The Catholic University of America

Hadronic calorimetry

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Science and Instrumentation of the 2nd Interaction Region for the EIC

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Yellow Report

Credits: Material by the EIC Yellow Report Initiative, Detector Calorimetry working group and Physics working group

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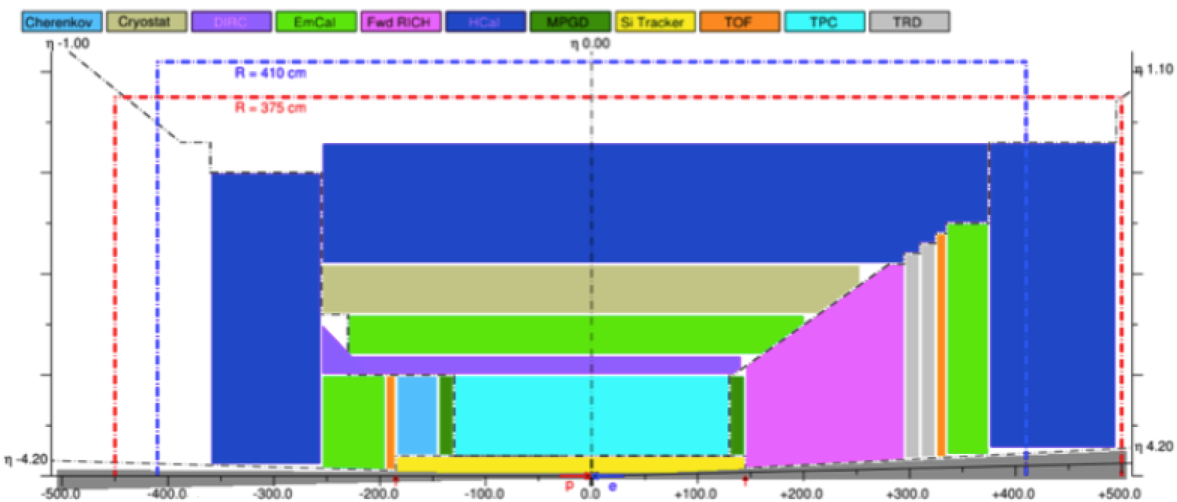
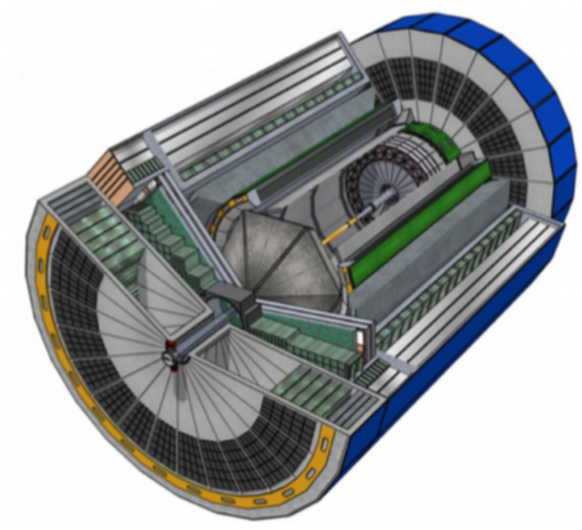
EIC Hadron Calorimetry specification and conservative option





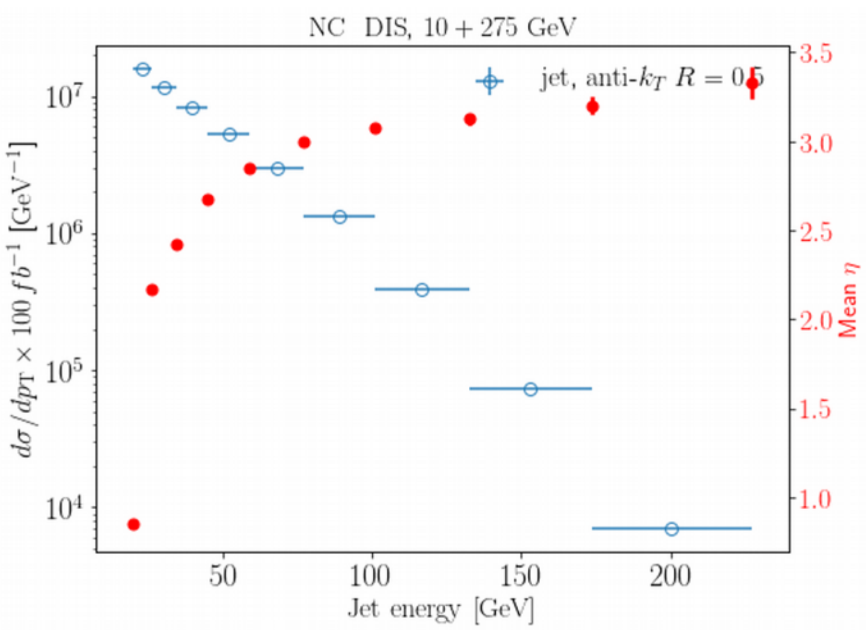
HCAL parameters from EIC specifications (YR, Vol. 2, Table 10.6) and for a technically conservative option

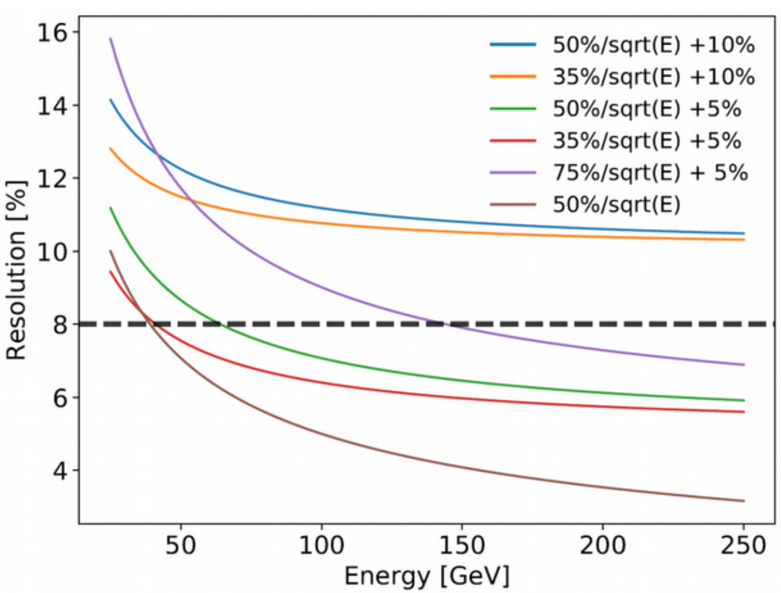
η	EIC specification		Conservative option	
	σ(E)/E, %	Emin, MeV	σ(E)/E, %	Emin, MeV
-4.0 to 3.5	50/√E+6	500	50/√E+10	500
-3.5 to -1.0	45/√E+6	500	50/√E+10	500
-1.0 to +1.0	85/√E+7	500	100/√E+10	500
+1.0 to +3.5	35/√E	500	50/√E+10	500

Physics requirements by Jets-HF WG

η	Requested σ(E)/E, %
-3.5 to -1.0	50/√E + 10
-1.0 to +1.0	85/√E + 10
+1.0 to +3.0	50/√E + 10
+3.0 to +3.5	50/√E + 5
+3.5 to +4.0	50/√E + 5

HCal resolution of 50%/√E +10% was found to be adequate in the region 1.0 < η < 3.0 where tracking performance is generally good and jet energies are relatively low.
For η > 3, the constant term of roughly 5% is needed as jet energies rapidly increase in this region while tracking resolution significantly degrades, enhancing the importance of the HCal energy resolution, which is dominated by the constant term at these energies

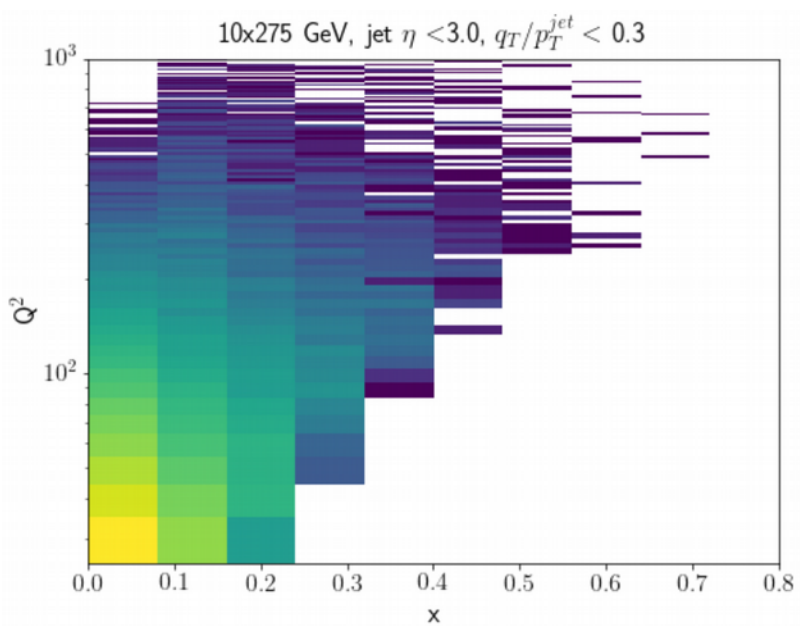


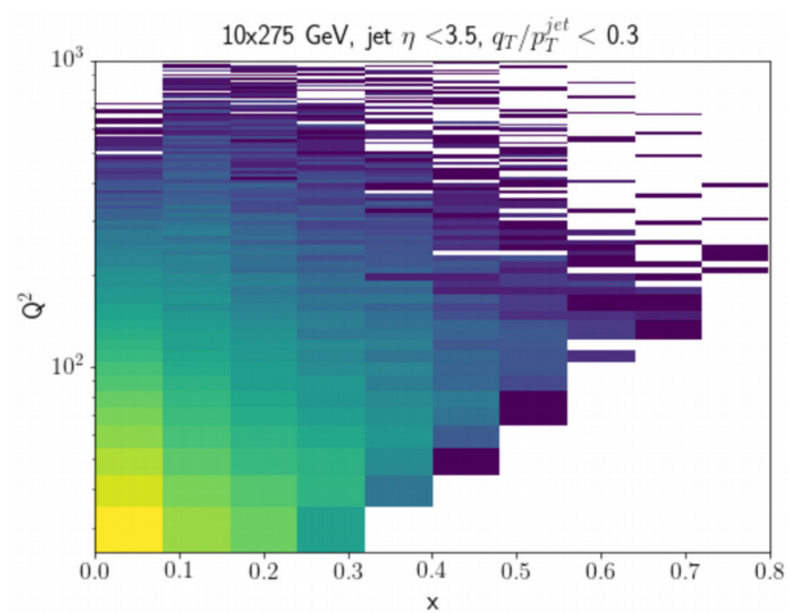


Physics requirement by Jets-HF WG

η	Requested σ(E)/E, %
-3.5 to -1.0	$50/\sqrt{E} + 10$
-1.0 to +1.0	$85/\sqrt{E} + 10$
+1.0 to +3.0	$50/\sqrt{E} + 10$
+3.0 to +3.5	$50/\sqrt{E} + 5$
+3.5 to +4.0	$50/\sqrt{E} + 5$

The HCal acceptance need to be extended from $\eta < 3.5$ to $\eta < 4.0$. This will provide access to the highest bjorken x regions as seen in the figures below. As tracking will be absent in for $\eta > 3.5$, good HCal resolution will be imperative for maintaining good overall jet energy resolution. This will be necessary to allow differential TMD measurements with jets such as the electron-jet Sivers asymmetry in the valence region and mid to high Q2. The phasespace gained with HCAL up to 4.0 is crucial given that existing DIS data with transversely-polarized targets stops at about x=0.3



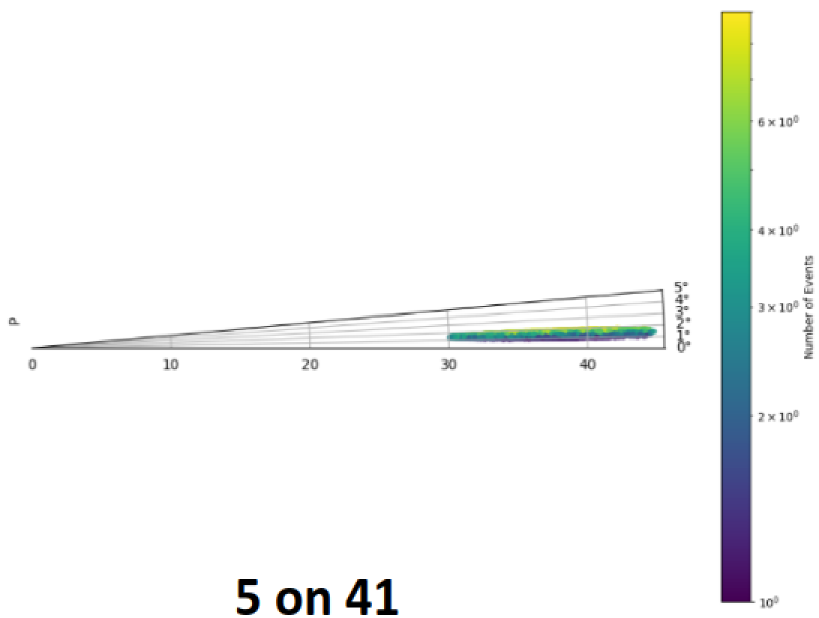


Physics requirements by Diffractive reactions-Tagging WG

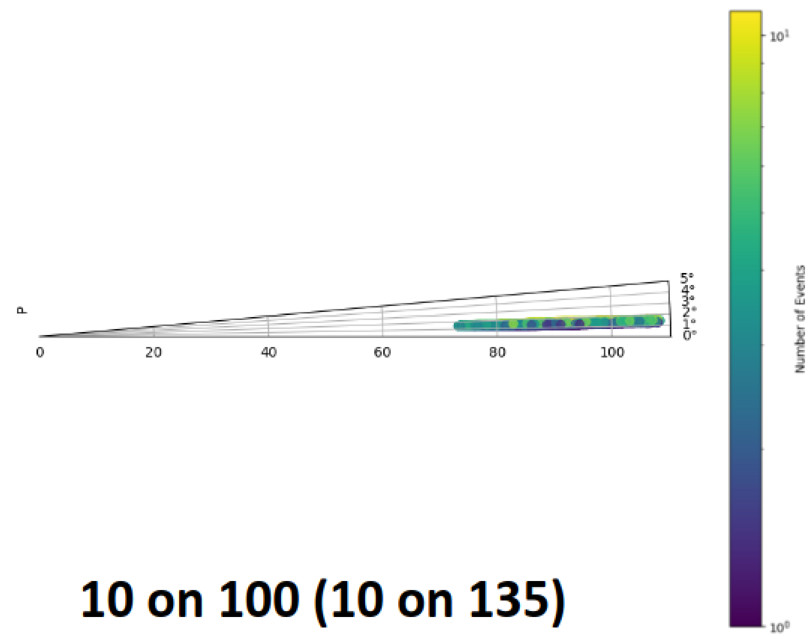
η	Requested σ(E)/E, %
-3.5 to -1.0	$50/\sqrt{E} + 10$
-1.0 to +1.0	$85/\sqrt{E} + 10$
+1.0 to +3.0	$50/\sqrt{E} + 10$
+3.0 to +3.5	$35/\sqrt{E}$

For large-x processes need delta x < 0.1, where HCAL resolution determines delta x

- For a 50 GeV hadron/jet energy and $35\%/\sqrt{E}$ → delta x=0.05



5 on 41



10 on 100 (10 on 135)

Hadronic calorimetry properties for EIC

- Desired properties for the EIC calorimeters, beyond the requirement on energy resolution, are: compactness and mechanical sturdiness, minimizing the space required for passive mechanical support structures

- Can be achieved with a steel absorber - would also eliminate dead material between Emcal and HCal which degrades the overall performance

- W/ScFi for the EM part simplifies the construction of an EM calorimeter with high sampling frequency and small sampling fraction (approximately being compensated)

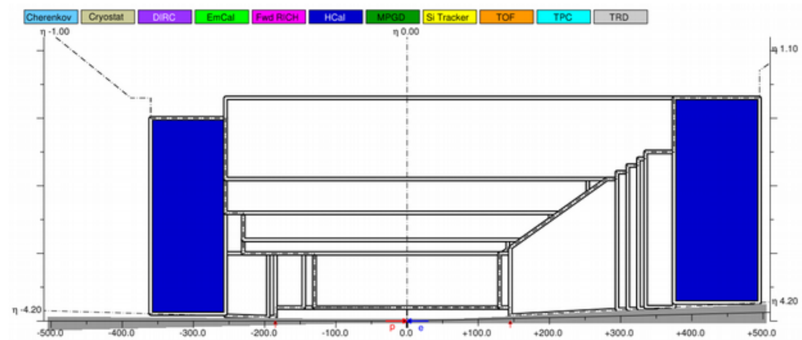
η	Total depth, cm	Hadronic interaction length	Energy resolution σ(E)/E, %	Spacial resolution σ(X), mm	Granularity mm^2	Technology examples
-4.0 to -2.0	105	~5 λ	50/√E + 10	50/√E + 30	100x100	Fe/Sc
-2.0 to -1.0	105	~5 λ	50/√E + 10	50/√E + 30	100x100	Fe/Sc
-1.0 to +1.0	110	~5 λ	100/√E + 10	50/√E + 30	100x100	Fe/Sc
+1.0 to +4.0	105	~5 λ	50/√E + 10	50/√E + 30	100x100	Fe/Sc

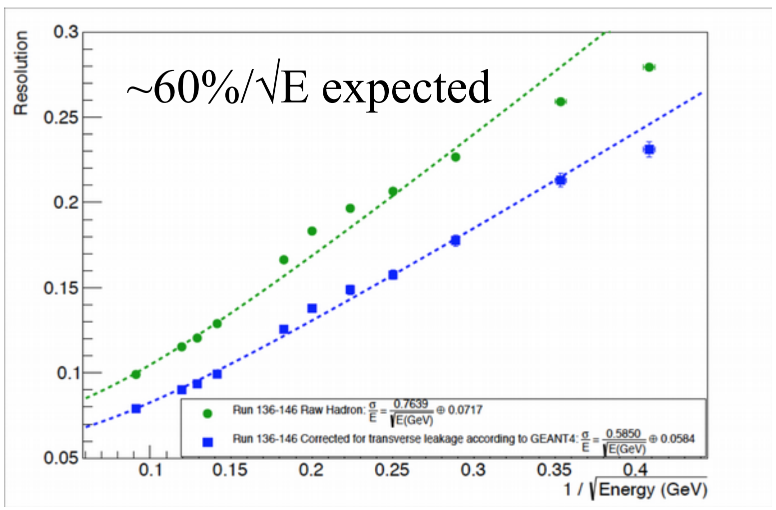
Expected performance

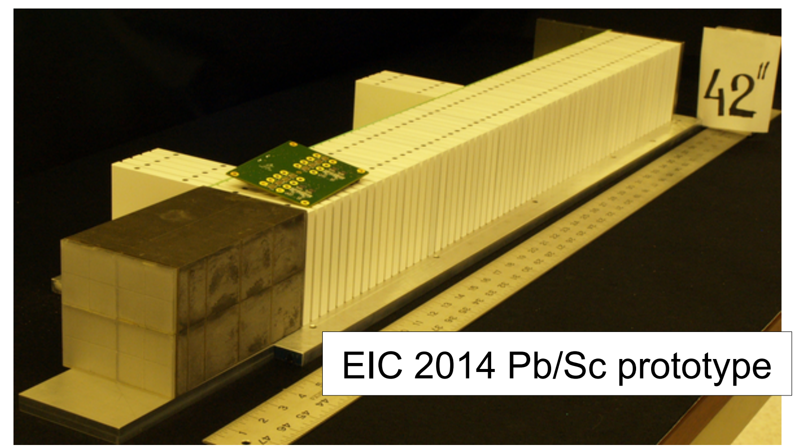
As shown at previous slides: there is a desire to have an insert for η>3 with higher resolution - better than ~40%/√E with a constant term of ~ 5%

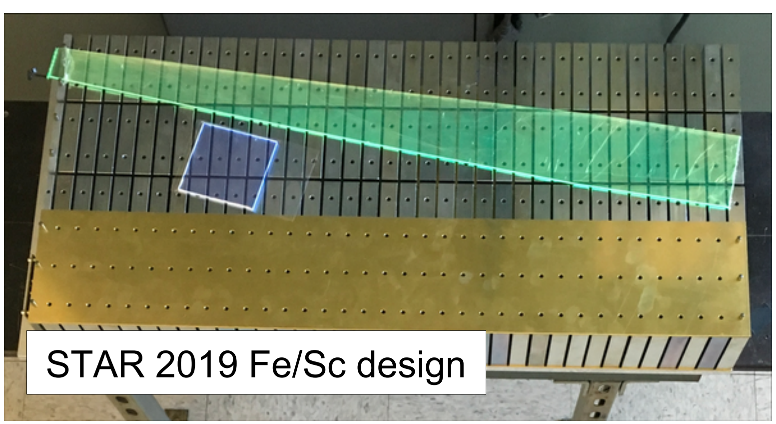
HCAL options in endcap

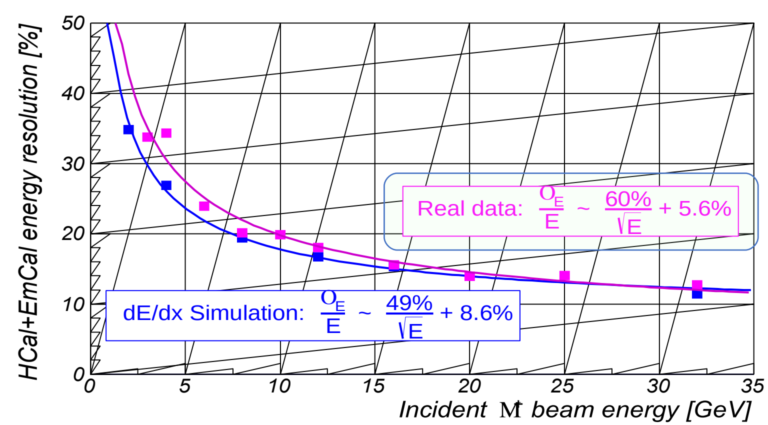
- HCAL in endcap
- Compact LEGO-style design
- Can be used with a mixed Fe/Pb absorber





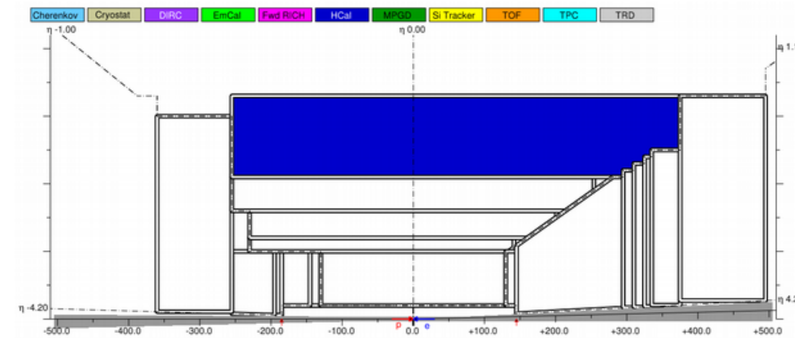


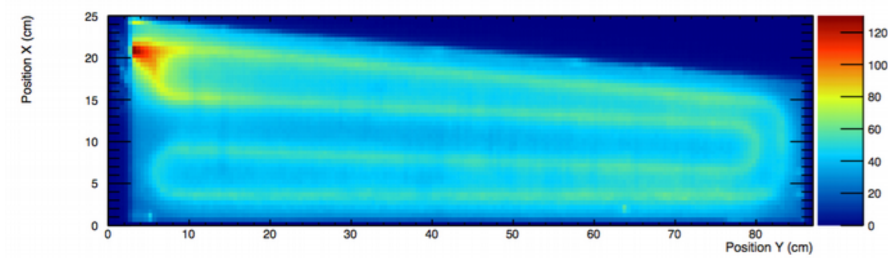




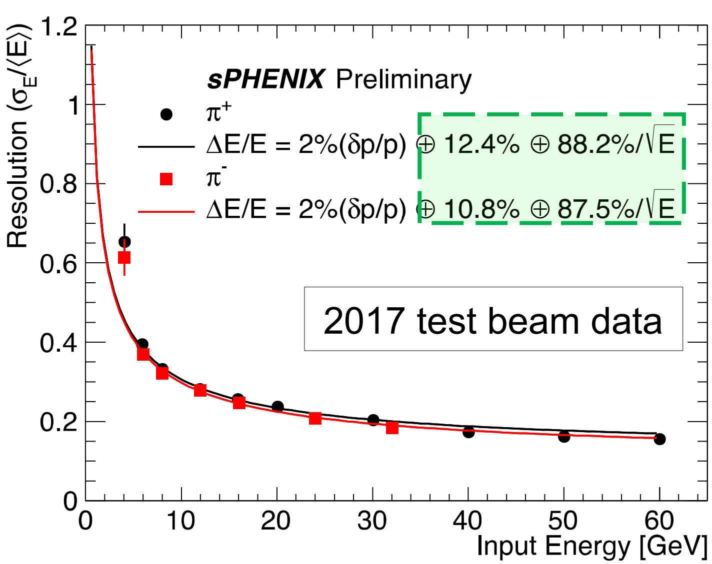
HCAL option in barrel

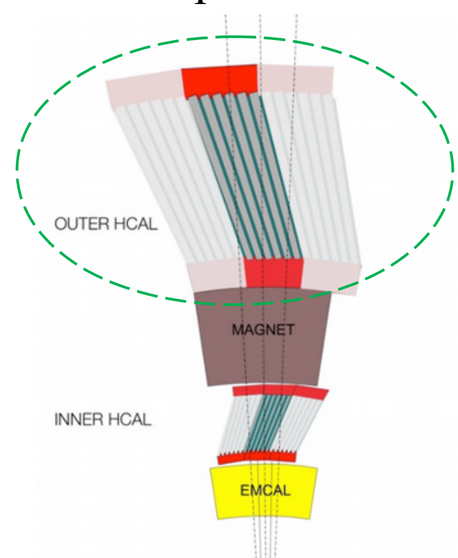
- Similar as used in sPHENIX
- Solid 32-sector steel frame, but only ~3.5 λ
- Moderate energy resolution





Scintillator plate with embedded WLS fiber

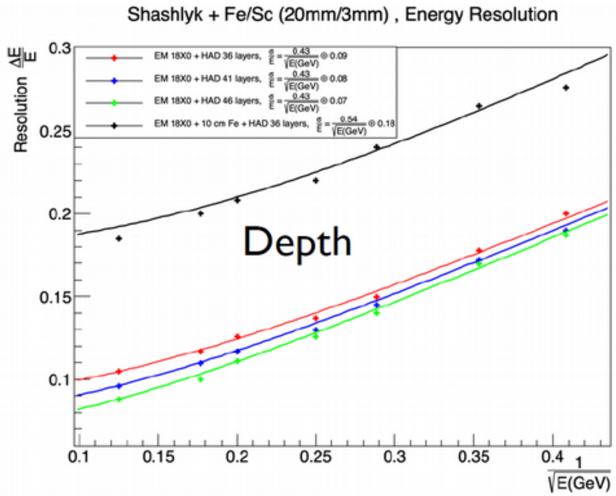




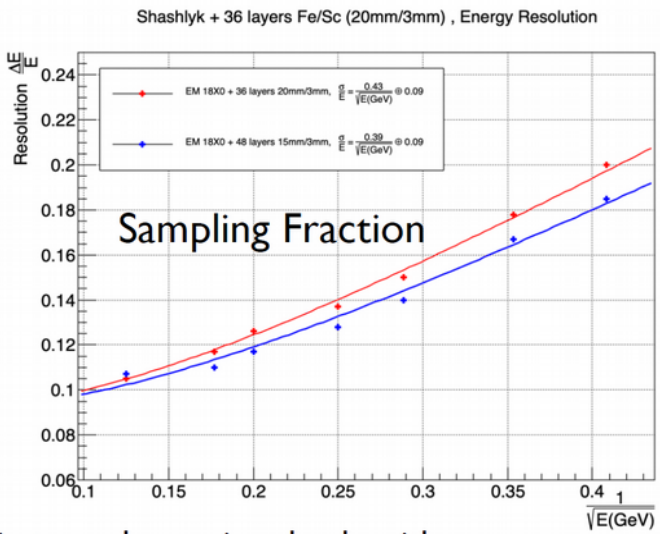
High resolution hadron calorimetry notes

O. Tsai (UCLA), EIC YR Calorimetry working group meeting, 04.07.20

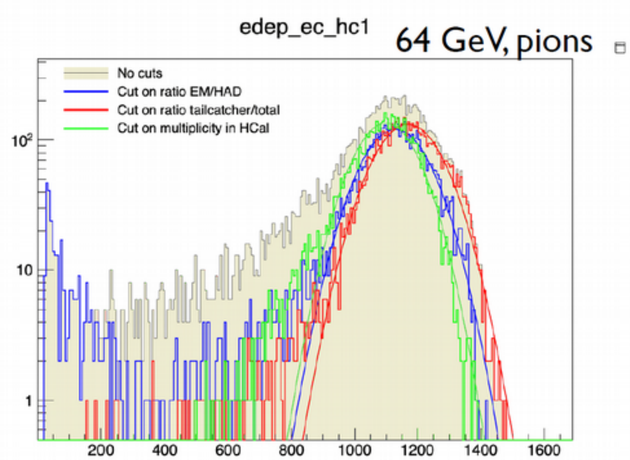
For high resolution HCal one need lot of space and high sampling fraction. As an illustration.

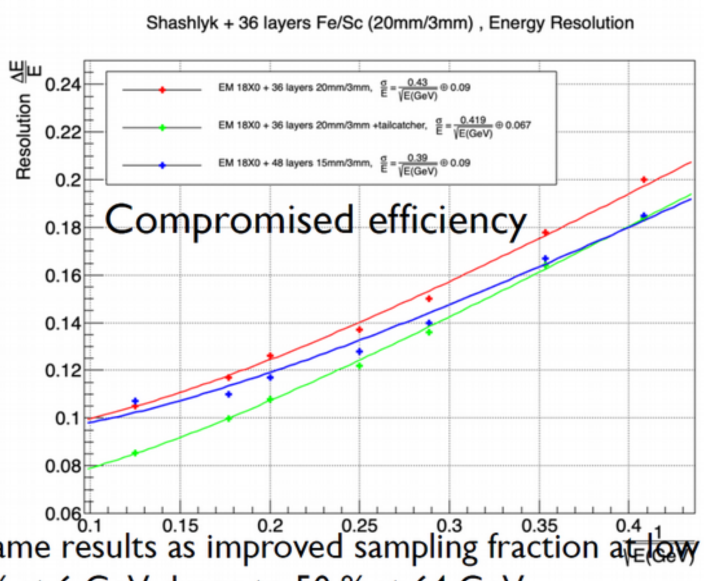


Constant term decreasing slowly with increased depth. log dependence.



Stochastic term decreasing slowly with increased sampling fraction. (10% improvement vs 30% increase in cost



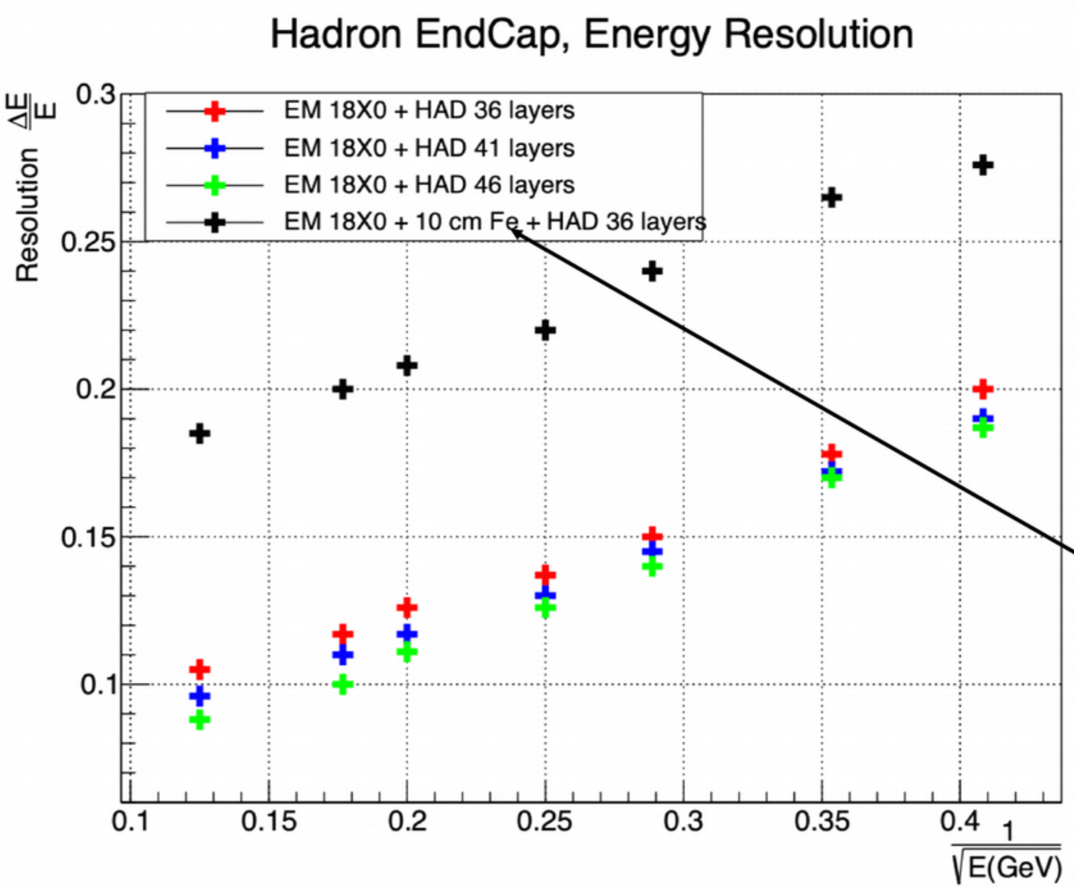


Trade off. Cheap tail catcher gives same results as improved sampling fraction at low energies, But for the cost of 'efficiency', ~ 90% at 6 GeV drops to 50 % at 64 GeV

Limiting factors for high resolution HCALs

O. Tsai(UCLA), HCAL high resolution, EIC YR Temple meeting, 04.07.20

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.

Compensated high resolution HCALs

O. Tsai(UCLA), EIC YR Calorimetry working group meeting, 04.07.20

- All operational high resolution HCALs were compensated:

ZEUS	~35%/√E+2.0%	DU/Sc	(Longitudinal leakages treated with BCAL)
WA80	~33%/√E+1.3%	DU/Sc	(Zero Degree Calorimeter, full absorption)
E864	~34%/√E+3.5%	Pb/ScFi	(Full absorption, copied from R.W.SPACAL)

- Resolution was dominated by sampling fluctuations
- Used high sampling fraction or high sampling frequency (Pb)
- Compensation were extensively studied at that time
- One of the first compensated calorimeter was ZEUS Pb/Sc prototype
- There are many factors one has to take into account to achieve compensation
  At zero order, compensation defined by ratio of thickness of passive and active medium,
  DU/Sc ~1, Pb/Sc ~4

These high resolution HCALs require a lot of space, e.g.

ZEUS: 4 meters with ~2 meters occupied by DU/Sc, the rest by the backing calorimeter
SPACAL: 2 meters for Pb/ScFi plus 0.7m for readout

STAR FCS and eRD1 EIC R&D

- STAR forward upgrade developed a non-compensated calorimetry system consisting of Pb/Sc shashlik for EM part (utilizing existing EM blocks from PHENIX experiment) and Fe/Sc hadronic part
- A small prototype of this system was built and tested at FNAL in 2019
- Accounting for transverse leakages in the test beam prototype energy resolution for STAR FCS system is close to $60\%/\sqrt{E} + 6\%$
- An earlier tested compensated prototype (W/ScFi for EM and Had section copying ZEUS Pb/Sc) had approximately 30% better hadronic energy resolution compared to the non-compensated version
- With some additional R&D efforts a similar system with W/ScFi option for EmCal might meet the requirements for the EIC detector

High resolution HCALs are challenging – need additional R&D to demonstrate

Dual Readout method for high resolution HCALs concept

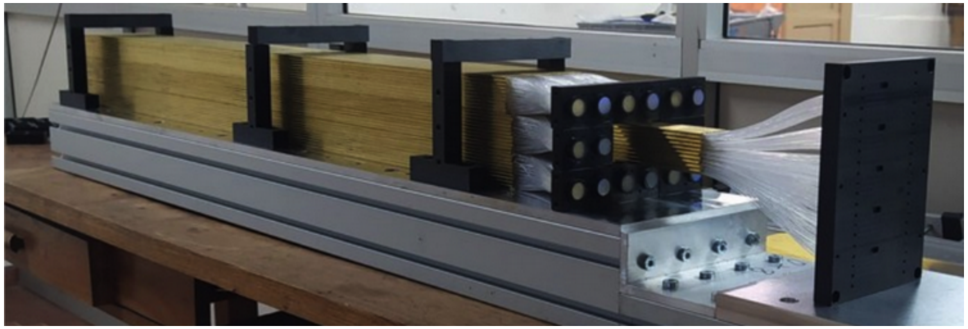
- By comparing the signals produced by scintillation light and Cherenkov light in the same detector, and considering the timing and spatial characteristics of the showers, the EM shower fraction can be determined for individual events.

- 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)

- The EM shower fluctuations are the main culprit for problems encountered with hadronic calorimetry. The validity of this principle has been demonstrated with the DREAM fiber calorimeter. A realization of the dual readout at EIC would have to take into account the relatively low energy of hadrons and the spacial constrain

- Some examples discussed at recent EIC calorimetry workshop:
  Roberto Ferrari talk Dual Readout Calorimeter:
  https://indico.phy.ornl.gov/event/38/contributions/181/attachments/223/761/EIC_DR_ferrari.2021.03.14.pdf
  Tanja Horn talk EIC Backward Calorimetry Project:
  https://indico.phy.ornl.gov/event/38/contributions/188/attachments/226/766/EEEMCal-EIC-Calorimeter-WS-March2021-v2.pdf



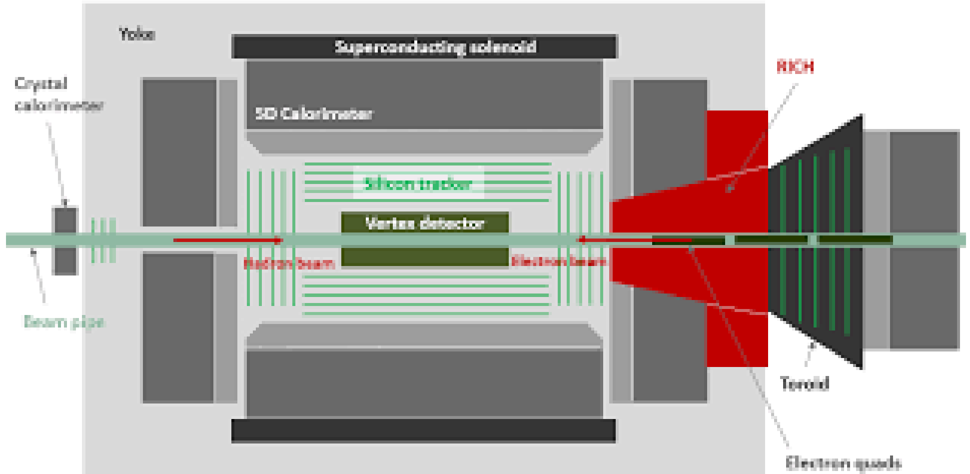
Digital calorimeter as alternative method for high resolution HCAL

- Alternative concepts of designing the whole detector where role of calorimeters is quite different to what was traditionally used were initially driven by HEP for future linear collider development with requirement of extremely high energy resolution for jets

- Hadron calorimeters in these concepts are essentially digital devices with hundreds of millions of channels to track every single particle in hadronic showers, required for particle flow algorithms. Example CMS high granularity calorimeter:
  https://indico.phy.ornl.gov/event/38/contributions/245/attachments/216/757/20210315_EIC_V2.pdf

- This approach requires significant space for detector, appropriate design of the magnet and perfect tracking performance at all rapidity

- TOPSiDE concept of the EIC detector is an example of such approach. The TOPSiDE concept does not put any special requirements on the calorimetry system, and the reference detector calorimetry requirements could be met by a wide variety of designs and technologies, all capable of integrating within the TOPSiDE concept
  See Chao Peng talk : https://indico.bnl.gov/event/10677/contributions/46284/attachments/33143/53137/TOPSiDE%20Detector.pdf



Summary

- EIC requirements up to $\eta\sim3$ may be achieved with existing technologies tried by eRD1 consortium and STAR Forward upgrade with some additional R&D efforts to improve on performance of STAR like forward calorimeter system
- A high resolution HCal insert for $\eta>3$ will require additional R&D efforts, e.g. to develop high density fiber calorimeter with SiPM readout or another suitable technology
- Alternative options several R&D efforts ongoing