Status of backward HCal development

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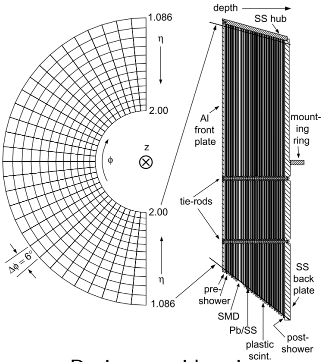
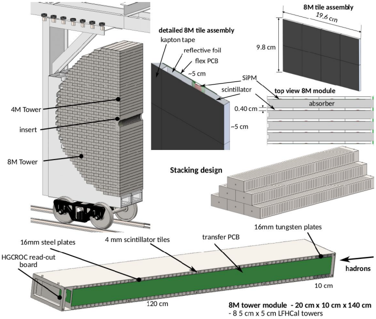
THE OHIO STATE UNIVERSITY

Outline

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

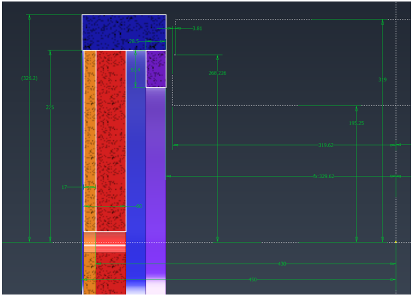
A future backward HCal shall provide functionality of a tail catcher for the high resolution e/m calorimeter in electron identification, as well as for jet kinematics measurement at small Bjorken x





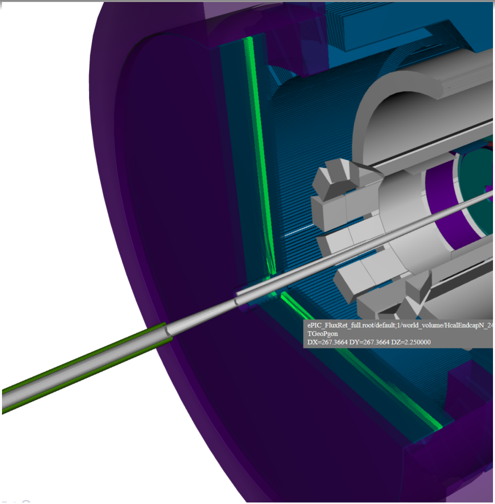
- Design considerations:
  - High efficiency for low energy neutron detection to study jets from low-x partons
  - Good spatial resolution to distinguish neutral/charged hadrons
- Follow similar solutions as Forward HCal instead of STAR EEMC megatiles
  - Due to required quick dissassembly of STAR -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

- 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 - follow forward HCal, can be thicker
- 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 or EICROC)

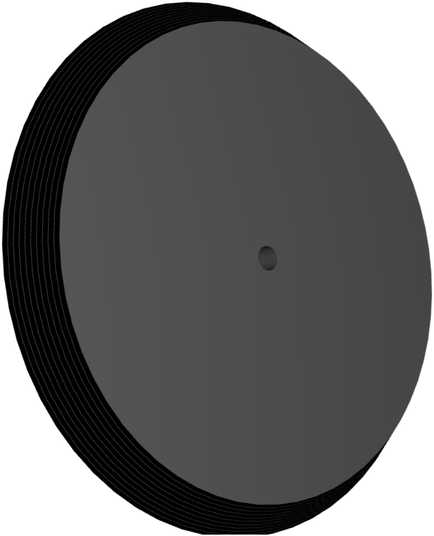


- nHCal decoupled from the magnetic steel $\Rightarrow$ more flexibility

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



60 ϕ bins
12+10 η bins: STAR EEMC tiles+extrapolation

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    81.6805*cm 90.9878*cm 100.89*cm 111.395*cm 122.516*cm 134.229*cm
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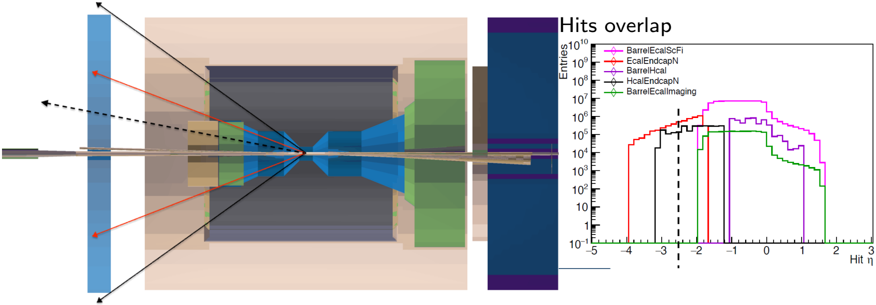
- A simplified version with STAR EEMC tiles already present in the simulation campaigns up to November
  - Good enough for basic checks

Overlap of calorimeters

Acceptance

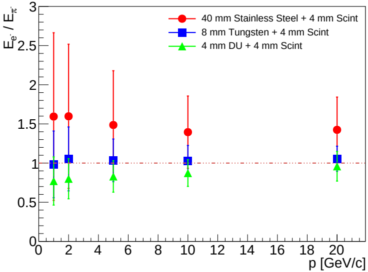


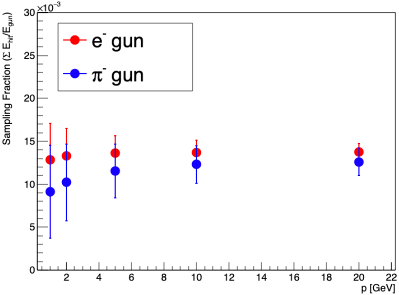
Subhadip Pal, CTU

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

Electron/hadron response

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

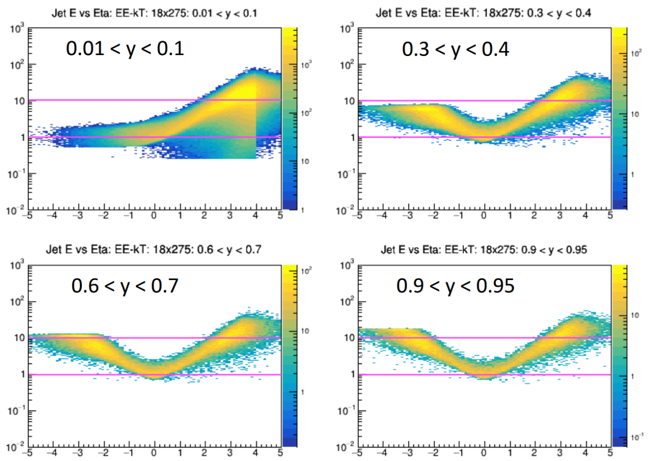




Subhadip Pal, CTU

- Current design provides compensation - not crucial
- Sampling fraction $\approx 1\%$ - may need to be increased
  - This means a 1 GeV hadron leaves similar signal to a $E_{MIP} = 7.5\ \mathrm{MeV}$ across 10 layers
- Tungsten provides good performance
  - May add a few layers in front like for LFHCAL
- Idea to consider: enhance e/h to easier distinguish charged/neutral hadrons

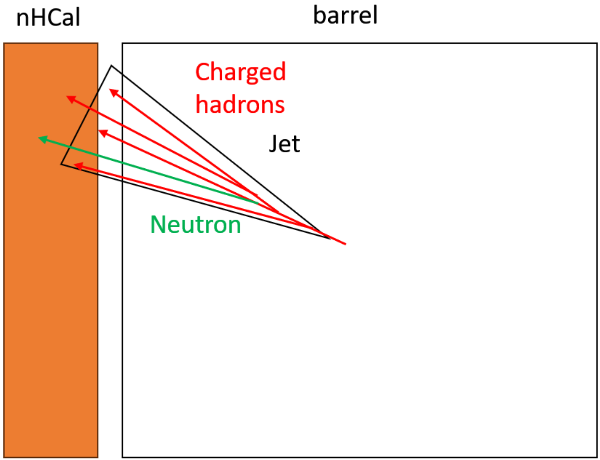
Low energy neutrons in jets



$0.1 < Q^2 < 1.0$

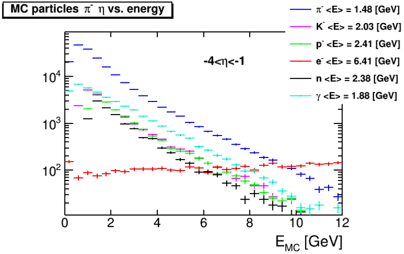
Brian Page, BNL

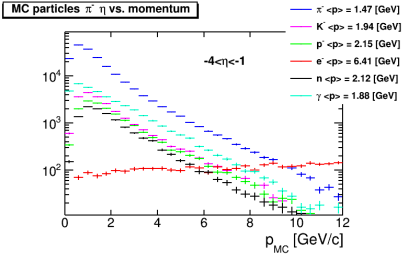
- Backward-going jets coming from low-x partons and high y events
  - Interesting physics!
- See more in presentation by Brian: `https://indico.bnl.gov/event/20679/`



- 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 hitting nHCal
- 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 $p = 0\,\mathrm{GeV}$

Total energy

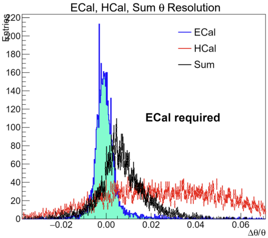
η	$< E >$ GeV inclusive n	$< E >$ GeV primary n
$-4 < \eta < -1$	2.38 GeV	2.38 GeV
$-2 < \eta < -1$	1.65 GeV	1.65 GeV
$-3 < \eta < -2$	2.52 GeV	2.52 GeV
$-4 < \eta < -3$	3.84 GeV	3.84 GeV

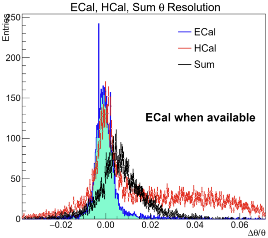
Momentum

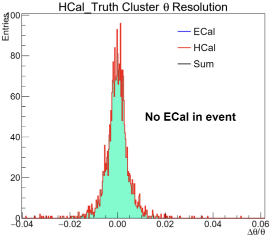
η	$< p >$ GeV/c inclusive n	$< p >$ GeV/c primary n
$-4 < \eta < -1$	2.12 GeV/c	2.12 GeV/c
$-2 < \eta < -1$	1.32 GeV/c	1.32 GeV/c
$-3 < \eta < -2$	2.29 GeV/c	2.29 GeV/c
$-4 < \eta < -3$	3.67 GeV/c	3.68 GeV/c

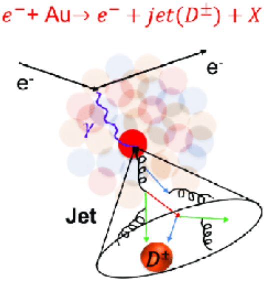
- Secondary neutrons have $< E >_{-4<\eta<-1} = 1.0$ GeV and $< p >_{-4<\eta<-1} = 0.27$ GeV - constant vs. η

Alexandr Prozorov, CTU



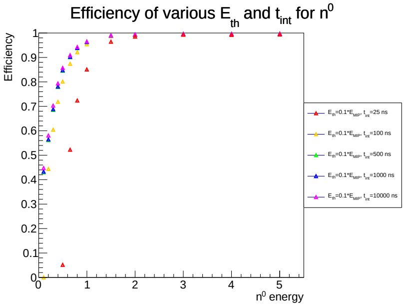




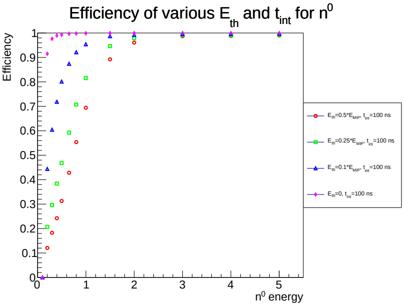


- 50% of neutrons scatter in backward EMCal
- Scattered neutron may fall out of a jet reconstruction cone
- We need to study this in coordination with Jet-HF PWG

Integration time dependence



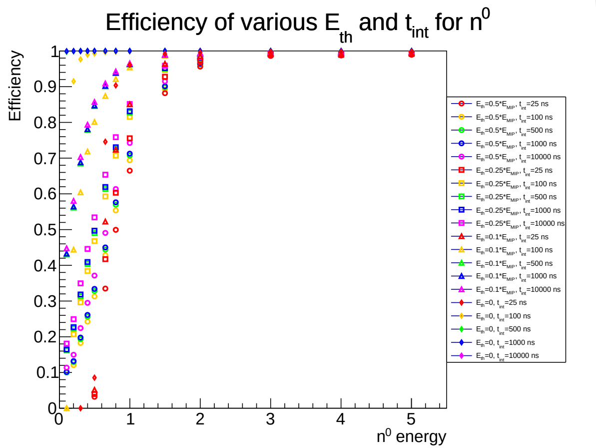
Threshold dependence



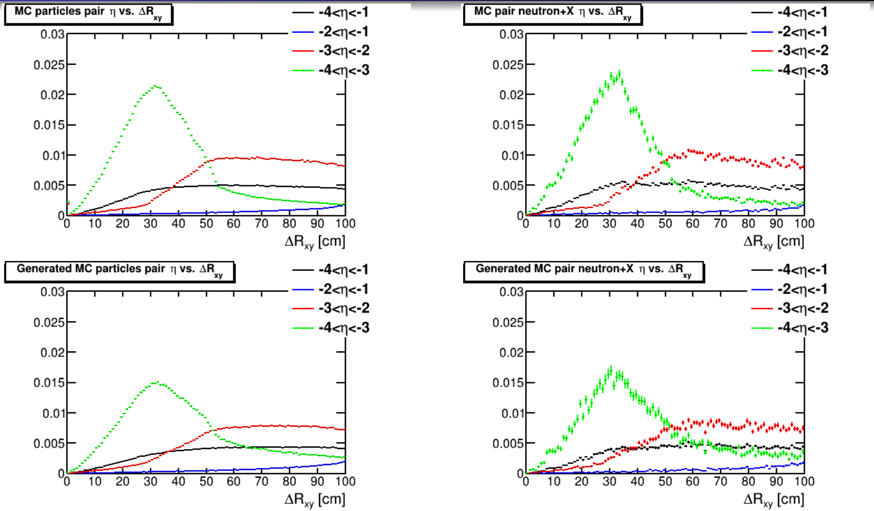
Sam Corey, OSU

- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}, $t_0 = 0$ (t_0 from first hit - see backup)
- 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 detection efficiency

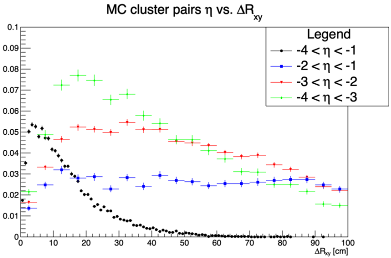


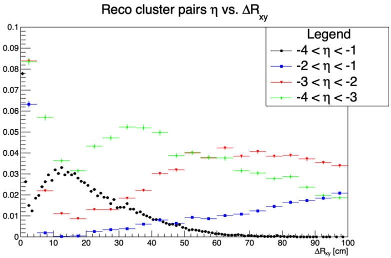
- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- E_{MIP} is 0.75 MeV per layer
- $E_{th} = 0.1 \times E_{MIP} = 75\,\mathrm{keV}$ and 100 ns provides good performance
- Need lower threshold and longer signal integration for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



- 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 $0 < \Delta R_{xy} < 100$ cm

Distance between clusters





Work in Progress: Nick Jindal, OSU

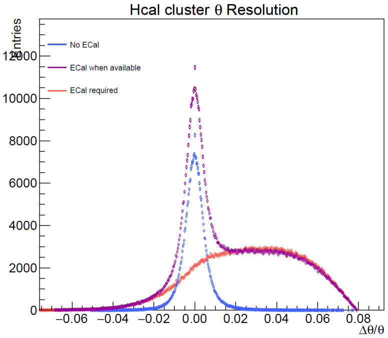
- Similar results for clusters, qualitatively consistent with MC particle straight line projections
- Resolution of 20 cm seems good enough, peak at 30 cm for reco clusters (20 cm for MC)
- Hit merging across layers was disabled here
  - Clusters from different layers overlap in XY, cause excess around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

$$\Theta_{reco} = (w_{EMCal} * \Theta_{EMCal}) + (w_{HCal} * \Theta_{HCal})$$
$$\phi_{reco} = (w_{EMCal} * \phi_{EMCal}) + (w_{HCal} * \phi_{HCal})$$

$$w_{EMCal} = \frac{1.49 * E_{Emcal}}{E_{reco}} \; ; \; w_{HCal} = \frac{E_{Hcal}}{E_{reco}}$$

$$E_{reco} = 1.49 * E_{EMCal} + E_{HCal}$$

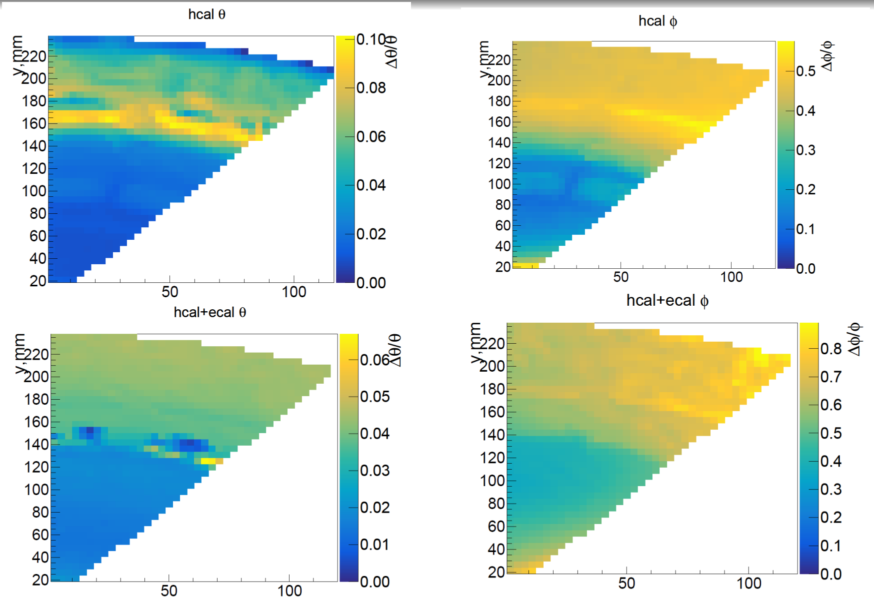
Used reconstructed energy fractions as weights to combine truth cluster positions



Subhadip Pal, Alexandr Prozorov, CTU

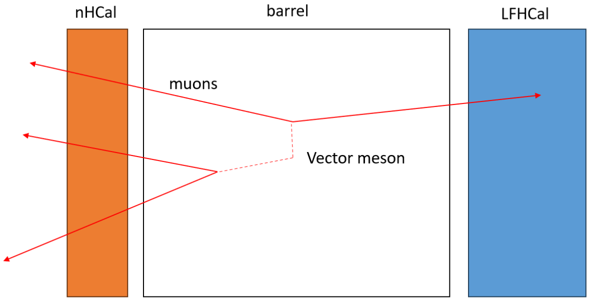
- Scattering in EMCal affects the position resolution

Position resolution study



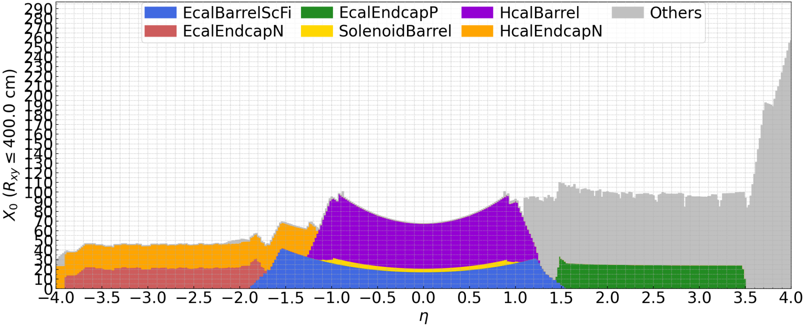
- Scattering in EMCal and barrel affects the position resolution
- Good resolution, but scattering makes it worse, especially in overlap region with barrel

Vector meson studies

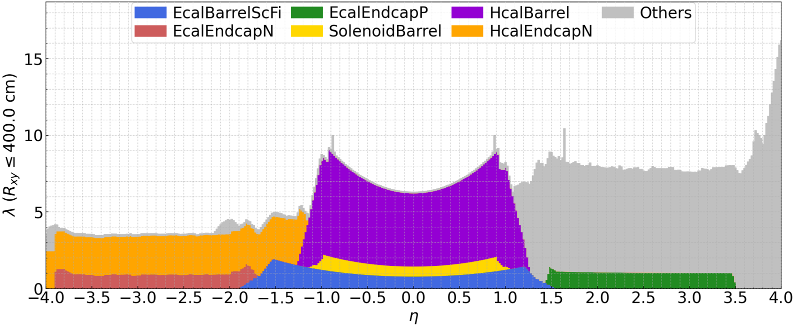


- Important for high y or low-p_T vector mesons - depends on type
- Increases acceptance
- Need projected MIP tracks and MIP signals in backward HCal and EMCal
  - μ/π distinction important, position resolution...
- Study of impact required for TDR

Radiation length - brycecanyon geometry



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

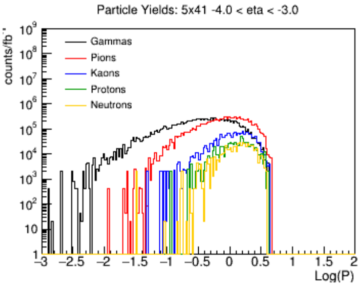


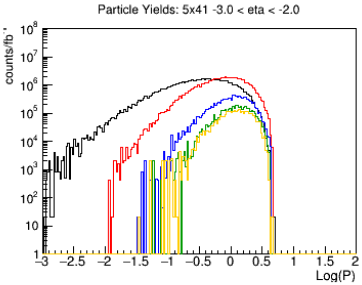
- $\sim 2.4\lambda_0$ for backward HCal
- Scintillator tiles do not cover the same volume as steel absorber yet

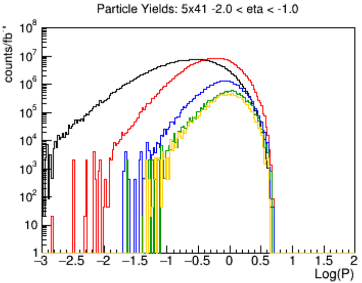
Conclusions

- Presented basic concept for backward HCal for ePIC
- Simplified geometry already in simulation campaign for STAR EEMC geometry+extensions and LFHCAL-style (December)
- Neutron detection possible down to $E = 0.3\,\mathrm{GeV}$
- Position resolution study in progress, but needs to be $\approx 20\,\mathrm{cm}$
- Work in progress on neutron reconstruction with machine learning

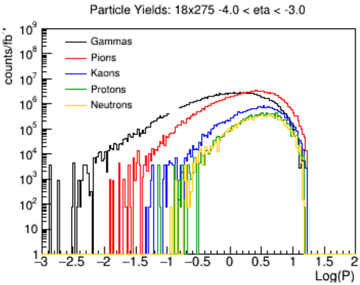
BACKUP

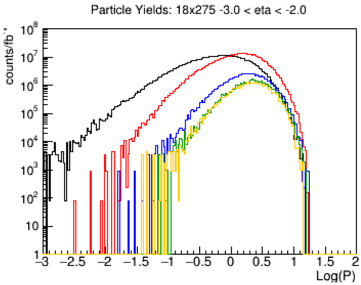


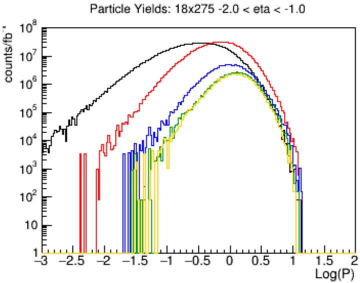




- Pythia simulation by Brian Page







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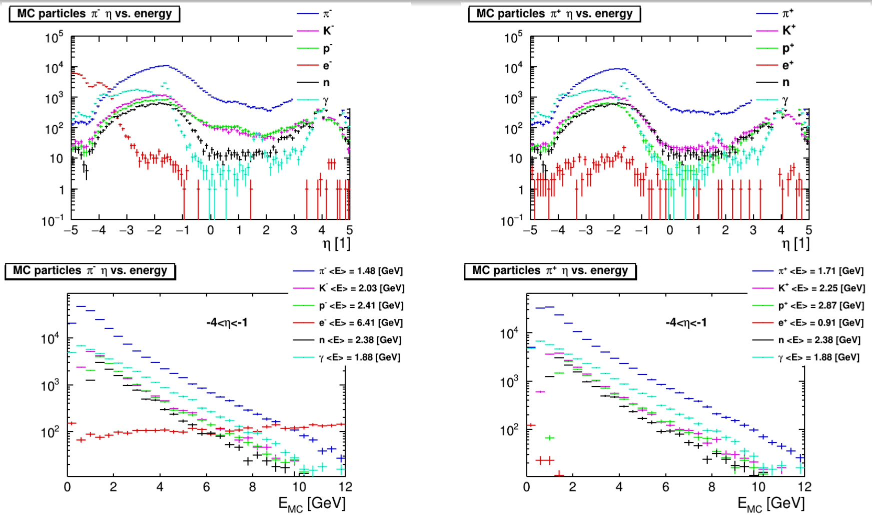
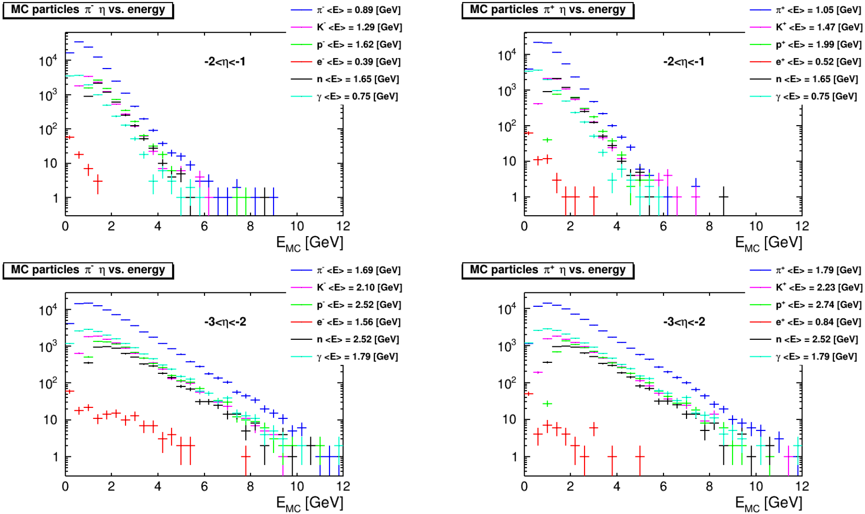


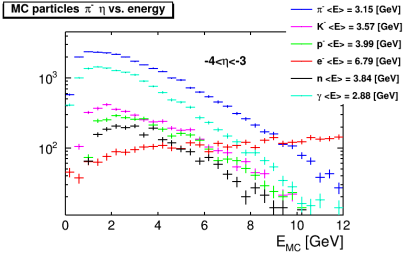
- Primary (generated) MC particles hitting nHCal
- Mean energy of neutrons $< E >= 2.38\ \mathrm{GeV}$
- Large number of high E e^- - from beam? (but these should have generator status=4)

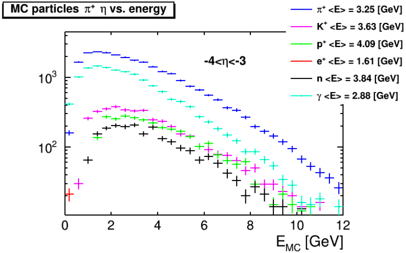
Primary particle distributions - Energy vs. eta



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

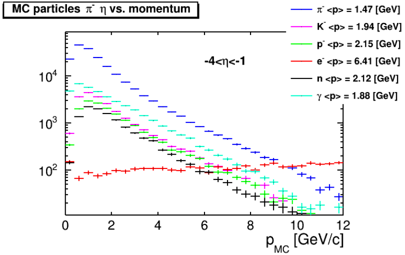
Primary particle distributions - Energy vs. eta

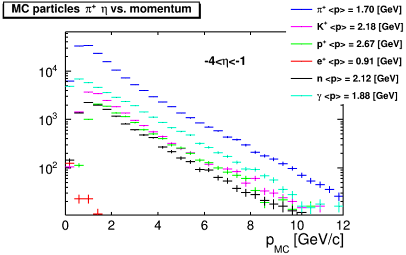




- Primary (generated) MC particles hitting nHCal
- Mean energy of neutrons $< E >_{-4<\eta<-3} = 3.84\ \mathrm{GeV}$

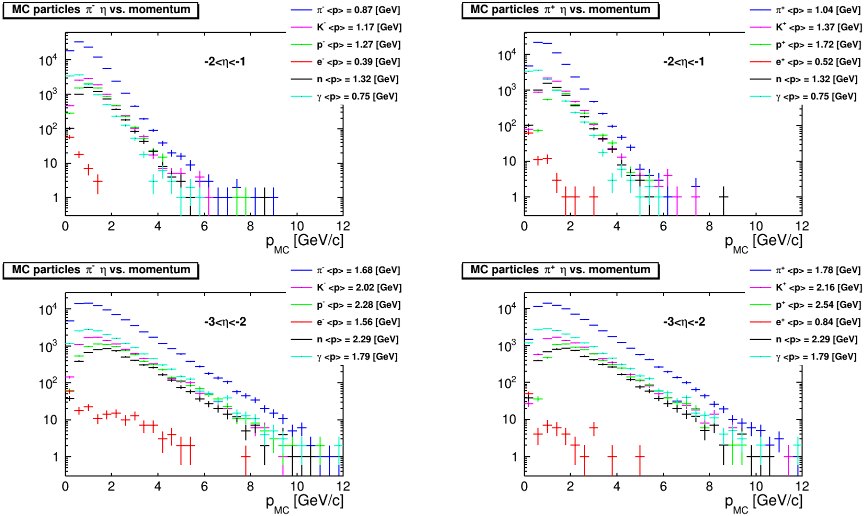
Primary particle distributions - Momentum



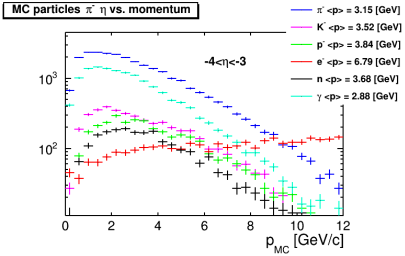


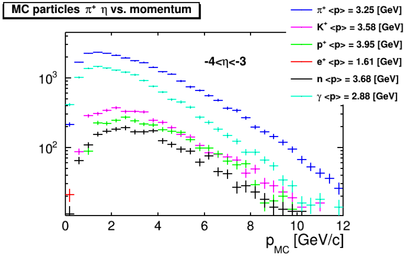
- Primary (generated) MC particles hitting nHCal
- Mean momentum of neutrons $< p >= 2.12\,\mathrm{GeV/c}$

Primary particle distributions - Momentum vs. eta



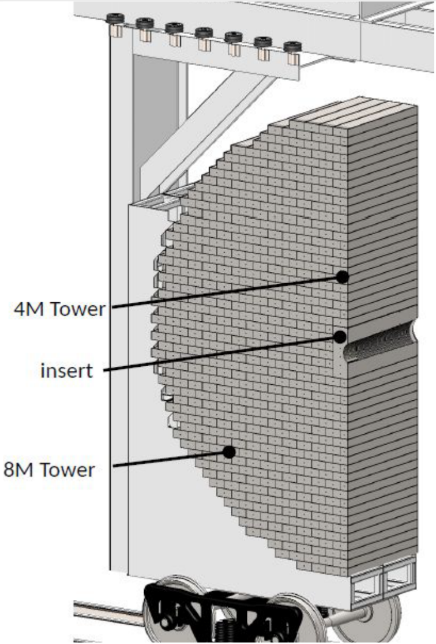
- Primary (generated) MC particles hitting nHCal
- Mean momentum of neutrons $< p >_{-2<\eta<-1} = 1.32\ \mathrm{GeV/c}$ and $< p >_{-3<\eta<-2} = 2.29\ \mathrm{GeV/c}$



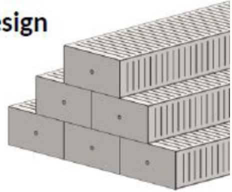


- Primary (generated) MC particles hitting nHCal
- Mean momentum of neutrons $< p >_{-4<\eta<-3} = 3.68\ \mathrm{GeV/c}$

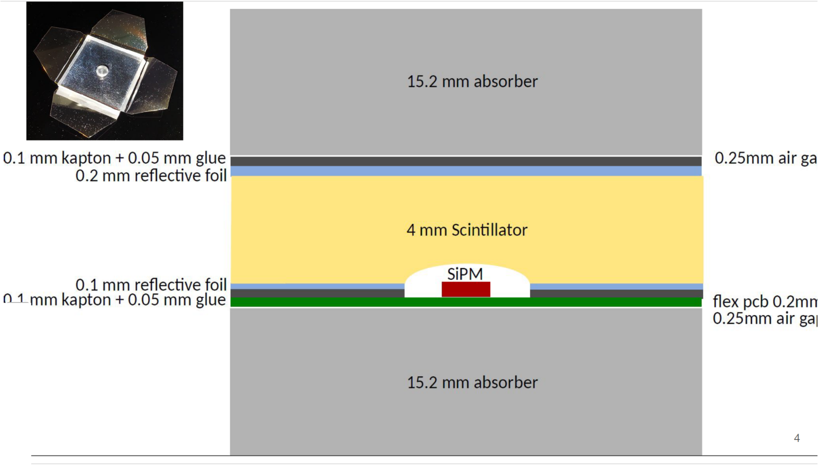
LFHCal design



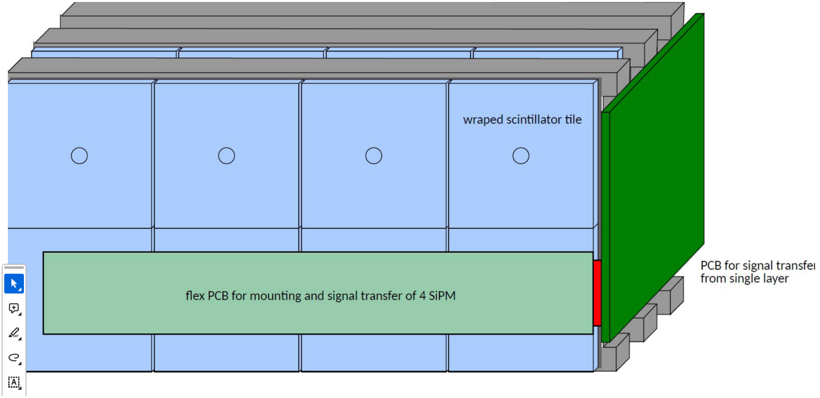
Stacking design



LFHCal layers

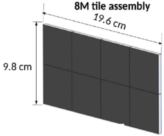


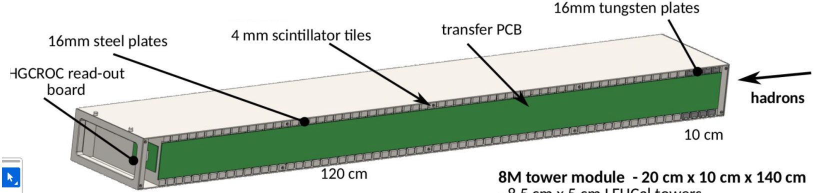
LFHCal PCBs



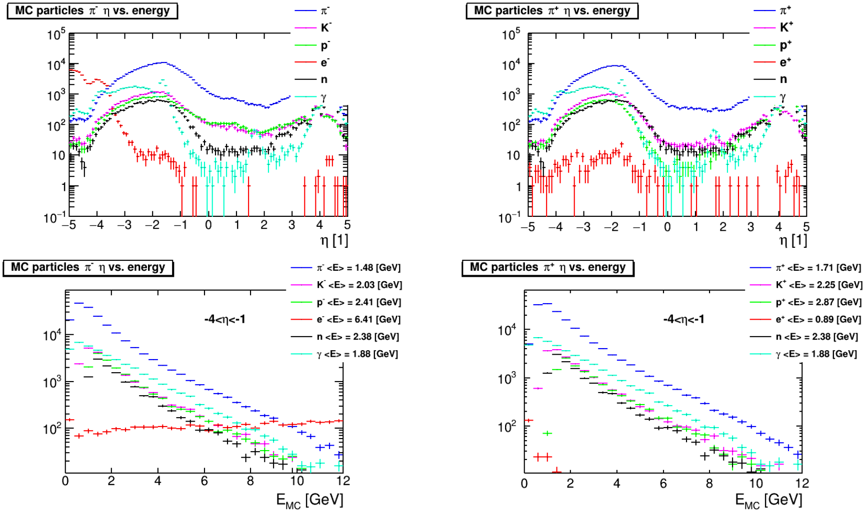
wraped scintillator tile
flex PCB for mounting and signal transfer of 4 SiPM
PCB for signal transfe
from single layer

LFHCal PCBs



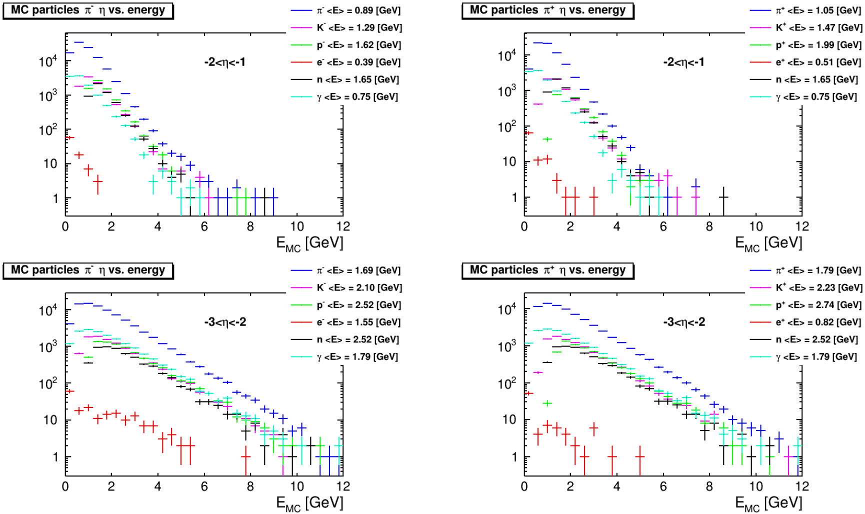


8M tower module - 20 cm x 10 cm x 140 cm
- 8 5 cm x 5 cm LFHCal towers



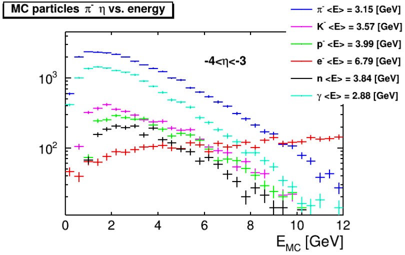
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >= 2.38\ \mathrm{GeV}$
- Large number of high E e^- - from beam?

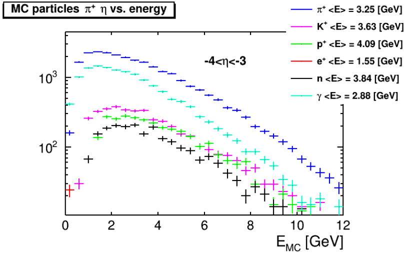
Particle distributions - Energy vs. eta



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

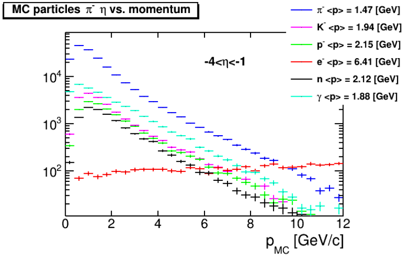
Particle distributions - Energy vs. eta

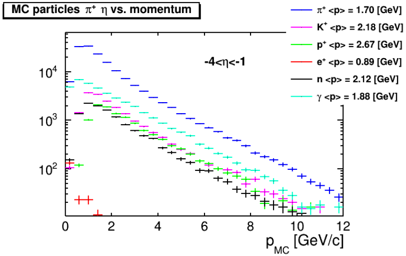




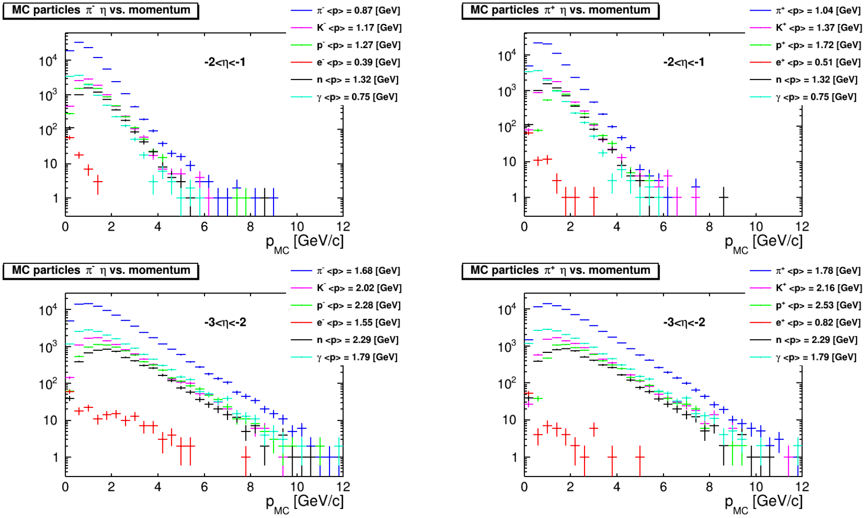
- All MC particles hitting nHCal
- Mean energy of neutrons $< E >_{-4<\eta<-3} = 3.84\,\mathrm{GeV}$

Particle distributions - Momentum

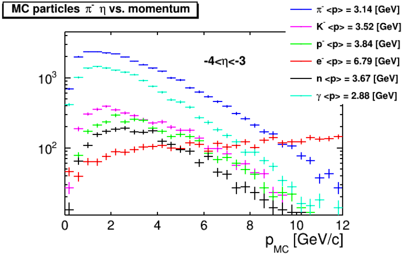


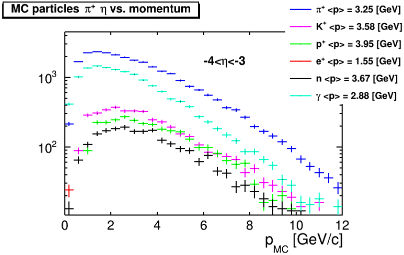


- All MC particles hitting nHCal
- Mean momentum of neutrons $< p >= 2.12\,\mathrm{GeV/c}$



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

Summary table

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

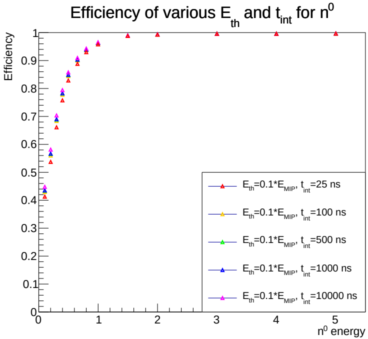
Momentum

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

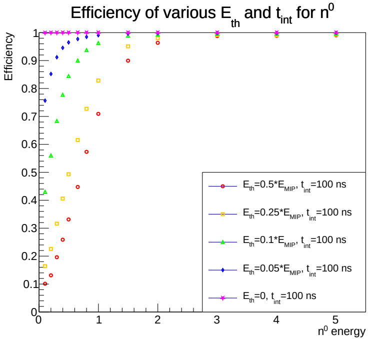
- Secondary neutrons have $< E >_{-4<\eta<-1} = 1.0\ \mathrm{GeV}$ and $< p >_{-4<\eta<-1} = 0.27\ \mathrm{GeV}$ - constant vs. η

Neutron detection efficiency

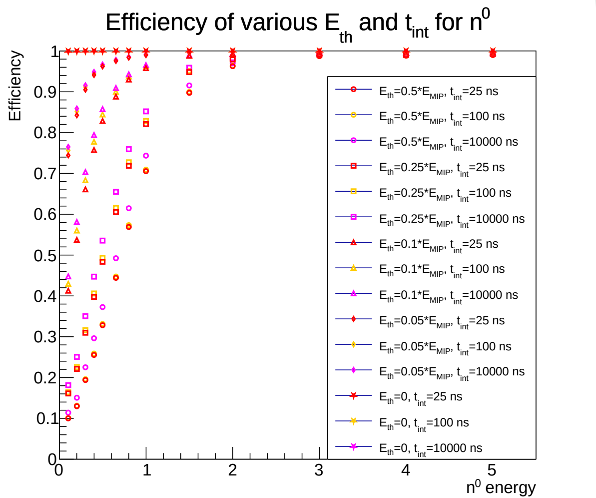
Integration time dependence



Threshold dependence

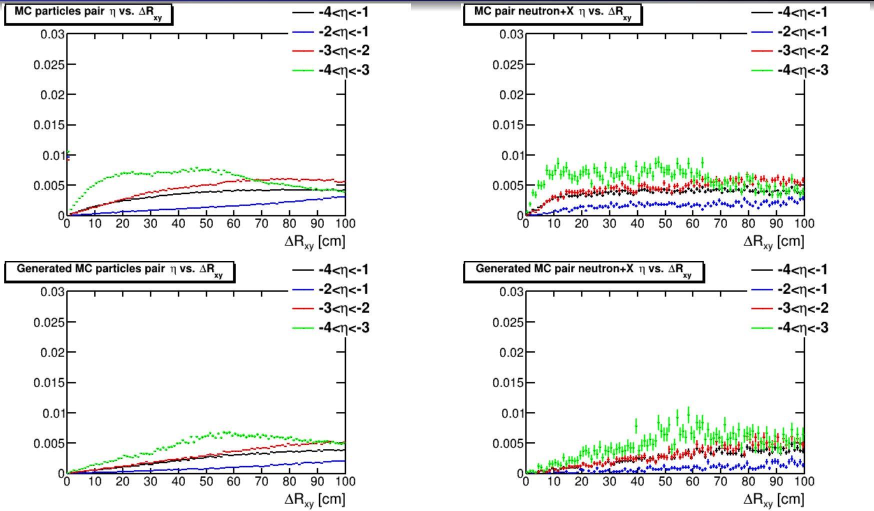


- Efficiency of requiring a hit with a sum of hit contributions energy integrated up to t_{int} and passing a threshold E_{th}
- Checked with simulation only - no digitization
- E_{MIP} is 0.75 MeV per layer
- E_{th} has the biggest impact
- 100 ns is good enough, but lower energy neutrons may need longer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

Distance between particle projections in nHCal, both in $-4\eta < -1$



- Both particles in $-4\eta < -1$
- Resolution of $20\,\mathrm{cm}$ 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 $0 < \Delta R_{xy} < 100\,\mathrm{cm}$