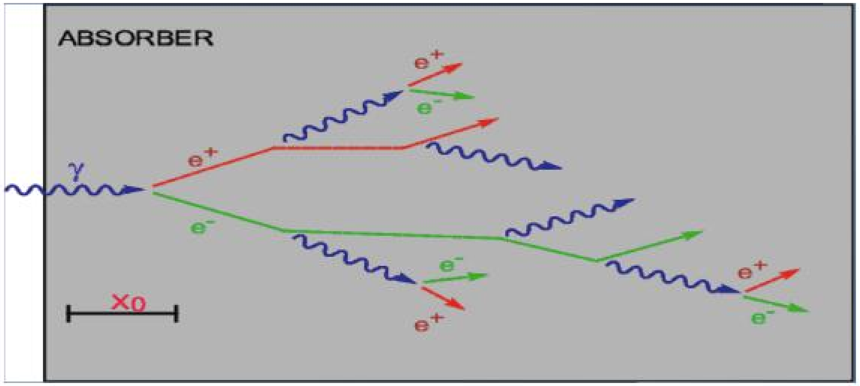
In nuclear and particle physics calorimetry refers to the detection of particles, and measurements of their properties, through total absorption in a block of matter, the calorimeter

Common feature of all calorimeters is that the measurement process is destructive

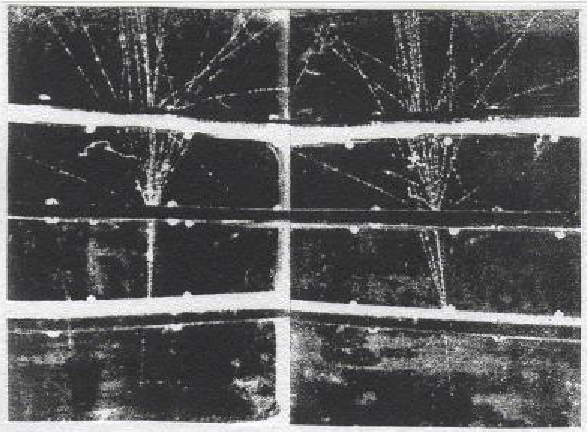
- Unlike, for example, wire chambers that measure particles by tracking in a magnetic field, the particles are no longer available for inspection once the calorimeter is done with them.
- The only exception concerns muons. The fact that muons can penetrate a substantial amount of matter is an important mean for muon identification.

In the absorption, almost all particle's energy is eventually converted to heat, hence the term calorimeter

X_0 is the characteristic scale

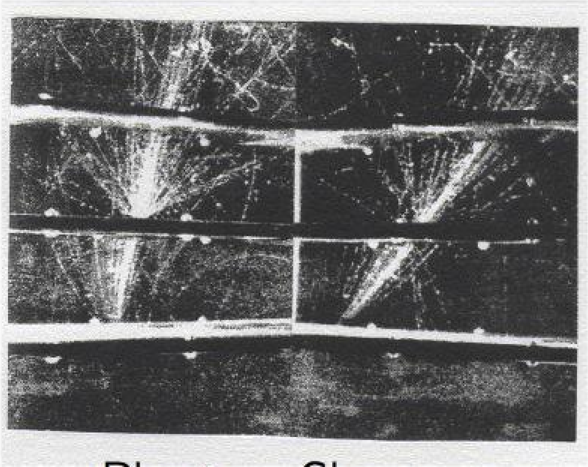


L.Fussel 1939



Electron Shower

L.Fussel 1939



Photon Shower

NPS Scientific program overview

- The neutral-particle spectrometer (NPS) offers **unique scientific capabilities** for studies of the transverse spatial and momentum structure of the nucleon in Hall C

- Five experiments have been fully approved by the JLab PAC to date:

NPS ERR 2019

  - **E12-13-007:** Measurement of Semi-inclusive $\pi 0$ production as Validation of Factorization
  - **E12-13-010:** Exclusive DVCS and $\pi 0$ Cross Section Measurements in Hall C
  - **E12-14-003:** Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
  - **E12-14-005:** Wide Angle Exclusive Photoproduction of $\pi 0$ Mesons
  - **E12-17-008:** Polarization Observables in Wide-Angle CS at large s, t and u

- One conditionally approved experiment

  - **C12-18-005:** Timelike Compton Scattering off a transversely polarized proton

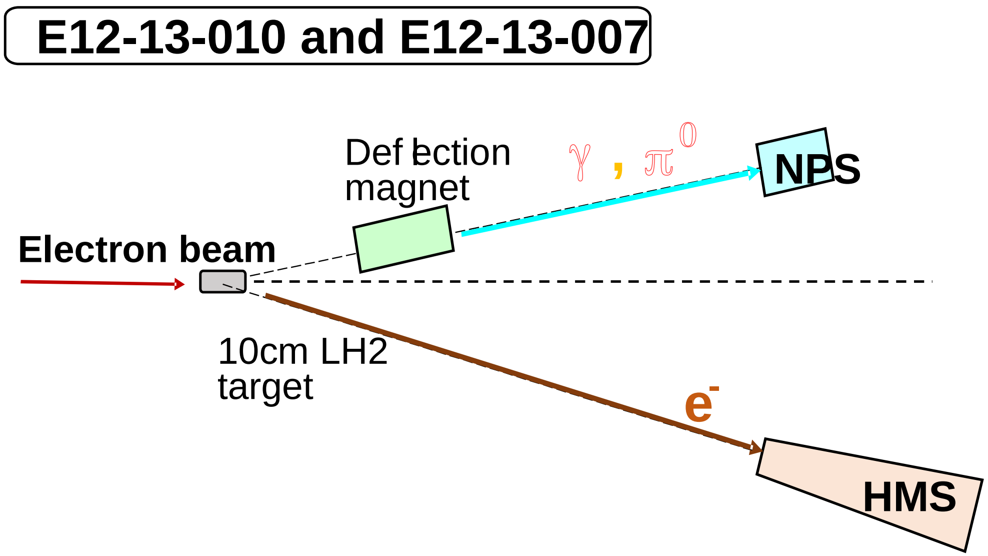
- Total of **160 PAC days** approved: **~ 20%** of all **approved beam time in Hall C**!

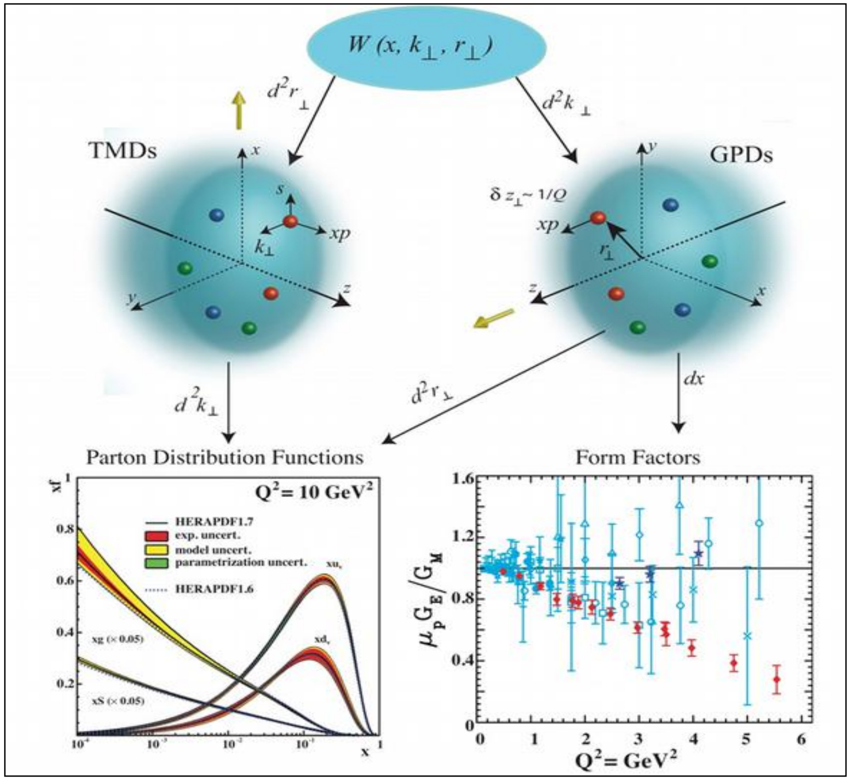
- Scheduling request for **E12-13-010/E12-13-007** (run group) has been submitted

Details on NPS ERR: https://wiki.jlab.org/cuawiki/index.php/NPS_ERR

Motivation of NPS Experiments: Validation of Reaction mechanism

- To extract the rich information on nucleon structure encoded in **GPD** and **TMDs** one needs to show that the scattering process is understood
  - Neutral final states offer unique advantages





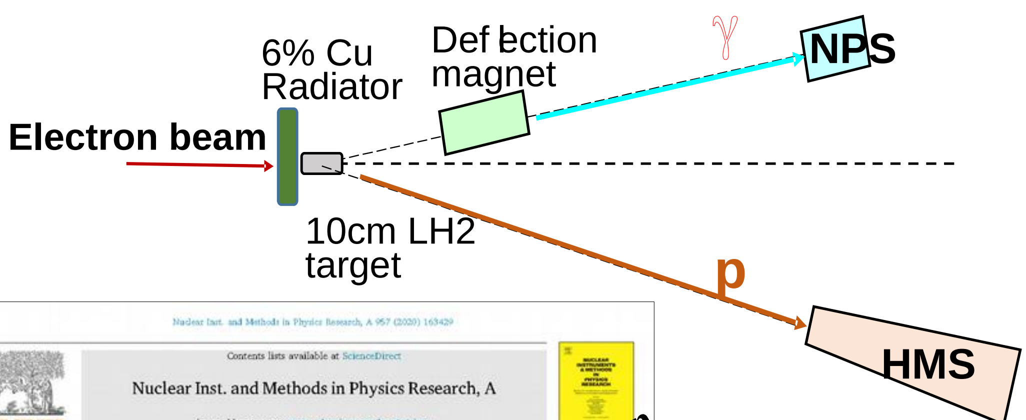
- **E12-13-010** - provides precision measurements of the deeply-virtual Compton scattering cross section at different beam energies to extract the real part of the Compton form factor without any assumptions. Also provides π0 L/T cross section data to validate the exclusive meson production mechanism – if sL large, access to regular GPDs, if sT large, then access to transversity may become possible

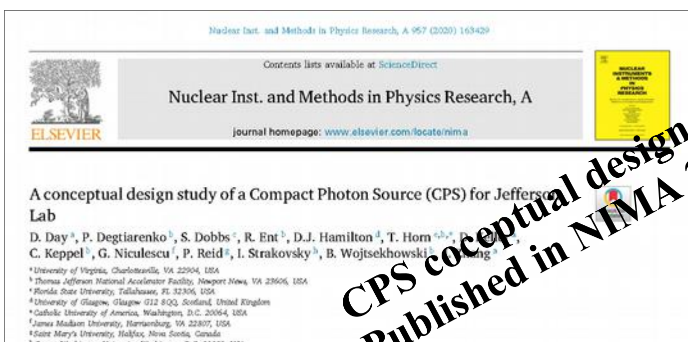
- **E12-13-007** - measure the basic semi-inclusive neutral-pion cross section in a kinematical region where the QCD factorization scheme is expected to hold, crucial to validate the foundation of this cornerstone of 3D transverse momentum imaging

Combine NPS with Compact Photon Source (CPS)

- Much progress in imaging nucleon structure can be made with electron-scattering reactions, yet experiments with high-energy photons play a unique complementary role
- Small scattering probabilities of exclusive reactions demand high-intensity photon beams
- Understanding strengthened by imaging longitudinally-polarized and transversely-polarized nucleons

E12-14-003, E12-14-005 and E12-17-008




Nuclear Inst. and Methods in Physics Research, A 957 (2020) 163429

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ELSEVIER

A conceptual design study of a Compact Photon Source (CPS) for Jefferson Lab

D. Day[a], P. Degtiarenko[b], S. Dobbs[c], R. Ent[b], D.J. Hamilton[d], T. Horn[e,b,*], D. Keller[a], C. Keppel[b], G. Niculescu[f], P. Reid[g], I. Strakovsky[h], B. Wojtsekhowski[b], J. Zhang[a]

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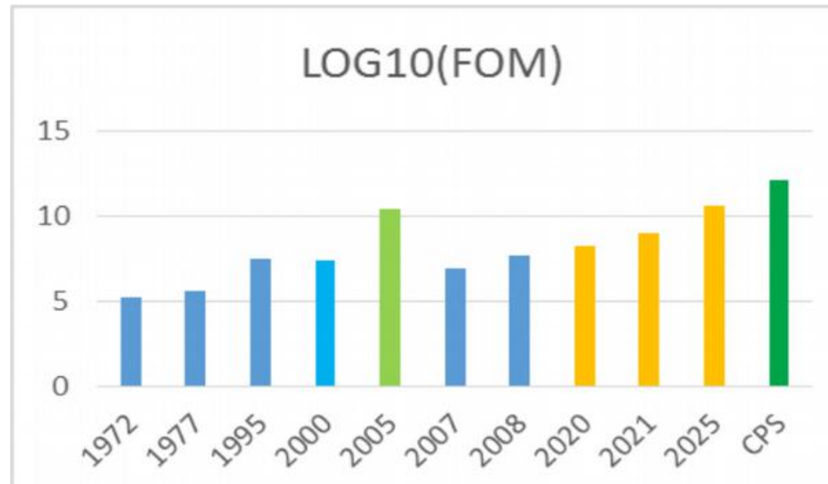
CPS coceptual design
Published in NIMA 2020

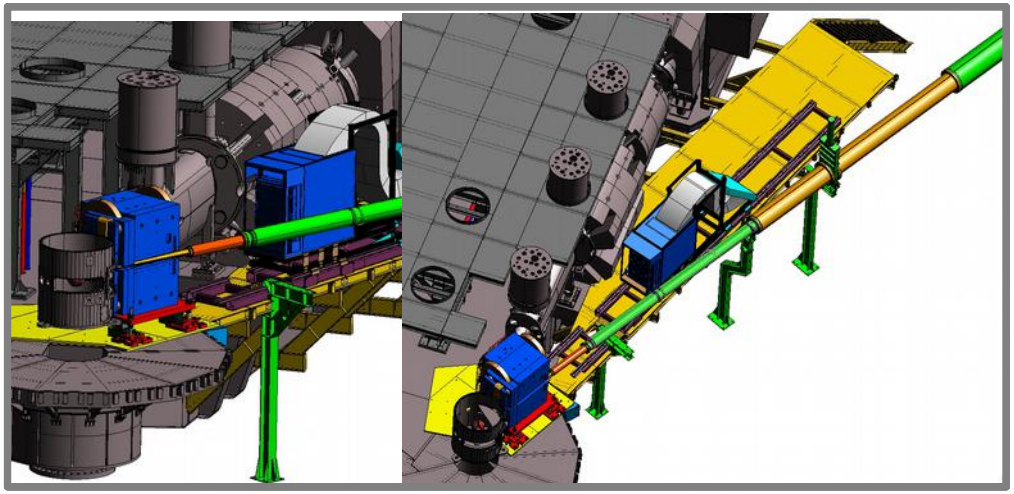


CPS enables a gain of a factor of 30 in figure-of-merit! Enables a new suite of high-energy photon scattering experiments to image and understand the dynamical nucleon structure

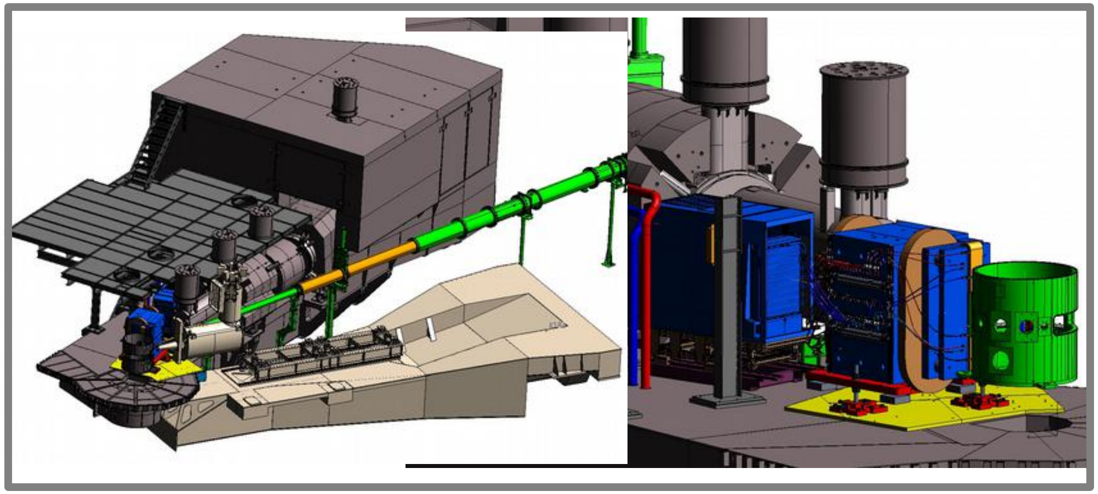
- **E12-17-008** - investigate the mechanisms behind RCS – provides crucial insight into the nature of exclusive reactions and proton structure
- **C12-18-005** - first fundamental test of the universality of the GPDs, as the GPDs extracted from TCS should be comparable with those extracted from the analogous space-like (electron) scattering process - DVCS

The Neutral Particle Spectrometer

Supported by NSF MRI PHY-1530874



Small angles (6°-23°) configuration



Large angles (23°-57.5°) configuration

- ~25 msr neutral particle detector consisting of ~1080 PbWO4 crystals (30x36 matrix) in a temperature controlled frame including gain monitoring and curing systems
- HV distribution bases with built in amplifiers for operation in a high rate environment
- Essentially deadtime less digitizing electronics to independently sample the entire pulse form for each crystal Jlab developed Flash ADCs
- A vertical-bend sweeping magnet with integrated field strength of 0.3 Tm to suppress an eliminate charged background
- Cantilevered platforms off the Super High Momentum Spectrometer (SHMS) carriage to allow for remote rotation. For NPS angles from 6 to 23 degrees, the platform will be on the left of the SHMS carriage for NPS angles 23-57.5 degrees it will be on the right
- A beam pipe with as large opening/critical angle for the beam exiting the target/scattering chamber region as possible to reduce beamline-associated backgrounds

The NPS sweep magnet

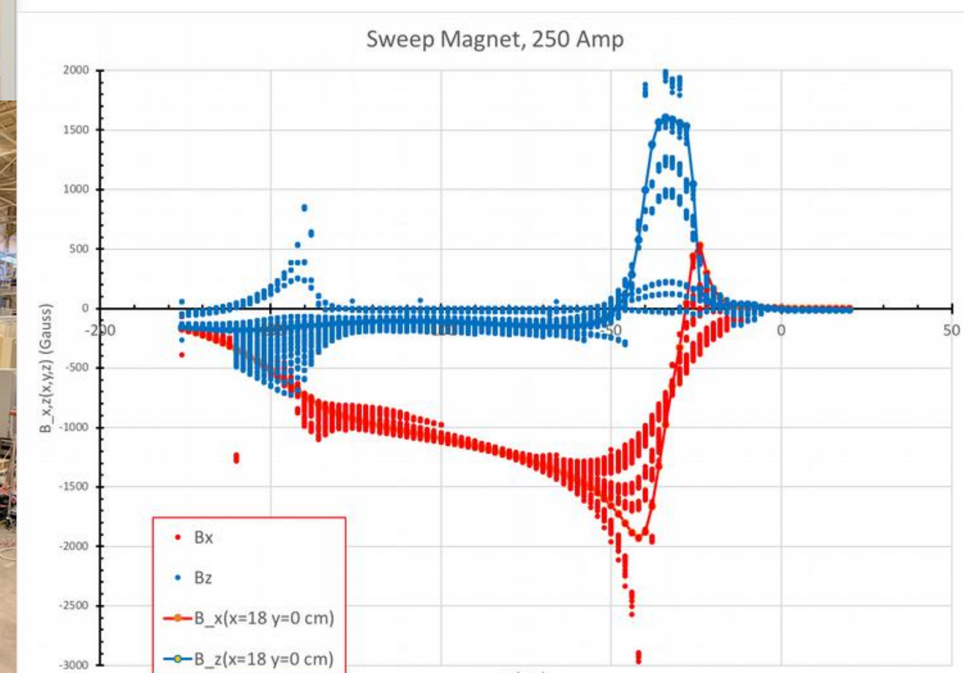
Supported by NSF MRI PHY-1530874

NPS magnet and power supply in test lab

- Normal resistive iron dominated magnet provided by CUA and ODU
- Fully assembled and being tested at JLAB
- Completed fringe field mapping at 25% of full current – next: compare to calculation
- Planning full current tests in Hall C – will there be an opportunity this year (2020)?

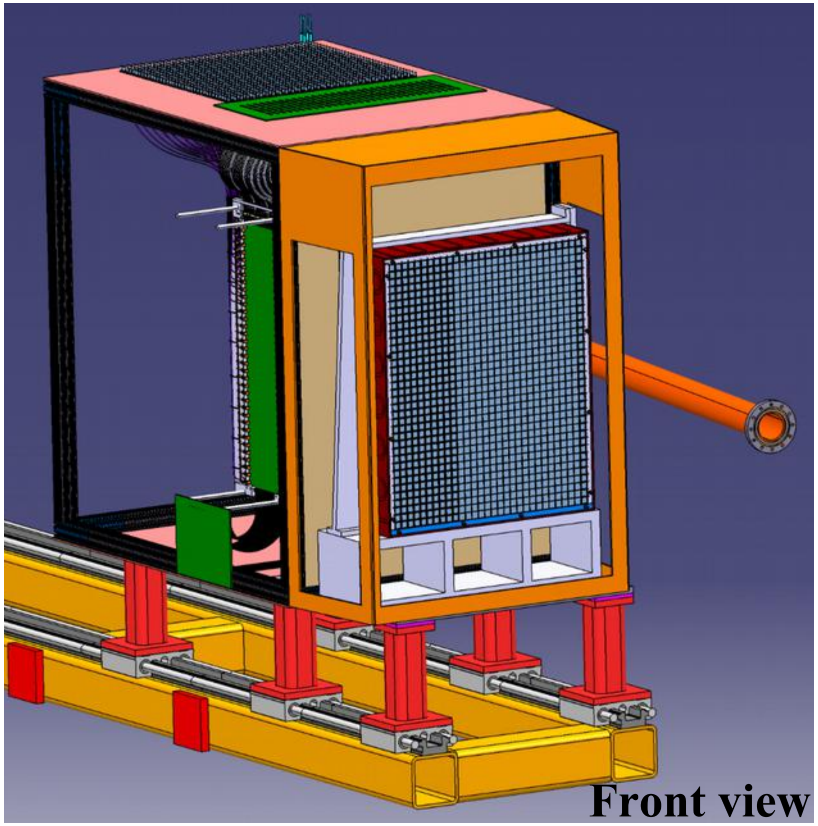
Max Current (Amp)	990
R @ 20°C (Ohm)	0.1
ΔV Max (V)	110
Cooling medium	LCW
ΔP (psi)	130
ΔT (°C)	30
Corrector Max (Amp)	520

Mapping equipment



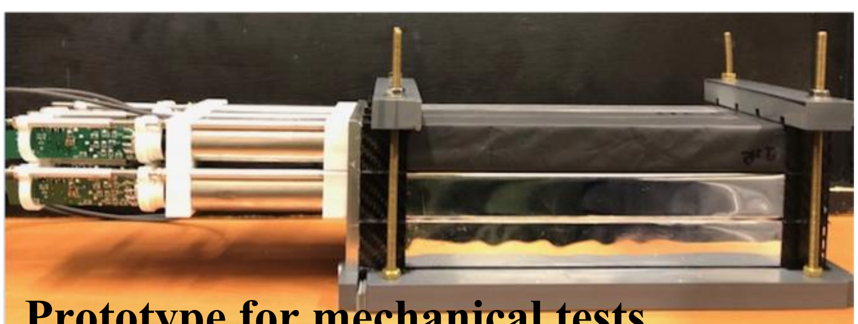
Results from mapping – lots of data acquired!

Calorimeter conceptual design

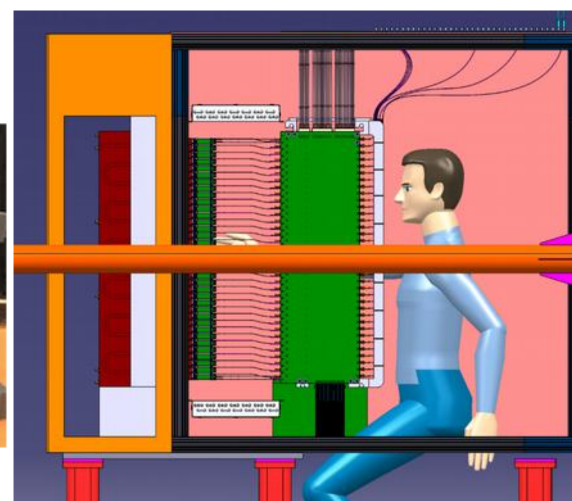


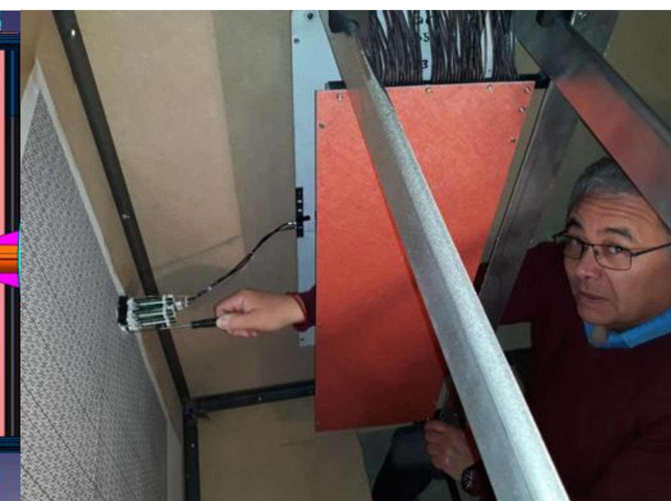
Front view

- 30x36 (1080) $PbWO_4$ crystals of size: 2x2x20 cm^3
- Hamamatsu R4125 PMTs with custom active HV bases provided by Ohio U.
- Design completed at IPN Orsay
  - Crystals placed in a 0.5 mm-thick carbon frame to ensure good positioning
  - PMTs accessible from the back side to allow for maintenance
  - Calibration and radiation curing with blue LED light though quartz optical fibers



Prototype for mechanical tests



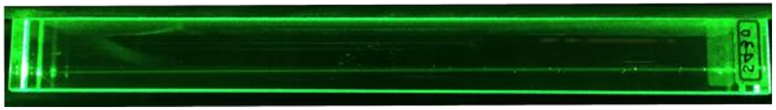


Human size detector!

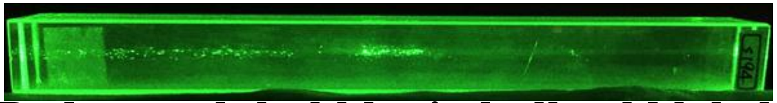
NPS calorimeter: PbWO4 crystals

Supported by NSF MRI PHY-1530874

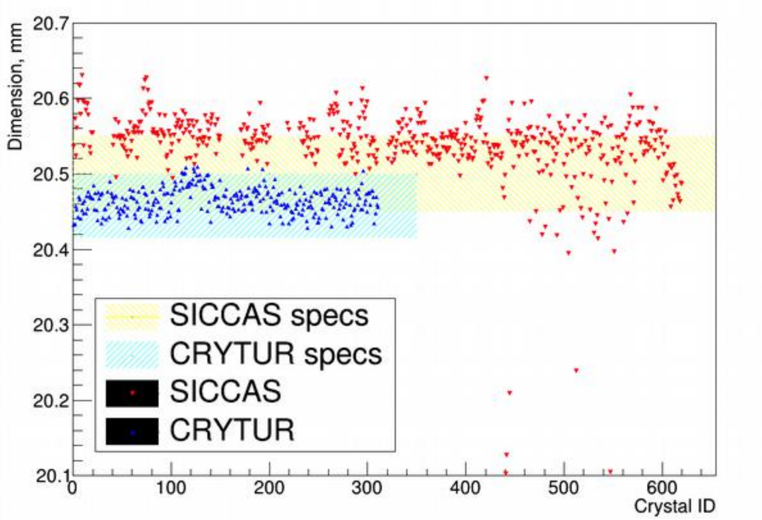
- Only two vendors of PbWO4 crystals available worldwide
- SICCAS/China: failure rate ~30% of crystals produced in 2014-19 due to major mechanical defects
- CRYTUR/Czech Republic: Strict quality control procedures – so far 100% of crystals accepted
- NPS calorimeter crystal coverage:
  - CRYTUR crystals will cover 78.7% of the active volume
  - SICCAS crystals will cover 21.3% (edges)



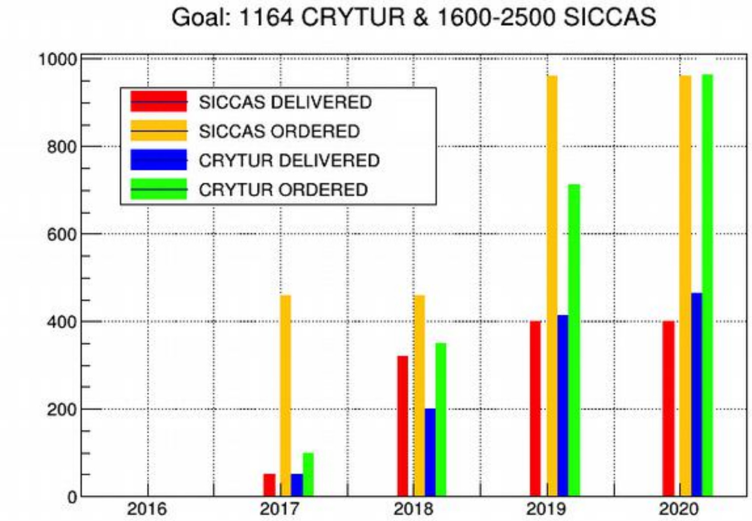
Good crystal



Bad crystal: bubbles in bulk, old labels ...



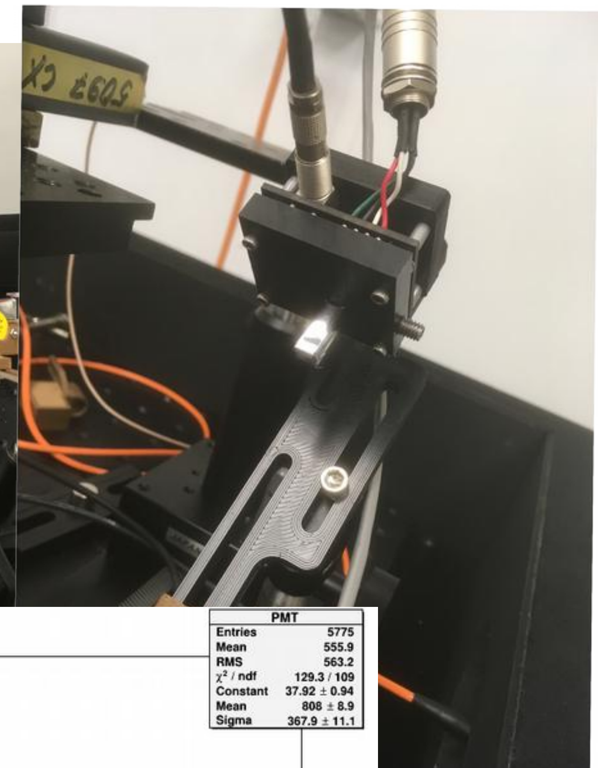
Quality check: dimension uniformity

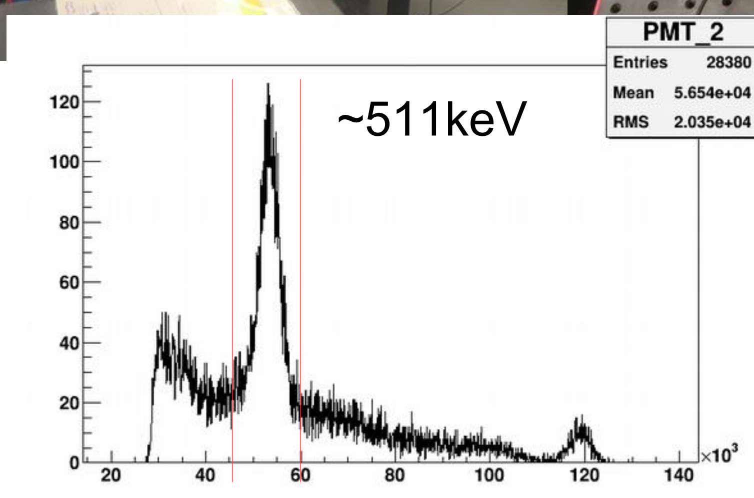


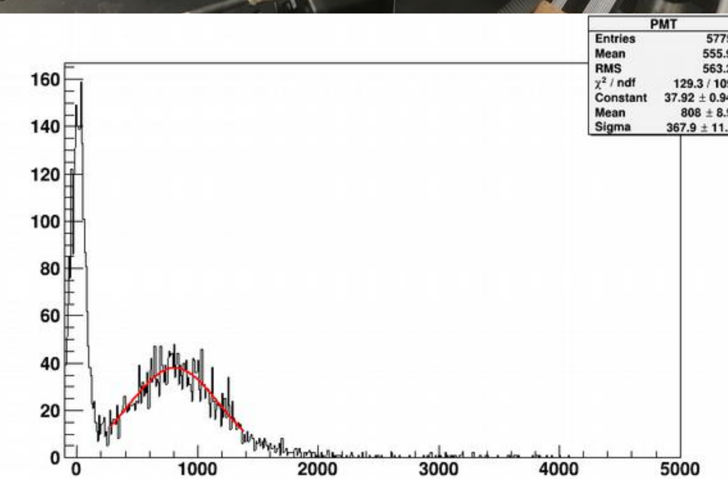
Crystal delivery timeline

New measurement setups: Light Yield in NPS cleanroom

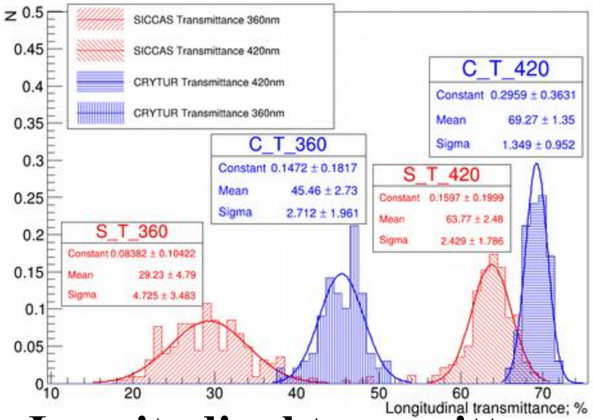
- New setup with SiPM+LYSO trigger arm, Na-22 source, fast 2in PMT Hamamatsu
- Good for quick QA of Crytur crystals, no need to move offsite
- Temperature not controlled
- Useful for R&D projects (glass ceramic studies, SiPM calorimeter readout and etc.)



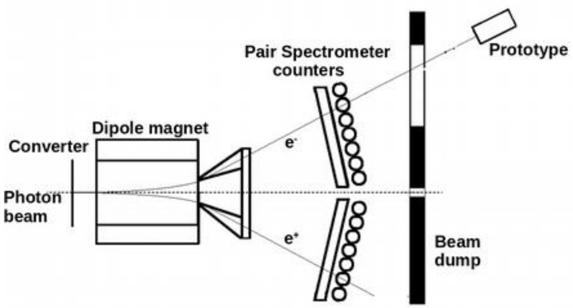




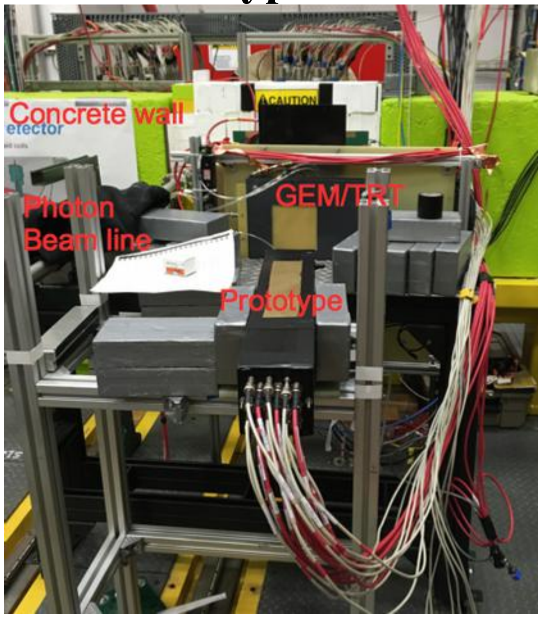
PbWO4 crystal properties and performance tests



Longitudinal transmittance



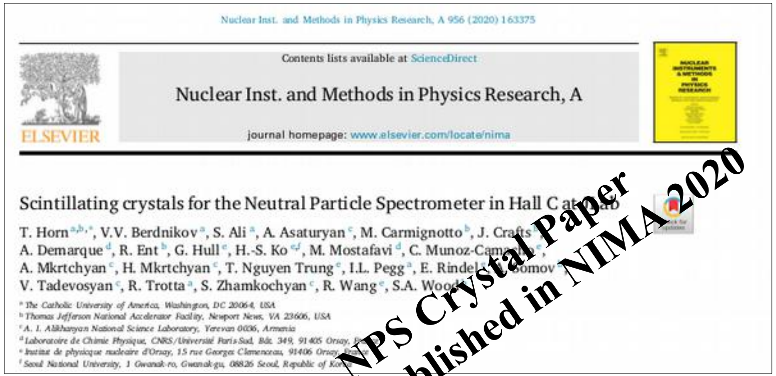
3x3 Prototype



Crystal test stand

- **Primary quality assurance of the crystals:**
  - Precise dimension measurements and visual inspections
  - Optical transmittance measurements
  - Light yield measured using a radioactive source Na-22 and 2in PMT inside of thermo-controlled darkbox

- **Crystal/glass beam test program in HallD:**
  - Installed the 3x3 prototype behind the PS (2018,2019,2020)
  - Energy resolution measurement
  - Readout chain optimization
  - Glass-ceramic scintillator tests
  - Streaming readout
  - Crystal test stand 12 crystal measured at the same time (2020)
  - Studies of crystal defects, light guides, cookies and etc.



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Scintillating crystals for the Neutral Particle Spectrometer in Hall C at JLab

T. Horn [a,b,*], V.V. Berdnikov [a], S. Ali [a], A. Asaturyan [c], M. Carmignotto [b], J. Crafts [b], A. Demarque [d], R. Ent [b], G. Hull [e], H.-S. Ko [e,f], M. Mostafavi [d], C. Munoz-Camacho [e], A. Mkrtchyan [c], H. Mkrtchyan [c], T. Nguyen Trung [e], I.L. Pegg [a], E. Rindel [e], A. Somov [b], V. Tadevosyan [c], R. Trotta [a], S. Zhamkochyan [c], R. Wang [e], S.A. Wood [b]

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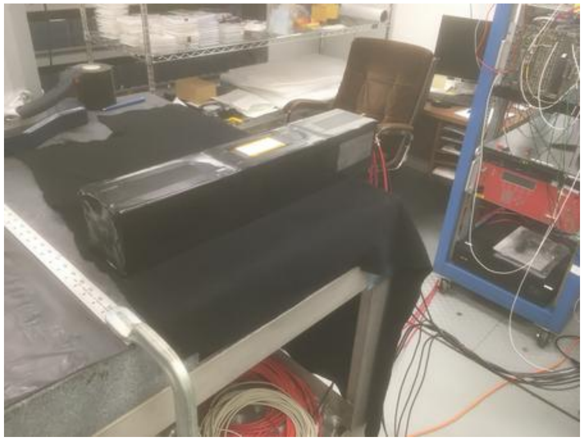
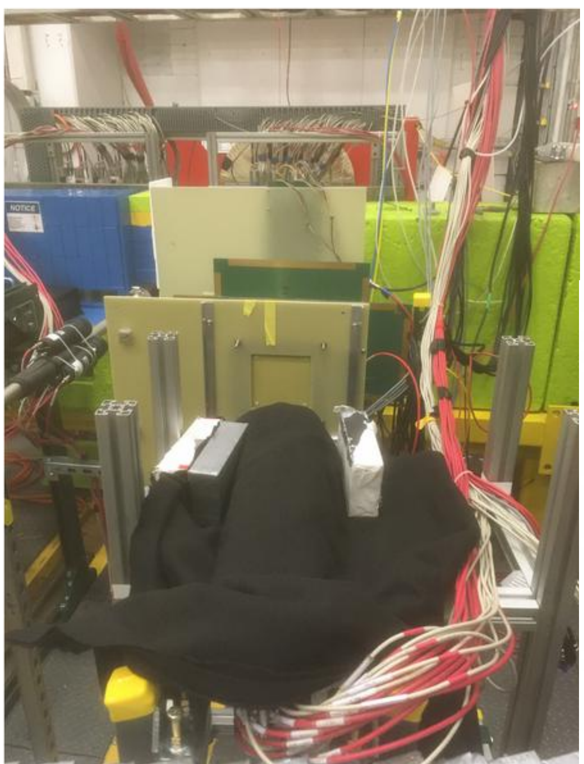
NPS Crystal Paper Published in NIMA 2020

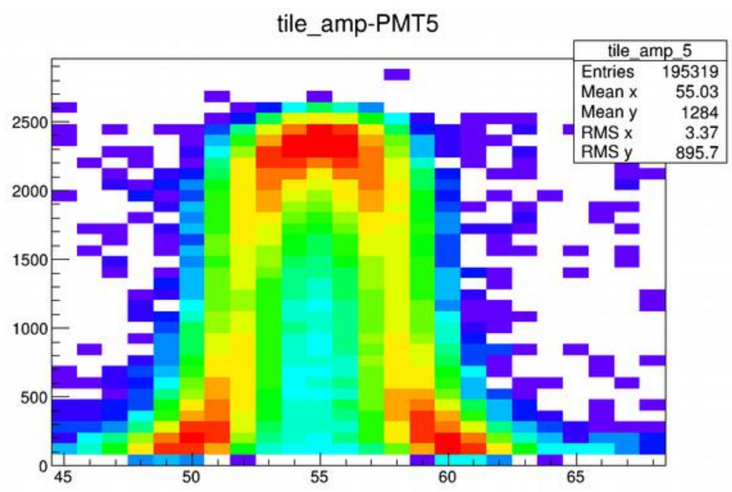
Baseline measurements with PMT based 3x3 prototype

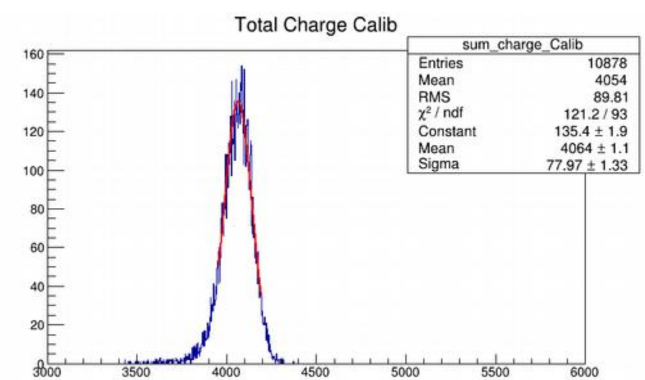




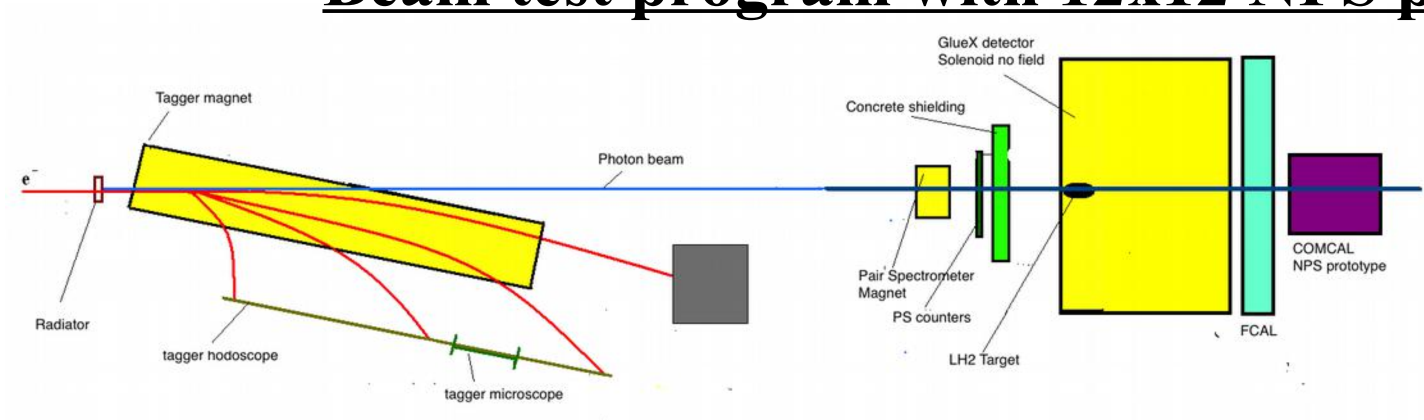
- **Baseline measurement with 3x3 PMT based PWO prototype**
- **Prototype installed, surveyed and aligned**
- **HV connected, tested (remote control)**
- **FADC250 RO channels, PS trigger bit**
- **Readout with GlueX data stream (parasitic)**
- **Energy resolution ~1.9% for ~4GeV lepton**
- **Calibration made by regression algorithm**

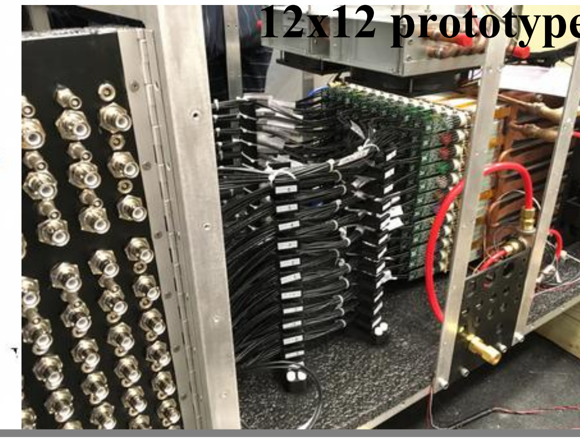
$$\begin{bmatrix} \sum\limits_{events} A_1 A_1 & \sum\limits_{events} A_i A_1 & \sum\limits_{events} A_{Nseg} A_1 \\ \vdots & \vdots & \vdots \\ \sum\limits_{events} A_1 A_j & \ddots \sum\limits_{events} A_i A_j \ddots & \sum\limits_{events} A_{Nseg} A_j \\ \vdots & \vdots & \vdots \\ \sum\limits_{events} A_1 A_{Nseg} & \sum\limits_{events} A_i A_{Nseg} & \sum\limits_{events} A_{Nseg} A_{Nseg} \end{bmatrix} * \begin{bmatrix} k_1 \\ \vdots \\ k_j \\ \vdots \\ k_{Nseg} \end{bmatrix} = \begin{bmatrix} \sum\limits_{events} E_{ps} A_1 \\ \vdots \\ \sum\limits_{events} E_{ps} A_j \\ \vdots \\ \sum\limits_{events} E_{ps} A_{Nseg} \end{bmatrix}$$





Beam test program with 12x12 NPS prototype

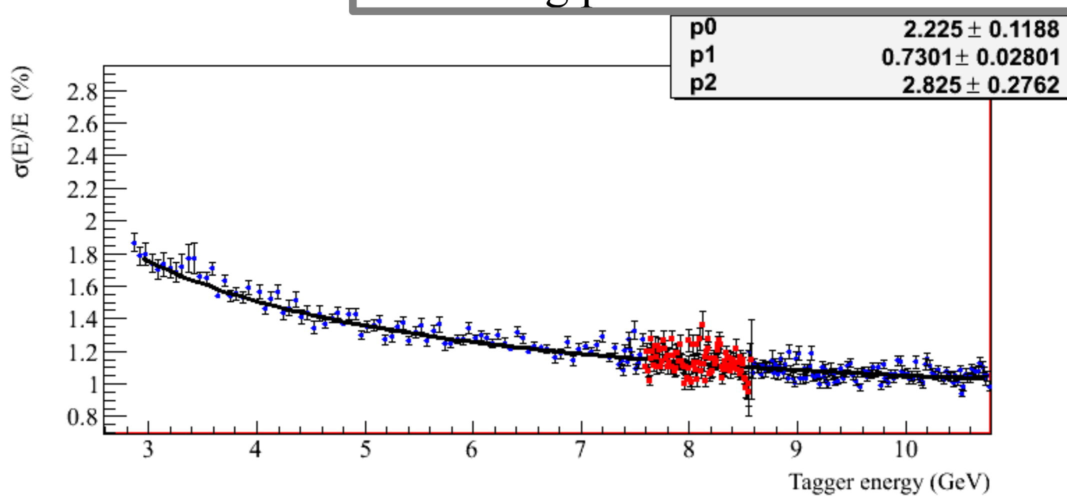




- Built a 12x12 detector for more detailed studies compared to quick checks with the 3x3 prototype
  - Allows for studies of energy resolution in wide energy range, stability, rate dependence, etc.
  - But, not as flexible as 3x3 since cannot run in parasitic mode and has to be installed in the beamline - requires scheduling, crane installation, alignment, slow controls, integration to data stream...

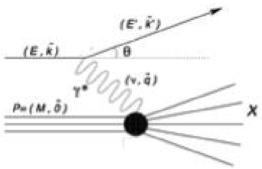
Detector design major components:
- 12x12 Matrix (140 crystals)
- NPS HV divider
- 250 fADC readout
- Environment control:
  - Temperature, humidity, light sensors
- Monitoring system consisting of LED and α-source
- Moving platform

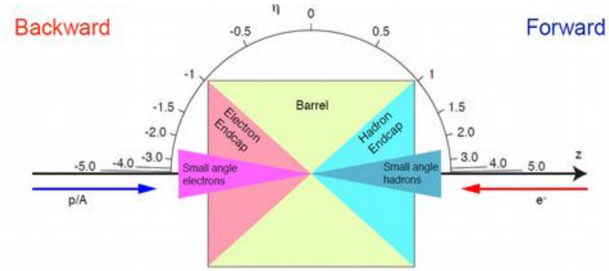
- Beam test program completed in 2019
  - Initial results show energy resolution: ~**2.83%/E+2.23%/√E+0.73%**
  - Ongoing studies to improve linearity
  - Preparing publication on beam test results – to be submitted to NIMA in next few months



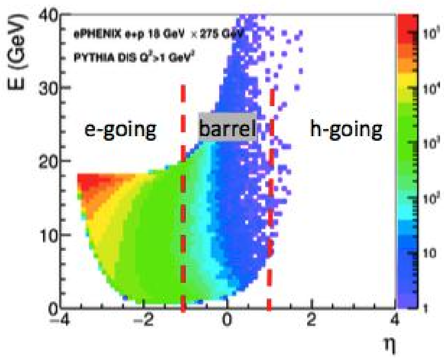
EIC Electromagnetic Calorimetry

Inclusive DIS: scattered electron

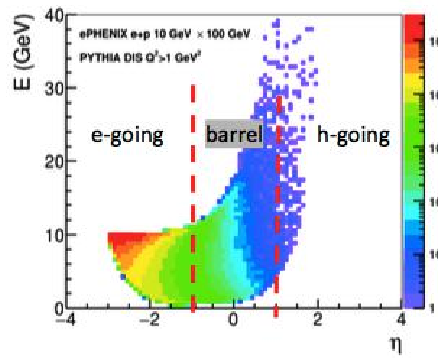




e+p 18x275 GeV

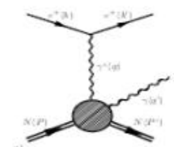


e+p 10x100 GeV

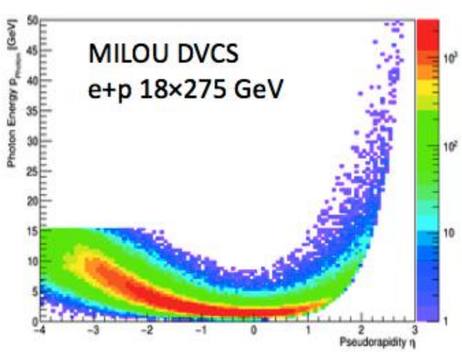


- **Electrons mostly scattered in backward (e-going) and barrel**
- **Electrons energy varies from 0 to e-beam energy in backward**
- **Higher electron energies in barrel and forward (h-going) region**
- **Good resolution needed at η < -2**
- **Wide rapidity coverage is crucial**

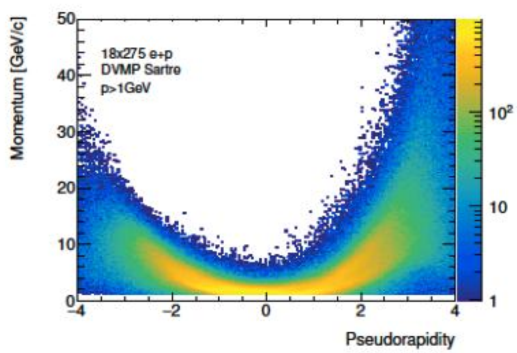
Exclusive DIS: DVCS and DVMP



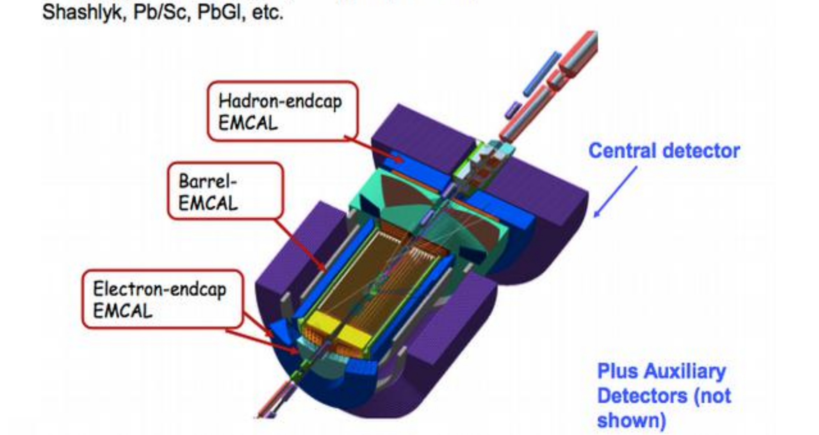
DVCS photon kinematics



J/ψ→ee kinematics

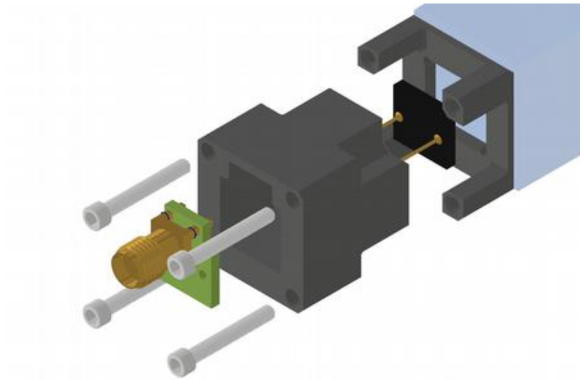


Several options including crystals, glass, W/SciFi, Shashlyk, Pb/Sc, PbGl, etc.



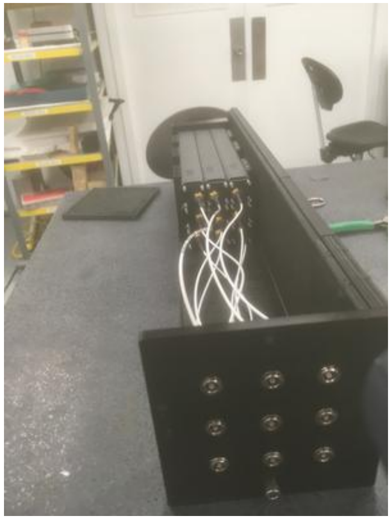
EIC White paper; EIC R&D Handbook;
A. Bazilevsky talk Initial Considerations for the EMCal of the EIC detector

SiPM based 3x3 PWO prototype assembly

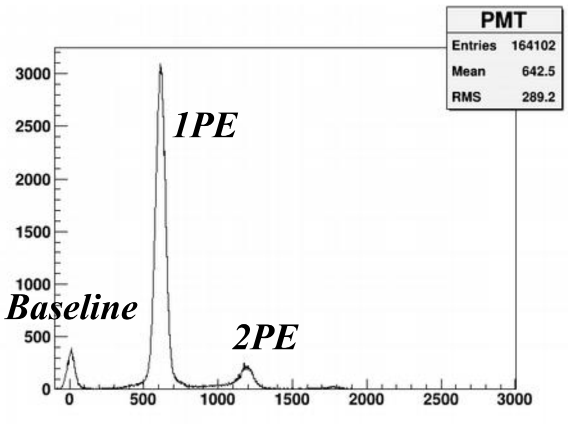


- Improved prototype with new SiPM based assembly
- Same size 3D printed frame as PMT based version
- Two peace SiPM holder concept developed
- Holders are 3D printed (PLA plastic)
- PEEK plastic will be used in real detector
- Silicon based glue for frame, no SiPM glueing to crystal
- SiPM soldered to circuit board with SMA connector
- 25um cell SiPM for beam tests installed (75um second option)
- LEMO output at the detector patch panel (BIAS/Preamp or Waveboard application)
- Assembled and sanity checked
- Ready for beam tests

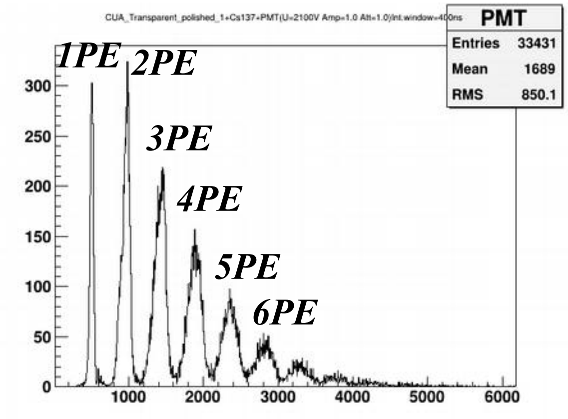





SiPM and SiPM+PWO performance tests in the darkbox

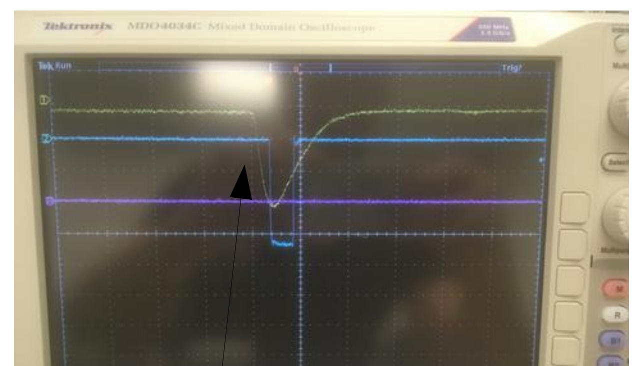


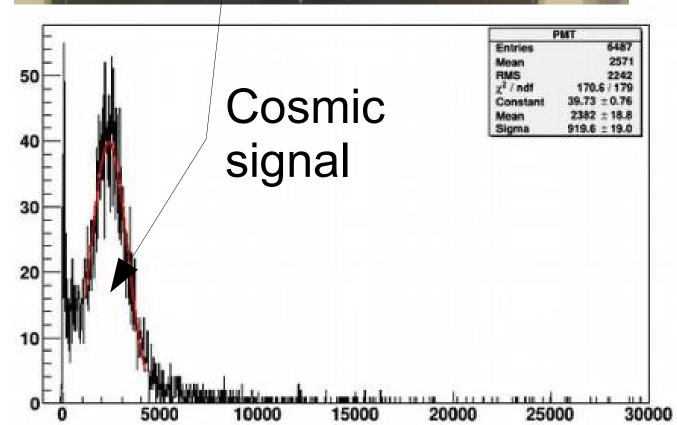
LED OFF



LED ON

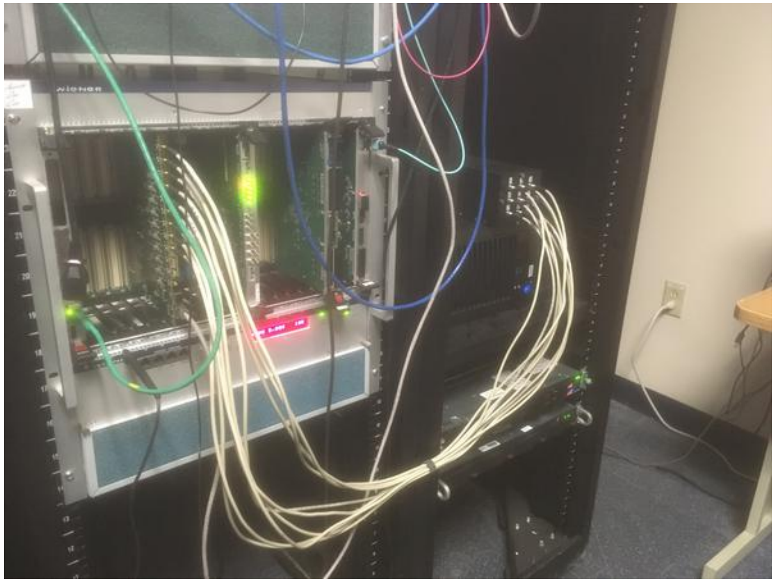
- **25um and 75um 6x6 mm^2 SiPM Hamamatsu S13360**
- **Performed tests with LED ON/OFF**
- **BiAS board + Preamp board**
- **FADC250 self trigger, threshold level under baseline**
- **CODA based DAQ**





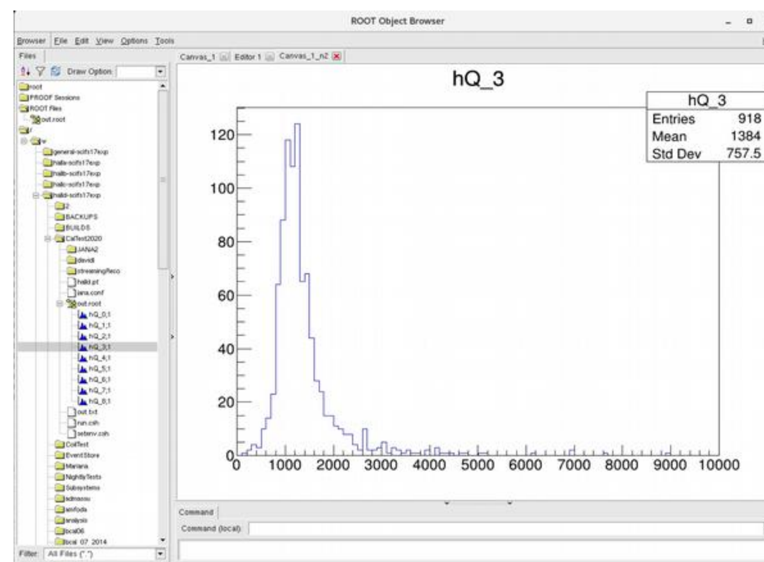
- **SiPM coupled with PWO crystal (ESR wrapped)**
- **Cosmic tests**
- **BiAS board + Preamp board**
- **FADC250, trigger coincidence between two plastic scintillator pads with SiPM readout**
- **CODA based DAQ**
- **~50Photoelectrons for ~15MeV energy deposit mean ~3.3 PE/MeV**

SiPM prototype tests with Waveboard in INDRA lab



- Prototype moved to INDRA lab and connected to Waveboard, interaction via INDRAlab machine
- The parameters for Waveboard set to perform cosmic measurements (HV calibrated, gain value, thresholds and etc.)
- First quick tests, data streamed to host machine, pulses make sense, analyzed via DbgParser code
- Full readout chain tested SiPM+Waveboard+TRIDAS, data analyzed via JANA-2+SRO plugin
- Calorimeter calibration is ongoing
- Full Readout chain+analyzer is working

```
 0x00   0x00    9    0x0209D0C3          0       0x10CC      0x10CC      0x000F      0x0008      0x0000   0x0007
 0x00   0x00   10    0x020D5D5A          0       0x0000      0x0000      0x0000      0x0000      0x0000   0x0007
 0x00   0x00   11    0x020B34E9          0       0x0000      0x0000      0x0000      0x0000      0x0000   0x0007
root@wvb_daq_axis:~# ./ReadParam
CRATE#  SLOT#  CHAN#  PEDESTAL*4096  RATE MON (Hz)  START THR  STOP THR  LEAD LENGTH  TAIL LENGTH  CONTROL  STATUS
 0x00   0x00    0    0x010E75BA        700       0x10CA      0x10CA      0x000F      0x0008      0x000A   0x0004
 0x00   0x00    1    0x020B4B7D          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    2    0x02101660          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    3    0x02097806          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    4    0x020AD5B4          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    5    0x020AEFF6          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    6    0x020B8D01          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    7    0x020CB3D2          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    8    0x020BE940          0       0x10CC      0x10CC      0x000F      0x0008      0x000A   0x0007
 0x00   0x00    9    0x0209D038          0       0x10CC      0x10CC      0x000F      0x0008      0x0000   0x0007
 0x00   0x00   10    0x020D5726          0       0x0000      0x0000      0x0000      0x0000      0x0000   0x0007
 0x00   0x00   11    0x020B295F          0       0x0000      0x0000      0x0000      0x0000      0x0000   0x0007
root@wvb_daq_axis:~# 
```

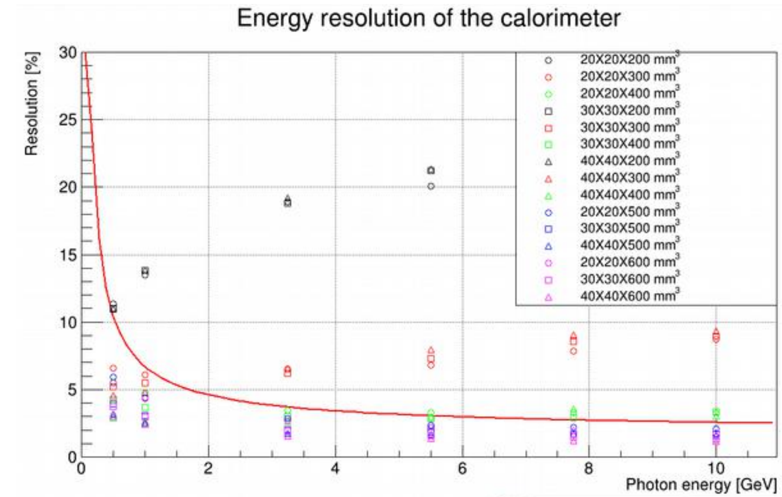


Electron endcap EmCal DSB:Ce glass

- **Ongoing EIC R&D program (eRD1)**
- **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**

SCINTILEX

- **Ongoing preparation for beam tests: bars need to be polished (flatness, rectangularity etc.), quality assurance, testing with gamma sources, cosmic**

1cm x 1cm x 0.5cm

2cm x 2cm x (2-4)cm

2.0cm x 2.0cm x 20.0cm

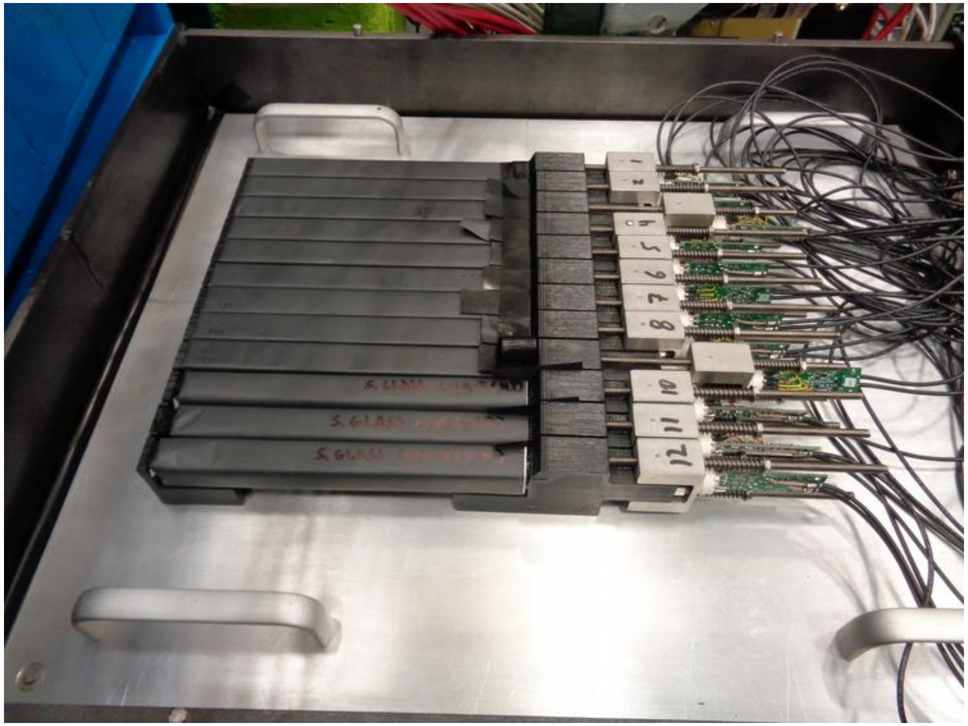
4.0cm x 4.0cm x 40.0 cm

2019

2020

2021


S.GLASS CUA-2(F.)
S.GLASS CUA-1(F.P.)
17 18 19 20 21 22 23 24 25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