EM Calorimeter Technologies for EIC

Tanja Horn

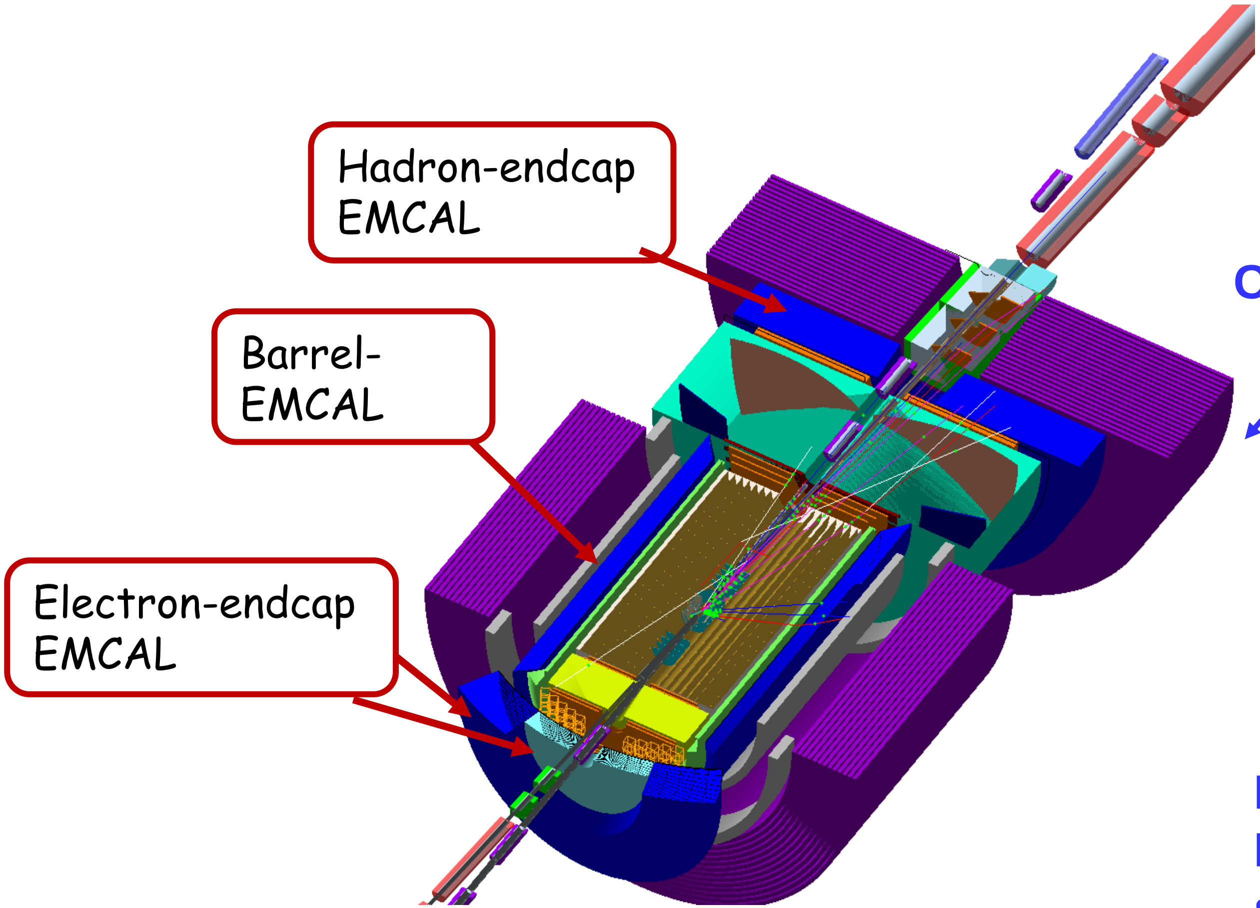
in collaboration with eRD1 (and many others):

S. Ali, A. Asaturyan, M. Battaglieri, V. Berdnikov, J. Bettane, M. Bondi, A. Celentano, J. Crafts, D.Damenova, R. DeVita, G. Hull, M. Josselin, J. Paez Chavez, I.L. Pegg, M. Purschke, L.Marsicano, C. Munoz-Camacho, P. Musico, H. Mkrtchyan, E. Nguyen, M.Osipenko, E. Rindel, M. Ripani, H. San, A. Somov, S. Stoll, V. Tadevosyan, M.Taiuti, R. Trotta, C. Walton, R. Wang, C. Woody, R-Y. Zhu

A.I. Alikhanyan National Science Laboratory/Yerevan, Catholic University of America, The Vitreous State Laboratory, Institut de Physique Nucleaire d'Orsay/France, Jefferson Laboratory, Brookhaven National Laboratory, Caltech

EM Calorimetry at EIC

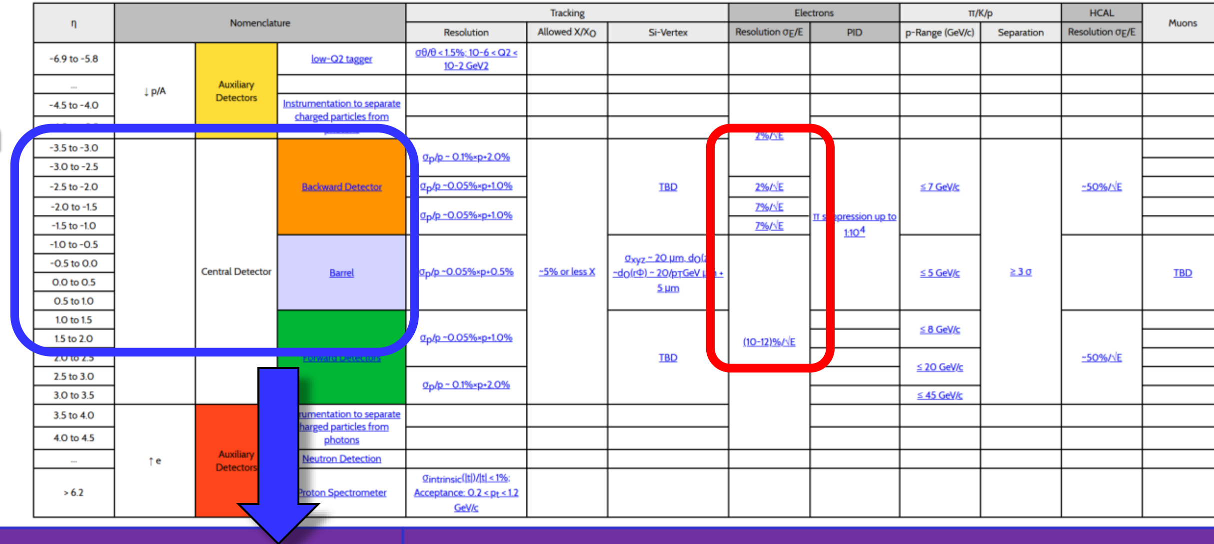
- Several options including crystals, glass, W/SciFi, Shashlyk, Pb/Sc, PbGl, etc.



Central detector

Plus Auxiliary Detectors (not shown)

EM Calorimeter requirements based on EIC White Paper and eRD1



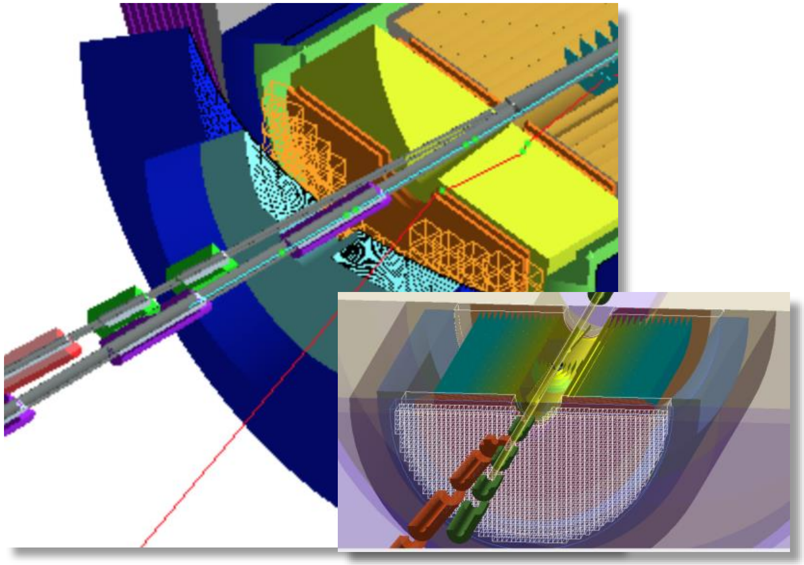
η	Nomenclature			Tracking: Resolution	Tracking: Allowed X/X_0	Tracking: Si-Vertex	Electrons: Resolution σ_E/E	Electrons: PID	π/K/p: p-Range (GeV/c)	π/K/p: Separation	HCAL: Resolution σ_E/E	Muons
-6.9 to -5.8	↓ p/A	Auxiliary Detectors	low-Q2 tagger	σθ/θ < 1.5%; 10-6 < Q2 < 10-2 GeV2								
...												
-4.5 to -4.0			Instrumentation to separate charged particles from photons									
[illegible]												
-3.5 to -3.0		Central Detector	Backward Detector	σ_p/p ~ 0.1%×p+2.0%	~5% or less X	TBD	2%/√E	π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3 σ	~50%/√E	
-3.0 to -2.5												
-2.5 to -2.0				σ_p/p ~0.05%×p+1.0%			2%/√E					
-2.0 to -1.5				σ_p/p ~0.05%×p+1.0%			7%/√E					
-1.5 to -1.0							7%/√E					
-1.0 to -0.5			Barrel	σ_p/p ~0.05%×p+0.5%		σ_{xyz} ~ 20 µm, $d_0(z)$ ~$d_0(r\Phi)$ ~ 20/p_TGeV µm + 5 µm			≤ 5 GeV/c			TBD
-0.5 to 0.0												
0.0 to 0.5												
0.5 to 1.0												
1.0 to 1.5			Forward Detectors	σ_p/p ~0.05%×p+1.0%		TBD	(10-12)%/√E		≤ 8 GeV/c		~50%/√E	
1.5 to 2.0												
2.0 to 2.5									≤ 20 GeV/c			
2.5 to 3.0				σ_p/p ~ 0.1%×p+2.0%								
3.0 to 3.5									≤ 45 GeV/c			
3.5 to 4.0	↑ e	Auxiliary Detectors	Instrumentation to separate charged particles from photons									
4.0 to 4.5												
...			Neutron Detection									
> 6.2			Proton Spectrometer	$\sigma_{intrinsic}(\|t\|)/\|t\|$ < 1%; Acceptance: 0.2 < p_t < 1.2 GeV/c								

Regions and Physics Goals	Calorimeter Design
Lepton/backward: EM Cal ○ Resolution driven by need to determine (x, Q^2) kinematics from scattered electron measurement ○ Prefer 1.5%/√E + 0.5%	**Inner EM Cal for for η < -2:** ➢ Good resolution in angle to order 1 degree to distinguish between clusters ➢ Energy resolution to order (1.5%/√E+0.5%) for measurements of the cluster energy ➢ Ability to withstand radiation down to at least 2-3 degree with respect to the beam line. **Outer EM Cal for -2 < η < 1:** ➢ Energy resolution to 7%/√E ➢ Compact readout without degrading energy resolution ➢ Readout segmentation depending on angle
Ion/backward: EM Cal ○ Resolution driven by deep exclusive measurement energy resolution with photon and neutral pion ○ Need to separate single-photon from two-photon events ○ Prefer 6-7%/√E and position resolution < 3 mm	
Barrel/mid: EM Cal ○ Photons and neutral pions from SIDIS and DES in range 1-10 GeV, so absolute energy uncertainty in photon should be 100 MeV ○ Leads to order 10%/√E	**Barrel, EM calorimetry** ➢ Compact design as space is limited ➢ Energy resolution of at least order 10%/√E, and likely better

Electron Endcap EMCAL

- Homogeneous calorimetry with high resolution inner part and more relaxed requirements at larger angles (eRD1)
  - Glass provides a cost effective option in regions where resolution requirements are less stringent

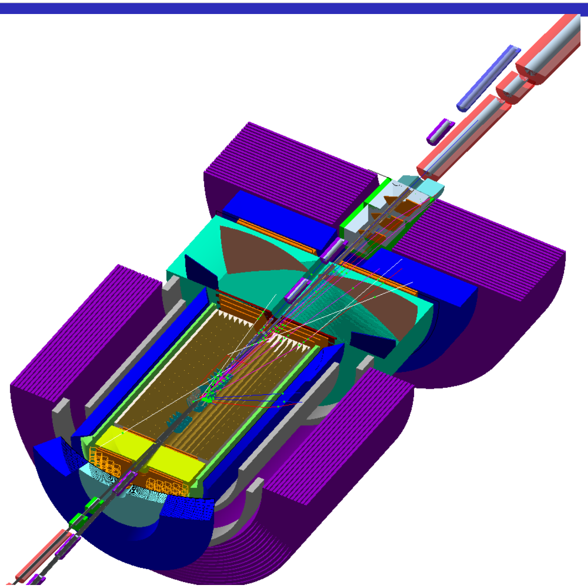
- Benefits from synergies with other projects: Neutral Particle Spectrometer (NPS) and FCAL at JLab, PANDA
  - Resources, prototypes, software development



Technology	Performance (energy resolution)	Estimated number of blocks for EIC	Time needed until mass production
$PbWO_4$ (inner part: 12cm < R < 60cm)	~2%/√E+0.7% (measured over 3x3)	2500 (2x2x20 cm^3)	Available from two vendors (SICCAS, CRYTUR)
Glass (DSB:Ce) (outer part: 60cm < R < 120 (130)cm)	TBD	2400-3400 (4x4x40 cm^3)	2-3 years

Barrel EMCAL

- ❑ W/SciFi: eRD1 R&D is complete
  - ➢ W/Shashlik: R&D to address non-uniformities and improve energy resolution
- ❑ Glass-Ceramics (DSB:Ce) – alternative, flexible geometries, cost effective
  - ➢ R&D includes segmentation and readout out
- ❑ Existing EMCal, e.g BCAL, PHENIX, etc.

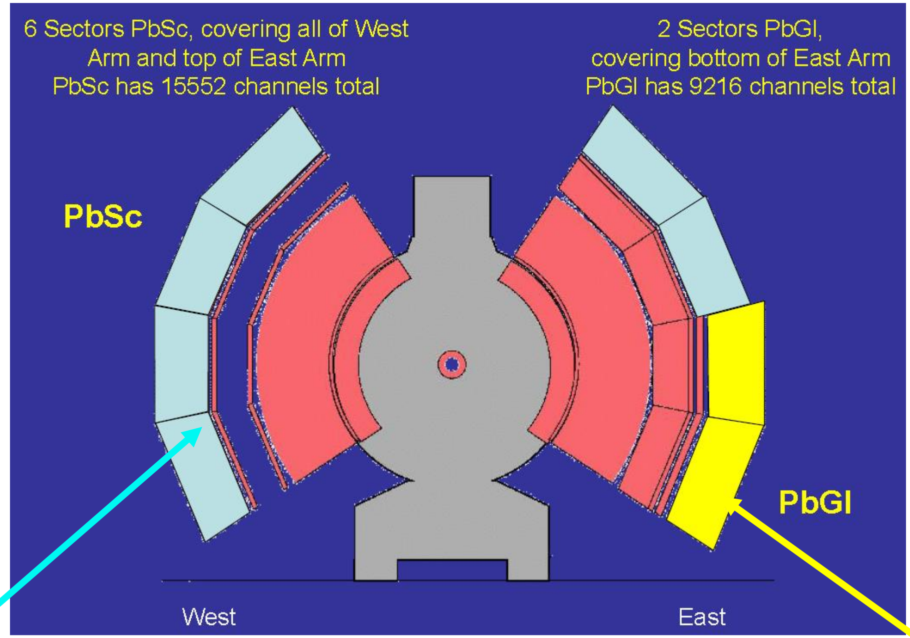


Technology	Performance (energy resolution)	Estimated number of blocks for EIC	Time needed until mass production
W-powder/SciFi with SiPM readout	~16%/√E+3.2% (8x8 tower)		Full industrial scale production available
High-density shashlyk	TBD		2-3 years
Glass (DSB:Ce) (~8cm towers, 95 modules)	TBD	4750 (4x4x40 cm^3)	2-3 years
PbSc PbGl	~8%/√E+2.1% ~6%/√E+0.8%	15552 (5.5x5.5x33 cm^3) 9216 (4x4x40 cm^3)	Phenix EMCal
Pb/Sc	~5.4%/√E+2.3%		JLab BCAL

Barrel EMCAL – PHENIX EMCal

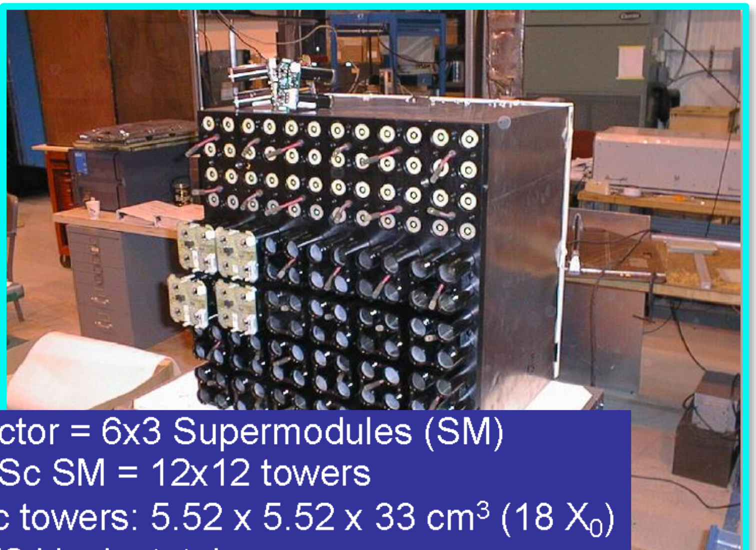
1 PbSc tower:
- 66 sampling cells
- 1.5 mm Pb, 4 mm Sc
- Ganged together by penetrating wavelength shifting fibers for light collection
- Readout: FEU115M phototubes

1 FEM reads out 1 Supermodule

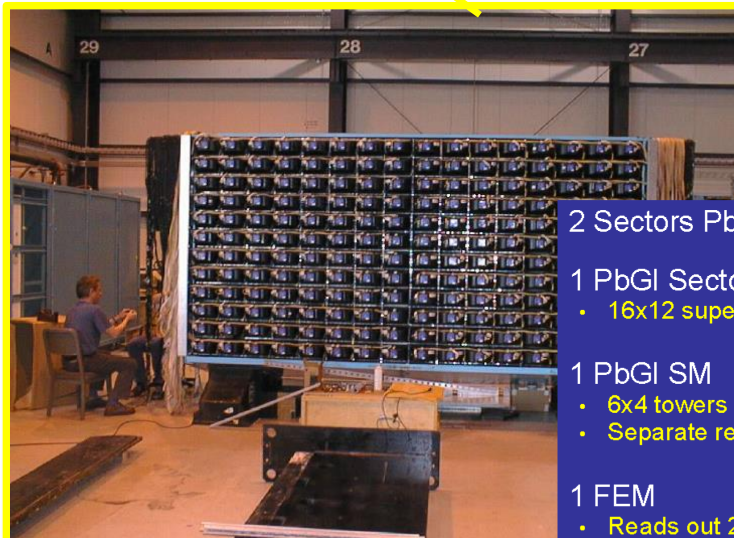


- TF1 PbGlass
- 51% Pb-Oxide
- Wrapped with aluminized mylar foil
- New developed HV-bases

10080 modules:
- leadglass blocks (TF1) 4x4x40 cm^3
- FEU-84 phototubes
- active HV-bases (Cockcroft-Walton generators)



- 1 Sector = 6x3 Supermodules (SM)
- 1 PbSc SM = 12x12 towers
- PbSc towers: 5.52 x 5.52 x 33 cm^3 (18 X_0)
- 15552 blocks total



2 Sectors PbGl

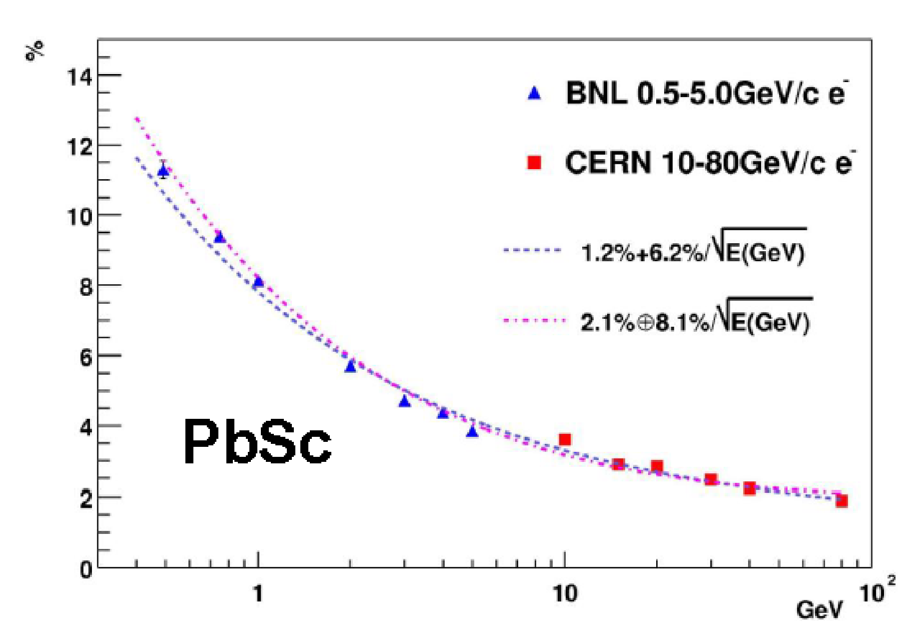
1 PbGl Sector
- 16x12 supermodules (SM)

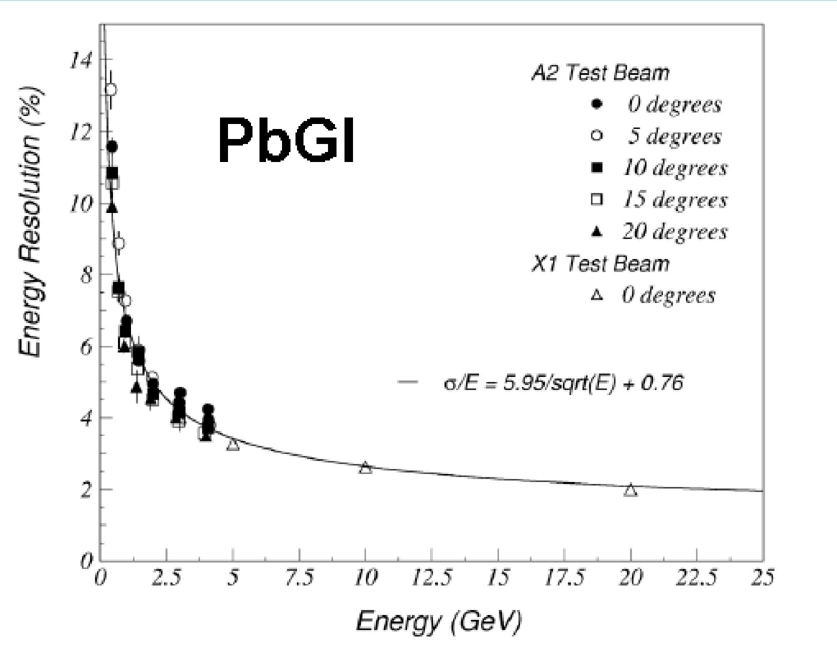
1 PbGl SM
- 6x4 towers
- Separate reference system

1 FEM
- Reads out 2x3 supermodules or 12x12 towers

Barrel EMCAL – PHENIX EMCal

$$\frac{\sigma_E}{E} = \frac{8.1\%}{\sqrt{E}} \oplus 2.1\%$$

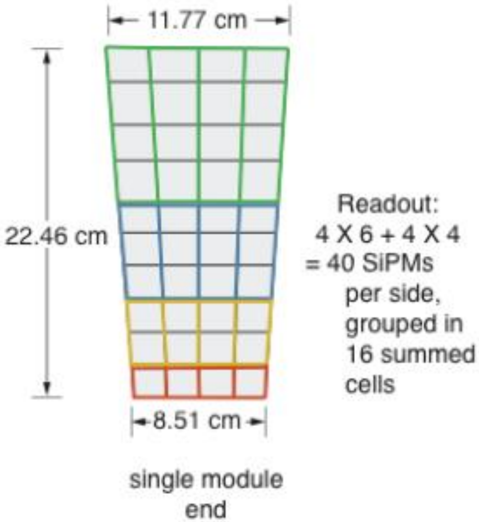


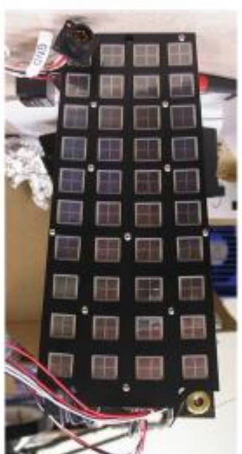


$$\frac{\sigma_E}{E} = \frac{5.95\%}{\sqrt{E}} \oplus 0.76\%$$

Barrel EMCAL – JLab BCAL

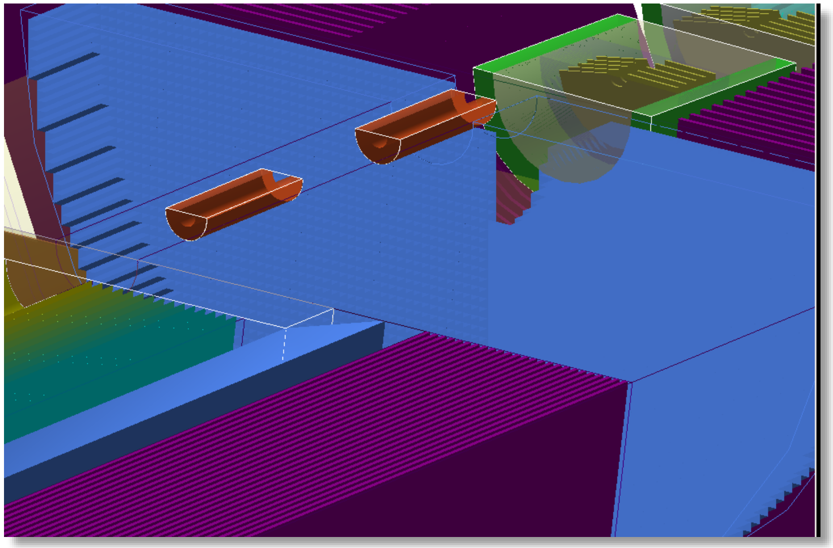
Barrel 390 cm long, 65 cm ID

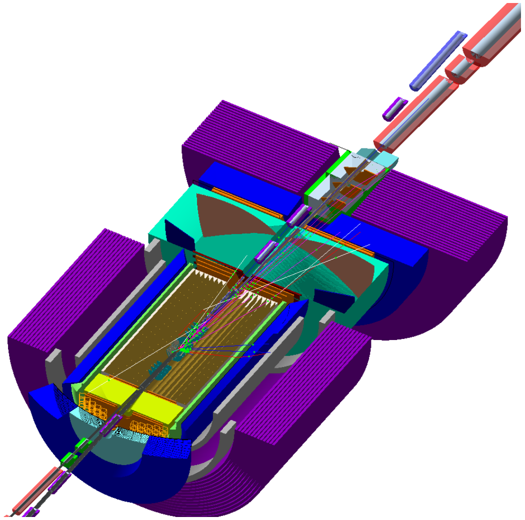




- Lead 0.5 mm thick, Scin.fibers 1 mm OD
- 191 layers Pb/Sc/Glue 37/49/14
- 48 modules, both sides readout
- One side: 40 lightguides, 40 SiPMs
- 40 SiPMs $\rightarrow$ 16 fADC250 + 12 F1TDC
- Timing $\Rightarrow$ Z coord $\sigma_Z \approx 3$ cm
- SiPM (MPPC) 3840 $12 \times 12 \text{mm}^2$
- 1536ch fADC-250MHz (4 rings)
  1152ch F1TDC (3 rings)
- $\sigma_E/E \approx 5.4\%/\sqrt{E} \oplus 2.3\%$

Hadron Endcap EMCAL





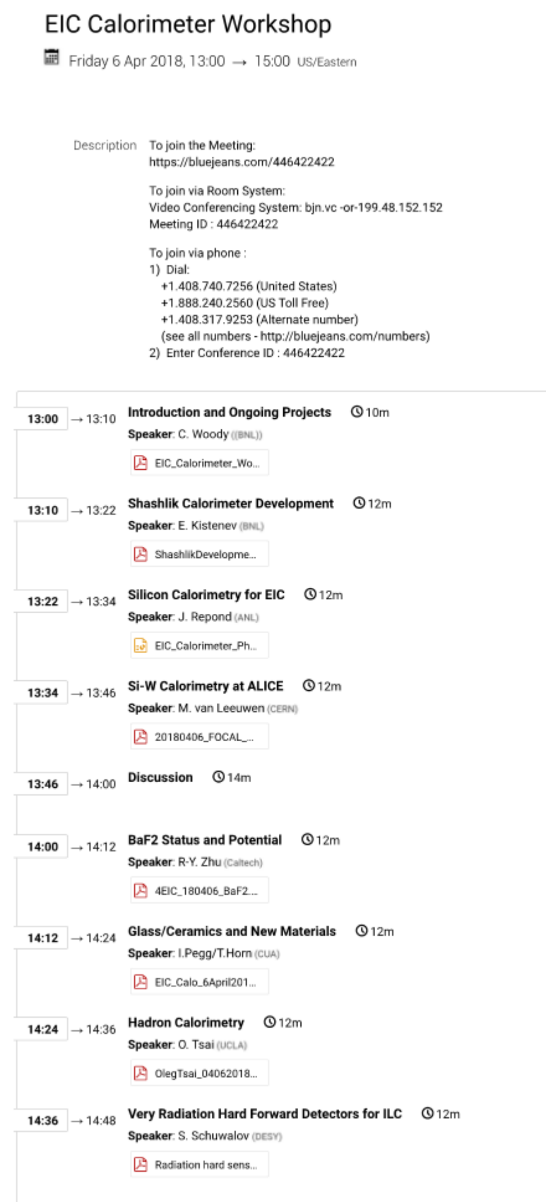
Technology	Performance (energy resolution)	Estimated number of blocks for EIC	Time needed until mass production
Glass (DSB:Ce) (20cm < R < 200cm)	TBD	7500 (4x4x40 cm^3)	2-3 years

See Oleg's presentation in this session for more on HCAL

Technologies: Auxiliary Detectors

- Examples: Luminosity monitors, low Q^2 tagger, ZDC
  - Much overlap with other groups, e.g, forward detectors
- Discussions about possible concept strategies at the Calorimeter Ad-Hoc Workshop on 6 April 2018 (https://indico.bnl.gov/event/4468/)
  - Very radiation hard detectors - ILC FCAL
  - Si-W - ALICE
  - Very radiation resistant $PbWO_4$ - PANDA
  - Glass (DSB:Ce)

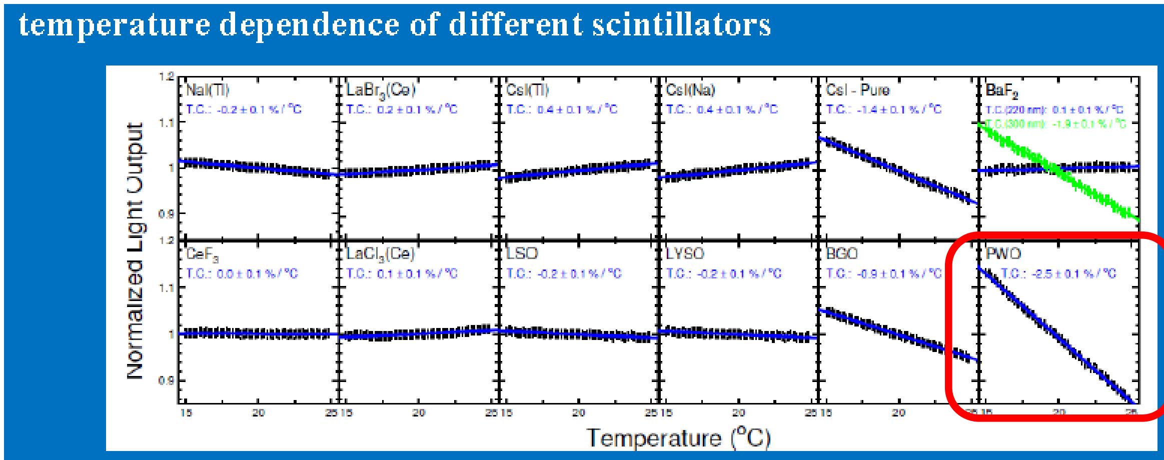
Technology	Performance	Estimated number of channels for EIC
ZDC (50x50cm, granularity ~5cm, ~100 towers?)	TBD	100 towers?
Low Q^2 tagger (5 planes GEM?)	TBD	10000?
Luminosity monitors	TBD	



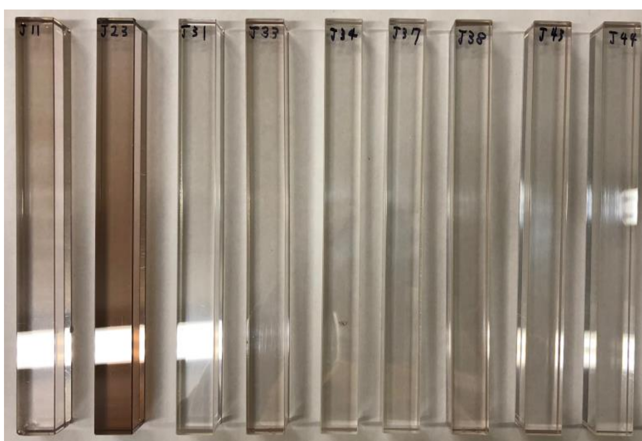
See Forward Detectors/IR integration, lumi, ancillary detectors session

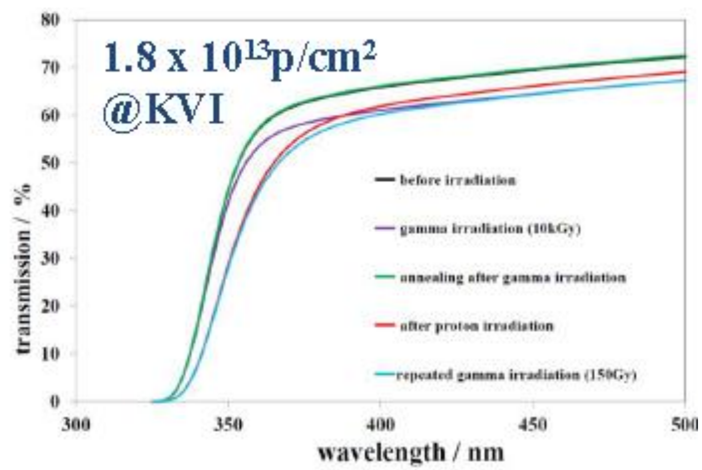
Crystals in EMCal: $PbWO_4$

- ❑ $PbWO_4$ material of choice for many EMCals – high density, fast response, large and granular solid angle, etc., but also limitations, e.g. hadron radiation damage



$PbWO_4$ light yield temperature dependence: 2%/°C

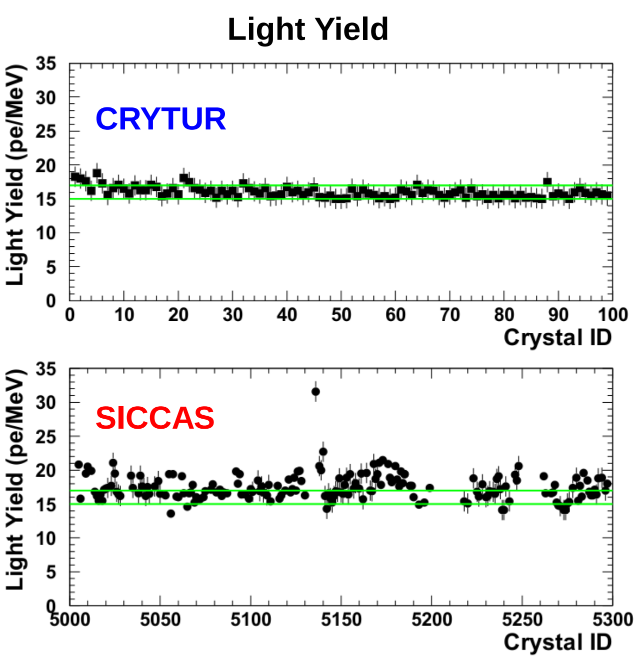


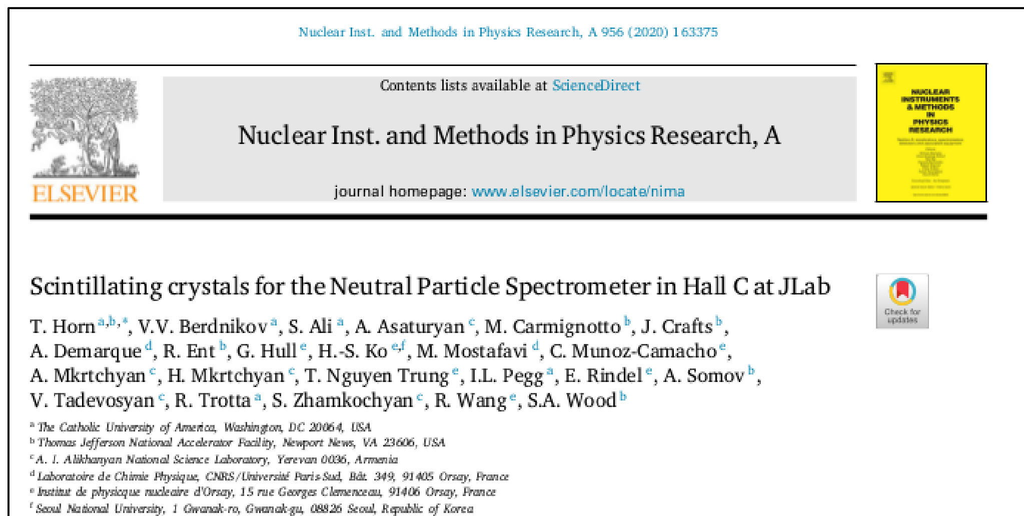


$PbWO_4$ radiation resistance

Crystals in EMCal: $PbWO_4$

- Another consideration: expensive ($15-25/cm^3) and manufacturing uncertainty
  - Despite progress (work with SICCAS and now also CRYTUR) still a struggle to work with vendors to get reliable $PbWO_4$ crystals that would be compatible with experiment requirements, e.g. JLab/NPS, EIC EMCal





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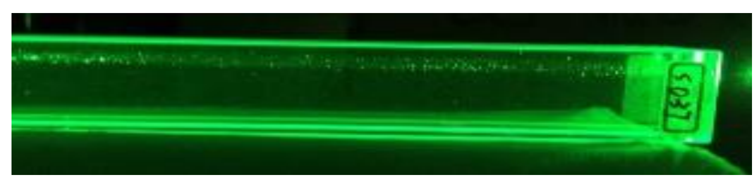
Scintillating crystals for the Neutral Particle Spectrometer in Hall C at JLab

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]

[a] The Catholic University of America, Washington, DC 20064, USA
[b] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[c] A. I. Alikhanyan National Science Laboratory, Yerevan 0036, Armenia
[d] Laboratoire de Chimie Physique, CNRS/Université Paris-Sud, Bât. 349, 91405 Orsay, France
[e] Institut de physique nucléaire d'Orsay, 15 rue Georges Clemenceau, 91406 Orsay, France
[f] Seoul National University, 1 Gwanak-ro, Gwanak-gu, 08826 Seoul, Republic of Korea



- Crytur: 100% acceptance, but capacity limited, also raw material availability
- SICCAS: 30-40% rejection, Q&A concerns

Glass Scintillators for Detector Applications

An alternative active calorimeter material that is more cost effective and easier to manufacture than, e.g. crystals

Material/ Parameter	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
($BaO*2SiO_2$):Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
($BaO*2SiO_2$):Ce glass loaded with Gd	4.7-5.4	2.2		~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

Also: ($BaO*2SiO_2$):Ce shows no temperature dependence

Shortcomings of earlier work:

- Macro defects, which can become increasingly acute on scale-up
- Sensitivity to electromagnetic probes

The Vitreous State Laboratory – unique expertise

- Premier materials science facility with unique capabilities and expertise in glass R&D

- Current R&D program includes
  - Nuclear and hazardous waste stabilization
  - Glass and ceramic materials development
    - Formulation optimization
    - Characterization
    - Property-composition models
  - Materials corrosion and characterization
  - Off-gas treatment
  - Water treatment, ion exchange
  - Cements, flyash
  - Geopolymers
  - Biophysics
  - Nano-materials
  - Thermoelectrics
  - Spintronics
  - Scintillation detectors

The Vitreous State Laboratory – unique facility

- Designing, constructing and testing large glass production systems
  - VSL Joule Heated Ceramic Melter (JHCM) Systems:
    - The largest array of JHCM test systems in the US
    - The largest JHCM test platform in the US

PILOT SYSTEM SCALE-UP

DM10 and DM100 JHCM Systems at VSL

VSL DM1200 HLW Pilot Melter System

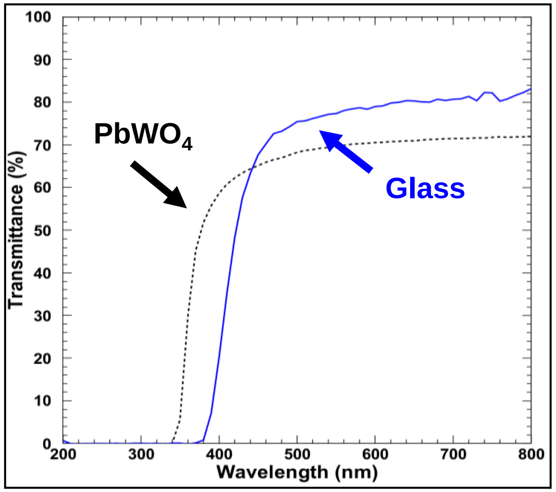
About 400,000 kg glass made from about 1 million kg feed

Glass Scintillator – optical and radiation hardness

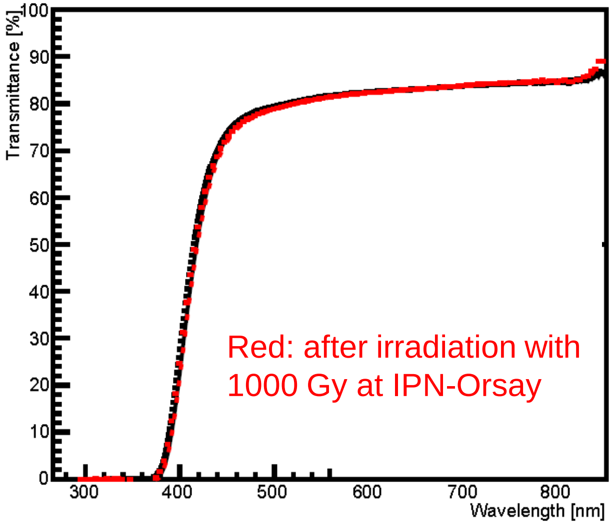
- Glass scintillators being developed at *VSL/CUA/Scintilex*
  - Optical properties comparable or better than $PbWO_4$
  - Preliminary tests on radiation damage look promising
  - Ongoing optimization work

Scintilex samples

Transmittance



Radiation Hardness



Light Yield

Material/ Parameter	$PbWO_4$	Sample 1	Sample 2	Sample 3	Sample 4
Luminescence (nm)	420	440	440	440	440
Relative light output (compared to $PbWO_4$)	1	35	16	23	11

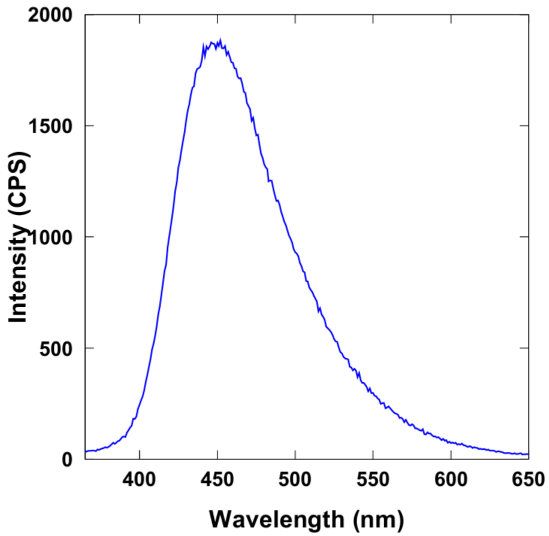
SCINTILEX

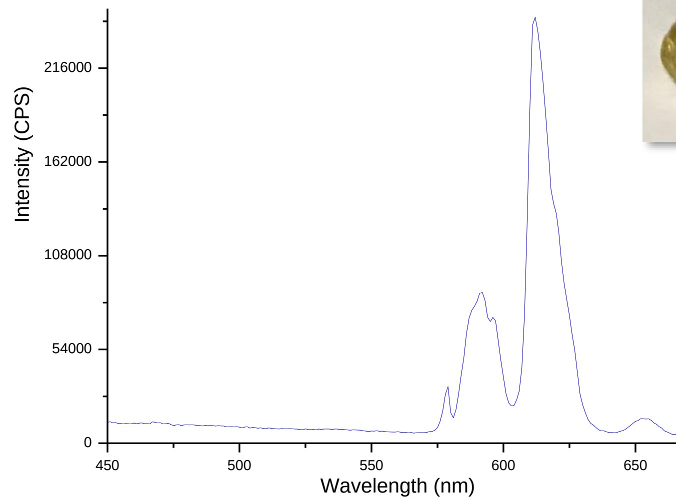
Glass Scintillator – formulation

- Two main glass formulations for calorimeter application

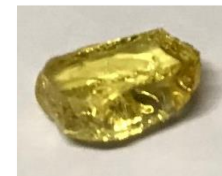
VSL-Scintilex-G4 (nominal)

Emission wavelength





VSL-Scintilex-SC1



- Nominal: optimized LY, timing, radiation hardness, etc. ✔

Scintillation light

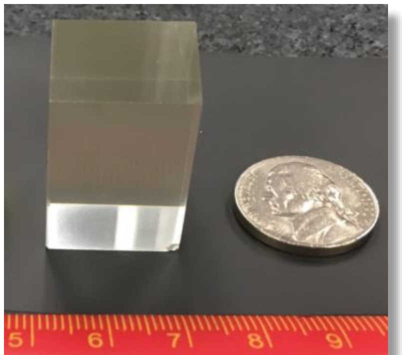
- Very high-density compared to nominal, emits at >550nm, good LY

SCINTILEX

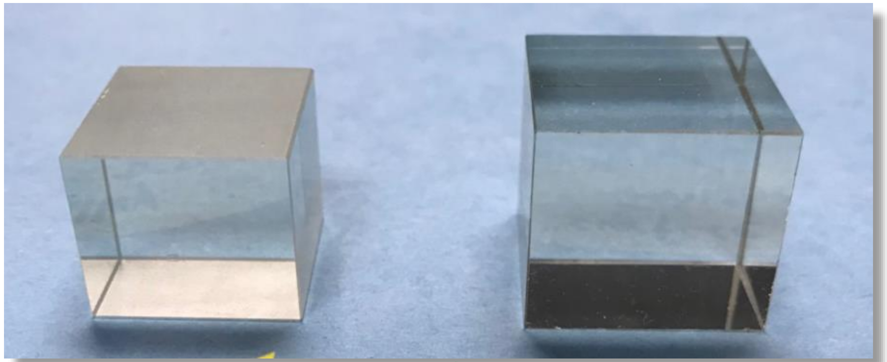
Glass Scintillator – polishing

SCINTILEX

- Testing and optimizing different methods (specifications on: flatness, roughness, parallelism, perpendicularity)

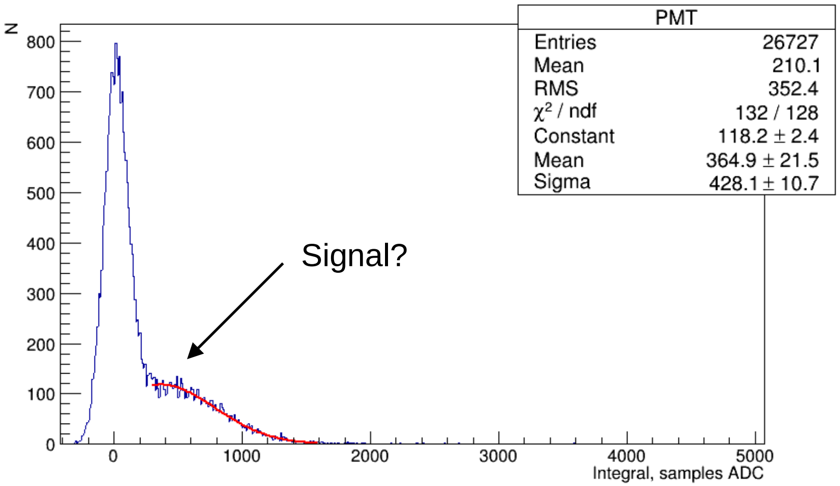


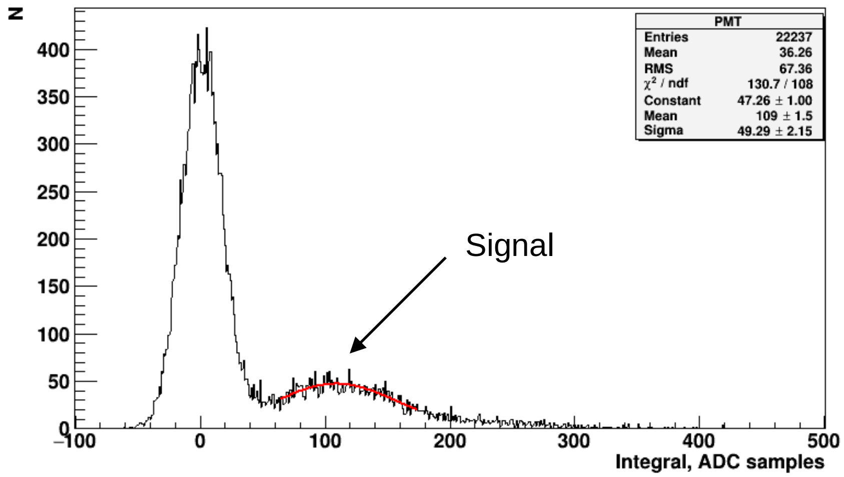
Method 1



Method 2

Method 3





Glass Scintillator – Scale-Up

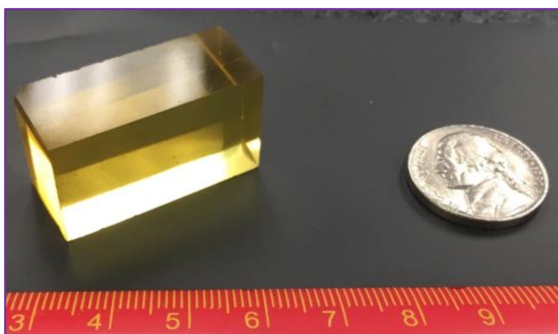
SCINTILEX

- Progress with scale-up – $2x2x20cm^3$ samples produced, issues associated with further scale-up identified, solutions are being implemented and tested

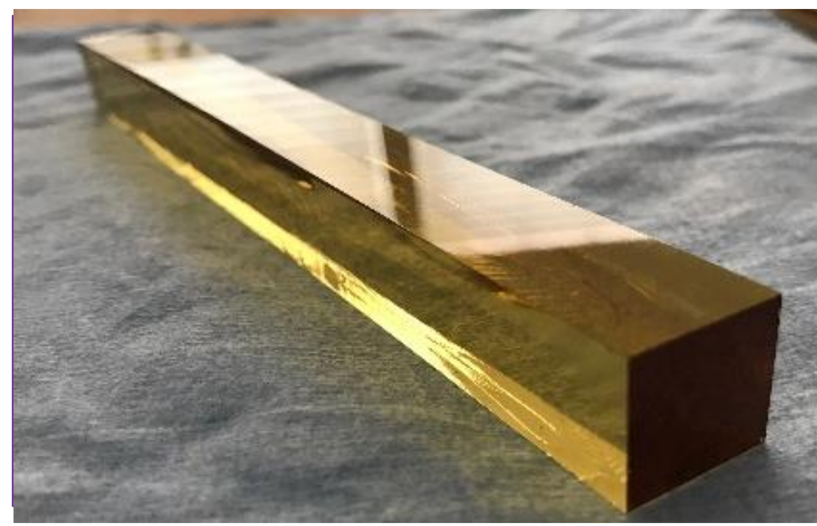
Example: SC1 glass

1cm x 1cm x 0.5cm (test size)

2cm x 2cm x 4cm (medium size)



2cm x 2cm x 20cm (larger size)



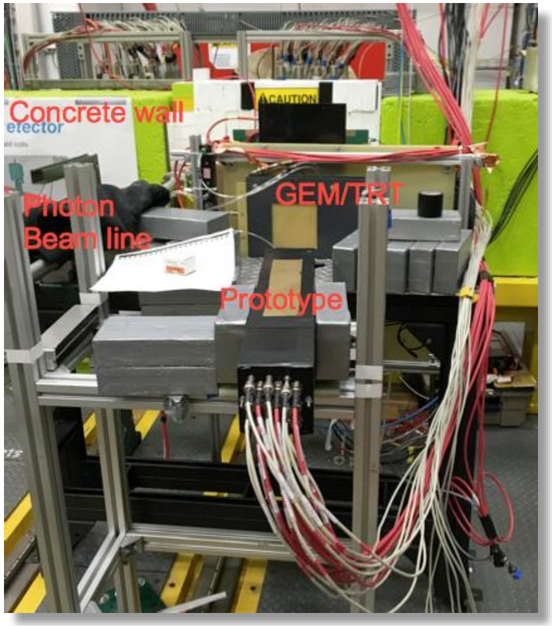
2019 → 2023

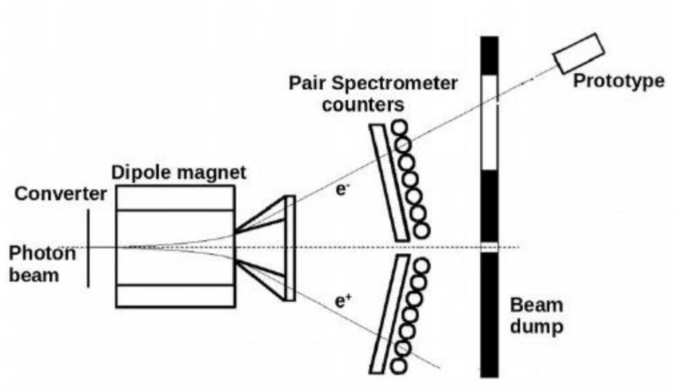
1cm x 1cm x 0.5cm → Up to 4cm x 4cm x 40cm

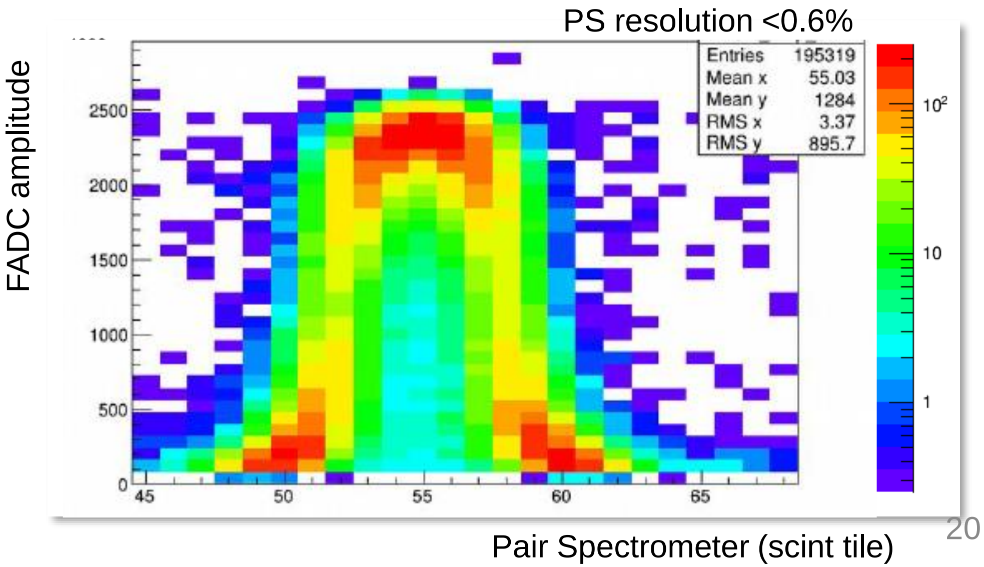
Initial Beam Test Program JLab 2020

- Constructed a 3x3 prototype of geometry representative of NPS and EIC EMCal

- Completed detector checkout and baseline with crystal+PMT, next: glass performance, alternative readout
  - Beam energy provided by pair spectrometer - select electrons going through the center of the middle crystal





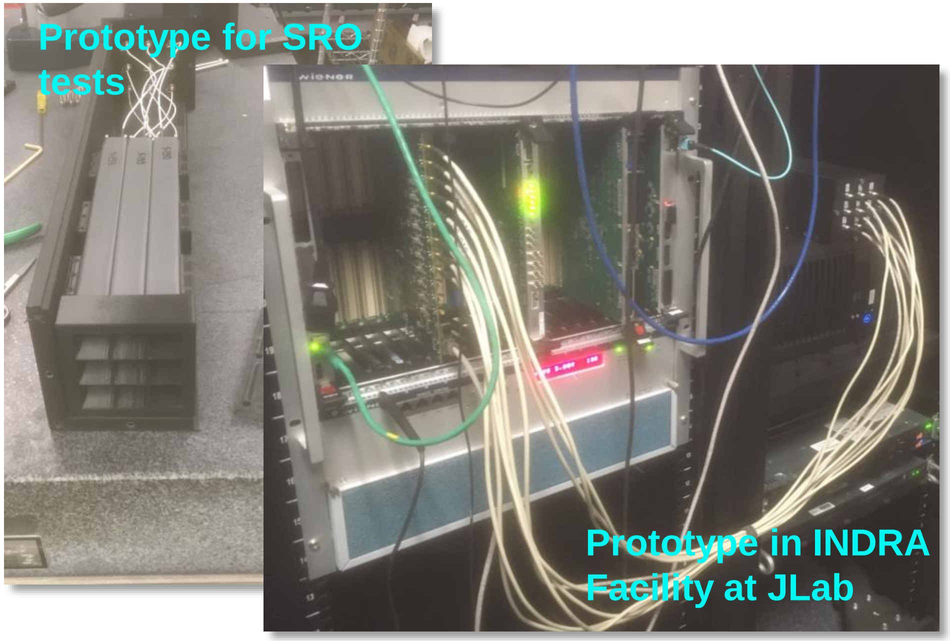


Glass Scintillator – Streaming Readout 2020

- ❑ Instrumenting 9 channels to test and optimize the entire readout chain: SiPM, preamps, fADC, and Streaming DAQ system

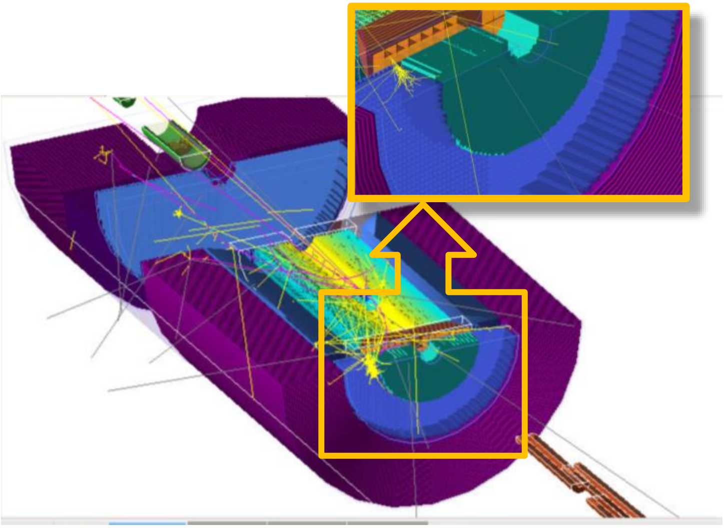
- ❑ Tests in Hall-D with TRIDAS will have 4 configs:
    1. (proto-PMT+VTP+fADC 250)
    2. (proto-PMT+WB)
    3. (protoSIPM+VTP+fADC 250)
    4. (proto-SIPM+WB).
- ❑ Configs 1-2-4 are ready, config 3 requires preamps+bias boards

- ❑ Planned test dates: March/April 2020



Glass Scintillator Outlook

- ❑ Finalize optimization of glass composition - patent
- ❑ Larger samples (2x2x20cm^3) for full characterization tests
  - ➢ Transmittance and light yield
  - ➢ Radiation hardness
  - ➢ Decay kinetics
  - ➢ Other
- ❑ Full-size samples (up to 4x4x40cm^3) for comparison to PWO



- ❑ EIC Monte Carlo simulations to:
  - ➢ Optimize configuration for electron endcap using ML methods
  - ➢ Explore glass and suitable readout for barrel
- ❑ Initial prototype tests in Hall D ongoing – full tests planned for 2021/22

Summary

- Several options for EIC EMCal including crystals, glass, W/SciFi, Shashlyk, Pb/Sc, PbGl, etc.
  - eRD1 has been exploring many of these options
  - Also have existing detectors, e.g. PHENIX EMCAL, JLab BCAL

- Physics requirements are different for each region – most stringent in electron endcap

- $PbWO_4$ crystals are ideal for precision EMCal, e.g. in the electron endcap, but also have limitations – and are expensive

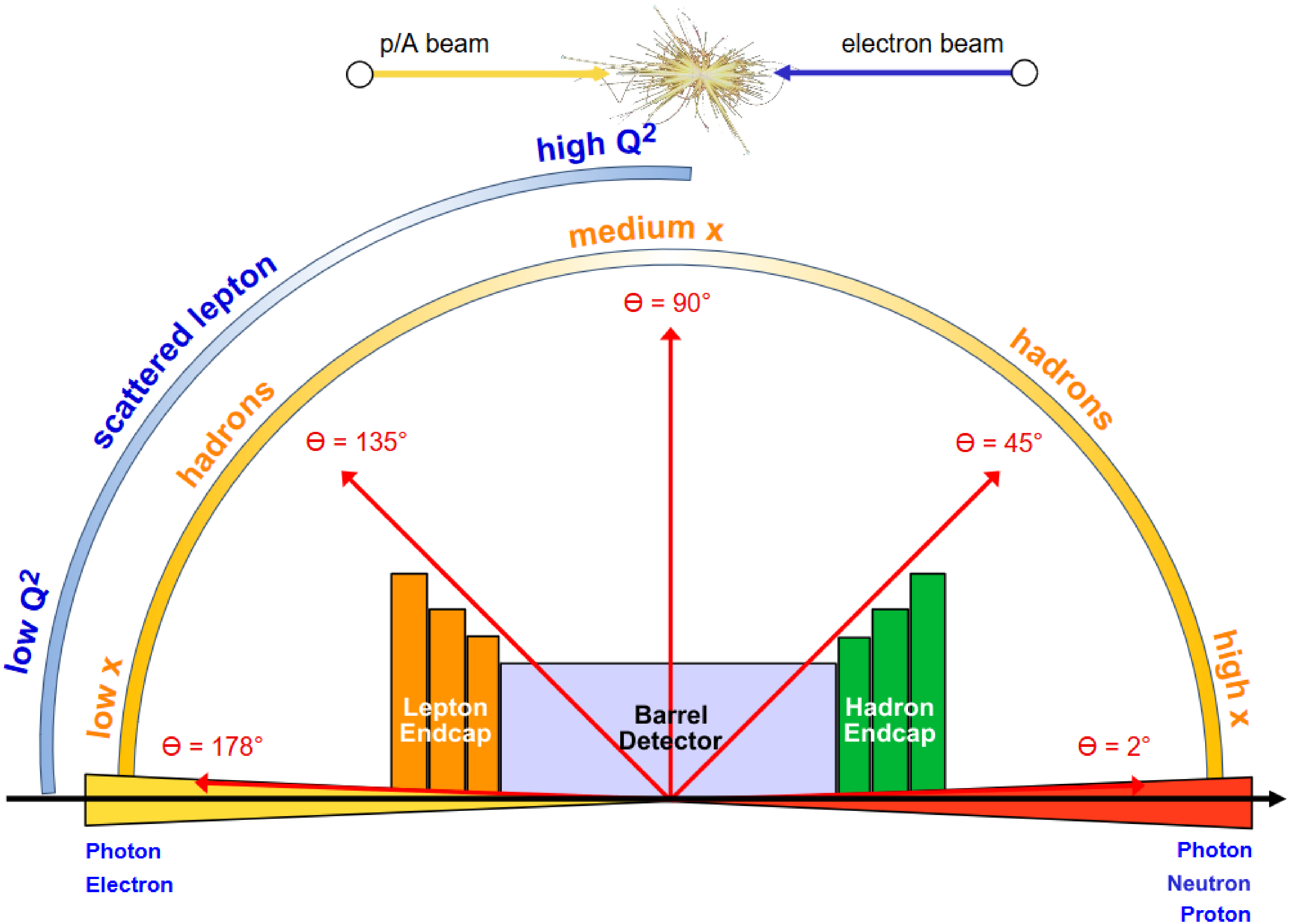
- Glass-based scintillators are cost-effective alternative to crystals, in particular EMCal regions with relaxed resolution requirements – ongoing R&D in eRD1 and through SBIR/STTR
  - Initial small samples produced at CUA/VSL have properties comparable or better than $PbWO_4$ and are radiation hard
  - New fabrication method eliminates bubbles, a major problem in earlier work
  - Initial scale-up successful

Glass/crystal – Schedule for TDR 2023

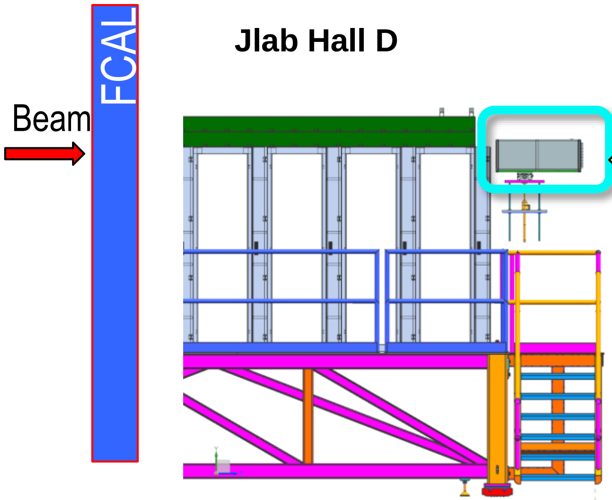
- **What achievements are required for TDR 2023 readiness**
  - Finalize glass formulation and fabrication method
  - Completion of crystal/glass design in simulation
  - Validation of performance with prototype

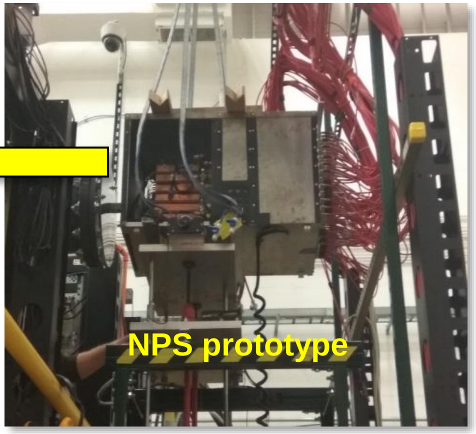
- **How much time do you envision to complete your ongoing project**

Item	Task	2019				2020				2021				2022				2023			
					FY20				FY21				FY22				FY23				
Glass fabrication	Composition optimization					■	■														
	Characterization					■	■	■													
	Scale up and additional geometries							■	■												
	Show uniformity and reproducibility									■	■	■	■	■							
	Fabrication process optimization									■	■	■	■	■							
	Performance tests with prototype										■	■	■	■	■	■					
	Process design verification to scale up														■	■	■	■			
	Large scale production study																		■		
Software	Prototype				■	■	■	■	■	■											
	Design options								■	■	■	■	■								
	Cost/performance optimization								■	■	■	■	■	■	■	■					
Prototype	Base version				■																
	Initial commissioning						■	■	■	■											
	Upgrade and commissioning											■	■	■							
Beam test	Beam test					■					■	■			■						
	Data analysis					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	


p/A beam
electron beam
high Q2
scattered lepton
low Q2
medium x
hadrons
hadrons
low x
high x
Θ = 90°
Θ = 135°
Θ = 45°
Θ = 178°
Θ = 2°
Lepton Endcap
Barrel Detector
Hadron Endcap
Photon
Electron
Photon
Neutron
Proton

Crystals in EMCal: $PbWO_4$

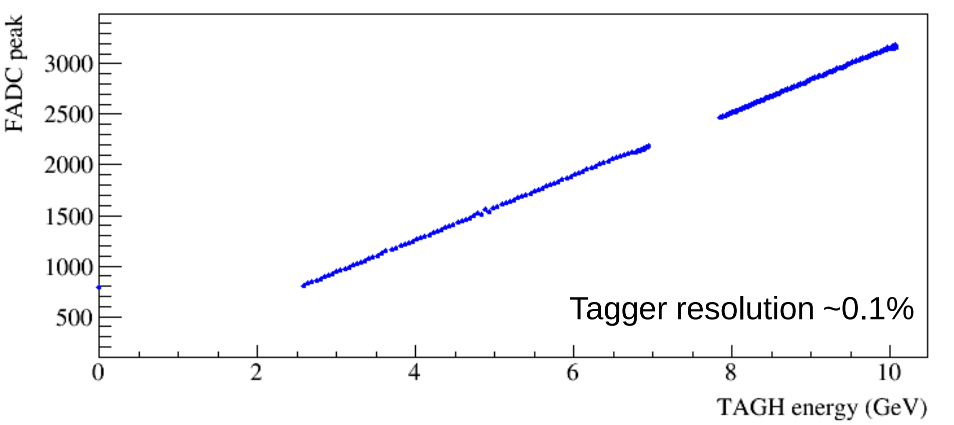




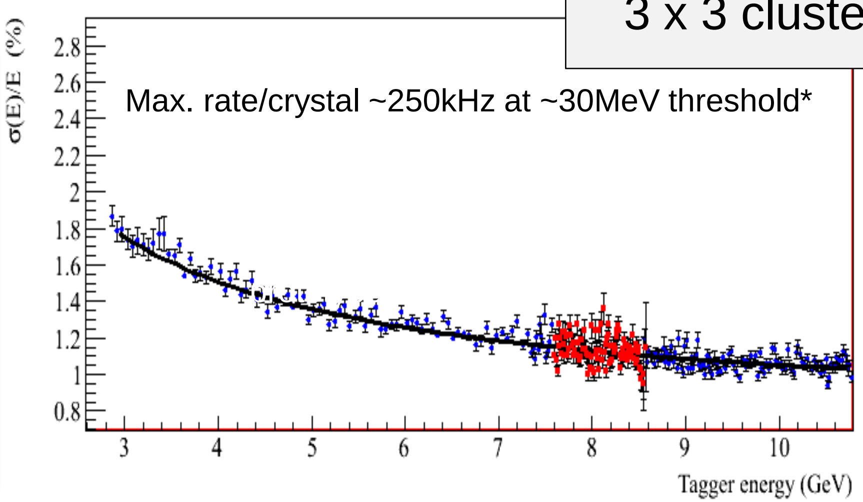
- Commissioned a 12 x 12 prototype
- Beam energy provided by tagger hodoscope
- Allows for data over larger energy range and also study of linearity

- Preliminary energy resolution for 3x3 cluster: $\sigma(E)/E = 0.7 + 2.2/\sqrt{E} + 2.8/E$

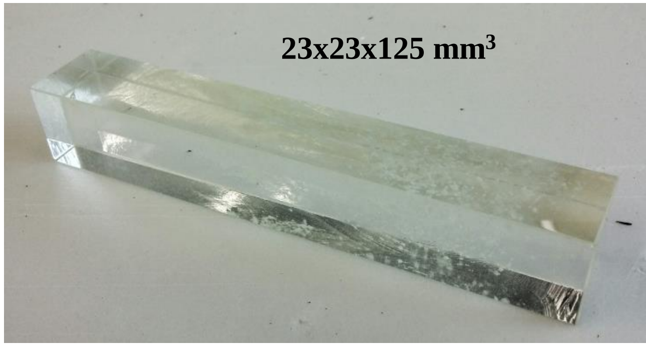
FADC amplitude as a function of the tagger hodoscope energy



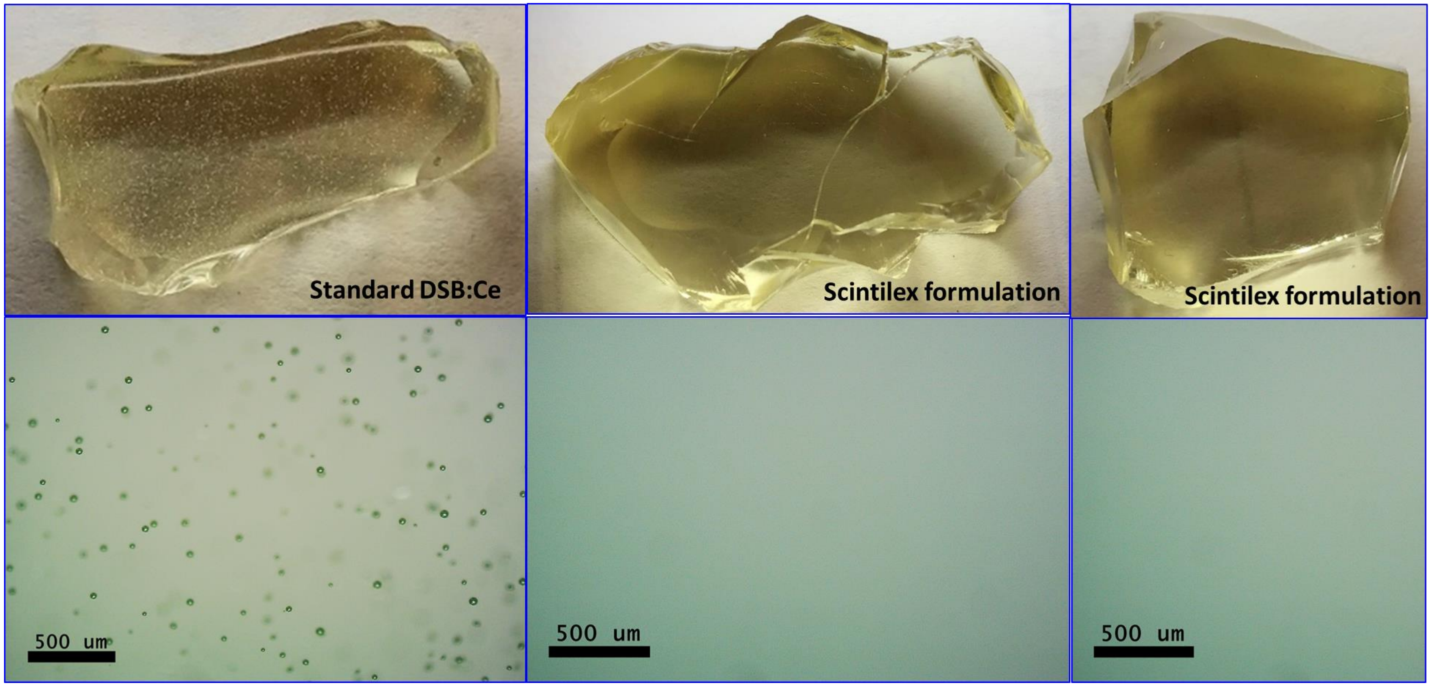
3 x 3 cluster



Glass Scintillator – fabrication process and uniformity



- Uniformity remains a concern – manufacturing process requires optimization – progress with new method at CUA/VSL/Scintilex



Sample made at CUA/VSL based on previous DSB:Ce work

Samples made at CUA/VSL/Scintilex with our new method

SCINTILEX