Calorimeter technology & opportunities for collaboration

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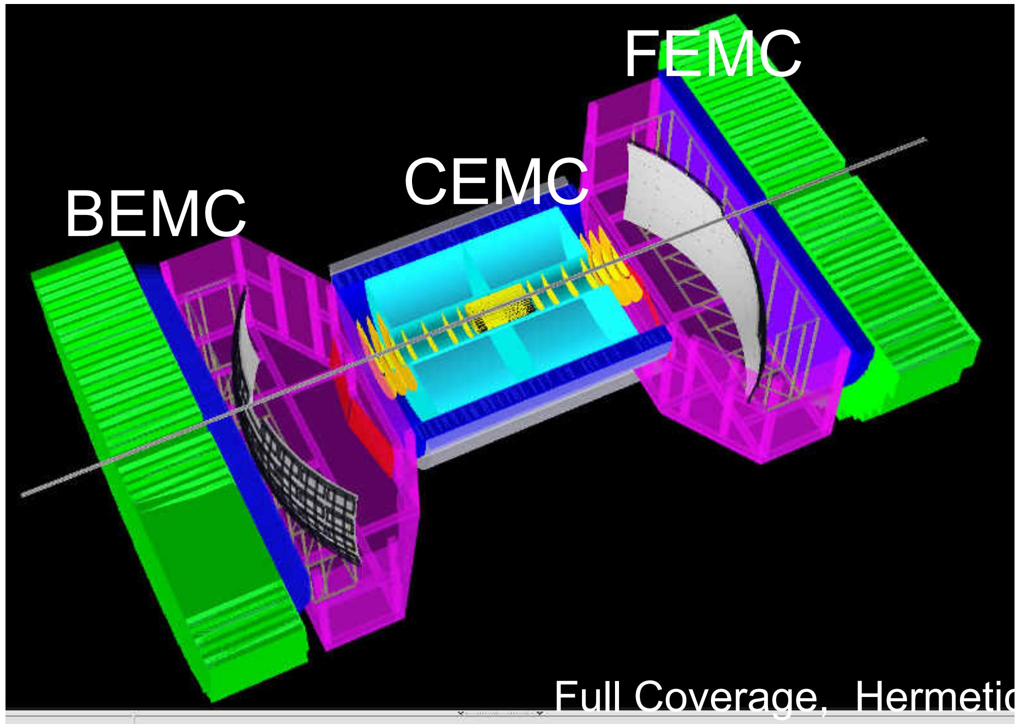
UC EIC Meeting, LBNL, July 22 2016

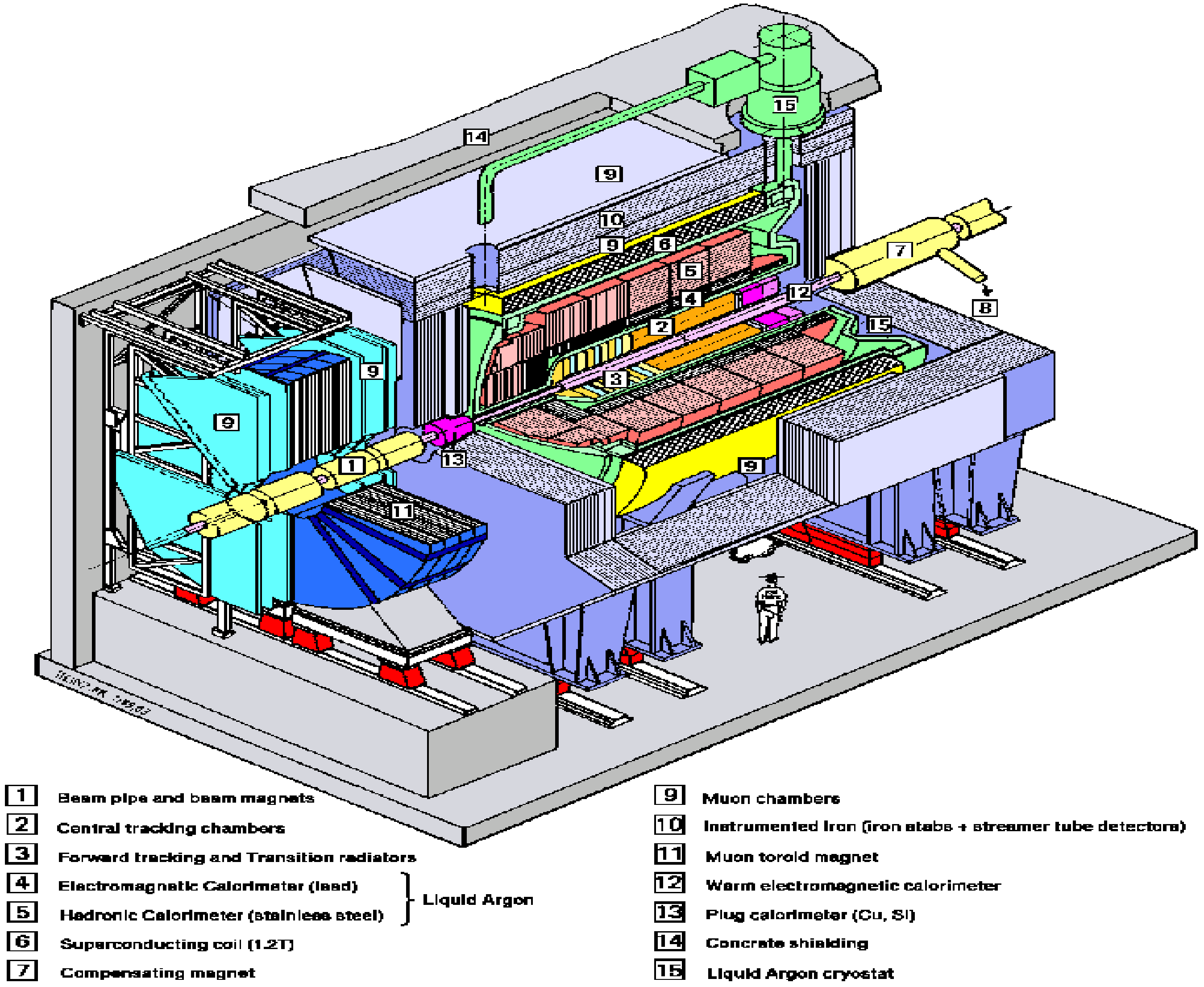
Why are we doing calorimeter R&D for a generic central detector?

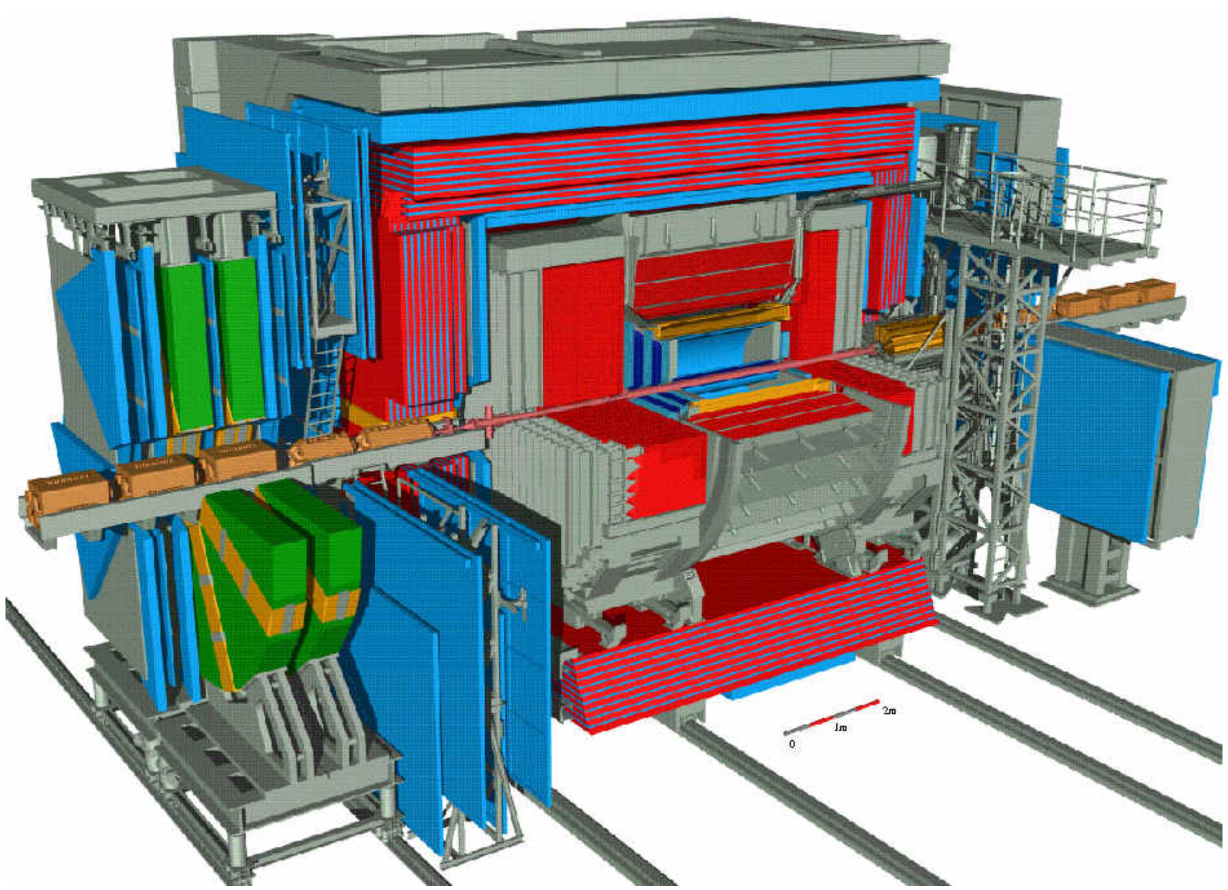


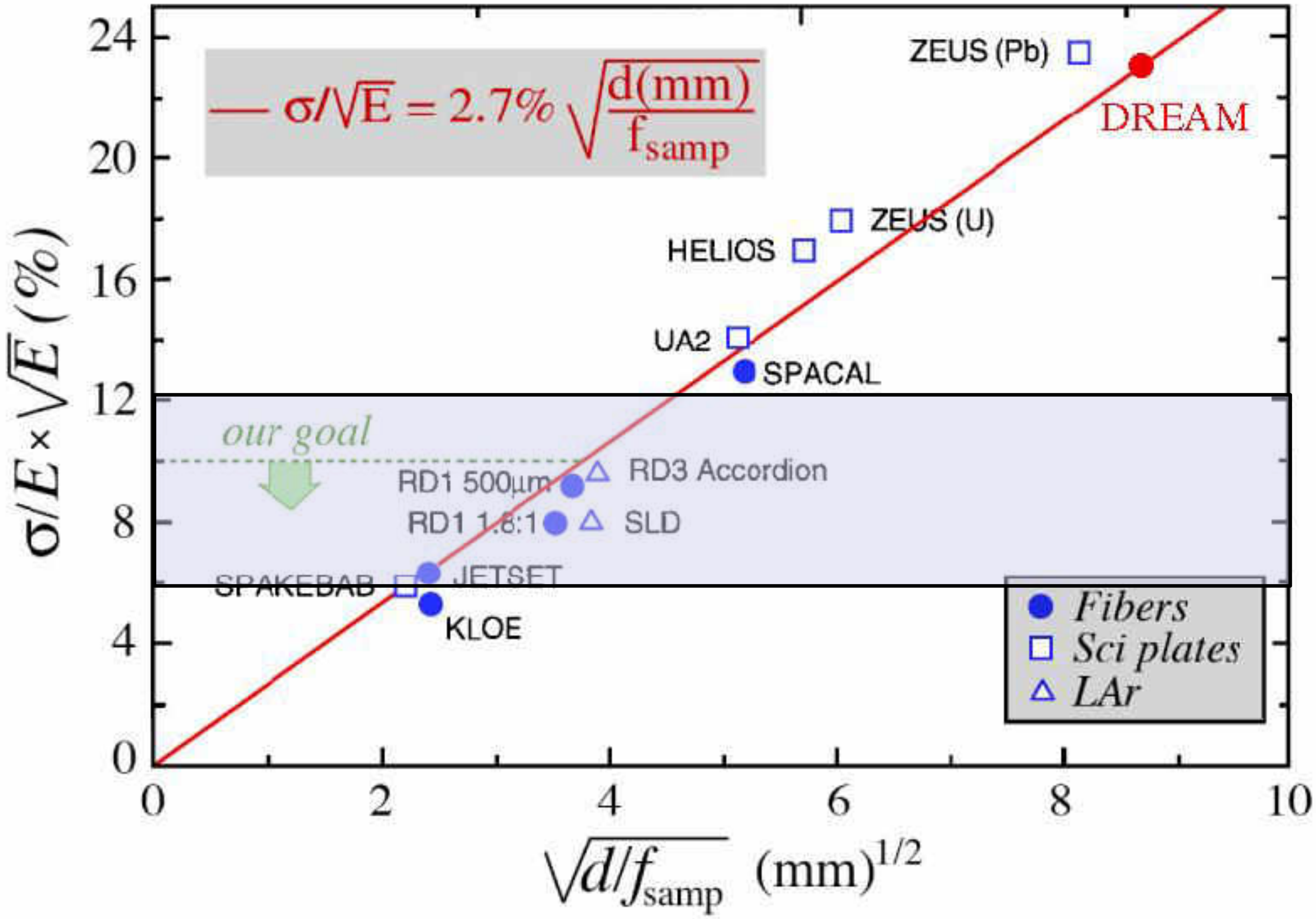
Calorimetry wise, we wanted to have similar performance of H1/ZEUS in much more compact package and for a fraction of cost.

EIC Detectors 9m long (4pi PID)
HERA Detectors 15 m long (no PID)
Cost of ZEUS Calorimeters ~ $90M **(if I scale correctly)**

Advances in micro pattern detectors.
Advances in photodetectors. (APD, SiPMs)







EIC EM
Sampling
Calorimeters

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

H1

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

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

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

Small d, Small Fs (A)

SciFi calorimeters.

Good energy , position resolution.
Fast, compact, hermetic.
Problems are;
Projectivity, high cost (1/10th of crystals).
Example (H1)

Rm 1.8 cm
X0 0.7 cm
Energy reso. ~ 10% /√(E)
Density ~ 10 g/cm^3
Number of fiber/tower~ 600 (0.3 mm diameter, 0.8mm spacing)

Small d, Large Fs (B)

“Shashlik” type.

Excellent energy resolution
Reasonably fast
Small dead areas
Problems are:
Low density, projectivity.
Moderate cost
Example (KOPIO/PANDA)

6 cm
3.4 cm
4%/√(E)
2.5 g.cm^3
0.3 mm Pb/1.5 mm Sc
400 layers

Large d, Large Fs (C)

Tile/Fiber type.

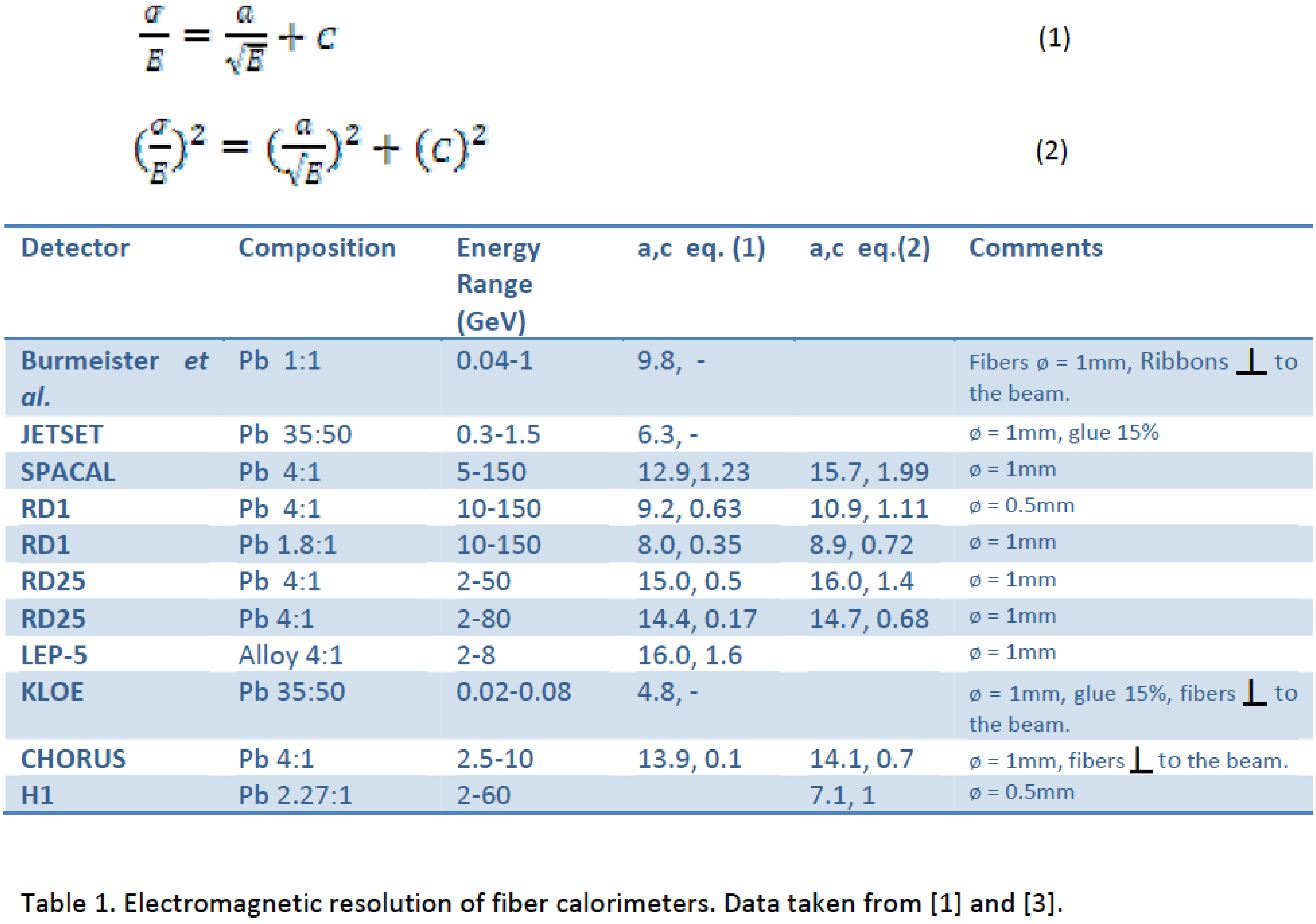
Ok energy resolution
Reasonably fast
Very cost effective
Problems are:
Moderate density, large dead areas.
Example (STAR BEMC)

3 cm
1.2 cm
15%/√(E)
6 g/cm^3
5mm Pb/ 5mm Sc
20 layers

We are proposing to develop new technology for (A) with the price tag comparable to the cost of tile/fiber type calorimeters.

eRD1 proposal. ScFi technology, new method of construction.

https://wiki.bnl.gov/conferences/images/d/d4/RD-1_RDproposal_April-2011.pdf



$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} + c \qquad (1)$$

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{a}{\sqrt{E}}\right)^2 + (c)^2 \qquad (2)$$

Detector	Composition	Energy Range (GeV)	a,c eq. (1)	a,c eq.(2)	Comments
Burmeister *et al.*	Pb 1:1	0.04-1	9.8, -		Fibers ø = 1mm, Ribbons ⊥ to the beam.
JETSET	Pb 35:50	0.3-1.5	6.3, -		ø = 1mm, glue 15%
SPACAL	Pb 4:1	5-150	12.9,1.23	15.7, 1.99	ø = 1mm
RD1	Pb 4:1	10-150	9.2, 0.63	10.9, 1.11	ø = 0.5mm
RD1	Pb 1.8:1	10-150	8.0, 0.35	8.9, 0.72	ø = 1mm
RD25	Pb 4:1	2-50	15.0, 0.5	16.0, 1.4	ø = 1mm
RD25	Pb 4:1	2-80	14.4, 0.17	14.7, 0.68	ø = 1mm
LEP-5	Alloy 4:1	2-8	16.0, 1.6		ø = 1mm
KLOE	Pb 35:50	0.02-0.08	4.8, -		ø = 1mm, glue 15%, fibers ⊥ to the beam.
CHORUS	Pb 4:1	2.5-10	13.9, 0.1	14.1, 0.7	ø = 1mm, fibers ⊥ to the beam.
H1	Pb 2.27:1	2-60		7.1, 1	ø = 0.5mm

Table 1. Electromagnetic resolution of fiber calorimeters. Data taken from [1] and [3].

eRD1 2012. Motivation:

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.

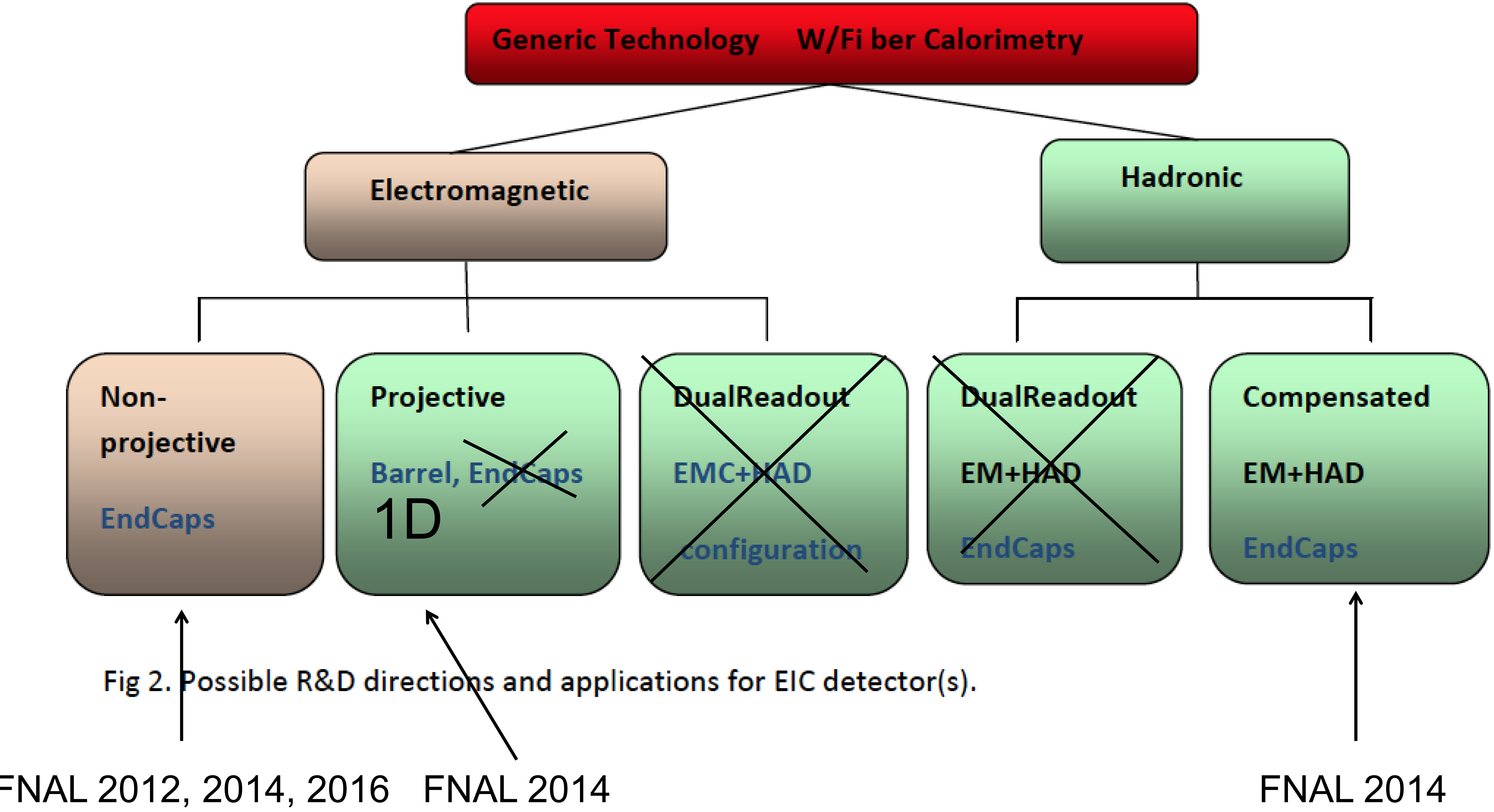
Flexible – tuneable for particular experimental requirements.

Motivation reflects experience building STAR BEMC.
Built by universities/national labs.

PHENIX used different approach – “industry”/national lab.

eRD1 proposal in 2011. Road map.

https://wiki.bnl.gov/conferences/images/d/d4/RD-1_RDproposal_April-2011.pdf



Generic Technology W/Fiber Calorimetry

Electromagnetic

Hadronic

Non-projective

EndCaps

Projective

Barrel, ~~EndCaps~~

1D

~~**DualReadout**~~

~~EMC+HAD~~

~~configuration~~

~~**DualReadout**~~

~~**EM+HAD**~~

~~EndCaps~~

Compensated

EM+HAD

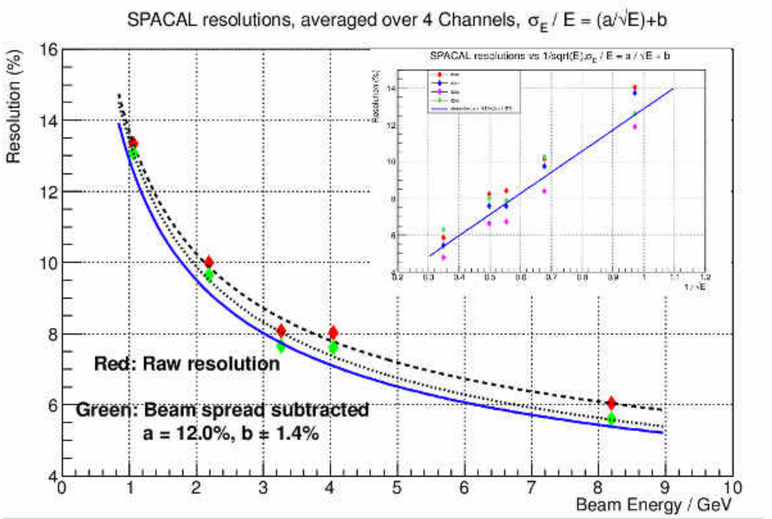
EndCaps

Fig 2. Possible R&D directions and applications for EIC detector(s).

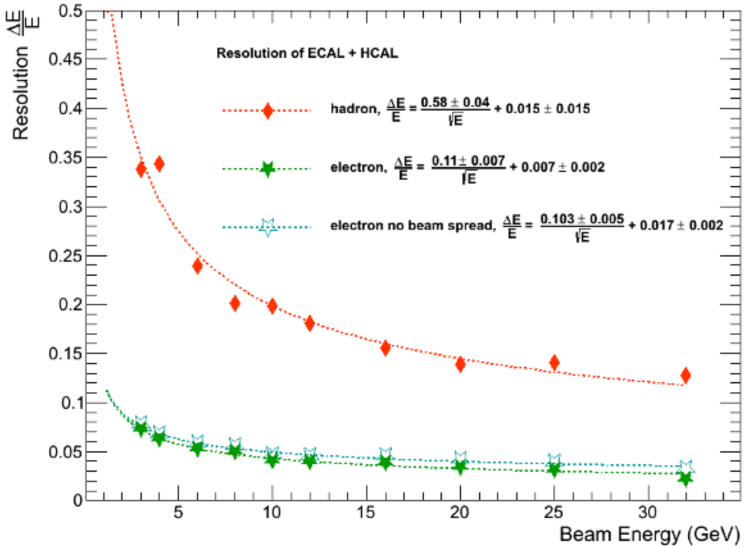
FNAL 2012, 2014, 2016

FNAL 2014

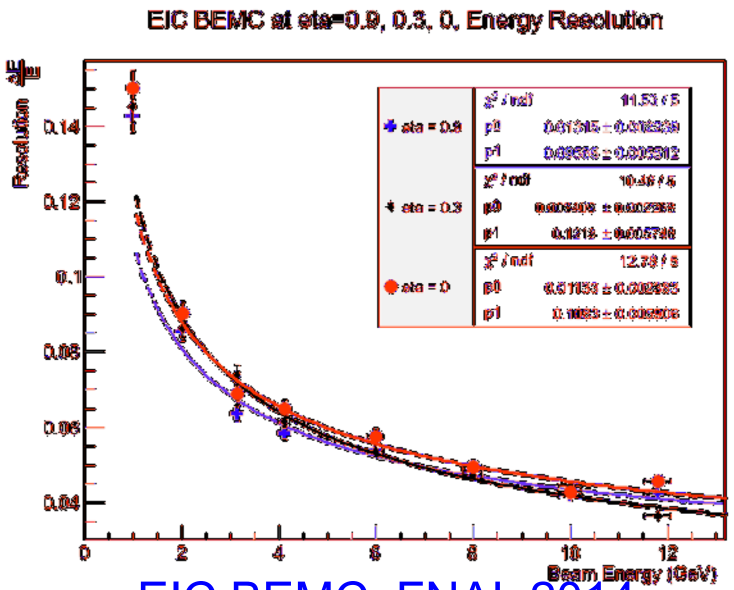
FNAL 2014



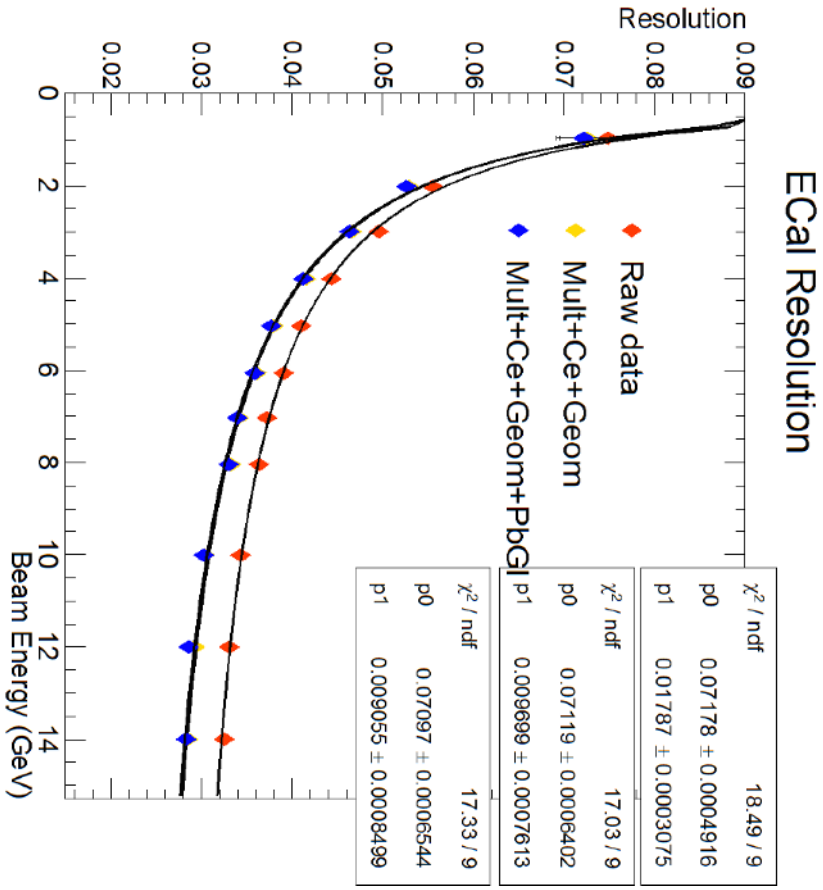
Proof of principle. FNAL 2012



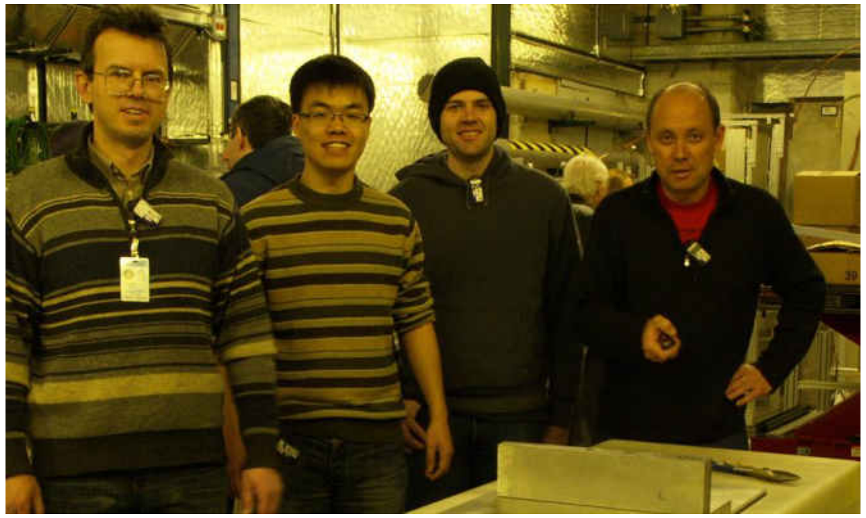
EIC Forward, FNAL 2014



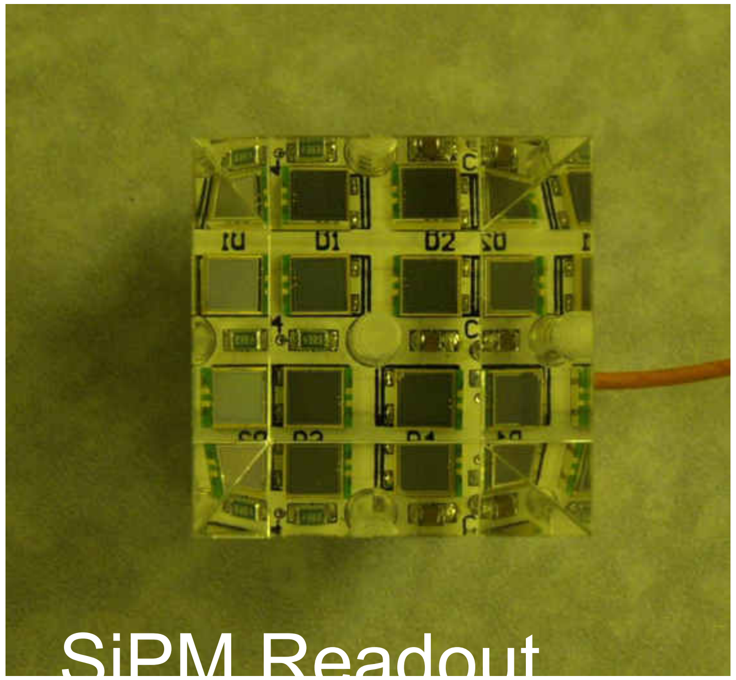
EIC BEMC, FNAL 2014

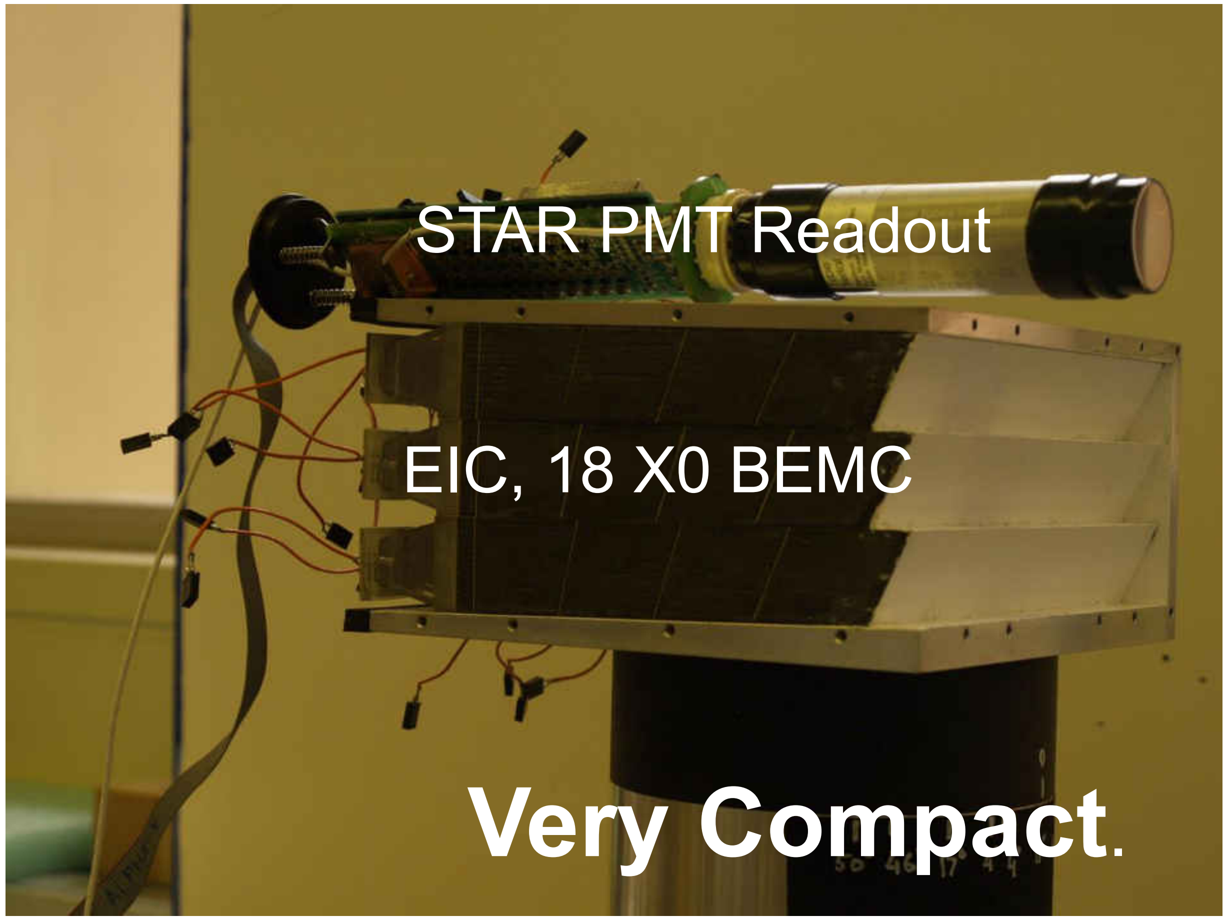


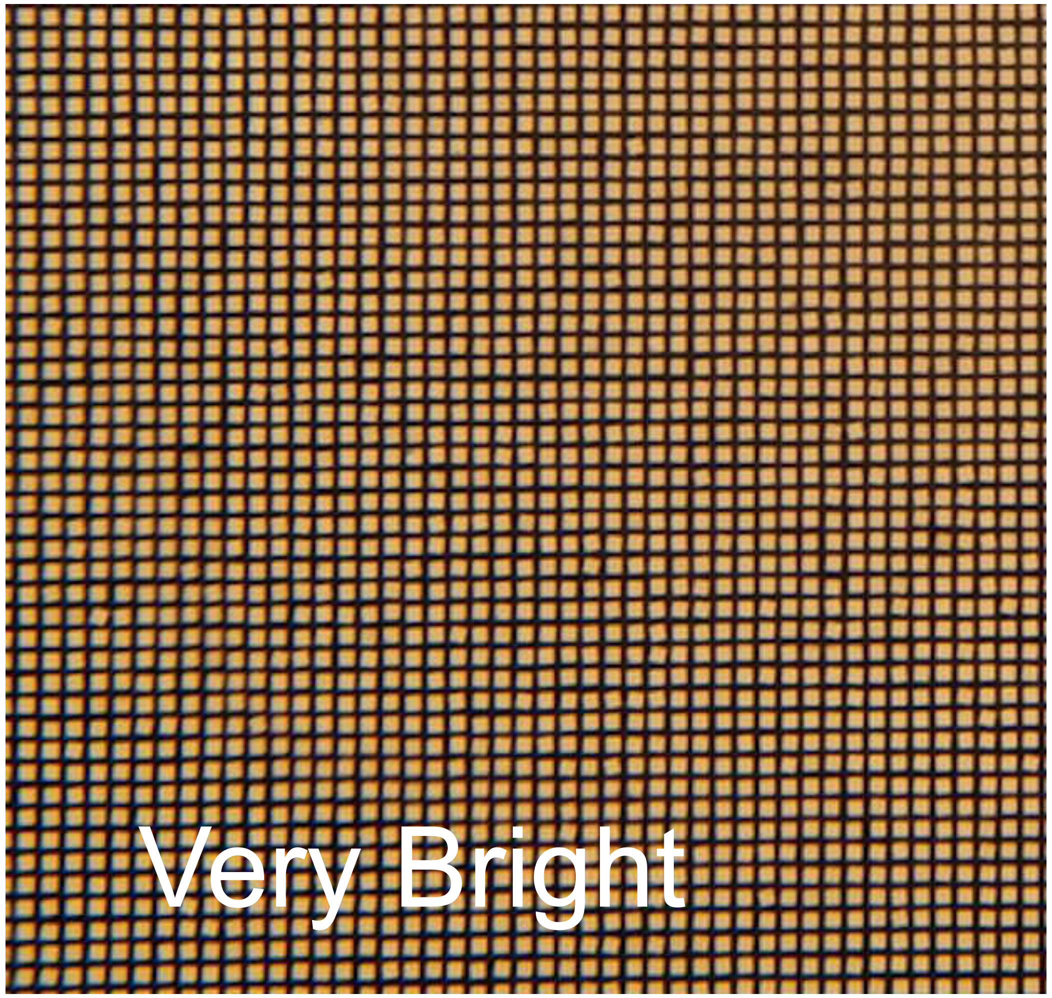
EIC Forward, FNAL 2016



Test Runs 2012 -2016

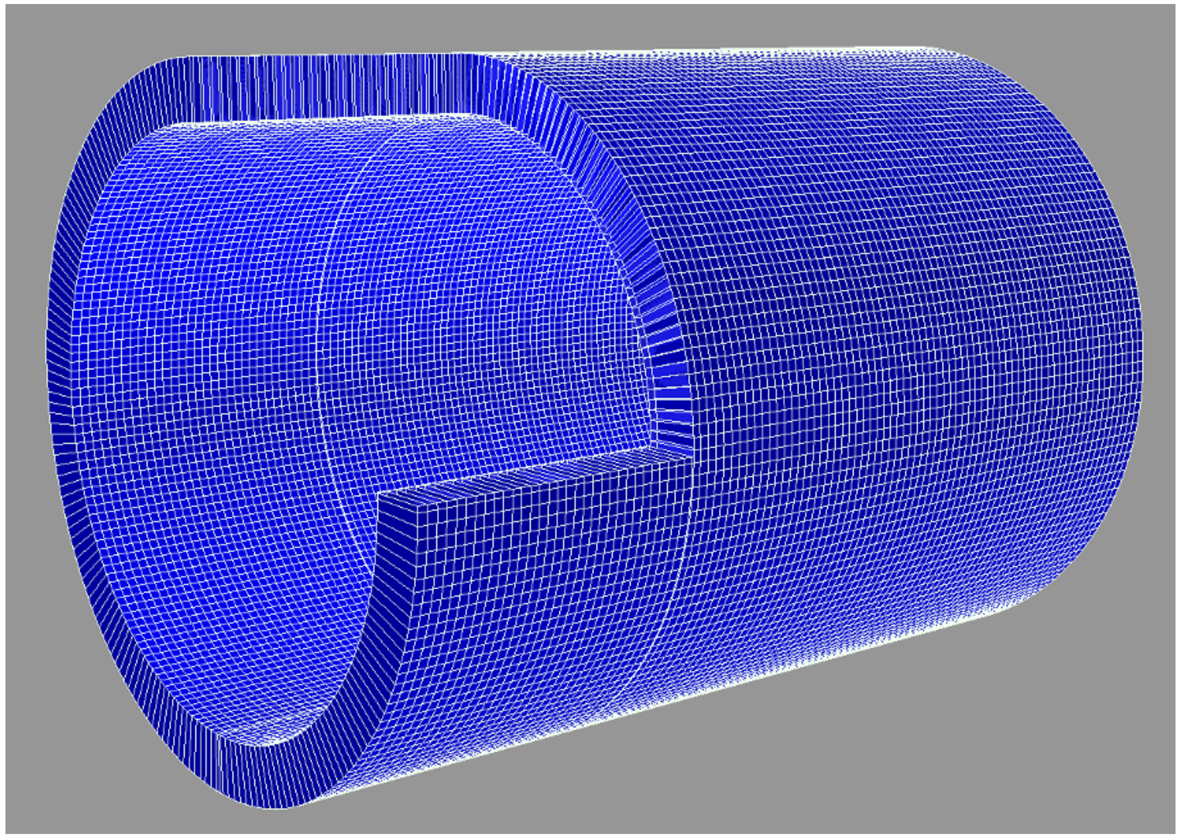


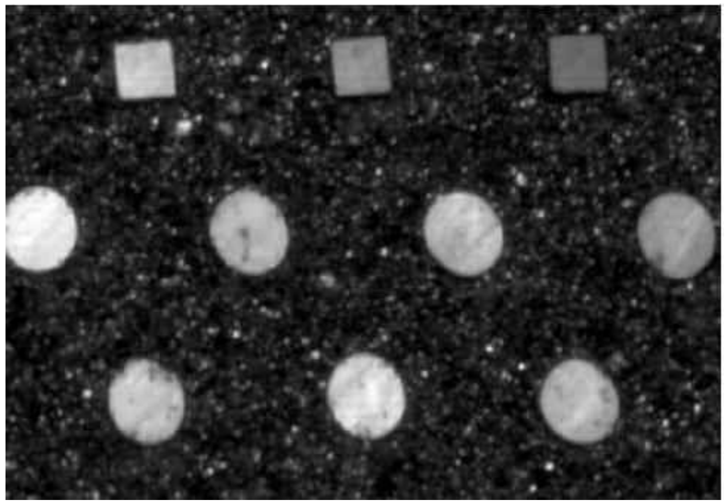




6 Different Prototypes Built to meet EIC Requirements and Tested at FNAL

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

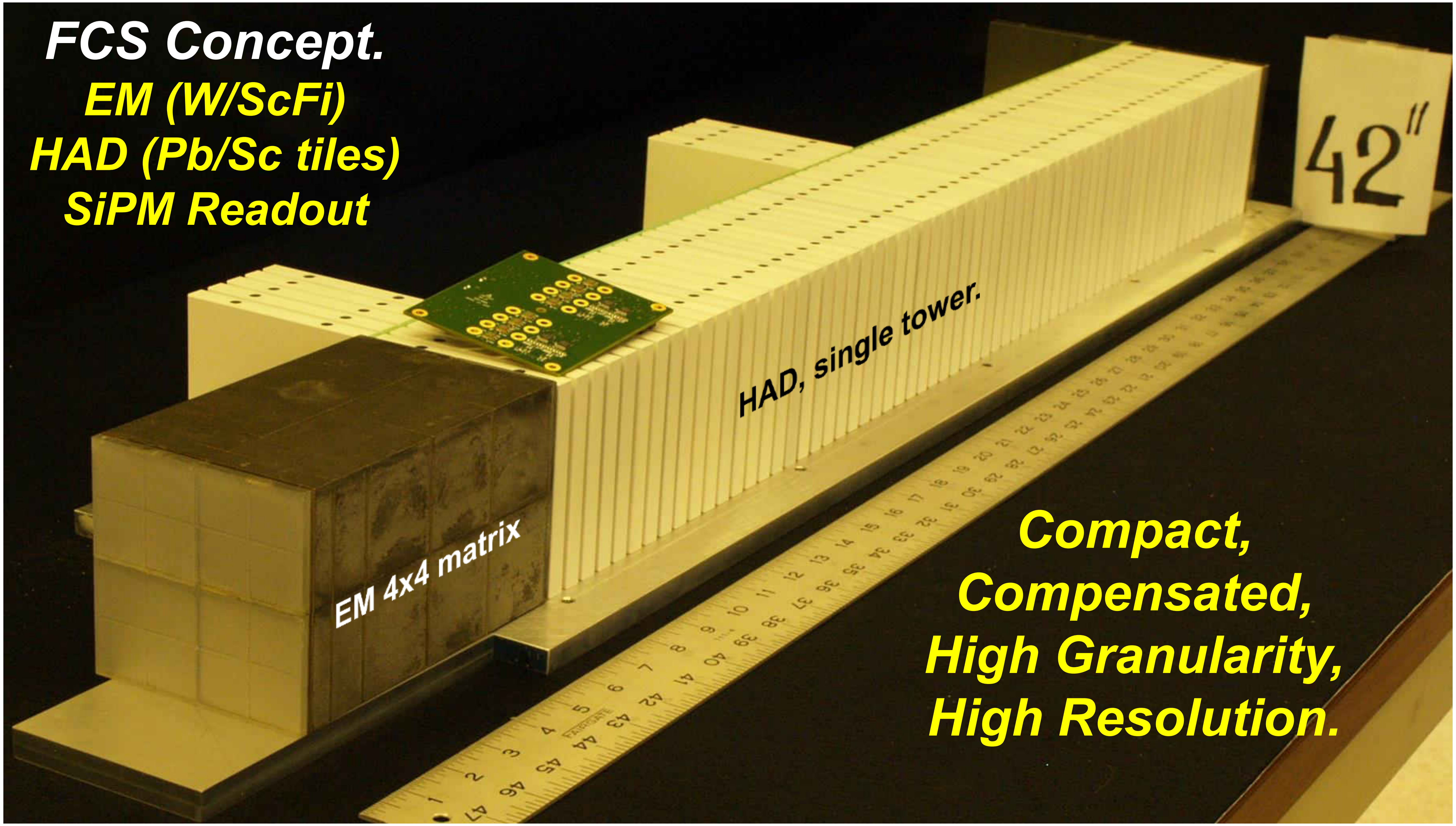
Parameters close to construction steel

- 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

STAR Forward, EIC Forward. Combine H1/ZEUS



FCS Concept.

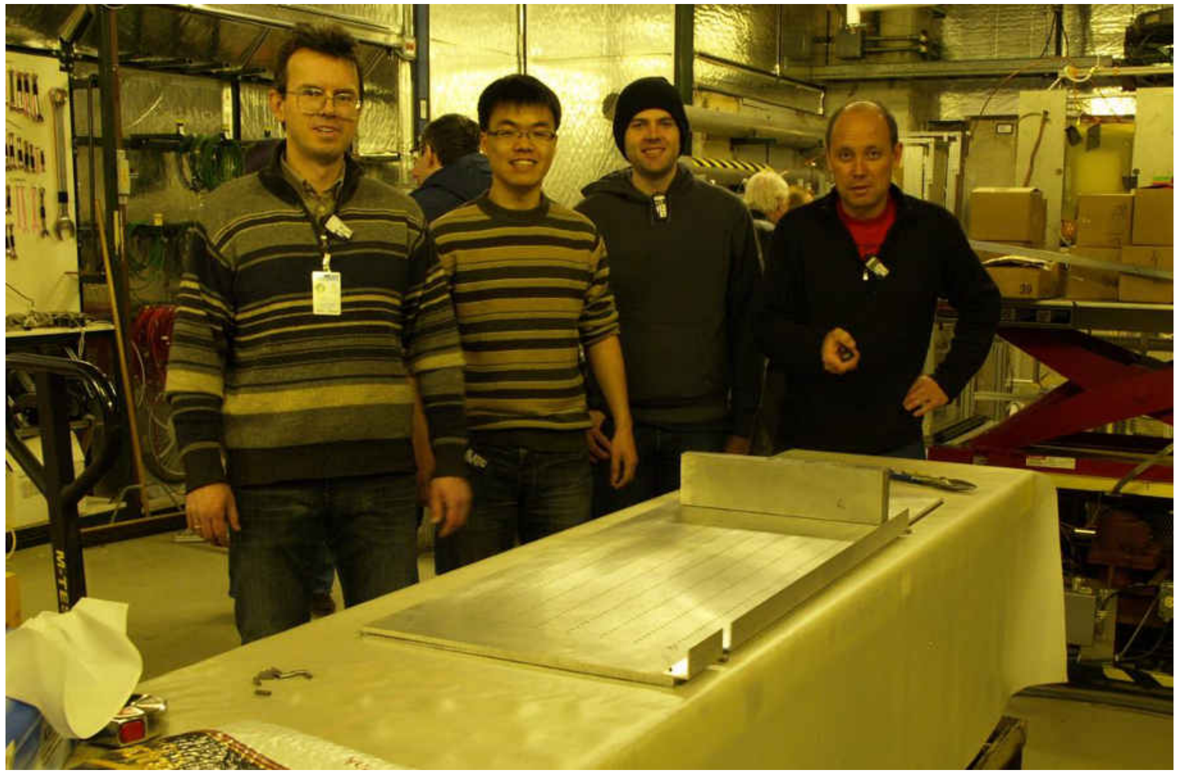
EM (W/ScFi)

HAD (Pb/Sc tiles)

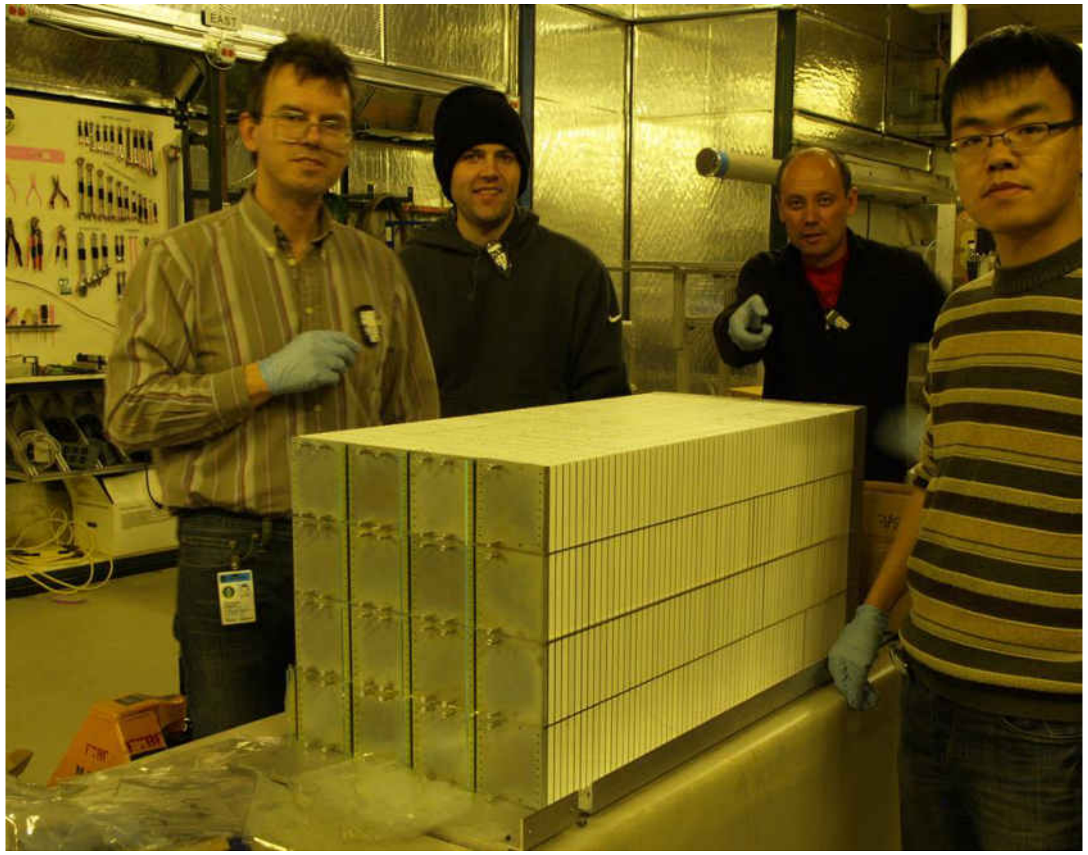
SiPM Readout

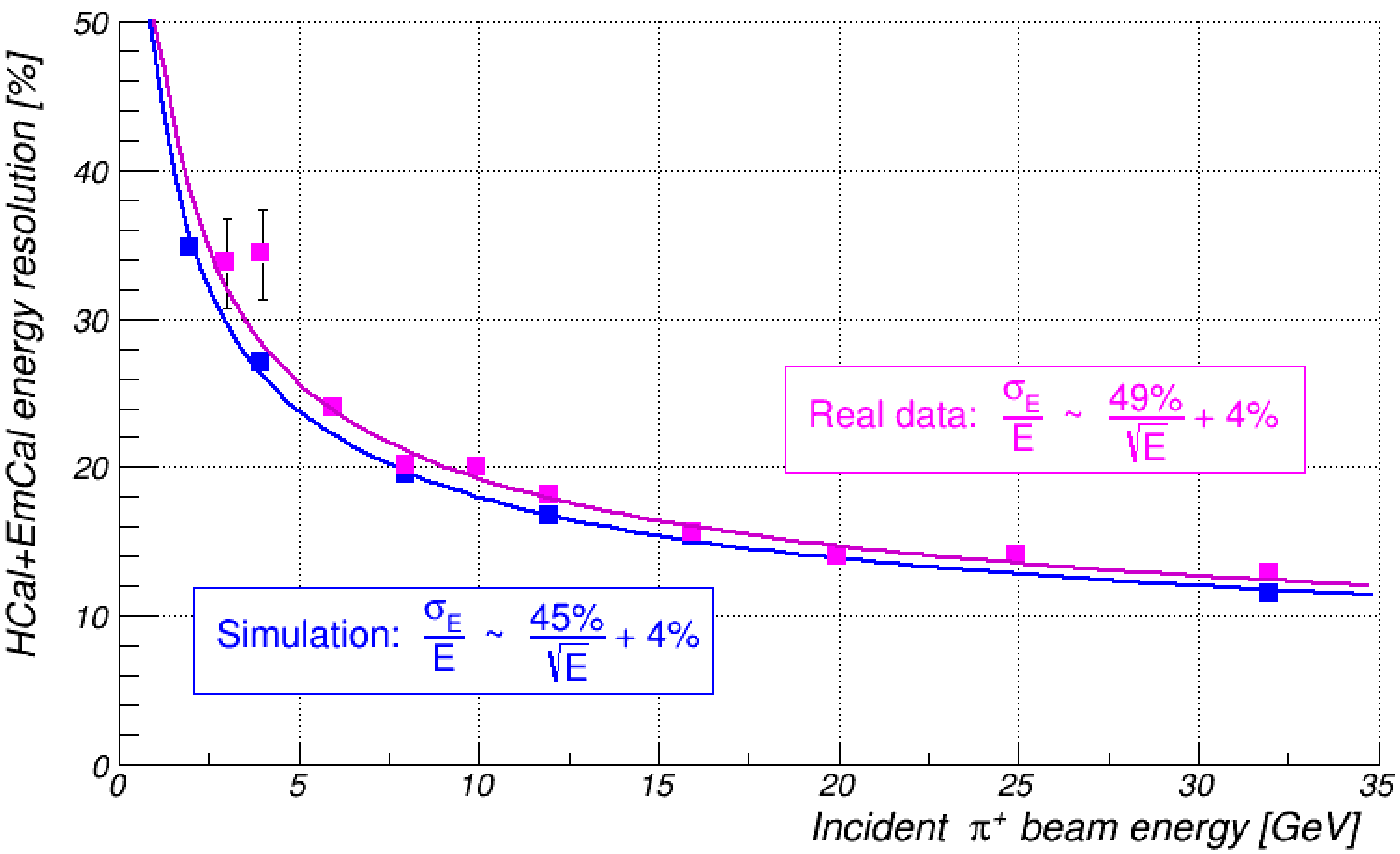
Compact,
Compensated,
High Granularity,
High Resolution.

Assembling HCal Onsite. Feb 26, 2014. FNAL

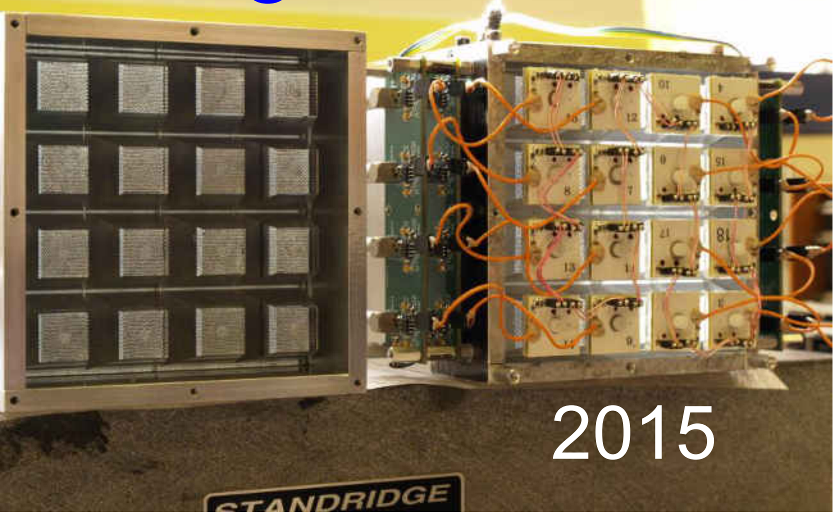


After two hours first layer done.





High Resolution Sampling BEMC, 2016 R&D.



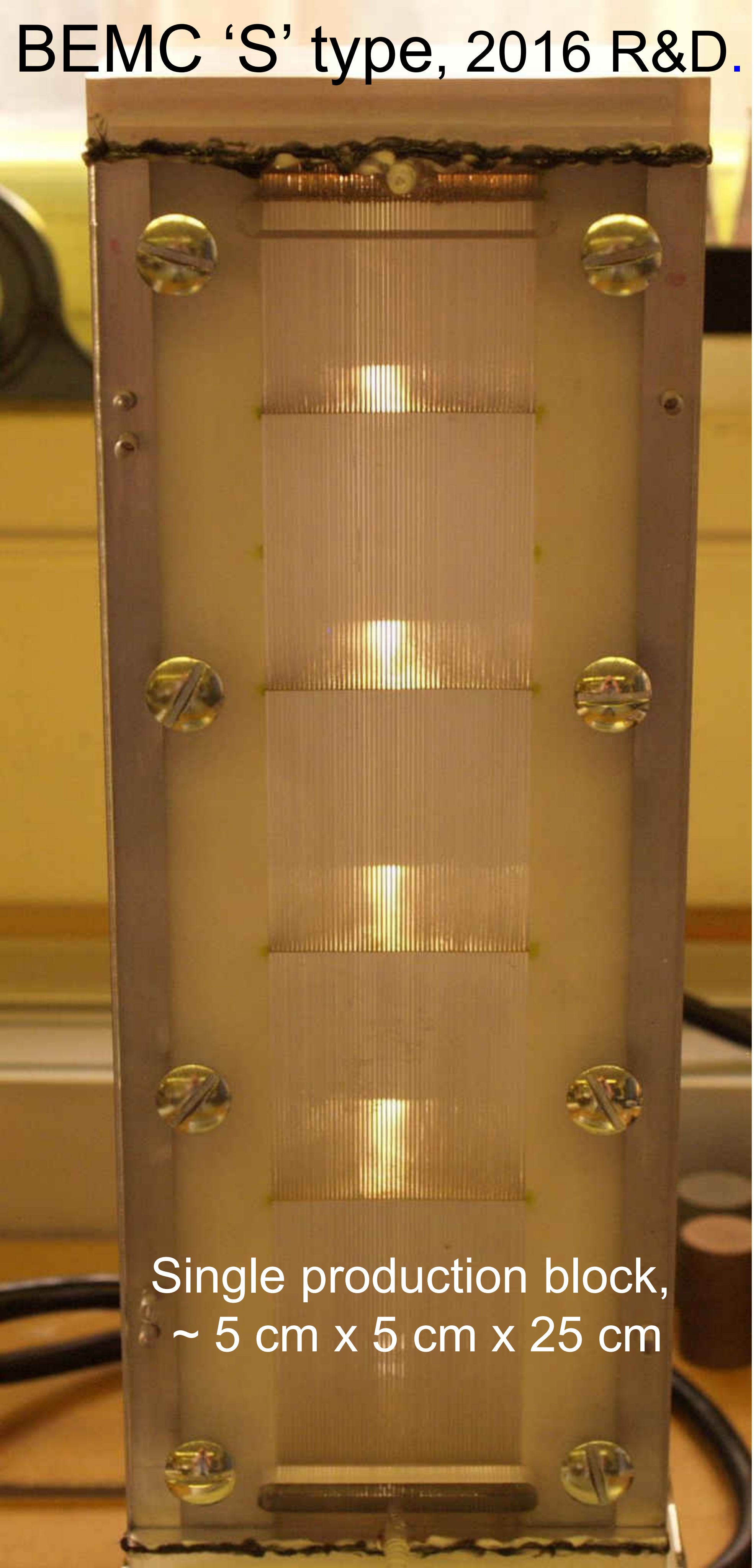
'is W/ScFi technology still feasible towards high-resolution calorimeters with future development?' (After 2015 Test Run)

Potential problems with the first 'O' HR prototype in 2015:

- homogeneity of the composite absorber
- consistency of the sampling frequency with thin fibers
- damage at the end of the fibers due to machining
- efficiency of light collection with compact readout.

In 2016 we proposed to build an additional 'S' prototype which did not have complications with the homogeneity of absorber and consistency of sampling frequency. This prototype consisted of thicker, square fibers and an absorber of 100% W-powder.

Detector	Fibers SCSF 78	Absorber	Sampling Frequency	Composition by weight	Number of fibers in superblock
"Old" High sampling frequency	Round, 0.4mm	75% W 25% Sn	0.671 mm Staggered Pattern	W -0.665 Sn – 0.222 Sc – 0.057 Epoxy- 0.056	25112 Damaged 3
"Square" High sampling fraction	Square, 0.59 x 0.59 mm^2	100% W	0.904 mm Square Pattern	W – 0.858 Sc- 0.075 Epoxy- 0.067	11664 Damaged 0



BEMC ‘S’ type, 2016 R&D.

Single production block, ~ 5 cm x 5 cm x 25 cm

Why to try square scintillation fibers?

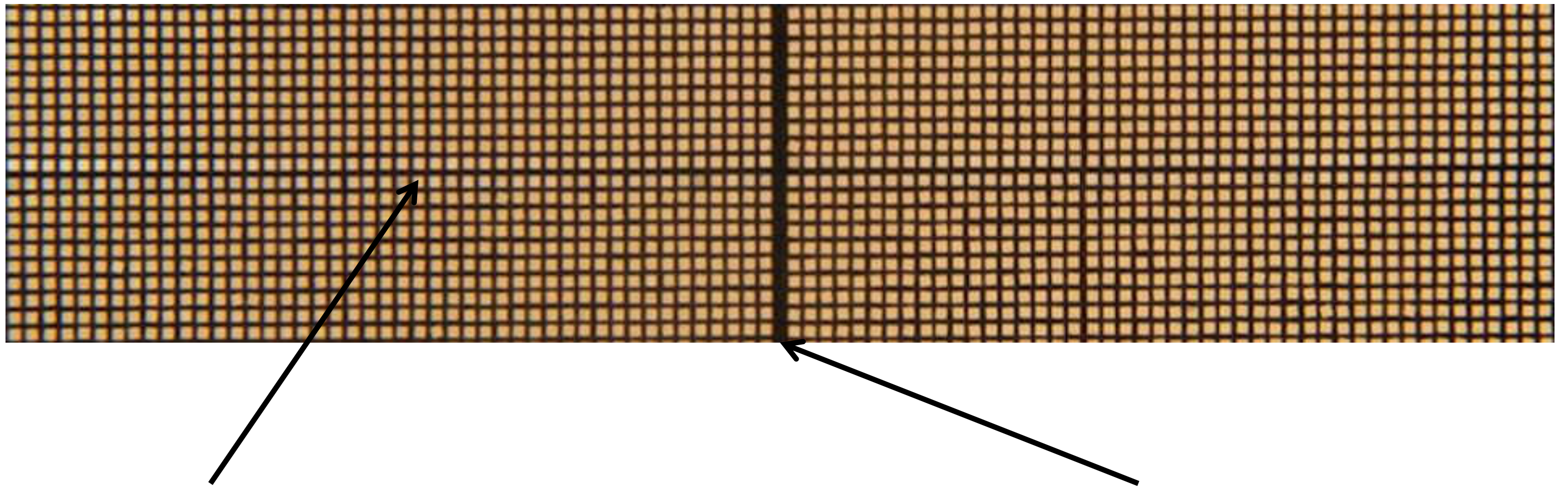
No ScFi calorimeters in the past were built with square fibers.

Pros:

- better light yield (according to Kuraray ~ 30% better trapping efficiency compared to round fibers, which is particularly interesting for compact light collection scheme)
- internal structure of the detector can be made more homogeneous
- easier to preserve sampling fraction and frequency within and between superblocks (glued from four production blocks).
- larger surface area for a given volume

Cons:

- more expensive
- more difficult to feed through the set of screens



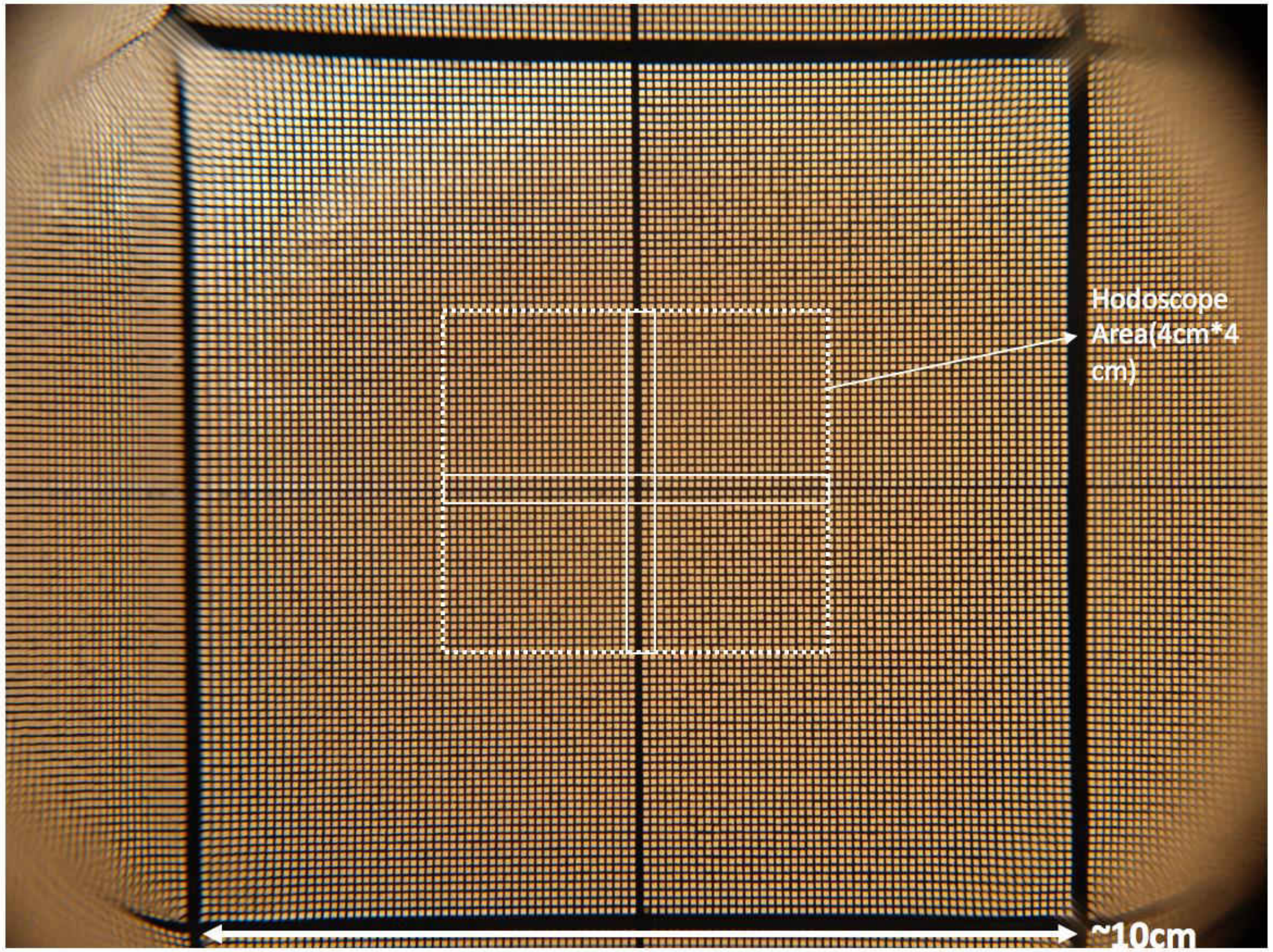
Joint between two production blocks

Joint between two doublets (‘Crack’)

Test Run 2016 FNAL, May 4-11:

Questions we want to understand:

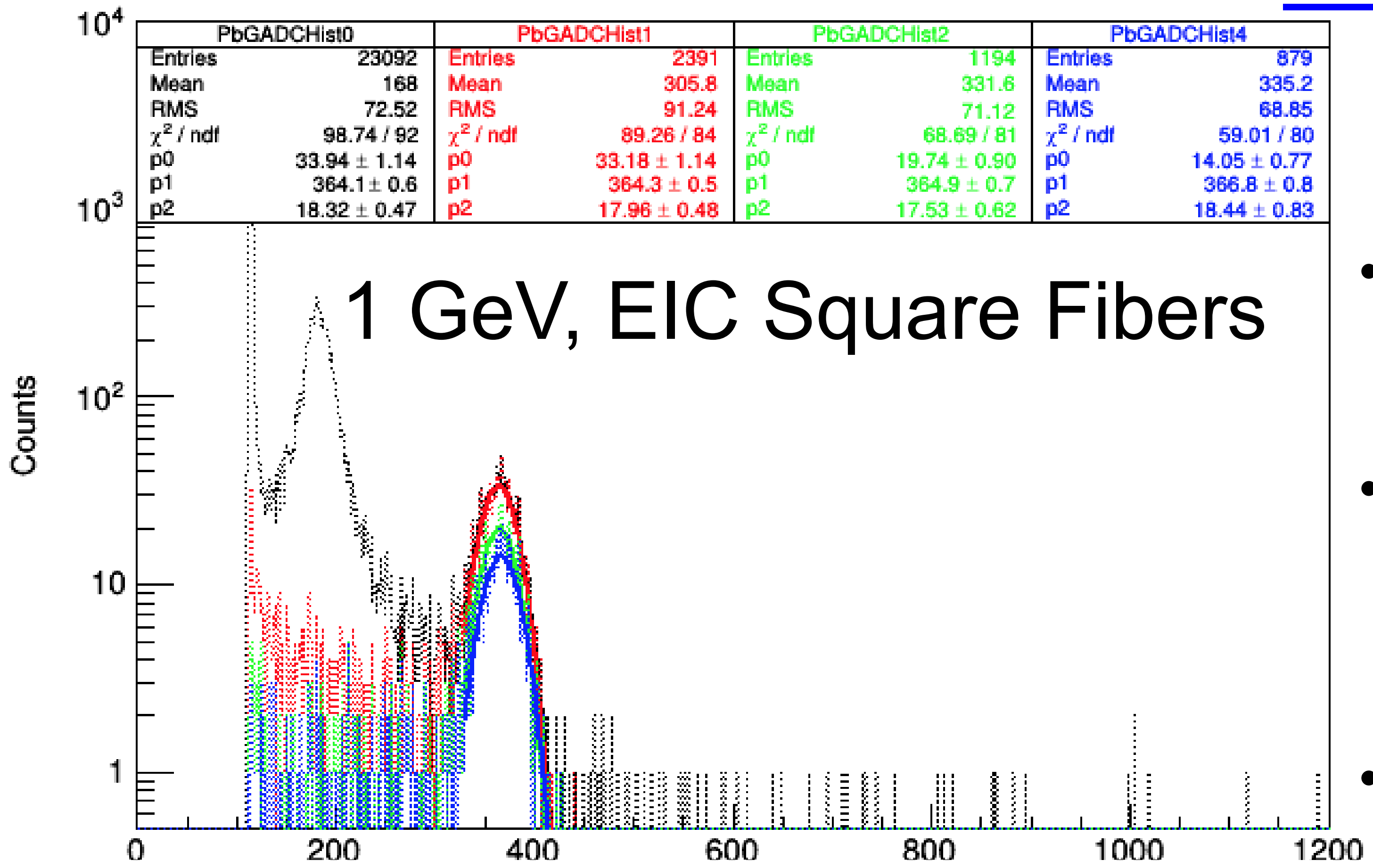
- Is production homogentity of the block sufficient? (SF kept within +-0.2% (weight) from block to block during production)
- Is local density/composition variations are under control? (W/Sn composite absorber during packing)
- Is light yield is sufficient to think about compact readout with Si sensors in future?
- What is the effect of 'dead' area between superblocks.
- What are benefits of using square fibers?

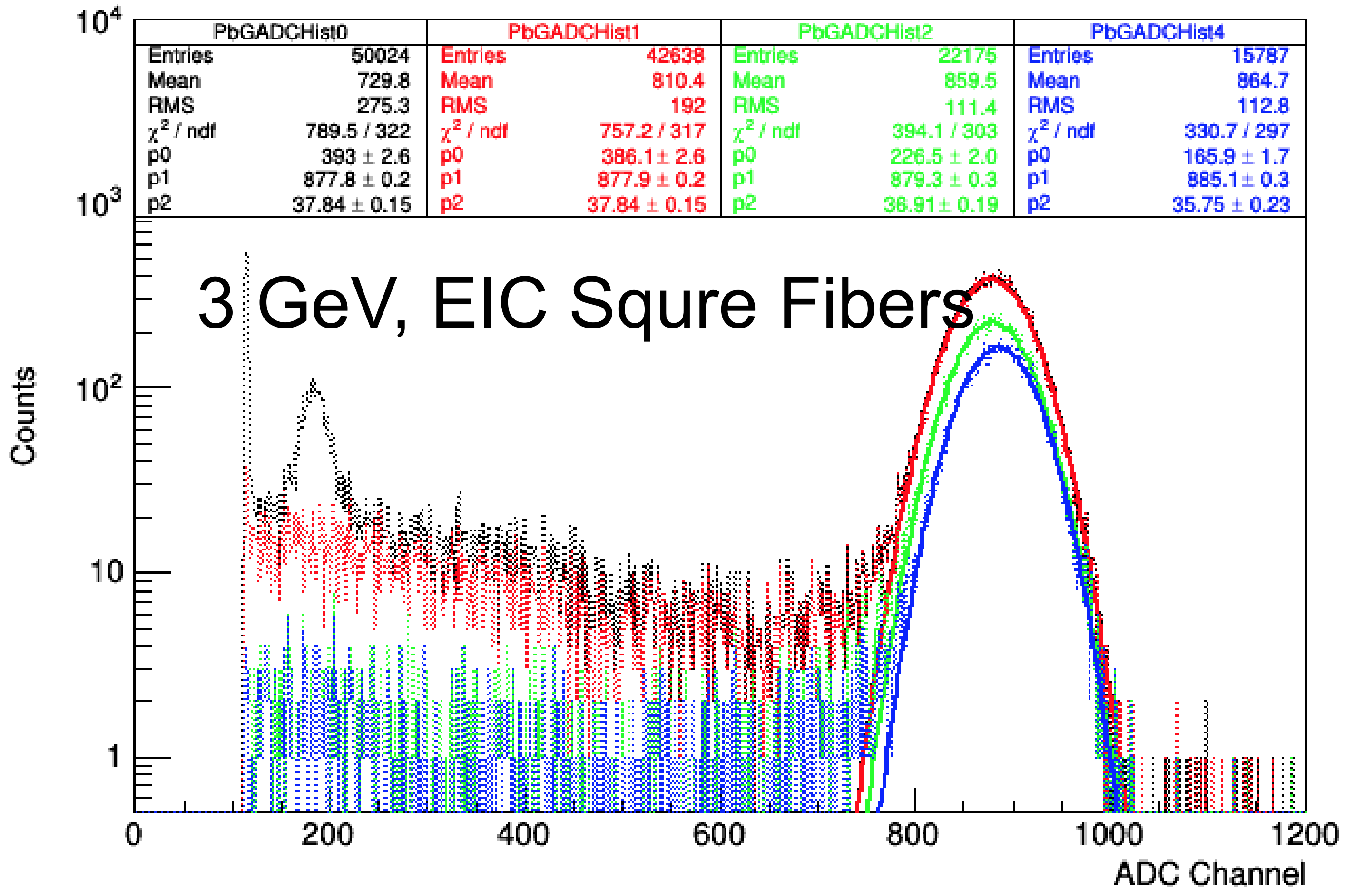


Results presented for the worst case scenario.

- Impact hits selected with sc. Hodoscope centered between four blocks.
- Impact angle 10 degrees (minimal angle for EIC configuration).
- Energy scans taken with orientation of 'wide' central gap being vertical as shown and horizontal, i.e. for cases when narrow core of EM showers sample or integrate dead area.
- 'S' and 'O' tested one by one using the same calibrated PMT

Test Run 2016 FNAL, May 4-11:





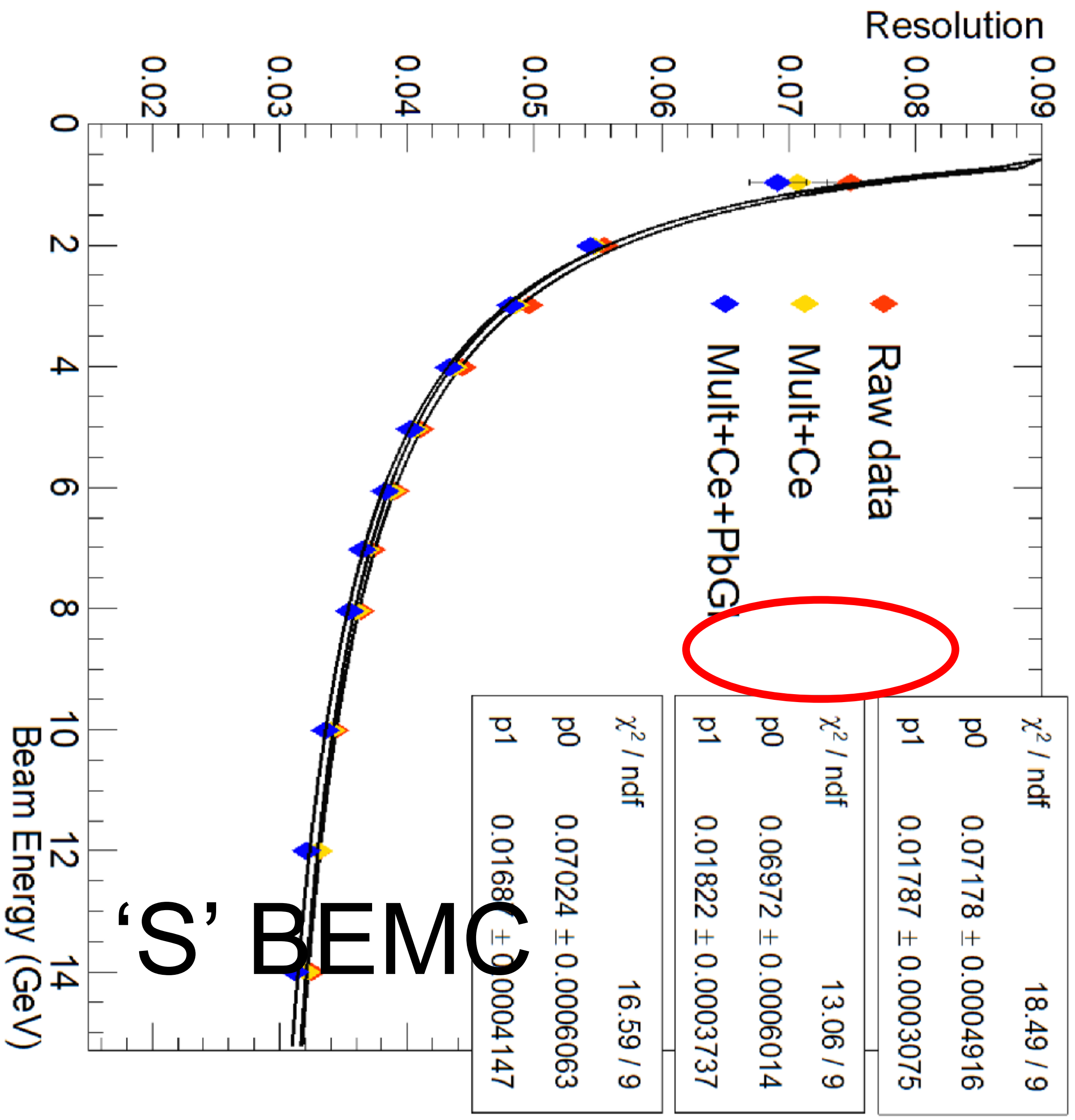
Notes on analysis:

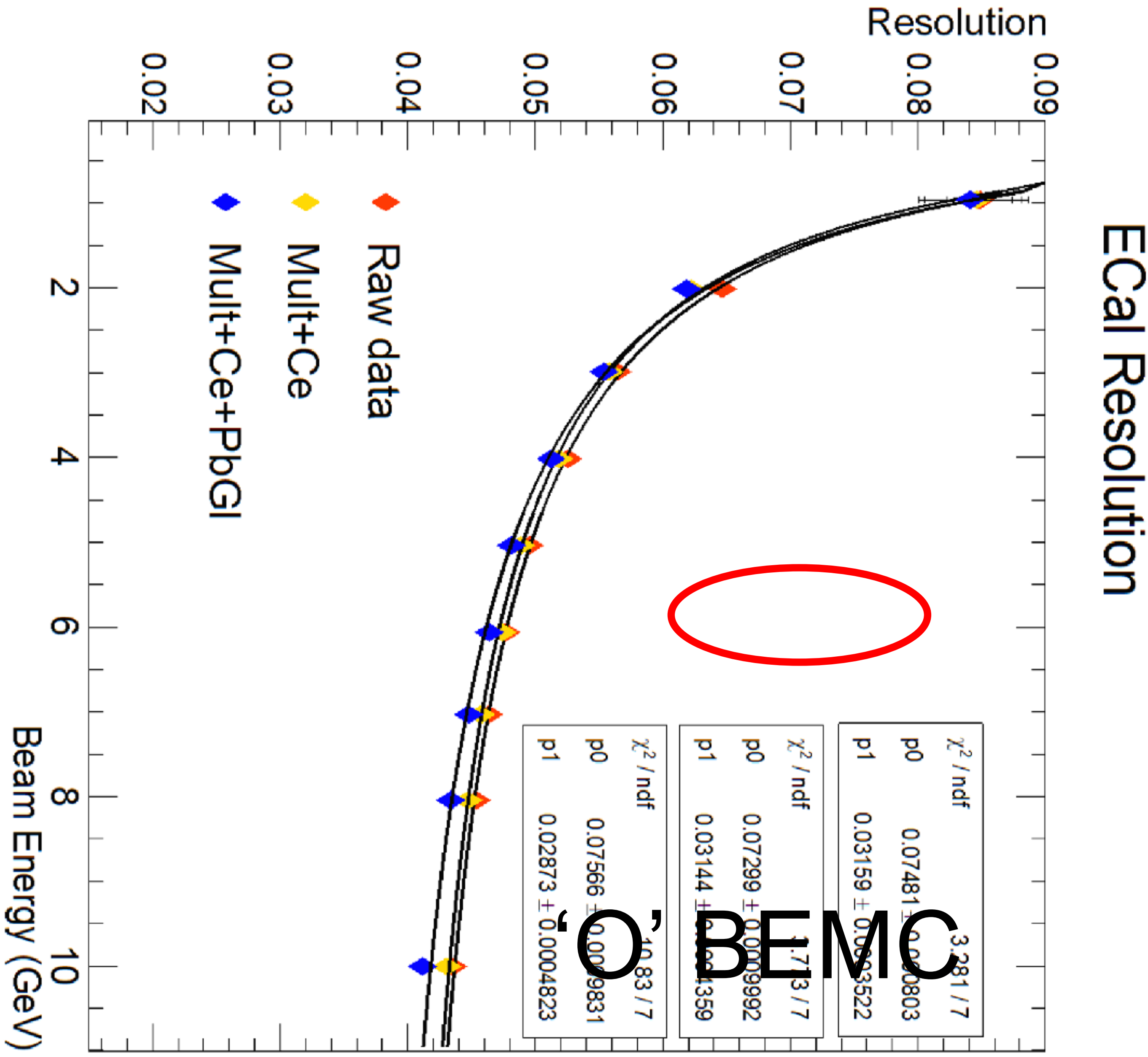
- Beam momentum spread estimated using FTBF PbGl Calorimeter is 1.8%
- Fitting range -2 + 5 sigma for energies below 3 GeV. (Radiative losses in the beam line, range guided by MC).
- Above 2 GeV fitting range -+ 5 sigma.
- Notes about test run conditions and student's analysis reports can be found at https://wiki.bnl.gov/eic/index.php/RD-Calo-2016-05-11#Agenda

Cuts Color Scheme:
Black – Raw Data
Red – Cherenkov, Electron ID
Green - Cherenkov + One Hit in Sc. Hodoscope
Blue – Cherenkov + One Hit in Hodoscope + Geometry

Test Run 2016 FNAL, May 4-11:

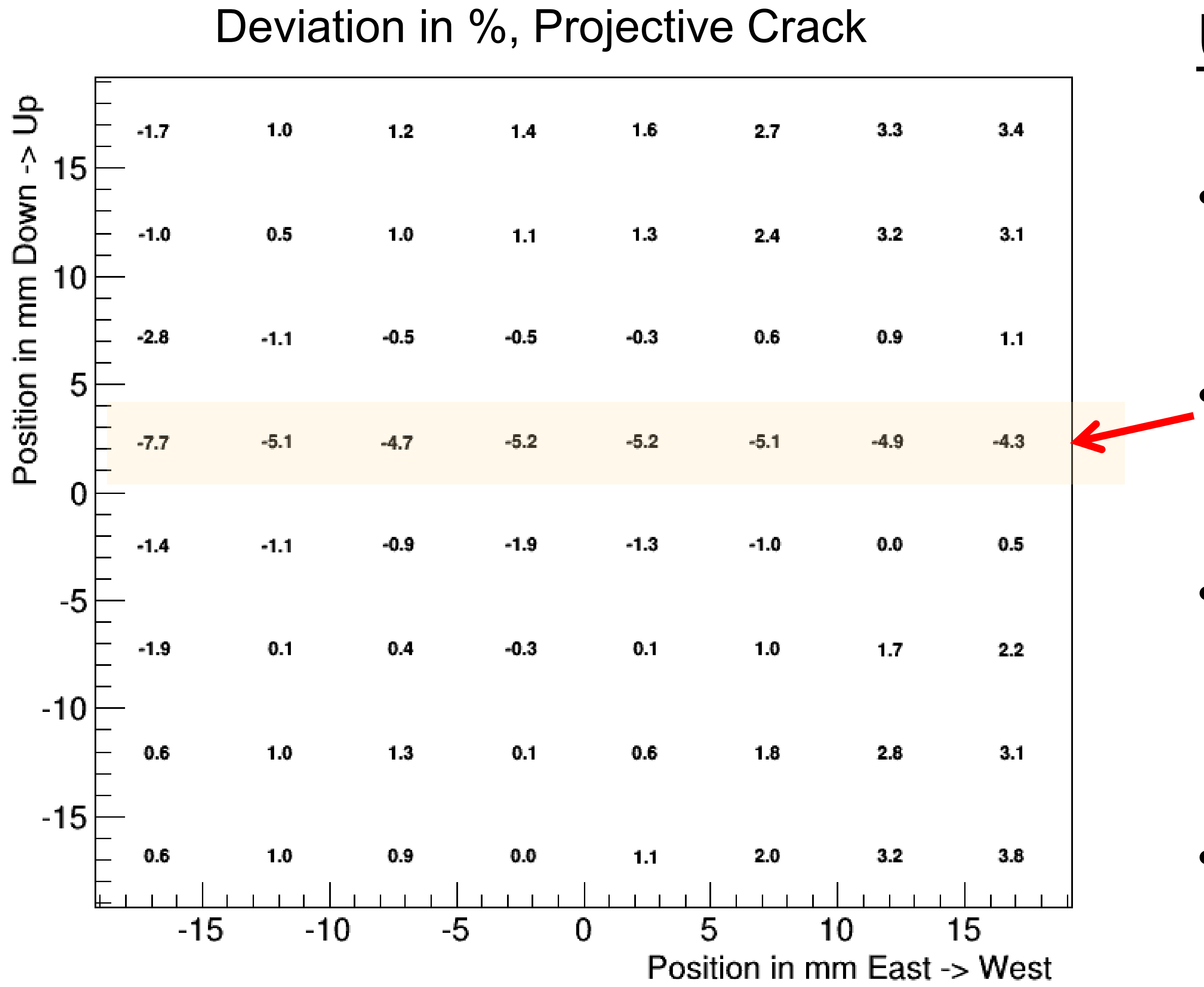
Minimal set of cuts





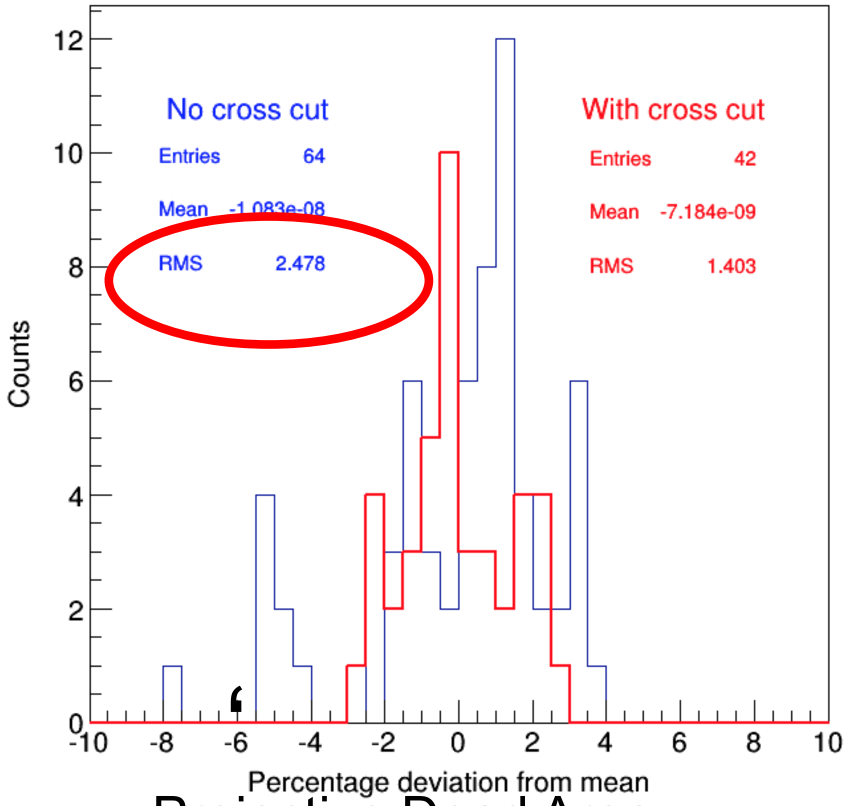
- 'S' has about 20% better resolution at 1 GeV
- 'S' constant term 1.7% compare to 2.9% for 'O'
- 'S' Light Yield ~ 5000 p.e./GeV, 'O' LY – 3500 p.e./GeV

Mult – one hit in Sc. Hodoscope, Ce – electrons ID using Cherenkov, PbGl – veto on hits in the PbGl

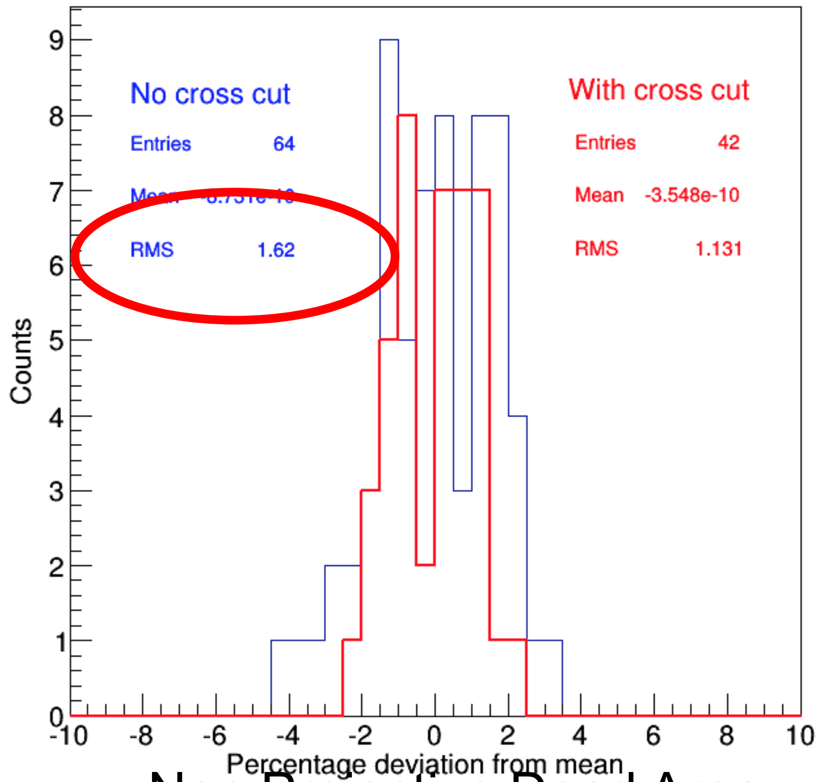


Uniformity Studies:

- Data sample 4 GeV electrons, 1k e- evt. in pixel 5mm x 5mm
- ‘Cracks’ clearly seen for hits within +- 2.5 mm to the crack
- Projective dead areas (horizontal orientation of the ‘crack’) increases constant term by ~ 50%.
- Projective dead areas increases dip near the ‘crack’ by ~ 100%.



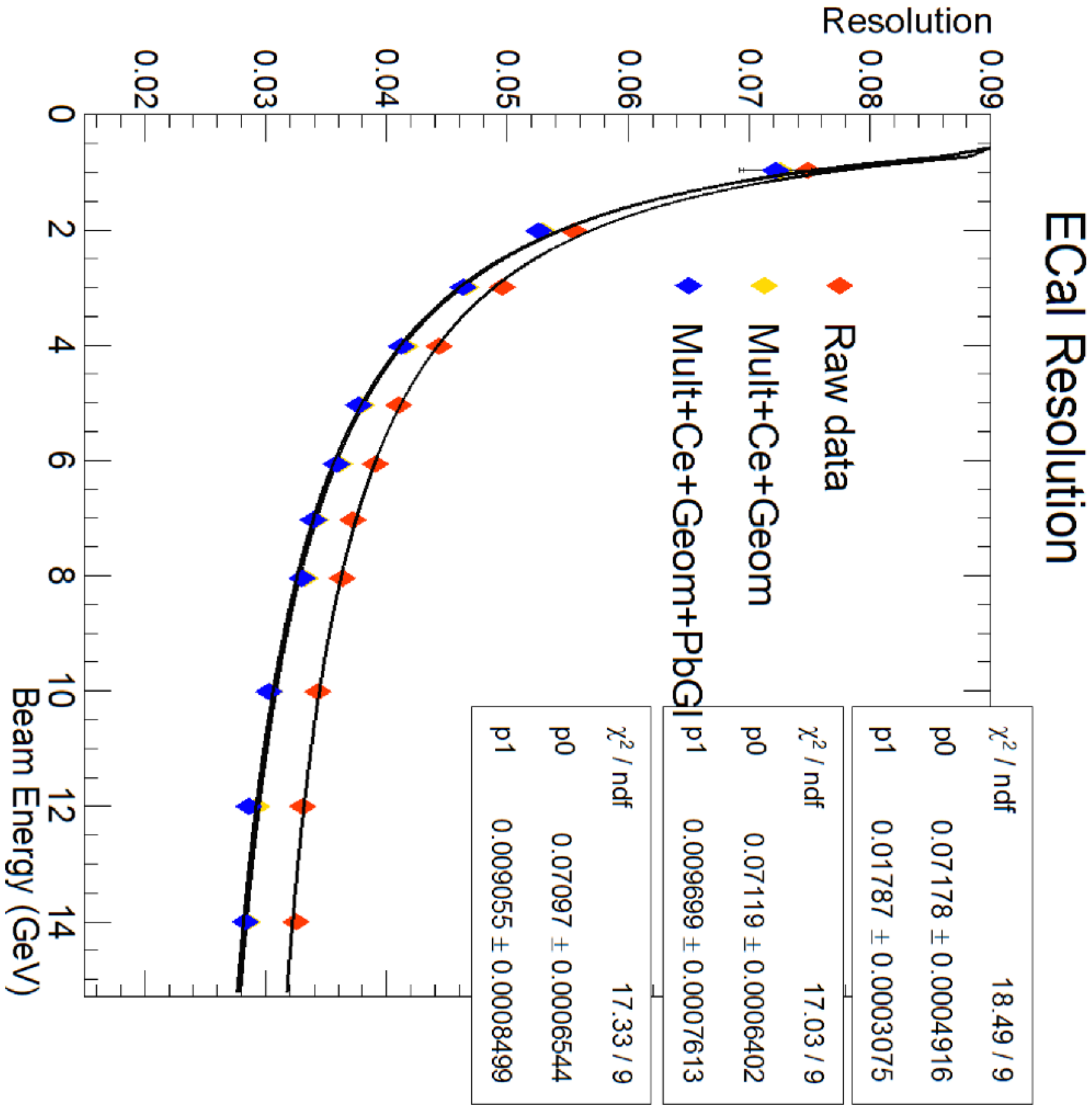
Projective Dead Area

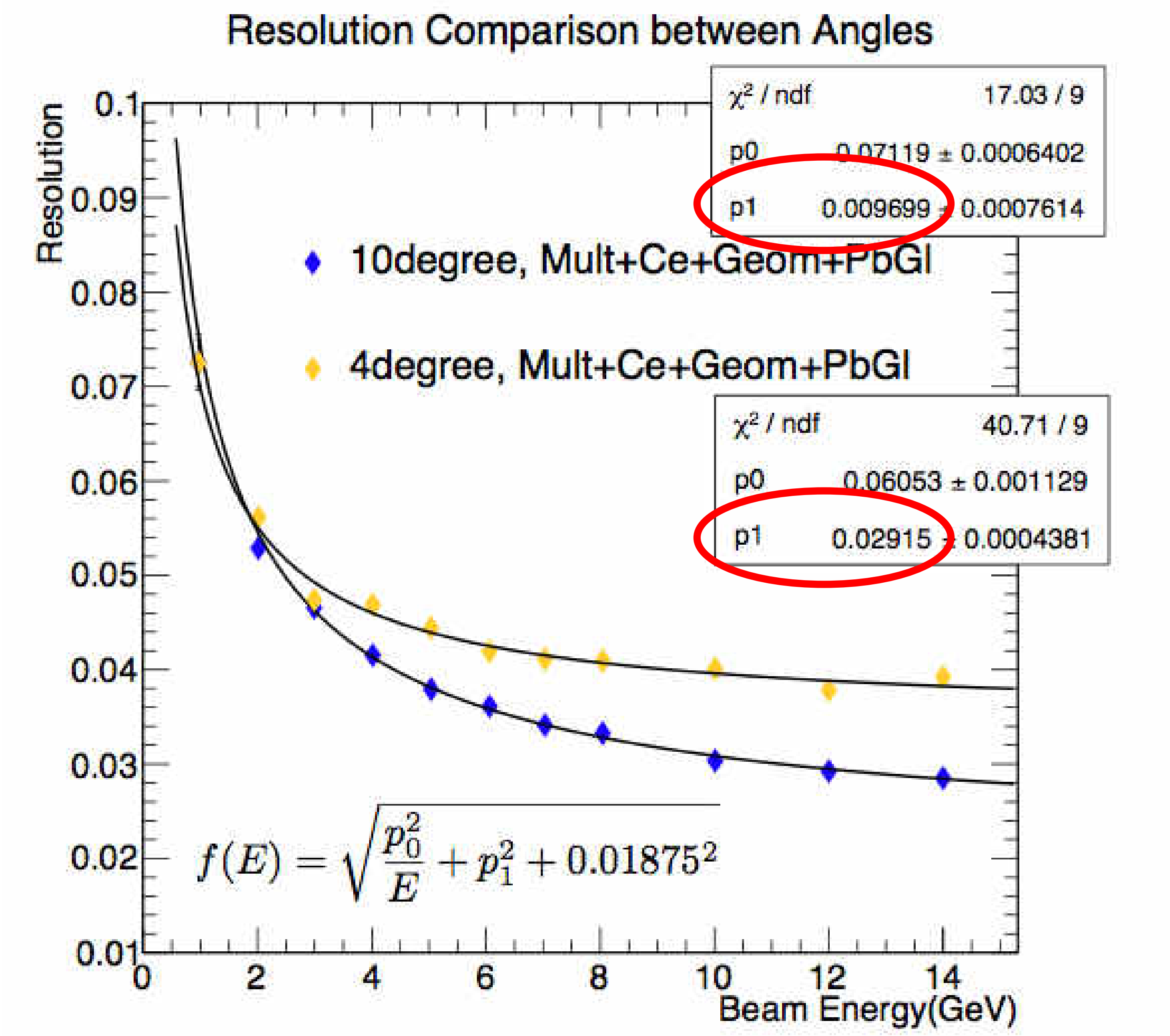


Non Projective Dead Area

Test Run 2016 FNAL, May 4-11:

‘S’ BEMC, and Projectivity





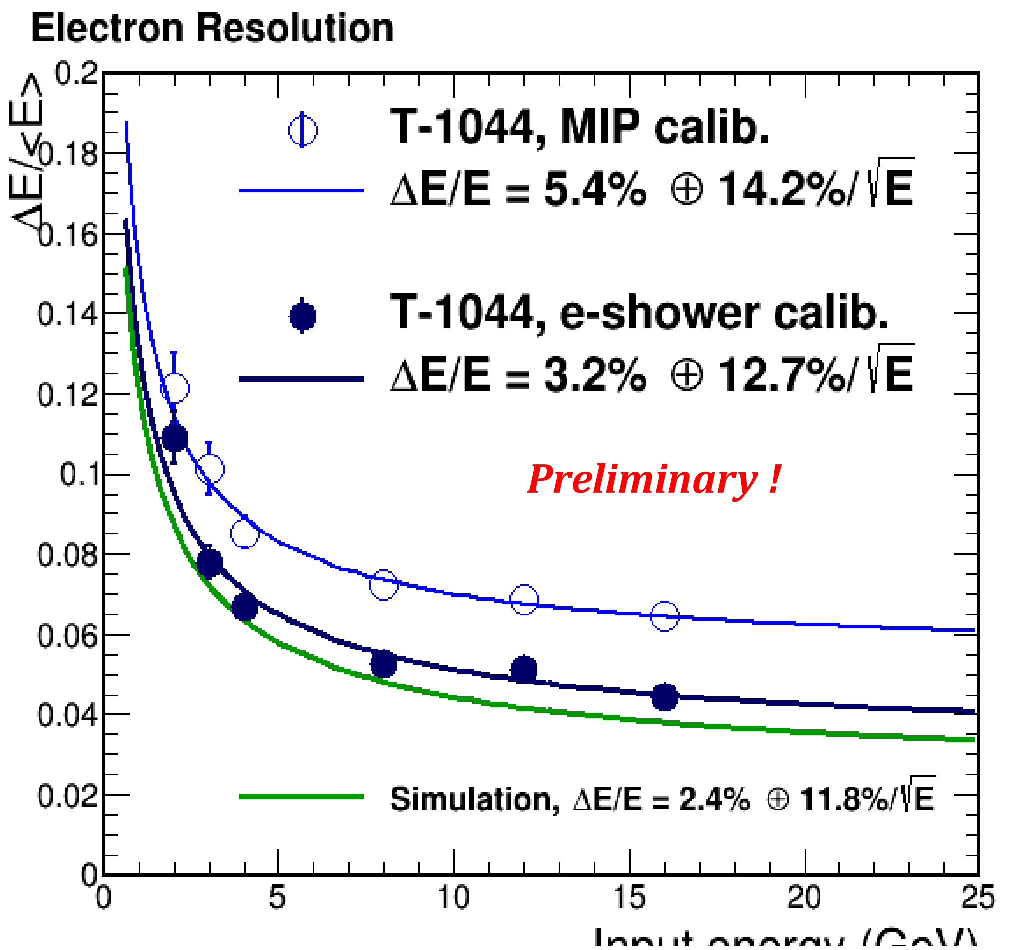
Excluding hits within +-2.5 mm within crack. Non-projective dead area.

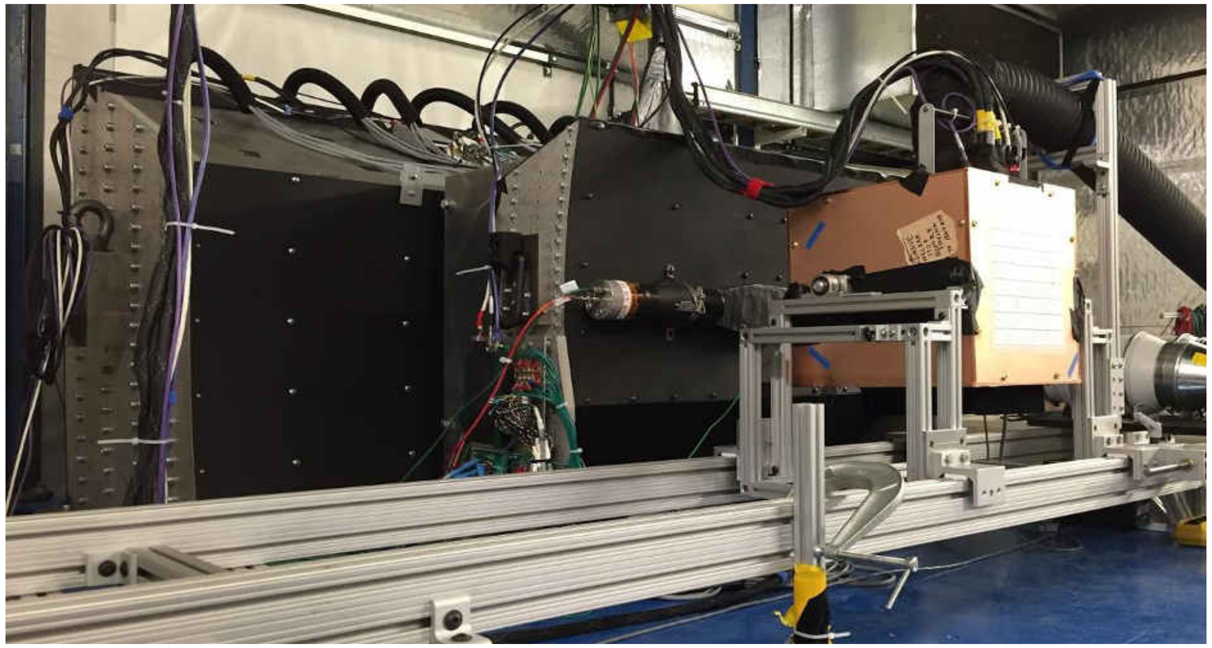
- 1% constant term at 10 degrees.
- 2.9% constant term at 4 degrees.

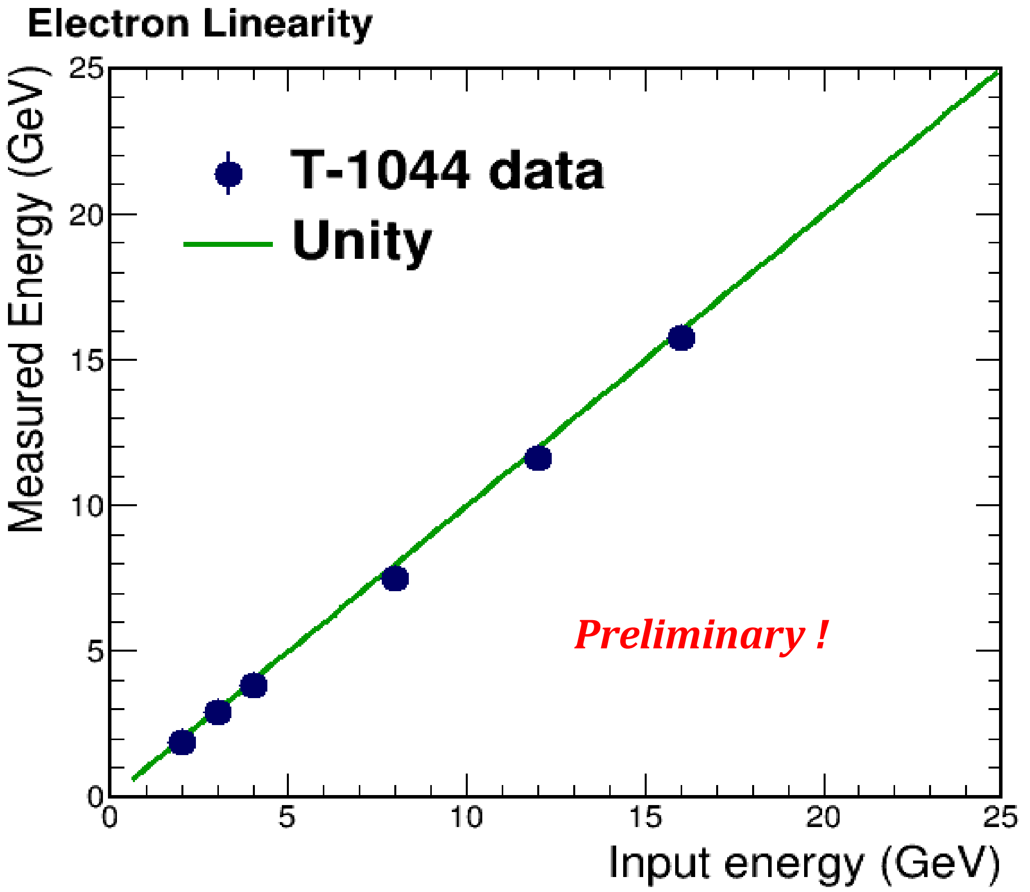
- A similar analysis was made for the ‘O’ prototype. With the same ‘Geom’ cut used for ‘S’ detector, the constant term is about 2.6% at 10 degrees. The only explanation for this is that the combination of composite absorber and thin fibers does prevented us from keeping the sampling fraction within production blocks sufficiently uniform.

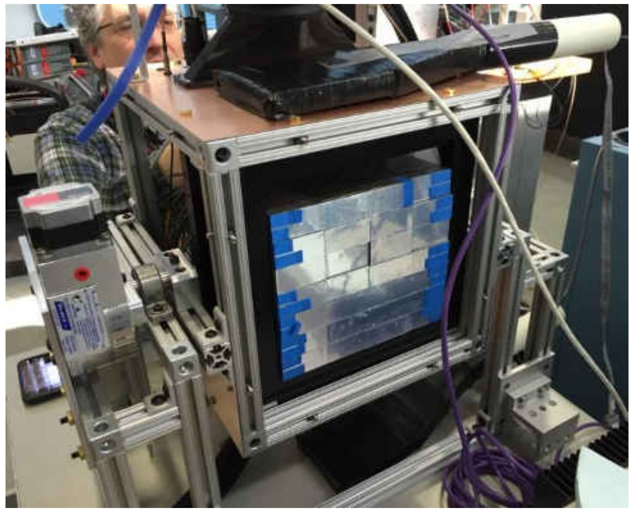
sPHENIX, Test Run 2016 FNAL

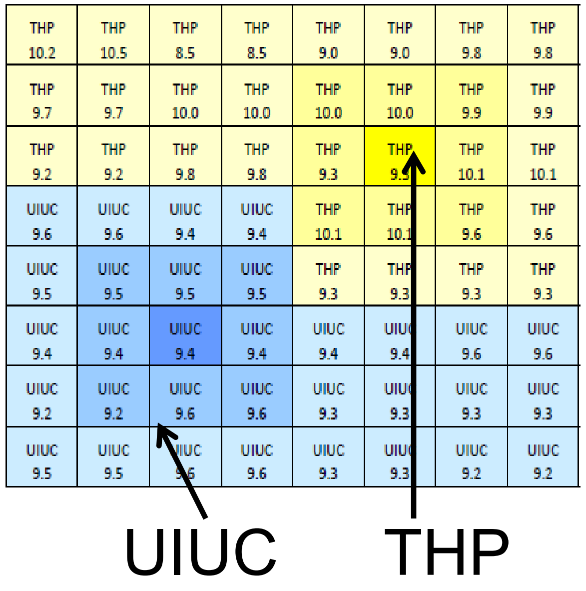
- Main goal for this R&D period was to build and test sPHENIX EMcal prototype using a process that could lead to mass production of the absorber blocks.
- The analysis of the test beam data is still under way. Preliminary results shown here were not corrected for beam momentum spread which is believed to be about 2%.





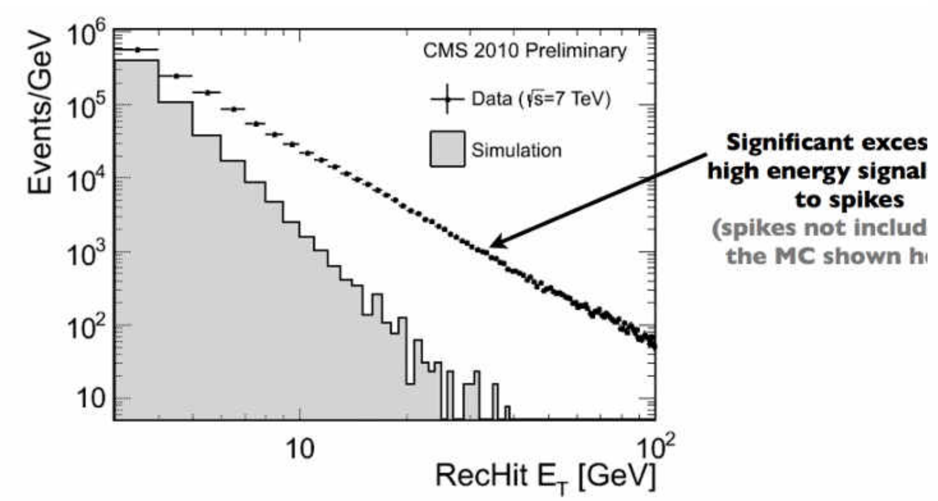


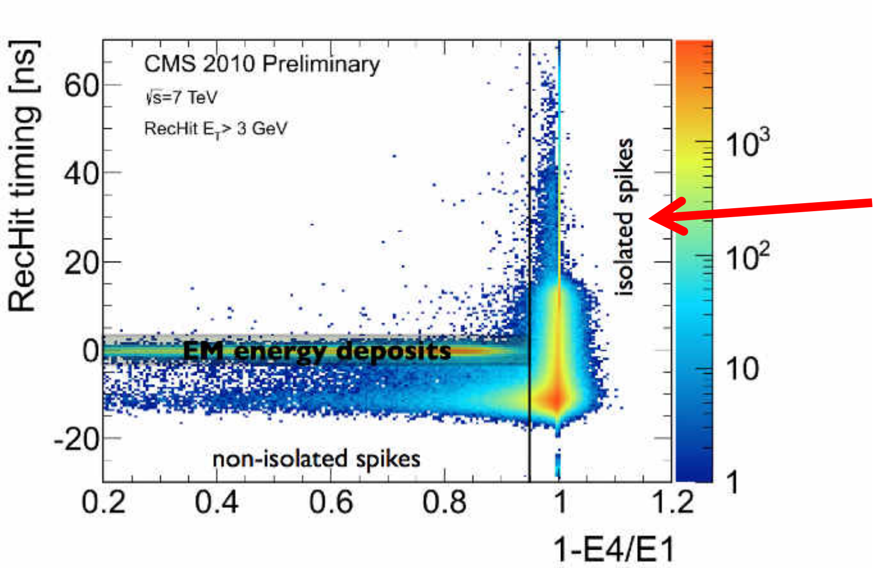


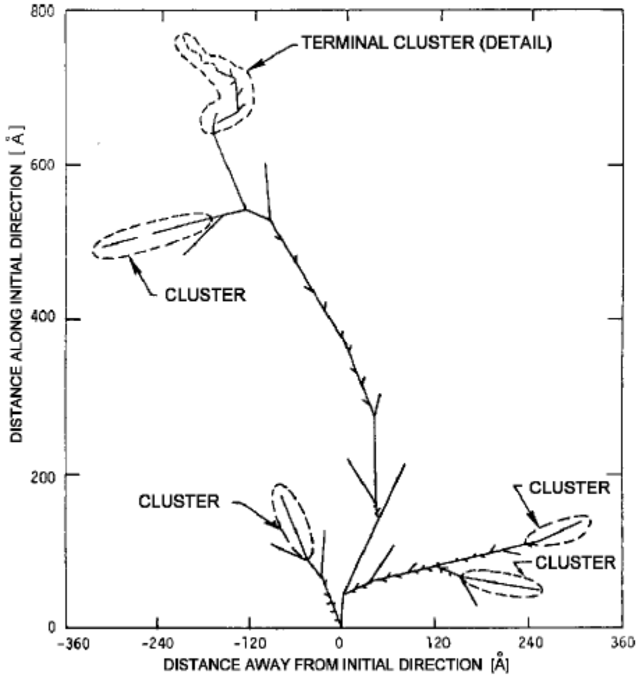


THP 10.2	THP 10.5	THP 8.5	THP 8.5	THP 9.0	THP 9.0	THP 9.8	THP 9.8
THP 9.7	THP 9.7	THP 10.0	THP 10.0	THP 10.0	THP 10.0	THP 9.9	THP 9.9
THP 9.2	THP 9.2	THP 9.8	THP 9.8	THP 9.3	THP 9.3	THP 10.1	THP 10.1
UIUC 9.6	UIUC 9.6	UIUC 9.4	UIUC 9.4	THP 10.1	THP 10.1	THP 9.6	THP 9.6
UIUC 9.5	UIUC 9.5	UIUC 9.5	UIUC 9.5	THP 9.3	THP 9.3	THP 9.3	THP 9.3
UIUC 9.4	UIUC 9.4	UIUC 9.4	UIUC 9.4	UIUC 9.4	UIUC 9.4	UIUC 9.6	UIUC 9.6
UIUC 9.2	UIUC 9.2	UIUC 9.6	UIUC 9.6	UIUC 9.3	UIUC 9.3	UIUC 9.3	UIUC 9.3
UIUC 9.5	UIUC 9.5	UIUC 9.6	UIUC 9.6	UIUC 9.3	UIUC 9.3	UIUC 9.2	UIUC 9.2

Critical Tests SiPMs and APDs in ’realistic’ conditions:



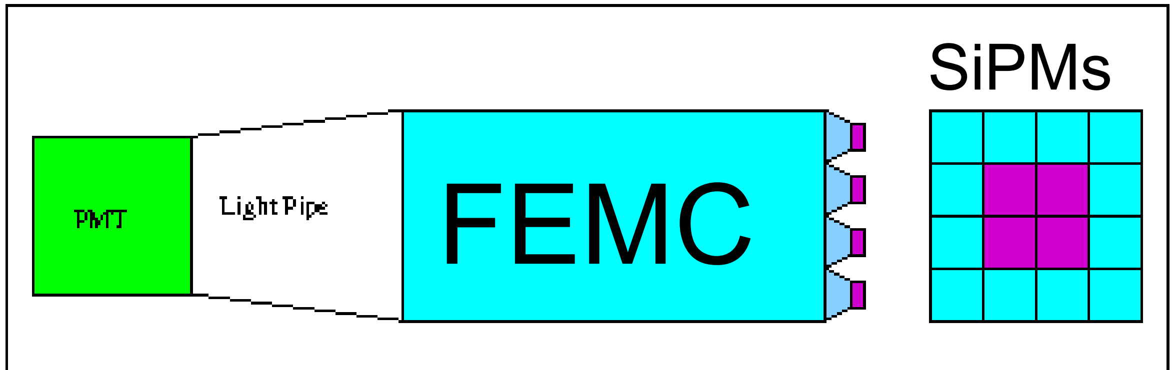


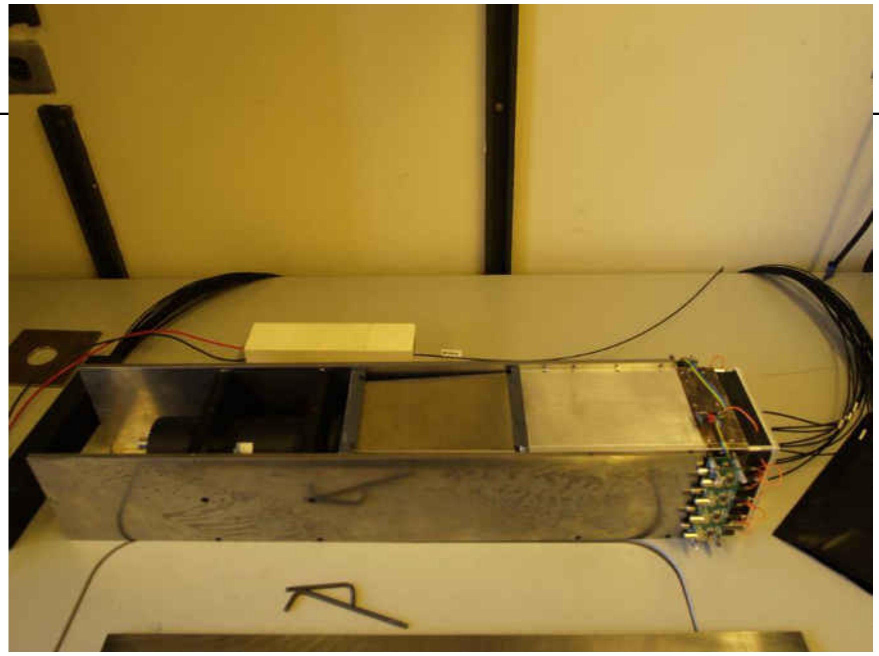


50 keV, PKA

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

- 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?



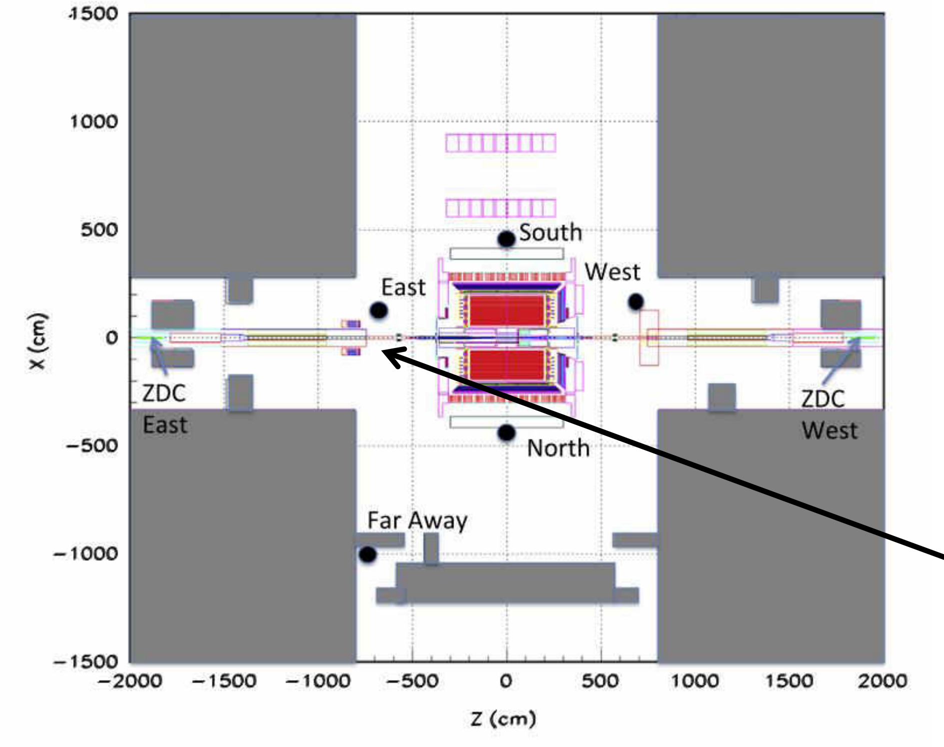


Test at STAR IP during Run16:

- 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).
- Installed at the East Side of the STAR Detector about 1 meter away from the beam pipe.
- SiPM HT. data set taken during AuAu run.
- APDs HT. data set taken during dAu run. Gap in data taking is due to test run at FNAL.

SiPMs and APDs in ’realistic’ conditions:

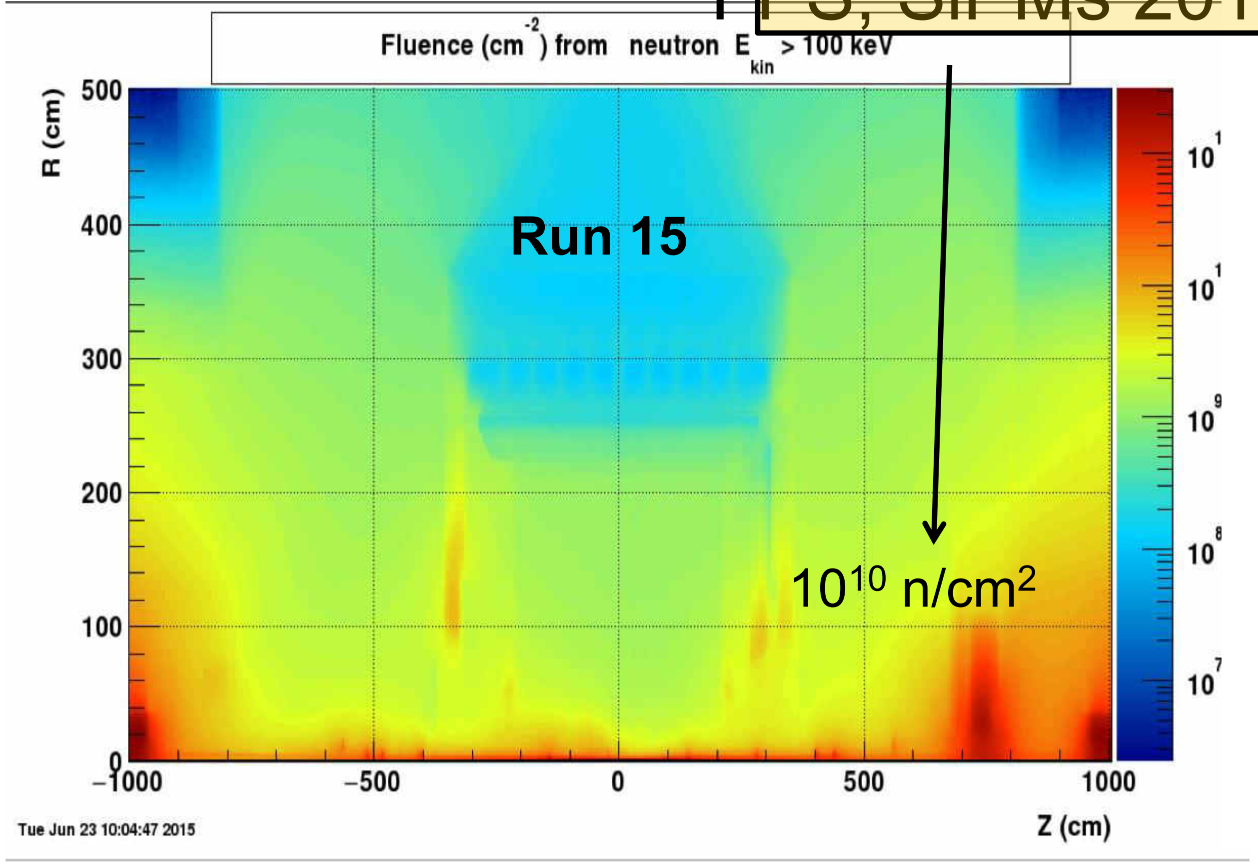
- STAR IP ideal test place for EIC. Well understood conditions (measurements in 2013 thermal neutrons, 2015 ‘MeV’ neutrons with Forward Preshowers (FPS) SiPMs + MC).
- EICRoot tuned using STAR data.
- Conditions for FEMC in BeAST very close to one we have in STAR now.

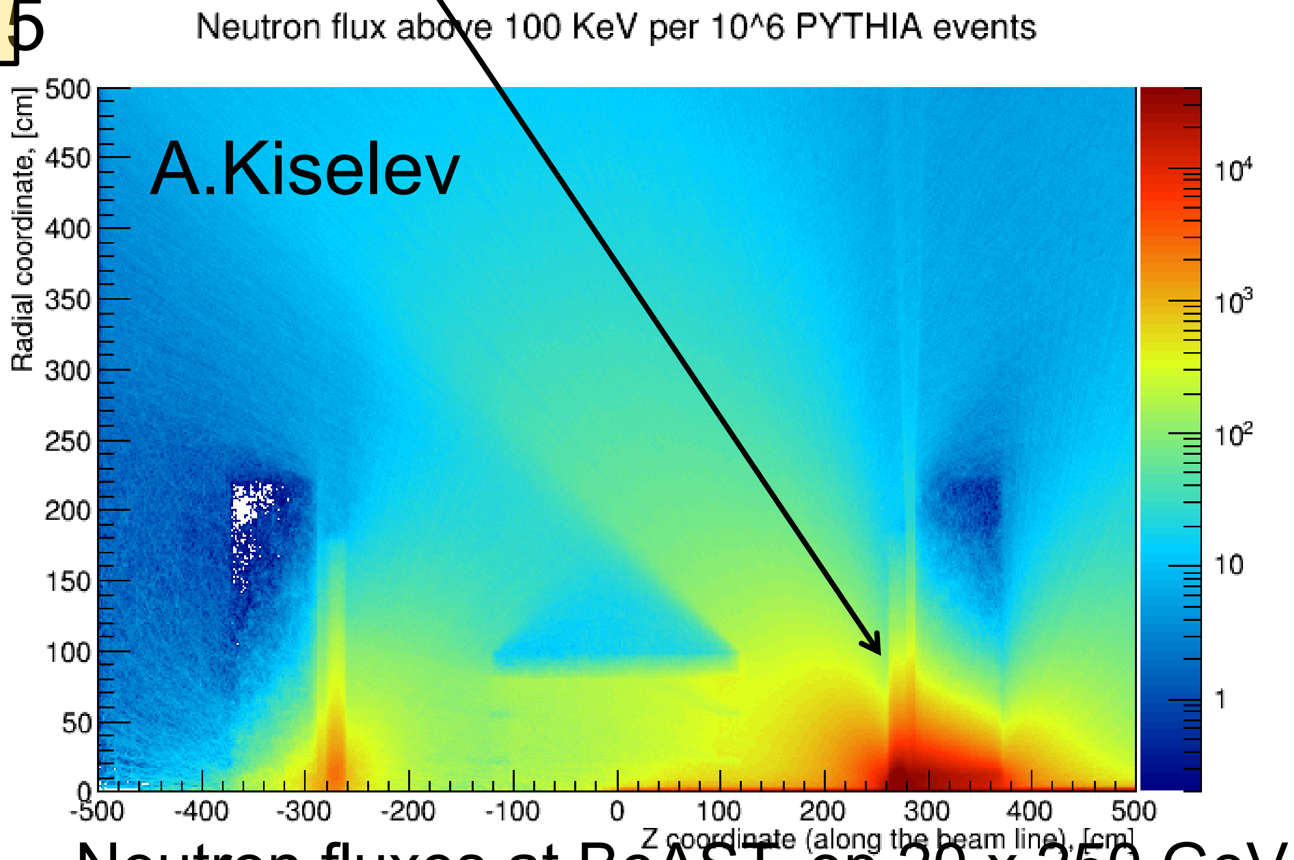


Y.Fisyak, et.al NIM A756

FEMC, 2016

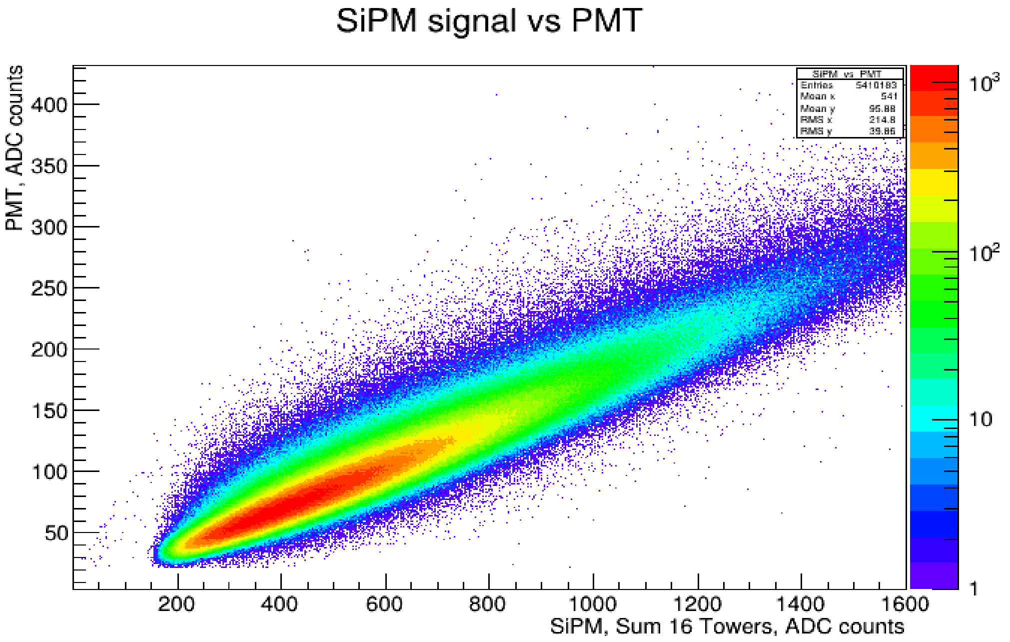
FPS, SiPMs 2015

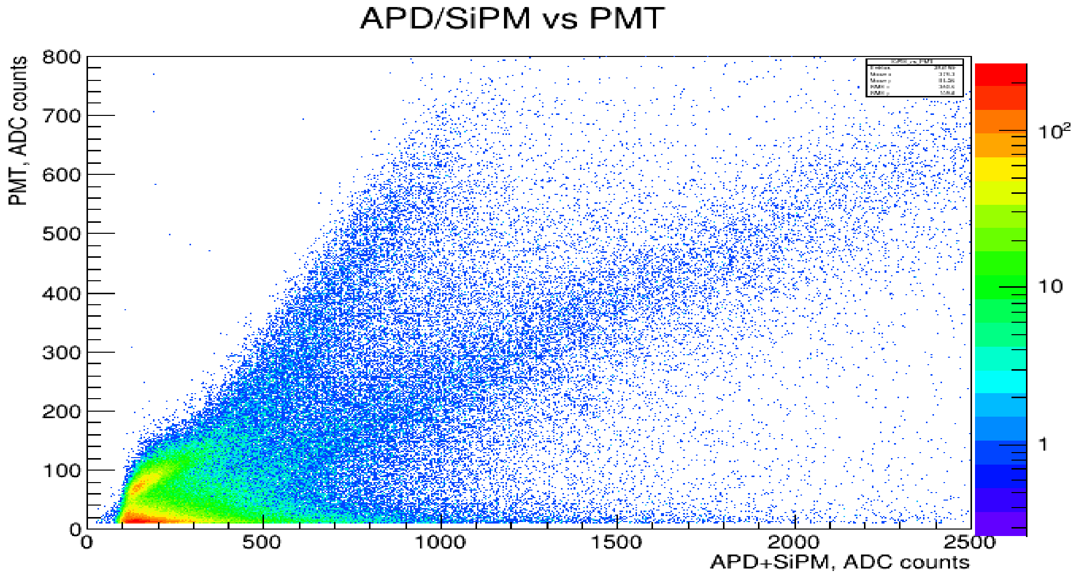


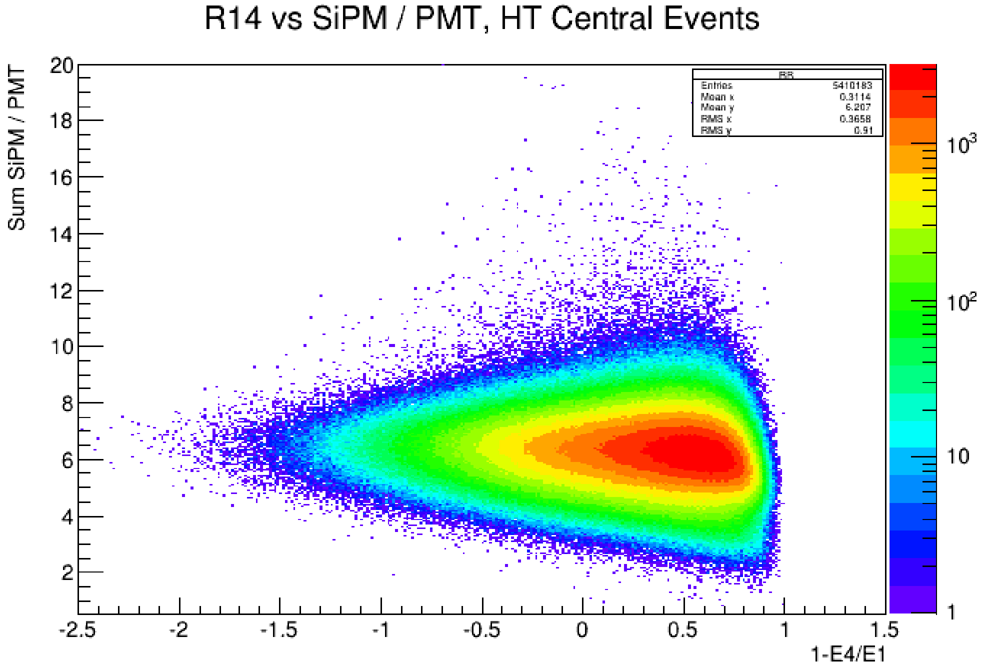


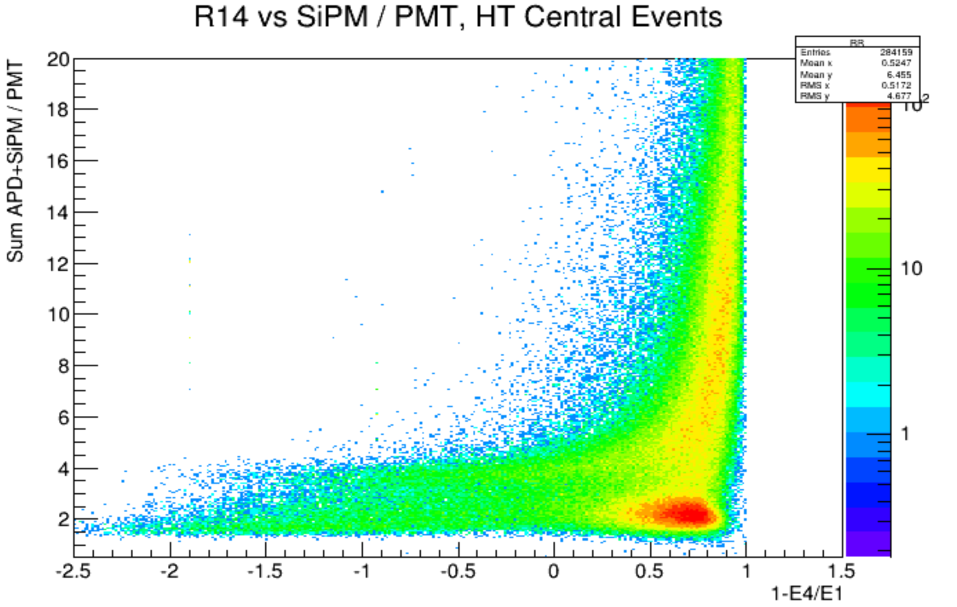
Neutron fluxes at BeAST, ep 20 x 250 GeV

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


SiPM signal vs PMT

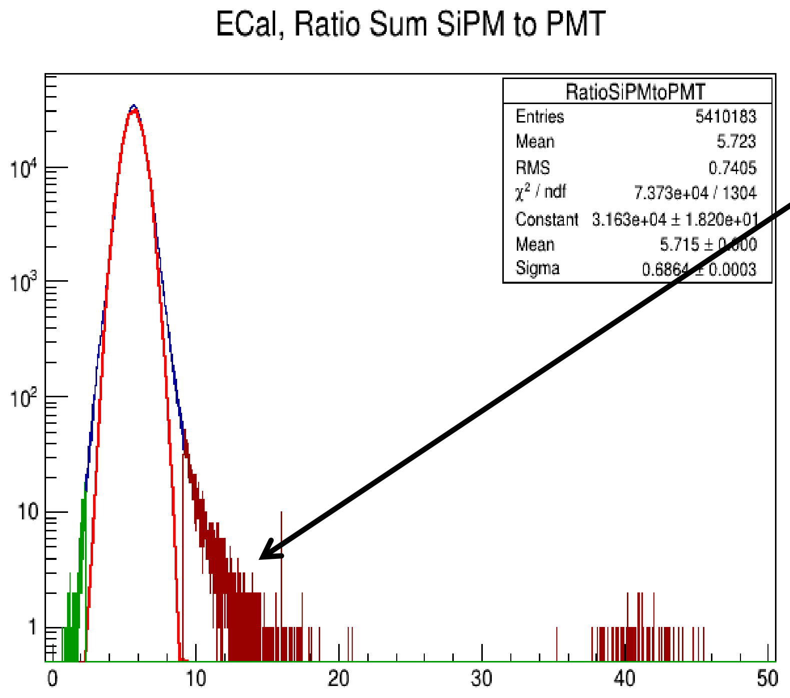

APD/SiPM vs PMT

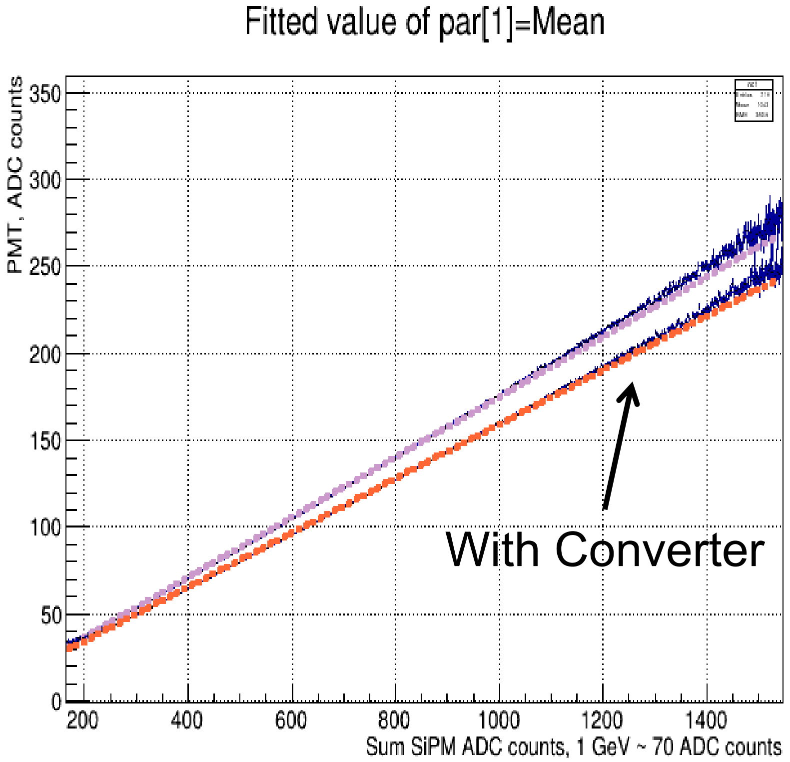

R14 vs SiPM / PMT, HT Central Events


R14 vs SiPM / PMT, HT Central Events

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

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

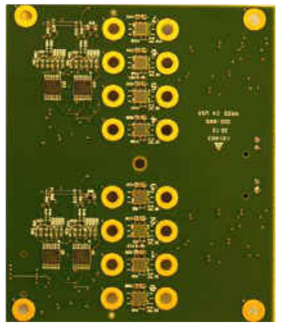




- Fraction of signals outside 5 sigma is about 4 *10 $^{-4}$ for SiPM readout.
- Origin of these signals is not clear.

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. Preliminary 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?)
- We may also need to reconsider absorber for HAD (move from Pb to Fe).
- 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.

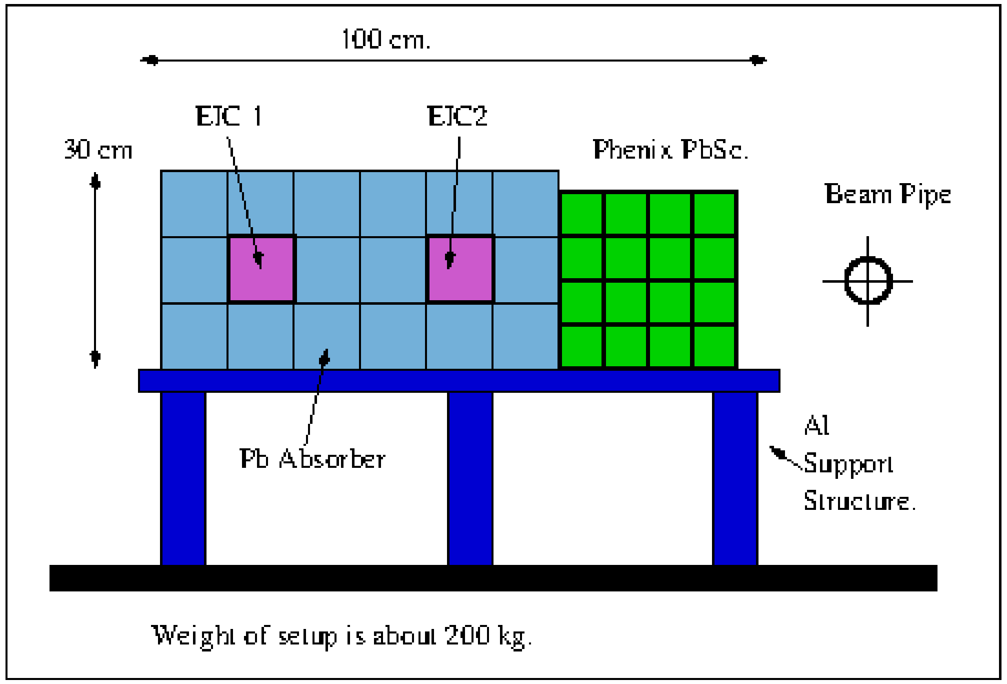
- We’ll need to continue these studies (more systematically) next year during 500 GeV pp Run 17 at RHIC.

- 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.

Priorities for R&D, sampling calorimeters FY17:

- Systematic study of behavior of Si sensors in realistic conditions.



Modify FEMC (light guide for PMT, two sets of SiPM readouts, one being blind to scintillation light.)

Modify 'O' or 'S' similar to FEMC, keep SiPMs downstrem.

- Optimization of compact light collection for FEMC. (Goal to have final version).
- sPHENIX: analysis of test run data, development for 2D projective blocks and 'industrialization' for 1D blocks, SiPM rad damage studies <- all covered from sPHENIX funds.

Future planning (~2018/2019). Sampling calorimeters & UC sys. Collaboration

- Build full scale FEMC (256 ch EM + 16 ch. HAD)
- Use it as a permanently running test stand to optimize FEEs, digitizers, DAQ, trigger, monitoring, slow control systems.
- Operate all these systems during RHIC running.

Backup Slides.