# Calibration of the HyCal calorimeter for the PRad Experiment at JLab[1]

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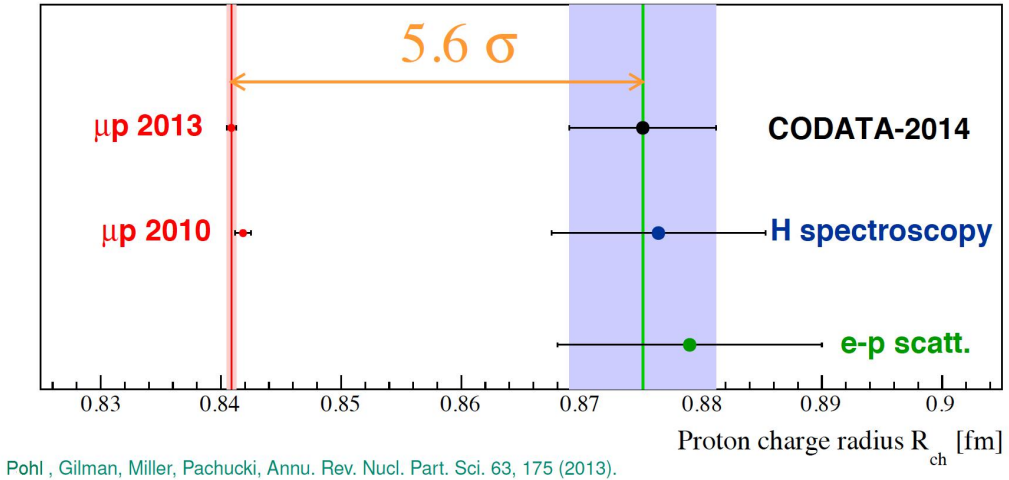
# *Outline*

- ***PRad Physics goals***
- ***Experimental setup***
- ***Calibration Methods***
- ***Trigger Efficiency***
- ***Summary***

# The Proton Charge Radius Puzzle

Existing data :
1.electron-proton elastic scattering measurements
2.Lamb shift measurements in atomic hydrogen
3.Lamb shift measurements in muonic hydrogen




Pohl , Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

- Muonic hydrogen Lamb shift experiment at PSI (2010,2013)
- **$r_p$ = 0.84184(67) fm ➡ Unprecedented less than 0.1% precision**
- **~ 5.6 σ discrepancy from most of previous experimental results and analyses**

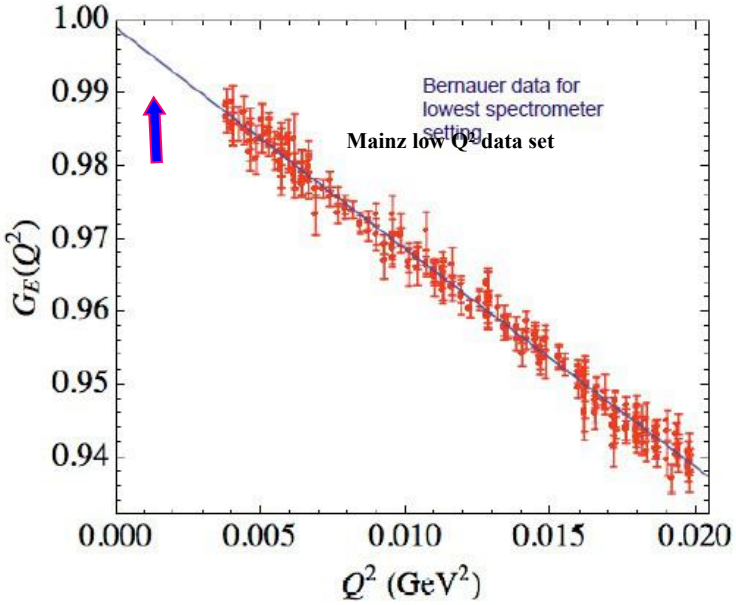
# The PRad Experiment (E12-11-106)

- Experimental goals:
  - reach very low $Q^2$ range (~ 10 times less than the Mainz experiment)
  - reach sub-percent precision in $r_p$ extraction

- Novel Techniques Used:
  1) Non-magnetic-spectrometer method:
     use high resolution high acceptance calorimeter and high position resolution GEM detector
     - reach smaller scattering angles: ($\Theta$ = $0.5^0$ – $7.5^0$ )
       ($Q^2 = 2\times10^{-4}$ – $6\times10^{-2}$ ) GeV/$c^2$
       essentially, model independent $r_p$ extraction

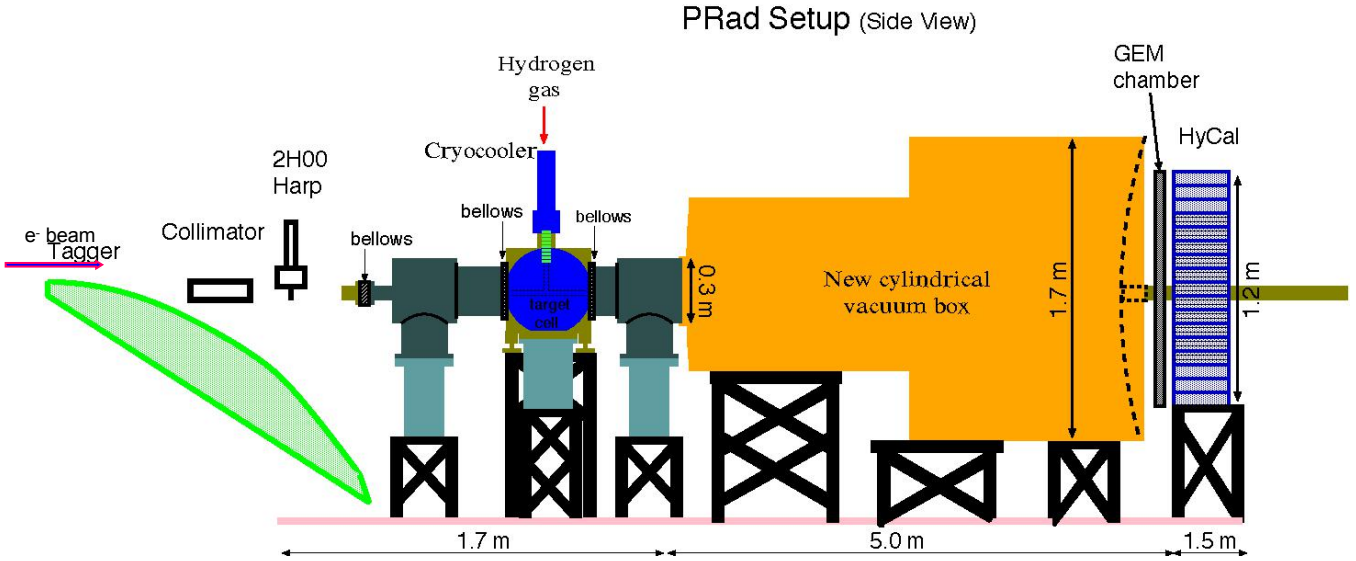
  2) Simultaneous detection of *ee* → *ee* Moller scattering
     - (best known control of systematics)

  3) Use high density windowless H2 gas flow target:
     - beam background fully under control with high quality CEBAF beam
     - minimize experimental background




- Two beam energies: $E_0$ = 1.1 GeV and 2.2 GeV to increase $Q^2$ range: ($2\times10^{-4}$ – $6\times10^{-2}$ ) GeV/$c^2$
- Will reach sub-percent precision in $r_p$ extraction

# PRad Experimental Setup (schematics)




- High resolution, Hybrid calorimeter (Magnetic Spectrometer Free)
- Windowless, high density H2 gas flow target (Reduced backgrounds)
- Simultaneous detection of elastic and Moller electrons (control of systematics)
- Vacuum box, one thin window, large area GEM chambers (improved resolution)
- $Q^2$ range of $2\times10^{-4} - 6\times10^{-2}$ GeV$^2$ (lower than all previous electron scattering expts.)

# Windowless $H_2$ Gas Flow Target

- Target chamber is differentially pumped with four high speed turbos.
- Kapton orifices up- and downstream from the cell reduce the beam line vacuum.
- A four-axis motion mechanism positions the target cell, with approximately ±10 μm accuracy.

**Target specs:**

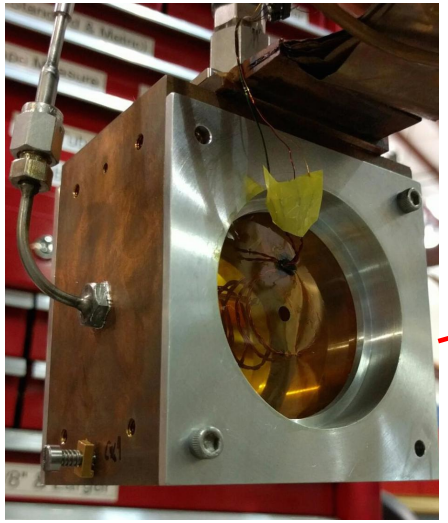
**Cell:** 30 μm thick Kapton, length 4 cm

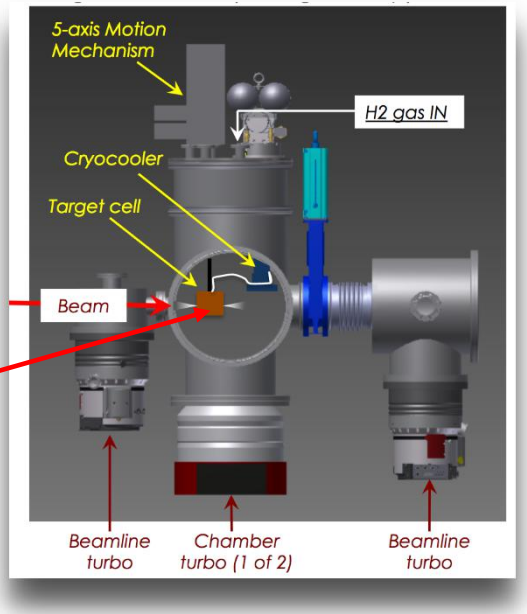
- ✓ diameter 8 cm with 2 mm diameter holes for the beam to pass through
- ✓ Cell pressure 0.5 torr

**Target:** $H_2$ input gas temp. 19.5 K

- ✓ thickness $2\times10^{18}$ **(atoms)** / $cm^2$
- ✓ density $2.75\times10^{17}$ **(molecules)** / $cm^3$
- ✓ Cell / chamber / vacuum tank pressure: 470 mtorr / 2.3 mtorr / 0.3 mtorr

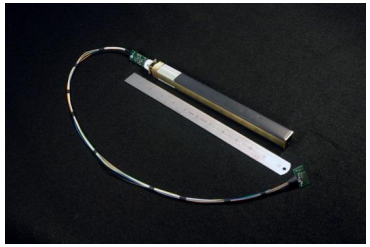
Funded by a NSF MRI grant

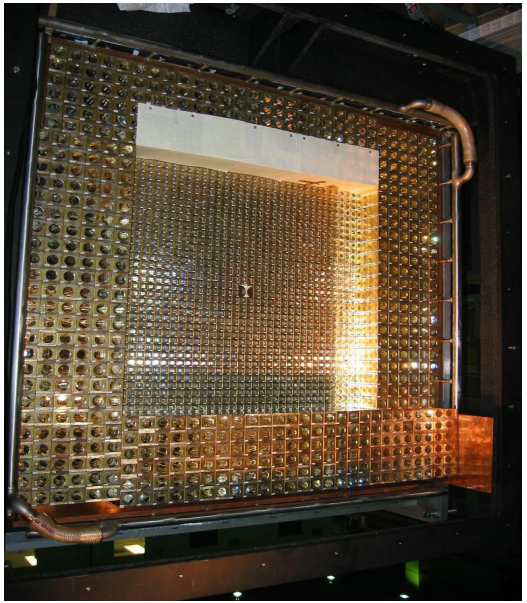




# Electromagnetic Calorimeter (PrimEx HyCal)

- Combination of $PbWO_4$ and Pb-glass detectors (118x118 $cm^2$)
- 34 x 34 matrix of 2.05 x 2.05 x 18 $cm^3$ $PbWO_4$ shower detectors
- 576 Pb-glass shower detectors (3.82x3.82x45.0 $cm^3$)
- 2 x 2 $PbWO_4$ modules removed in middle for beam passage
- 5.5 m from $H_2$ target (~0.5 sr acceptance)



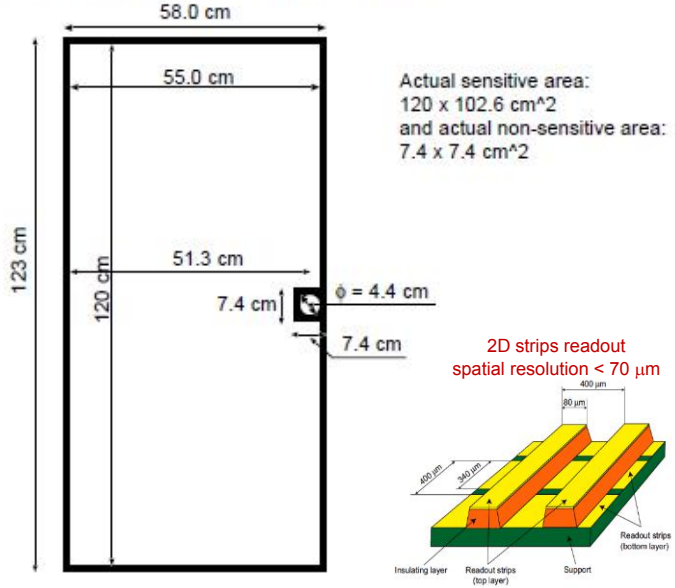


- Moved back to Hall B in June, 2014:

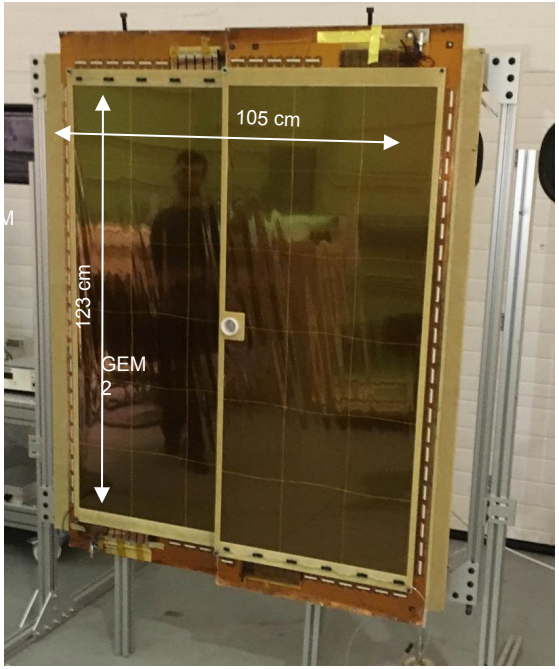
  Cabling system with infrastructure reassembled
  - Trigger, analog and HV electronics are reinstalled
  - Cooling system is operational
  - LMS checked and repaired
  - All individual detectors checked and repaired
  - DAQ is operational (HyCal readout part)
  - Transporter is reinstalled/repaired and operational

# PRad GEMs: Design & Specifications

Desired Sensitive area: 116.4 x 116.4 cm^2
central hole: diameter 4.4 cm, including the frame max allowed
maximum allowable non-sensitive region 7.8 x 7.8 cm^2




Two modules mounted on the holding frame in PRad GEM configuration before the cosmic run in EEL (March 2016)

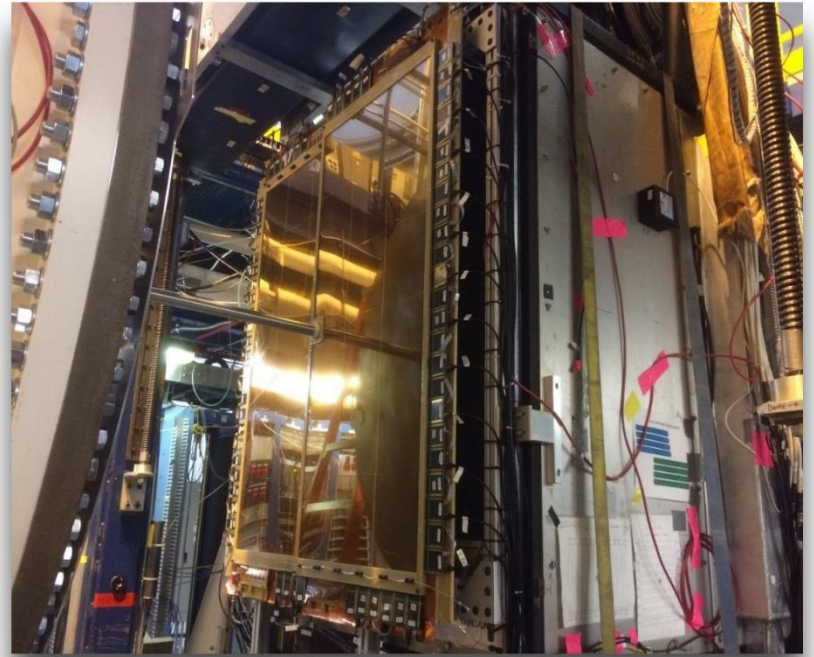



- Largest GEM detector ever built in the world
  - Each module(123 cm x 55 cm)
  - The two modules overlap in the central part for the alignment of the beam pipe hole
- COMPASS-like strip readout (1.3 m long strips in the vertical direction ⇨ capacitance noise still OK)

# PRad in Jefferson Lab Hall B

Beam-side view


GEMs mounted on HyCal



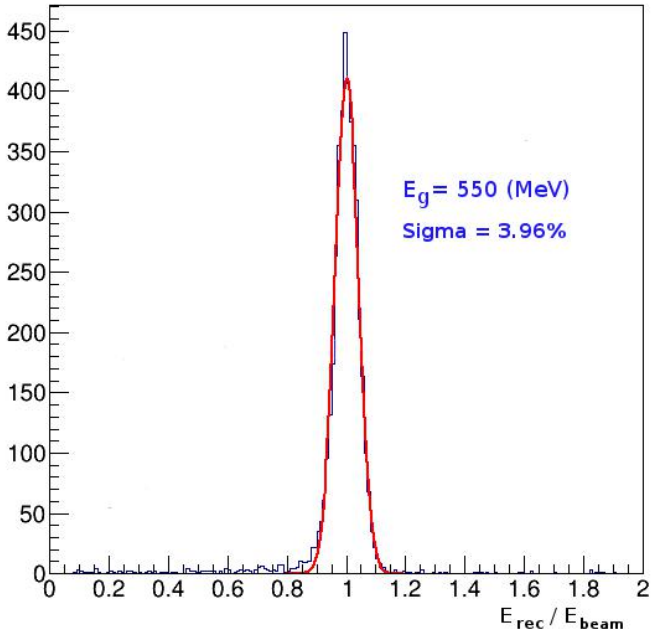
# Calorimeter Calibration Method

- Gains controlled by Light Monitoring System (LMS)
- Two different calibration modes:
  - Before physics data collection: Scan with 250~1050 MeV tagged photon beam incident on each module
    → study of resolution, efficiency and non-linearity
  - During physics data collection:
    With Moller and ep elastic events
- Iterative method:

  $\mathbf{gain}_{module}(n+1) = \mathbf{gain}_{module}(n)/\langle \mathbf{E}_{measured}/\ \mathbf{E}_{expected} \rangle$
- Two different clustering algorithms used for cross check

# Calorimeter Calibration Example

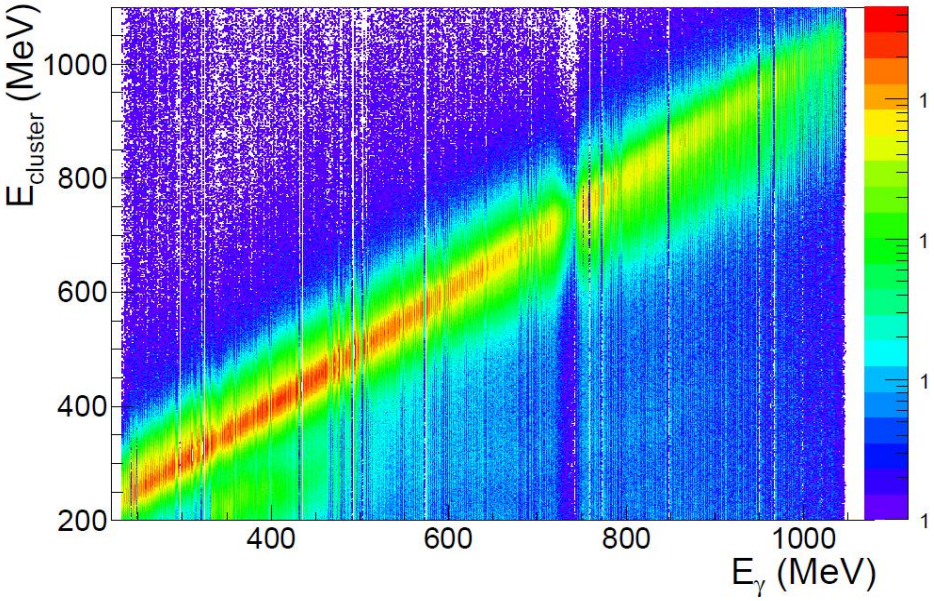
Example for PbWO4 module W222



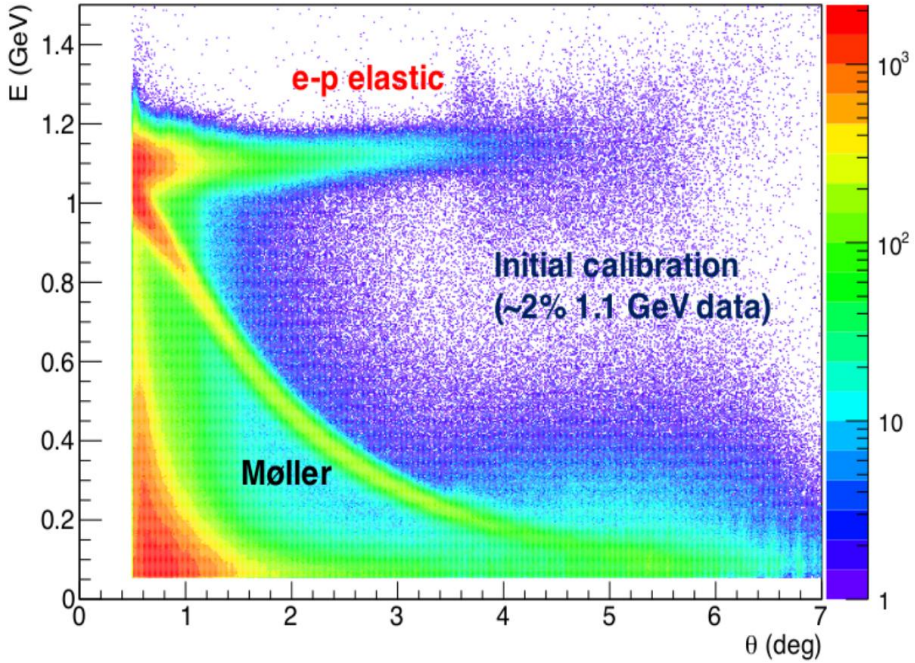

plot of reconstruct energy / beam energy

# Reconstruction After Calibration

Calibration with tagged photon beam

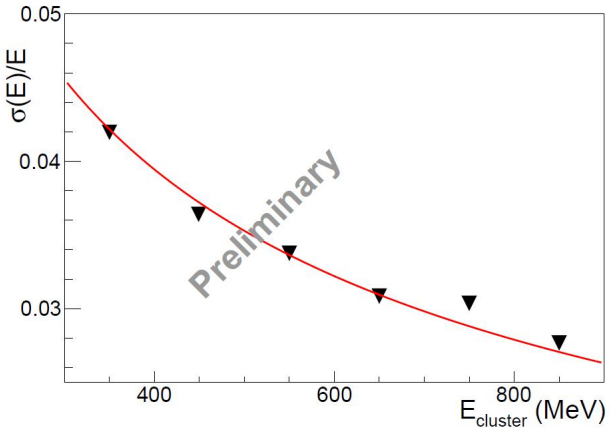



Physics Calibration

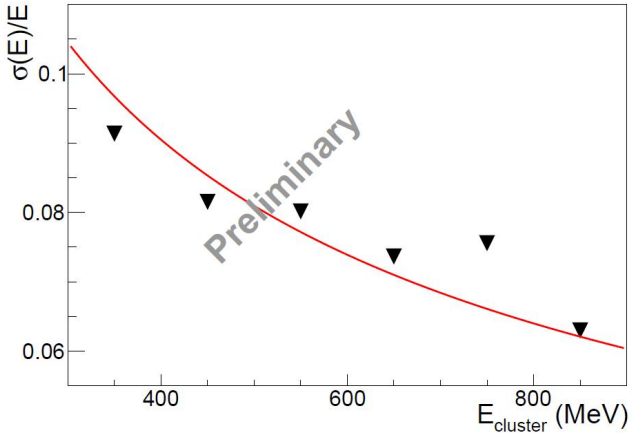


# Preliminary Energy Resolution

$$\frac{\sigma(E)}{E} = \frac{r}{\sqrt{E(GeV)}}$$



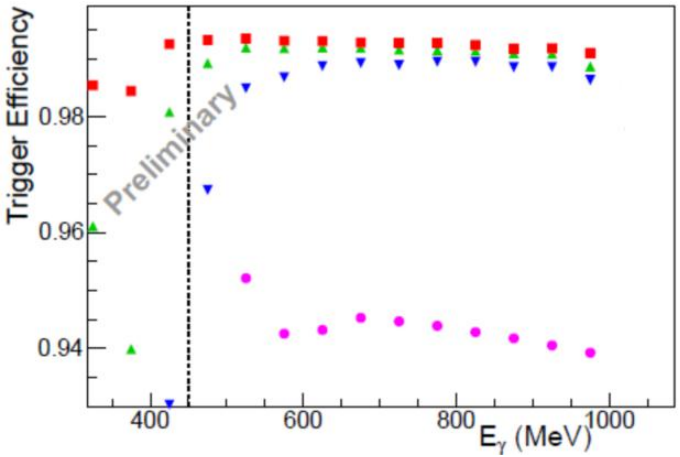

PbWO4
resolution at 1 GeV: 2.5%



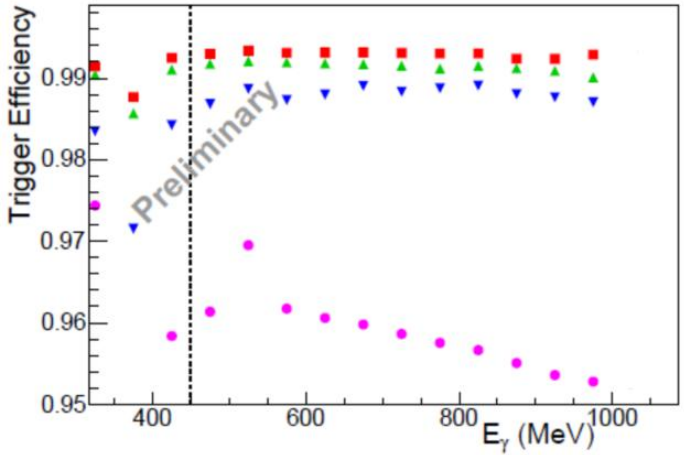

Lead Glass
resolution at 1 GeV: 6.1%

# Trigger Efficiency

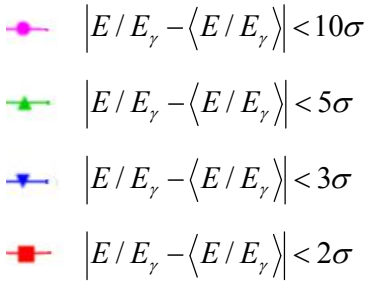
- Three triggers: 1.LeadGlassSum, 2.TotalSum, 3.Tagger
- Plateau above 450 MeV with 0.994 efficiency
- Good uniformity




PbWO4




Lead Glass



# Summary


- ✓ The Proton Radius Puzzle is still unsolved
- ✓ The PRad experiment was uniquely designed to address the Proton Radius Puzzle
- ✓ HyCal calibration and alignment are finalized
  → good energy resolution , high and uniform efficiency
- ✓ The physics analysis will start soon!