Upcoming X17 experiment in Hall B, JLab

Rafayel Paremuzyan

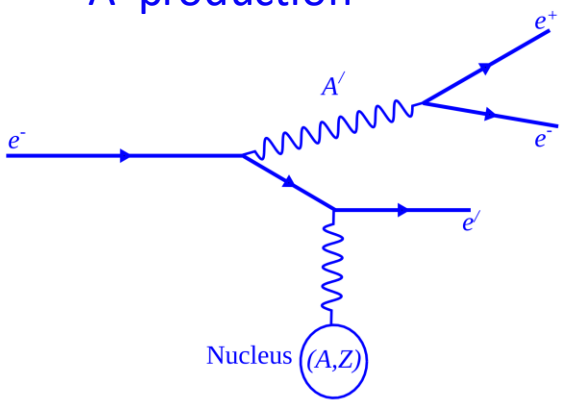
HPS collaboration meeting, June 3-5, 2025, JLab

The goal of the experiment

- 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.
- Search for a dark photon in the mass range M ∈ (3 MeV - 60 MeV) through it's $\mathbf{A' \rightarrow e^- e^+}$ decay.

$$e^- + Ta \rightarrow e^- e^- e^+$$

A' production



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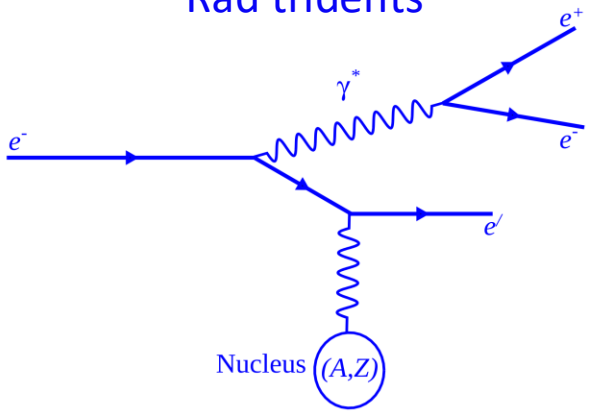
Rad tridents



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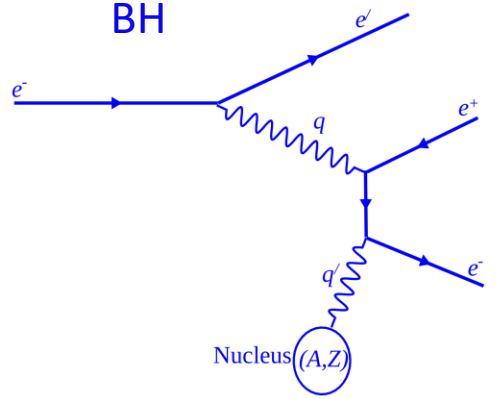
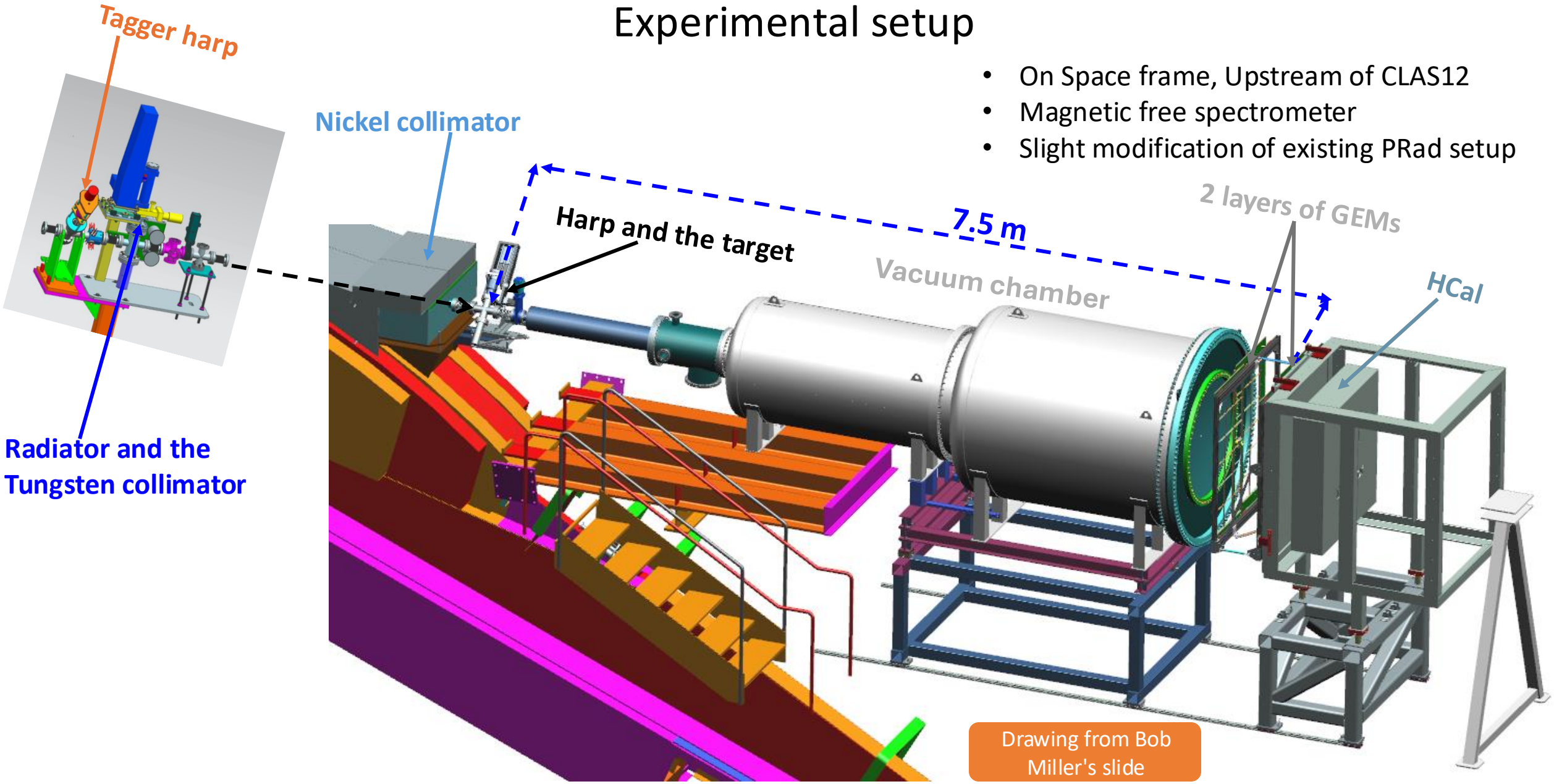


- Detection of all three final state particles $e^{'}$, e^- and e^+.
- Magnetic-spectrometer-free experimental setup.
  - Particle energies are measured with a PbWO4 part of HyCal calorimeter.
  - Two-layers GEMs allow to suppress photon background.
  - GEMs also allow to cut charged tracks originating from the beam pipes.
  - High resolution calorimeter along with GEMs provide good precision target constrained mass resolution.

Experimental setup

- On Space frame, Upstream of CLAS12
- Magnetic free spectrometer
- Slight modification of existing PRad setup

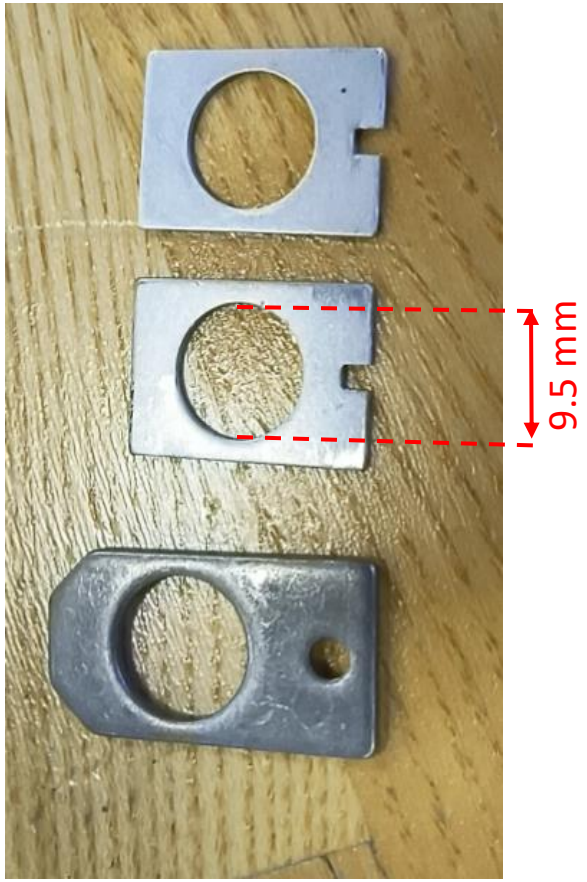


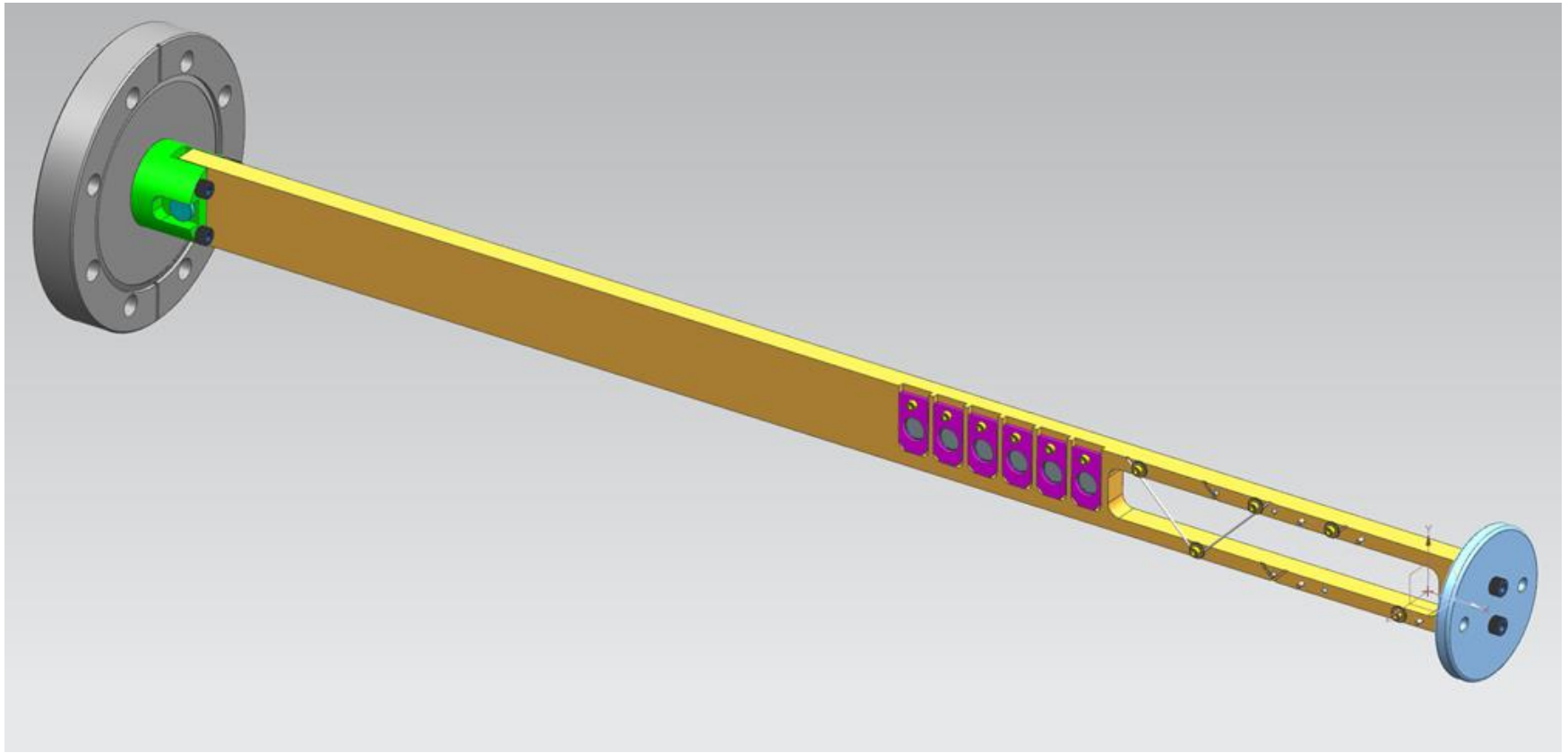
6 target slots:

- 1 μm Ta: x2, the main target
- 2 μm Ta: x1, in case the non target bgr is high
- 4 μm Ta: x1, in case the non target bgr is high
- 50 μm C12: x1 (for calibration runs)
- Empty: To estimate non-target background

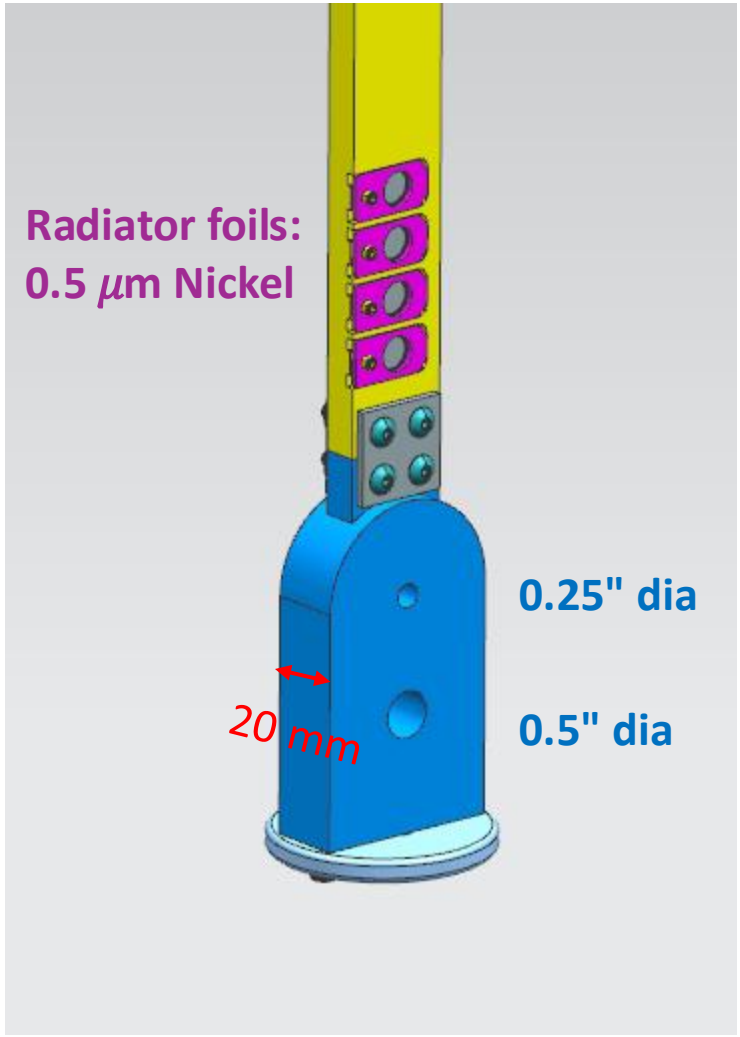
Target foil is sandwiched between two Al frames and fixed inside the corresponding slot by an Al holder.

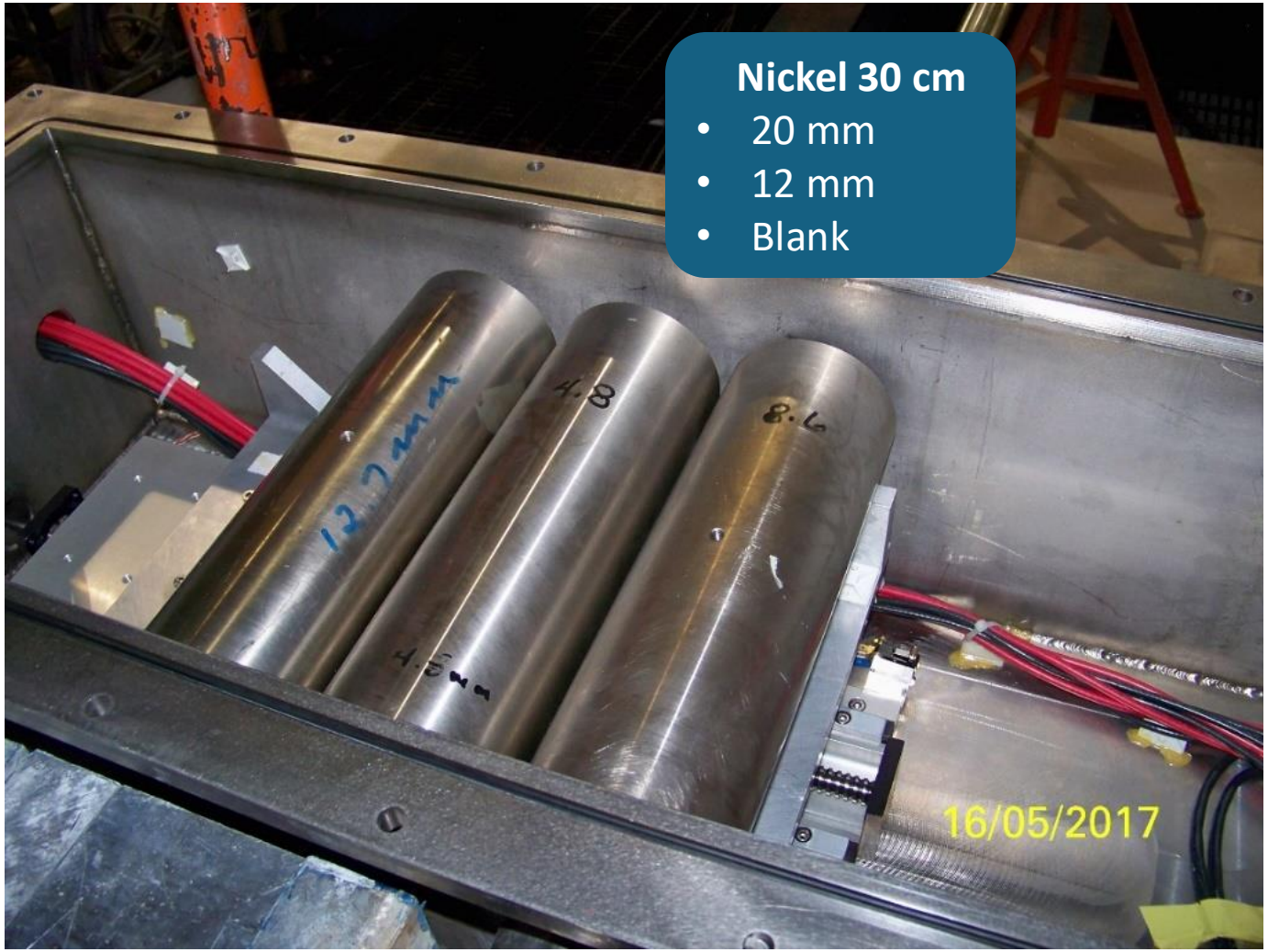
Targets foils are ready. Delivered today.





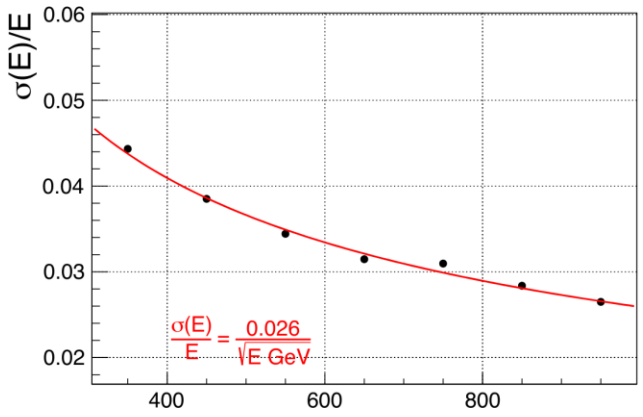
Upstream collimators



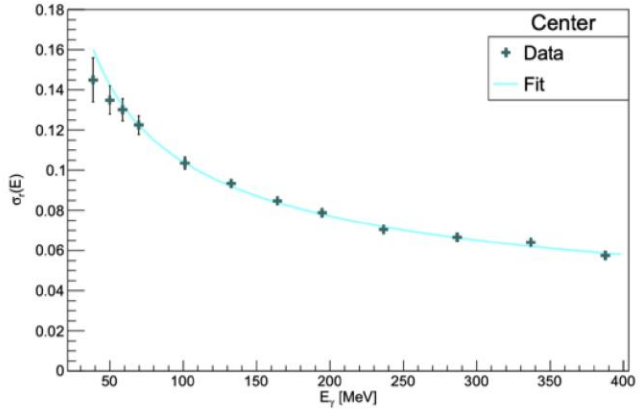


HyCal calorimeter

PrimEx measurement



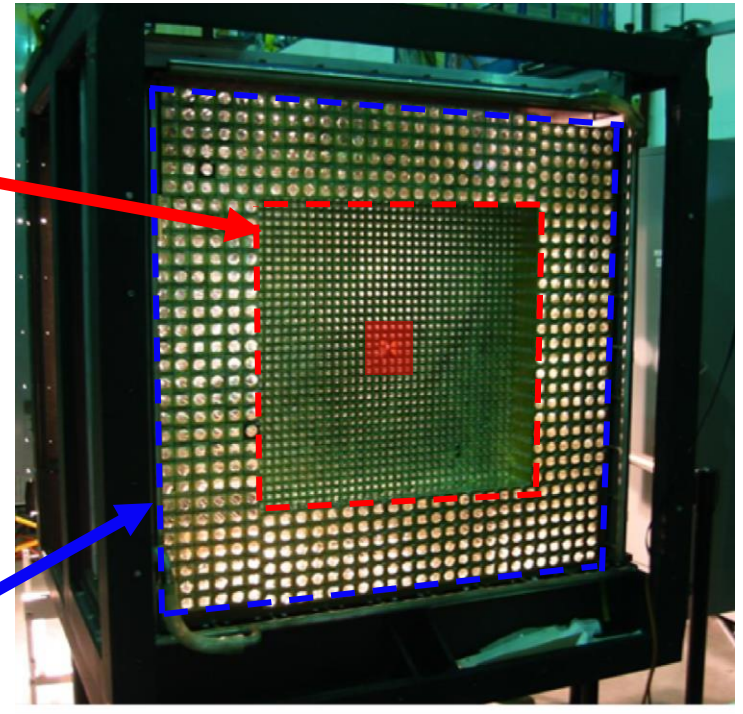
Mainz experiment



Outer part of the HyCal will not be used for X17

Lead Tungstate: PbWO4: inner part

- Provide trigger
- 2.05 × 2.05 cm^2 x 18 cm (20 X0)
- 34 × 34 square matrix
- Inner 2x2 crystals are removed
- In addition, two Innermost layers will not be used
- Full azimuthal coverage
- Very forward angles (0.47° - 3.78°)
- $\sigma E/E = 2.6\%/\sqrt{E}$
- $\sigma xy = 2.5mm/\sqrt{E}$



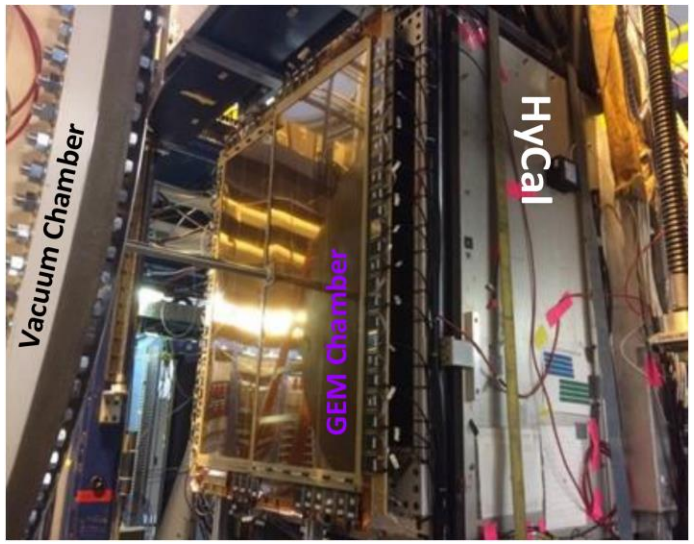
Lead glass

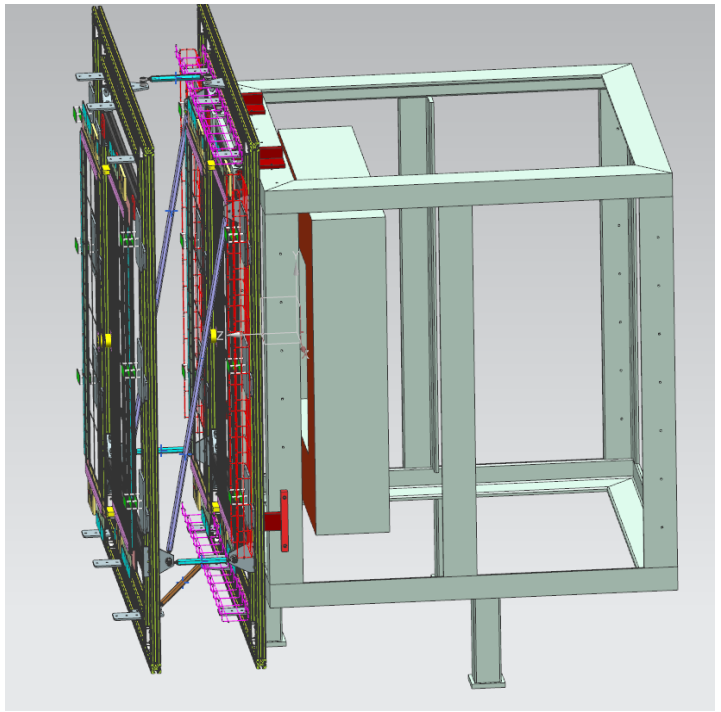
- 3.82x3.82 cm^2 x45 cm
- 576 crystals
- Will not be used for the X17 experiment

Will be read out by fADC250

GEMs

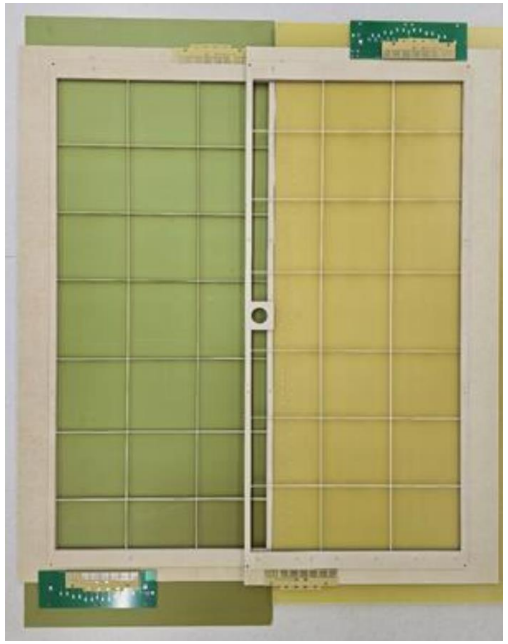
2016 PRad run





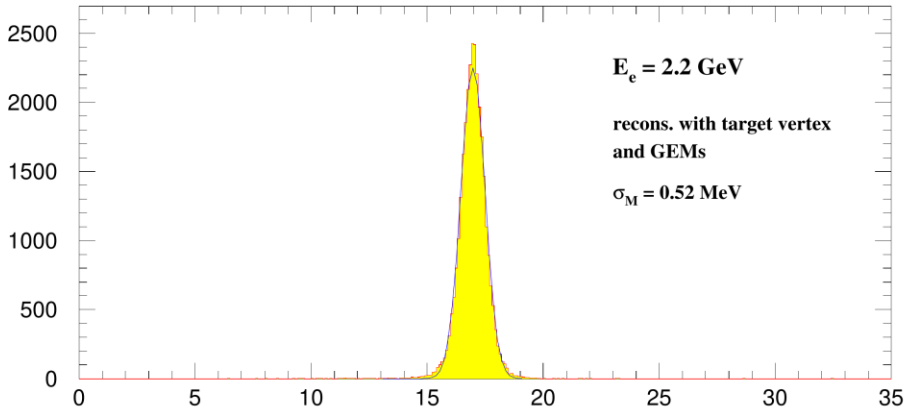
- To Veto/select neutrals
- Same as PRad GEMs.
- 2 layers displaced wrt each other by 40 cm
  - 1 layer is composed of 2 GEMs
- Double GEMs to reduce the material budget
- 123 cm X 123 cm
- A hole 4 cm x 4 cm to allow beam pipe to pass through
- Better than 100 um position resolution
  - PRad achieved 70 um resolution
- 1 pair will be sent to JLab this month (June)
  - 2nd pair will be sent by September.

GEM frames of a single layer

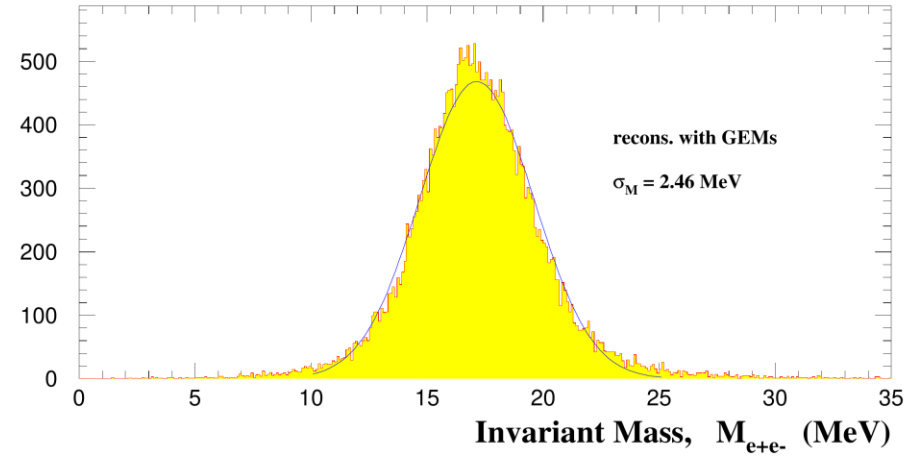


Experimental resolutions

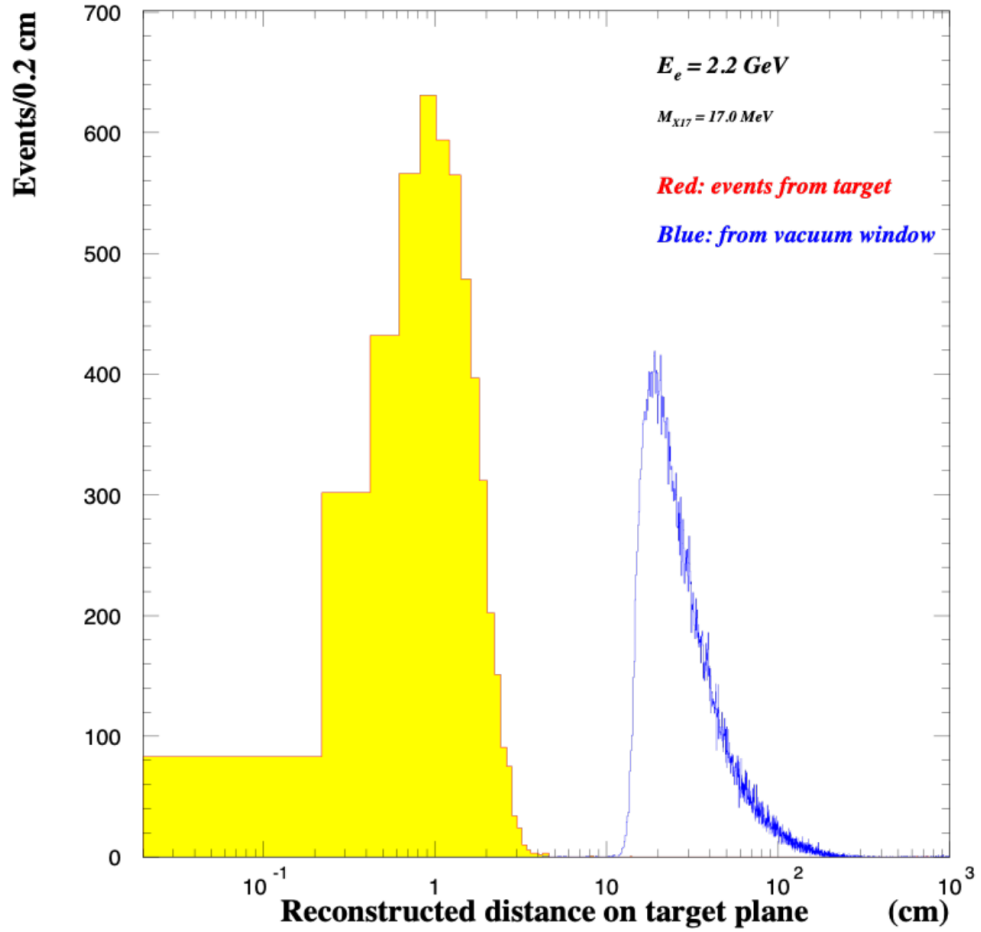
Target constrained mass resolution



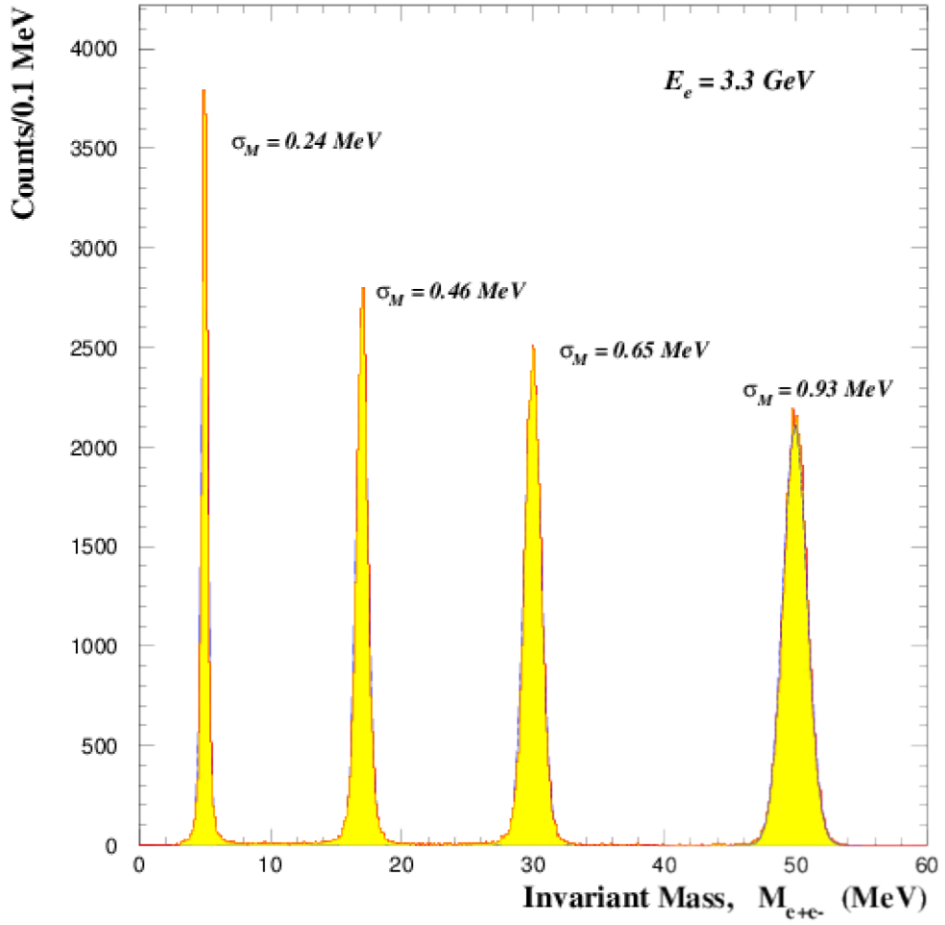
Unconstrained mass resolution

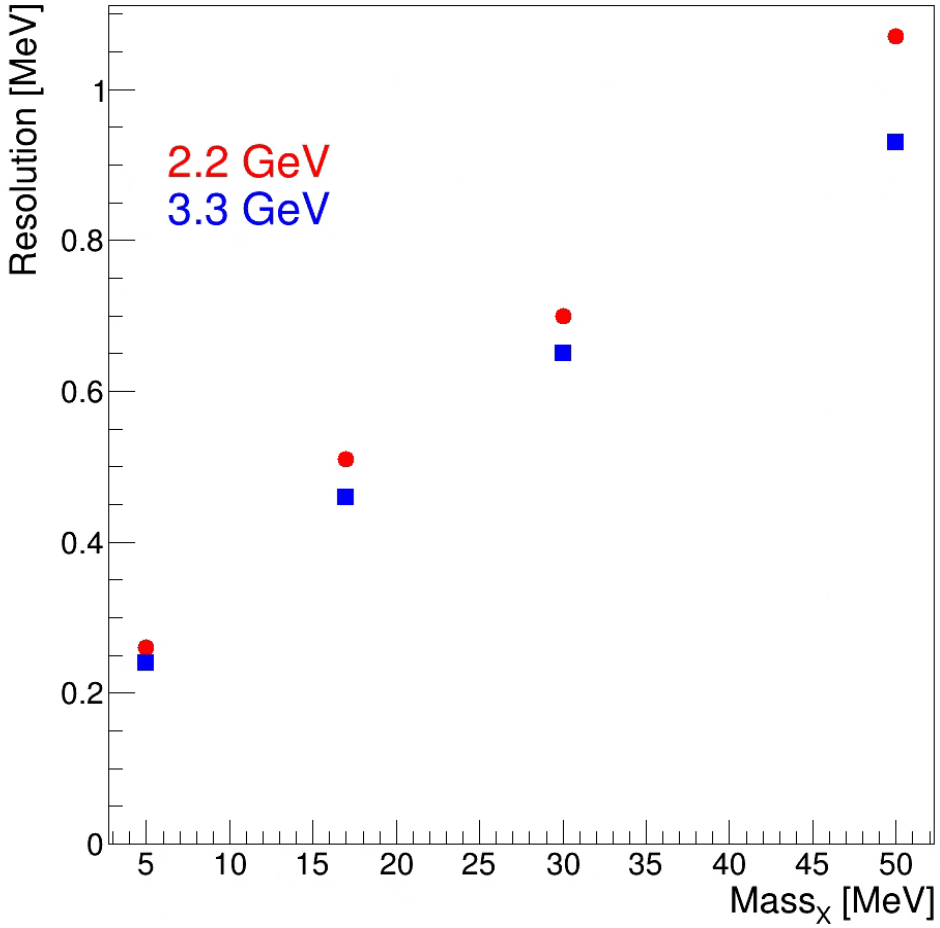


Particles originating from the vacuum window will be effectively cleaned.



Mass resolutions





Efficiency of the signal

Acceptance calculation in the proposal:

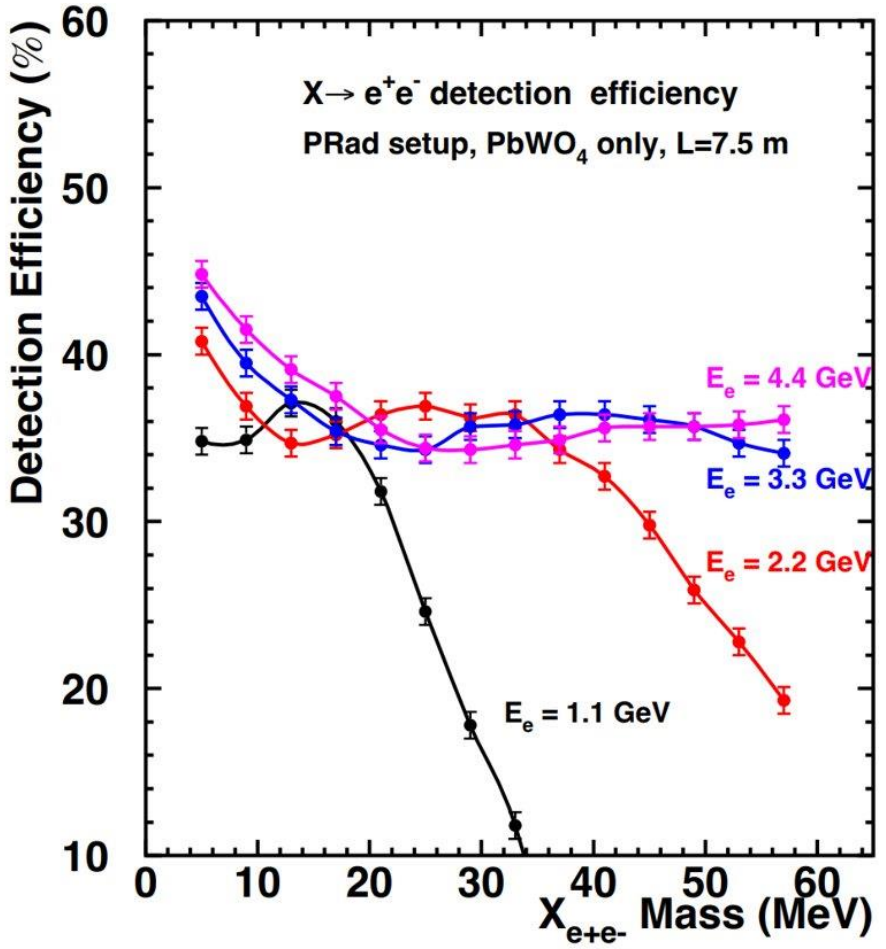
- Beam electron momentum and angle generated uniformly inside the HCal
- A' decayed into e^-e^+ isotopically in CM frame then boosted to lab frame.
- **This gave overestimation of the acceptance especially at higher beam energies.**

- Trigger configuration:
  - Total energy sum in calorimeter: $\boldsymbol{\Sigma}E_{clust} > 0.7E_{beam}$.
  - 3 clusters in PbWO4 calorimeter;
  - each cluster energy: $0.03*E_{beam} < Eclust < 0.8xE_{beam}$ (rejects the elastic scattered electrons)

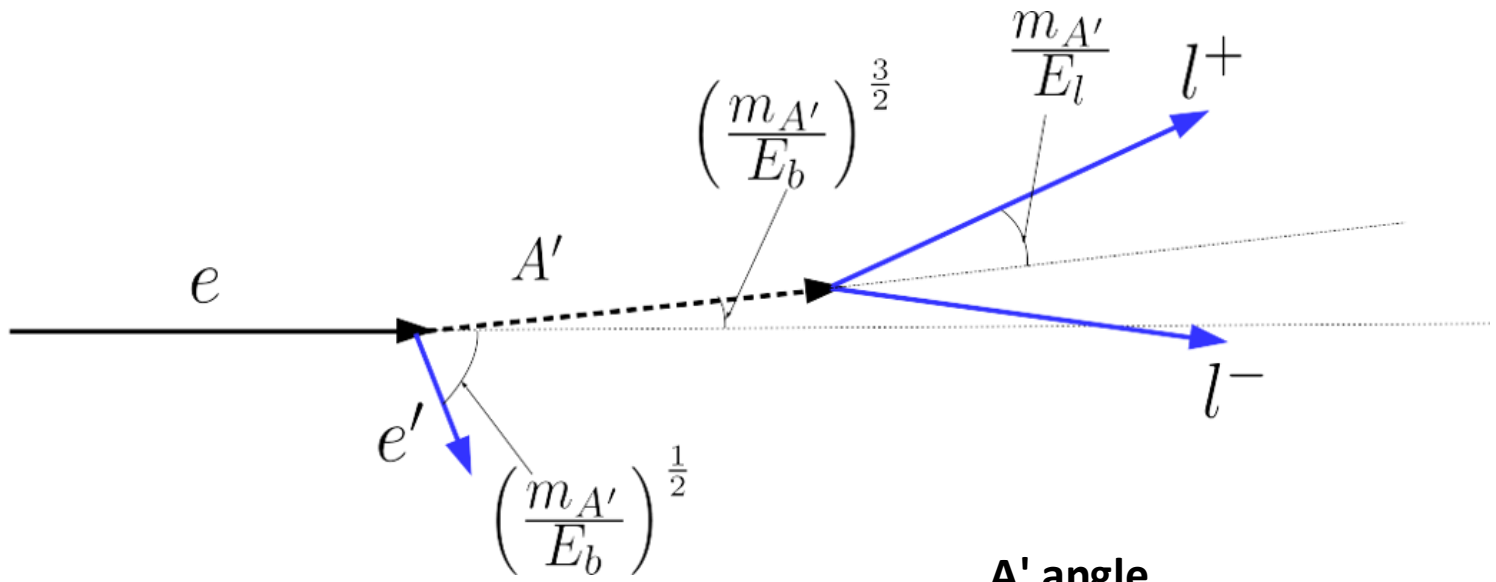
Initial proposal was submitted for 2.2 GeV and 3.3 GeV beam energies, however 3.3 GeV being non-standard CEBAF energy, we were offered to choose between 2.2 GeV and 4.4 GeV beams.

New studies for choosing the beam energy were now done with MadGraph for both the signal and the background.

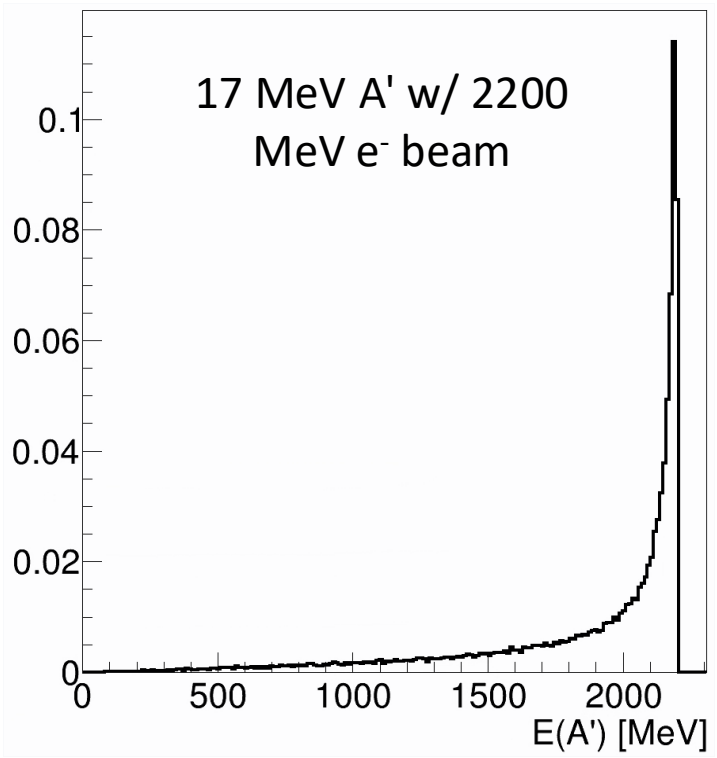
A' acceptance in the proposal

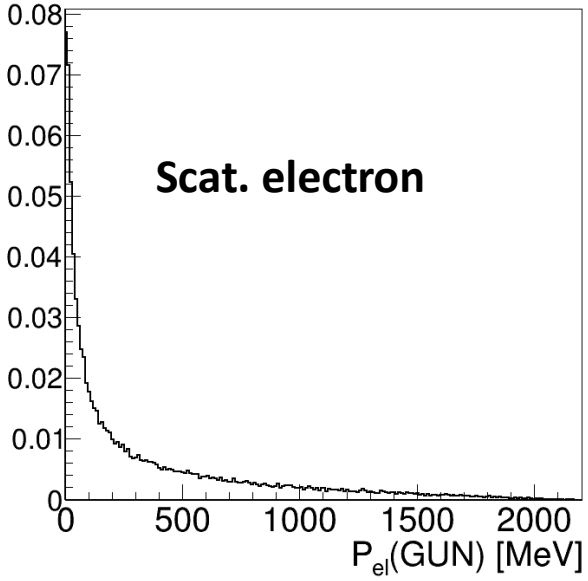


Signal kinematics from MadGraph

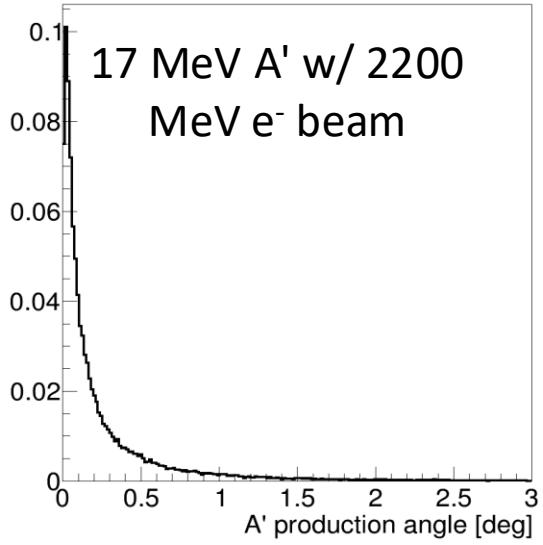


A' energy





A' angle



The Full simulation

MadGraph (tritrig and A') production → GEANT4 → Reconstruction → Analysis

$$e + Ta \rightarrow Ta\, e^- e^+ e^-$$

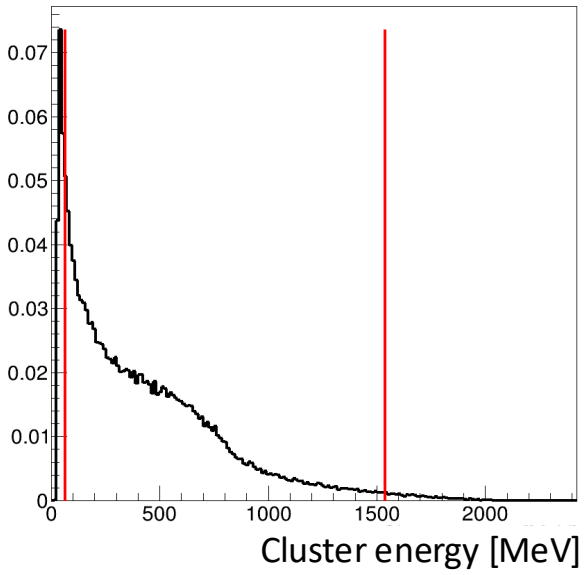
A' is generated for 5 different masses - M [MeV]: 10, 17, 25, 35, 55

Analysis conditions

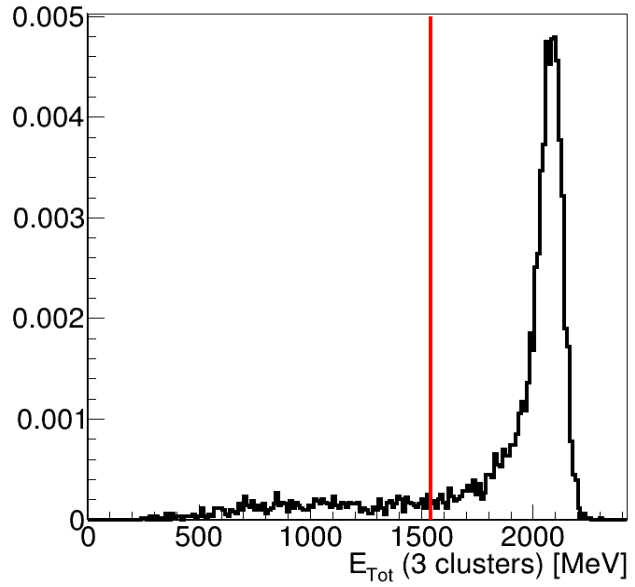
- Three or more clusters
- All clusters are charged,
- 0.03*Eb < Cluster energy < 0.7*Eb
- Sum of all three cluster energies > 0.7 *Eb

An example for 2200 MeV Beam and 17 MeV A'

Single cluster energy

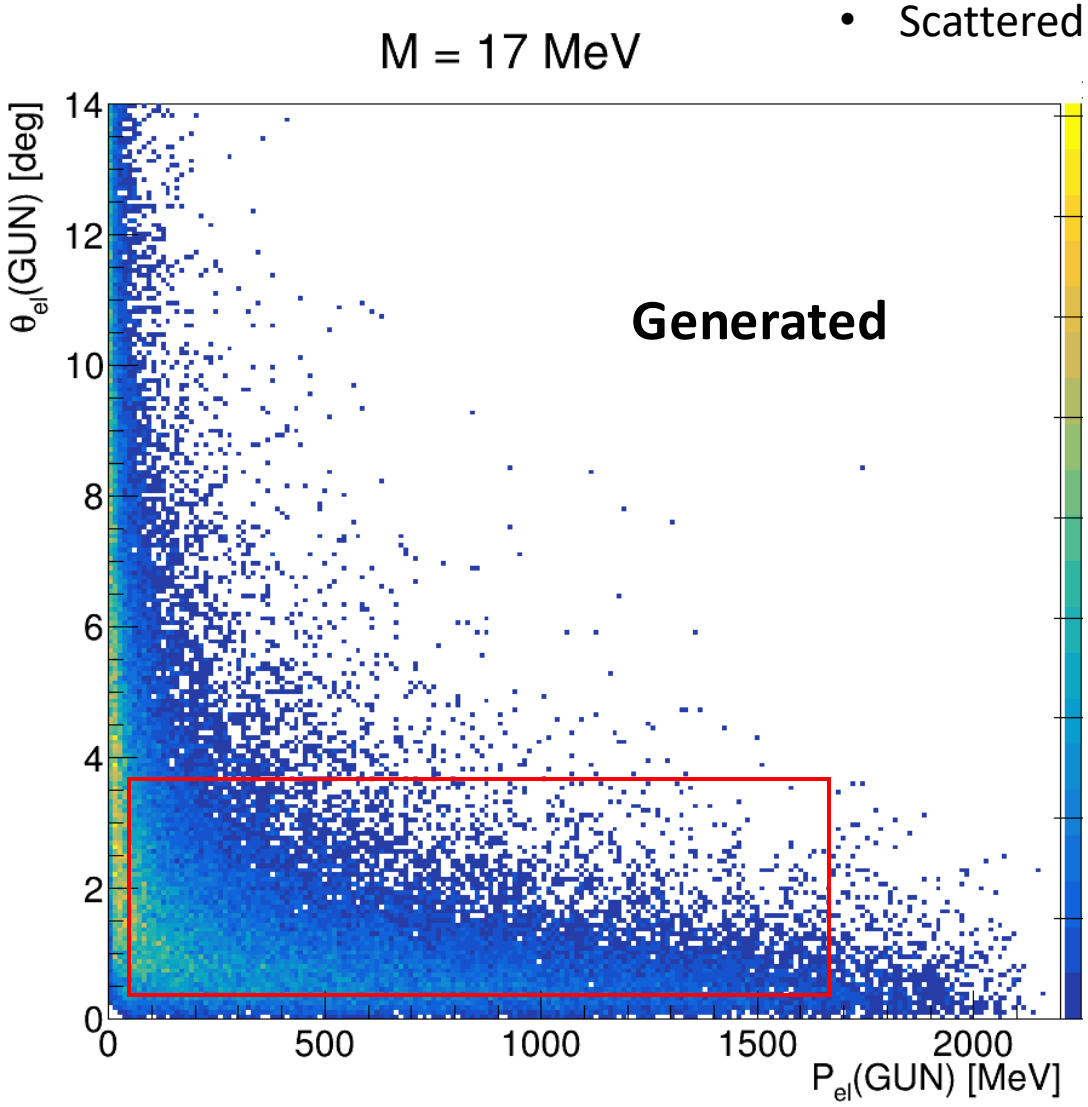


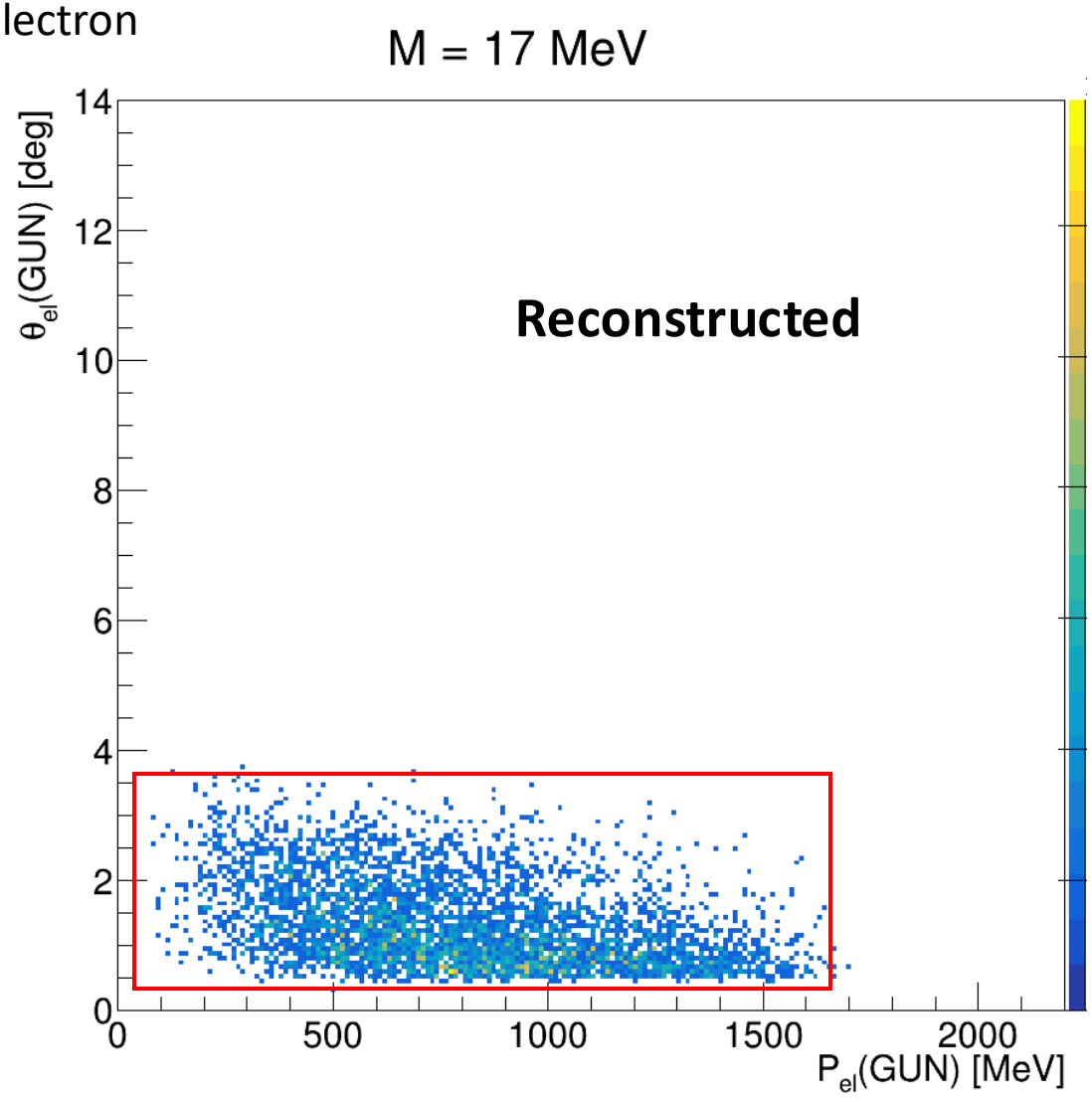
Energy sum of three clusters



Kinematics of the **scattered beam electron**

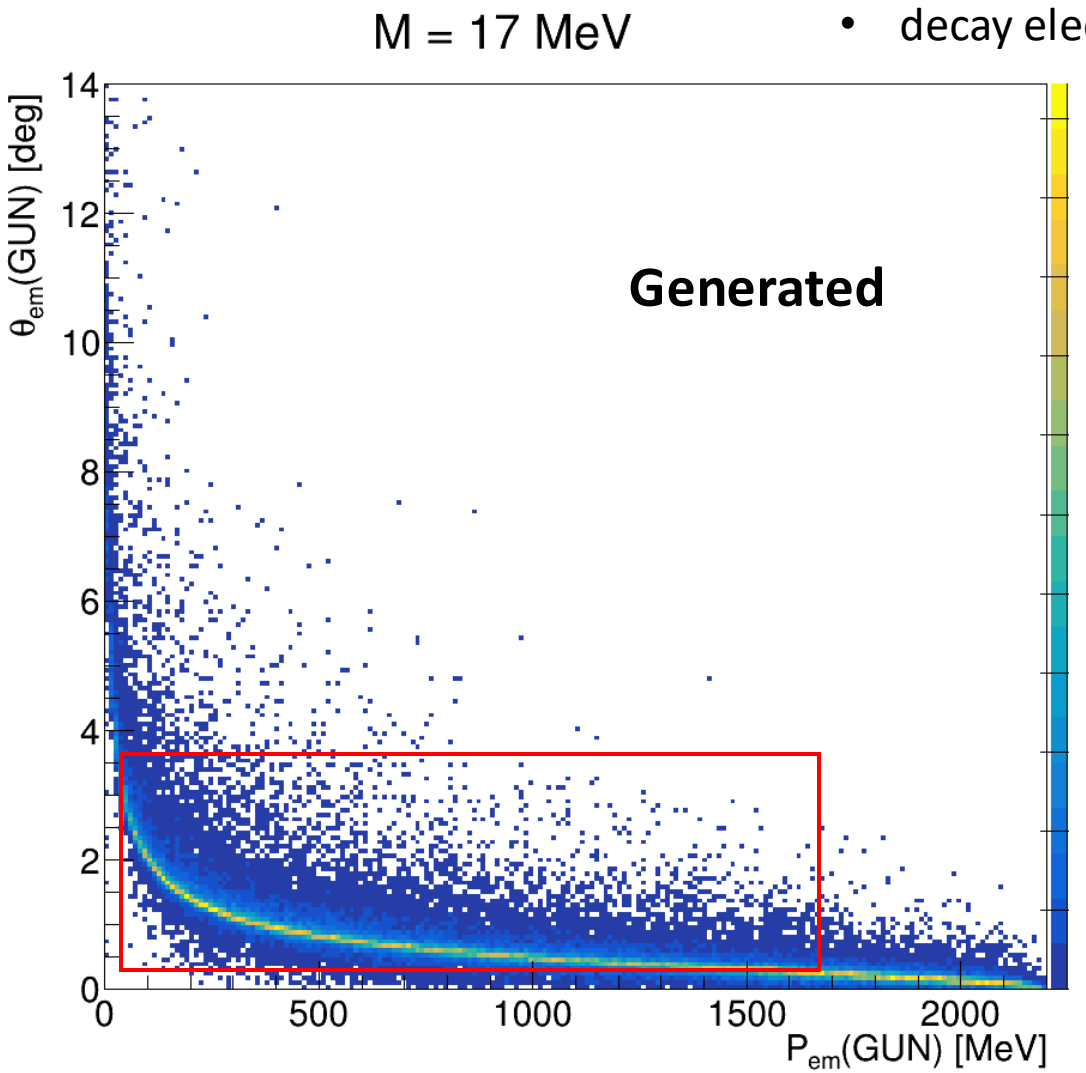
- Eb = 2200 MeV
- M(A') = 17 MeV
- Scattered beam electron

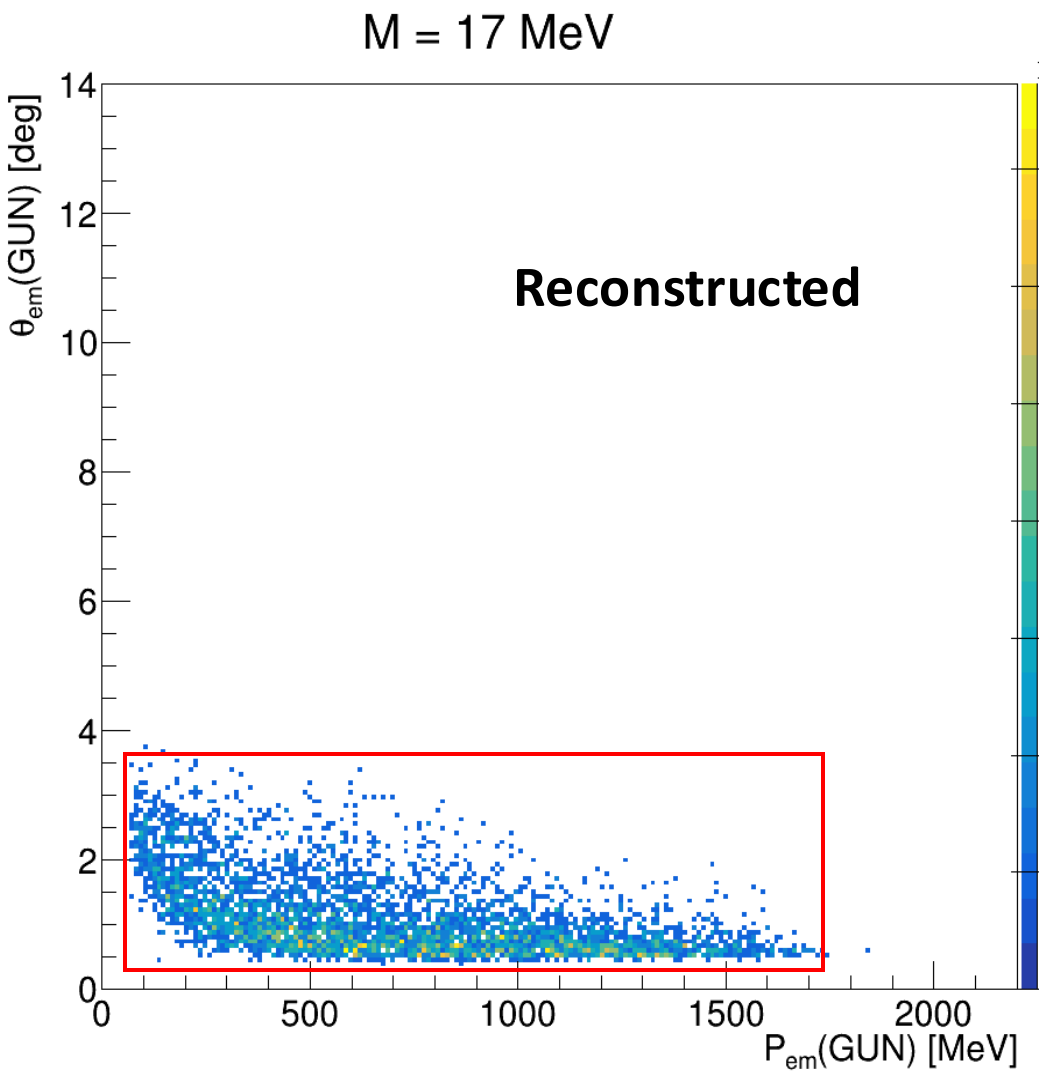




Kinematics of the **decay electron**

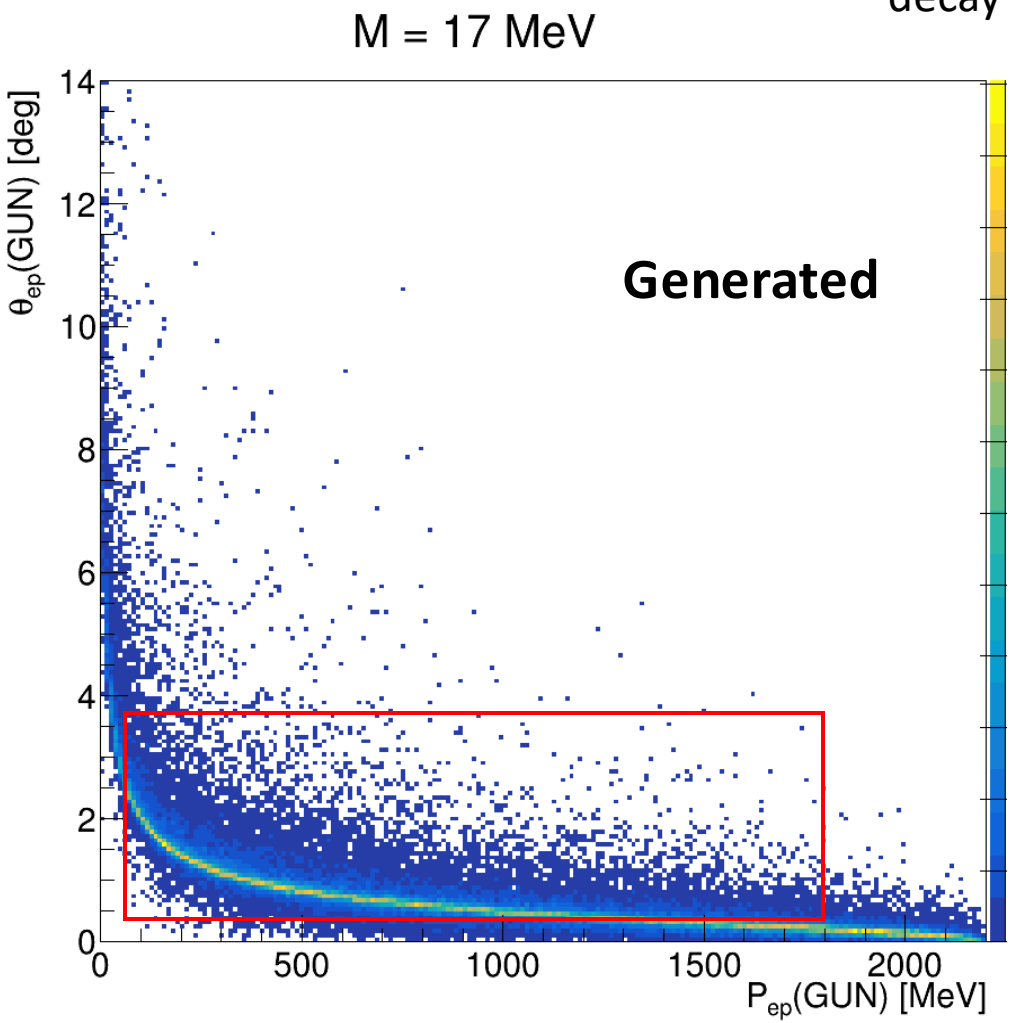
- Eb = 2200 MeV
- M(A') = 17 MeV
- decay electron

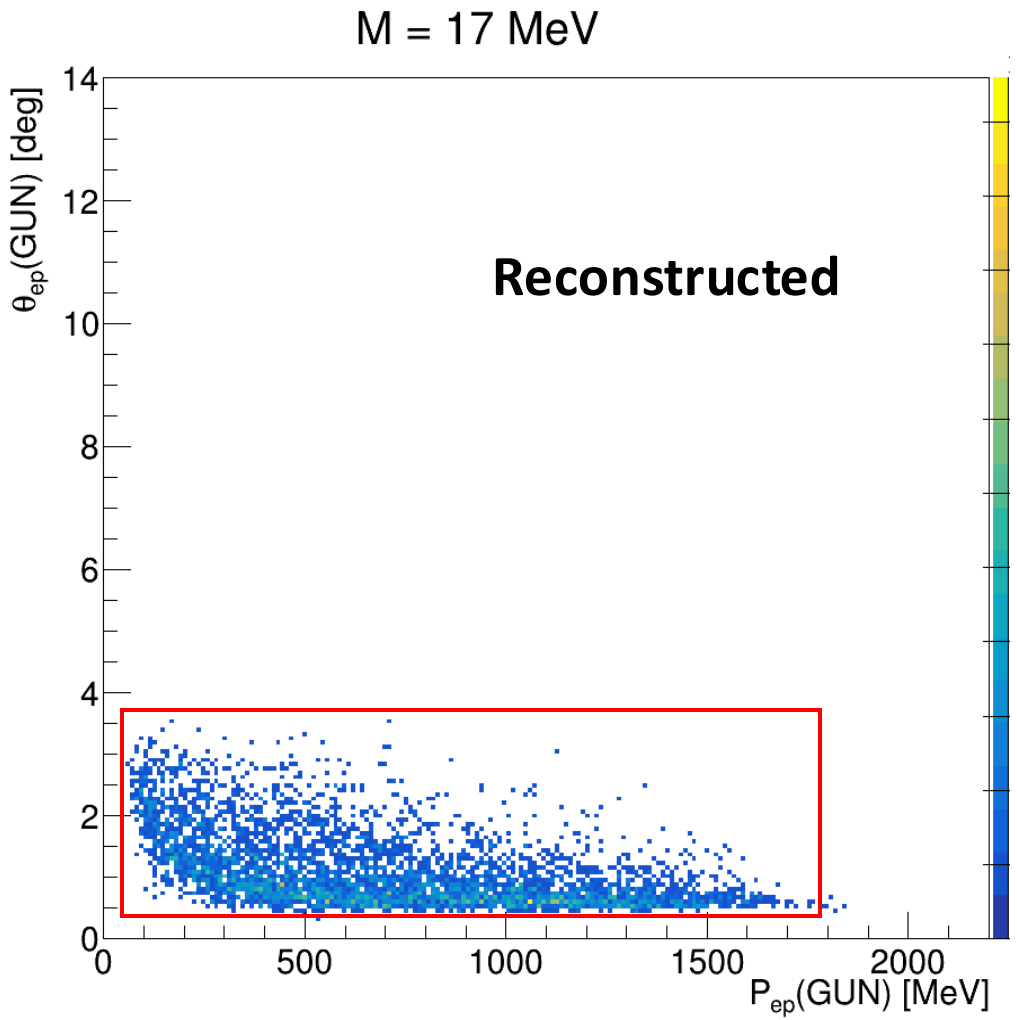




Kinematics of the **decay positron**

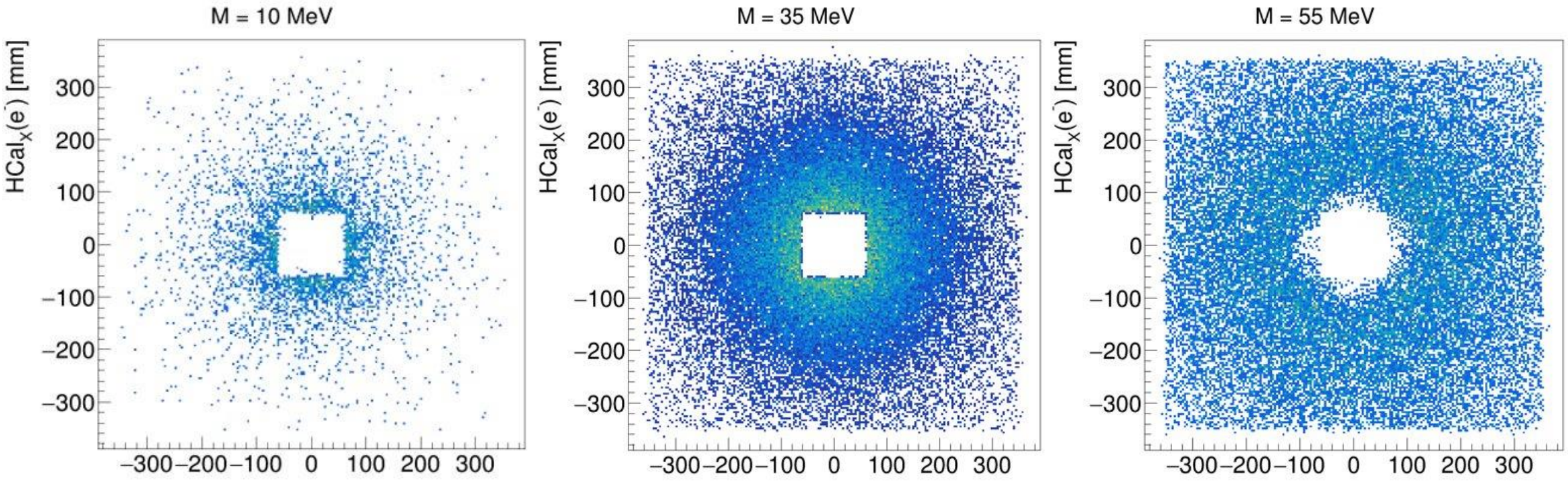
- Eb = 2200 MeV
- M(A') = 17 MeV
- decay positron





Distribution on HCal face

Beam energy = 2200 MeV
Decay electron

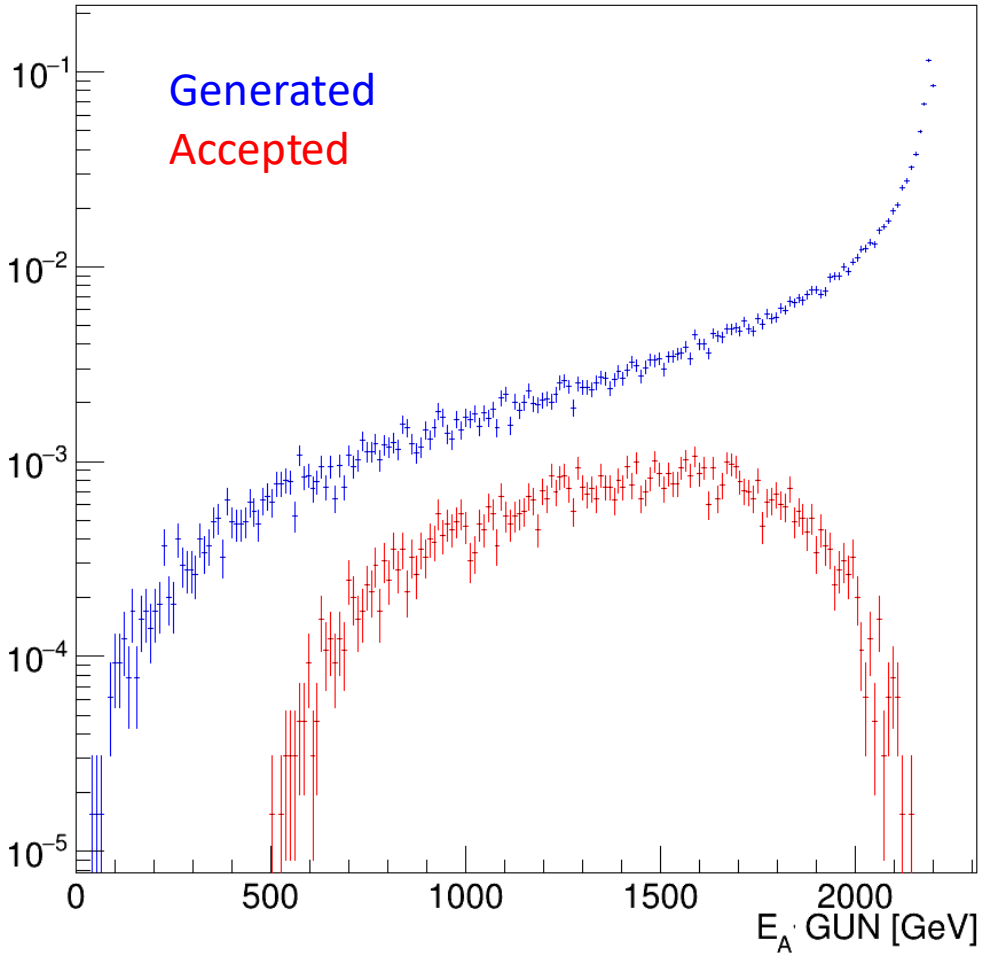


- Small Masses: Lose of the acceptance is mainly due to decay e-,e+ escape through the inner Hole of the HCal.
- High Masses: Lose of the acceptance is mainly due to particles get a large transverse kick and miss the HCal.

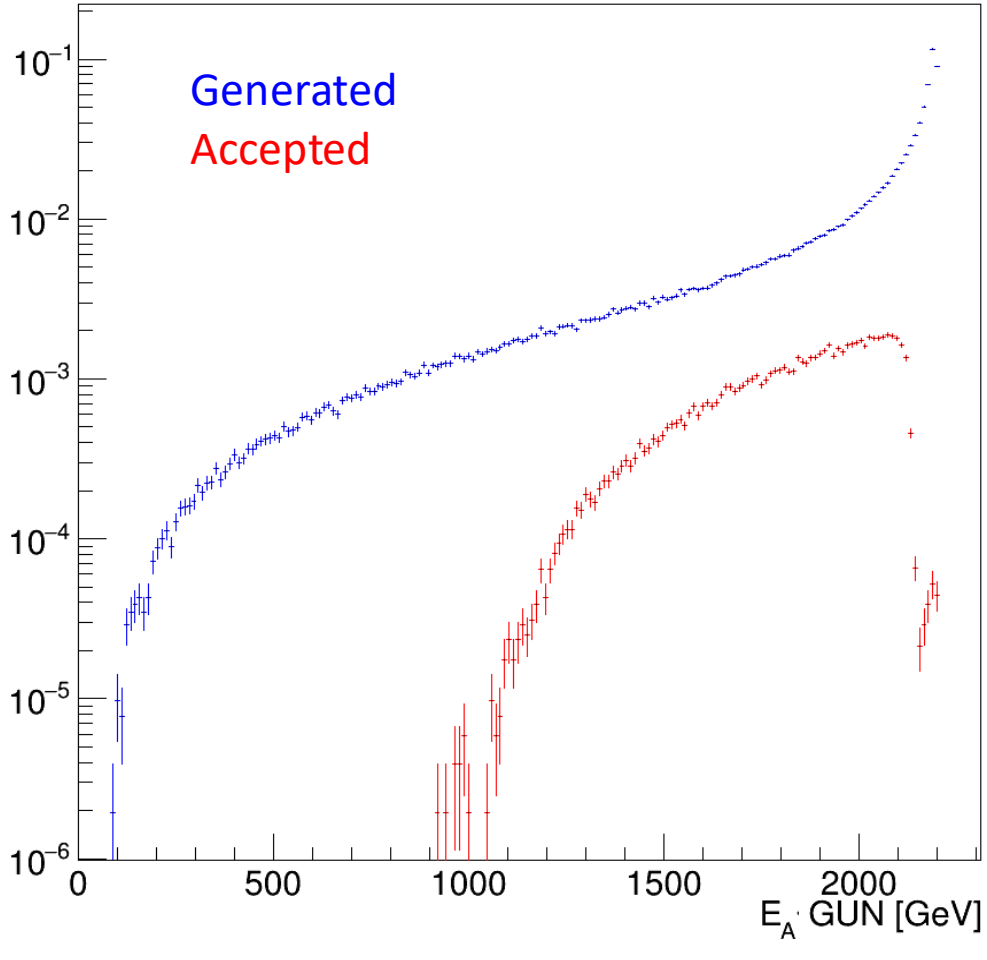
Energy sum distributions

Because of the Lorentz boost, smaller masses have low acceptance at high PSum.

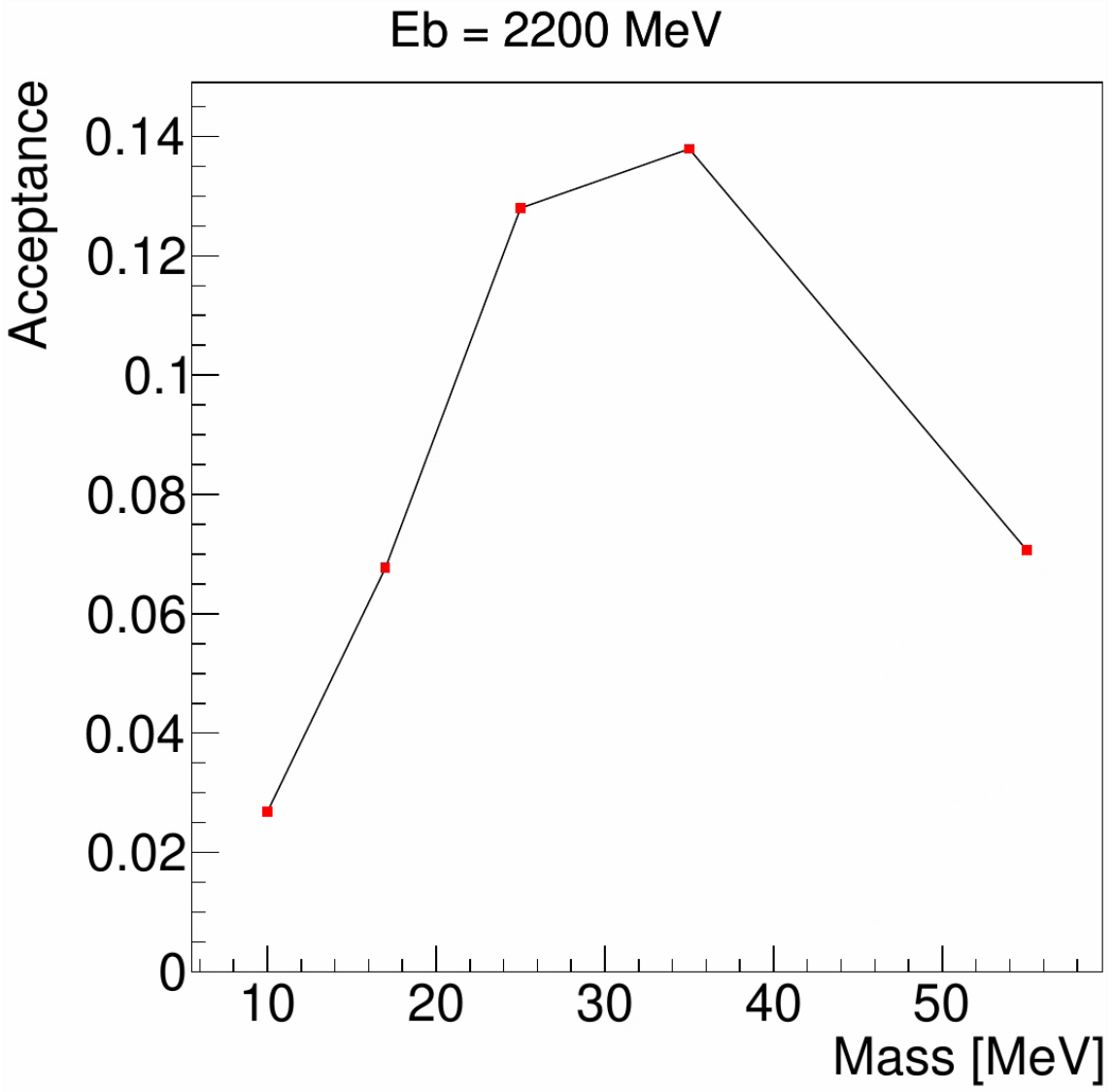
M = 17 MeV



M = 55 MeV



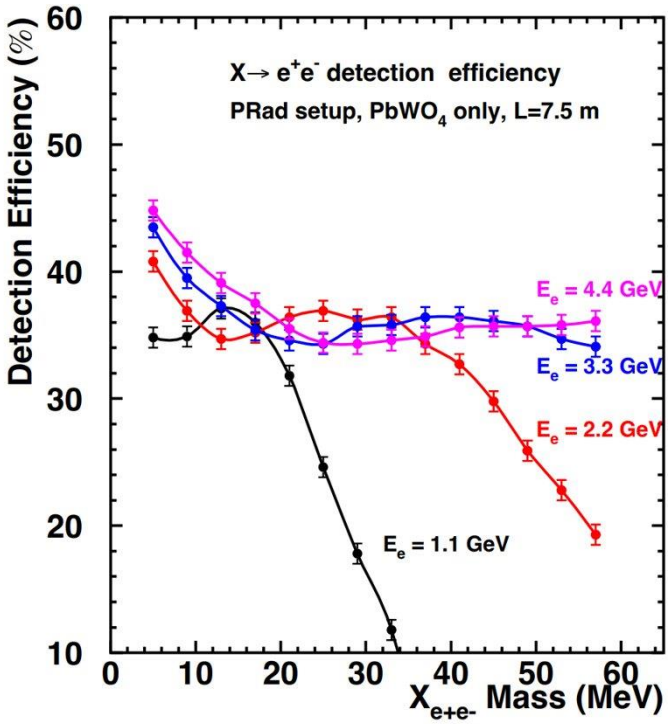
The acceptance



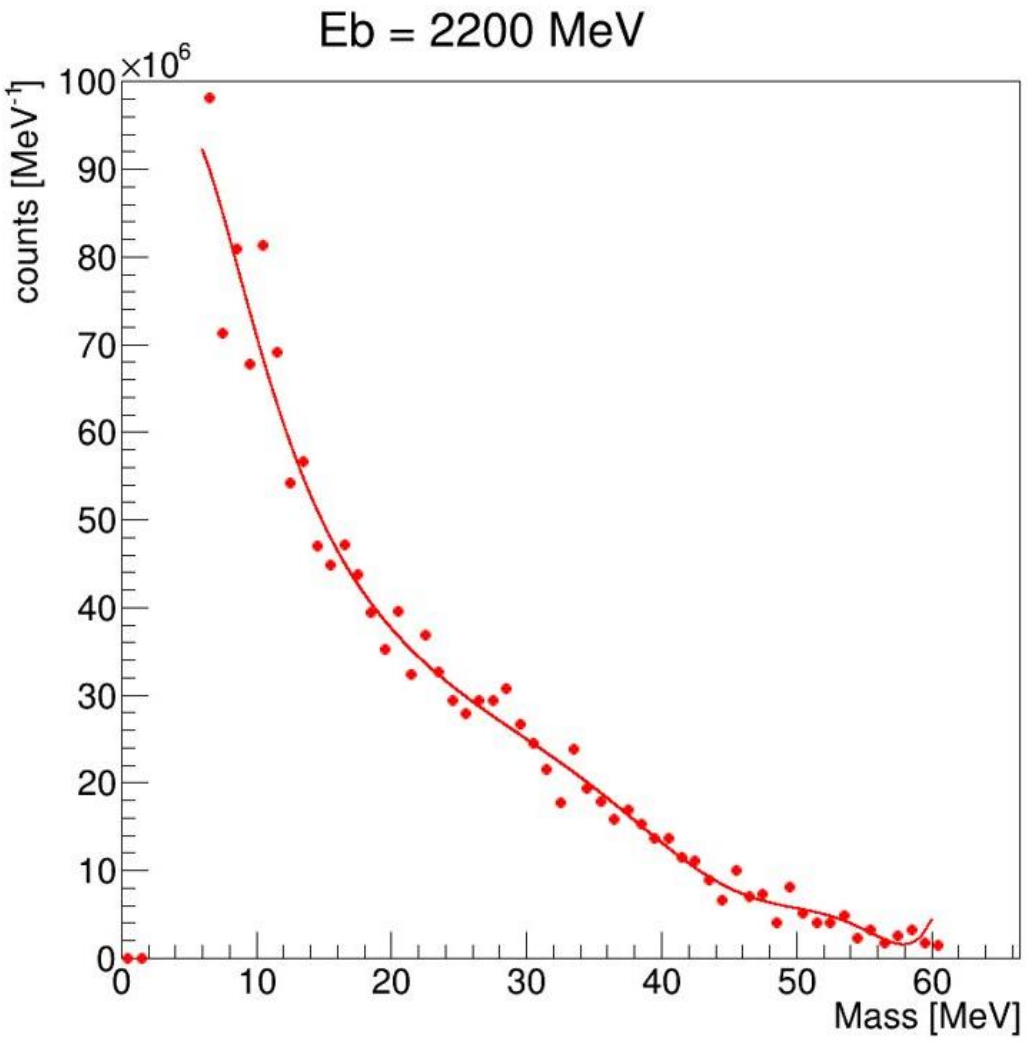
The acceptance drop at 55 MeV is because of the large scattering angle of the beam electron and a large transverse kick of A' decay leptons.

At higher energies 3.3 GeV and 4.4 GeV the acceptance is smaller.

Proposal acceptance



Background

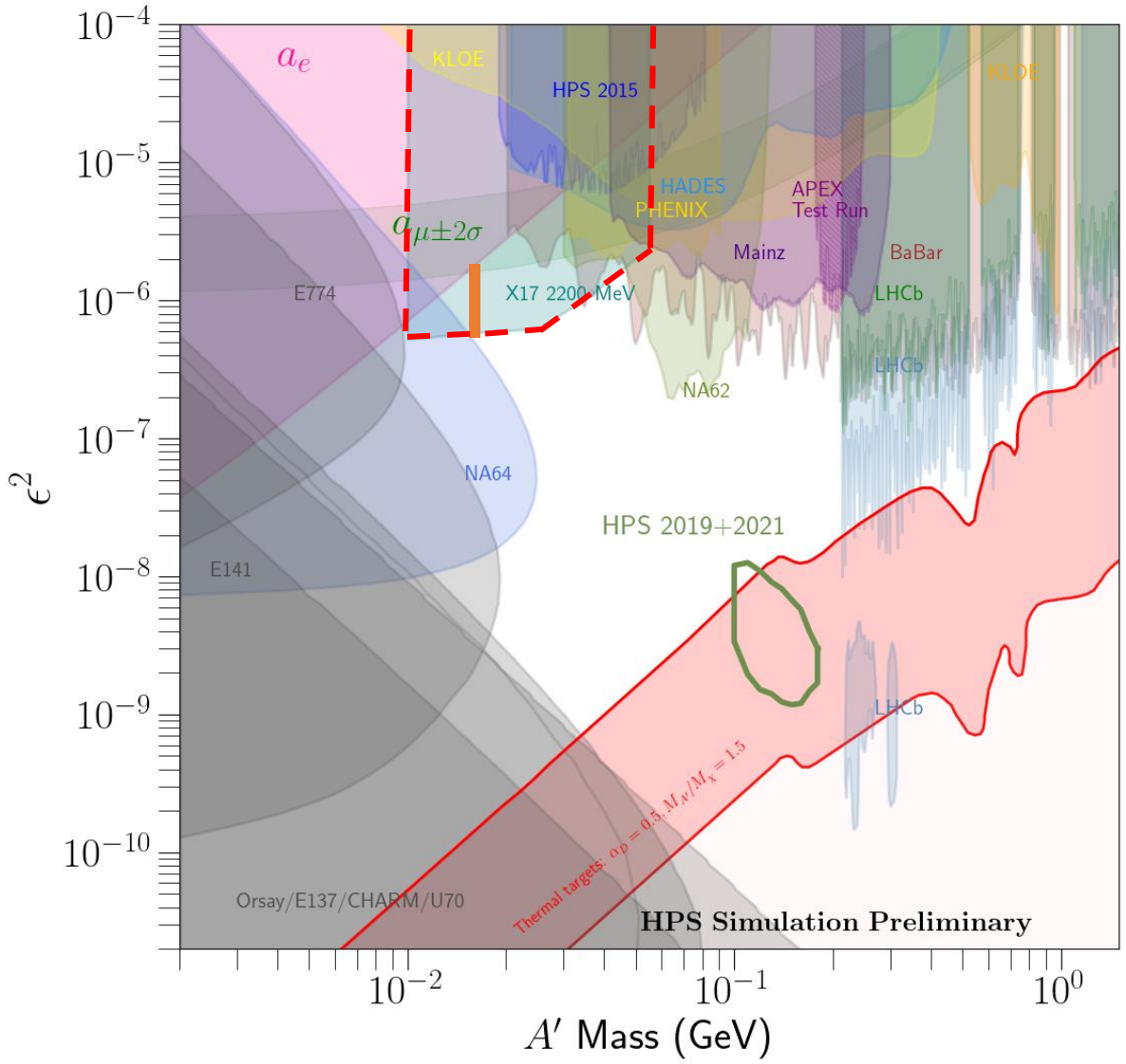


- Background (tritrig + Geant4) is scaled for Luminosity of **40 days at 50 nA on 1 um Ta**.
- Points are fit with 9-th order polynomial.
- For the given mass Bgr counts are calculated as the integral of the function in the "**Mass +/- 2σ**"
  - **σ** Is the mass resolution

$$\epsilon^2 = \frac{\frac{N_X}{Acc}}{5 \times N_e T \frac{m_e^2}{m_X^2}} \qquad N_X \text{ as } 5 \times \sqrt{N_B}$$

This is still not calculated using Rad. Fraction (had some difficulties running Rad Tridents at JLab), but after the acceptance correction, should be close enough the reach with f_rad method.

The expected reach



Experimental Readiness Review

The ERR for both PRad II and X17 was scheduled on May 8-9.

Both PRand and X17 passed the ERR, with couple of Recommendations (must be addressed) and comments (suggestions).

One Recommendation and several comments on X17 part.

Recommendation:
Provide and track an itemized breakdown of Engineering, Procurement, and construction/modification of remaining components with schedule, responsible persons, and contingencies. Being that the 2 experiments are strongly tied together, a fully integrated resource schedule should be made and tracked to help ensure that there is a good understanding of the consequences of a delay of any one item on the schedule. It appears that the initial installation timeframe of one month is very optimistic. It also does not match the timeframe of GEM availability in November.

The schedule was worked out and sent to the committee last Friday.

Some of suggestions from ERR related to X17 setup.

Comments:

- The background should include GEM and trigger inefficiencies.
- The detection efficiency should account for GEM and trigger efficiencies.
- It was suggested to establish two independent working groups, shielded from management: one based at the lab, led by laboratory staff; and one outside the lab, led by a user.
- It was suggested that, before data taking, a 90 % CL upper limit be derived from simulation, and that the bump-hunt code be tested by injecting signals at 17 MeV and 40 MeV.
- An itemized list detailing the contributing phenomena in the simulation's background would clarify the rationale and methodology for decisions elsewhere in the experiment.

Current status

- Engineering design of all beamline components are finalized, parts are ordered, and partially delivered
- Every channel of HyCal was successfully tested wit LMS.
  - One channel might need a repair.
- 7 new VXS crates have been received and tested, and are in the hall
- All new fADCs have arrived and tested
- Construction of new GEM detectors is on track, 2 GEMs will be soon (This month) sent to JLab, and two more will be send by September.
- Both PRad II and X17 passed the ERR in May 8-9, and are preliminary scheduled to start running Feb (PRadII) and May (X17) of 2026.

Installation and the run schedule

- Hall work will begin on ~~August 25~~ (September 3) right after the RG-L (ALERT) experiment.
  - Clear space in Space frame, remove ALERT, BAND, HTCC, beamline etc.

- Installation work of the PRad II and X17, Sep 2025 – Jan 2026

- Jan 23 Commissioning of PRad II, about 6 days

- Feb 2 – Apr 27 PRad II experiments with three beam energies 0.7 GeV, 1.4 GeV and 2.1 GeV

- About 6 days to change from PRadII to X17

- May 5 to July 26: The X17 experiment runs

Note: this is a preliminary schedule, and because of the current run extension the whole schedule will likely shift by at least a 2 weeks.

Summary

- It is a cost-effective, mostly ready-to-run experiment to:
  - Validate existence or set an experimental upper limit on a search for hypothetical X17 particle
  - Search for hidden sector new particles (resonances) in [3 ÷ 60] MeV mass range.
- Combination of a GEM tracker with the calorimeter provide very good mass resolutions
- Magnetic free experimental setups allows to avoid complications related to the tracking in a magnetic field
- The experiment is on track for start running in May of 2026

Backup

Reach from the initial proposal