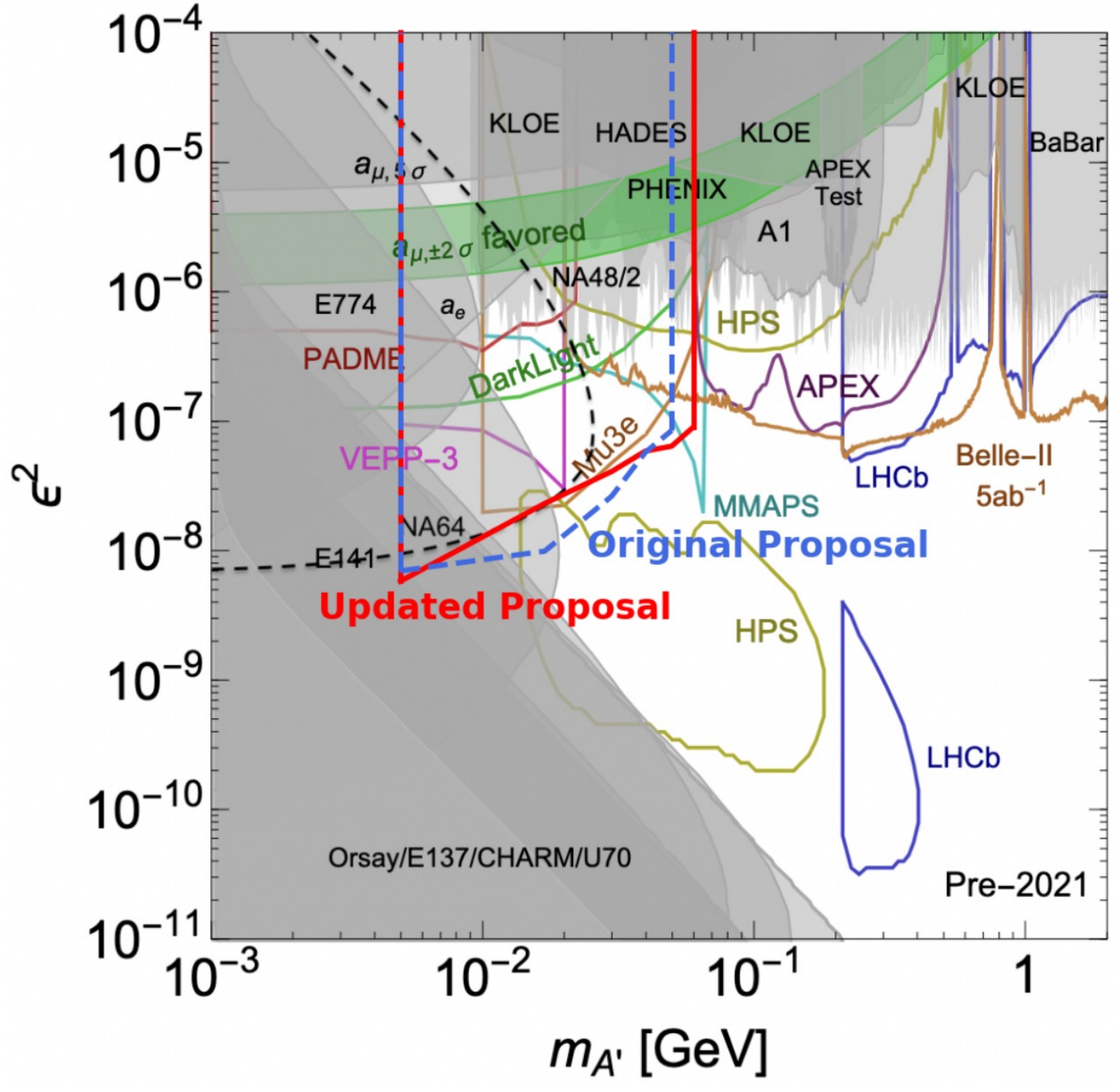


Parameter Space (ε^2 *vs.* Mass), Physics Reach

- 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.

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



X17 Current Status

- ✓ Conceptual design of all beamline elements (including the target) are finalized.
  Engineering design is in progress.

- ✓ Test of all HyCal modules started in the Environmentally Controlled Building.

- ✓ Construction of two GEM detectors are on track to be ready by summer of 2025 (UVA group)
    - construction, late 2024
    - cosmic tests in JLab, starting from summer of 2025

- ✓ All fADC modules with 5 crates are ordered for the HyCAL $PbWO_4$ part (JLab).

- ✓ Work on cables and other communications is underway in Hall B.

- ✓ ERR review is tentatively scheduled for this September.

Summary and Outlook

- It is a cost-effective, mostly 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 (resonances) 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.

- Experimental preparations are actively underway, detector testing and checkout process started, we expect to run starting from Fall of 2025.

- We welcome the HPS collaboration to participate in this experiment with their accumulated expertise.

My current research work is supported in part by research award NSF PHY-PHY-2111233

Summary and Outlook

- Cost effective, magnetic-field-free experiment based on PRad setup for search of low mass resonances (3 MeV - 60 MeV)

- Focusing on hypothetical X17 particle.

- Major advantage of the experiment:
  - Detection of all three particles allows to ensure the exclusivity of the reaction

- Experiment planned to be ready for run: fall 2025

- Participation of HPS collaboration is welcomed.

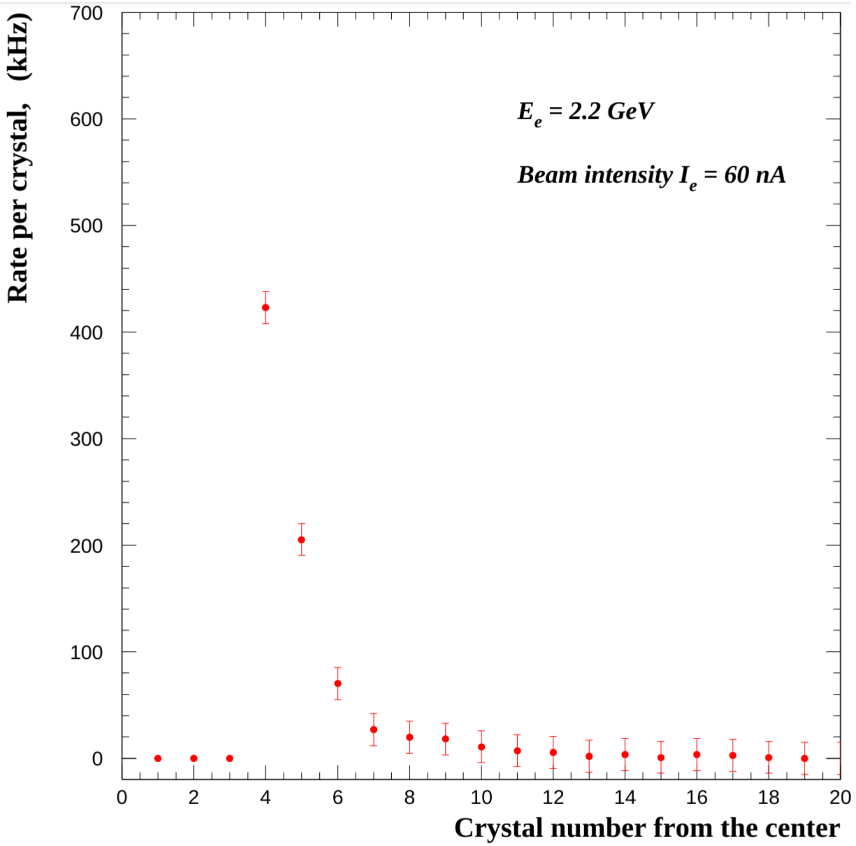
My current research work is supported in part by research award NSF PHY-PHY-2111233

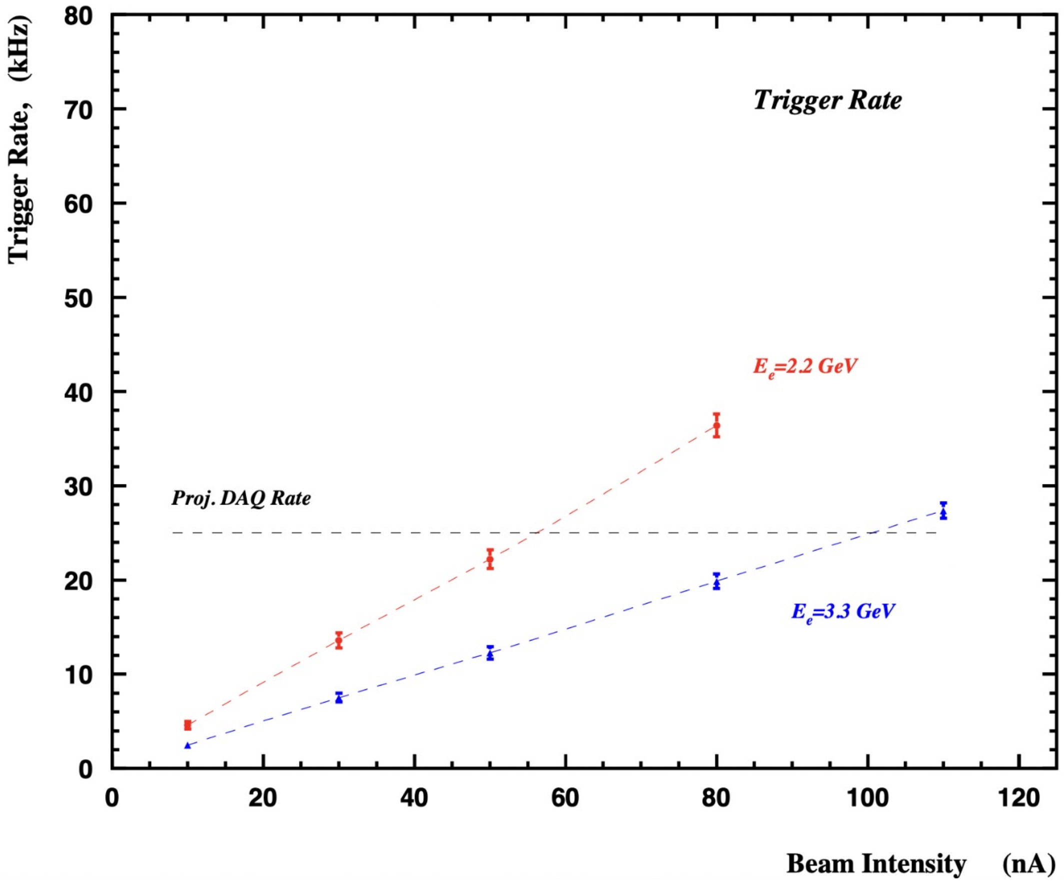
Backup Slides

Rate on HyCAL Inner Crystals and Trigger Rate

- Three clusters in the calorimeter
- Cluster energy ∈ (200 MeV – 0.85*Eb)
- Total Calorimeter energy > 0.75*Eb

Two or three +/- 3 crystals ?

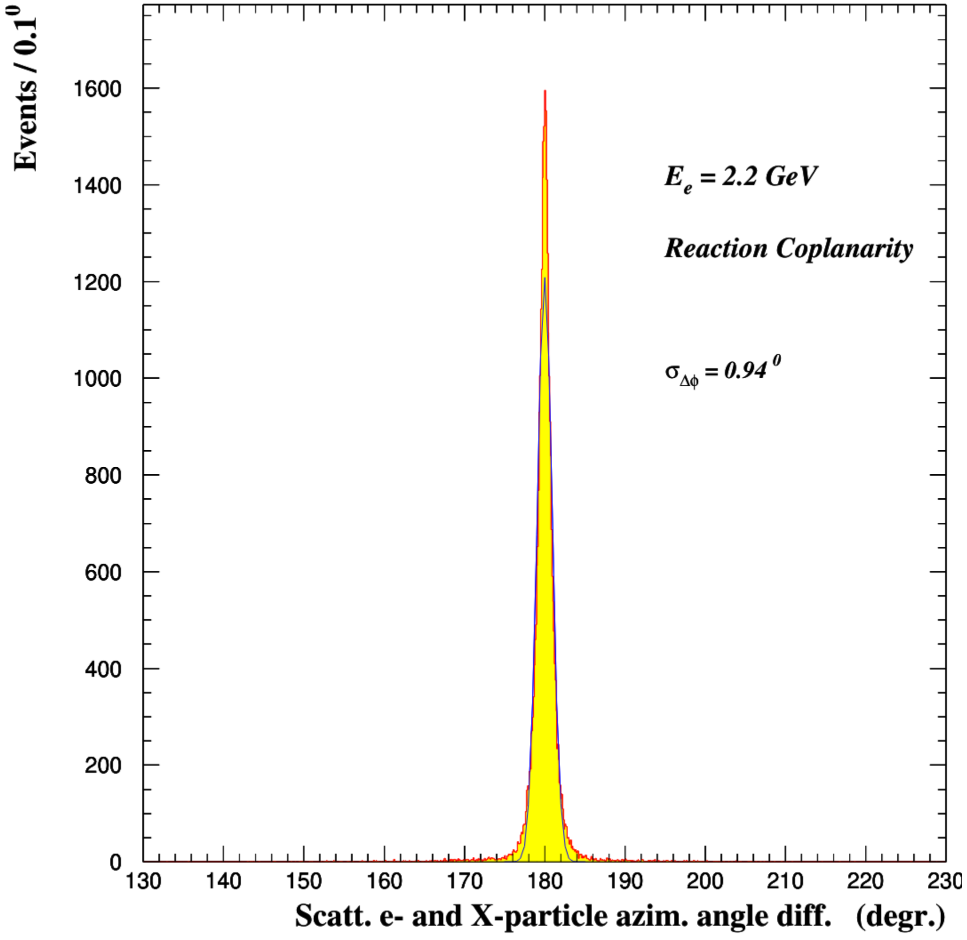


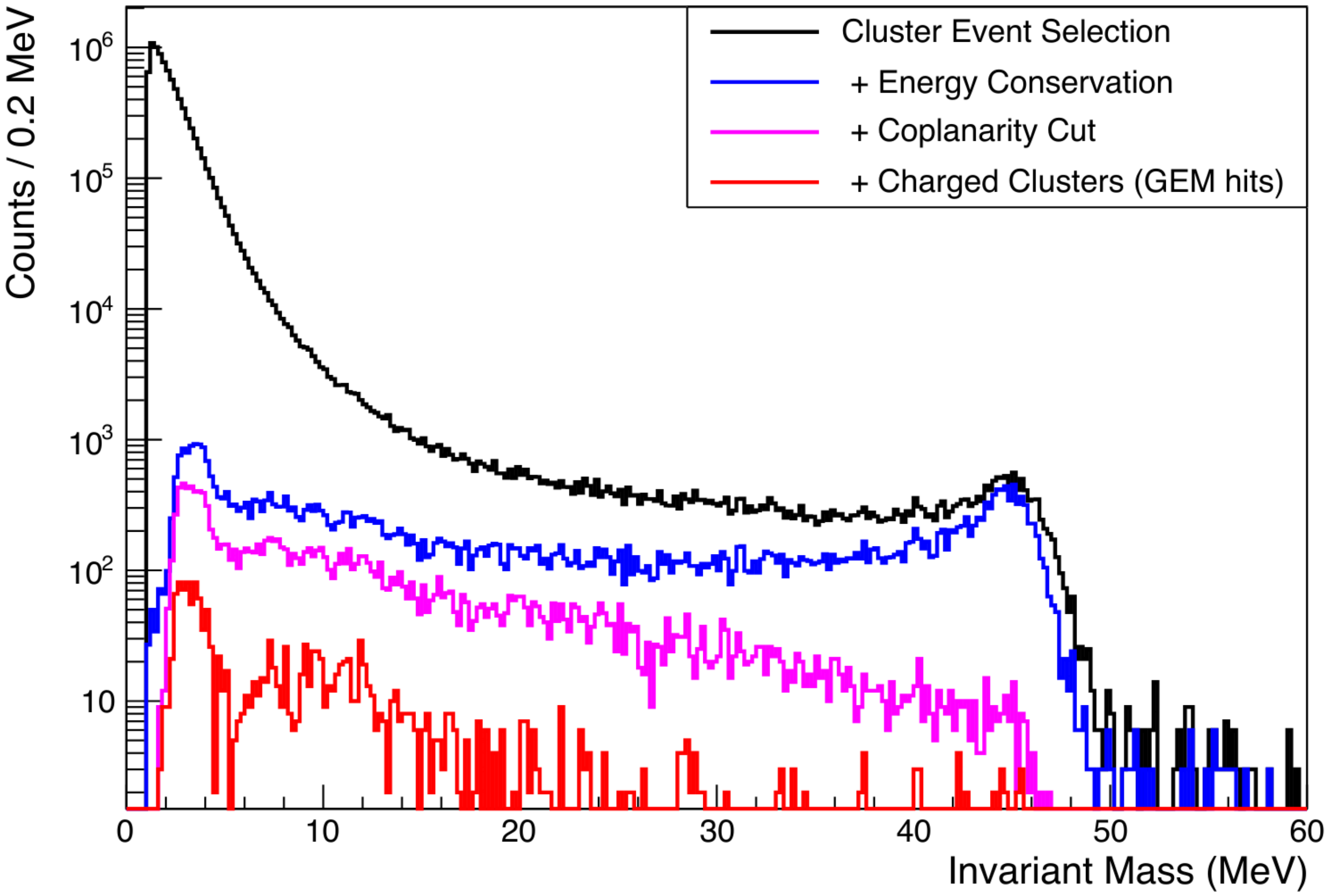


Exclusivity cuts

Make sure each cluster vector is coplanar with sum of other two clusters.

Are these accidentals only?





Expected Physics Reach

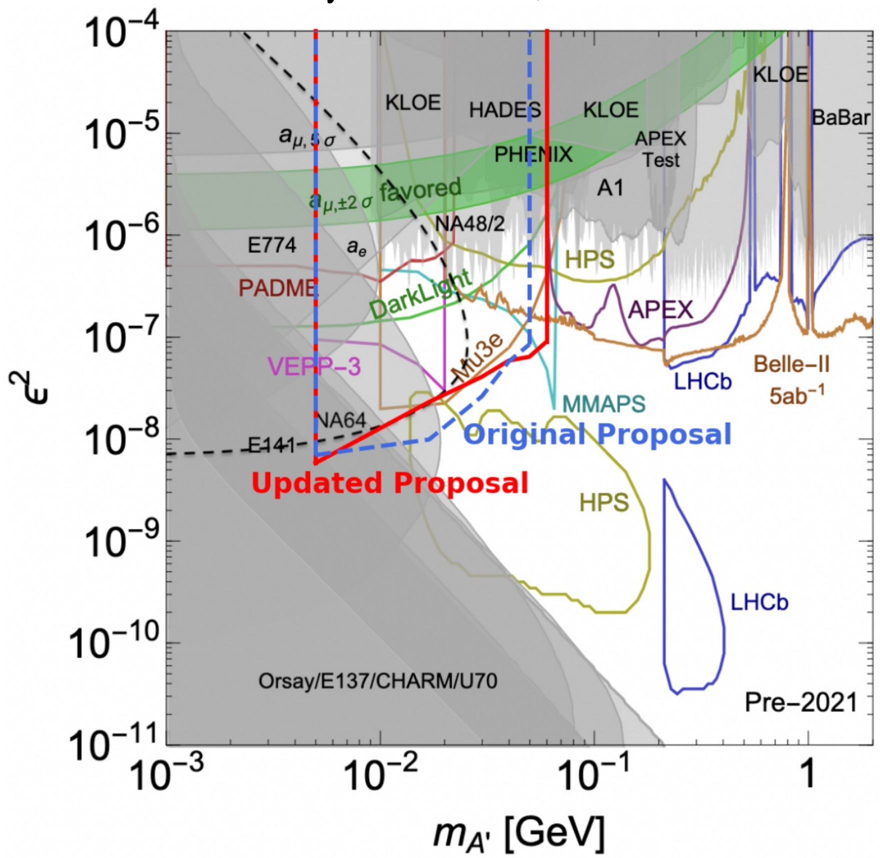
$$\epsilon^2 = \frac{N_X}{5 \times N_e T \frac{m_e^2}{m_X^2}}$$

Eq. 14 of Phys. Rev. D 80, 075018 (2009)

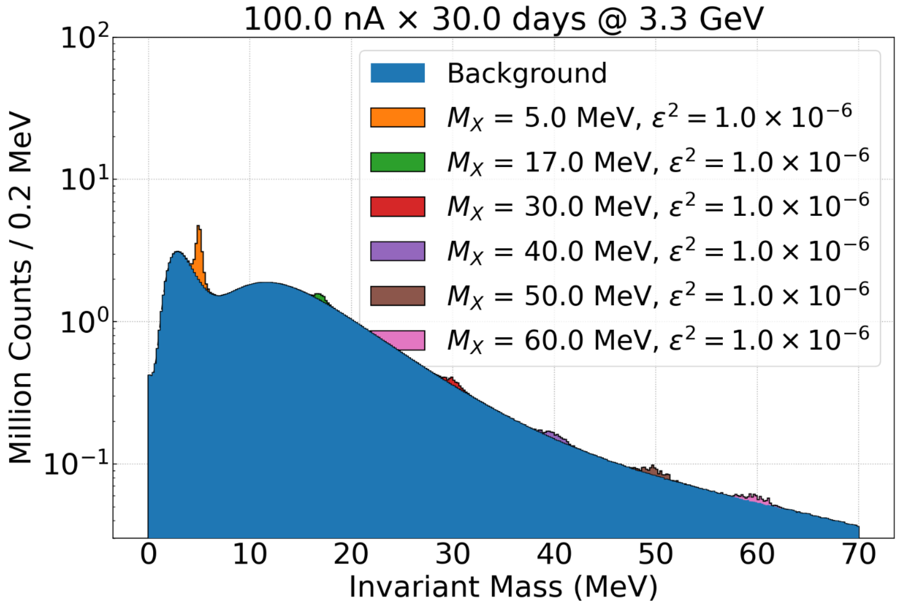
$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{signal}} + N_{\text{bgd}}}} \geq 5$$

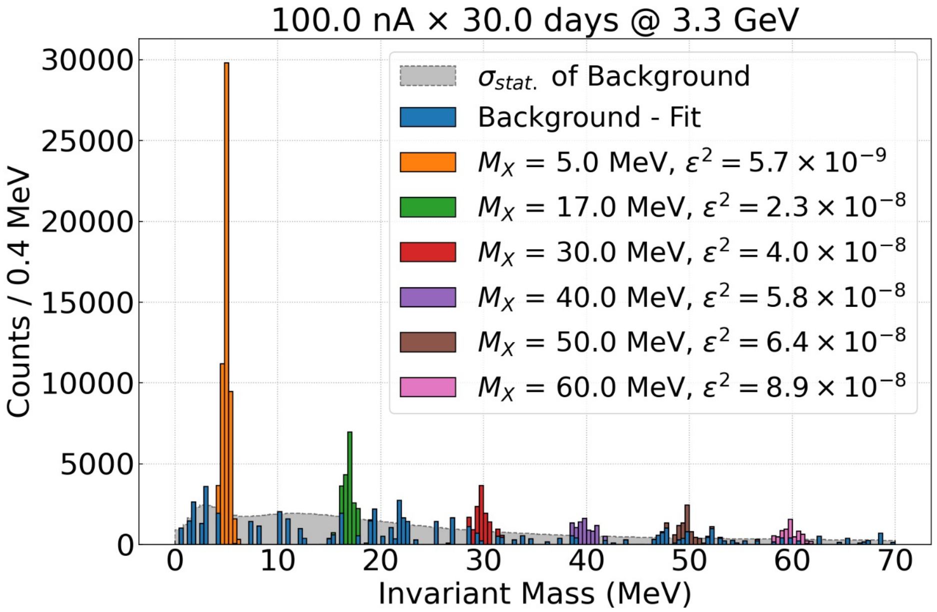
5-sigma to compensate additional uncertainties coming from the uncertainty of the background shape.

- 20 days at 2.2 GeV, 50 nA
- 30 days at 3.3 GeV, 100 nA



"Big" signals overlayed to the background



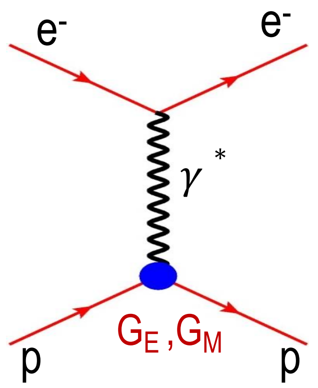


Proton Radius from ep→ep Scattering Experiments

- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

$$Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



- Structureless proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2\left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

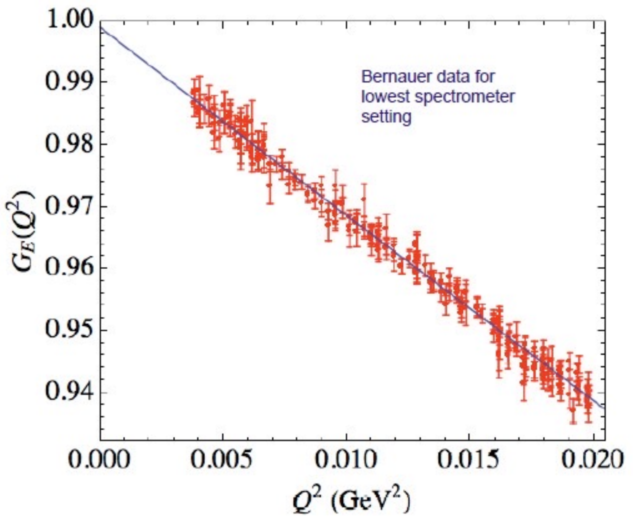
- G_E and G_M can be extracted using Rosenbluth separation
- for extremely low Q^2, the cross section is dominated by G_E
- Taylor expansion of G_E at low Q^2

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

derivative at $Q^2 = 0$:

definition of the proton rms charge radius →

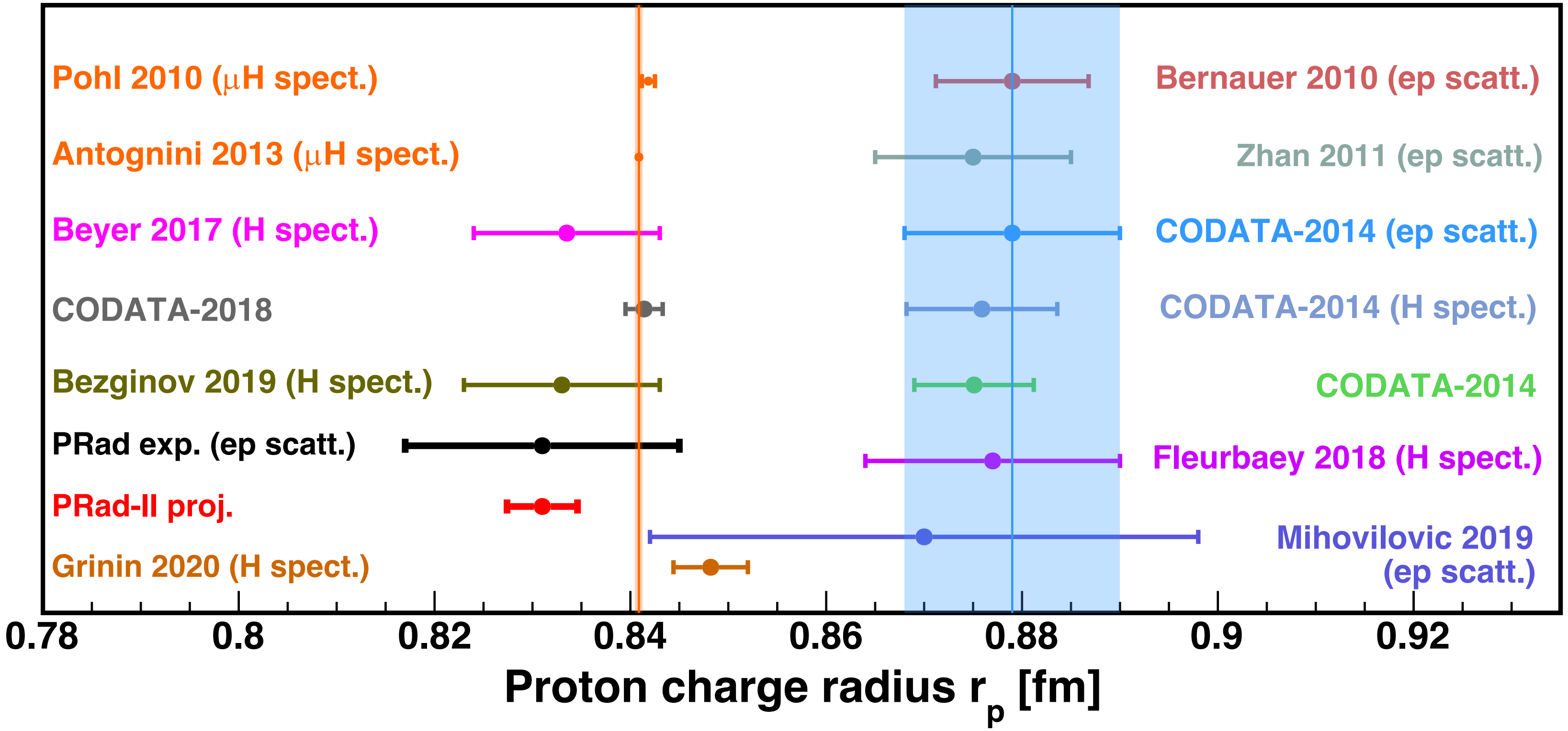
$$\langle r^2\rangle = -6\left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

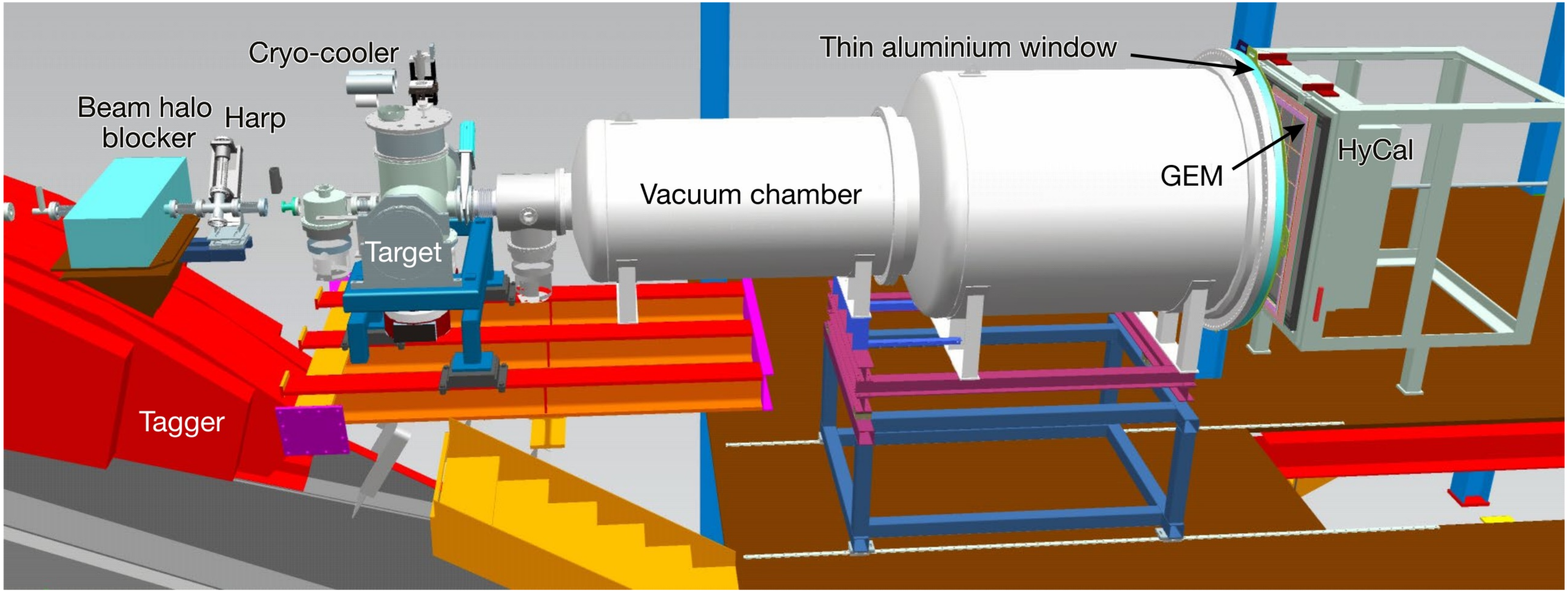
PRad-II: Projected Result

- Approved by JLab's PAC-48 in August, 2020
- Projected total uncertainty on radius: 0.43%

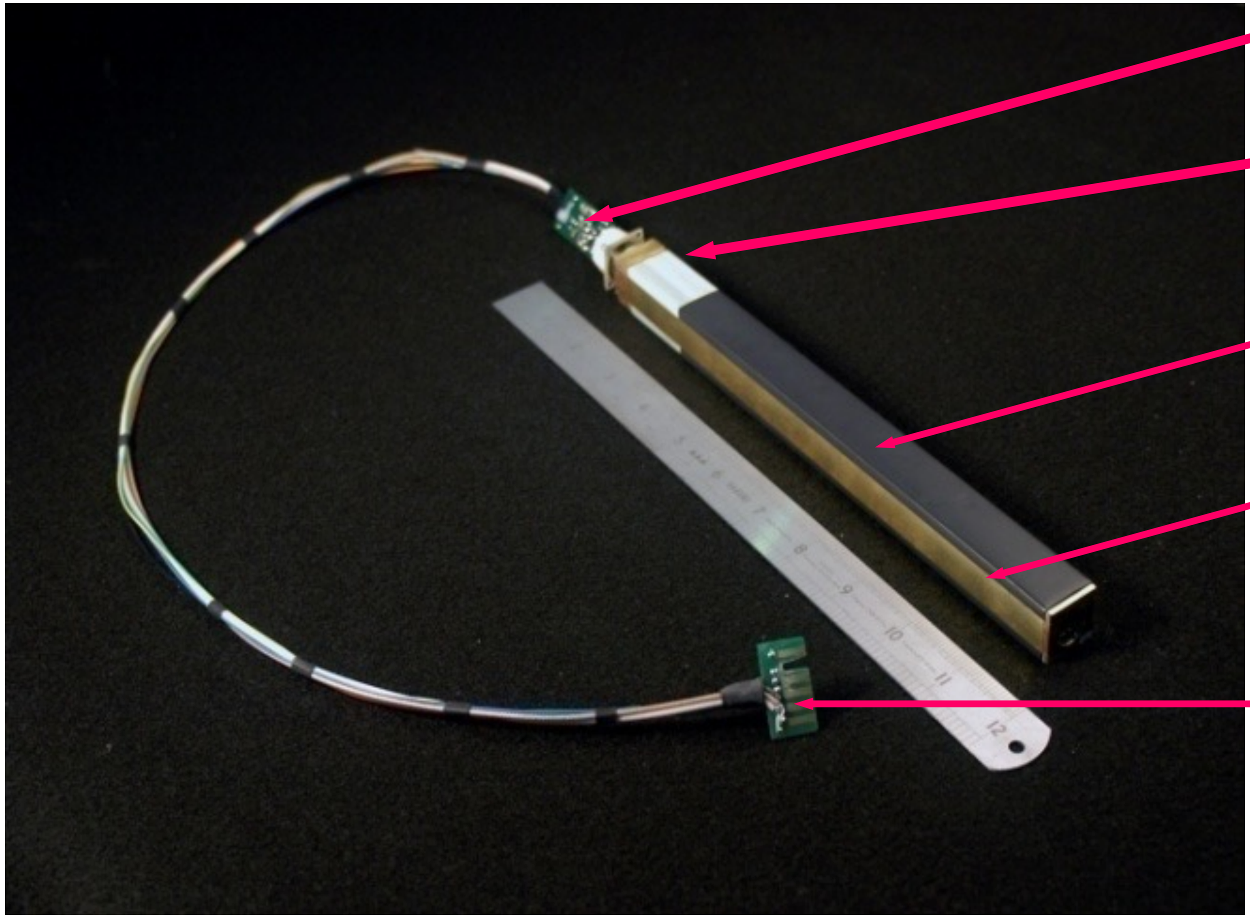


PRad Experimental Setup

The experimental setup is based on the Proton Radus (PRad) experiment, which run on May–June of 2016.
Located on the space frame in between the tagger magnet and the CLAS12 detector.
The most significant change is the replacement of the windowless hydrogen gas target with a d=30 cm, l= 1.7 m beam pipe.



$PbWO_4$ Shower Detector Module



HVD

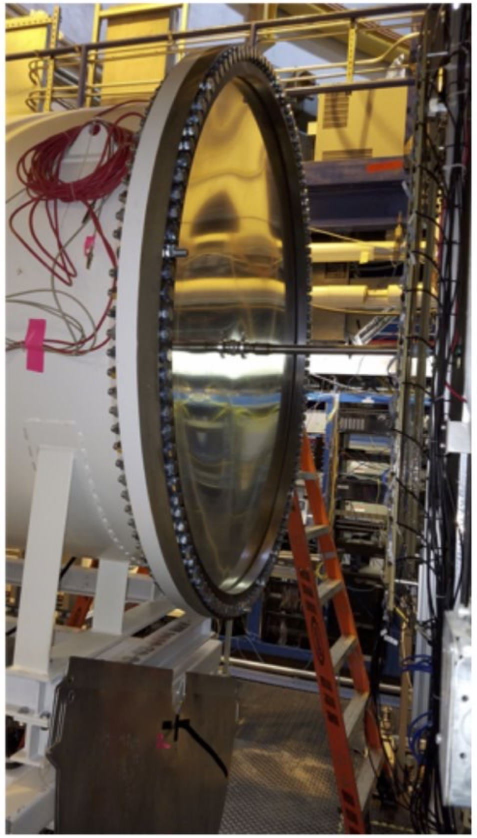
G10 PMT housing
with R4125HA tube

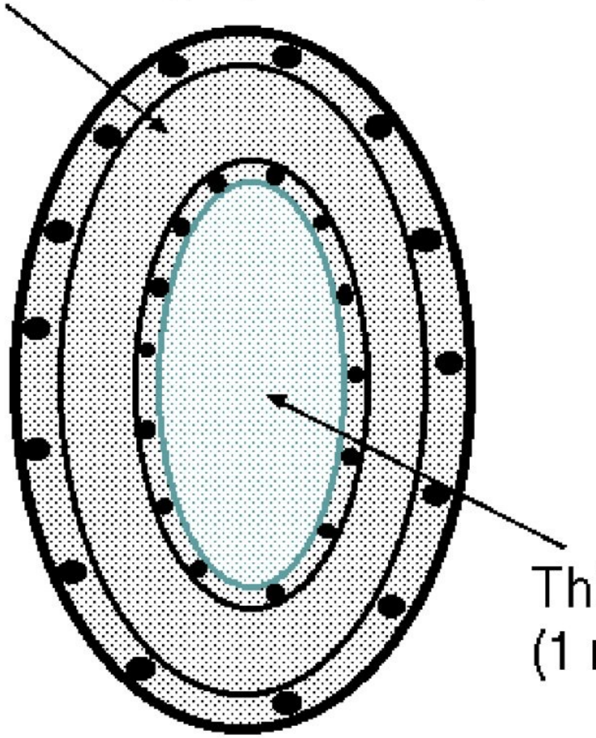
VM-2000 and Tedlar
wrapping (38.1 micrometer)

25 micrometer brass strips

Readout cable

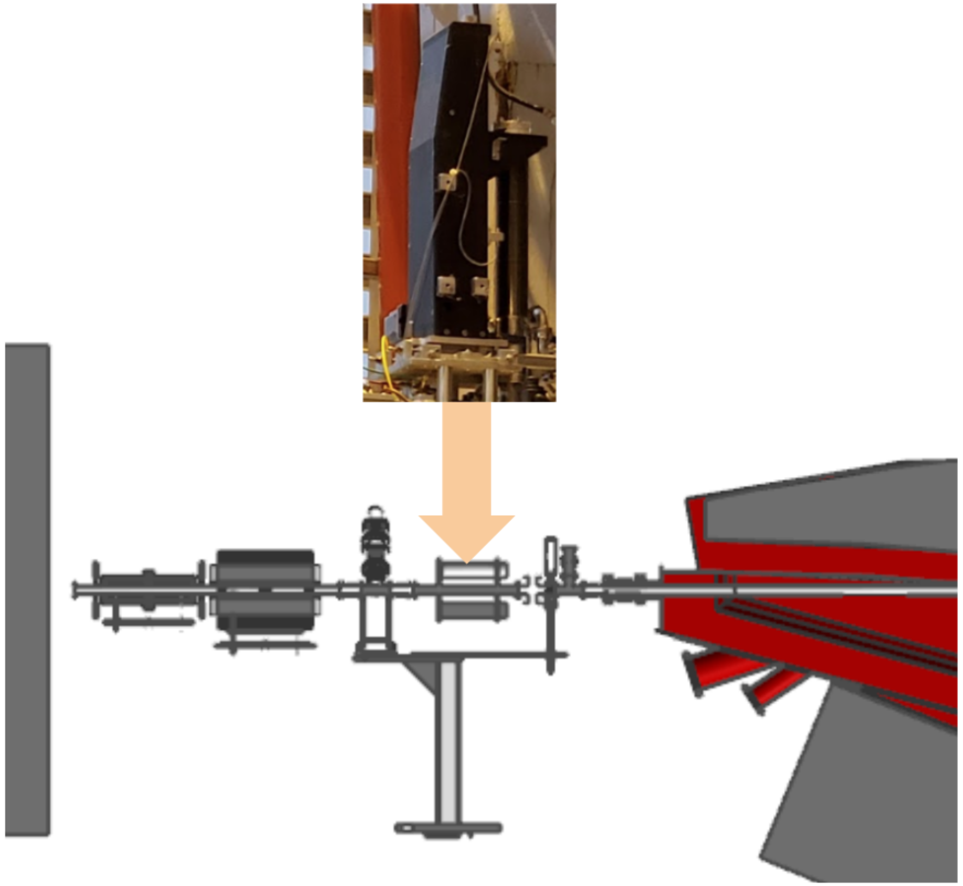
Vacuum Window Reducer
(to use tinner window material)





Upstream collimator and the radiator

The collimator along with the radiator will be placed in between the tagger harp and the tagger.



Collimator Tungsten