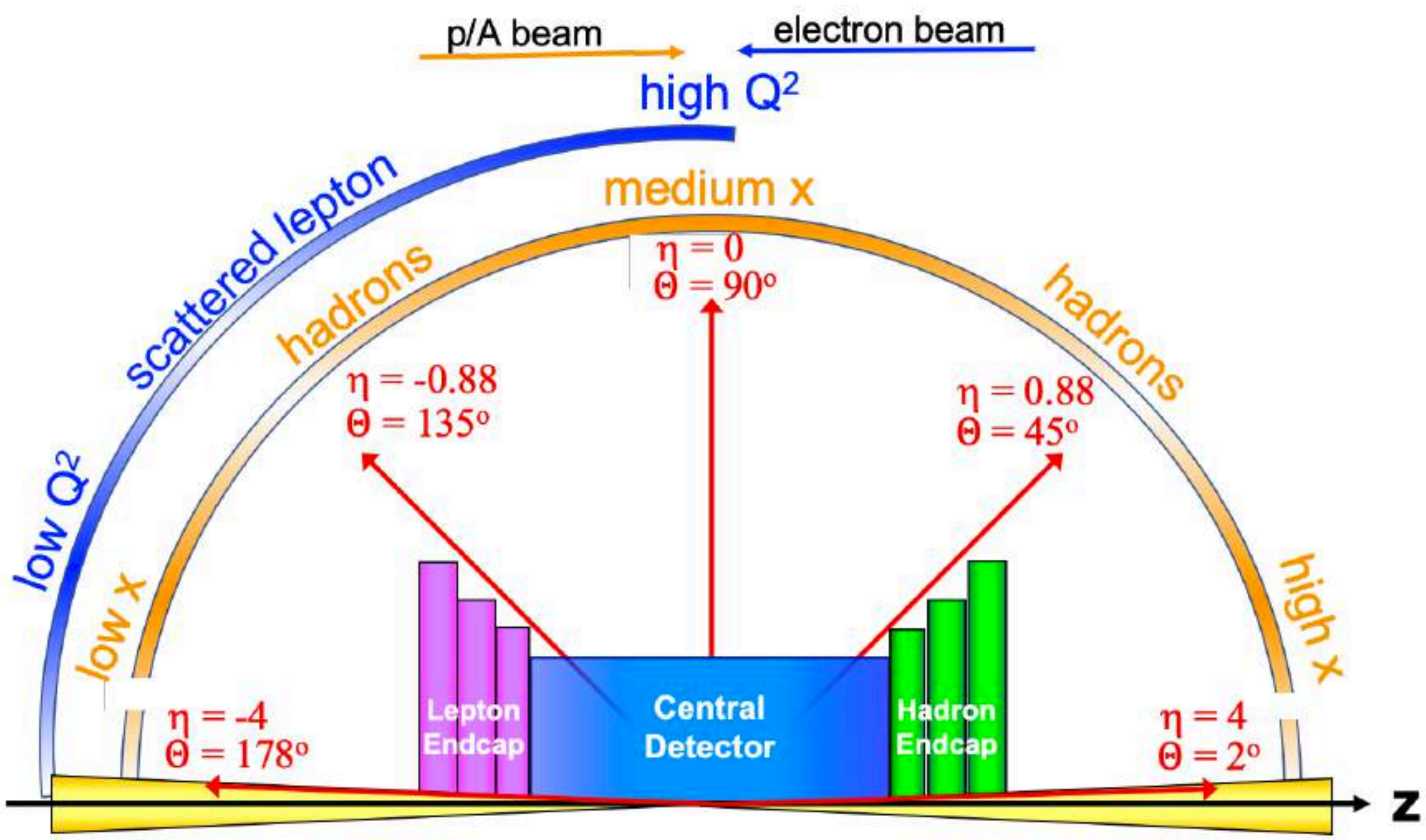
Hadronic Calorimetry.

O.Tsai (UCLA)

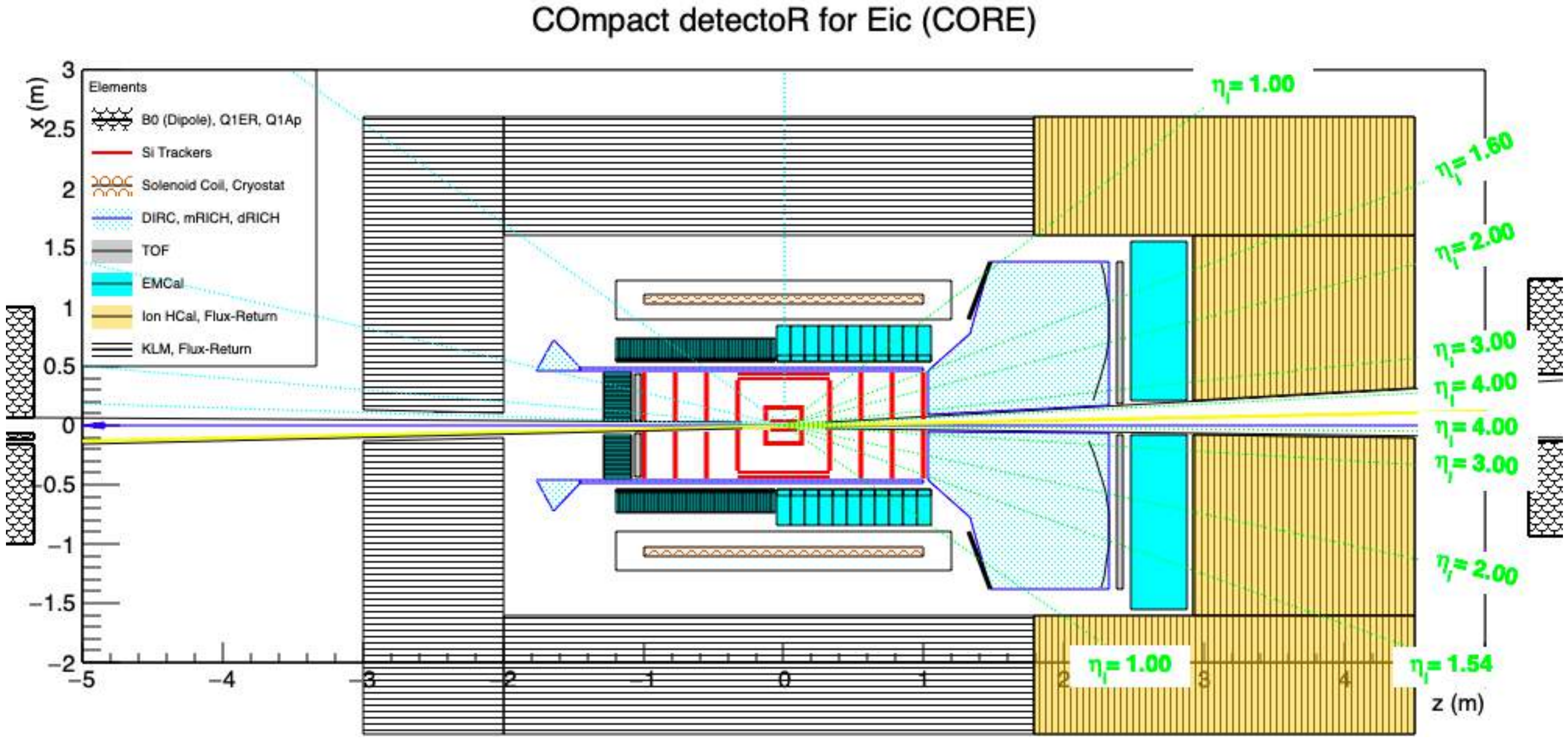


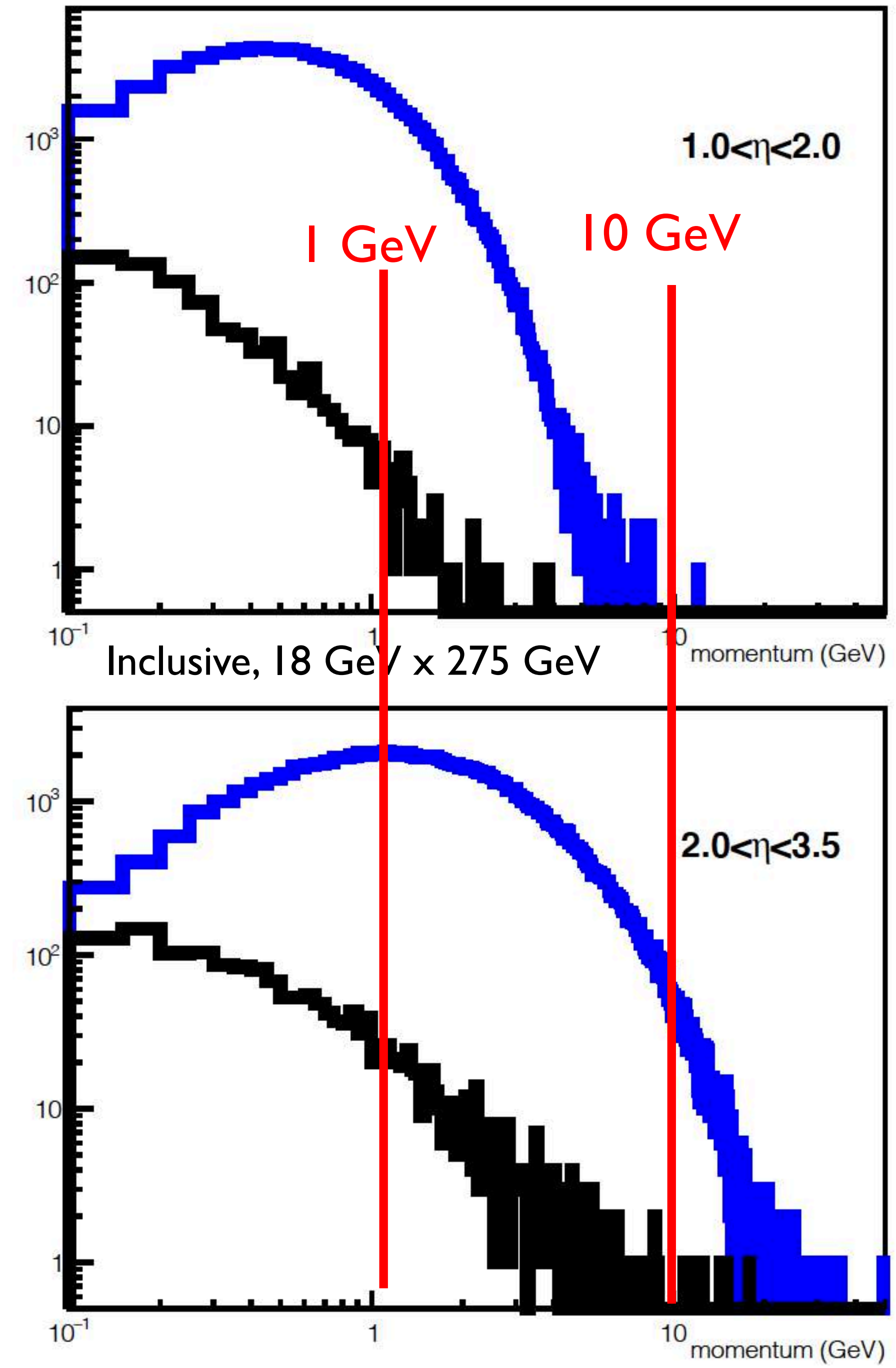
- eRD1/STAR Optimization of forward calorimeters system for EIC reference detector.
- Construction of STAR Forward Calorimeter System.

Synergy between STAR FCS and EIC Calorimetry R&D lead to:

- development of EIC reference detector concept and technologies.
- helped to ensure these technologies are now well established within EIC user community.

Hadron Side EndCap.





- Requirements in YR, resolution 50%/√E + 10%. 6% constant term for eta>3 is desired
- Desired as good as possible 35%/√E + X%. (N.B. there is no discussion in YR text to support these numbers.)
- Requires outstanding Hcal/Ecal system to achieve this.

Conditions at EIC Hadron EndCap:

- Particles Energy – low, difficult for calorimeters
- Interaction Rate – low, < 500kHz
- Occupancy – low
- Radiation Exposure – low
- Neutron Fluxes – some concern.
- Beam Pipe Hole limit acceptance to eta ~ 3, hadron showers are wide, will leak into beampipe up to 40% lost at high eta (https://indico.phy.ornl.gov/event/38/ talk by F. Bock)

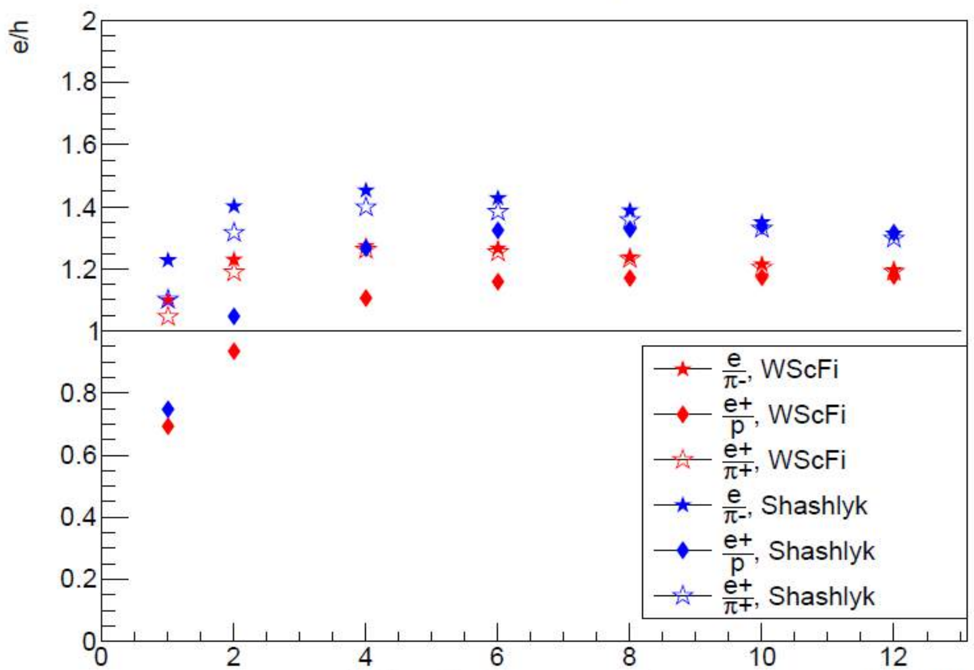
⟷ Standard detector technologies should work fine.

Hadron calorimeter systems. EIC Challenges.

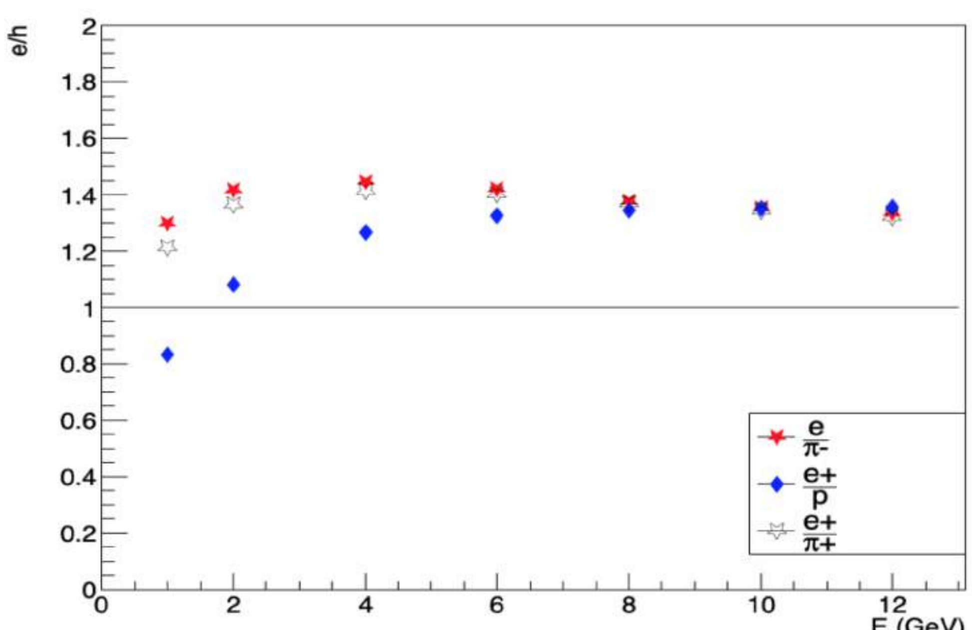
- $e/h \neq 1$
- $e/h\_ecal \neq e/h\_hcal$
- $e/h = f(E)$
- $e/p \neq e/\pi$
- $f_{em} = 0.11 \ln[E(GeV)]$

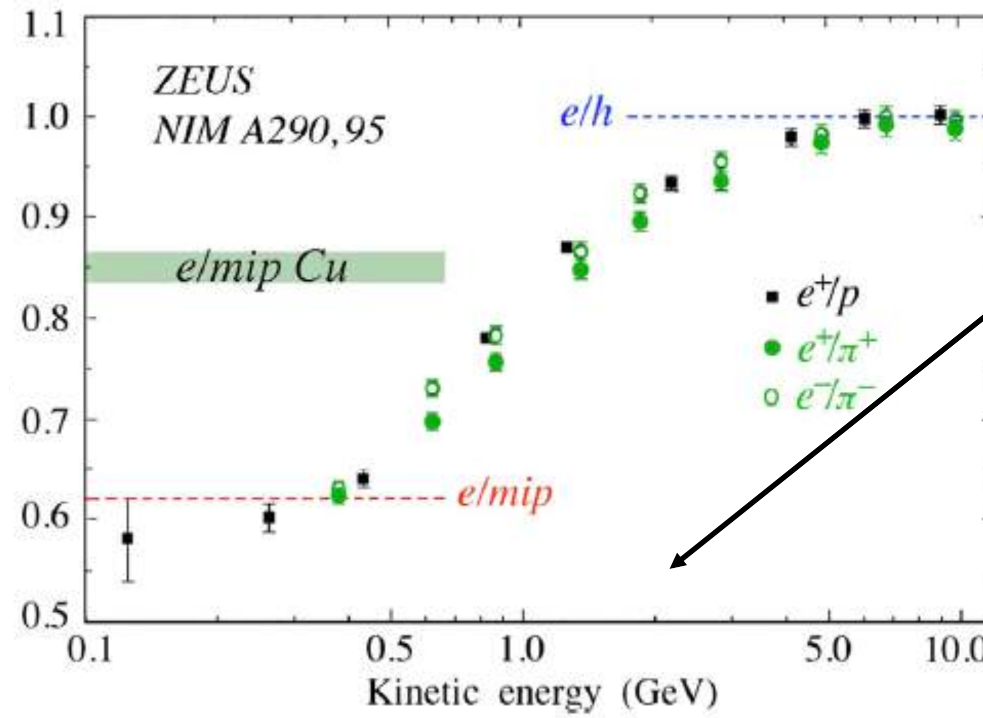
Jet energy resolution is always poorer than for a single hadron. Despite ~ 20% of jet energy (em) measured very accurately by Ecal.

e/h for WScFi vs Shashlyk at 20 degree

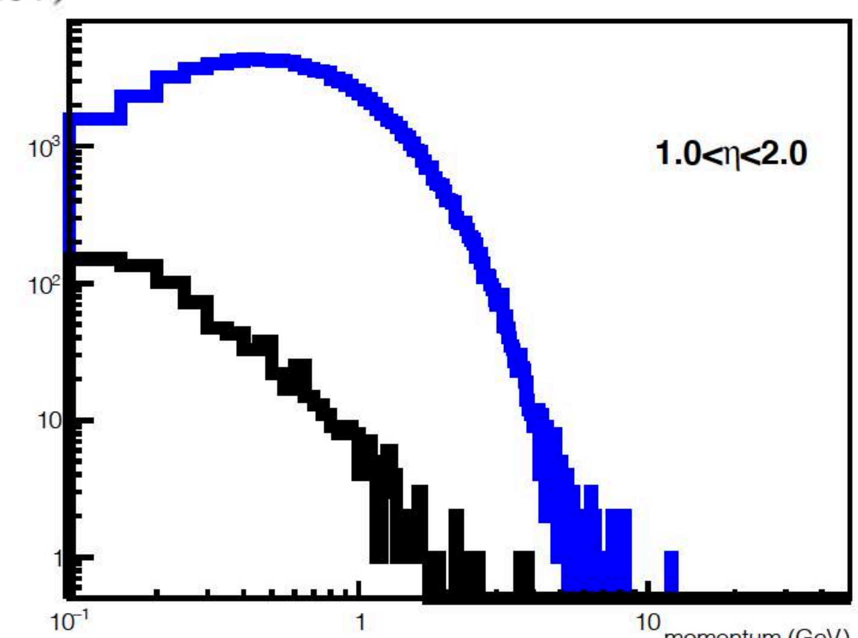


e/h for Fe/Sc at 20 degree





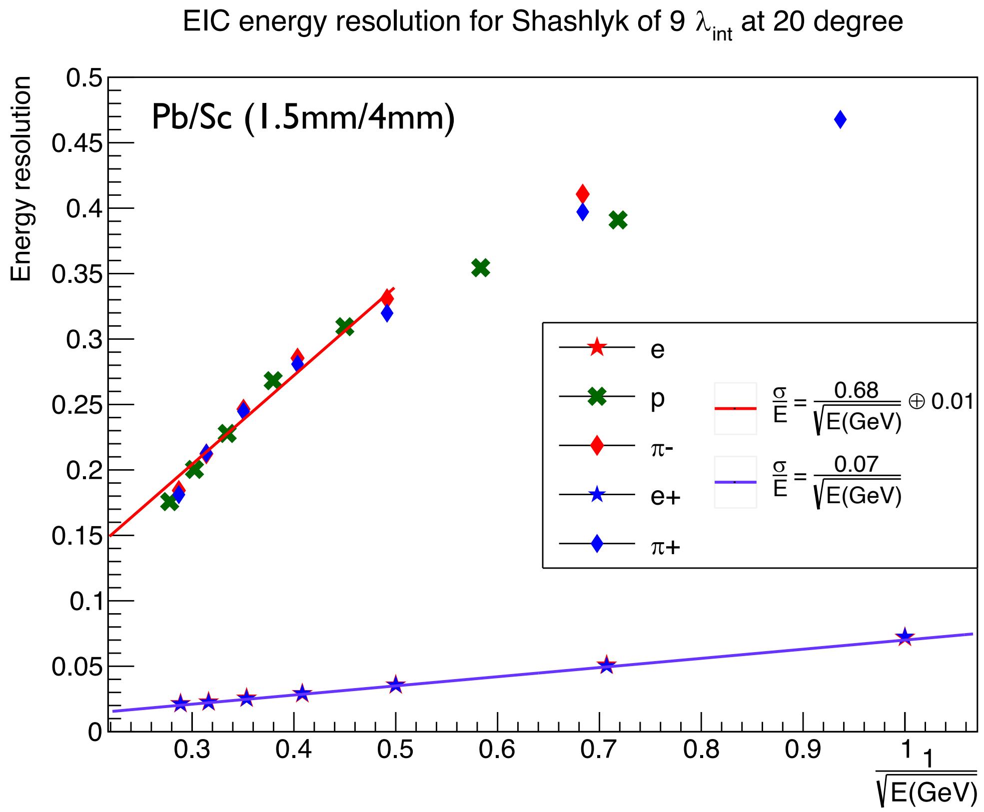
EIC Calorimetry need measurements In this energy range.

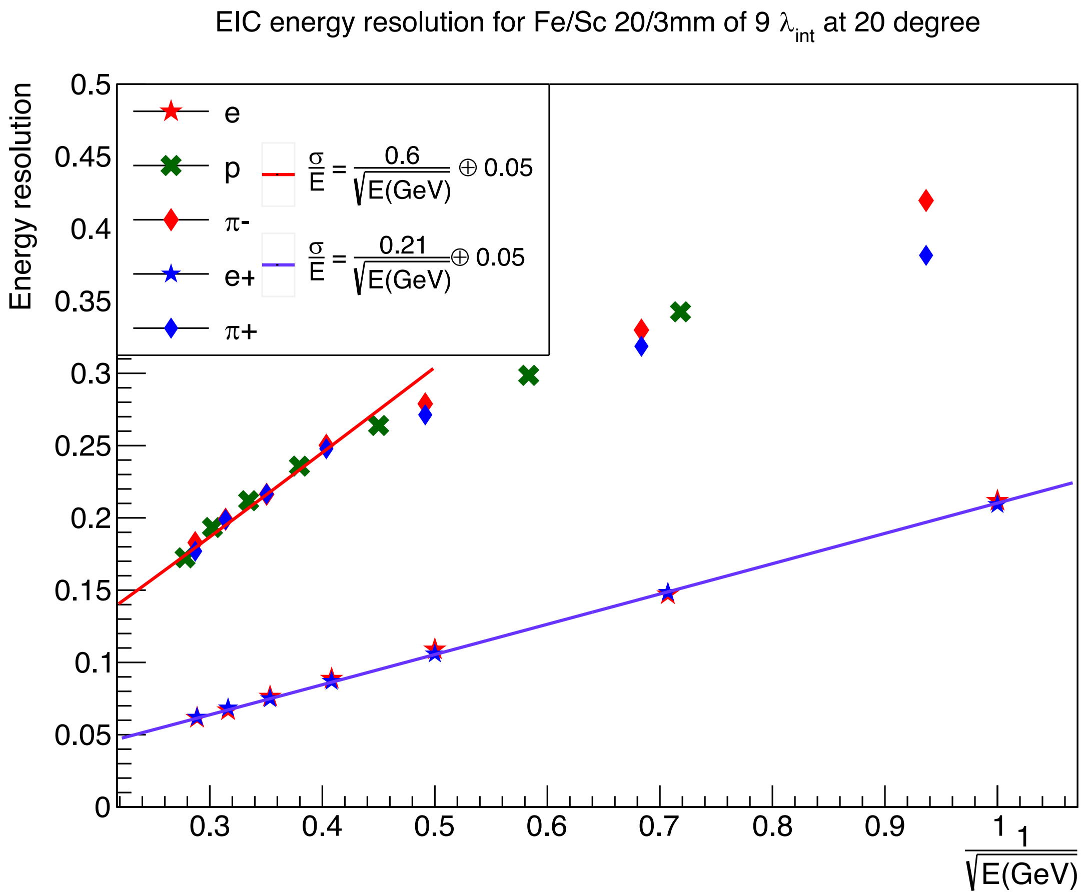


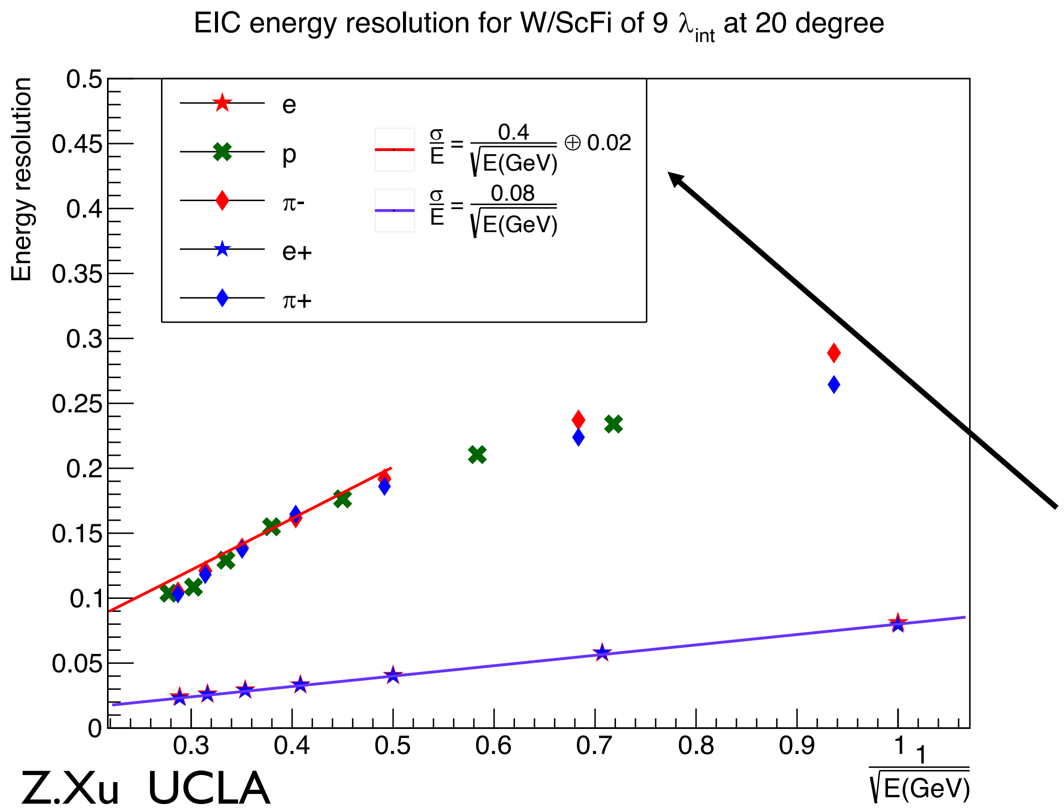
Inclusive, 18 GeV x 275 GeV

- ZEUS are experimental results
- eRD1 – GEANT4 with physics list validated for LHC.
- Validation of MC can be done only using experimental data form detector with correct chemical composition.

How important to tune e/h value? Hypothetical Configurations.







Z.Xu UCLA

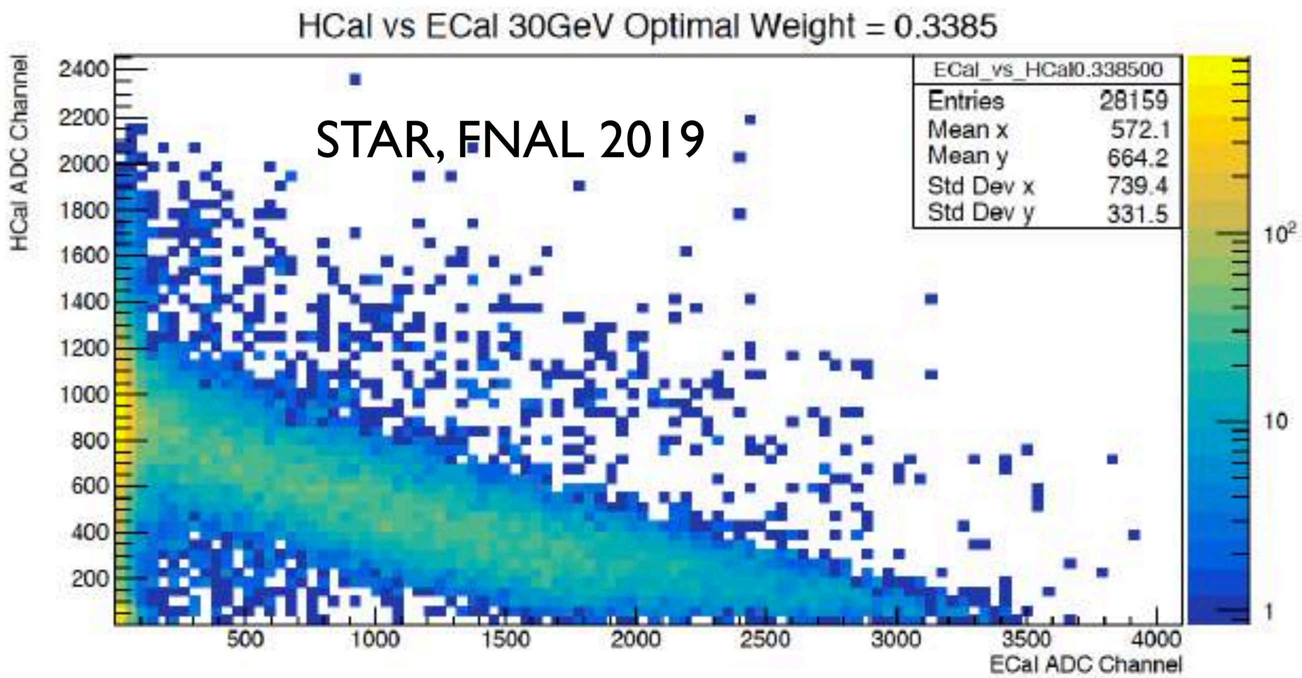
Hypothetical variant, 9 interaction lengths long calorimeters. Same structure for Ecal and Hcal sections. Three different technologies:

- SHASHLYK (Phenix, STAR Forward)
- WScFi (STAR Forward 2014)
- Fe/Sc (STAR Forward 2020)

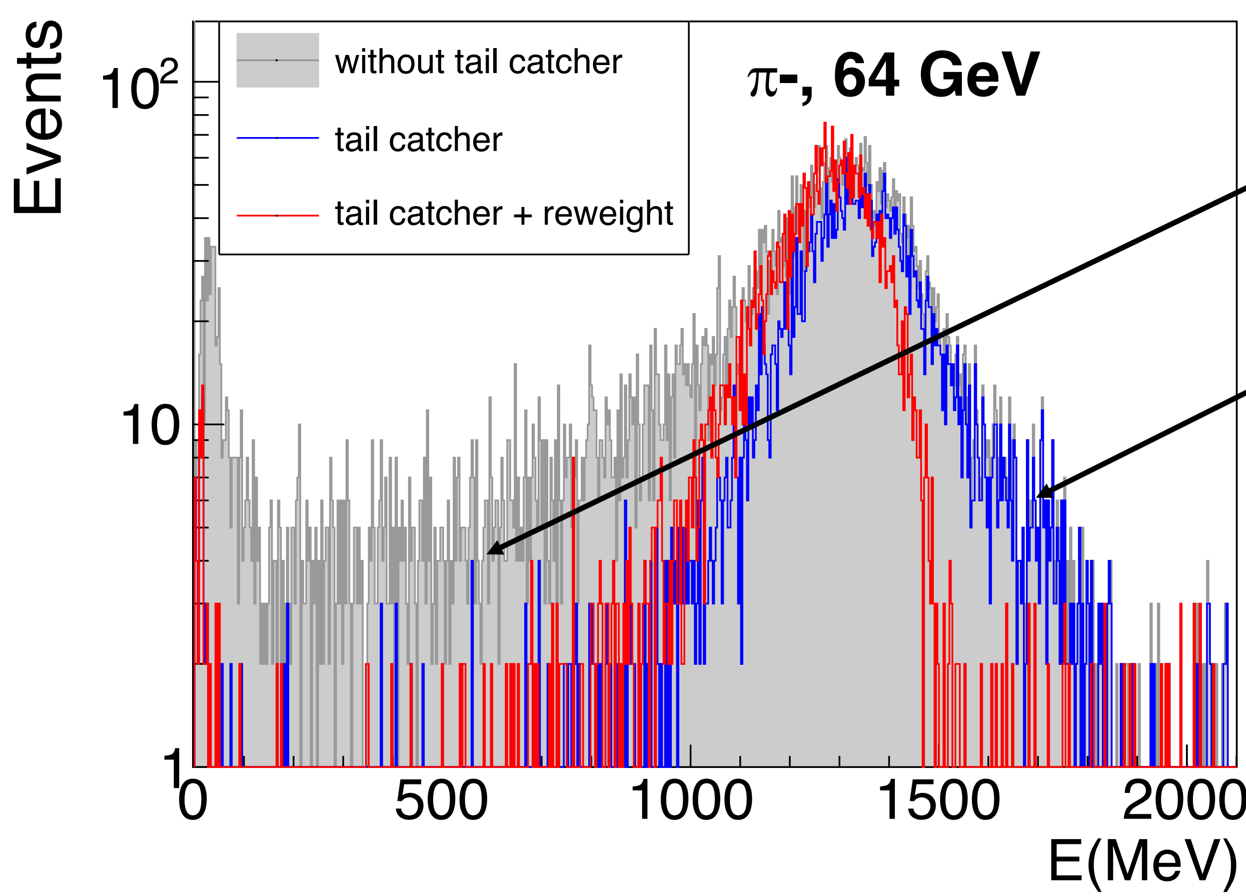
Proper detector composition required for good hadronic resolution. I.e. desired to keep e/h as close as practically possible to 1.

N.B. these are MC not an experimental results.

Realistic Configurations, i.e. binary systems Em + HAD.



- E_t= w*E_em+E_had
- Cut on tail catcher
- 'Shower Shape'
- Re-weighting Hcal towers. $E_i' = E(1 - \frac{C}{E_{tot}} E_i)$



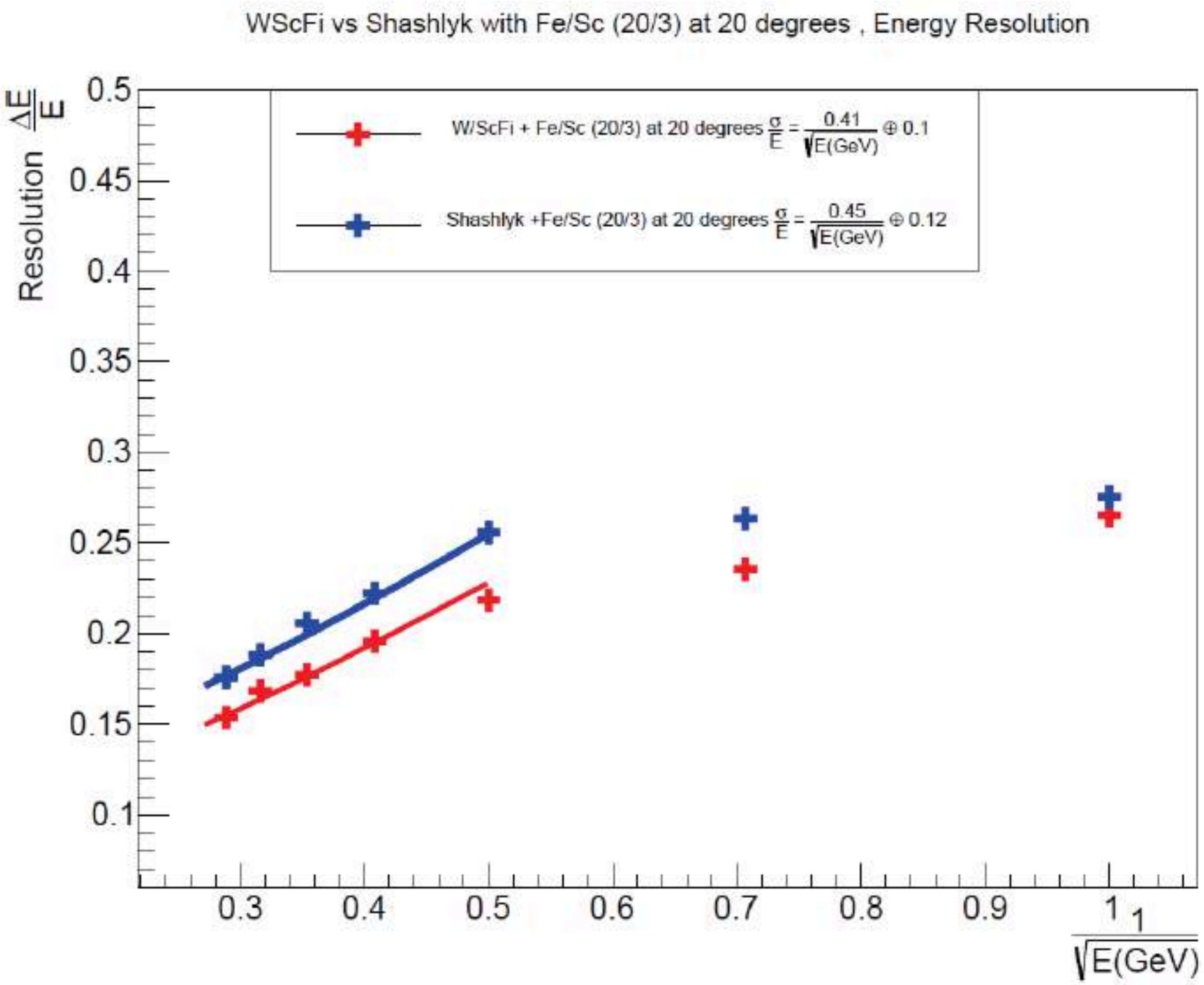
Tail catcher, handle to controls leakages.

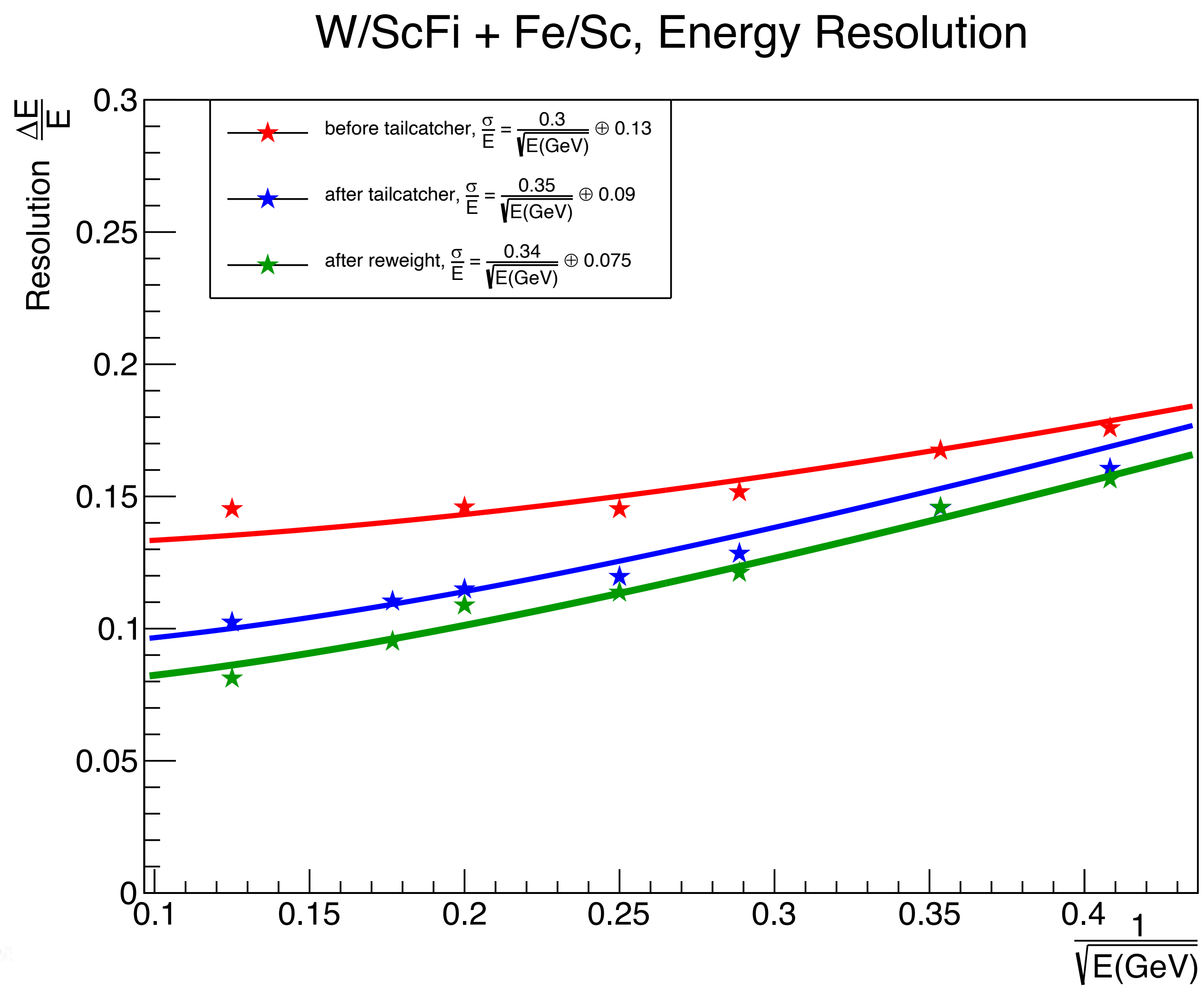
Re-weighting Hcal towers helps to deal with abnormally high f_{em} events.

Z.Xu UCLA

WScFi, ECAl

Cut on tail catcher + re-weighting Hcal towers





Z.Xu (UCLA)

At lower energies (EndCap eta range 1- 2) stochastic term almost always will dominate.

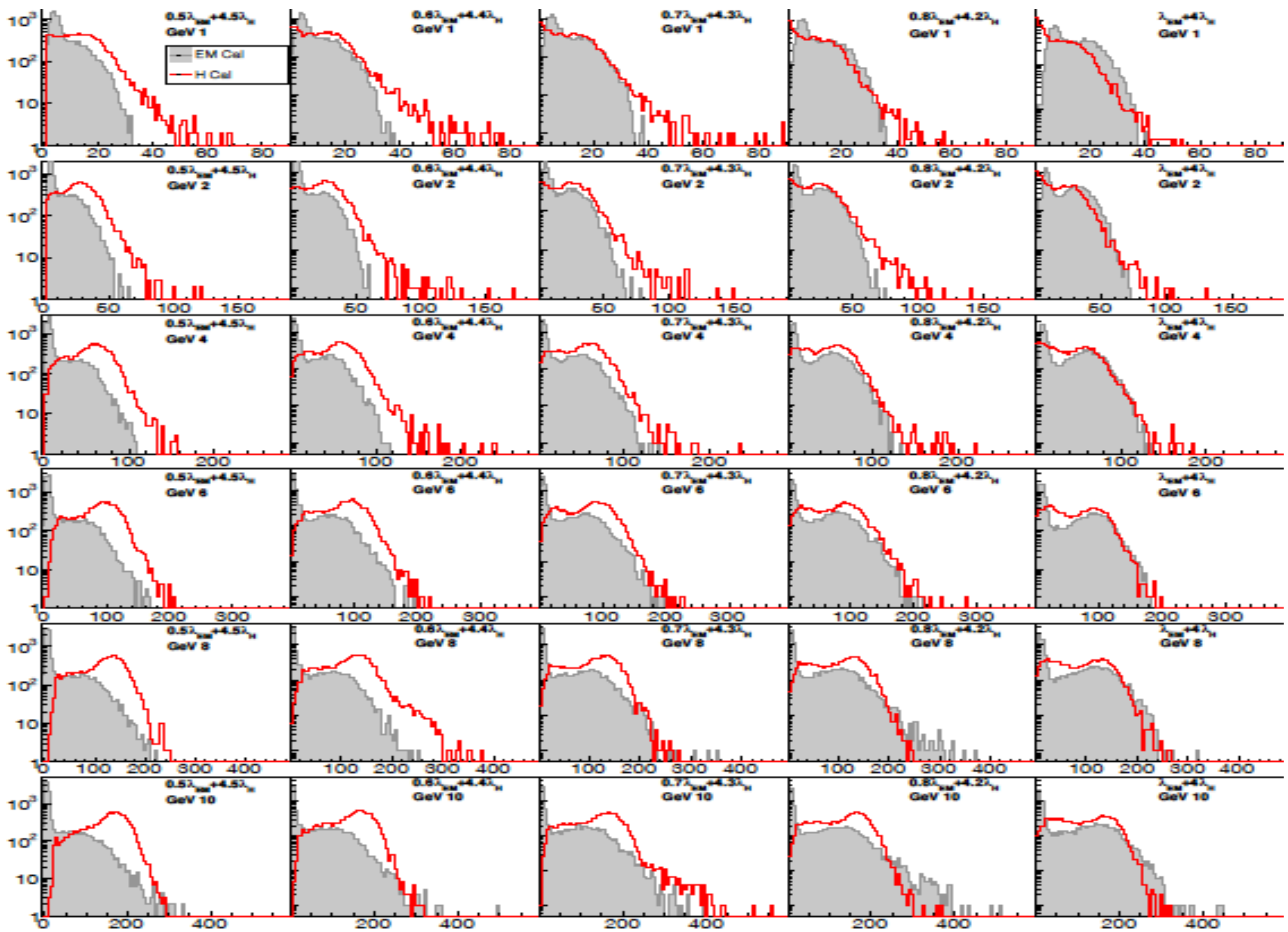
N.B. no cuts on tail-catcher or re-weighting was applied here.

WScFI 23 X0 vs SHASHLYK 18X0
(both depth and better e/h plays role)

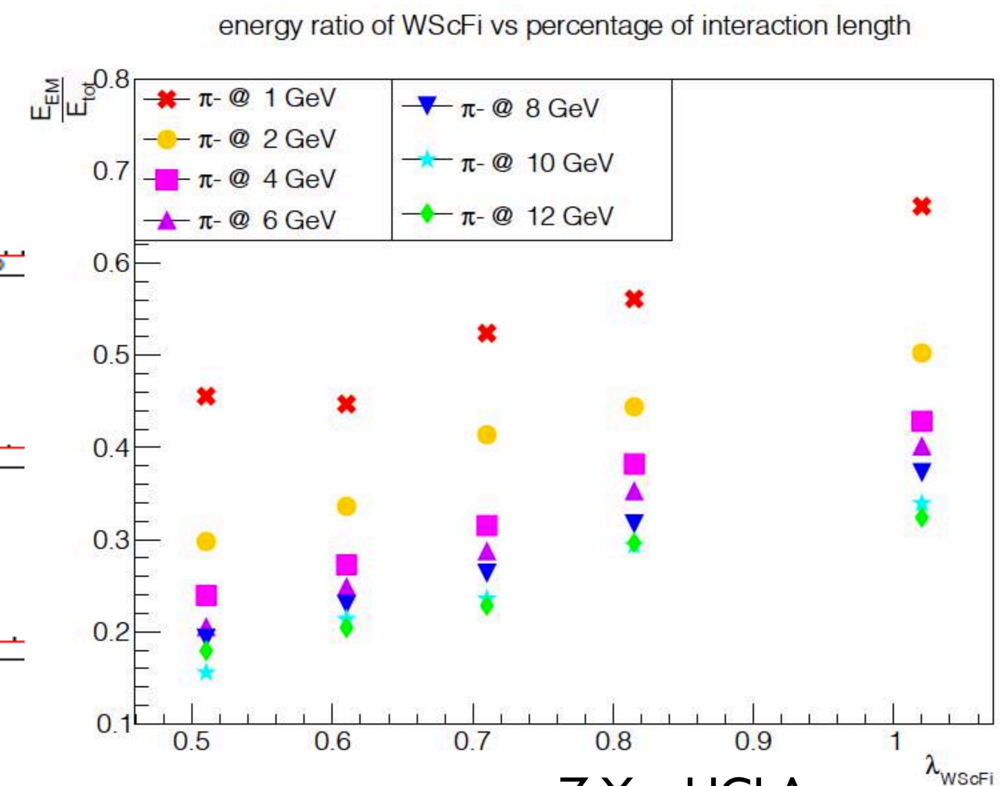
At higher energies (EndCap eta range 2- 3) constant term start to dominate.

With cut on tail catcher and re-weighting Hcal towers GEANT4 resolution looks very good with stochastic term at ~35% and constant term at ~7% (N.B. efficiency, fit).

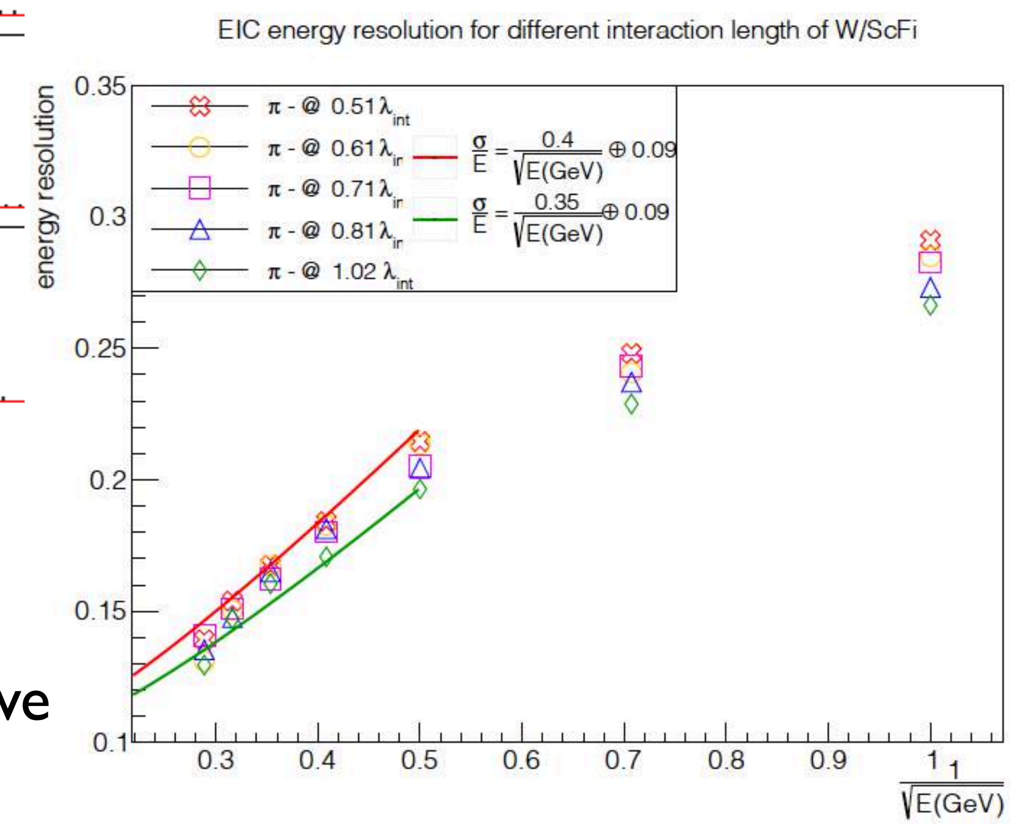
Does deeper Ecal helps to reconstruct low energy hadrons?



Increased depth of ECal



Z.Xu UCLA



Increased depth of Ecal does help a bit to improve energy resolution of the system for low energy hadrons. Assuming we have good PID, additional e/h (TRD etc.,) you can do that.

What about advanced HCals ? (no PFA, calorimeters only).

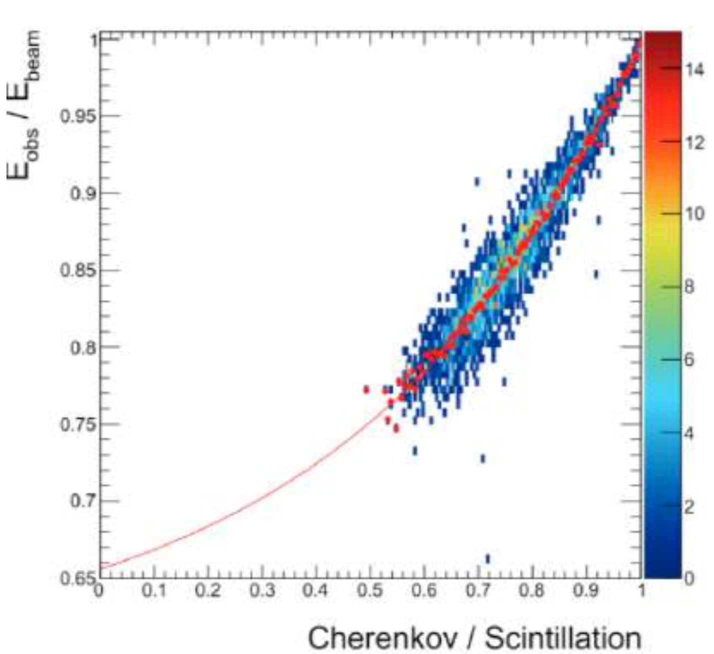
Compensated detectors. Record holder is SPACAL ~ 30%/sqrt(E)
But, below 10 GeV compensation does not work, and looks like there is no solution (at least known)

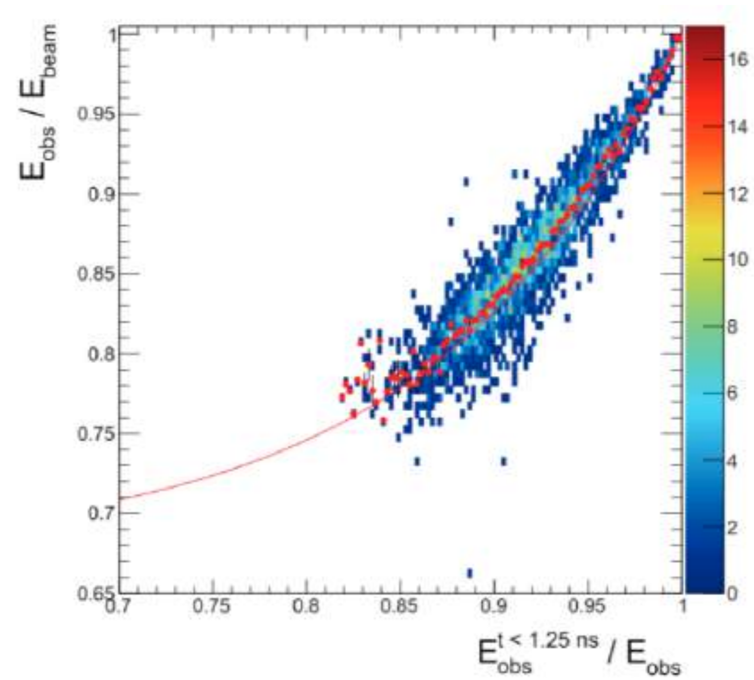
- Dual readout methods developed by HEP during past 20 years or so, DREAM project.
- There is no real detector implementations beyond prototypes.
- There are few talks related to DR at latest CPAD https://indico.fnal.gov/event/46746/
- There are also 3D imaging concepts CALICE, IDEA and such (100s M of channels + timing)

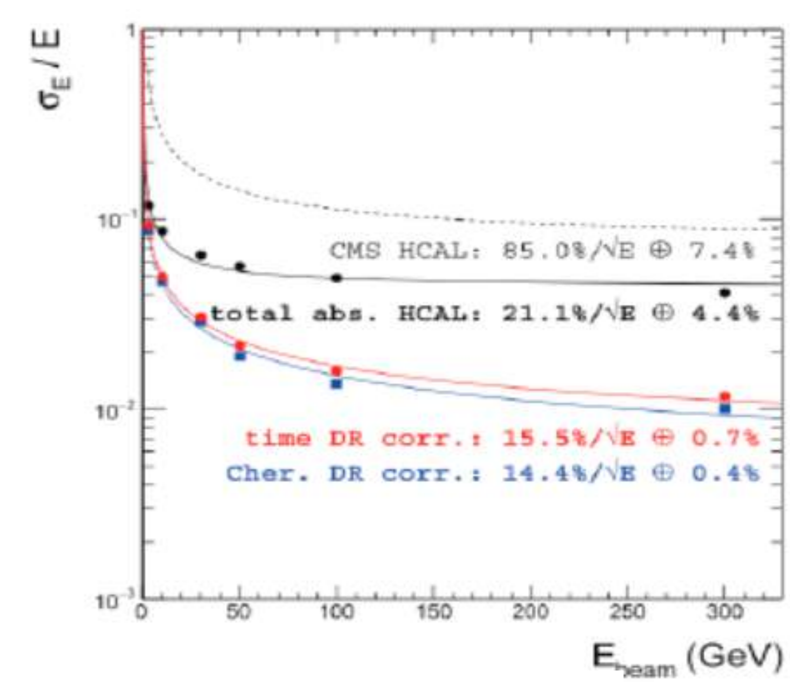
What is DR?

- Find observable which correlates with number of neutrons (kinetic energy of n correlates with 'invisible' energy). Observables can be C/S, Time, Spatial characteristics of shower etc. Unlike compensation dose not require precise tuning of chemical composition of detector.
- E-by-E correct detected energy using this observable. Or 3D imaging + ML

Theoretically hadronic resolution can be as good as 20%/sqrt(E) (Fe/Sc (20/3)), i.e. em type resolution
On practice very difficult to realize and costly.

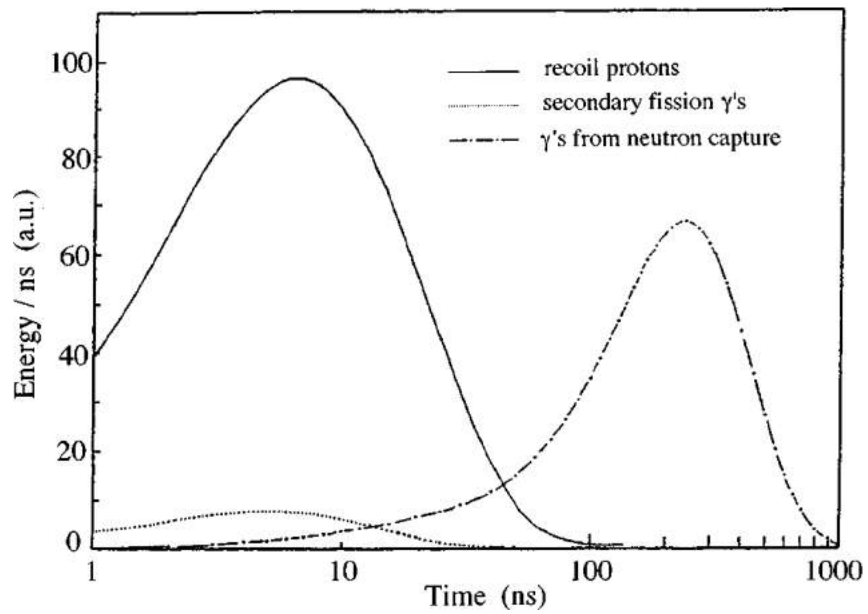






A. Bengalia et.al. IEEE Trans. Nucl. Sci. V63, N2, 2016

Time scales for HCAL signals, 1 GHz digitizers
eRD 1 (Fe/Sc Hcal, FNAL 2019)



ZEUS, NIM A263, 136 (1988)

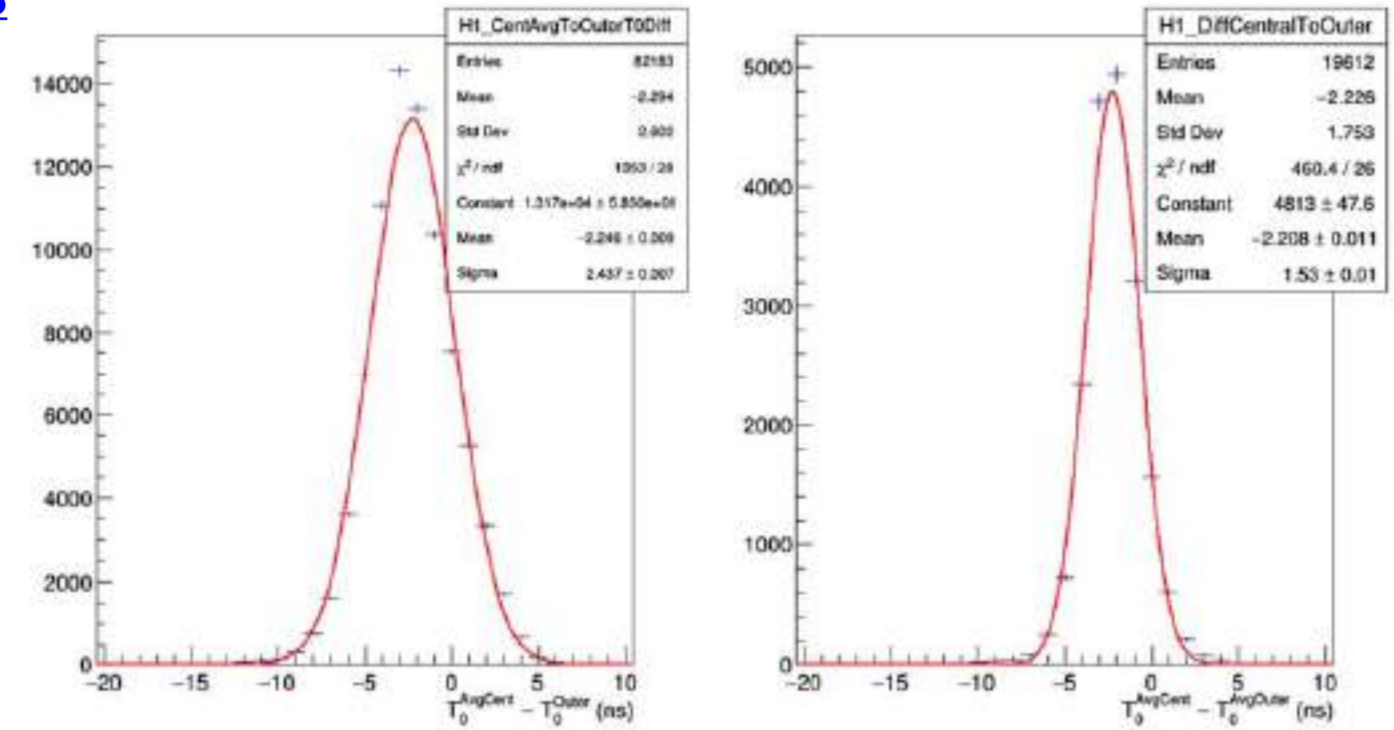


Figure 2. Difference in To in central and peripheral towers of HCAl.

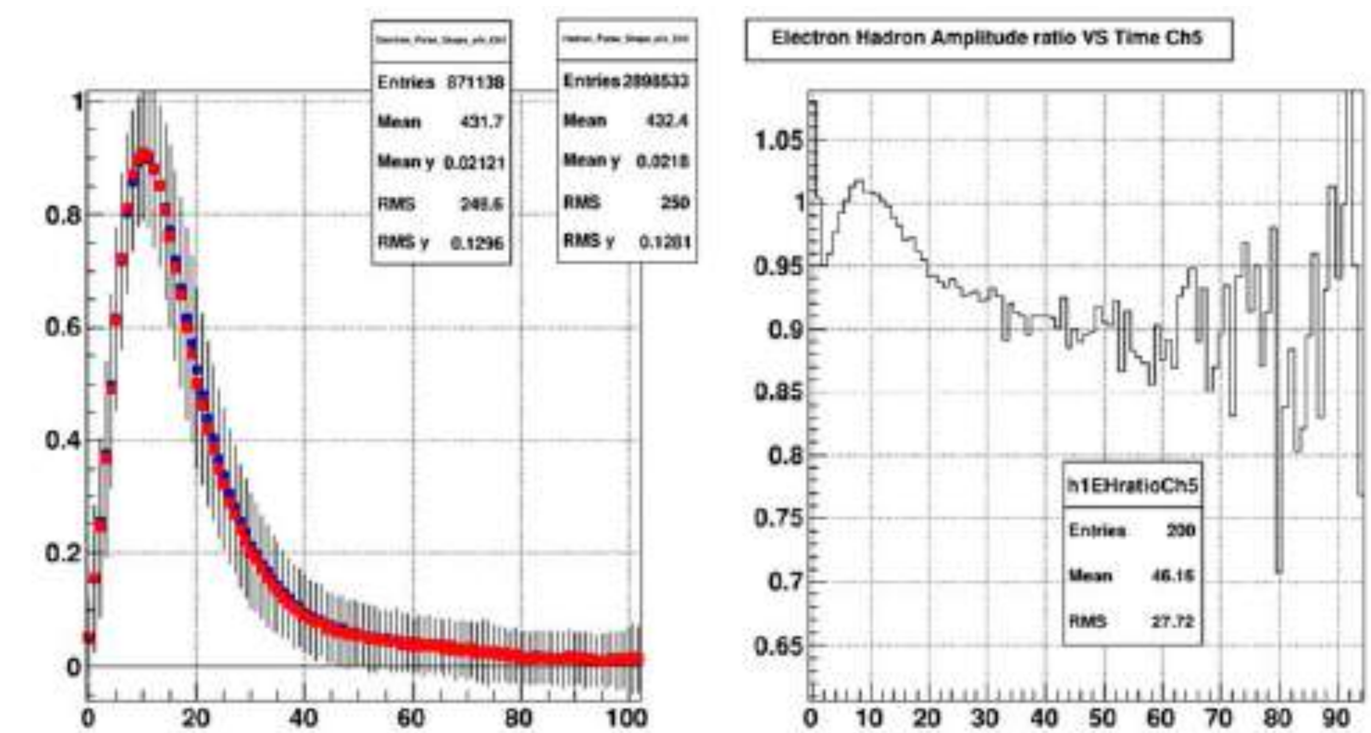


Figure 3. Shape of signals for 20 GeV electrons and pions. X axis bin size 1 ns.

- 'Sanity check', T_0 difference between central and peripheral towers in Hcal.
- Direct comparison of signal shapes from electromagnetic showers and hadronic showers shows hints of contribution from recoil protons.
- Signal is too week to make e-by-e corrections, i.e. no correlations observed for short/long integration time and total energy.
- (Fe/Sc) structure was not optimized in any sense for such purposes.
- Pb/Sc structure (17mm/6mm) was studied by A. Kiselev – found very weak dependence.

IMHO, realization of DR methods at EIC will be difficult.

- Timing will not work for Tile/WLS well no matter what type of absorber will be used (eRD1 conclusion after 2019 tests)

- Timing may work with SPACAL type, no MC tried. Need high Z to generate enough neutrons, but then had to think about flux return. Too many neutrons may be problematic for SiPMs. There are some problems with fiber type DREAM detectors (see latest CPAD, Tile configuration DREAM approach).

- Shower shape may be difficult due to relatively low energy of hadrons. And it is not clear how well it will work in compact detector at forward rapidities for jets. Magic with ML, AI ☺, may be?

- C/S may work with SPACAL types. HCal is a flux return, had to be made from steel.

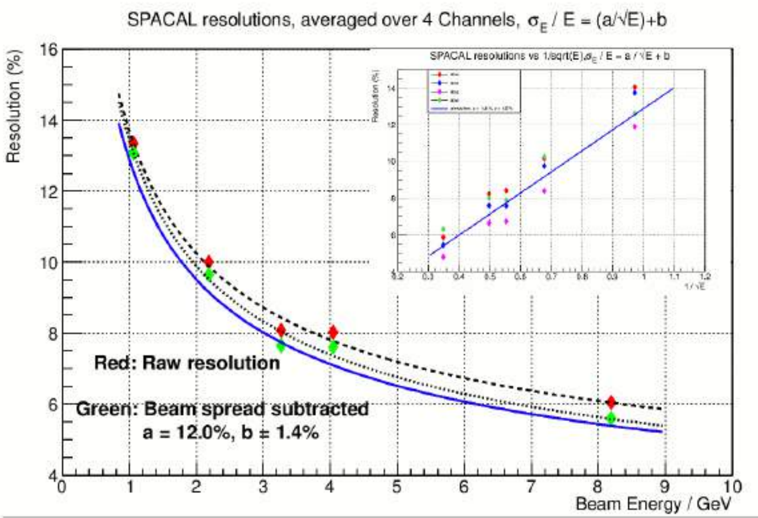
Practical realization of any DR approaches are challenging: fast digitizers, C/S separation, high granularity, integration issues…

With CD2 in Jan 2023, they are out of reach. For long term upgrades it is possible they may be worked out (SciGlass ?)

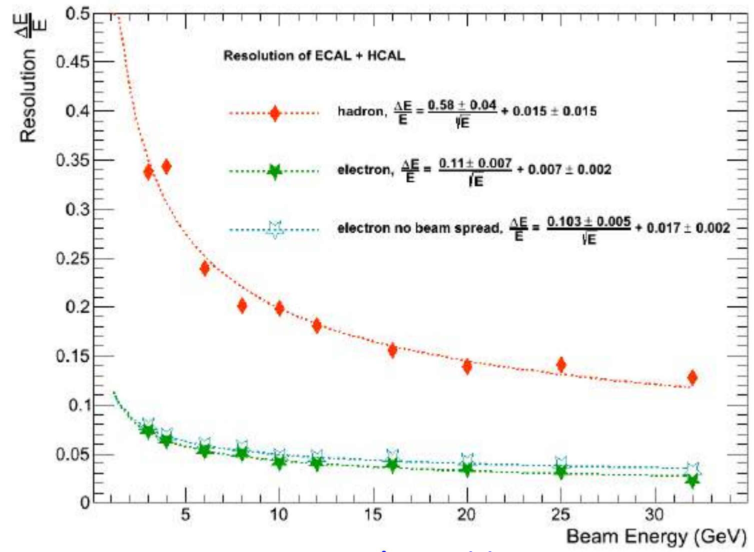
Reference EIC Hadron EndCap studies summary (eRD1 reports 2019-2020):

- There are some tricks which may help improve resolution of reference hadron endcap system, may be by 20%, without escalating the cost.
- It is little to no room to improve e/h for Fe/Sc section.
- WScFi, e/h good as it is (may be improved a little, but need experimental data).
- Tail catcher will allow to control leakages from the back. (Easy to integrate).
- Dead material between Ecal and Hcal is not an issue, because it is not needed.
- Different Instrumental effects, like light collection non-uniformities in hcal section has little effect on resolution, checked with gSTAR.
- With cut on tail catcher and re-weighting Hcal towers GEANT4 resolution looks very good with stochastic term at ~35% and constant term at ~7% (N.B. efficiency, fit).
- Need to think a bit more about increasing depth of Ecal – that may be important for Barrel, due to magnet coils between Ecal and Hcal.

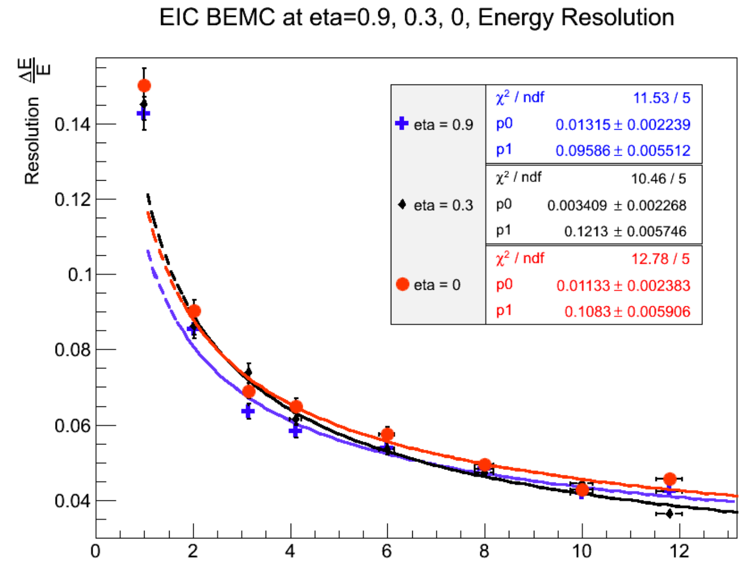
Transition to targeted R&D…



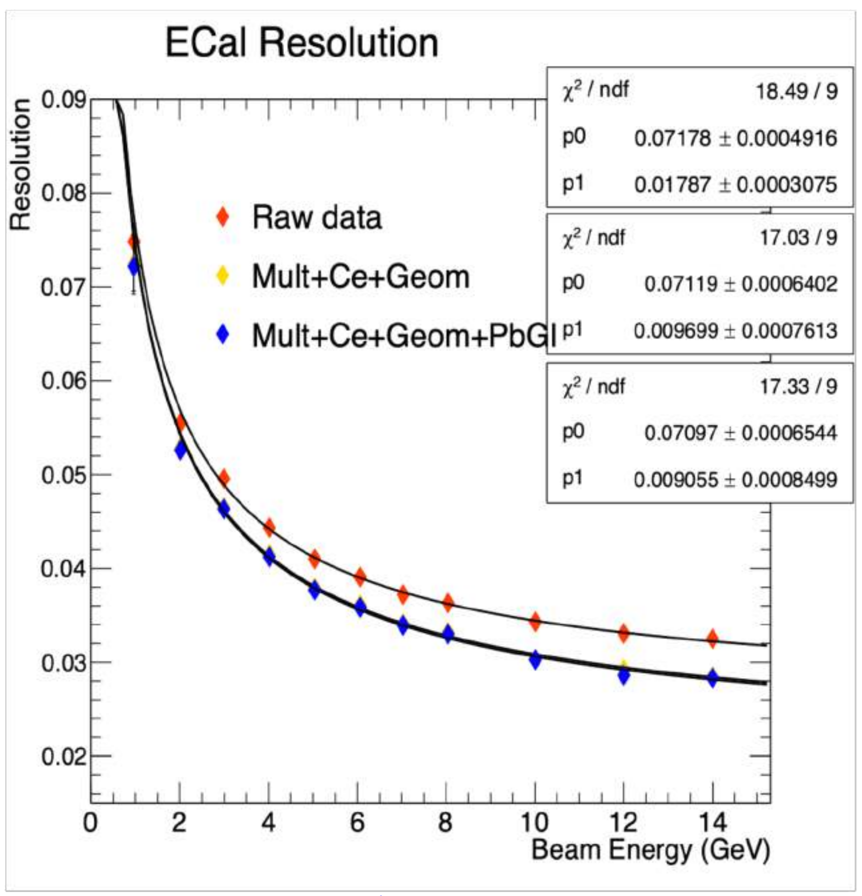
Proof of principle. FNAL 2012



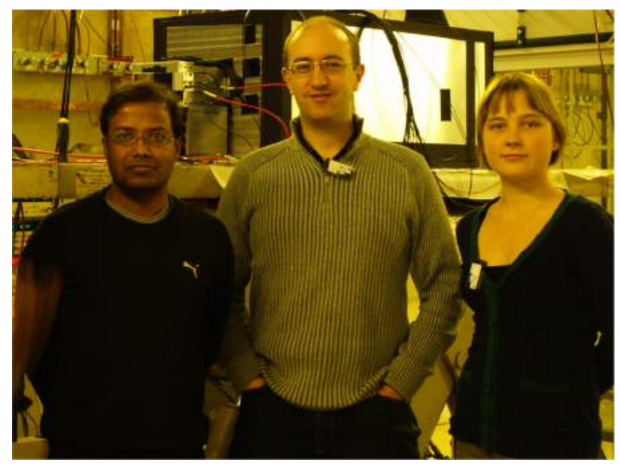
EIC Forward, FNAL 2014

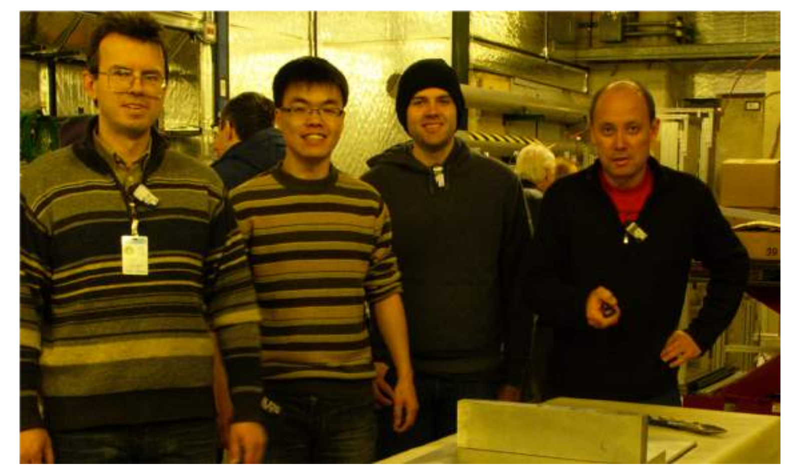


EIC BEMC, FNAL 2014



EIC Forward, FNAL 2016



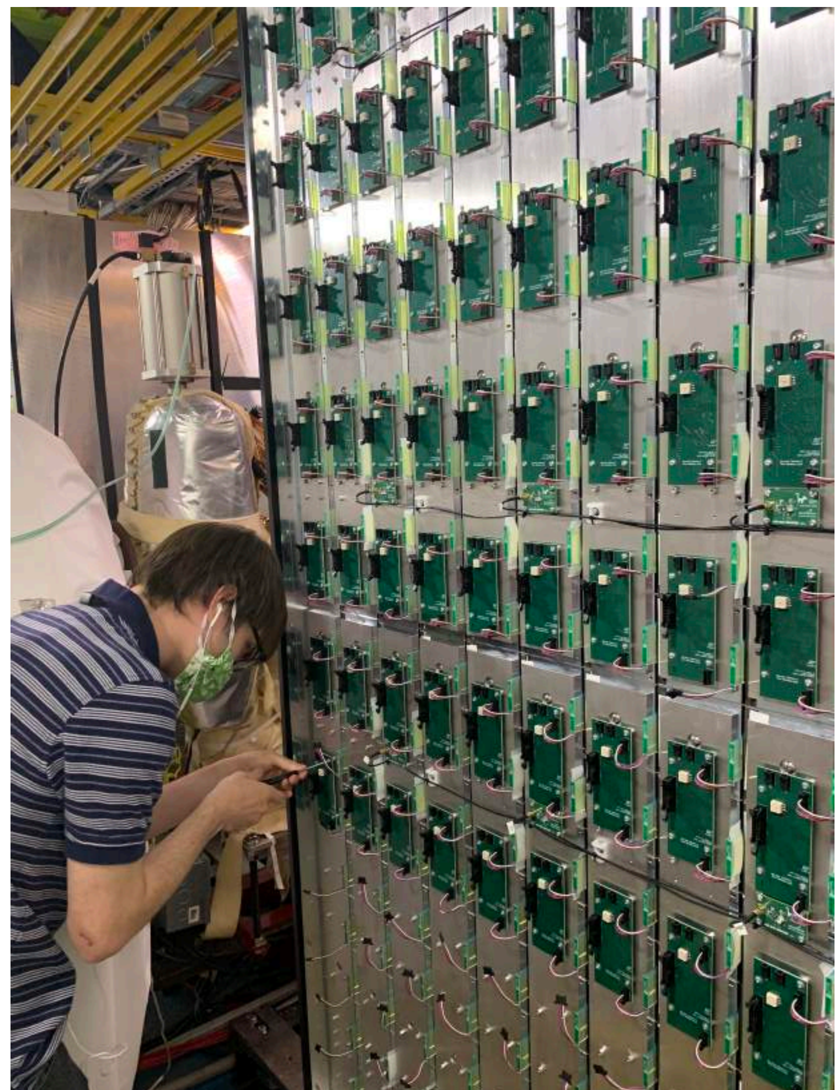


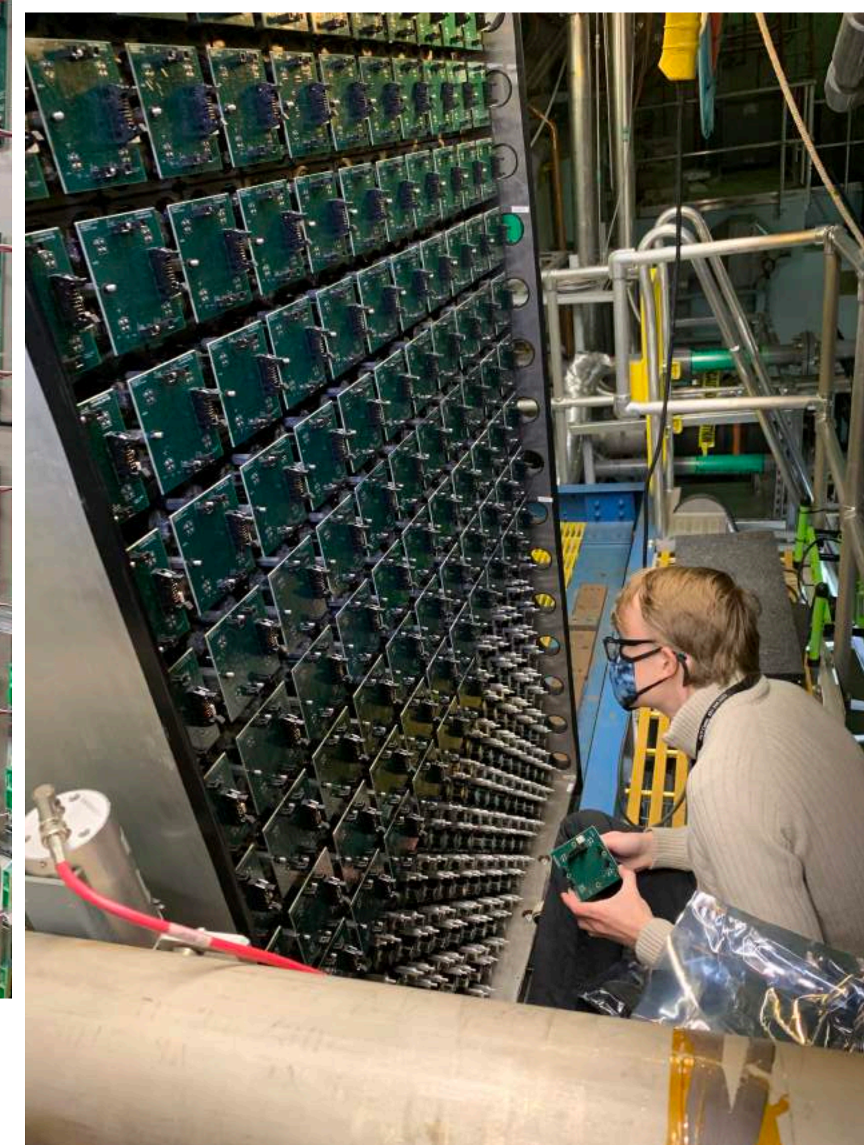
Test Runs 2012 -2016

STAR Forward Calorimeter System (FCS), 2020

Forward Calorimeter System (FCS)

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





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

Large group of STAR collaborators actively engaged in all aspects of the project: ACU, BNL, UCLA, UCR, Indiana University CEEM, UKU, OSU, Rutgers U., Temple U., Texas A&M U., Valparaiso U.

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!