Brookhaven National Laboratory · Jefferson Lab · U.S. DEPARTMENT OF ENERGY

nHCal (backward hadronic calorimeter)

simulation, design, assembly, and schedule

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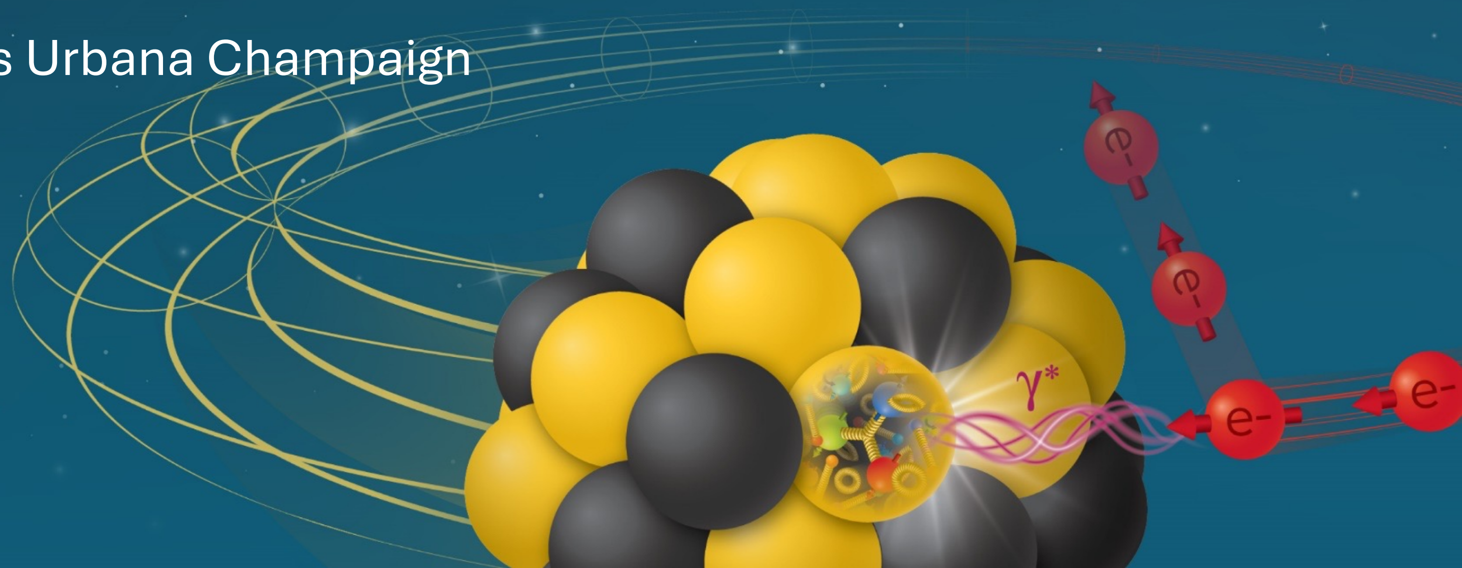
Preliminary Design Review

October 30-31, 2025

Electron-Ion Collider



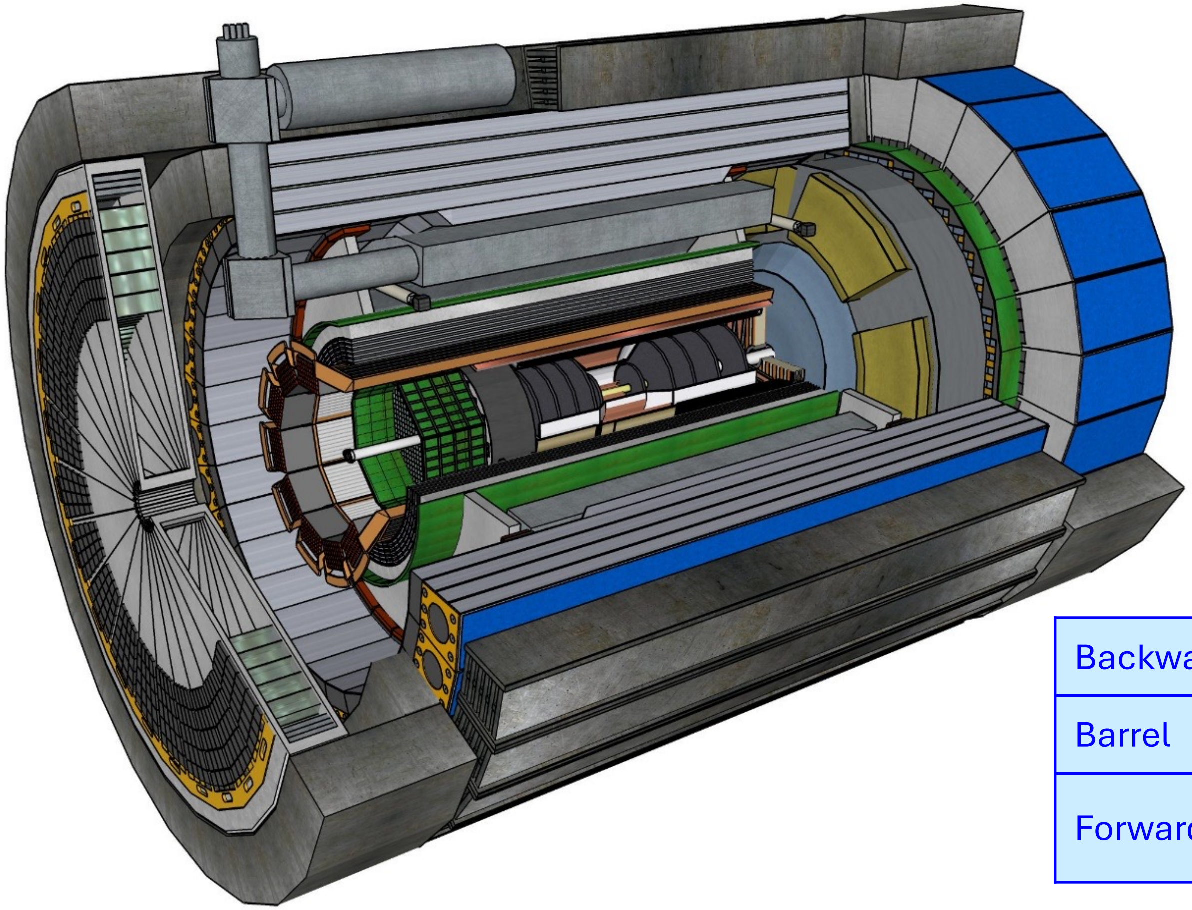
Charge Questions

The review covers the **design and performance** of these detectors with respect to the physics program and **requirements**, ranging from **construction and integration** to **operating conditions and background radiation**. This is an assessment of the readiness of these detector systems in particular towards the upcoming project reviews for **CD-2 (baseline)** for which the design maturity is expected to be 60% or higher.

1. Are the technical performance requirements appropriately defined and complete for this stage of the project?
2. Is the design of the various detector systems advanced enough and appropriately documented for this stage of the project? Are the current detector plans likely to achieve the performance requirements for the lifetime of the EIC physics program?
3. Are the assumptions for construction and fabrication of the various detector components sound and are assembly plans reasonable and consistent with the overall detector schedule?
4. Have ES&H and quality assurance considerations been adequately incorporated into the plans at the present stage?
5. Have recommendations from previous reviews been adequately addressed?

Hadronic Calorimetry

- **Energy resolution:** particle flow reconstruction (combined with tracking and em-calorimetry)
- **Granularity:** neutral cluster isolation and jet substructure measurements
- **Flux return** for solenoid magnet



Backward	**NHCal**	Steel/scintillator calorimeter
Barrel	**BHCal**	Refurbished from sPHENIX
Forward	**LFHCal**	Longitudinally segmented steel/scintillator

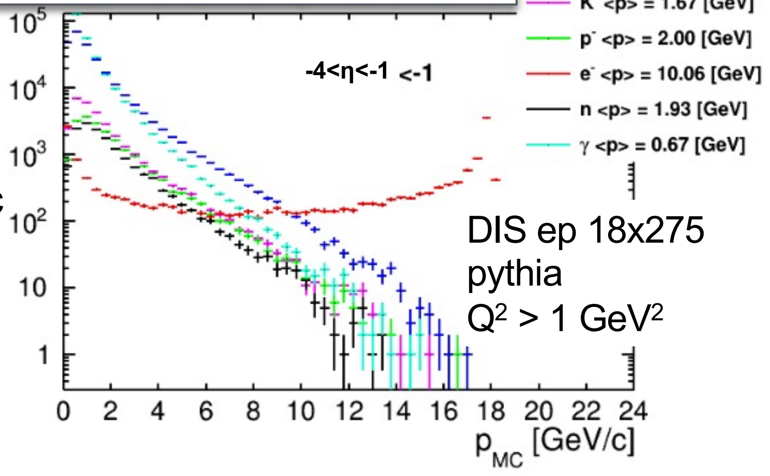
Main purpose of nHCal

Charge 1

- Tail catcher calorimeter in the backward (electron-going) direction
- Important for low-x and -Q2, high-y (high gluon densities) - **core aspects of EIC physics mission**
  - Diffraction, neutral and charged jets
  - Neutron detection and muon ID
- Lessons learned from HERA / H1 backward SPACAL NIMA 386 (1997), 397-408 PLB 665 (2008), 139-146
- Tail-catcher: design optimized for particles in the few to 10s of GeV range

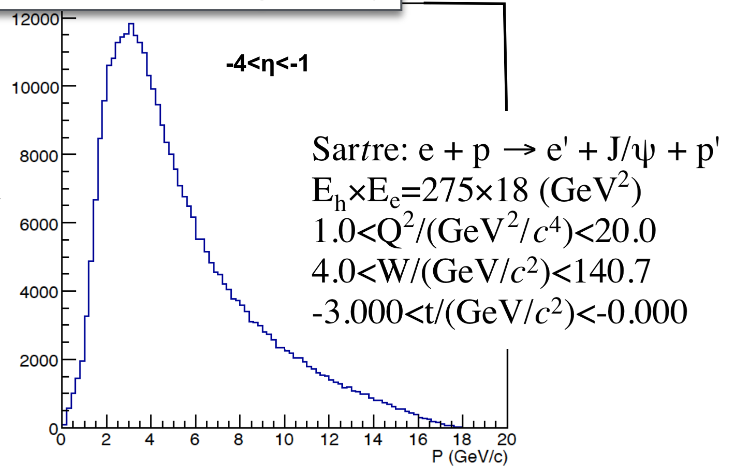
neutrons and negatively charged particles

neutrons in nHCal:
<p>=1.9 GeV/c
<E>=2.2 GeV



muons from diffractive J/ψ decay

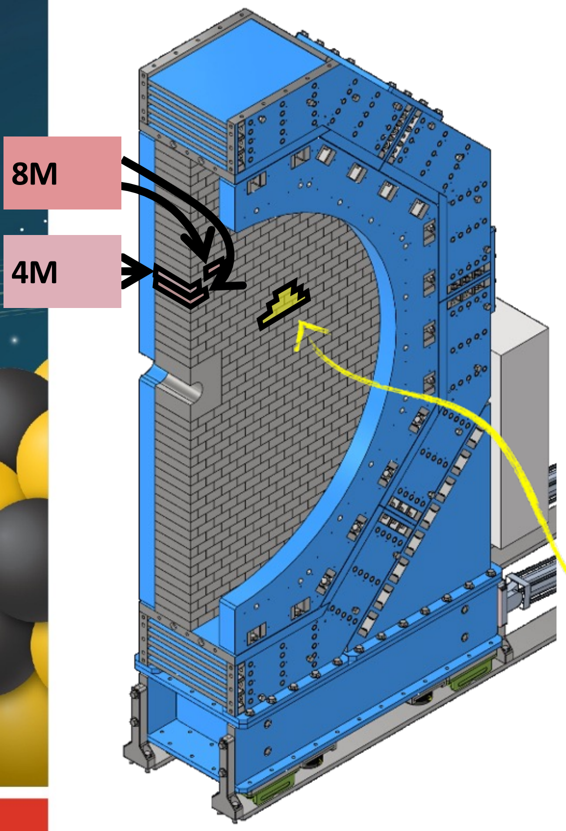
muons in nHCal:
<p>=5.3 GeV/c
<E>=5.3 GeV



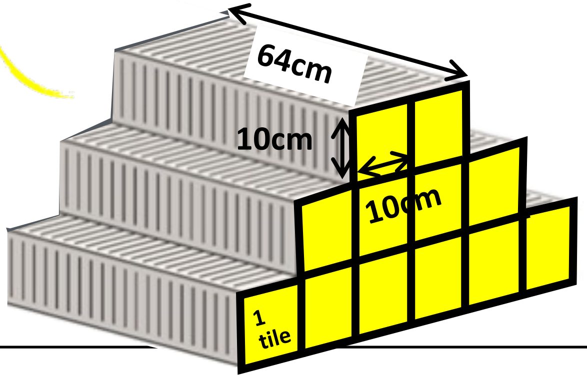
Backward (electron-going) hadronic calorimeter - nHCal

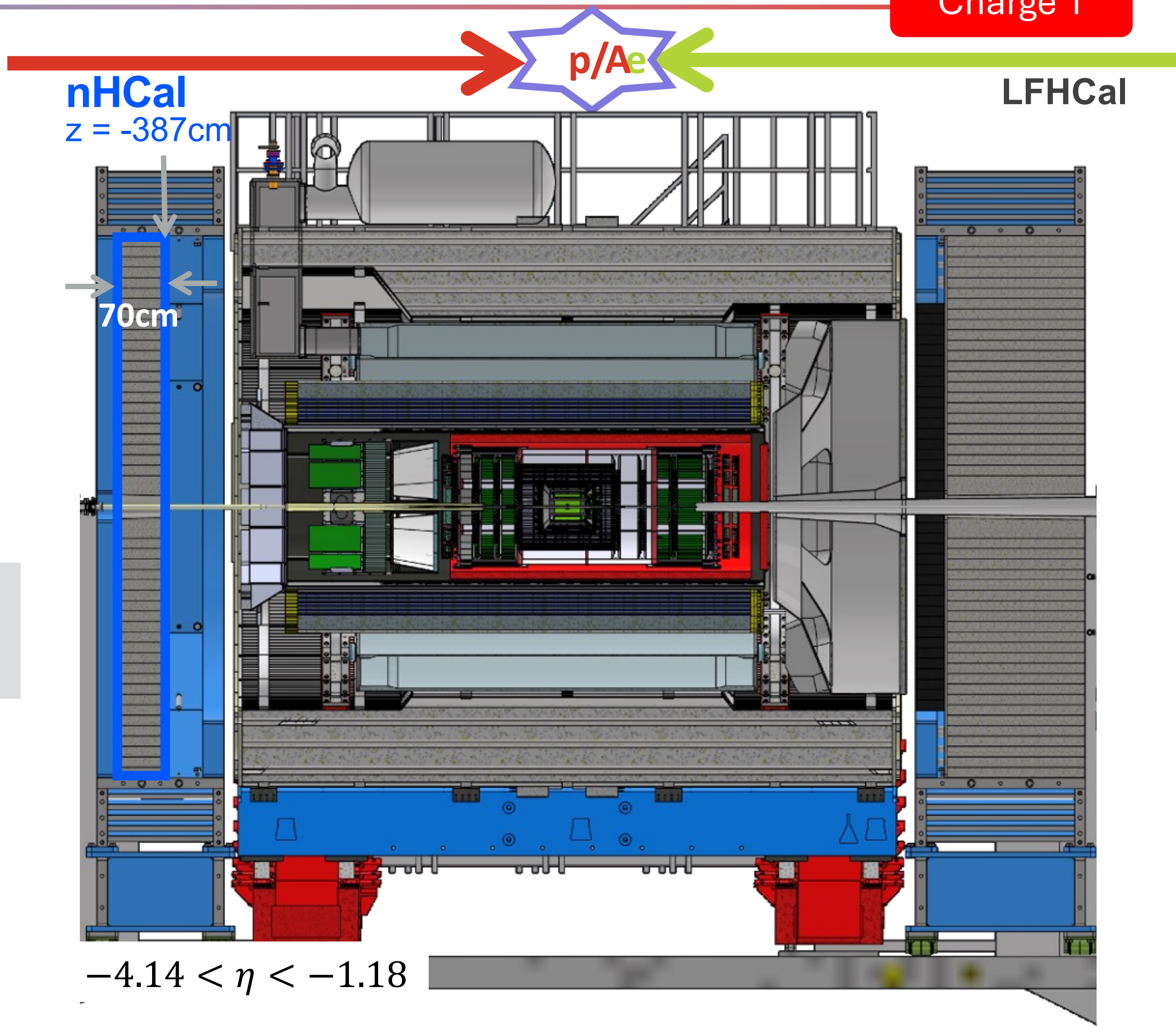
Charge 1

- Tail catcher calorimeter with sampling approach, alternating Fe / Sci Tiles layers
  - Synergies with LFHCal (choice of technology)
  - Interaction lengths: ~2.4 (LFHCal: 6)
  - up to ~70cm available (including electronics)



10 layers of each: **4 cm steel** + 2.4 **cm scintillator**
+ Initial scintillator layer (2.4 cm)





$-4.14 < \eta < -1.18$

Daniel Brandenburg (OSU),
Caroline Riedl (UIUC)

nHCal design optimization via simulations - overview

Charge 1/2

Readout:
- Utilize CALOROC (32ch) along with other HCALs

Design optimization

- Parameters: transverse tile size, number of layers, scintillator & absorber thickness
- nHCAL: 1st layer (nearest IP) is scintillator
  - Improve neutral vs. charged hadron separation
- Dedicated simulations
  - Single particle, DIS, Diffractive events
- Absorber material fixed by external constraints
  - Non-magnetic material (magnet system)
  - Risk + cost prohibit use of e.g. W, depleted U

Physics impact ➡ Design parameter ⬇	σ_E/E	Eff	μ/π sep.	λ_{int}
Gross length	X	X		
Tile configuration	X	X		
Z-layer readout	X		X	
Sampling fraction, absorber/scintillator ratio				X
Absorber material	X			X

5x5 or 10x10	scintillator thickness	0.4				0.6	2.4	1.2
[cm]	absorber thickness	4	3	2	1.5 2	2	4	2
10 layers		45					64	
12 layers		54						
13 layers			46					
15 layers		68						
20 layers				50		54	58	64
28 layers					57			

gross length

nHCal configuration (10x10 tiles)

LFHCal configuration (5x5 tiles)

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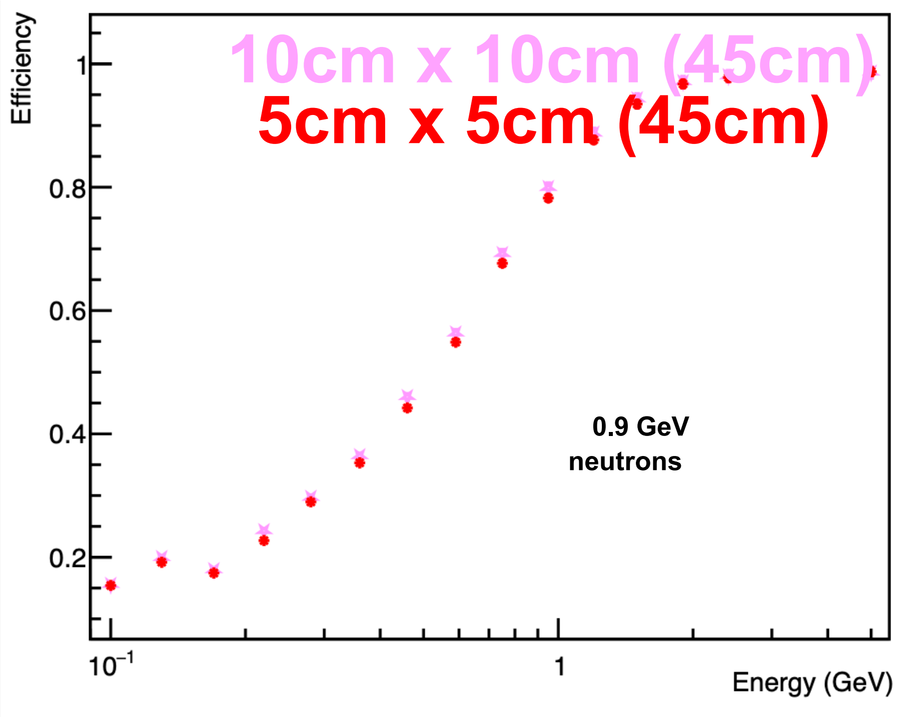
Caroline Riedl (UIUC)

Design Optimization: Efficiency for neutrons

Charge 2

As a tail-catcher, low energy neutron detection is key design metric for nHCAL

- Tile size has negligible impact
- Efficiency increases with
  - Number of layers (⇒ length of calorimeter):
    10 → 15 layers increases efficiency by about 5% for 1 GeV neutrons
  - Scintillator / absorber ratio:
    scintillator 4mm → 8mm increases efficiency by nearly 20% for 0.5 GeV neutrons



Constraints on gross length, tile configuration, absorber/scintillator ratio

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Caroline Riedl (UIUC)

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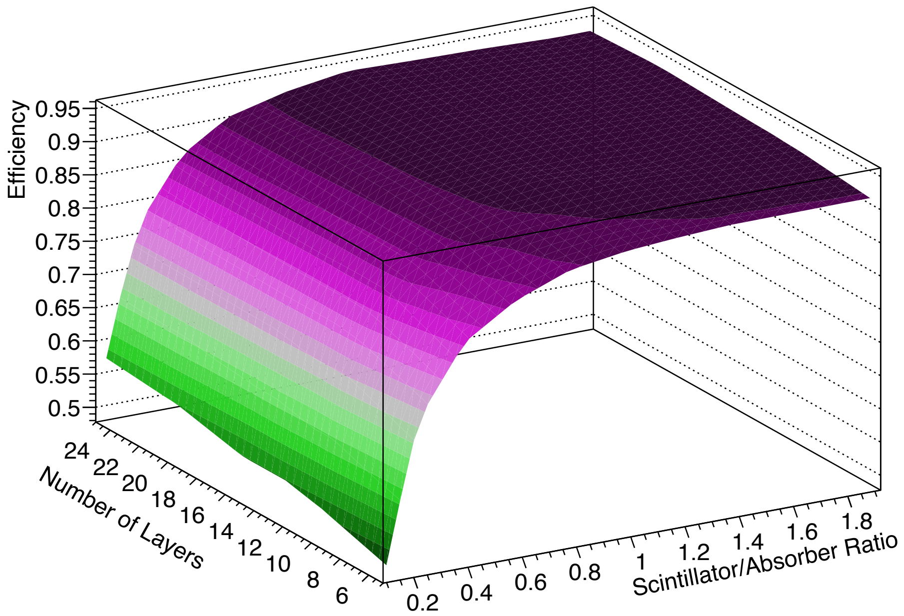


0.9 GeV neutrons

R=0.6 gives optimal efficiency for designs with >10 layers

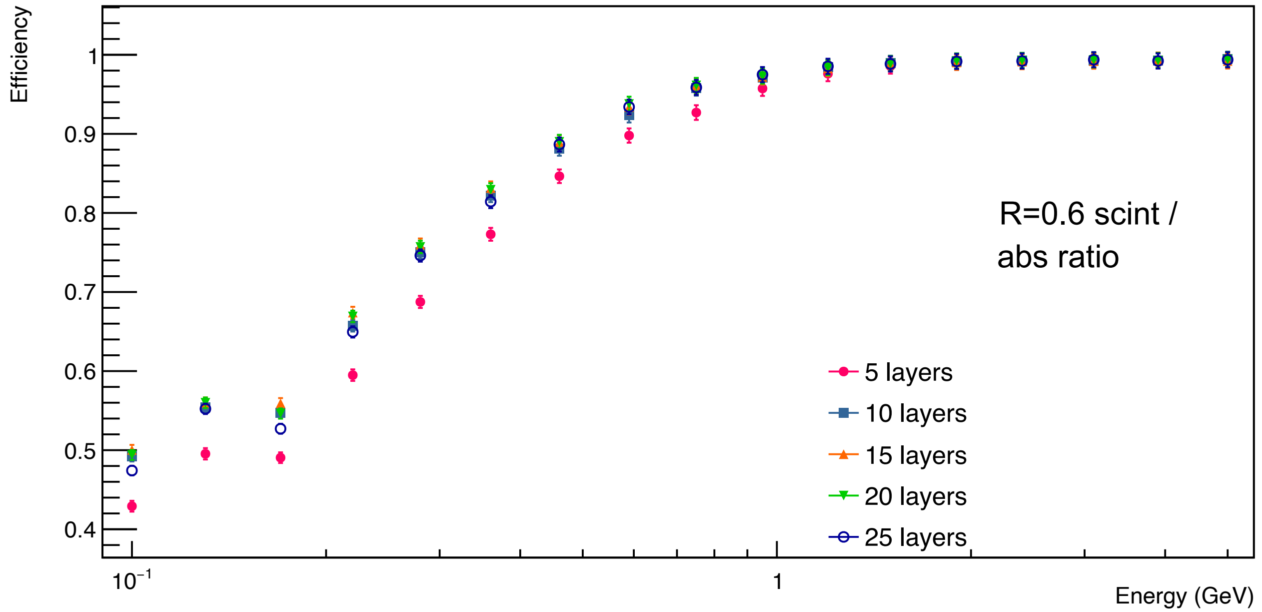
Constraints on gross length, tile configuration, absorber/scintillator ratio

Design Optimization: Efficiency for neutrons

Charge 2

As a tail-catcher, low energy neutron detection is key design metric for nHCAL

- Tile size has negligible impact
- Efficiency increases with
  - Number of layers (⇒ ~length of calorimeter):
    >5 layers increases efficiency by about 5% for ~1 GeV neutrons
  - Scintillator / absorber ratio:
    scintillator 4mm → 8mm increases efficiency by nearly 20% for 0.5 GeV neutrons



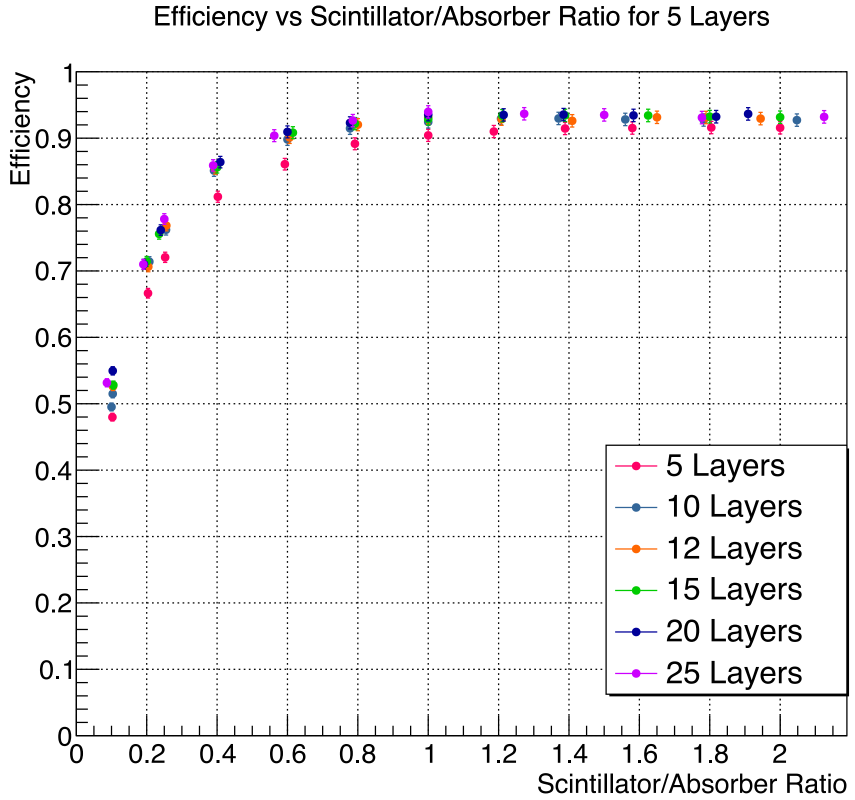
Constraints on gross length, tile configuration, absorber/scintillator ratio

Design Optimization: Efficiency for neutrons

Charge 2

As a tail-catcher, low energy neutron detection is key design metric for nHCAL

- Tile size has negligible impact
- Efficiency increases with
  - Number of layers (⇒ ~length of calorimeter): >5 layers increases efficiency by about 5% for ~1 GeV neutrons
  - Scintillator / absorber ratio: scintillator 4mm → 8mm increases efficiency by nearly 20% for 0.5 GeV neutrons.
  - Optimal for >=10 layers R> ~0.6



0.9 GeV neutrons

R=0.6 gives optimal efficiency for designs with >10 layers

Constraints on gross length, tile configuration, absorber/scintillator ratio

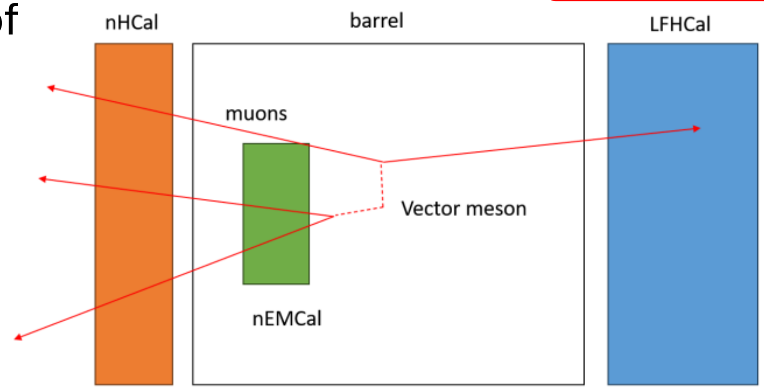
VM decays & muon Identification

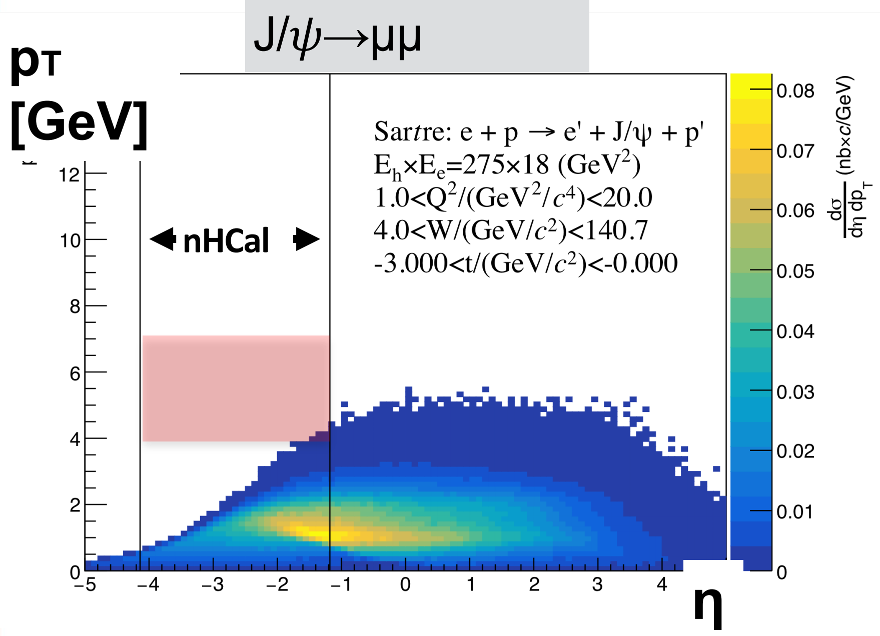
Charge 2

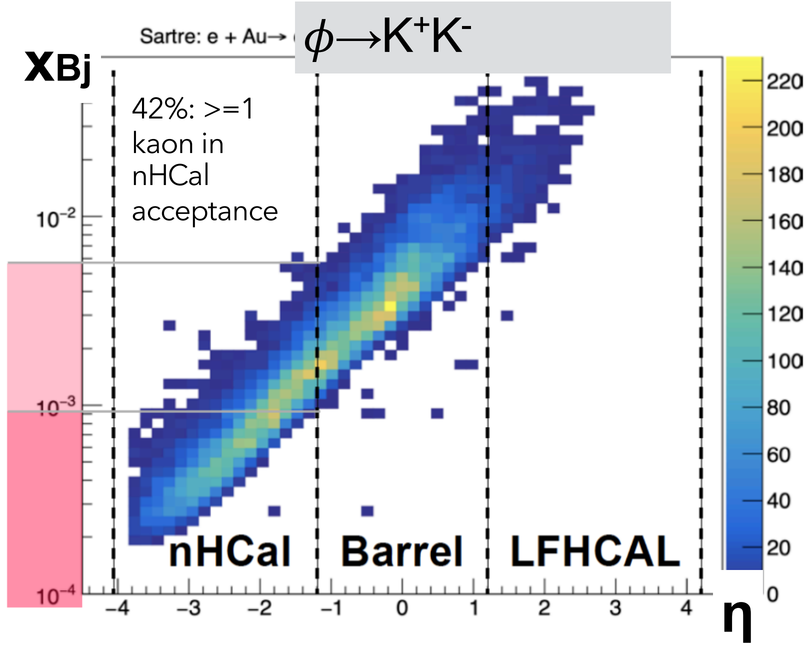
- Additional backward acceptance provides access to a more complete set of vector-meson decay topologies
  - nHCal crucial for low-x
  - non-ambiguous channels (vs. e^+e^- final states)
- <u>nHCAL: significant at low-x</u>

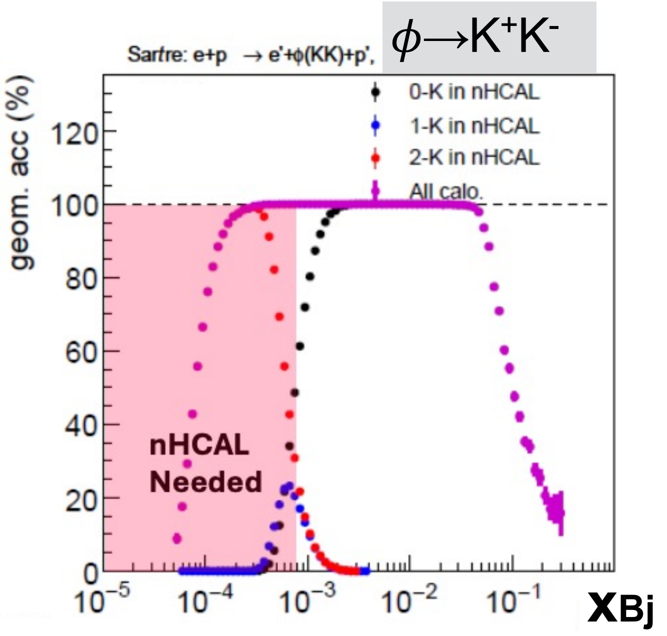
Charge 5

Constraints on <u>gross length</u>, <u>tile configuration</u>, <u>readout</u>









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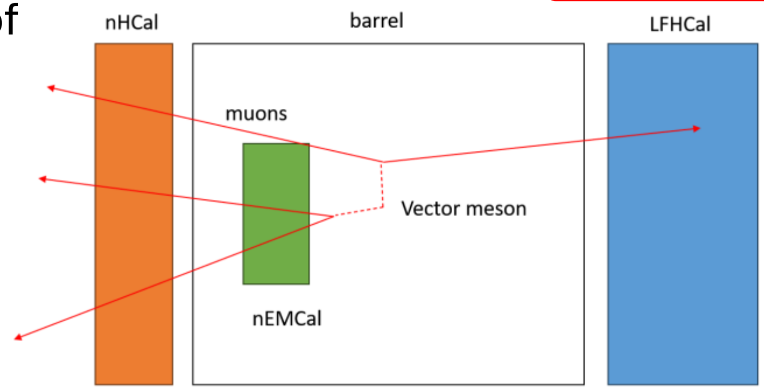


Design Optimization for Muon ID

Charge 5

- Muon optimization metric = $\varepsilon_\mu(p,\eta) / \sqrt{\alpha_{h\rightarrow\mu}}$
  - With ε_μ = muon efficiency, $\alpha_{h\rightarrow\mu}$ = hadron mis-id rate
  - MIP efficiency can be ~100%, so design configuration primarily driven by hadron mis-id rate
  - Studies on-going in single particle events, diffractive events, DIS

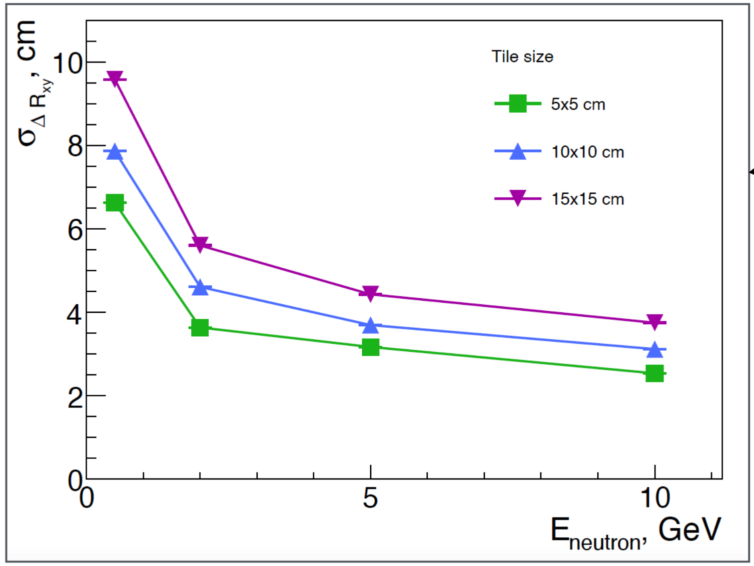
Constraints on gross length, tile configuration, readout

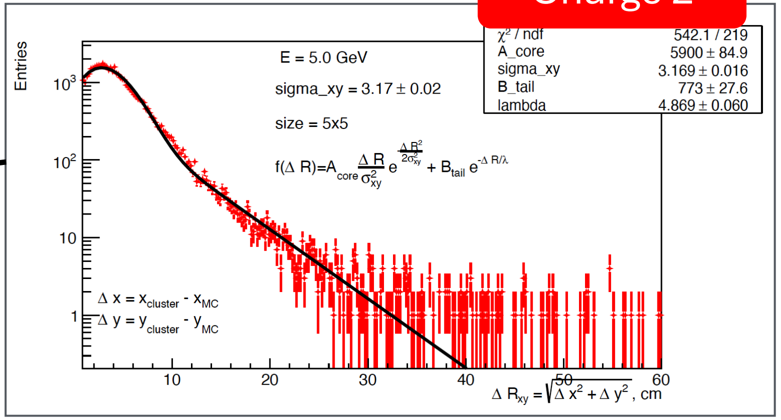
Position resolution for neutrons

Constraints on tile configuration, readout

Charge 2

- Transverse position resolution
  - Test position resolution varying tile size
- Neutron position resolution insensitive to tile size
  - As expected due to large transverse size of clusters
- Neutron and pion clusters can be distinguished when separated by ~30cm

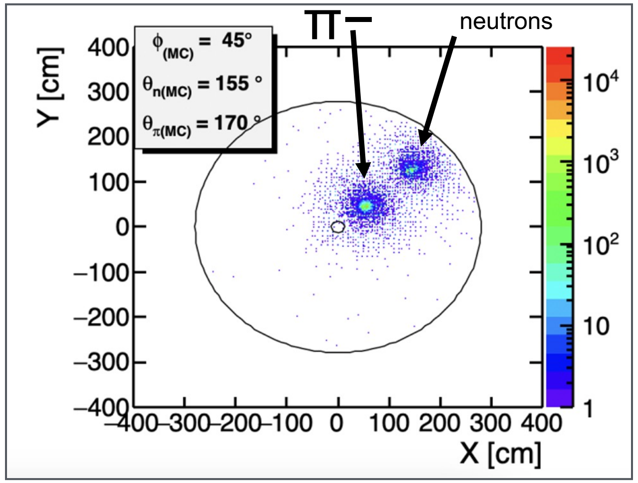


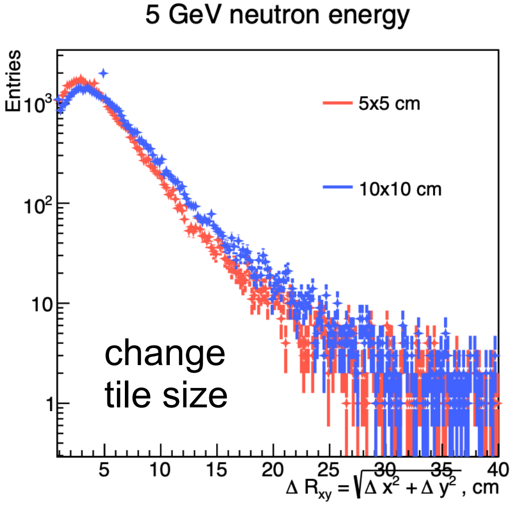


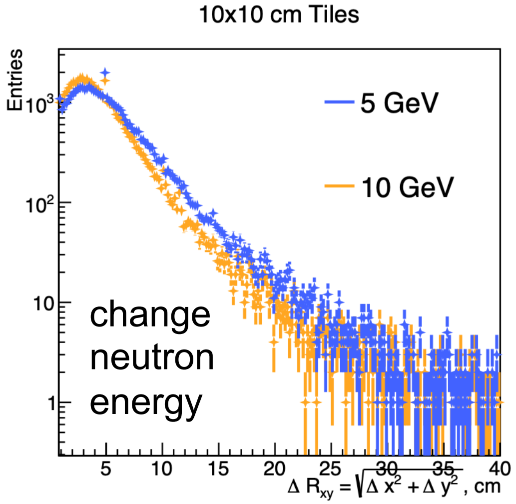
$$\Delta R_{xy} = \sqrt{\Delta x^2 + \Delta y^2}$$

$\Delta x = x_{cluster} - x_{MC}$

$\Delta y = y_{cluster} - y_{MC}$







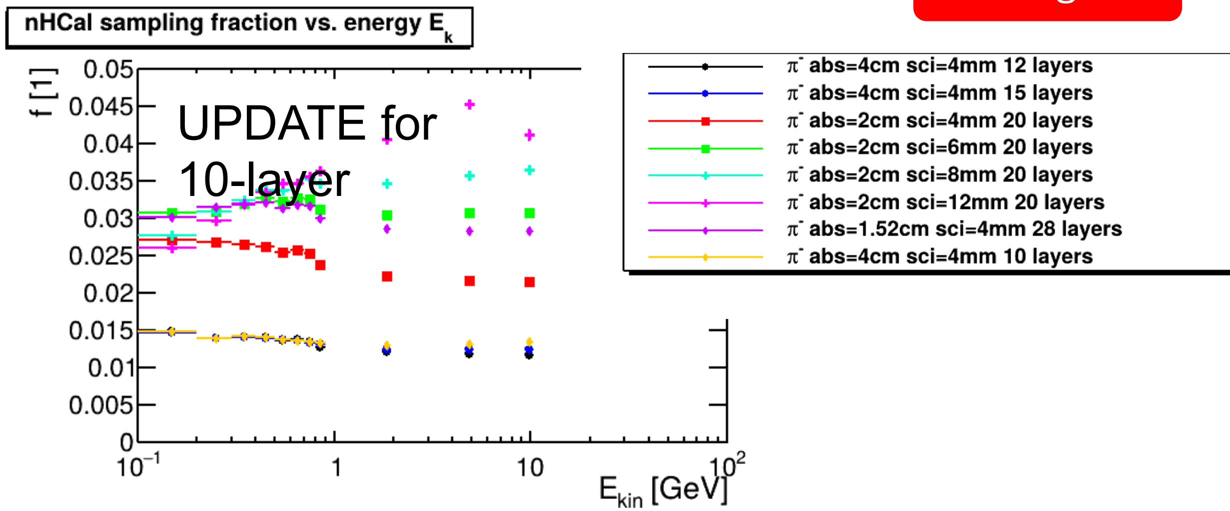
Sampling fractions and gross detector length

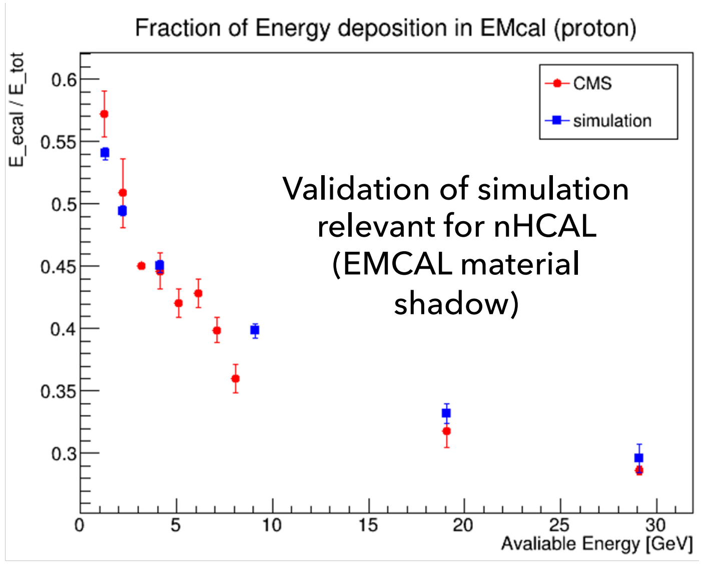
Charge 2

Sampling fraction = energy deposit in absorber / incident energy

- ~ 3-4% for optimal design (10x10, 20 layers, 2cm absorber, 1.2cm scintillator)
- Not dependent on particle species (n or π^-)
  - reflects how much of a particle shower can be sampled
- Not dependent on tile size (10x10, 5x5) but ratio abs/sci
- Design optimization driven by other parameters for tail-catcher (i.e. neutron eff, muon id, etc.)

- Also validated understanding and simulation uncertainty of the material budget upstream of nHCal (primarily backward EMCAL)





CMS EMCal + HCal beamtest
https://cds.cern.ch/record/1046333

Charge 5

Constraints on gross length

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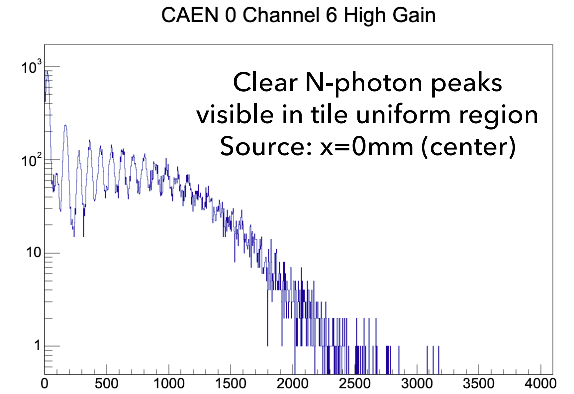
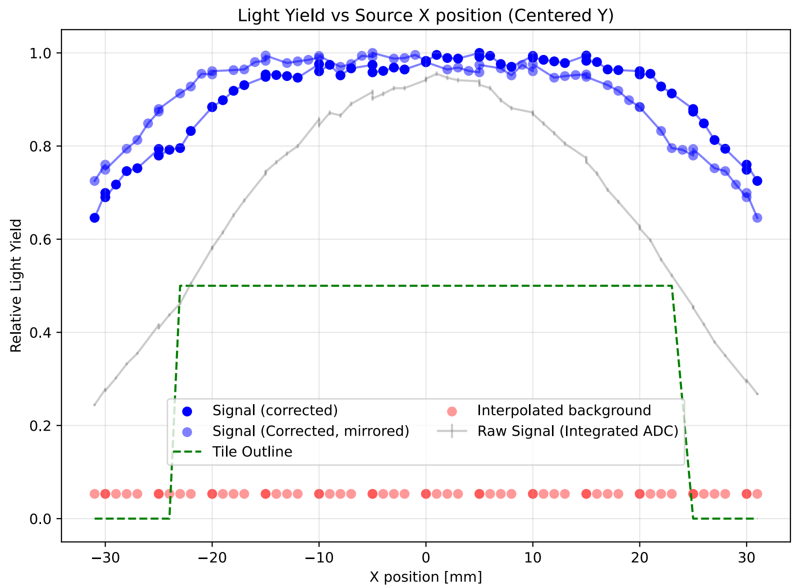
nHCal performance evaluation

Charge 2

Scintillator tile testing

- Cosmics and Sr source
  - Vary tile size (2x2, 5x5, 10x10)
  - Vary tile thickness (4, 6, 8, 12mm)
  - Vary SiPM placement (center, corner, edge)
- Performance evaluation
  - Light yield per MIP, uniformity, cross-talk



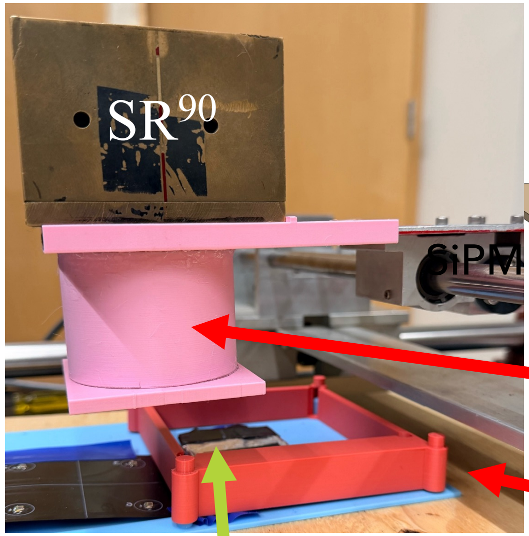


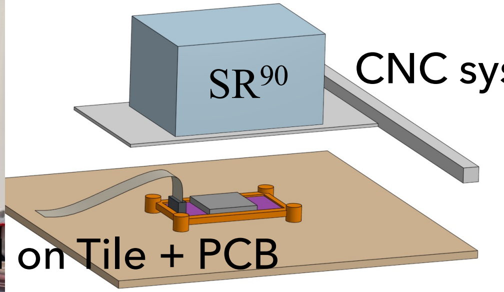
Light uniformity study:
4.7 x 4.7 cm (LFHCAL)
wrapped tile

Work in progress

GOAL: verification of 10x10 cm tile configuration

Fully automated (CNC driven) tile-testing apparatus





CNC system

SiPM on Tile + PCB

Pb collimator provides ~5mm beam profile FWHM

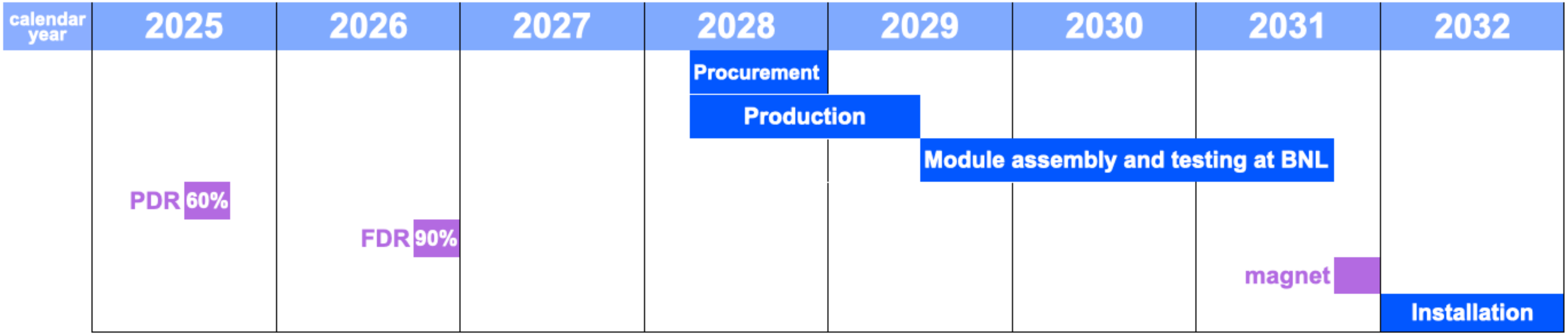
3D printed custom flexible PCB holder & light shield

Tile being tested

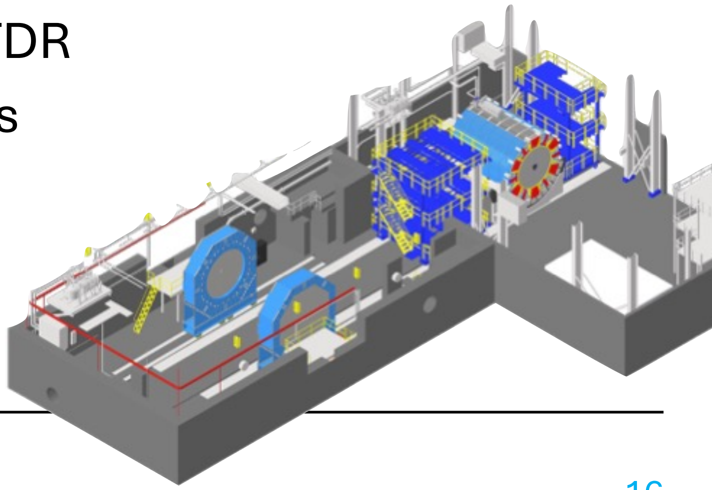
CAEN module for SiPM bias and DAQ

nHCal baselining and start of construction

Charge 3



- Majority of design parameters have been optimized by simulation-based studies (TBD: readout layer integration)
- Detector studies, optimization, and physics impact documented in preTDR
- The nHCal can be delivered later than most other detectors because it is decoupled from the flux return and does not need to be in place for the solenoid field mapping



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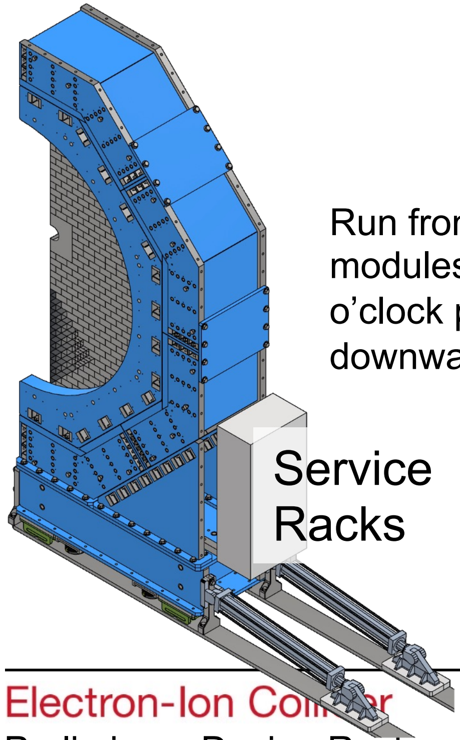
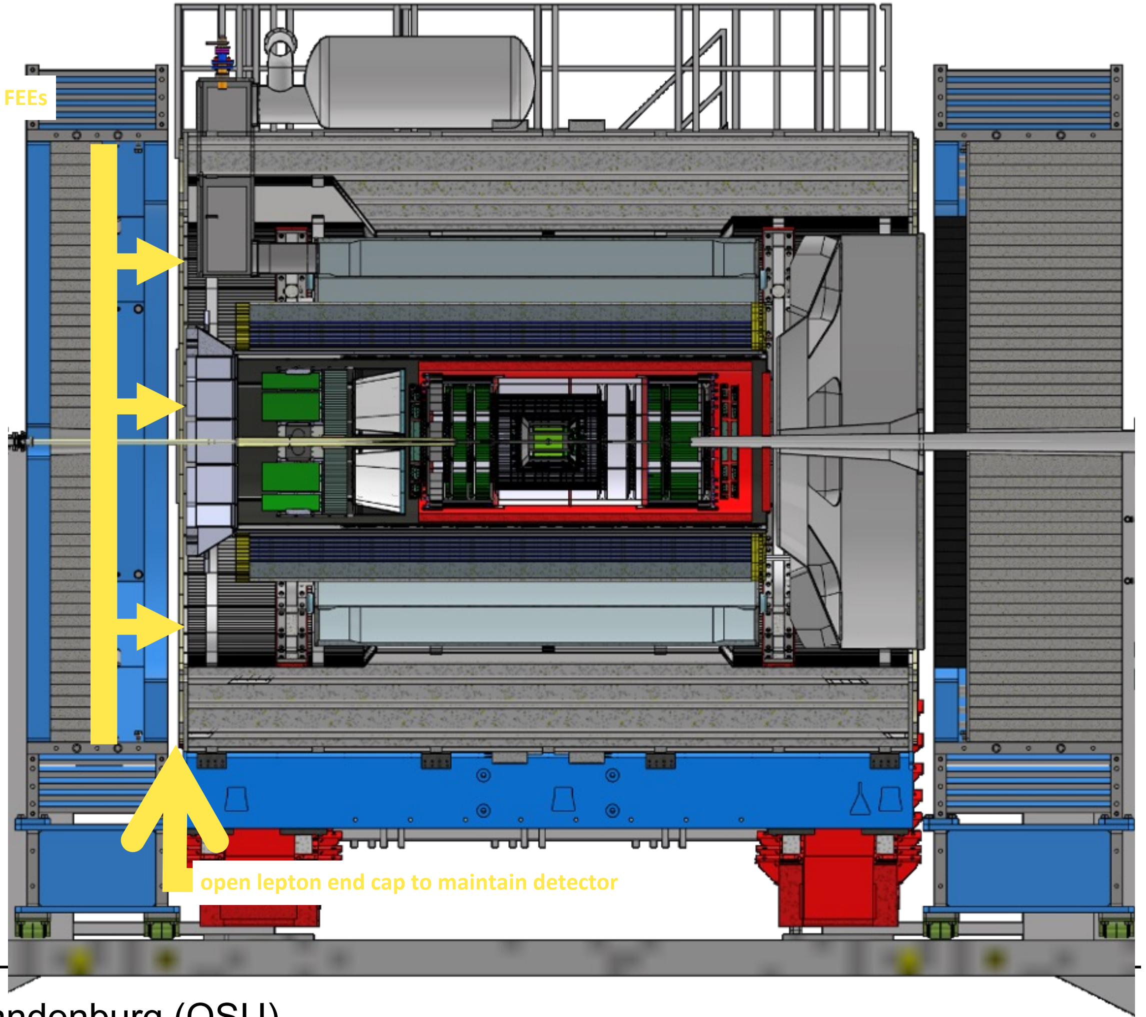
nHCal integration and planning for installation & maintenance

Charge 3

- Integration: services (LV, signal, slow control cables) and possibly cooling
  - Total dissipated heat: 0.5-2.4 kW (10cmx10cm tiles)
  - FEEs towards the IP ⇒ nHCal has to be serviced and maintained from the front (unlike LFHCal)



Run from the front face of the HCAL modules near the 3 o'clock and 9 o'clock positions and are routed downward to service racks.



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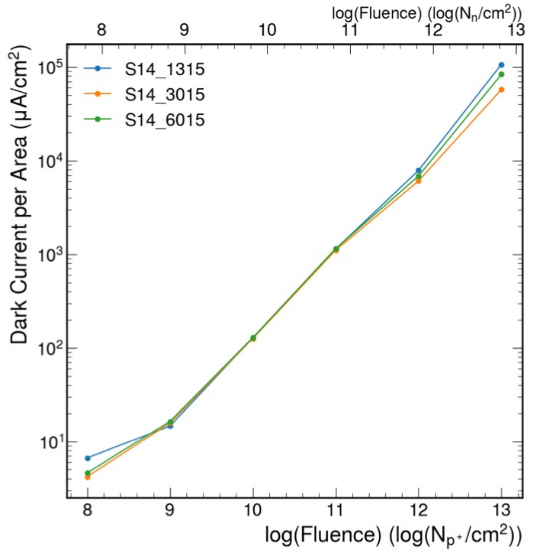
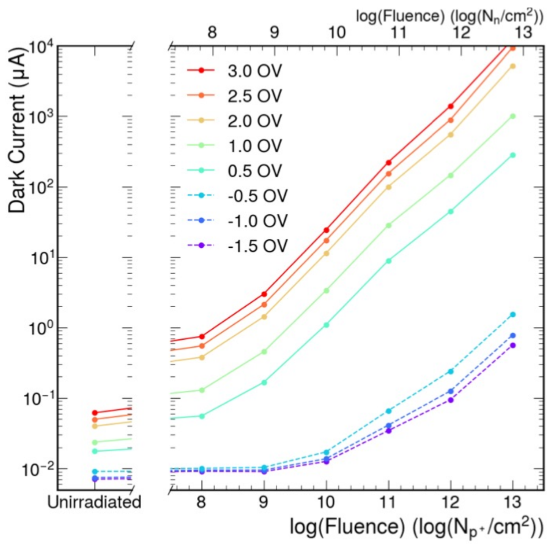
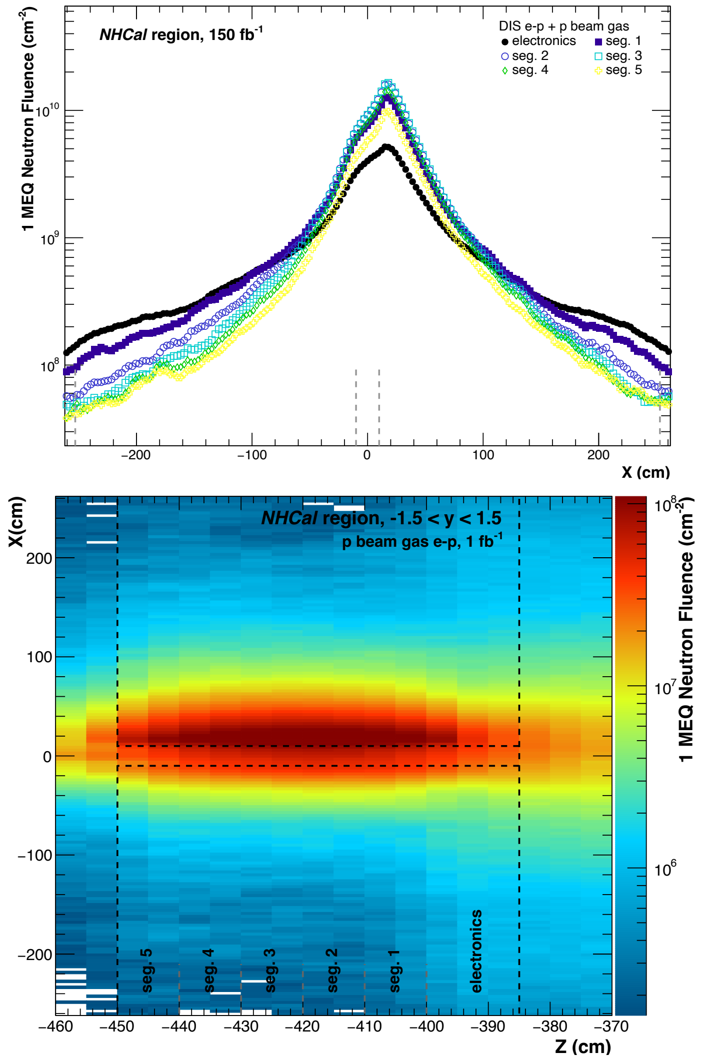
SiPM ES&H and QA Considerations

Charge 4

- Degradation of SiPMs due to radiation damage has been studied https://arxiv.org/pdf/2503.14622
- Expected SiPM lifetime sufficient for > 15 years of anticipated dosage in backward direction
- The nHCAL does not includes an insert = avoid highest radiation dose near the beam







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SiPM ES&H and QA Considerations

Charge 4

- Procurement includes 1% margin for possible production and assembly process losses
- SiPM & module assembly testing process foreseen:
  - SiPM vendor testing and V_{op} classification within 0.1 V per batch
  - Flex PCB vendor to test PCB connectivity
  - V_{op} spot checks for 5% of the SiPMs
  - Tile assembly testing connectivity after assembly (also verifies vendor QA process)
  - Cosmics tile assembly testing and classification (5-10%)
  - Cosmics module testing prior to installation
  - Cosmics data taking after installation

Synergy with LFHCAL

Steel ES&H and QA Considerations

Charge 4

- Procurement includes property assessment of material:
  - Material composition and magnetic permeability (AISI 1020) by vendor and test samples
  - Inspection of dimensional tolerances according to technical drawings, including nickel-plating
- Test setup of the eight 8M modules included in the procurement planning:
  - Final qualification of performance (beam test verification of configuration)
  - Cosmic measurement of final modules
- Calorimeter absorber chosen for safety, magnetic constraints, physics motivations.
- Use of radioactive sources for testing follow all local & institutional guidelines

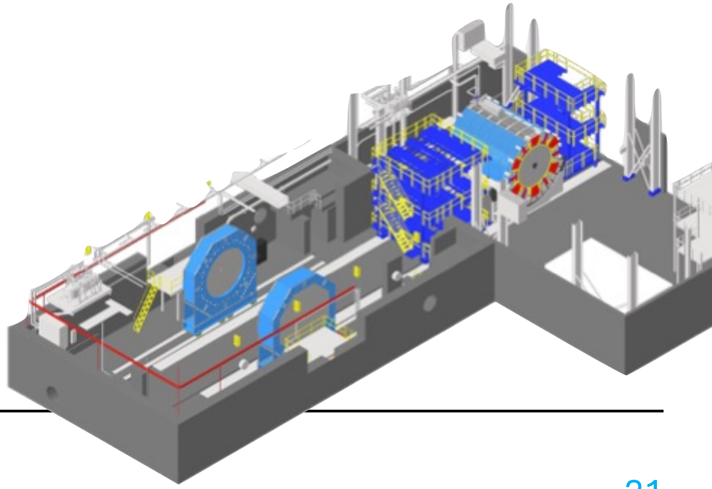
From technical drawings

NOTES

1. ITEM 9 WILL BE ORIENTED WITH THE TAPPED HOLES FACING UP, ITEM 4 WILL BE ORIENTED WITH CLOSE HOLE PATTERN HOLES TOWARDS TOP.
2. ITEM 9 TO BE PLACED IN POSITION #1, 15, 30, 45, & 60 (IN REFERENCE FROM ITEM 3) FOR ALL ABSORBER PLATES. MATCH UP HOLE PATTERN ON ITEM 5 & 9 TO VERIFY PRIOR TO WELDING. THESE PLATES (ITEM 9) TO BE INSTALLED AND WELDED FOR PROPER ALIGNMENT PRIOR TO THE ADDITIONAL PLATES (ITEM 8).
3. E-BEAM WELD ALONG CENTERLINE OF CONTACTING FACES ALL ITEMS 3, 5, 6, & 9. START AT ITEM 4, AND WORK FORWARD, PERFORMING A STAGGERED STITCH WELD AS SHOWN IN DETAIL A. ALLOW 1/8" CLEARANCE FROM WELDS TO ALL HOLES AND EDGES. DO NOT WELD ITEM 7. USE A JIG AND SPACING PLATES TO ENSURE PROPER PLATE SPACING AND FINAL ASSMEBLY GEOMETRY. NOTE THAT ITEM 5 & 6 WILL SHRINK APPROXIMATLY 0.080" DURING THE WELDING PROCESS, THIS GAP IS ACCEPTABLE AND ITEM 3 IS TO BE WELDED ALONG CENTERLINE OF CONTACTING FACE TO ENSURE OVERALL ASSEMBLY LENGTH IS MAINTAINED. E-BEAM WELD SHALL PENETRATE WITH SUFFICIENT DEPTH TO ENSURE AT LEAST 0.020" WELD WIDTH AT ALL PART INTERFACES. WELDING PROCEDURE TO BE DETAILED, DEMONSTRATED, APPROVED BY ORNL PRIOR TO FULL SCALE PRODUCTION.
4. POST MACHINE AND/OR STRAIGHTEN AS NECESSARY POST WELDING TO ACHIEVE FINAL DIMENSIONING AND TOLERANCING. VERIFY THE INTEGRITY OF ALL WELDS AFTER ALL POST MACHINING PROCESSES.
5. ALL WELDING AND WELD INSPECTIONS PER AWS D1.1/D1.1M - 2010.
6. ALL WELDS SHALL RECEIVE A VISUAL INSPECTION. SELLER SHALL PROVIDE VISUAL EXAMINATION CERTIFICATION OF COMPLIANCE CERTIFYING THE PERFORMANCE OF THE INSPECTION AND THE ACCEPTABILITY OF THE WELDS.
7. PERSONNEL PERFORMING VISUAL INSPECTIONS SHALL BE CERTIFIED WELD INSPECTORS UNDER AWS QC-1 OR AS VISUAL TESTING LEVEL II OR LEVEL III IN ACCORDANCE WITH SNT-TC-IA.
8. ELECTROLESS NICKEL PLATE FINAL WELDMENT (EXCLUDING ITEM 1, 2, & 7) TO 0.001" THICKNESS MINIMUM / 0.002" THICKNESS MAXIMUM PER ASTM B766.

Path to CD-2 and beyond

- **Continue to utilize technologic synergy with LFHCAL** — Charge 5
- **Incorporation of muon identification and acceptance into HCAL system design** — Charge 5
- **Study Impact on vector meson acceptance**
- **Detector optimization based on tail-catcher role and lessons learned from H1 SPACAL** — Charge 5
- **Full simulation studies with backgrounds**
- **Study nHCAL impact on event kinematic reconstruction and background rejection** — Charge 1/2
- **Prototype development and testing** — Charge 1/2
- **Beam tests (nHCAL + with EMCAL modules)**
- **Perform QA on procurements**



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nHCal summary

- Status:
  - Synergy with LFHCAL technology, with design of nHCAL optimized for ‘tail-catcher’ role in ePIC
- Involved institutions: OSU, UIUC, CTU, BNL
- Design optimization for Tail-Catcher role in ePIC
  - Neutron efficiency at low energy
  - Charged particle detection at low energy
  - Muon and Kaon Identification
  - Impacts on low-x, low Q^2, and high y events
- Design parameters to be verified in beam tests + full simulations with backgrounds
- The nHCal can be delivered later than most other detectors because it is decoupled from the magnetic flux return
- Baseline configuration determined & plan for CD-2 and beyond outlined

nHCal performance evaluation

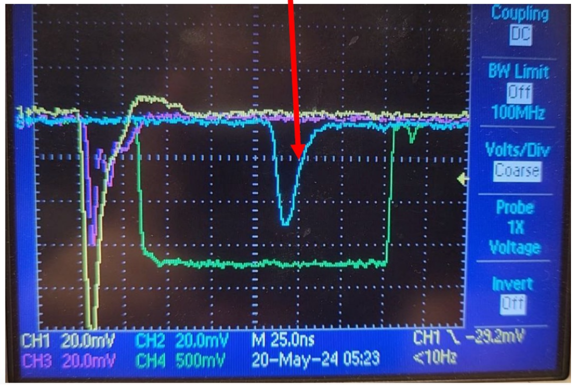
Charge 2

Scintillator tile testing

- Cosmics and Sr source
  - Vary tile size (2x2, 5x5, 10x10)
  - Vary tile thickness (4, 6, 8, 12mm
  - Vary SiPM placement (center, corner, edge)
- Performance evaluation
  - Light yield per MIP, uniformity, cross-talk

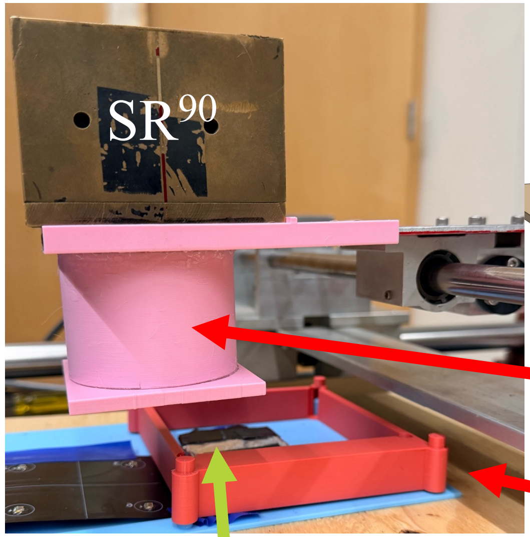
GOAL: verify 10x10 cm tile configuration

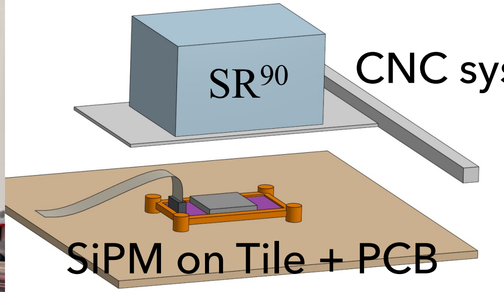
signal from SiPM-on-tile



CAEN module for SiPM bias and DAQ

Fully automated (CNC driven) tile-testing apparatus





Pb collimator provides ~5mm beam profile FWHM

3D printed custom flexible PCB holder & light shield

Tile being tested

- Backup:
  - Studies of Light non-uniformity impact in simulation
  - nHCAL effect on y_JB
  - nHCAL mip identification