Backward Hadronic Calorimeter for ePIC

Overview and status

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The Ohio State University

Joint Kent State and Ohio State University meeting 24.5.2024

The Ohio State University

Outline

Introduction and organization

Webpage set up - see for up to date info

https://wiki.bnl.gov/EPIC/index.php?title=Backward_Hcal

Mailing list

epic-backward-hcal-l@lists.bnl.gov

Mattermost channel

https://chat.epic-eic.org/main/channels/det-hcal-backward

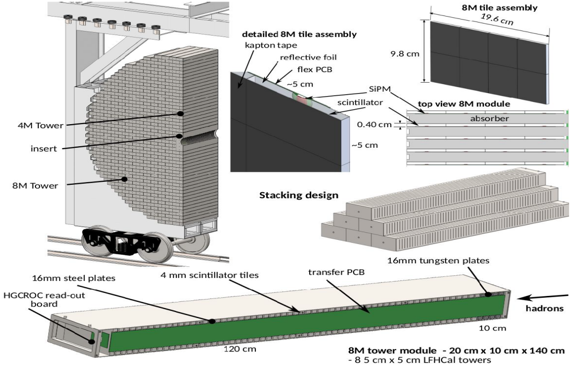
Institutions

OSU, CTU in Prague, UNH, BNL (help), UIUC (joined)

Introduction - backward HCal (nHCal)

Requirements: https://eic.jlab.org/Requirements/

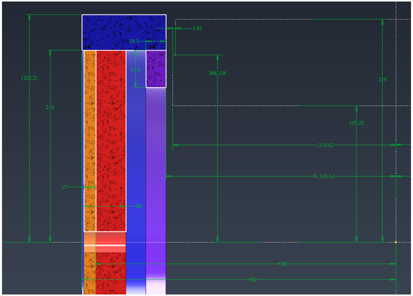
A future backward HCal shall provide functionality of a tail catcher for the high resolution e/m calorimeter in electron identification, as well as for jet kinematics measurement at small Bjorken x



- Design considerations:
  - High efficiency for low energy neutron detection
  - Good spatial resolution to distinguish neutral/charged hadrons
- Follow similar solutions as Forward HCal instead of STAR EEMC megatiles
  - Due to required quick dissassembly of STAR - the EEMC megatiles are no longer an option
  - Can make adjustments to Forward HCal (LFHCAL) design, but no need to reinvent the wheel

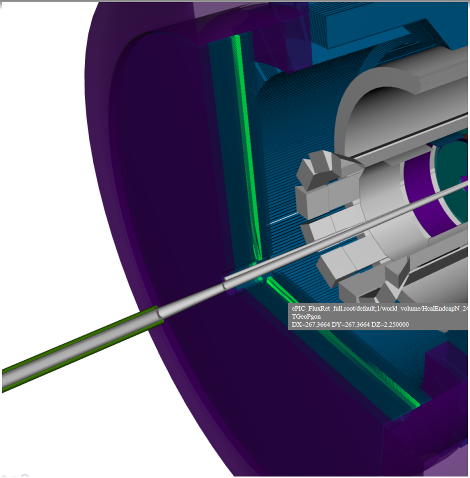
Design

- Sampling calorimeter with 10 alternating layers, $2.4\lambda^0$ (red), similar to Belle-II KLM:
  - non-magnetic steel 4 cm
  - plastic scintillator 4 mm - to be adjusted
- Light collection by SiPM:
  - Candidate (to verify): S14160-1315PS `https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/mppc_mppc-array/S14160-1315PS.html`
- Electronics to follow solutions of other calorimetry systems HGCROCv3
- FEEs placed in front of nHCal



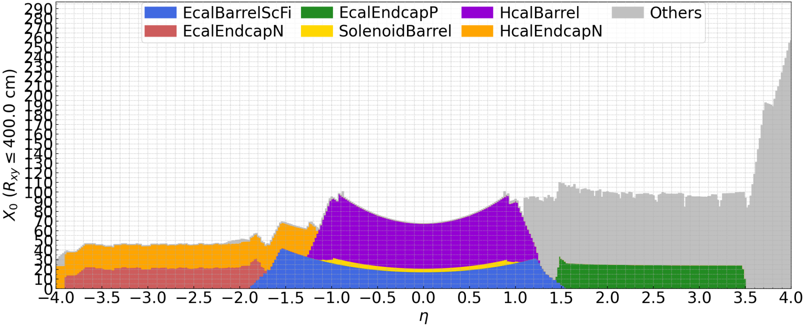
- nHCal decoupled from the magnetic steel ⇒ more flexibility
- Support structures design required for TDR

Geometry implementation in dd4hep



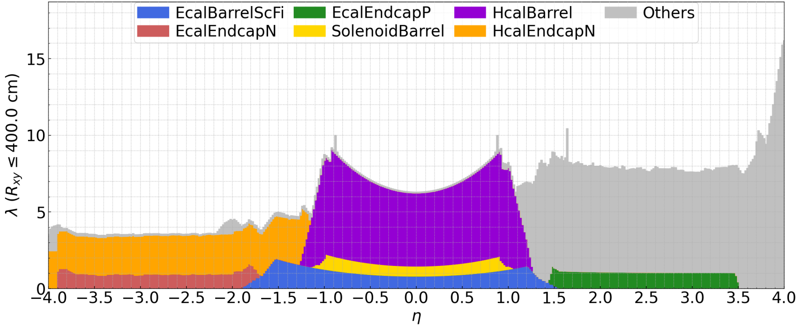
- A simplified version with STAR EEMC tiles already present in the main ePIC branch and included in the simulation campaigns up to November, stainless steel as an absorber
  - Good enough for basic checks
- Forward HCal-type geometry with $10\,\mathrm{cm} \times 10\,\mathrm{cm}$ tiles implemented for December campaign
- Flux return steel surrounding nHCal (purple) in private branch ready for commit into main

Radiation length - brycecanyon geometry

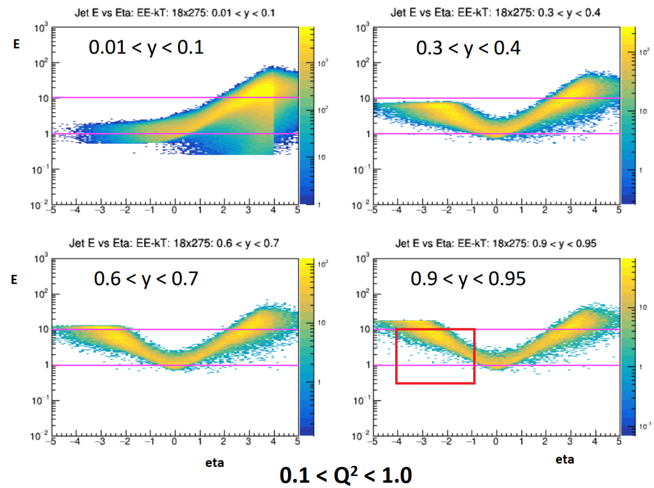


- $\sim 24X_0$ for backward HCal
- Scintillator tiles do not cover the same volume as steel absorber yet

Interaction length - brycecanyon geometry



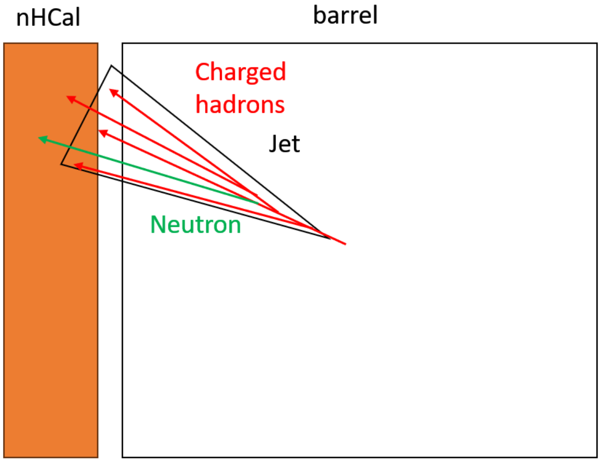
- $\sim 2.4\lambda_0$ for backward HCal
- Scintillator tiles do not cover the same volume as steel absorber yet



Brian Page, BNL

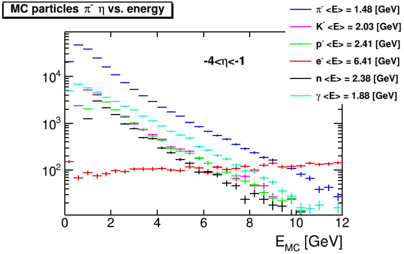
- Backward-going jets coming from low-x partons and high y events
  - Interesting physics!
- See more in presentation by Brian: `https://indico.bnl.gov/event/20679/`

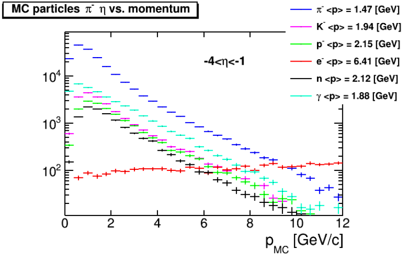
Neutral hadron reconstruction in a jet



- Jets reconstructed with charged hadron showers
- Missing a neutron will degrade the energy resolution of jets
- Need good low energy neutron:
  - detection efficiency
  - position resolution to distinguish from charged hadrons
- Need track-cluster matching to be able to see impact on neutrons vs. charged hadrons within jets - Required for TDR

Particle distributions going into nHCal

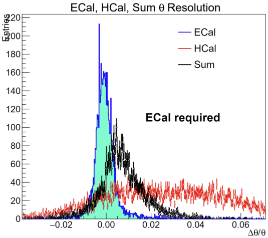


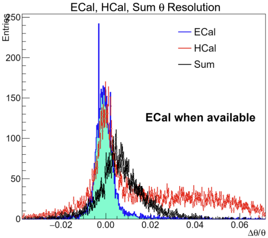


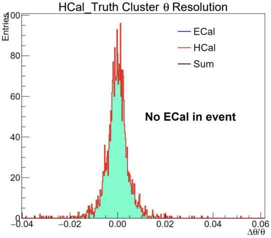
- All MC particles going into nHCal direction
- Mean energy (total) of neutrons $<E>= 2.38\ \mathrm{GeV}$, lowest $E = 1\ \mathrm{GeV}$
- Mean momentum of neutrons $<p>= 2.12\ \mathrm{GeV/c}$, lowest $p = 0\ \mathrm{GeV}$

Scattering may be a problem for jet energy reconstruction

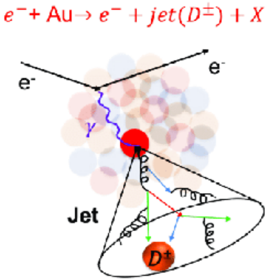
Alexandr Prozorov, CTU



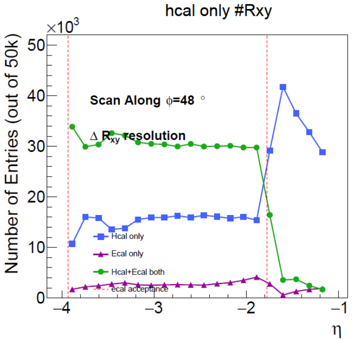




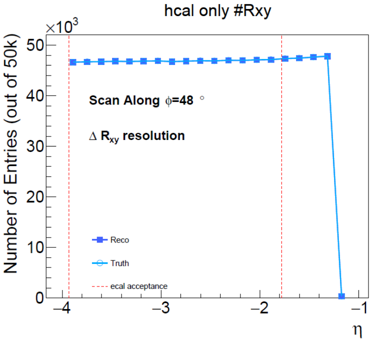
- 38% of neutrons scatter in backward EMCal
- Scattered neutron may fall out of a jet reconstruction cone
- We need to study this in coordination with Jet-HF PWG
- Work in progress on software compensation and neutron reconstruction with machine learning
- Following a study by LFHCAL group: `https://arxiv.org/abs/2310.04442`



Alexandr Prozorov, CTU



full epic

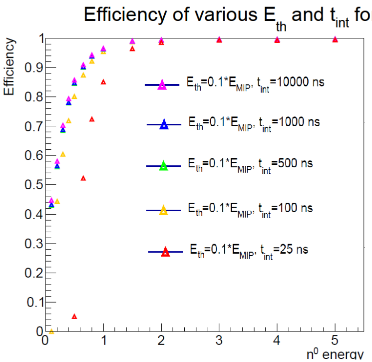


hcal only

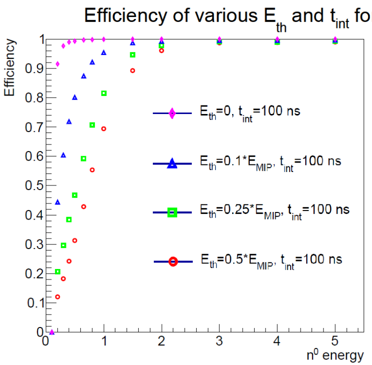
- 38% of 5 GeV neutrons scatter in backward EMCal (as expected with $\sim 1\lambda_0$)
- 93% cluster reconstruction efficiency for 5 GeV neutrons
- Tianhao with Maria Stefaniak to verify it with the world data

Neutron detection efficiency

Integration time dependence



Threshold dependence

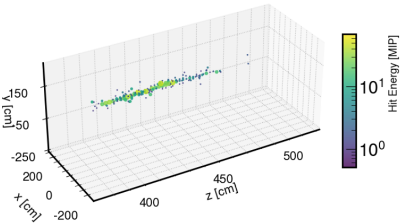


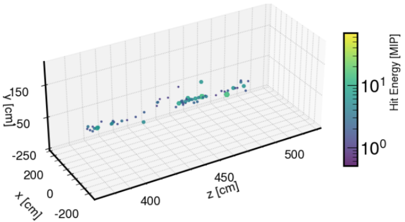
Sam Corey, OSU

- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}, $t_0 = 0$
- Checked with simulation only - no digitization
- E_{MIP} is 0.75 MeV per layer
- E_{th} has the biggest impact
- 100 ns is good enough, but lower energy neutrons may need longer times
- 60% efficiency for $E = 300\,\mathrm{MeV}$ neutrons $E_{th} = 0.1 \times E_{MIP} = 75\,\mathrm{keV}$ and 100 ns

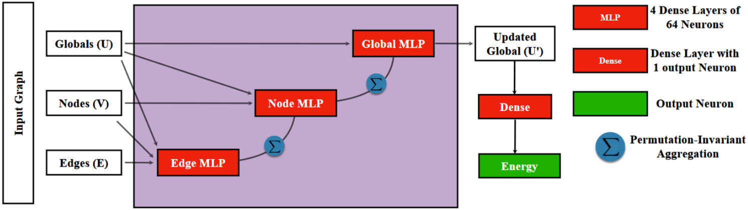
Neutron shower reconstruction with machine learning

Daniel-Han, OSU (started by) David Ruth, UNH





GNN Model



- Work in progress on software compensation and neutron reconstruction with machine learning
- Following a study by LFHCAL group: `https://arxiv.org/abs/2310.04442`
- Use of Graph Neural Networks to reconstruct showers

Neutron shower reconstruction with machine learning

LFHCAL results taken from https://arxiv.org/abs/2310.04442

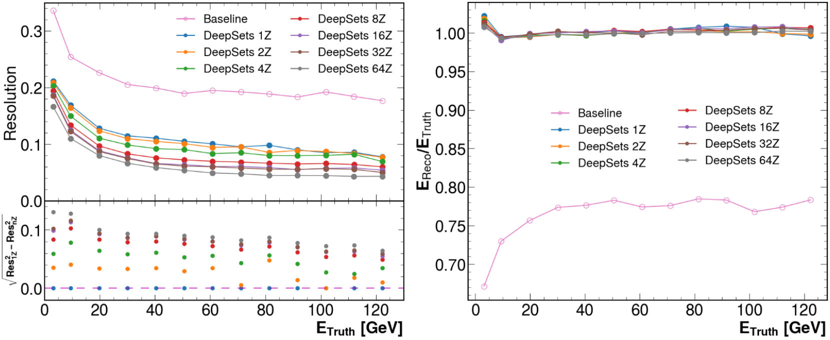
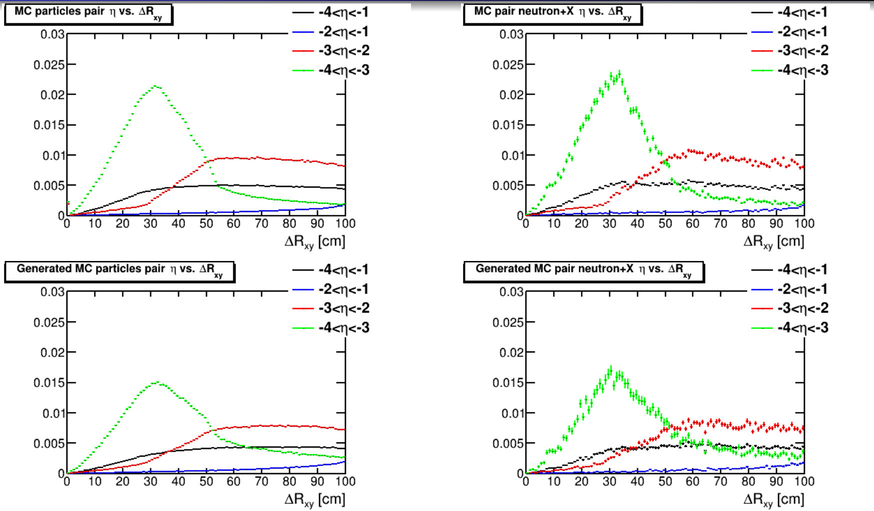
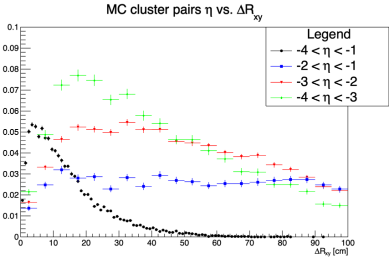


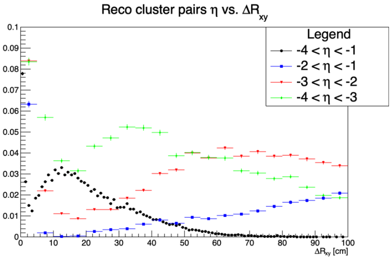
FIG. 4. Energy resolution (left) and energy scale (right) of calorimeter with different number of Z-sections along the longitudinal direction. The bottom panel of resolution plot shows the square root of difference in squares of resolution of 1 Z-section and the given Z-sections.

- GNNs provide much better performance than standard reconstruction
- Need to investigate it with staggered design (not a priority right now)



- Straight line projections (no proper projections available at that time)
- Resolution of 20 cm at high η good enough to separate most particles
- Can be even larger at smaller η
- Generated particles = primaries only
- Distributions normalized over the entire range, but zoomed in $0 < \Delta R_{xy} < 100\,\mathrm{cm}$



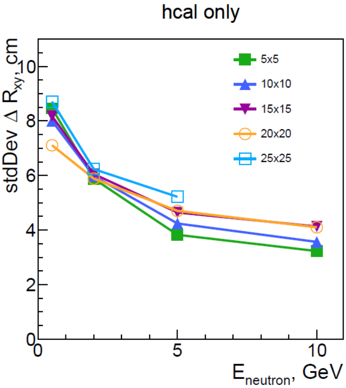


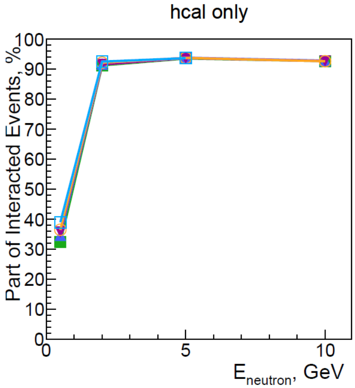
Nick Jindal, OSU

- Similar results for clusters, qualitatively consistent with MC particle straight line projections
- Resolution of 20 cm seems good enough, peak at 30 cm for reco clusters (20 cm for MC)
- Hit merging across layers was disabled here
  - Clusters from different layers overlap in XY, cause excess around 0

Position resolution study

Alexandr Prozorov, CTU



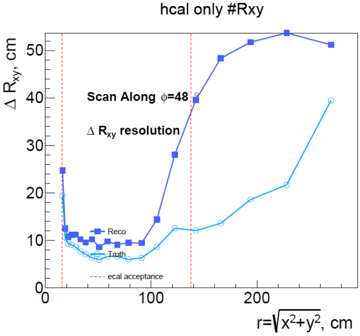


- Shoot single neutrons and compare ideal projections to RECO clusters
- Vary energy and tile size to obtain scaling
- Even large tiles up to 25 cm seem to be OK
- Need track projections and cluster matching in realistic DIS events - next steps

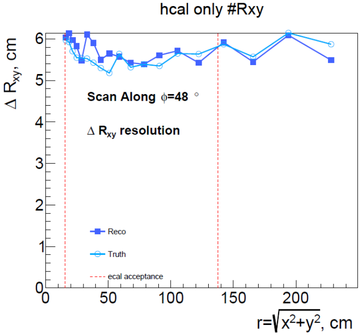
Position resolution full ePIC vs. nHCal only

Alexandr Prozorov, CTU

Exploiting ϕ symmetry (see details), make a scan along single ϕ angle

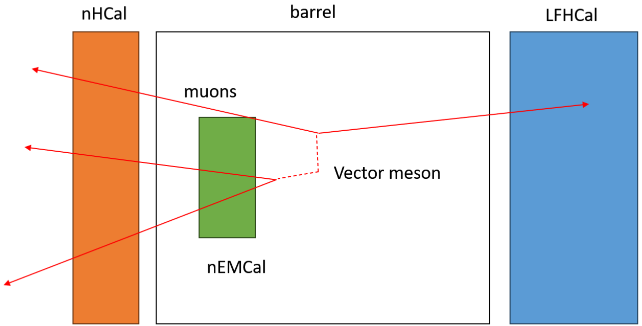


full epic



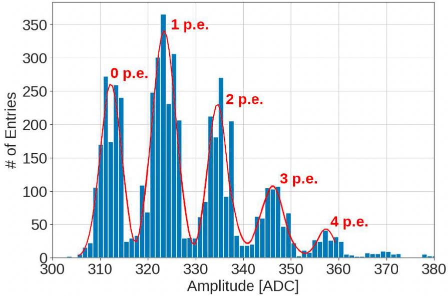
hcal only

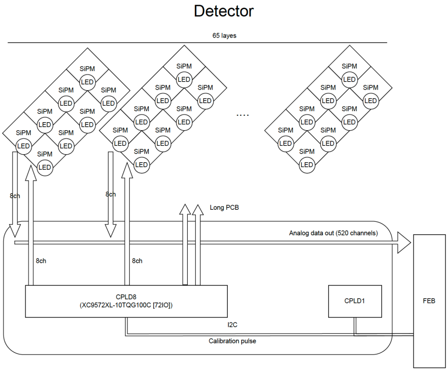
- Barrel materials in front deteriorate the position resolution due to scattering



- Important for high y or low-p_T vector mesons - depends on type
- Increases acceptance
- Need projected MIP tracks and MIP signals in backward HCal and EMCal
  - μ/π distinction important, position resolution...
- Performance estimate required for TDR

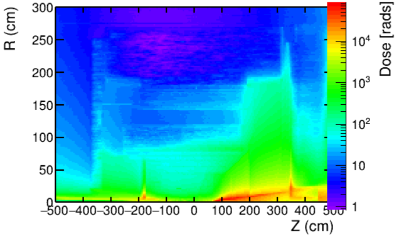
- **2mm²:**



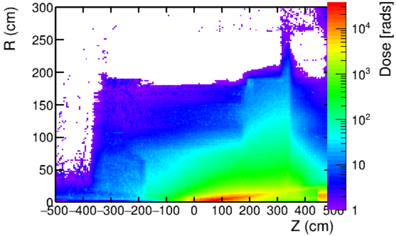


- 1 LED per channel operated via I^2C
- Use single photon spectra to calibrate the response
- Can simulate any pattern: realistic showers etc.
- Check for cross-talk and light leakage
- Design by Norbert Novitzky (LFHCAL group, ORNL) - need channel topology

EM dose

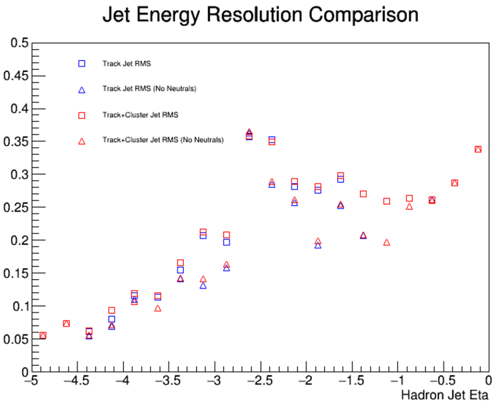


Hadronic dose



- Looked at radiation studies here:
  `https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses`
- Took root files and scaled to 10 years:
  `https://bnlbox.sdcc.bnl.gov/index.php/s/2sxywCQQgHP4ESn`
- Integrated doses between $-440 < z < -395\,\mathrm{cm}$
- EM dose $26.3k\,\mathrm{rad}$, hadronic dose $0.897k\,\mathrm{rad}$
- May need to re-run simulations with updated geometry

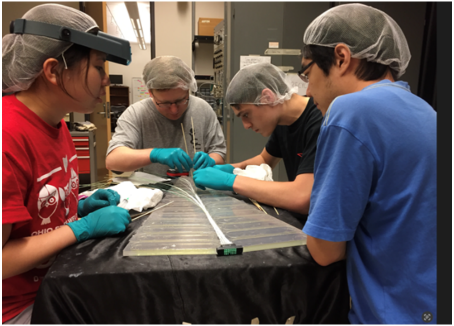
Brian Page, BNL



- Triangles below squares by several percent in each bin
  - Sample with no neutrons will have better resolution
- Blue is often slightly better than red
  - Adding neutral cluster information to the jet finding degrades resolution very slightly – energy fluctuations from calorimeter

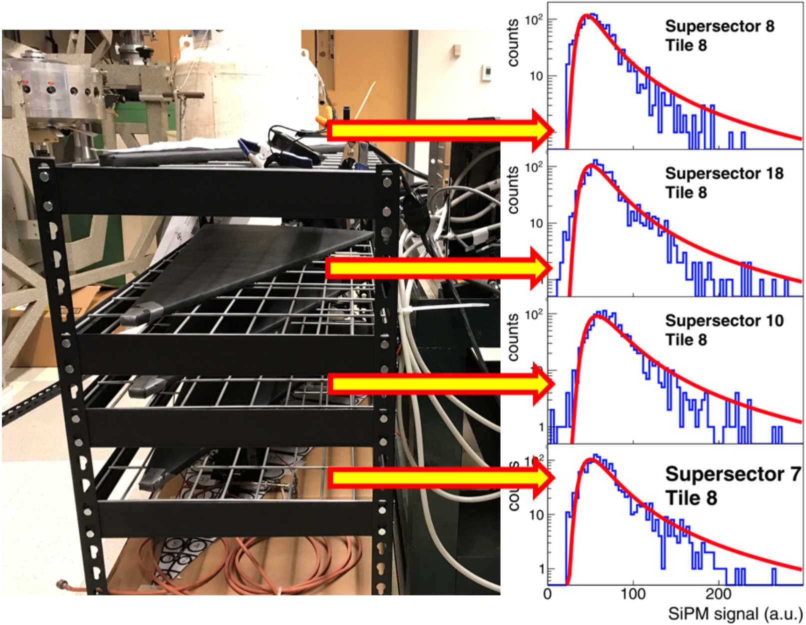
- Isolating neutral (20 – 25% of all jets) and charged jets already improves the resolution by 20 – 30%
- Unavoidable deterioration of resolution when adding clusters
  - Tracking offers better resolution in this kinematic range
  - However hadron measurements still needed for neutrals!
- Need track projections and cluster matching in DIS events for a realistic study

Testing and work by university groups

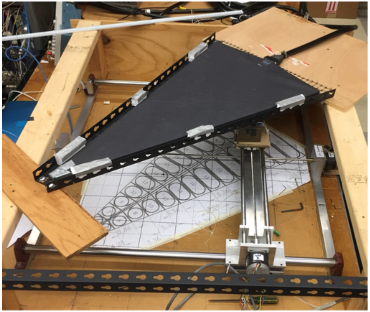


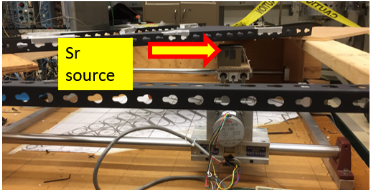
- Backward HCAL construction project well-matched for university group
  - subsidized shops with CNC, etc
  - characterization/testing with simple CAMAC systems etc
  - student-scale physical work

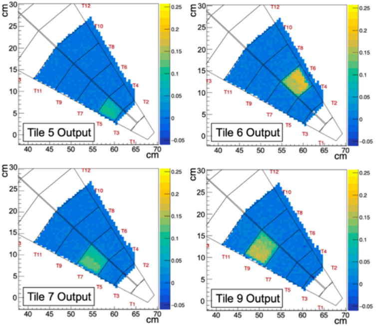
Tile characterization with cosmics



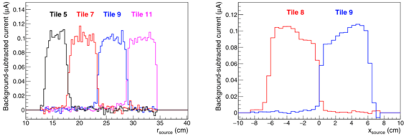
Uniformity, isolation characterization with source & translation table







(a) Response of tiles 5,6,7 and 9 in one supersector, as a function of source position. Colors indicate background-subtracted current in μA.



Conclusions

- Presented basic concept for backward HCal for ePIC
- Simplified geometry already in simulation campaign:
  - for STAR EEMC geometry+extensions until November
  - for LFHCAL-style starting from November
- Work in progress on neutron detection with machine learning
- Position resolution study with single particles done
  - $10\ \mathrm{cm} \times 10\ \mathrm{cm}$ is a good choice (can use up to $25\ \mathrm{cm} \times 25\ \mathrm{cm}$)
  - Need realistic study with track projections and cluster matching in DIS events
- Jet performance study:
  - Shown first results, well on track
  - Continue in realistic DIS events
- Growing Detector Subsystem Collaboration: OSU, CTU, UNH, BNL, UUIC

BACKUP

Dataset - simulation campaign

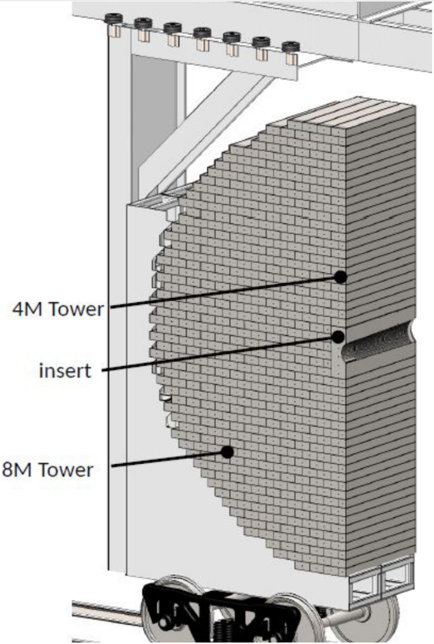
- Motivation:
  - Check distance between pairs of MC particles projected to nHCal surface
  - Check distance between neutrons and other particles
- Analysis of data from the simulation campaign:
  - $18 \times 275\ \mathrm{GeV}$ $e + p$ collisions, $0 < Q^2 < 1\ \mathrm{GeV}^2$
  - 1.3M SIDIS events simulated with PYTHIA
  - Brycecanyon geometry

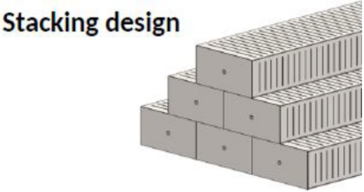
Listing: Files selection

```
S3/eictest/EPIC/FULL/23.06.1/epic_brycecanyon/SIDIS/pythia6/ep_18x275/hepmc_ip6/noradcor/
ep_noradcor.18x275_q2_0_1*edm4hep.root
```

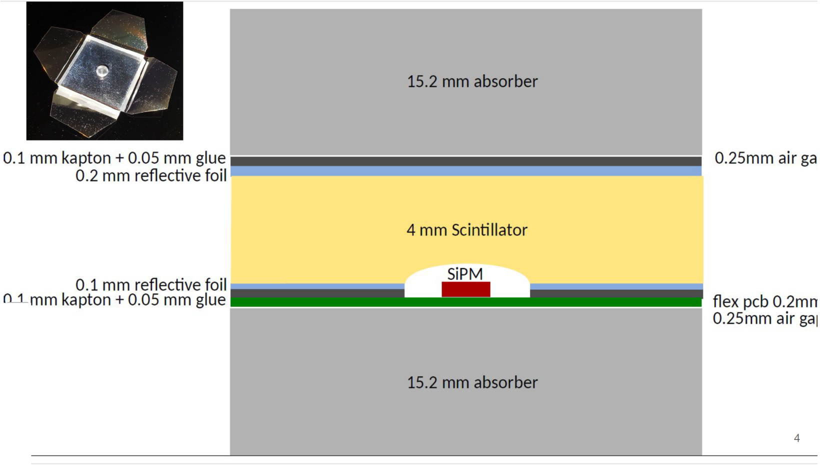
- Particle cuts:
  - primaries with start vertex $z > -395\ \mathrm{cm}$ (in front of HCal)
  - secondaries with start vertex $z > -300\ \mathrm{cm}$ (in front of HCal, after EMCal)
  - cut out e, γ, π^0, η
- Projected MC particles using straight line along their momentum direction to nHCal surface (simple check - neglects B field)

LFHCal design

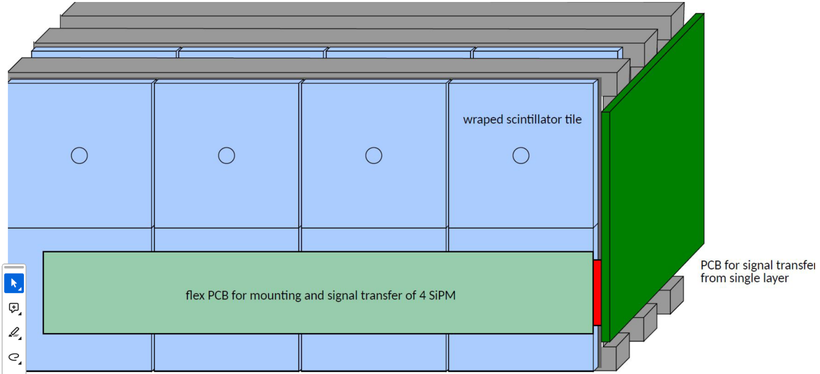




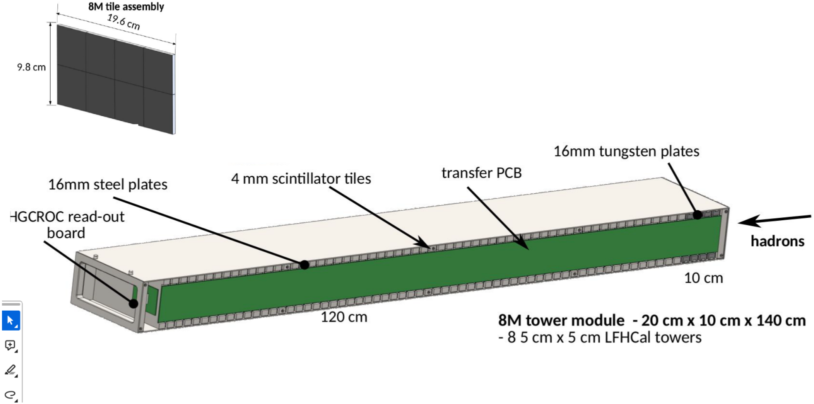
LFHCal layers



LFHCal PCBs

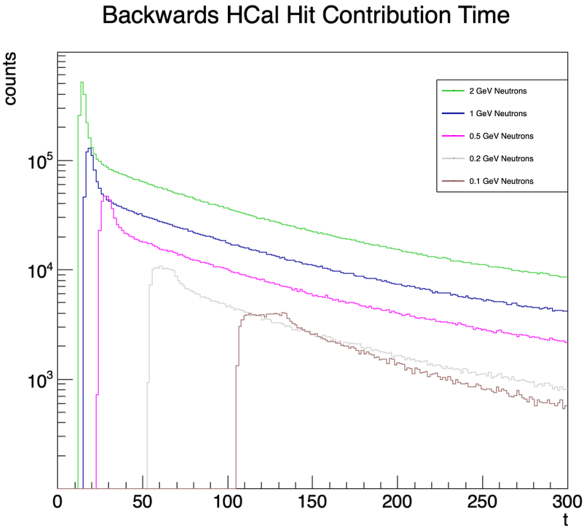

wraped scintillator tile
flex PCB for mounting and signal transfer of 4 SiPM
PCB for signal transfer
from single layer

LFHCal PCBs

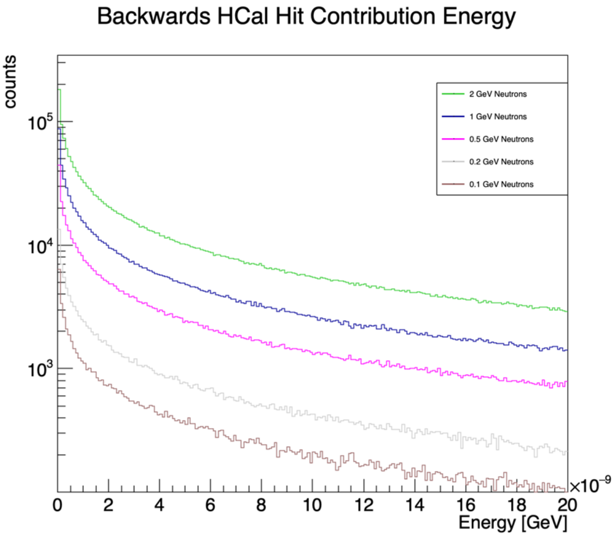


8M tower module - 20 cm x 10 cm x 140 cm
- 8 5 cm x 5 cm LFHCal towers

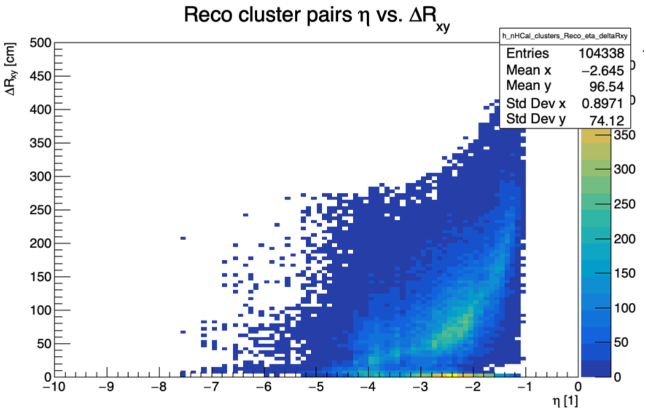
Hit contribution time



- Neutrons at lower energy are delayed

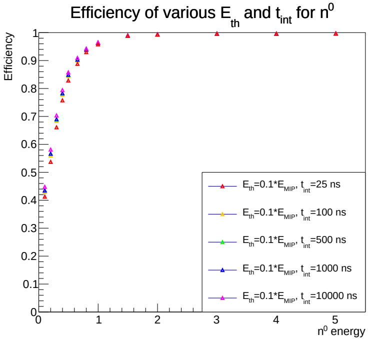

Backwards HCal Hit Contribution Energy
counts
10^5
10^4
10^3
2 GeV Neutrons
1 GeV Neutrons
0.5 GeV Neutrons
0.2 GeV Neutrons
0.1 GeV Neutrons
0
2
4
6
8
10
12
14
16
18
20
×10^-9
Energy [GeV]

Cluster Rxy vs. eta

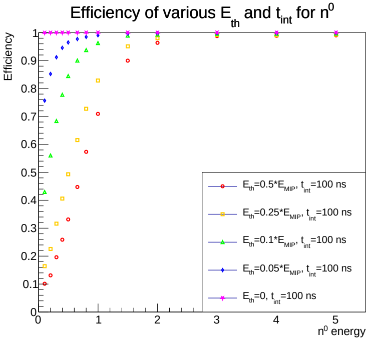


Neutron detection efficiency

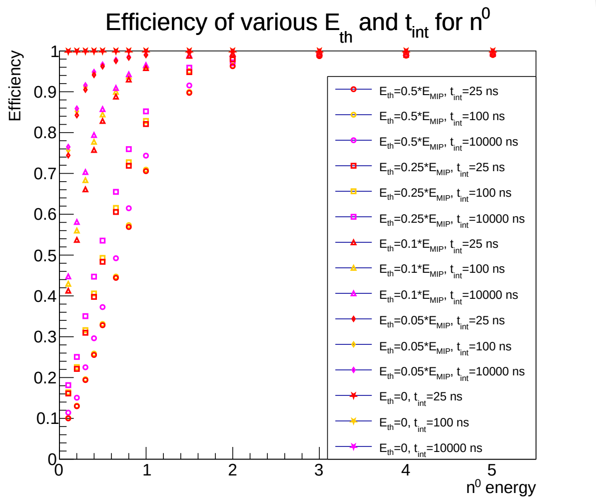
Integration time dependence



Threshold dependence

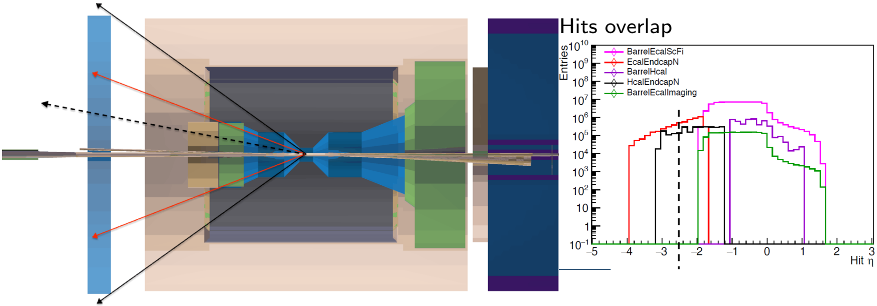


- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- Checked with simulation only - no digitization
- E_{MIP} is 0.75 MeV per layer
- E_{th} has the biggest impact
- 100 ns is good enough, but lower energy neutrons may need longer times
- t_0 starting from the first hit



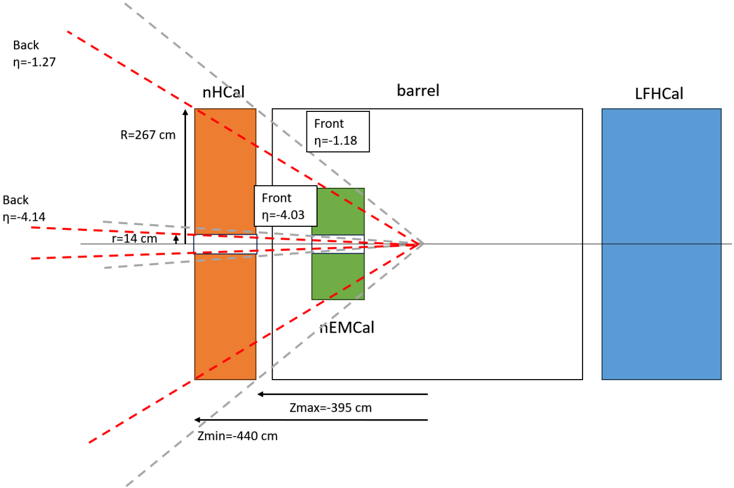
- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- E_{MIP} is 0.75 MeV per layer
- $E_{th} = 0.1 \times E_{MIP} = 75\,\mathrm{keV}$ and 100 ns provides good performance
- Need lower threshold and longer signal integration for better performance at low energy

Acceptance

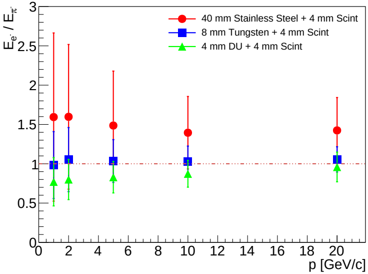


- Acceptance $-3.5 < \eta < -1.27$ - TO BE CHECKED
- Overlaps with backward and barrel EMcals
- Scattering may be important in these overlap regions

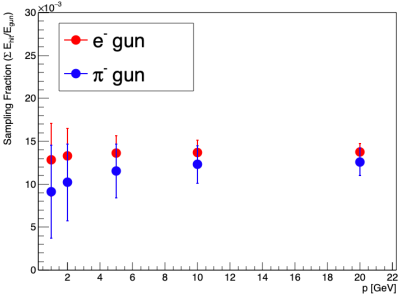
Acceptance check



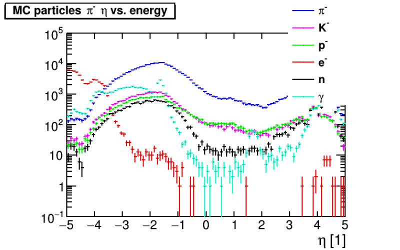
- Front geometry limit: $-4.03 < \eta < -1.18$
- Back geometry limit: $-4.14 < \eta < -1.27$
- Clusters: $-3.95 < \eta < -1.25$

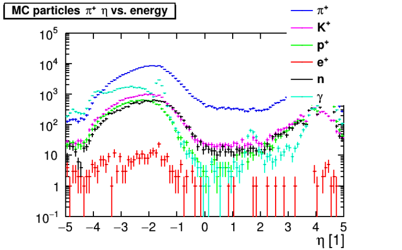


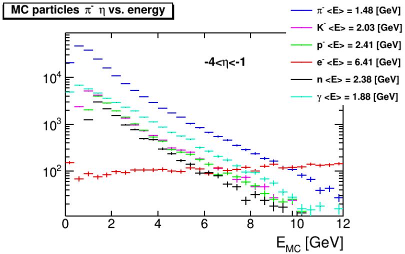
40 layers of 40 mm stainless steel+4 mm scintillator (for cross-check)

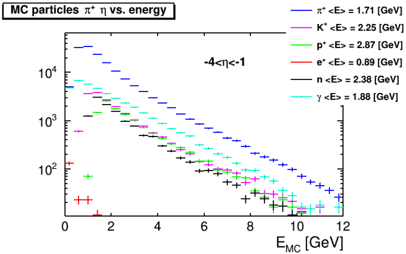


- Current design provides compensation
- Sampling fraction $\approx 1\%$
  - This means a 1 GeV hadron leaves similar signal to a E_{MIP} = 7.5 MeV across 10 layers
- Tungsten provides good performance
  - May add a few layers in front like for LFHCAL



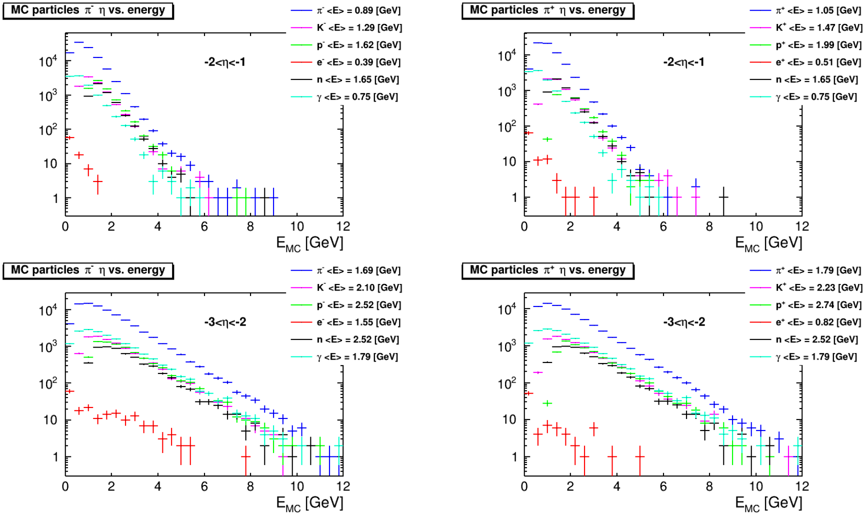






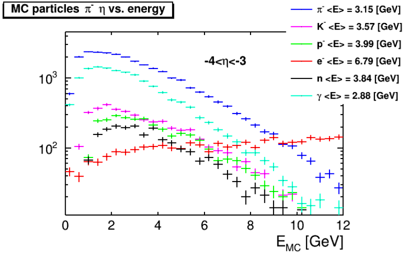
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >= 2.38\,\mathrm{GeV}$
- Large number of high E e^- - from beam?

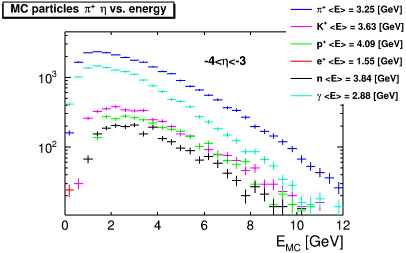
Particle distributions - Energy vs. eta



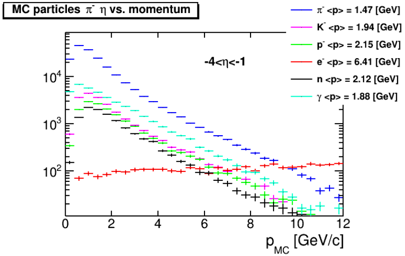
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >_{-2<\eta<-1} = 1.65\ \mathrm{GeV}$ and $< E >_{-3<\eta<-2} = 2.52\ \mathrm{GeV}$

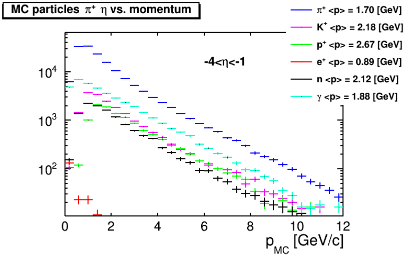
Particle distributions - Energy vs. eta



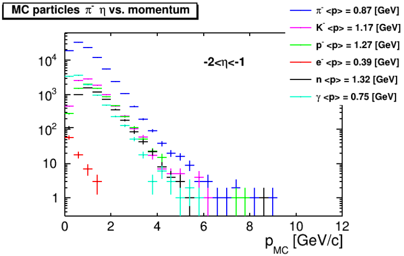


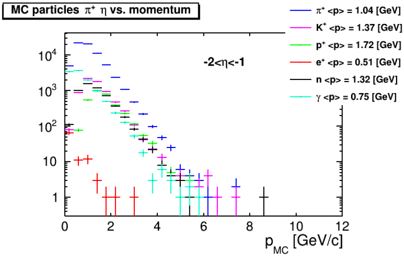
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >_{-4<\eta<-3} = 3.84\ \mathrm{GeV}$

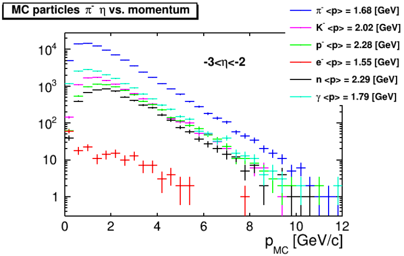


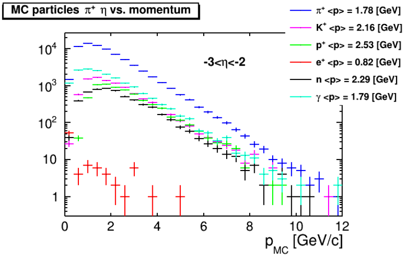


- All MC particles hitting nHCal
- Mean momentum of neutrons $< p >= 2.12\,\mathrm{GeV/c}$

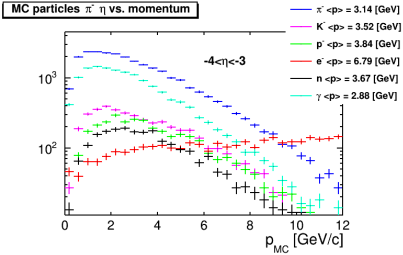


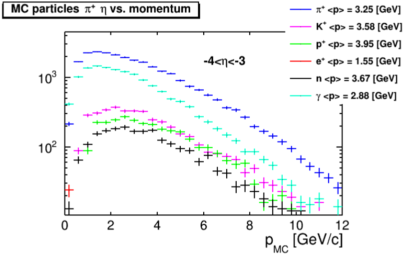






- All MC particles hitting nHCal
- Mean momentum of neutrons $< p >_{-2<\eta<-1} = 1.32\ \mathrm{GeV/c}$ and $< p >_{-3<\eta<-2} = 2.29\ \mathrm{GeV/c}$





- All MC particles hitting nHCal
- Mean momentum of neutrons $< p >_{-4<\eta<-3} = 3.67\ \mathrm{GeV/c}$

Energy

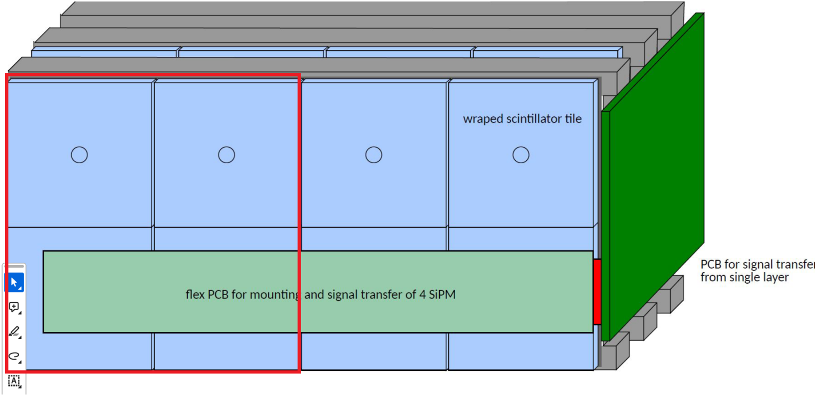
η	$< E >$ GeV inclusive n	$< E >$ GeV primary n
$-4 < \eta < -1$	2.38 GeV	2.38 GeV
$-2 < \eta < -1$	1.65 GeV	1.65 GeV
$-3 < \eta < -2$	2.52 GeV	2.52 GeV
$-4 < \eta < -3$	3.84 GeV	3.84 GeV

Momentum

η	$< p >$ GeV/c inclusive n	$< p >$ GeV/c primary n
$-4 < \eta < -1$	2.12 GeV/c	2.12 GeV/c
$-2 < \eta < -1$	1.32 GeV/c	1.32 GeV/c
$-3 < \eta < -2$	2.29 GeV/c	2.29 GeV/c
$-4 < \eta < -3$	3.67 GeV/c	3.68 GeV/c

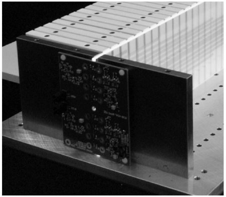
- Secondary neutrons have $< E >_{-4<\eta<-1} = 1.0 \text{ GeV}$ and $< p >_{-4<\eta<-1} = 0.27 \text{ GeV}$ - constant vs. η

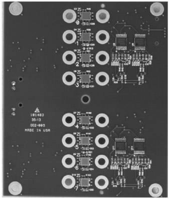
Design option 1 - LFHCAL style



- SiPM on tile with 5 $\mathrm{cm} \times 5\ \mathrm{cm}$ tiles
- Use 2x2 5 $\mathrm{cm} \times 5\ \mathrm{cm}$ tile modules similar to 4M module of LFHCAL
- Connect outputs of 2x2 tile module to integrate the signal and create an effective $10\ \mathrm{cm} \times 10\ \mathrm{cm}$ segment
- Can readout each layer independently or integrate 5 forward and 5 backward layers to save costs
- No need to optically isolate tiles, only the whole module

Design option 2 - STAR FCS style



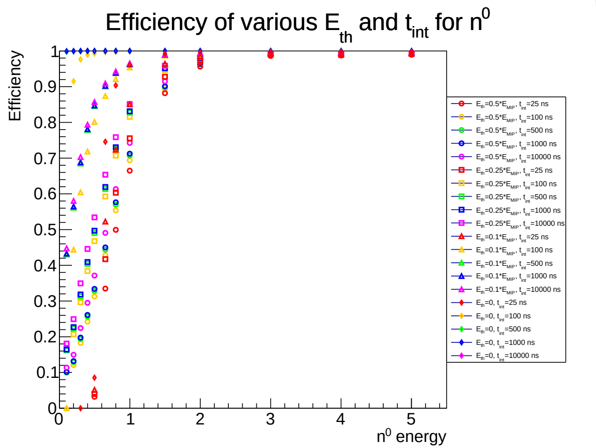


- $10\,\mathrm{cm} \times 10\,\mathrm{cm}$ tile modules similar to STAR FCS
- Light collection with SiPMs through WLS plate (middle)
  - Collects light from all 10 layers
  - Maybe can isolate WLS plate into 2 segments to collect light from 5 forward and 5 backward layers independently

Design option	light collection	features	readout
1 SiPM on tile LFHCAL style	SiPM on tile	light collection closer to source	various configurations possible eg: each layer independently 2x2 tile signal adding
2 WLS plate to SiPM STAR FCS style	SiPM via WLS plate	collects light from all layers better light propagation	combined from 2x2 tile segment integrated cross layers 5+5 layer configuration possible

- Comparison in progress
- $\approx 21k$ channels with independent readout from each of 10 layers (cost $1.76M\$$)
  - Savings of factor of 5 on electronics ($\approx 4k$ channels) if integrated 5 front and 5 back layers (cost $1.53M\$$)
  - Savings of factor of 10 on electronics ($\approx 2.1k$ channels) with WLS plates (cost $1.5M\$$)

Neutron detection efficiency



- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- E_{MIP} is $0.75\,\mathrm{MeV}$ per layer
- $E_{th} = 0.1 \times E_{MIP} = 75\,\mathrm{keV}$ and $100\,\mathrm{ns}$ provides good performance
- Need lower threshold and longer signal integration for better performance at low energy