Detector Matrix – Forward HCAL resolution

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Forward HCAL resolution requirements

https://physdiv.jlab.org/DetectorMatrix/

<table>
<tr><th>η</th><th>θ</th><th colspan="2" rowspan="2">Nomenclature</th><th></th><th colspan="6">Tracking (B = 1.5 T)</th><th colspan="3">Electrons and Photons</th><th colspan="2">π/K/p</th><th colspan="2">HCAL</th><th rowspan="2">Muons</th></tr>
<tr><th></th><th>(mrad)</th><th>Resolution</th><th>Relative momentum</th><th>Allowed X/X_0</th><th>minimum-pT</th><th>Trasverse pointing res.</th><th>Longitudinal pointing res.</th><th>Resolution σ_E/E</th><th>PID</th><th>min E photon</th><th>p-Range (GeV/c)</th><th>Separation</th><th>Resolution σ_E/E</th><th>Energy</th></tr>
<tr><td>-4.0 to -3.5</td><td></td><td></td><td rowspan="6">Backward Detector</td><td></td><td colspan="13">reduced performance</td><td rowspan="10">muons useful for bkg, improve resolution</td></tr>
<tr><td>-3.5 to -3.0</td><td></td><td rowspan="14">Central Detector</td><td></td><td rowspan="2">σp/p ~ 0.2%×p ⊕ 5%</td><td rowspan="14">~5% or less X</td><td rowspan="5">to be determined</td><td rowspan="3"></td><td></td><td rowspan="3">1%/E⊕2.5%/√E⊕1% (for 40 cm space)</td><td rowspan="3">π suppression up to 1:1E-4</td><td rowspan="3">20 MeV</td><td rowspan="5">≤ 10 GeV/c</td><td rowspan="14">≥ 3 σ</td><td rowspan="5">50%/√E⊕10% (Better resolution required more space and R&D)</td><td rowspan="14">~500 MeV</td></tr>
<tr><td>-3.0 to -2.5</td><td></td><td></td><td></td></tr>
<tr><td>-2.5 to -2.0</td><td></td><td></td><td rowspan="3">σp/p ~ 0.04%×p ⊕ 2%</td><td></td></tr>
<tr><td>-2.0 to -1.5</td><td></td><td></td><td rowspan="2">dca(xy) ~ 40/pT µm ⊕ 10 µm</td><td rowspan="2">dca(z) ~ 100/pT µm ⊕ 20 µm</td><td rowspan="2">2%/E⊕(4-8)%/√E⊕2% (Upper limit achievable with 50 cm space *Better resolution requires ~65 cm space allocated)</td><td rowspan="2">π suppression up to 1:(1E-3 - 1E-2)</td><td rowspan="2">50 MeV</td></tr>
<tr><td>-1.5 to -1.0</td><td></td><td></td></tr>
<tr><td>-1.0 to -0.5</td><td></td><td rowspan="4">Barrel</td><td></td><td rowspan="4">σp/p ~ 0.04%×p ⊕ 1%</td><td rowspan="4">100 MeV/c with 50% acceptance (similar for pi and K)</td><td rowspan="4">dca(xy) ~ 30/pT µm ⊕ 5 µm</td><td rowspan="4">dca(z) ~ 30/pT µm ⊕ 5 µm</td><td rowspan="4">2%/E⊕(12-14)%/√E⊕(2-3)% for 30 cm space A better stochastic term can be achieved with more space: 2.5% with crystals 35cm 10% sampling 40cm 4% SciGlass 65cm</td><td rowspan="4">π suppression up to 1:1E-2</td><td rowspan="4">100 MeV (50 MeV if higher resolution)</td><td rowspan="3">≤ 6 GeV/c</td><td rowspan="4">100%/√E+10%</td></tr>
<tr><td>-0.5 to 0.0</td><td></td><td></td></tr>
<tr><td>0.0 to 0.5</td><td></td><td></td></tr>
<tr><td>0.5 to 1.0</td><td></td><td></td><td>≤ 6 GeV/c</td></tr>
<tr><td>1.0 to 1.5</td><td></td><td rowspan="5">Forward Detectors</td><td></td><td rowspan="3">σp/p ~ 0.04%×p ⊕ 2%</td><td rowspan="5">to be determined</td><td rowspan="2">dca(xy) ~ 40/pT µm ⊕ 10 µm</td><td rowspan="3">dca(z) ~ 100/pT µm ⊕ 20 µm</td><td rowspan="5">2%/E⊕(4*-12)%/√E⊕2% Upper limit achievable with 40cm space *Better resolution requires ~65 cm space allocated</td><td rowspan="5">3σ e/π up to 15 GeV/c</td><td rowspan="5">50 MeV</td><td rowspan="5">≤ 50 GeV/c (worse approaching 3.5)</td><td rowspan="5">50%/√E +10% (35%/√E not achievable)</td><td></td></tr>
<tr><td>1.5 to 2.0</td><td></td><td></td><td></td></tr>
<tr><td>2.0 to 2.5</td><td></td><td></td><td rowspan="3"></td><td></td></tr>
<tr><td>2.5 to 3.0</td><td></td><td></td><td rowspan="2">σp/p ~ 0.2%×p ⊕ 5%</td><td></td><td></td></tr>
<tr><td>3.0 to 3.5</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3.5 to 4.0</td><td>↑ e</td><td></td><td></td><td colspan="13">Reduced performance</td><td></td><td></td></tr>
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Forward HCAL performance seems not aligned with physics requirements

Physics Requirements – Forward HCAL resolution

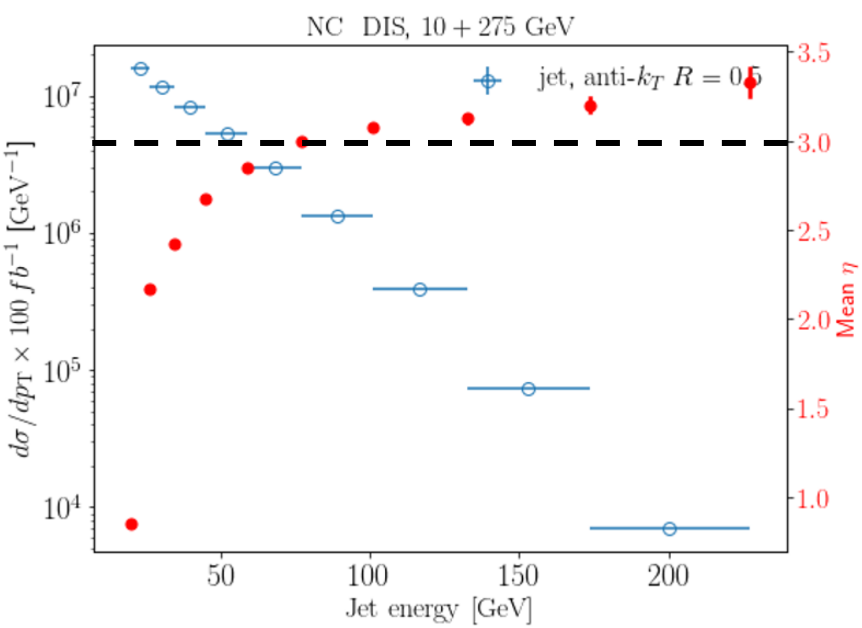
https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Physics_Jets-HF

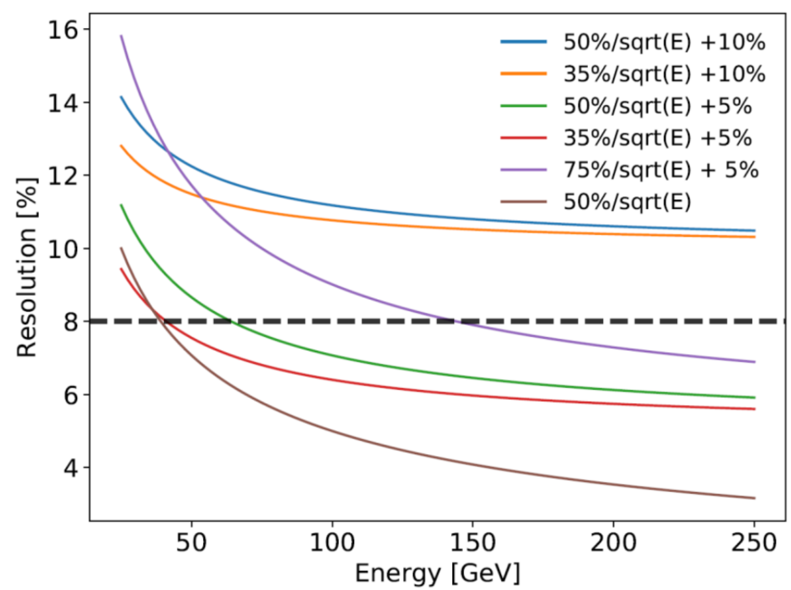
HCal Energy Resolution

Eta Range	Default Resolution (σE/E)	Requested (σE/E)
-3.5 < η < -1.0	50%/√E	Same (~10% constant term is acceptable)
-1.0 < η < 1.0	N/A	85%/√E + 10%
1.0 < η < 3.0	50%/√E	50%/√E + 10%
3.0 < η < 3.5		50%/√E + 5%
3.5 < η < 4.0	N/A	

For η > 3, a constant term of ~5% is needed as jet energies rapidly increase in this region while tracking resolution significantly degrades

- ➢ energy resolution is important
- ➢ energy resolution dominated by the constant term





Physics Requirements – Forward HCAL resolution

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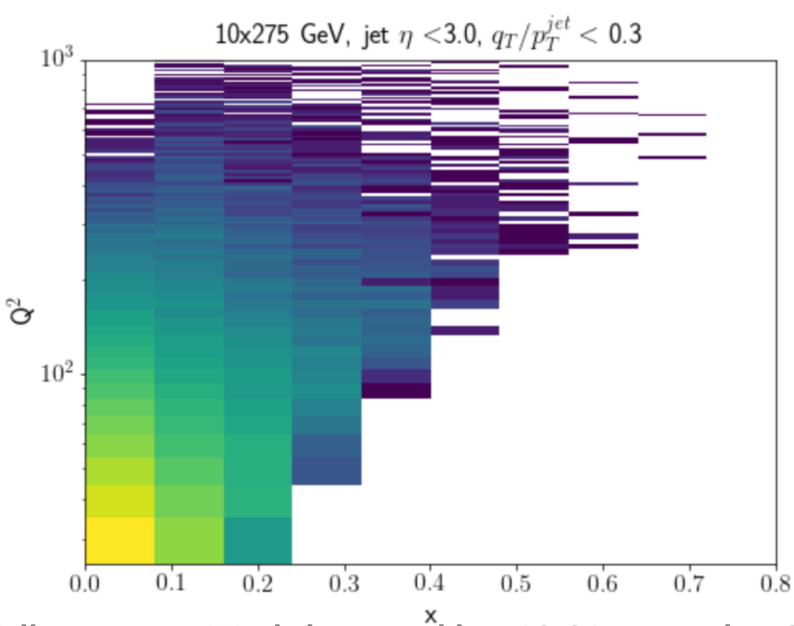
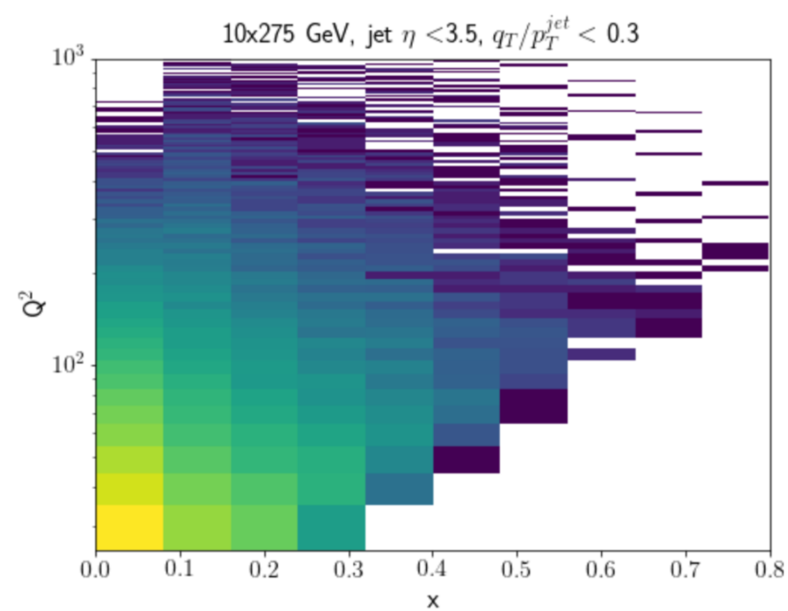
HCal Energy Resolution

Eta Range	Default Resolution (σE/E)	Requested (σE/E)
$-3.5 < \eta < -1.0$	50%/√E	Same (~10% constant term is acceptable)
$-1.0 < \eta < 1.0$	N/A	85%/√E + 10%
$1.0 < \eta < 3.0$	50%/√E	50%/√E + 10%
$3.0 < \eta < 3.5$		50%/√E + 5%
$3.5 < \eta < 4.0$	N/A	

As tracking will be absent for η > 3.5, good HCal resolution will be imperative for good overall jet energy resolution.

- differential TMD measurements with jets, e.g. electron-jet Sivers asymmetry in the valence region and mid to high Q^2.





Physics Requirements – Forward HCAL resolution

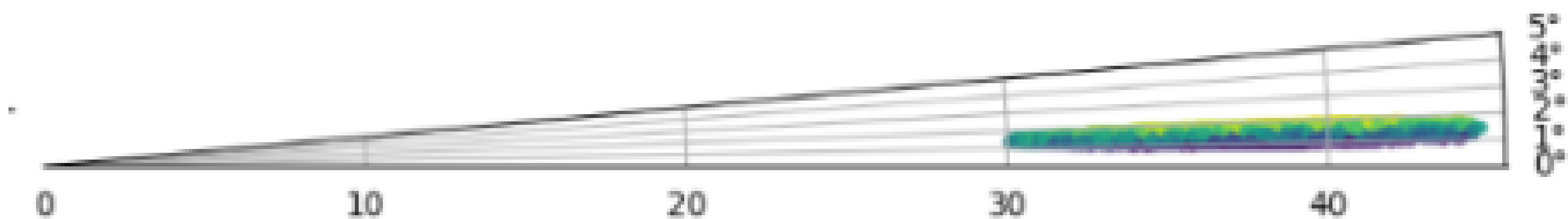
https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Physics_Diffractive_Reactions_-_Tagging

HCal Energy Resolution

Eta Range	Default Resolution (σE/E)	Requested (σE/E)
-3.5 < η < -1.0	50%/√E	Same (~10% constant term is acceptable)
-1.0 < η < 1.0	N/A	85%/√E + 10%
1.0 < η < 3.0	50%/√E	50%/√E + 10%
3.0 < η < 3.5		35%/√E
	N/A	

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

- For a 50 GeV hadron/jet energy and 35%/√E → delta x=0.05



Physics Performance – Forward HCAL resolution

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

η	total depth, cm	Energy resolution σE/E, %	Spacial resolution σX, mm	Granularity, mm^2	Technology examples
-4.0:-2.0	105	$50/\sqrt{E}\oplus10$	$50/\sqrt{E}\oplus30$	100×100	Fe/Sc
-2.0:-1.0	105	$50/\sqrt{E}\oplus10$	$50/\sqrt{E}\oplus30$	100×100	Fe/Sc
-1.0:1.0	110	$100/\sqrt{E}\oplus10$	$50/\sqrt{E}\oplus30$	100×100	Fe/Sc
1.0:4.0	105	$50/\sqrt{E}\oplus10$	$50/\sqrt{E}\oplus30$	100×100	Fe/Sc

- ❑ 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).

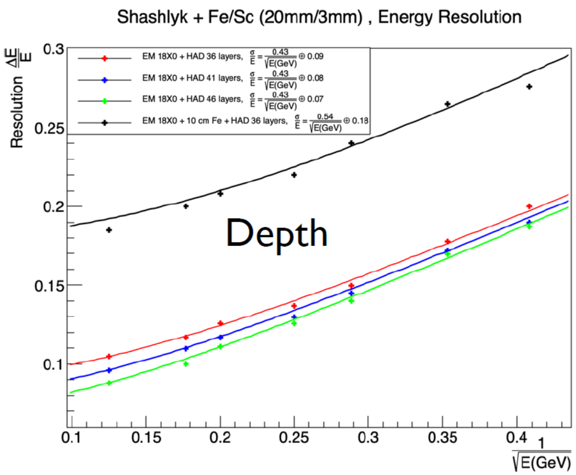
Expected performance

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

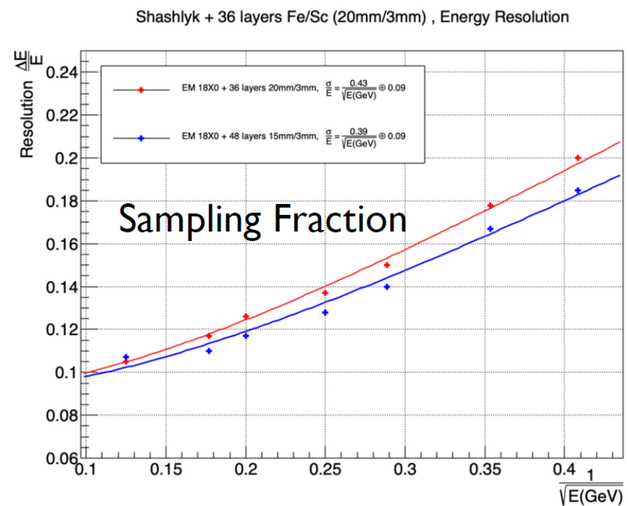
Notes on high-resolution hadron calorimetry

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

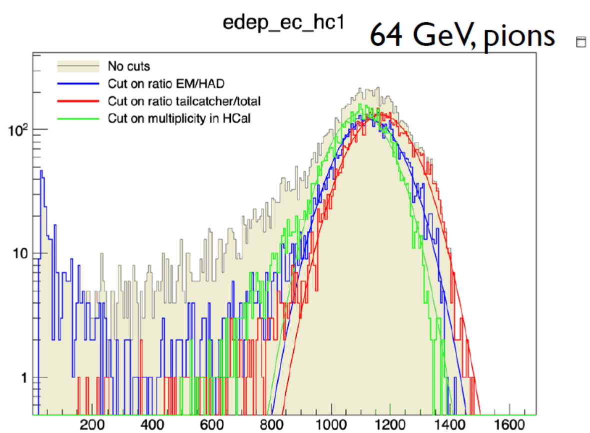
For high resolution HCal one need lot of space and high sampling fraction. As an illustration.

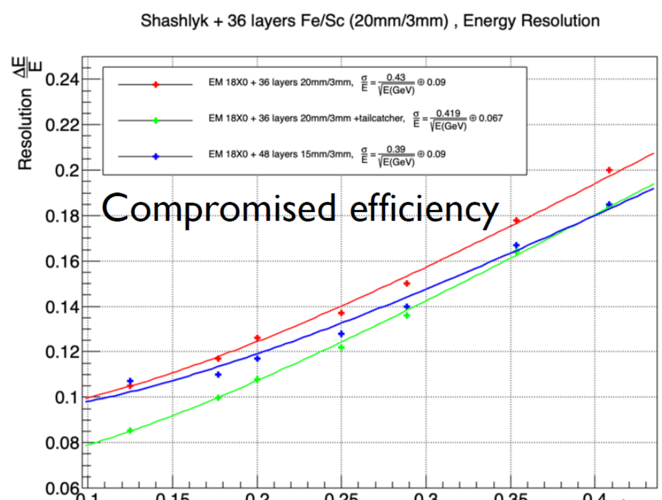


Constant term decreasing slowly with increased depth. log dependence.



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



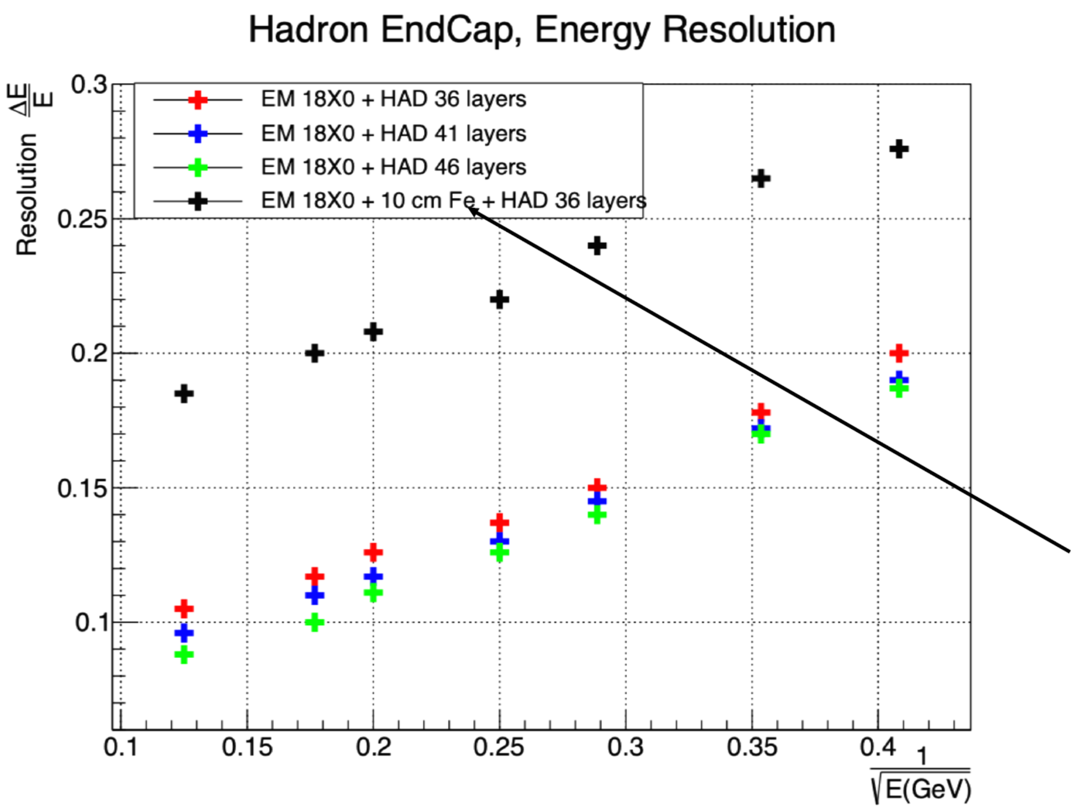


Trade off. Cheap tail catcher gives same results as improved sampling fraction at low energies,
But for the cost of 'efficiency', ~ 90% at 6 GeV drops to 50 % at 64 GeV

Notes on high-resolution hadron calorimetry

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

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.

Notes on high-resolution hadron calorimetry

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

1. All operational high resolution HCals were compensated

Quoted energy resolutions:

ZEUS ~ $35\%/\sqrt{E} \oplus 2\%$ DU/Sc (longitudinal leakages treated with BCAL)

WA80 ~ $33\%/\sqrt{E} \oplus 1.3\%$ DU/Sc (Zero Degree Calorimeter, full absorption)

E864 ~ $34\%/\sqrt{E} \oplus 3.5\%$ Pb/ScFi (full absorption) (copied from R.W. SPACAL)

2. Resolution was dominated by sampling fluctuations.

3. Used high sampling fraction or high sampling frequency (Pb).

4. Compensation were extensively studied at that time.

5. First compensated calorimeter was ZEUS Pb/Sc prototype.

6. 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 calo
- SPACAL: 2 meters for Pb/ScFi plus 0.7m for readout

eRD1 EIC R&D and STAR FCS

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

- ❑ 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

Alternative methods for high resolution HCALs (1)

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

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 $20\%/\sqrt{E}$, small constant term, good linearity).

Alternative methods for high resolution HCALs (2)

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

- 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.

- 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.

Discussion high resolution HCALs

https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Detector_Calorimetry

- ❑ EIC requirements up to η~3 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 η>3 will require additional R&D efforts, e.g. to develop high density fiber calorimeter with SiPM readout.