THE CATHOLIC UNIVERSITY of AMERICA

Jefferson Lab

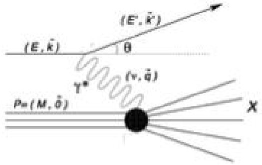
EEEMCAL consortia beam tests program at DESY and JLab

Vladimir V. Berdnikov (CUA)
for EEEMCAL consortia

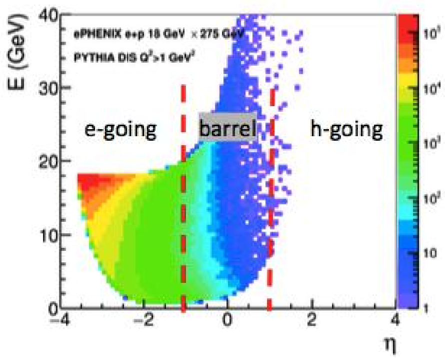
Jlab EIC meeting. January 28 2022

Electromagnetic Calorimetry in EIC

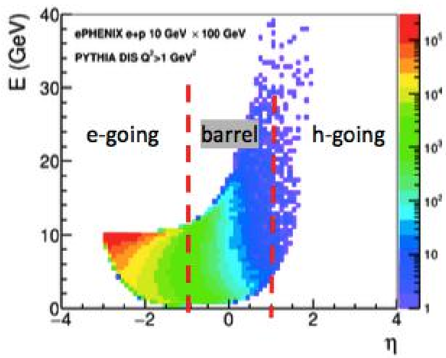
Inclusive DIS: scattered electron



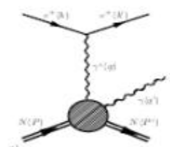
e+p 18x275 GeV



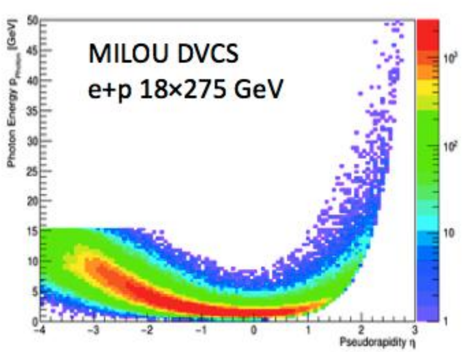
e+p 10x100 GeV



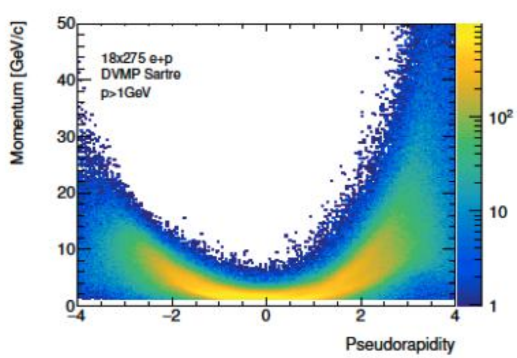
Exclusive DIS: DVCS and DVMP



DVCS photon kinematics

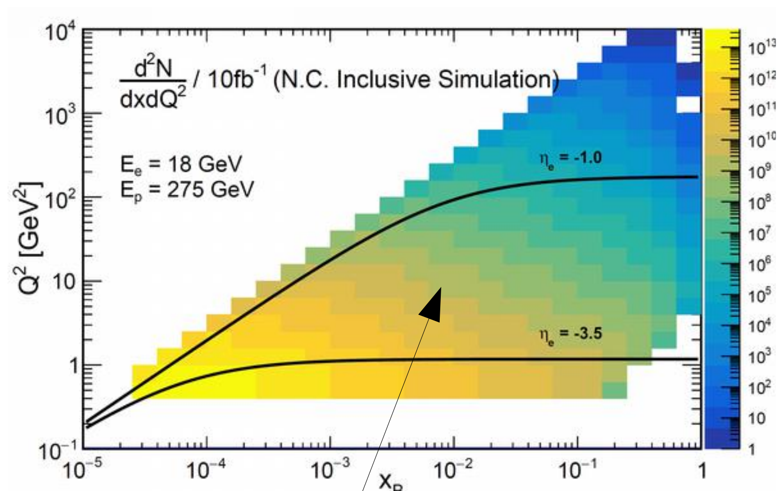


J/ψ→ee kinematics



EIC Yellow Report. Chapter 11. Detector Aspects

- **EM calorimetry plays a crucial role at the EIC in all regions of the detector**
- **Nearly all physics processes require the detection of the scattered electron in the electron endcap**
- **The requirement of high-precision detection is driven mainly by inclusive DIS where the scattered electron is critical to determine the event kinematics**



Region of physics enabled by EEEMCAL

EEEMCAL consortia

The Electron-Endcap Electromagnetic Calorimeter (EEEmCal) will enable unique detector capabilities for scattered electron and f inal-state photon detection crucial at the EIC

EEEMCAL consortium

Institutions (9):
CUA (contact: Tanja Horn), Lehigh U. (contact: Rosi Reed), MIT and MIT-Bates Research and Engineering Center (contact: Richard Milner), U. Kentucky (contact: Renee Fatemi), AANL (contact: Ani Aprahamian/Hamlet Mkrtchyan), FIU (contact: Lei Guo), Charles U.-Prague (contact: Miroslav Finger), IJCLab-Orsay (contact: Carlos Munoz-Camacho), James Madison U. (contact: Gabriel Niculescu)

eRD105
Dedicated EIC project R&D on SciGlass

includes many of the EEEEMCAL consortium

A. Asaturyan, M. Battaglieri, V. Berdnikov, J. Bettane, M. Bondi, A. Celentano, J. Crafts, R. DeVita, T. Horn, G. Hull, M. Josselin, I.L. Pegg, S. Mayilyan, C. Munoz-Camacho, A. Mkrtchyan, H. Mkrtchyan, M. Murray, N. Pilleux, A. Shahinyan, P. Stepanov, V. Tadevosyan, R. Trotta, H. Voskanyan

A.I. Alikhanyan National Science Laboratory/Yerevan, Catholic University of America, The Vitreous State Laboratory, IJCLab-Orsay/France, INFN-GE, Jefferson Laboratory, U of Kansas

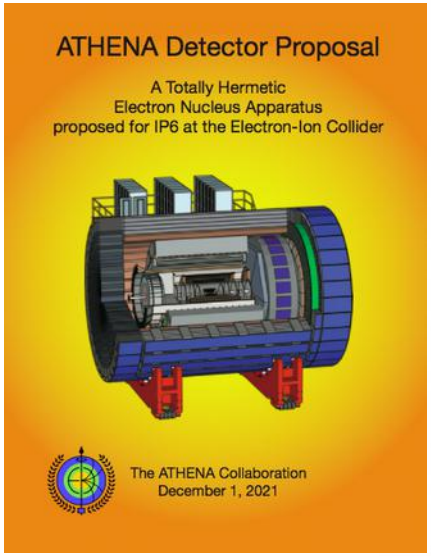
The Catholic University of America · IJCLab Irène Joliot-Curie · A. Alikhanyan National Laboratory · SCINTILEX · Jefferson Lab · INFN · KU The University of Kansas

EEEMCAL is very active working group, meetings started 2020 , every 2-3 weeks

See details **Wiki page:** https://wiki.jlab.org/cuawiki/index.php/Electron-Ion_Collider_Detectors:_EEEMCal

EOI: https://wiki.jlab.org/cuawiki/images/7/77/Expression_of_Interest_%28EOI%29_-EEEmCal-10312020.pdf

EEEMCAL in EIC detector proposals



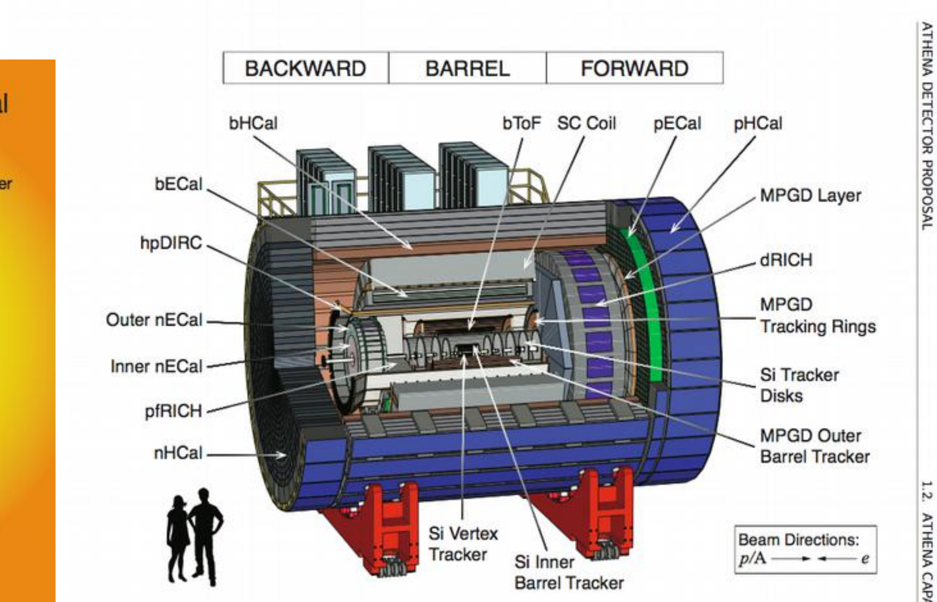
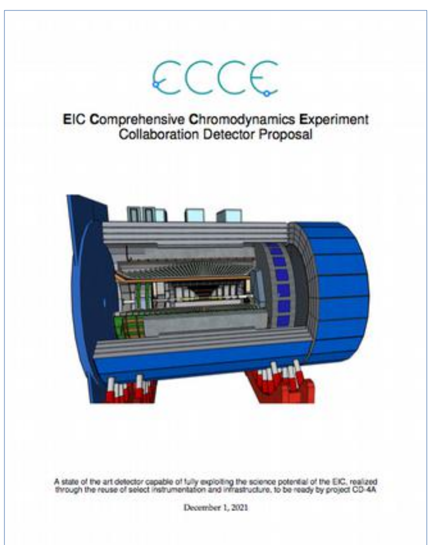


Figure 1.1: Crosscut view of the ATHENA central detector. The detector acronyms are defined in the text and are summarised in the Glossary.

EEEMCAL project is well-defined and could fit with any global EIC detector concept providing high precision EM calorimetry

PWO and SciGlass based EMCalorimetry is also considered in other regions of the central detectors, e.g., the barrel, and some auxiliary detectors



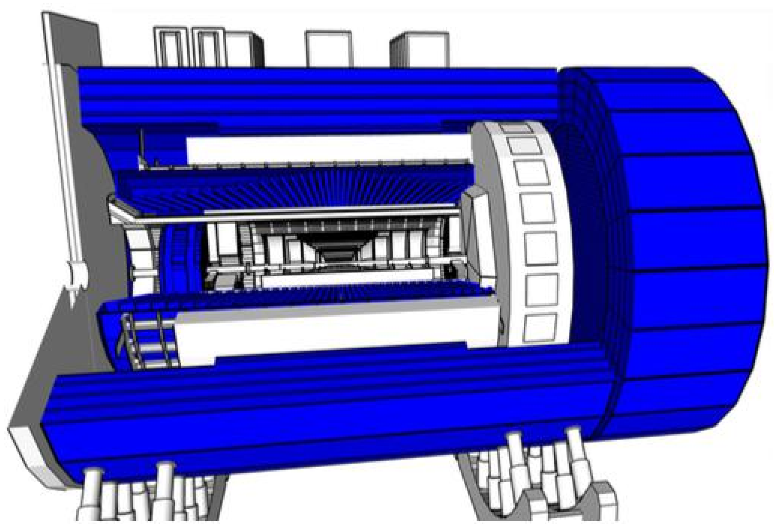
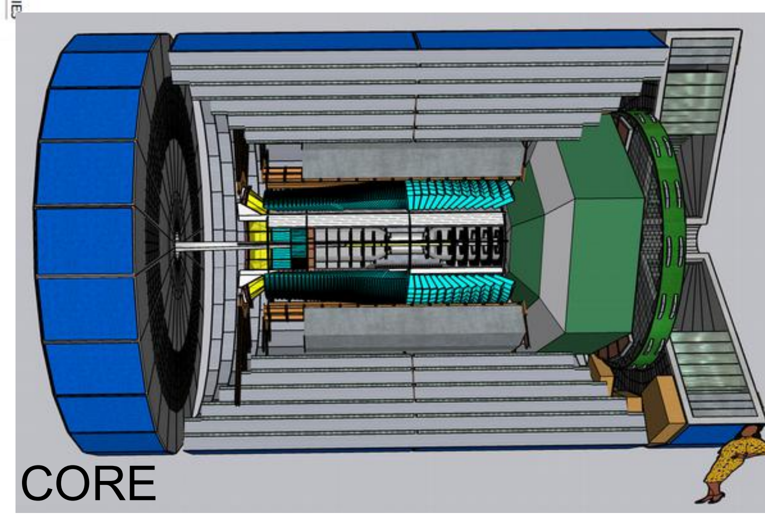
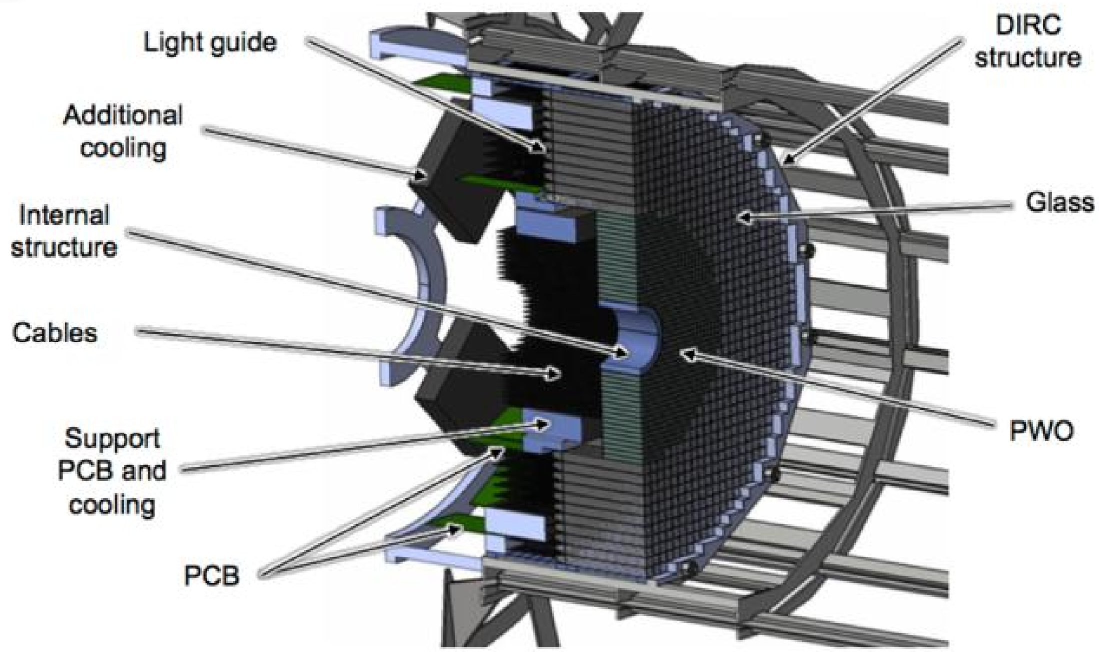


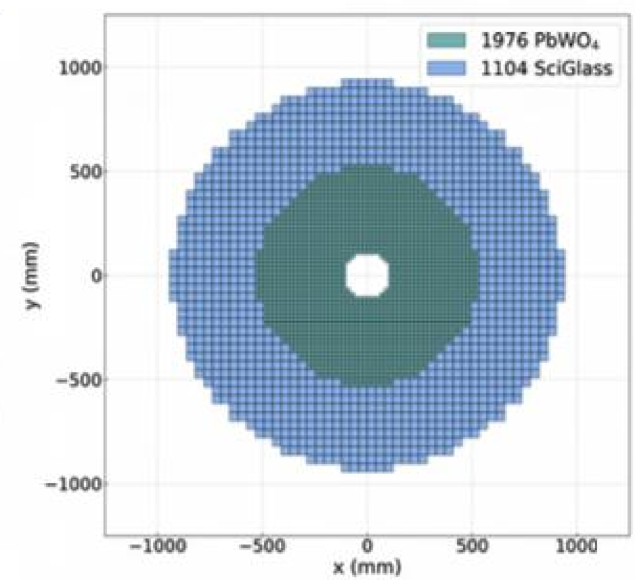
Figure 2.18: The electromagnetic and hadronic calorimeters in ECCE



EEEMCAL Preliminary Mechanical Design



The example how the EEEMCAL might look like in the EIC electron endcap



Overall Length	60 cm
Bore	16 cm
Radius	82 cm
Support Sides	17
Support Radius	100 cm
Offset	199 cm in Lepton Direction
Total Volume	1.27 m³

Geometry:

- z=-195cm
- R_in=11 cm (eta ~ -3.5) = R_min_PWO
- R_max_PWO=53 cm (eta ~2)=R_min_Glass
- R_max_total=100cm (eta ~ 1.4)=R_max_Glass

Modules **PWO 1976** (2x2x20 cm^3)
Modules **Glass 1104** (4x4x40 cm^3)
All PWO for this volume: ~7600 PWO modules
Weight: 5-6 tons

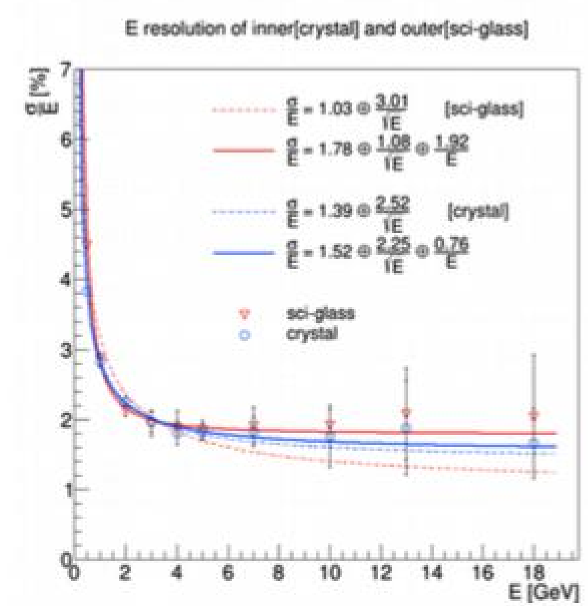
PWO: compact, radiation hard, luminescence yield to achieve high energy resolution, including the lowest photon energies
Sensor: SiPMs
SciGlass: EIC eRD1
radiation hard, luminescence yield similar or better than crystals depending on longitudinal length
Sensor: SiPMs

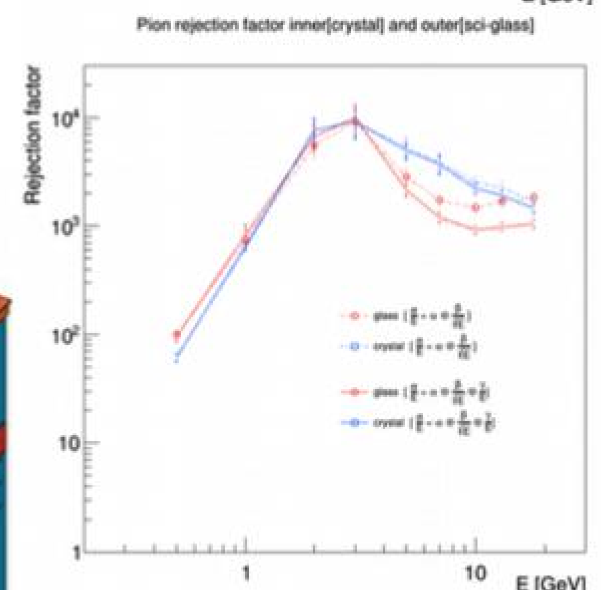
https://wiki.jlab.org/cuawiki/images/e/e5/EEEMCAL_Mechanical_design_2.pdf

EEMCAL activities

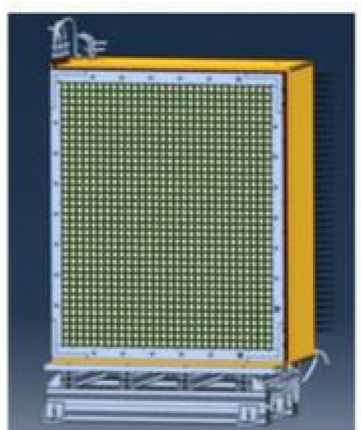
EEEmCal consortia items of interest and ongoing activities:

- Radiator: crystal/glass fabrication and characterization
- Frame design/construction – to hold the crystal/glass bars
- Prototype construction/commissioning and beam tests
- Monte Carlo simulations and comparison with test beam results
- Readout, electronics, detector cabling and infrastructure
- Slow controls and online software
- Calibration and monitoring of performance

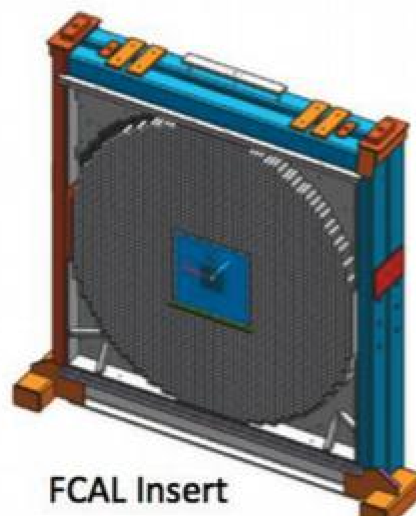




Questions:
- Cost vs Resolution
- Monolithic vs Hybrid



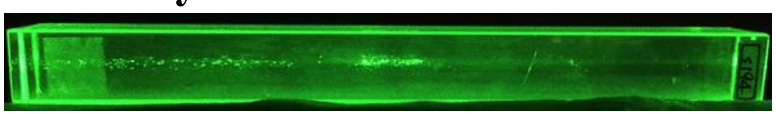
NPS



FCAL Insert

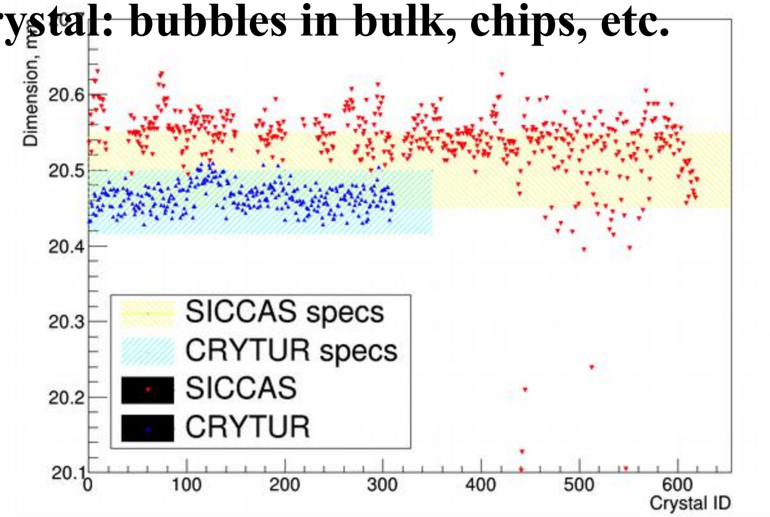
EEEMCAL lead tungstate scintillating crystals

Good crystal

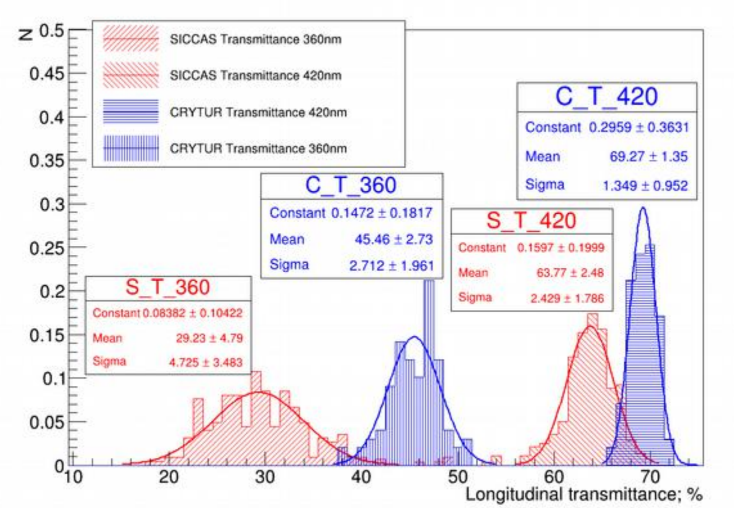


Bad crystal: bubbles in bulk, chips, etc.

- Much effort into crystal evaluation over the last decade
- Benef its from synergies with other projects: Neutral Particle Spectrometer (NPS) and FCAL-2 at JLab, PANDA
  - Resources, prototypes, software development
- Long lead item ! Production ~50 crystals per month
- Crystal dimensions 20.5x20.5x200 mm3
- Vendors exist, but only two available worldwide
- R&D related to raw crystal material powder completed
- SICCAS/China: failure rate ~30% of crystals produced in 2014-2020 due to major mechanical defects
- CRYTUR/Czech Republic: Strict quality control procedures – 100% of crystals accepted from more than 1500



Quality check: dimension uniformity



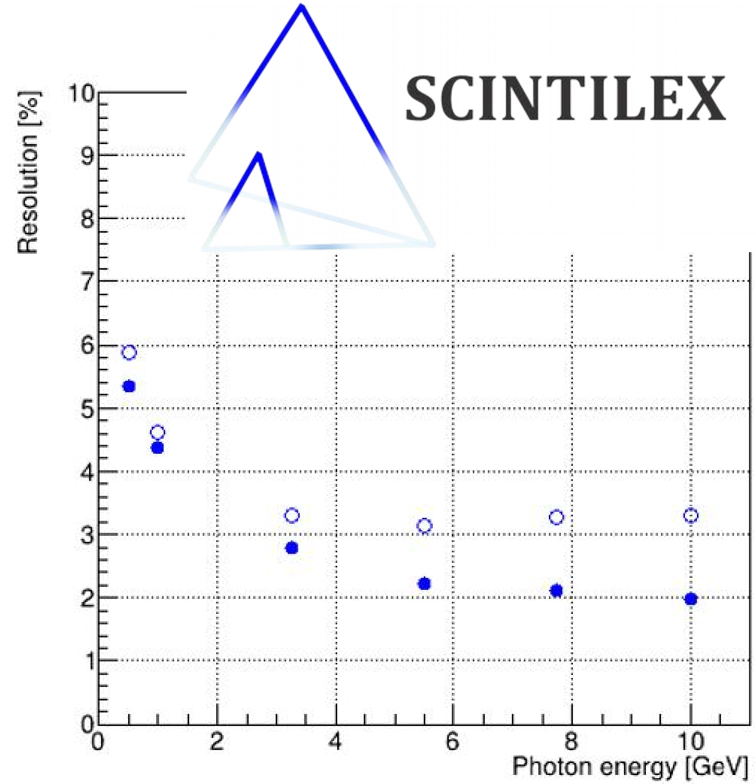
Longitudinal transmittance

EEEMCAL Scintillating Glass

- **Ongoing EIC project R&D program (eRD105)**
- **Simulation suggests a resolution comparable to PbWO4**

$$\frac{\sigma_E}{E} = \frac{2.5\%}{\sqrt{E}} \oplus \frac{2.7\%}{E} \oplus 1.5\%$$

- **Assumes that 40cm long glass bars with these properties will be available**
- **SCINTILEX has developed the scale-up and can now fabricate 20cm long glass bars – further scale up optimization ongoing. Within one year achieved scale-up to 20cm and improving manufacturing. Goal: 40x40x400 cm3**
- **Ongoing preparation for beam tests: bars need to be polished (flatness, rectangularity etc.), quality assurance, testing with gamma sources, cosmic**



MC results for 40 and 50 cm long bars

1cm x 1cm x 0.5cm — 2cm x 2cm x (2-4)cm — 2.0cm x 2.0cm x 20.0cm — 4.0cm x 4.0cm x 40.0 cm

2019 — 2020 — 2021

Scintillating Glass beam performance in the past

Performance of a scintillating glass calorimeter for electromagnetic showers, 1988

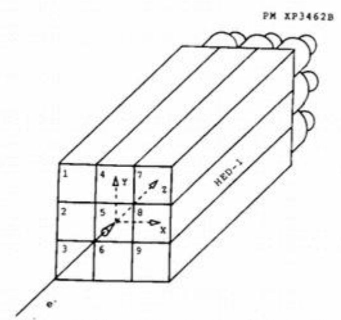


Fig. 3. Layout of the calorimeter setup in the test bea

U. Buchner et al. / A scintillating glass calorimeter for electromagnetic showers 701

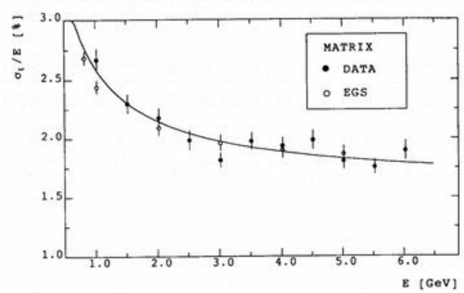


Fig. 12. Energy resolution as a function of the electron energy (black circles) and the EGS prediction (open circles). The line shows the parametrization (4) described in the text.

8x8x66 cm^3

ER=1.46%/E+2.4%/sqrt(E)+1.63%

https://inspirehep.net/literature/261664

The Experiment 705 Electromagnetic Shower Calorimeter, 1993

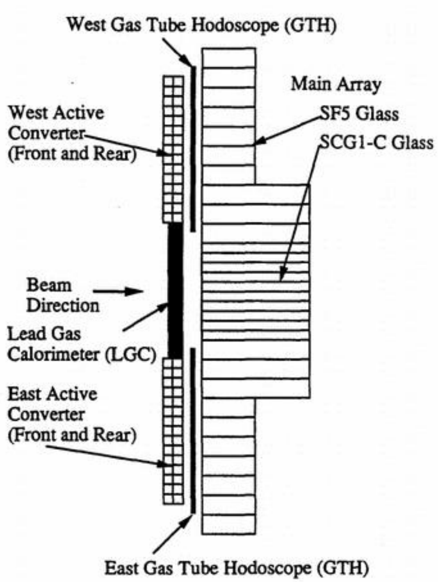


Figure 1. Plan view of the major components of the Experiment 705 calorimeter

	SCG1-C	SF5
Composition (by weight)	BaO 43.4% SiO2 42.5% Li2O 4.0% MgO 3.3% K2O 3.3% Al2O3 2.0% Ce2O3 1.5%	PbO 55% SiO2 38% K2O 5% Na2O 1%
Density	3.36 g/cm3	4.08 g/cm3
Radiation Length	4.25 cm	2.47 cm
Absorption Length (30-200GeV/c^2 pions)	45.6 cm	42.0 cm

Table 1. Properties of SCG1-C Scintillating and SF5 Lead Glass

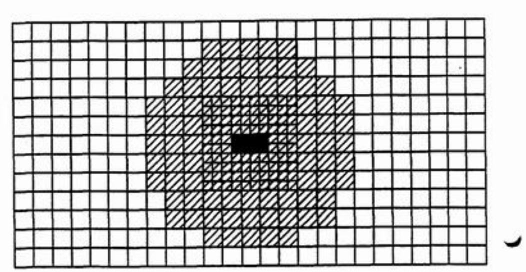


Figure 2. Beam view of the Main Array (SCG1-C scintillating glass is cross-hatched)

15.x15.x89 cm^3
7.5x7.5x89 cm^3

Resolution for mixed calorimeter LeadGlass and SCG-1 Glass

Rad. Length 20.9 X0

ER=0.99%+4.58%/sqrt(E)

https://inspirehep.net/files/1299a6aa1e200e01f9d7f208800a81f6

Results from 1980s scintillating glass calorimeters encouraging
Need to establish performance for SciGlass (different formulation)

EEEMCAL beam test program

Test beam facilities:

1. **DESY**

   - **EIC PWO prototype with PMT readout**

2. **JLAB**

   - **EIC PWO prototype with SiPM readout**
   - **EIC PWO prototype with SiPM matrix readout**
   - **EIC SciGlass prototype with PMT readout**

   - **EIC PWO prototype and Streaming RO DAQ**

DESY beam test

DESY Test Beam Run - 15–29 November, 2021

Tests with a 5x5 lead tungstate calorimeter

- lead tungstate crystals generously on loan from Tanja Horn, CUA
- measurements performed at the DESY test beam facility area TB24

Multiple reasons for the tests

- performance of $PbWO_4$ calorimeter, compare with MC simulation
  - EIC EmCal
  - TPEX
- run with triggered and streaming data acquisition systems in parallel
  - triggered DAQ using CAEN QDC
  - streaming DAQ using JLab FADC250
  - streaming DAQ using CAEN digitizer

Mostly very successful !

DESY beam test

Test Beam Configuration

DESY beam test

Data Collection

With 2x2 mm^2 collimator aperture

Following scans made at beam energies of 2, 3, 4, and 5 GeV

Horizontal scans -60 mm to +60 mm in 5 mm steps

- at Y = 0, -5, -10, -15, and -20 mm
- similar vertical scans
- unfortunately made before disconnecting FADC250

Detailed horizontal scans -15 mm to +15 mm in 3 mm steps

- at Y = 0, -3, -6, -9, -12, and -15, mm

Repeat detailed horizontal scans with 3.7, 7.8, 15.6, and 23.4 mm Pb

Repeat detailed horizontal scans with calorimeter rotated $\sim 6^\circ$

Jlab beam tests 2021

Beam test	Layout	Photosensor
Radiator material characterization, detector performance		
1	EEEMCAL (3x3) PWO + PMT	PMT Hamamatsu R4125-01
2	EEEMCAL (3x3) PWO + SiPM (INFN RO)	SIPM Hamamatsu S13360-6025CS
3	EEEMCAL 3x3 PWO+ matrix SiPM (CRYTUR RO)	SIPM Hamamatsu
4	EEEMCAL SciGlass + PMT+Amp.	PMT Hamamatsu R4125-01
5	EEEMCAL SciGlass + PMT without Amp.	PMT Hamamatsu R4125-01
Trigger and trigger-less DAQ options comparison		
6	PWO & Streaming RO	PMT R4125 and SiMP S13360-6025CS

Tests prepared and performed in collaboration with Jlab staff, big thanks to:

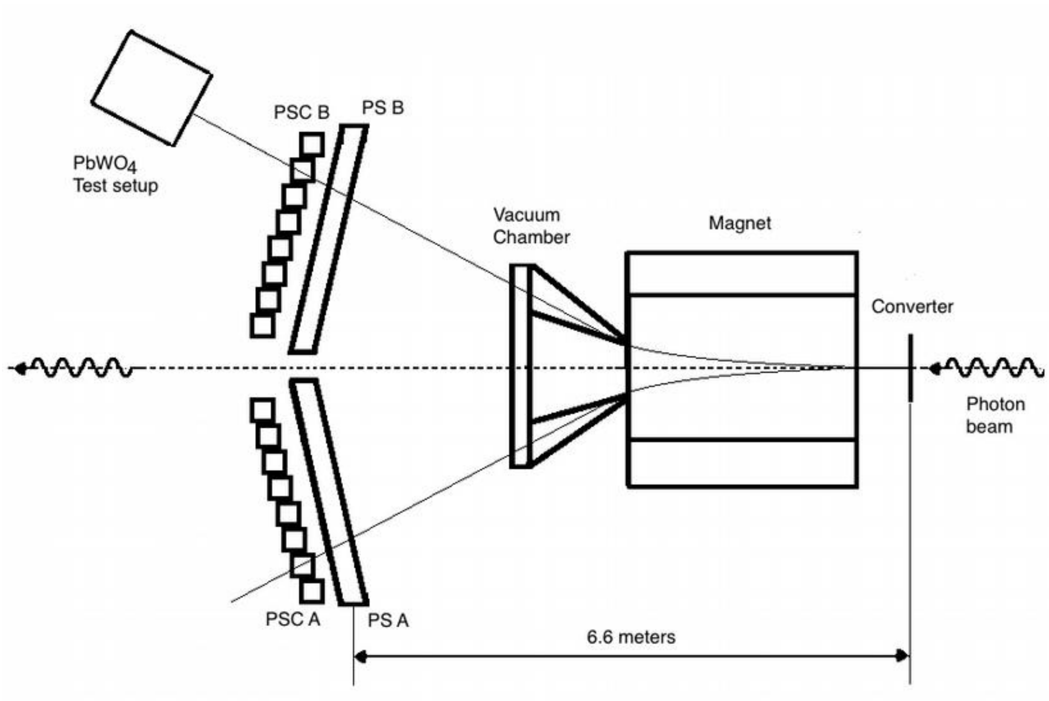
HallD: Sasha Somov, Tim Whitlatch, Robert Bunton

HallB: Sergey Boyarinov

Fast Electronics: Fernando Barbosa, Chris Stanislav

EPSCI: David Lawerence, Nathan Brei

Calorimetry beam tests behind Pair Spectrometer in HallD

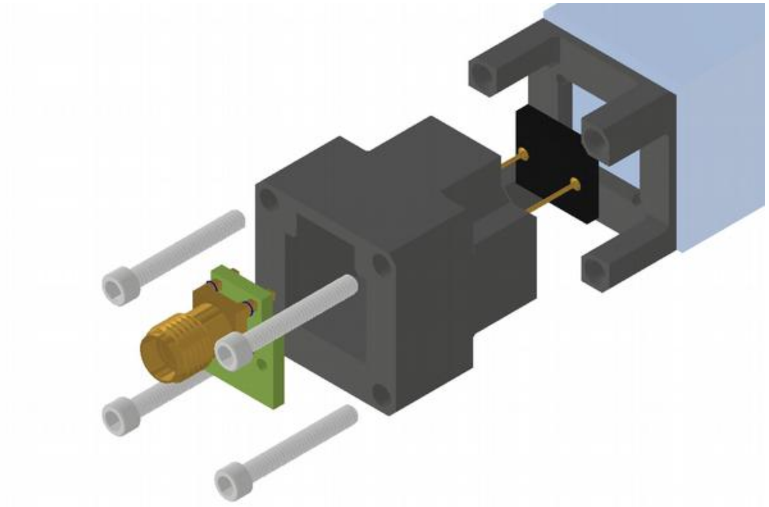


Calorimetry beam tests method established 2018

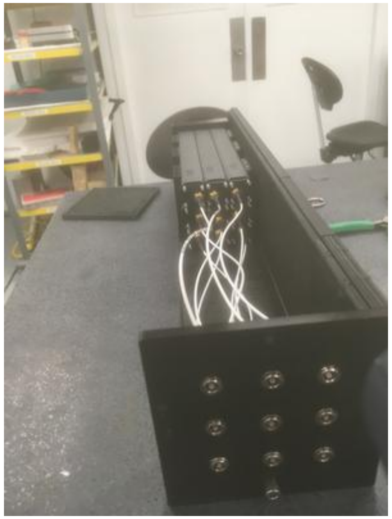
- **The prototypes/test-stand installed in Hall-D downstream of the pair spectrometer (PS)**
- **Electron-positron pairs are produced by the primary photon beam interacting with 750 m beryllium converter. Lepton pairs are def lected in a 1.5 T dipole magnet and detected using two layers of scintillation counters positioned symmetrically around the photon beam line.**
- **Each arm consists of 8 coarse counters and 145 high-granularity counters. The high-granularity hodoscope is used to measure the lepton momentum; the position of each counter corresponds to the specif ic energy.**
- **Each detector arm covers the lepton momentum range 3–6.2 GeV/c.**
- **The energy resolution of the PS is estimated to be better than 0.6%.**
- **The position of the prototype was surveyed and aligned with respect to the beam line and the center of the pair spectrometer magnet, such that the lepton beam's spot is focused on the center row of the prototype, perpendicular to the front face of the crystals.**

Configuration #1: EIC PWO prototype with SiPM readout

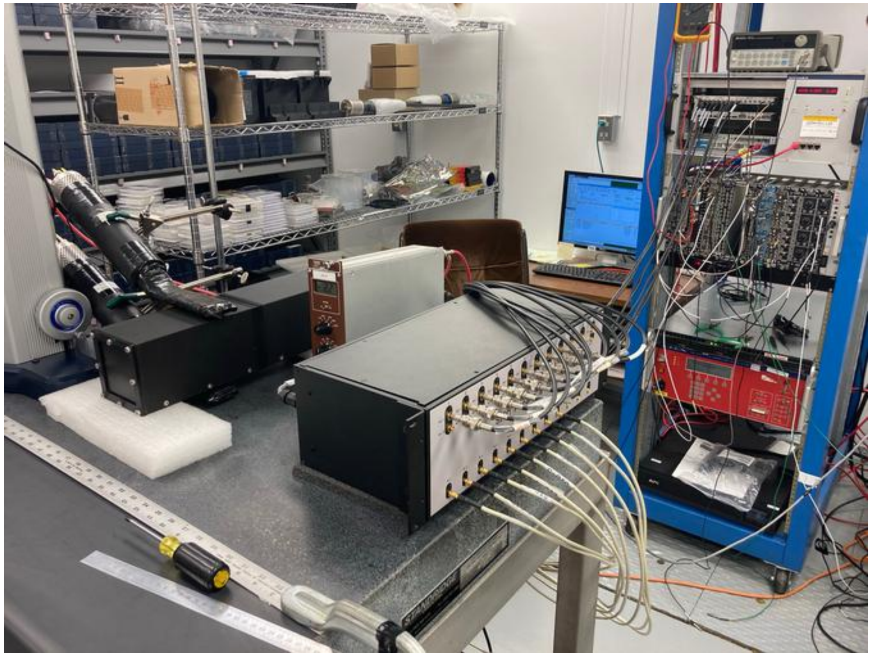
Goal of the tests: Optimize and test SiPM readout chain with new generation PWO crystals



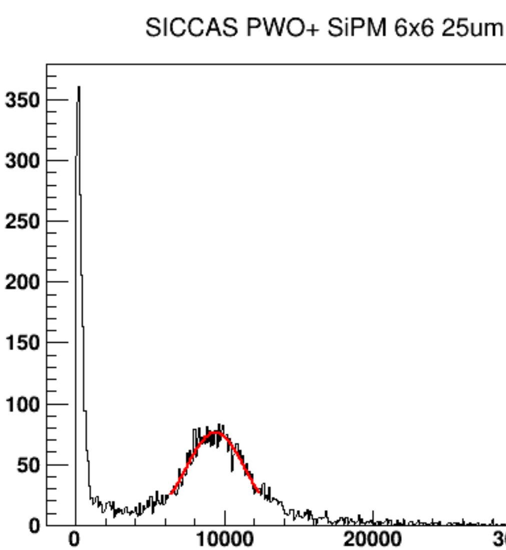
- **Improved prototype with new SiPM based assembly**
- **3D printed frame (PLA plastic)**
- **Two piece SiPM holder concept, holders are 3D printed**
- **PEEK plastic will be used in real detector**
- **Silicon based glue for frame, no SiPM glueing to crystal**
- **SiPM soldered to circuit board with SMA connector**
- **25um cell Hamamatsu SiPM for beam tests installed**
- **LEMO output at the detector patch panel (BIAS/Preamp or INFN Waveboard application)**

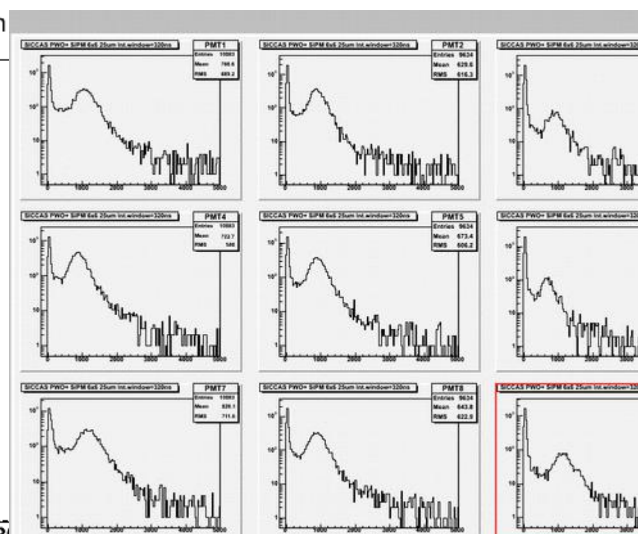


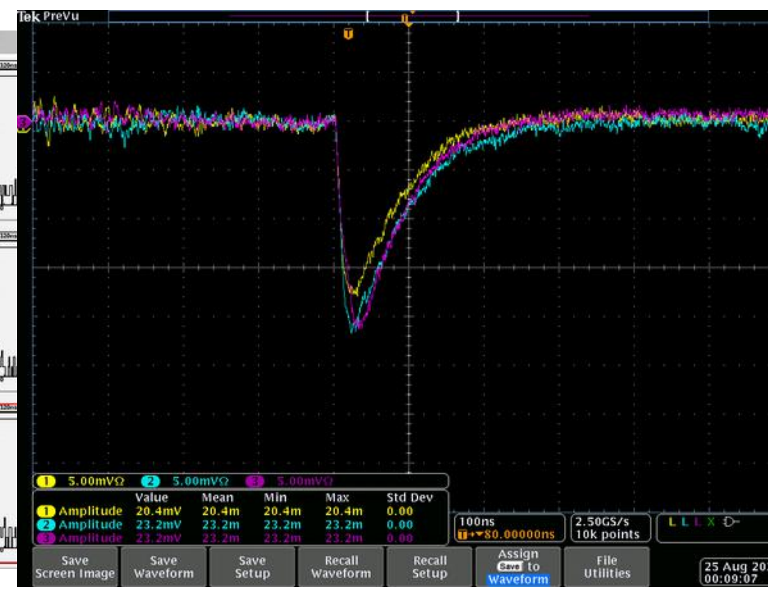
Configuration #1: EIC PWO prototype with SiPM readout



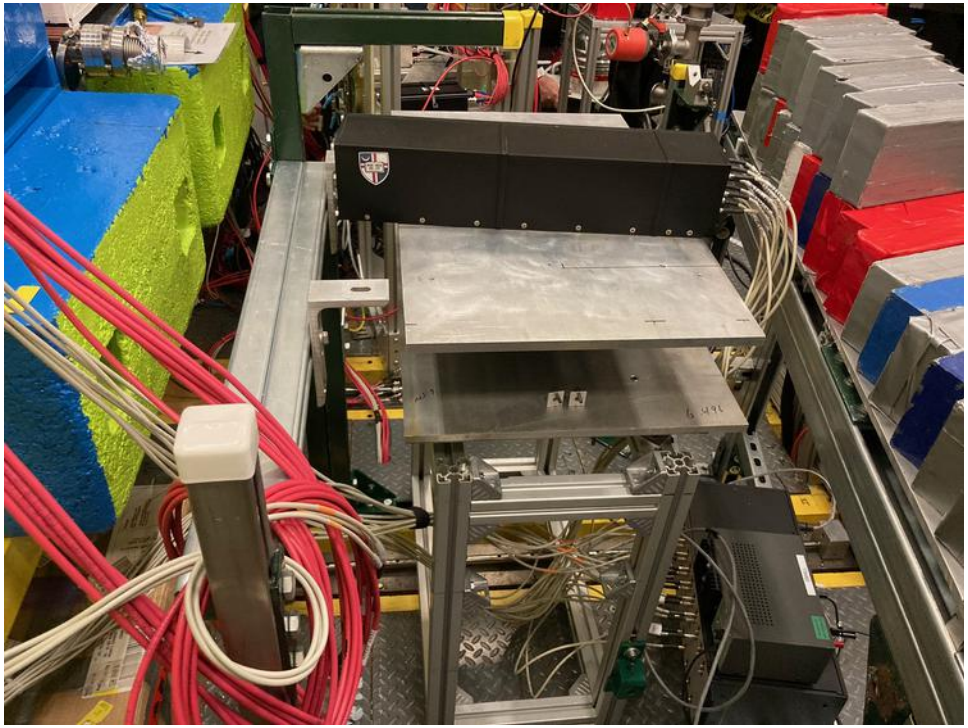
- **Sanity checks of the detector and readout**
- **Tests in cleanroom with cosmic**
- **Muon perpendicularly cross the detector and form the trigger**
- **Tests performed with coda based DAQ, signal digitized by fADC250**
- **Preamplif ier gain adjusted for dynamic range**



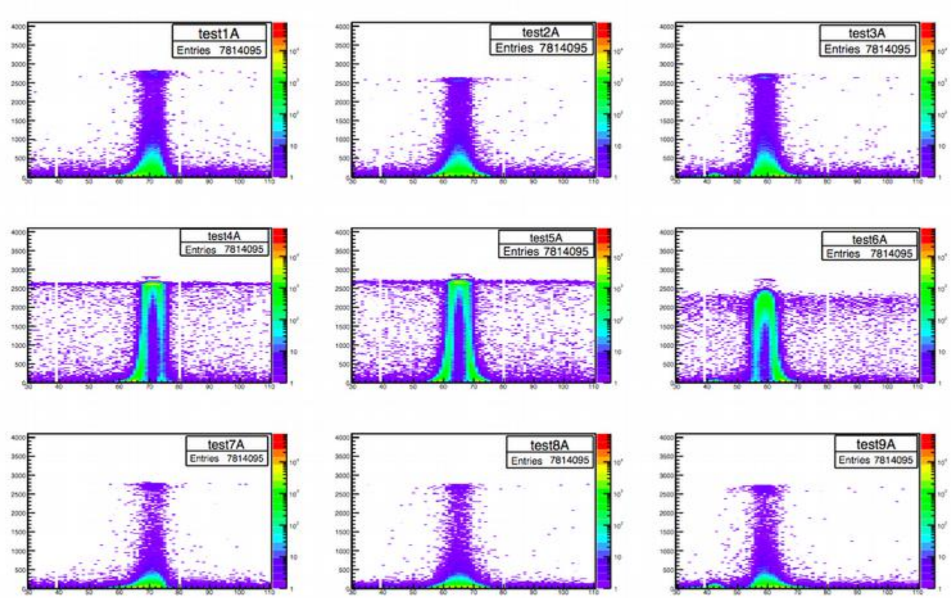


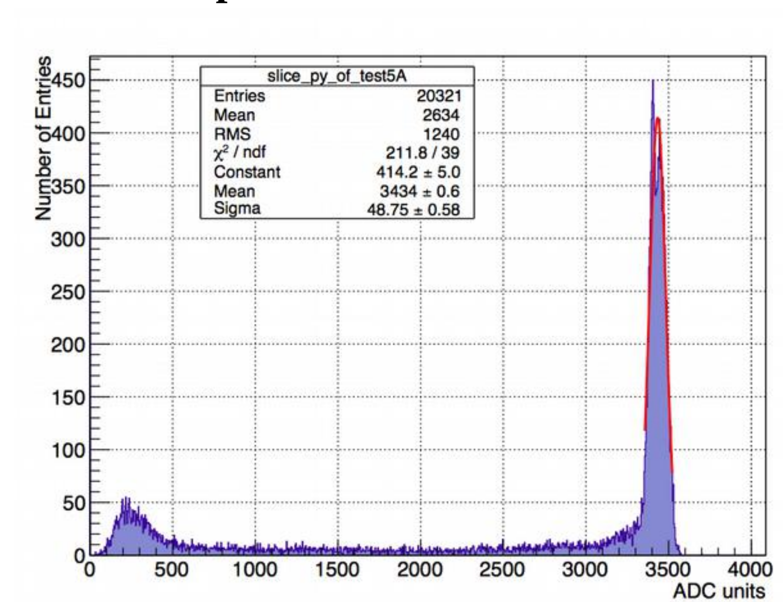


Configuration #1: EIC PWO prototype with SiPM readout



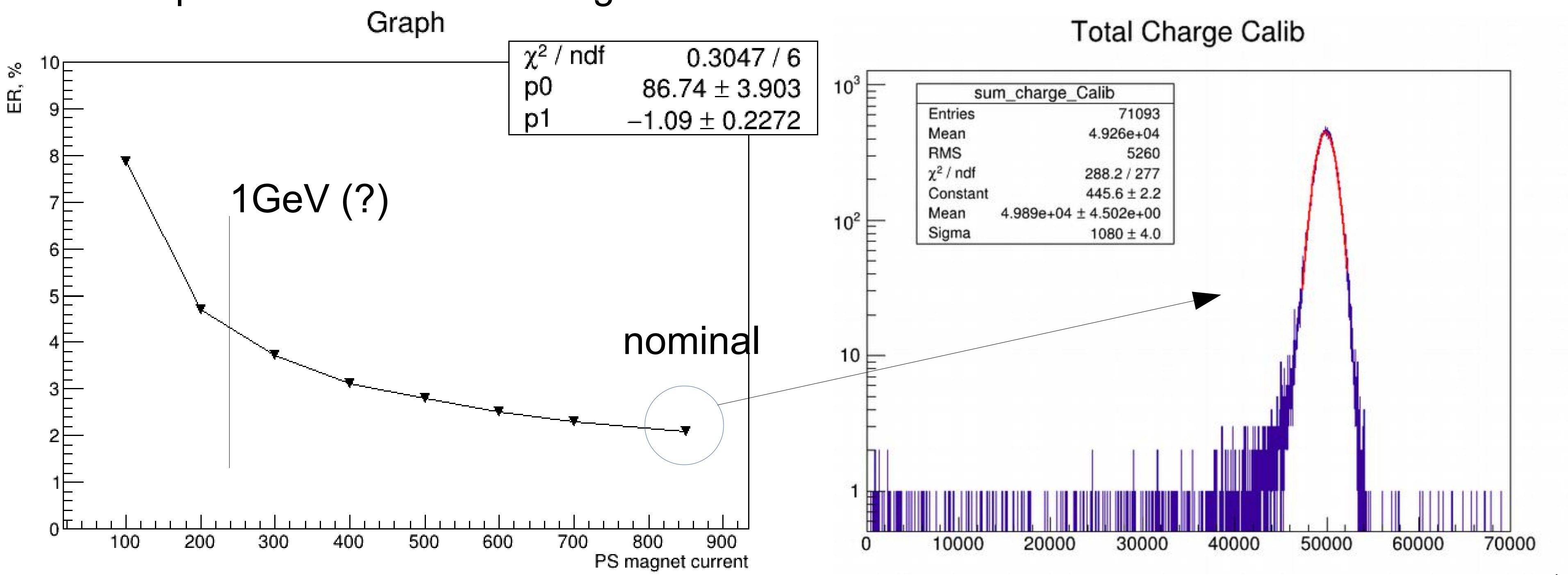
- **Prototype tested with ~4.7 GeV electrons**
- **Stable detector performance**
- **Good energy resolution**
- **Light density or amount of photolectrons per cm^2 measured in fADC250 units**
- **Test bench measurements needed at the lab with light sources to convert ADC units to actual pixels f red**
- **Detector disassembled for lab measurements**
- **Next step is installation of new SiPM with smaller pixel size**





Configuration #1: EIC PWO prototype with SiPM readout

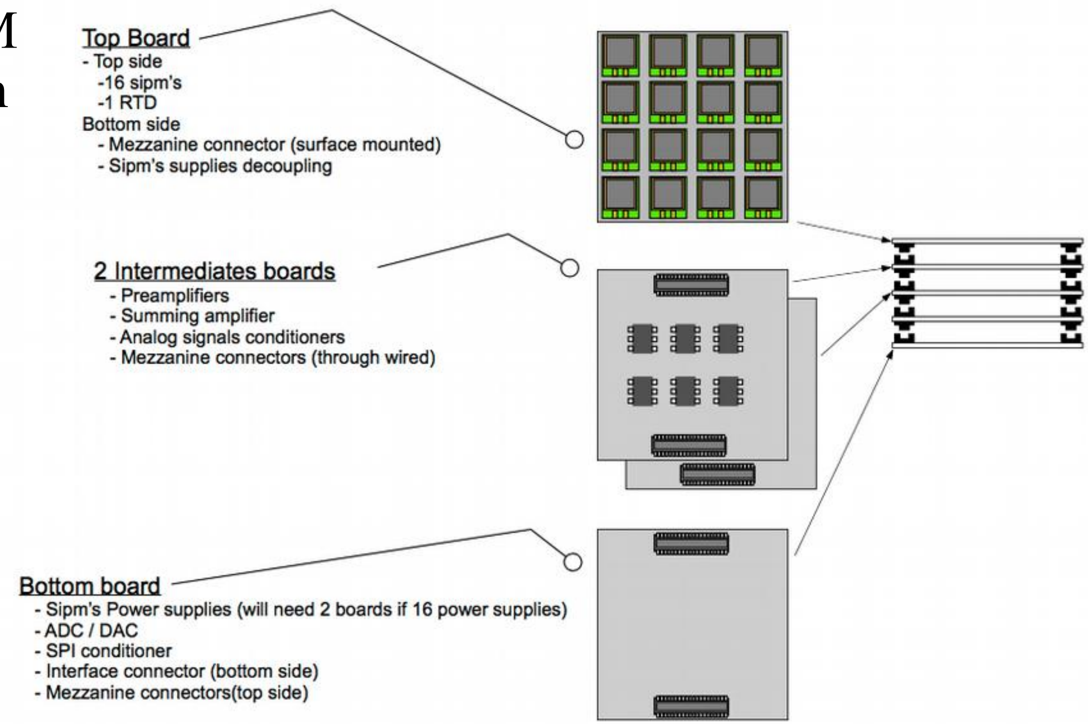
- Exciting opportunity to measure energy resolution (stochastic term) of the prototype in wider energy range, especially below 1GeV
- Reducing momentum of leptons by reducing magnetic field of the pair spectrometer
- Monte Carlo simulations ongoing to calculate new lepton energy.
- Important to separate effects of Pair Spectrometer from detector effects.
- Not parasitic tests scheduling needed

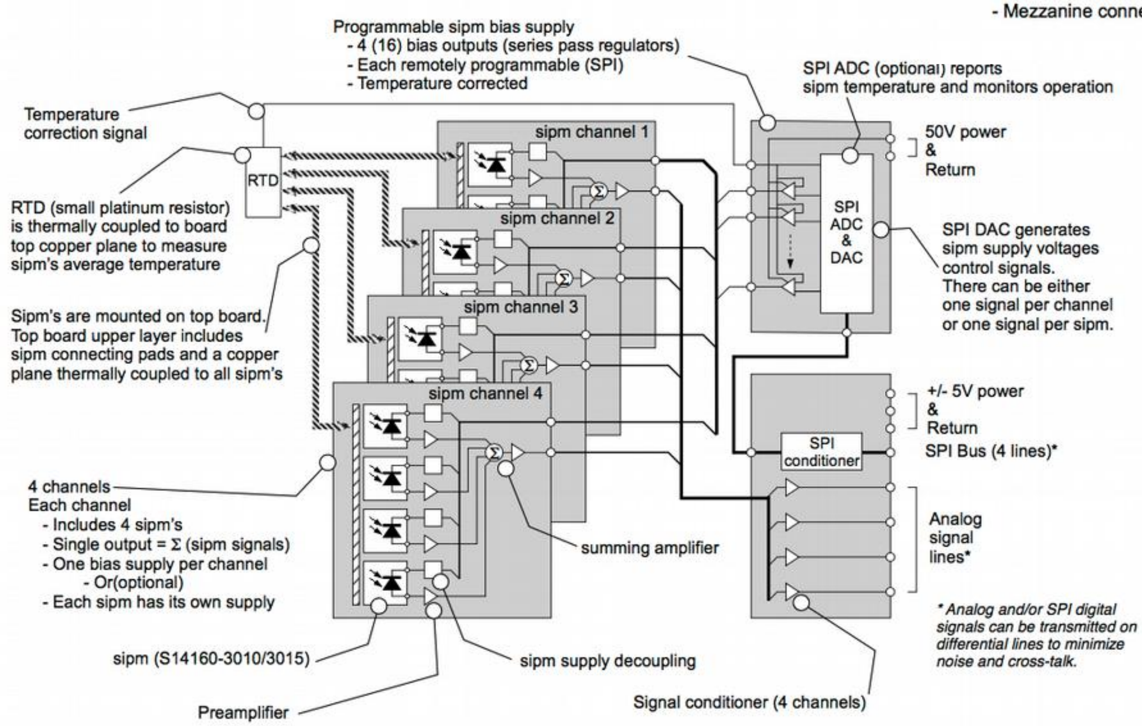


Configuration #2: EIC PWO prototype with SiPM matrix readout

Goal of the tests: Optimize and test SiPM matrix readout chain with new generation PWO crystals

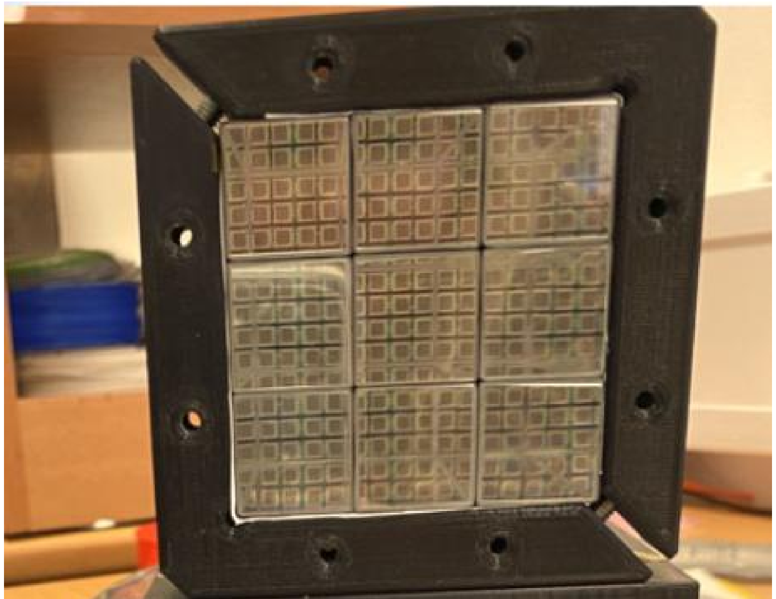
- **CRYTUR USA concept**
- **9 CRYTUR crystals**
- **16 SiPMs per crystal**
- **3x3 mm^2 SiPMs**
- **~90k cells per SiPM**
- **Plug-n-play prototype**
- **First working RO version for EIC**



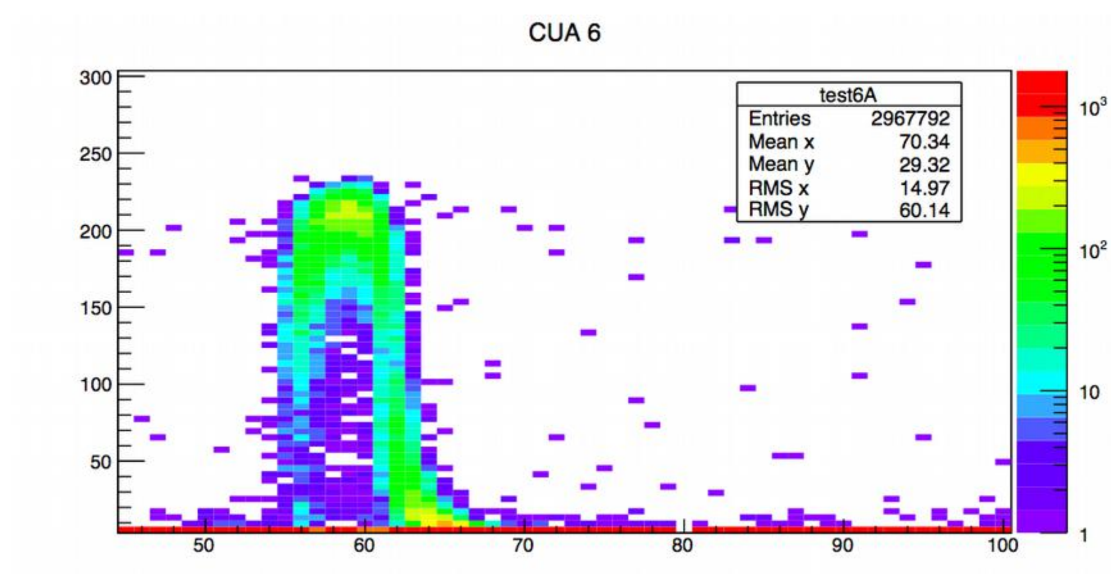


- **Direct performance comparison with 3x3 PMT version, INFN SiPM version**
- **Energy resolution studies**
- **Noise studies**
- **Light collection studies**
- **Linearity studies**
- **Threshold studies**

Configuration #2: EIC PWO prototype with SiPM matrix readout



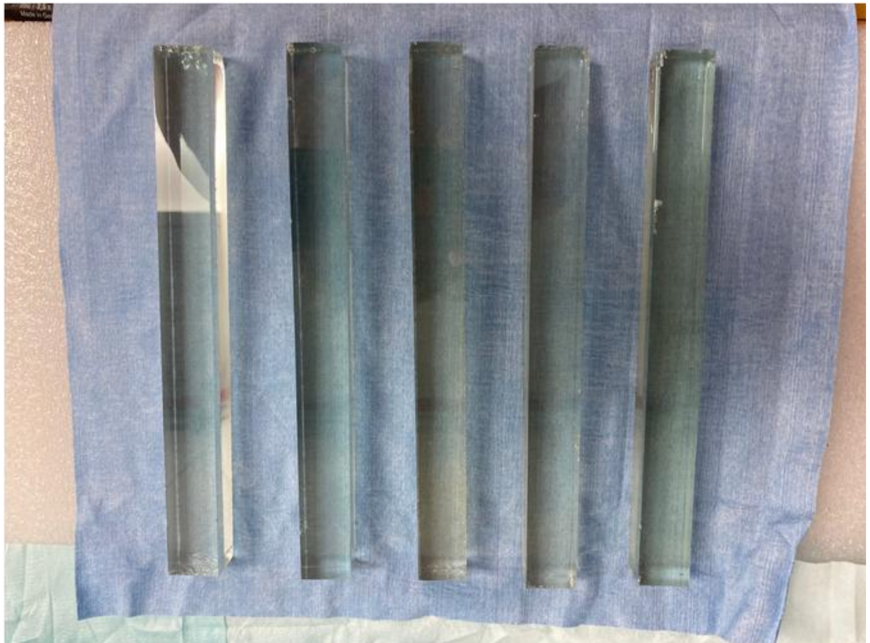
- **Due to COVID related issues prototype delivered at Jlab at the very last day**
- **Detector have been installed and tested with the beam**
- **Issue observed with the SiPM matrix preamplifiers cooling. Performance degradation with the time.**
- **Direct feed-back to CRYTUR with lot of useful and detailed information for improvements**
- **New prototype delivery expected in Fall 2022**



Lead tungstate EEEMCAL prototype beam test results

N	Layout	Photosensor	GlueX Run	Energy, GeV	ER, % raw	ER,% calib
1	PWO+PMT	PMT Hamamatsu R4125-01	81386	4.698+-0.013	2.1%	1.8%
2	PWO+SiPM (INFN RO)	SIPM Hamamatsu S13360-6025CS	81518	4.698+-0.013	2.3%	2.1%
3	PWO+SiPM (CRYTUR RO)	SIPM Hamamatsu	81704	5.504+-0.013	-	-

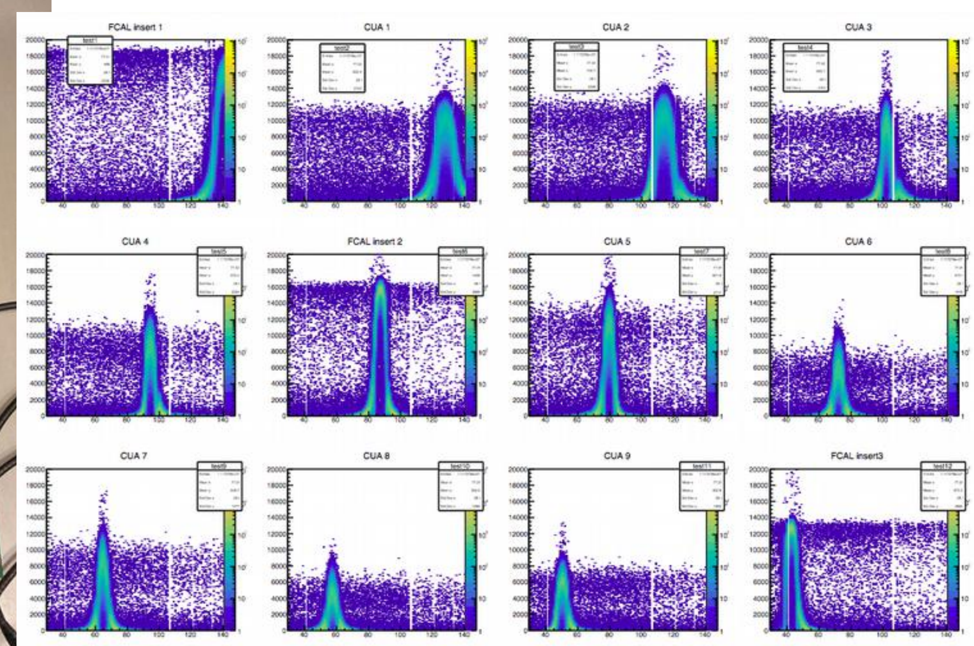
Configuration #3: EIC SciGlass prototype with PMT readout



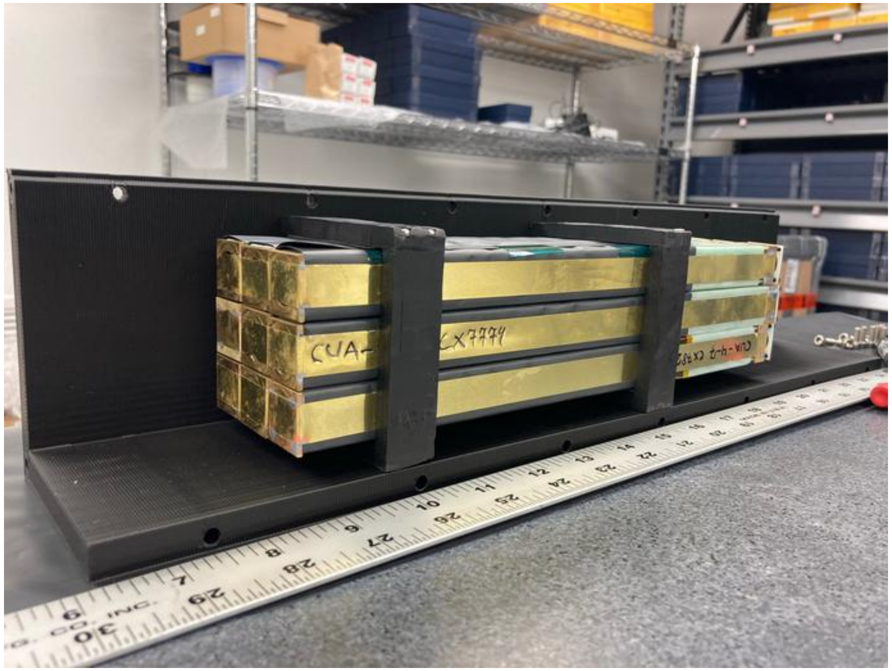
- **SCINTILEX SciGlass blocks have been delivered to Jlab**
- **Glass characterizations and visual inspections performed**
- **Calorimeter towers wrapped with teflon reflector**
- **CCAL tower mechanic assembly**
- **PMT Hamamatsu R4125-01**
- **9 towers prepared for tests**
- **Cosmic test performed to set proper applied HV**

Configuration #3: EIC SciGlass prototype with PMT readout

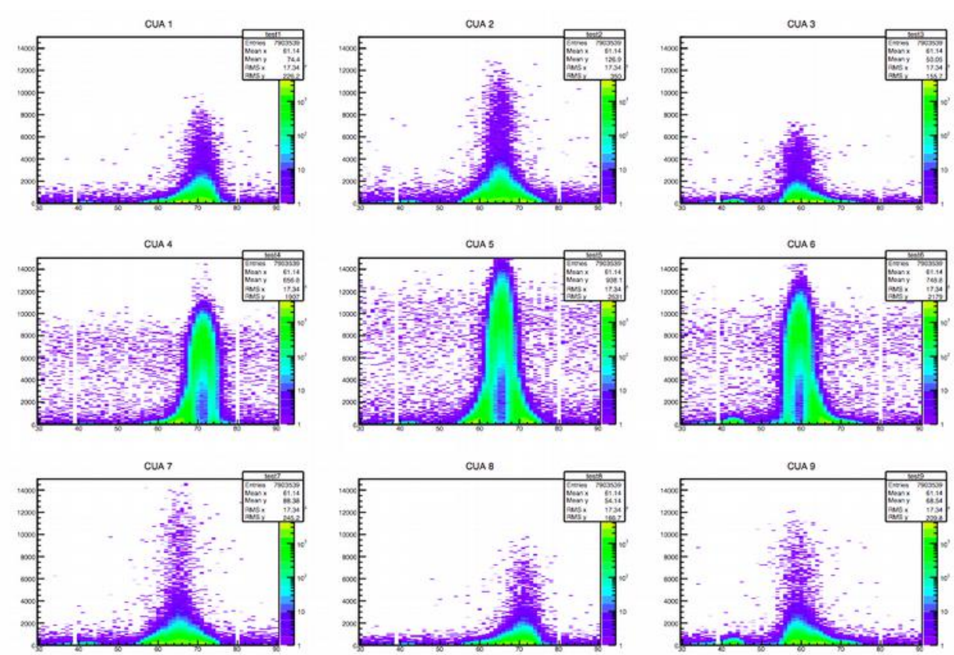
- Glass blocks tested with the beam using 12x1 scintillator test stand at the calorimetry arm
- FCAL-2 blocks inserted as reference
- All SciGlass blocks showed good performance

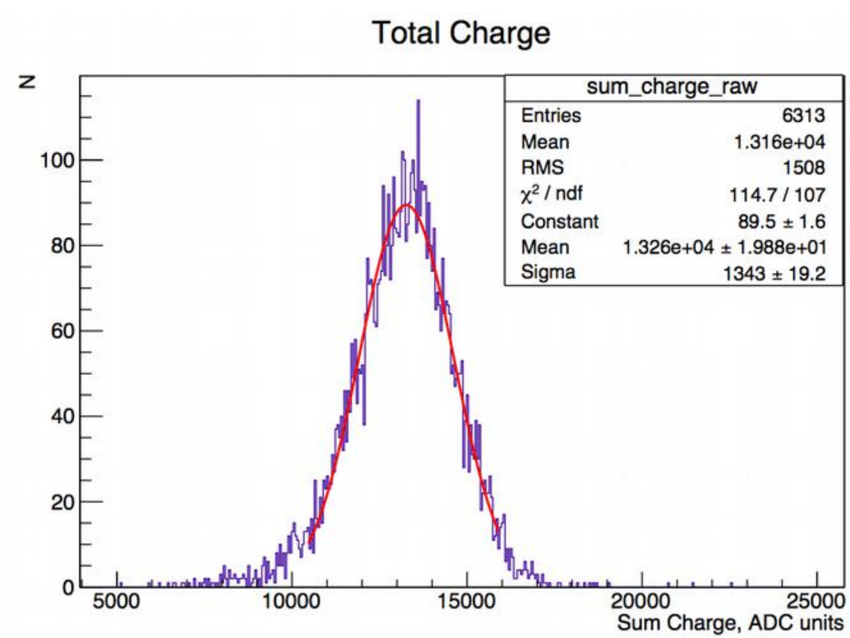


Configuration #3: EIC SciGlass prototype with PMT readout



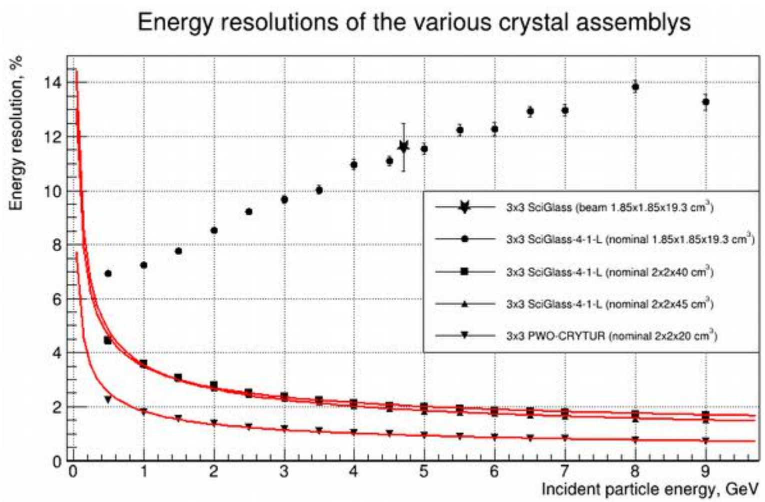
- 3x3 glass tower matrix assembled
- Detector installed and tested with the beam
- Energy resolution measured for 3 different energies
- First EM shower measurements of SCINTILEX scintillator glass
- Next steps and plans for 2022:
  - 5x5 assembly with ~7 X0 blocks
  - 3x3 assembly with ~20 X0 long blocks





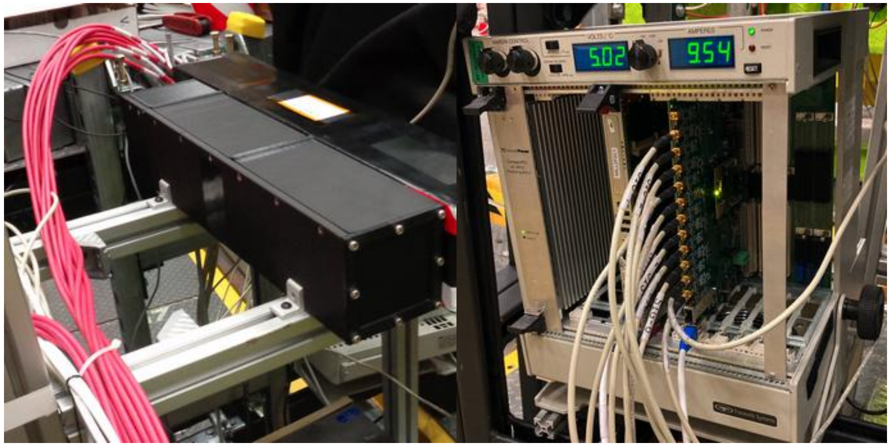
SciGlass EEEMCAL prototype beam test results

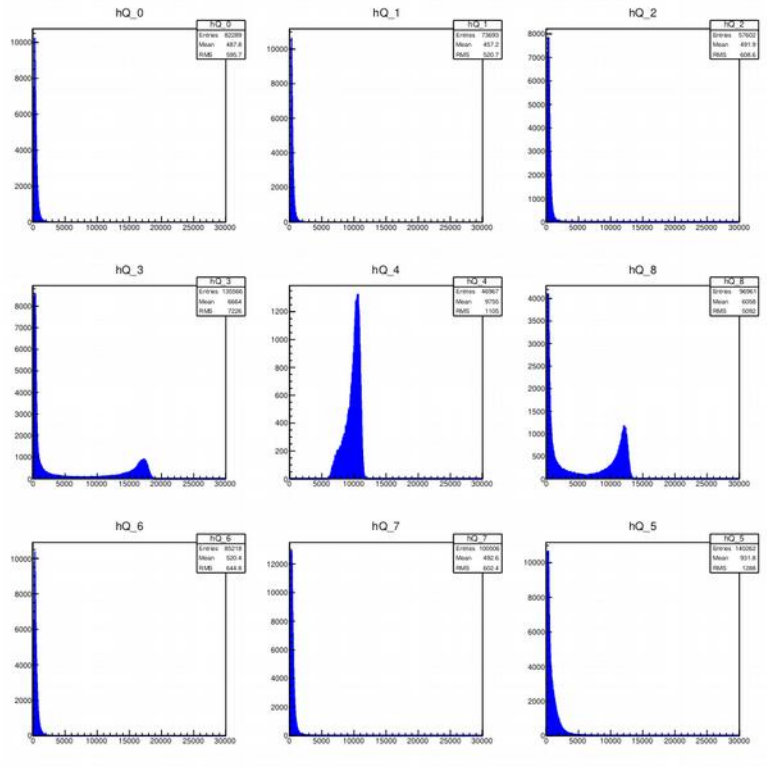
N	Configuration	Photosensor	GlueX Run	Energy, GeV	ER, % raw	ER,% calib
1	Glass+PMT+Amp	PMT Hamamatsu R4125-01	81489	4.698+-0.013	10%	9.1%
2	Glass+PMT without Amp	PMT Hamamatsu R4125-01	81526	4.698+-0.013	12.3%	11.6%
3	Glass+PMT without Amp	PMT Hamamatsu R4125-01	81564	3.918+-.0.013	12.5%	12.2%
4	Glass+PMT without Amp	PMT Hamamatsu R4125-01	81594	5.504+-0.013	11.1%	10.6%



- **Promising results for ~7 X0 blocks**
- **Matching with Geant4 predictions**
- **More data needed in wider energy range**

Configuration #4: EIC PWO prototype and Streaming RO

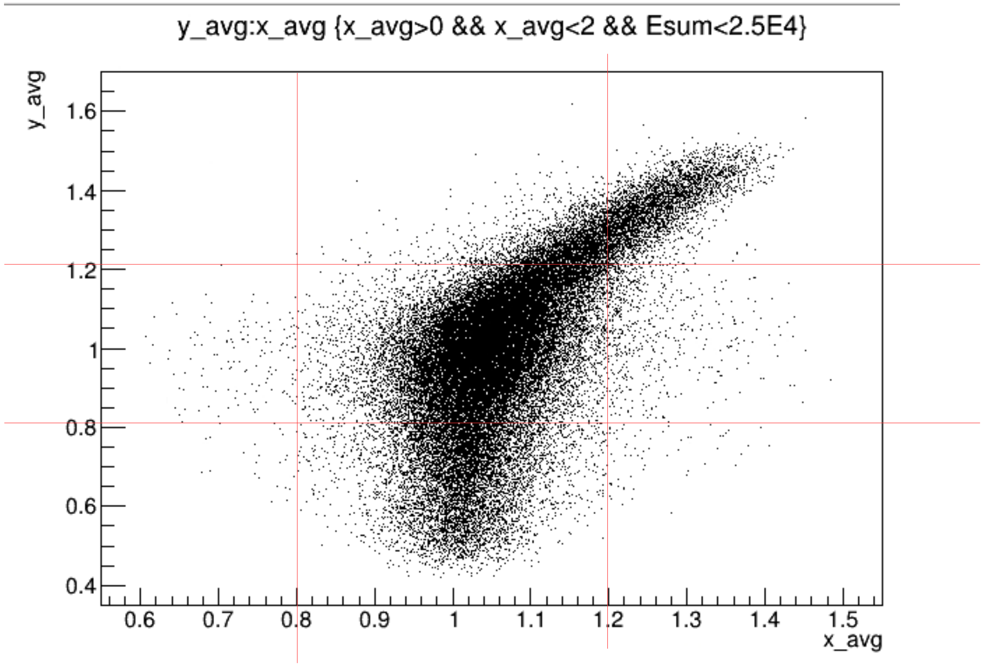


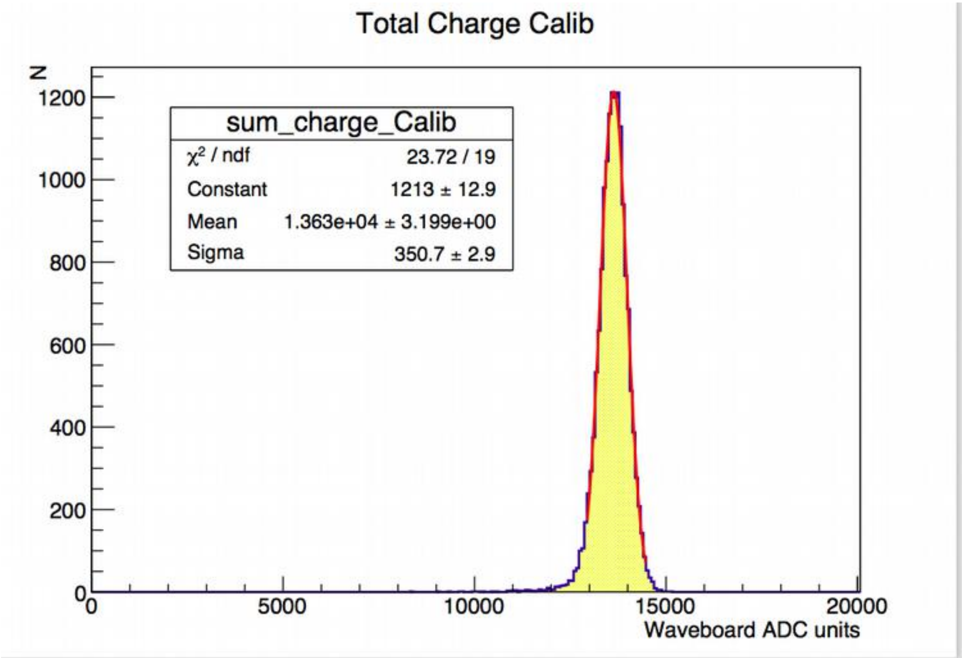


- **SRO tests performed in 2021 during GlueX HighLuminosity run (350nA photon beam)**
- **Waveboard read-out 9 calorimetry channels (PMT`s)**
- **~1.5 kHZ rate per channel with BEAM ON , no issues observed**
- **Waveboard+TriDAS+JANA2 DAQ chain tested**
- **Beam data acquired:**
  - **Binary data (Waveboard stand alone)**
  - **Without L2 software trigger (Waveboard+TriDAS)**
  - **With different combinations of L2 trigger(Waveboard+TriDAS+JANA2)**
- **JANA2 reconstruction and calibration off lne plugin**

Configuration #4: EIC PWO prototype and Streaming RO

- The SRO data analysis was performed within the JANA2 framework, where a dedicated clustering algorithm was implemented.
- The selection algorithm identified events with a large energy deposited in the central crystals (assumed to be the EM shower seed) and summed all hits in the other channels within a time window of 100 ns.
- The cut on the energy-weighted x-y hit position was used to exclude events hitting the side crystals after a rough inter-channel energy calibration





Detailed description in "Streaming readout for next generation electron scattering experiments" article in preparation for EPJA journal

Outlook

- **EEEMCAL will enable unique detector capabilities for scattered electron and final-state photon detection crucial at the EIC**
- **Detector performance validations with beam data is absolutely pivotal piece of information**
- **The method for calorimetry beam tests behind PS in hallD established with series of successful measurements since 2018**
- **Different PWO vendors compared, CRYTUR crystals made with new powder tested**
- **Forth generation Scintilex SciGlass measurements with the beam, results are promising**
- **Different electronics readout chains PMT`s and SiPM`s tested, optimizations ongoing**
- **Readout using SiPM matrix considered and development ongoing**
- **Trigger and trigger-less(SRO) DAQ options tested**
- **Considering different EIC prototype configurations during 2022 run including PWO crystals and new generation SciGlass bars, different photosensor readout and DAQ options**
- **Stay tuned for new results**