nHCal (backward hadronic calorimeter)

simulation, design, assembly, and schedule

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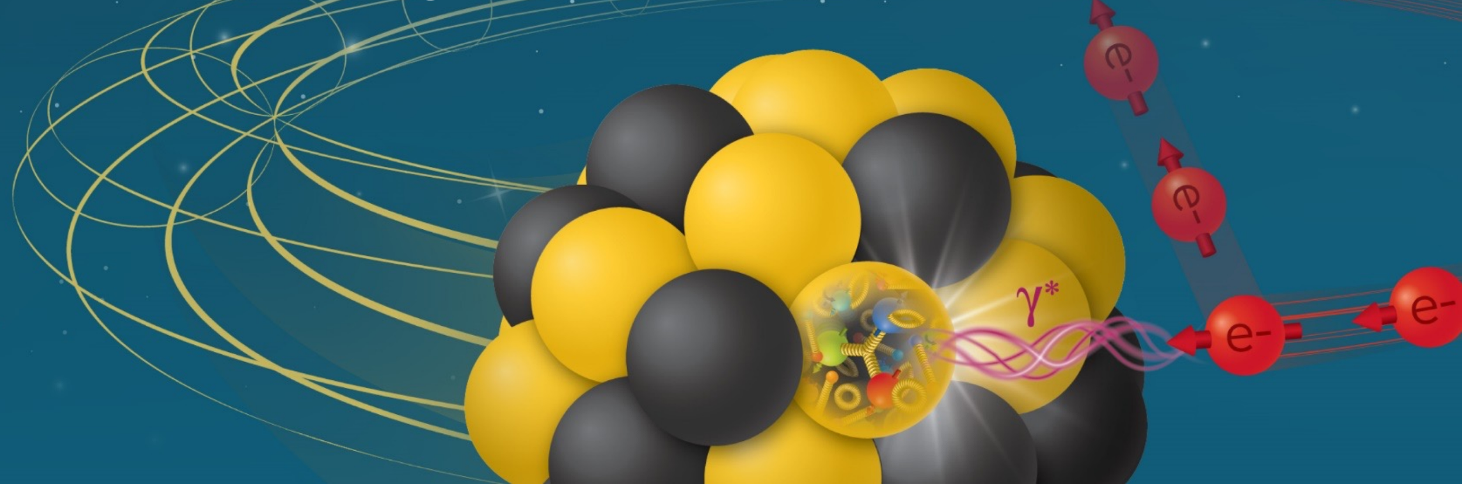
Preliminary Design Review

October 30-31, 2025

Electron-Ion Collider



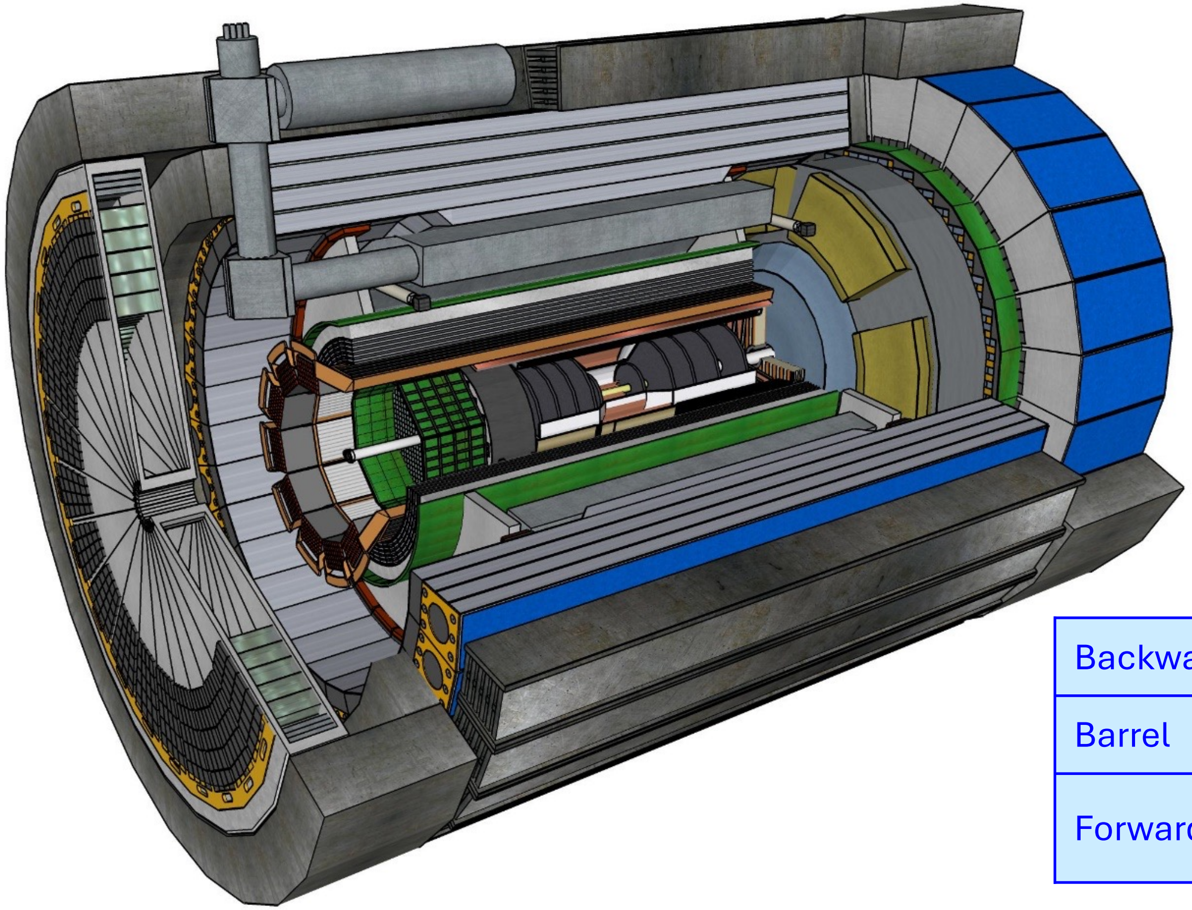
Charge Questions

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

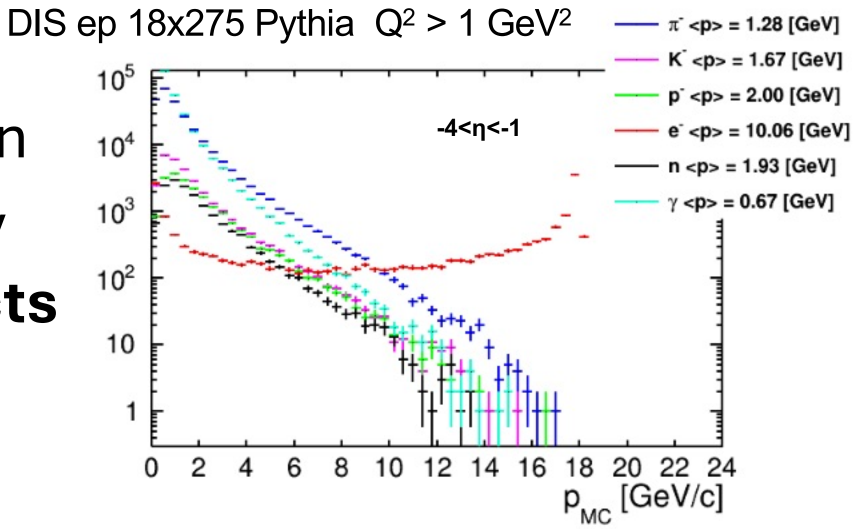
Main purpose of nHCal

Charge 1

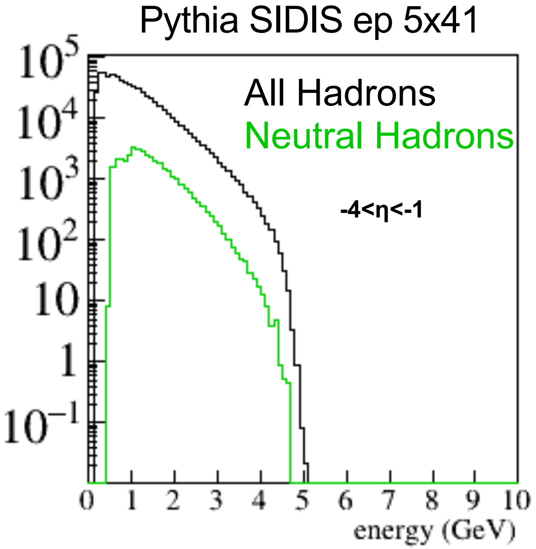
- Tail catcher calorimeter in the backward (electron-going) direction
- Important for low-x and -Q2, high-y (high gluon densities) - **core aspects of EIC physics mission**
  - Diffraction, neutral and charged jets
  - Neutron detection and muon ID
- Lessons learned from HERA / H1 backward SPACAL [NIMA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

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

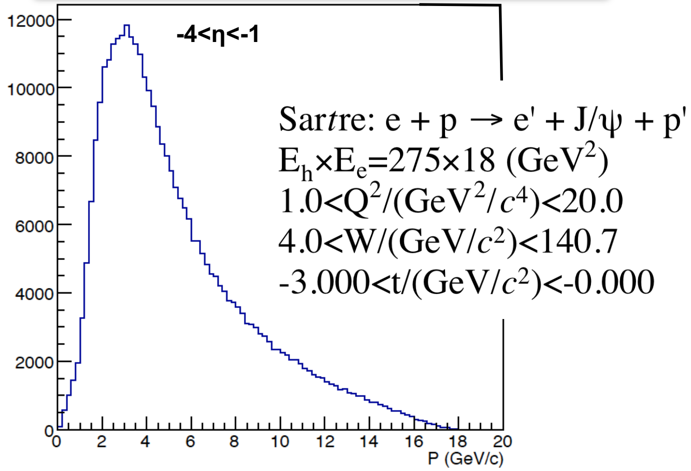
muons in nHCal:
<p>=5.3 GeV/c
<E>=5.3 GeV



neutrons and charged particles



muons from diffractive J/ψ decay

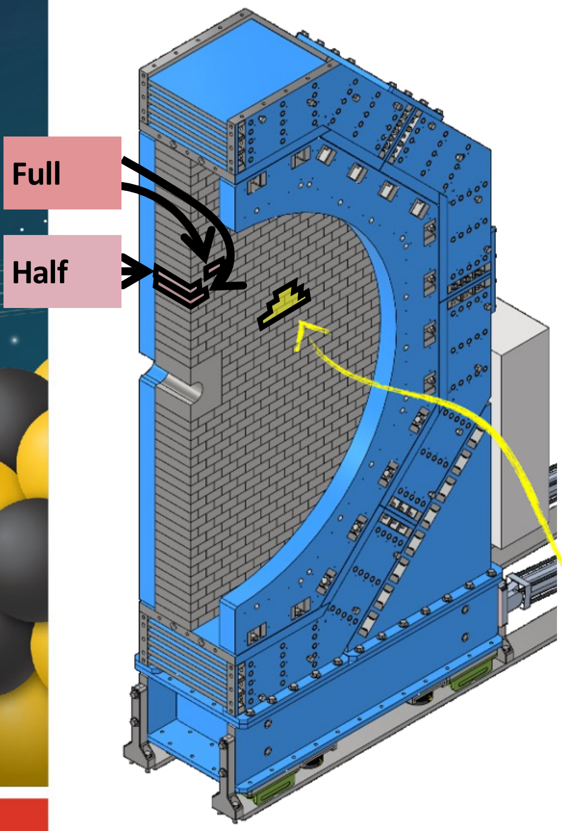


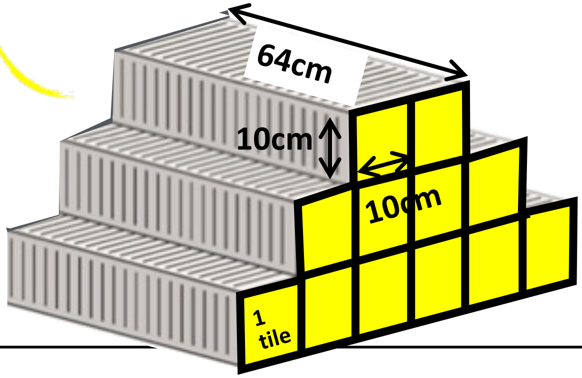
Backward (electron-going) hadronic calorimeter - nHCal

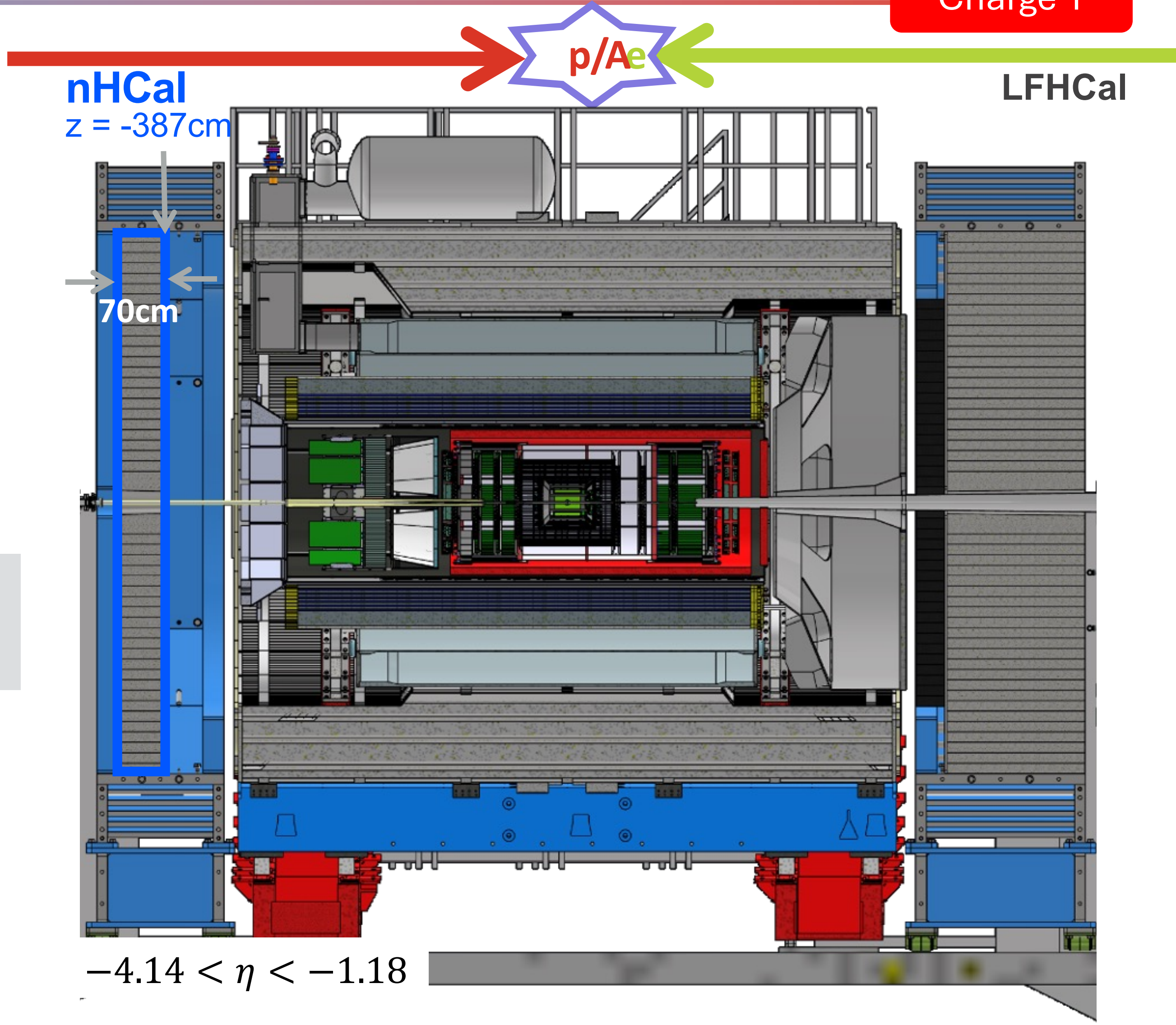
Charge 1

- 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)







nHCal design optimization via simulations - overview

Charge 1/2

Readout:

- Utilize CALOROC (36ch) along with other HCALs
- (1058 (full) x 2 + 72 (half)) * 10 layers = 21,880 channels
- Each CALOROC has 36 ch.
  - CALOROC can handle 1 full module (20 channels) or 2 half modules

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

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

5x5 or 10x10	scintillator thickness	0.4				0.6	2.4	1.2
[cm]	absorber thickness	4	3	2	1.52	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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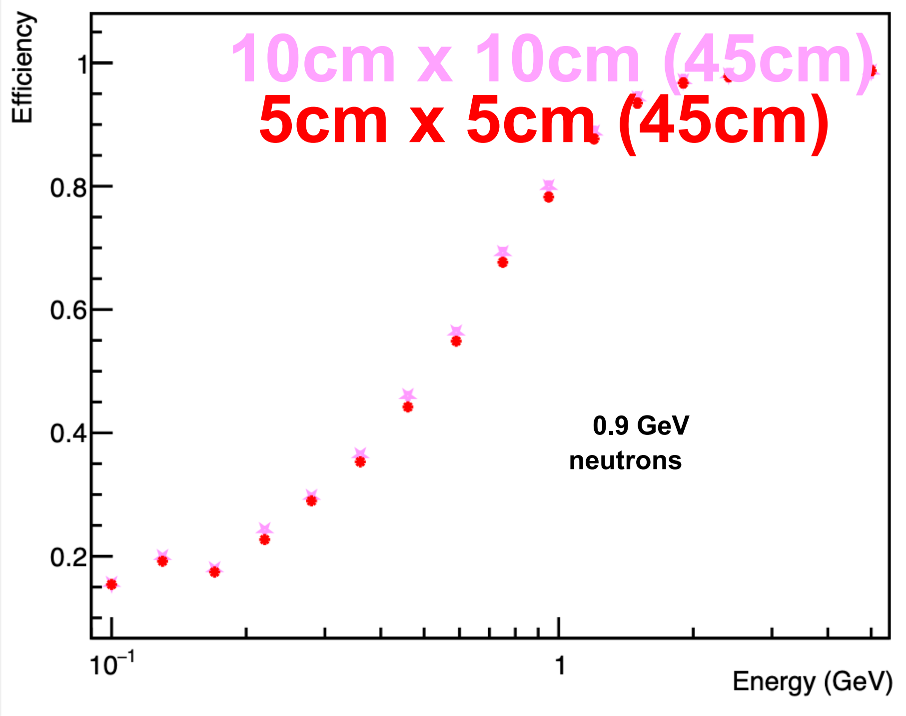
Caroline Riedl (UIUC)

Design Optimization: Efficiency for neutrons

Charge 2

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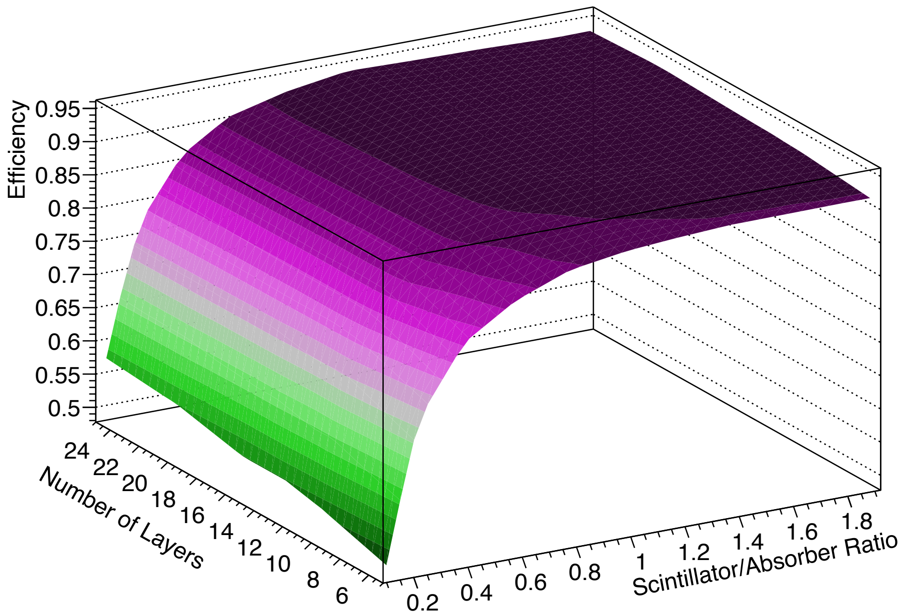

0.9 GeV neutrons

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

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

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

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- Efficiency increases with
  - Number of layers (⇒ ~length of calorimeter):
    >5 layers increases efficiency by about 5% for ~1 GeV neutrons
  - Scintillator / absorber ratio:
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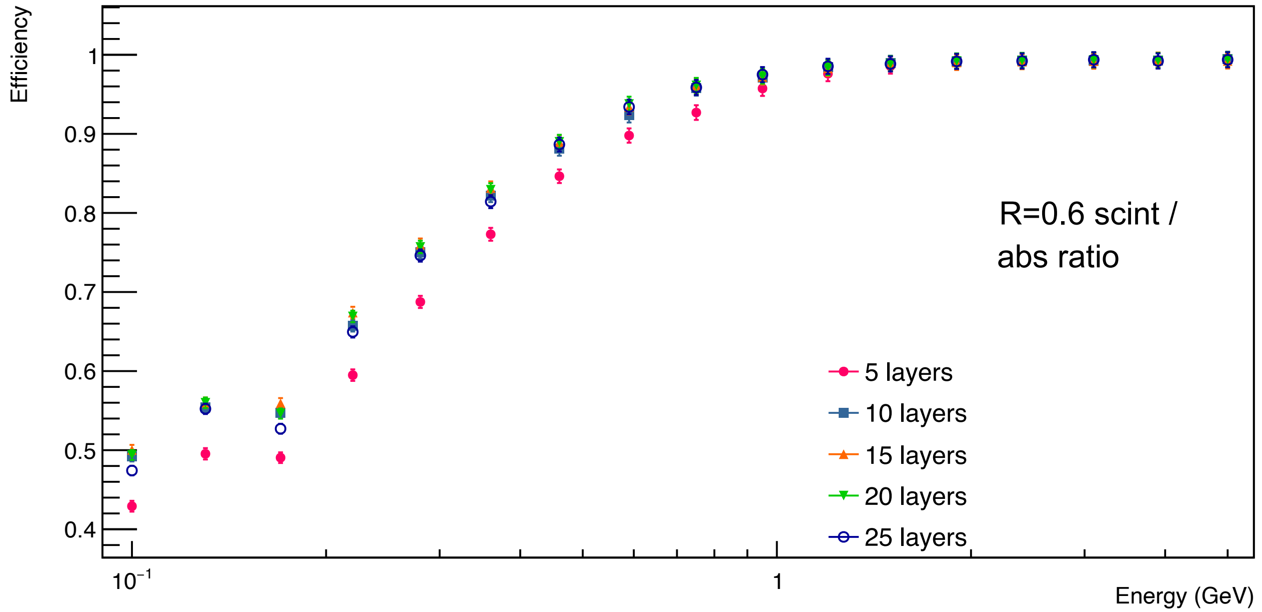

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  - Scintillator / absorber ratio:
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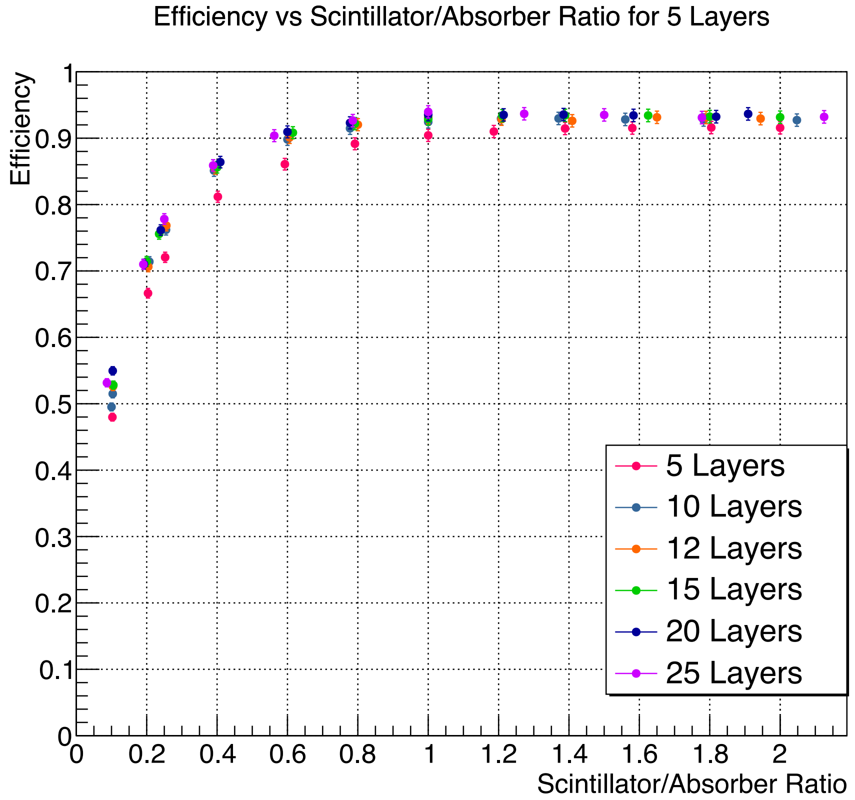
  - Optimal for >=10 layers R> ~0.6



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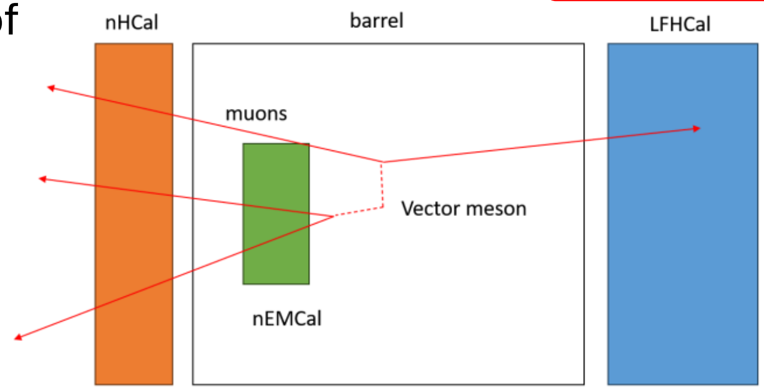
Constraints on gross length, tile configuration, absorber/scintillator ratio

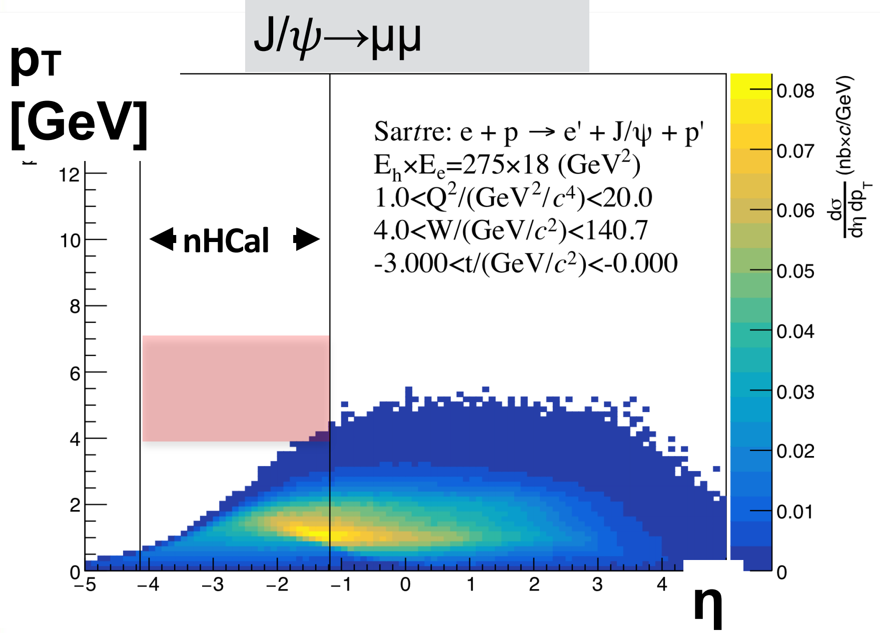
VM decays & Muon Identification

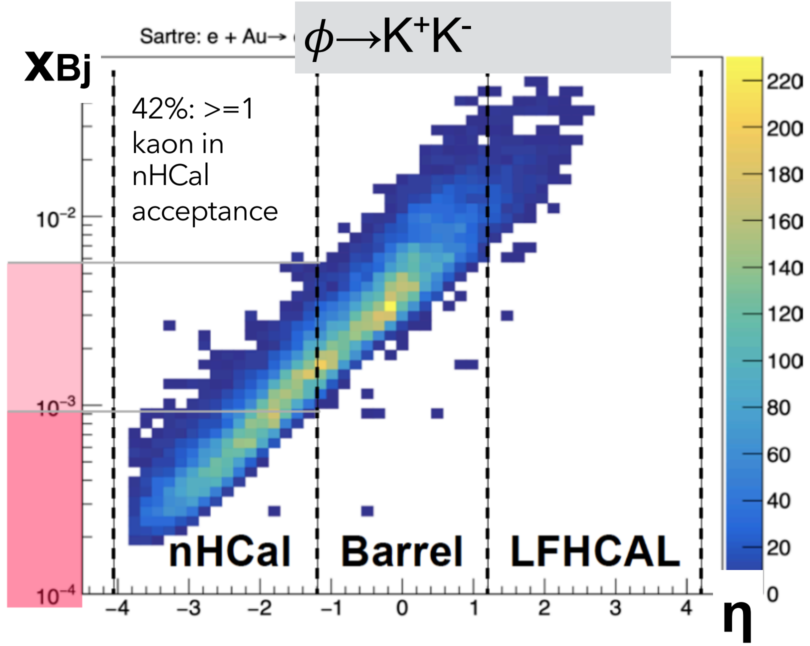
Charge 2

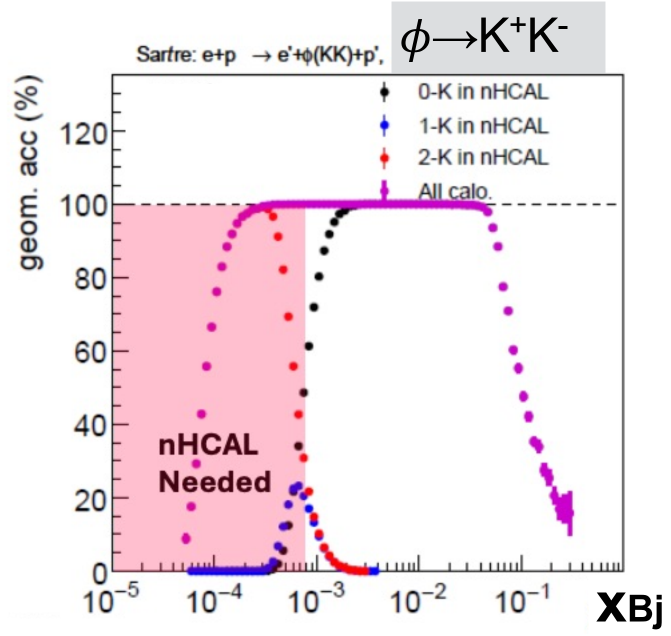
- Additional backward acceptance provides access to a more complete set of vector-meson decay topologies
  - nHCal crucial for low-x
  - Non-ambiguous channels (vs. e^+e^- final states) Charge 5
- <u>nHCAL: significant at low-x</u>

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









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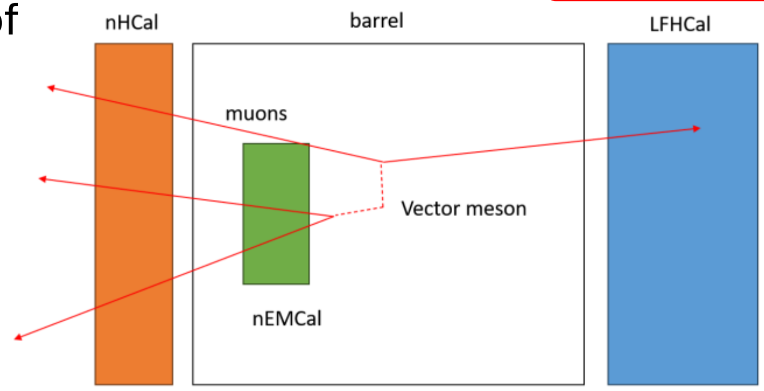


Design Optimization for Muon ID

Charge 5

- Muon optimization metric = $\varepsilon_\mu(p,\eta) / \sqrt{\alpha_{h\to\mu}}$
  - With ε_μ = muon efficiency, $\alpha_{h\to\mu}$ = 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

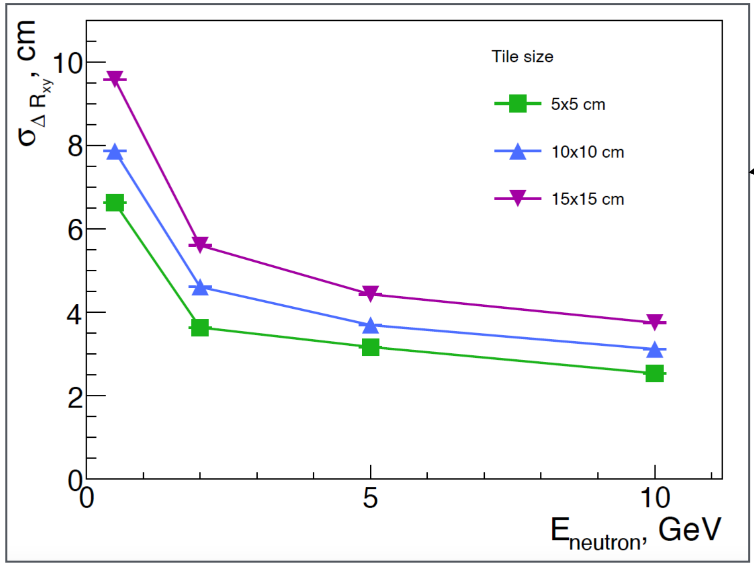
Constraints on <u>gross length</u>, <u>tile configuration</u>, <u>readout</u>

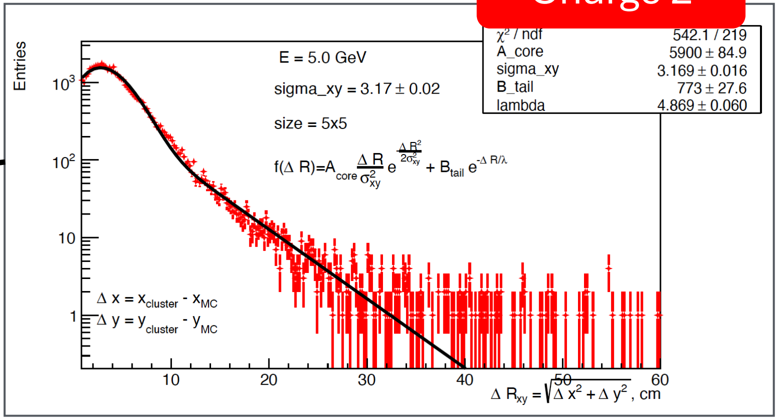
Position resolution for neutrons

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

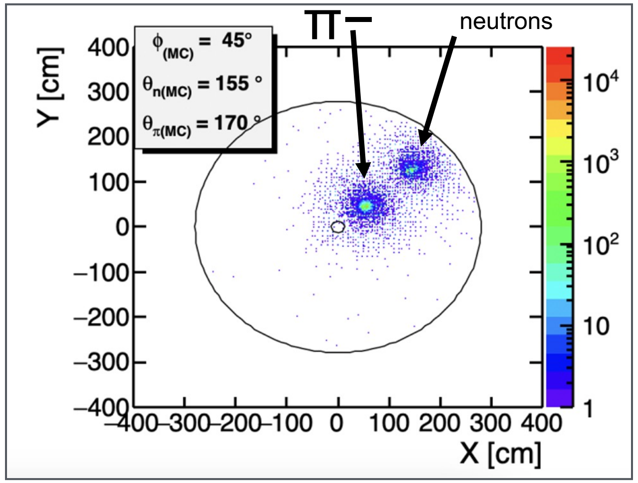




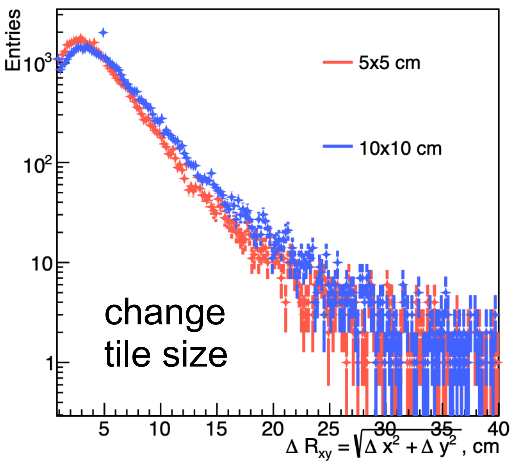
$$\Delta R_{xy} = \sqrt{\Delta x^2 + \Delta y^2}$$

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

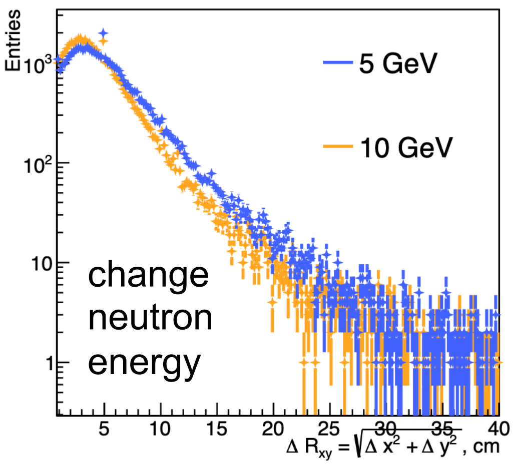
$\Delta y = y_{cluster} - y_{MC}$



5 GeV neutron energy



10x10 cm Tiles

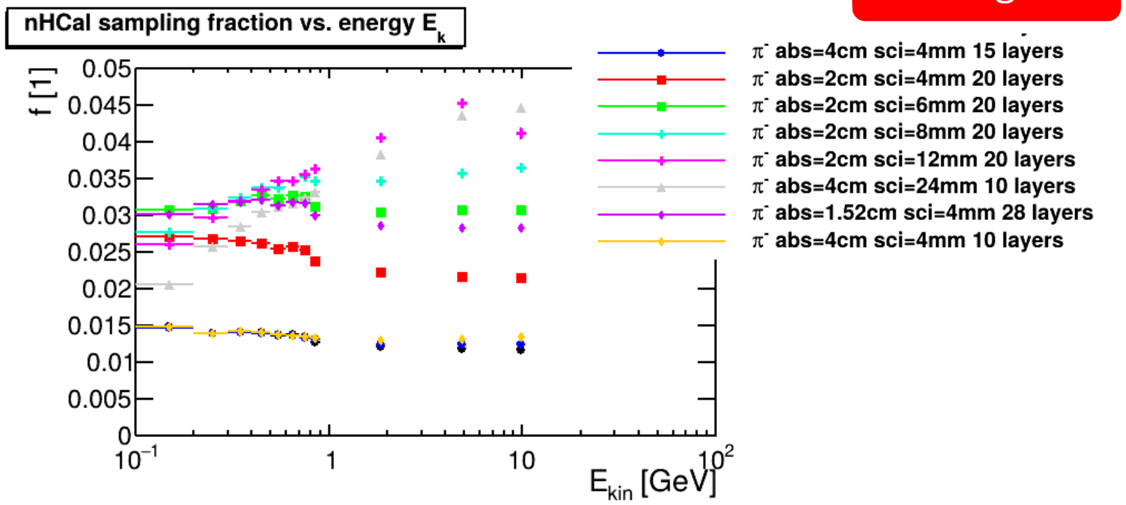


Sampling fractions and gross detector length

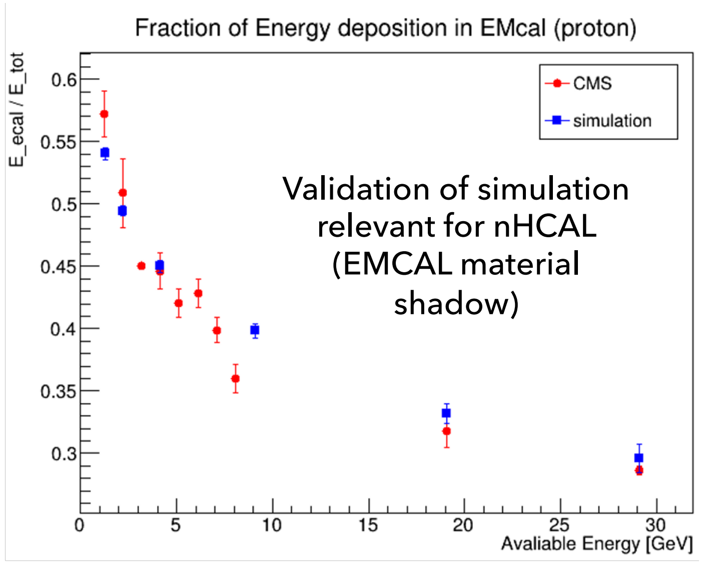
Charge 2

Sampling fraction = energy deposit in active material / incident energy

- ~ 3-4.5% for optimal design (10x10, 10 layers, 4cm absorber, 2.4cm 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

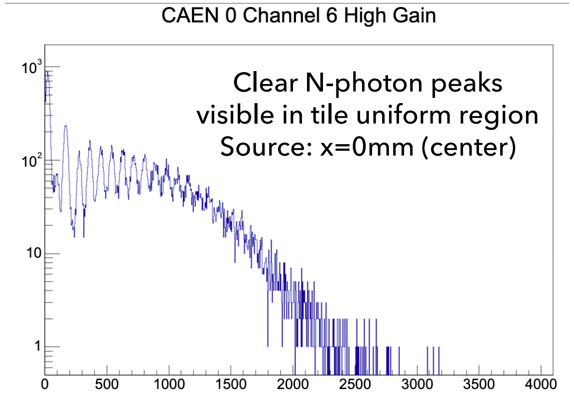
Daniel Brandenburg (OSU),
Caroline Riedl (UIUC)

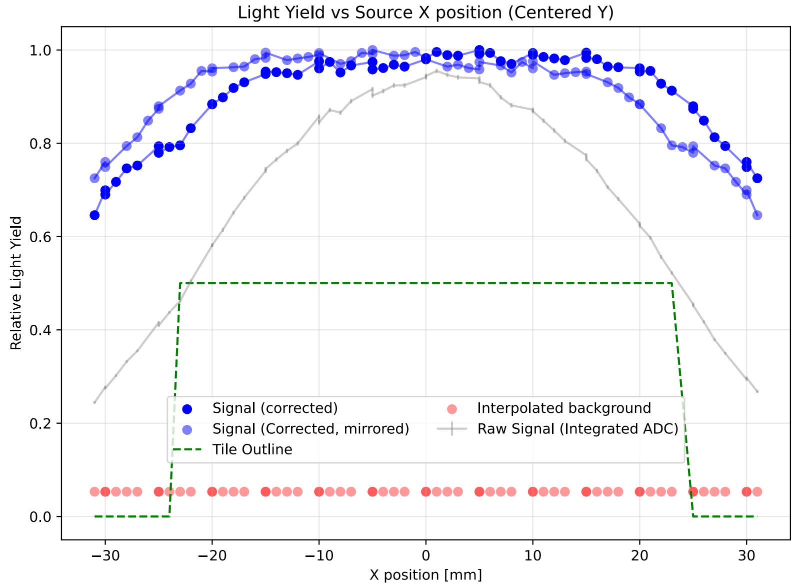
nHCal performance evaluation

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

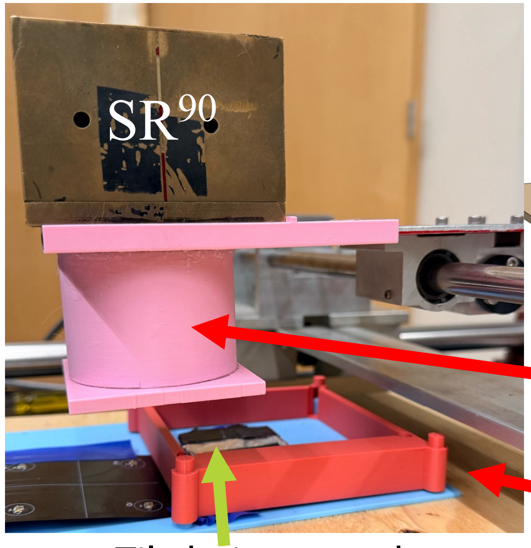




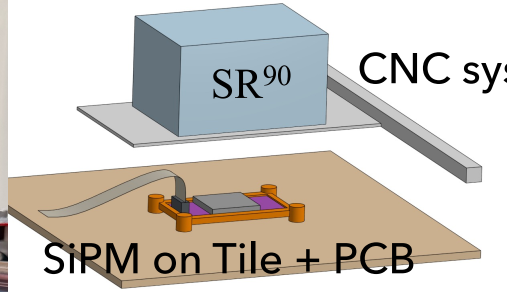
Light uniformity study:
4.7 x 4.7 cm (LFHCAL) wrapped tile

Work in progress

Fully automated (CNC driven) tile-testing apparatus



Tile being tested



Pb collimator provides ~5mm beam profile FWHM

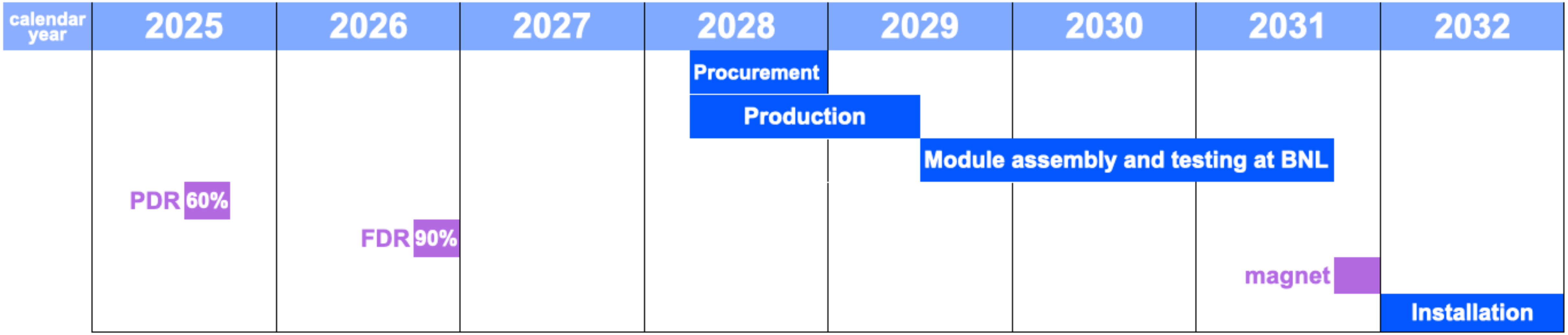
3D printed custom flexible PCB holder & light shield

CAEN module for SiPM bias and DAQ

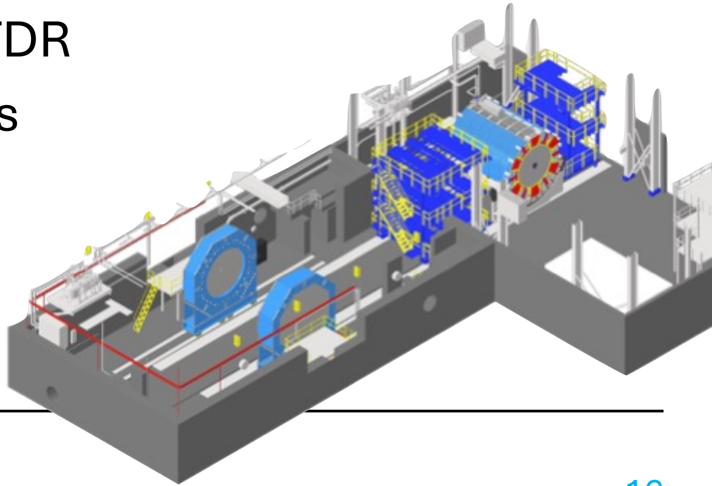
GOAL: verification of 10x10 cm tile configuration

nHCal baselining and start of construction

Charge 3



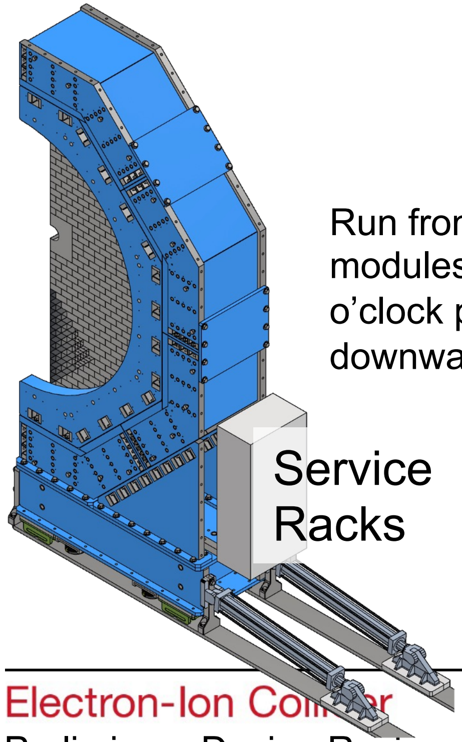
- Majority of design parameters have been optimized by simulation-based studies (TBD: readout layer integration)
- Detector studies, optimization, and physics impact documented in preTDR
- The nHCal can be delivered later than most other detectors because it is decoupled from the flux return and does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



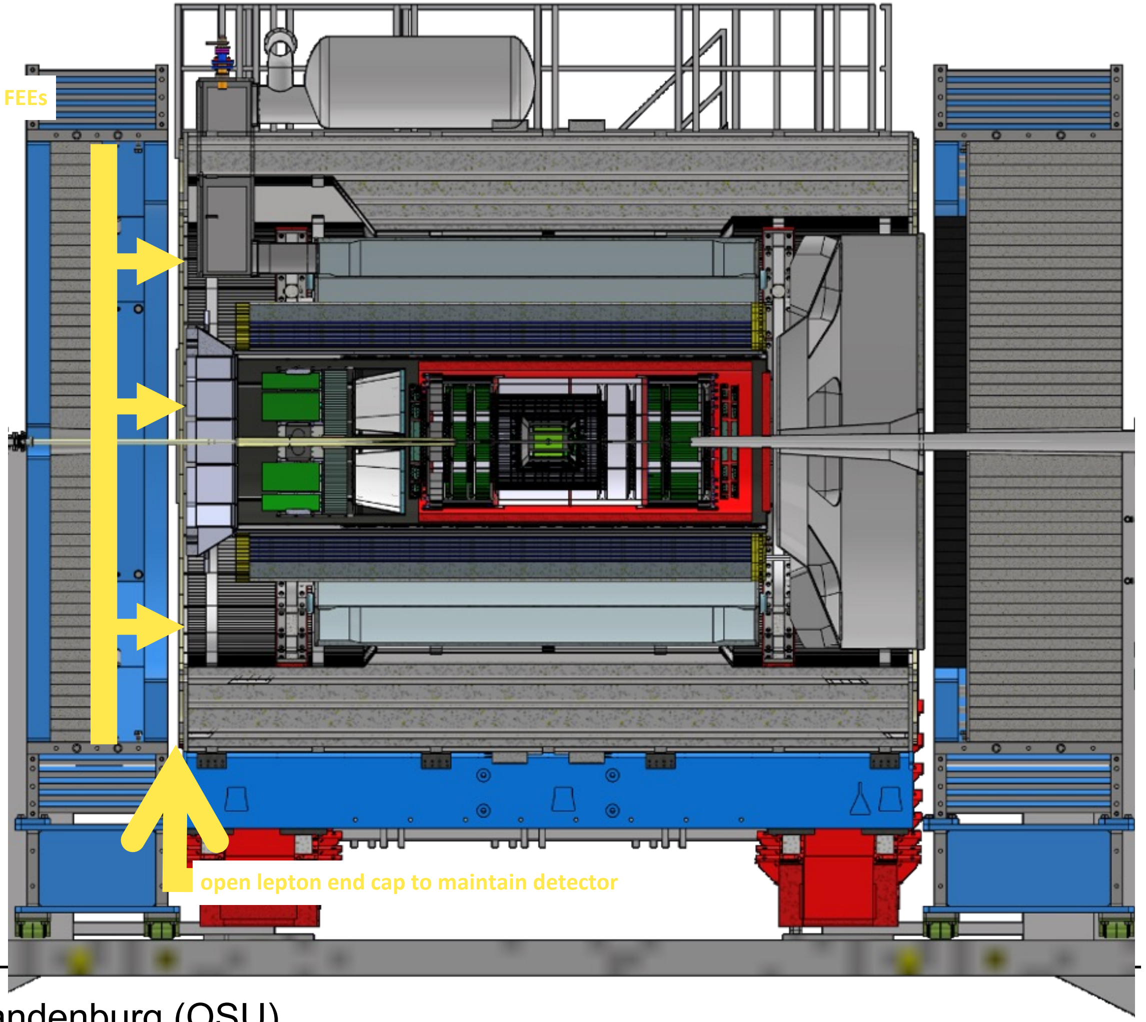
nHCal integration and planning for installation & maintenance

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)



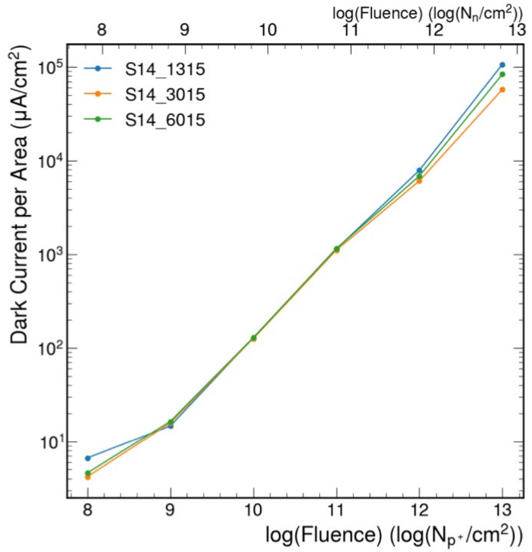
Run from the front face of the HCAL modules near the 3 o'clock and 9 o'clock positions and are routed downward to service racks.

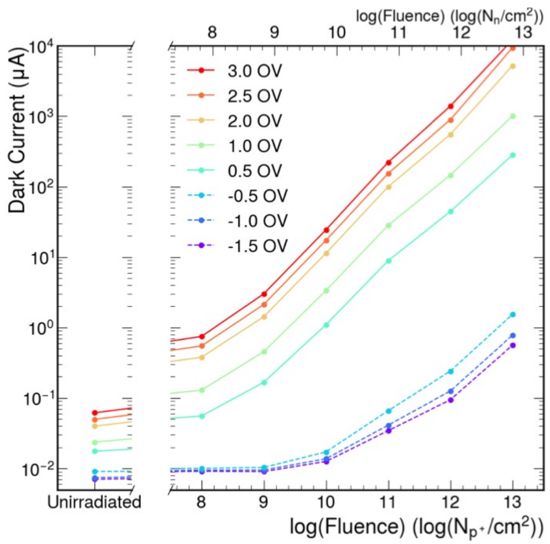


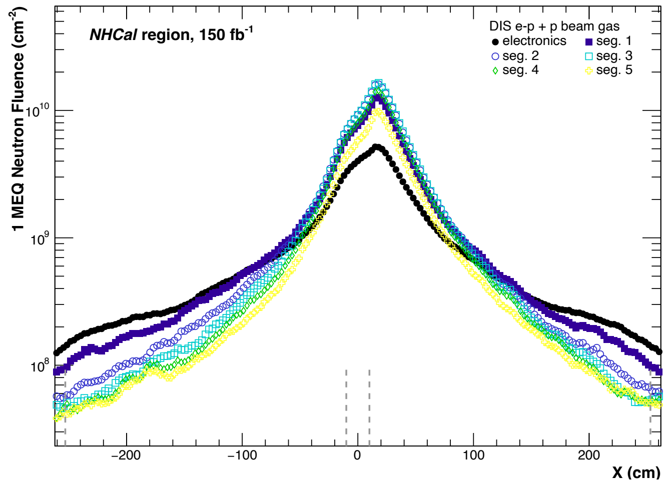
SiPM ES&H and QA Considerations

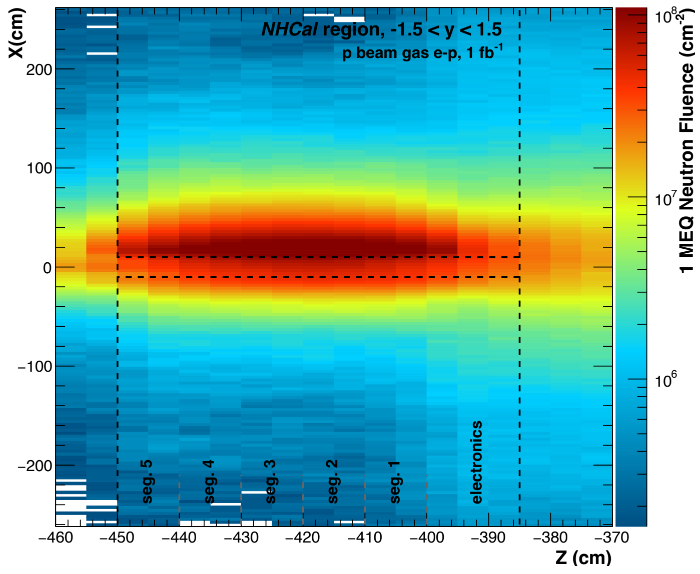
Charge 4

- Degradation of SiPMs due to radiation damage has been studied[1]
- Expected SiPM lifetime sufficient for anticipated dosage in backward direction over > 15 years ($\mathcal{L}$ = 150 fb^{-1}) of running









[1] https://arxiv.org/pdf/2503.14622

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 module testing prior to installation
  - Cosmics data taking after installation

Synergy with LFHCAL

- Procurement includes property assessment of material:
  - Inspection of dimensional tolerances according to technical drawings, including nickel-plating
- Calorimeter absorber chosen for safety, magnetic constraints, physics motivations.
- Use of radioactive sources for testing follow all local & institutional guidelines

Path to CD-2 and beyond

Well defined plan

- Continue to utilize technologic synergy with LFHCAL
- Detector optimization based on tail-catcher role and lessons learned from H1 SPACAL

Milestones

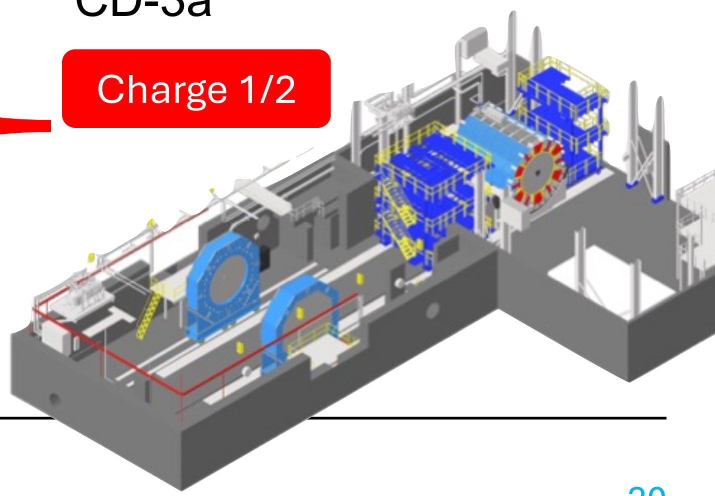
- Incorporation of muon identification and acceptance into HCAL system design
- Develop MIP/muon identification utilities in the ePIC software
- Explore benefits of AI/ML for energy resolution/scale corrections
- Study impact on vector meson acceptance
- Full simulation studies with backgrounds
  - preTDR will be based on October ePIC simulation campaign which includes beam backgrounds
- Study nHCAL impact on event kinematic reconstruction and background rejection
- Prototype development and testing
- Finalize readout configuration and DAQ to determine channel count
- Investigate cost saving alternatives to electron beam welding

Motivated/encouraged by past feedback

Charge 5

Readiness for CD-2 / CD-3a

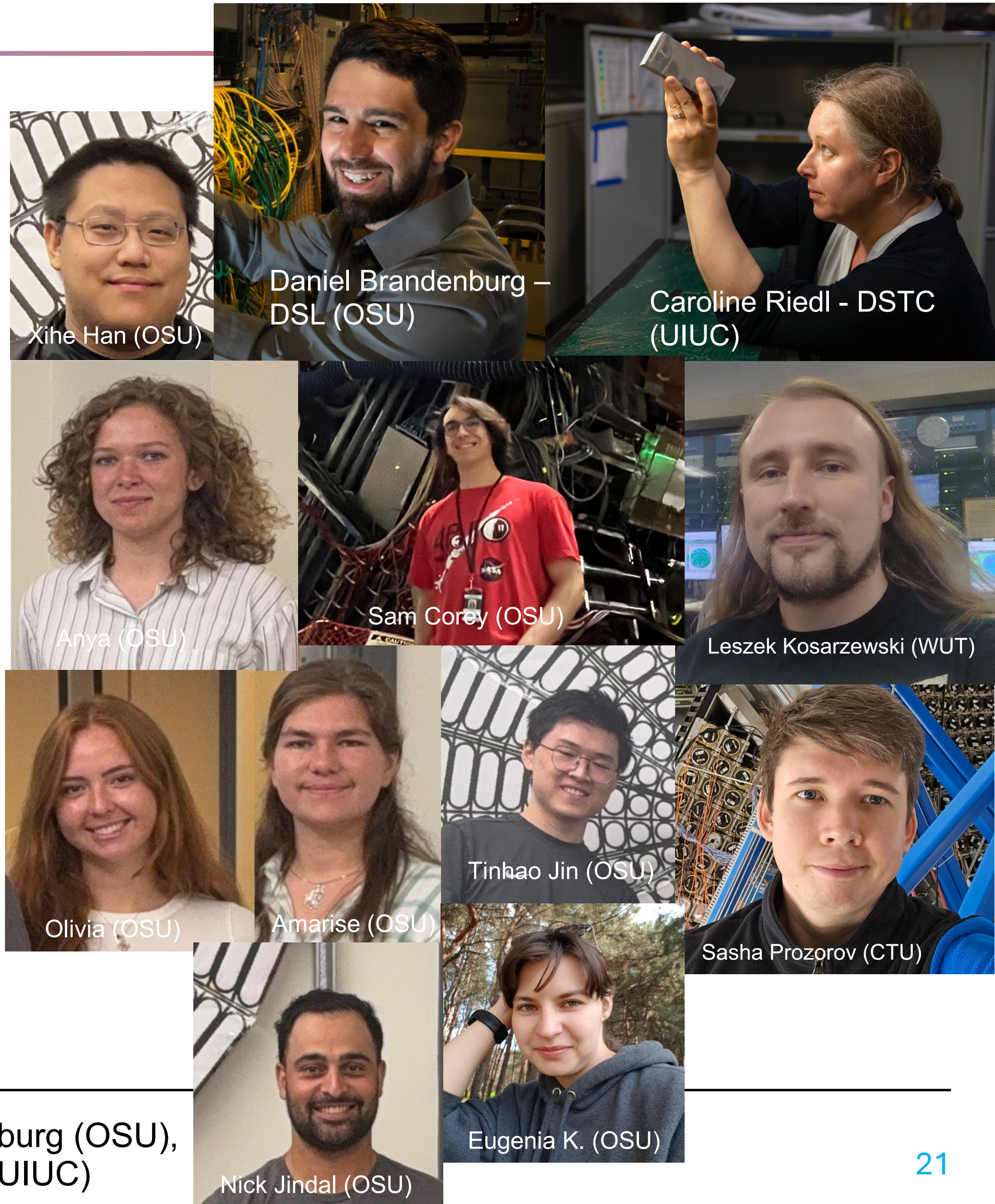
Charge 1/2



nHCal summary

Status:

- Synergy with LFHCAL technology, with design of nHCAL optimized for 'tail-catcher' role in ePIC
- Involved institutions: OSU, UIUC, CTU, BNL, WUT
- 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
- October campaign including full simulations with beam backgrounds will be used for preTDR
- 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 with milestones



nHCal performance evaluation

Charge 2

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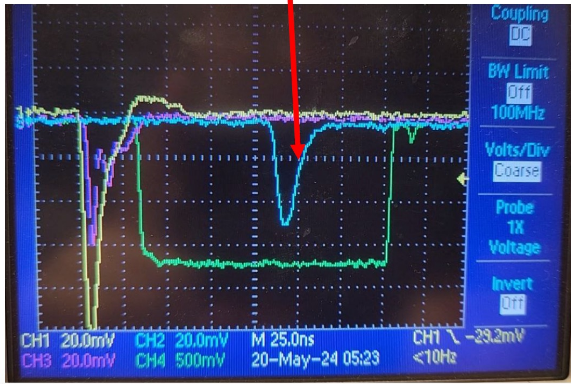
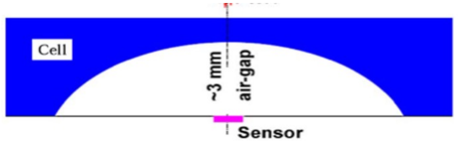
  - Vary tile thickness (4, 6, 8, 12mm
  - Vary SiPM placement (center, corner, edge)
- Performance evaluation
  - Light yield per MIP, uniformity, cross-talk

GOAL: verify 10x10 cm tile configuration

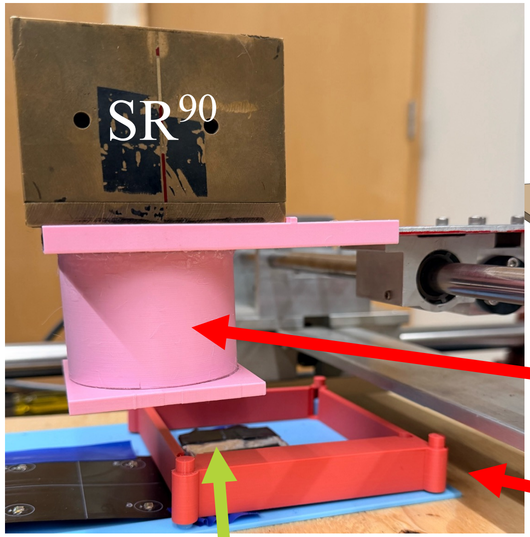
signal from SiPM-on-tile

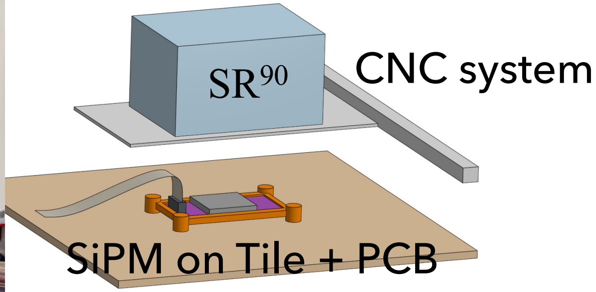




CAEN module for SiPM bias and DAQ

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