Longitudinally separated Forward HCal (LFHCal) and Insert Update

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Simulation progress:

- Major integration in epic software is concluded
- Current on-going studies: muon performance, justification of 4 layers of W, acceptance studies for outer LFHCal radius (will be presented in LFHCal meeting)

Mechanical design progress: (Eliott's presentation)

- Insert absorber geometry ready for quote (DRW)
- Received magnetic force map for studies on stack integrity & deformation

## Read-out & electronics design progress:

- Setup at ORNL nearly complete for SiPM testing
- HGCROC v3 test progressing

Cost & Schedule:

- Worked with Miguel on integrating insert into LFHCal worksheet
- New quotes for machined steel, tungsten, machined scintillator, ESR foil

- Started machining tiles ORNL in LFHCal geom
- First tiles a with a bit of problems (redoing)
- Additionally will produce machined tiles with same dimensions as FNAL CMS ~ 3.5 cm tiles for comparative measurements
- Will produce tiles with different dimple sizes/shapes
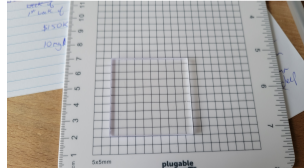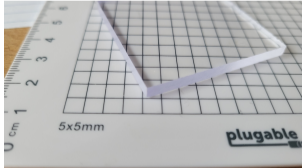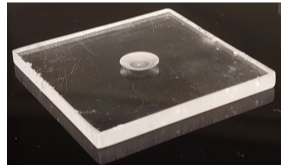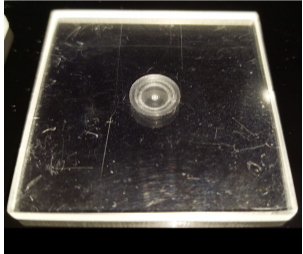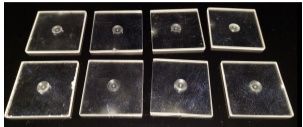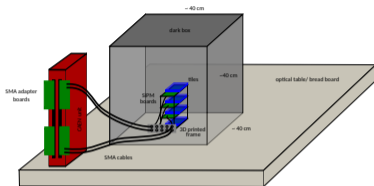
- Most parts for dark box at ORNL, will assemble this week
- SiPMs: noise spectra, single pixel calibrations
- Tiles: Lightyield, uniformity with cosmics
- Readout with oscilloscope and/or CAEN DT5202
- Large volume for whatever the future holds...
- Yale is constructing equivalent setup
  - Same CAEN readout unit
  - Will receive PCBs, SiPMs, tiles from us
  - 3 students + postdoc
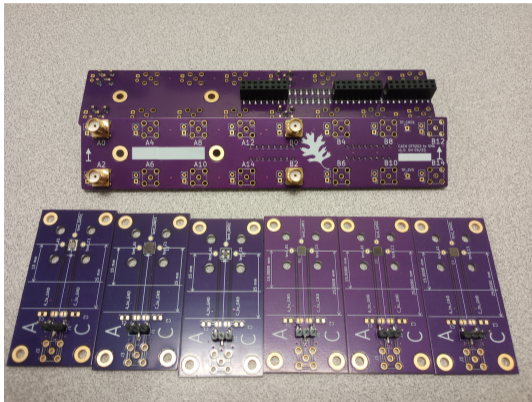
- Breakout board CAEN DT5202 to SMA (up to 32 channels)
- Available SiPMs at ORNL:
  - Hamamatsu S14160-1315 (15μm, $1.3 \times 1.3\,mm^2$), thanks to Miguel!
  - Broadcom AFBR-S4K33 (15μm, 35μm, 47μm), AFBR-S4N33 (30μm)
  - OnSemi MICROFC-10010 (10μm, $1 \times 1\,mm^2$), MICROFC-30035 (35μm, $3 \times 3\,mm^2$)
  - All on test boards
- Will order enough 1.3mm Hamamatsu SiPMs to equip 2 8M modules in coming week
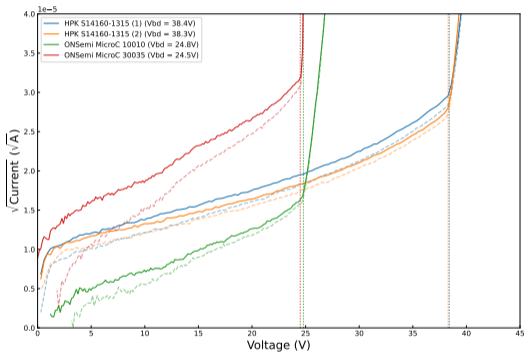
- Quick IV measurement for each available SiPM type
- Summer student Jacob Mireles (UTEP) working on automated extraction of V_{bd} from IV curves
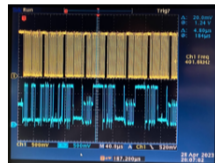
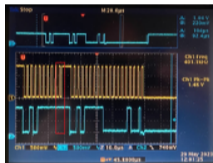## HGCROC Test setup at ORNL:

Signal integrity issue on FCMD/CLK320 MHz:
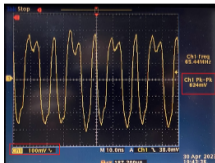
I2C Problems:

- Standard I2C is not working sometimes
- chip does not responds and get stuck

Problems solved now in the FW
GUI for the running is ready:
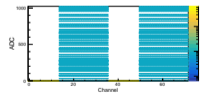
Getting the start up procedure done correctly

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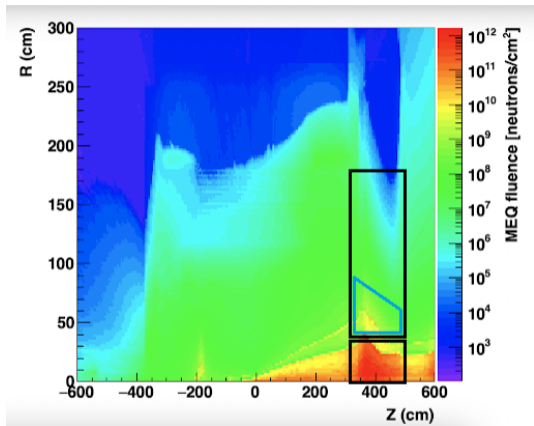
(Adapted from Alex Jentsch)

- Latest neutron background simulations indicate strong irradiation gradient in LFHCAL volume
- Baseline mitigation plan:
  - Cast tiles in high radiation area (higher lightyield, better S/N)
  - Larger area SiPMs in high radiation area (higher lightyield, better noise scaling)
  - (n.b.: CMS HGCAL does exactly the same thing)
- Needs more detailed and quantitative studies
- Expect $\sim 10\%$ of LFHCAL tiles to be in "high radiation" area
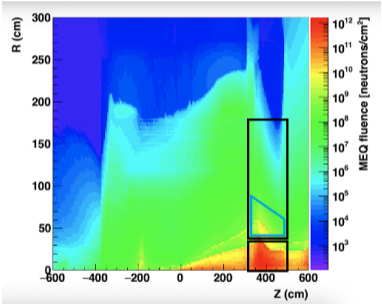
- Reconsidered molded vs. casted/machined tiles
  - Radiation damage larger up to $R \approx 1m$ & in front of towers
  - Use casted tiles ($\approx 30\%$ higher light yield) in those areas + possibly larger SiPMs (3x3mm) $\sim 10-12\%$ tiles
  - Remaining area molded tiles
- Move Scintillator out of LLP, take tungsten in instead
- New budgetary quotes with proper geometry for scintillator (machined), steel & tungsten components, ESR foil
- Included cost for LED (quote) & connectors (guess)
- More solid estimate for other electronics (HV supplies, cables,...) underway

Current total cost (full area LFHCal): 16.1 M (escalated 18.4M)

- Worked with Miguel on integrating insert into LFHCal costing table & refining respective costs on both ends (updating quotes ...)
- With insert LFHCal reduction of modules 8M: 1077, 4M:75 (default 8M: 1091, 4M: 76, 2M: 2, 1M: 4): **Total cost: 15.98M (esc. 18.98M)**

6.5K channel layering

layers 0-9: W absorbers
20.5 cm (1.7 λ_{n}s)

layers 10-65: Fe absorbers
114.8 cm (5.9 λ_{n}s)

layers 0-6   layers 7-13
A=9 cm²   A=33 cm²
2.5k chan. 0.7k chan.
1.2 λ_{n}s   0.9 λ_{n}s

layers 14-64
A=52 cm²
3.3k chan.
5.5 λ_{n}s

total channels: 6.5k
right side channels: 4.1k
left side channels: 2.4k
total length: 134.8 cm
total λ_{n}s: 7.6
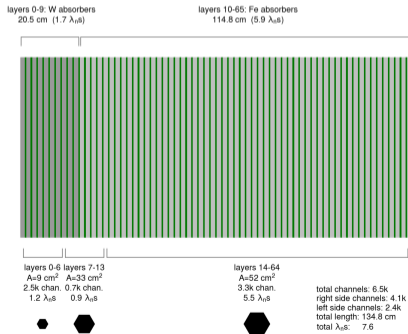
- Costed insert with either 6.5K or 23.4K channels
- 6.5K version would have larger tile size starting from 7th layer than LFHCal (room for optimization)
- 1st estimates include reasonable labor for assembly + material (needs refinements based on quotes)
- No splitting yet done for project vs. in kind
- SiPMs assumed to be LLP, nothing else
- **Insert cost:**
  - 6.5K channels: **700K (833.5K esc.)**
  - 23.4K channels: **992K (1.2M esc.)**

Mechanical:

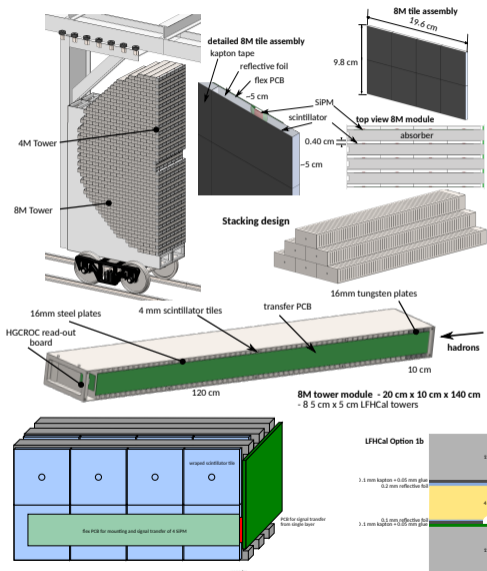- Could we get the latest STL files of the pECal?

Finances:

- eRD109, eRD107 & PED - all funding received
- Funding for injection molding FNAL on track
- Travel funds to test beam in September/October

Backup

- Same general design as LFHCal with SiPM on tile option and single wrapped tiles (5x5cm)
- Transfer of signals via small flex PCB to side of 8M module + long PCB to the end
- Signal summing of individual SiPMs at the end, same readout granularity at the end
- FEB boards removable similar, SiPMs not
- Simplified machining of absorber plates
- Upgrade option 1b+: Readout every SiPM by adding more HGCROCs & removing summing board, liquid cooling would be needed
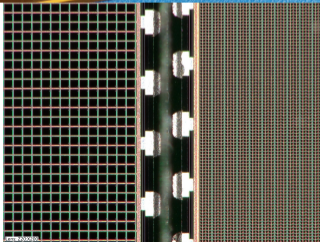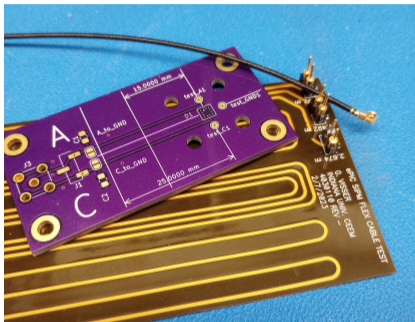
- Received first flex PCB prototype from Gerard (via BNL)
- Received 1.3mm diameter micro-coax samples from John Lajoie
- Received SiPM carrier PCBs
- Received CAEN DT5202 64ch CITIROC SiPM readout unit
- SiPMs at ORNL: Broadcom AFBR-S4K33 (15μm, 35μm, 47μm), AFBR-S4N33 (30μm)
  - ▶ Test PCBs produced and available
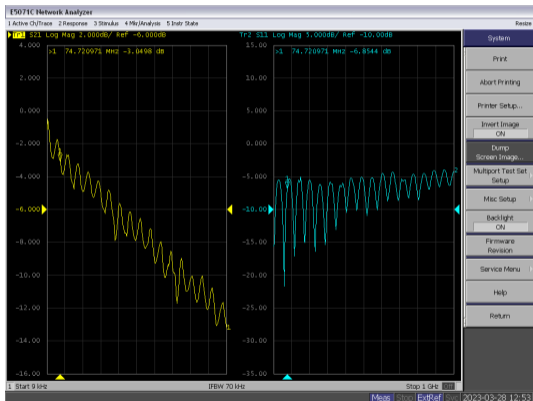
- Did a "quick and dirty" test with PCB on 2port VNA (not useful yet)
- Found a 4port VNA we are free to use eventually (will be very useful in the future)
- Received LFHCal eRD109 funds to produce more flex prototypes as needed
- Started looking into suitably thin connectors: Custom SAMTEC Z-Ray? Pogo pins?
- Can do full chain tests very soon with VNA, scope, CAEN, HGCROC...
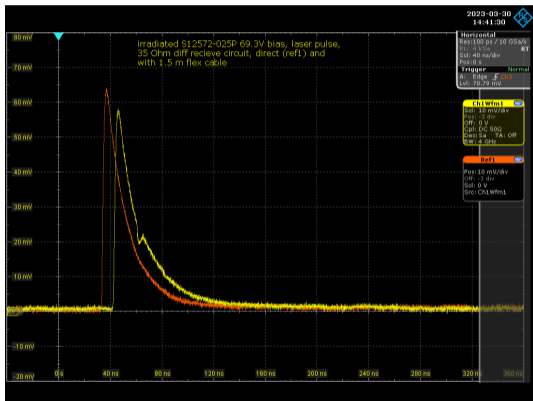
- Gerard has managed a full chain test
- Some reflection from impedance mismatch, but can be optimized, likely irrelevant in practice
- **The flex transfer works on a single channel!**
- More R&D needed for crosstalk, noise etc...
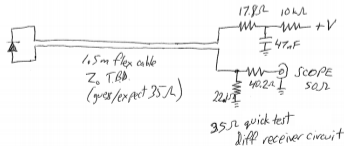
	A	B	C	D	E	F
1	**Manufacturer**	**Type**	**Size**	**N pixels**	**Comment**	
2	Hamamatsu	S13360-1325PE	1.3x1.3	2668	for SiPM-on-tile	
3	Hamamatsu	S14160-1315PS	1.3x1.3	7284	for SiPM-on-tile	
4	Hamamatsu	S13360-3025PE	3.0x3.0	14400	for fiber-based design	
5	Hamamatsu	S14160-1315PS	3.0x3.0	39960	for fiber-based design	
6						
7	OnSemi	MicroC 10010	1.0x1.0	2880	for SiPM-on-tile	
8	OnSemi	MicroC 30020	3.0x3.0	10998	for fiber-based design	
9	OnSemi	MicroJ 30020	3.0x3.0	14410	for fiber-based design	

- Identified potential sensors for SiPM-on-tile option
- Project plans to request samples on behalf of EIC?
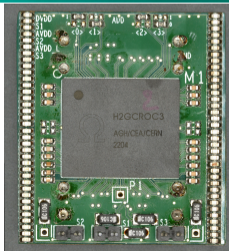
In ORNL we have now:

- 5 Carrier boards
- 2 working mezzanine boards with H2GCROC3
- KCU105 board from Xilinx (Ultrascale)
- I2C communication already tested and works

Plan for this week(s):

- Setup the PC with for the readout
- Firmware/software from the Omega group
  - ▶ With custom firmware we have an issue with the PLL lock so far
- Start testing the different signals/capabilities
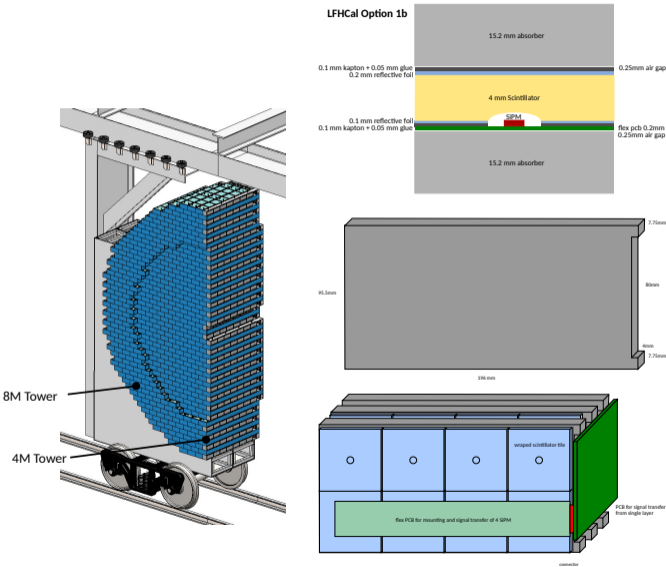- Update powering/ signal cable needs for costing

Option 1 (Default)

Plastic (Polystyrene)

8M LFHCal Scintillator Tile

19.6 cm

0.5 mm WLS fiber

9.8 cm

laser etched lines refilled with epoxy TiO₂

0.5 mm groove refilled with epoxy

notch 0.125cm

0.40 cm

Stacking design

8M Tower

4M Tower

16mm steel plates

4 mm scintillator tiles

16mm thungsten plates

7x 10 fibers read-out by SiPM

120 cm

20 cm

8M tower module - 20 cm x 10 cm x 150 cm
- 8 5 cm x 5 cm LFHCal towers

Concept:

- PSD [link TDR] inspired inspired Fe/W-Scint calorimeter
  4 layers of W $_{(160\,mm)}$-Sci plates $_{(4mm)}$61 layers of Steel $_{(160\,mm)}$-Sci plates $_{(4mm)}$ +

- Multiple towers combined in one module to reduce dead areas, increase granularity

- WLS fibers running into each tile, read out at the end

- Read-out:
  - 7 signals per tower (signals combined from 10 Sci-plates, 5 in tungsten section)
  - 63.3K channels read out

- Modules of different sizes (8M, 4M, 2M, 1M) to maximize coverage & assembly efficiency

Option 1b (Buried SiPM)

LFHCal Option 1b

15.2 mm absorber

0.1 mm kapton + 0.05 mm glue
0.2 mm reflective foil
0.25mm air gap

4 mm Scintillator

SiPM

0.1 mm reflective foil
0.1 mm kapton + 0.05 mm glue
flex pcb 0.2mm
0.25mm air gap

15.2 mm absorber

7.75mm
80mm
4mm
7.75mm

95.5mm

196 mm

wraped scintillator tile

flex PCB for mounting and signal transfer of 4 SiPM

PCB for signal transfer from single layer

connector

8M Tower
4M Tower

- Same general design as LFHCal option 1 replacing WLS fibers in each layer with SiPM on tile option and single wrapped tiles (5x5cm)
- Transfer of signals via small flex PCB to side of 8M module + long PCB to the end
- Signal summing of individual SiPMs at the end, same readout granularity at the end
- FEB boards removable similar to option 1, SiPMs not
- Simplified machining of absorber plates
- Upgrade option 1b+: Readout every SiPM by adding more HGCROCs & removing summing board, liquid cooling would be needed
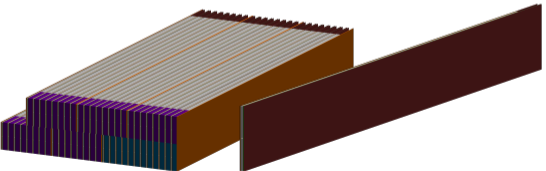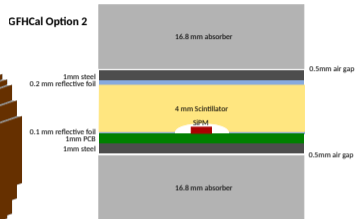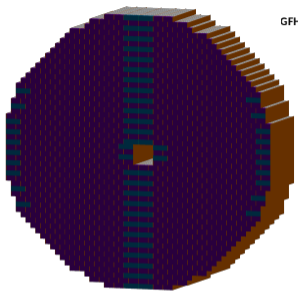
- Outer module dimensions + stacking stay largely the same replacing 4M with 12M modules
- Internal module design rotated by $90°$ absorber running in z direction
- Electronics + Scintiallator tiles pulled out towards the back in cassets
- SiPM on tile option with 5x5cm tiles
- Transfer of signals via long flex PCB to the end
- HGCROCs sitting in the back of HCal, cooling needed only in the back
- Signal summing of individual SiPMs at the end (2 tiles each) $\rightarrow$ increased granularity
- Simplified machining of absorber plates compared to option 1
- Upgrade option 2b+: Readout every SiPM by adding more HGCROCs & removing summing board, more liquid cooling would be needed
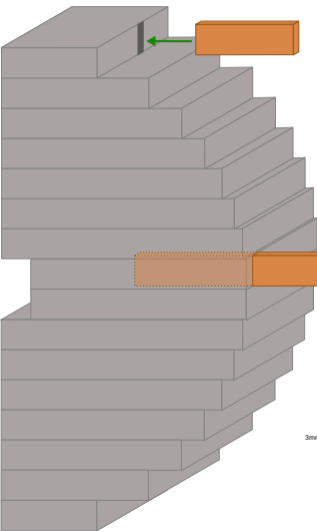
- Full redesign of everything
- Closest concept to HGCCal or CALICE AHCal SiPM on tile (5x5cm) & could incorporate insert with higher granularity
- Absorber structure of half detector (shell) + cradle build as a whole with slots on side for insertion of cassets
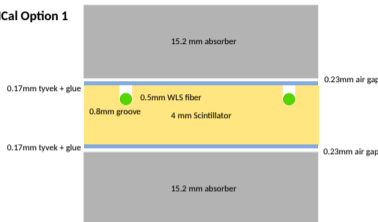- Cassets ~ 30cm x 250cm in worst case (center) with all scintillators + readout electronics inside
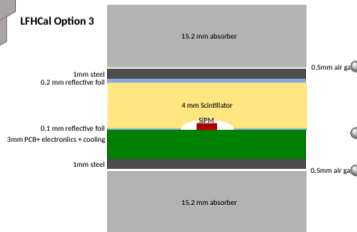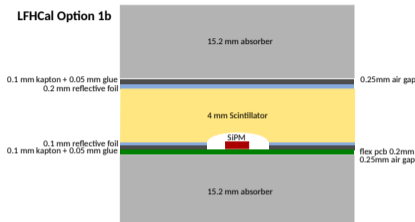
- HGCROCs would need to be integrated in layers
- Cooling absolutely necessary in layers
- Electronics + SiPM servicable no ganging trivially possible

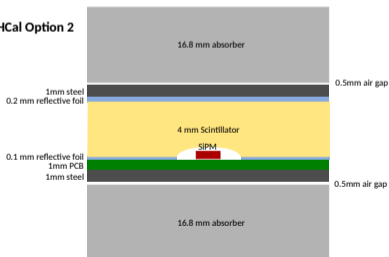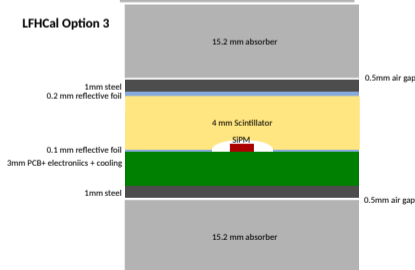- Due to different needs, i.e. connections, cooling, readout out significant differences in sampling fraction
- Can't be fully adapted by changing layer thickness of steel/thungsten

Electronics comparsion

	Option 1	Option 1b	Option 1b+	Option 2	Option 3
Channel #	63,280	63,280	601,160	253036	601,160
SiPM $	63,280; 3x3mm 506	601,160; 1.5x1.5mm 4210	601,160; 1.5x1.5mm 4210	506,072; 1.5x1.5mm 3550	601,160; 1.5x1.5mm 4210
Summing board	No	Yes (10channel)	No	Yes (2channel)	No
# HGCROC (FEB) k$	~1,100 22	~1,100 22	~10,450 210	~4,500 90	~10,450 210
ECON-D (FEB) k$			1,800 9	750 1.5	1,800 9
FPGA (RDO) k$	46 90	46 90	90 180	37 150	90 180
PCB	135	135	270	113	270
Cooling	0	back	back	back/inner	inner
Cables, etc	?	?	?	?	?
Total cost k$	753	4457	4880	3829	4880

- Can one drive & readout the SiPM over $> 1m$ using PCB or capton flex without applification?
- If not cooling might become necessary
- Do we wanna gang SiPMs
- Do we wanna go for injection molded tiles'?
- For option B, what does it to the physics?
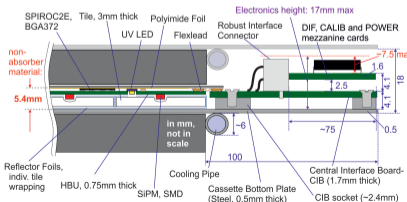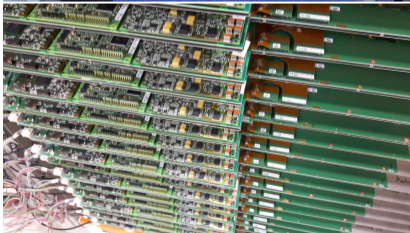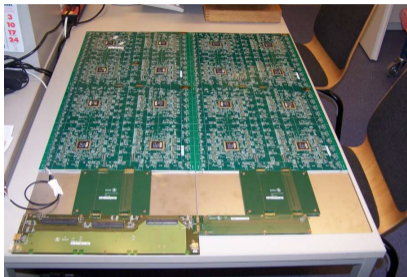
CMS:

- In full cryo container, liquid Nitrogen
- No possibility to service HGCROCs or SiPMs ever

AHCAL:

- Cassets with fully integrated electronics ~ 6mm on inside, 3mm electronics
- Clearance around casset ~ 1 mm on both sides

Costing

Updated Cost Estimate - option 1

Example 8M module costs:

Material procurement	Units	Unit Pricing
Absorber plates W	4	$445
Absorber plates Steel	61	$60
module support	1	$320
Scintillator plates	65	$65
tyvek + capton	4.04	$0.4
WLS fibers	1360	$2
8M module cost:	1091	**$12770**

Assembly labor	hours	cost
installing fiber mech. engineer	17.5 h	$2680.5
tile wrapping PhD students	7 h	$140
tower assembly mech. engineer	0.083 h	$12.8
tower assembly PhD Student	1.92 h	$38.4
tower assembly Undergrad	11 h	$220
tower testing Postdoc	1 h	$71
tower testing PhD Student	4.5 h	$90
8M module cost:	1091	**$3252.7**

Electronics	Units	Unit Pricing
SiPMs	56	$8
SiPM mounting + summing boards	1	$90
HGCROC	1	$20
cable+HV/LV	1	~$822
8M module cost:	1091	**$1392**

Additional costs:

- R&D cost: 393K
- Tooling: 200K
- Support Structure: 100K
- Installation: 382K
- FPGAs: 90K

Total costs:

- estimated for:
  1091x8M module, 76x4M modules, 2x2M modules, 4x1M modules
- Module prices don't exactly scale as labor doesn't scale
- Cost adapted to most recent quotes for 8M steel, WLS, tungsten (not included before), scintillator with realistic design
- Labor hasn't been modified
- **total unescaled cost: $20.7M**

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ePIC

Example 8M module costs:

Material procurement	Units	Unit Pricing
Absorber plates W	4	$364
Absorber plates Steel	61	$45
module support	1	$320
Scintilator tiles (wrapped)	520	$7
reflective wrap	4.04	$50
flexcables	130	$2
SiPMs	520	$7
8M module cost:	1091	**$12003**

Assembly labor	hours	cost
tower assembly mech. engineer	0.083 h	$12.8
tower assembly PhD Student	2 h	$40
tower testing Postdoc	1 h	$71
tower testing PhD Student	4.5	$90
8M module cost:	1091	**$213.8**

| Electronics	Units	Unit Pricing
FEB + summing boards	1	$20
HGCROC	1	$20
cable+HV/LV	1	~$822
8M module cost:	1091	**$1392**

Additional costs:

- R&D cost: 393K
- Tooling: 200K
- Support Structure: 100K
- Installation: 382K
- FPGAs: 90K
- Robotic assembly: 460K

Total costs:

- estimated for same as std. option 1
- Assumed cost for absorber in option 1, 0.5 machining, scaled to 0.25
- not costed: long PCB on side, connectors layers & high density, testing of electric components and SiPMs, LEDs for each tiles
- **total unescaled cost: $16.8M**

# Thanks!
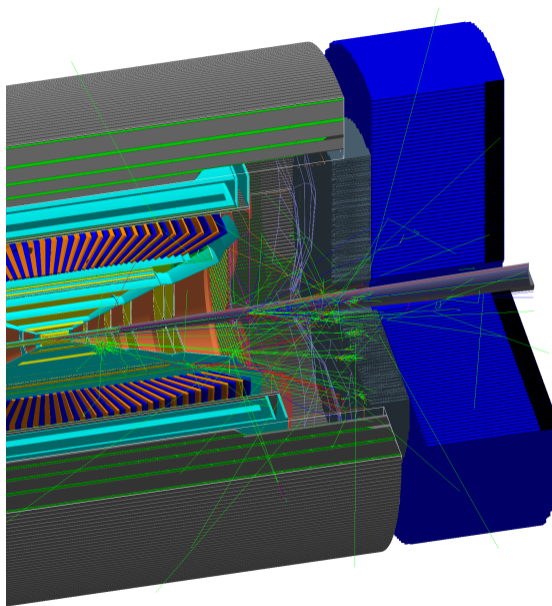
Current 8M Scintillator Plate Design

- Most scintillator plates produced as 1 unit of 100x200mm plates (8 single tower tiles)
- Separation of tiles edged into the plate (95%) through, refilled with Epoxy-TiO$_2$ mix
- Wrapped in Tyvek paper and Kapton tape or painted with TiO$_2$ rich paint

8M LFHCal Scintillator Tile

Plastic (Polystyrene)
19.6 cm
0.5 mm WLS fiber
9.8 cm
laser etched lines refilled with epoxy TiO$_2$
0.5 mm groove refilled with epoxy
notch 0.125cm
0.40 cm

- Fiber thickness chosen for minimal light loss while bending (0.5mm)
  $\rightarrow$ other geometries for embedding under consideration (i.e. 1/4 circle)
- Originally costed from Uniplast as 1 unit of assembly + material
- Updated estimate including (material, fiber installation by engineer, wrapping by students, tooling)
  $\rightarrow$ new estimate driving by labor for fiber installation
- Exploring possible robot supported options for tile assembly
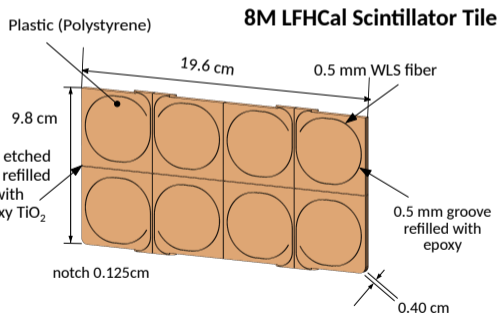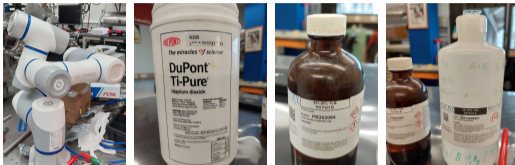
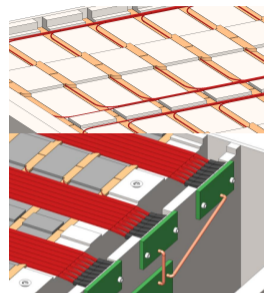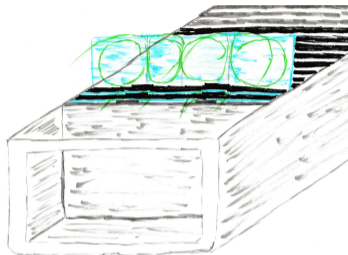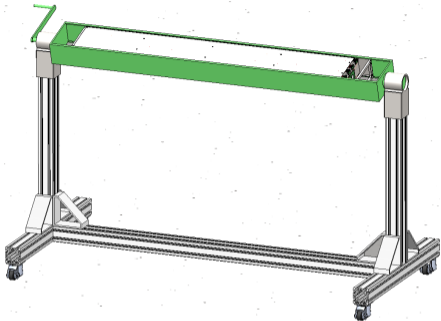1. Refilling of gaps with TiO_2-Epoxy mix using collaborative robot

2. Measuring fiber quality & cutting to desired length

3. Laying WLS-fibers in groove, fixating them using a few glue dots

4. Roll WLS-fibers up on try with tile

5. Might need additional coating with white paint

6. Stack trays & transport to 8M assembly site
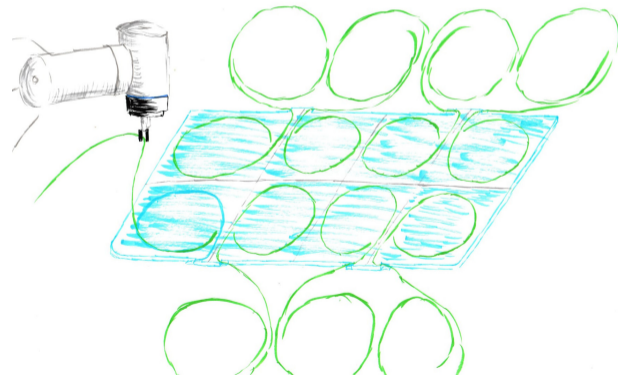
a) Mount assembled steel/tungsten frame in pivot
b) Slot scintillator tiles in frame from back to front
   Fibers for bottom side slotted through, caught by tray on bottom
c) After 10 tiles sort fibers 5/5 & place plastic strip as separator, tape on top
d) Continue till top side finished & cut length of fibers to fit readout
e) install cover plate
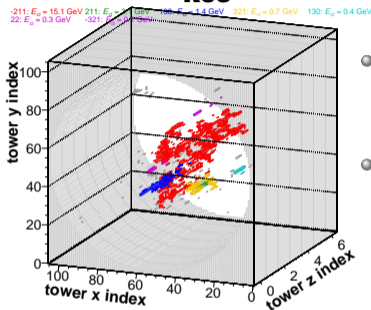f) Flip module in pivot, remove tray
g) Sort fibers & assemble as on top
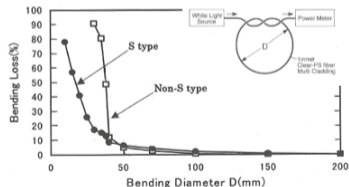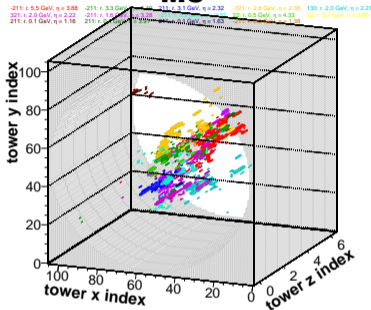
MC — Rec

LFHCal, Event 30
e-p: 18× 275 GeV, Q² > 100 GeV

- High granularity needed to try to distinguish shower maxima close to beam pipe
- **HCal**:
  read out in 7 layers longitudinally desirable min measurable tower energy 3-5 MeV, max 20-30 GeV in single tower segment

- LFHCal 1 SiPM per 10 fibers (7 per tower) -i.e Hamamatsu S13360-3025PE (14.4K pixels)
- HCal readout at end of module (max. 10cm)
- Small light collection prisms might be needed infront of SiPM
- Idea use each 1 H2GCROC3 (up to 70 channels) for readout of HCal (ideally common chip/board design with WSciFi-ECal & ALICE FoCal-H)

Current Read-out Concept
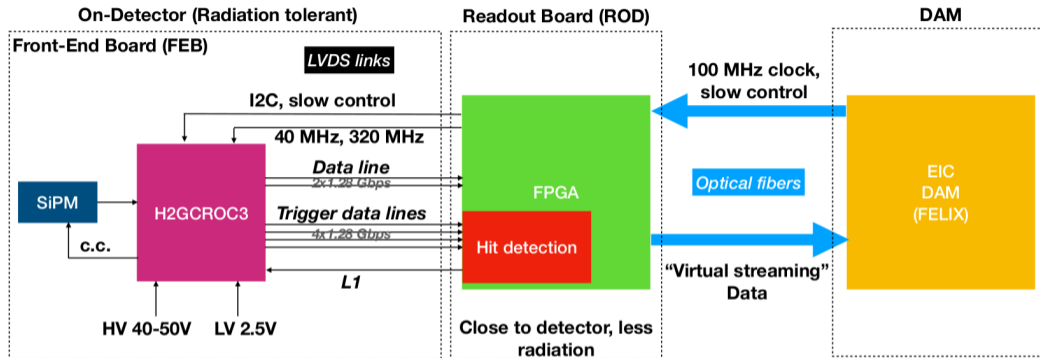
- The H2GCROC3 requires the L1 trigger for readout, with the maximum speed of 960 kHz
- The expected hit rate in one channel of LFHCal is up to 50 kHz:
  - With possible 4 sample readout we would reach a maximum of 200 kHz
  - "Virtual" streaming readout towards the EPIC DAQ system
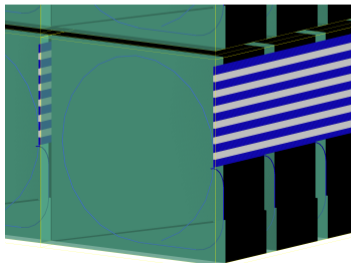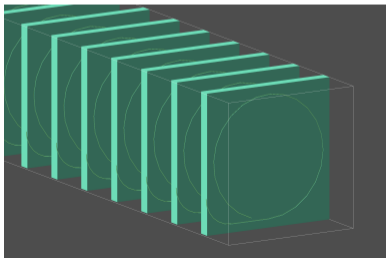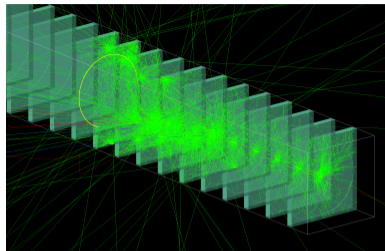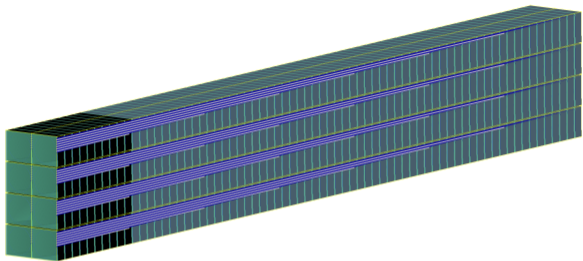
- largely realistic implementation of geometry , refinements for module edges needed
- first light propagation studies, cross checks planned with test sub-tiles at ORNL (fiber routing)
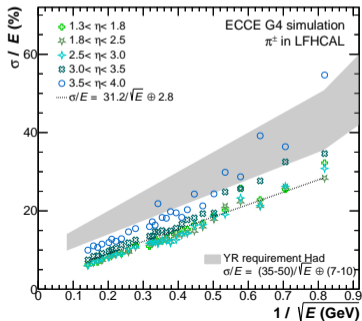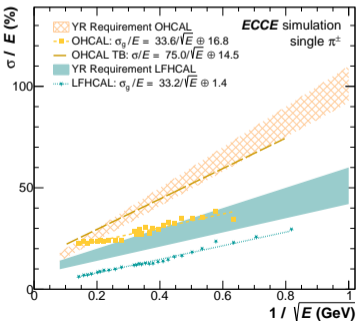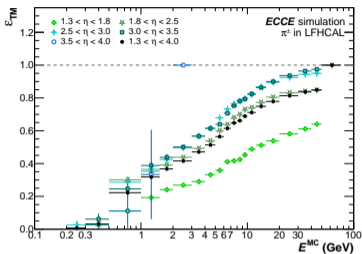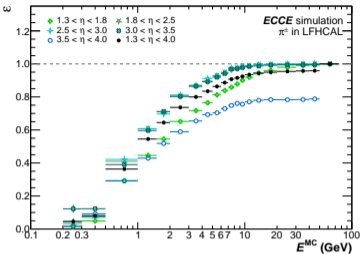
- Cluster finding and track matching efficiencies good in center of LFHCAL, losses towards edges
- Performance overestimated with standard response implementation in GEANT4 (1.5x from other setups)
- Small η dependence for energy resolution
- Exploring possibility for high granularity insert with different composition & changing granularity of readout as function of R
- Studies to improve clusterization further using ML started

R&D activities & plans

eRD107 - Plans & Milestones

1. **Prototype tile production using machining & injection molding (04/23)**
   - Assembled prototype tiles using machined scintillator plates
   - Assembled prototype tiles using injection molded scintillator tiles
   - Documentation of procedures for manual assembly of tiles & WLS fibers

2. **Reconstruction optimization (09/23)**
   - Write-up of optimization results from simulations

3. **Sensor board development (07/23)**
   - First prototype of sensor board for Si-PM readout (together with eRD109)
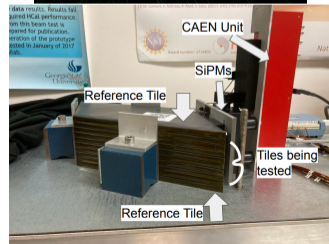
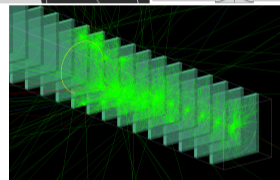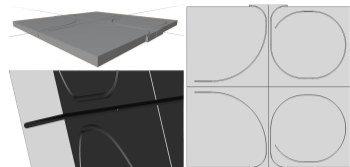4. **Small test module assembly (07/23)**
   - First prototype of single segment of 8M module
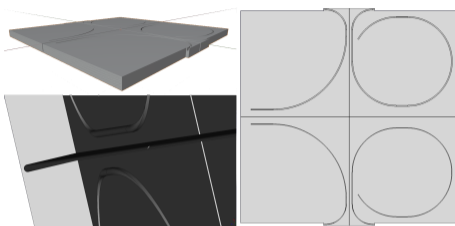
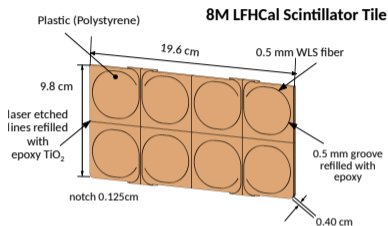5. **First automated scintillator tile assembly (08/23)**
   - Assembled prototype tiles
   - Documentation and Evaluation of procedures for automated assembly of tiles & WLS fibers

6. **Tile Characterization (08/23)**
   - Write-up of test bench & test beam measurement for all assembled tile-prototypes

Prototype tile production & assembly

Plastic (Polystyrene)

8M LFHCal Scintillator Tile

19.6 cm

0.5 mm WLS fiber

9.8 cm

laser etched lines refilled with epoxy TiO_2

notch 0.125cm

0.5 mm groove refilled with epoxy

0.40 cm

Prototype tile production using machining & injection molding

- Vendor replacement needed for Uniplast
  - a) Machining plastic scintillator plates ($\sim$ \$80/tile)
  - b) Injection molding tile ($\sim$ \$4 − 6/tile)
- Opportunity for significant cost reduction w/ injection molding
- Performance and mechanical stability tests needed in both cases

First automated scintillator tile assembly

- Tile assembly time & labor extensive w/ classical methods
- Exploring automated assembly using collaborative robots for:
  - ▶ Refilling sub-segmentation with TiO_2
  - ▶ Fiber laying and fixating in groves
  - ▶ Automatic measurements of WLS-fiber quality

- Characterization of assembled tiles according to:
  - ▸ Light yield
  - ▸ Cross-talk among different tiles
  - ▸ Response uniformity
  - ▸ Durability and mechanical stability
- Initial geometry optimization using TracePro simulations
- Usage of available test-stands at universities for tile characterization
- Possibility to test multiple scintillator materials/dopant concentration in particular for injection molding
- Development of a SiPM board and WLS fiber connector suitable for production module
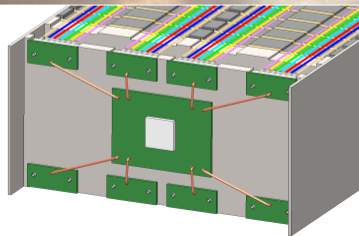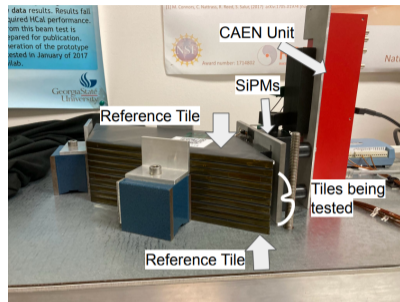
- Successively-larger R&D prototype assembly
  1. Scintillator tiles
  2. Single segment of 8M module (20cm) including initial read-out design
  3. Full mechanical mock-up of 8M module
  4. Full 8M modules including initial read-out design
- Main measurements
  - Characterization of spatial distribution and uniformity of MIP response for different tile types
  - Saturation behavior of combined tile and SiPM readout system for single segment
  - Measuring the individual and combined response of tiles to EM-showers
  - Spatial and energy resolution of partial and full module LFHCAL module
  - Combined test-beam w/ pECal to characterize LFHCal partial and full module response behind ECal
- Current Read-out electronics design based on CMS-SiPM-HGCROC (ASIC)
  Final electronics R&D for EIC specific readout board within eRD109 based on same ASIC with possible small modifications

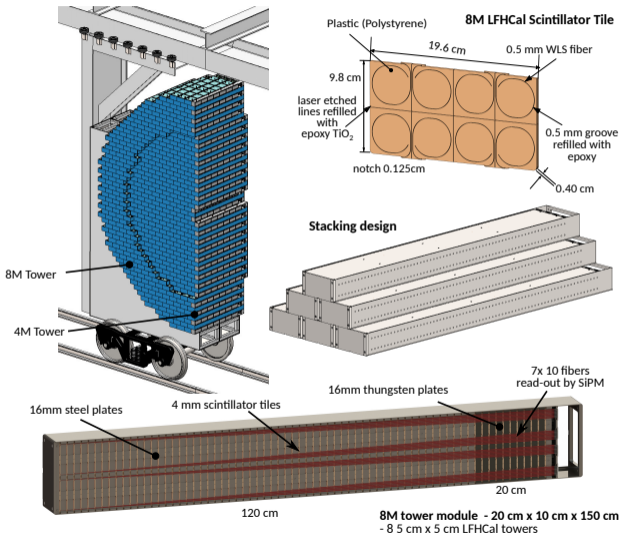| activity	cost in FY23 k$									total cost
	ORNL	FNAL	BNL	UTK	GSU	Yale	ISU	Valpo	UCR	in FY23 k$
Machined Tiles	11.7	0	0	0	0	0	0	0	0	11.7
Injection Molded Tiles	2.0	52.9	0	0	0	0	0	0	0	54.9
Auto Tile Assembly	20.0	0	0	0	0	0	0	0	0	20.0
Tile Char. (Lab)	16.0	0	0	0	0	0	0	0	0	16.0
Sensor Board	12.2	0	0	0	0	0	0	0	0	12.2
LFHCAL Mechanics	21.7	0	0	0	0	0	0	0	0	21.7
Tile Char. (Beam)	1.0	0	2.0	2.0	2.0	2.0	2.0	1.0	2.0	14.0
Total	84.6	52.9	2.0	2.0	2.0	2.0	2.0	1.0	2.0	**150.5**

institute	cost in FY23 k$	material	equipment	travel	total cost
	eng. and tech.				in FY23 k$
ORNL	29.8	16.8	36.0	2.0	84.6
FNAL	52.9	0	0	0.0	52.9
BNL	0	0	0	2.0	2.0
UTK	0	0	0	2.0	2.0
GSU	0	0	0	2.0	2.0
Yale	0	0	0	2.0	2.0
ISU	0	0	0	2.0	2.0
Valpo	0	0	0	1.0	1.0
UCR	0	0	0	2.0	2.0
Total	82.7	16.8	36.0	15.0	**150.5**

- Largest fraction of funding for engineers and technicians
- Additional funds used for material, test equipment & travel for test beam campaigns
- Significant in-kind contribution from universities and laboratories for assembly, simulation and data analysis ($\sim$ 2140h)
- Parallel PED request for mechanical & electrical engineering support will be submitted to further final design of LFHCAL

Task	Estimated cost in $ per year		
	FY24	FY25	FY26
mechanical engineering	40K	40K	20K
electrical engineering	30K	30K	20K
materials	30K	30K	40K
test beam support	10K	10K	10K
total	110K	110K	90K

ORNL — OAK RIDGE National Laboratory

ePIC

8M LFHCal Scintillator Tile

Plastic (Polystyrene)
19.6 cm
0.5 mm WLS fiber
9.8 cm
laser etched lines refilled with epoxy TiO$_2$
0.5 mm groove refilled with epoxy
notch 0.125cm
0.40 cm

Stacking design

8M Tower
4M Tower

16mm steel plates
4 mm scintillator tiles
16mm thungsten plates
7x 10 fibers read-out by SiPM
20 cm
120 cm

8M tower module - 20 cm x 10 cm x 150 cm
- 8 5 cm x 5 cm LFHCal towers

parameter	LFHCal
inner radius (envelope)	17 cm
outer radius (envelope)	270 cm
η acceptance	$1.2 < \eta < 3.5$
tower information	
x, y ($R < / > 0.8$ m)	5 cm
z (active depth)	140 cm
z read-out	10 cm
# scintillor plates	70 (0.4 cm each)
# aborber sheets	60 (1.6 cm steel)
	10 (1.6 cm tungsten)
weight	~ 30.6 kg
interaction lengths	6.9 λ/λ_0
Molière radius R_M	21.1 cm ($\pi^\pm$ shower)
Sampling fraction f	0.040
# towers (inner/outer)	9040
# modules	
8M	1091
4M	76
2M	2
1M	4
# read-out channels	7 x 9,040 = 63,280

activity	cost in FY23 k$		total cost in FY23 k$
	ORNL	BNL	
Support structure desgin & integration with pECal	75	0	75
Rail/slide design	0	50	50
test production of module	20	0	20
tooling design + function test	50	0	50
Total	145	50	195
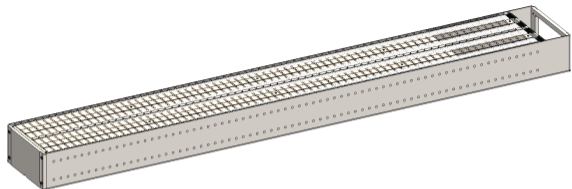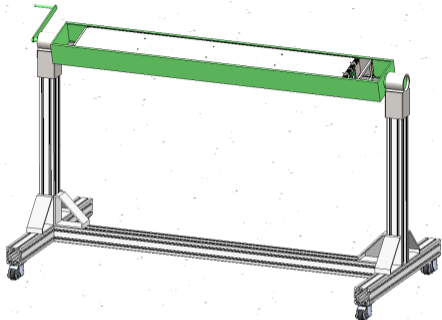
a) single tile assembly (fiber embedding, glueing, wrapping)
b) tile testing
c) assembly of module, alternating steel plate first kept in place by
   e-beam point welding then Scint-tile
d) fiber channels layed out on front on back
e) SiPM & read-out card installation
f) tower testing
g) close up module with cover plates
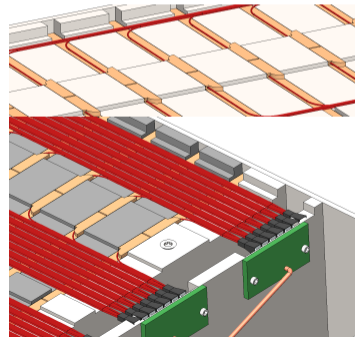
eRD107: Detailed cost table

| Institute	Item	Cost per item in $	Number of items	Total cost in $	To be compl. by
	Machined Scintillator Tiles:				Q1/2023
ORNL	BC-408 plastic scintillator sheet	~150	20	3K	
ORNL	BCF-91A WLS fiber	1500	1	1.5K	
ORNL	tile machining	180/h	40h	7.2K	Q4/2022
ORNL/UTK	tile assembly		40h	(in kind) 0K	Q4/2022
	Injection Molded Scintillator Tiles:				Q2/2023
FNAL	mold design + production	50 000	1	50K	Q4/2022
ORNL	travel			2K	
FNAL	raw material + dopant			(in kind) 0K	
FNAL	injection molder setup + operation	180/h	16h	2.9K	Q1/2023
ORNL/UTK	tile assembly		40h	(in kind) 0K	Q1/2023
	Automated Tile Assembly:				2024
ORNL	robotic arm	20 000	1	20K	
ORNL	robot programming and evaluation		40h	(in kind) 0K	Q3/2023
	Tile Characterization (Lab Bench):				Q3/2023
ORNL/UTK	scintillator material characterization		20h	(in kind) 0K	Q2/2023
ORNL	waveform sampling readout (8ch)	16000	1	16K	
GSU/Yale/UCR	tile lightyield testing		160h	(in kind) 0K	Q3/2023
ISU/BNL	tile simulation		160h	(in kind) 0K	Q3/2023
	Sensor Board:				Q1/2023
ORNL	mechanical engineer	180/h	15h	2.7K	
ORNL	sensors: silicon photomultipliers	30	300	9K	
ORNL	sensor board production, assembly	50	10	0.5K	Q1/2023
	Reconstruction Optimization:				2025
UTK/Yale/BNL	simulations/digitization/reconstruction/analysis		640h	(in kind) 0K	
	LFHCAL Mechanics:				Q3/2023
ORNL	mechanical engineer	180/h	105h	18.9K	
ORNL	absorber material + fasteners	40	70	2.8K	
UTK/Yale	absorber machining	100/h	20h	(in kind) 0K	Q2/2023
	Tile Characterization (Test Beam):				Q3/2023
ORNL	assembly and shipping			1K	
All	test beam travel			13K	
ORNL/UTK	test beam preparation		80h	(in kind) 0K	Q2/2023
ORNL	test beam		120h	(in kind) 0K	Q3/2023
Yale	test beam		120h	(in kind) 0K	Q3/2023
BNL	test beam		120h	(in kind) 0K	Q3/2023
UTK	test beam		120h	(in kind) 0K	Q3/2023
GSU	test beam		120h	(in kind) 0K	Q3/2023
ISU	test beam		120h	(in kind) 0K	Q3/2023
Valpo	test beam		120h	(in kind) 0K	Q3/2023
UCR	test beam		120h	(in kind) 0K	Q3/2023
Total				**150.5K**	
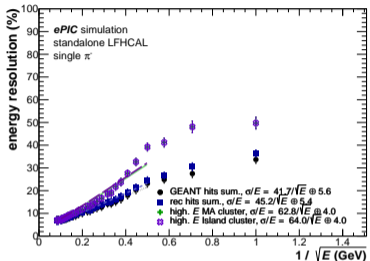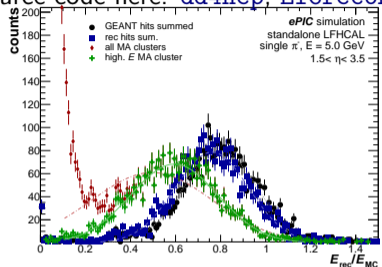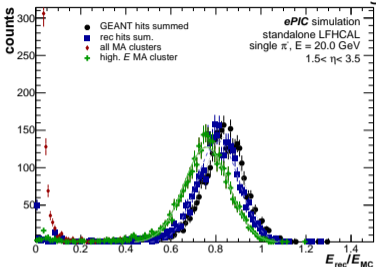
source code here: dd4hep, EICrecon

- Full implementation of hit chain (including basic noise simulation) & first version of clustering
- All simulations done with only HCal & single particle simulations
- Resolution calculated with time & energy cut offs
- Fitting restricted to > 4 GeV (as for CALICE data) resulting in more realistic $1/\sqrt{E}$- term
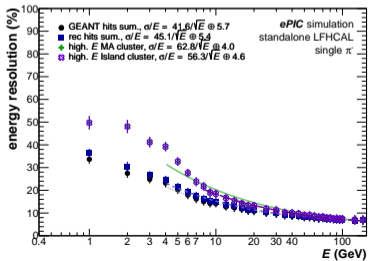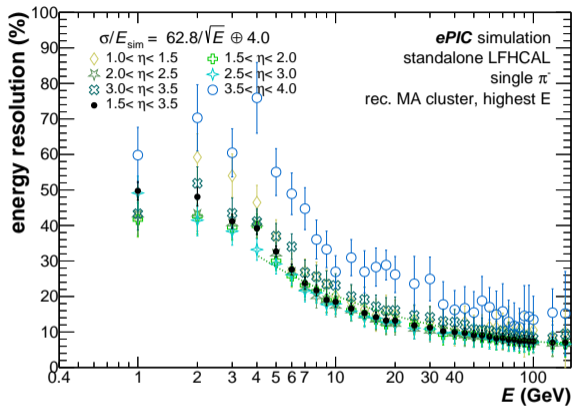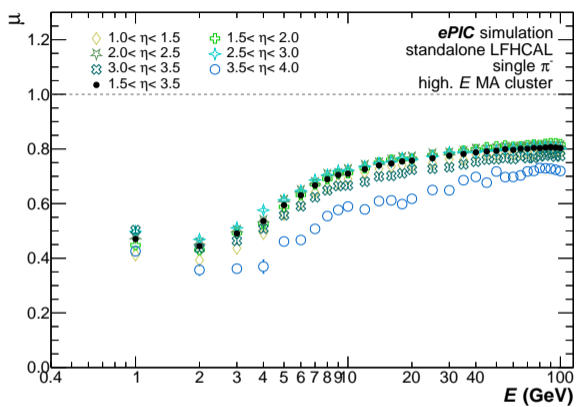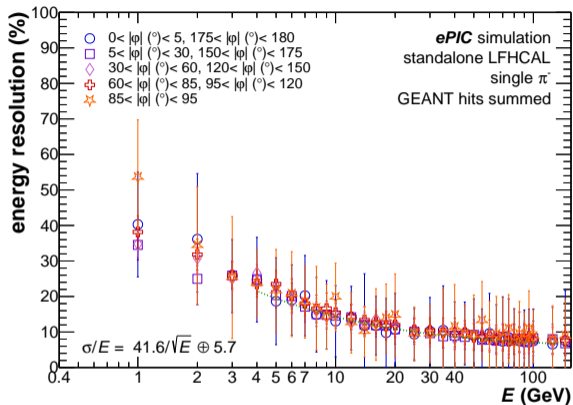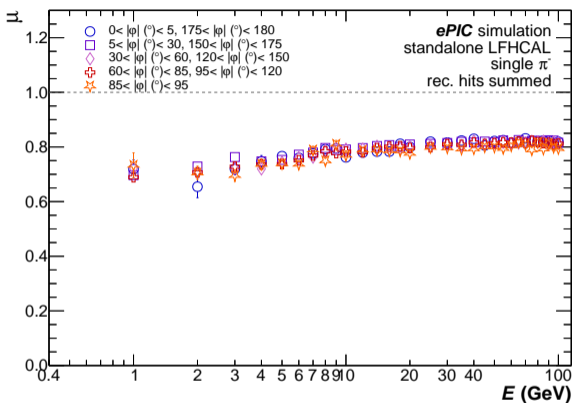
- Current implementation without insert
- Mild eta dependence $1.5 < \eta < 3.0$
- Small leakage seen for $1.0 < \eta < 1.5$ & $3.0 < \eta < 3.5$, significant losses beyond $\eta = 3.5$

- Current implementation without insert
- No phi dependence

gFHCal detector setup

source code here: `GFHCAL_geo.cpp`

Alternative forward HCal design with longitudinal instead of transverse absorbers and scintillators

- Longitudinal absorber plates 120cm steel and 10cm tungsten
  $\rightarrow$ 16.8mm thickness, average sampling fraction: $f = 0.027$
  $\rightarrow$ additional version with more layers: $f = 0.036$ (LFHCal $f = 0.033$)
- Longitudinal $0.4{\times}5{\times}10\text{cm}^3$ Scintillator tiles
- Removable Scintillator+pcb mini frames
  $\rightarrow$ 1mm PCB space in current simulation
- Detector made of $20{\times}10$cm and $30{\times}10$cm front face modules
  $\rightarrow$ violet and cyan colors in right figure, respectively
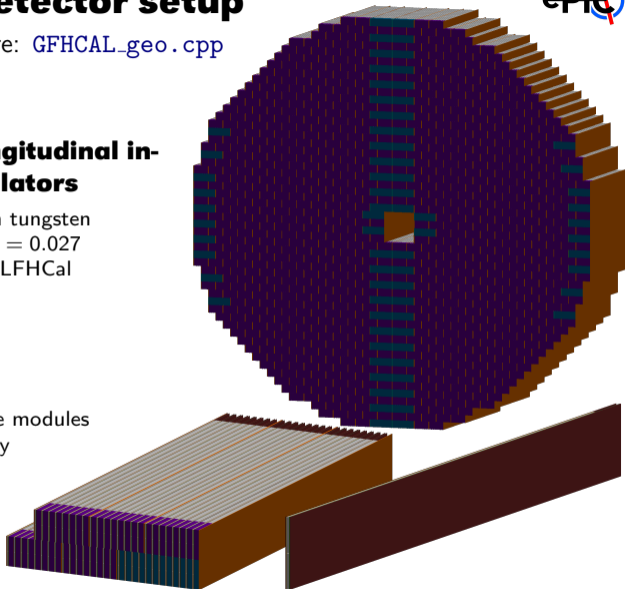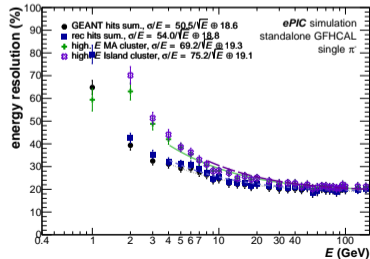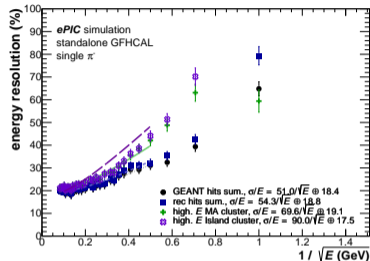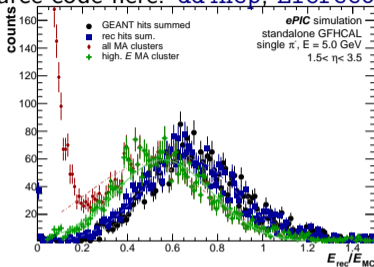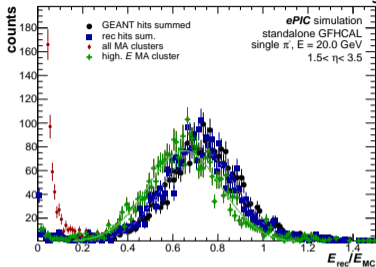
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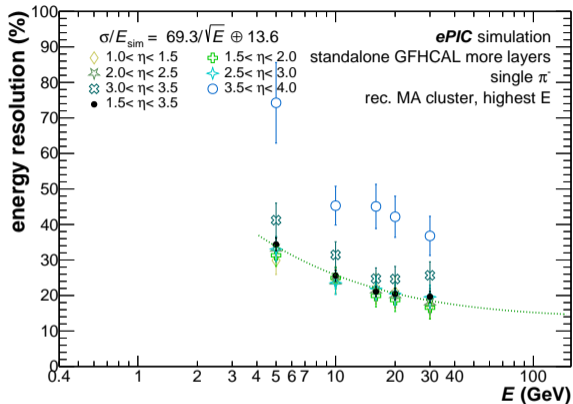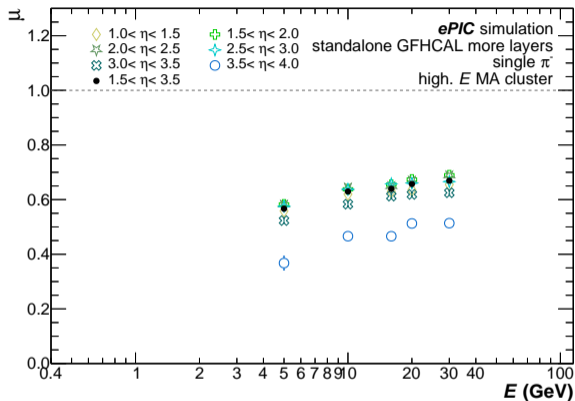- Significantly larger constant term than for LFHCal
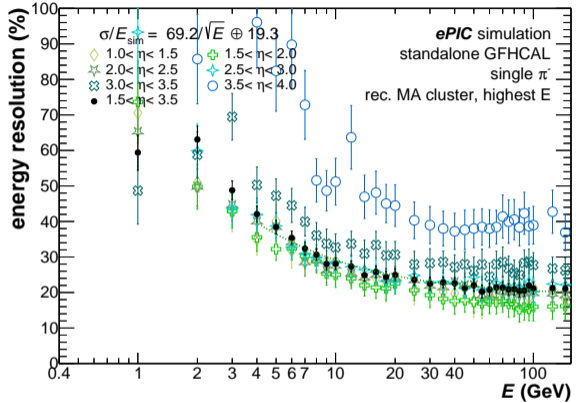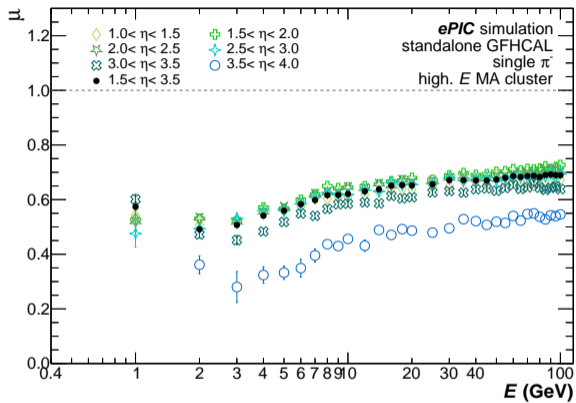
- Current implementation without insert
- Mild eta dependence $1.0 < \eta < 3.0$
- significant losses beyond $\eta = 3.0$, as expected
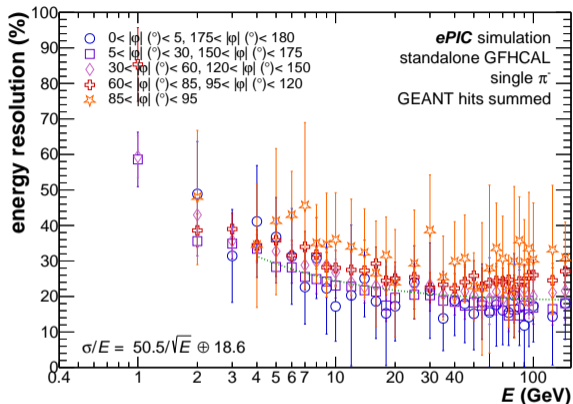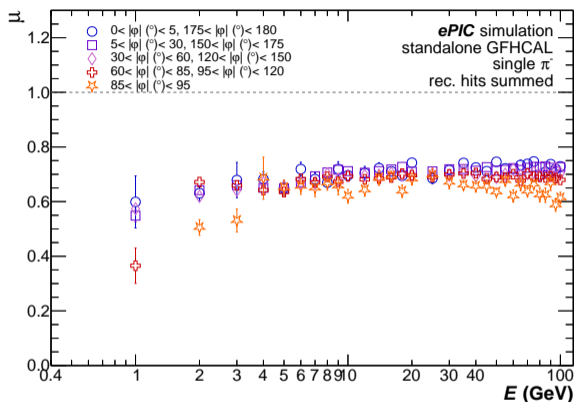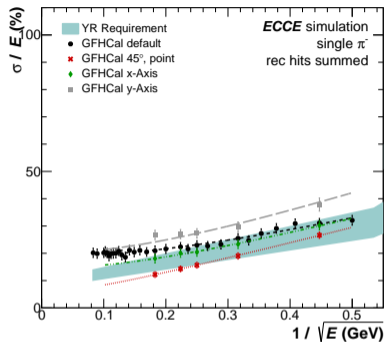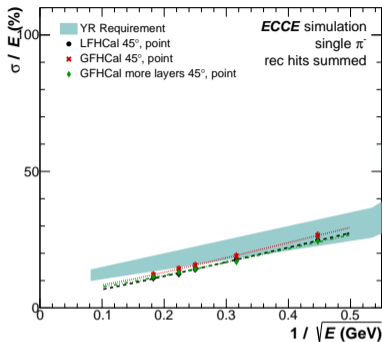
- Current implementation without insert
- Strong phi dependence, as expected (orange along y-axis, blue along x-axis)

- Current implementation without insert
- Mild eta dependence $1.0 < \eta < 3.0$
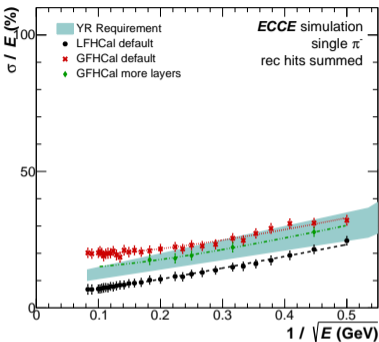- significant losses beyond $\eta = 3.0$, as expected
- Improved constant term compared to default setup

Undestanding the simulations (1)

- Left: Comparison of different detector setups full η/φ
- Middle: Comparison of different detector setups at 45∘ in center of detector
  very similar performance GFHCal more layers & LFHCal
- Right: Cmparison of default GFHCal in different regions
  Significant losses along y-axis (channeling) and even along the x-axis
  Particle hitting center of detector similar performance as LFHCal