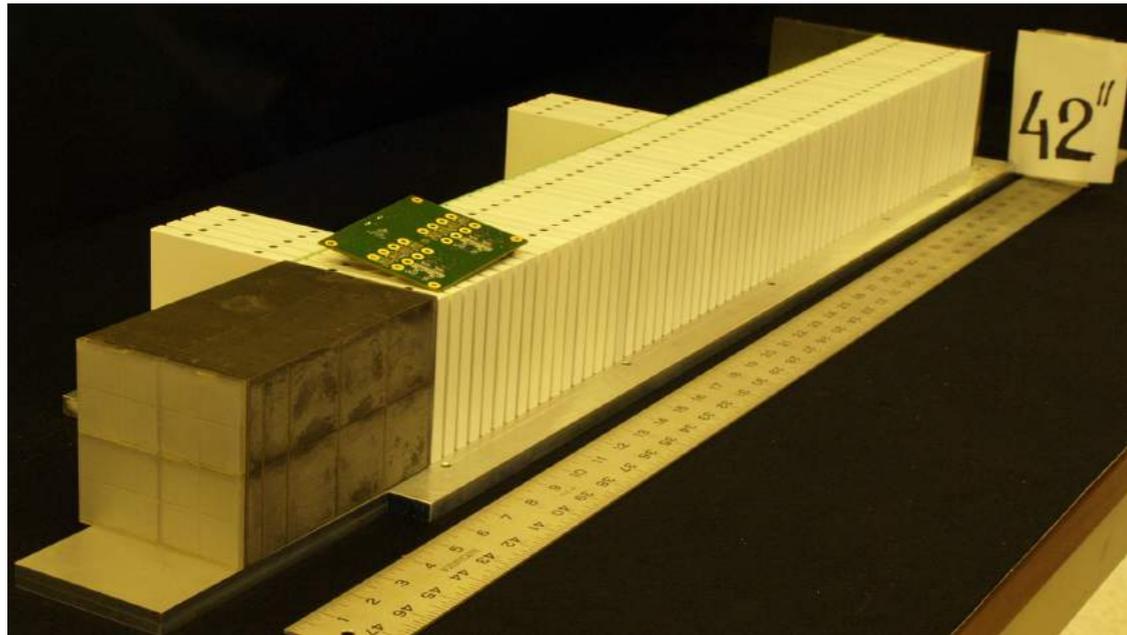


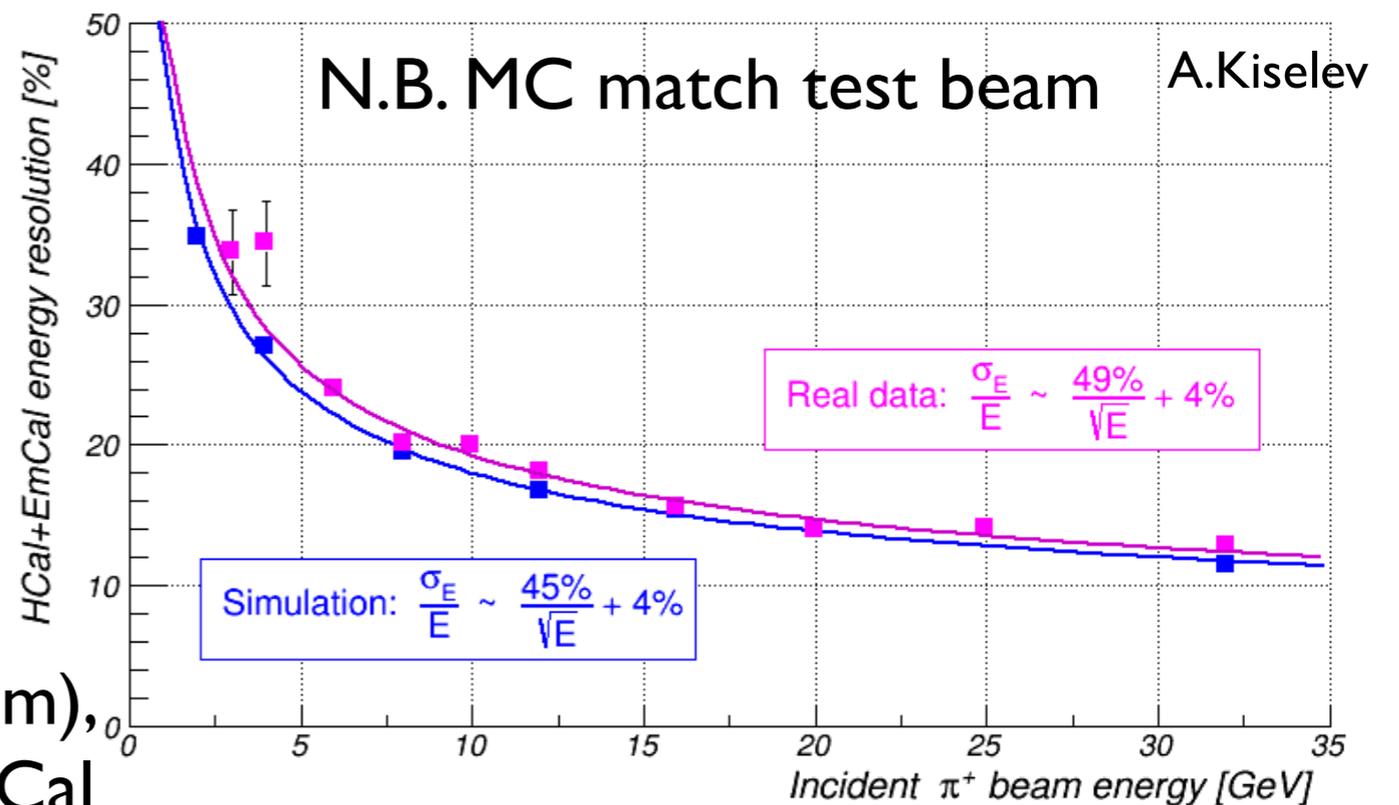
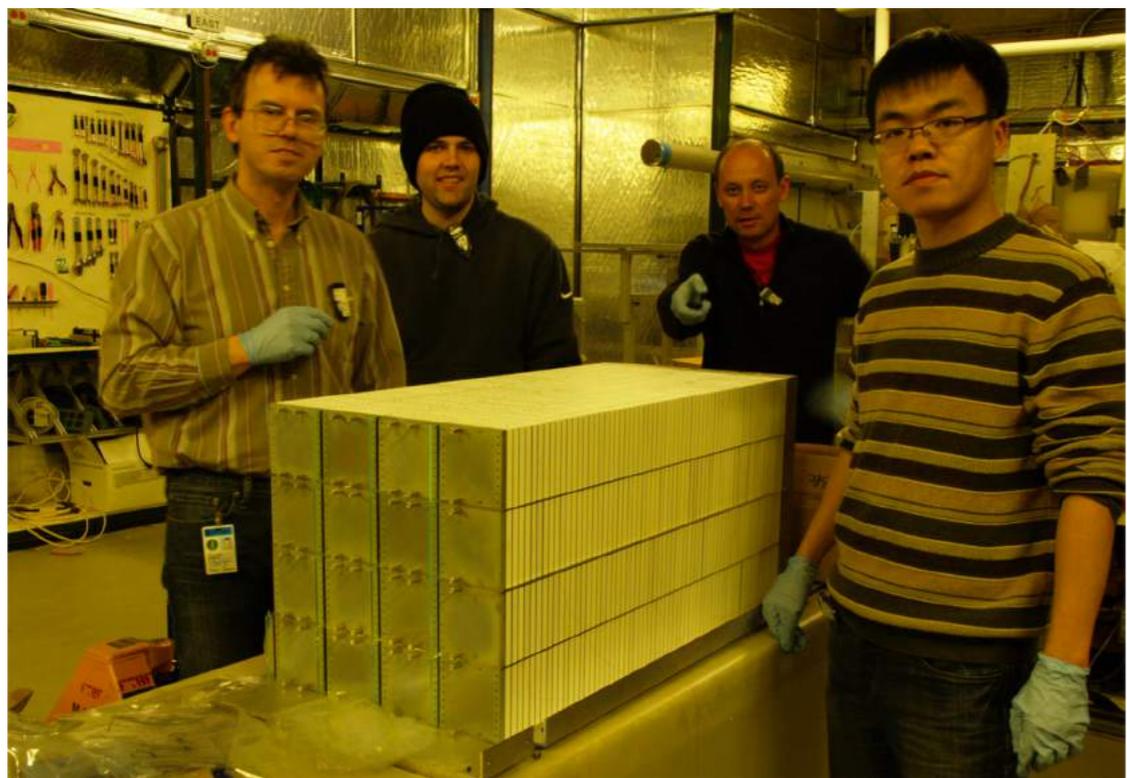
# STAR Forward Calorimeter System, Details, for ECCE calor meeting 05/25/21



# First Iteration, Compensated version. Feb 26, 2014. FNAL

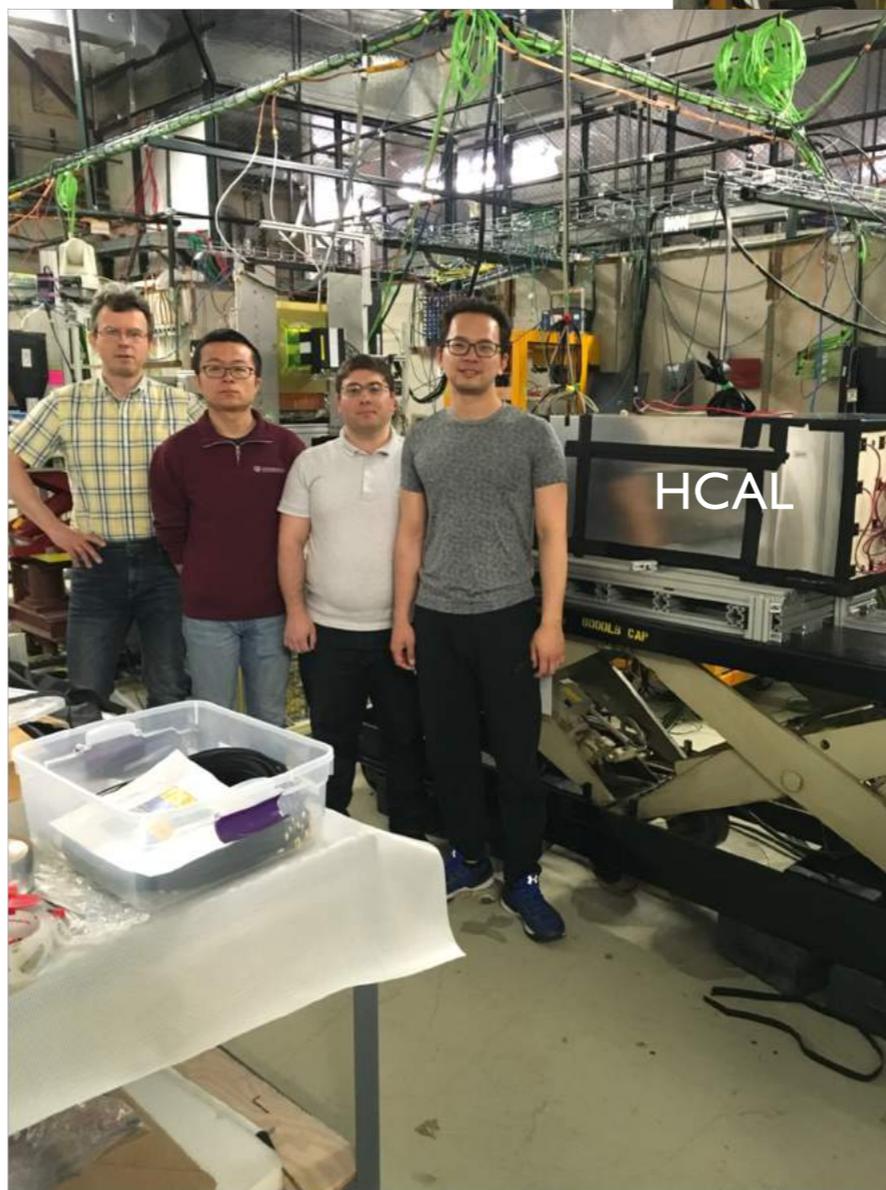
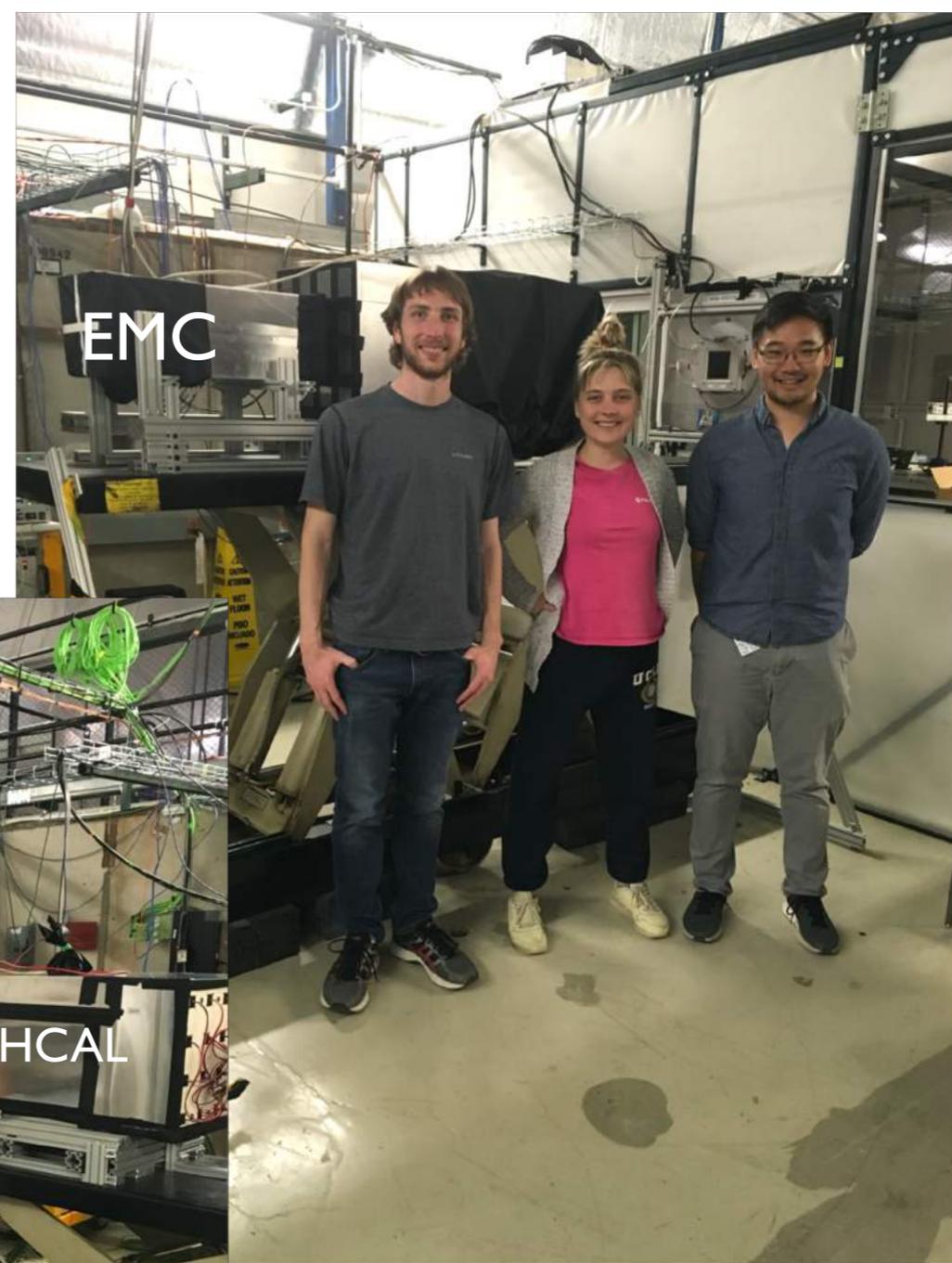
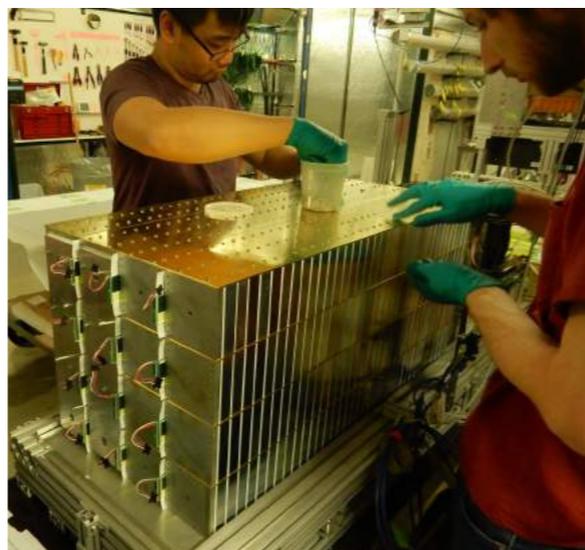
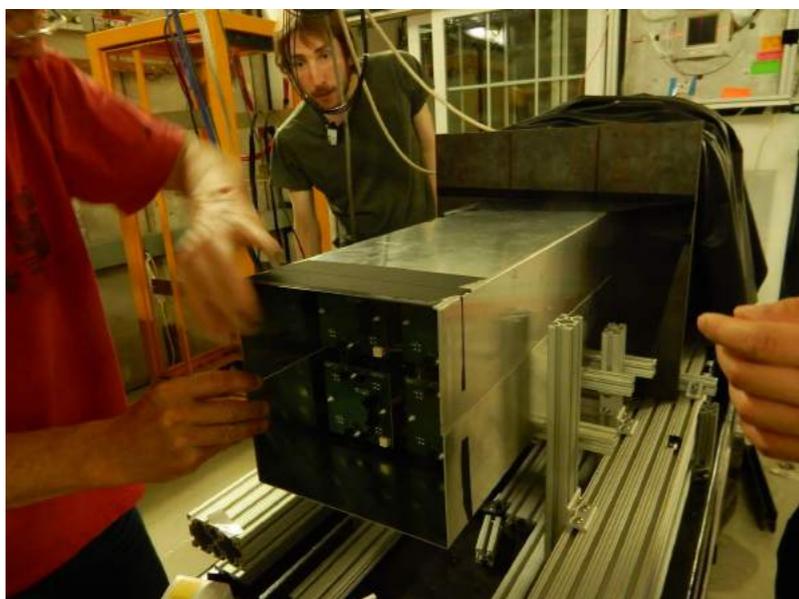


After two hours first layer done.



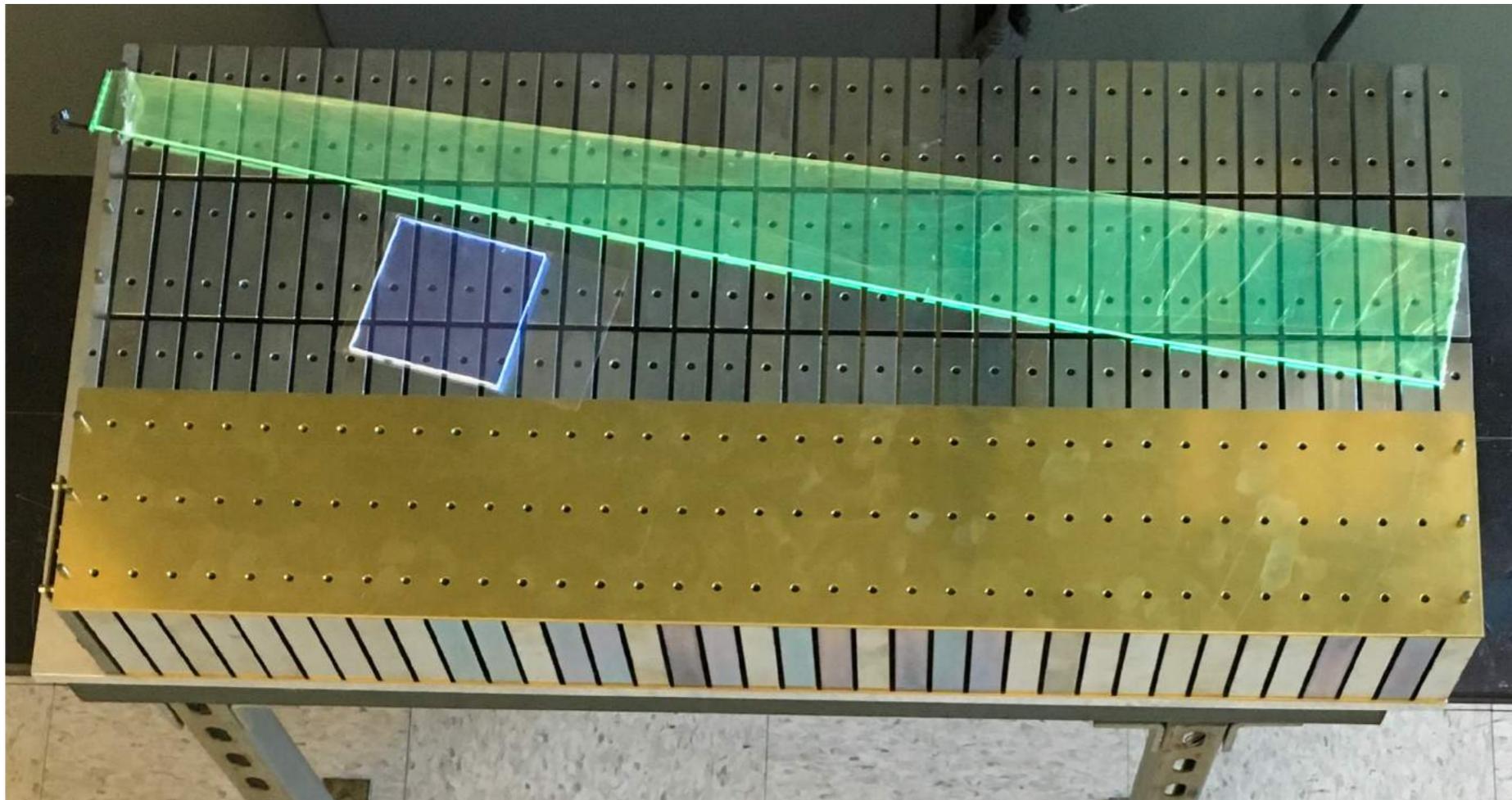
23X0 WScFi + 63 layers Pb/Sc (10/2.5mm),  
5cm Thick Fe plate between Ecal and HCal

Second version. Pb/Sc+Fe/Sc  
Cost/Timeline  
FNAL Test Beam, 2019  
4x4 Ecal, 4x4 HCal



A.Kiselev (BNL)  
T. Lin (TAMU)  
D. Kapukchyan (UCR)  
D. Chen (UCR)  
G. Visser (IUCF)  
O. Tsai (UCLA)

D. Neff (UCLA)  
M. Sergeeva (UCLA)  
B. Chan (UCLA)



Simple design.

- Simple Parts.
- Industrial Production.\*
- Standard processes.
- No interdependencies.



\* Machining, painting of Sc.Tiles at MRI Universities.

Parts: Absorber, Scintillator, WLS Bars, InterLink plates.

Optimized 2017 version:

Absorber – 20mm steel

Scintillator – 3 mm

Number of layers – 36

Light collection – tapered WLS

Number of sensors – 6

2014 Version:

10 mm Pb

2.5 mm

63

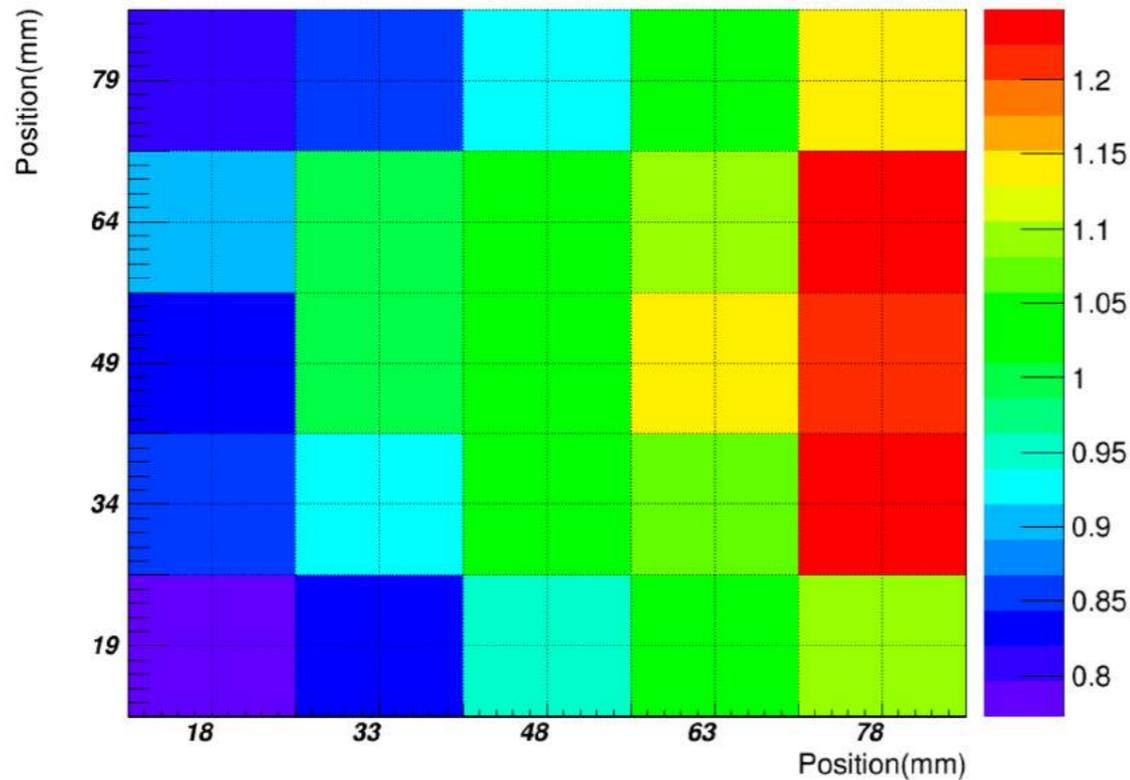
Filter

8

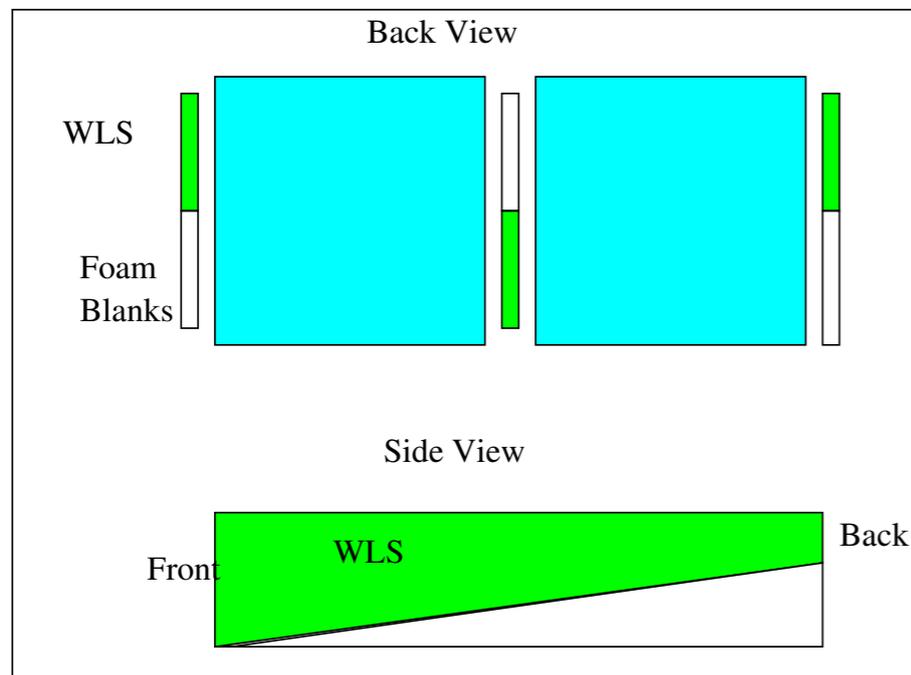
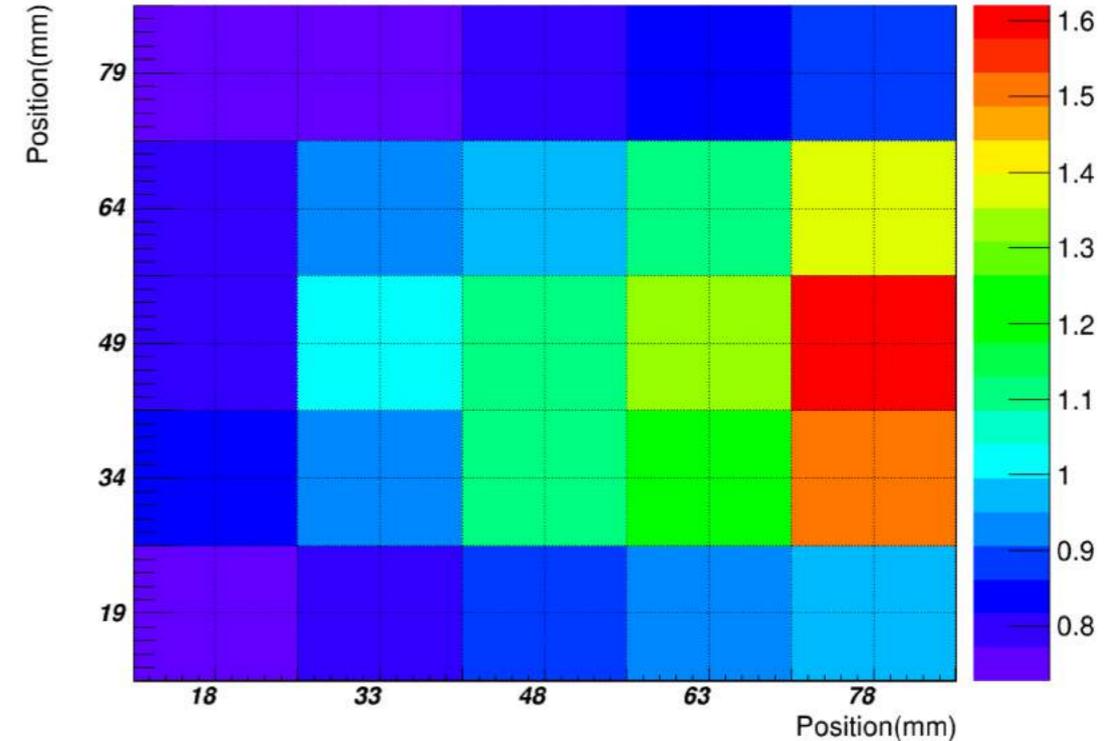


# Light Collection Details. Transverse non-uniformities

UV LED 4.90V, 370mm / 77cm



UV LED 4.90V, 370mm / 9cm



It was believed that due to wide hadronic shower such large transverse non-uniformities will have little effect.

Turned out to be true.

# Light Collection Details. Longitudinal non-uniformities

hCal Calibration

WLS Bars Attenuation/Compensation FNAL 2019

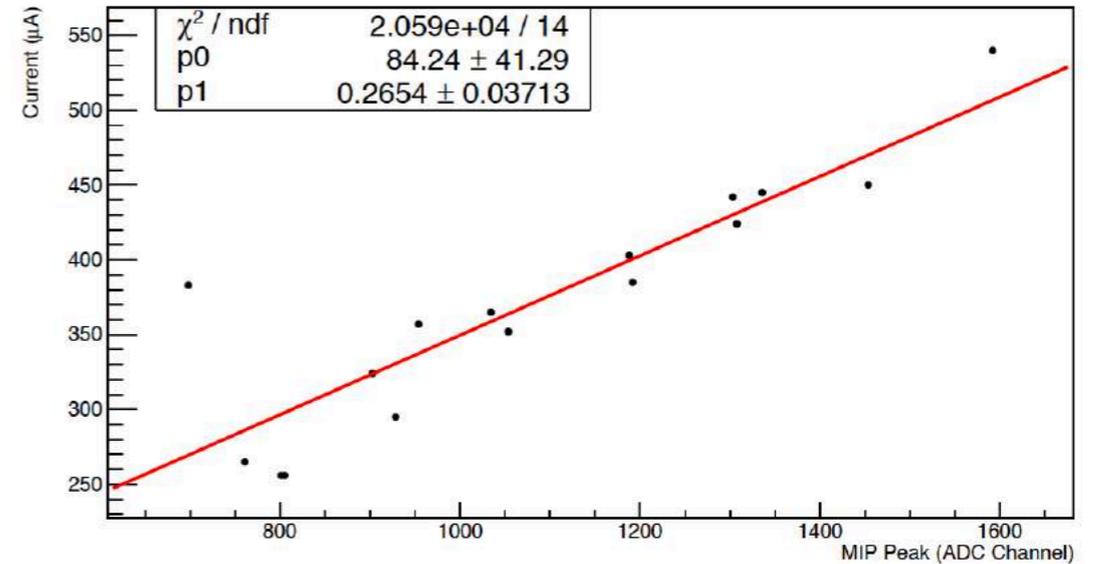
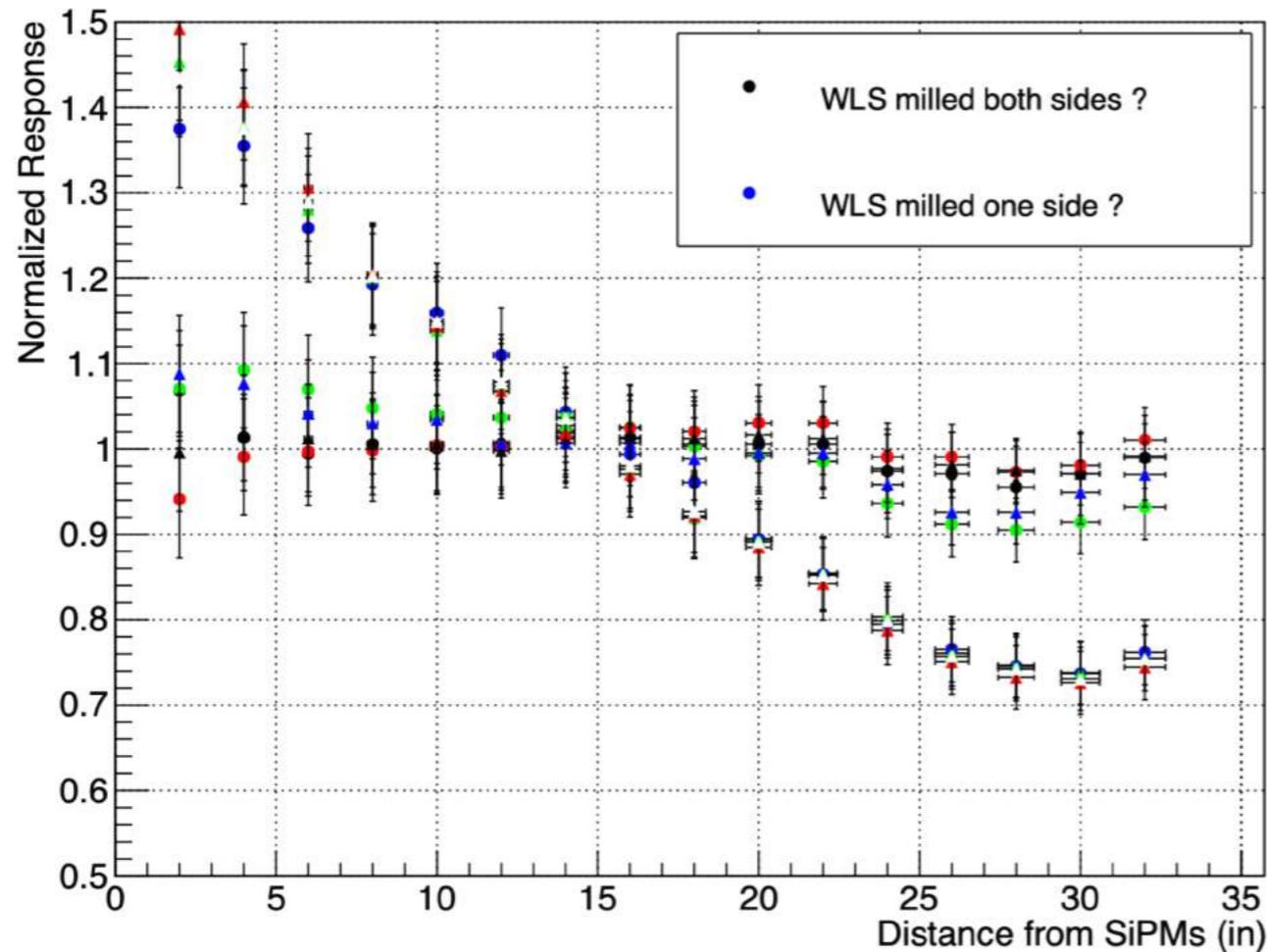


Figure 9. Correlation between muon peak position and LY measured in the lab.

Turned out that in FNAL prototypes we had mixed set of WLS bars.

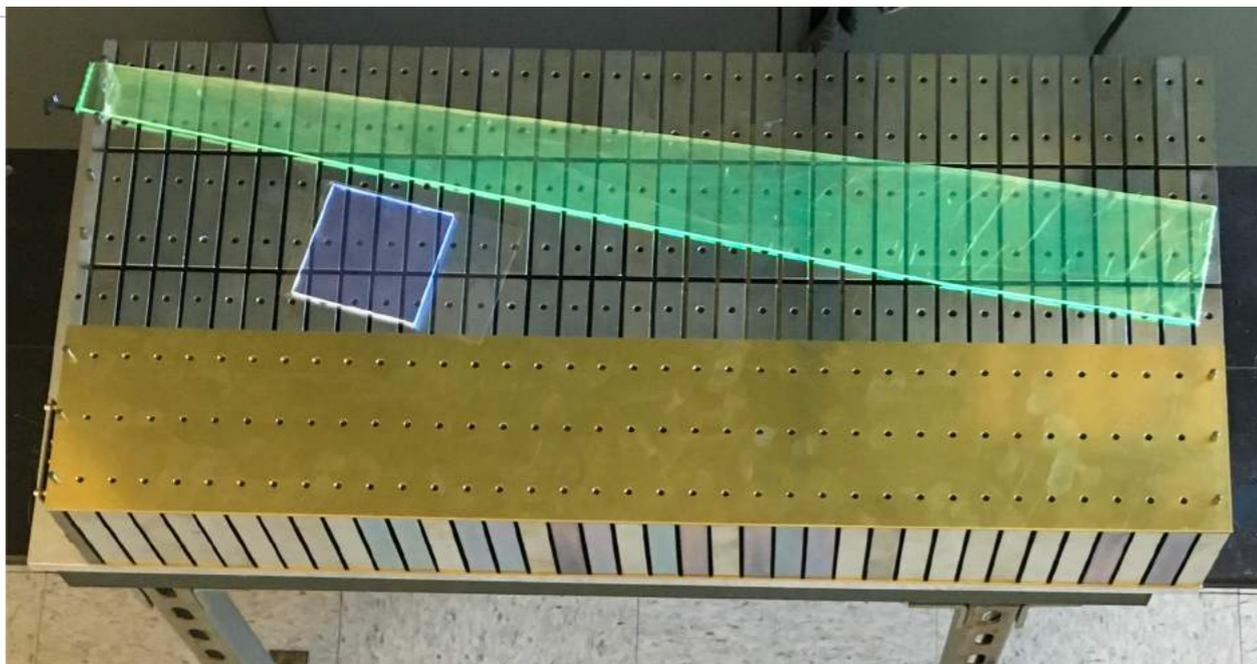
Which lead to a different type of non-uniformities, along the length of the towers.

In pervious MC we learned that this type of non-uniformities degraded resolution substantially.

Large constant term (15%) for compensated version of FCS.

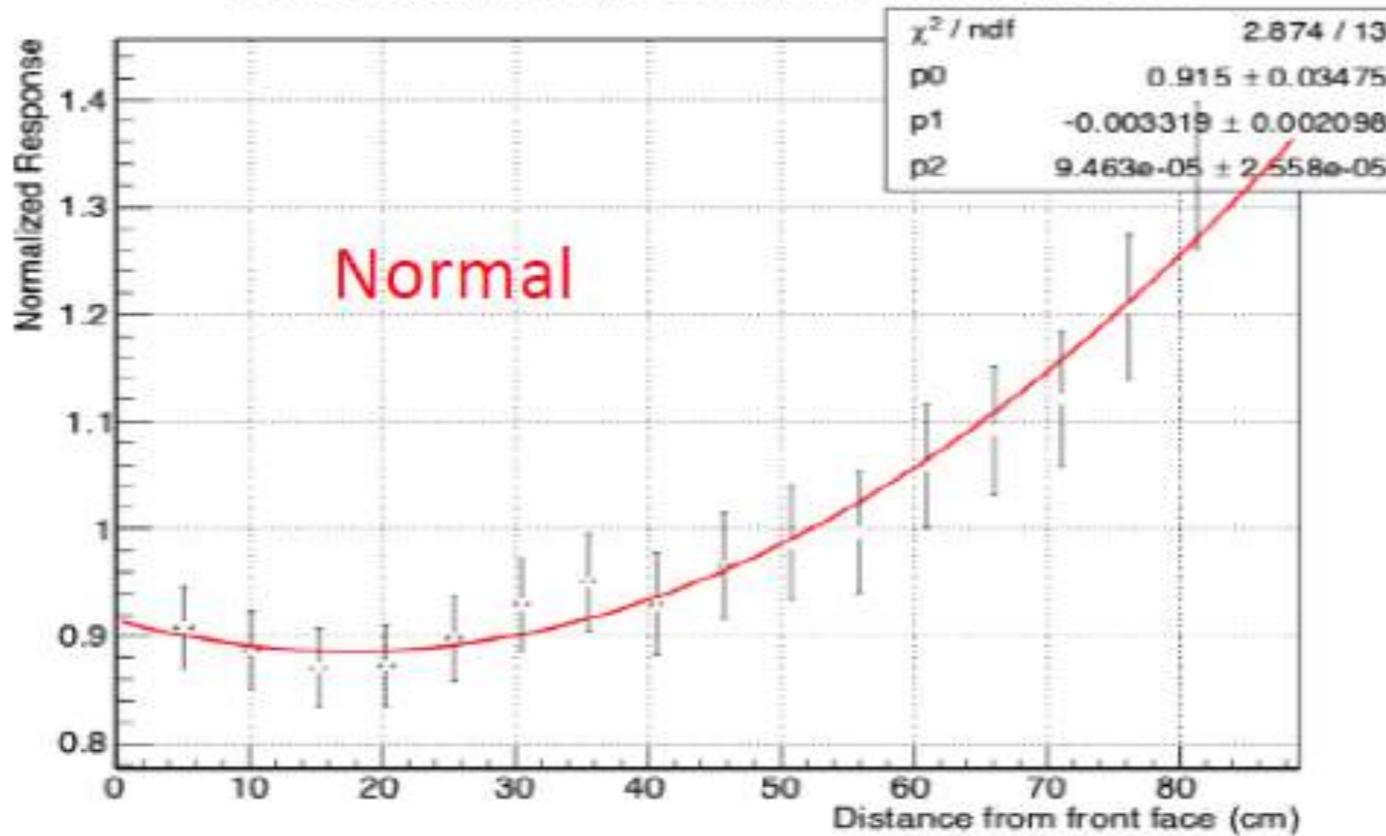
GEANT4, very little effect with Fe/Sc version, Puzzling!

Possible explanation,  
Pb vs Fe absorber localization of EM

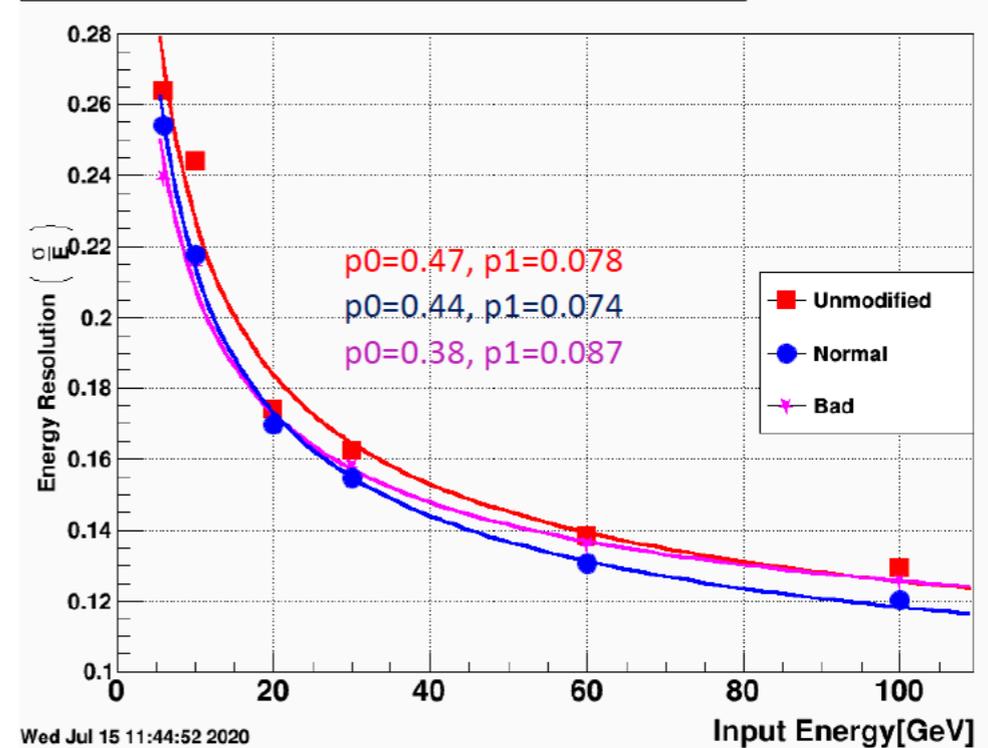


# Light Collection Details. Longitudinal non-uniformities

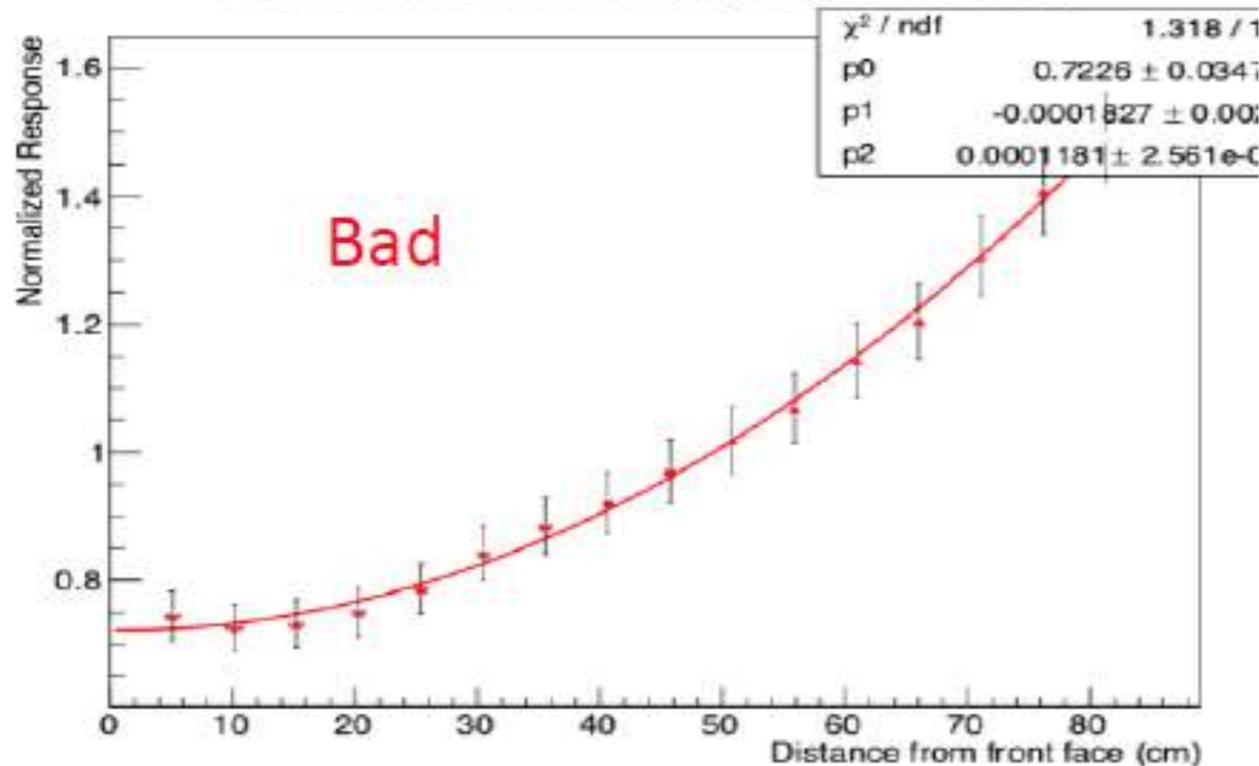
WLS Bars Attenuation/Compensation FNAL 2019



Energy Resolution of  $\pi^+$  with ECal+HCal



Bad WLS Bars Attenuation/Compensation FNAL 2019

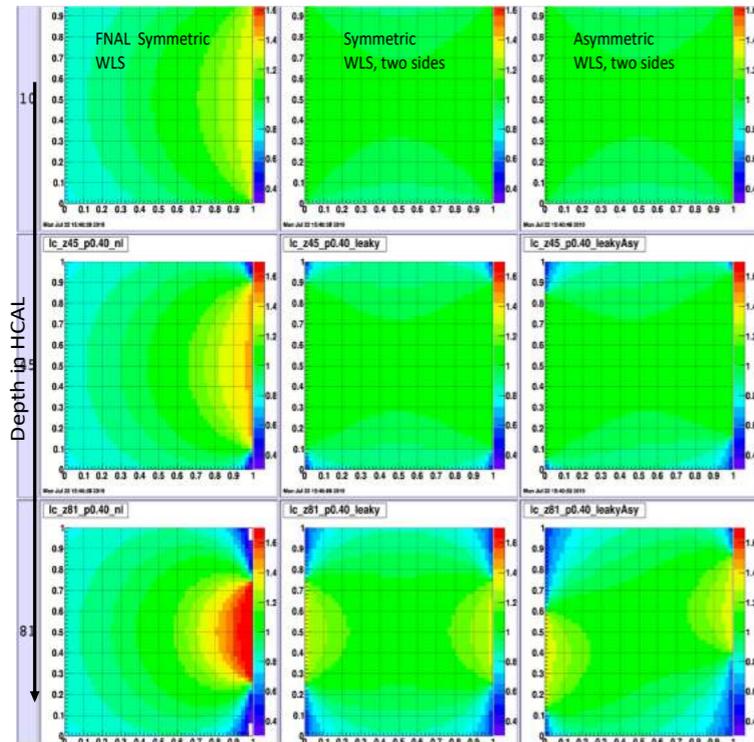


Large constant term (15%) for compensated version of FCS.

gSTAR or GEANT4, very little effect with Fe/Sc version, Puzzling!

Possible explanation, Pb vs Fe absorber localization of EM

# Light Collection Details. Non-uniformities



Tested three different schemes of light collection from Sc tiles.

- Very little impact on resolution.
- GEANT3 (gSTAR, A.Ogawa (BNL) + T.Lin (TAMU)).

All kind of non-uniformities  
Has very little effect on resolution.

N.B. we always compared ideal implementation of calorimeter to test beam data. Ecal was very small, very long, and big gap between Ecal and Hcal, not apple to apple.

Comparison with different leaky options, optimized Ecal weight

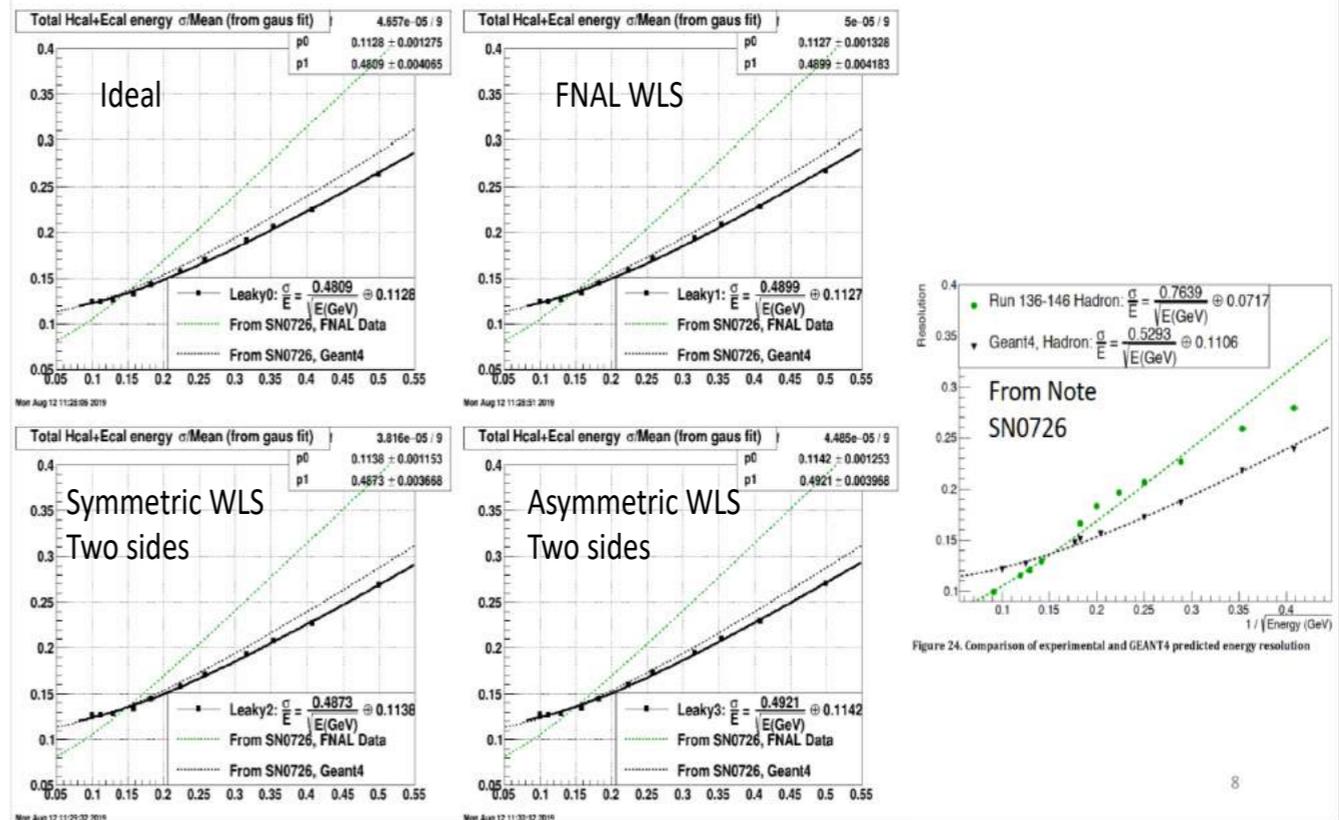
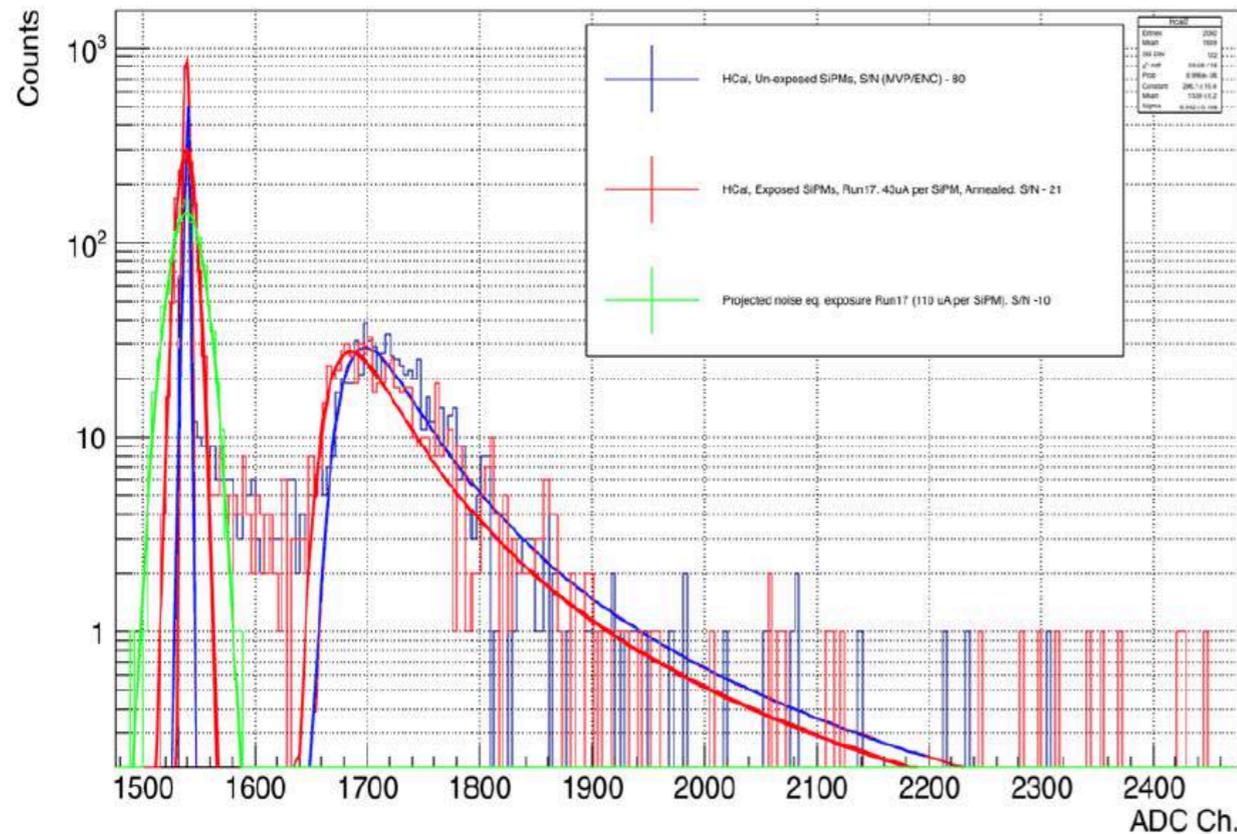


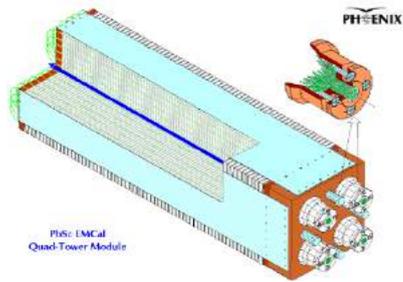
Figure 24. Comparison of experimental and GEANT4 predicted energy resolution

# Readout HCal

- Run 17 EIC R&D. Degradation of SiPMs required to reduce number of sensors and increase light yield to improve S/N -> Tapered WLS, 6 SiPMs.
- Tested with cosmic muons, LY is about 270 p.e.
- ENF after exposure (green pedestal) is about 100 MeV/tower.
- To compare, expected resolution for single hadron at 100 GeV  $\sim 8$  GeV  
ENF (cluster 4 x 4 towers)  $\sim 400$  MeV

Noise due to degradation of SiPMs is not a big concern for STAR FCS, EIC ?  
Well, EIC will have much less neutrons....



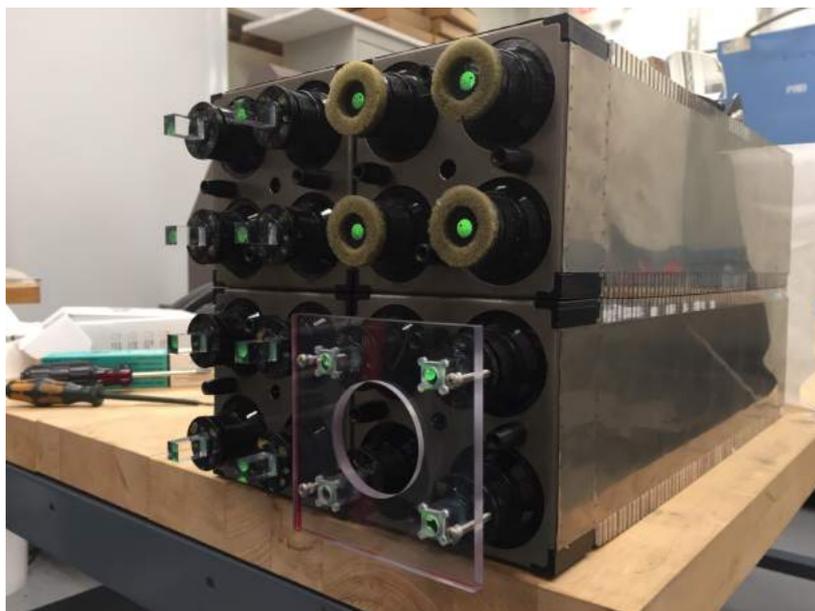


### EM Module.

- Module has four independent towers.
- Penetrating WLS fibers for light collection.
- Sector is 6 x 6 EM modules.
- Extracting individual module from sector is trivial operation (worked with 20 modules during R&D, 374 total in FCS)
- One PHENIX SuperSector will be in the STAR Assembly bldg. in early 2019 (648 EM modules).

### Modifications:

- Gluing four light guides/mixers at the end of the WLS bundles.
- Gluing SiPM currying boards to LG (4 SiPM/tower, 5984 total)
- Attaching FEE (Pogo pins, utilizing existing holes in EM module)



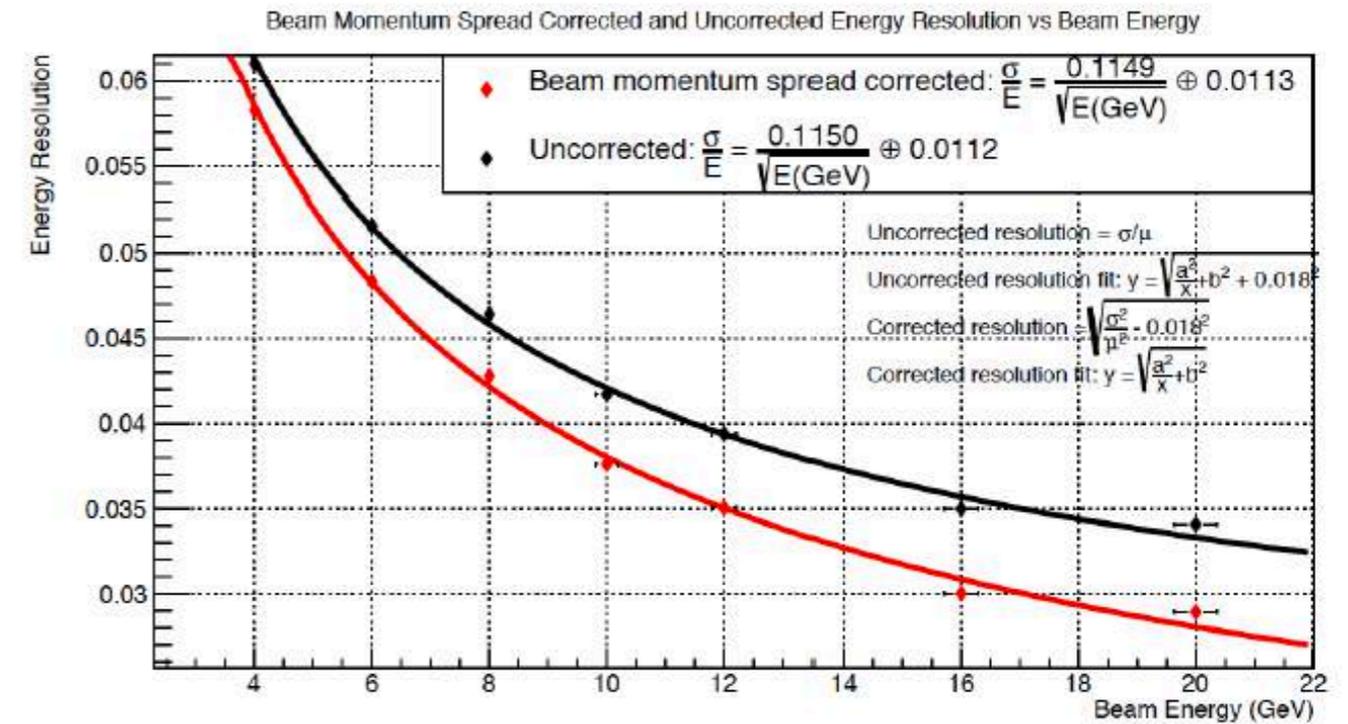
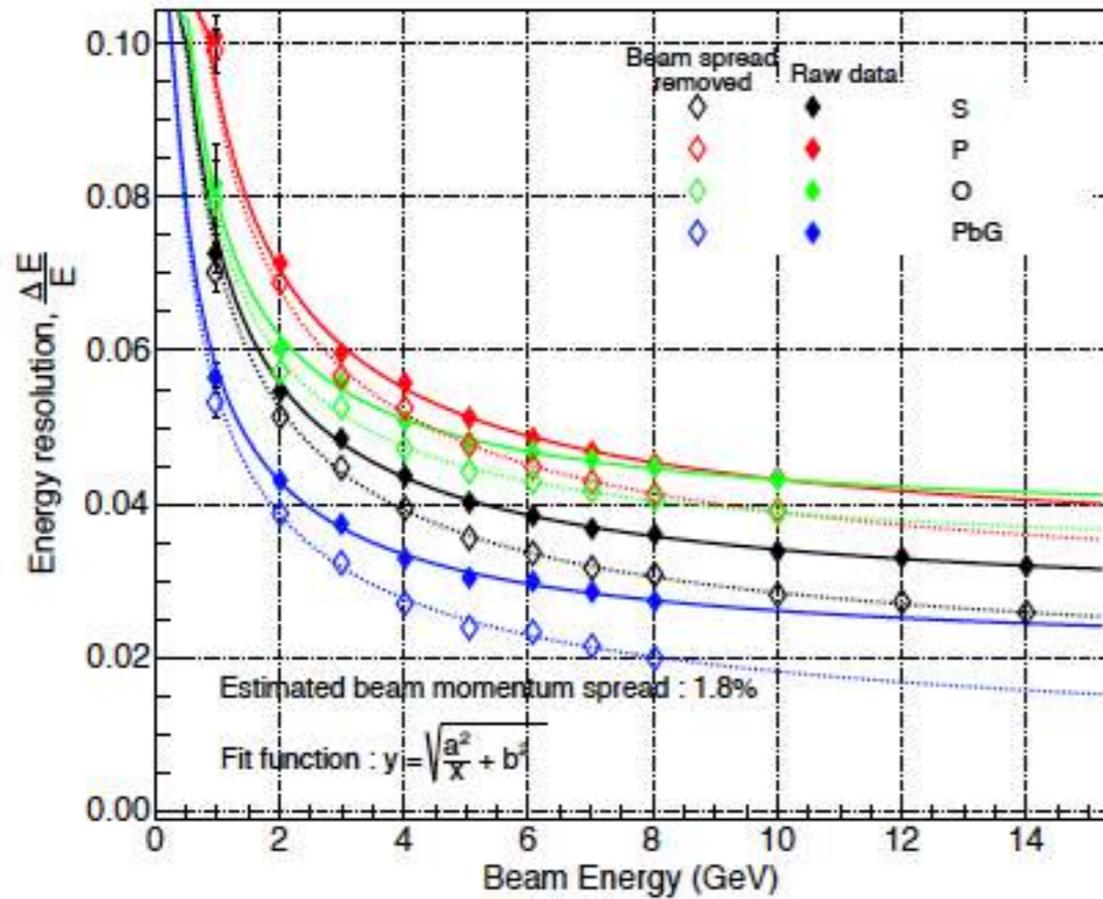
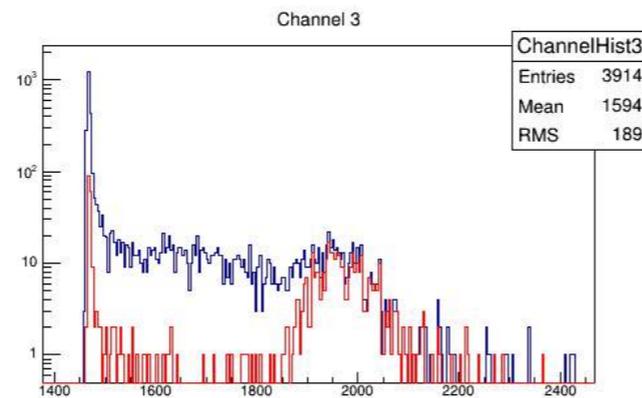
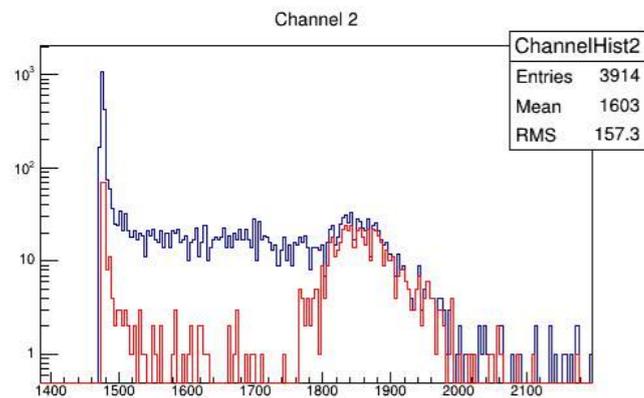
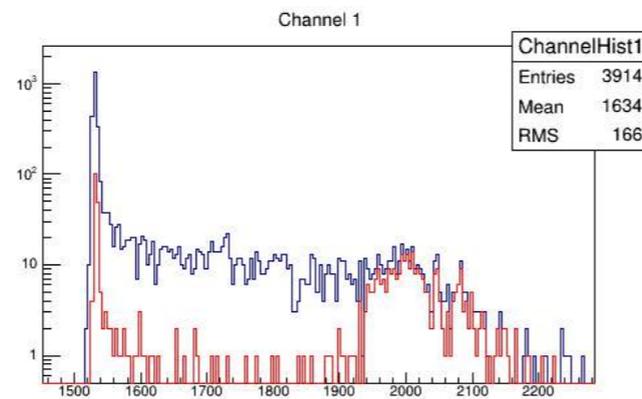
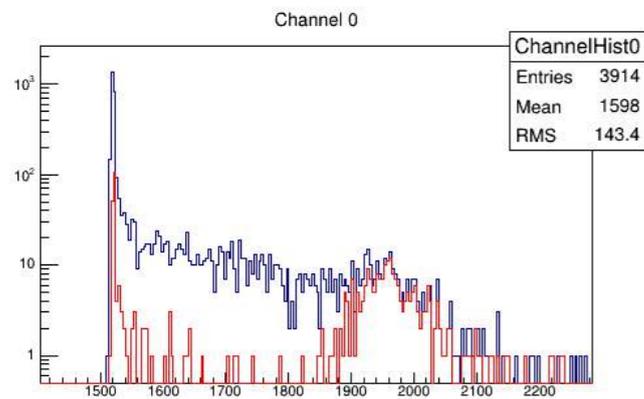


Figure 16. Energy resolution for EMcal, raw and beam momentum spread corrected.

Energy resolution  $\sim 9\%/\sqrt{E}$  constant term  $\sim 3\%$ , FNAL 2016 with PMT

Somewhat consistent with old test run data for PHENIX ECAL.

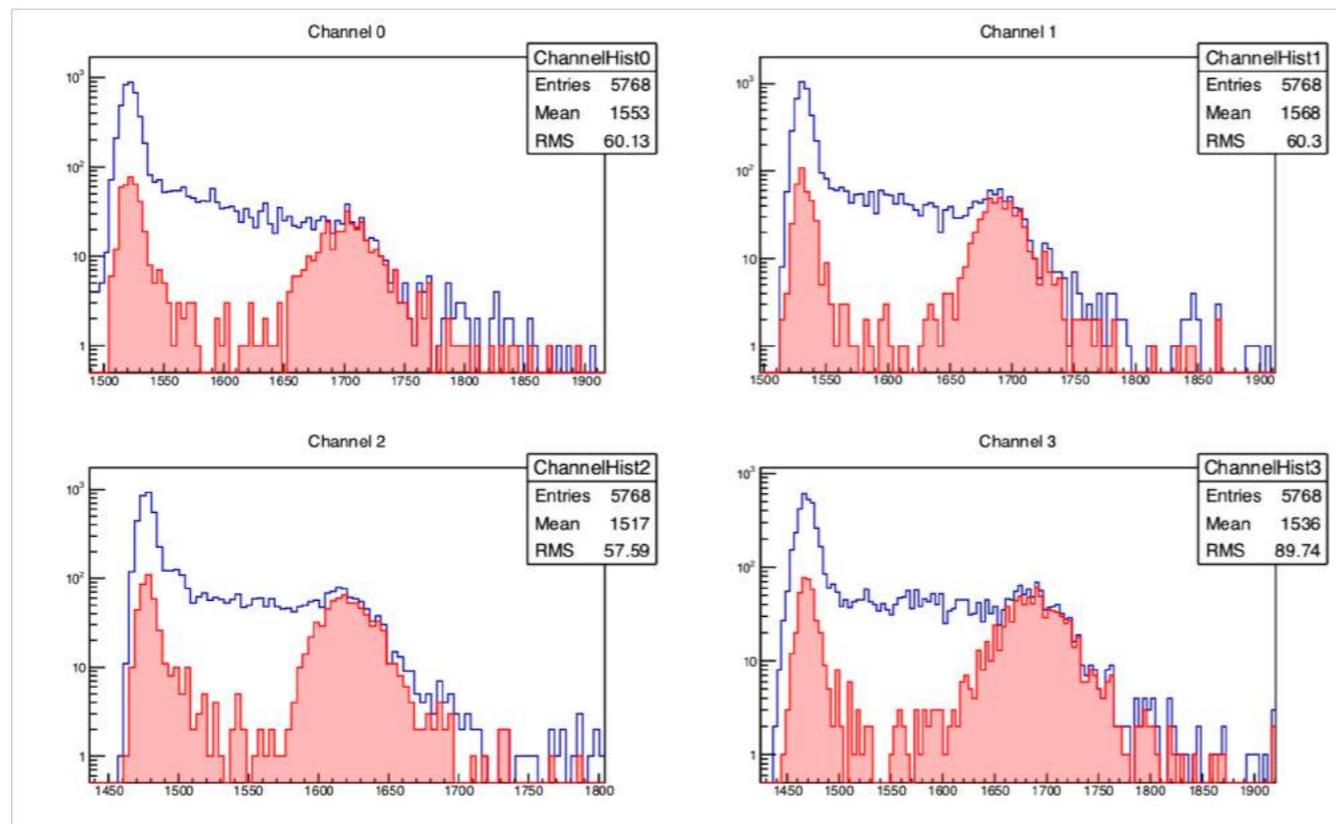
Energy resolution degraded, light guide (spreader) design for FCS is not optimal (not important for FCS) for EIC may be improved if needed. In principle, no reasons to get same resolution as with PMTs (cost of lightguides).



Cosmic Muons with un-exposed SiPMs  
ENF  $\sim 1.7$  MeV

- SiPMs Degrade with exposure (details later in talk).
- 500 GeV pp (Run 17) was the worst case in terms of exposure.

- Cosmic Muons with exposed (Run17) SiPMs, ENF - 10 MeV/tower



- For comparison, resolution at 100 GeV is about 3 GeV, noise adds about 30 MeV (cluster 3x3). Increased noise due to rad damages is not a concern.

- No degradation of optical components after Run 17 observed, as expected.

Both meet design requirements.

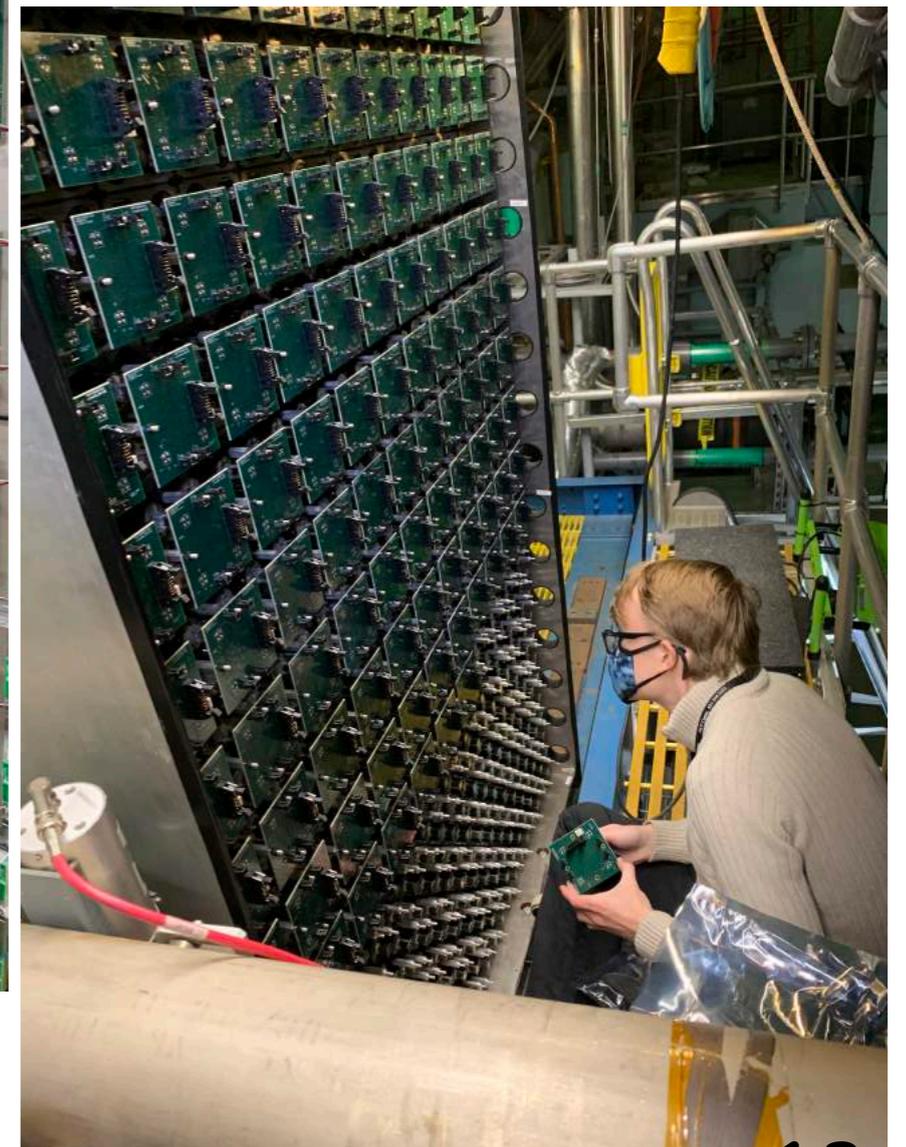
# FCS Assembly in place, 2020

## Forward Calorimeter System (FCS)

- ECal – 1496 channels ~ 8 tons
- HCal – 520 channels ~ 30 tons.
- SiPM Readout Bias ~ 67V
- New digitizers + Trigger FPGA = DEP<sub>boards</sub>



STAR Collaborators,  
Members of UC EIC Consortia  
Assembling FCS in Dec. 2020, BNL





**Very efficient construction method.  
HCal was assembled in tight place during COVID in just 20 days!  
Data taking through Run21. Trigger Commissioned!**

# EIC configuration with W/ScFi and Fe/Sc

- EM part is W/ScFi of  $18 X_0$
- Hadron part (HAD) is Fe/Sc of 20 mm Fe and 3 mm plastic scintillator layers
- The Fe/Sc part has 51 layers for  $6 \lambda_I$
- Front size is  $800 \times 800 \text{ mm}^2$
- Primary particles are generated at  $3^\circ$  along  $x$  and  $1^\circ$  along  $y$ , in the front middle of W/ScFi part

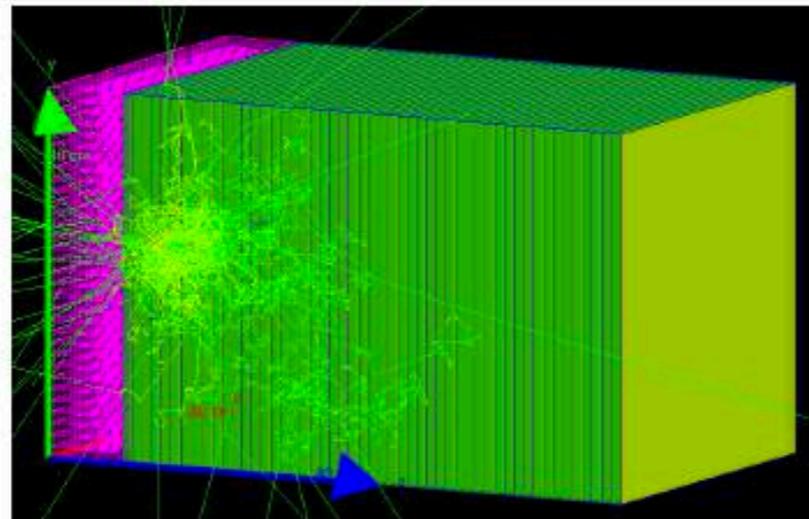


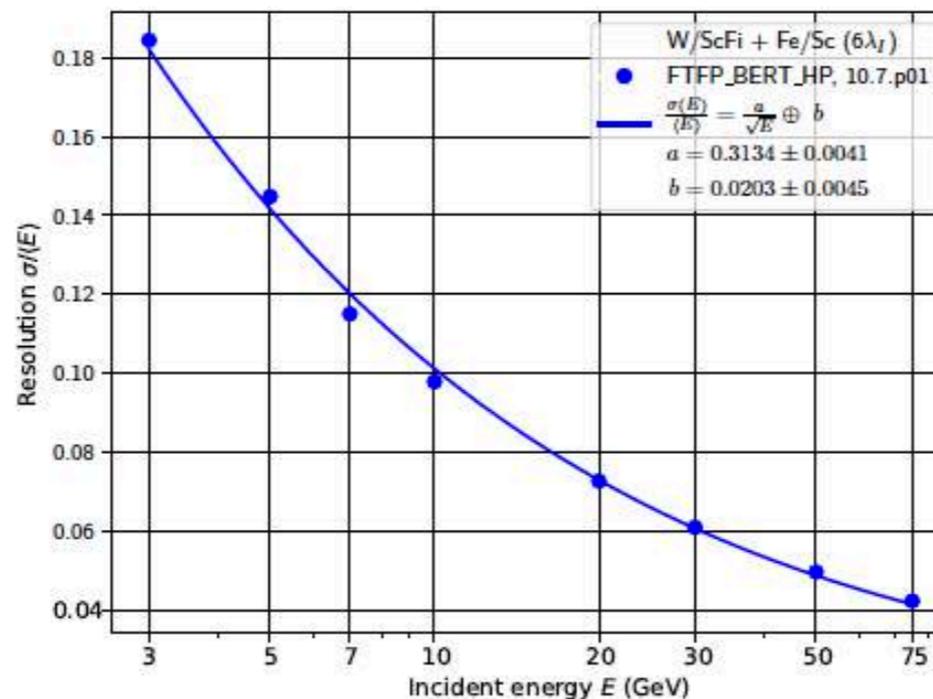
Figure: Event of  $\pi^+$  at 20 GeV in EM (magenta) and HAD (green and yellow) parts

Good Hadron EndCap  
ECCE  
ATHENA  
We all need it.

Super Good numbers in MC  
Have to check it experimentally  
Large Scale Prototype.

## Hadron energy resolution for EIC configuration

- Following the same procedure as for ZEUS results
- Gaussian fit to  $\alpha$ -weighted energy deposition, ratio of width to mean at each incident  $\pi^+$  energy
- The result is about 30% stochastic term and a small constant term



MC has to be tuned.

Under scaled prototypes not that useful IMHO.

Joint efforts?

Let's think how we can do it.

## From generic R&D and YR to targeted R&D.

- Technologies for WScFi and Fe/Sc (construction method) are well established and spread in community (STAR and sPHENIX). Developed during generic EIC detector R&D.
- Performance of reference detector Hadron EndCap is very good on paper. Well exceed requirements of YR.

## What we need to do before CD2 (Jan. 2023)?

- A full scale prototype WScFi + Fe/Sc with transverse size 0.6m x 0.6m, with integrated tail catcher for hadron endcap.
  - a) HCAL part is IP independent.
  - b) HCAL part is endcap independent (e or h side)
- A test beam or two (FTBF at FNAL may be OK, BNL A2 will be nice to revive)

Timescale is doable. Construction of prototype will take 1 or 1.5 years, cost ~ \$300k  
There are few small R&D topics which has to be finished (light collection efficiency and such) these are already funded by EIC generic detector R&D (Funds for FY2020 have not been received yet).

# Thanks!

## Assesment eRD1 (UCLA lead sub-projects):

- Experimental proof of feasibility of W/ScFi technology for very compact sampling electromagnetic calorimeters with energy resolutions varying from (7%-12%)/sqrt(E) for stochastic and (1-2)% for constant term. Several designs of prototype calorimeter utilizing the W/ScFi technology were built and tested with beams at FNAL during 2012-2016 period.
- Demonstration of new effective construction technology for sampling hadron calorimeters with good energy resolution. Two prototypes were built and tested at FNAL in 2014, 2019. A 30 ton HCal for the STAR Forward Calorimeter System was constructed in 2020 using this innovative technology.
- Multi-year studies of SiPM characteristics in beam conditions close to those expected at high luminosity EIC. Notably, during Run 2017 at RHIC with 500 GeV pp data, our observation led to new understanding of mechanism responsible for the degradation of SiPMs responses after exposure to neutrons and ionization particles.
- Development of compact readout schemes using SiPMs for W/ScFi and Shashlyk type calorimeters (e.g., the STAR Forward Calorimeter System using SHASHLYK EMCal ~ 1500 channels instrumented in 2020) and WLS/SiPM for HCals (STAR Forward HCal 520 channels).