Backward Hadronic Calorimeter for ePIC

Overview and status

Leszek Kosarzewski

The Ohio State University

ePIC Collaboration meeting at Lehigh University 25.7.2024

THE OHIO STATE UNIVERSITY

Outline

Introduction and organization

- A lot of work and updates since last meeting, UUIC joined

Many updates on the main webpage

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

Development document

https://www.overleaf.com/read/gbchmtcrhcns#5a12d2

Weekly meetings page

https://indico.bnl.gov/category/549/

Mailing list

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

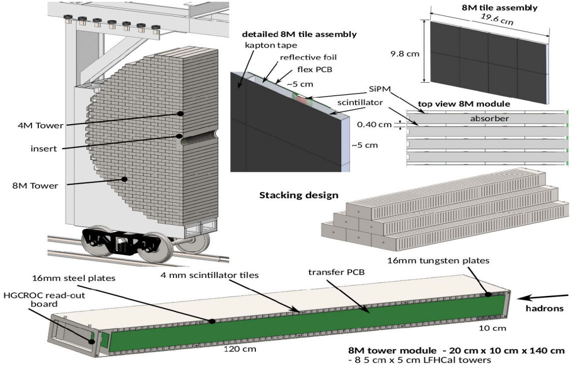
Mattermost channel

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

The Ohio State University ČVUT České vysoké učení technické v Praze Brookhaven National Laboratory University of New Hampshire University of Illinois Urbana-Champaign

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

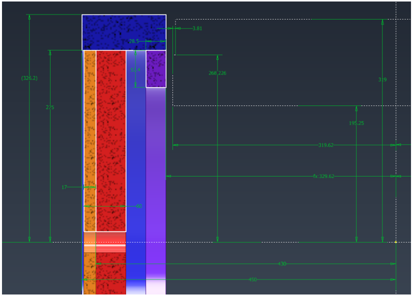
A future backward HCal shall provide functionality of a tail catcher for the high resolution e/m calorimeter in electron identification, as well as for jet kinematics measurement at small Bjorken x



- 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

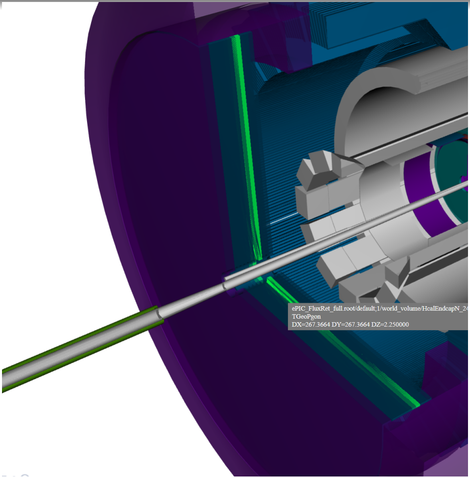
Design

- 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

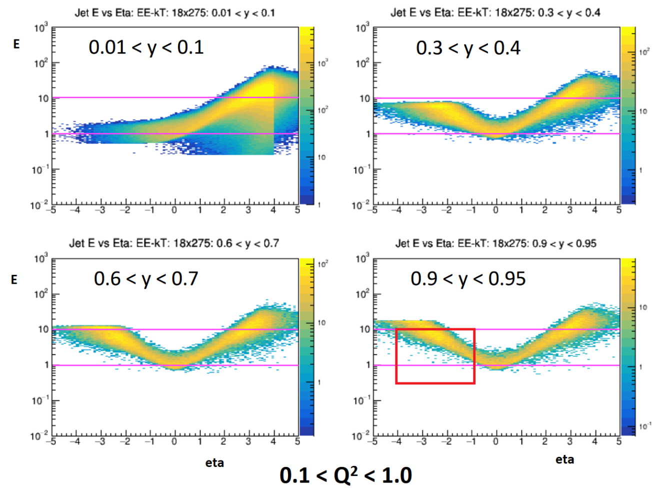


- nHCal decoupled from the magnetic steel $\Rightarrow$ more flexibility
- Support structures design required for TDR - to follow after physics performance studies

Geometry implementation in dd4hep



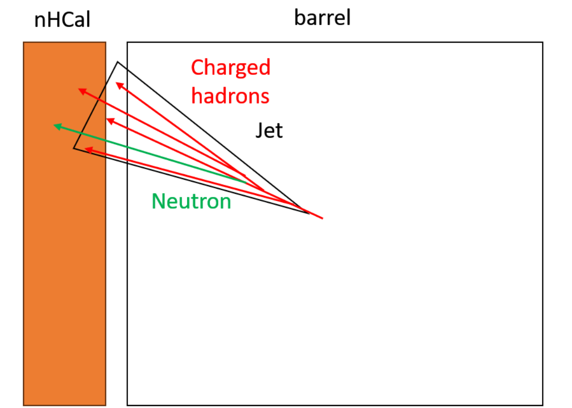
- A simplified version with STAR EEMC tiles already present in the main ePIC branch and included in the simulation campaigns up to November, stainless steel as an absorber
  - Good enough for basic checks
- Forward HCal-type geometry with $10\,\mathrm{cm} \times 10\,\mathrm{cm}$ tiles implemented for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



Brian Page, BNL

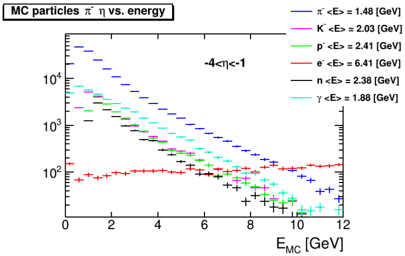
- Backward-going jets coming from low-x partons and high y events
  - Interesting physics!
- See more in presentation by Brian: `https://indico.bnl.gov/event/20679/`

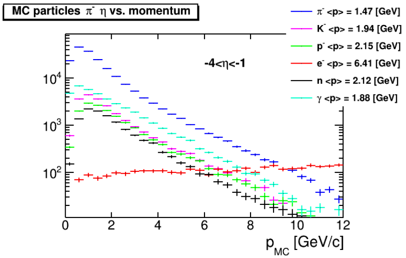
Neutral hadron reconstruction in a jet



- 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
- Track-cluster matching needed to be able to see impact on neutrons vs. charged hadrons within jets (Required for TDR)
  - Focusing on MC matching for now
  - Work in progress on machine learning method

Particle distributions going into nHCal

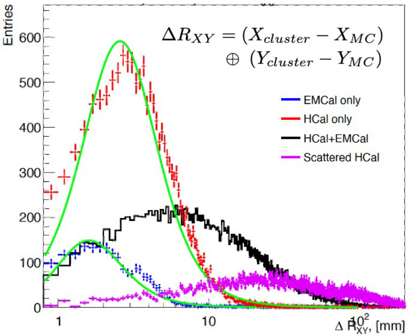


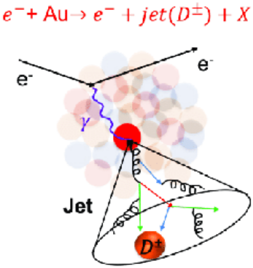


- All MC particles going into nHCal direction
- Mean energy (total) of neutrons $< E >= 2.38\,\mathrm{GeV}$, lowest $E = 1\,\mathrm{GeV}$
- Mean momentum of neutrons $< p >= 2.12\,\mathrm{GeV/c}$, lowest $p = 0\,\mathrm{GeV}$

Scattering may be a problem for jet energy reconstruction

Alexandr Prozorov, CTU

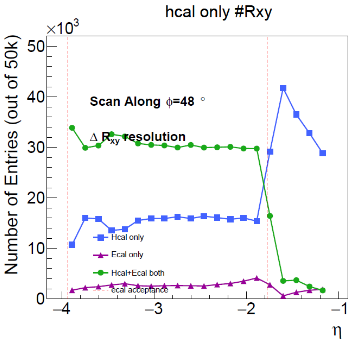




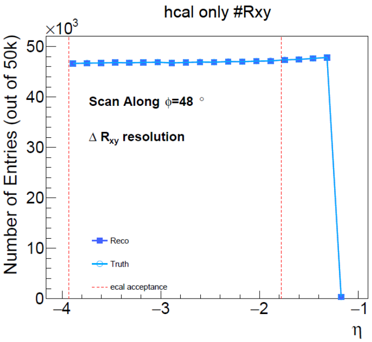
- $\sim$ 68% of neutrons scatter in backward EMCal (as expected with $\sim 1\lambda_0$)
- Scattered neutron may fall out of a jet reconstruction cone
- We need to study this in coordination with Jet-HF PWG

Interactions with HCal and EMCal

Alexandr Prozorov, CTU



full epic

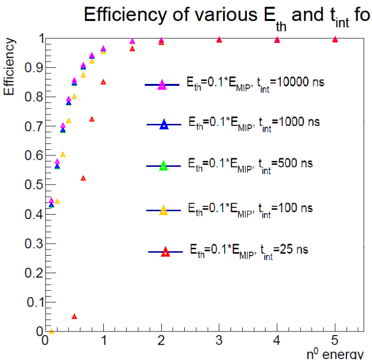


hcal only

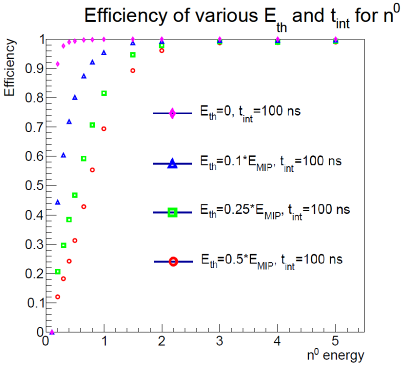
- $\sim$ 68% of 5 GeV neutrons interact and scatter in backward EMCal (as expected with $\sim 1\lambda_0$)
- 93% cluster reconstruction efficiency for 5 GeV neutrons
- Tianhao (OSU undergrad) works with Maria Stefaniak to verify simulations with the world data

Neutron detection efficiency

Integration time dependence



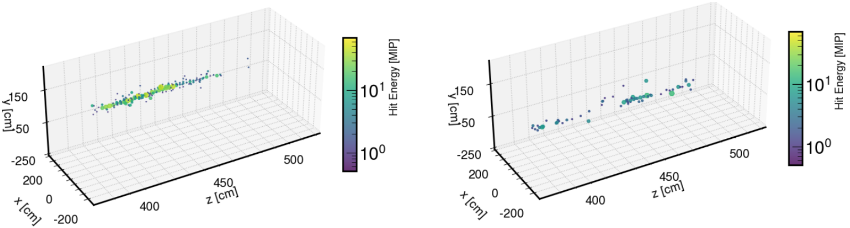
Threshold dependence



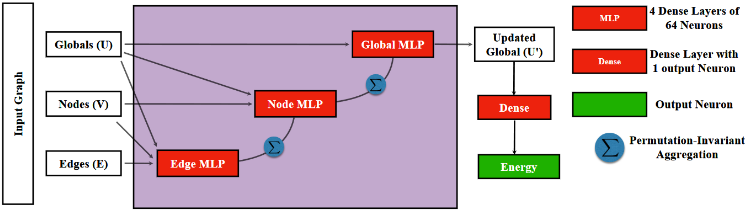
Sam Corey, OSU

- 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 $0.75\ \mathrm{MeV}$ per layer
- E_{th} has the biggest impact
- $100\ \mathrm{ns}$ 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 $100\ \mathrm{ns}$

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

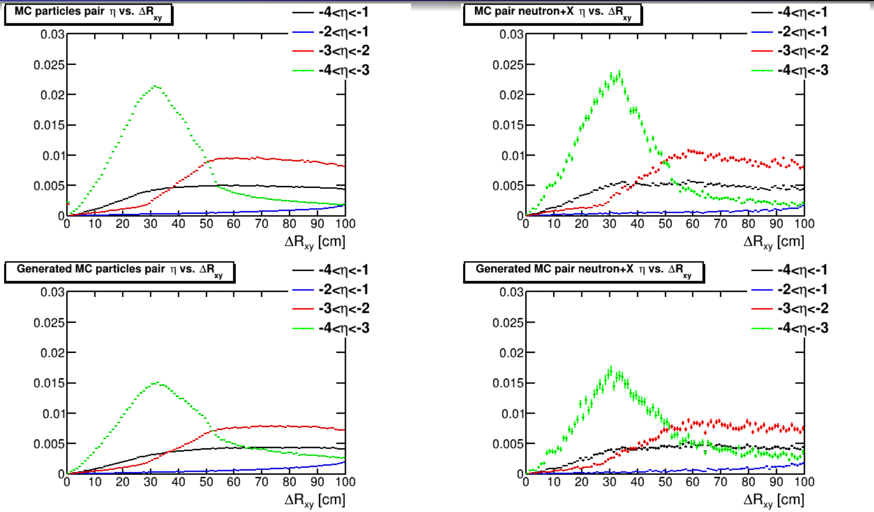


GNN Model



- 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 and isolate neutral component of showers

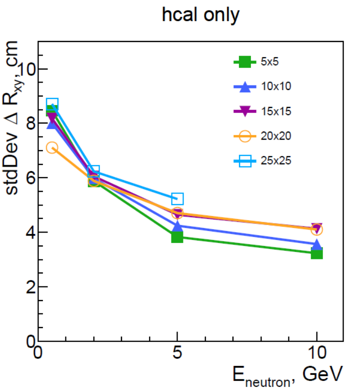
Distance between particle projections in nHCal

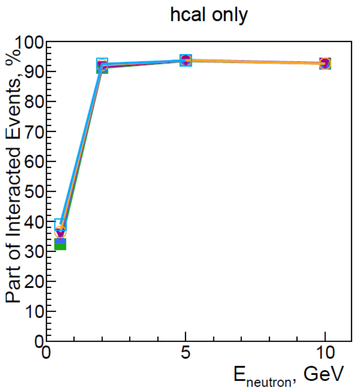


- Straight line projections (no proper projections available at that time)
- Resolution of 20 cm at high η good enough to separate most particles
- Can be even larger at smaller η
- Generated particles = primaries only
- Distributions normalized over the entire range, but zoomed in $0 < \Delta R_{xy}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

Position resolution study

Alexandr Prozorov, CTU



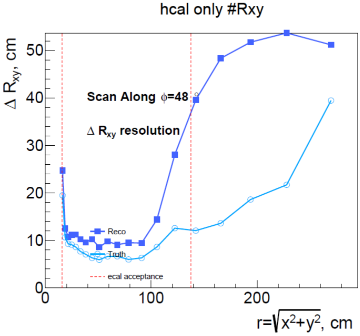


- Shoot single neutrons and compare ideal projections to RECO clusters
- Vary energy and tile size to obtain scaling
- Even large tiles up to 25 cm seem to be OK
- Need track projections and cluster matching in realistic DIS events - next steps

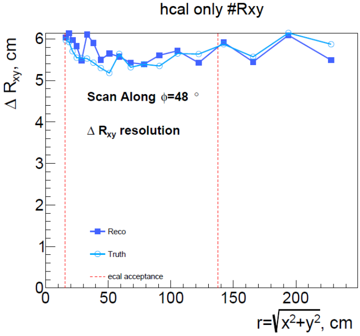
Position resolution full ePIC vs. nHCal only

Alexandr Prozorov, CTU

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



full epic



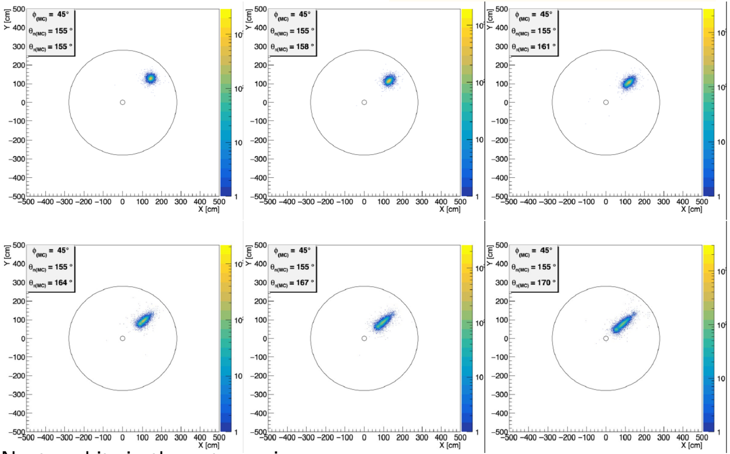
hcal only

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

Simulating pion and neutron in the same event. Neutron position fixed. Pion is position is varied.

- ❑ (1 n + 1 π^-) / event. ---- *Standalone ddsim*
- ❑ $\varphi = 45^\circ$
  - $\theta_n = 155^\circ$ ($\eta = -1.51$) ------ *fixed*
  - $\theta_\pi = 155^\circ$ ($\eta = -1.51$), 158° ($\eta = -1.64$), 161° ($\eta = -1.79$), 164° ($\eta = -1.96$), 167° ($\eta = -2.17$), 170° ($\eta = -2.44$)

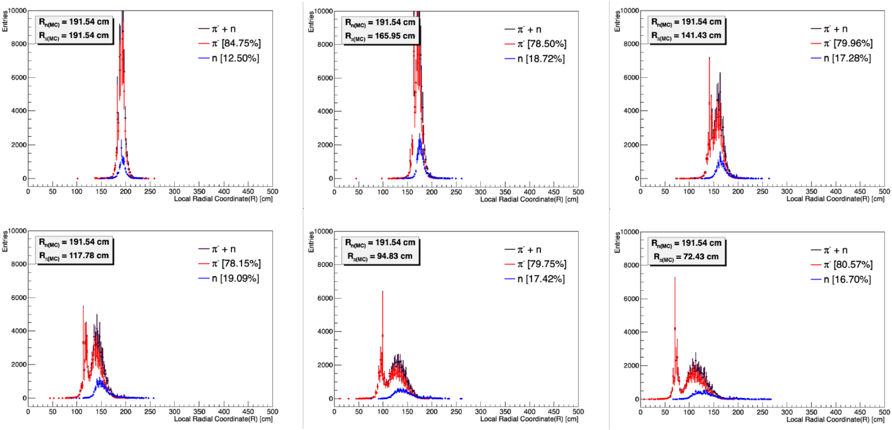
Subhadip Pal, CTU



- Neutron hits in the outer region
- Pion position is moved towards the beam
- Distributions become more smeared

2-particle MC clusters

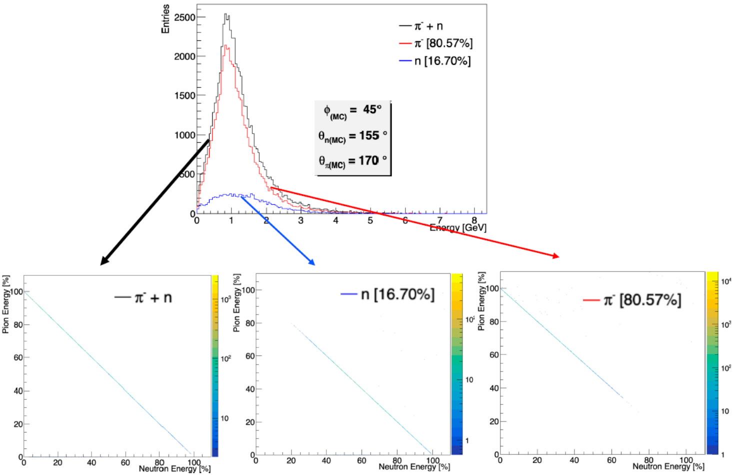
Subhadip Pal, CTU



- Clusters are dominated by pions
- Neutron clusters are shifted more inwards as the separation increases
- $\sim$ 80% of the clusters associated with pions
- $\sim$ 20% of the clusters associated with neutrons

2-particle cluster energy sharing

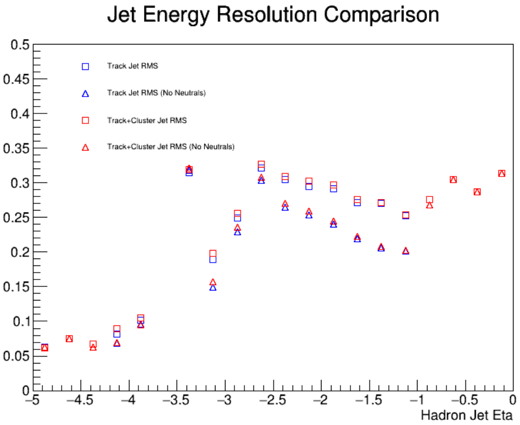
Subhadip Pal, CTU



- Checked energy of each recoHit forming cluster. The recoHits are tagged as pion/neutron hits based on the most energetic hit contribution of the mapped simHit.
- Assigned pion clusters have on an average 14% energy contribution from neutron recoHits and neutron clusters have 36% energy contribution from pions.

Jet with neutrals performance

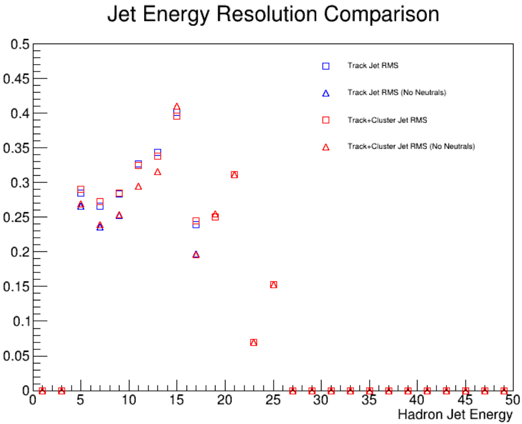
Brian Page, BNL



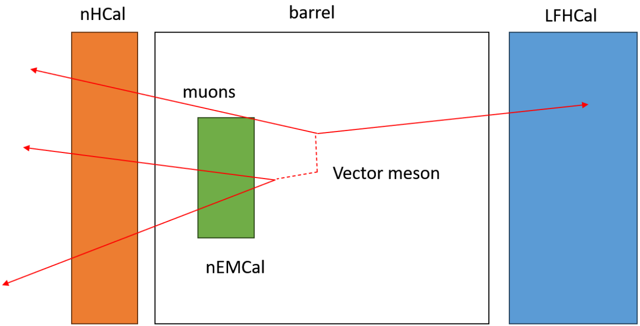
- RMS of the full distribution of jet $(E_{reco} - E_{generated})/E_{generated}$ vs. η_{jet}
- Isolating neutral $(20 - 25\%$ of all jets) and charged jets already improves the resolution by $\sim 20\%$
- Unavoidable deterioration of resolution when adding clusters
  - Tracking offers better resolution in this kinematic range
  - However hadron measurements still needed for neutrals!
- Need track projections and cluster matching in DIS events for a realistic study

Jet energy with neutrals

Brian Page, BNL

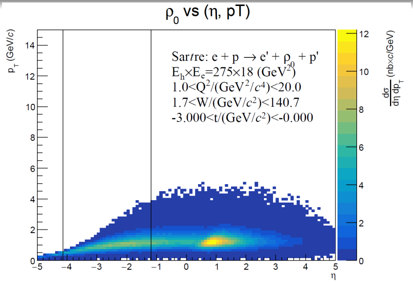


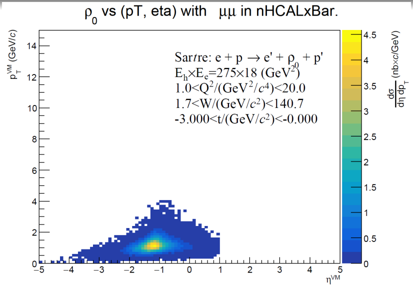
- RMS of the full distribution of jet $(E_{reco} - E_{generated})/E_{generated}$ vs. $E_{generated}$
- Mostly smooth dependence, increases with energy

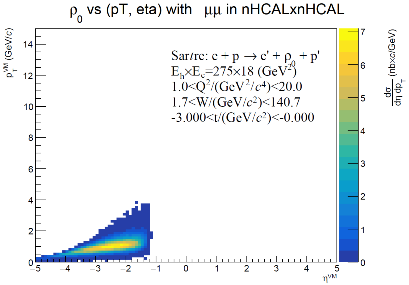


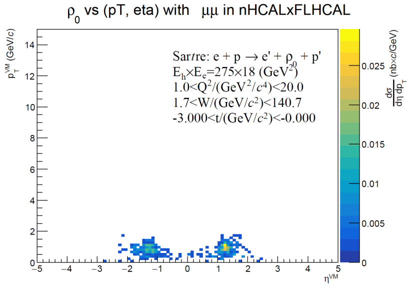
- Important for high y or low-p_T vector mesons - depends on type
- Increases acceptance
- Need projected MIP tracks and MIP signals in backward HCal and EMCal
  - μ/π distinction important, position resolution...
- Performance estimate required for TDR
- Simulations done by UIUC with event generators:
  - Simulated exclusive, diffractive $\rho_0, \phi, J/\psi, \rightarrow \mu\mu$ production in DIS regime with Sartre
  - Skipped PYTHIA8 for now, because of limitations of hard diffraction implementation
  - For ρ_0 and ϕ KK or even $\pi\pi$ decays may be more relevant than $\mu\mu$ due to low branching ratio

ρ_0 distributions with Sartre





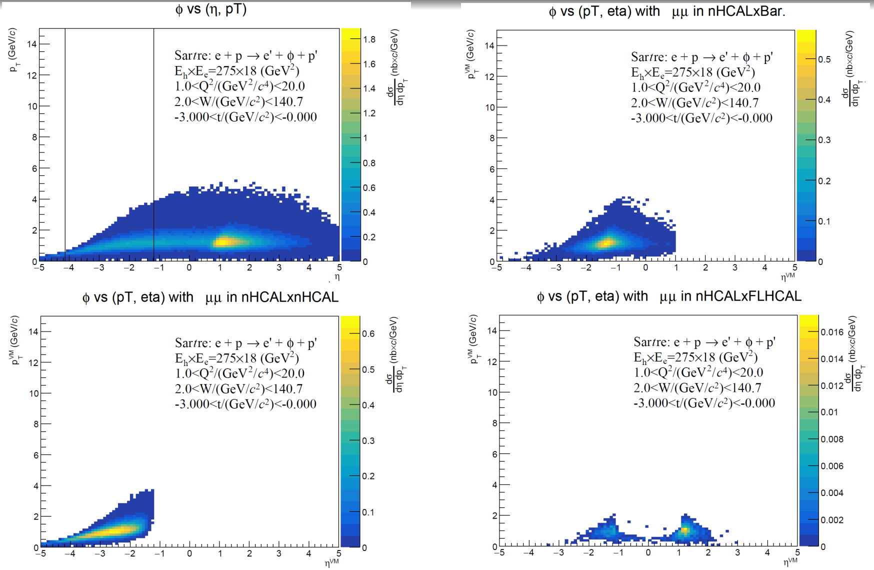




Vincent Andrieux, UIUC

- Branching ratio $\rho_0 \to \mu\mu$ not included
- nHCal can extend the rapidity range, better access to low-x physics

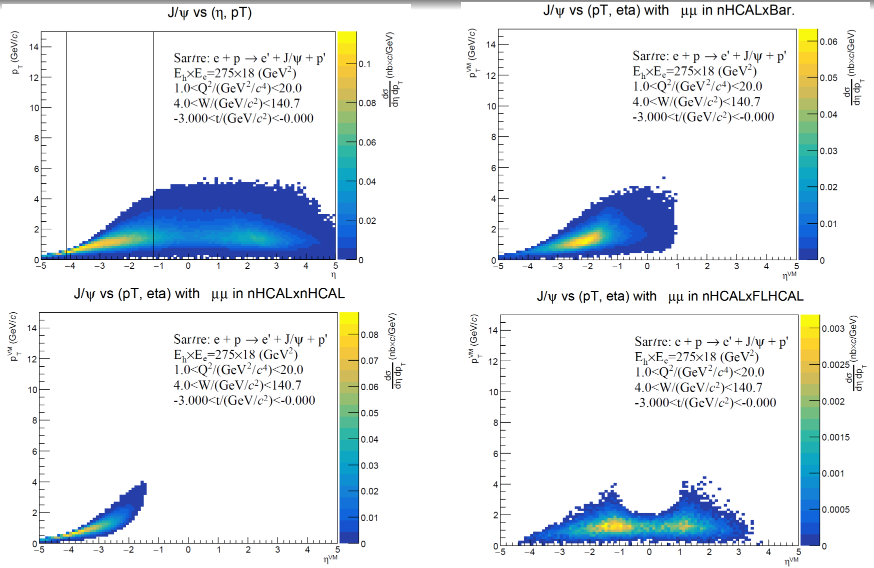
ϕ distributions with Sartre



Vincent Andrieux, UIUC

- Branching ratio $\phi \to \mu\mu$ not included
- nHCal can extend the rapidity range, better access to low-x physics

J/ψ distributions with Sartre



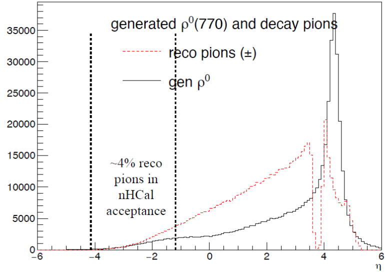
Vincent Andrieux, UIUC

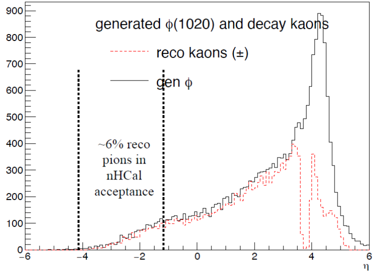
- Branching ratio $J/\psi \to \mu\mu$ not included
- nHCal is important for J/ψ study, what about Υ?

pythia8NCDIS_18x275_minQ2=1 large sample

reconstructed mesons from the decay of vector mesons

$\rho\to\pi^+\pi^-$ $\phi\to K^+K^-$





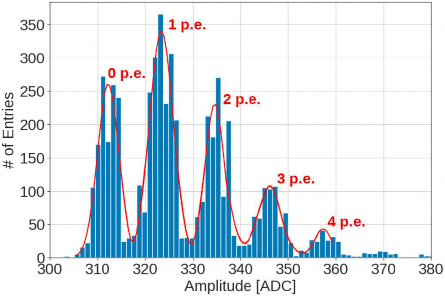
all available files of flavor "pythia8NCDIS_18x275_minQ2=1_beamEffects_xAngle=-0.025_hiDiv_1"

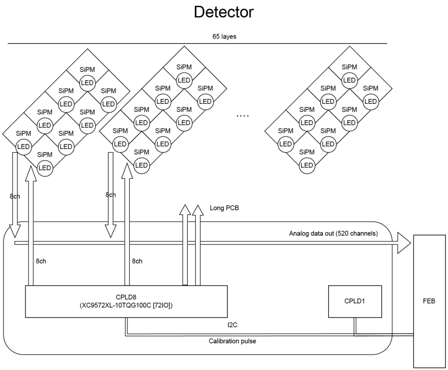
Caroline Riedl, UIUC

- $\sim 4 - 6\%$ of mesons from VM decay in nHCal acceptance
- centrally generated PYTHIA8 with full simulation of the ePIC detector and tracks reconstructed
- studied decays: $\rho_0(770) \to \pi^+\pi^-$, $\phi(1020) \to K^+K^-$

Calibration system with LEDs

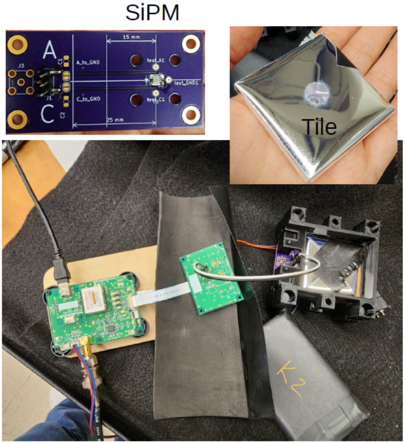
- **2mm²:**

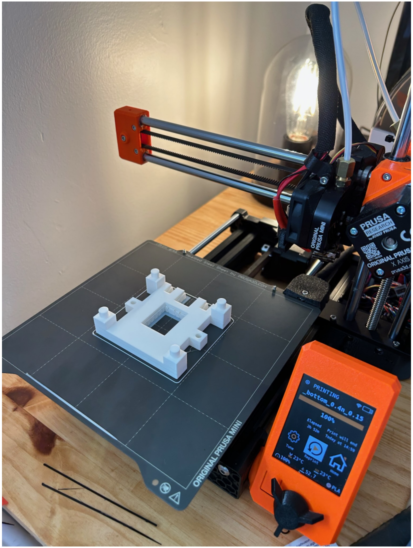




- 1 LED per channel operated via I^2C
- Use single photon spectra to calibrate the response
- Can simulate any pattern: realistic showers etc.
- Check for cross-talk and light leakage
- Design by Norbert Novitzky (LFHCAL group, ORNL) - need channel topology

Yevheniia Khyzhniak, OSU

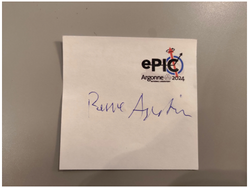




- Ongoing tests of tiles
- Received equipment and help from ORNL group, thanks!
- Plan to order more tiles for testing - in contact with Oleg Eyser

Good luck for ePIC from Pierre Agostini

Pierre Agostini during visit at OSU.



From the current Nobel Prize winner to the ePIC collaboration of "future" Nobel Prize winners.

Summary

Conclusions

- Presented basic concept for backward HCal for ePIC
- Work in progress on neutron detection with machine learning
- Position resolution study with single particles done, following with 2-particles
  - 10 $\mathrm{cm} \times$ 10 cm is a good choice (can use up to 25 $\mathrm{cm} \times$ 25 cm)
  - Need realistic study with track projections and cluster matching in DIS events
- Jet performance study:
  - Shown first results: 20% improvement with nHCal for jets with neutrals
  - Continue in realistic DIS events
- VM performance study:
  - Started - work in progress
  - nHCal especially important for J/ψ, while ρ_0, ϕ may need KK channel
- Ongoing tile tests at OSU
- Growing Detector Subsystem Collaboration: OSU, CTU, UNH, BNL, UUIC

BACKUP

Dataset - simulation campaign

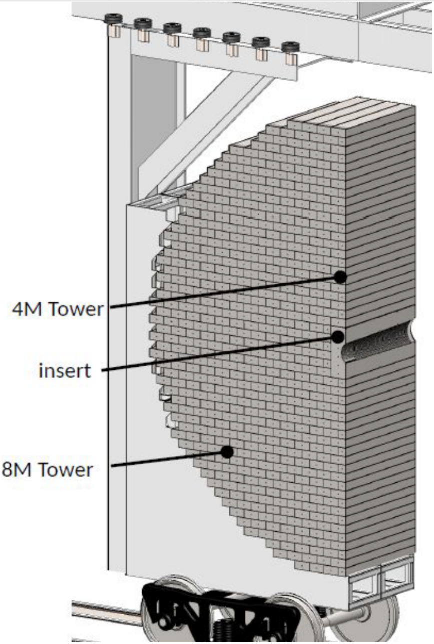
- Motivation:
  - Check distance between pairs of MC particles projected to nHCal surface
  - Check distance between neutrons and other particles
- Analysis of data from the simulation campaign:
  - $18 \times 275\,\mathrm{GeV}$ $e + p$ collisions, $0 < Q^2 < 1\,\mathrm{GeV}^2$
  - 1.3M SIDIS events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

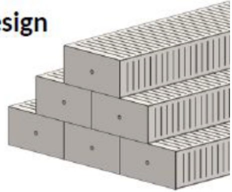
Listing: Files selection

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

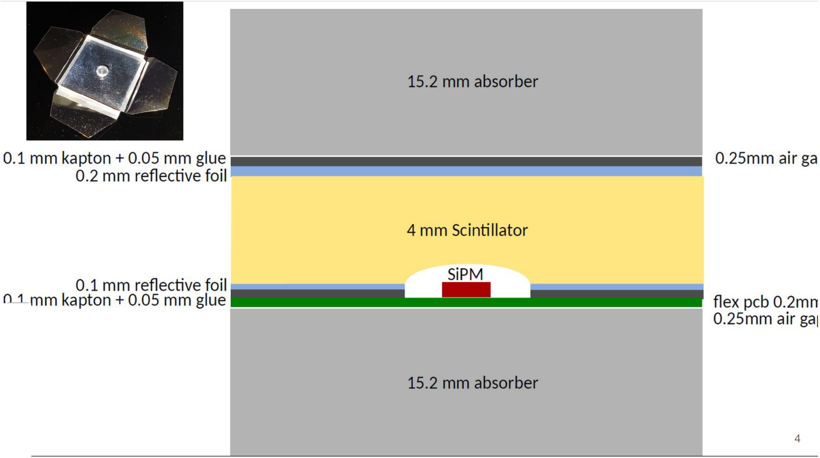
- Particle cuts:
  - primaries with start vertex $z > -395\,\mathrm{cm}$ (in front of HCal)
  - secondaries with start vertex $z > -300\,\mathrm{cm}$ (in front of HCal, after EMCal)
  - cut out e, γ, π^0, η
- Projected MC particles using straight line along their momentum direction to nHCal surface (simple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

LFHCal design

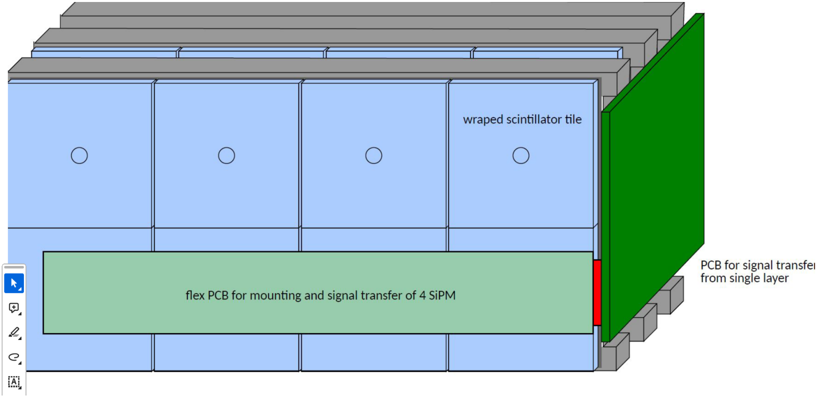




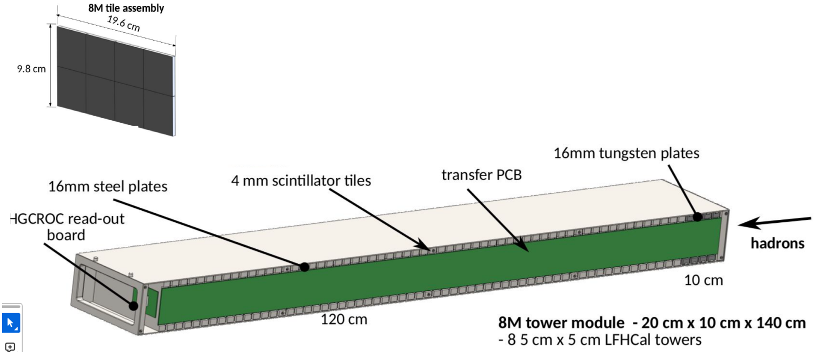
LFHCal layers



LFHCal PCBs

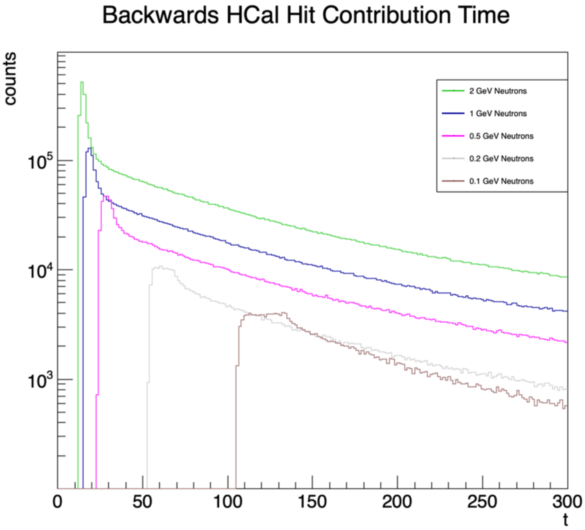

wraped scintillator tile
flex PCB for mounting and signal transfer of 4 SiPM
PCB for signal transfer
from single layer

LFHCal PCBs

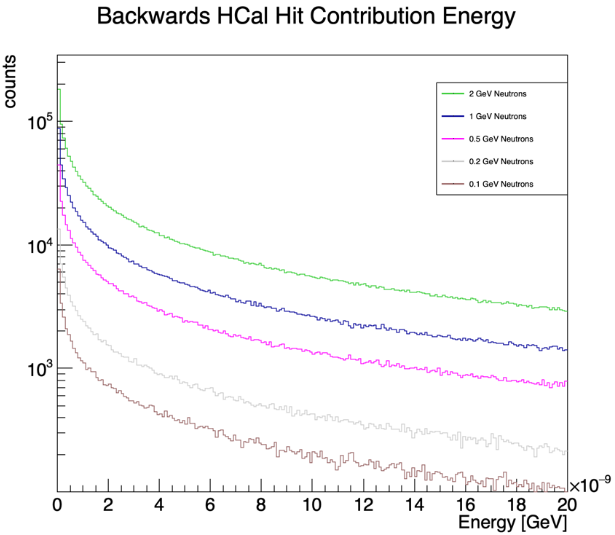


8M tile assembly
19.6 cm
9.8 cm
16mm tungsten plates
transfer PCB
4 mm scintillator tiles
16mm steel plates
HGCROC read-out board
hadrons
10 cm
120 cm
8M tower module - 20 cm x 10 cm x 140 cm
- 8 5 cm x 5 cm LFHCal towers

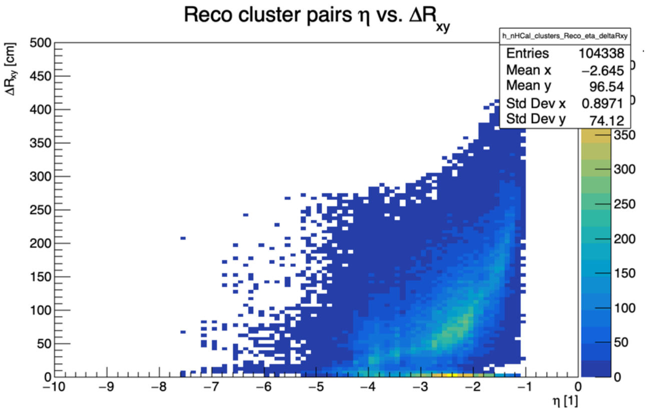
Hit contribution time



- Neutrons at lower energy are delayed

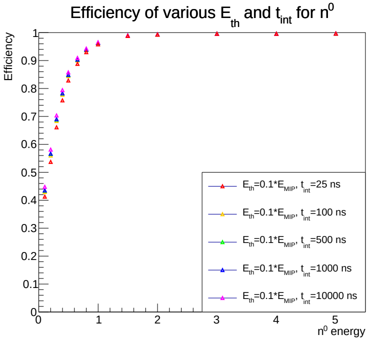

Backwards HCal Hit Contribution Energy
counts
10^5
10^4
10^3
2 GeV Neutrons
1 GeV Neutrons
0.5 GeV Neutrons
0.2 GeV Neutrons
0.1 GeV Neutrons
0
2
4
6
8
10
12
14
16
18
20
$\times 10^{-9}$
Energy [GeV]

Cluster Rxy vs. eta

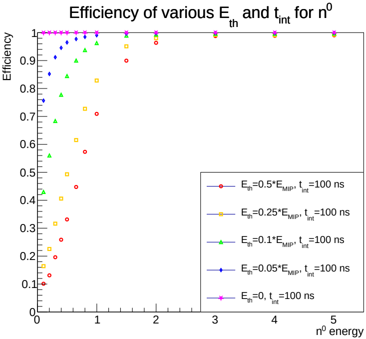


Neutron detection efficiency

Integration time dependence

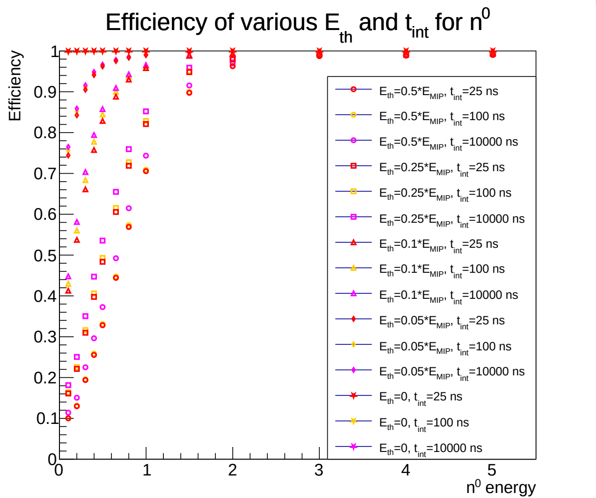


Threshold dependence



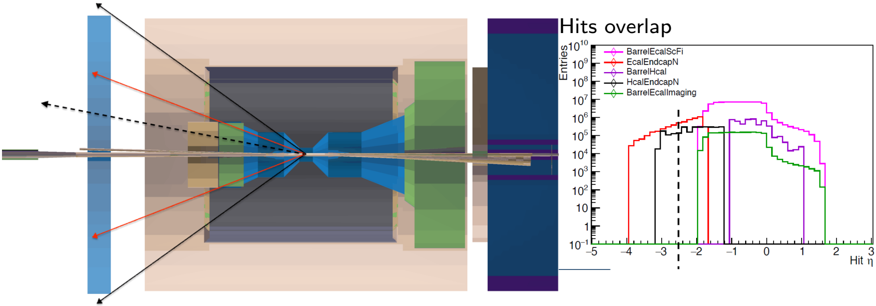
- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- Checked with simulation only - no digitization
- E_{MIP} is 0.75 MeV per layer
- E_{th} has the biggest impact
- 100 ns is good enough, but lower energy neutrons may need longer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

Neutron detection efficiency



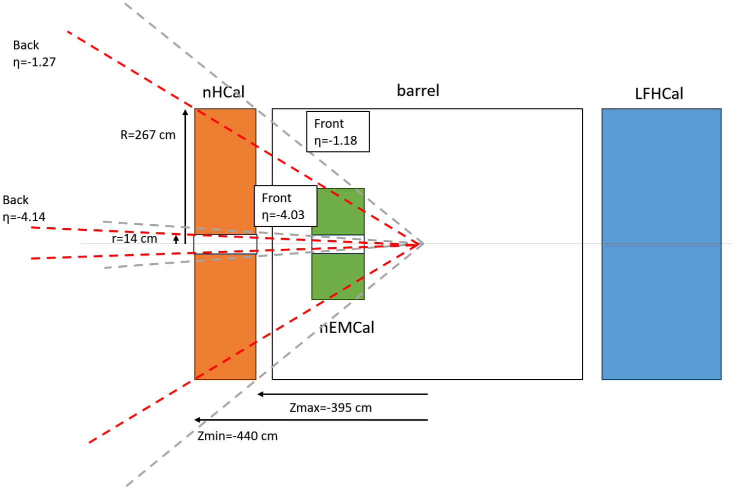
- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- E_{MIP} is 0.75 MeV per layer
- $E_{th} = 0.1 \times E_{MIP} = 75\,\mathrm{keV}$ and 100 ns provides good performance
- Need lower threshold and longer signal integration for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

Acceptance



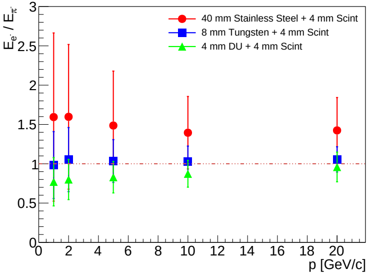
- Acceptance $-3.5 < \eta < -1.27$ - TO BE CHECKED
- Overlaps with backward and barrel EMcals
- Scattering may be important in these overlap regions

Acceptance check

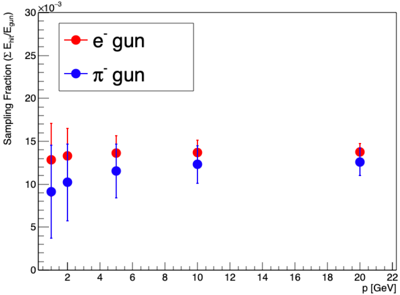


- Front geometry limit: $-4.03 < \eta < -1.18$
- Back geometry limit: $-4.14 < \eta < -1.27$
- Clusters: $-3.95 < \eta < -1.25$

Electron/hadron response

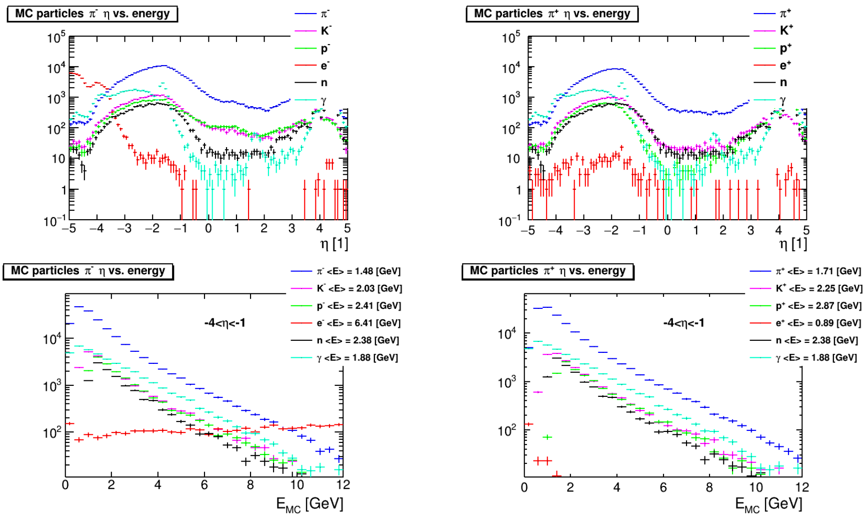


40 layers of 40 mm stainless steel+4 mm scintillator (for cross-check)



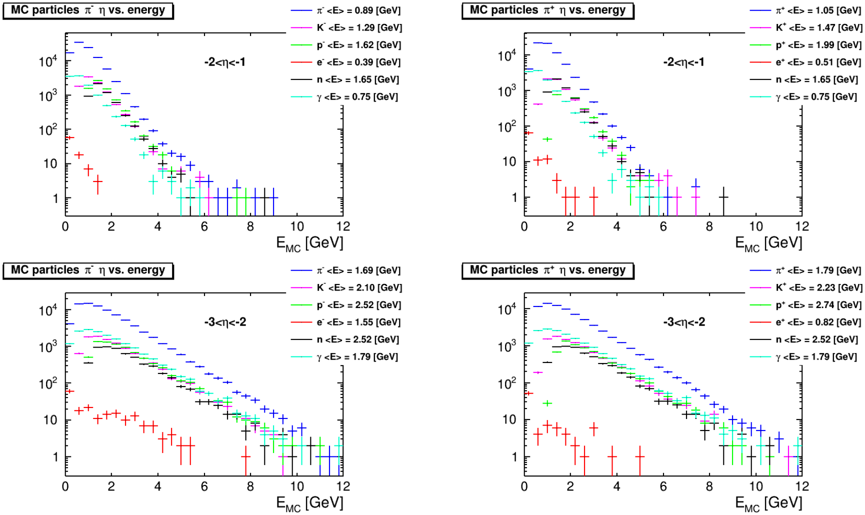
- Current design provides compensation
- Sampling fraction $\approx 1\%$
  - This means a 1 GeV hadron leaves similar signal to a $E_{MIP} = 7.5$ MeV across 10 layers
- Tungsten provides good performance
  - May add a few layers in front like for LFHCAL

Particle distributions - eta and energy

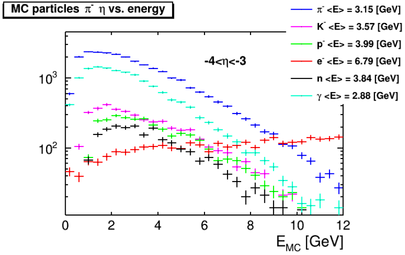


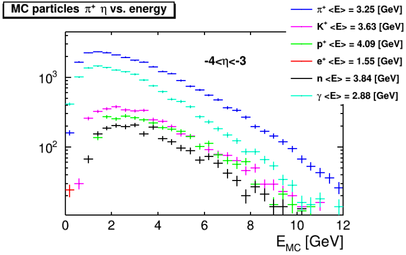
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >= 2.38\ \mathrm{GeV}$
- Large number of high E e^- - from beam?

Particle distributions - Energy vs. eta



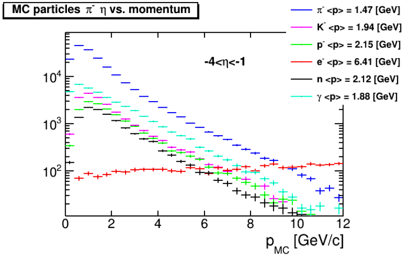
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >_{-2<\eta<-1} = 1.65\ \mathrm{GeV}$ and $< E >_{-3<\eta<-2} = 2.52\ \mathrm{GeV}$

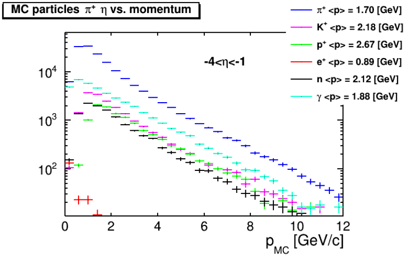




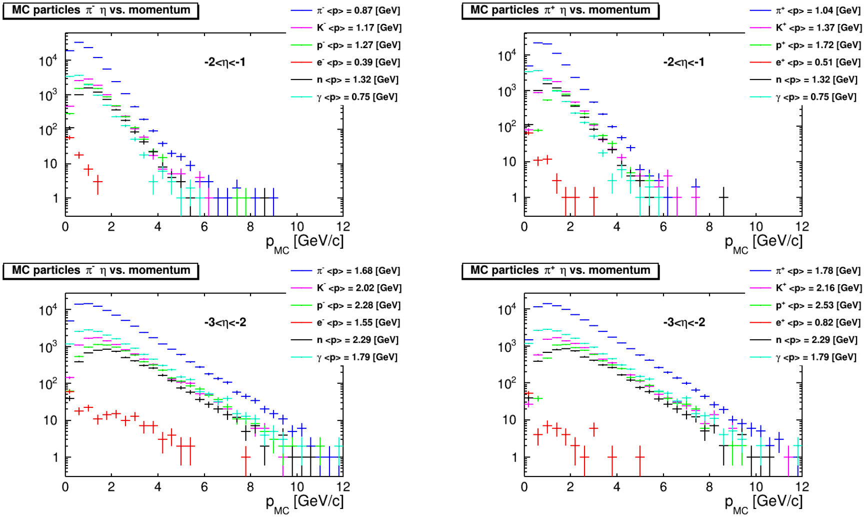
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >_{-4<\eta<-3} = 3.84\ \mathrm{GeV}$

Particle distributions - Momentum

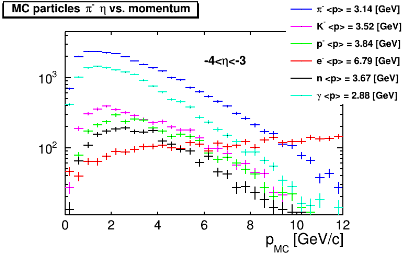


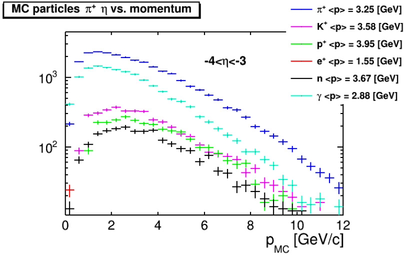


- All MC particles hitting nHCal
- Mean momentum of neutrons $< p >= 2.12\,\mathrm{GeV/c}$



- 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 $< p >_{-4<\eta<-3} = 3.67\ \mathrm{GeV/c}$

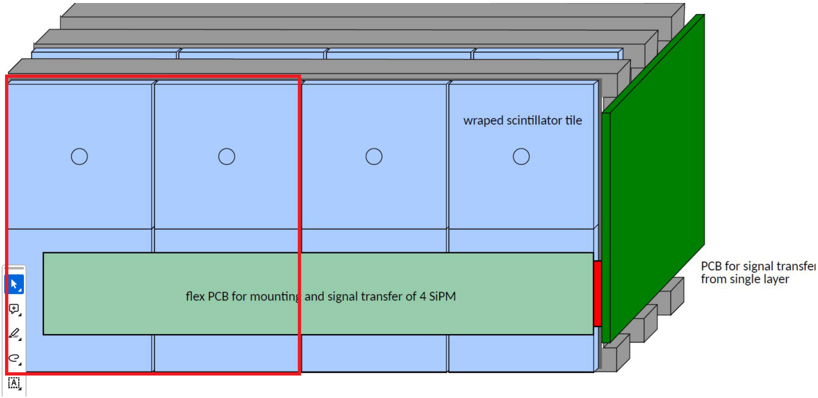
Energy

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

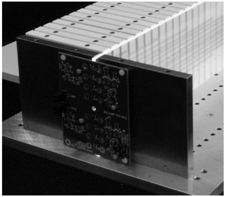
Momentum

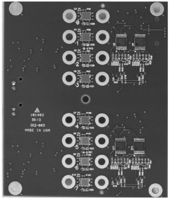
η	$< p >$ GeV/c inclusive n	$< p >$ GeV/c primary n
$-4 < \eta < -1$	2.12 GeV/c	2.12 GeV/c
$-2 < \eta < -1$	1.32 GeV/c	1.32 GeV/c
$-3 < \eta < -2$	2.29 GeV/c	2.29 GeV/c
$-4 < \eta < -3$	3.67 GeV/c	3.68 GeV/c

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



- SiPM on tile with 5 cm $\times$ 5 cm tiles
- Use 2x2 5 cm $\times$ 5 cm tile modules similar to 4M module of LFHCAL
- Connect outputs of 2x2 tile module to integrate the signal and create an effective 10 cm $\times$ 10 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





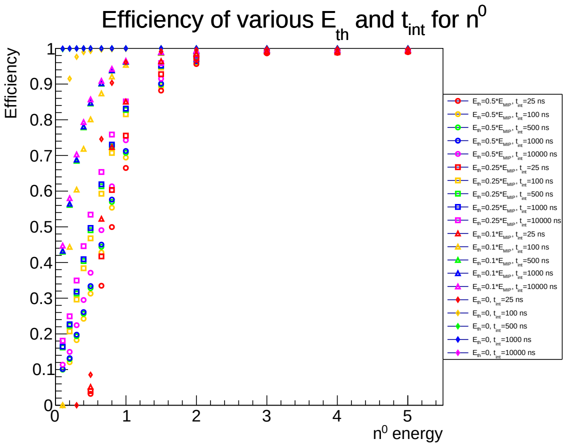
- $10\,\mathrm{cm} \times 10\,\mathrm{cm}$ tile modules similar to STAR FCS
- Light collection with SiPMs through WLS plate (middle)
  - Collects light from all 10 layers
  - Maybe can isolate WLS plate into 2 segments to collect light from 5 forward and 5 backward layers independently

Comparison of 2 options

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 $1.5M\$$)

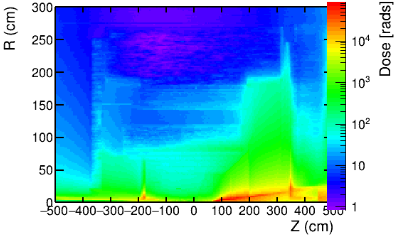
Neutron detection efficiency



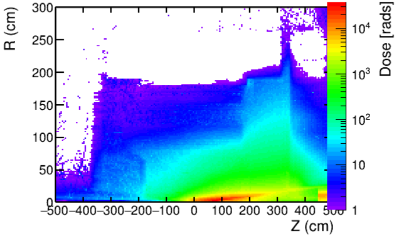
- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- E_{MIP} is 0.75 MeV per layer
- $E_{th} = 0.1 \times E_{MIP} = 75\,\mathrm{keV}$ and 100 ns provides good performance
- Need lower threshold and longer signal integration for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

10 year radiation dose for backward HCal

EM dose

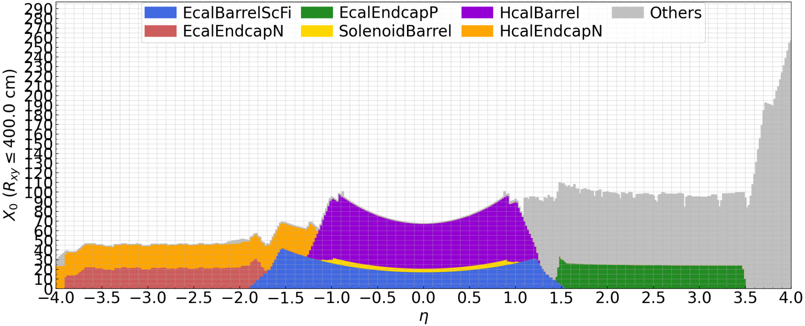


Hadronic dose



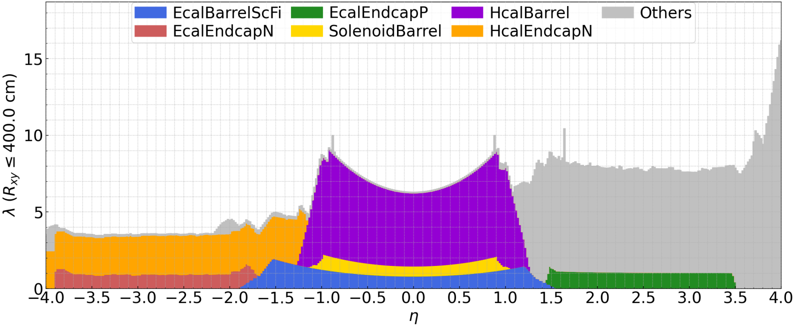
- Looked at radiation studies here:
  `https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses`
- Took root files and scaled to 10 years:
  `https://bnlbox.sdcc.bnl.gov/index.php/s/2sxywCQQgHP4ESn`
- Integrated doses between $-440 < z < -395\,\mathrm{cm}$
- EM dose $26.3k\,\mathrm{rad}$, hadronic dose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

Radiation length - brycecanyon geometry



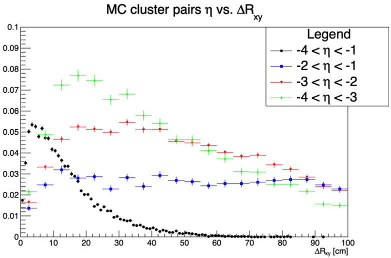
- $\sim 24X_0$ for backward HCal
- Scintillator tiles do not cover the same volume as steel absorber yet

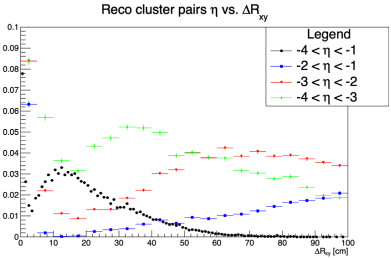
Interaction length - brycecanyon geometry



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

Distance between clusters - work in progress example





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

Neutron shower reconstruction with machine learning

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

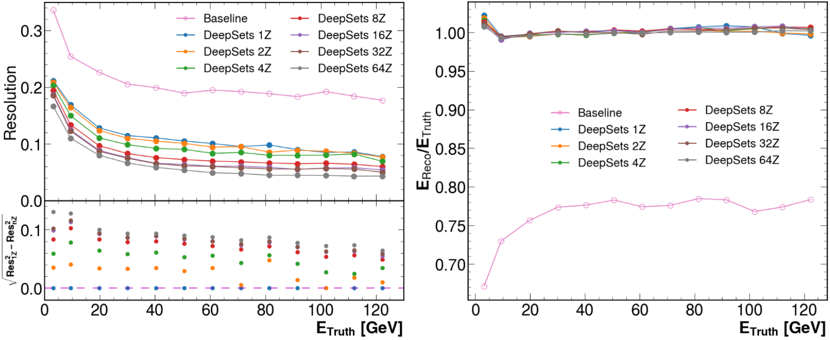
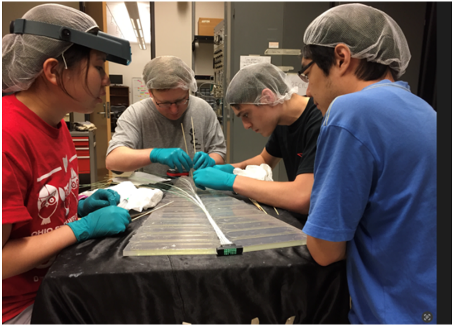


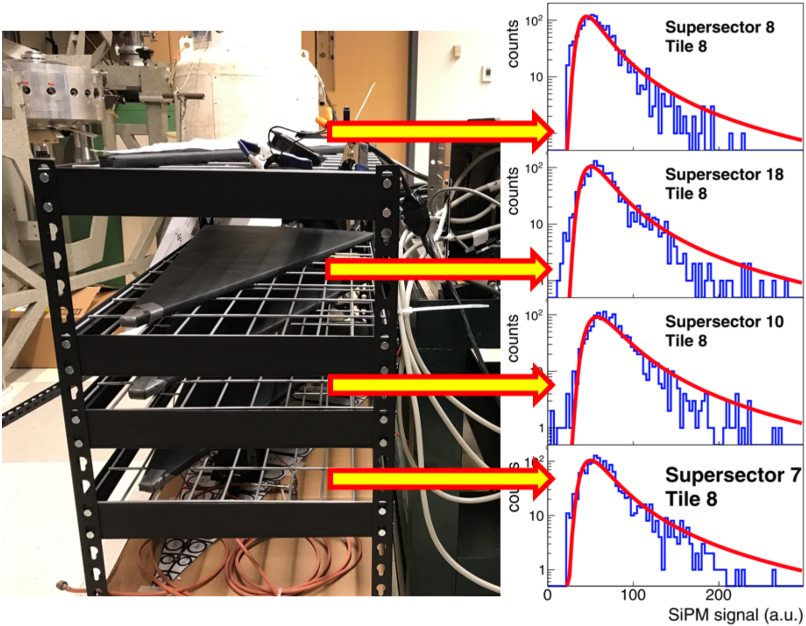
FIG. 4. Energy resolution (left) and energy scale (right) of calorimeter with different number of Z-sections along the longitudinal direction. The bottom panel of resolution plot shows the square root of difference in squares of resolution of 1 Z-section and the given Z-sections.

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

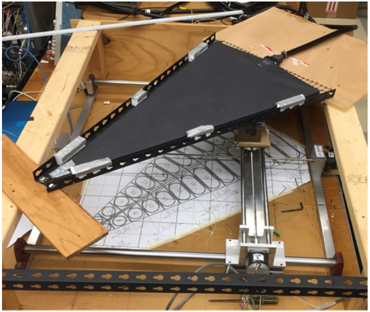


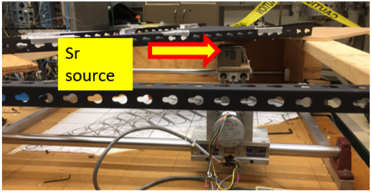
- Backward HCAL construction project well-matched for university group
  - subsidized shops with CNC, etc
  - characterization/testing with simple CAMAC systems etc
  - student-scale physical work

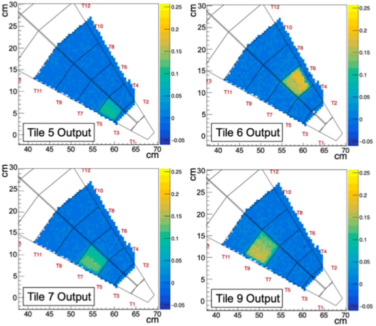
Tile characterization with cosmics



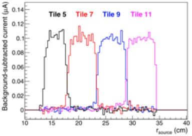
Uniformity, isolation characterization with source & translation table

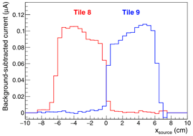




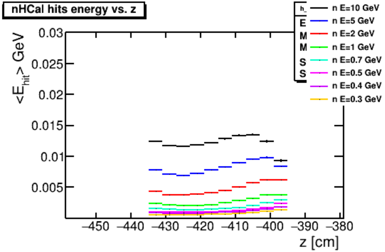


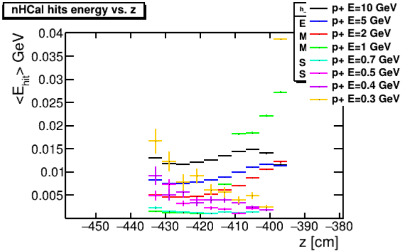
(a) Response of tiles 5,6,7 and 9 in one supersector, as a function of source position. Colors indicate background-subtracted current in μA.

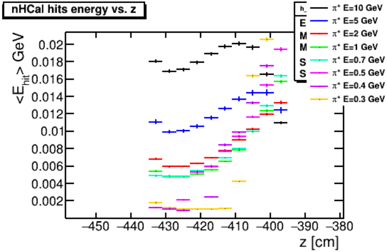




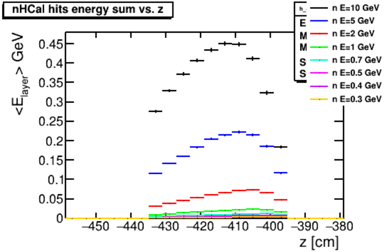
Study of longitudinal energy distribution

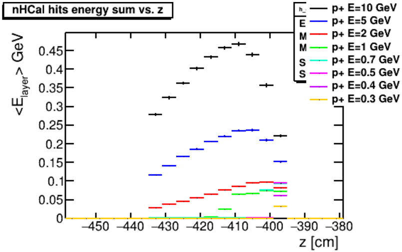


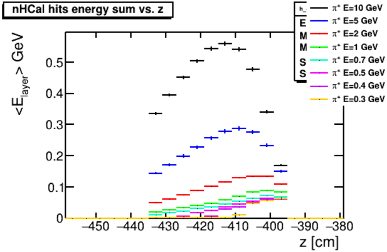




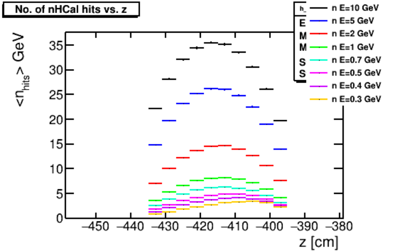
Study of longitudinal energy distribution - sum in a layer

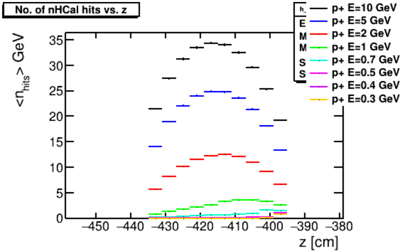


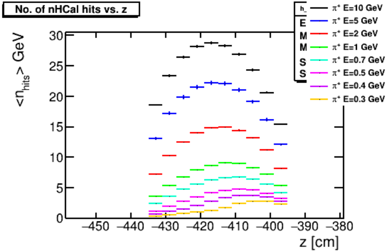


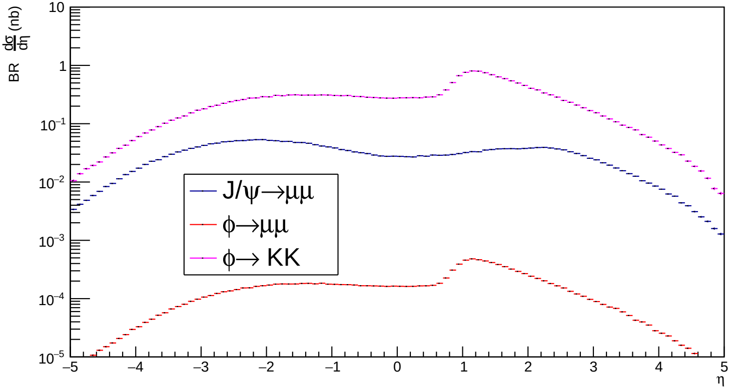


Study of longitudinal energy distribution - nHits



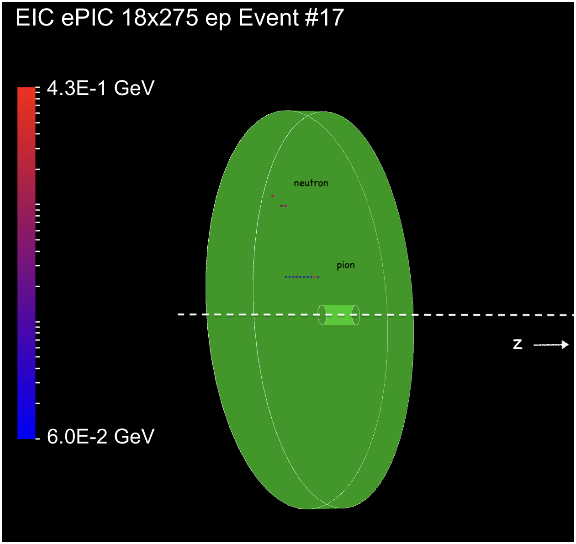






BR $\frac{d\sigma}{d\eta}$ (nb)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
–5
–4
–3
–2
–1
0
1
2
3
4
5
η
$J/\psi \to \mu\mu$
$\phi \to \mu\mu$
$\phi \to$ KK

Visualisation with VIRTUE



- neutron+pion event
- VIRTUE on Steam: `https://store.steampowered.com/app/2728380/VIRTUE/`