Calorimetry R&D

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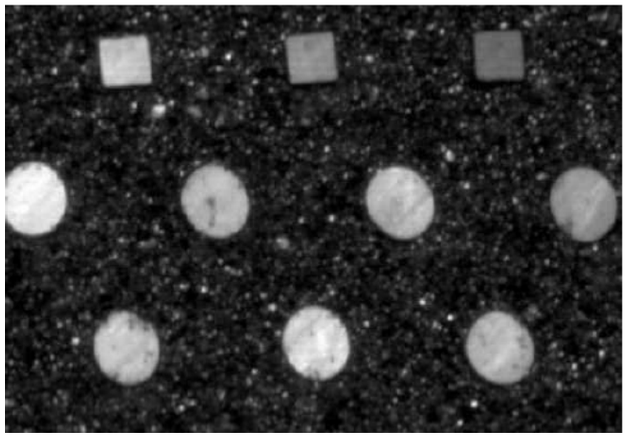
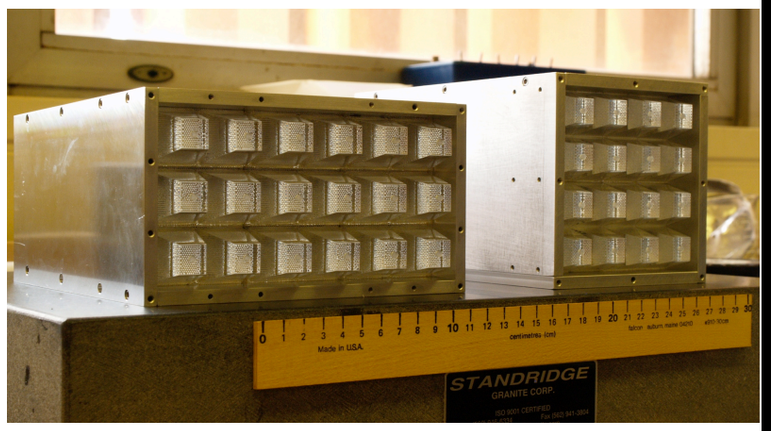
Spin and Forward Physics, June 12 2018

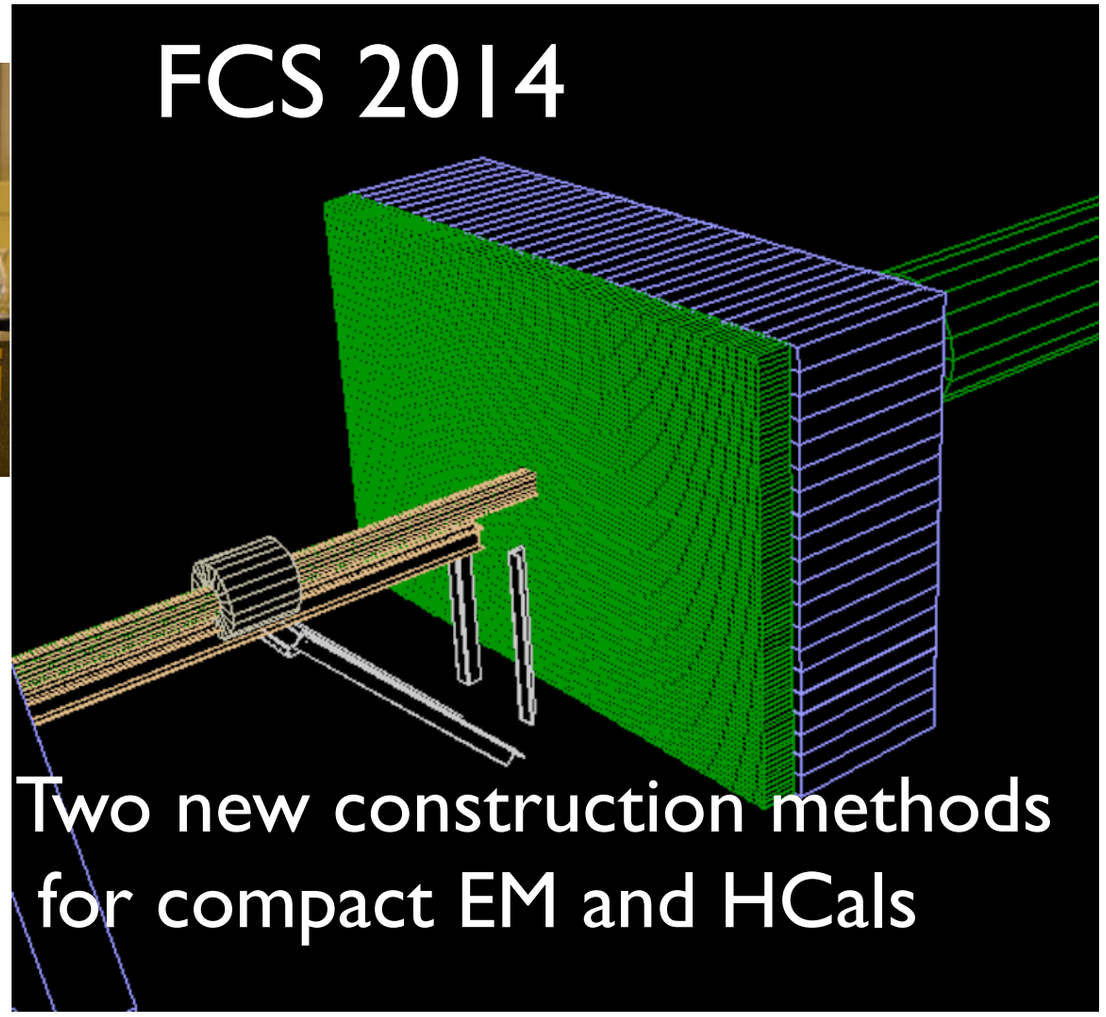
Some Results from STAR Forward Upgrade and EIC R&D 2012 - present

W/ScFi EM

- sPHENIX Barrel
- EIC BEAST Barrel & ENDcap
- EIC IP instrumentation Lumi monitors

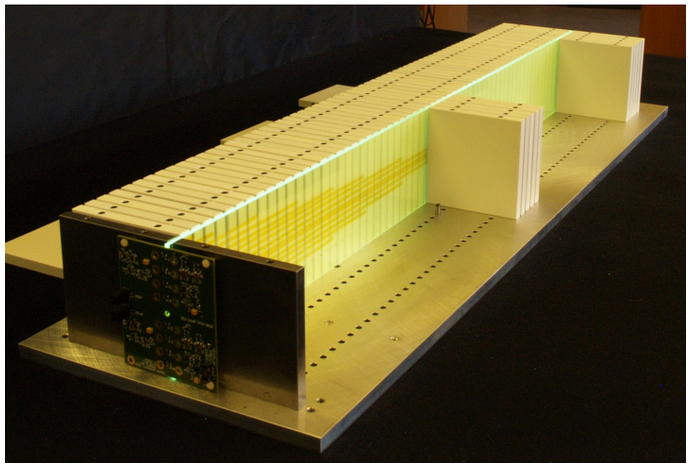


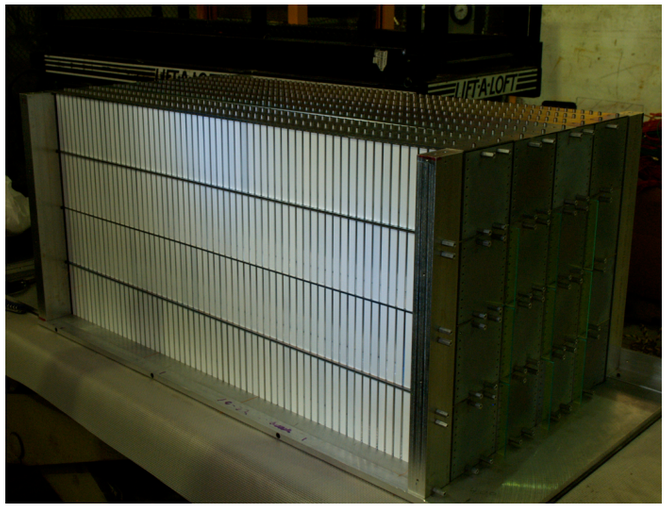




LEGO Hcal

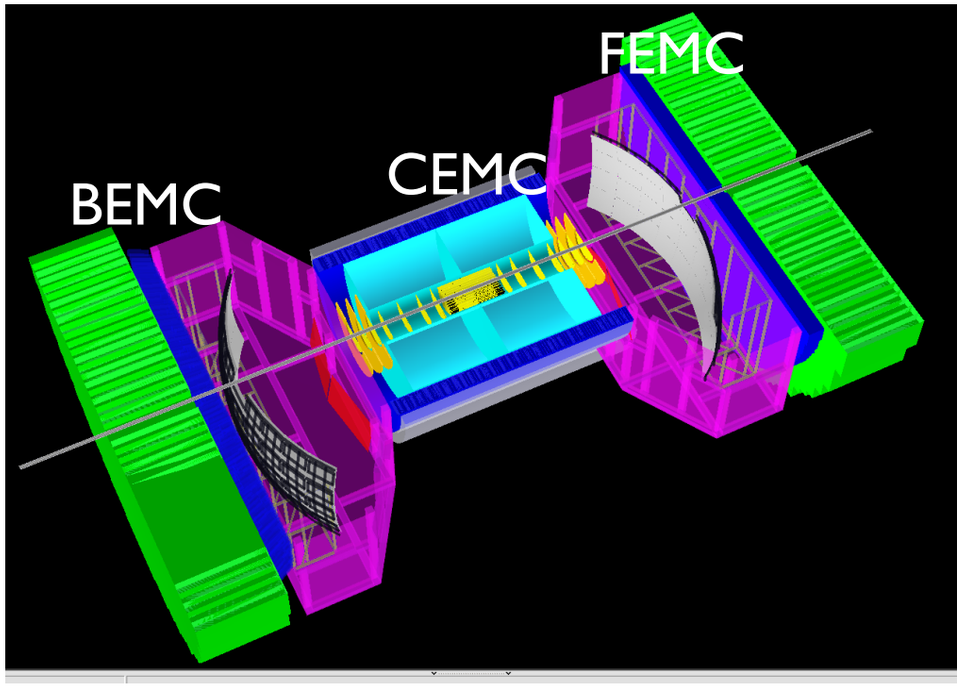
- STAR Forward
- EIC BEAST Hadron ENDcap
- EIC IP instrumentation (ZDC)





Keywords:
High Resolution, Compact, Simple, Cost Effective.

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



Calorimetry wise, we wanted to have similar resolutions of H1/ZEUS, but it has to be **more compact.**

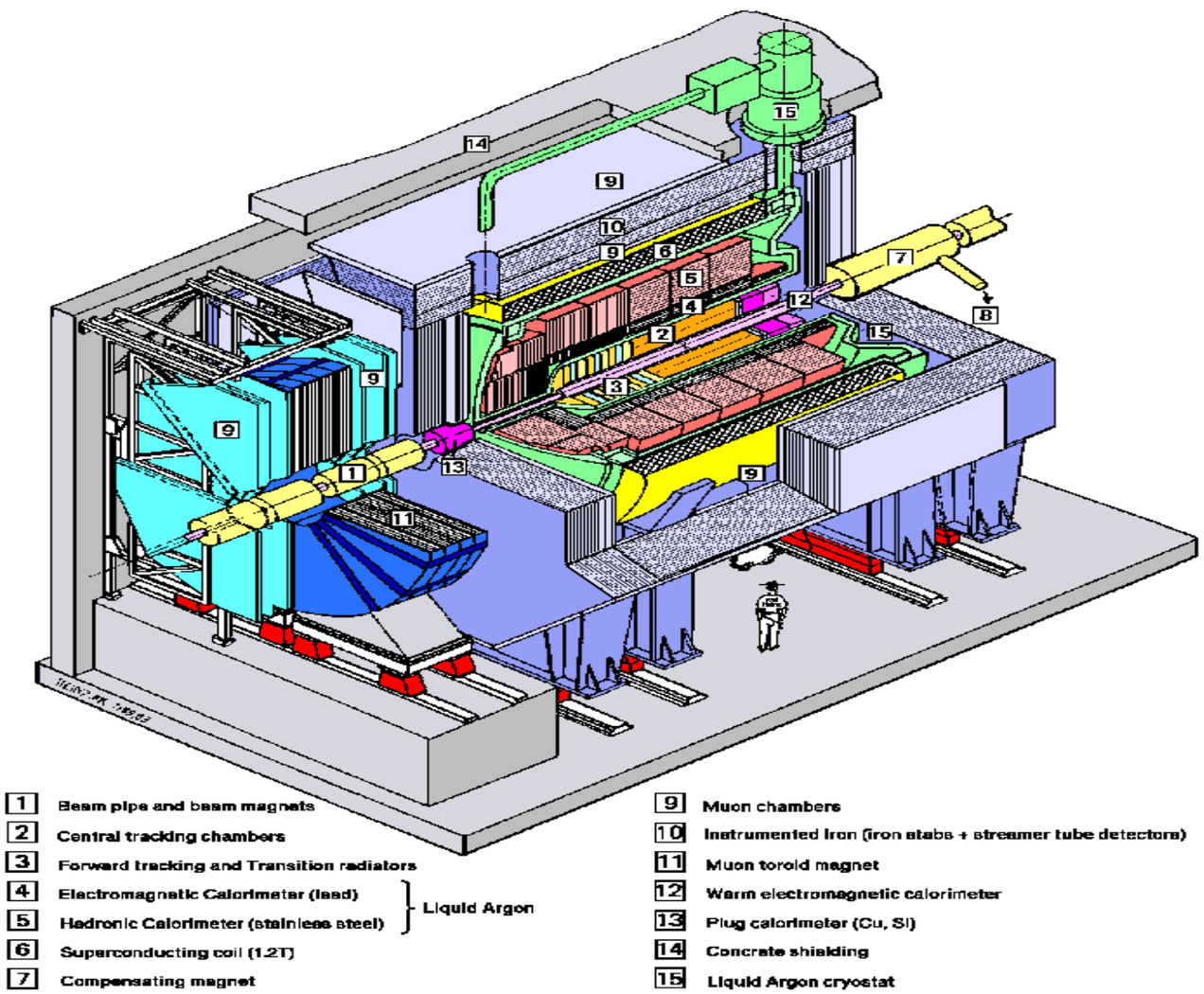
- Luminosity (IP design +- 4.5 meters)
- PID is much more important than at HERA

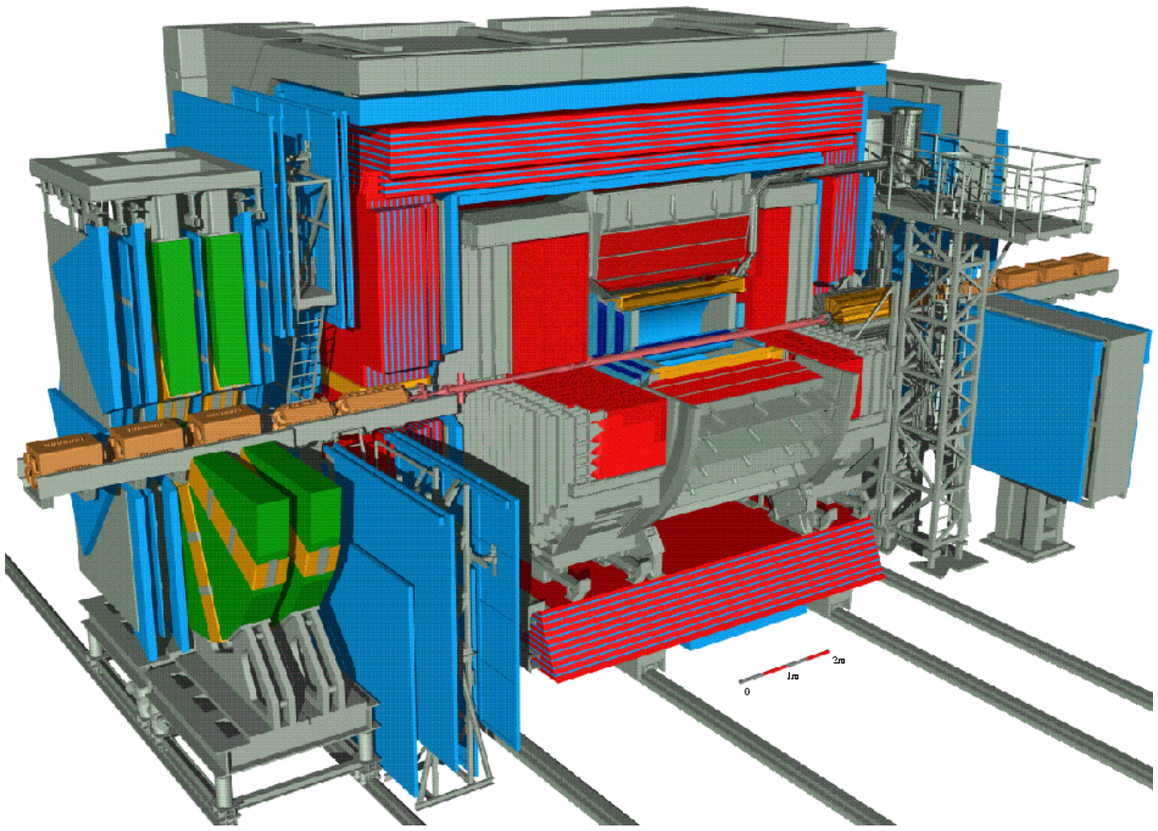
EIC Detectors 9m long (**4pi PID**)

HERA Detectors 15 m long

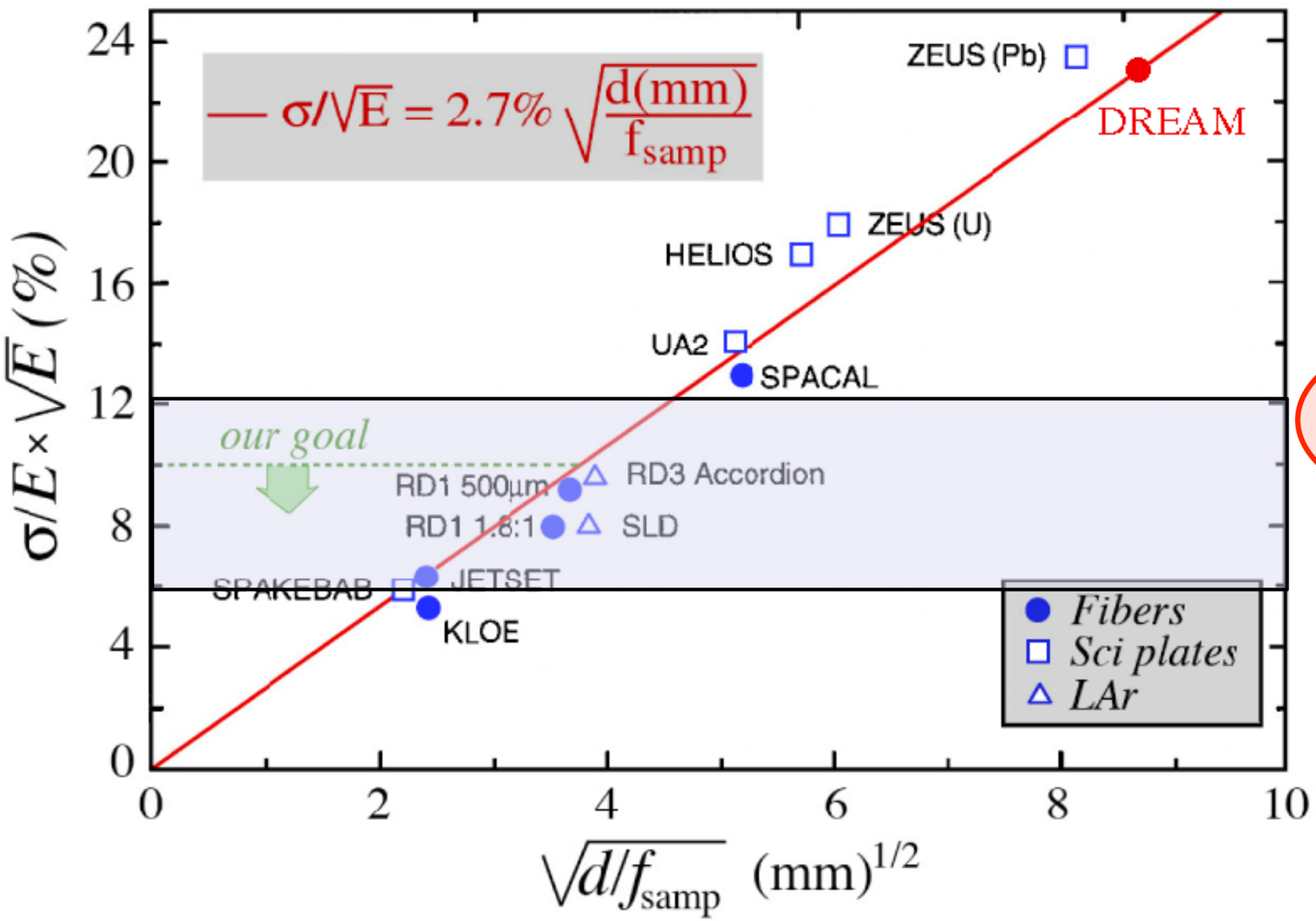
Advances in micro pattern detectors.

Advances in photodetectors. (APD, SiPMs)





EIC EM Sampling Calorimeters



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

HI

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

Calorimeters:

- Full Coverage,
- Hermetic.
- Compact.
- Operate in the magnetic field.
- Fast.
- Affordable.

ZEUS

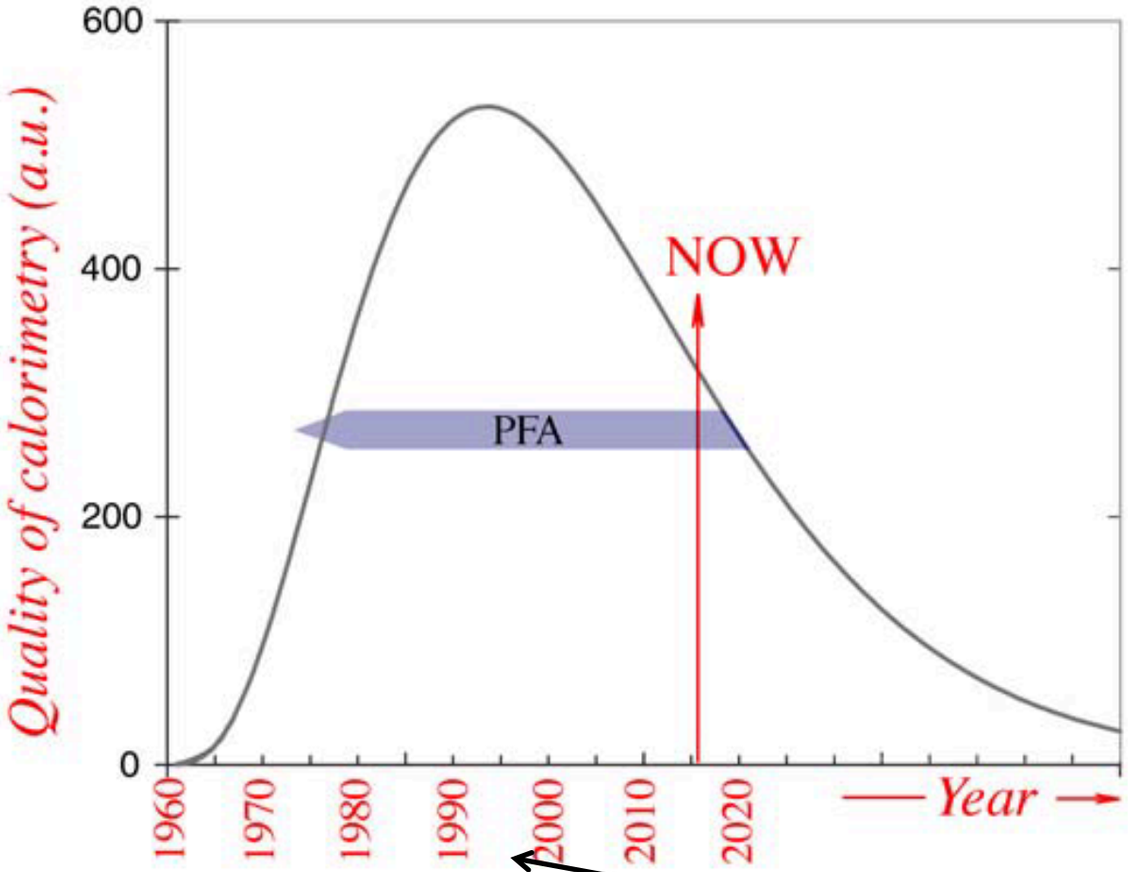
$$\frac{\sigma_{em}}{E} = \frac{18\%}{\sqrt{E(GeV)}} \qquad \frac{\sigma_{had}}{E} = \frac{35\%}{\sqrt{E(GeV)}}$$

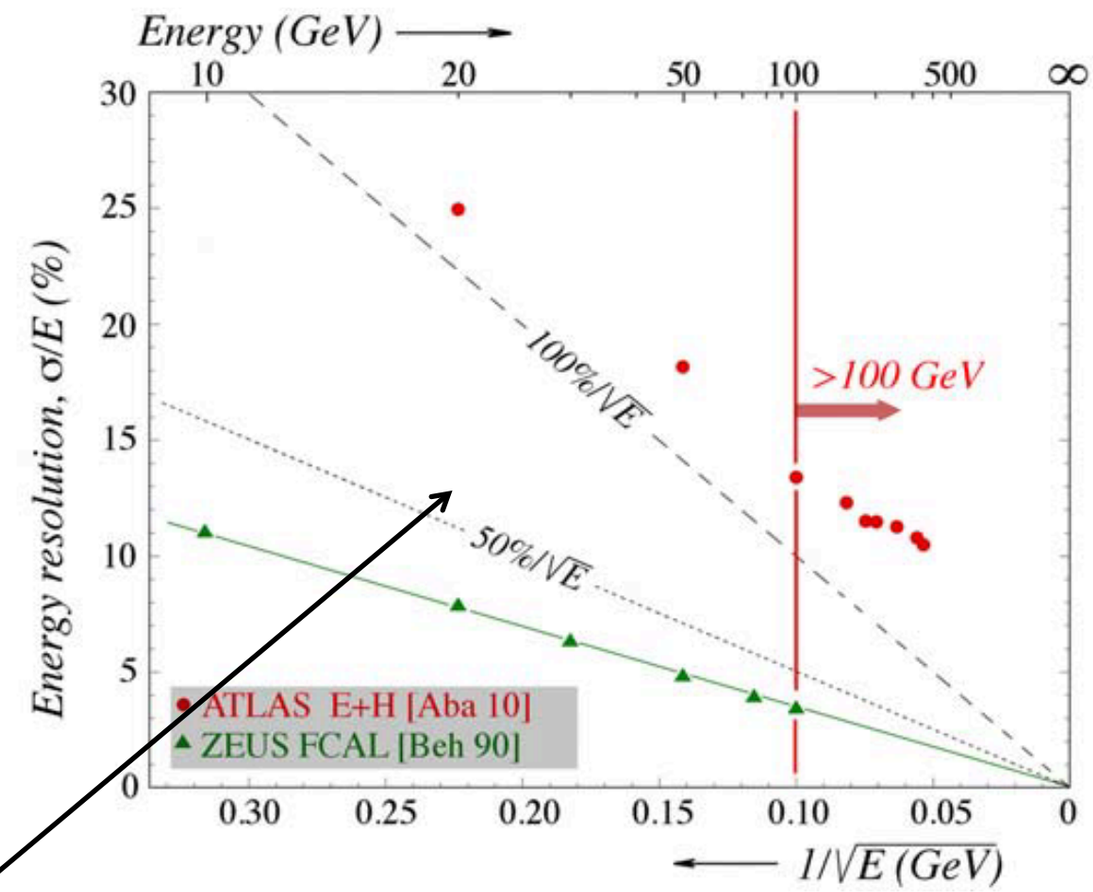
- For now most stringent requirement for had resolution is from ZDC.
- Central detector 60%/√(E), ZDC <40%/√(E) (< 30%/√(E))
- Constant term (forward E ~ 100 GeV) should be small

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

A: To advance existing technologies. Well....

Look at R.Wigmans talk at CALOR2016 (many people don't agree with such wiev)



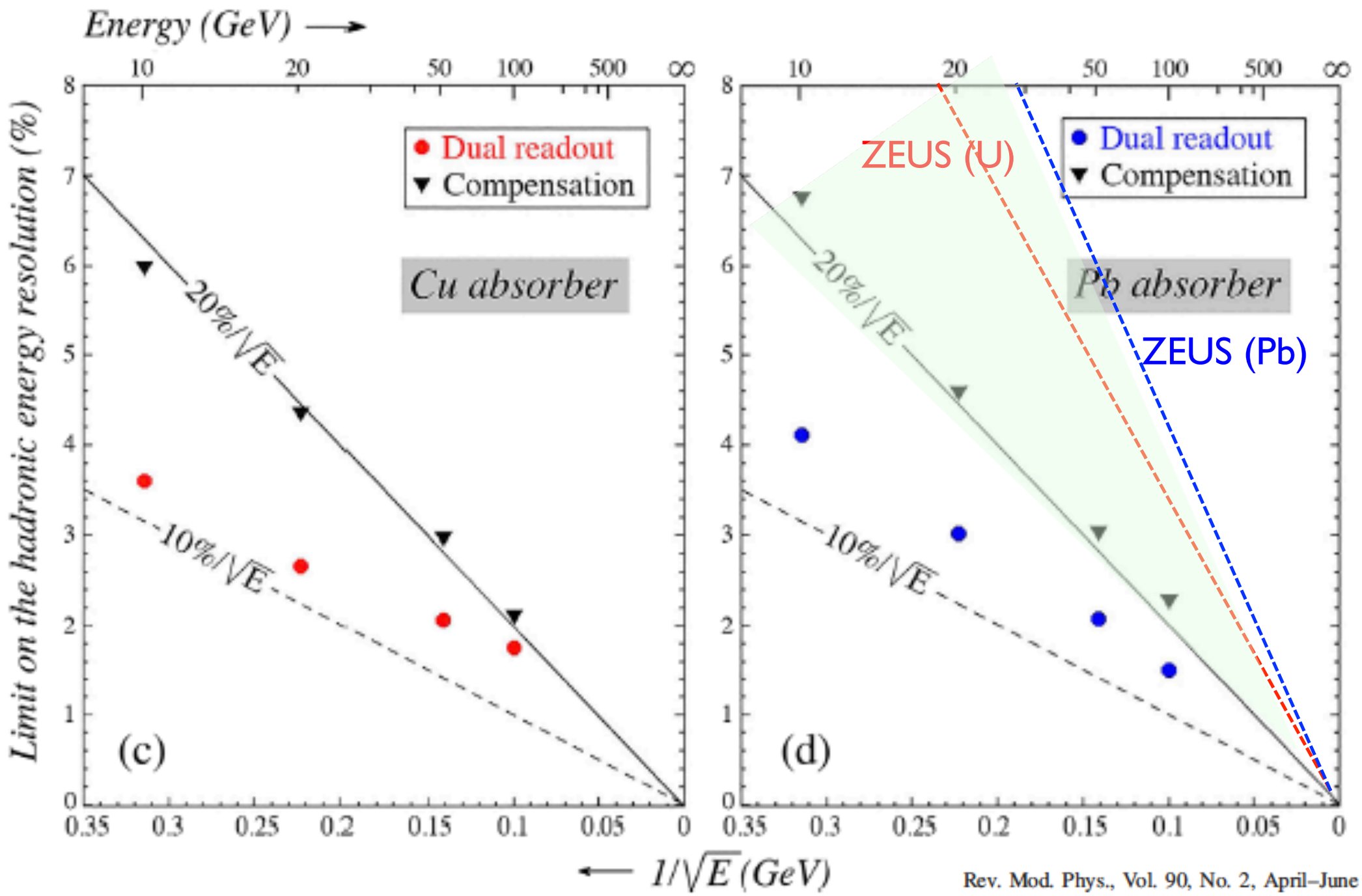


eRD1 proposal (keywords compensation, compactness, ZEUS, H1, adoptability) https://wiki.bnl.gov/conferences/index.php/Proposals-April2011

- FNAL Test Run 2014. Compact EM+HCAL, Compensated.
- What was not addressed (overall progress), Compensation, e/h energy dependence.
- Resolution for Jets. But there is no demand to push it for EIC (afaik)

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

A: EIC may need high resolution HCals.



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Limits very hard to reach in practice:

Containment, instrumental effects, calibration, cost etc.

New approaches may be needed to close the gap.

STAR PHYSICS PROGRAM AFTER BES-II

Mid-rapidity $-1.5<\eta<1.5$

A+A

Beam:
Full Energy AuAu

Physics Topics:
a deep look into the properties of the QGP: γ & e+e- pairs
- chiral symmetry restoration
- temperature and lifetime of hot, dense medium

Hypertriton Lifetime Measurement

Precision measurements of direct photon yields and v_n

p+p & p+A

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- Improve statistical precision
- ➢ TMD measurements, i.e. Collins, Sivers, ...
- ➢ Access s & Δs through Kaons in jets
- Measurement of GPD E_g through UPC J/Ψ
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

Forward-rapidity $2.8<\eta<4.2$

A+A

Beam:
Full Energy AuAu

Physics Topics:
- Temperature dependence of viscosity through flow harmonics up to η~4
- Longitudinal decorrelation up to η~4
- Global Lambda Polarization
  → strong rapidity dependence

p+p & p+A

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- TMD measurements at high x
  transversity → tensor charge
- Improve statistical precision for Sivers through DY
- $\Delta g(x,Q2)$ at low x through Di-jets
- Gluon PDFs for nuclei
- ➢ R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

2021: provides a nice opportunity to run 500 GeV polarized pp
All other data taking in parallel to sPHENIX data taking campaign

What shapes the design other than evolving physics requirements?

For FCS:

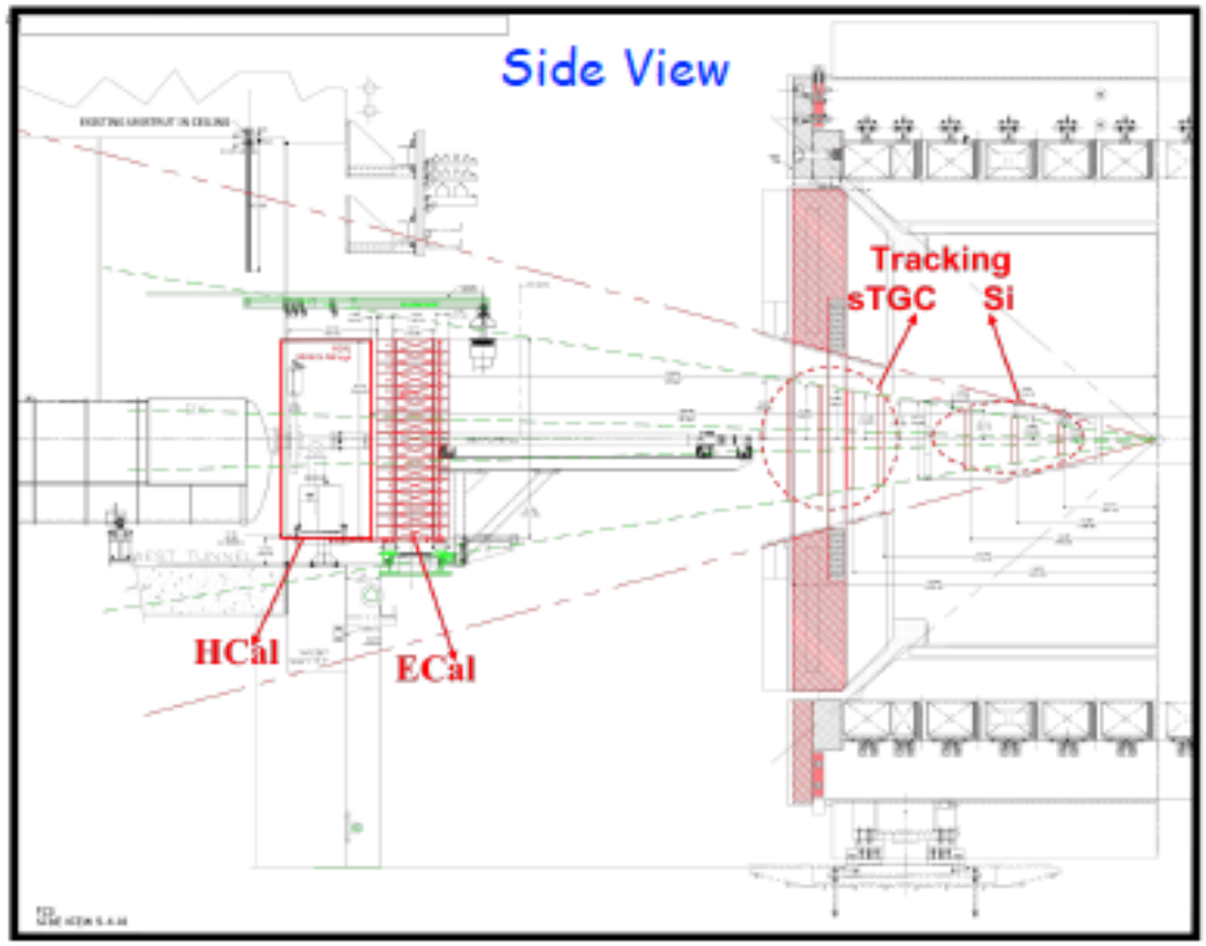
- Operational
- Mechanical Integration
- 'Modest' Uncertainties with Budget and Schedule

FCS and EIC detector:

- Limited space. Mechanical design, Sensors
- Radiation hardness. Materials
- Neutrons. Sensors. Light Collection.
- Reconfigured for future EIC Backward. Mechanical Design
- Magnetic Field. Sensors, Mechanical Design
- Manpower (build it with students) Mechanical design
- One year construction project < $2M budget. Design

Requirements from Physics:

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$



Calorimeter System:

Intensive R&D work on both ECal and Hcal as part of STAR and EIC Detector R&D

→ several beam test and STAR in situ tests

→ Projective geometry

→ system optimized for cost and performance

ECal:

- reuse PHENIX PbSC calorimeter with new readout on front phase significant cost reduction ☺ compared to building a new W/ScFi SPACAL
- Secured one Sector (2592 towers)
  PbSc towers: 5.52 x 5.52 x 33 cm3 (18 X_0)
  66 sampling cells with 1.5 mm Pb, 4 mm Sc
  Ganged together by penetrating wavelength shifting fibers for light collection

HCal:

- sandwich iron-scintillator plate sampling Calo

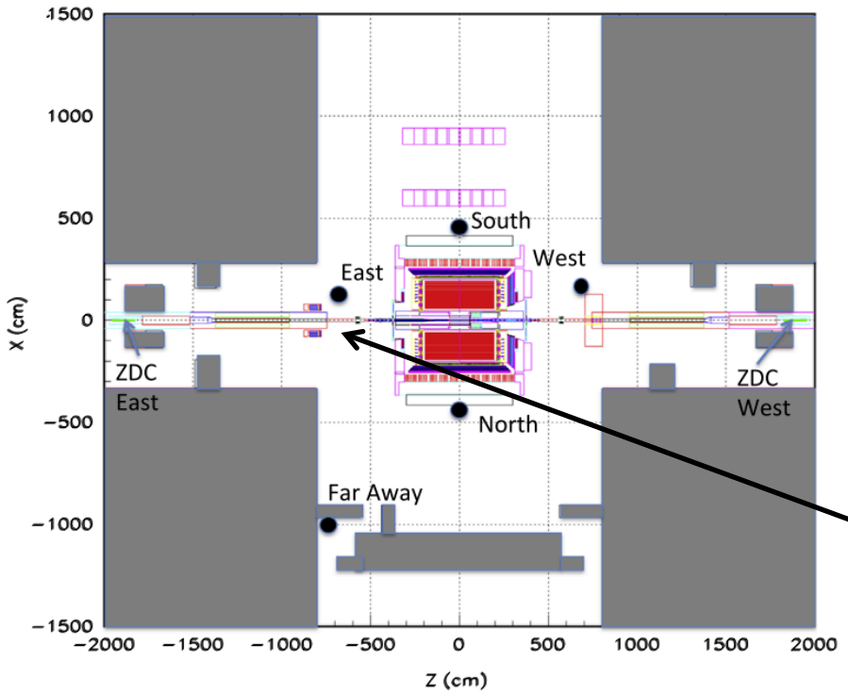
Same readout for both calorimeters → cost

Cost:

ECal: 0.41 M$
HCal: 1.56 M$
Preshower: 0.06 M$
} Total: ~2.0 M$

based on extensive experience from prototypes contingency (15-35%) and manpower included

SiPMs and APDs in 'realistic' conditions:

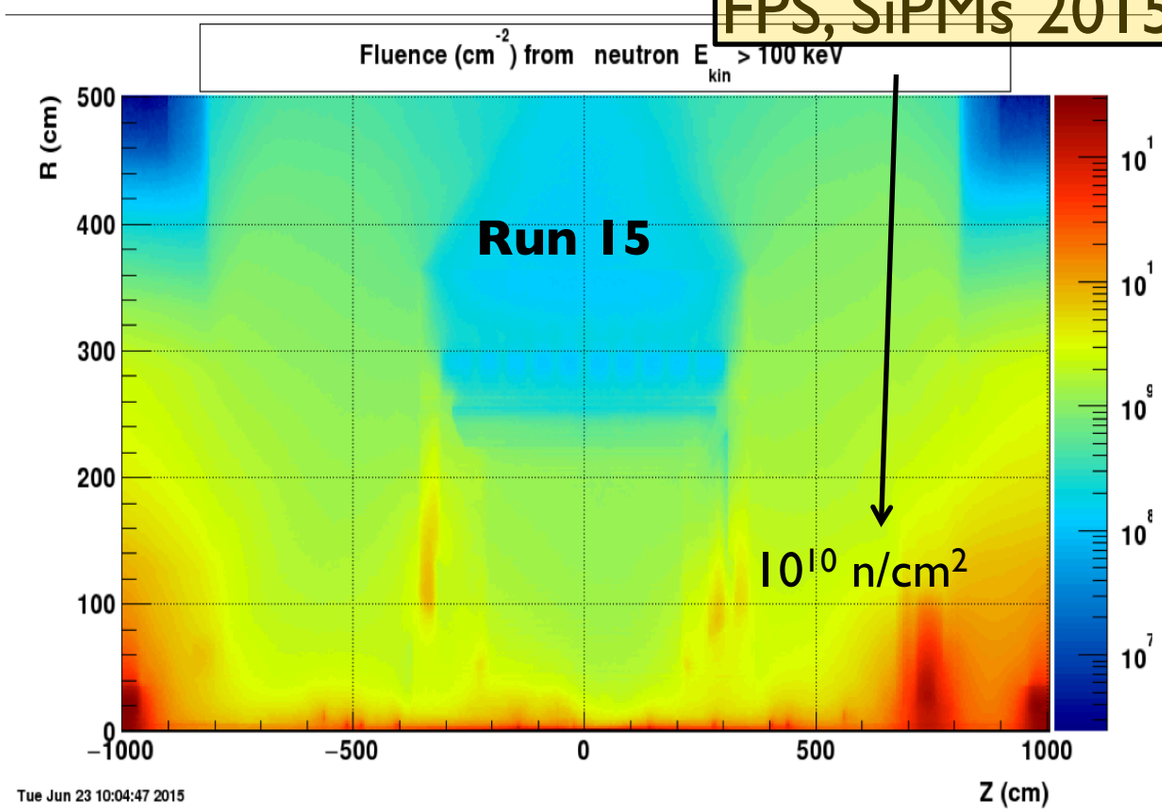


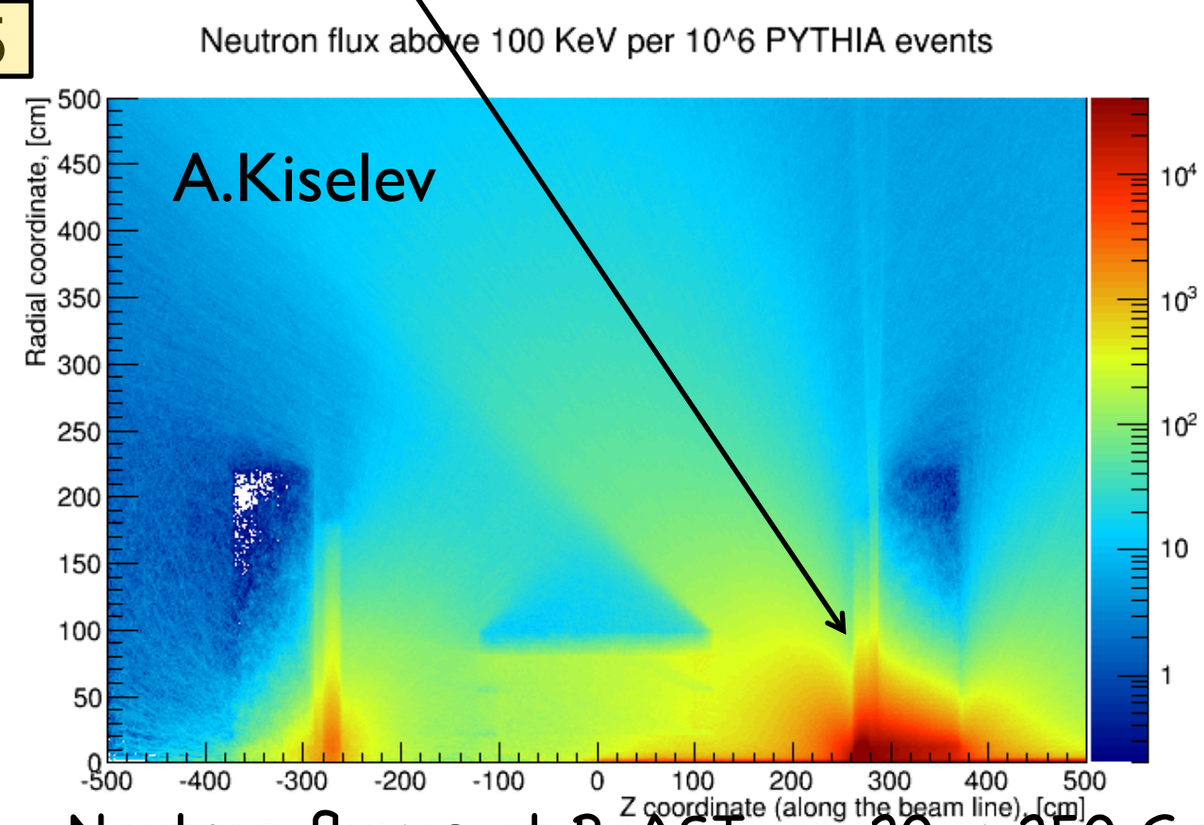
Y.Fisyak, et.al NIM A756

- **STAR IP ideal test place for forward calorimeters for EIC.** Well understood conditions (measurements in 2013 thermal neutrons, 2015 'MeV' neutrons with Forward Preshowers (FPS) SiPMs + MC).
- Conditions for FEMC in BeAST very close to one we have in STAR now.

FEMC, 2016

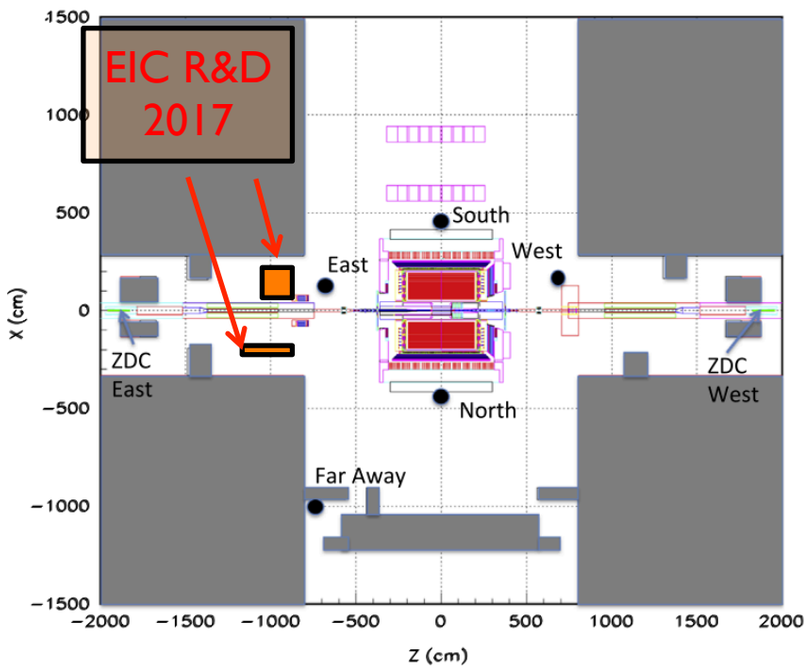
FPS, SiPMs 2015





Neutron fluxes at BeAST, ep 20 x 250 GeV

Large sample of SiPMs exposed in Run17 at RHIC STAR IP



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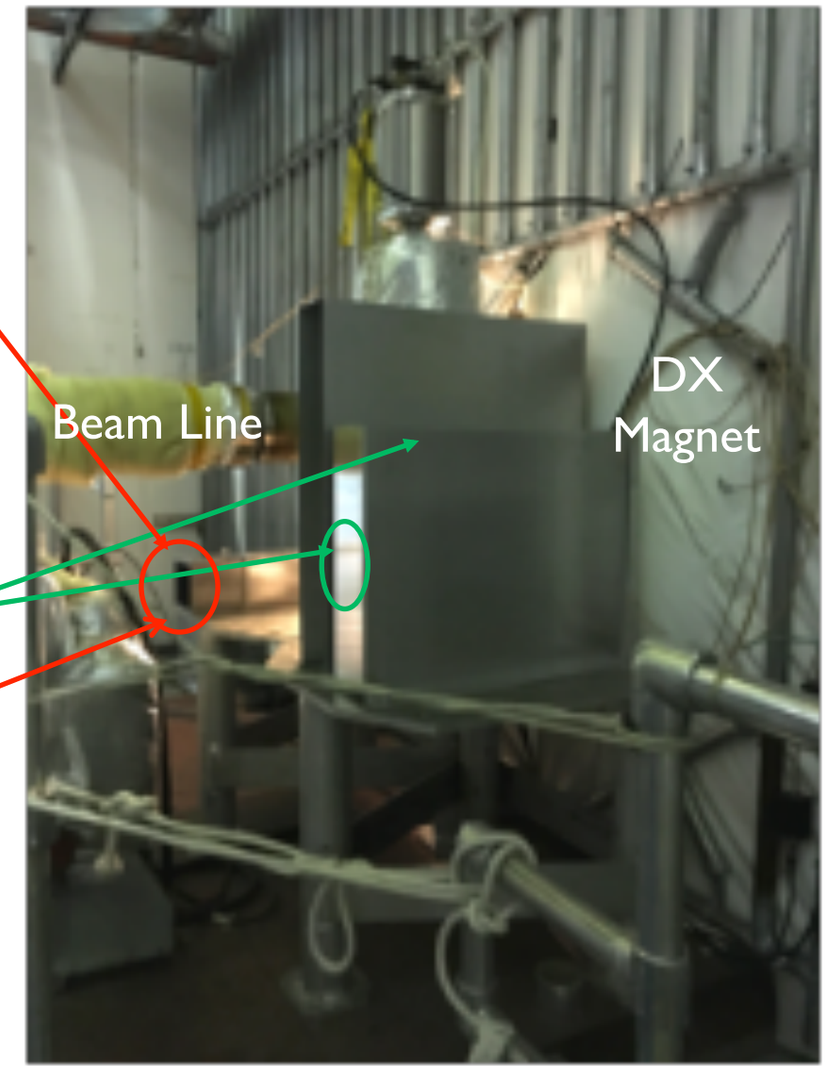
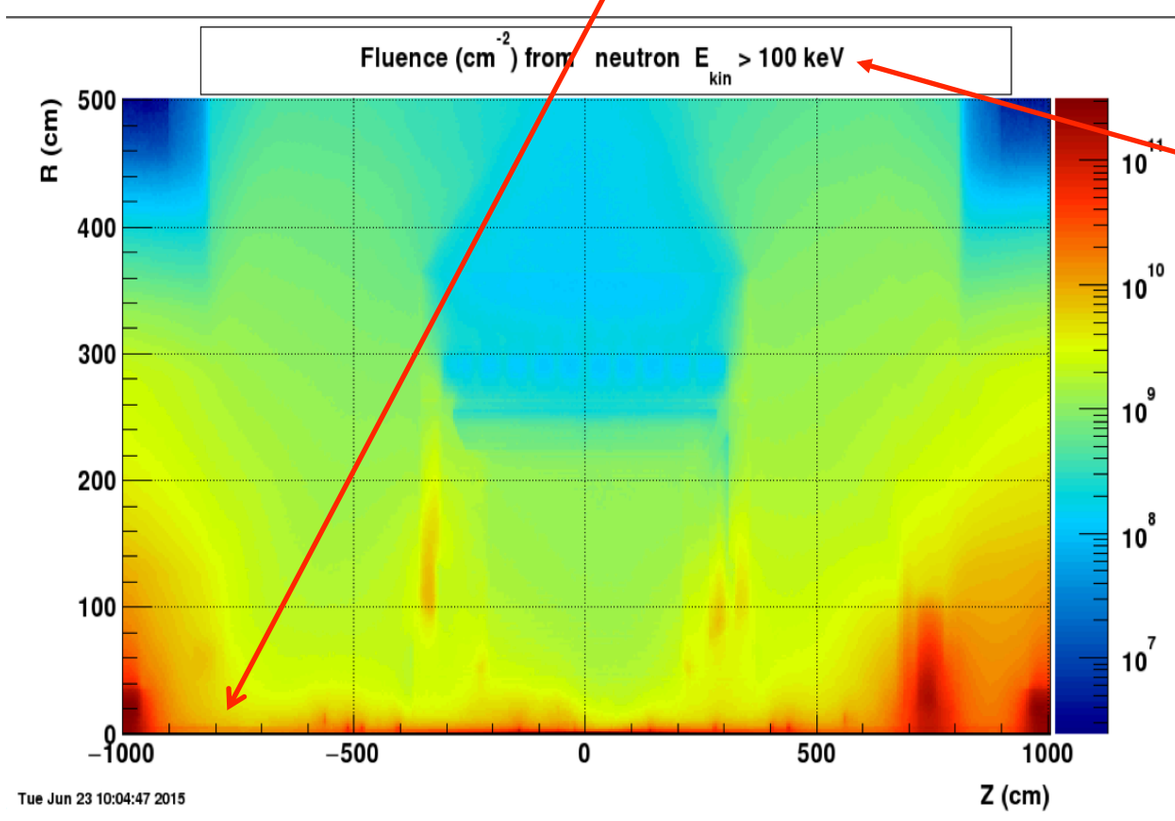
EIC, Run 17 STAR IP:

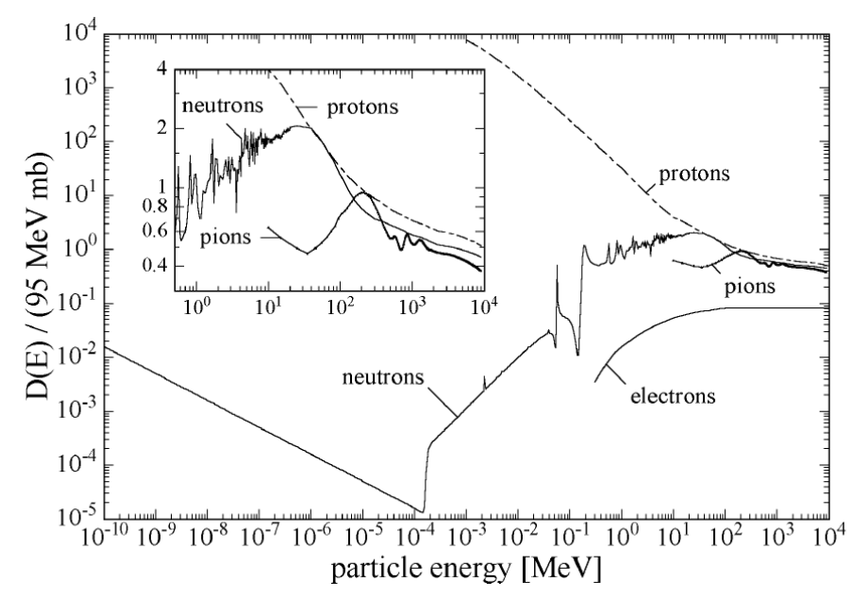
- 152 SiPM at ~135 cm (since Feb.) . All in Volume 10 x 10 x 2.5cm^3
- 26 SiPMs at ~45 cm (since April)
- APDs at ~45 cm, (since April)



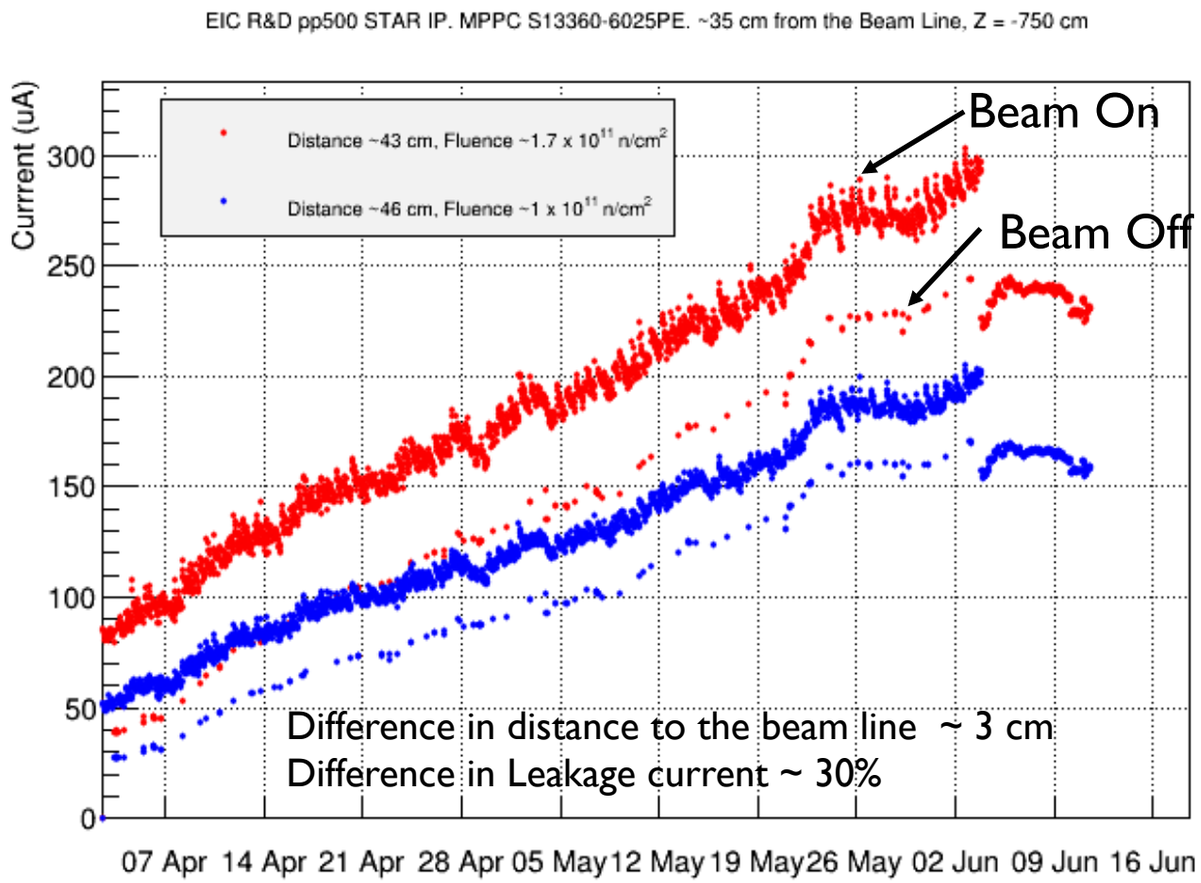
FEMC Run16, Run17, 18

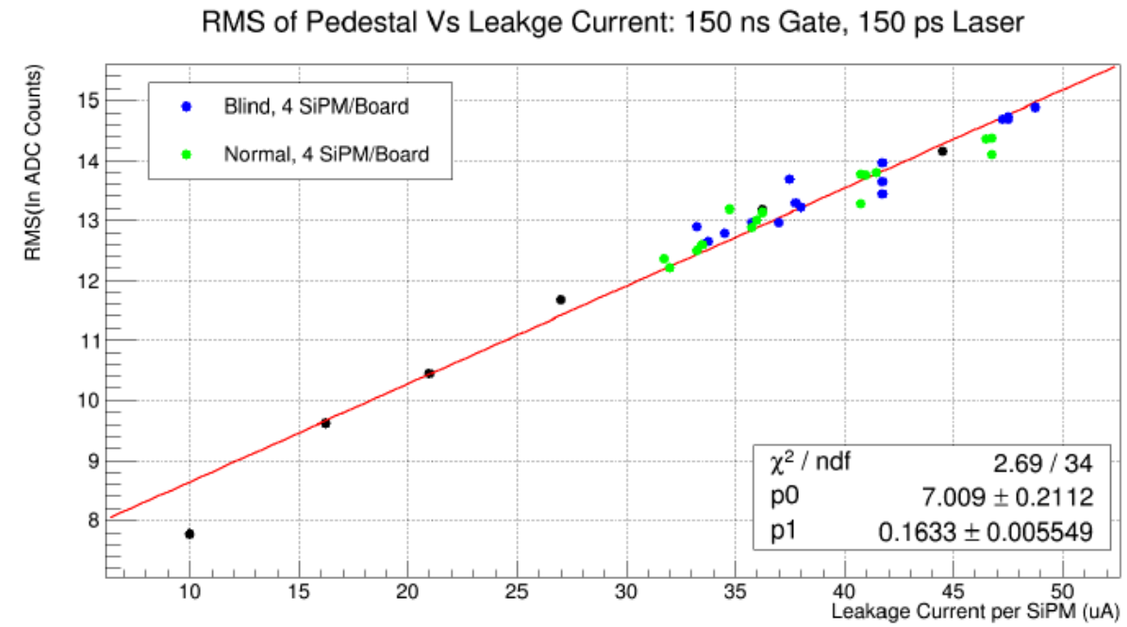


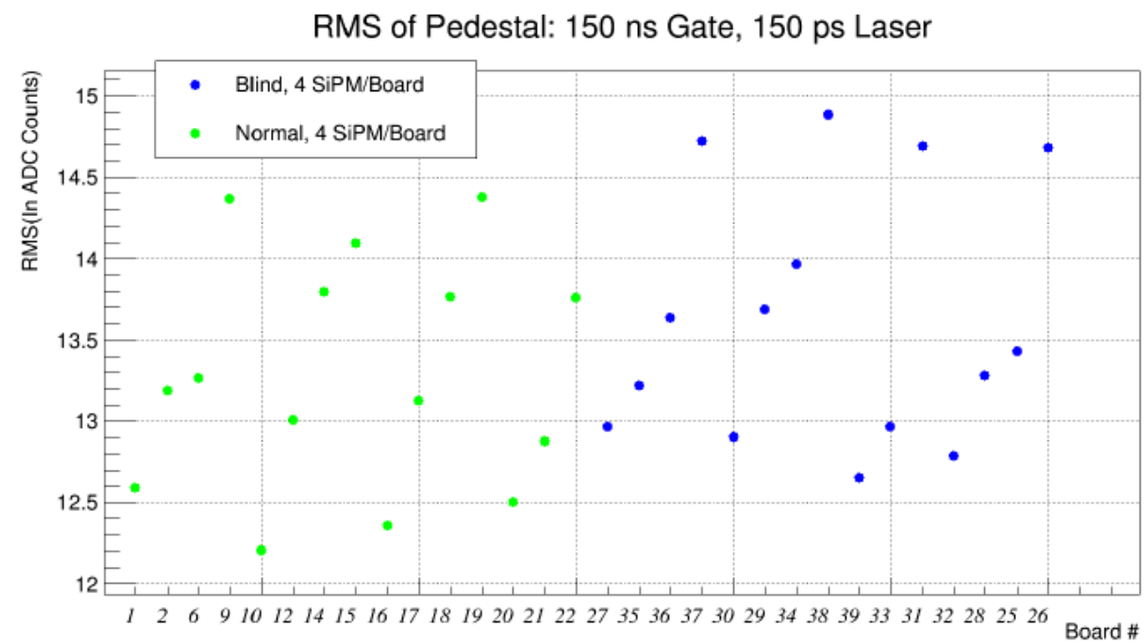
To accurately calculate damages this is not enough. Damage function for protons, pions etc. had to be included.



Run 17. Examples of Degradation.

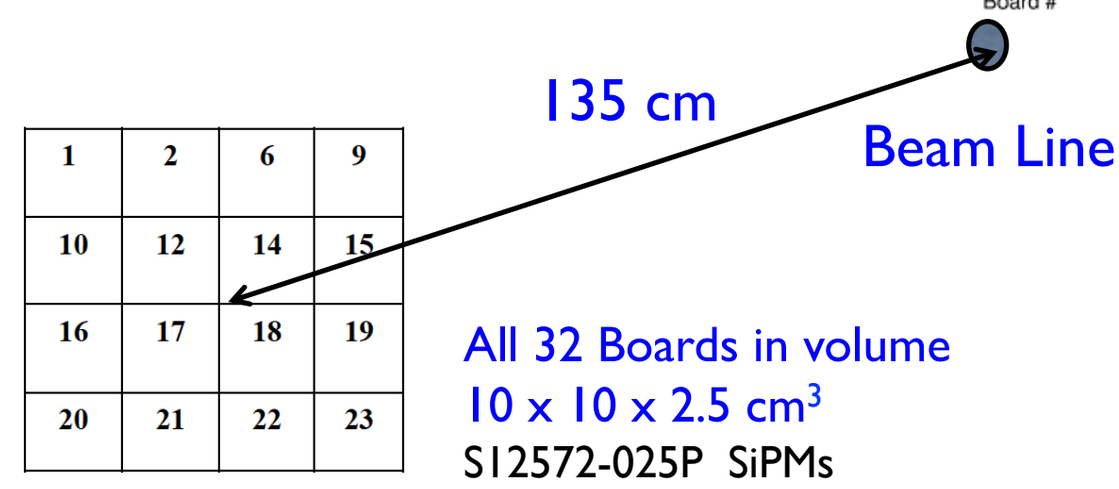




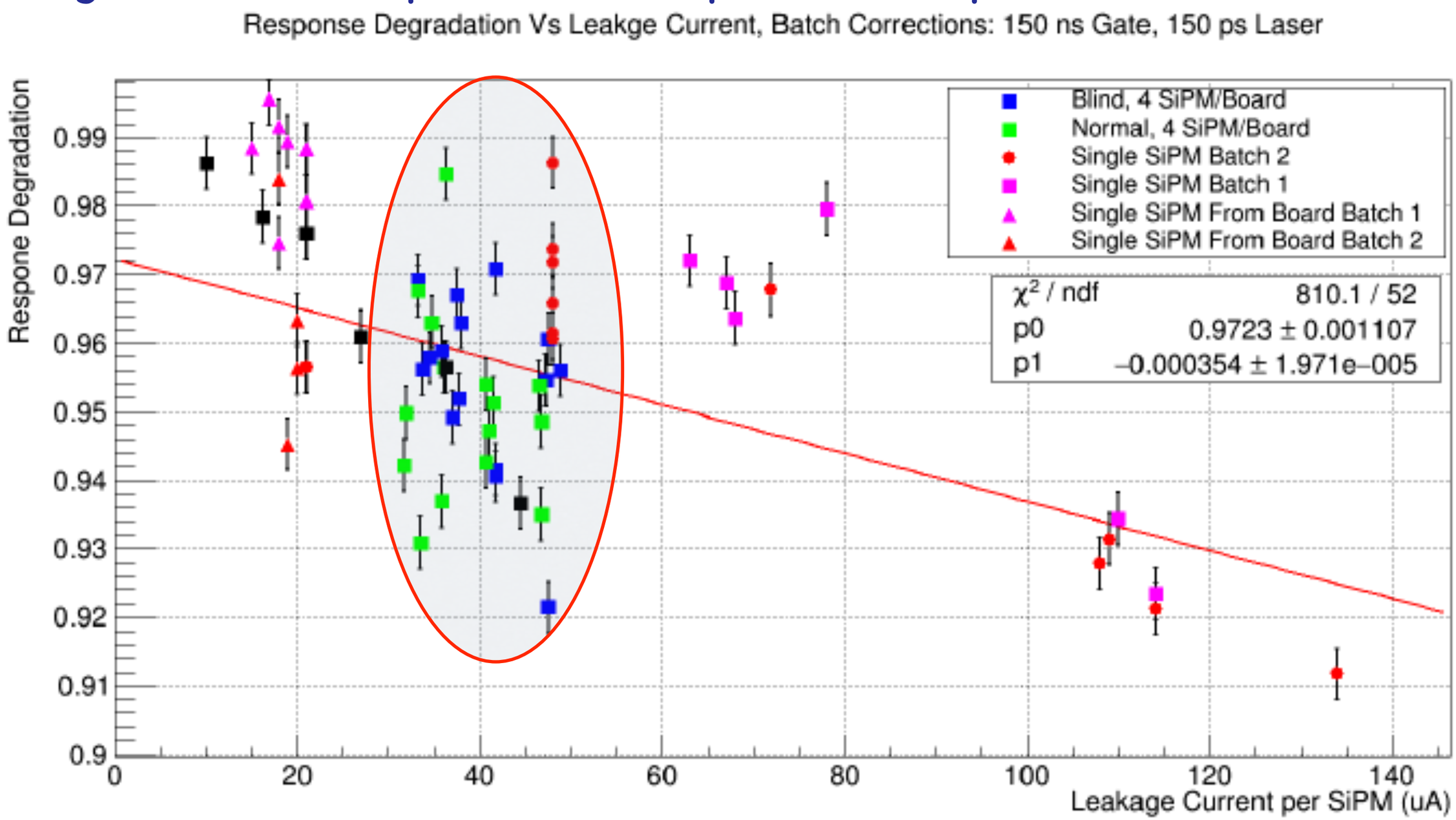


- Naive assumption that sensors are in the same conditions ("neutron gas") does not work well.
- Calorimeter is a source of background and also a shield.
- Probably need to know spectra and convolute these with damage functions.

- Yuri Fisyak were pointing to that long time ago, but it was not done. (lot of work and luck of test data).



Degradation of response with respect to unexposed sensors.



Problem for some designs. May need monitoring for each SiPM, unless

- Light is mixed, SiPMs bunched. Still need good monitoring system but per tower.
- Or, one can claim that can calibrate/monitor from physics. (has not been looked for EIC calorimeters)

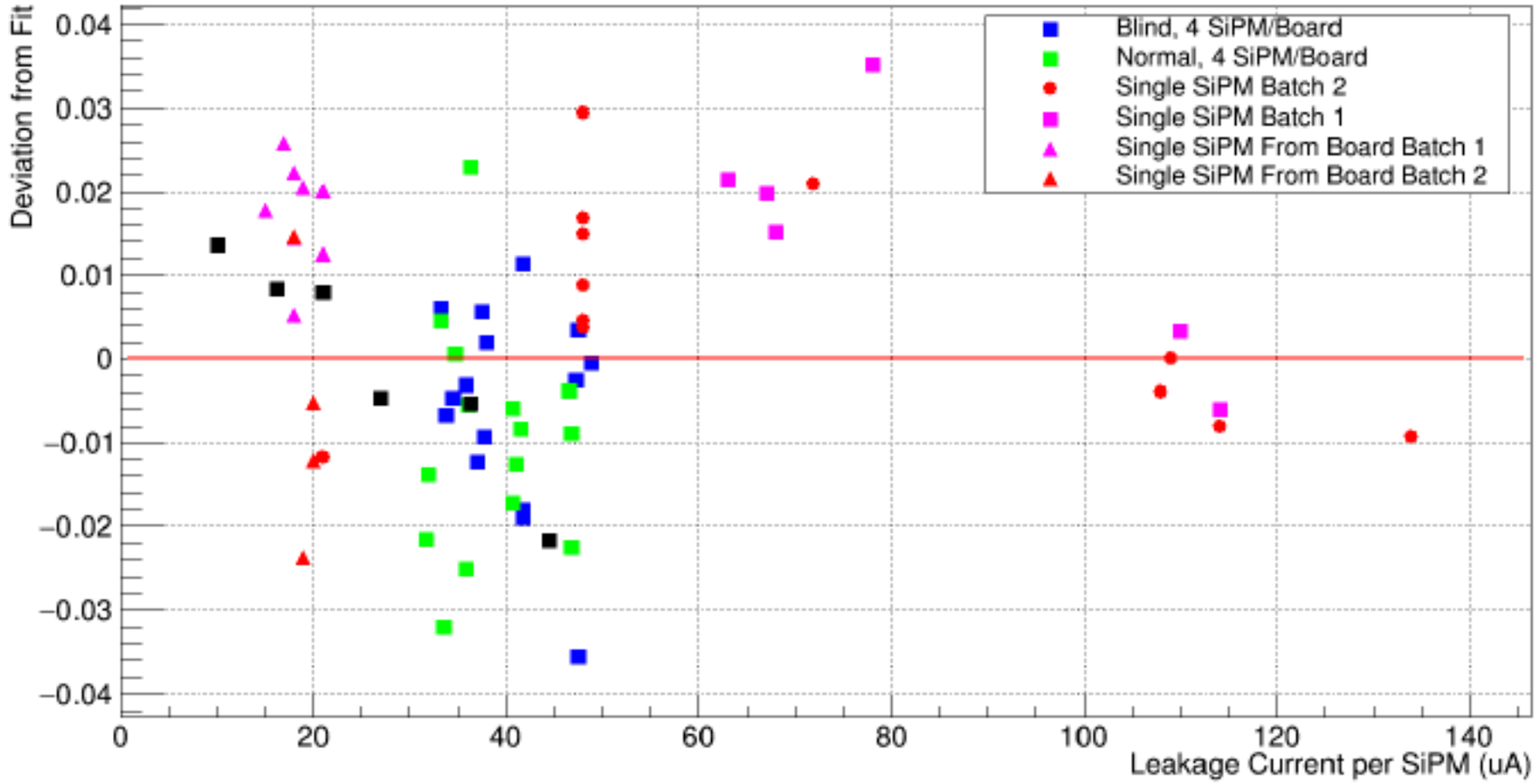
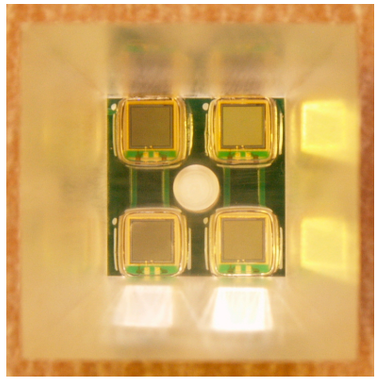


Figure 62: Deviation from fit for Leakage current versus response degradation with batch corrections. Sigma = 0.0155.

Correcting just on leakage current will increase constant term by 1.6%.



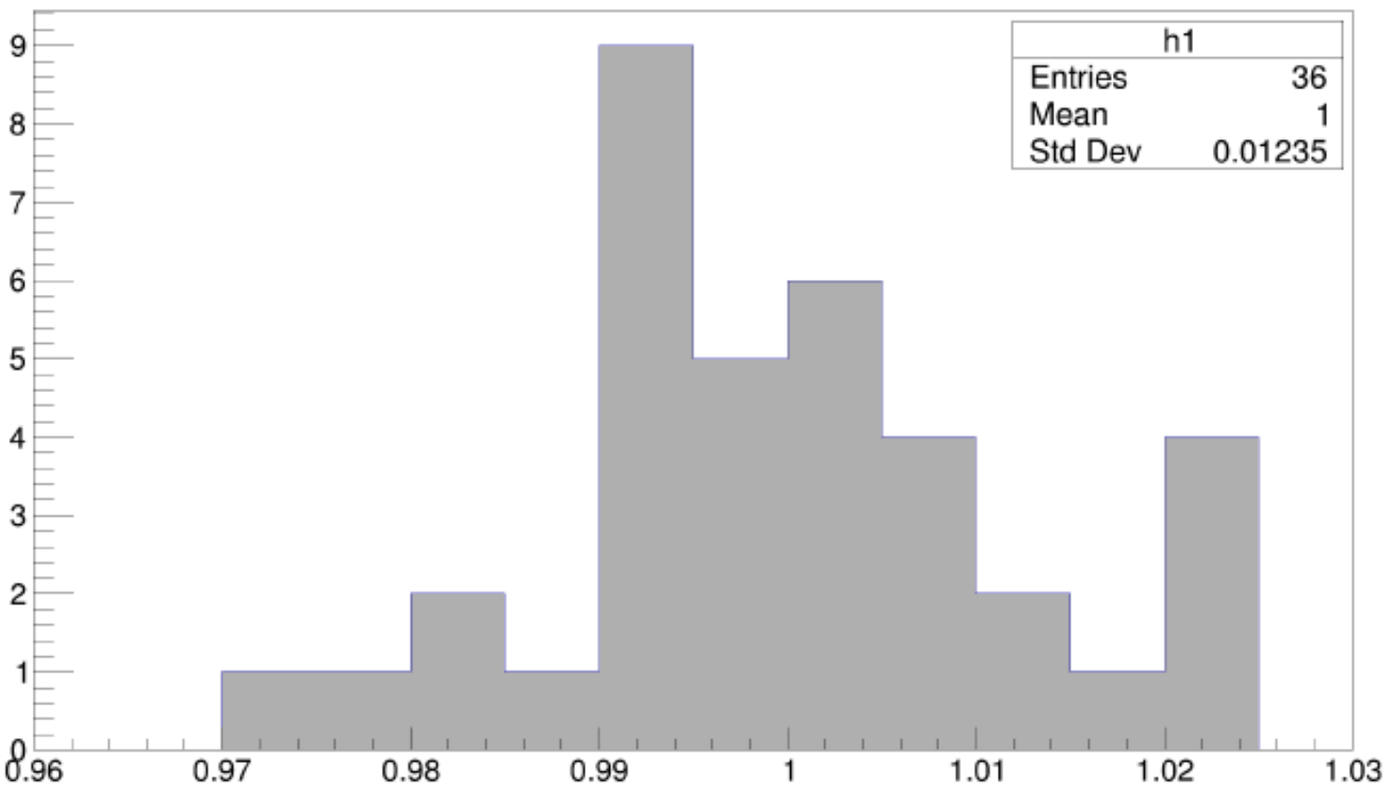


Figure 67: Differential degradation for single SiPMs

- SiPMs from a single tower degraded same way (distance between SiPMs ~ 7 mm).
- They were preselected at the beginning to have same operation voltage, (within 10 mV, using HPK data).
- Preselection should help for FEMC, BEMC or sPHENIX types of readout (in terms of keeping constant term inflated).

Naive assumption that Vop – Vbd is the same for the same gain (response) specified by HPK turned out to be wrong.

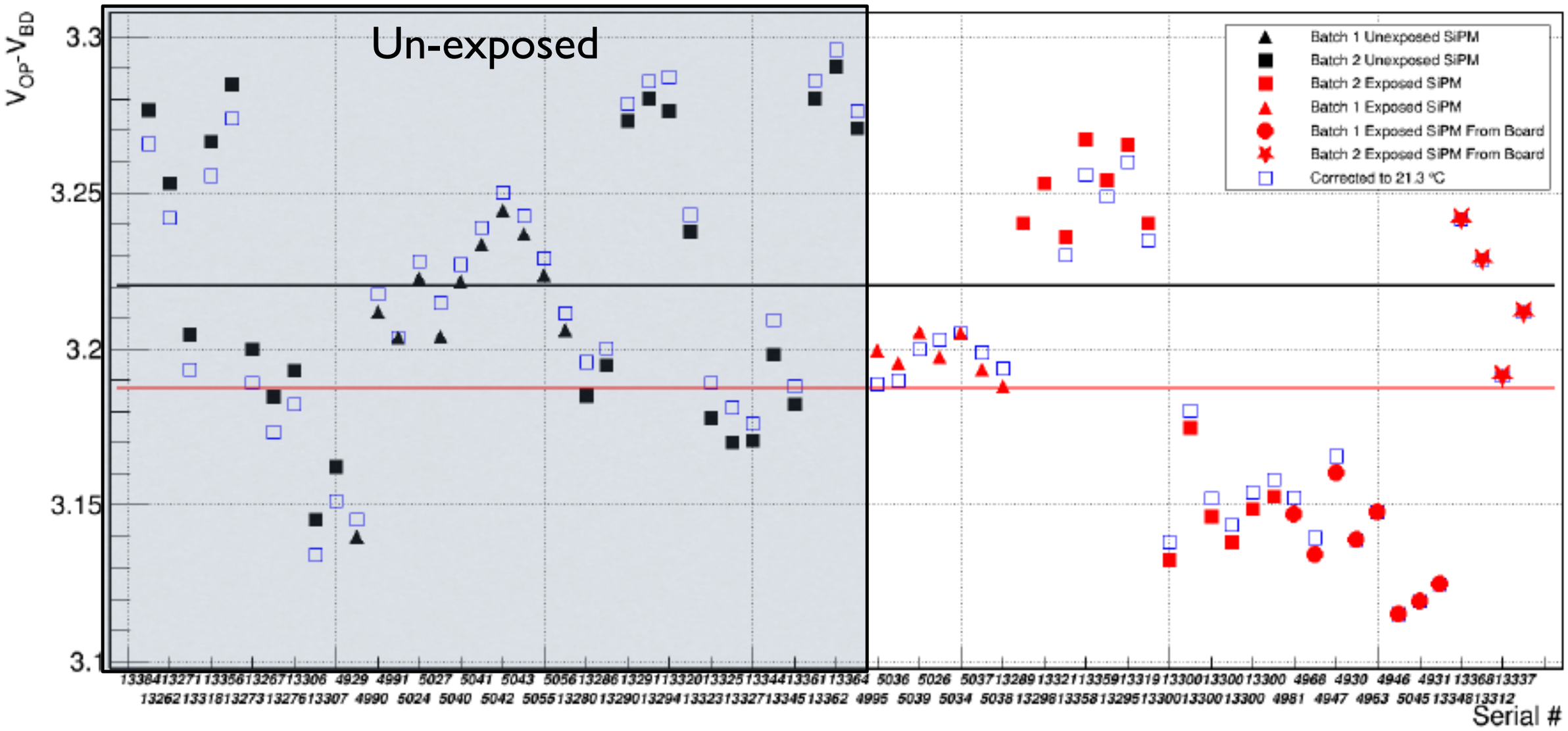


Figure 64: Operating voltage minus breakdown voltage for all single SiPMs.

- Average 30 mV shift for exposed sensors is plausible, but
- Not super convincing.

So far, safe approach is to think:

- SiPMs at EIC conditions will degrade.
- Each SiPM is 'unique' and will degrade differently.

Defence

- Choice of calorimeter design, which can amplify or play down problems related to degradations due to exposure, see slide 2.
- Good monitoring system.

Additional Efforts required.

- Reliable calculation of degradation will require more work than we did so far, that had also include such things as machine background.
- Calibration/monitoring in situ from physics.

To Be Continued

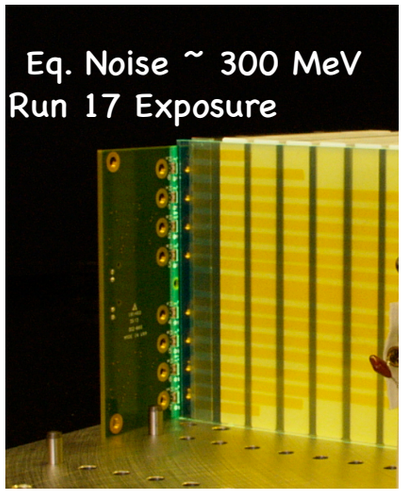
- These results are by-product of other measurements we did with these setups in Run17.
- Obviously, having fully characterised sensors before exposure will help to pin down things like change in Vbd.
- Will tape characterised sensors to the beam pipe during Run18. (Still there)

SiPMs/APDs , Eq. Neutrons, Light Collection Schemes...

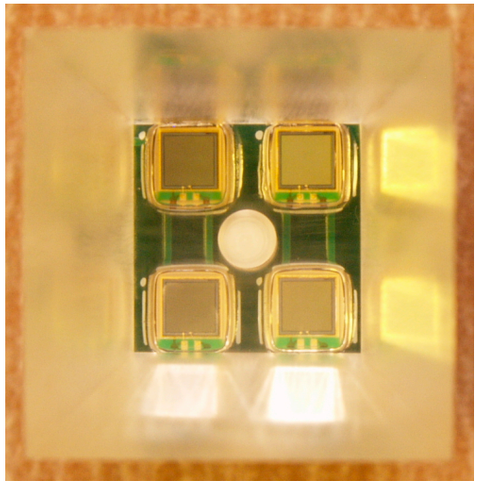
Sensor:
- Small Active Area
- Limited # pixels

Requires:
Multiple Sensors per tower

Calorimeter
- Light Collection Scheme
- Dynamic Range



Eq. Neutrons in IP
Degradation of Response
Is It Differential ?



Light perfectly Mixed

- Energy Resolution, term (1/E)
- Loss of Calibration Signals

Light partially Mixed

- Energy Resolution, term (1/E)
- Energy Resolution, constant term ?

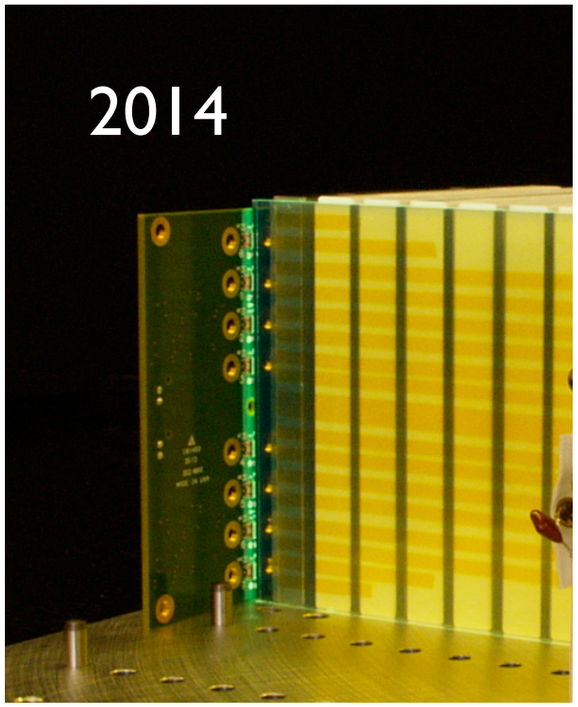
- Increase LY
- Focus and Mix Light
- Minimize # sensors

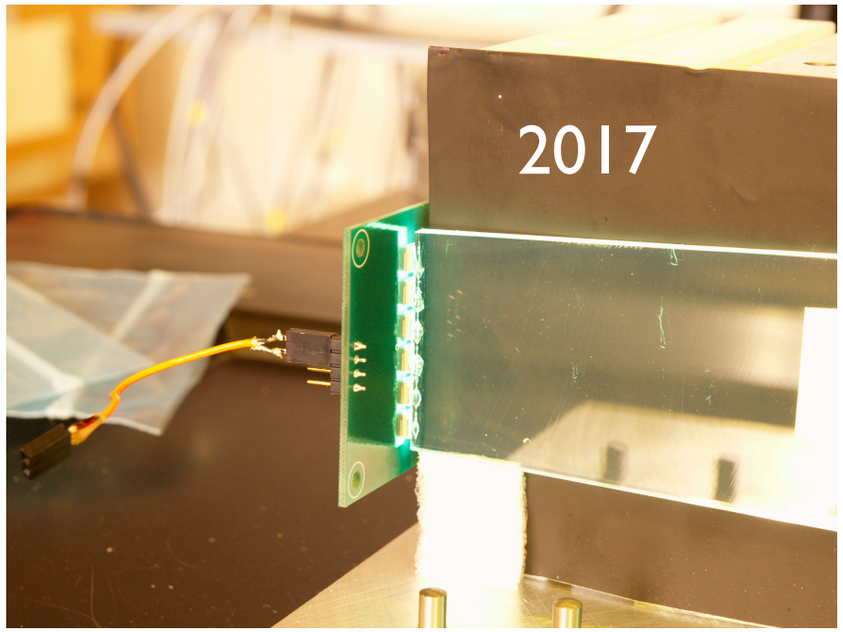
Post Run 17
HCAL, Re-designed
Light collection scheme.

- Consider alternative technologies for high n flux areas.
- Consider non Si based sensors for high resolution calorimetry.

Guided by 2017 SiPMs degradation studies

Re-designed, cheaper version of Hcal (Mixed Light, Increased LY, Decreased # of SiPMs)





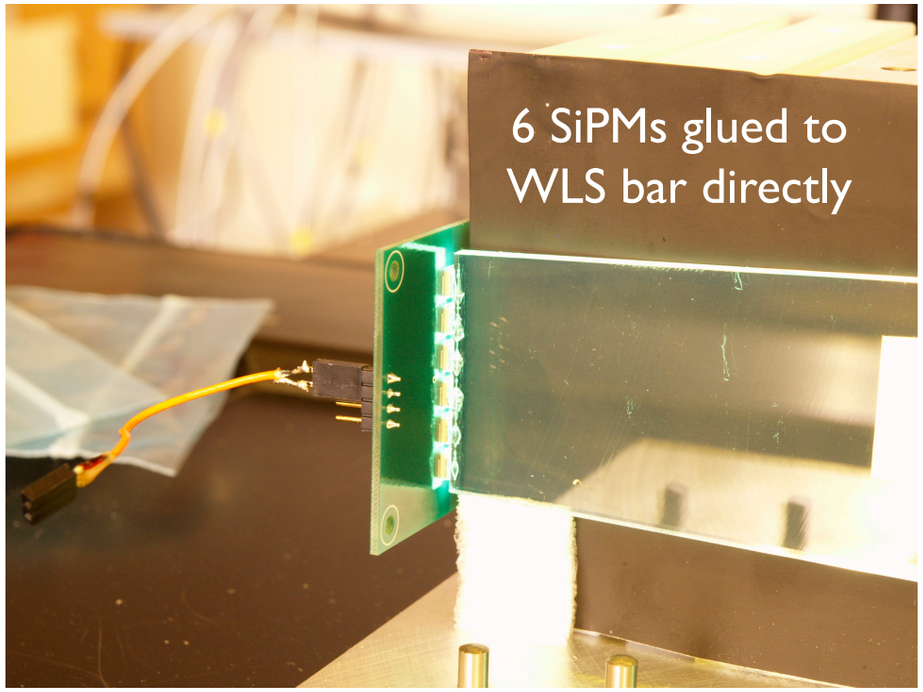
- Compared S8664-55 APDs with S12572-025P SiPMs. Exposed (Run17) and unexposed sensors.
- Found better S/N with SiPM readout version.
- With CMS/PANDA type APD sensors, performance may be close to what observed with SiPMs.

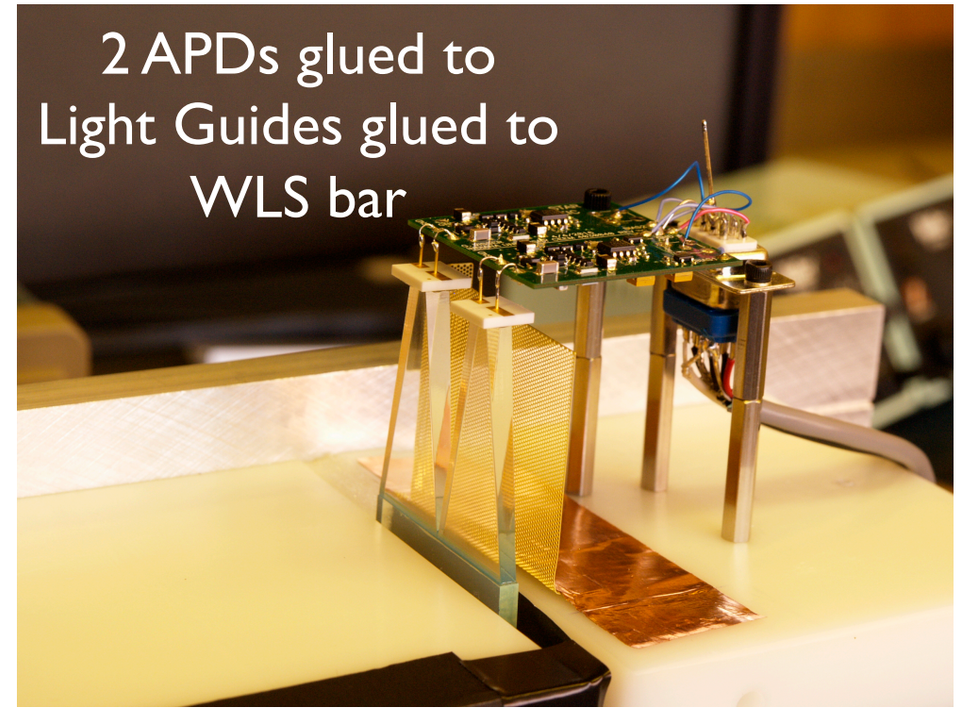
Light Collection Scheme for updated HCAL compare to HCAL version of2014:

- In 2014 we had 64 tiles (total thickness 160 mm), LY was 130 p.e./GeV with 8 SiPMs per tower.
- In 2017, there are 35 tiles (total thickness 105 mm), LY is ~ 270 p.e./MIP (pending MC, MIP is close to 1 GeV) with 6 SiPMs per tower.
- Light Collection efficiency significantly improved due to taper in WLS (focusing) and removing of compensation filter between Sc. Tiles and WLS bar which we had in 2014.

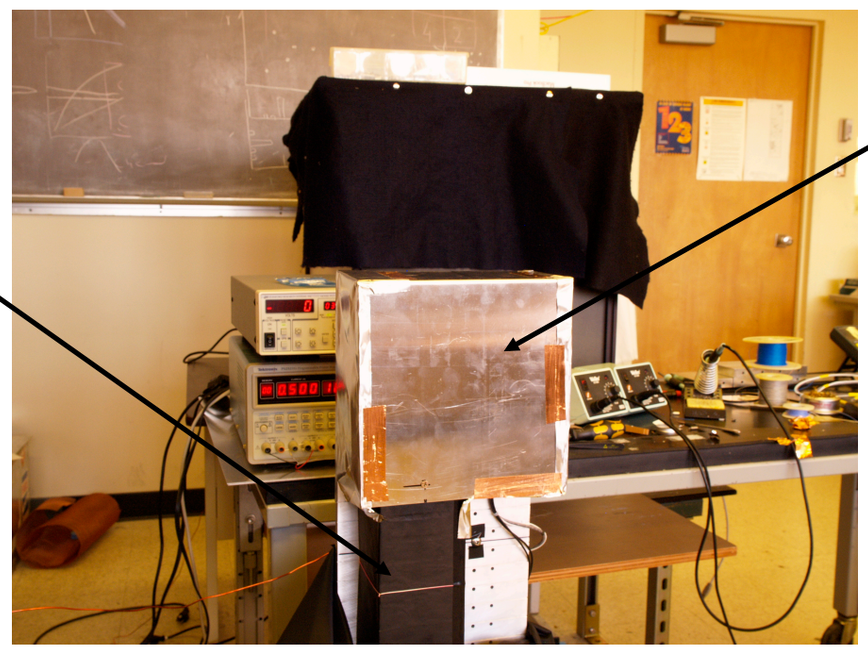
For sampling calorimeters at EIC.
Stick with SiPM readout, simpler and cheaper implementation.

Setup

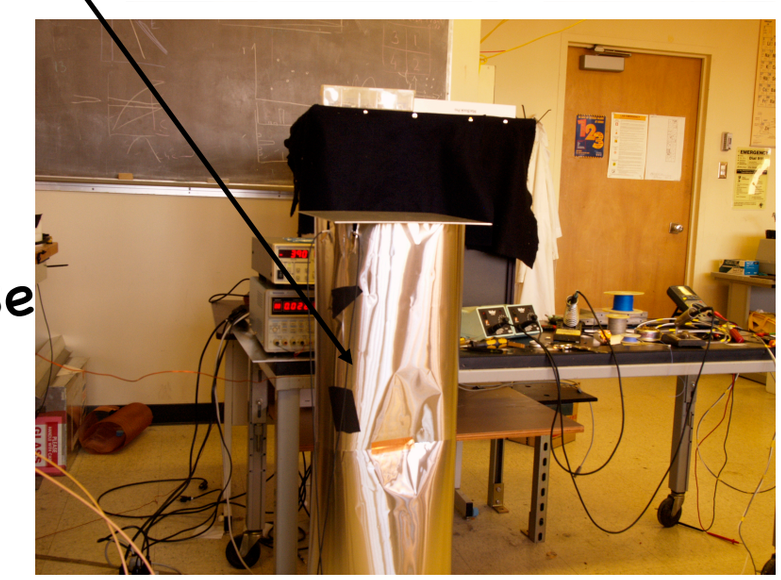




Hcal Tower

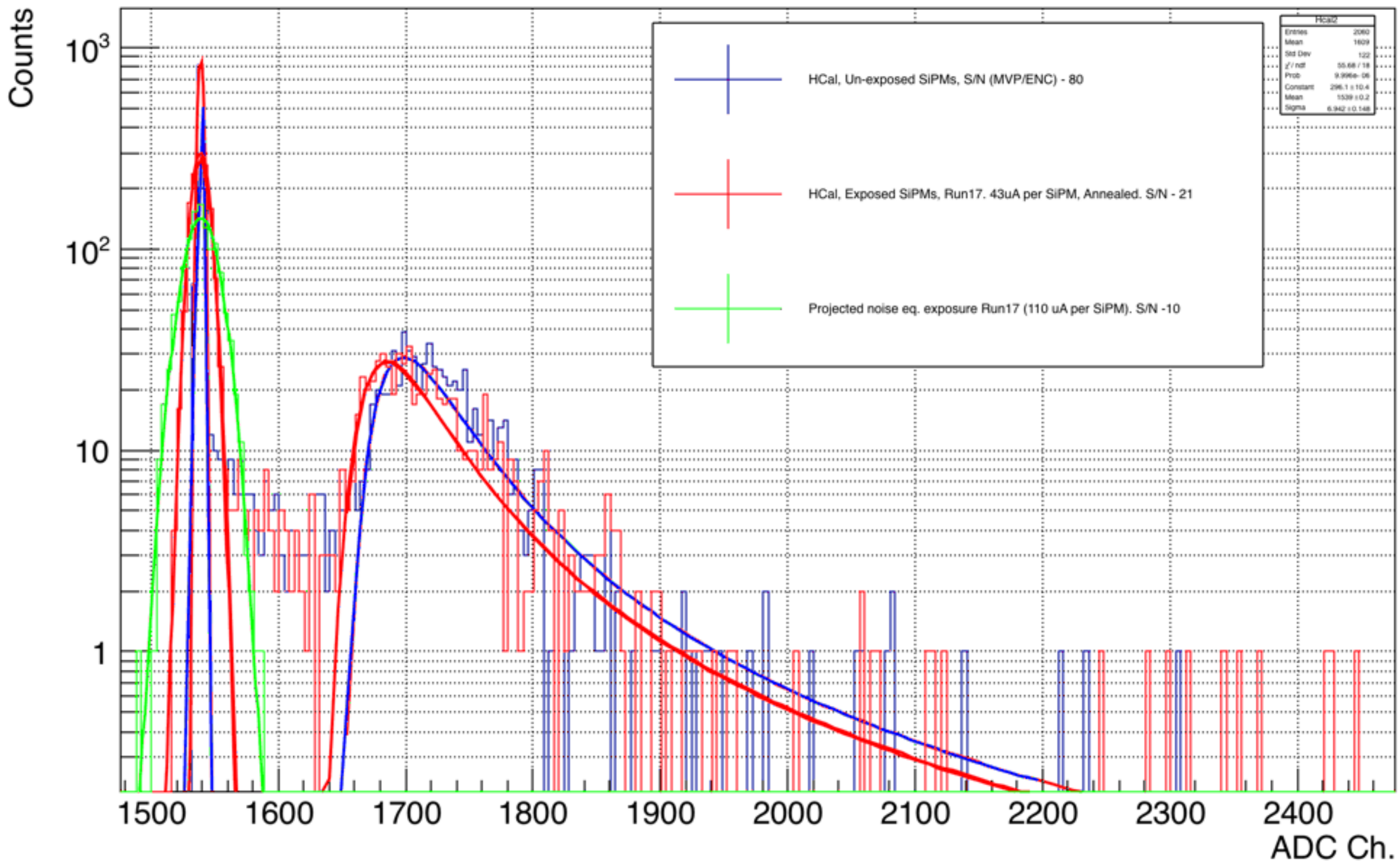


Shielding



APDs readout required 'extensive' shielding to handle noise pickup. Essentially it was a double Farady cage, which was not required for SiPMs version of readout.

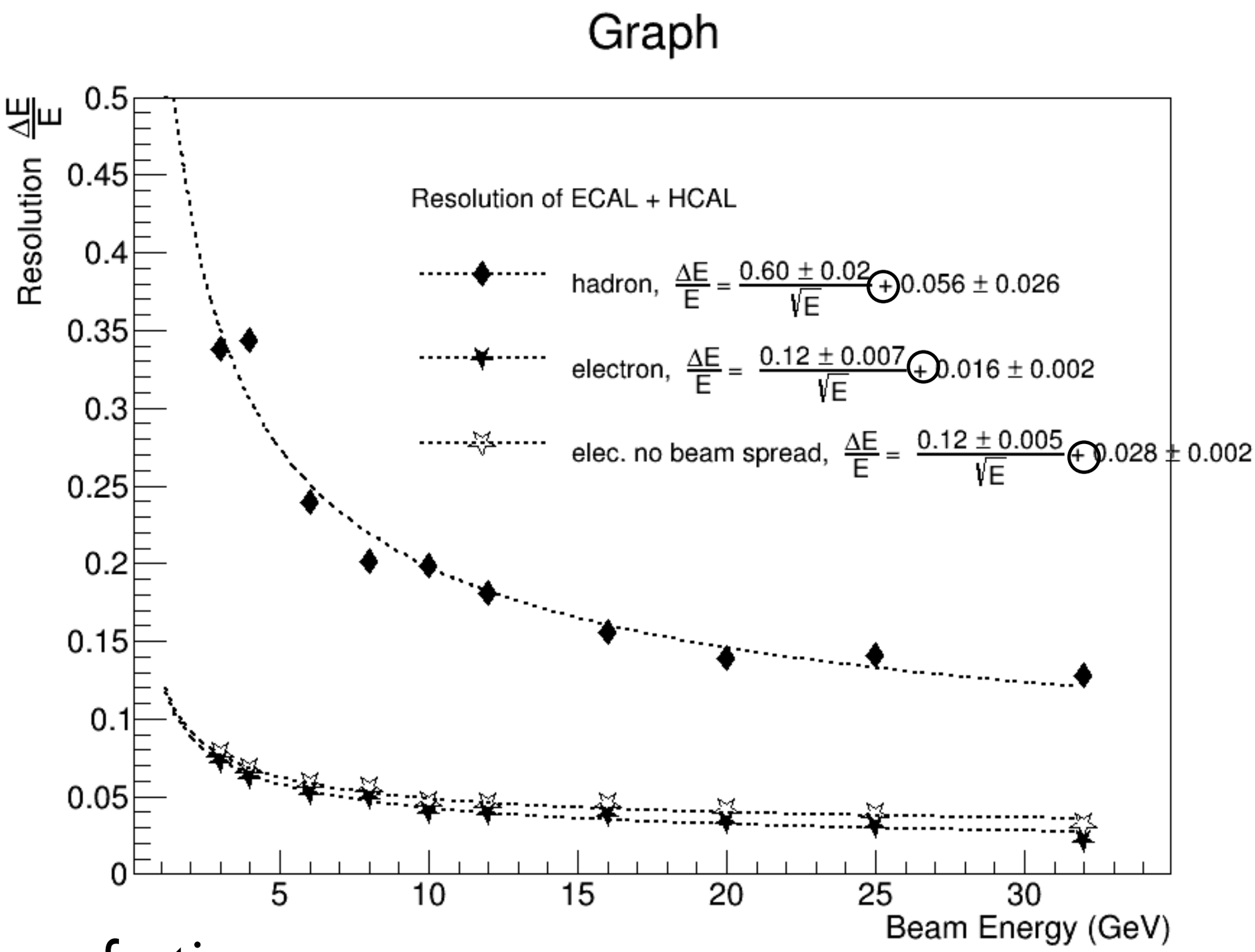
HCal, Muons with Exposed and Un-exposed SiPMs



Shift in MIP peak position may be due to mis-alignment of readout board during gluing to WLS , or degradation of SiPMs response after exposure as reported earlier.
S/N somewhat arbitrary, i.e S means MPV for Landau. N – sigma of pedestal peak.
(Excess noise due to degradation of SiPMs ~ 100 MeV/tower)

FCS Constant Term, FNAL 2014

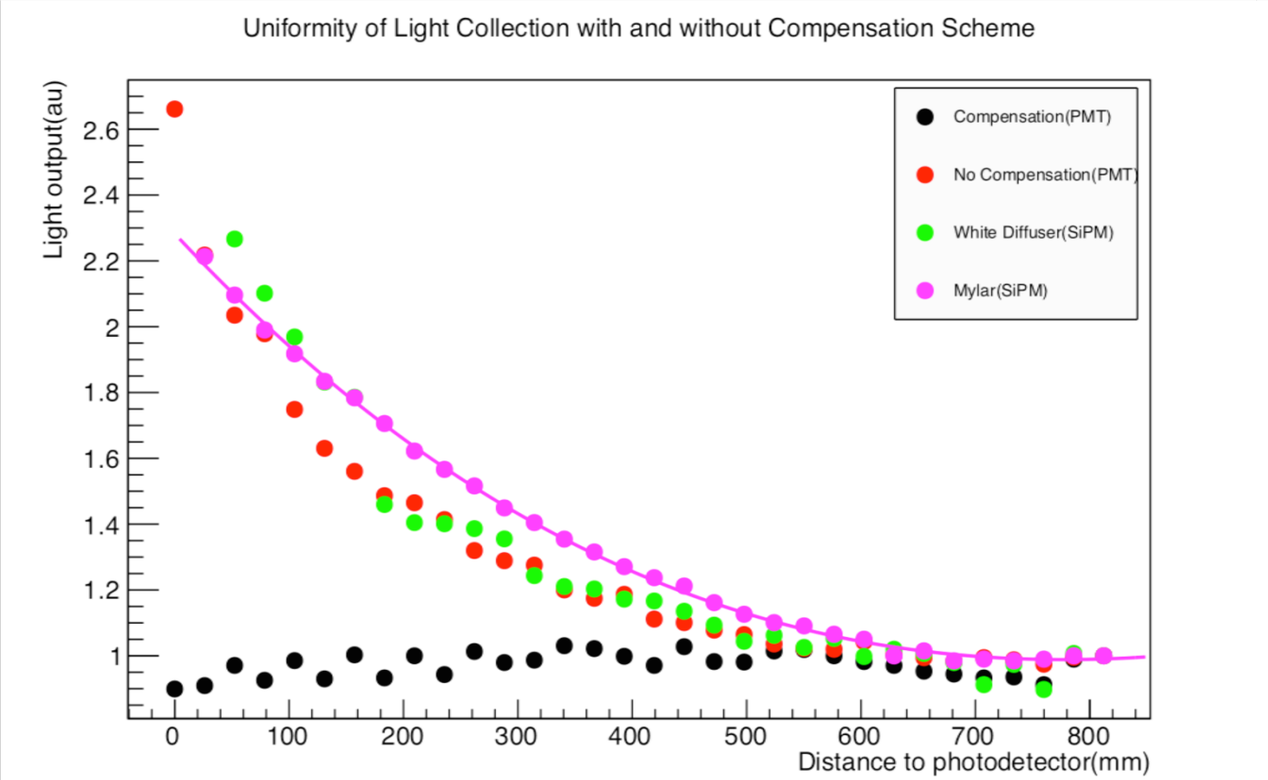
Advantages of compensated system

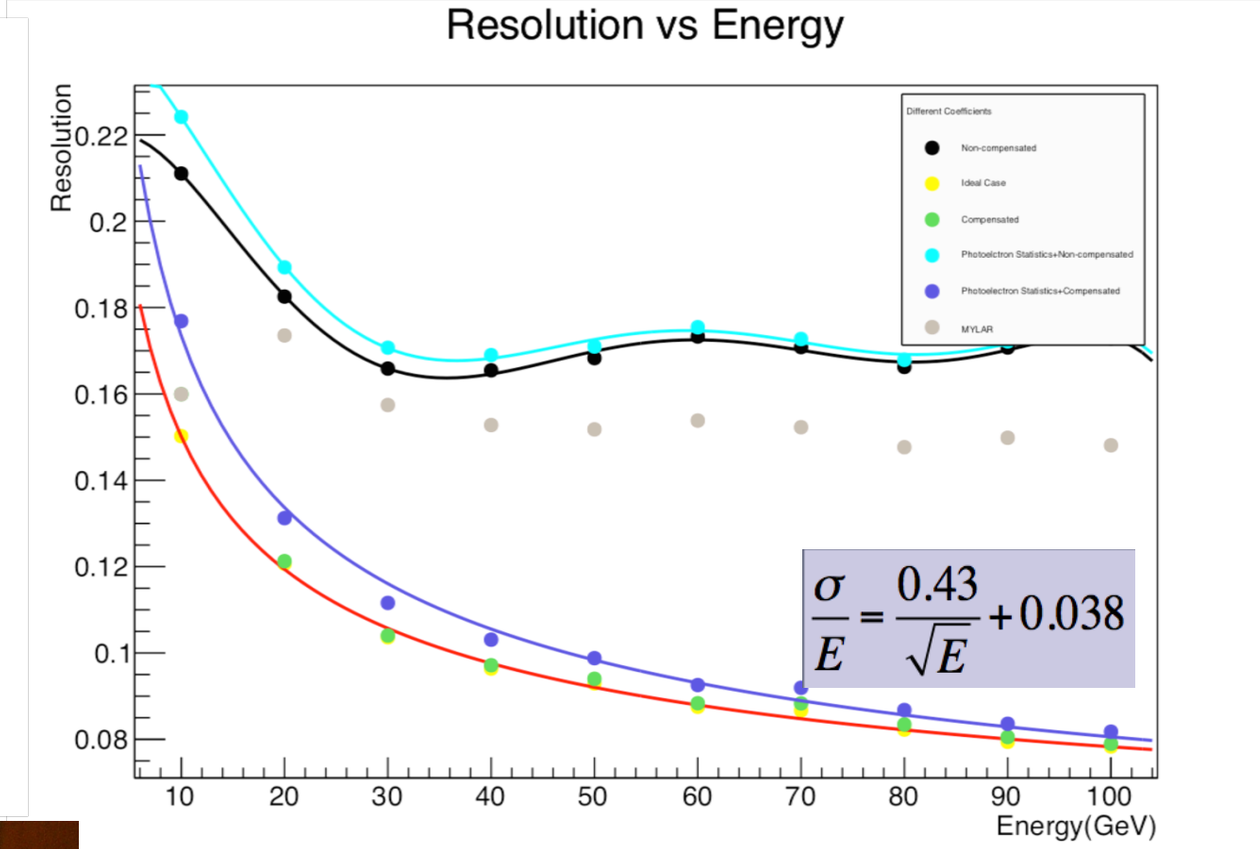


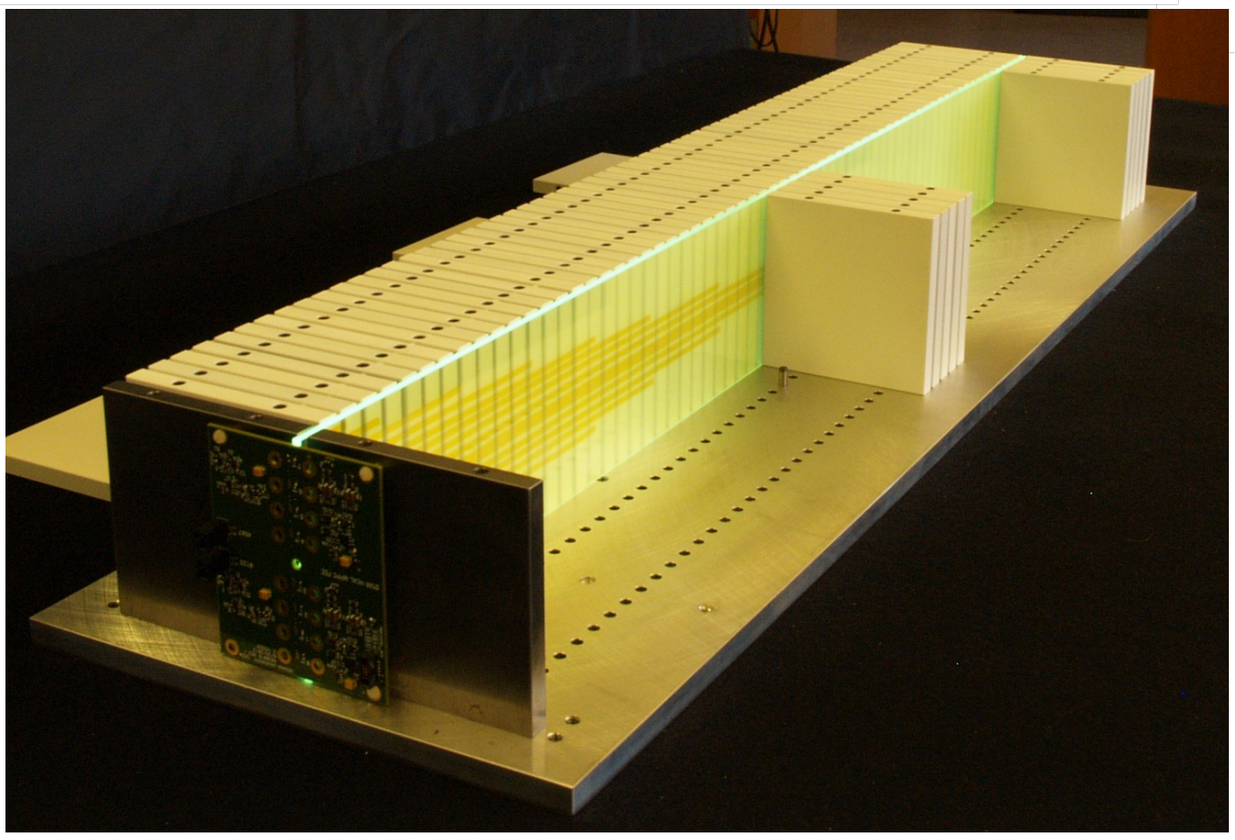
Imperfections:

- Thick steel plate between EM and HAD sections
- Leakages transverse and longitudinal

Instrumental effects are very important. FCS Constant Term







Uniform and Efficient light collection is very important. It is very easy to end up with constant term at 15% or so.

Fe/Sc Hcal, example NIM 180 (1981) 429-439. (H.Abramovich et.al. A.Para)

0.6 x 0.6 x 2 m³ (total absorption !), Fe/Sc (25/5 mm)

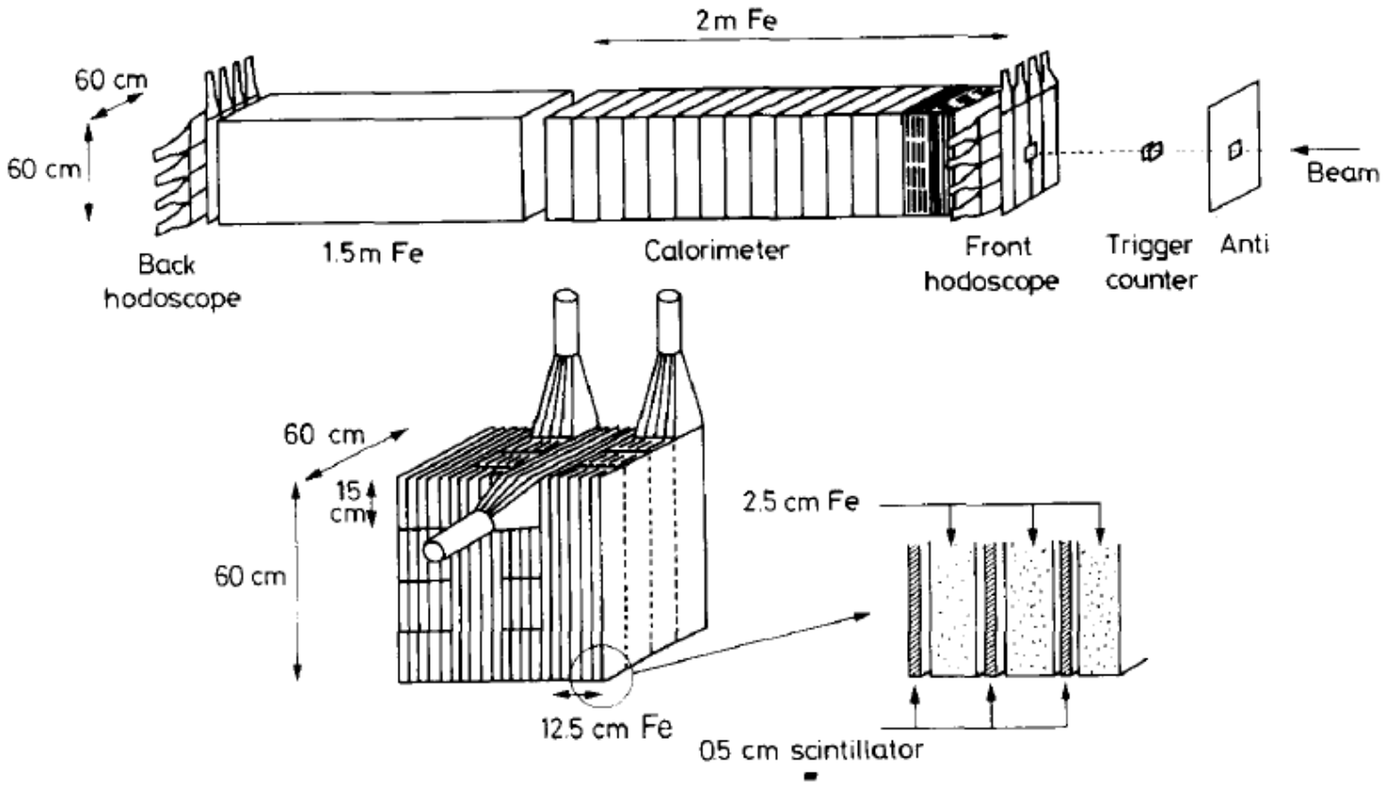
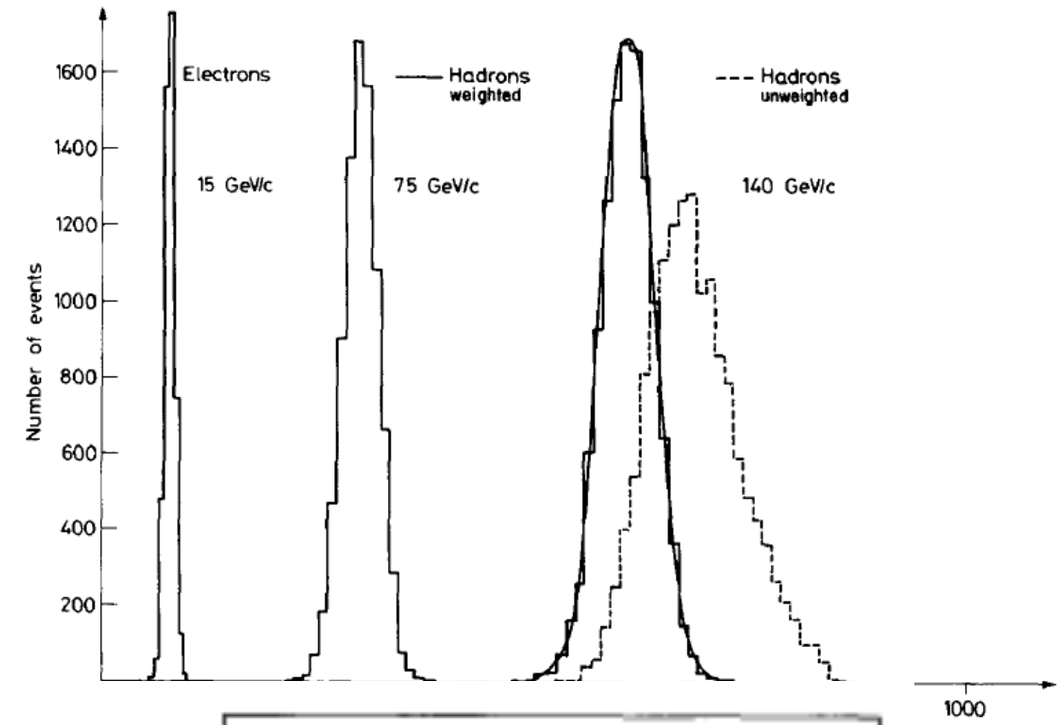
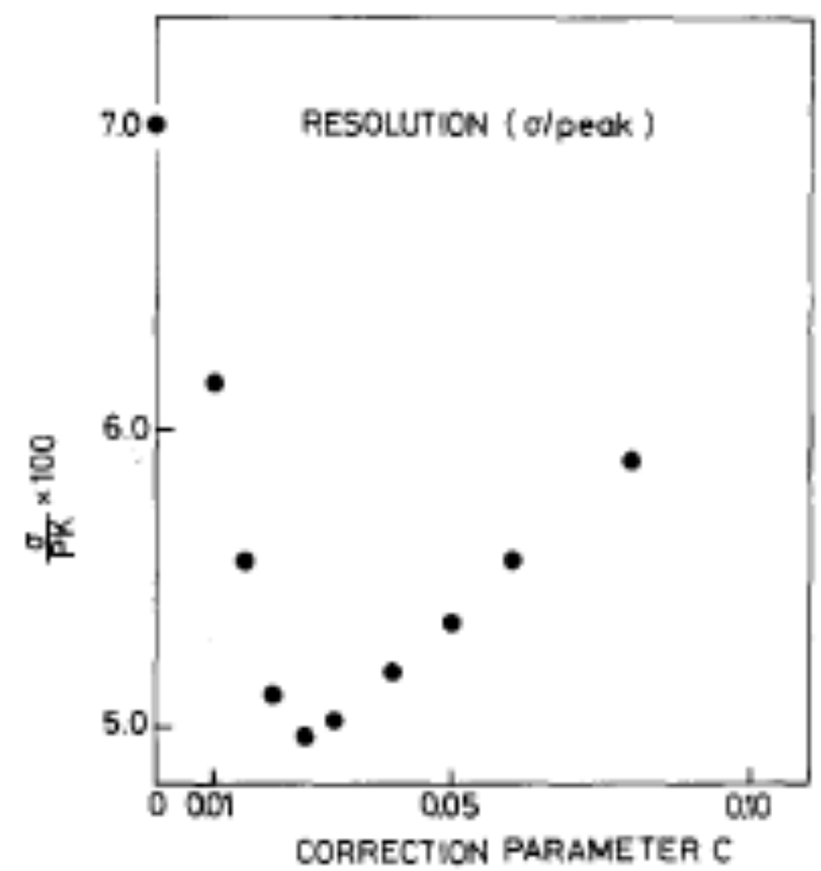


Fig. 1. The test calorimeter and the detailed structure of a module.



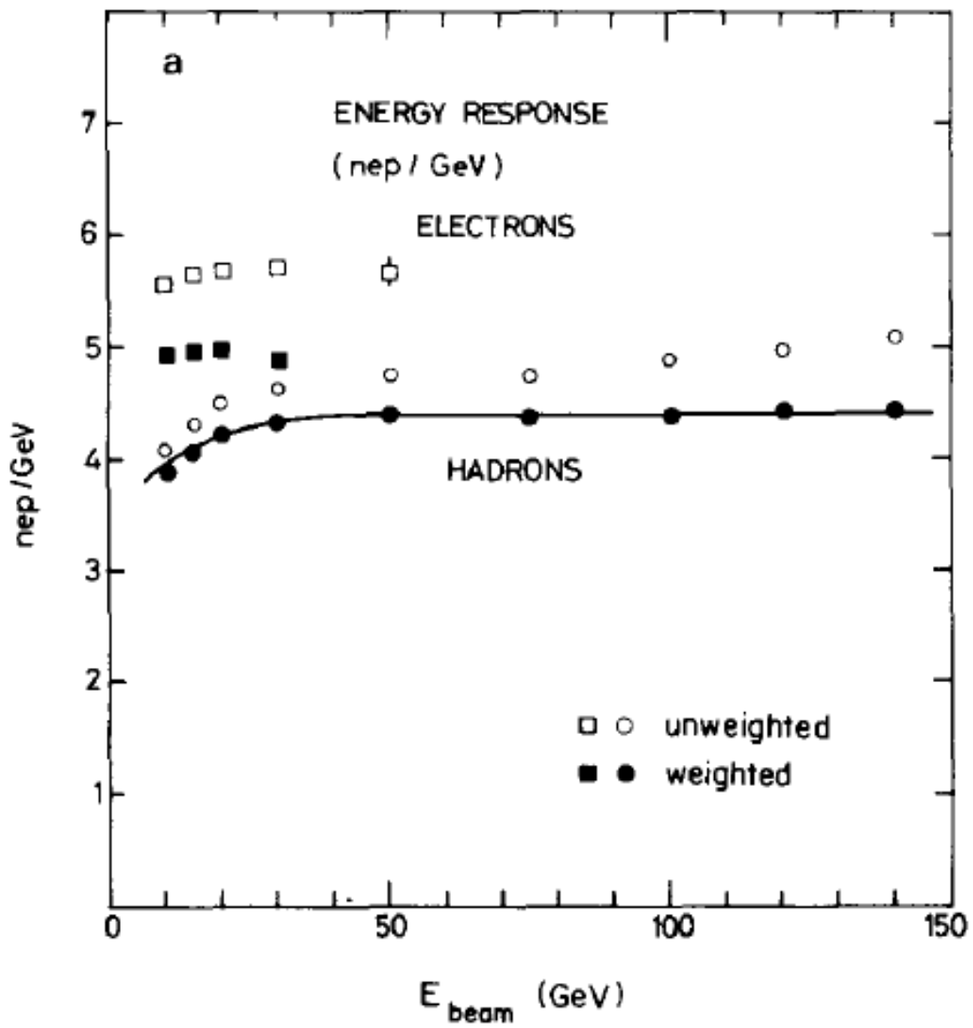


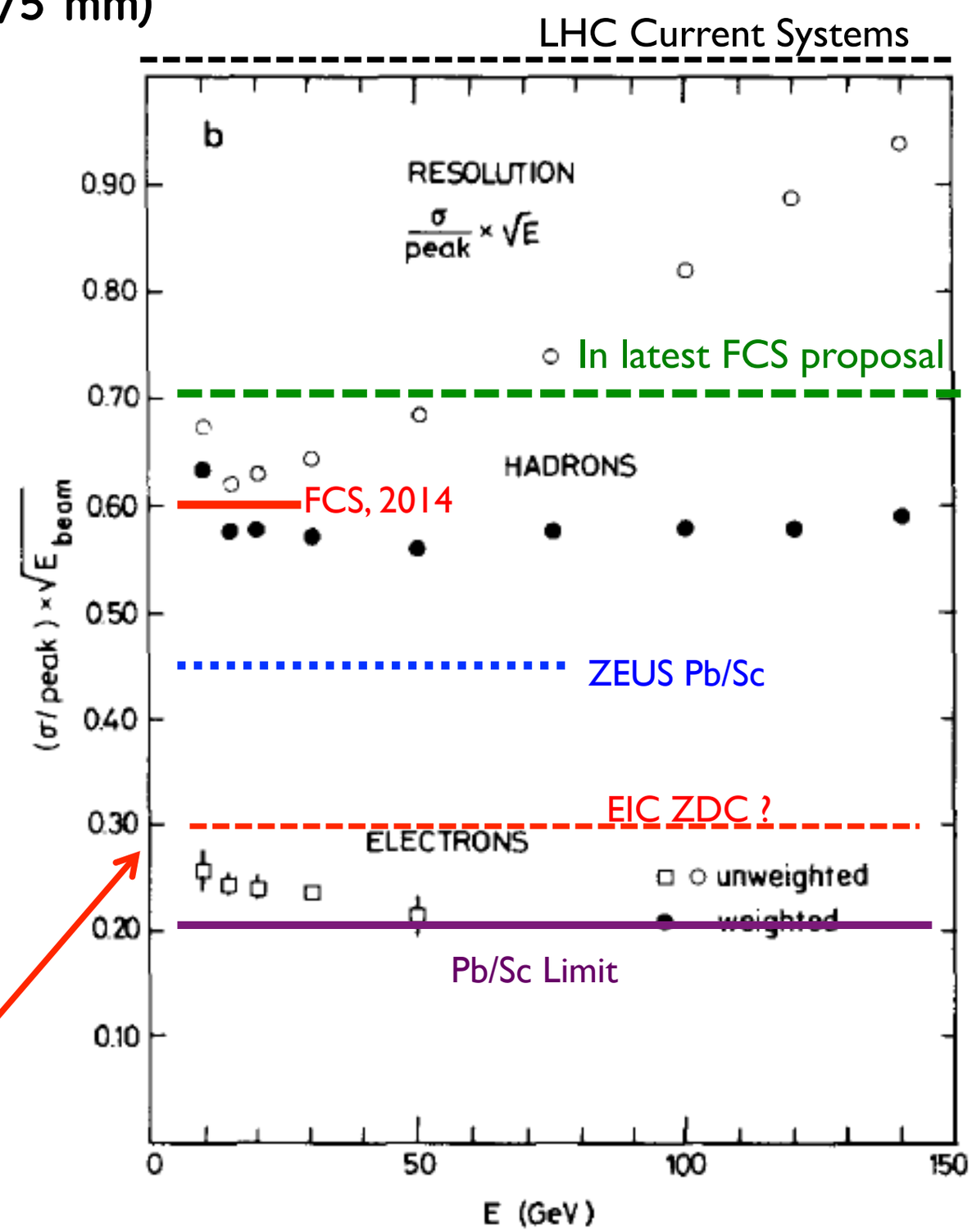
Replace compensated Pb/Sc with non-compensated cheap Fe/Sc

- Re-weight every cell to account for excessive f_e
- $E_i' = E_i(1 - C/\mathrm{sqrt}(E_{total})E_i)$
- Cell size 15 x 15 cm², not optimized.

Fe/Sc Hcal, example NIM 180 (1981) 429-439.

0.6 x 0.6 x 2 m³ (total absorption), Fe/Sc (25/5 mm)





Non linear response and cell weighting to get resolution.

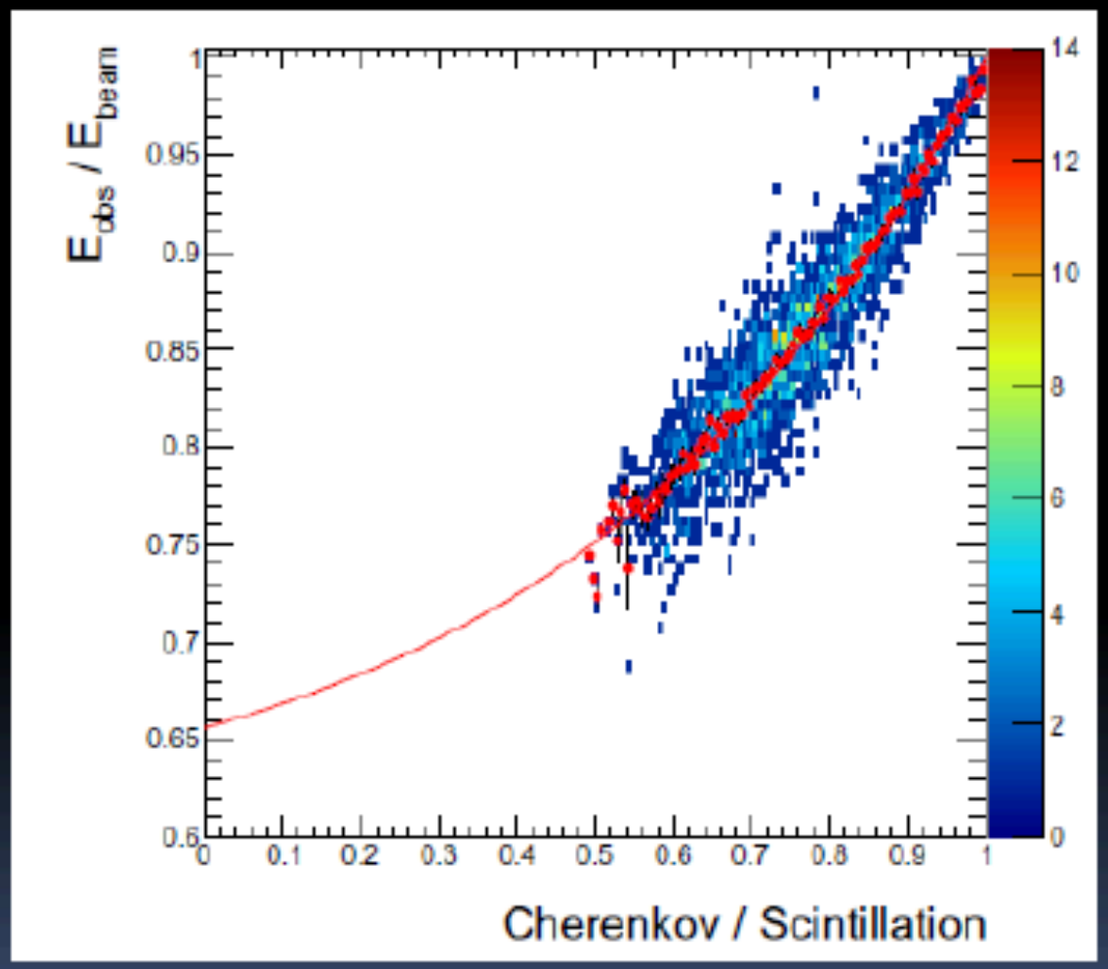
Can sandwich type calorimeters get there ?

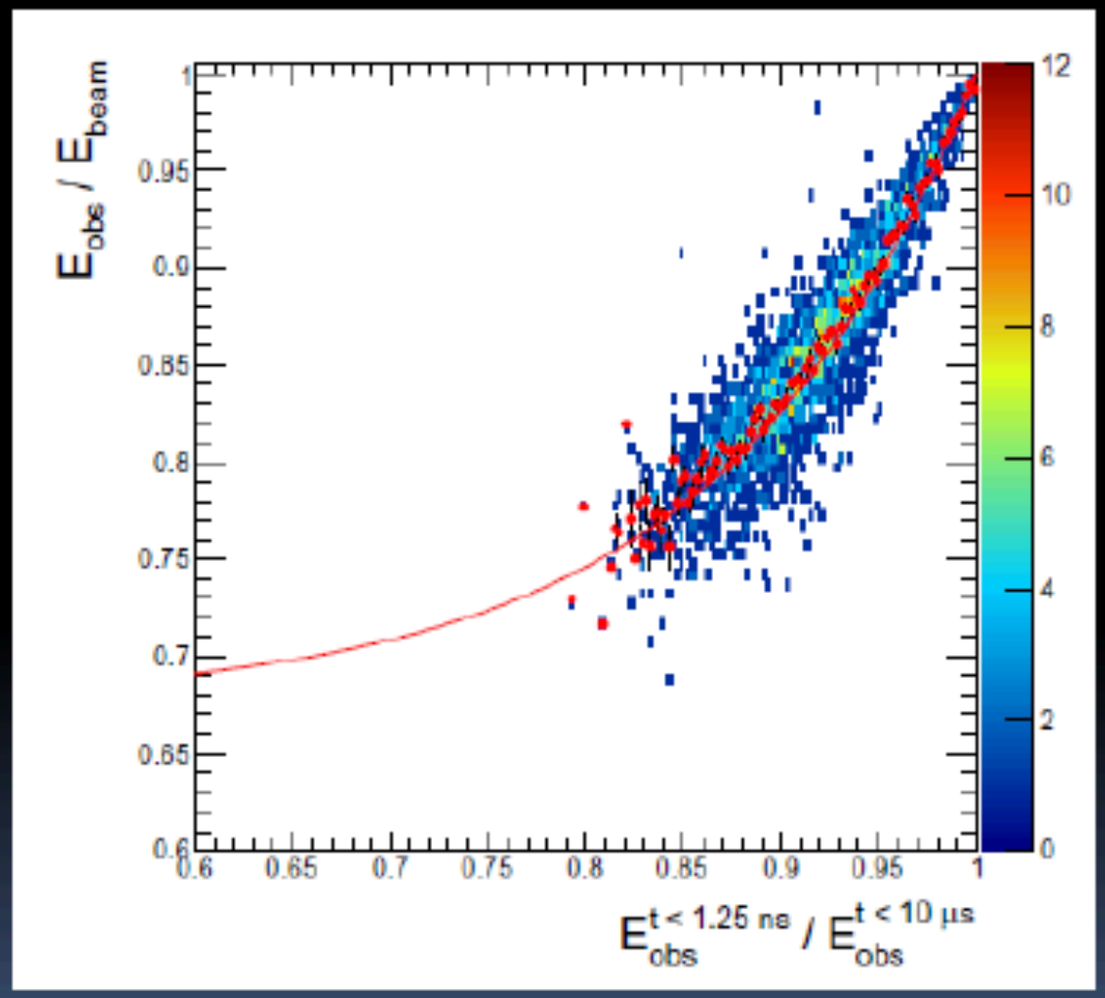
"Space-Time evolution of hadron showers and its use in hadron calorimetry" A. Para's talk at CPAD 2016.

Two Physics Principles of High Resolution, Hadron Calorimetry

- Total absorption: no sampling fluctuations and other sampling-related contributions (energy and particle dependent sampling fractions, for example). The dominant contribution to resolution: fluctuations of nuclear binding energy losses.
- 'Dual readout' : find an observable (in addition to the total energy) which is correlated with the total number of nucleons (mostly neutrons) released in the shower and use this correlation to make a correction to the observed energy. The resulting energy resolution will be limited by the degree of the correlation.
- An example of a possible second observable: Cherenkov – to Scintillation signal ratio

Dual Gate (Scintillation Only) vs Dual Readout Correction





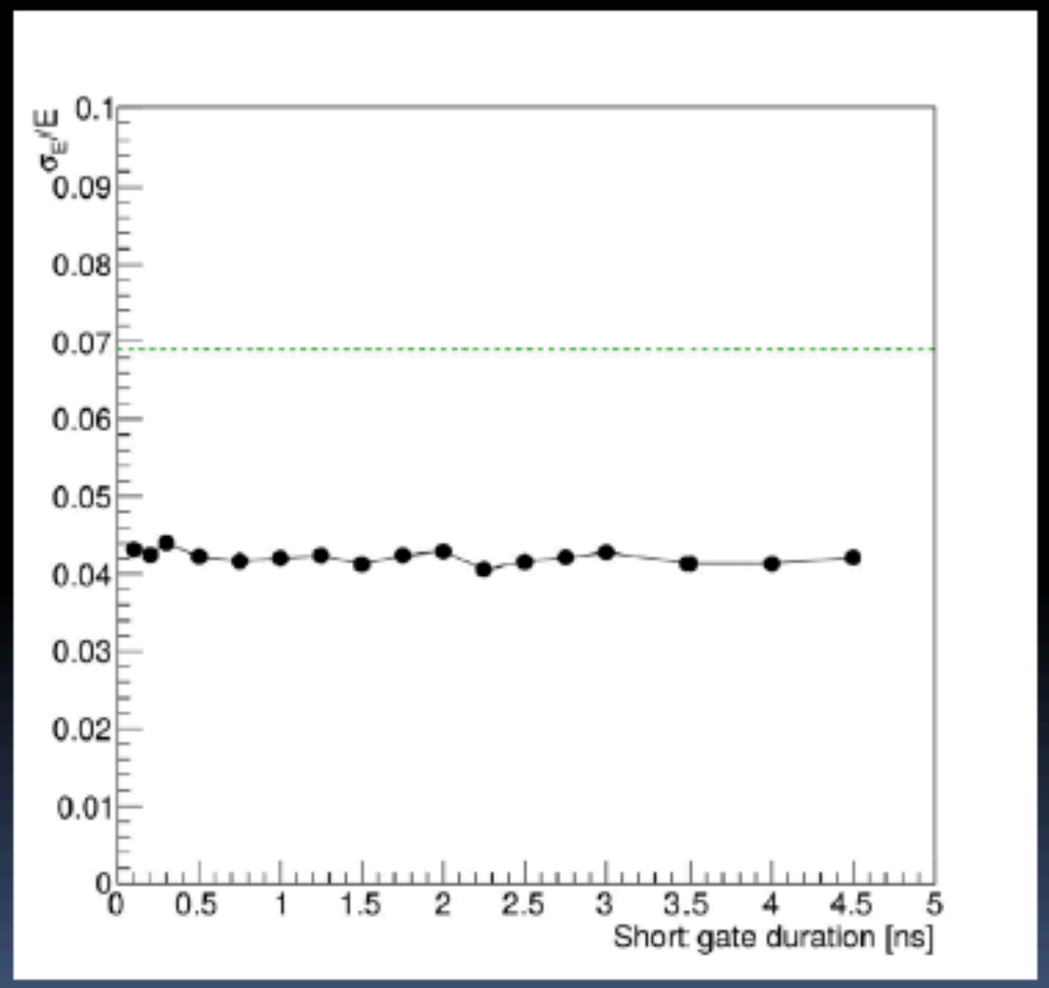
A. Para, CPAD 2016

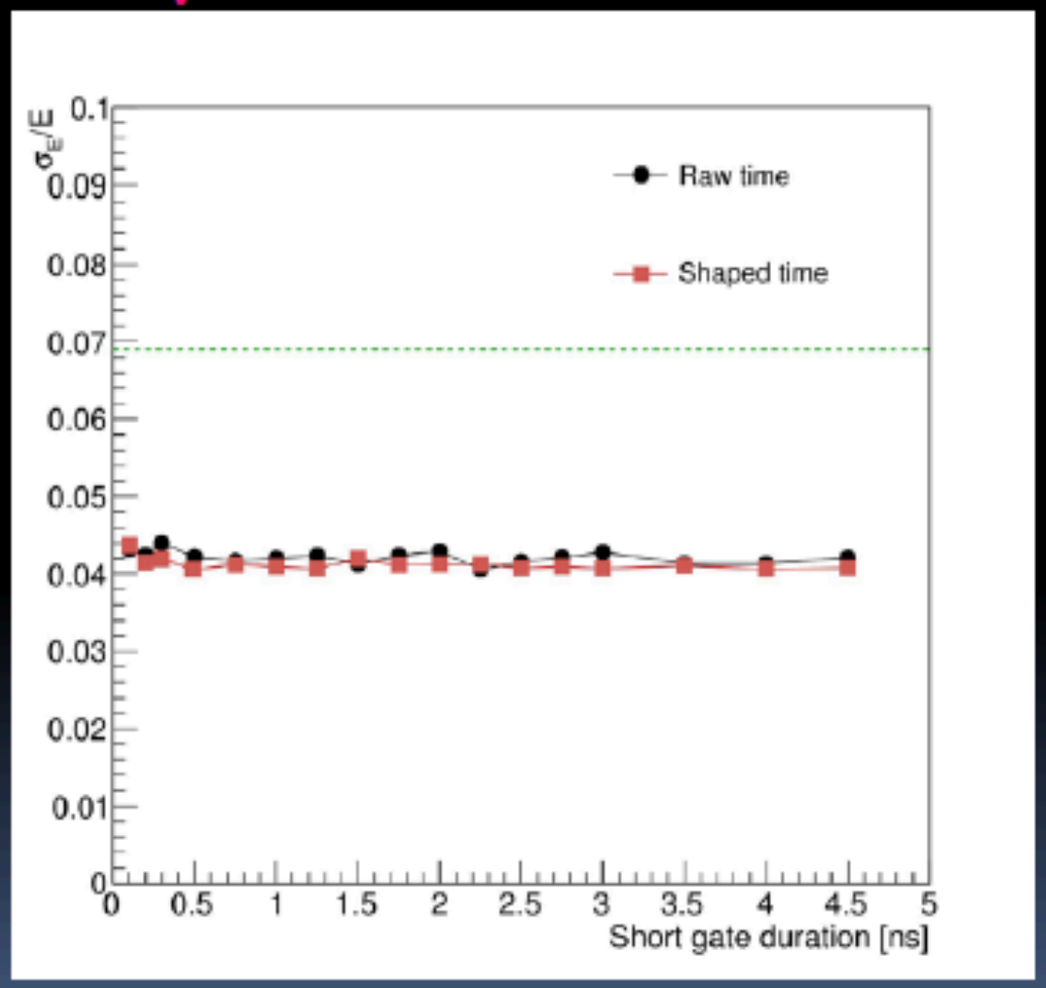
A. Para, CPAD 2016

Dual Gate Correction for the Sampling Calorimeter?

20 mm Fe + 5 mm LuAG

Same sampling, realistic response time





Major improvement even in the sampling calorimeter, resolution limited by sampling fluctuations

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STAR FCS is a vehicle to test this idea in 2019.

N.B. need relatively small additional funds to modify FCS.

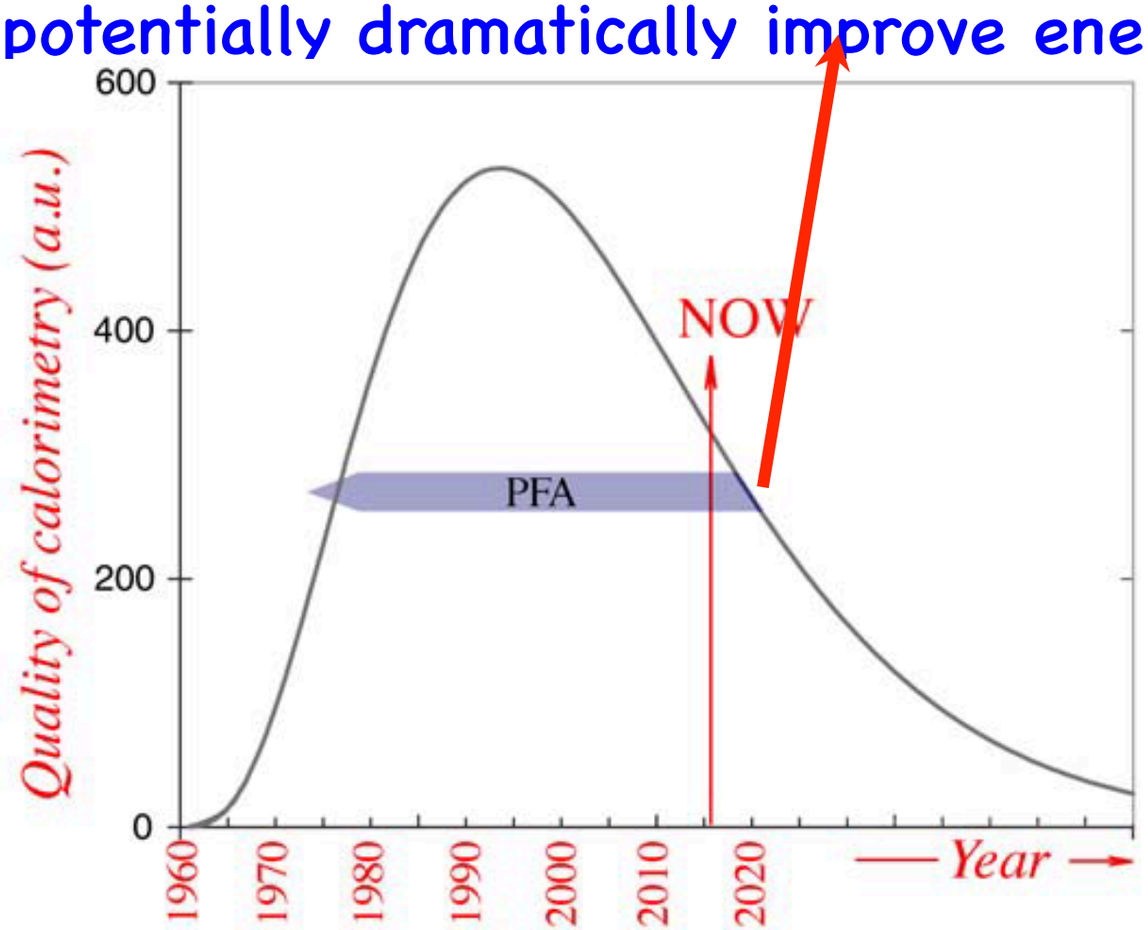
Summary

1. From the start (2012) very efficient joint R&D (STAR Forward and EIC)

2. In April 2019 we will have our second and final calibration test run for STAR FCS'.

3. In Run 19, Run 20 we will have full scale prototype operated at STAR IP, which is important to be ready for one shot (500 GeV run) in 2021.

4. Unique opportunity to use STAR FCS prototype to test new approach to potentially dramatically improve energy resolution of sampling HCals.



Let's do it!

Thanks.