Results of R&D for Sampling Calorimeters for Electron Ion Collider.

O.Tsai (UCLA)

On behalf of the EIC Calorimeter Consortium
(BNL, CALTECH, JLAB, IUCF, NPN Orsay, PSU, TAMU, UCLA, USTC, YPI)

CPAD 2016

What is the EIC:

A high luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$) polarized electron proton/ion collider with $\sqrt{s_{ep}}$ = 20 – 100 GeV upgradable to 140 GeV

Why an EIC:

Revolutionize our view of nucleon structure and the glue!

→a very diverse physics program impacting nuclear, heavy ion and high energy physics

Eur. Phys. J. A (2016) 52: 268 Electron-Ion Collider: The next QCD frontier

What is new/different:

Hera: factor 100 to 1000 higher luminosity

both electrons and protons / light nuclei polarized

nuclear beams: d to U

Fixed Target Facilities:

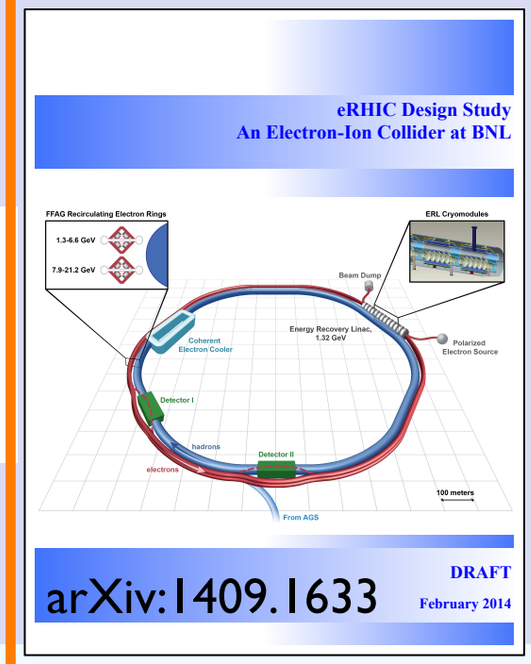
at minimum > 2 decades increase in kinematic coverage in x and Q^2

Electron Ion Colliders

Past and Possible Future

- We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.

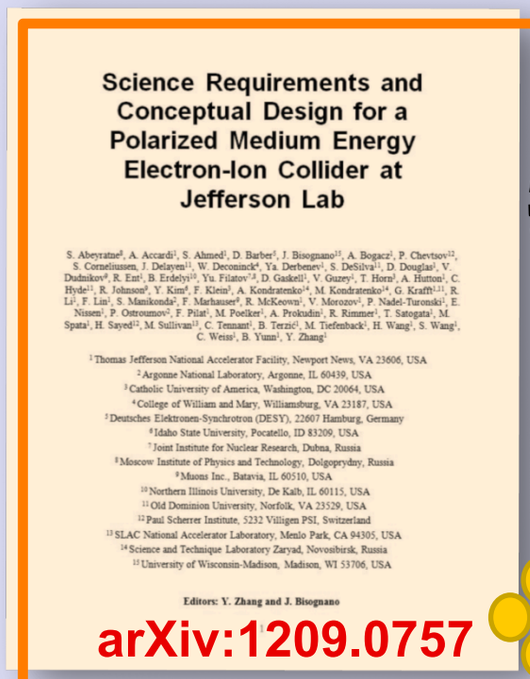
NSAC LRP 2007

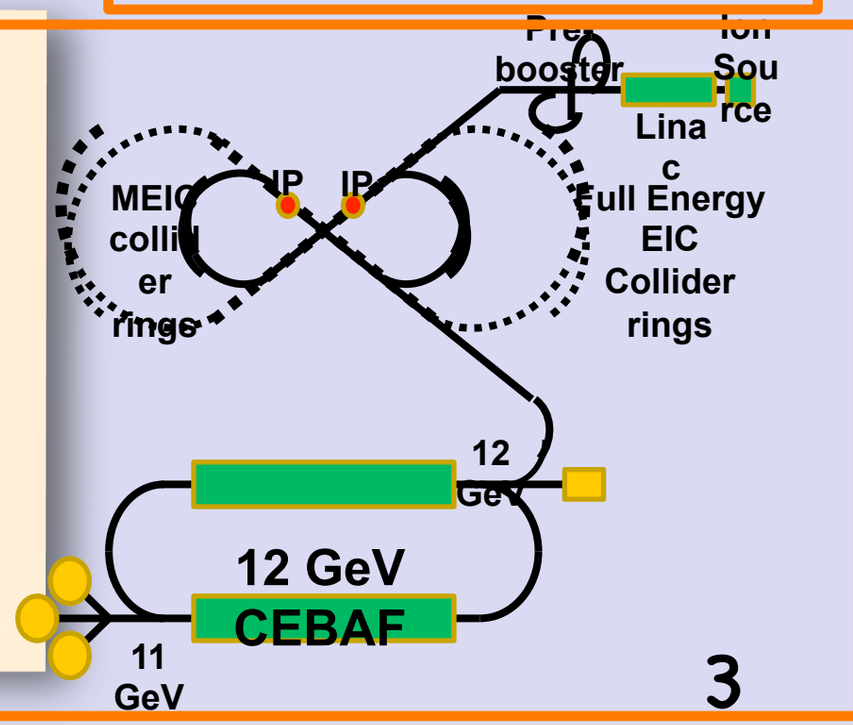


	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	MEIC/ELIC @ JLab	eRHIC @ BNL
√s [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton x_{min}	1×10^{-5}	5×10^{-7}	7×10^{-3} - 3×10^{-4}	5×10^{-3}	1×10^{-4}	5×10^{-5}
ion	p	p to Pb	p to U	p to ~^{40}Ca	p to Pb	p to U
polarization	-	-	p, d, ^{3}He	p, d	p, d, ^{3}He (^{6}Li)	p, ^{3}He
L [cm^{-2}s^{-1}]	2×10^{31}	10^{34}	10^{32-33} - 10^{35}	10^{32}	10^{33-34}	10^{33}
Interaction Points	2	1 (?)	1	1	2+	1-2
Year	1992 - 2007	post ALICE	2019 - 2030	upgrade to FAIR	post 12 GeV	2025

- **A high luminosity, high-energy polarized Electron Ion Collider (EIC) is the U.S. QCD Community's highest priority for future construction.**

NSAC LRP 2015





The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

EIC Project Status

The EIC received in the 2015 Long Range Planning of the NSAC the following recommendation

"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB"

http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

Next Steps:

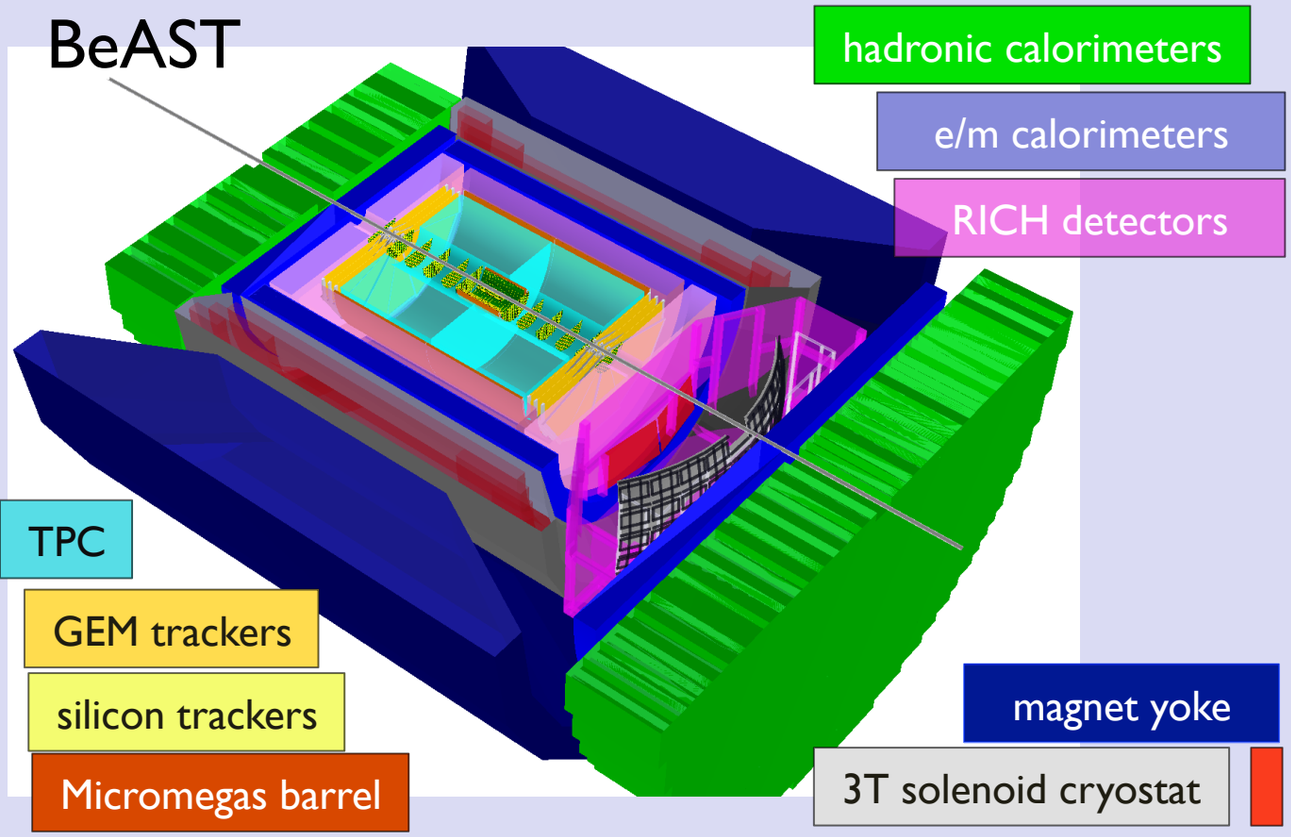
A National Research Council (National Academy of Science (& Engineering & Arts) review of the project is expected to begin soon,
and a report is expected in ~18 months. After the DOE will launch its Critical Decision (CD) process…

- CD0 soon after the NAS review…. (FY2018)
- CD1: site selection
- with a scenario of 1.6% growth in US nuclear science funding from now on

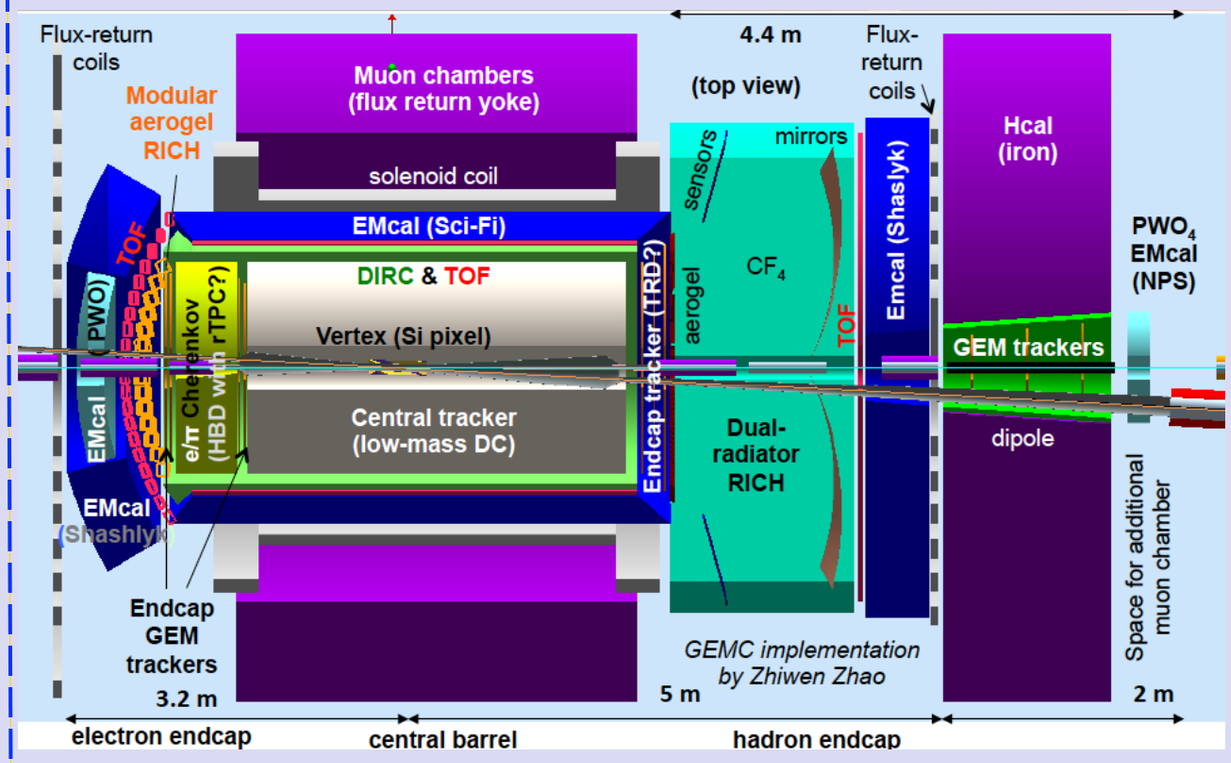
→ CD3 start of construction estimated in 2022/23

EIC Detector Concepts

eRHIC



JLEIC



Current emphasis on the design of a multipurpose detector

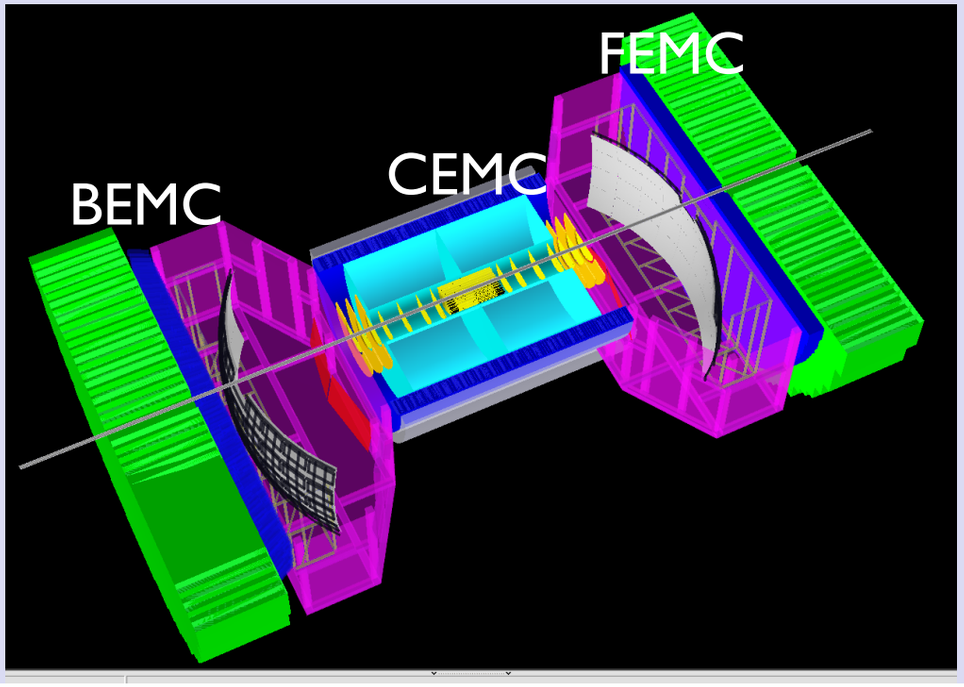
Both (eRHIC & JLEIC) IR-designs integrate auxiliary detectors from the beginning:

→ critical for physics program and to control systematics

- ❑ luminosity monitors
- ❑ large acceptance for diffractive proton detection and neutrons from nuclear breakup
- ❑ electron & hadron polarimetry
- ❑ low Q^2-tagger

E.C. Aschenauer

Why are we doing calorimeter R&D for a generic central detector?



Calorimetry wise, we wanted to have similar resolutions of H1/ZEUS, but it has to be more compact

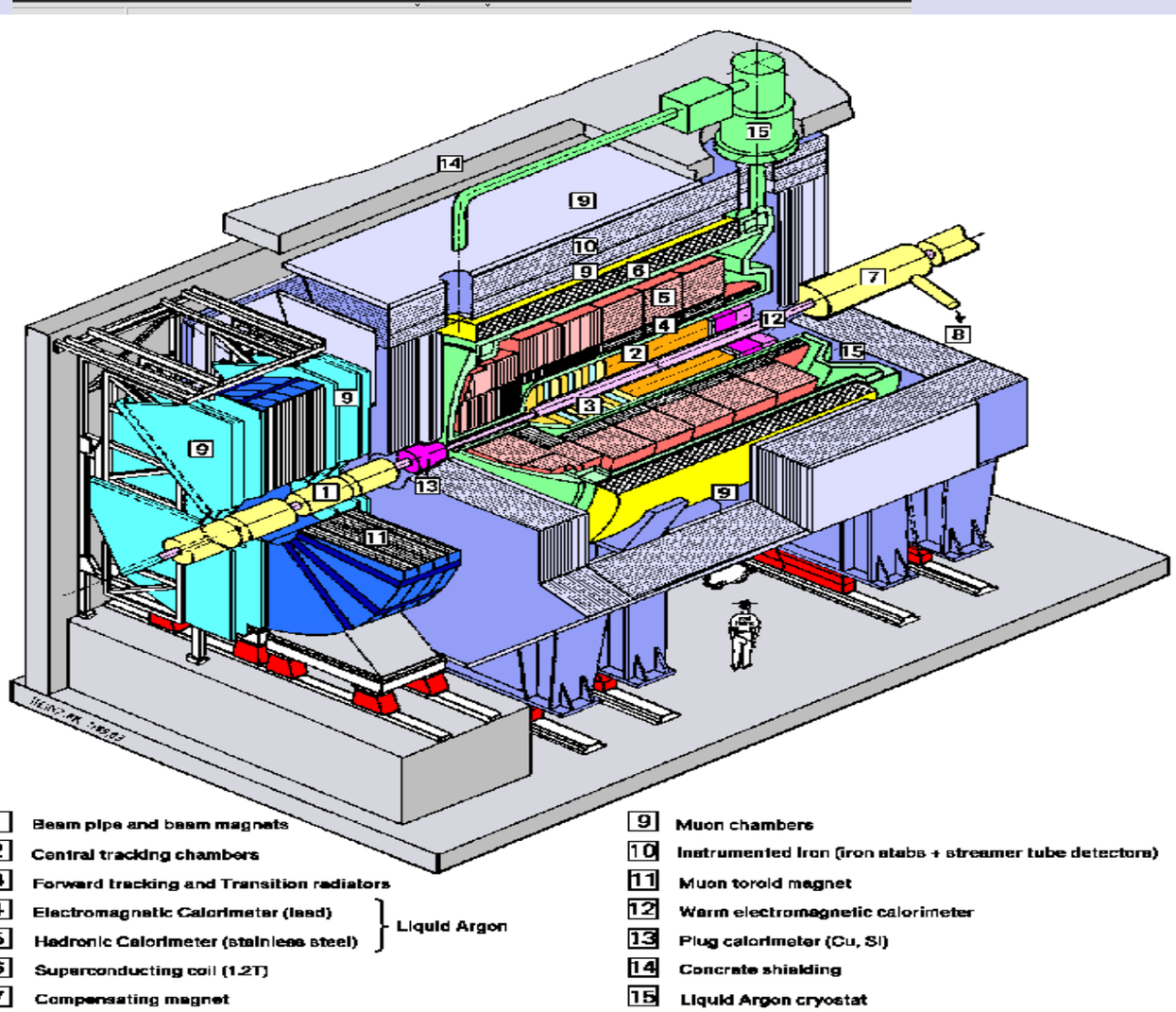
- Luminosity (IP design +- 4.5 meters)
- PID is much more important than at HERA

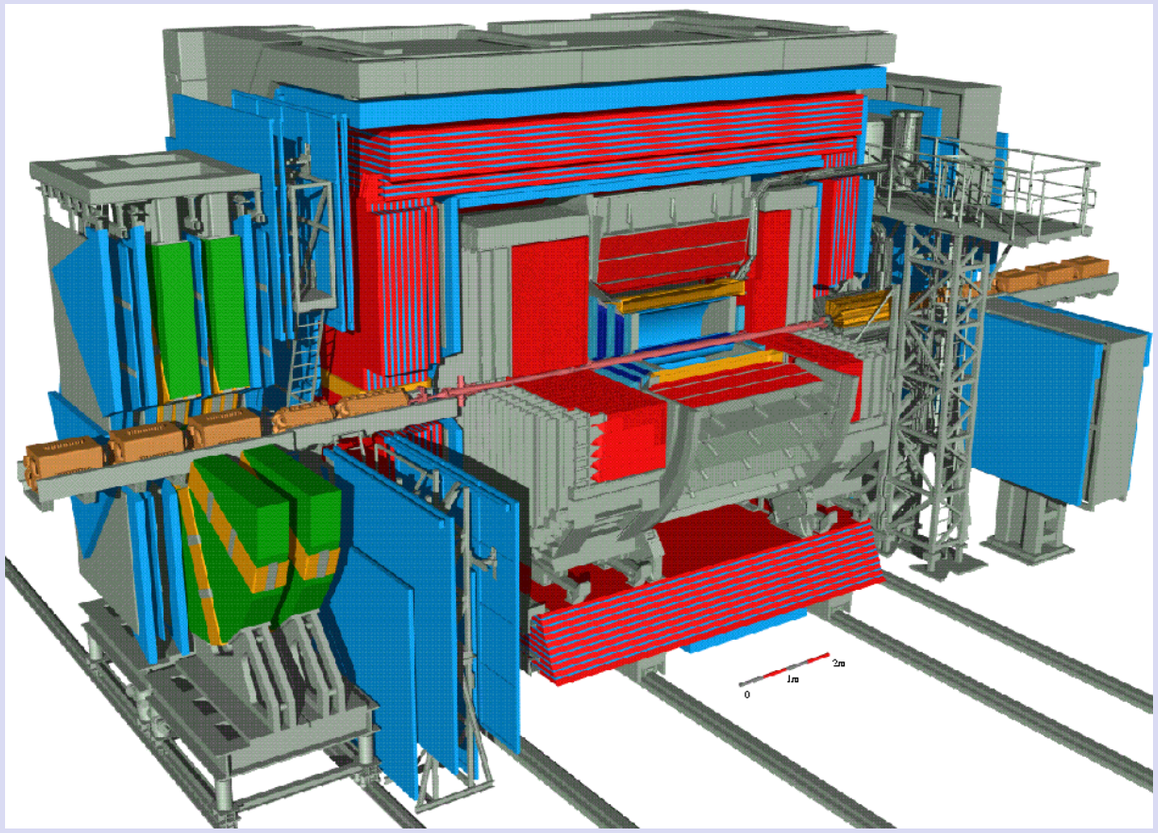
EIC Detectors 9m long (**4pi PID**)

HERA Detectors 15 m long

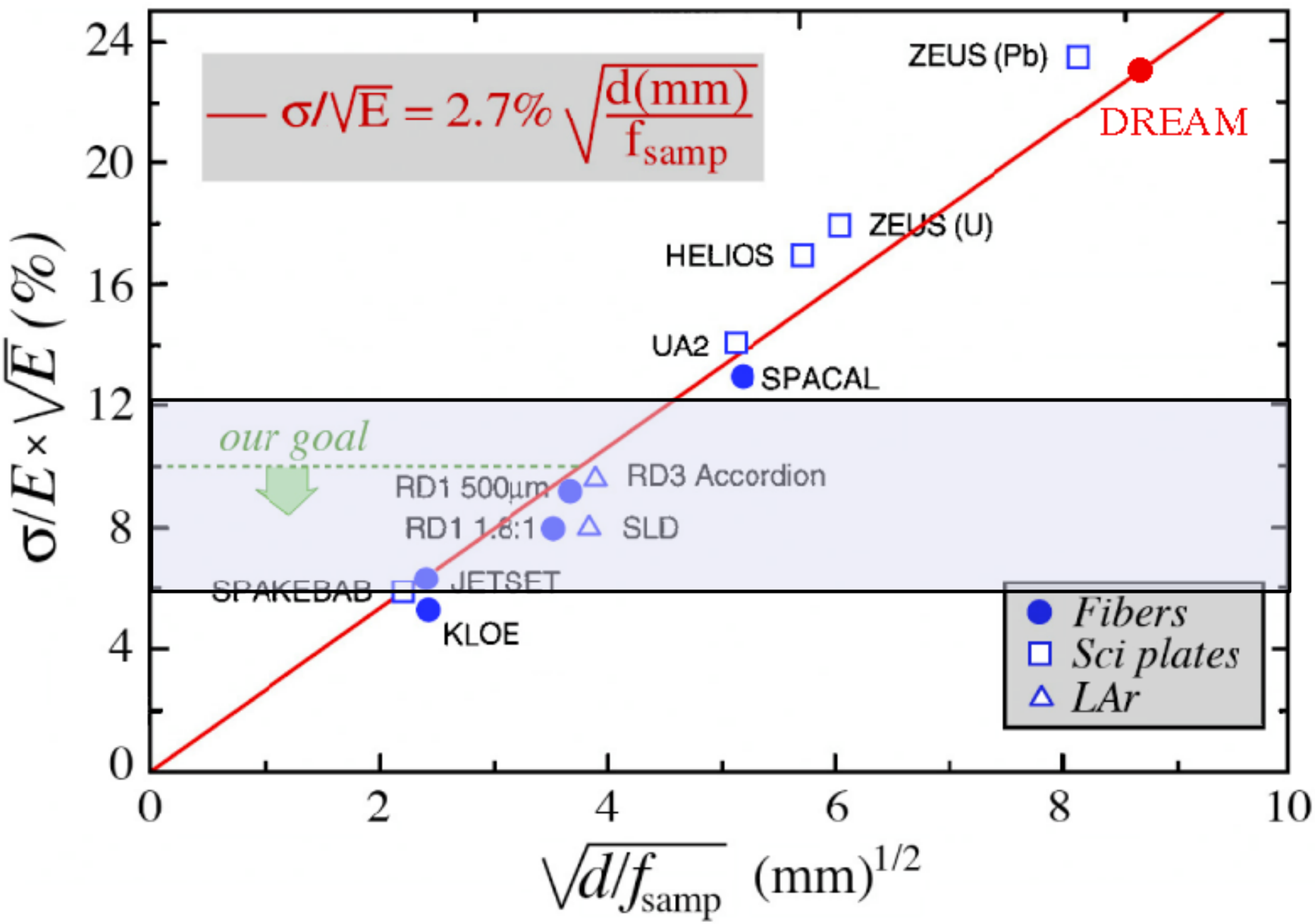
Advances in micro pattern detectors.

Advances in photodetectors. (APD, SiPMs)





EIC EM Sampling Calorimeters



$$\frac{\sigma_{em}}{E} = \frac{12\%}{\sqrt{E(GeV)}}$$

H1

$$\frac{\sigma_{em}}{E} = \frac{7.5\%}{\sqrt{E(GeV)}}$$

Calorimeters:

- Full Coverage,
- Hermetic.
- Compact.
- Operate in the magnetic field.
- Fast.
- Affordable.

ZEUS

$$\frac{\sigma_{em}}{E} = \frac{18\%}{\sqrt{E(GeV)}} \qquad \frac{\sigma_{had}}{E} = \frac{35\%}{\sqrt{E(GeV)}}$$

- Calorimetery, Complementarity H1 and ZEUS
- Complementarity, EIC1 and EIC2?

EIC Detector R&D Program started in 2011:

https://wiki.bnl.gov/conferences/index.php/EIC_R%25D#Received_Proposals

- Technology
- Seeds for future Collaboration(s)

Motivation for W/ScFi Calorimeter R&D:

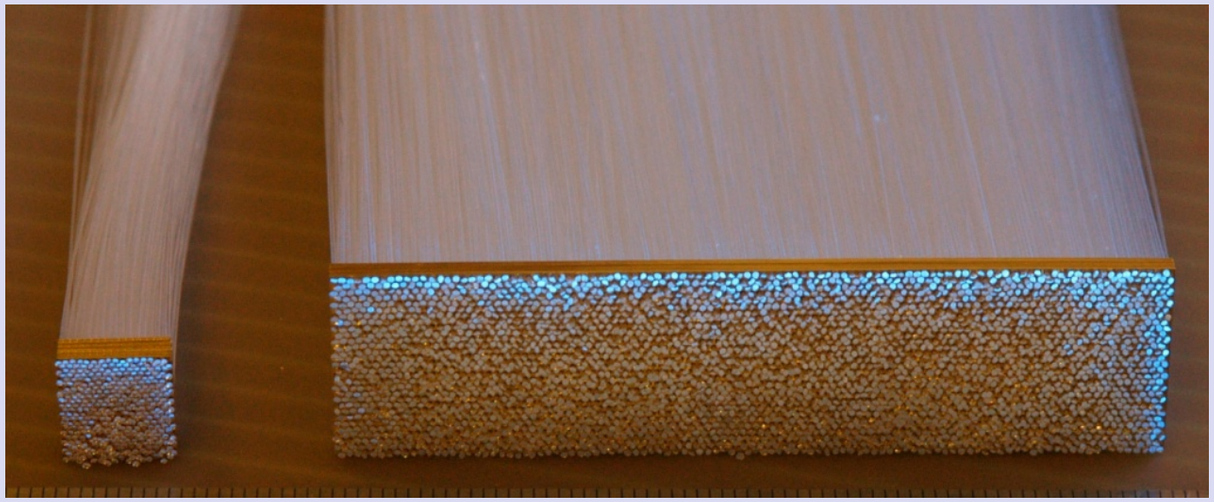
(Back in 2011. RD1 - UCLA, PSU, TAMU)

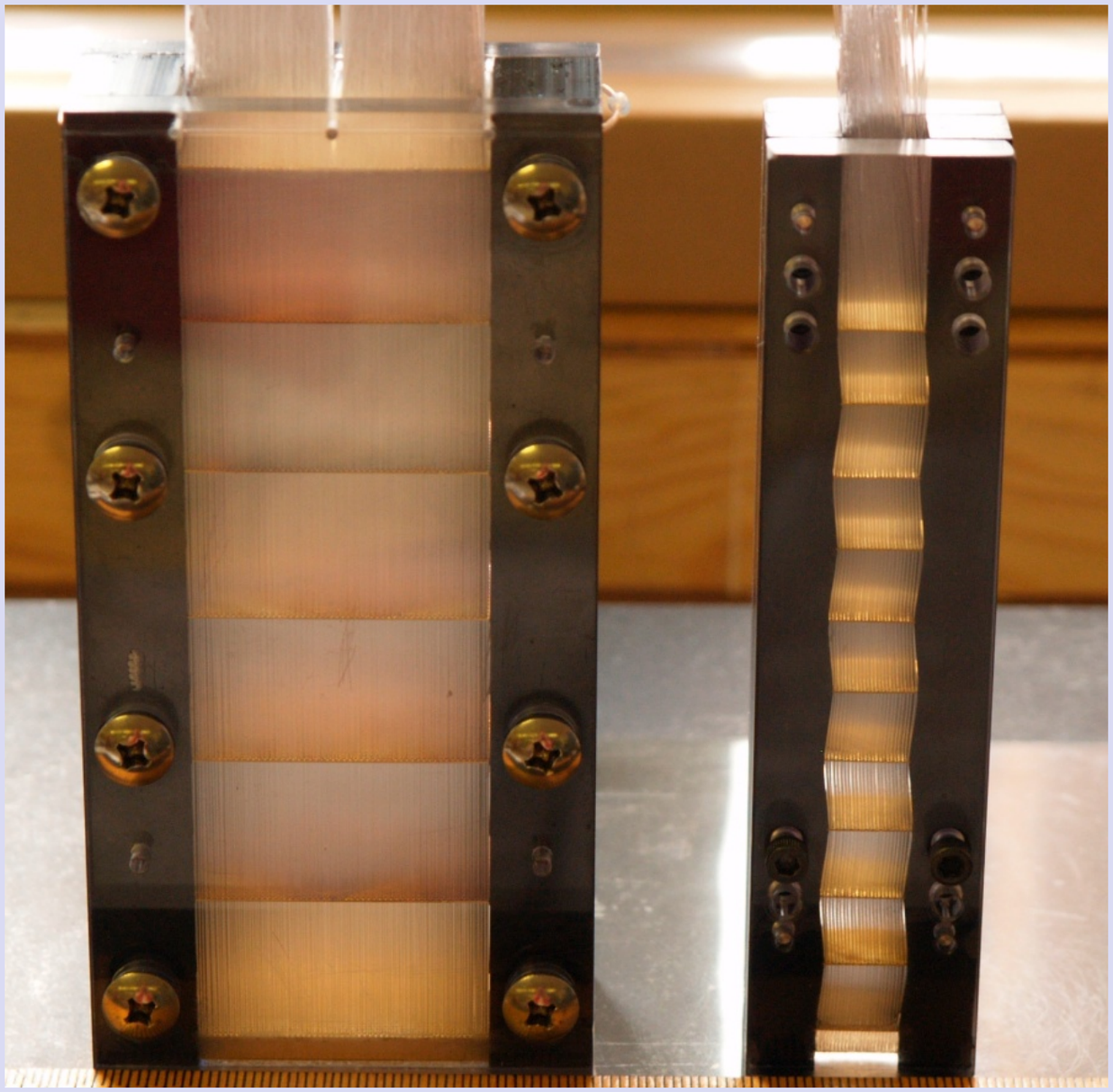
Develop *simple, cost effective, flexible* techniques to build *compact* sampling calorimeters with *good characteristics*.

- *Simple* - to the level that a typical university group can build it without heavy investments in "infrastructure".
- *Cost effective* - fraction of the cost of crystals.
- *Flexible* - tuneable for particular experimental requirements.

Construction Method:

- Form matrix of Fibers
- Pack it with W powder
- Replace air with epoxy





First SPACAL prototype. Year 1 R&D. FNAL 2012

Parameters:

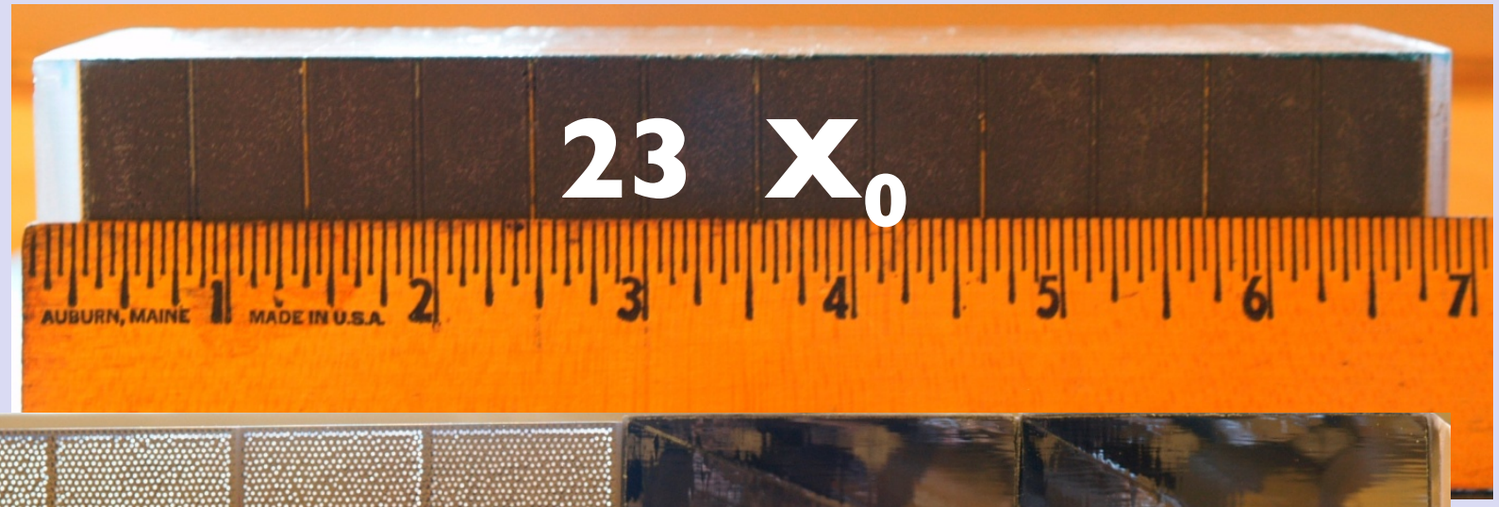
Final Density - 10.17 g/cm^3,
X_0 ~ 7 mm, R_m ~ 2.3 cm,
S_f -2.4% (electrons),
Sc. Fibers -SCSF78
Ø 0.47 mm
Spacing 1 mm center-to-center.

Supermodule 2x2 towers.
Details:

Dimensions 16.6 × 5.33 ×5.33 cm^3
Weight of supermodules (4567, 4651, 4627,4630 g.)
Number of fibers -3120

Resolution ~12%/√E

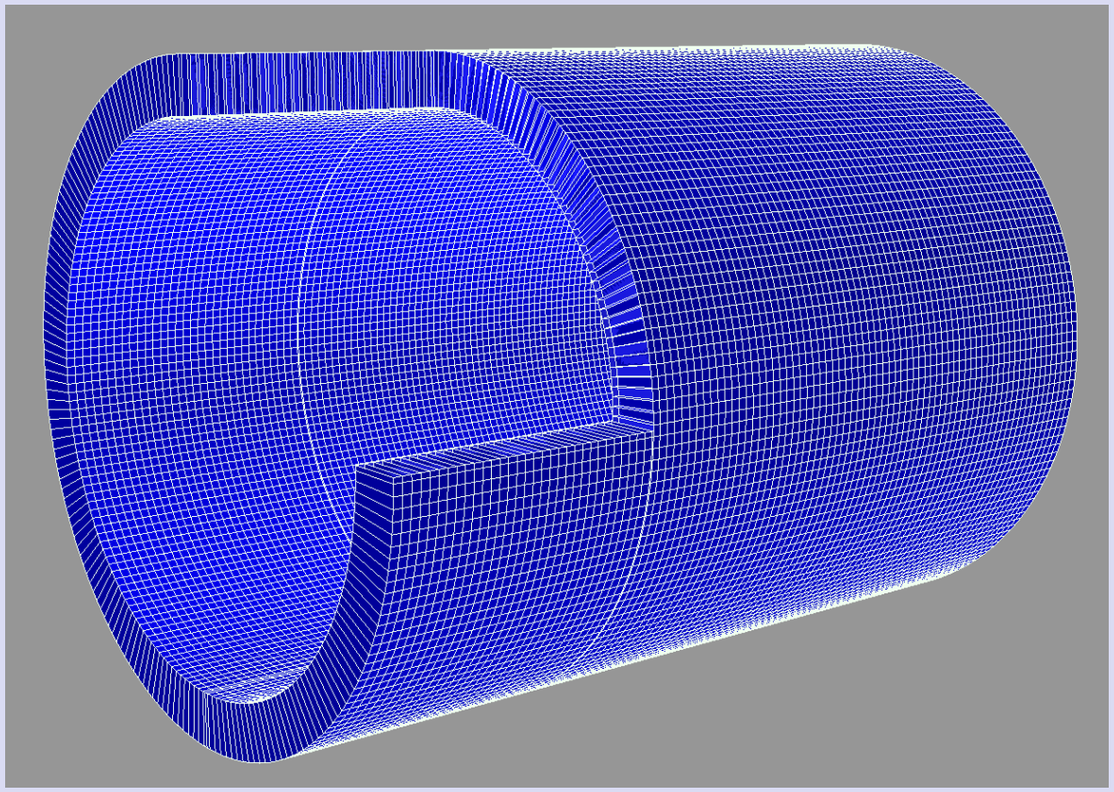
Light yield 2000 p.e./GeV

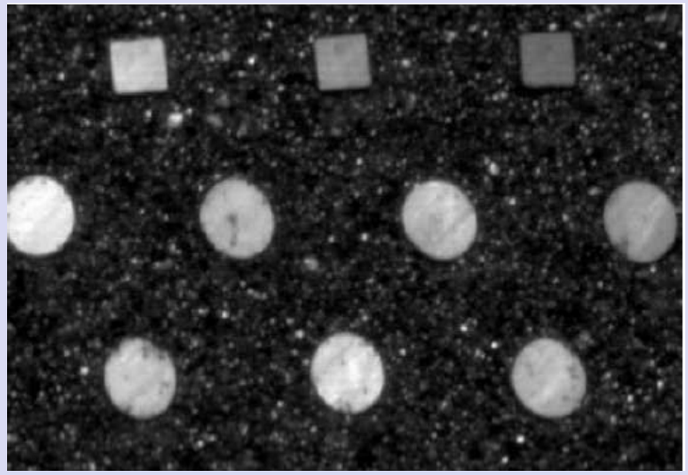


SiPM Readout Possible.

RD1 Collaboration, EIC R&D
Proof of principle, Jan 2012
Test Run at FNAL T1018

Central EM Calorimeter (BEMC) for EIC.





W/ScFi Compound Mechanical properties.

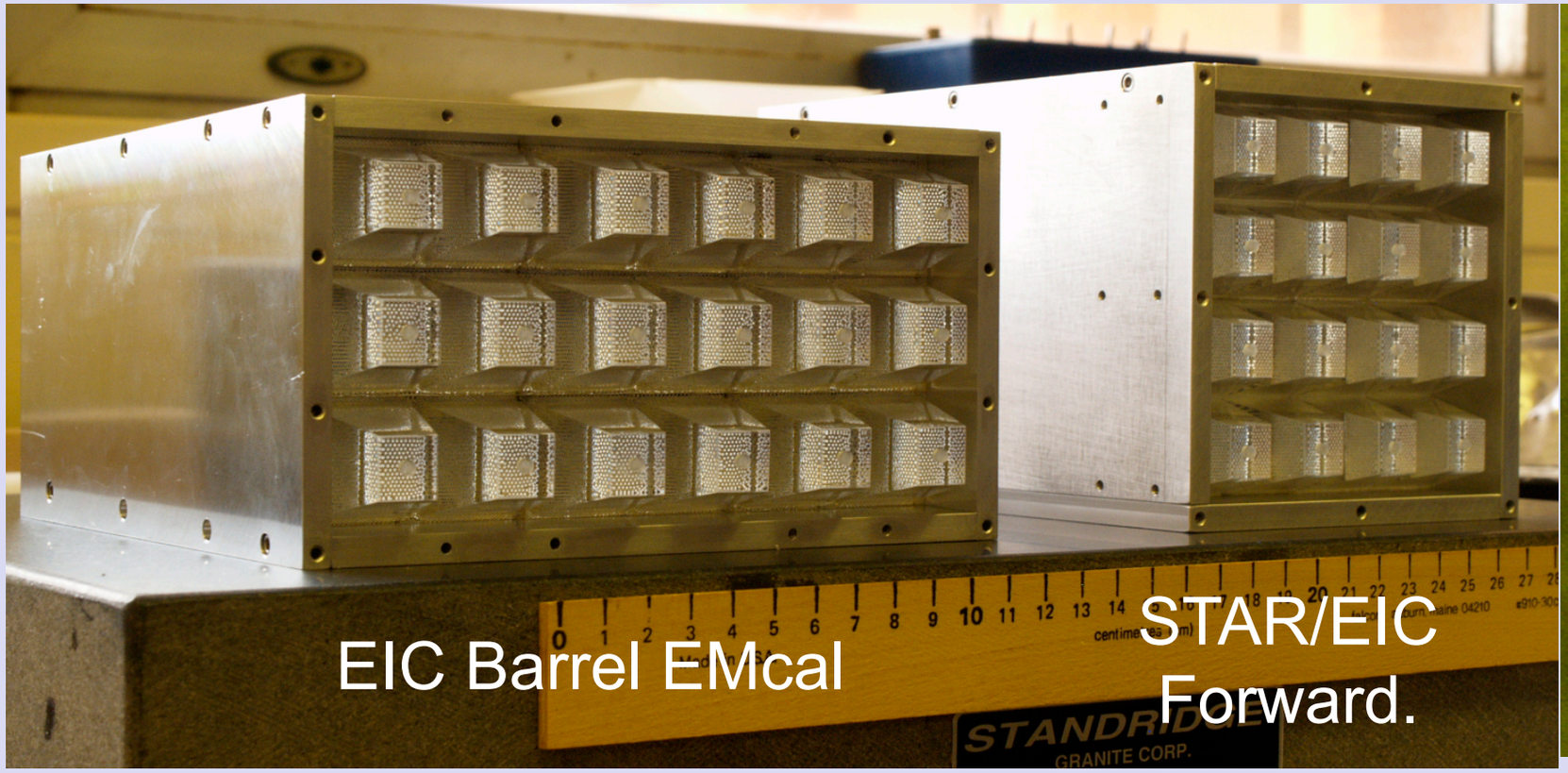
- Young's Modulus - 2 *10^{11} N/m^2
- Shear Modulus - 7.5 * 10^{10} N/m^2
- Bulk Modulus - 2.4 * 10^{11} N/m^2

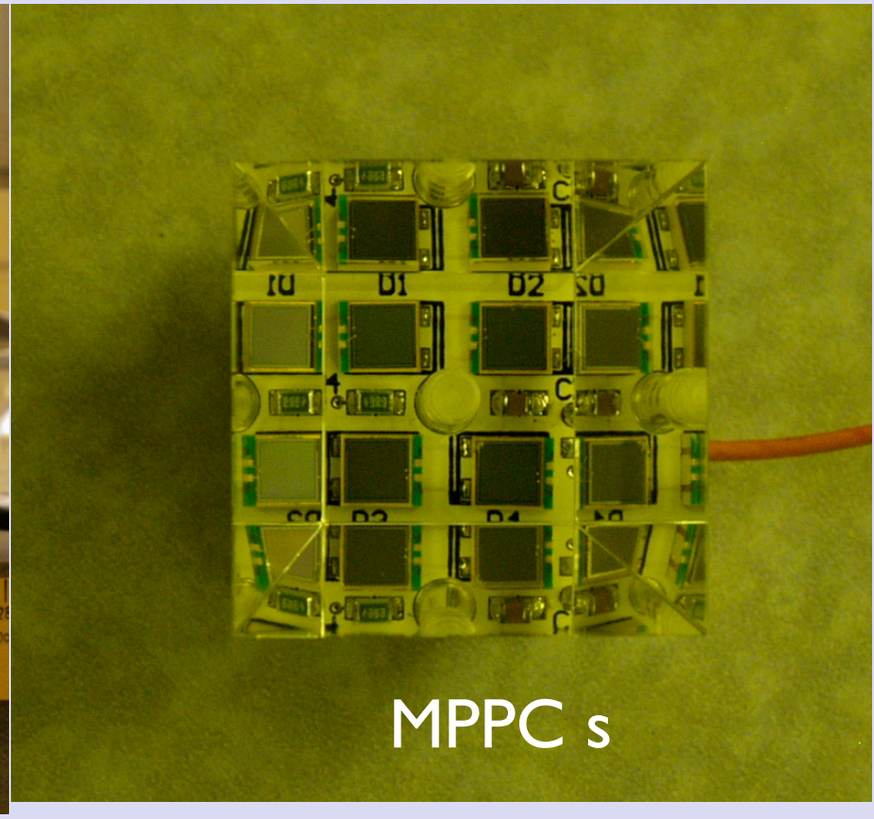
Parameters close to construction steel.

- same tungsten powder + fibers technology as FEMC,
- towers are tapered, sampling fraction along the tower depth is not constant.
- non-projective geometry; radial distance from beam line [815 .. 980]mm

-> simulation does not show any noticeable difference in energy resolution between straight and tapered tower calorimeters

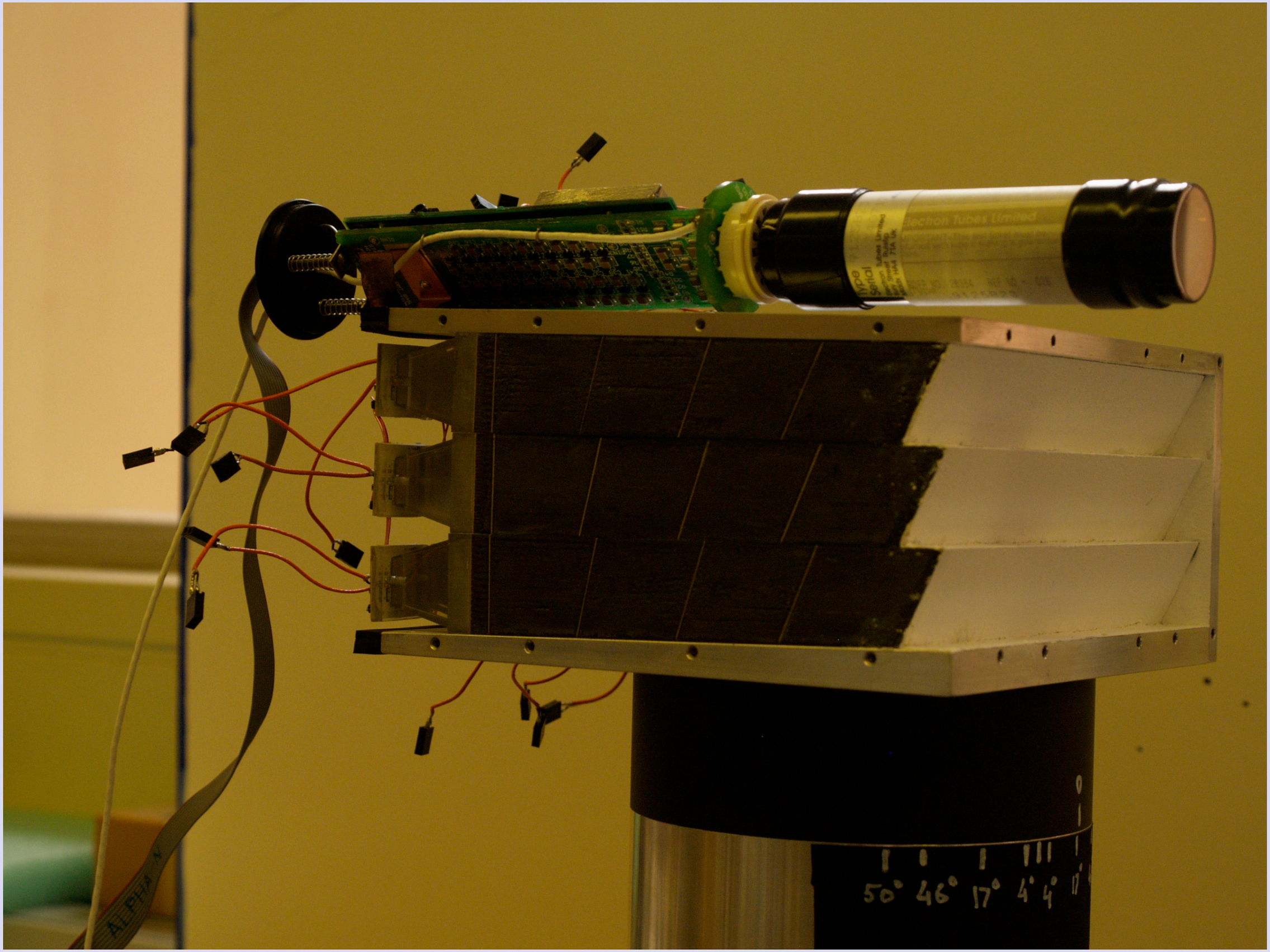
EM Calorimeters Prototypes. FNAL 2014





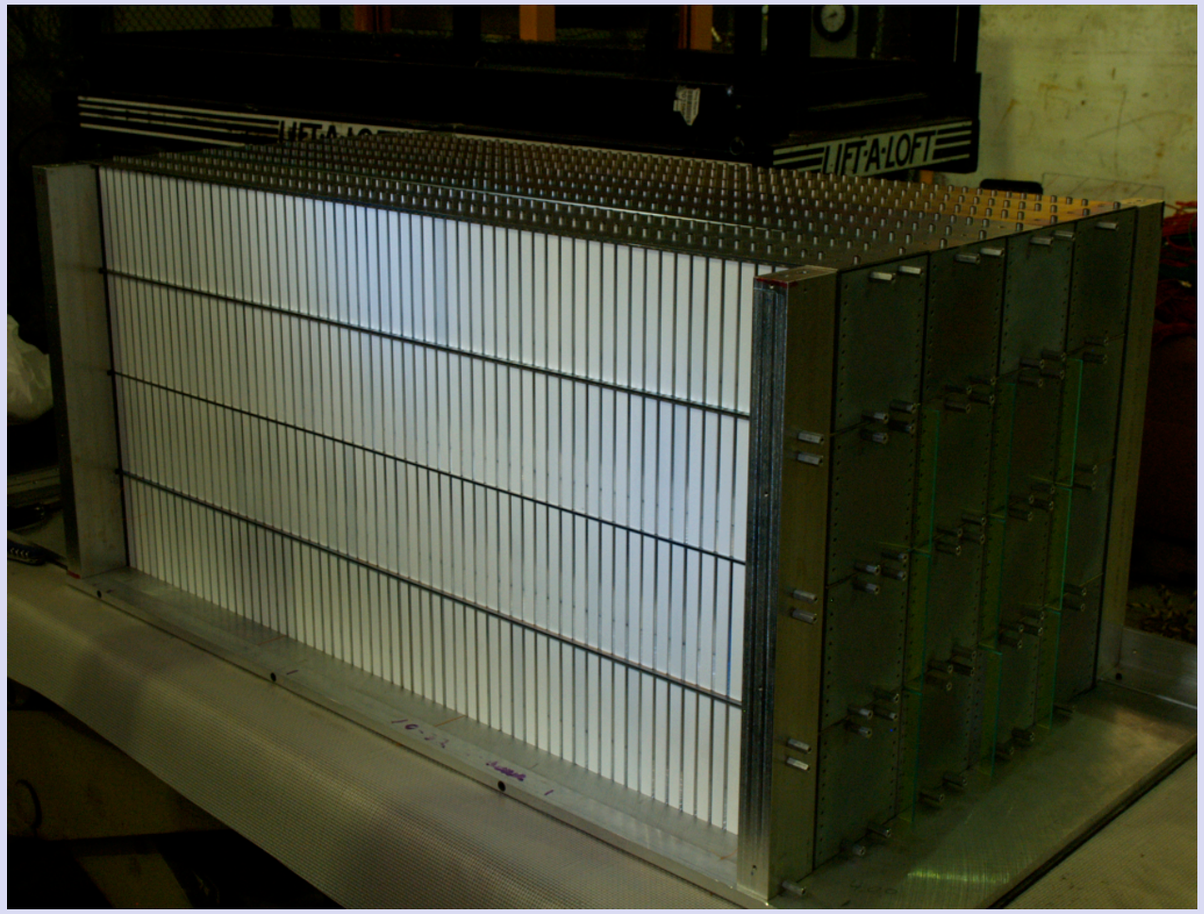
EIC BEMC. Tapered towers (for inner radius of EMCal of 120 cm). 18 towers, each 18Xo deep. Dimensions of tower at the outer radius is 2.5 x 2.5 cm. Fibers SCSF78M, diameter 0.5 mm. Initial reflector at the front end of the fibers ESR glued with silicone.

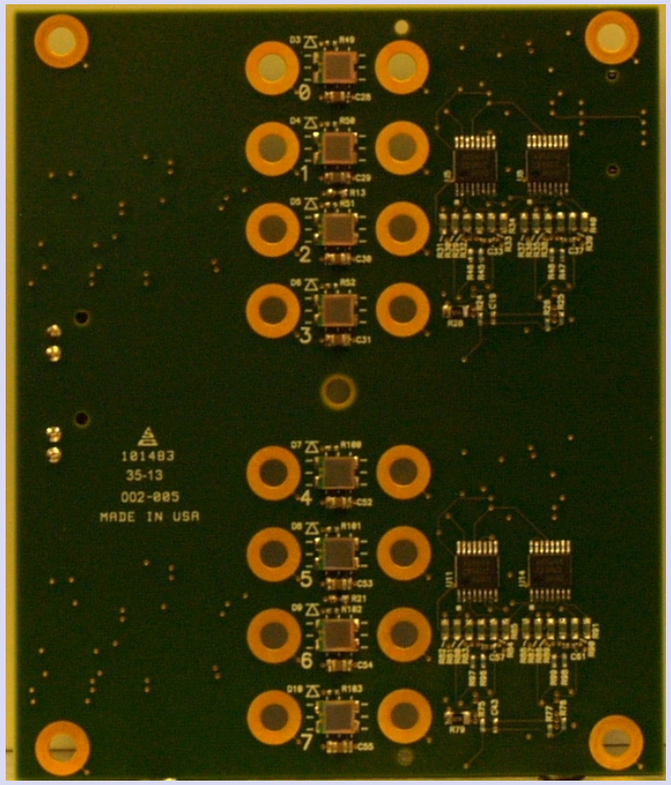
STAR EMCal. 16 straight towers. 23Xo deep. Dimensions of single tower 2.5 x 2.5 cm. Fibers SCSF78, diameter 0.47 mm. Reflector at the back end of the fibers Bicron BS620.



Compact $18X_0$ EIC CEMC

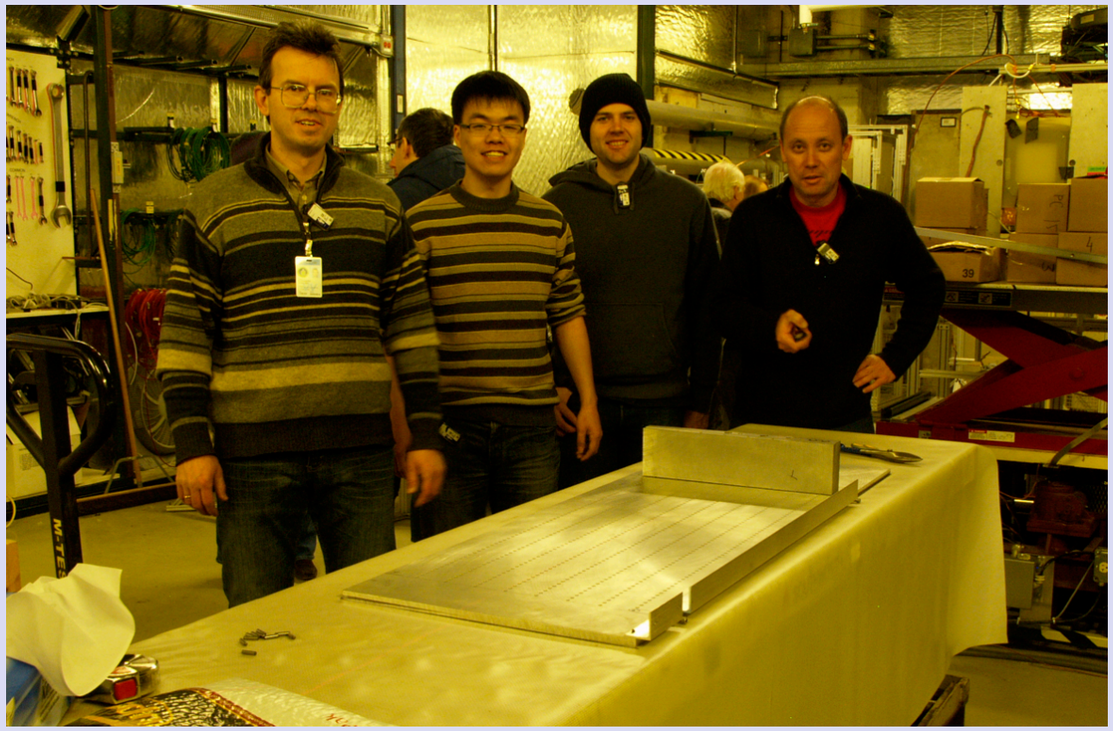
Hadronic Calorimeter Prototype at FNAL





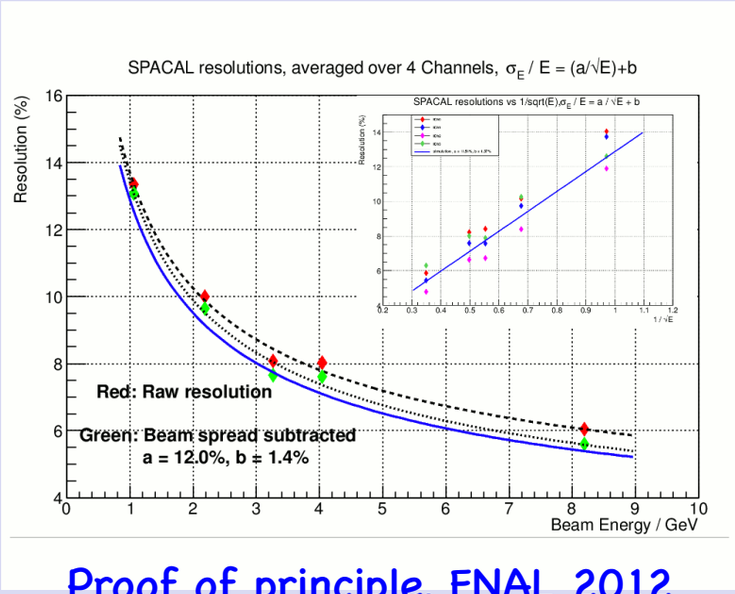
- HCal is ~4 interaction lengths Pb/scintillator.
- Readout is from Hamamatsu S10931-025p SiPMs attached to wavelength shifting plates which run the length of the detector.
- 16 individual towers.
- Total Volume 0.4 m x 0.4 m x 0.8 m

Assembling HCal Onsite. Feb 26, 2014. FNAL

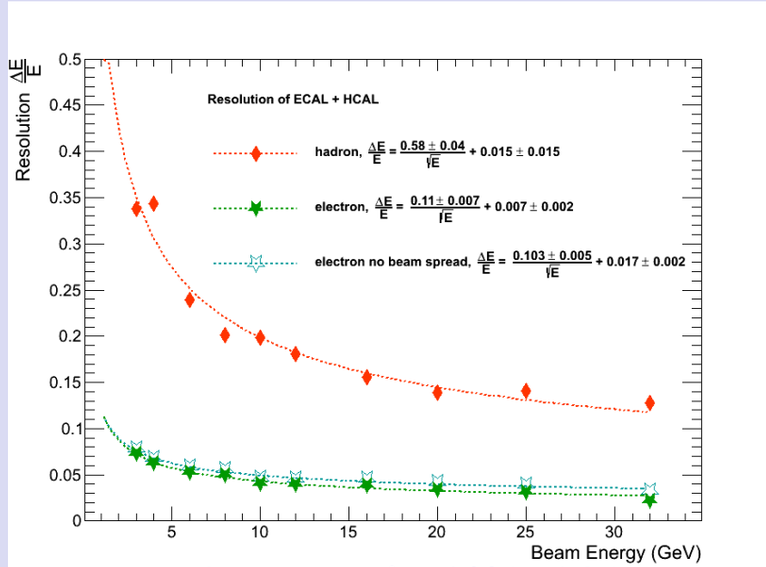


After two hours first layer done.

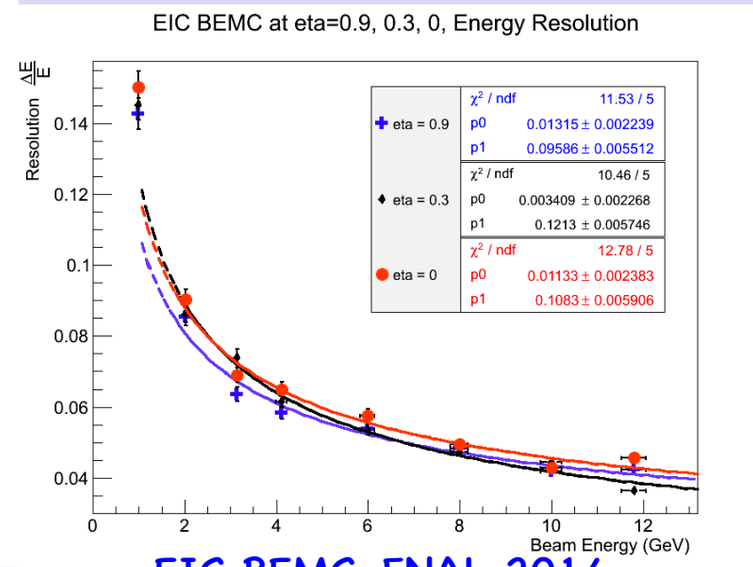
After 8 hours they told me "next time let undergrads do that".



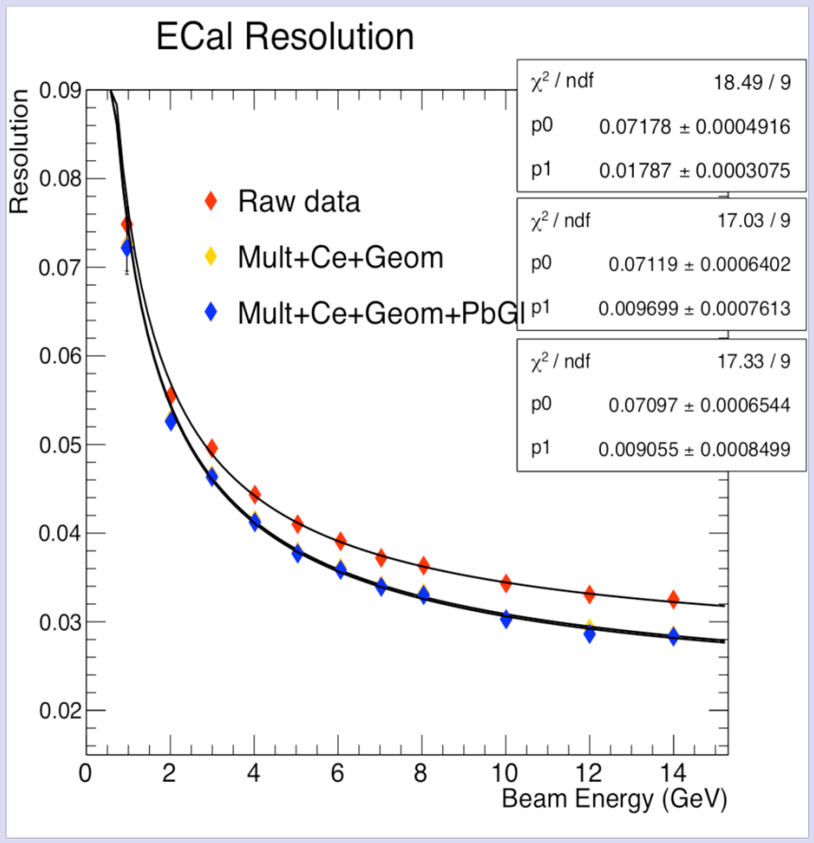
Proof of principle. FNAL 2012



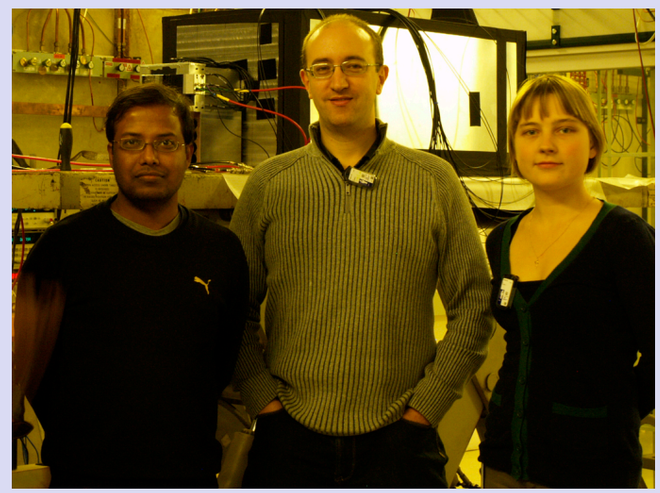
EIC Forward, FNAL 2014

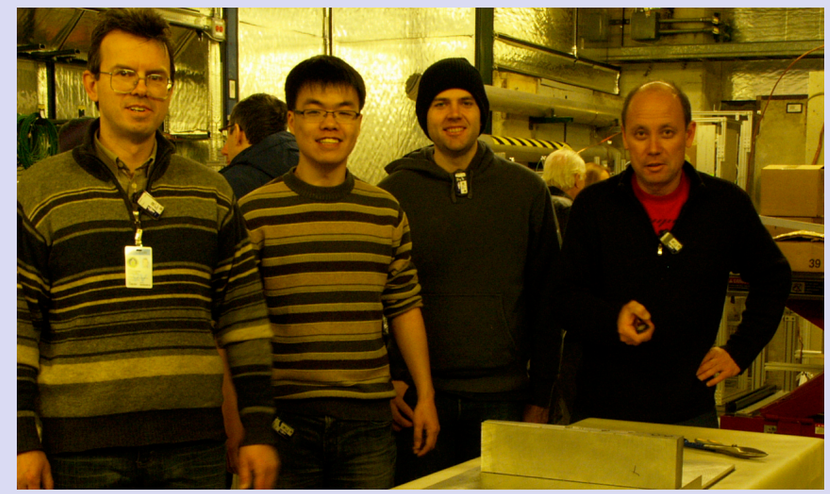


EIC BEMC, FNAL 2014



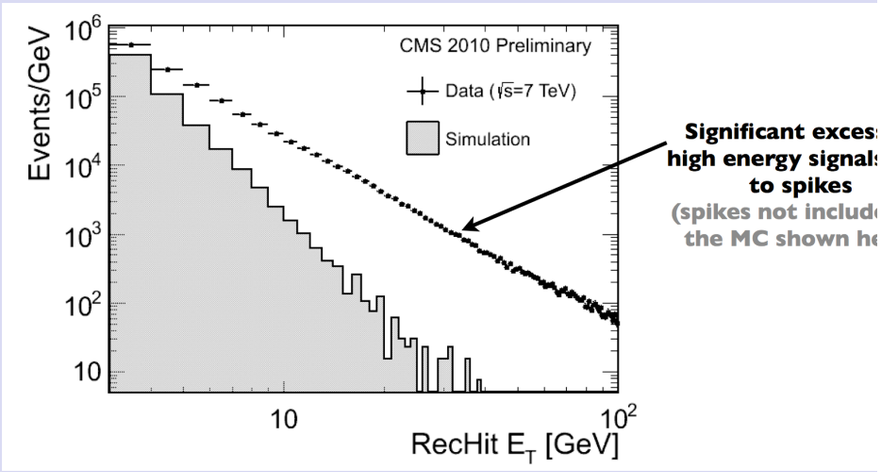
EIC Forward, FNAL 2016
(PMT Readout)

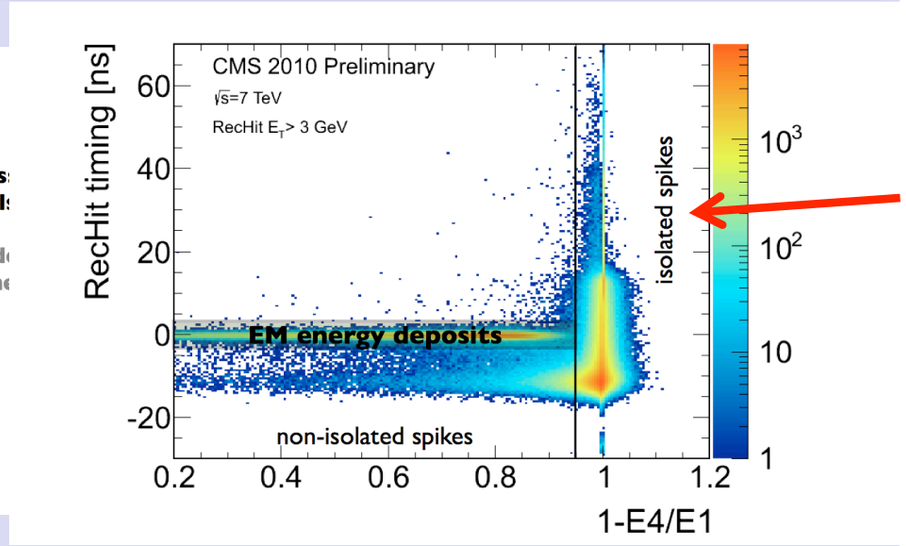


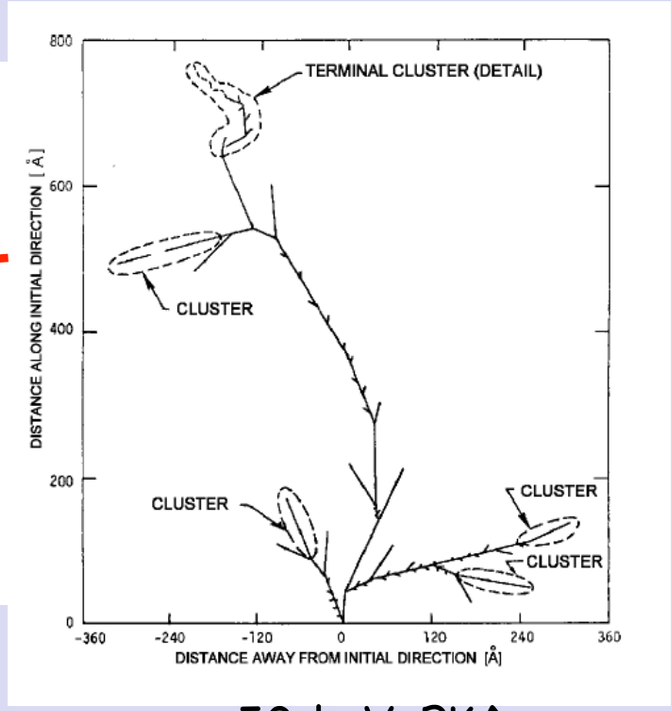


Test Runs 2012 -2016

Critical Tests SiPMs and APDs in 'realistic' conditions:



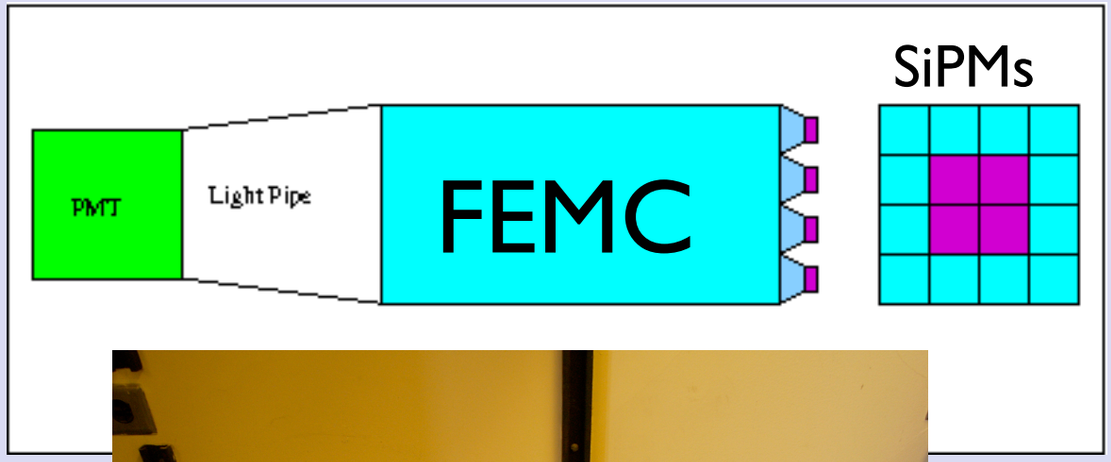


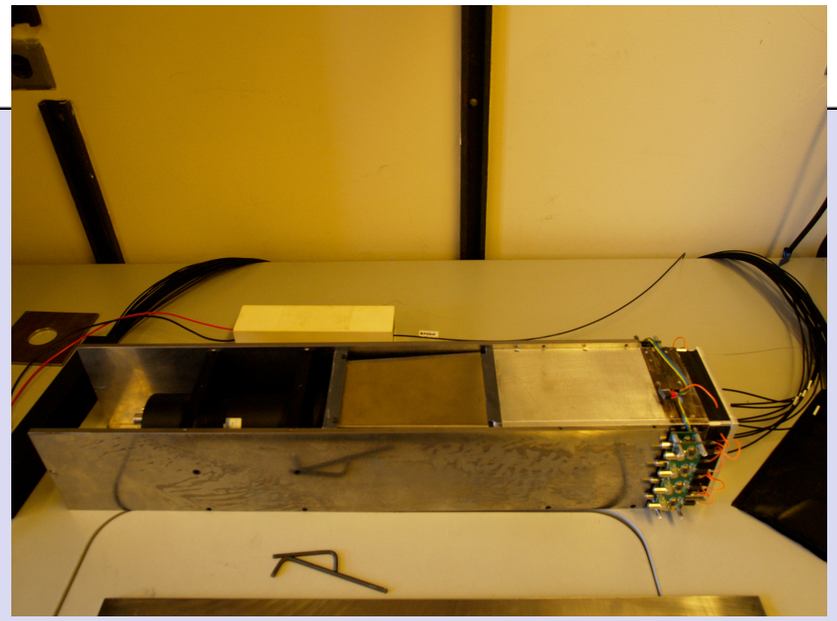


- You can't catch this in the test runs. Need collider environments.
- CMS and PANDA didn't know about this until LHC started and trigger system got choked!
- SiPMs in principle should be immune to Nuclear Counting Effects, but what about non-isolated spikes?

50 keV, PKA

- Large signal in APD,
- One pixel fired in SiPM

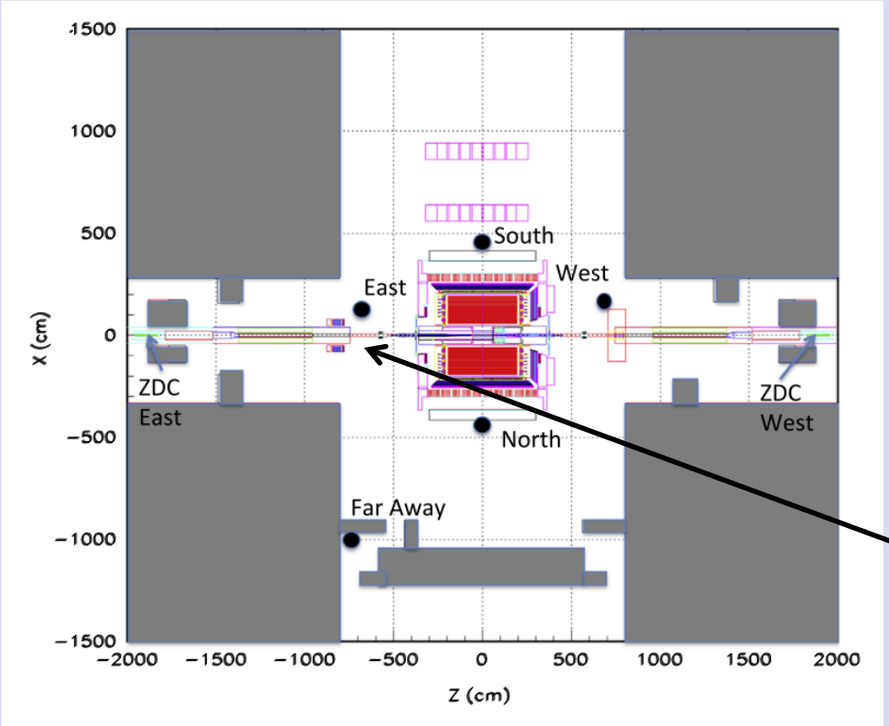




Test at STAR IP during Run16:

- FEMC equipped with dual readout to compare response of SiPMs (APDs) to PMT.
- High Tower (HT) Trigger for four central towers (range 4 – 2 GeV).

SiPMs and APDs in 'realistic' conditions:

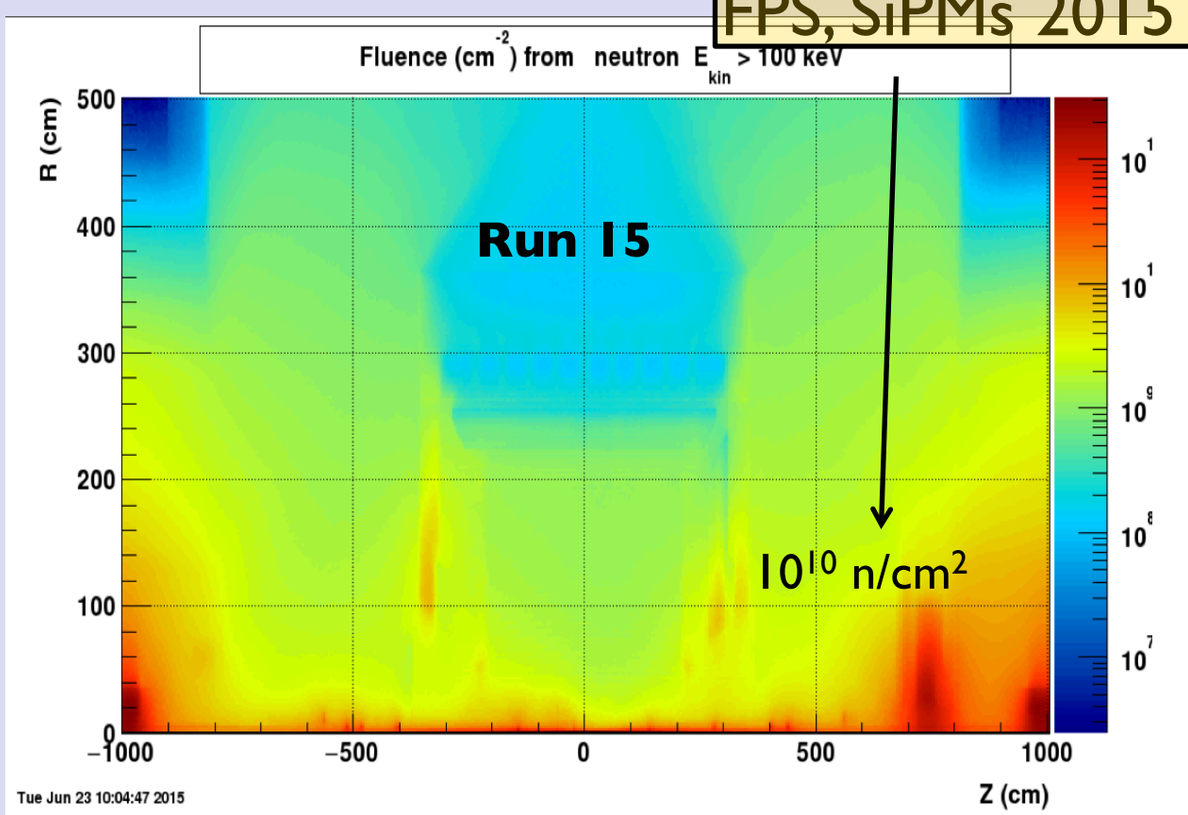


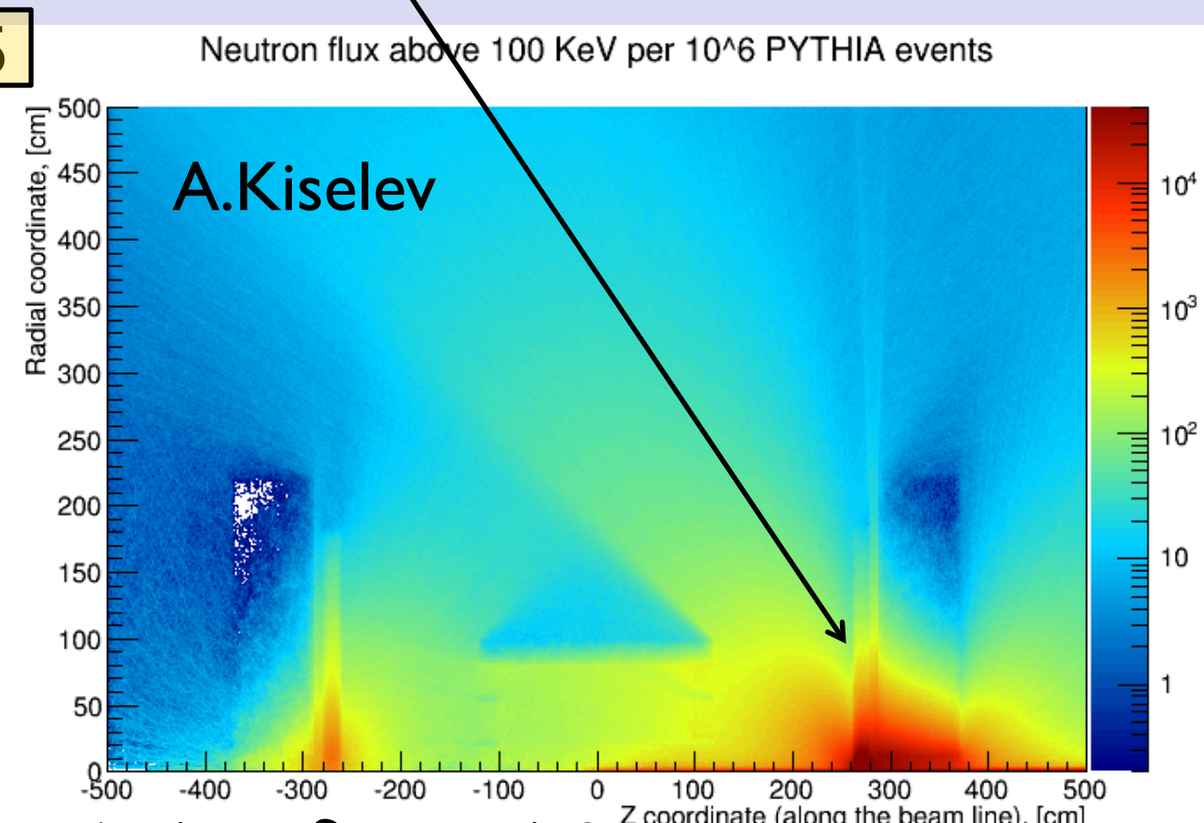
Y.Fisyak, et.al NIM A756

- STAR IP ideal test place for EIC. Well understood conditions (measurements in 2013 thermal neutrons, 2015 'MeV' neutrons with Forward Preshowers (FPS) SiPMs + MC).
- EICRoot tuned using STAR data.
- Conditions for FEMC in BeAST very close to one we have in STAR now.

FEMC, 2016

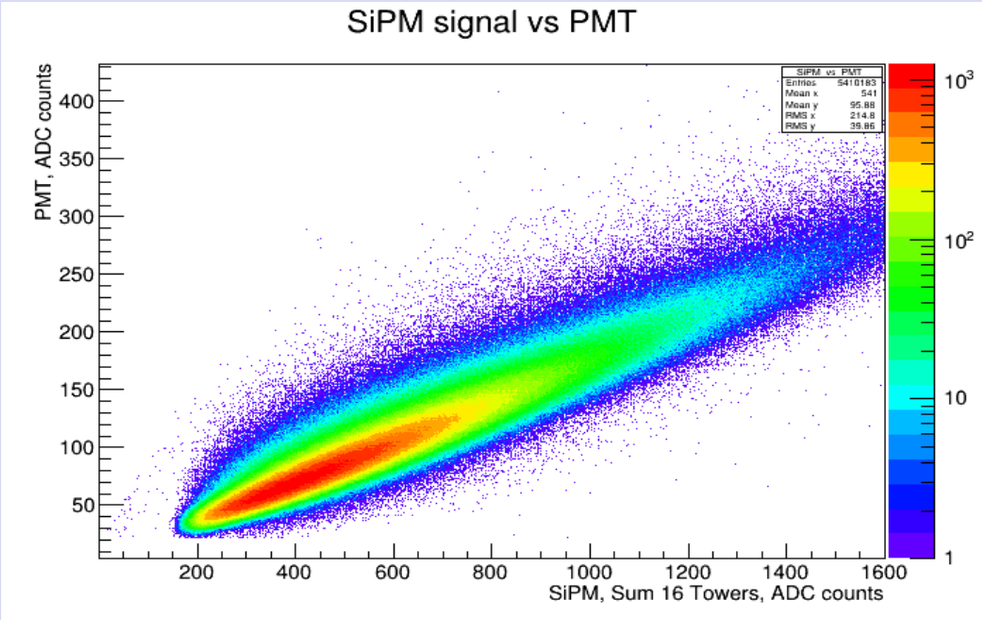
FPS, SiPMs 2015

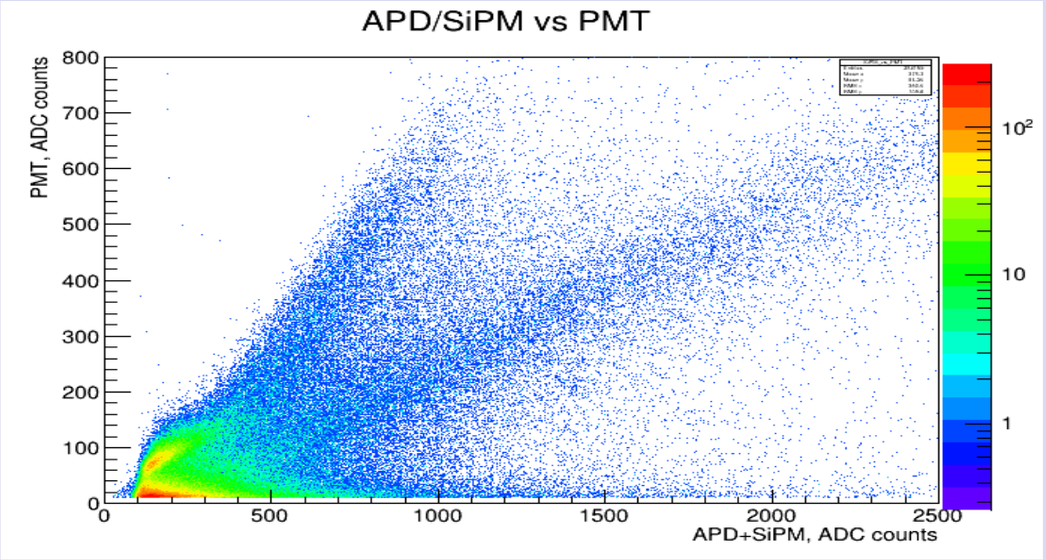


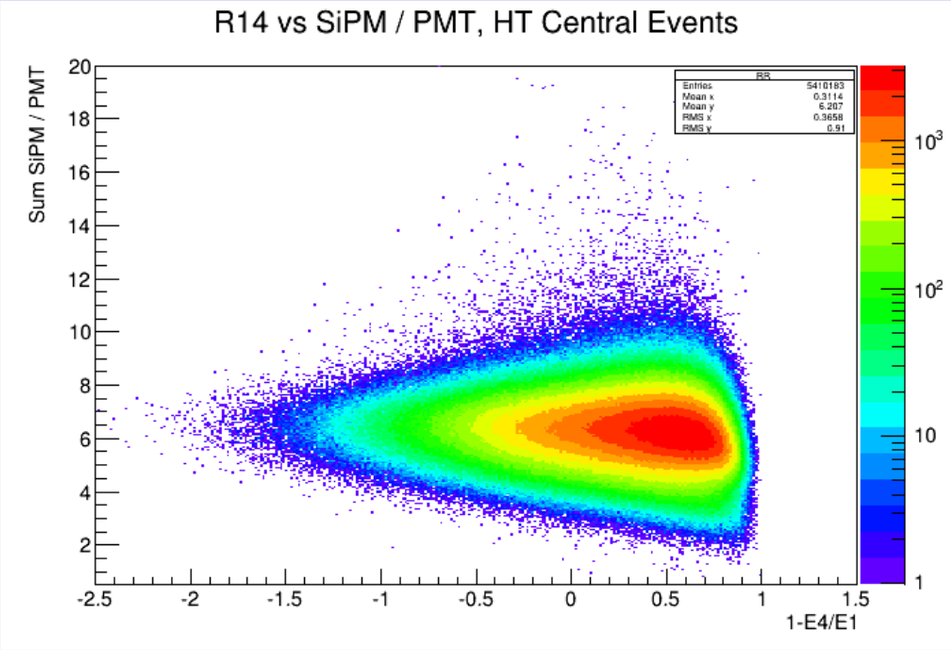


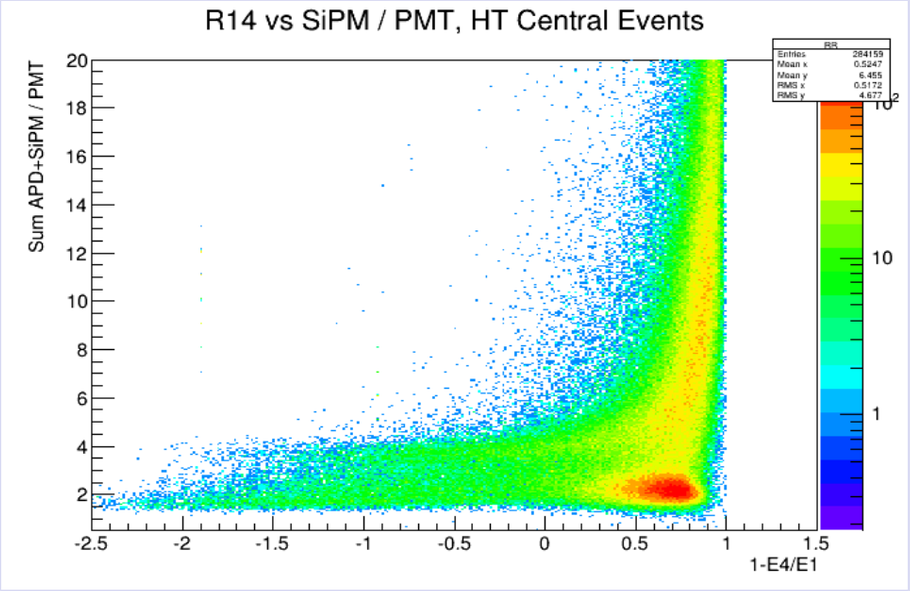
Neutron fluxes at BeAST, ep 20 x 250 GeV

FEMC, SiPMs (APDs) in 'realistic' conditions (all results are Preliminary):



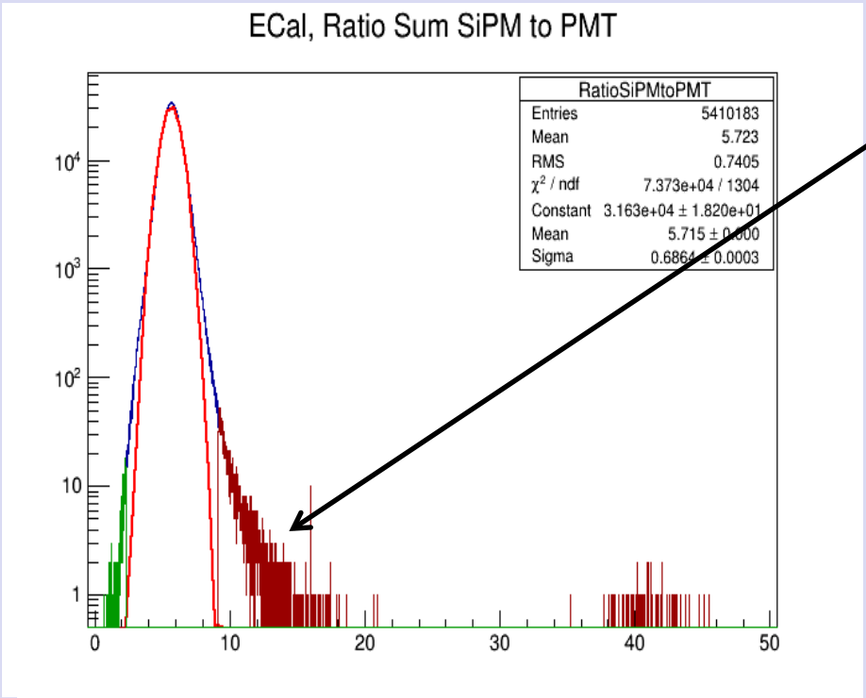


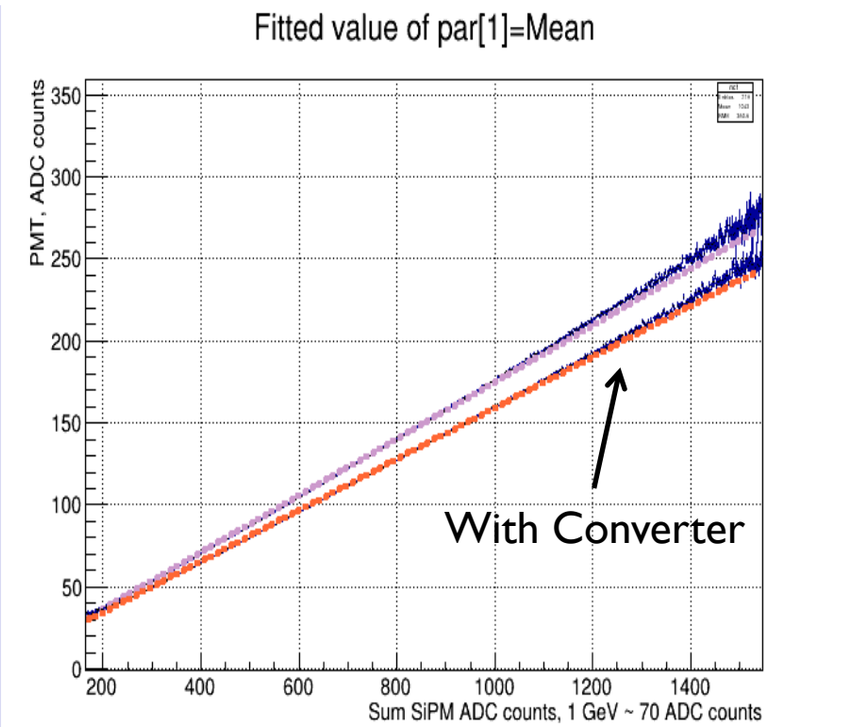




- SiPMs indeed immune to NCE
- APDs ~ 40% of High Tower Triggers are due to NCE

FEMC, SiPMs in 'realistic' conditions (Preliminary):

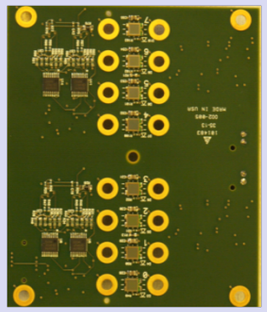




- Fraction of signals outside 5 sigma is about 4 *10 $^{-4}$ for SiPM readout.
- Origin of these signals is not clear.

Test with $2X_0$ converter in front of SiPMs (sensitivity to 'shower' particles)

- Excess of ~ 90 pixels/GeV may be due to the same things which produces non isolated spikes in CMS ?
- If true (not the artifact of light collection to PMT) this may be a problem when summing many SiPMs (especially if detector has low LY).
- Example, FEMC HAD readout, Sum 8 SiPMs. 130 pixels/GeV, Test Run 2014 at FNAL.



← Will this be better with two APDs ?

SiPMs and APDs 2016 tests. Summary:

- SiPMs insensitive to NCE.
- SiPMs may be sensitive to 'showers' (non-isolated spikes at CMS).
- Depending on environment, LY from the detector, speed of light collection one sensors may be better than the other (so far, seems, that all EM calorimeter will be better with SiPM, HAD may be better with APD).
- This may have impact on readout (timing requirement?)
- Efficiency for light collection for all calorimeters need to be improved. Optimism about dramatic improvement of PDE for SiPMs is fading away. Usage of filters should be reconsidered. Compensation from back side with mirrors creates problems and not always possible.
- Simple way of adding more sensors to increase efficiency of light collection may create problems.
- Aiming at sensors with smaller pixels (smaller PDE, larger number of pixels) may be a problem as well.

- We'll continue these studies (more systematically) next year during 500 GeV pp Run 17 at RHIC.

- This will be the best chance to study how sensors behave in conditions close to what will be at EIC. The next such opportunity (pp Run) will be only past 2021.

- Results may impact choice of design of many components of calorimeter system.

Summary I:

- We developed new method for construction of very compact sampling calorimeters for EIC supported from EIC generic detector R&D program.

- This method is now being adopted, refined, tuned etc. at IUCF, BNL, THP and continued developement at UCLA.

- EIC Calorimetry R&D Program allows five undergraduate and five (seven) graduate students participate at all stages of detector development (MC optimizations, design, building, testing and analyzing test run data).

Summary II:
Compensation:
Are we done with it?

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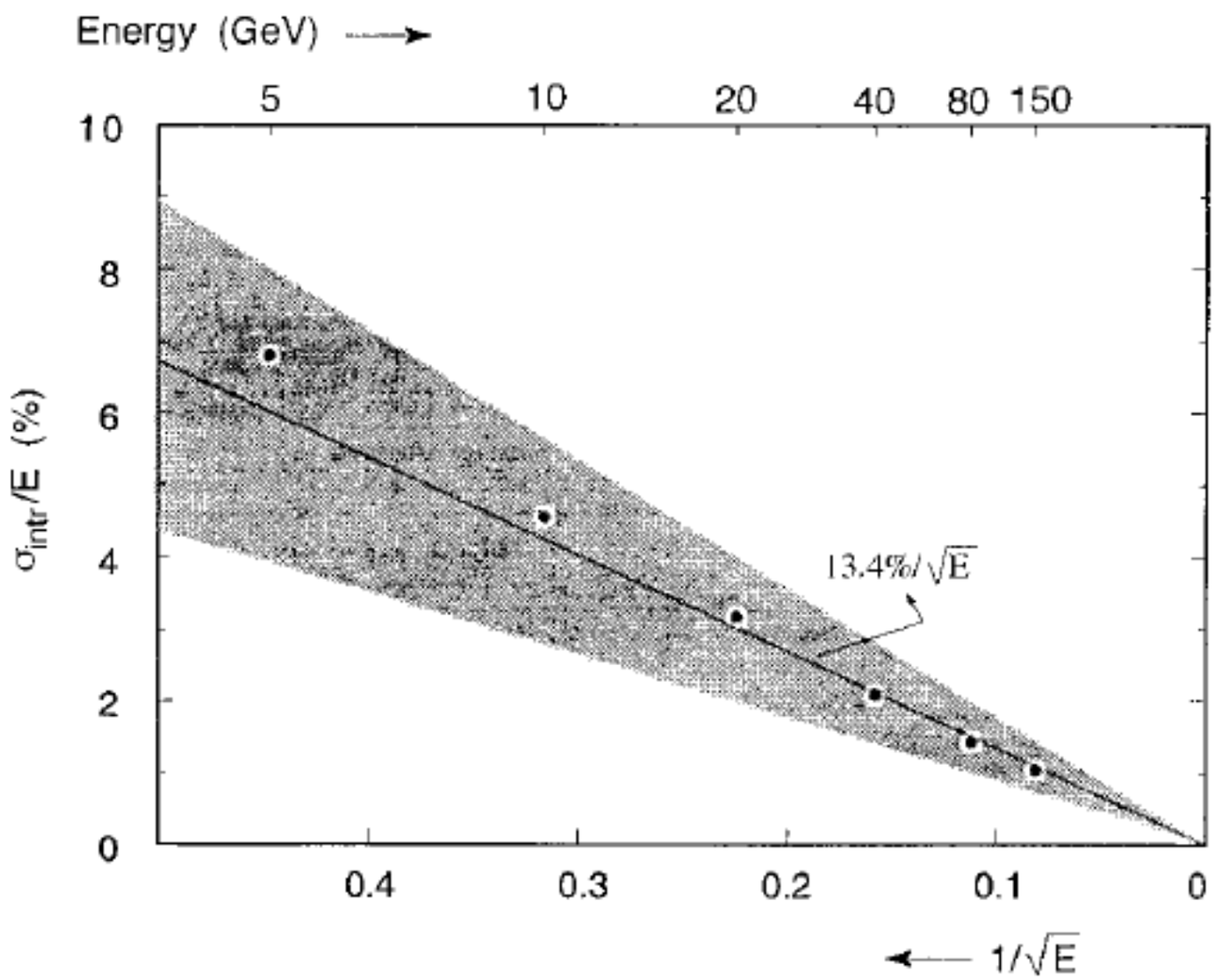
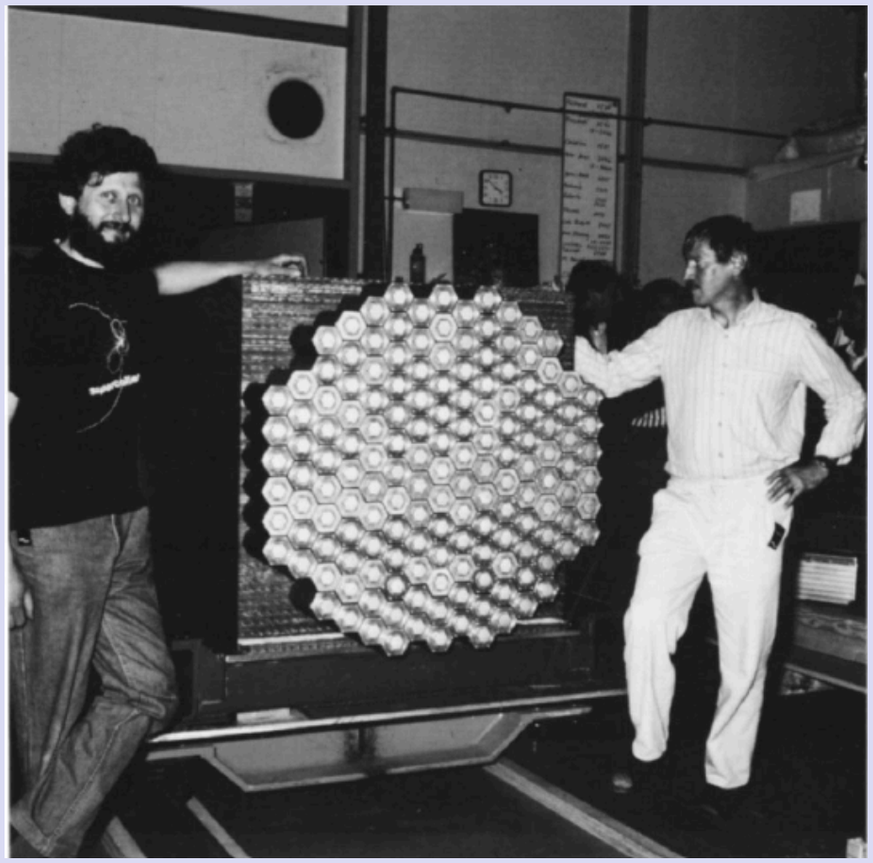


FIG. 11. The (calculated) contribution of fluctuations in the total kinetic energy carried by neutrons to the hadronic energy resolution of compensating Pb/plastic-scintillator calorimeters, as a function of energy (black dots). The measured value of the irreducible fluctuations in such calorimeters is indicated by the shaded area.



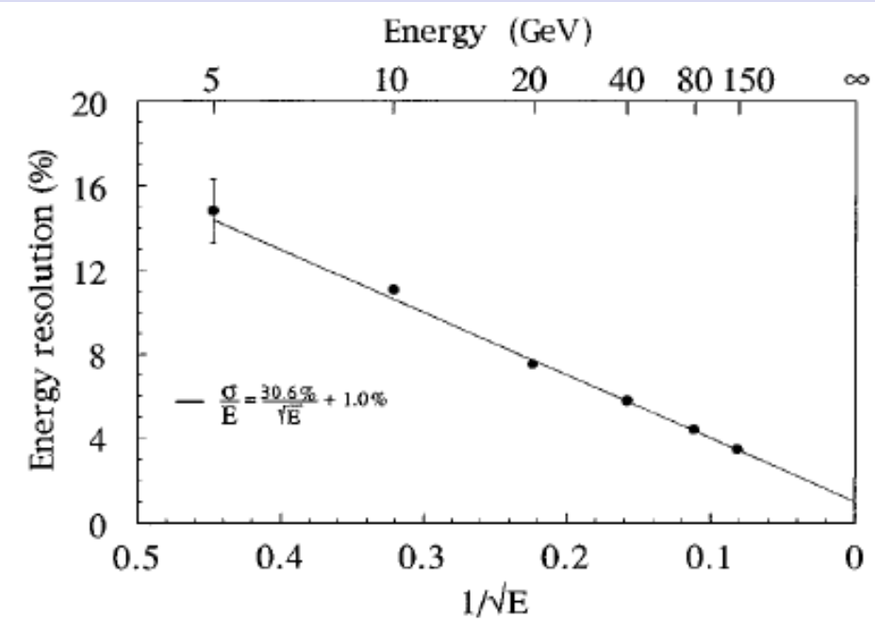


FIG. 10. Hadronic energy resolution as a function of energy, for the compensating SPACAL lead/plastic-scintillator calorimeter (Ref. 16).

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