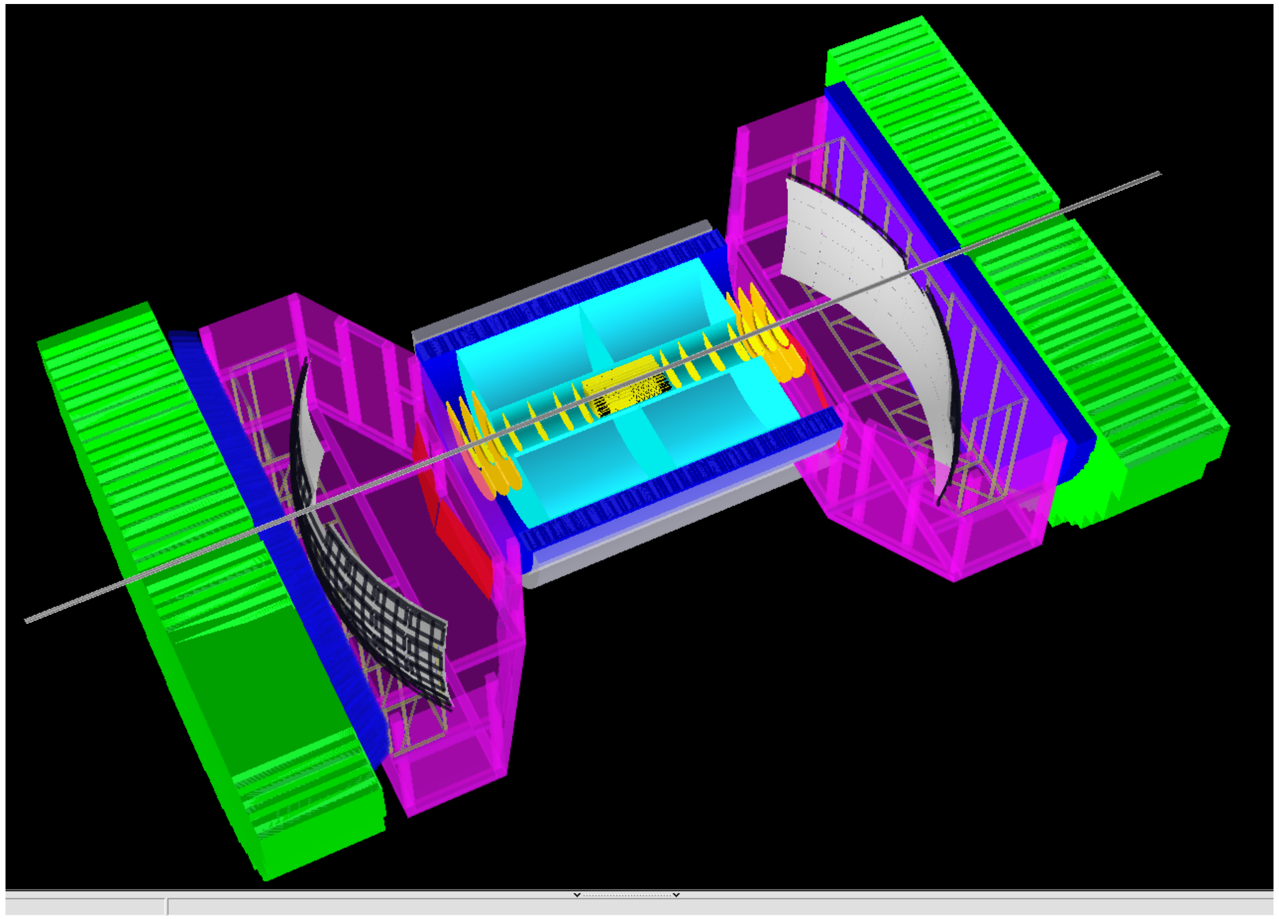
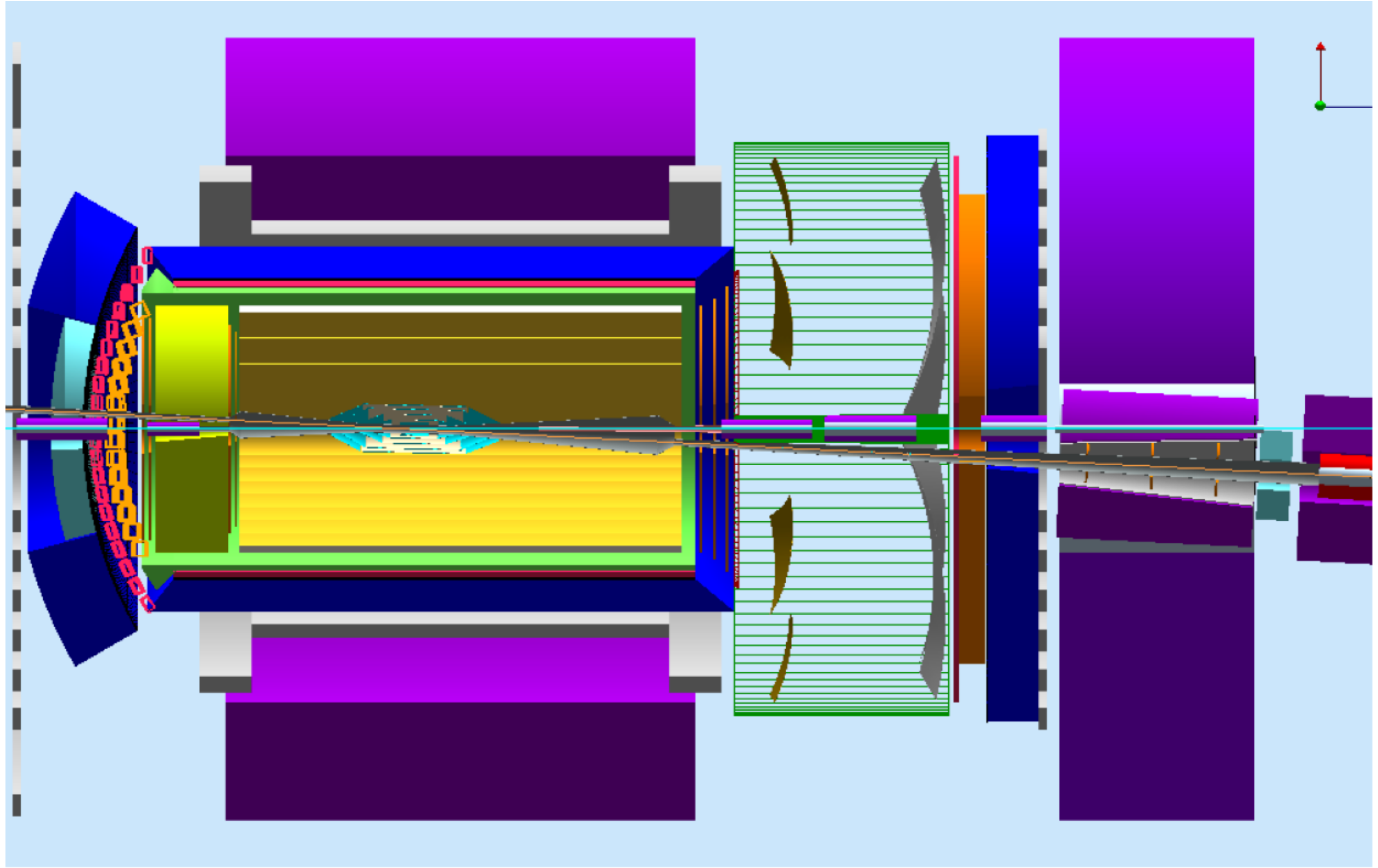
EIC YR workshop.

O.Tsai (UCLA)

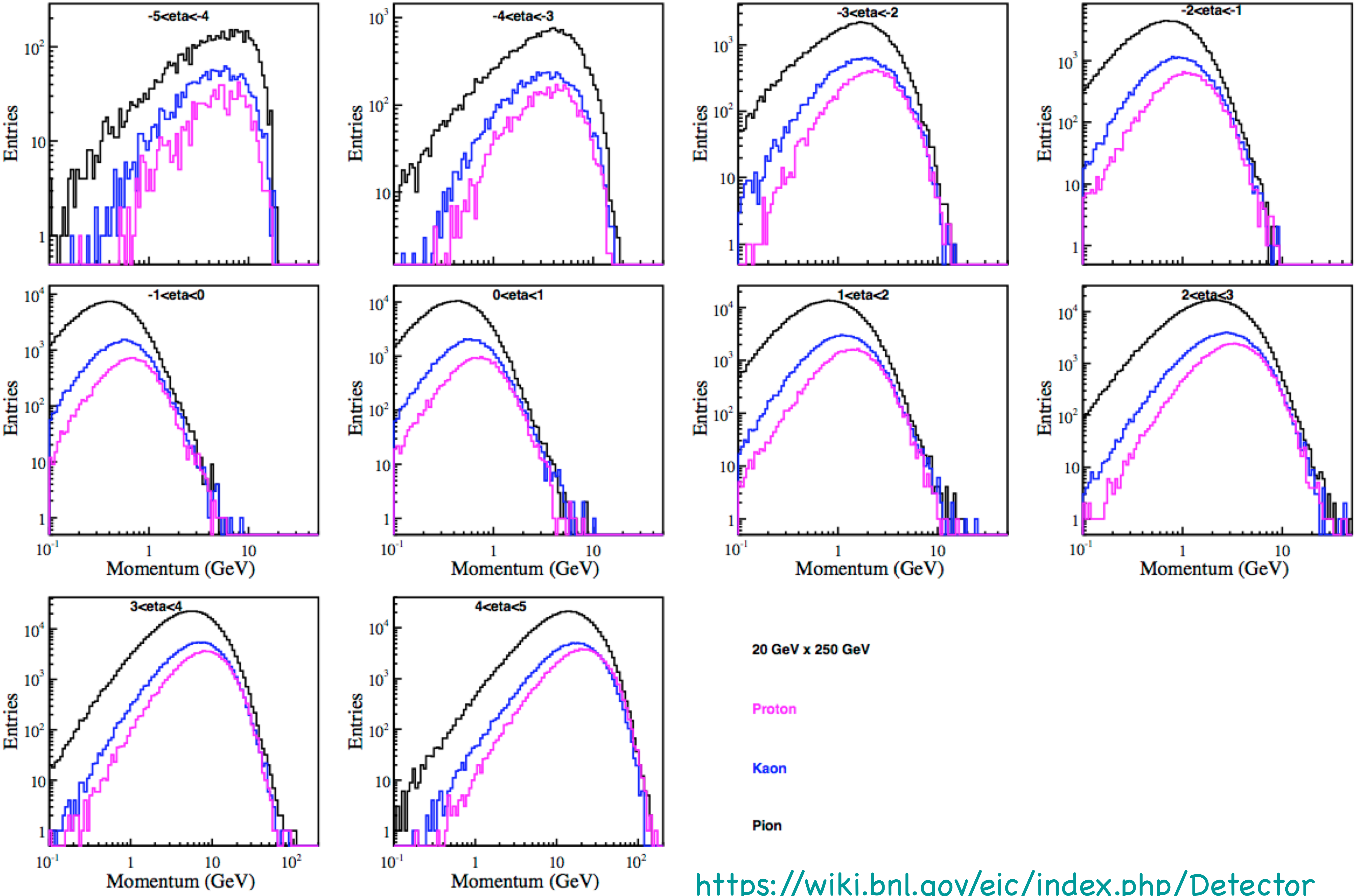
Temple. March 19

Hadron Calorimetery for EIC. (in particular Hadron EndCap).





Conditions. Energy range.



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

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)

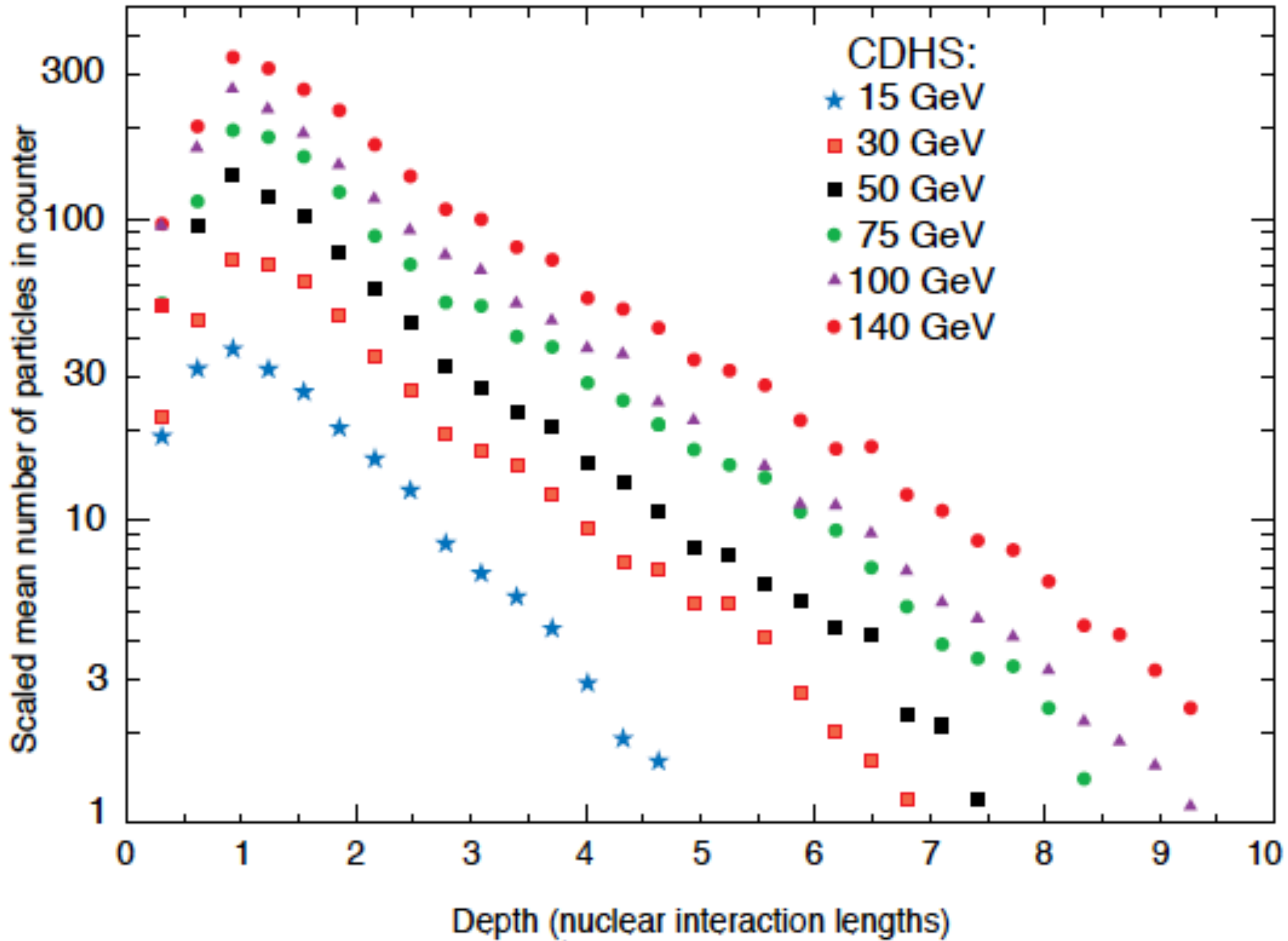
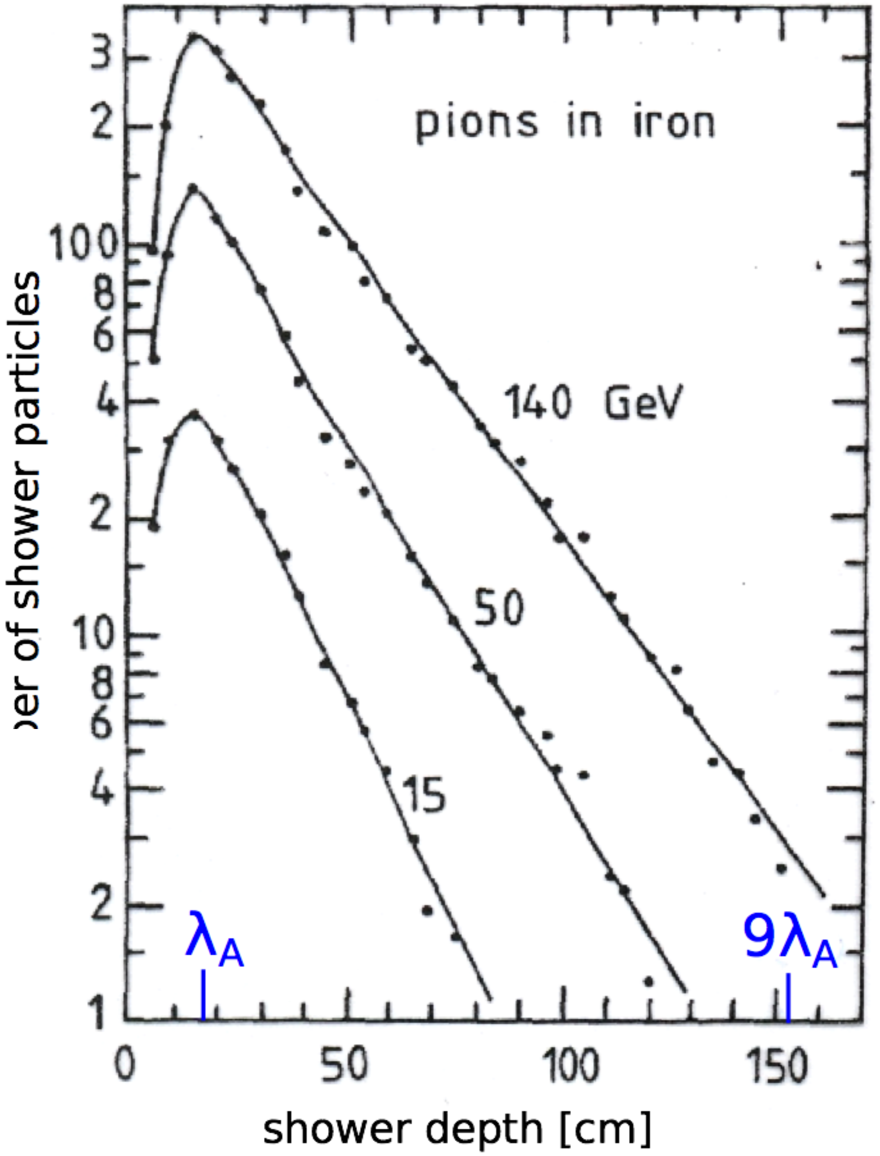


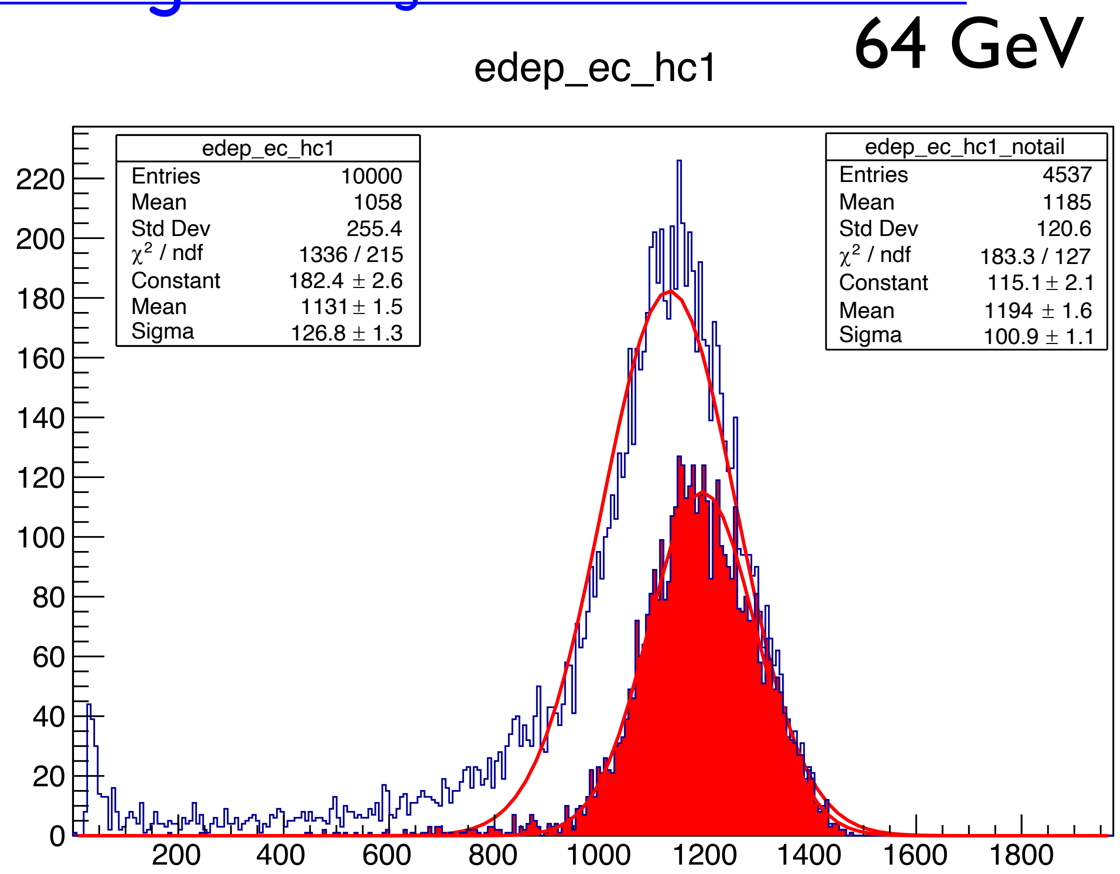
Figure 33.24: Mean profiles of π^+ (mostly) induced cascades in the CDHS neutrino detector [172]. Corresponding results for the ATLAS tile calorimeter can be found in Ref. 165.

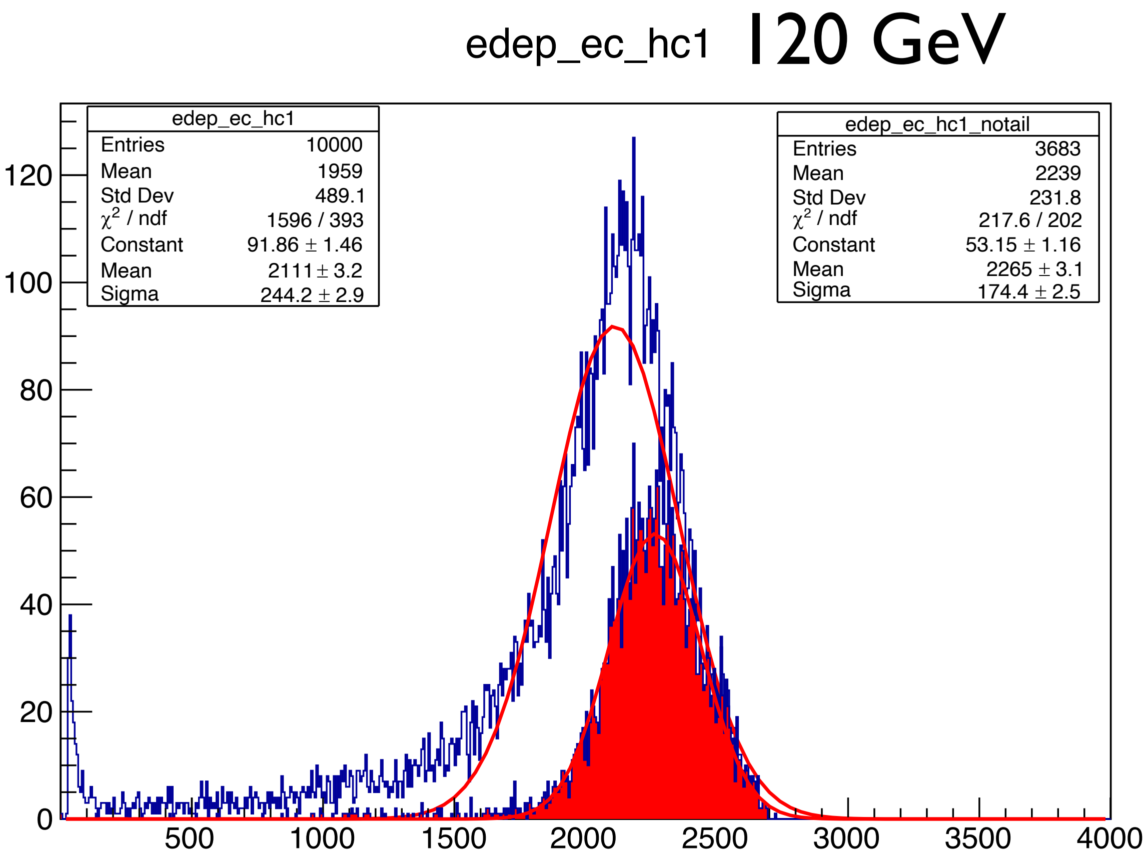


For Central Detector longitudinal containment is one of few limiting factors.

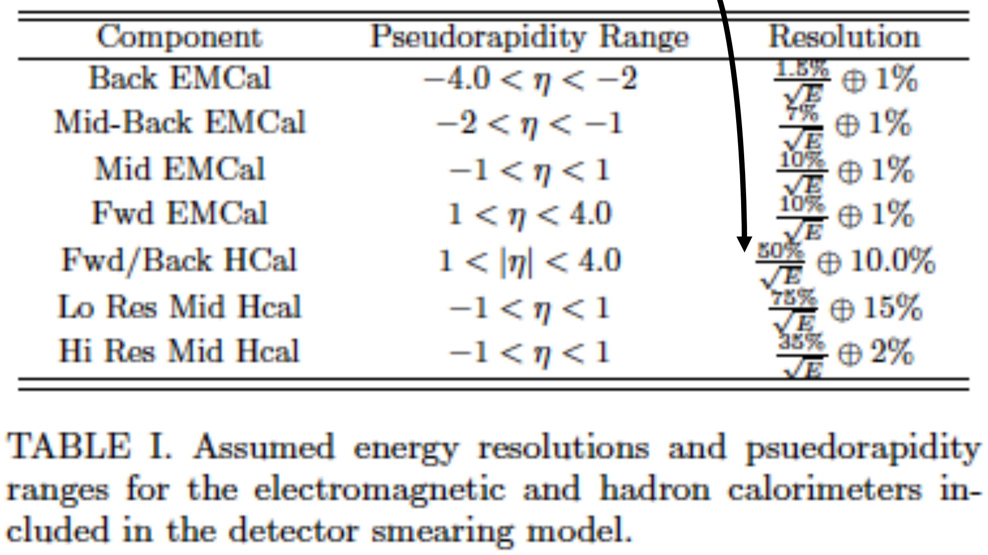
EndCap at highest rapidity.

Leakages. Mitigation with Tail catcher.





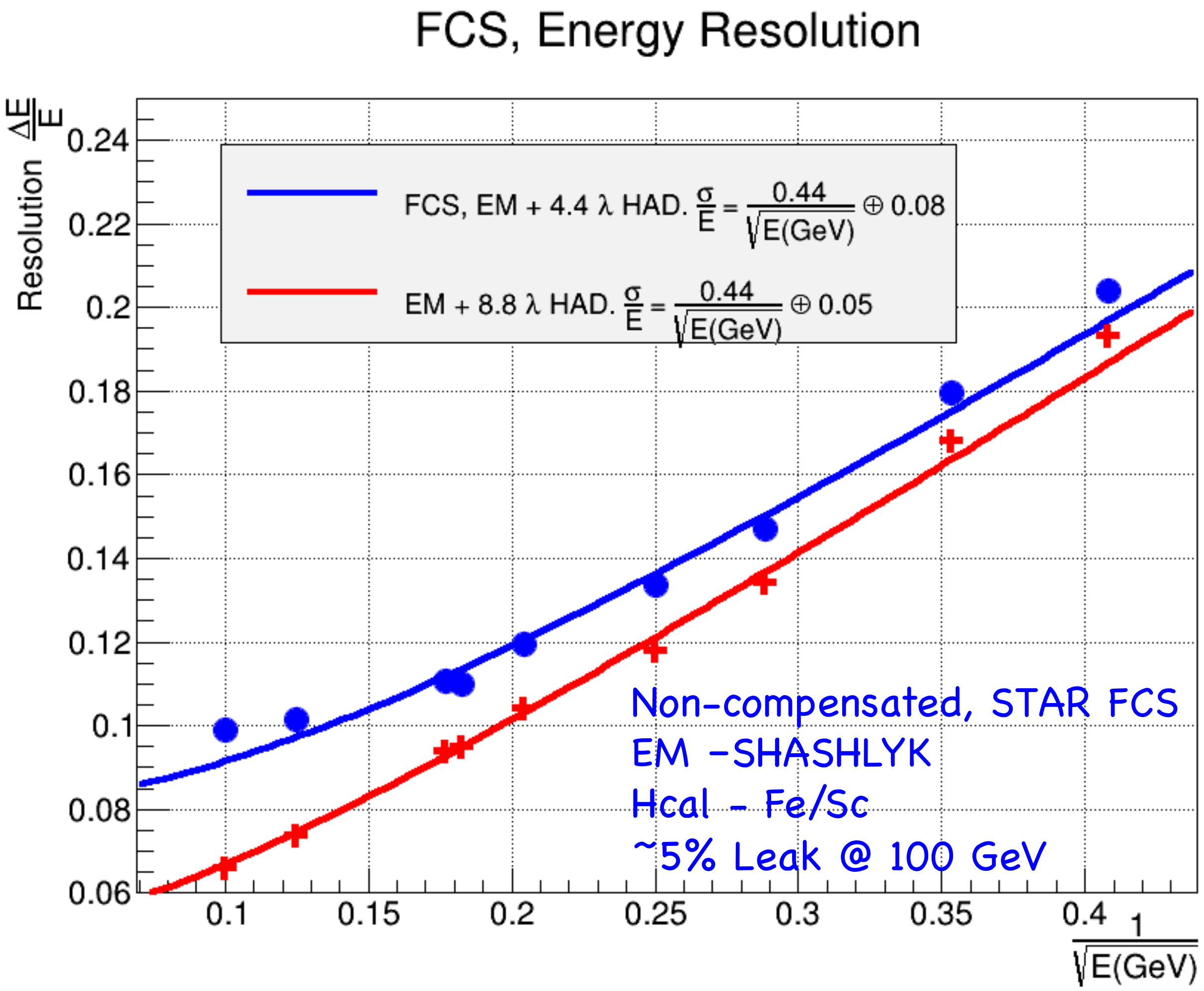
eRD1 R&D for Hadron EndCap.
Optimization for 4D systems:
a) Shashlyk + Fe/Sc (36 layers 20mm Fe, 3 mm Sc)
(improved STAR FCS, 2022)
b) W/ScFi + Fe/Sc



Component	Pseudorapidity Range	Resolution
Back EMCal	$-4.0 < \eta < -2$	$\frac{1.5\%}{\sqrt{E}} \oplus 1\%$
Mid-Back EMCal	$-2 < \eta < -1$	$\frac{7\%}{\sqrt{E}} \oplus 1\%$
Mid EMCal	$-1 < \eta < 1$	$\frac{10\%}{\sqrt{E}} \oplus 1\%$
Fwd EMCal	$1 < \eta < 4.0$	$\frac{10\%}{\sqrt{E}} \oplus 1\%$
Fwd/Back HCal	$1 < \|\eta\| < 4.0$	$\frac{50\%}{\sqrt{E}} \oplus 10.0\%$
Lo Res Mid Hcal	$-1 < \eta < 1$	$\frac{75\%}{\sqrt{E}} \oplus 15\%$
Hi Res Mid Hcal	$-1 < \eta < 1$	$\frac{35\%}{\sqrt{E}} \oplus 2\%$

TABLE I. Assumed energy resolutions and psuedorapidity ranges for the electromagnetic and hadron calorimeters included in the detector smearing model.

Ref.2



Non-compensated, STAR FCS
EM –SHASHLYK
Hcal - Fe/Sc
~5% Leak @ 100 GeV

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

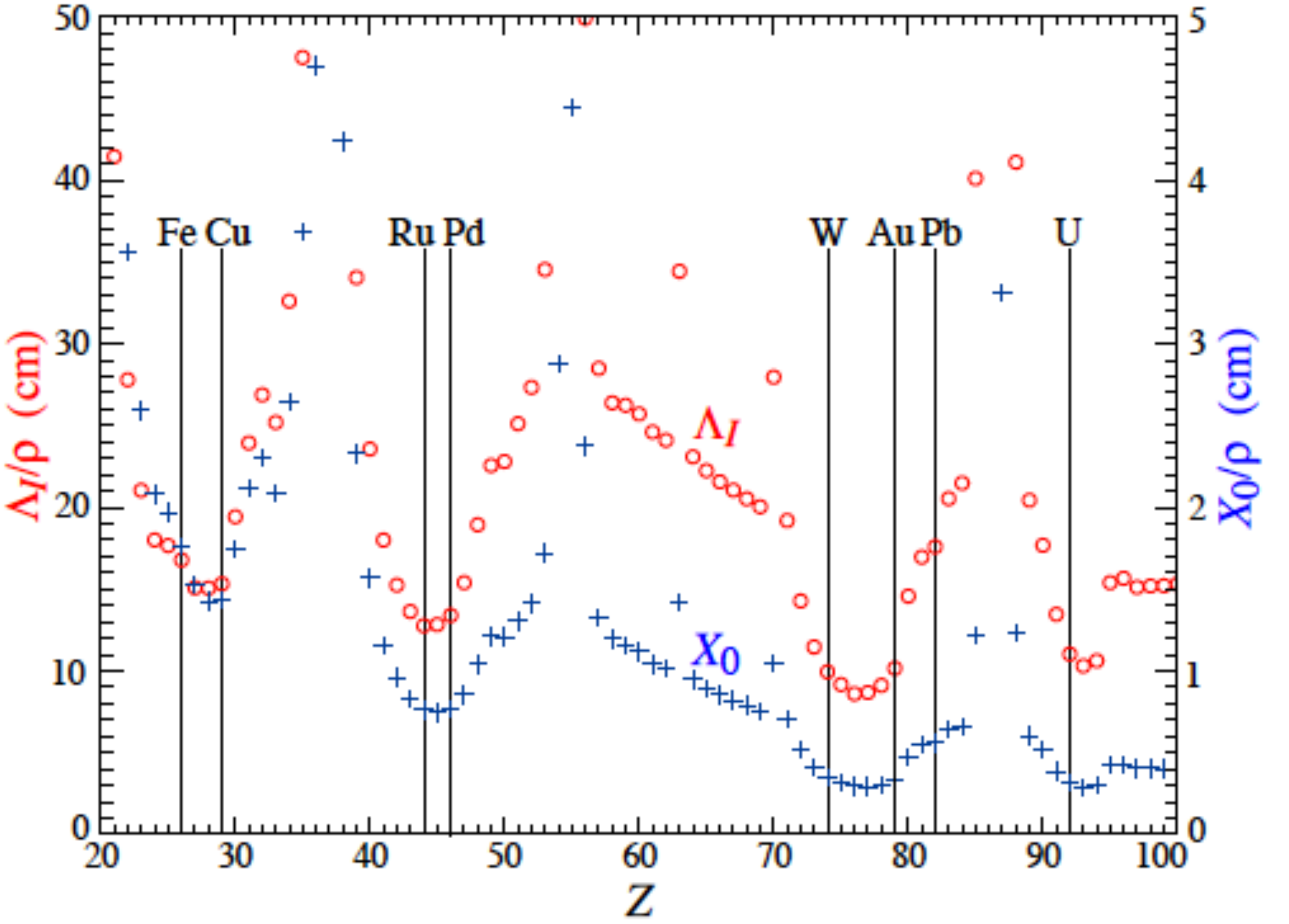


Figure 33.21: Nuclear interaction length λ_I/ρ (circles) and radiation length $X_0/$ (+'s) in cm for the chemical elements with $Z > 20$ and $\lambda_I < 50$ cm.

MEGA MILLIONS

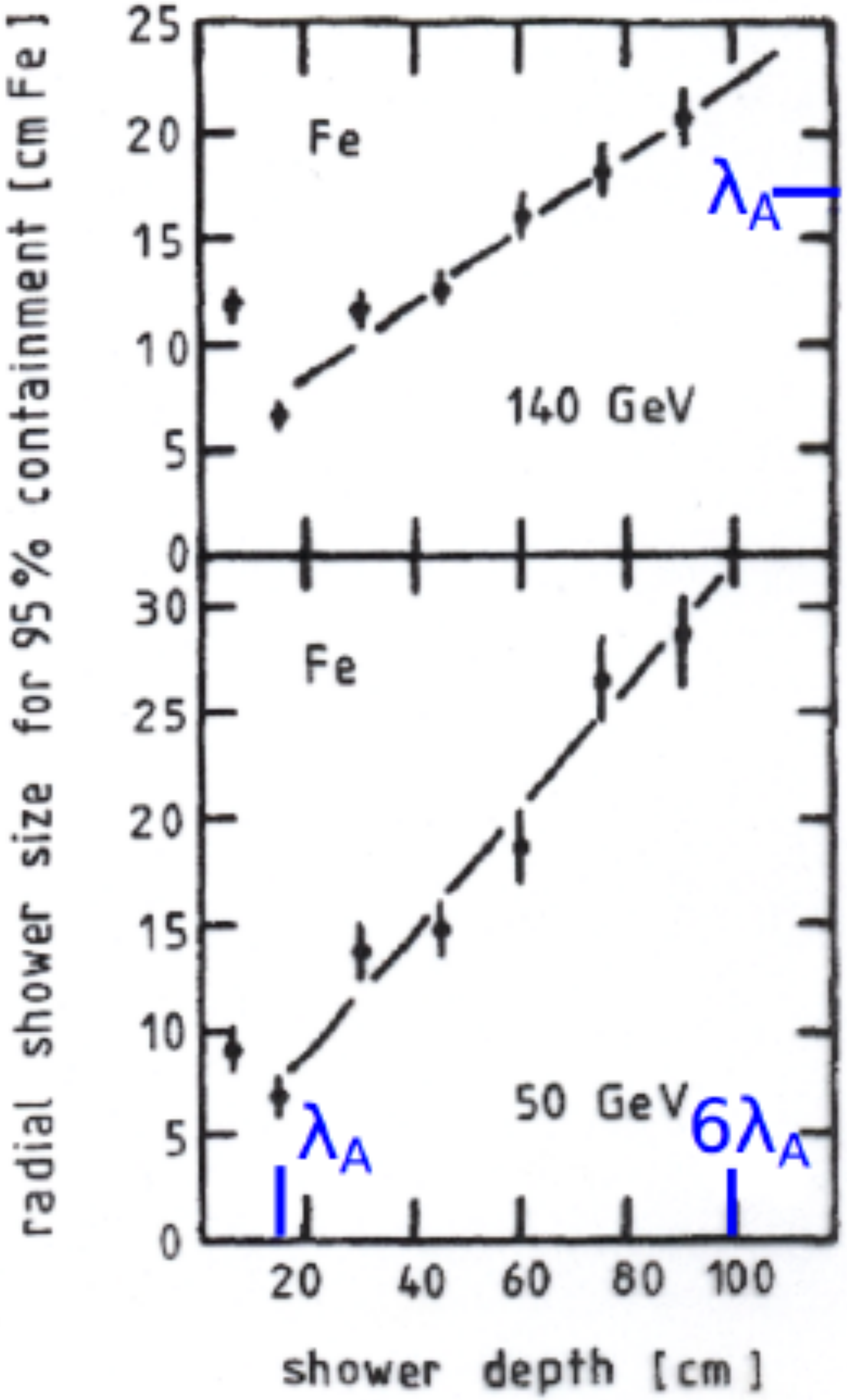
or, which is better

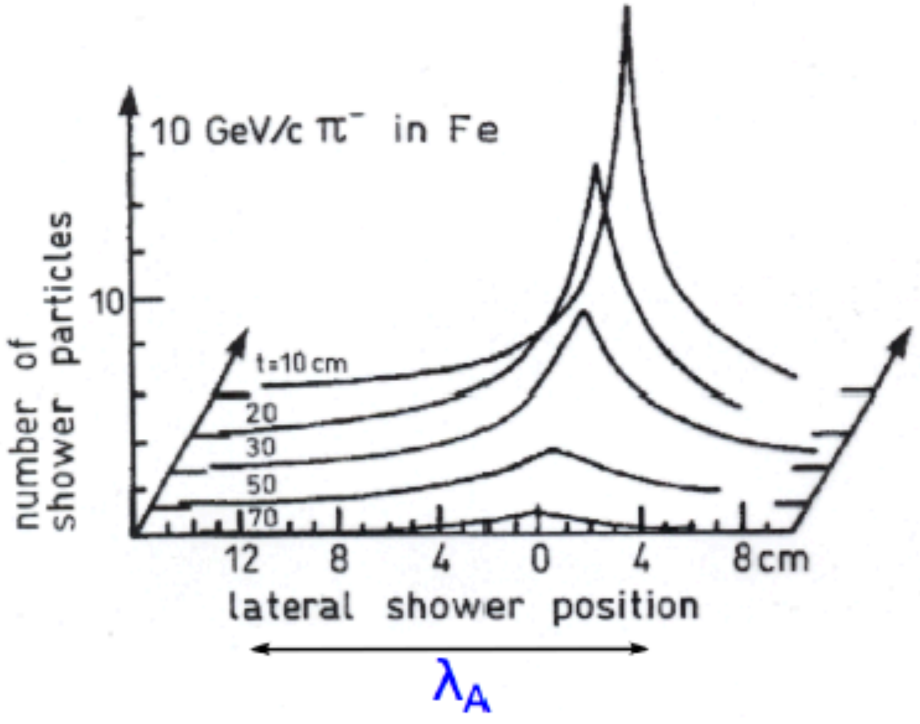
CMS Calorimeter

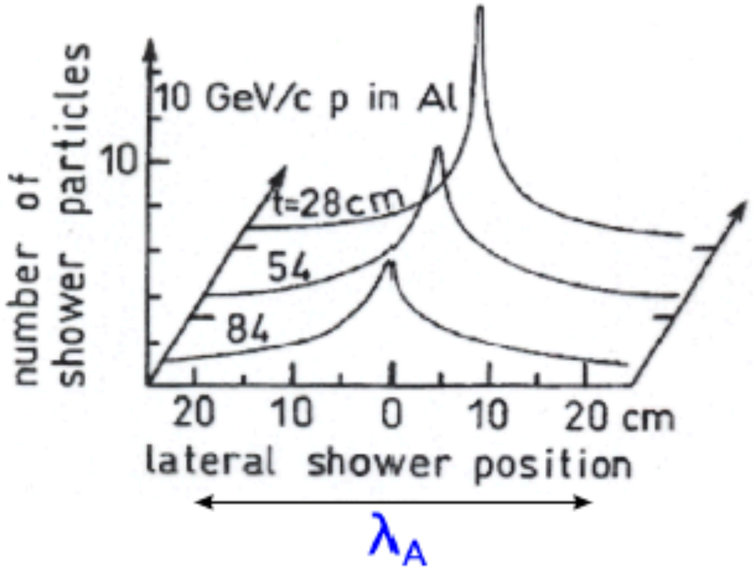
Weight of Fe EndCap for EIC
(R~3.5 m, 0.8 m) will be
about 180 metric tonnes

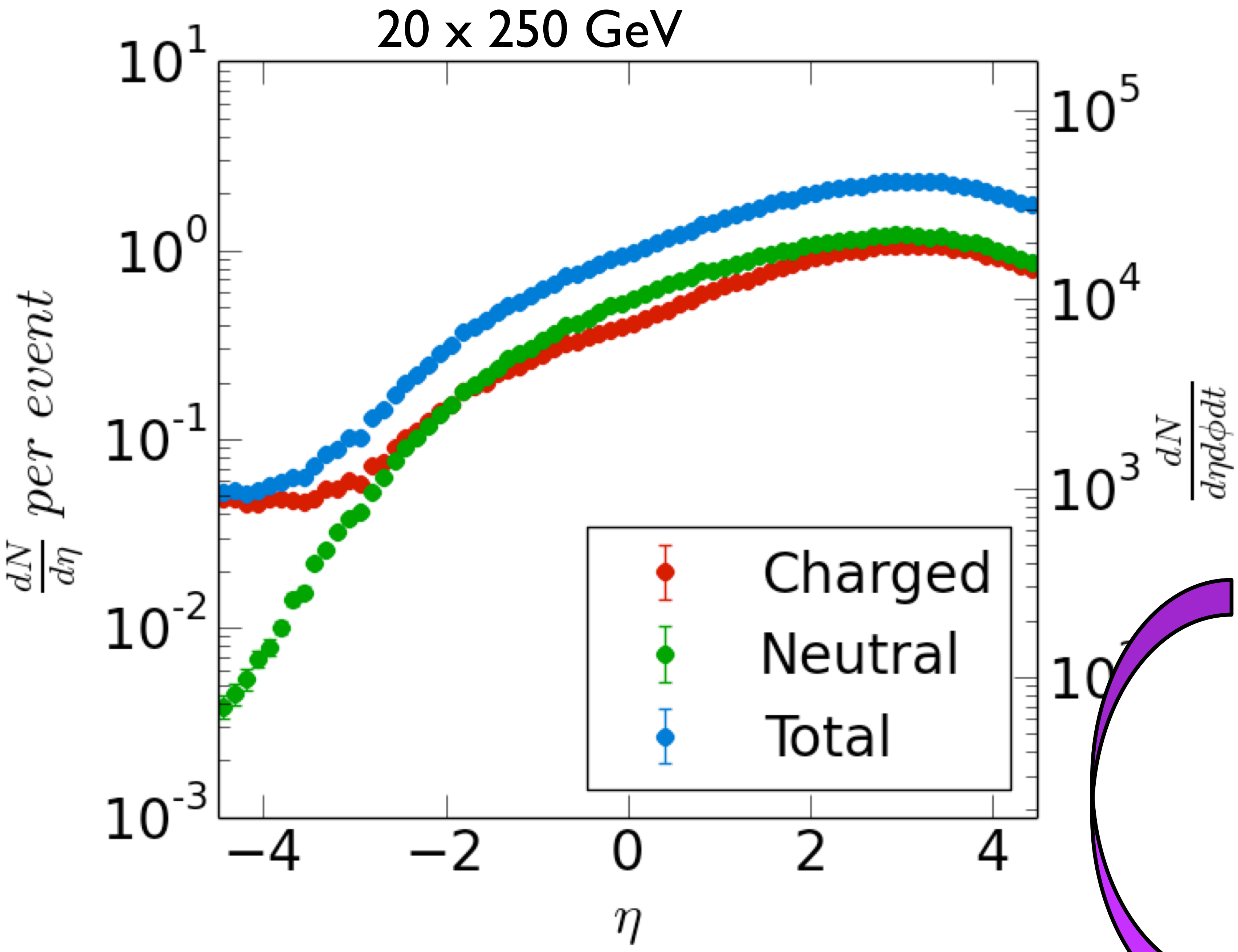
Containment, Lateral.

- $R_{95} \cong \lambda$ at Shower Max
- Cylinder to contain 95% of the shower is about 1.5 x λ
- Lateral size of the detector will be one of the limiting factors for high resolution ZDC.









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.

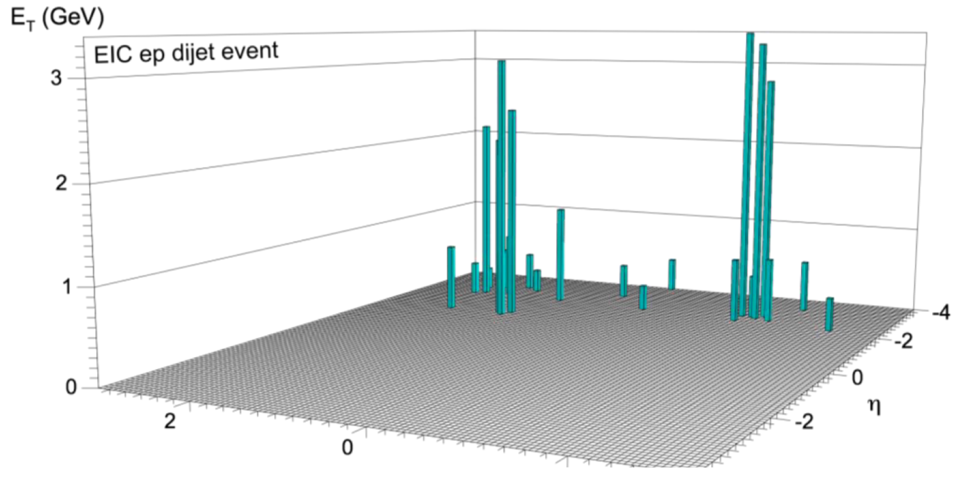
Detector Parameters:

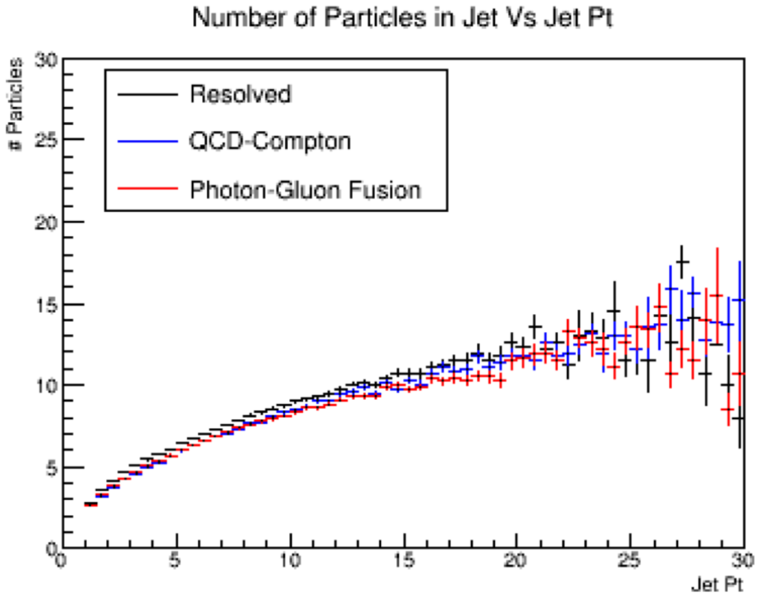
- HCal, signal integration over large detector volume is possible.
- Hcal, signal inegration over long time is possible.

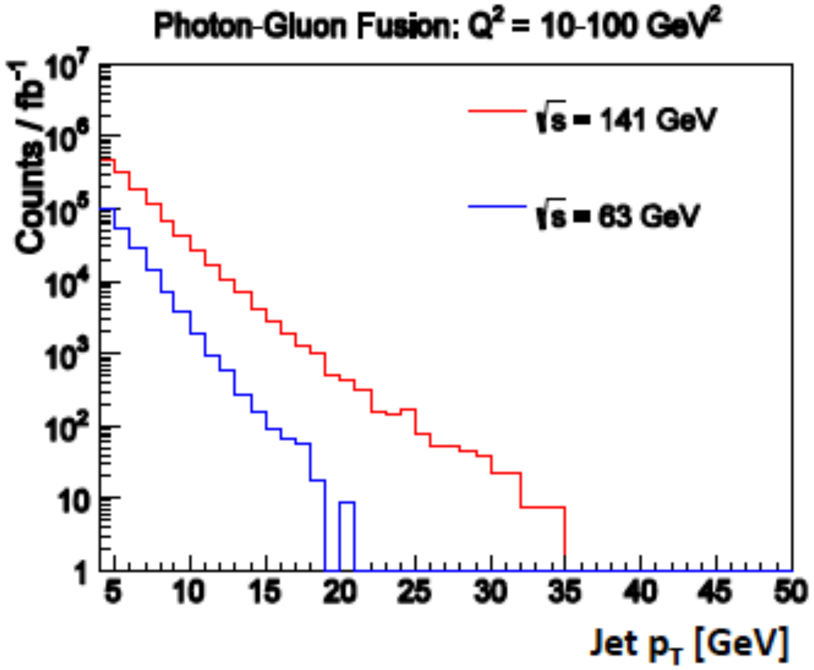
Techniques for High Resolution HCals:

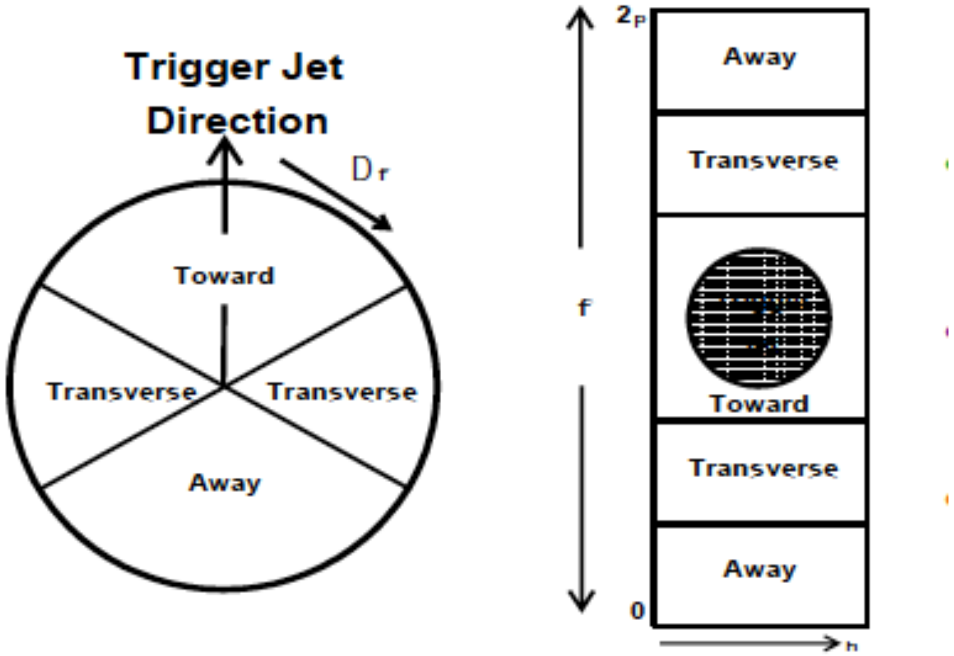
- ~~Compensation (2014).~~
- ~~Dual Readout using timing (2018).~~

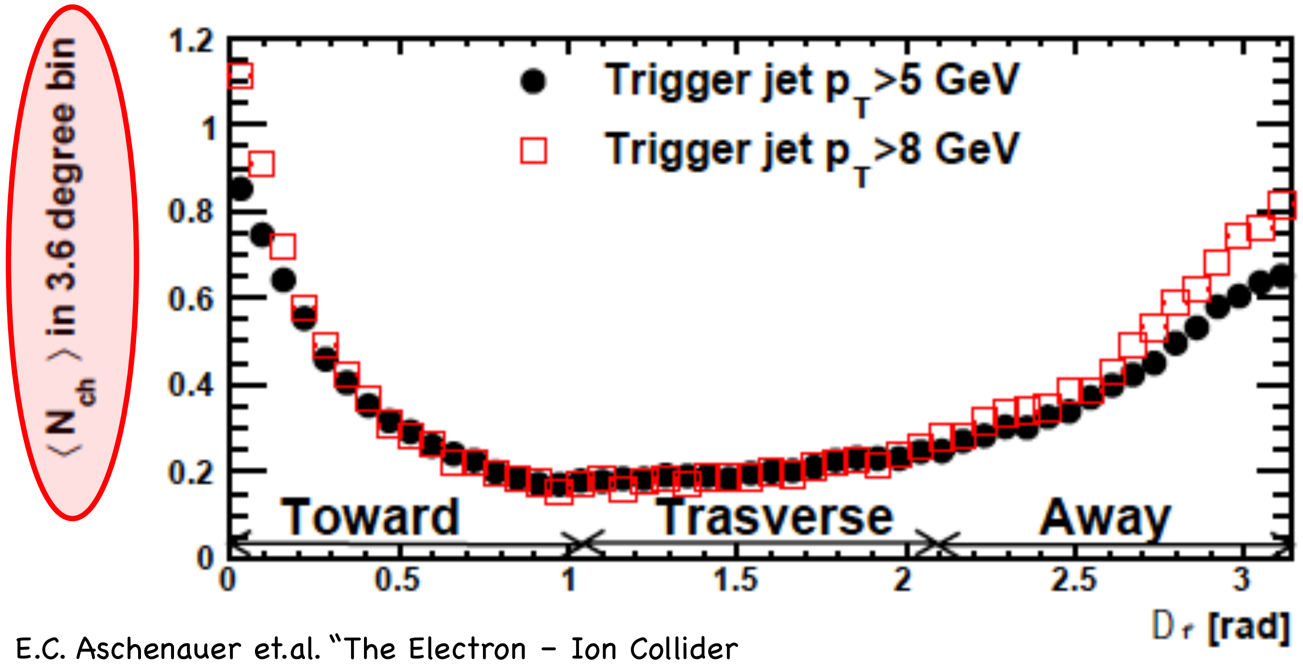
Jets at EIC











- E.C. Aschenauer et.al. "The Electron – Ion Collider Assessing the energy dependence of Key Measurements" arXiv:1708.01527v3
- B.Page, Santa Fe, Jets and Heavy Flavor Workshop, Jan 29, 2018

- Jets are soft, occupancy and rates are low.
- Large number of towers summed for R = 1.0
- Careful with the noise due to degradation of SiPMs. (Neutrons, Absorber type)

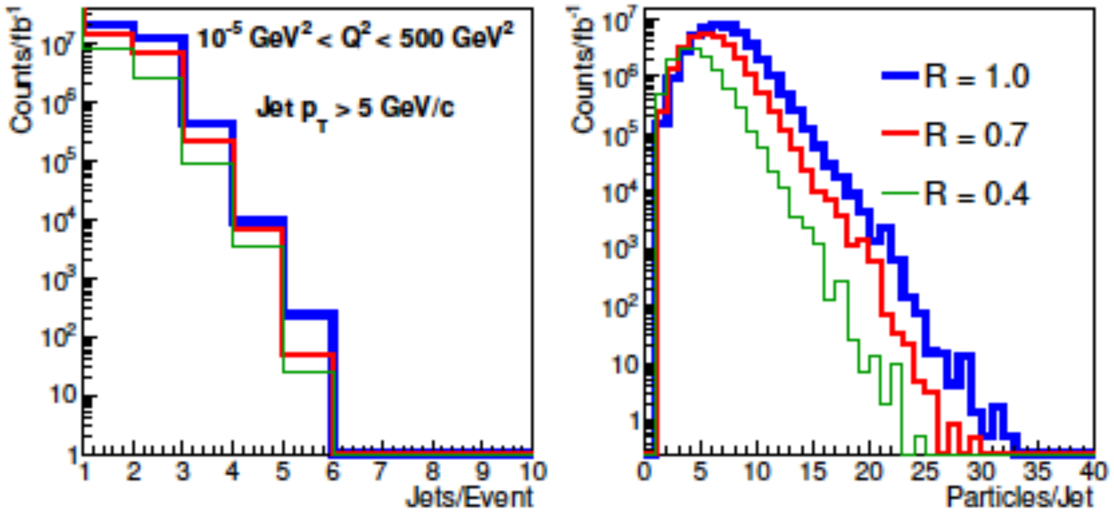
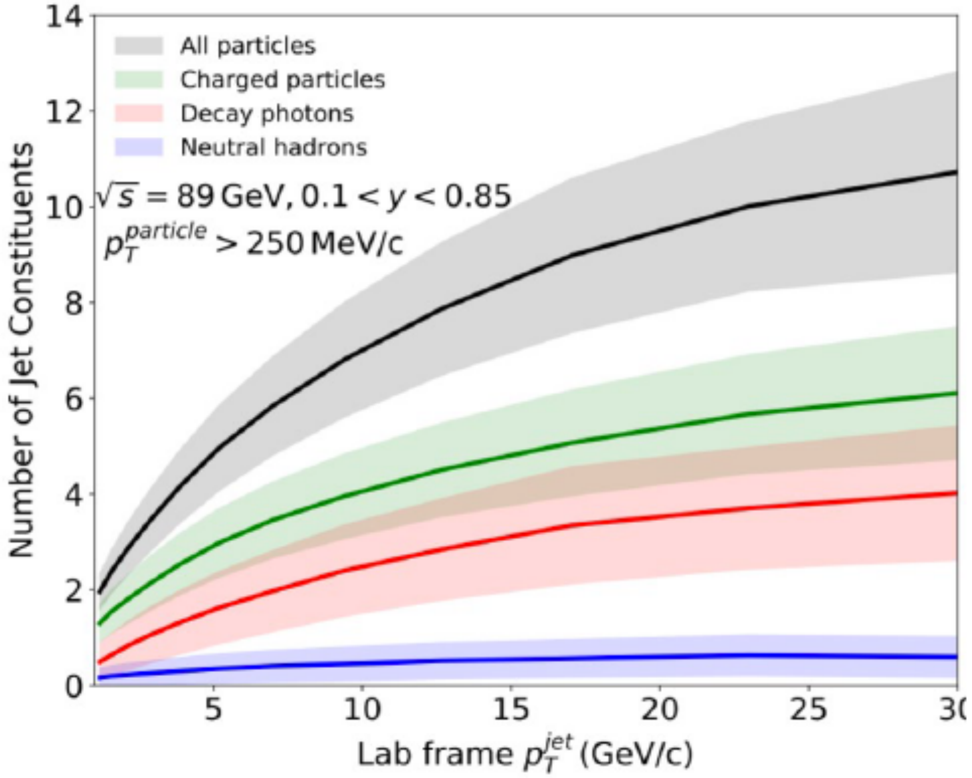
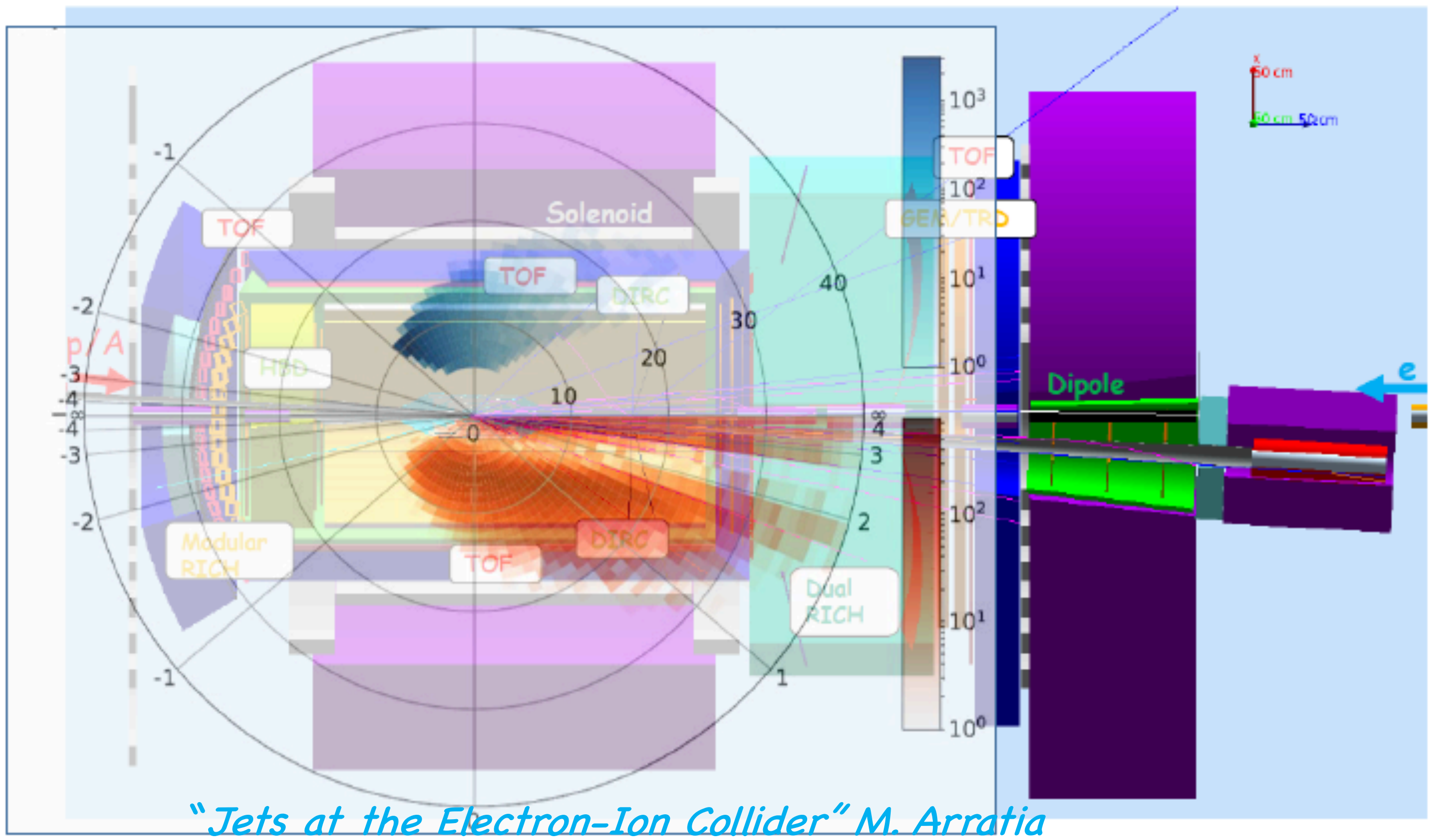


FIG. 2. [color online] Comparison of jet multiplicity (left panel) and particle multiplicity within the jet (right panel) for the anti-k_T algorithms and three resolution parameters R = 1.0, 0.7, and 0.4. The Q^2 range is between 10^{-5} GeV^2 and 500 GeV^2 and the Resolved, QCDC, PGF, and leading order DIS subprocesses have been combined.

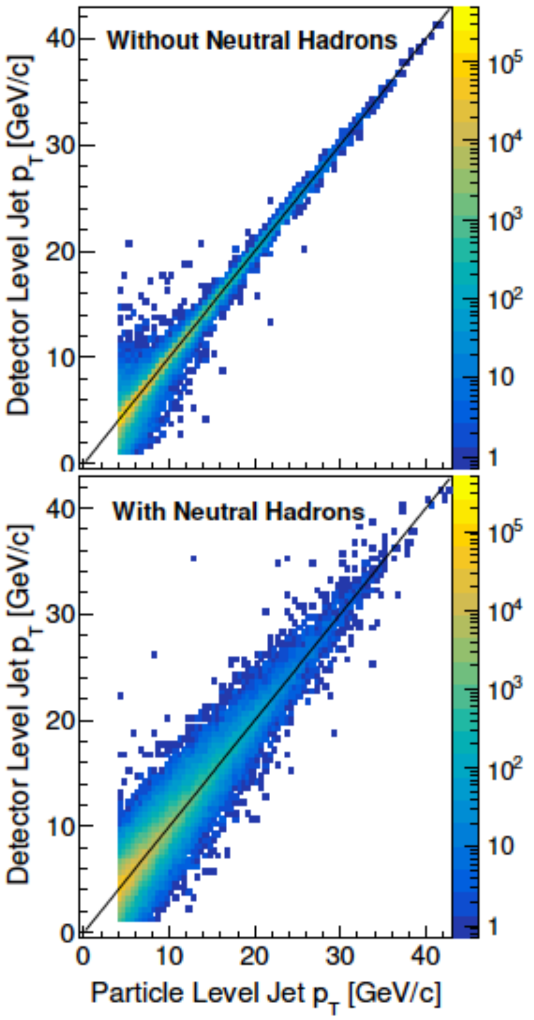
Ref.2



Gaps in calorimeter coverage could limit large-R jets...



"Jets at the Electron-Ion Collider" M. Arratia
NP Seminar, UCLA Feb.14 2020

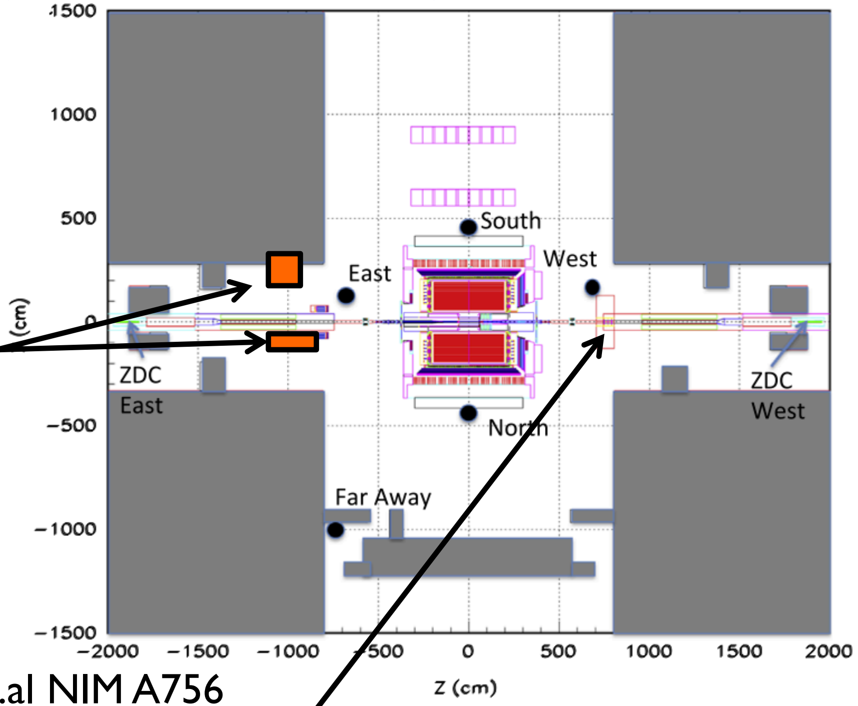


HCAl as a Veto? Ref.2

SiPMs and APDs in 'realistic' conditions: Large sample of SiPM exposed in Run17.

- STAR IP ideal test place for EIC.
- Conditions for FEMC in BeAST very close to one we have in STAR now.

EIC R&D 2017

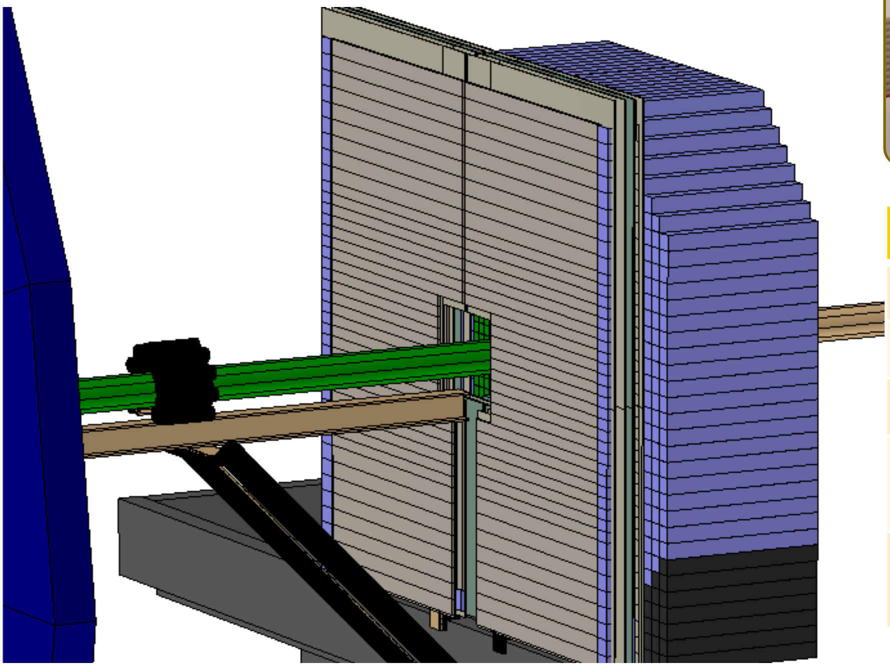


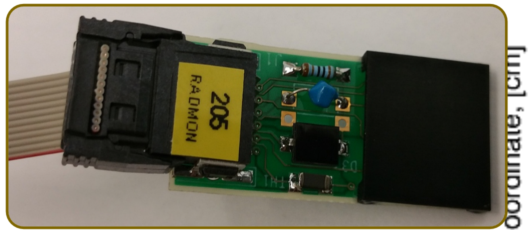
Y.Fisyak, et.al NIM A756

EIC, Run 17 STAR IP:

- 152 SiPM at ~135 cm (since Feb.)
- 26 SiPMs at ~45 cm (since April)
- APDs at ~45 cm, (since April)

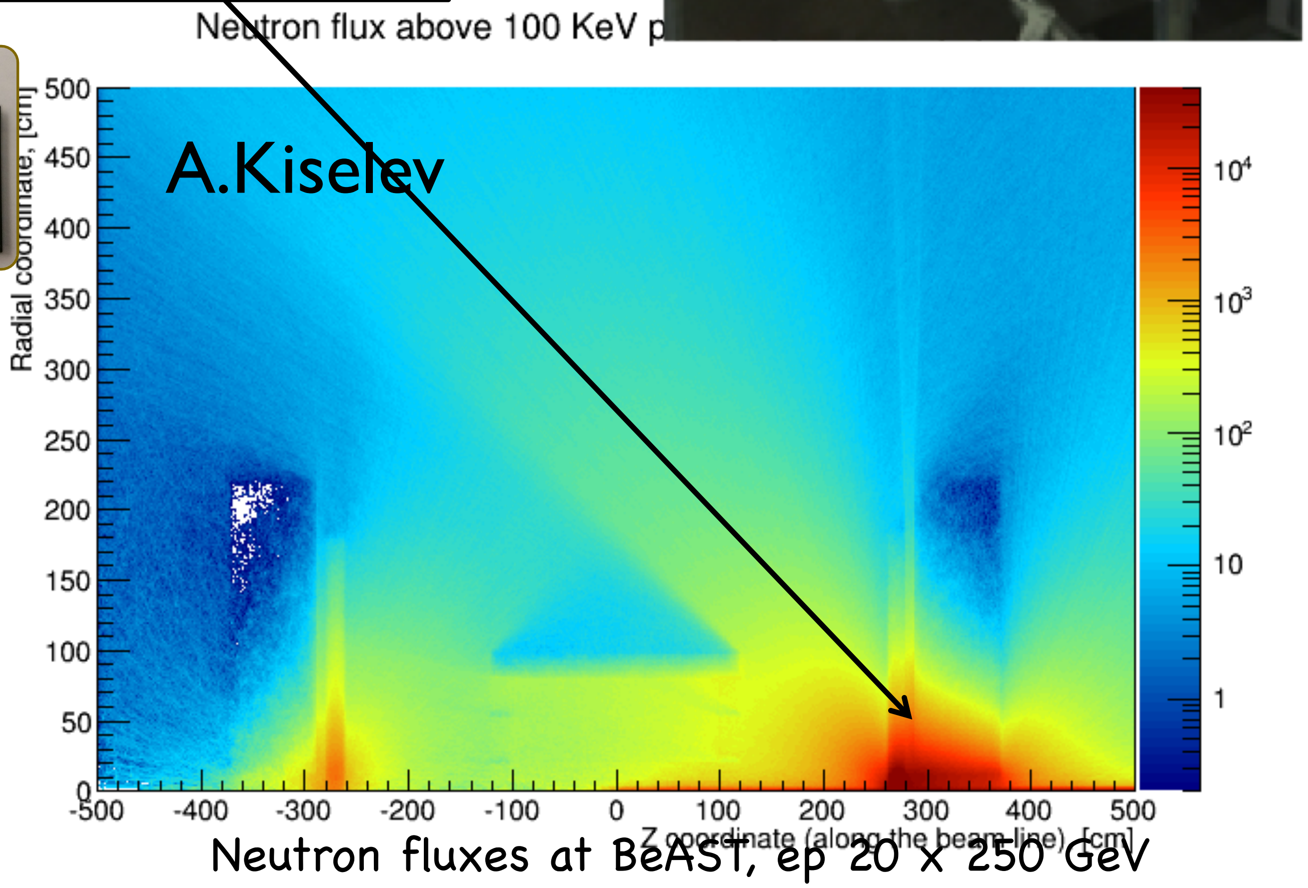
Forward Preshower (FPS)
Forward PostShower (FPOST)





No	Board	Location
1	205	near beam
2	206	FPS layer 2
3	207	FPS layer 3
4	208	FPOST layer 2/3
5	209	FPOST layer 4

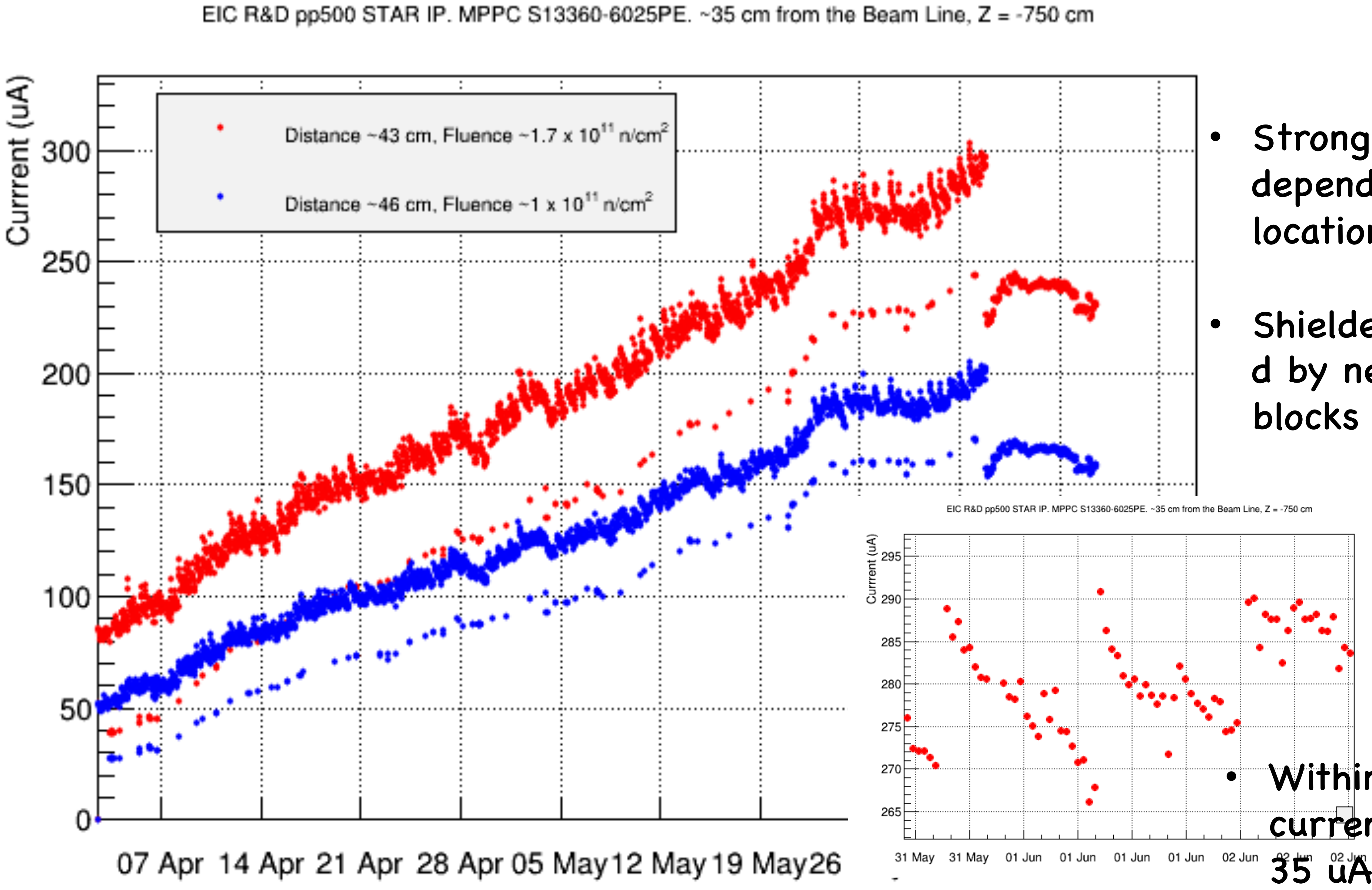
FEMC Run16, Run17



Neutron fluxes at BeAST, ep 20 x 250 GeV

Next opportunity to test EIC detectors, Run 22 500 GeV pp

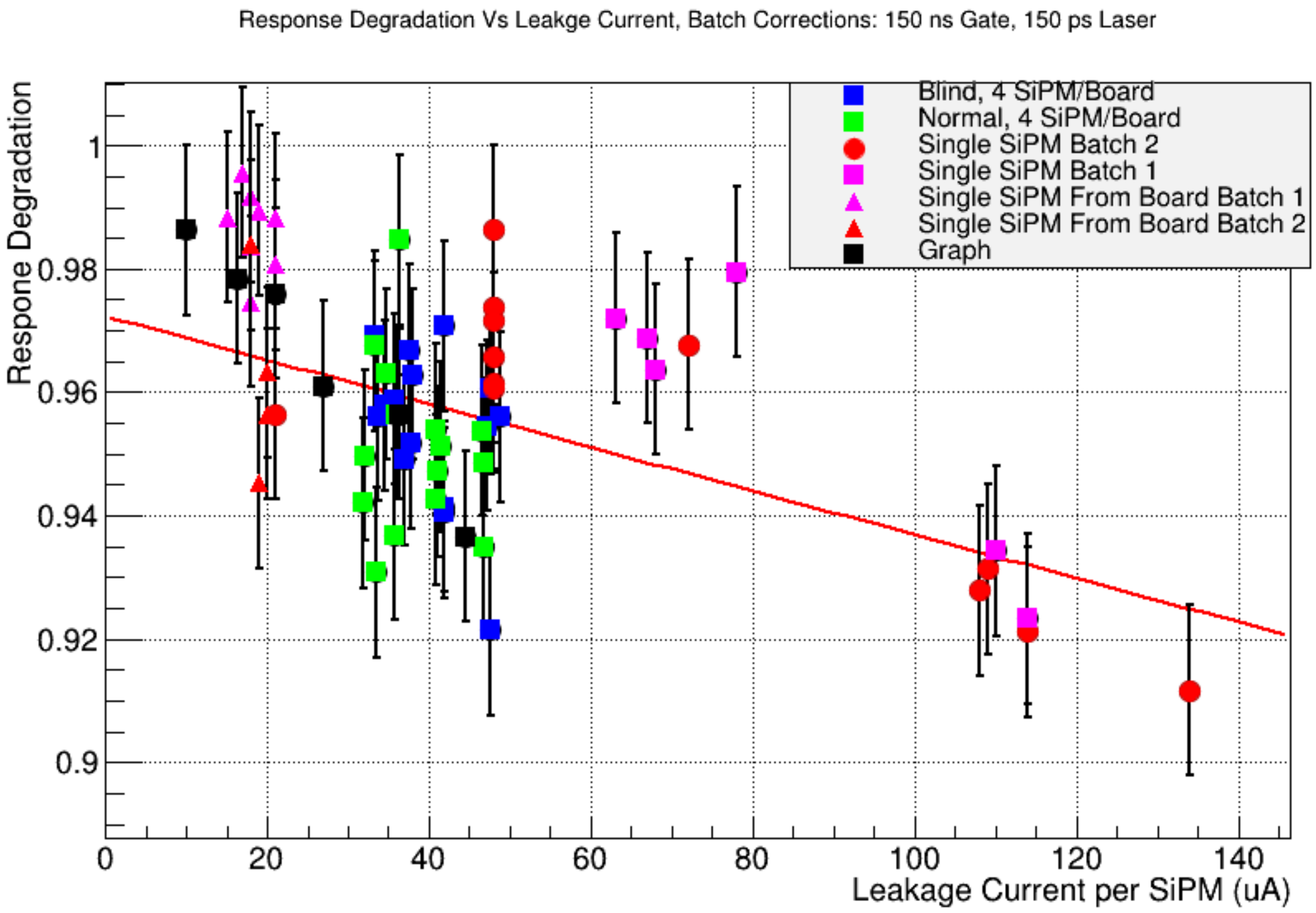
- Run 17. Conditions at STAR Forward close to what will be at EIC.



- Strong dependence on location.
- Shielded/unshielded by nearby EM blocks
- Within one fill current changes ~ 35 uA

- These are for 36 mm^2 SiPMs. For 3 x3 mm current will be about 100 uA at the end of the run.
- Gain was set ~ 3x10^5, Overvoltage 2.14V

- SiPMs, exposed in Run 17 – degradation of response caused by shift in Vbd. Reasons for changes of Vbd was not immediately clear.
- SiPM, exposed in Run 18, exposure is too low (1/20 Run 17), no changes in response observed.
- More studies performed by UCLA students to investigate reason for shift in Vbd.



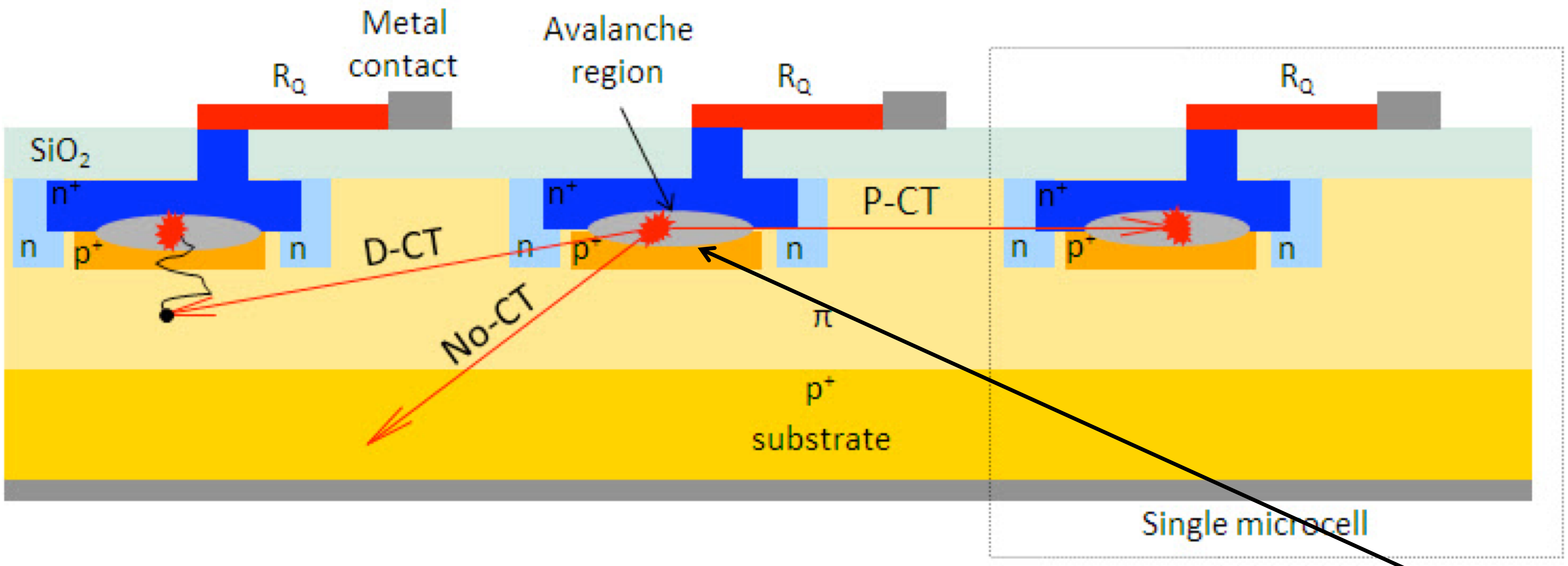
~ Eta 2.5

~ Eta 4

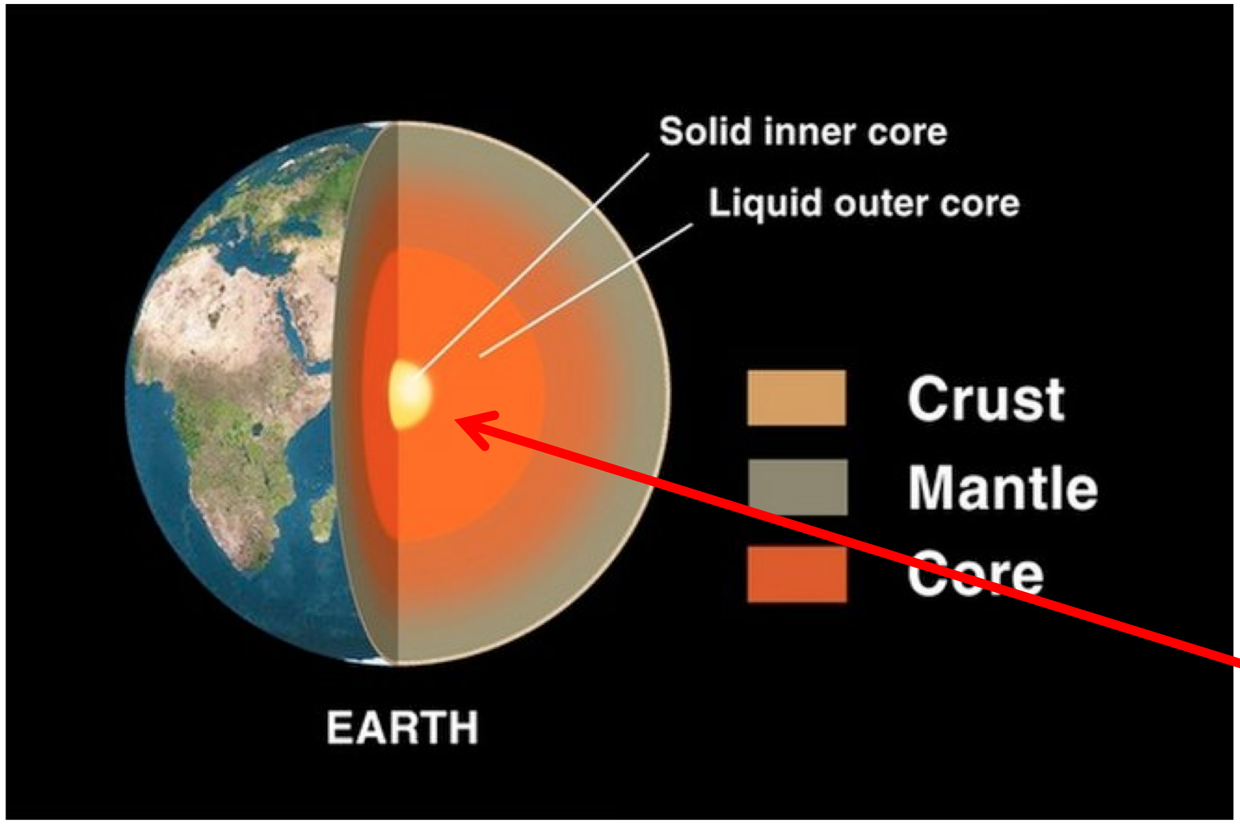
- 3 x 3 mm^2 SiPMs
- Run 17.
- Location spans Forward Calorimeter Area

Two effects:

- **Overall slope**
- **Dispersion**

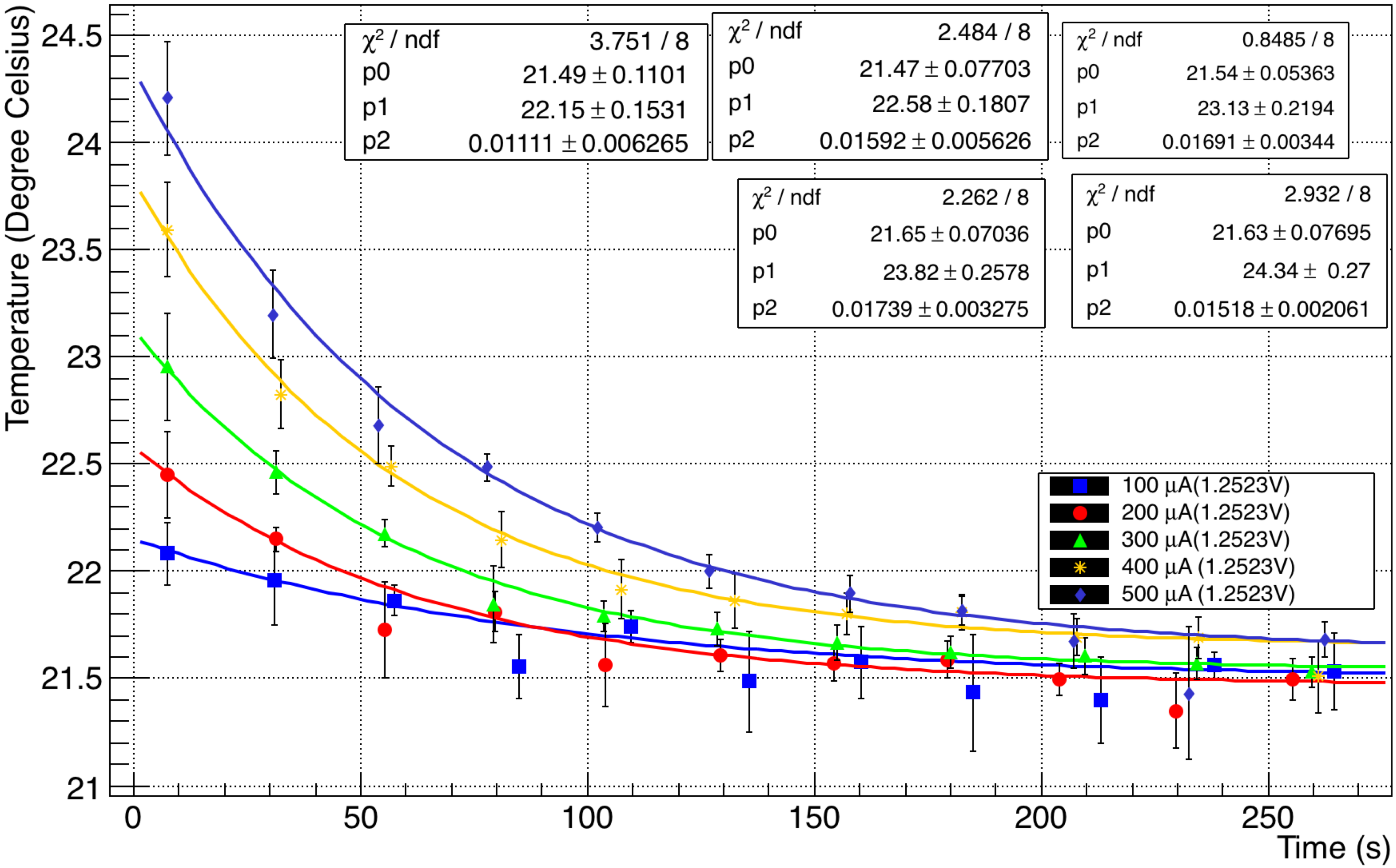


What is T over there
at experimental conditions?
(exposure + signal current)



Estimated T ~ 6000 C

Estimated @10 MHz dark noise, 5 um thick layer, 5V overvoltage, no heat dissipation. T rises ~1 deg/sec



- Knowing Vbd vs T (slide 4) we can calculate T in junction vs time.
- Fit with Newton's law of cooling (p1 – junction temperature at t=0, p0- ambient temperature. t=0 – time when LED intensity switched to low for IV scans)
- Example, for 100 uA steady current at experiment, T on junction increases ~ 0.6 degrees C above ambient 21.5 C. (More details in eRD1 report Jan. 2019)

SiPMs un-pleasant properties:

a) Response degrades with increased current flowing through SiPM (dark noise due to rad damages + from primary interaction (light from calorimeter), which heats junction). Expect up to 10% change for EIC Forward.
b) It may be large variations across forward calorimeter surface.
c) Possibly, each SiPM will degrade differently.

T compensation in Vbias does not handle this!

T on junction depends on current, which depends on

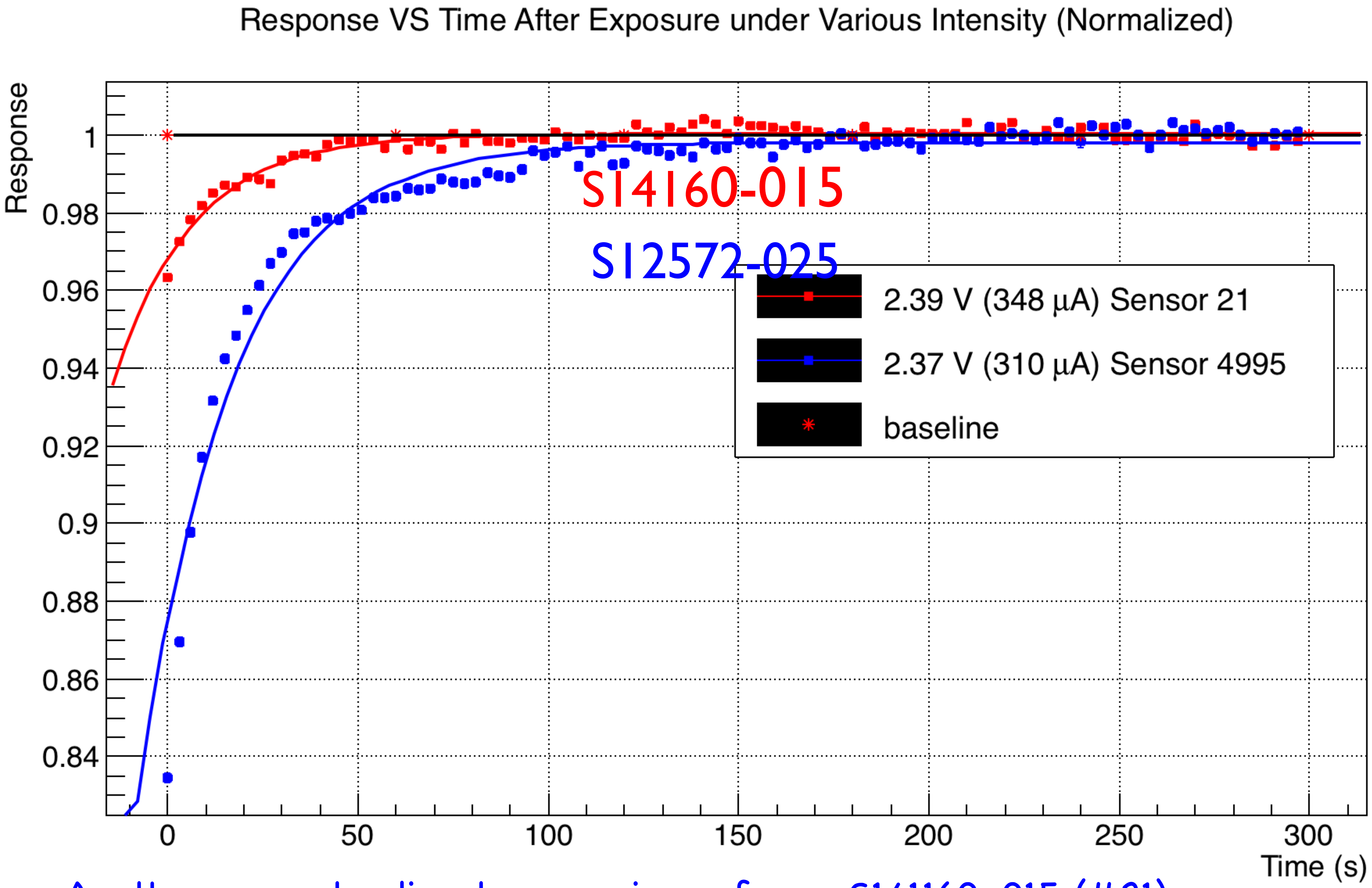
- location
- luminosity time profile
- integrated exposure
- ambient temperature
- overvoltage SiPM operates at

Partial hardware solutions for S12572 type:

a) Switch to 15 um sensors will help (lower gain)
b) Carefully chose operation bias. (Depends on LY in calorimeter, S/N).
c) Make sure, monitoring (interleaved with data, had to be taken at same average current flowing), i.e. LED runs between fills may not work well).

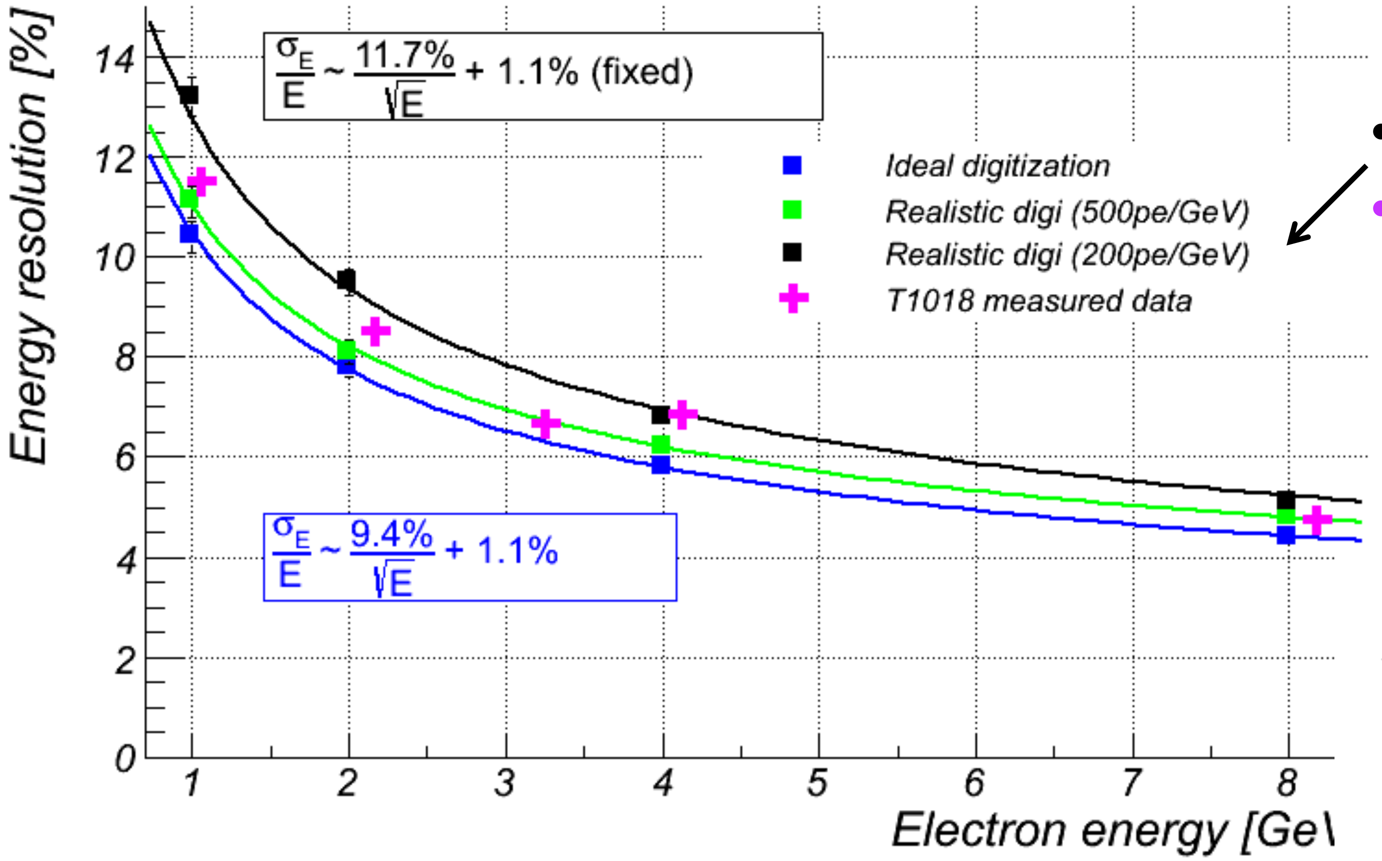
Efficient cooling for SiPMs, keep delta T (junction ambient) high, reduce leakage current etc. -> lots of complications with integration on the detector.

- SiPMs are constantly improving.
- Unfortunately, HPK was not been able to deliver needed amount of S14160 for STAR FCS.
- Run 22 (EIC conditions) STAR will run ~ 10k SiPMs (S12572 and S14160)



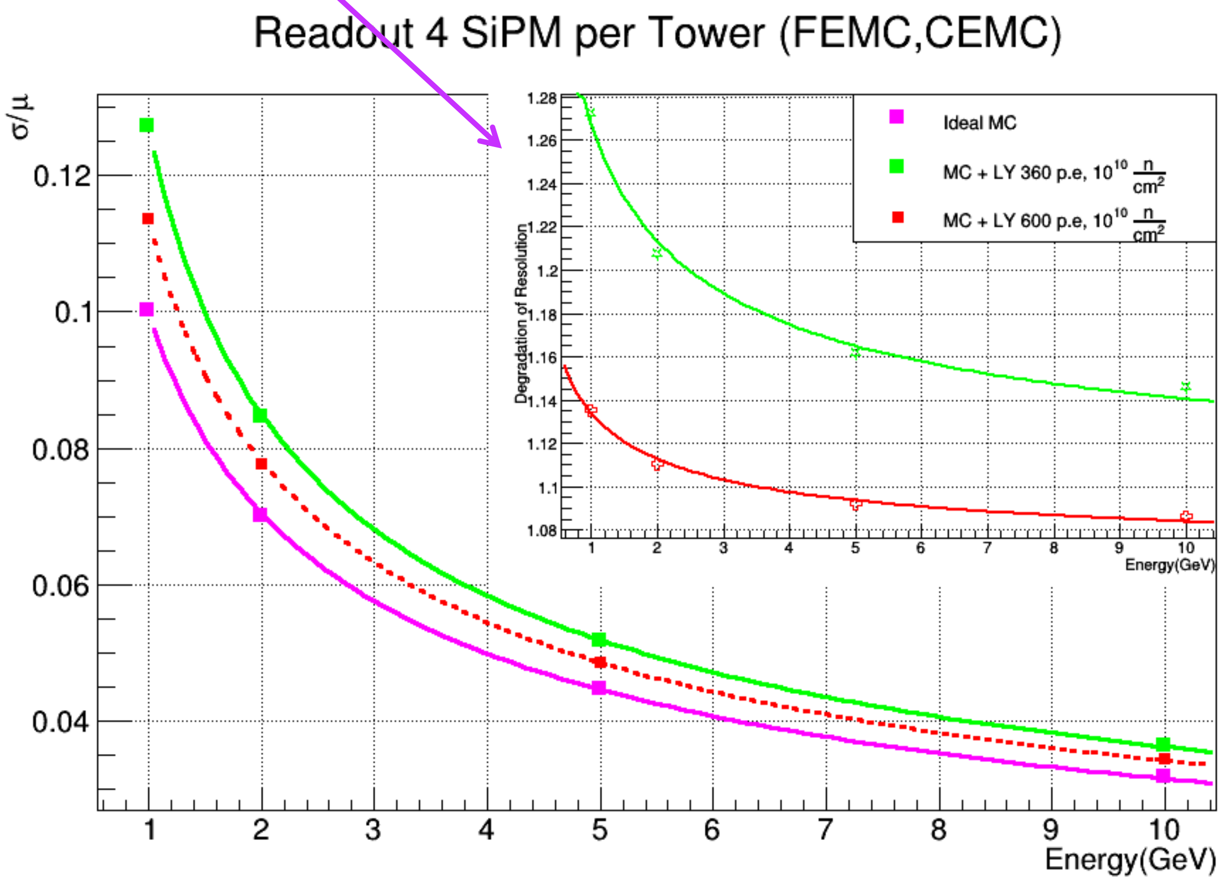
Another example, direct comparison of new S141160-015 (#21) vs old S12572_025 (#4995).

Energy Resolution, Light Yield, Noise and Granularity, Absorber.



FEMC energy resolution study (A.Kiselev 2013)

- **200 p.e./GeV is enough, but…**
- But there are SiPMs damages as we measured in 2015, 2016, 2017 at STAR IP (EIC conditions), resulting in degradation of energy resolution (single particle)



Neutron fluence 10^{10} n/cm^2. Cluster 3 x3 Eq. noise ~ 60 MeV

For Jets

- Assume granularity similar to what was used in prototypes or in the sPHENIX EMCal.
- Jet Patch (R=1) spans across ~ 7500 towers.
- **Eq. Noise due to degradation of SiPMs – 1.7 GeV/Jet Patch.**

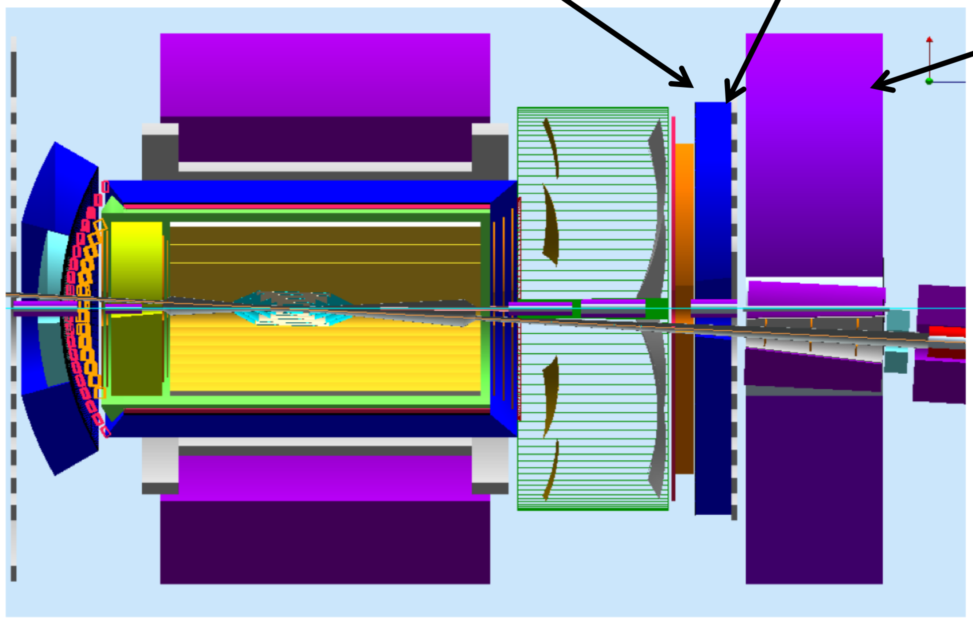
- Compensated, small sampling fraction, low LY. Very compact.
- Noise in SiPMs, integration window. (High Z absorber -> large integration time)
- Noise in SiPMs, integration over large area. (High Z absorber – neutron generation)

Important Limiting factors for high resolution HCals

EMCal (e/h =X)

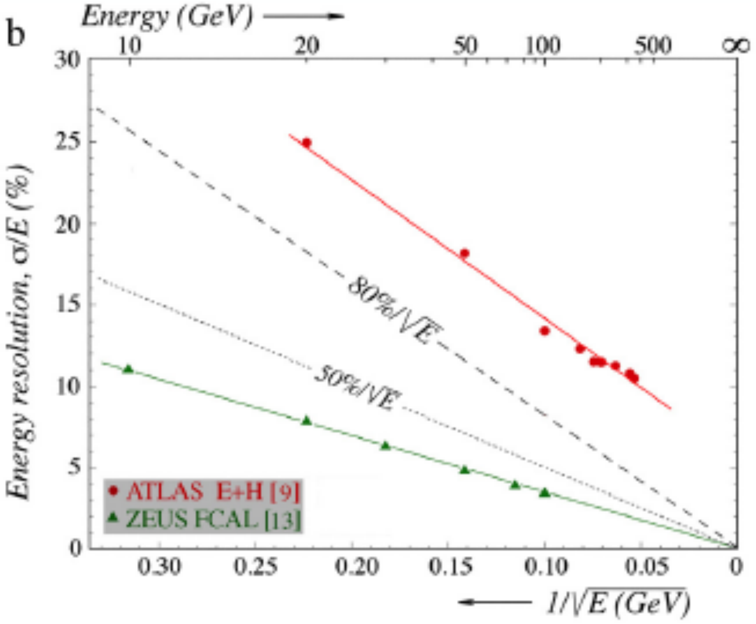
Dead Material

Hcal (e/h =Y)



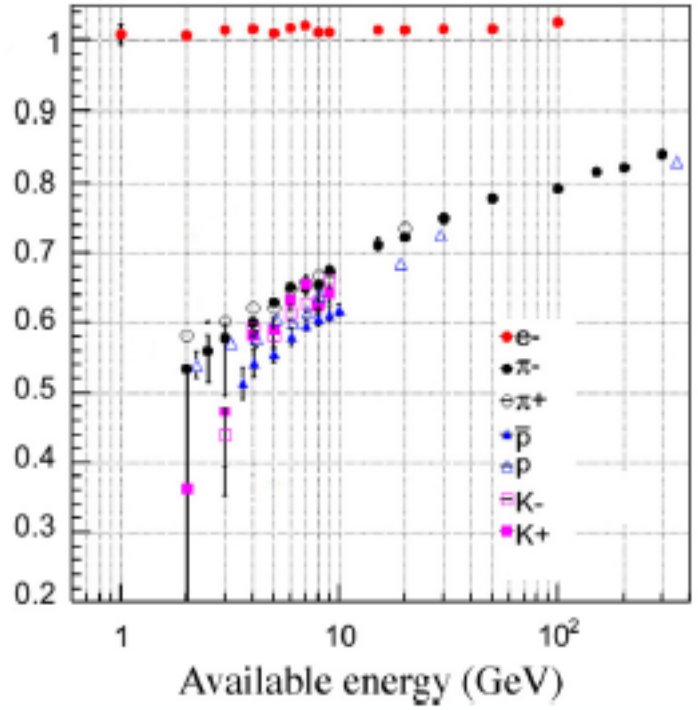
Deviation from 1/√E scaling in hadronic energy resolution

ATLAS Calorimeter



Non-linear response to hadrons

CMS Calorimeter

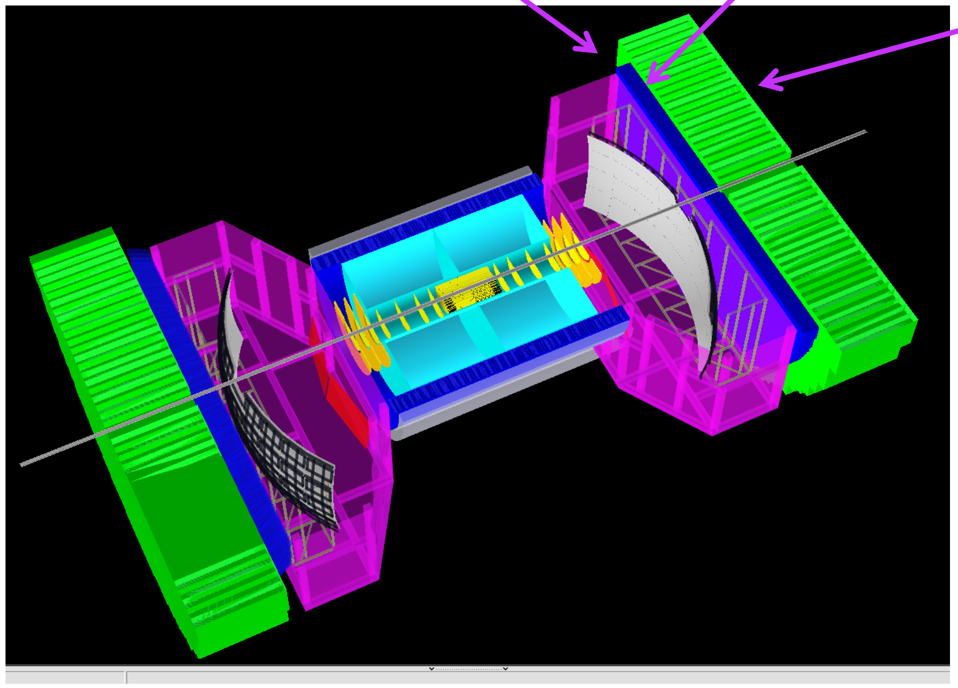


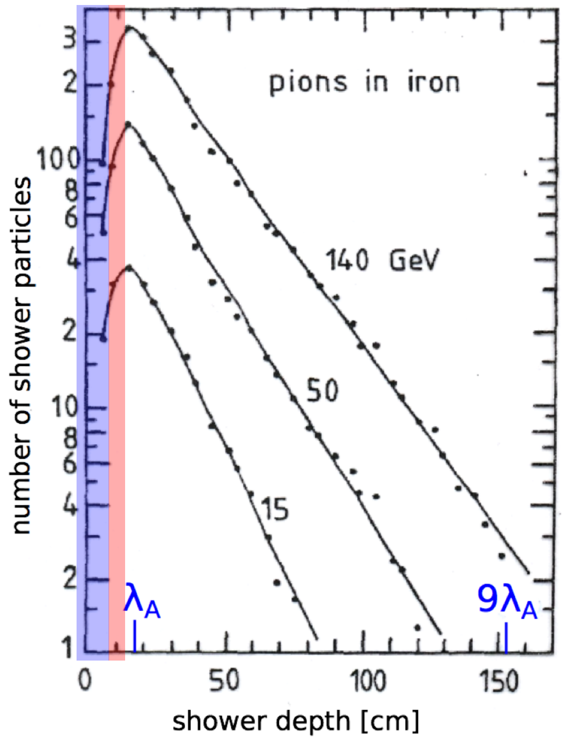
S.Lee, M.Livan, R.Wigmans CALOR 2018

Compensated EMCal (e/h =1)

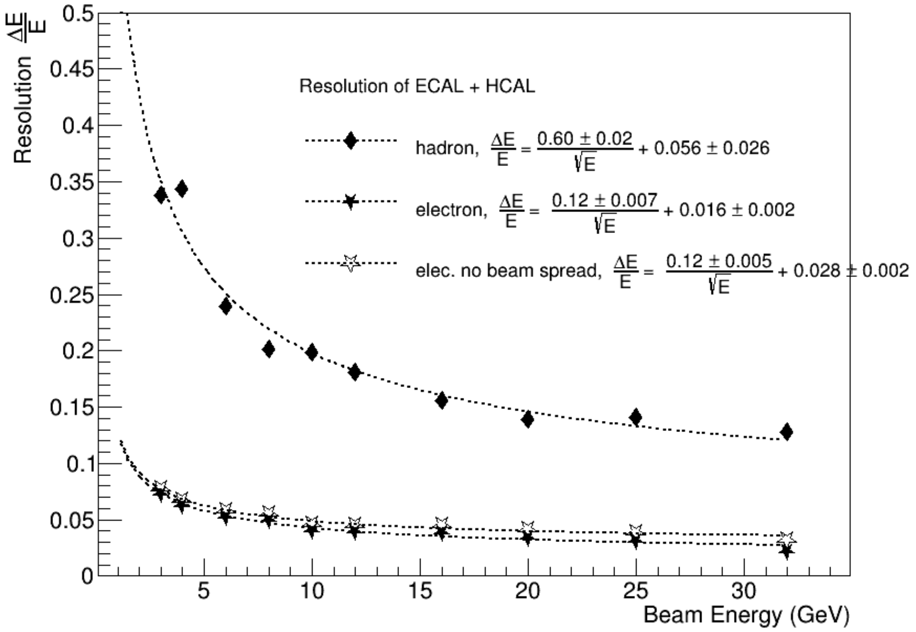
Dead Material
5cm Fe

Compensated Hcal e/h =1





Graph



Resolution of ECAL + HCAL

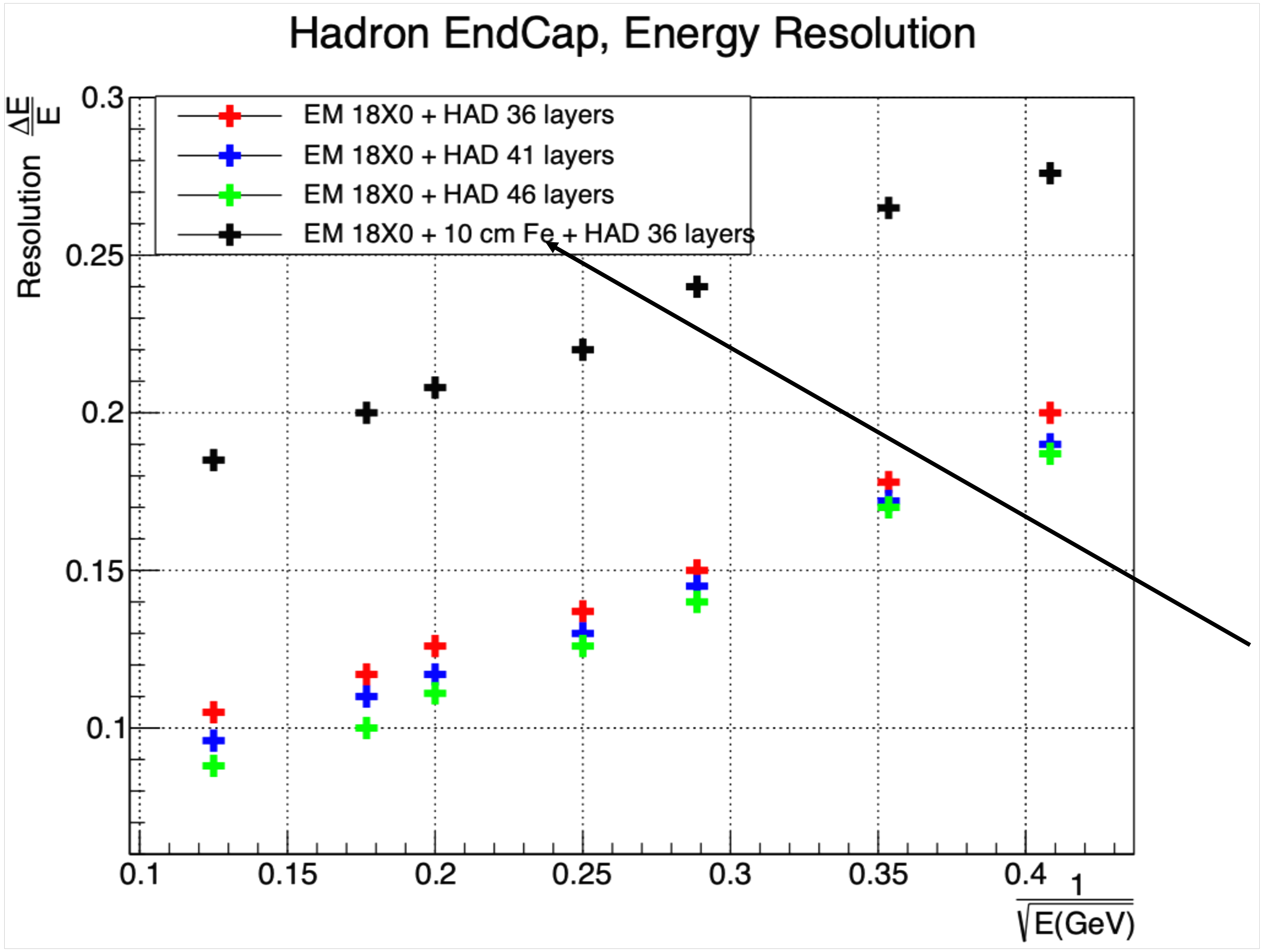
hadron, $\frac{\Delta E}{E} = \frac{0.60 \pm 0.02}{\sqrt{E}} + 0.056 \pm 0.026$

electron, $\frac{\Delta E}{E} = \frac{0.12 \pm 0.007}{\sqrt{E}} + 0.016 \pm 0.002$

elec. no beam spread, $\frac{\Delta E}{E} = \frac{0.12 \pm 0.005}{\sqrt{E}} + 0.028 \pm 0.002$

ZEUS, Pb/Sc ‘homogenius’, larger size – 44%/√E

Important Limiting factors for high resolution HCals

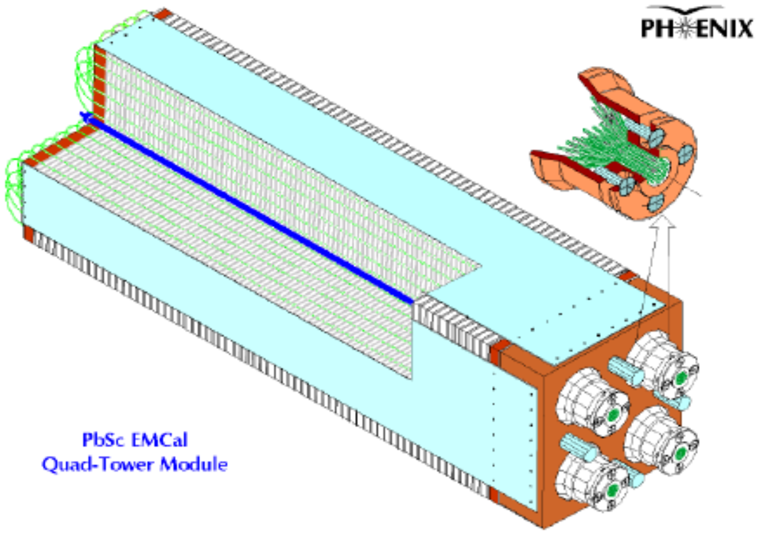


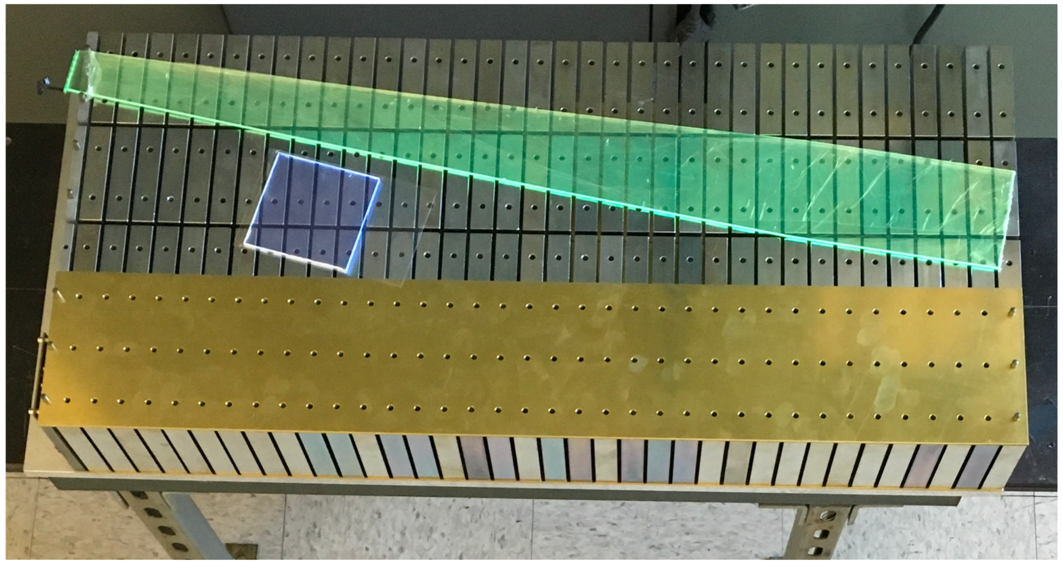
Example:

BaBar magnet for sPHENIX.
10 cm thick passive Fe endcap to keep magnetic field uniform for TPC.

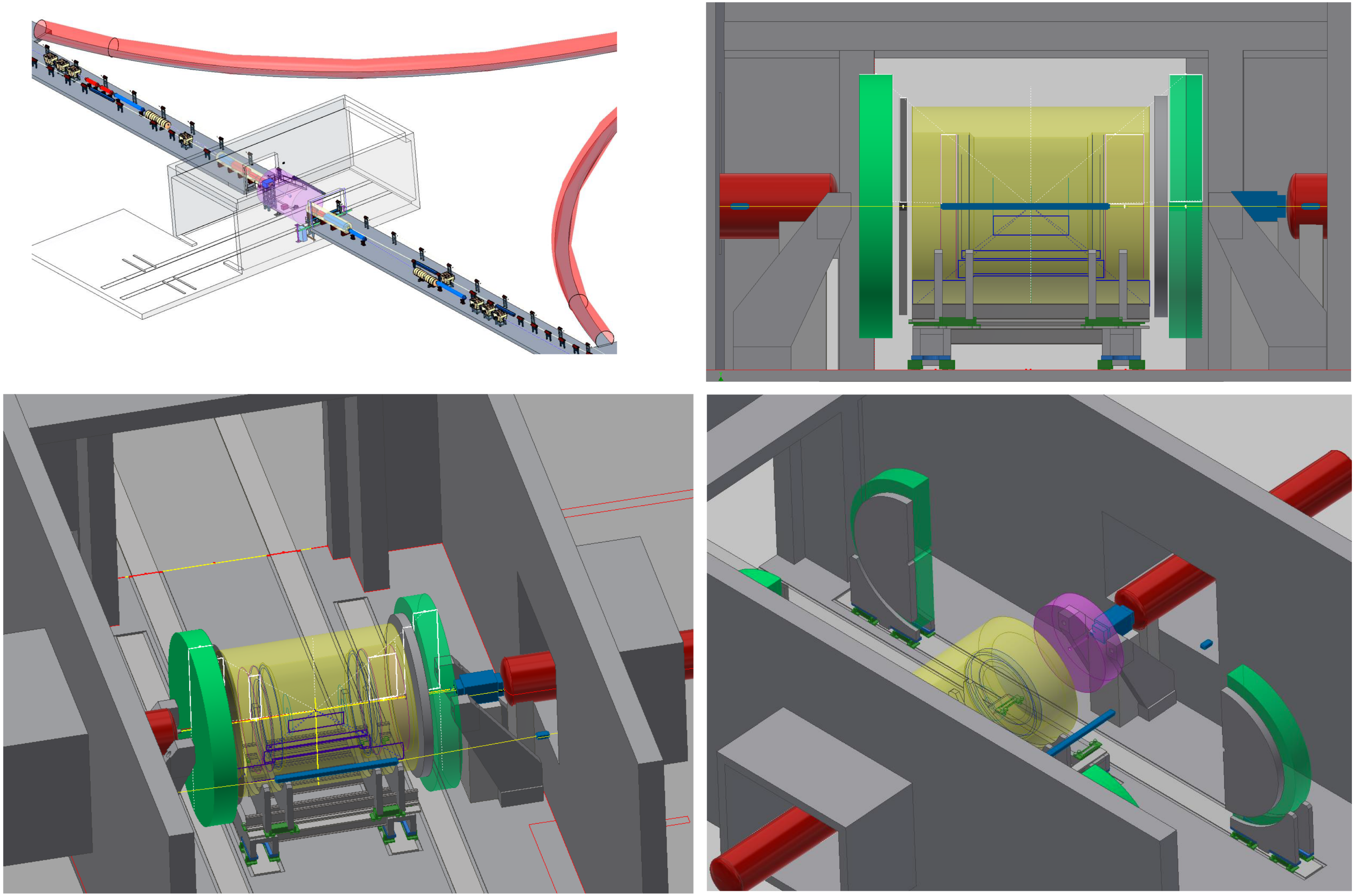
Huge penalty for dead material between EM and Hcal

Hcal should work as support structure for Emcal.





e-RHIC, BeAST @ IP6 (STAR IP). Practical limitations



BNL group, E.C.Aschenauer et.al.

Hadron EndCap, Diameter ~ 7m, Thickness 1.2 m, Weight 200 t,

Practical Consideration (Good, bad and ugly)

Compensation.

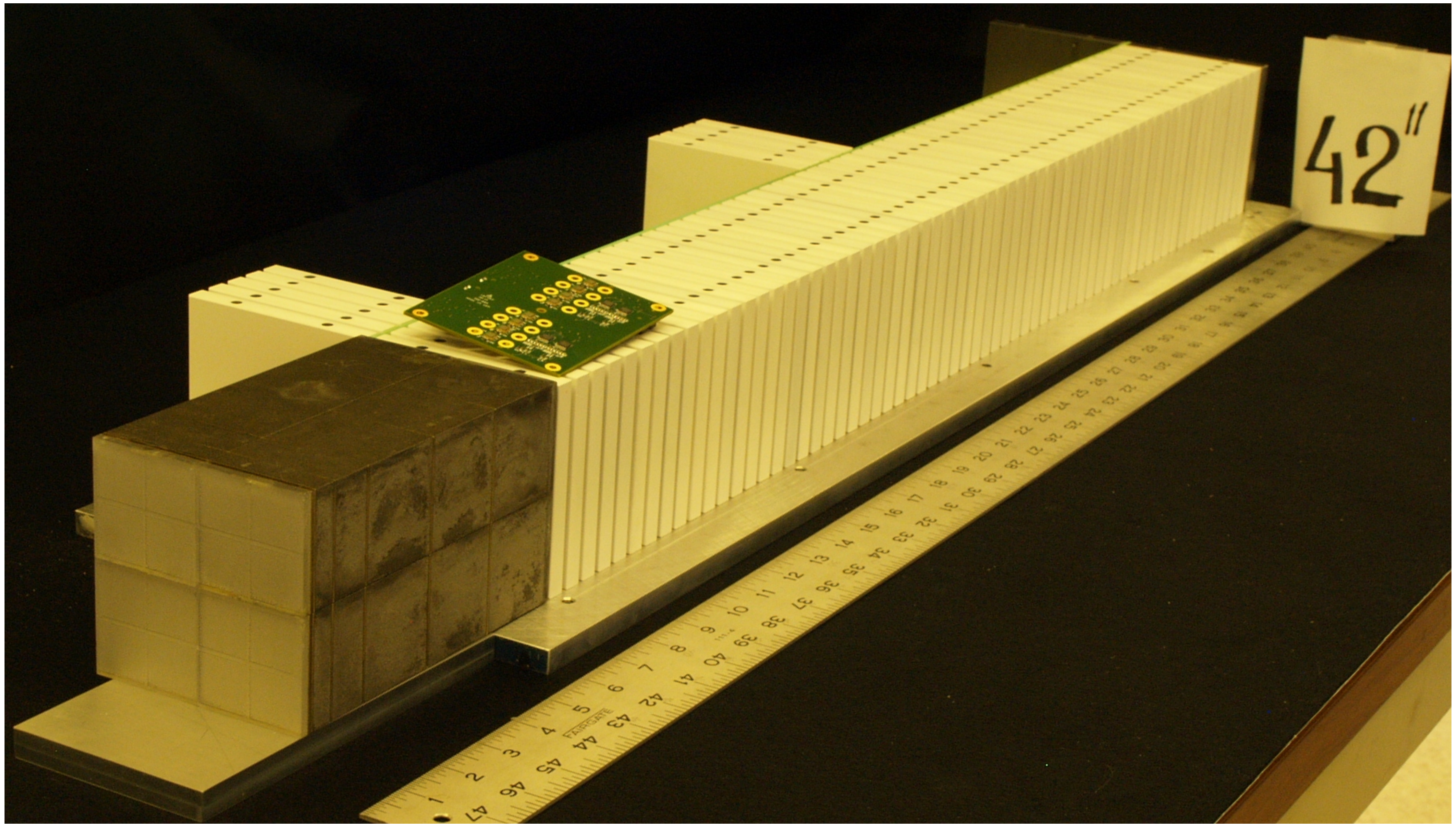
- Energy reconstruction straightforward. All high resolution operational calorimeters were compensated. Mechanism is well understood.
- Compact by design, small sampling fraction. Very efficient use of available space.
- Requires high Z, Pb is only practical material.
- Neutrons 20/GeV. Small sampling fraction- small LY. S/N due to degradation of SiPMs may be an issue.
- Cost.
- Pb as construction material will not work. Up to 2m high structures with appropriate treatment (Pb/Ca) self-supporting. R=3m - complicated mechanics.
- For EIC, dead material between EM and HCAL is unavoidable:
  a) to hold EMCal.
  b) additional steel/coils for magnet.

Non-compensated.

- Energy reconstruction is tricky. No high resolution calorimeters of this type, ops. or even in test runs, typical resolution is ~ $100\%/\sqrt{E}$ and large constant term.
- Sampling fraction is not limited – trade of with compactness.
- High Z not needed, smaller number of neutrons/GeV.
- Cost
- Potentially, no need for dead material between EM and Hcal.
- May be used for flux return.

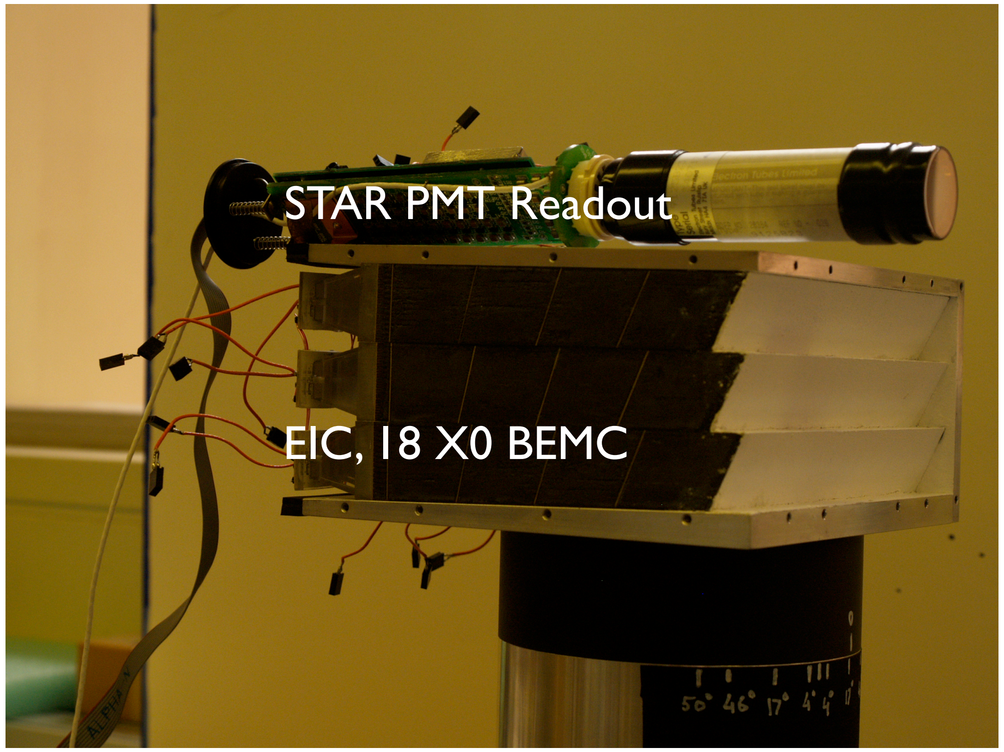
Can we get form non-compensated configuration something close to compensated? (2018)
Unfortunately, No (2019). Test Run at FNAL 2019.

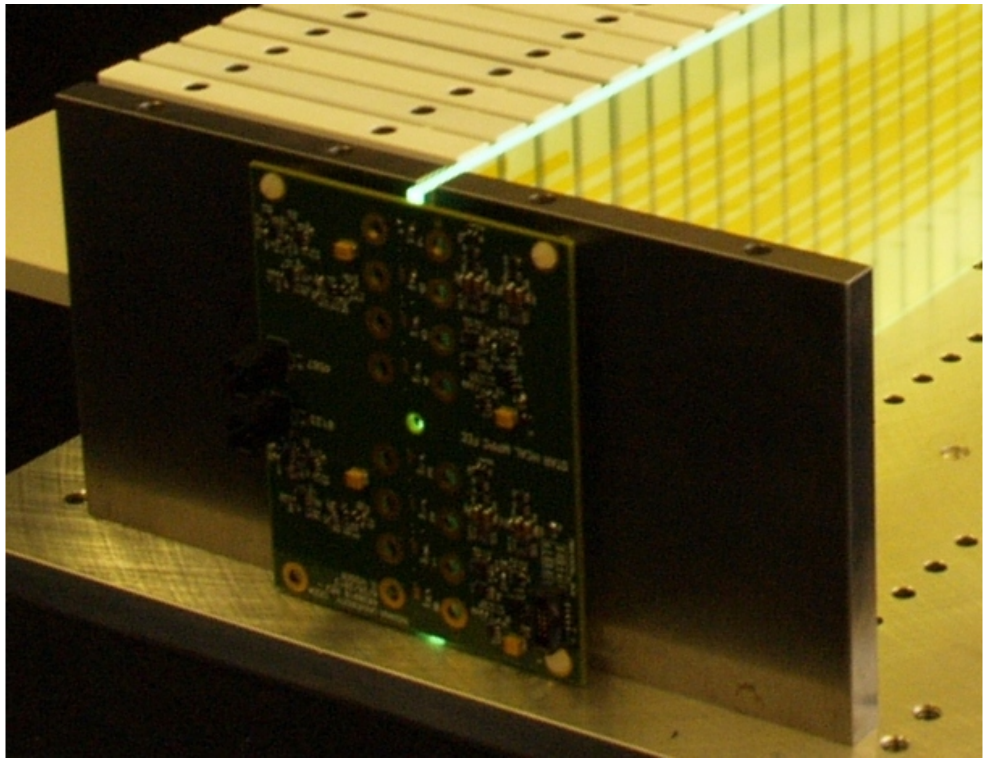
Compactness. Compensated 2014



Tile type structure with Sc as sensitive media hard to beat compactness wise.

Example, Pb/Sc, 63 Sc tiles 2.5 mm thick. Total air gaps inside the detector volume is 25.2 mm (0.4 mm per layer).





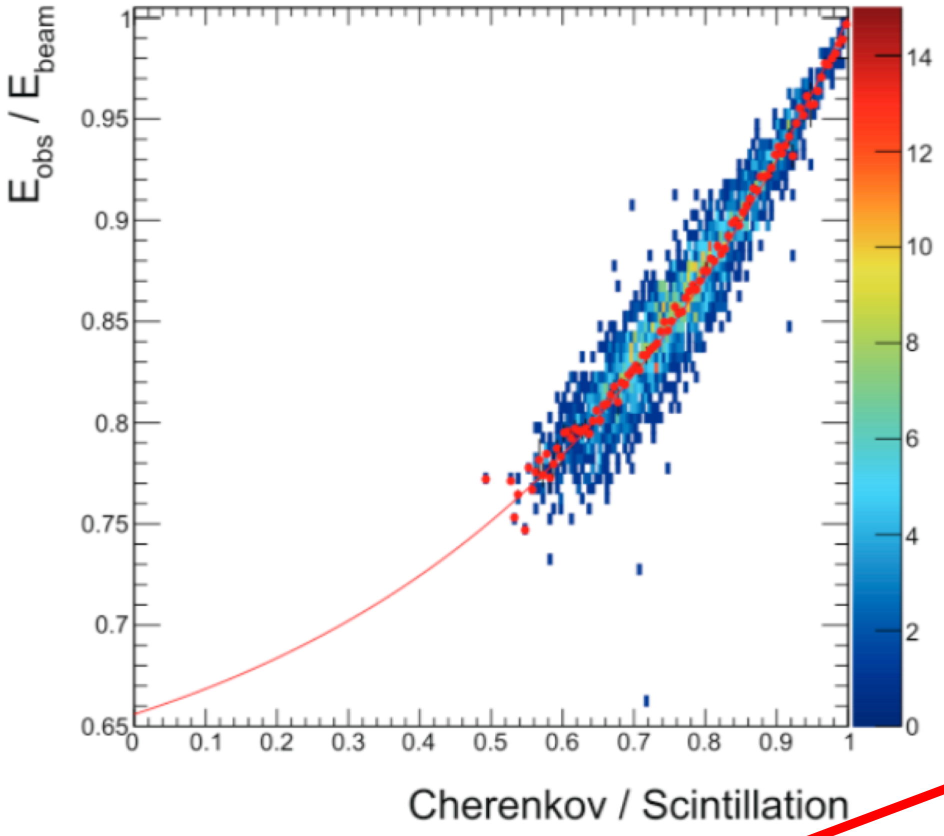
SiPMs to readout both EMCal and HCAL makes readout very compact and insensitive to magnetic field, but they will degrade with exposure.

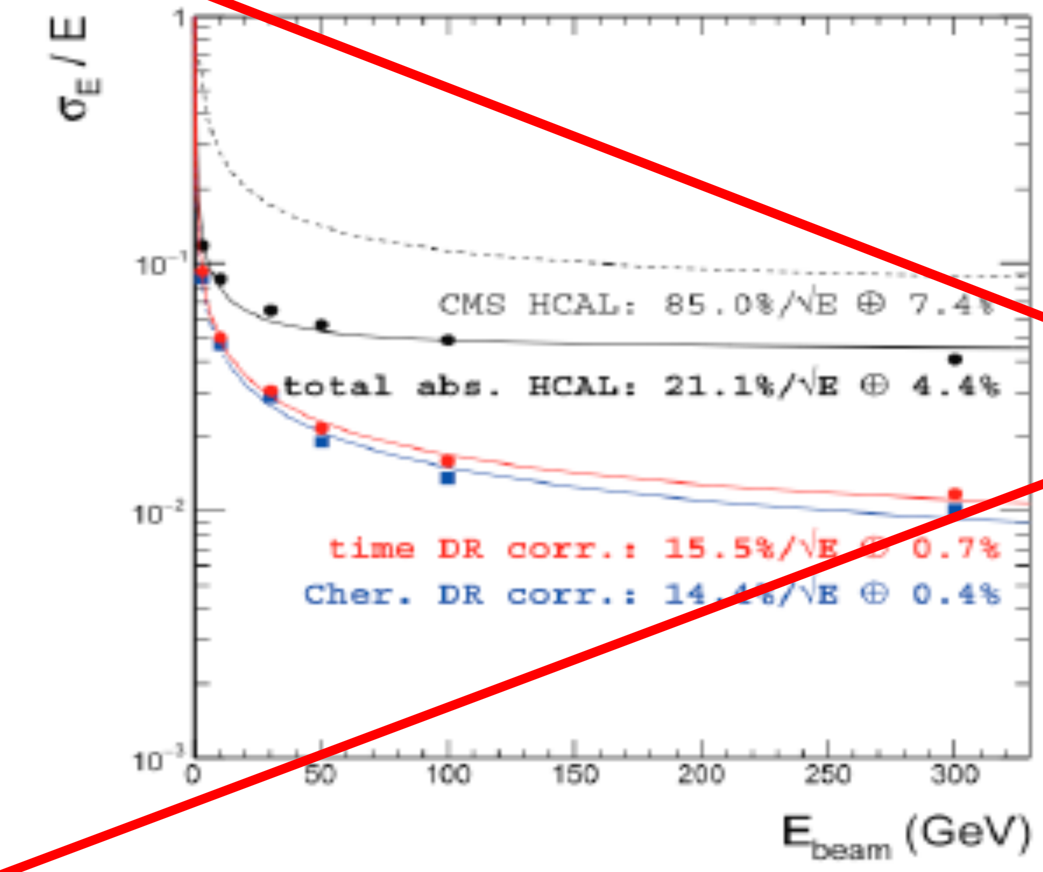
Dual Readout methods for high resolution HCals.

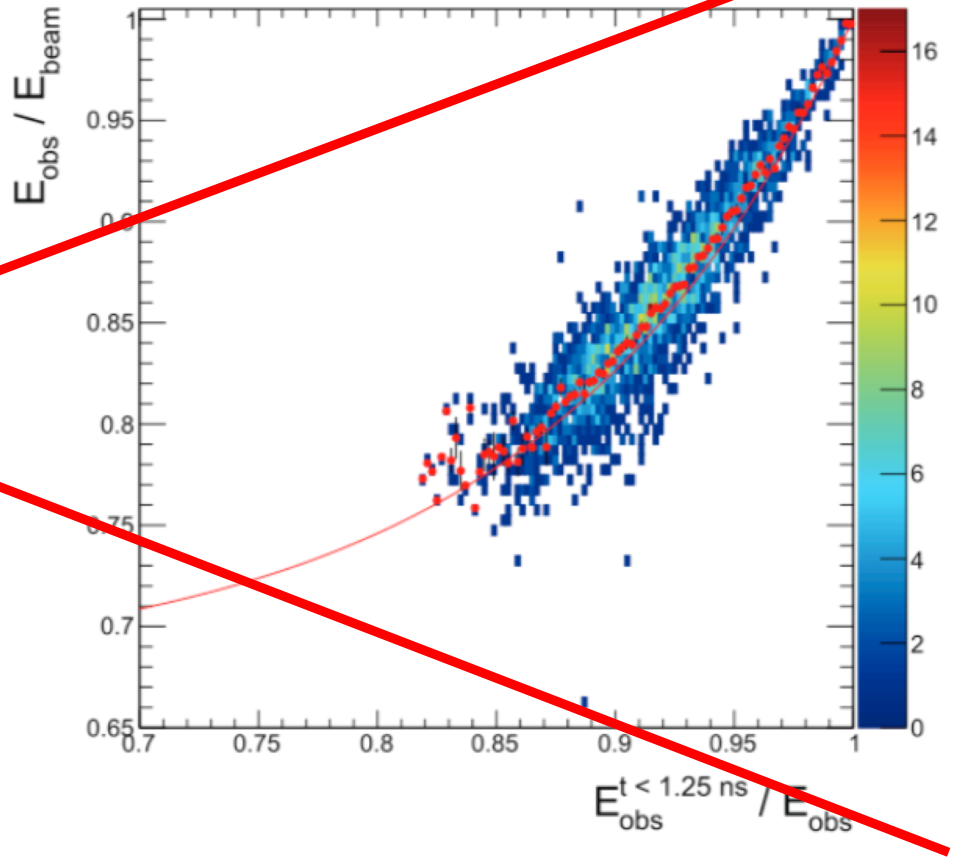
Concept

- 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).



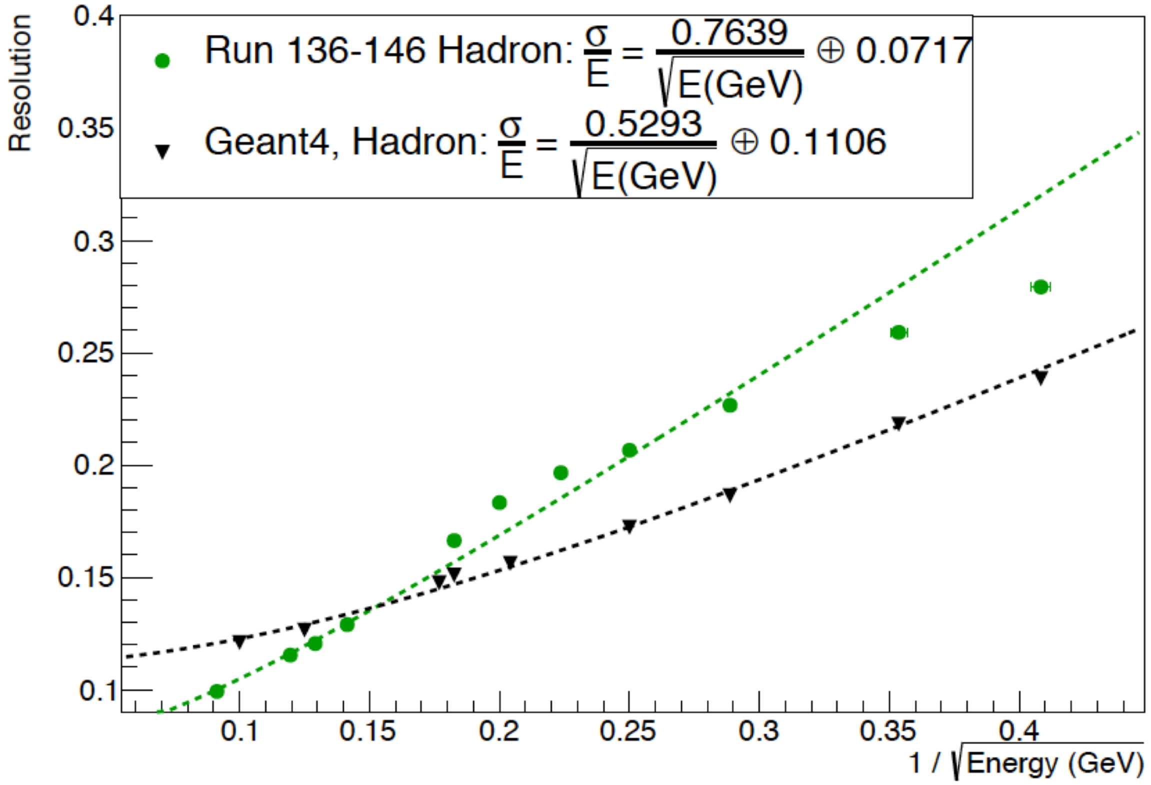


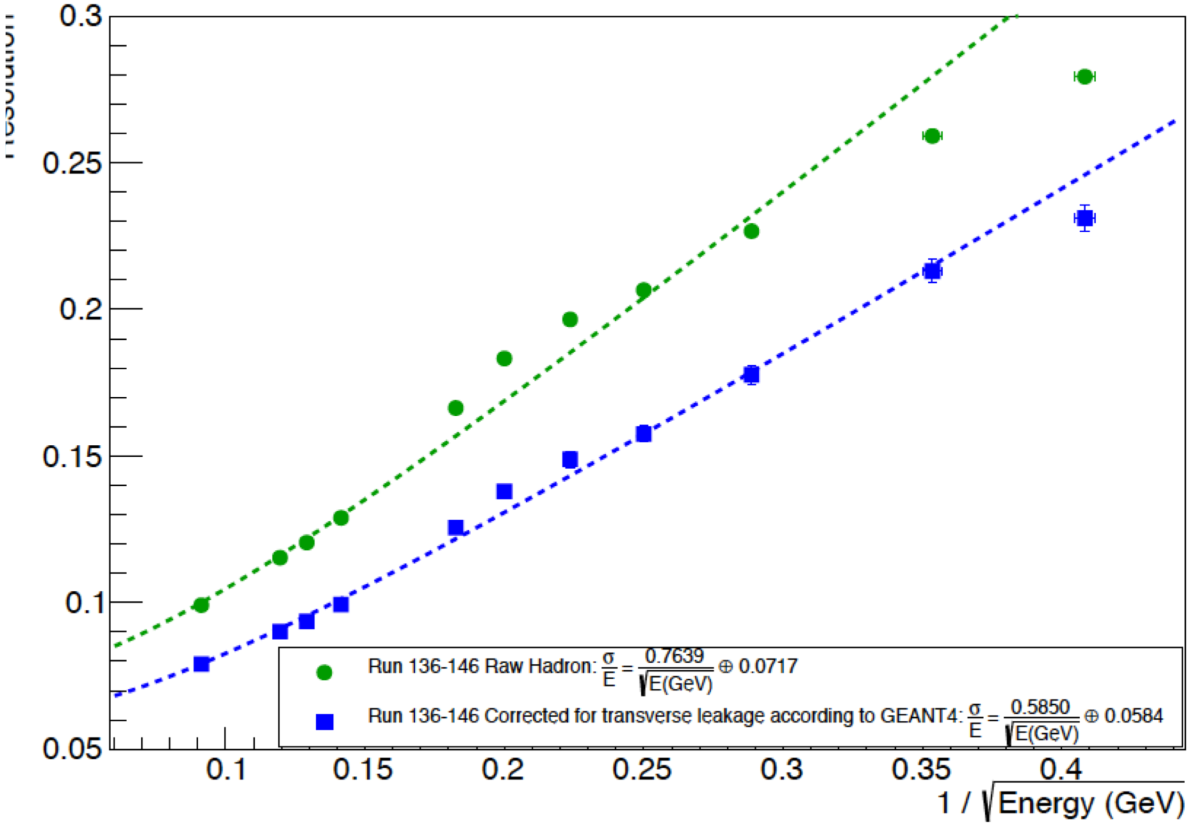


A. Bengalia et.al. IEEE Trans. Nucl. Sci. V63, N2, 2016

Path forward with re-aligned goals after 2019 Test Run at FNAL

1. Finish investigation of instrumental effects in connection with test beam results.
2. Optimization of W/ScFi+Fe/Sc system.





Why prototype underperformed?
Are we comparing apples to apples?

- Ideal vs detailed MC
- Instrumental effects (uniformities in light collection)

- For Shashlyk + Fe/Sc (slide 17)
- Corrected for leakages, resolution in test run is close to 60%/sqrt(E).
- How much it can be improved?

Conclusions.

- 'High resolution' hadron calorimetry is challenging.
- There are many constrains, not just cost.
- All previous high resolution calorimeters in operation were compensated, but for hadron endcap it is not well suited (ZDC is fine).
- We tried new idea for non-compensated HCal and it did not worked. R&D funding for hadronic calorimeters and time left are very tight.
- Currently, W/ScFi + Fe/Sc seems to be optimal configuration, which is under investigation.
- Energy resolution $\sim 50\%/\sqrt{E} \oplus 10\%$ is seemingly reachable, as Test Run results for STAR FCS is not far off.

Thank you!