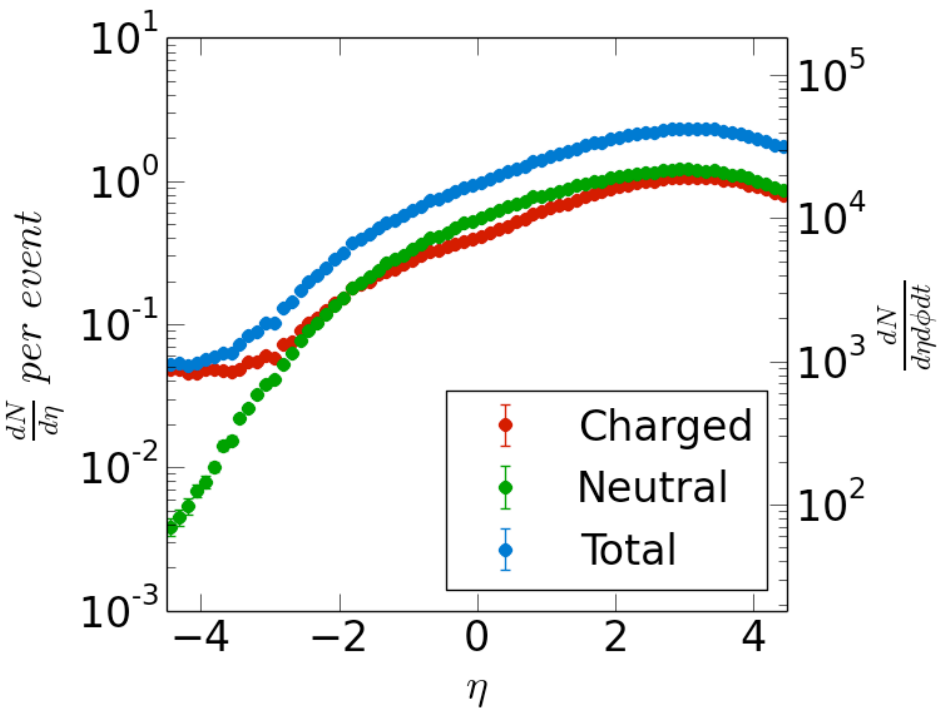
Calorimeter. Overview…

(limited to compensated sampling hadron calorimeters)

O.Tsai (UCLA)

Sep. 26, 2019

Joint CFNS&RBRC Workshop on Physics and Detector Requirements at
Zero-Degree of Colliders.



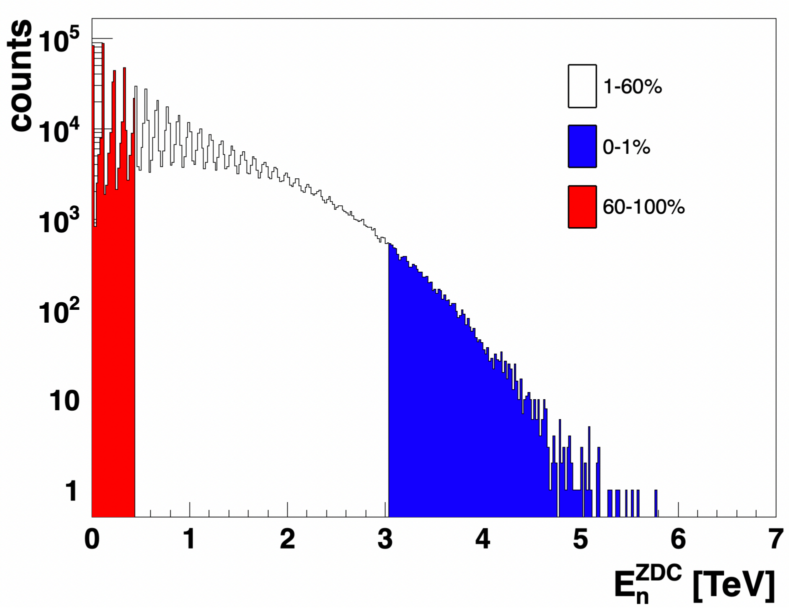
From what was presented during this workshop with respect to calorimeters, measurements:

- Single Particle Measurement.
- Rate ~ 500 KHz.
- Energy scale ~100 GeV for a single particle
- Position Resolution ~1.5 cm

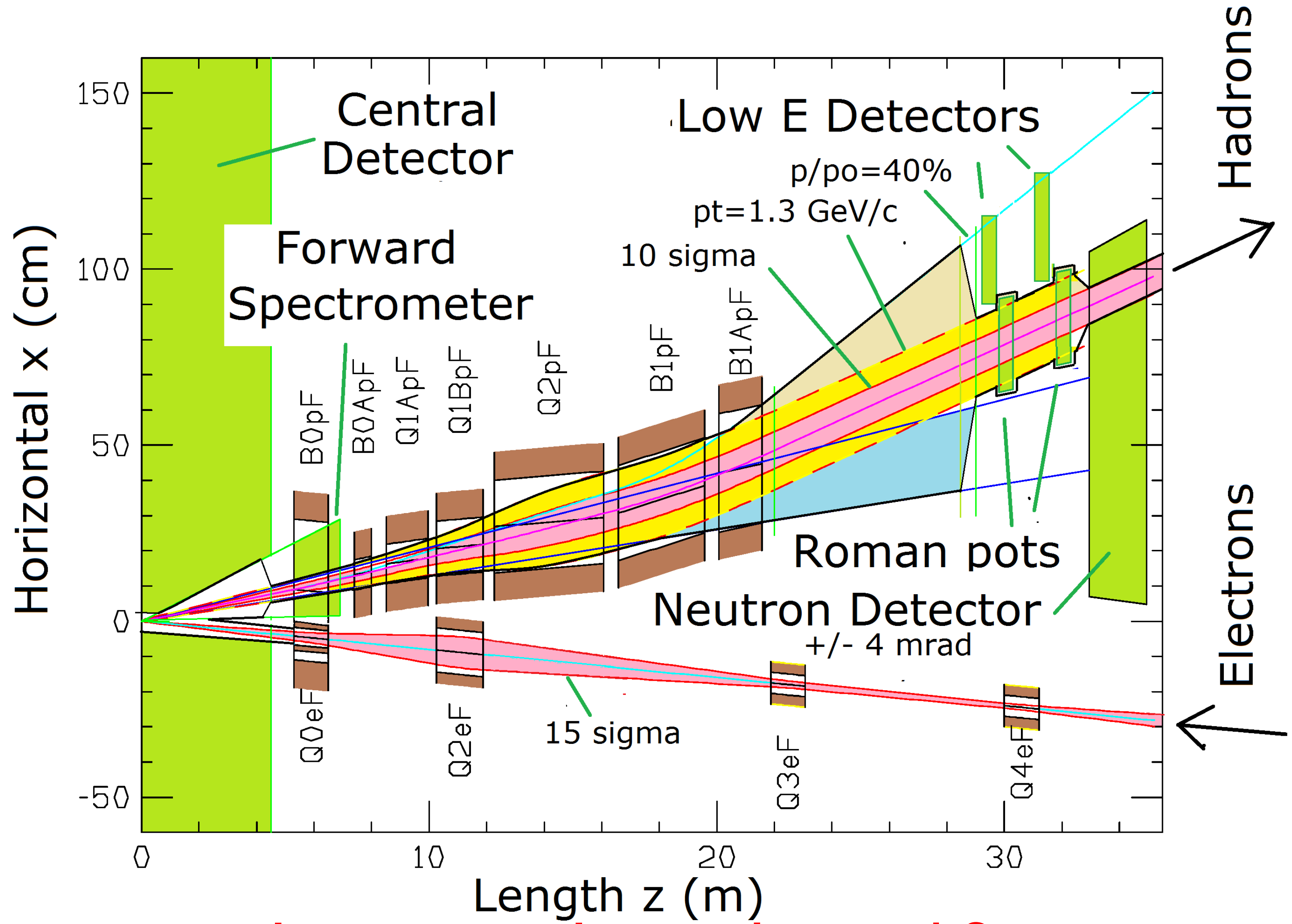
Energy resolution better than ~40%/$\sqrt{(E)}$ + few% is challenging. Requires R&D.

https://wiki.bnl.gov/eic/index.php/Detector_Design_Requirements

eRHIC L =10^{33} $cm^{-2}s^{-1}$



W. Chang's talk this workshop



Integration Issues, Limited Space

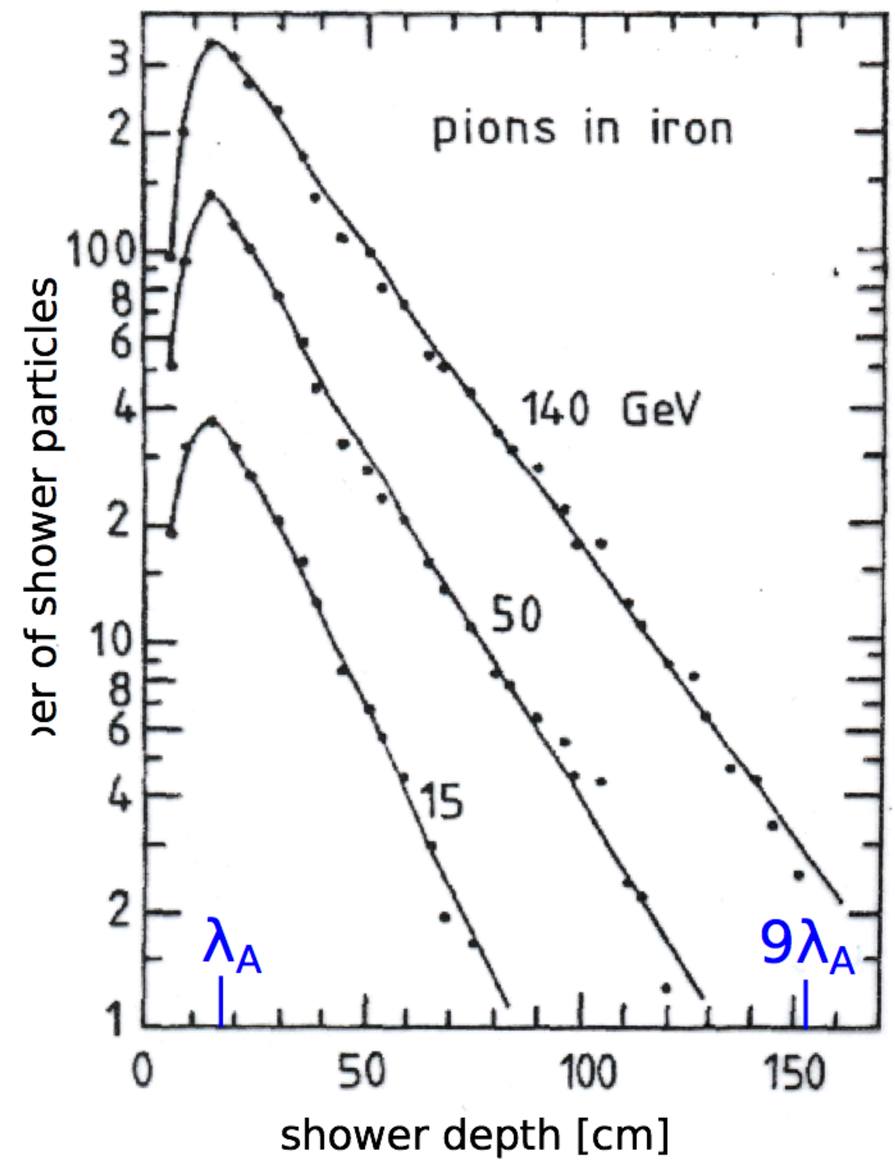
Containment. Longitudinal.

Shower depth:

$t_{max} \simeq 0.2 \ln E(\mathrm{GeV}) + 0.7$

95% of energy in $L_{95} = t_{max} + \lambda_{att}$

where $\lambda_{att} \simeq E^{0.3}$ (E in GeV, λ_{att} in units of λ_A)



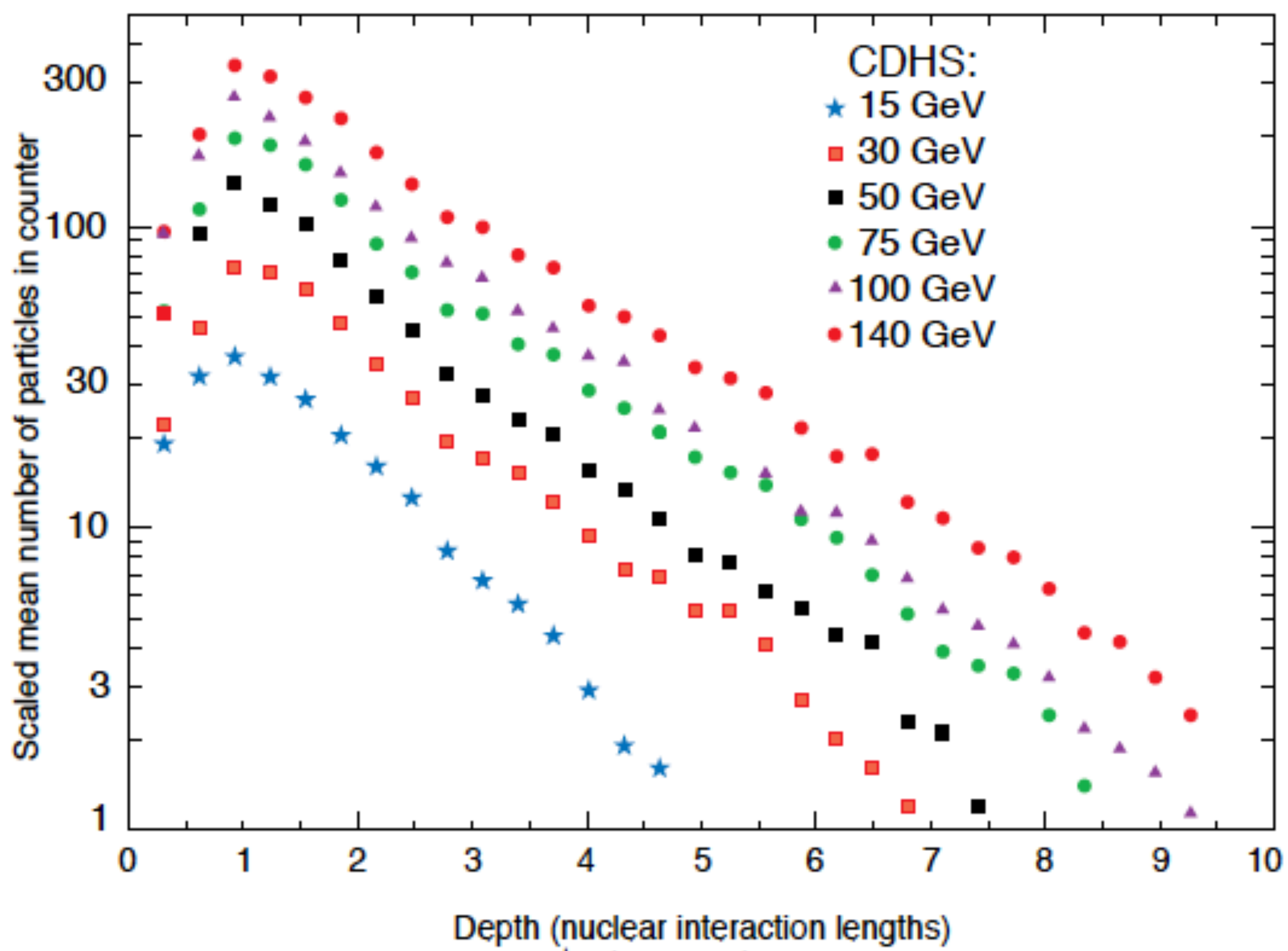
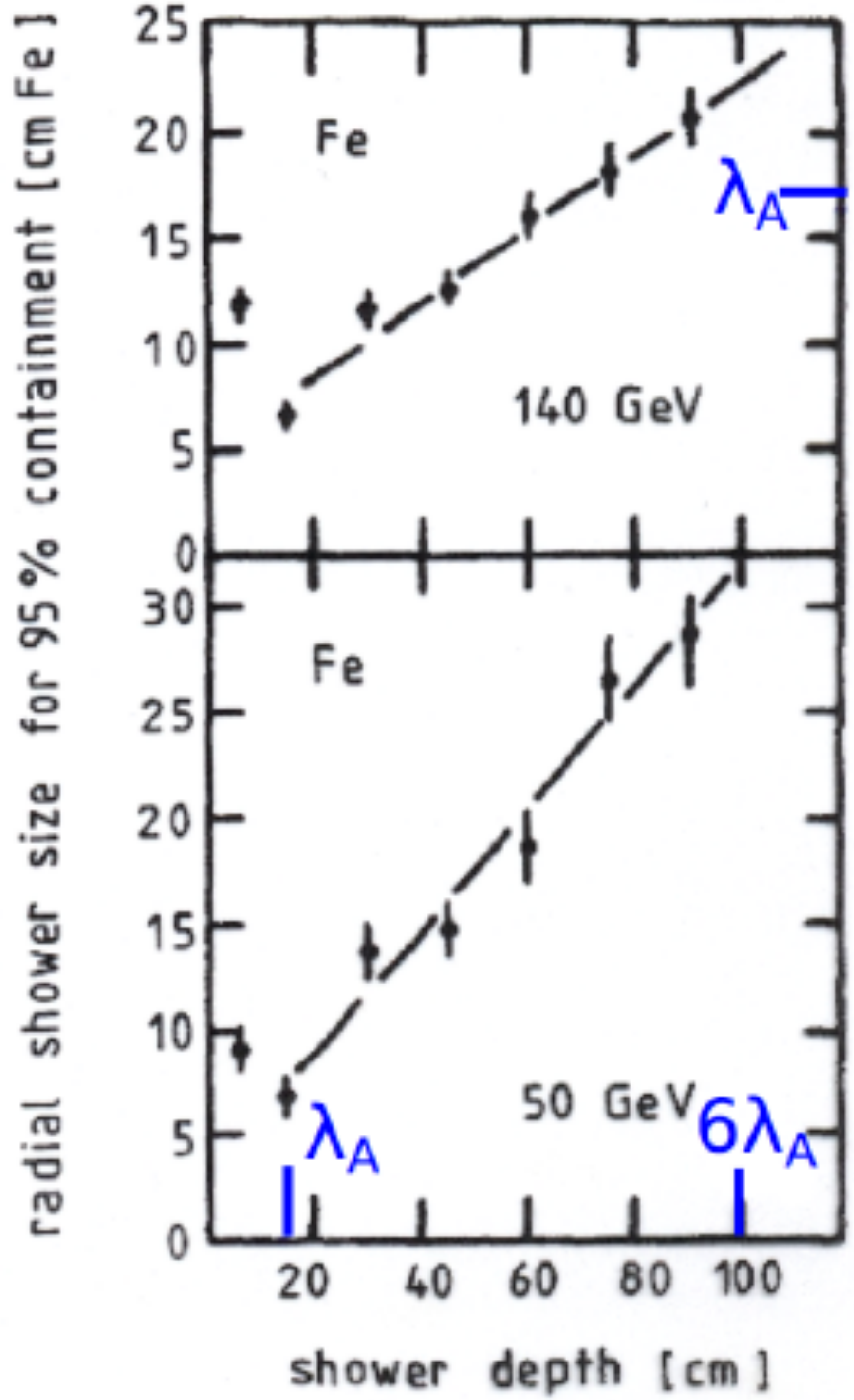


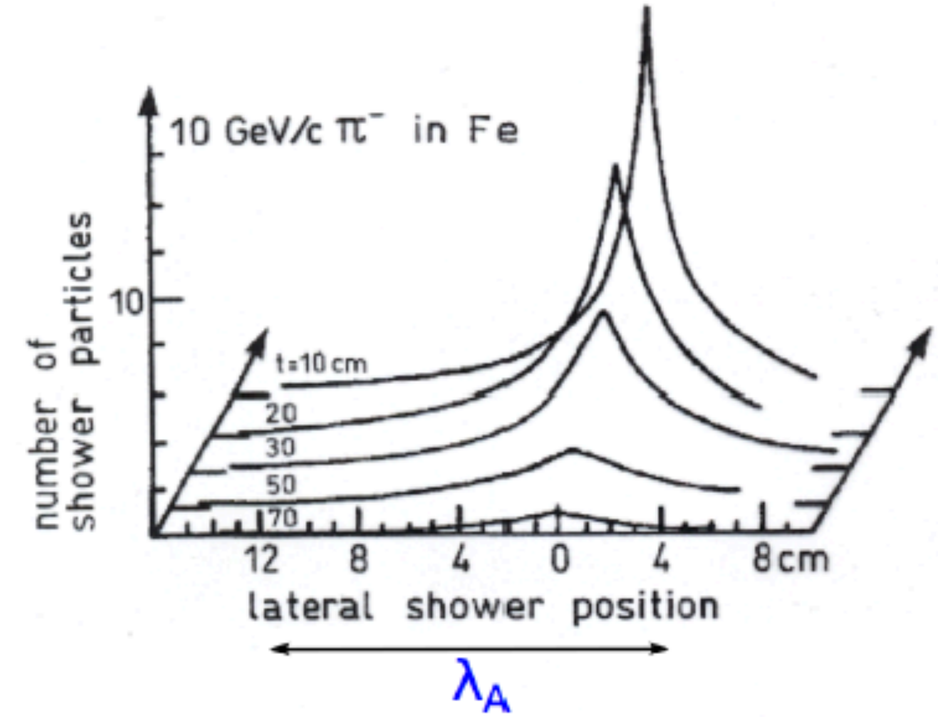
Figure 33.24: Mean profiles of π^+ (mostly) induced cascades in the CDHS neutrino detector [172]. Corresponding results for the ATLAS tile calorimeter can be found in Ref. 165.

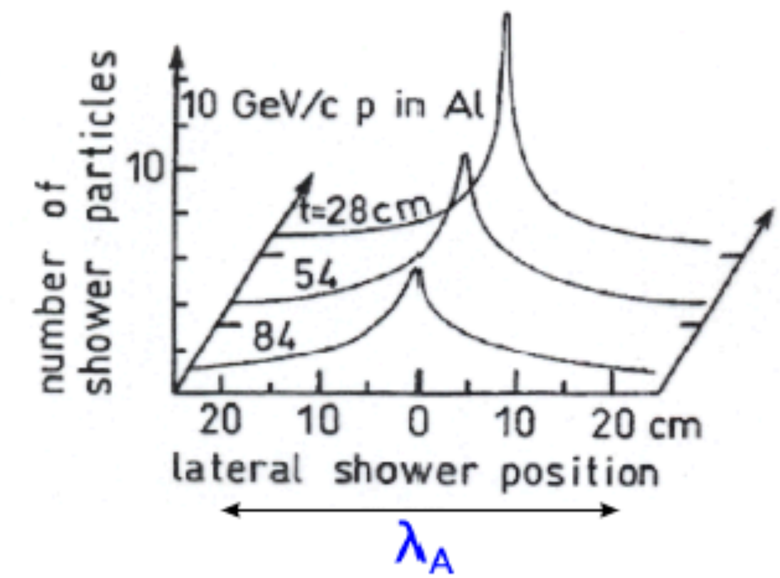
- **For ZDC ~ 9.5λ sufficient.**
- **Looks like space is not and issue.**

Containment, Lateral.

- $R_{95} \cong \lambda$ at Shower Max
- Cylinder to contain 95% of the shower is about 1.5 x λ
- Lateral size of the ZDC may be a problem.
- Integrated beam pipe will degrade resolution even more.







Containment, Longitudinal.

50 GeV – $L_{95} = 4.7\lambda$
100 GeV – $L_{95} = 5.6\lambda$

Absorber:	L_{95}(50 GeV)	L_{95}(100 GeV)
Fe	80 cm	94 cm
Pb	83 cm	99 cm
Cu	72 cm	86 cm
W	47 cm	56 cm
U	52 cm	61 cm

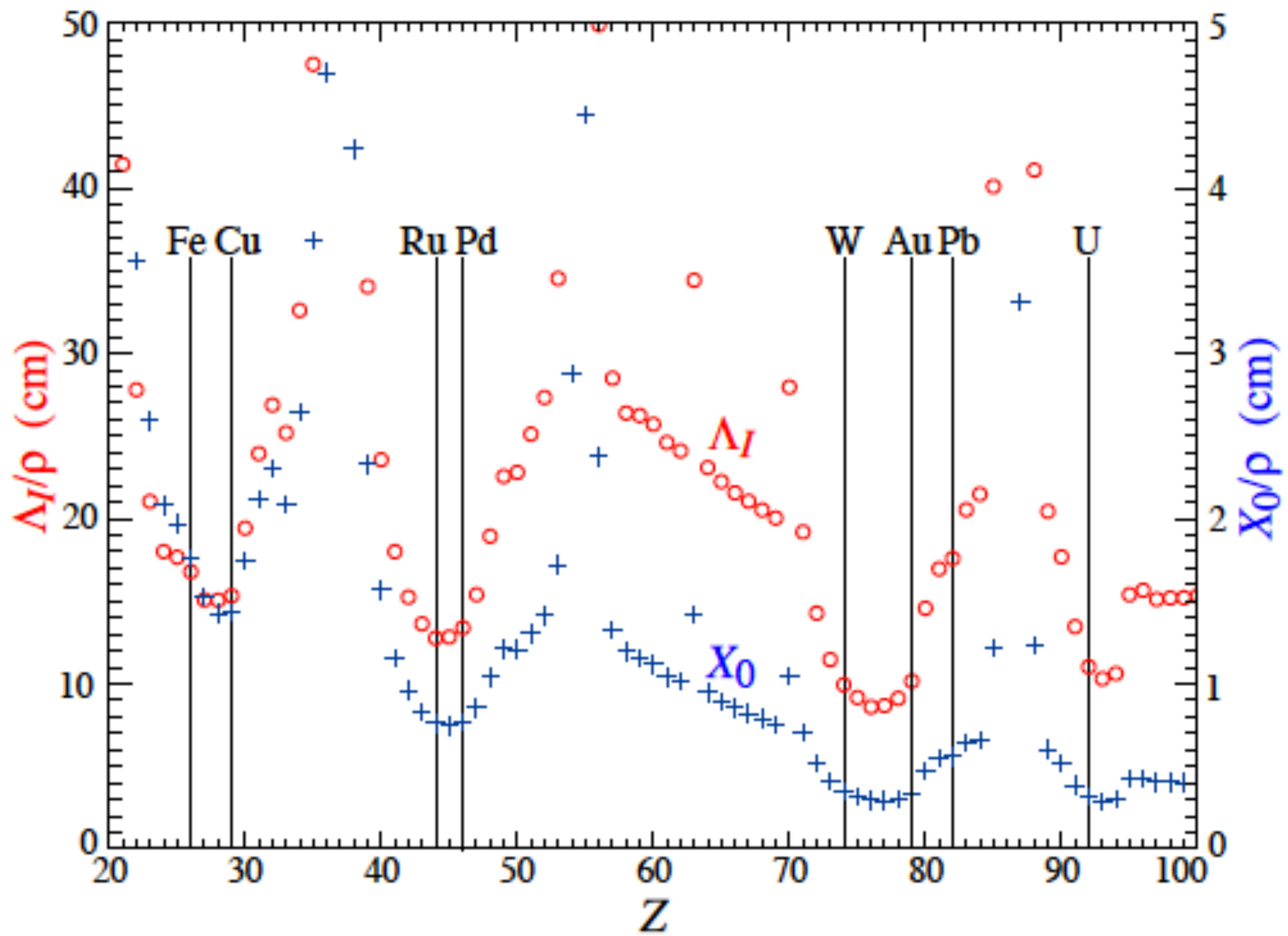
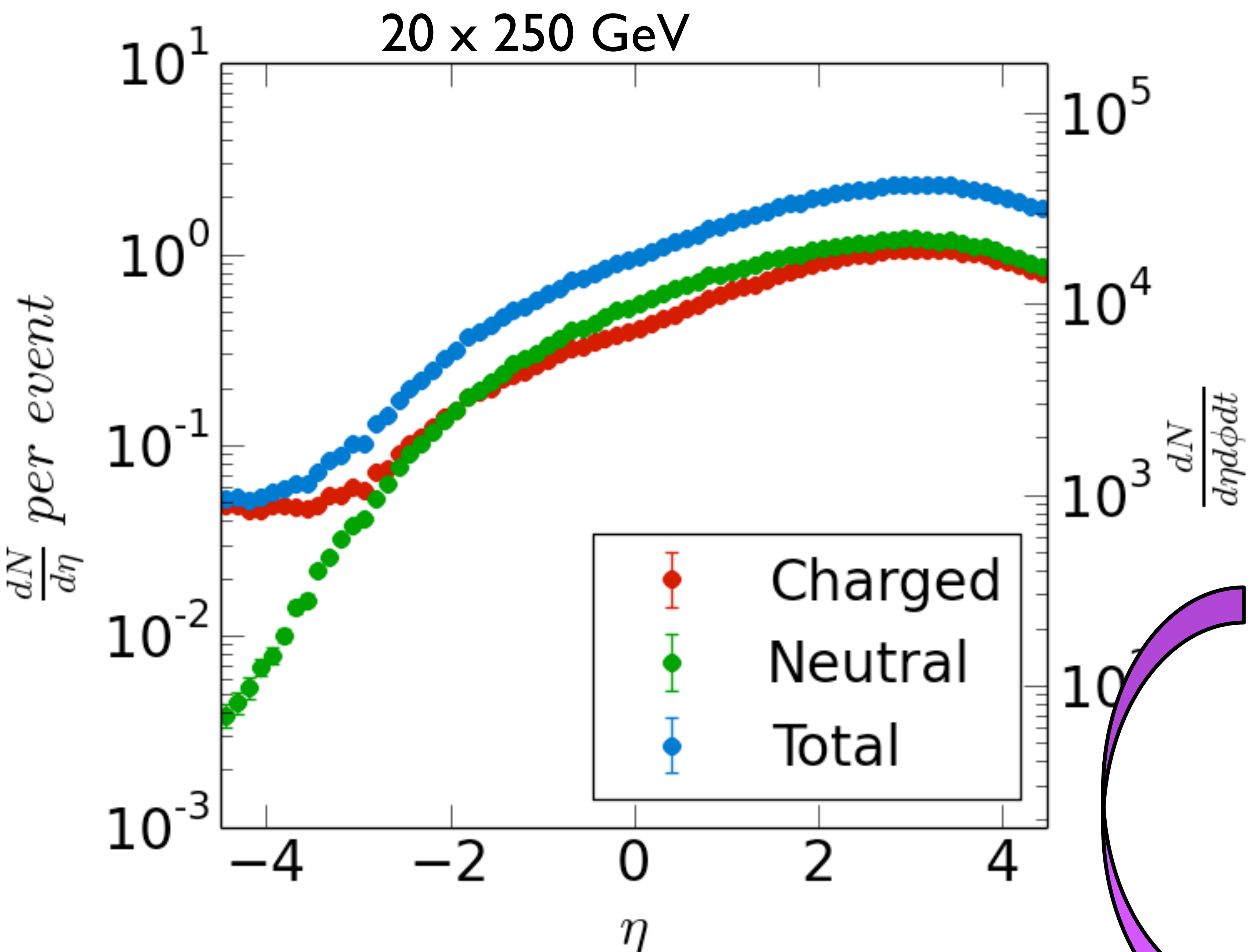


Figure 33.21: Nuclear interaction length λ_I/ρ (circles) and radiation length $X_0/$
(+'s) in cm for the chemical elements with $Z > 20$ and $\lambda_I < 50$ cm.

or, which is better

CMS Calorimeter

Weight of 60 x 60 x 2m ZDC
Will be about 8 ton



https://wiki.bnl.gov/eic/index.php/Detector_Design_Requirements

eRHIC L $=10^{33}$ $cm^{-2}s^{-1}$

Conditions in Central Detector:

- Low multiplicity.
- Low Rates.

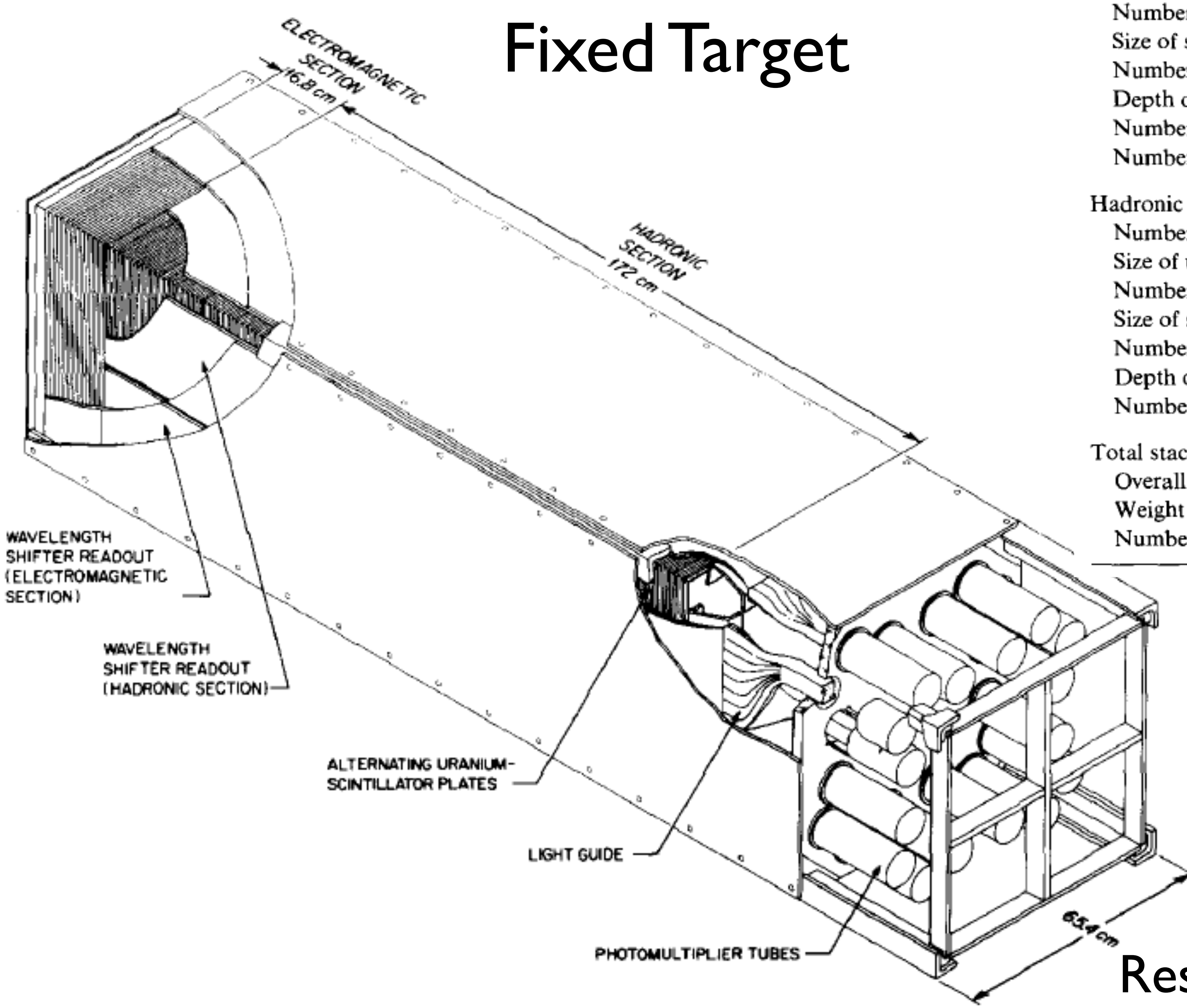
Detector Parameters:

- HCal, signal integration over large detector volume is possible.
- Hcal, signal inegration over long time is possible.

Techniques for High Resolution HCals:

- Compensation (2014).
- Dual Readout using timing (2018)?

WA80 ZDC
Fixed Target

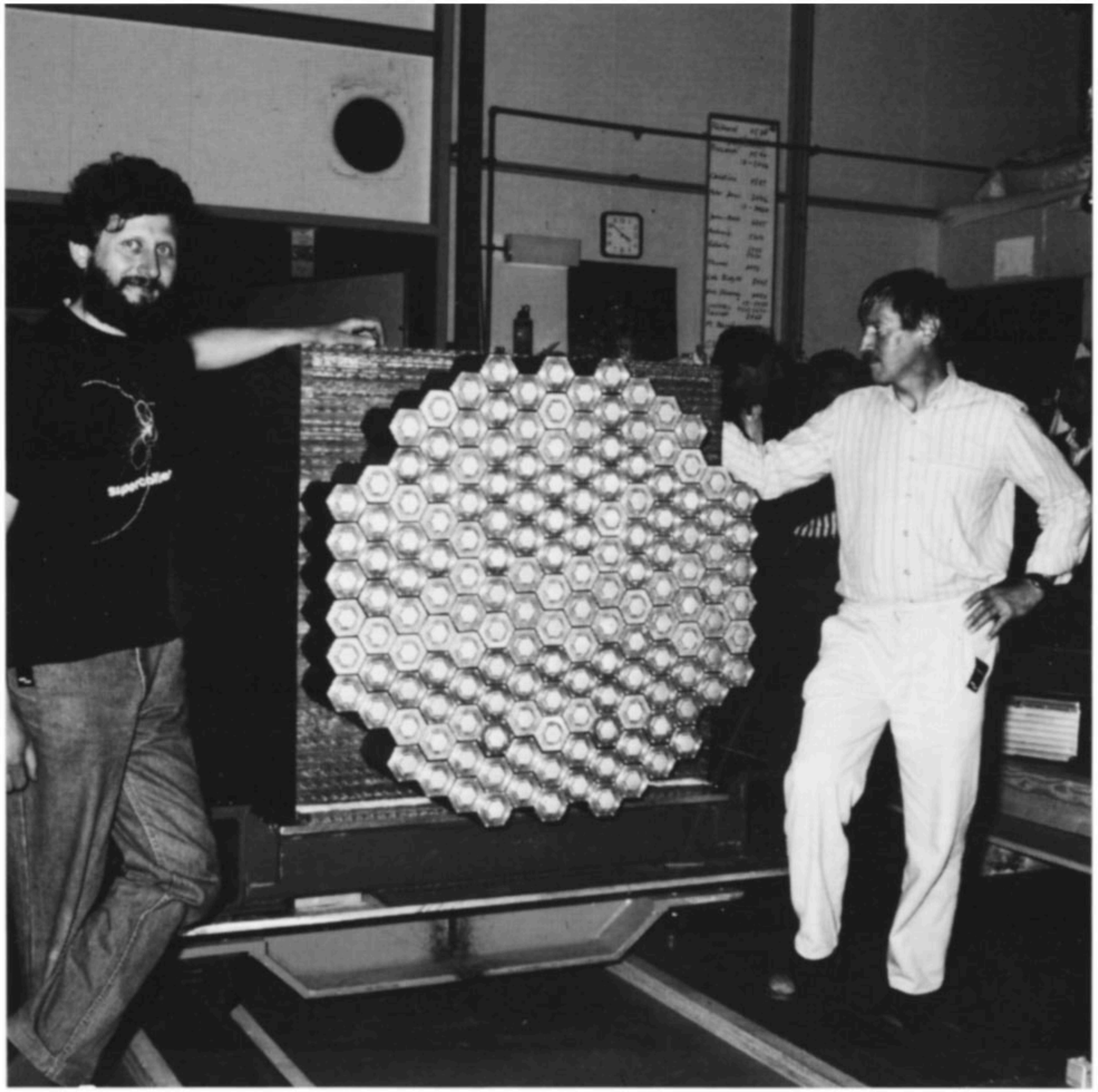


Mechanical properties of the ZDC

Electromagnetic front section	
Number of absorber plates	32
Size of uranium plates	$600\times600\times2$ mm^3
Number of scintillator plates	32
Size of scintillator plates	$614\times614\times3$ mm^3
Number of optical channels	8 (two per side)
Depth of electromagnetic section	160 mm
Number of radiation lengths	20.3
Number of absorption lengths	0.75
Hadronic section	
Number of uranium plates	275
Size of uranium plates	$600\times600\times3$ mm^3
Number of scintillator plates	275
Size of scintillator plates	$604\times604\times3$ mm^3
Number of optical channels	8 (two per side)
Depth of hadronic section	1650 mm
Number of absorption lengths	9.0
Total stack	
Overall length (including readout)	2500 mm
Weight	6.8 metric tons
Number of absorption lengths	10.75

Resolution for single pions
$0.013+0.33/\sqrt{E}$

G.R. Young et al., NIM A179 (1989) 503-517



SPACAL

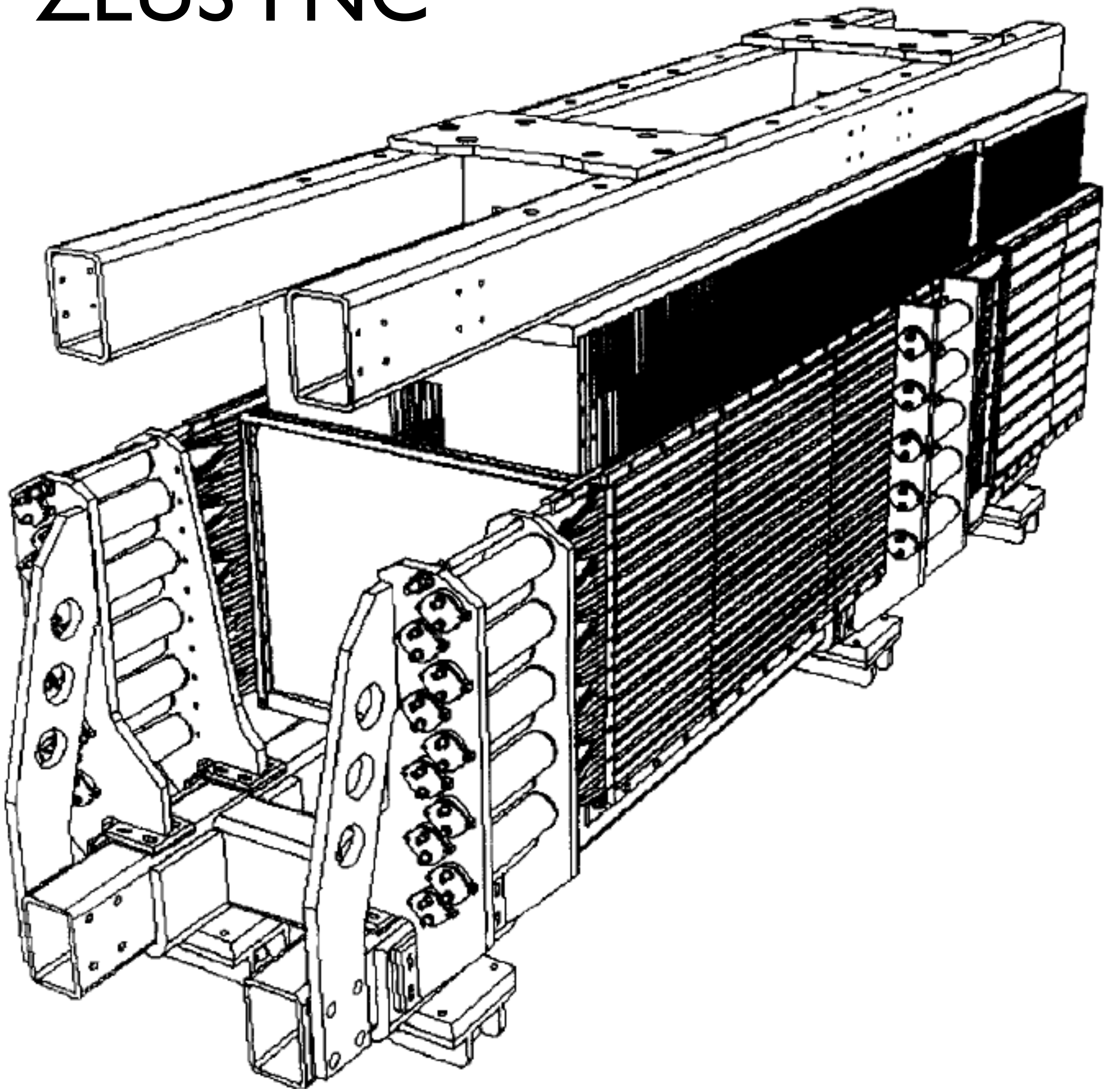
- 9.6λ deep
- 4.7λ across
- 13-ton

Resolution $\sim 30\%/\sqrt{E}$
Constant term is due to attenuation in fibers, can be, in principle, eliminated.

Acosta et al., NIM A308 (1991) 481-508

E864 Pb/ScFi replica of SPACAL, resolution $\sim 34\%/\sqrt{E}$
Armstrong et al., NIMA406 (1998) 227-258

ZEUS FNC



The structure of a unit cell of the FNC

Material	Depth (cm)	Absorption lengths λ_A
Pb	1.25	0.073
Scintillator	0.26	0.003
Paper	0.04	0
Air	0.1	0
Total	1.65	0.076
134 layers	221.1	10.2

Copied from ZEUS Pb/Sc (10mm / 2.5 mm) prototype. Resolution 44%/√E+~1% (ZEUS Pb/Sc prototype – first compensated calorimeter, R.Klanner et al.)

FNC structure were compromised to fit in available space.

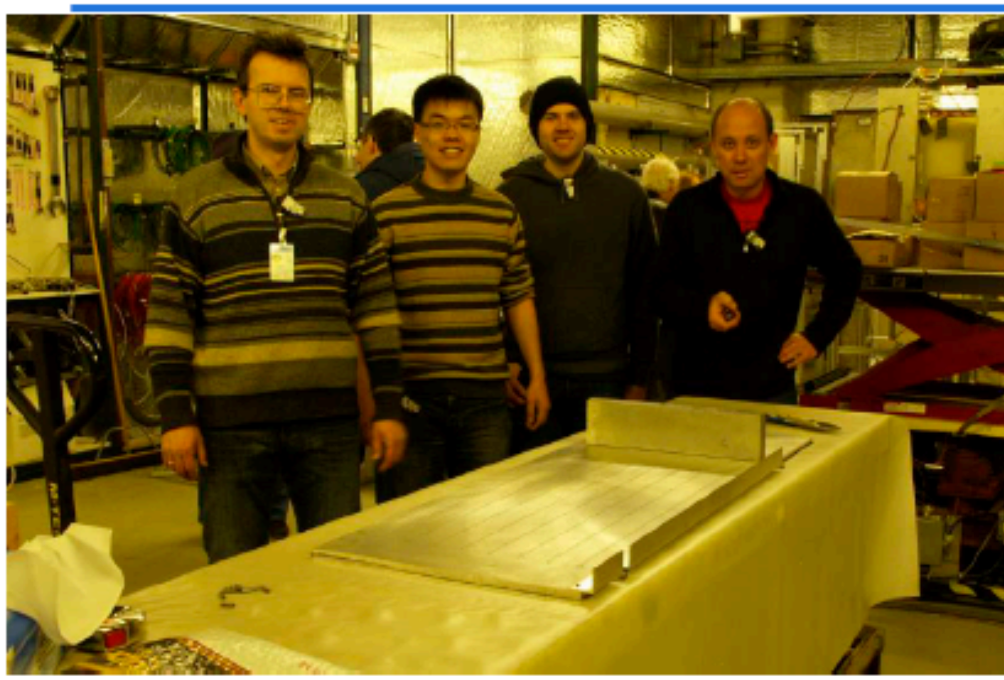
FNC Resolution ~ 58%/√E+3% (MC) No test beam for full configuration.

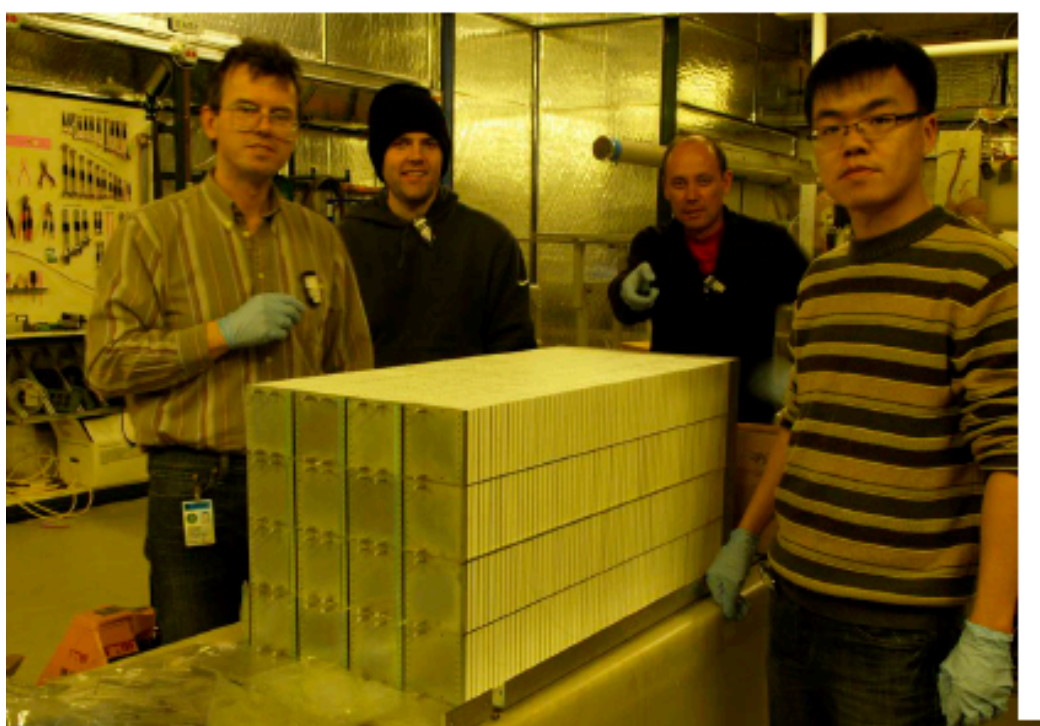
Bhadra et al., NIM A394 (1997) 121-135

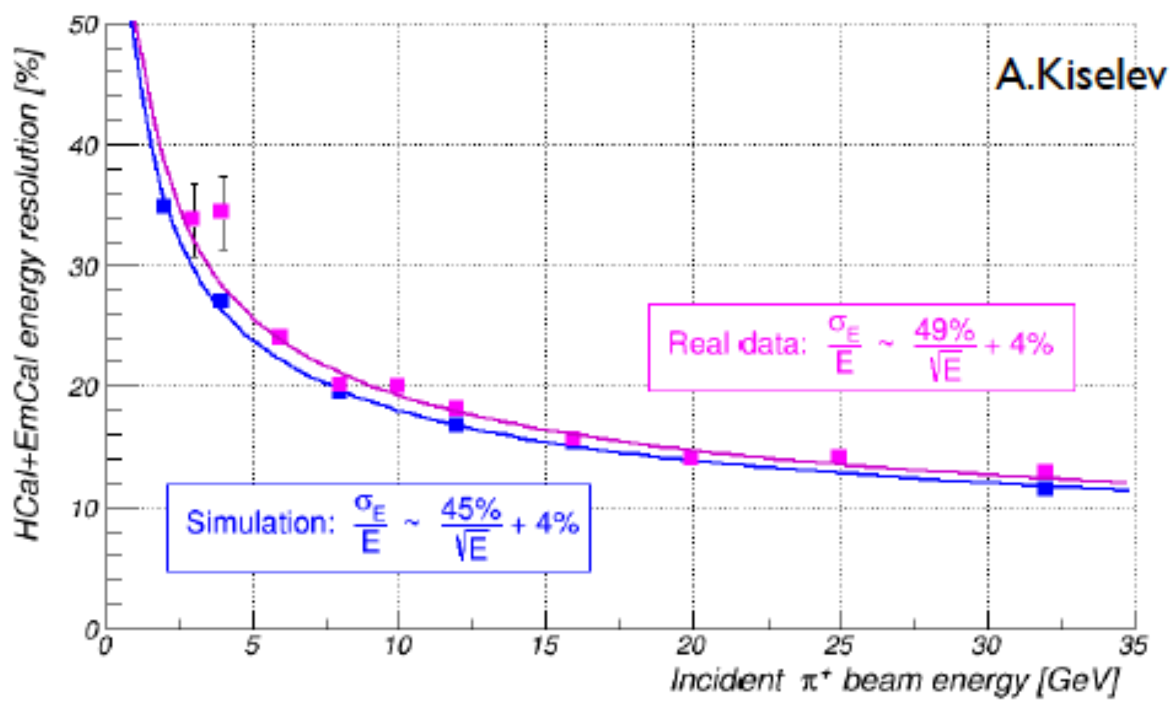
~30 years ago, some hadron calorimeters were quite good
All compensated.

- Back to present... ZEUS Pb/Sc prototype replica in 2014.
- Construction method tailored for STAR Forward Region.

Assembling HCal Onsite. Feb 26, 2014. FNAL

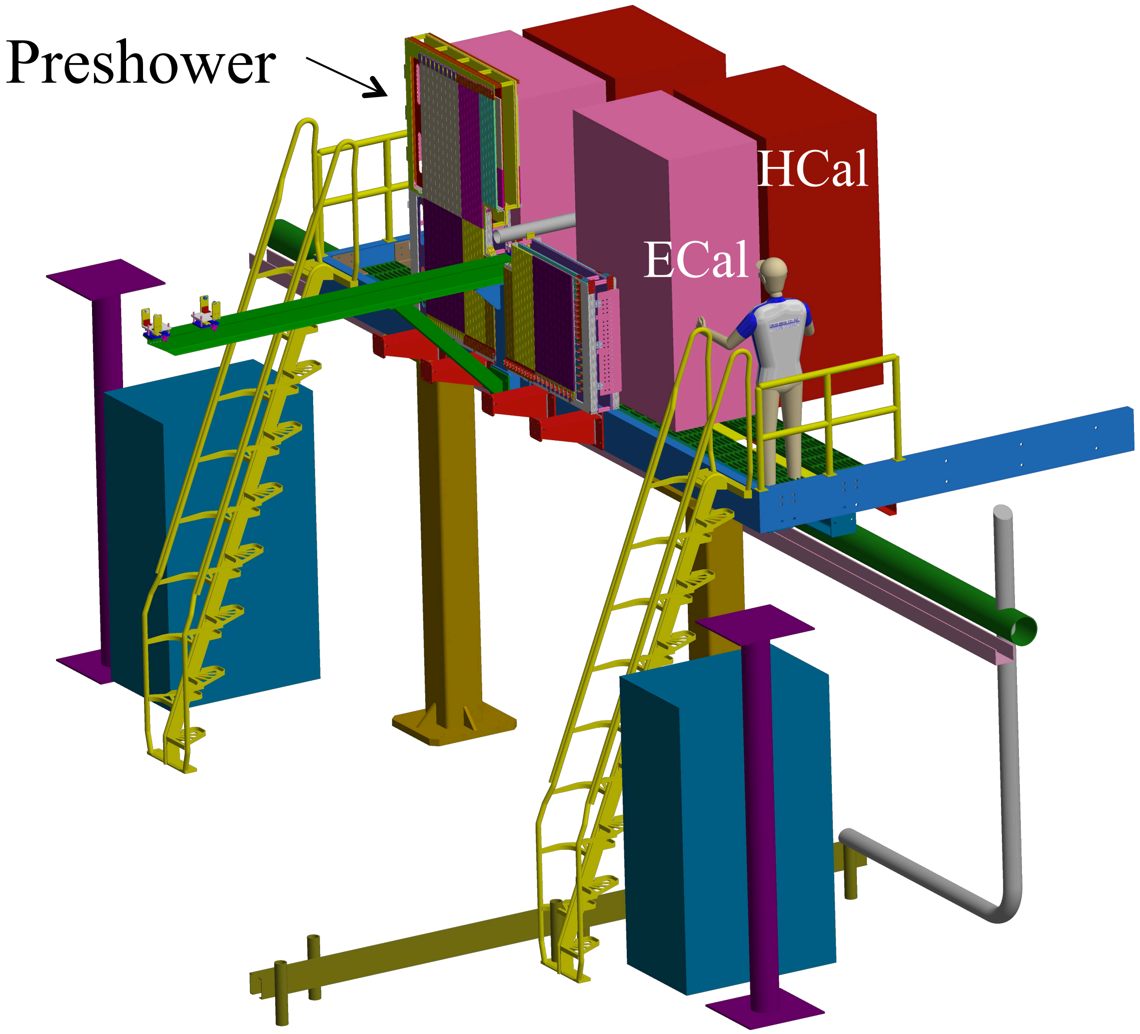






Original FCS was compensated (EM+HAD). STAR Prototype volume ~22% of ZDC

STAR Forward Upgrade finally is under construction.



Forward Calorimeter System (FCS):

- Preshower – 240 channels
- Emcal – 18 X0, ~0.5 λ, 1496 channels
- Hcal – ~4.4 λ, 520 channels
- Coverage 2.5 < η < 4
- SiPM Readout for all.

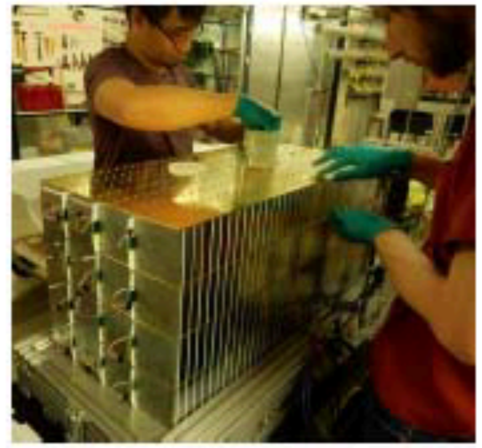
FCS performance requirements driven by Cold QCD physics:

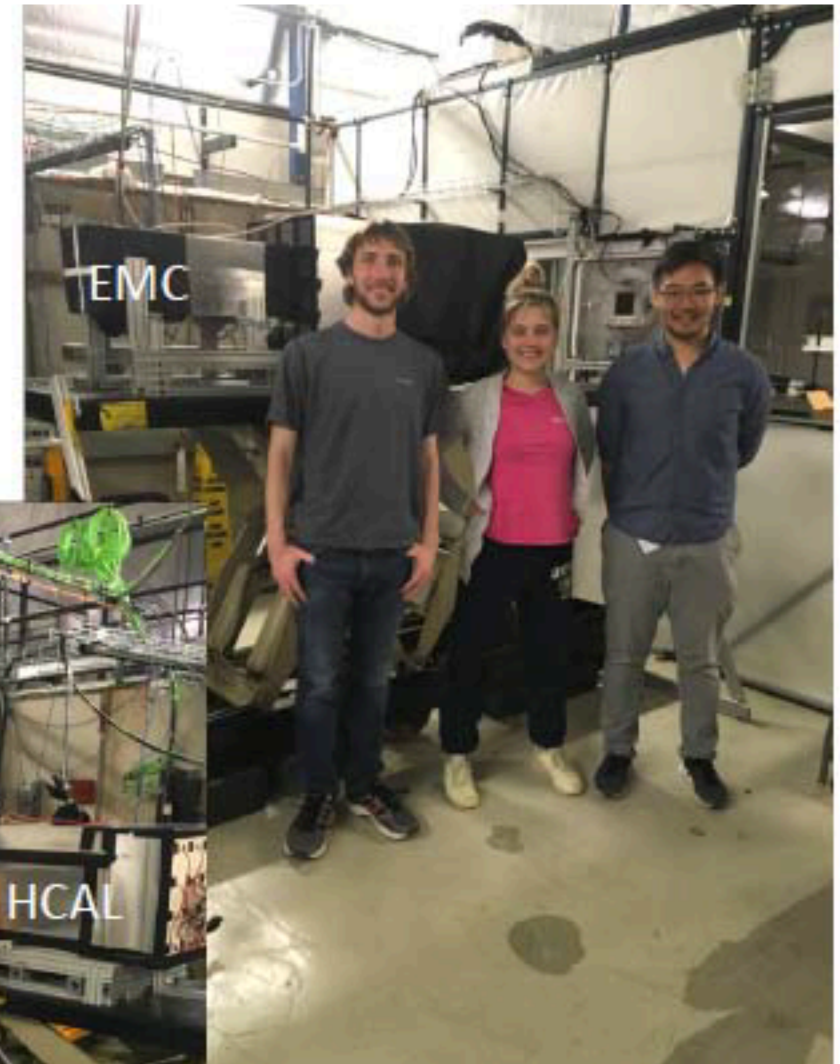
- Triggering capabilities e-, gamma, hadrons, jets
- Energy resolution for EM particles ~ 10%/√(E)+3%
- Energy resolution for hadrons ~ 50%/√(E) +10%
- System must be compact to fit in available space.
- Readout must work in magnetic field, neutron fluxes up to 10^{11} n/cm^2 and radiation exposures expected at FCS locations.

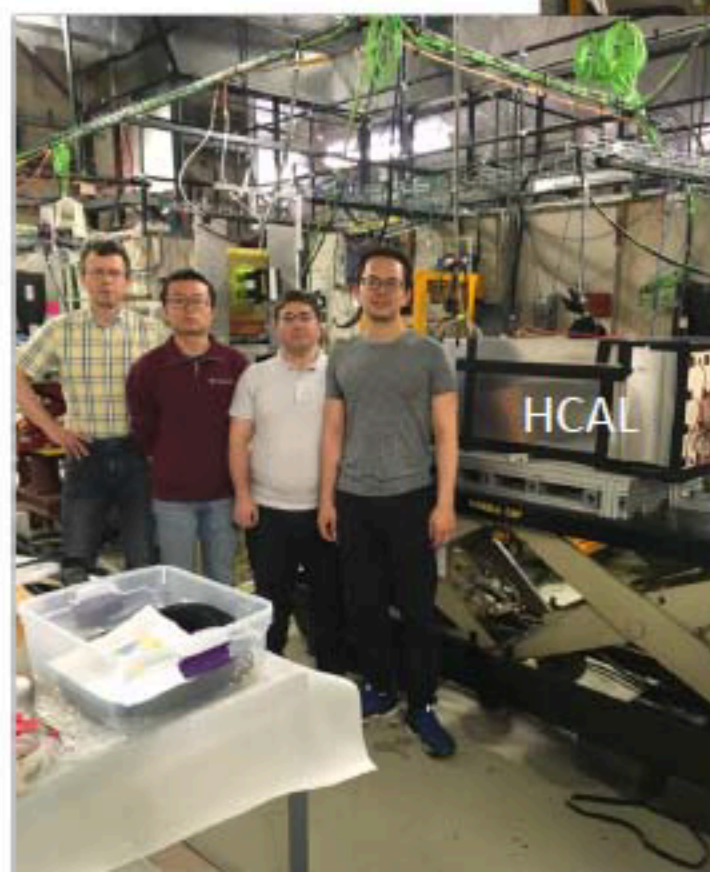
Original design of FCS (W/ScFi + Pb/Sc) scrapped due to cost.

- Re-used cold QCD Forward Calorimeter parts (Fe/Sc, 20mm/3mm),
- Changed readout from SiPM to PMTs added (thanks to Y. Goto for help).
- 1 GHz WFD DAQ (thanks to M. Putchke for help).

FCS, April 2019
FNAL Test Beam
4x4 Ecal, 4x4 HCal







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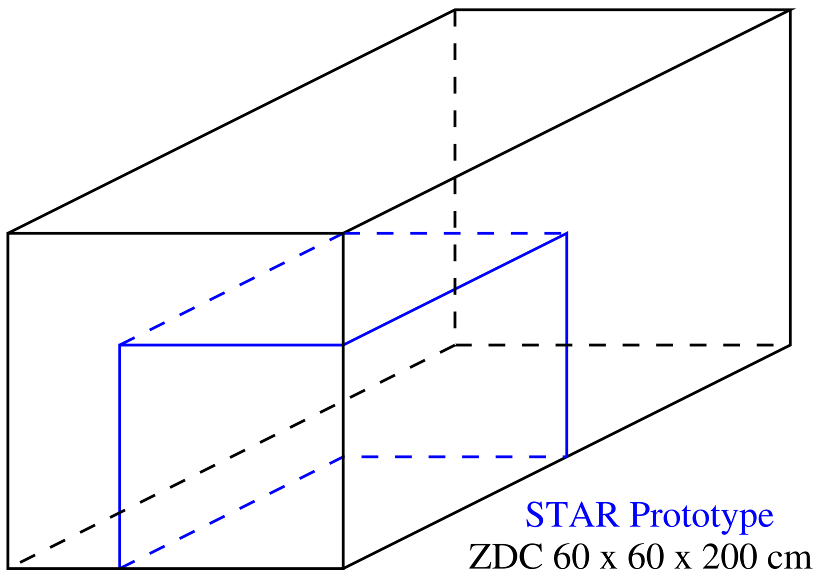
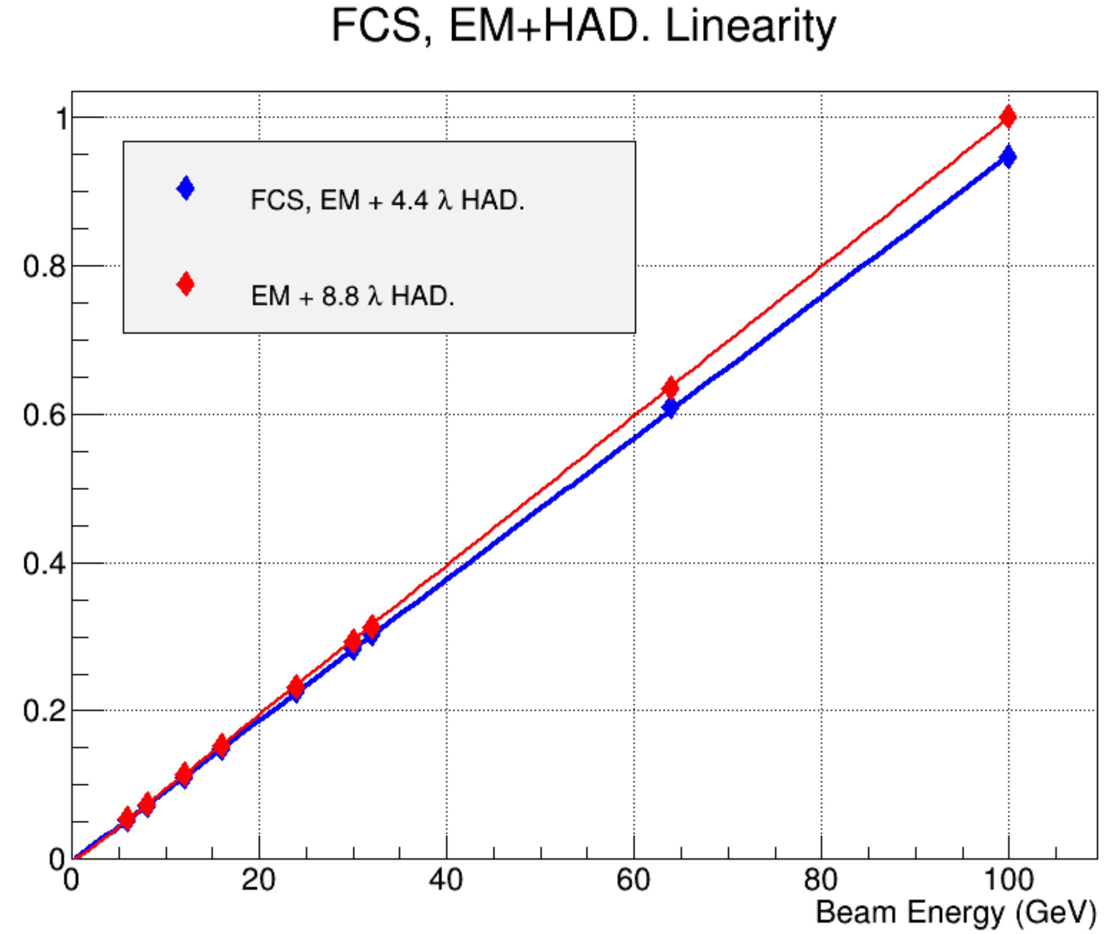
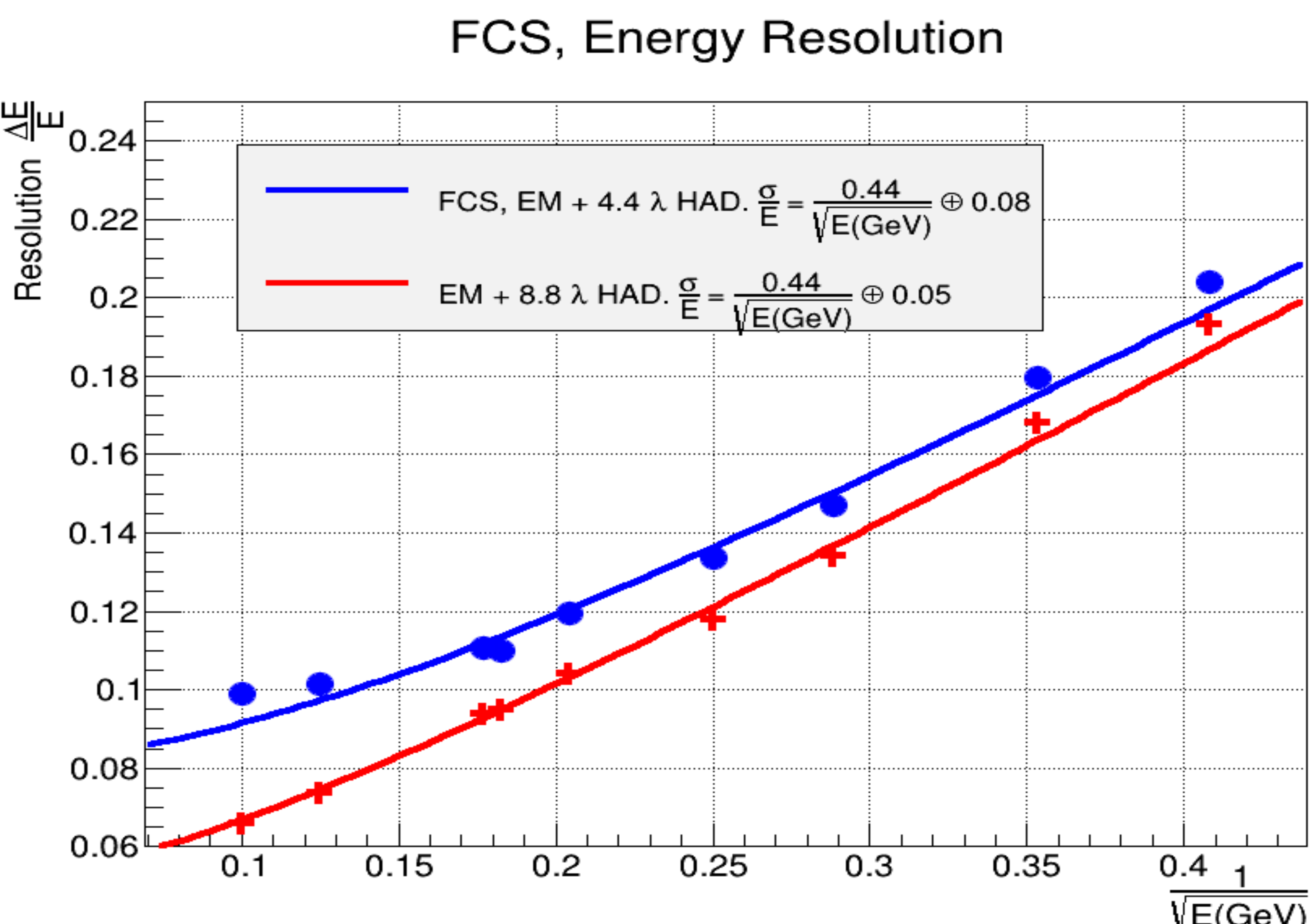
For EIC R&D goal was to measure timing properties of signals from Hcal.





~6% Leakage
At 100 GeV

~25% degradation of resolution at 100 GeV

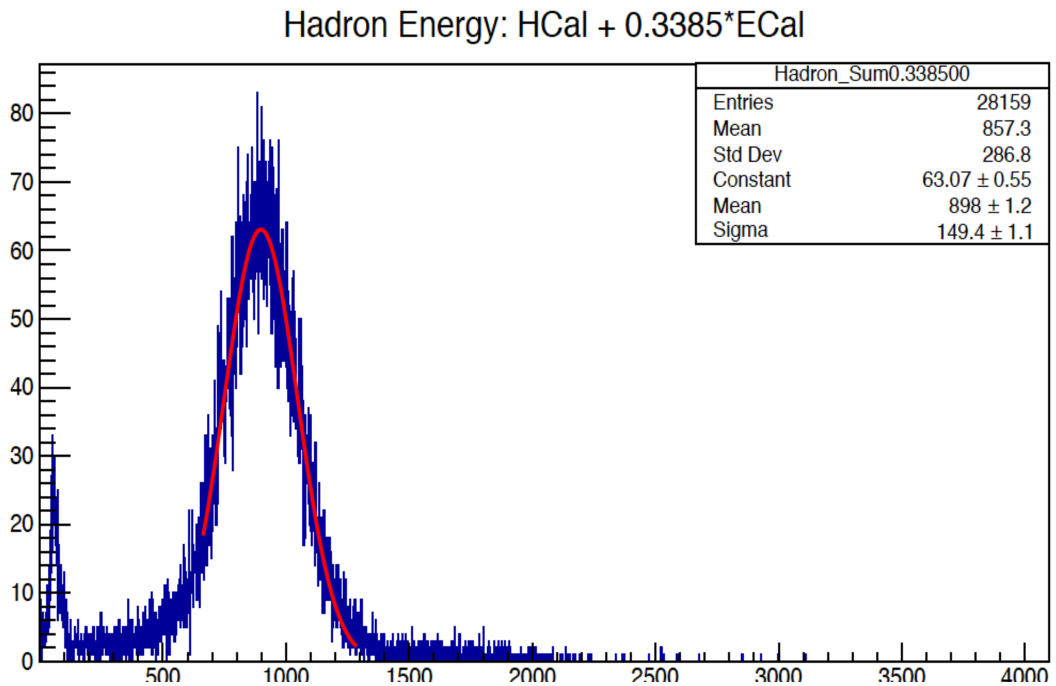


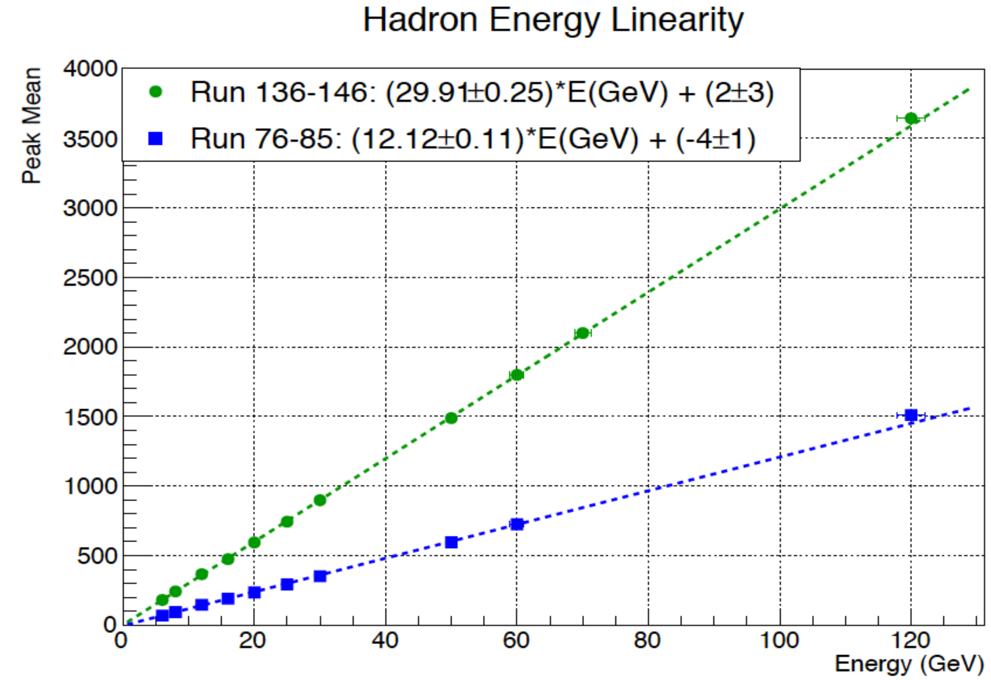
Simplified FCS' GEANT4 model.

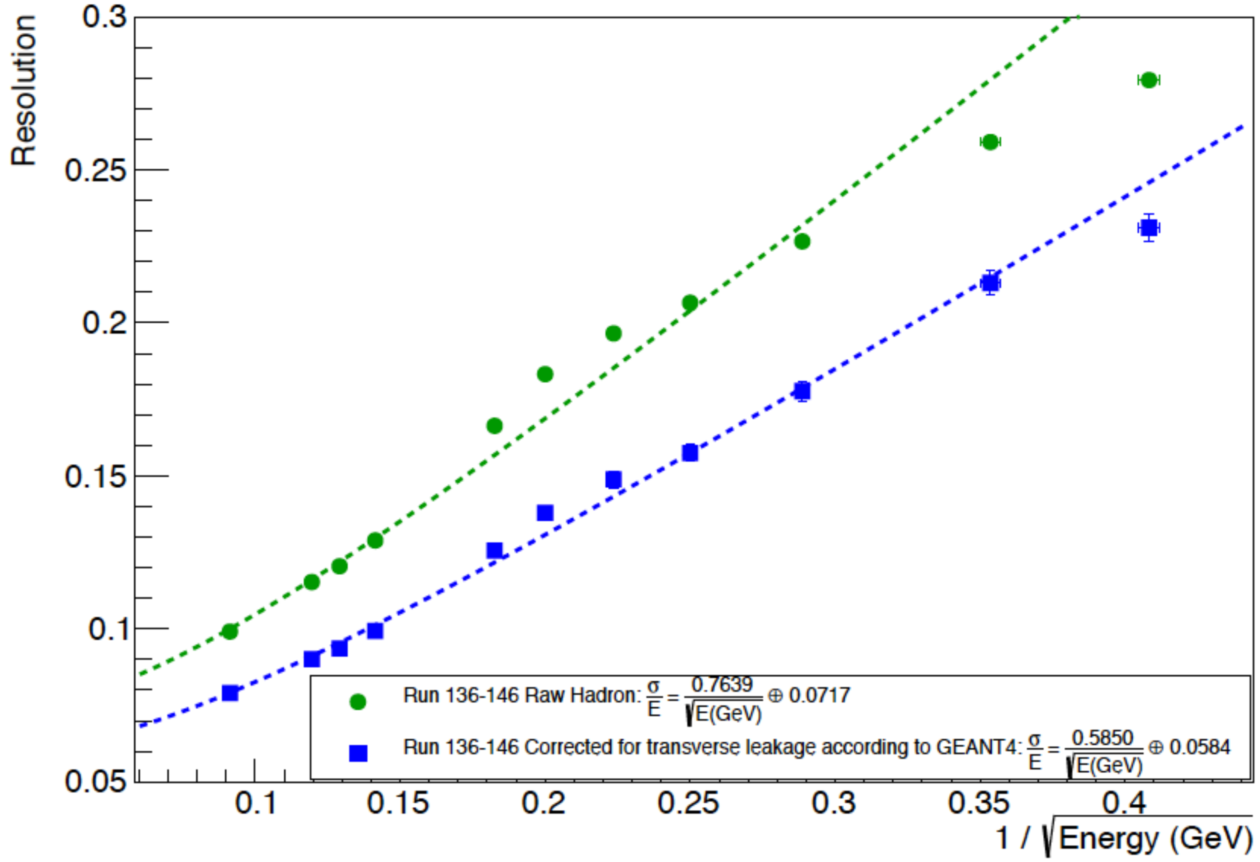
Surprisingly for non-compensated design Linearity is good. Spectra has no tails.

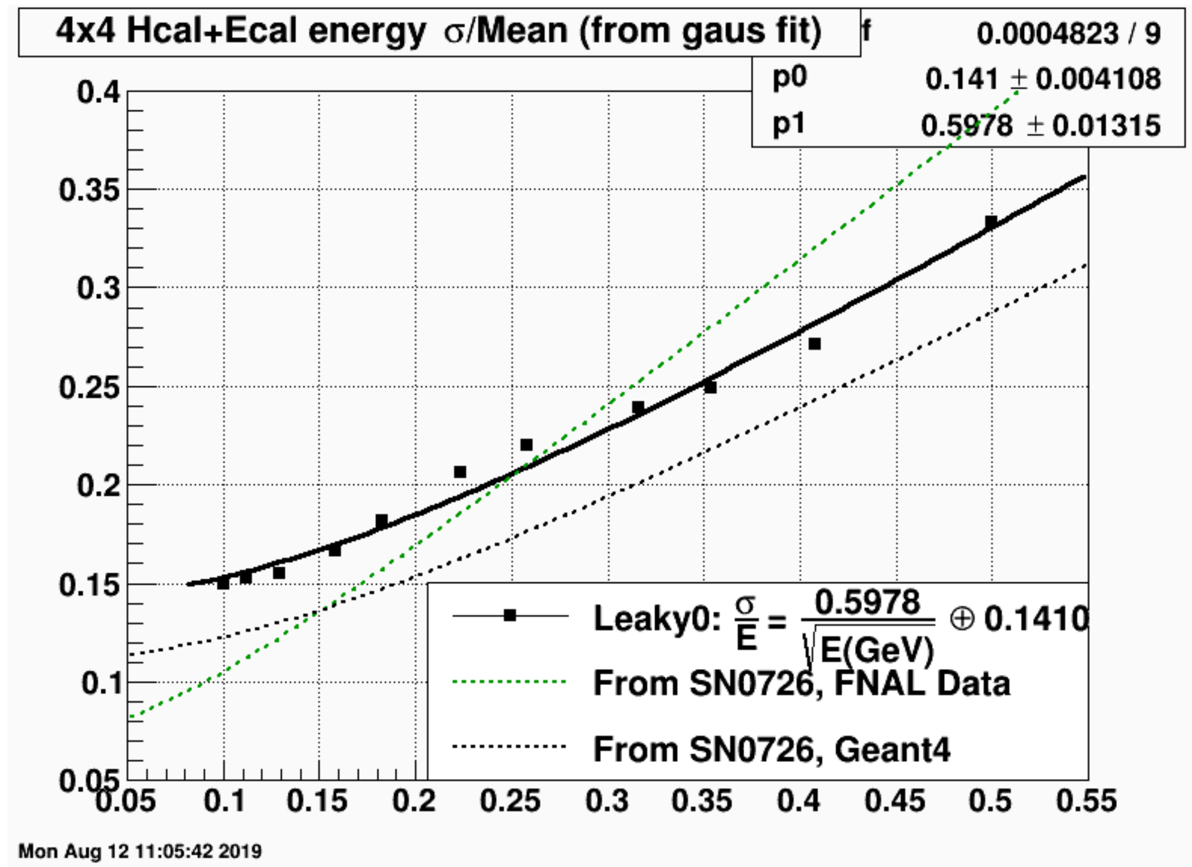
Leakages are important.

Typical problem for Test Runs, size of Prototype is small, rely on MC for final detector performance.









Still some discrepancies between FCS' FNAL data and MC.

STAR detailed model uses GEANT3, which is not optimal.

Had no problem with original compensated FCS A.Kiselev's detailed model reproduced data quite well.

Energy resolution better than ~40%/$\sqrt{(E)}$ + few(2)% is challenging. Requires R&D.

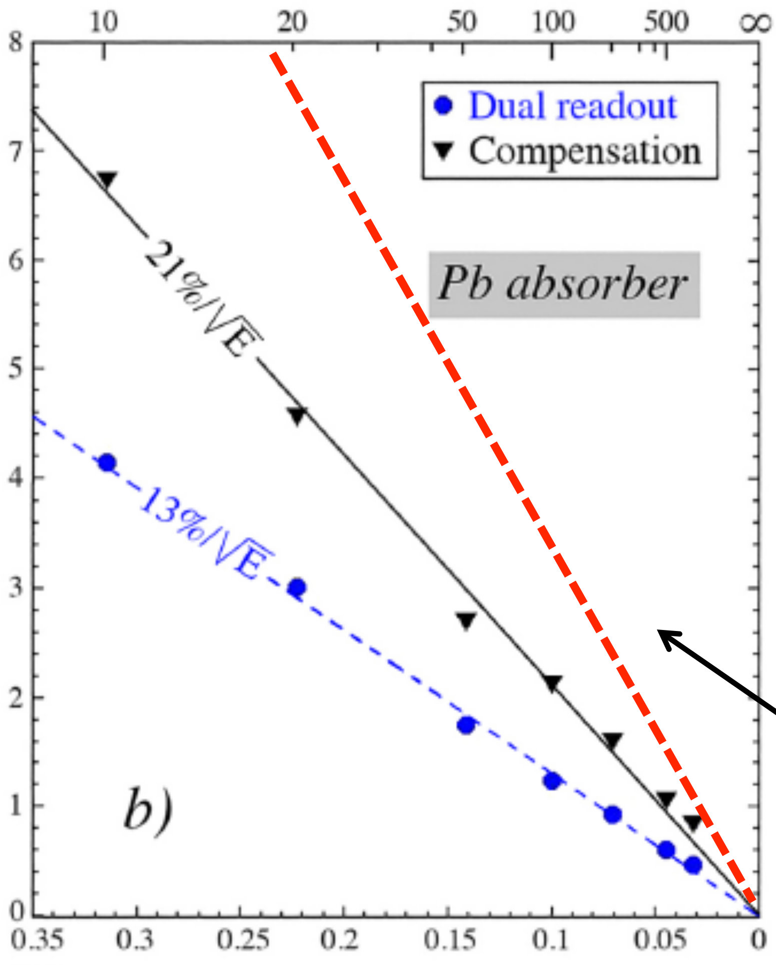
With compensated FCS we were close to 44%/$\sqrt{E}$. There is some room to increase sampling frequency. Practical limitation light collection from thin (<2mm) scintillation tiles probably will not allow for compensated sandwich calorimeters to be better than ~40%/$\sqrt{(E)}$ (guess at this moment).

Want it to be compensated with energy resolution around ~35%/$\sqrt{E}$, use SPACAL type. Ugly construction methods and cost. We may come back to original eRD1 proposal and try to extend powder/fiber technique for that. Not necessary to use W (cost), may consider brass of even Fe.

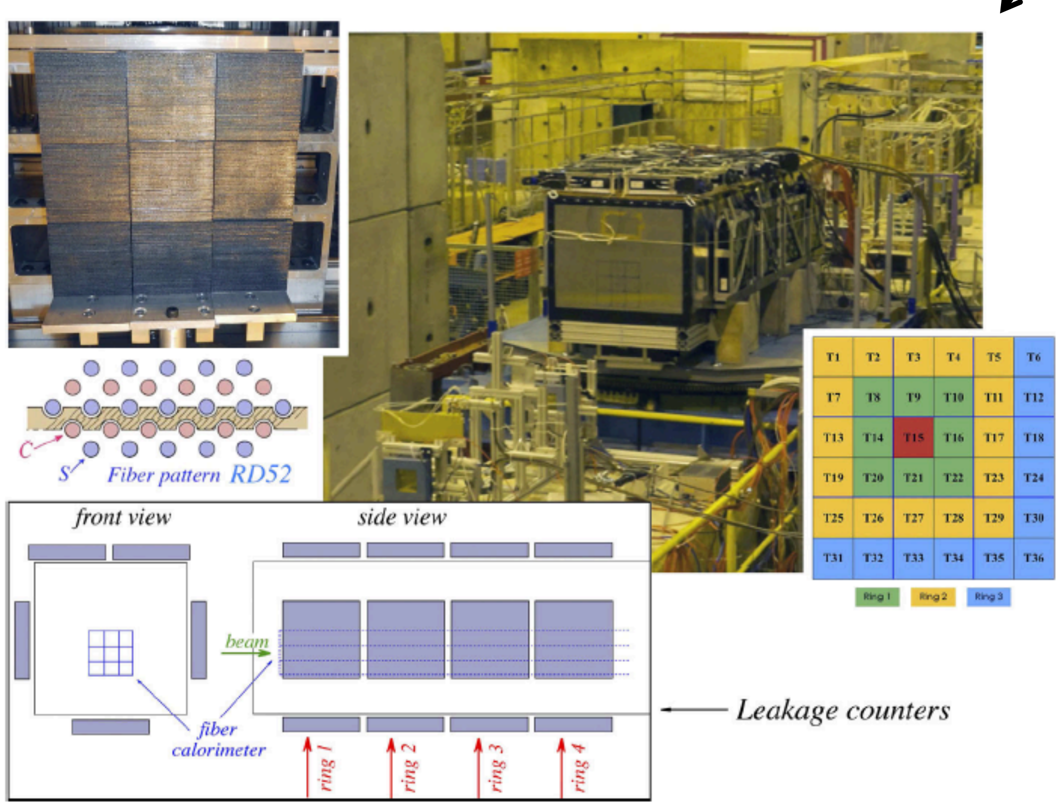
Or, with a big ? at this moment

Drop compensation, increase sampling fraction. Used 'dual readout' methods to correct for $f_{em.}$ We are trying to investigate if we can do it with timing.

Total funds received for HCAL developments from EIC detector R&D is $43k.



Plots from
S.Lee, M.Livan, R.Wigmans
CALOR 2018



General comments for high resolution HCals.

- Practical limitations important! (SPACAL as an example)

Record holder. 13t, full absorption. Only Test beam results with all hardware tricks available at that time.
It is about 50% off from theoretical limit.

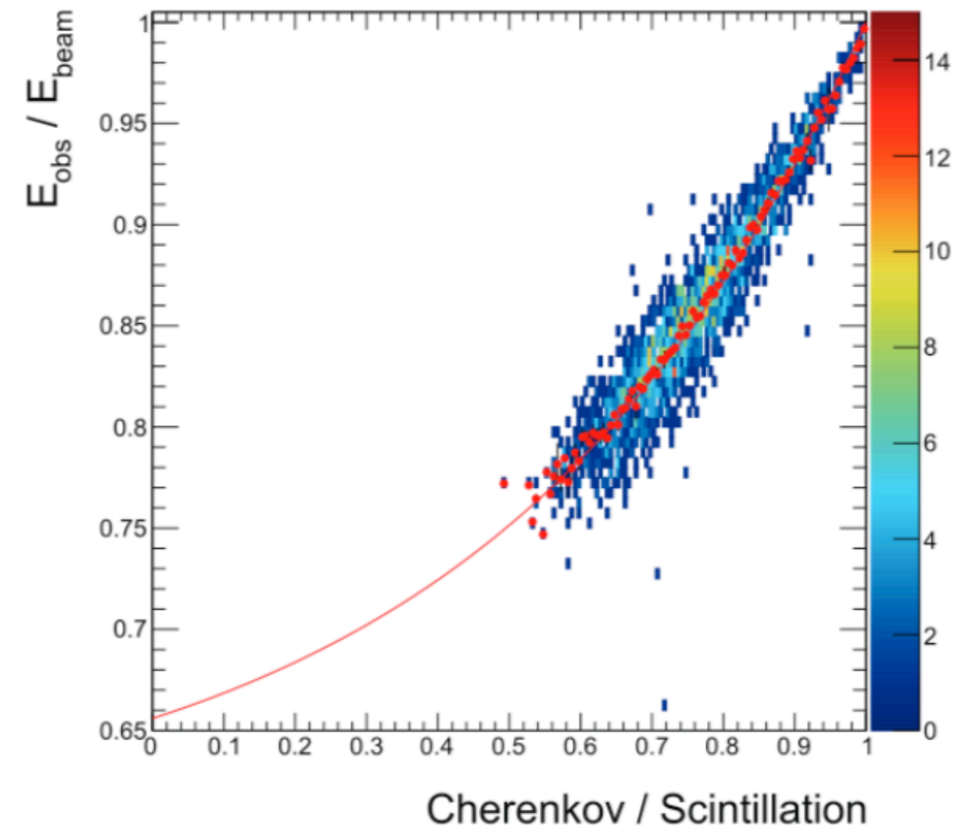
- For compact collider detector it will be even more challenging!
  - 15 years of the development of DREAM, RD52. Still no 100% proof it will deliver.
  - Size of the detector, practical limitations with S/C method.
  - Good thing, it spurred discussions and other approaches started to emerge.
  - Now some people think timing will be easier to implement in practice.
  - There were no other experimental investigations for dual readout techniques than DREAM, RD52

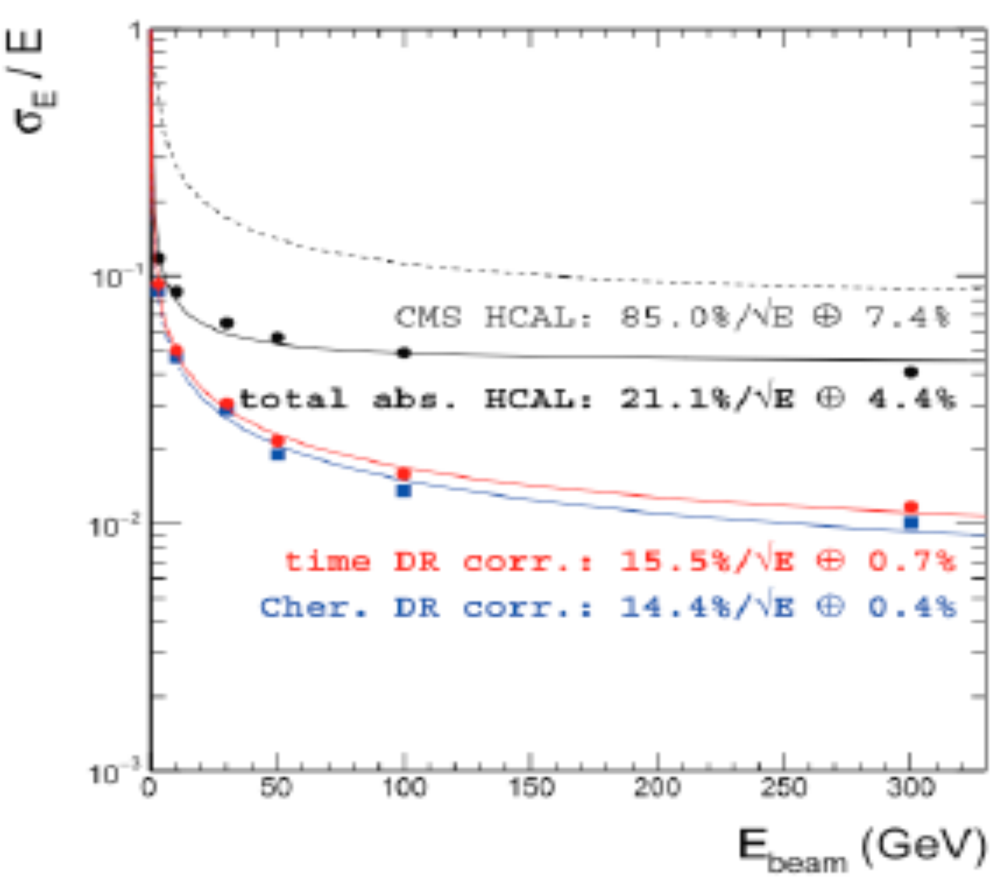
Dual Readout methods for high resolution HCals.

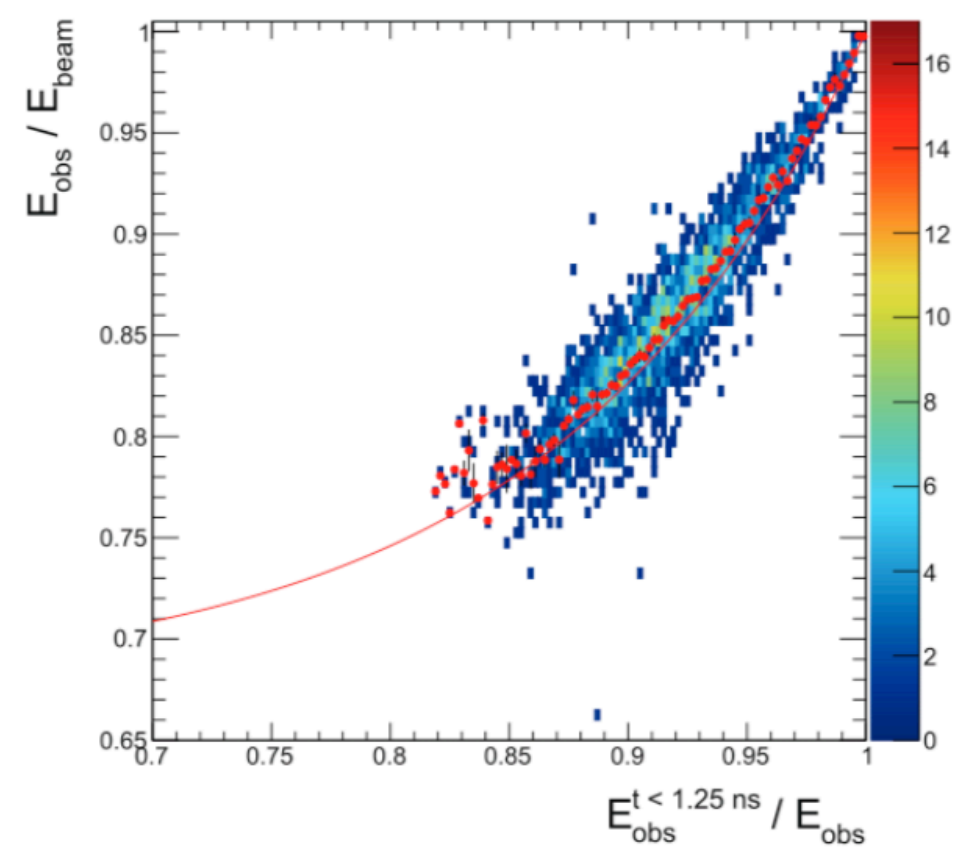
Concept

- Find observable which correlate with number of neutrons (C/S, Time, Spatial characteristics of shower).
- E-by-E correct detected energy using this observable.

Theoretically, believed, hadron resolution can be very good (below 20%/√E, small constant term, good linearity).

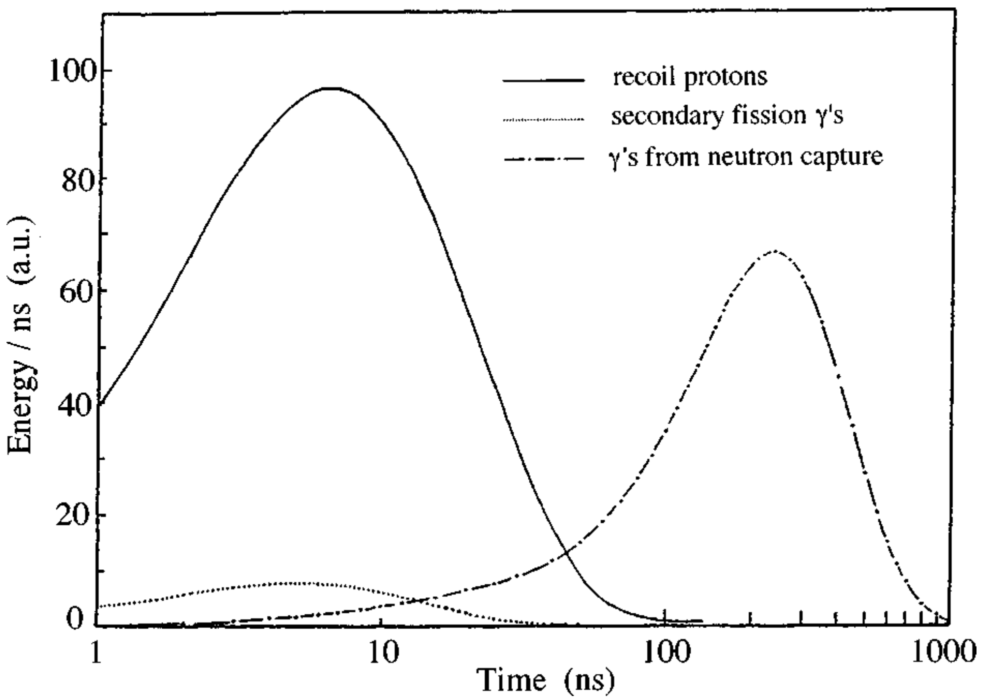




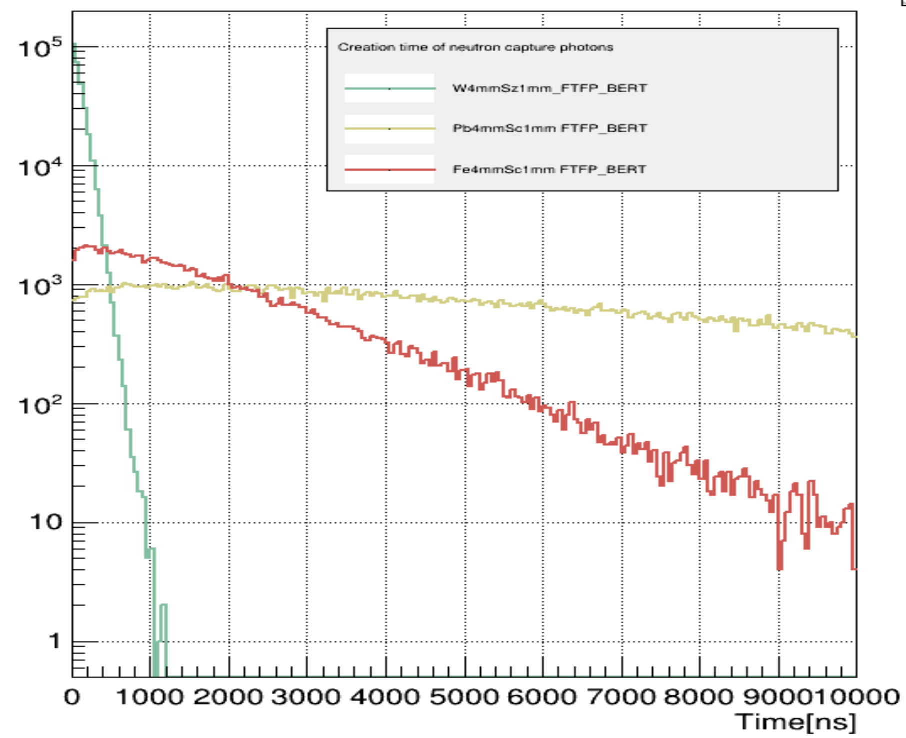


A. Bengalia et.al. IEEE Trans. Nucl. Sci. V63, N2, 2016

Time scales for HCAL signals.



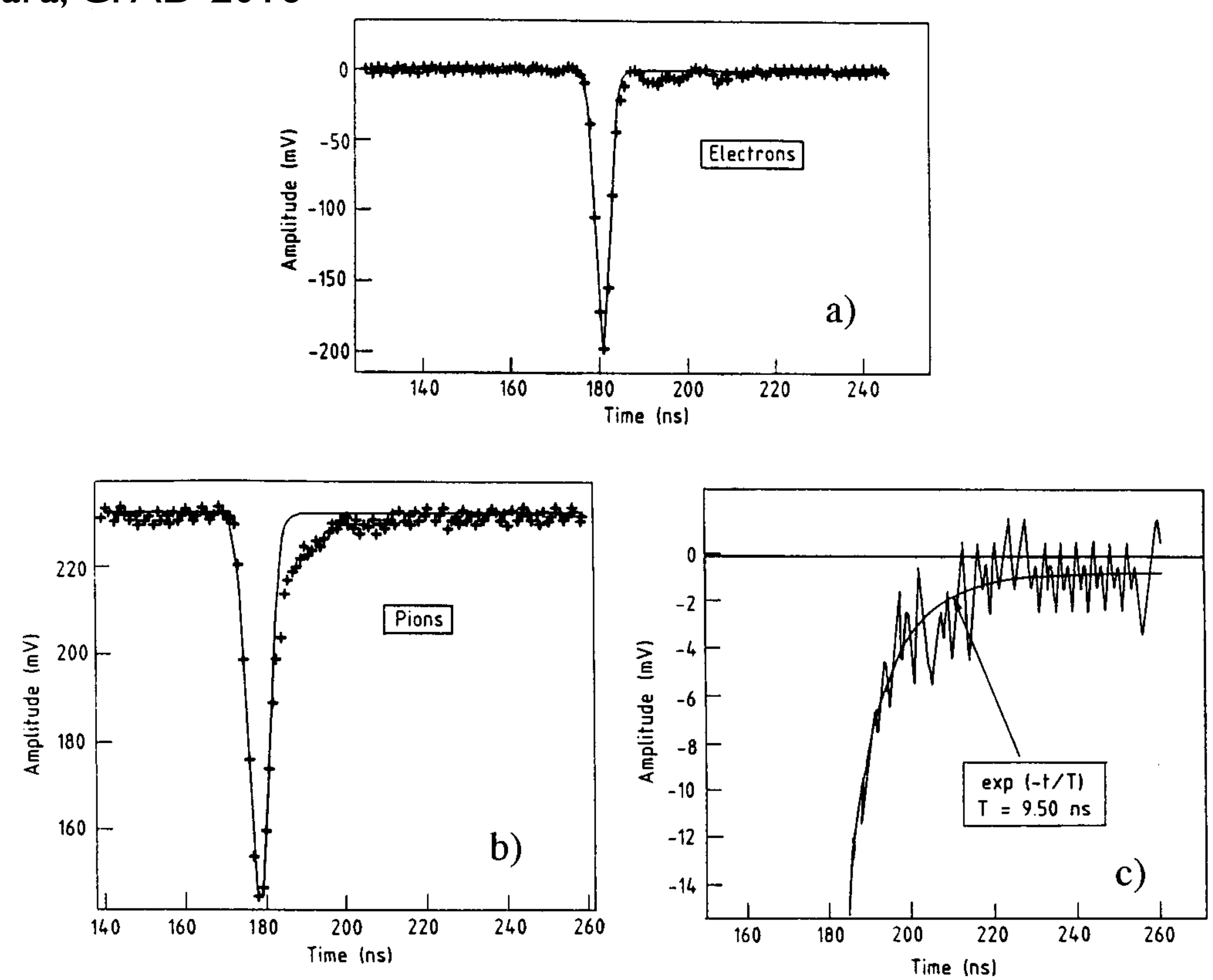
ZEUS, NIM A263, 136 (1988)



A.Para, CPAD 2016

Number of neutron produced thermalized and captured strongly depends on chemical composition. Associated timing parameters varies by orders of magnitude. Optimization.

- Increasing gate width did not improved resolution for ZEUS calorimeter, due to U noise.
- For ZDC we'll use PMTs.

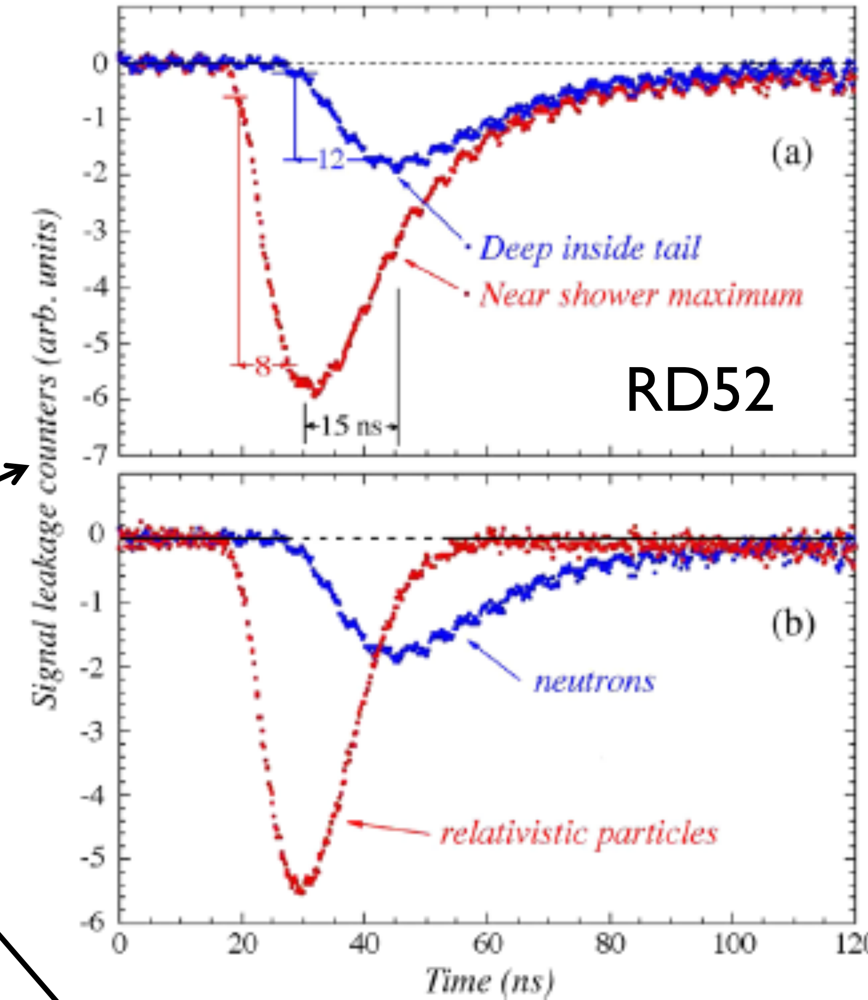


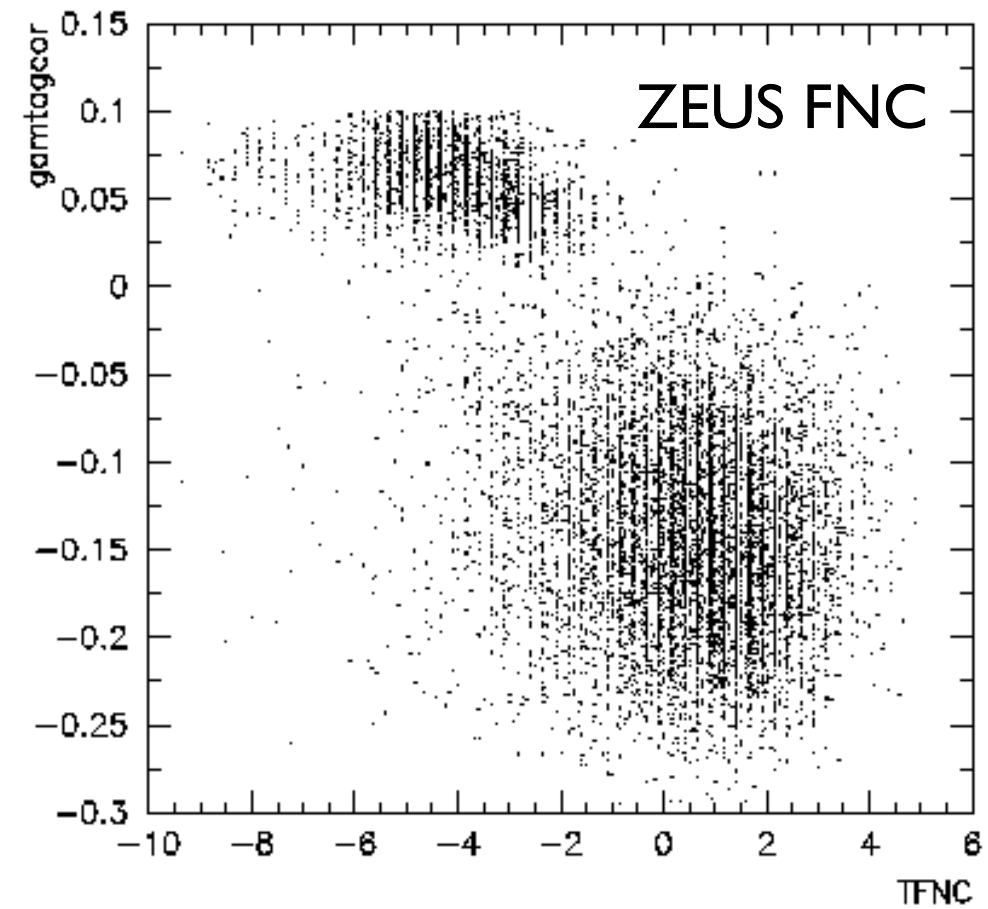
SPACAL, NIM A302, 36 (1991)

What was in the EIC R&D proposal for FY2019.

- Investigate if dual readout method will work for Tile/WLS type structures (method of construction we developed for 2014 HCAL prototype).
- Direct proof is out of reach due to size of the detector.
- Most likely we will end up (if it will work) with something similar measured by RD52 (fibers faster than Tiles/WLS).
- ZEUS FNC Tile/WLS method worked out by W. Schmidtke to use timing for e/h separation, i.e. timing is not hopeless for such structures, he joined our efforts now.
- Next year gives us opportunity to do such thing utilizing components from 'Cold QCD forward calorimeter, which is being constructed now (absorber tiles Fe, Pb, scintillating tiles).
- A. Kiselev, will run optimization, what can be built from this components to get 'proof of principle'. He also arranged 5Gs/s DAQ for the test run.

If method will work future steps are:
- MC optimization of ZDC.
- MC optimization of EndCap.
- Pursue LDRD to build ZDC and get final proof with testing it at FNAL.





Conclusion.

- High resolution hadron calorimetry is challenging.
- For ZDC integration/practical constrains made it more difficult.
- All previous high resolution calorimeters in operation were compensated. That was result of very extensive R&D program at that time.
- Recently, experimentally, it was single DREAM, RD52 development. ~15 years! Implement C/S method in practice is very difficult (IMHO).
- We proposed to investigate another method, using timing for our method of construction of HCals. EIC R&D FY 2019/20.
- First attempt with non optimized Fe/Sc yield negative result, somewhat expected. Pb/Sc still may work. Goal for FY20 to get Yes/No for future development of this particular technique, depend on funding.
- EIC R&D funding for HCAl is not sufficient.

Thank you!