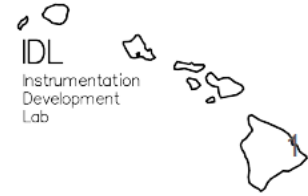


Hawaii Muon Beamline



Chris Ketter

Oskar Hartbrich

Ilknur Koseoglu

Alecander Paul

Richard Peschke

Harsh Purwar

Shivang Tripathi

Gary Varner

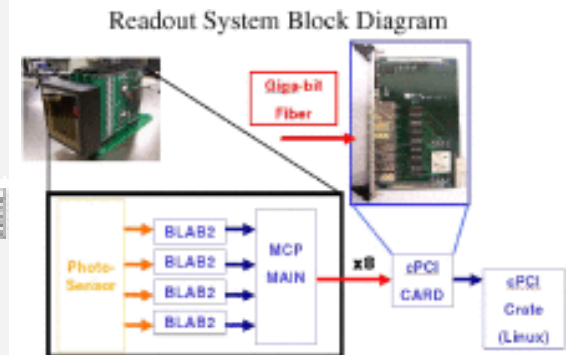
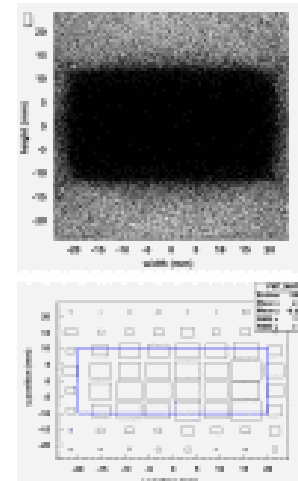
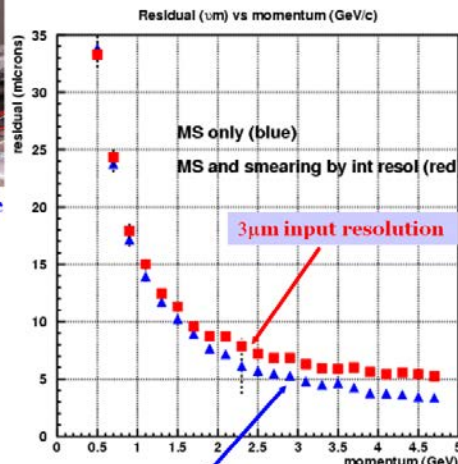
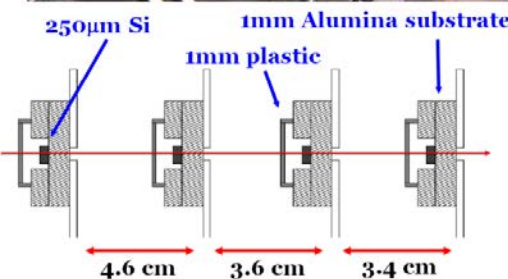
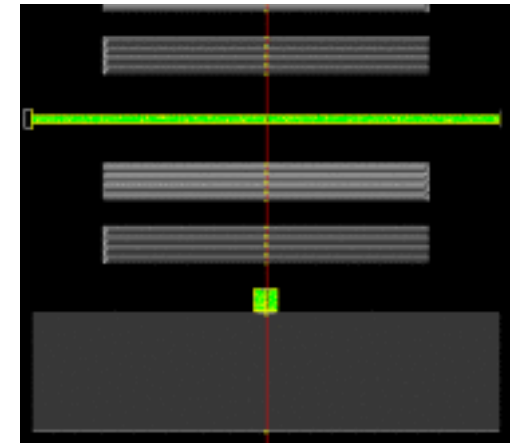
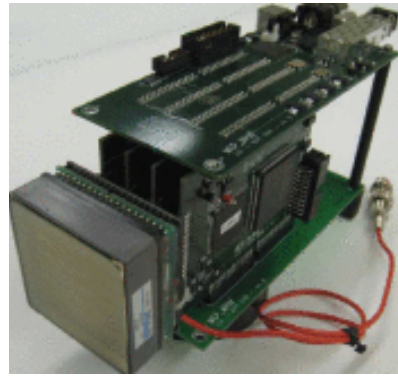
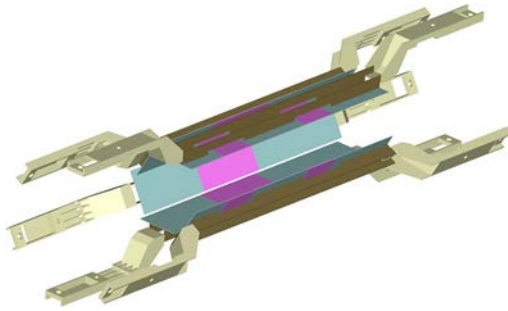
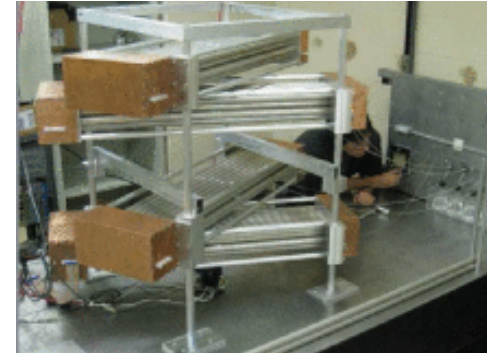
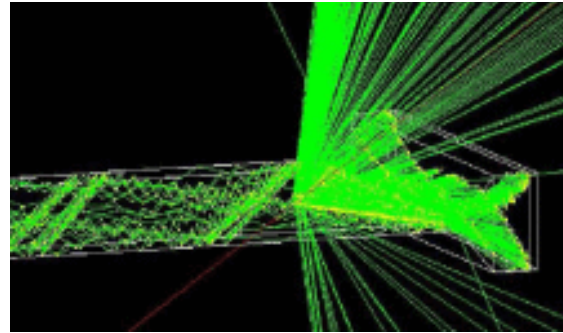
Salvador Ventura

Motivations:

- Number of beamlines world-wide limited (CF last FNAL run)
- Want to ensure everything working/tuned before travel
- Training platform

Hawaii Muon Beamline (HMB) v1

- **Version 1 (drift tubes)**
 - iTOP prototype development
 - Cluster counting
 - Fine-mesh PMTs + scint (T0)
 - **Poster on next slide**





The Hawaii Muon Beamline

A testbed for charged particle identification and vertexing devices

Instrument Development Laboratory

Department of Physics and Astronomy, University of Hawaii at Mānoa



Introduction

All detectors and electronics developed by the Hawaii Instrumentation Development Laboratory (ID Lab) ultimately require testing and validation before they can be deployed. For instrumentation related to the detection of charged particles, such testing has typically been performed using an appropriate beamline at an accelerator facility. However, this requires location of a suitable facility, availability of beam time, and mobilization of both the manpower and equipment to conduct the testing.

Upon its completion, the Hawaii Muon Beamline will allow a significant fraction of such testing to be conducted within the ID Lab. The beamline utilizes cosmic ray muons as a charged particle source, and is designed primarily for the testing of charged particle identification (PID) and vertexing systems.

Motivation

Particle Identification:

The ID Lab is participating in development of a particle identification device for application at Belle II [1]. Its primary function is to discriminate between charged pions and kaons in the momentum range of 2 GeV/c to 5 GeV/c.

At the Hawaii Muon Beamline, cosmic ray muons of varying momentum can be utilized to emulate pions or kaons. The relation between effective K/π momentum and incident cosmic ray muon momentum is shown in Figure 1. Muons in the momentum range of approximately 0.4 GeV/c to 4 GeV/c emulate the kaons and pions expected at Belle II.

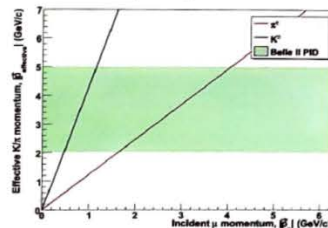


Figure 1. Effective momentum of a charged pion (red) or kaon (blue) for a given incident muon momentum. The shaded region indicates the desired range of K/π momentum coverage for the Belle II particle identification system.

For characterization of particle identification devices, the beamline must provide both tracking and momentum information for each incident muon.

Vertexing:

The beamline's tracking and momentum measurement systems also allow for characterization of vertexing devices, such as the ID Lab's Continuous Acquisition Pixel (CAP) sensor series [2].

Existing Muon Beamline Components

Construction of the beamline is partially completed. A photograph of existing components can be seen in Figure 2. Detailed descriptions of each component are given below, along with measured or simulated performance.

Drift tube array (Fig. 2a) – Primary muon tracking is performed using an array of 128 aluminum drift tubes, each 3' long. The tubes are separated into 4 superlayers of 32 tubes each. A single superlayer can provide 2D track reconstructions, but by rotating the first and third superlayer by 50° relative to the second and fourth, the full 3D track can be measured. While in operation, the central wire of each drift tube is held at a potential of 1.9 kV.

PID test device (Fig. 2b) – The region between the second and third drift tube superlayers is reserved for testing prototype PID devices. Currently, this region is occupied by a 2x4x120 cm³ quartz bar contained in a light tight enclosure. Incident muons emit Cerenkov light within the bar, some of which is totally internally reflected to the bar end, where it is detected by a Hamamatsu H8500 photomultiplier tube (PMT). Observed hit densities on the PMT anodes can be seen in Figure 3.

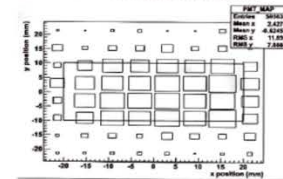


Figure 3. Observed hit densities on the 64 pads of the H8500 PMT. Each black box represents one anode, and the size of the box represents the number of hits observed, summed over many events. The blue region outlines the part of the PMT which is optically coupled to the quartz bar.

Precision timing module (Fig. 2c) – A set of four Hamamatsu fine mesh phototubes look into a small 6.35x6.35x6.35 cm³ lucite radiator just below the bottom superlayer of drift tubes. Coincidence of at least two of the fine mesh tubes is used to trigger the entire system, and defines the start time of any event.

Front end electronics (Fig. 2d) – The drift tubes, the PID prototype PMT, and the precision timing module are all read out by waveform digitizing electronics developed by the ID Lab. Currently, these utilize BLAB-series ASICs [3], but may be upgraded in the future. Sample BLAB2 waveforms are shown in Figure 4.

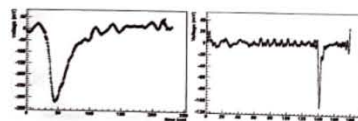


Figure 4. Sample BLAB2 signals observed from a drift tube (left) and the H8500 PMT (right).

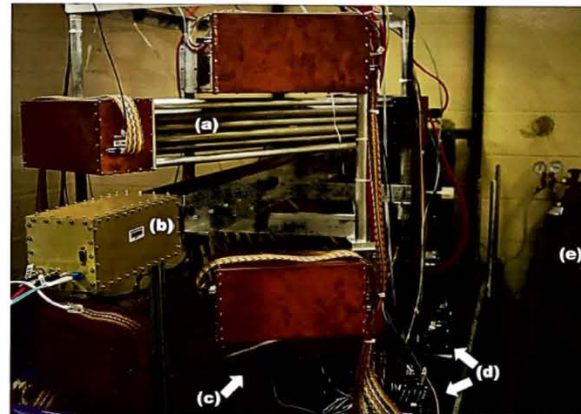


Figure 2. Photograph of the current muon beamline systems. Most components are mounted to the optical bench for ease of alignment.

Components Under Construction

Momentum spectrometer (Fig. 6a) – Two pairs of double sided silicon strip detectors (DSSD) are mounted above and below a permanent 0.5 T magnet. The simulated magnetic field profile is shown in Figure 7, and shows good uniformity over the 10 cm length of the DSSDs. Momentum of incident muons can be calculated using DSSD measurements of the track deflection due to the magnetic field.

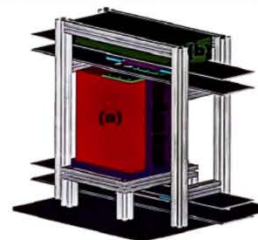


Figure 6. (Top left) CAD rendering of the momentum spectrometer assembly. The red box is the 0.5 T magnet. Above and below the magnet are pairs of DSSDs. The green box above the upper DSSDs is an area for testing prototype vertexing devices.

Figure 7. (Bottom left) Simulated magnetic field profile for the magnet shown in Figure 6a.

Prototype vertexing device (Fig. 6b) – The region above the upper two DSSDs is reserved for prototype vertexing devices, such as a pixel detector. Measurements of such a device can be compared to those of the DSSDs to evaluate its performance.

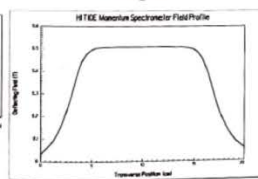


Figure 8. (Left) Projections of a reconstructed muon path through the two pairs of superlayers. Red circles indicate a tube with a measured hit. Blue circles represent the expected distance of closest approach in tubes through which the track passes. (Right) Measurement of muon impact parameter residuals after optimization of the drift time relation. The line is fit to a Gaussian with a width of approximately 2.5 microns.

Gas system (Fig. 2e)

A mixture of 90% Ar, 10% CO₂ is passed through the drift tubes during operation. During design and development, the GARFIELD/MAGBOLTZ software [4] was used to simulate the drift time properties of the gas mixture, though the final relation is determined from data, as shown in Figure 5.

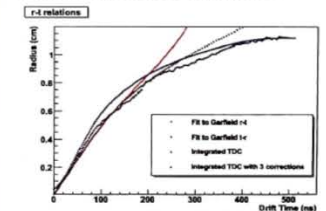


Figure 5. Relationships between the radius of closest approach of the muon track to the drift tube wire and the time of first signal on the drift tube. The brown and red points indicate fits to the simulated results. Light blue indicates a first estimate based on the timing signals seen in the drift tubes. This is further refined using an iterative correction procedure. The points in dark blue indicate the results after 3 iterations.

Preliminary Performance & Outlook

Existing system performance has been studied with cosmic ray runs. After iteratively correcting the drift time relations (see Figure 5), we find that our resolution for drift tube impact parameters is approximately 2.5 μ m. This result, and a sample fitted track is shown in Figure 8. Calibrations are ongoing, and the system is expected to be fully operational by summer 2010.

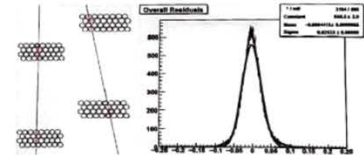


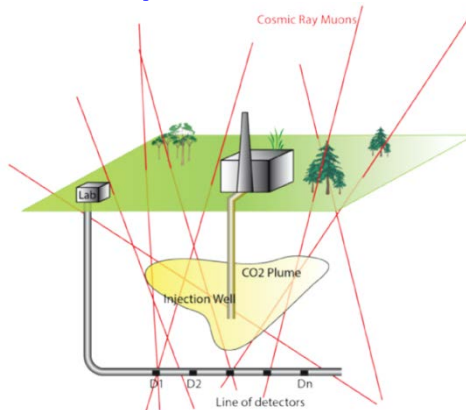
Figure 8. (Left) Projections of a reconstructed muon path through the two pairs of superlayers. Red circles indicate a tube with a measured hit. Blue circles represent the expected distance of closest approach in tubes through which the track passes. (Right) Measurement of muon impact parameter residuals after optimization of the drift time relation. The line is fit to a Gaussian with a width of approximately 2.5 microns.

Figure 9. (Left) CAD rendering of the momentum spectrometer assembly. The red box is the 0.5 T magnet. Above and below the magnet are pairs of DSSDs. The green box above the upper DSS

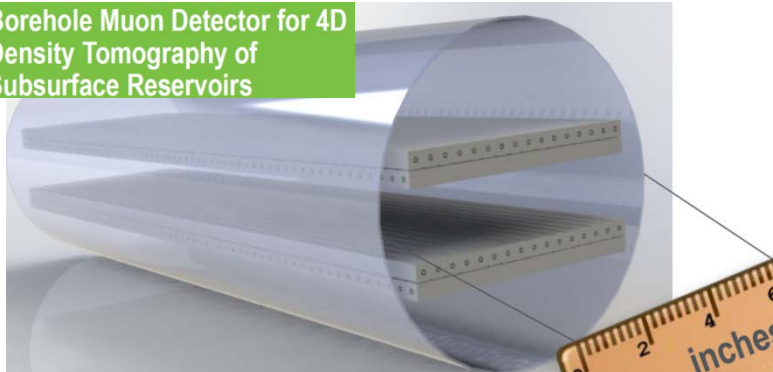
Hawaii Muon Beamline (HMB) v2

- **Version 2 (BMD trackers)**

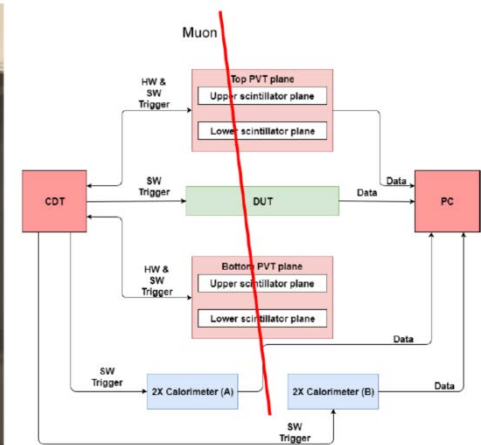
- Borehole Muon Detector
- Khahn and James thesis
- DOE (administration change)



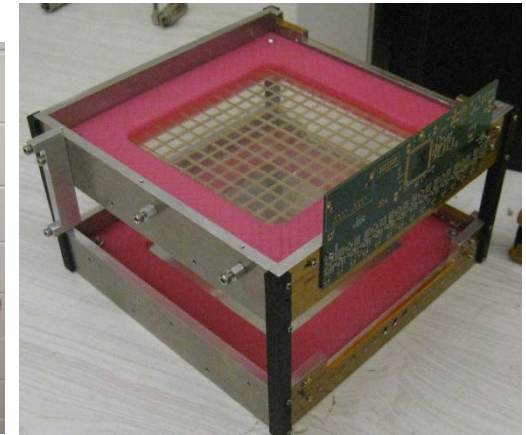
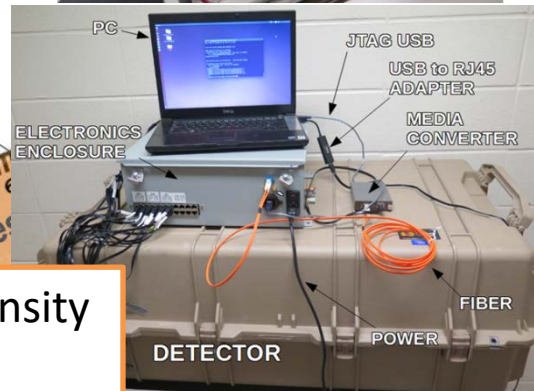
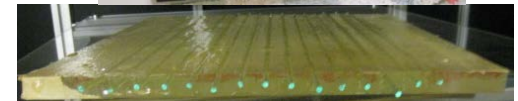
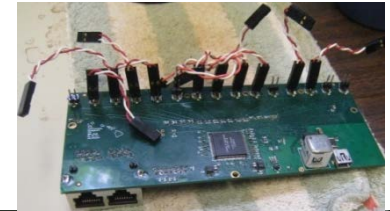
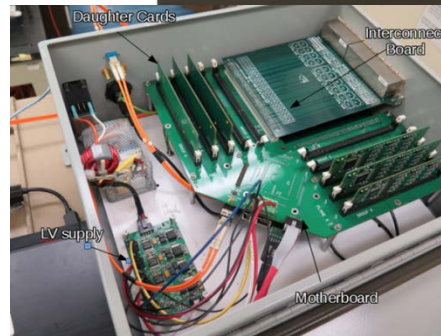
Borehole Muon Detector for 4D Density Tomography of Subsurface Reservoirs



A novel muon detector for borehole density tomography, NIM **A851** p. 108 (2017)



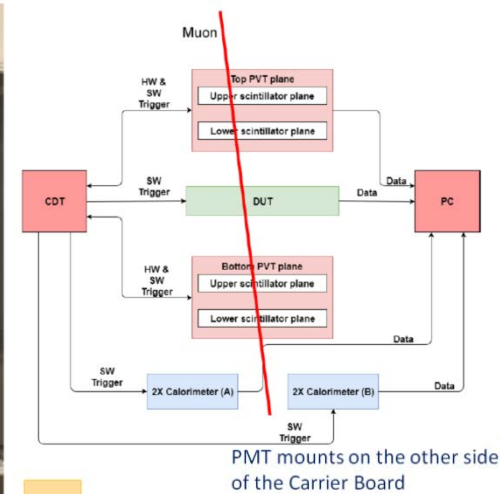
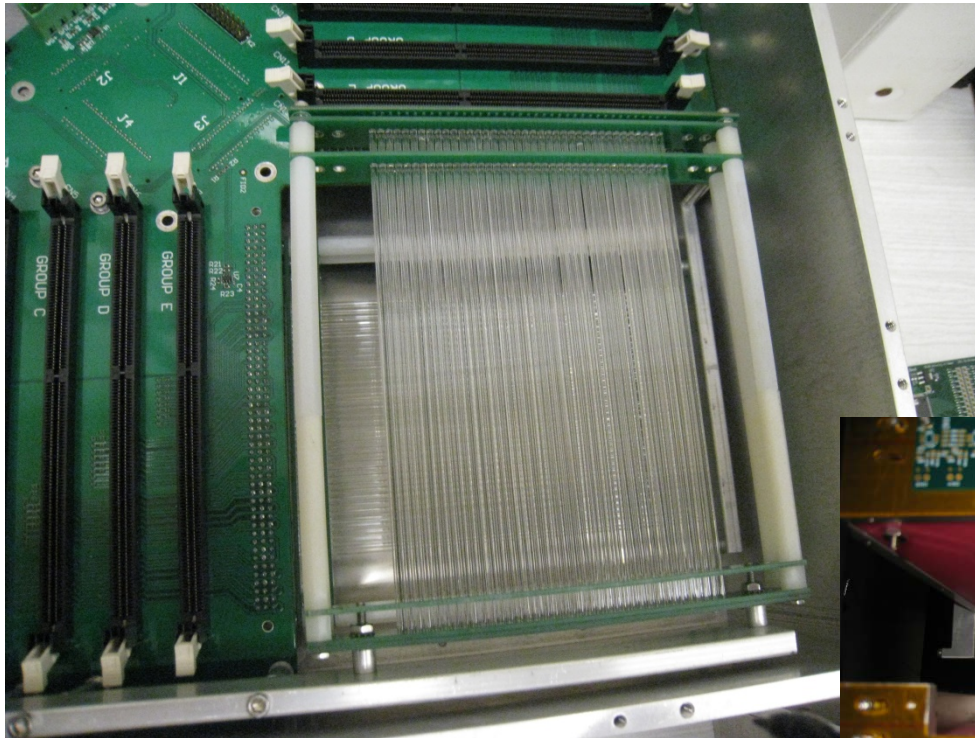
v2 never finished



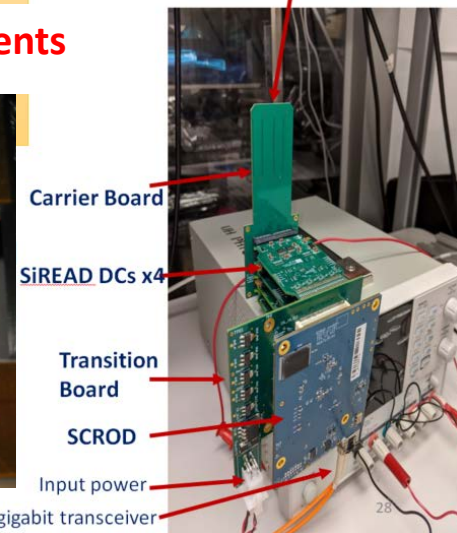
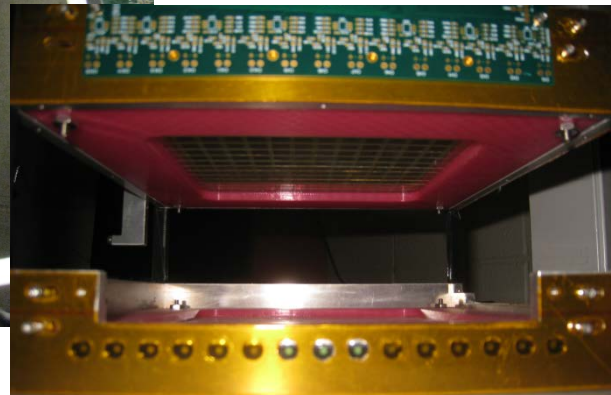
Hawaii Muon Beamline (HMB) v3

- **Version 3 (scint planes)**

- **EIC PID readout (Shivang)**



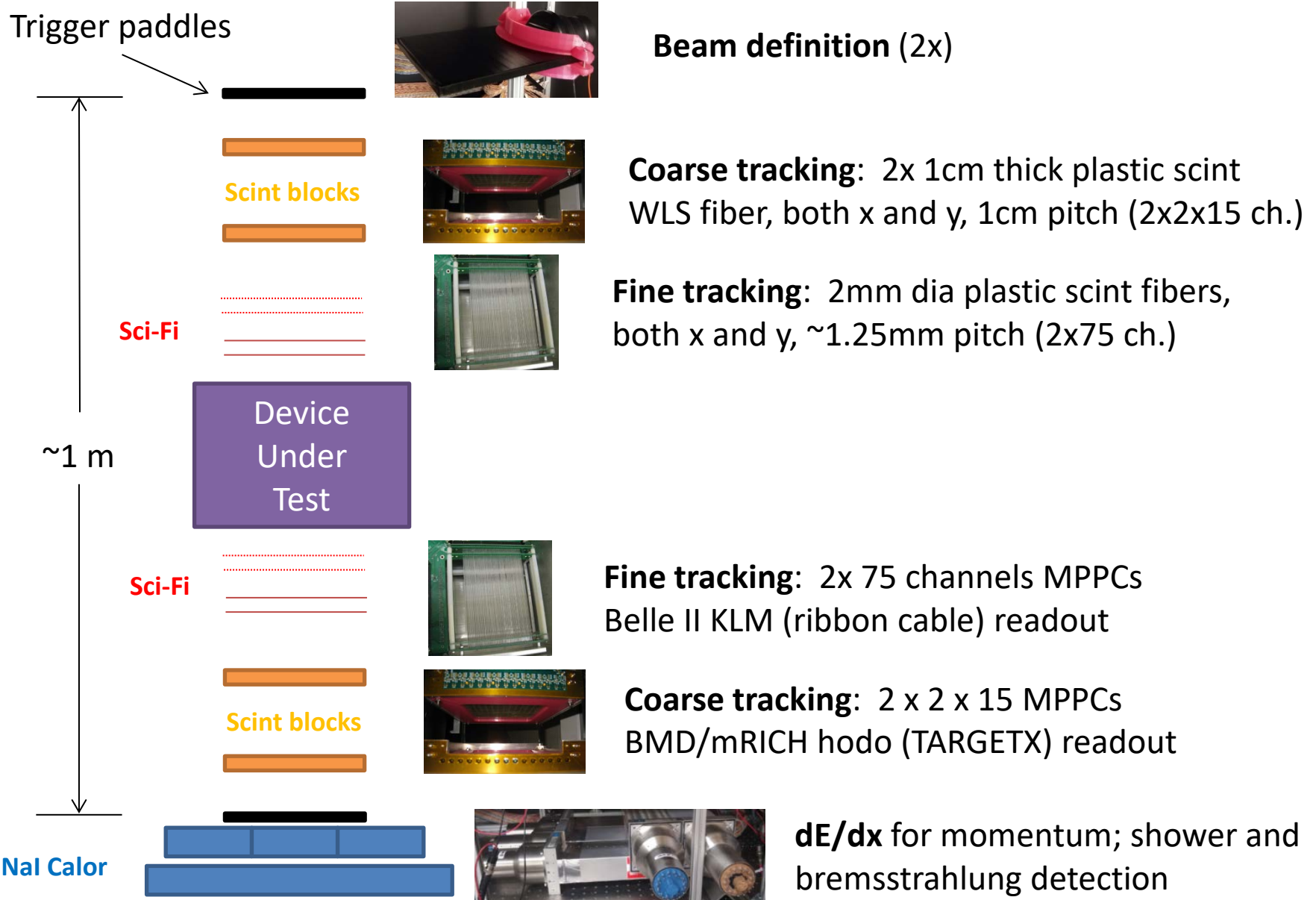
- **Alignment requirements**



- **Training platform**

- Mechanical Design (SolidEdge), Simulation (GEANT4), Pynq (Xilinx/Zynq) python + PL Firmware (Vivado) for DAQ, I/F board (Altium/Allegro), data acquisition (Jupyter notebooks), display (matplotlib), analysis (root)

General Configuration

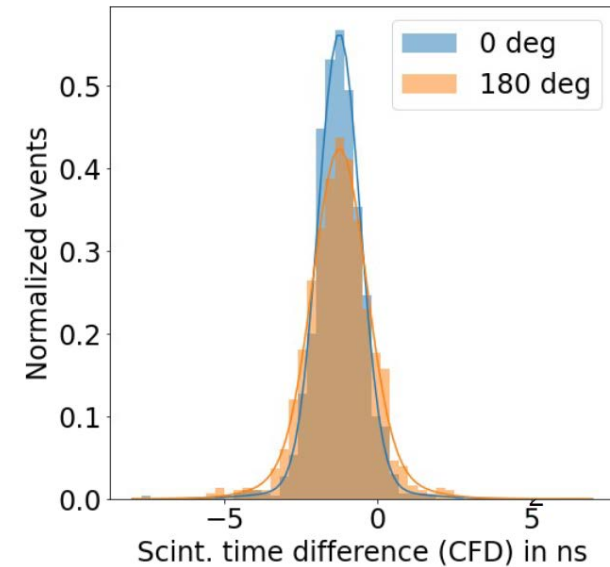


Beam definition counters

Note:

Oskar Hartbrich

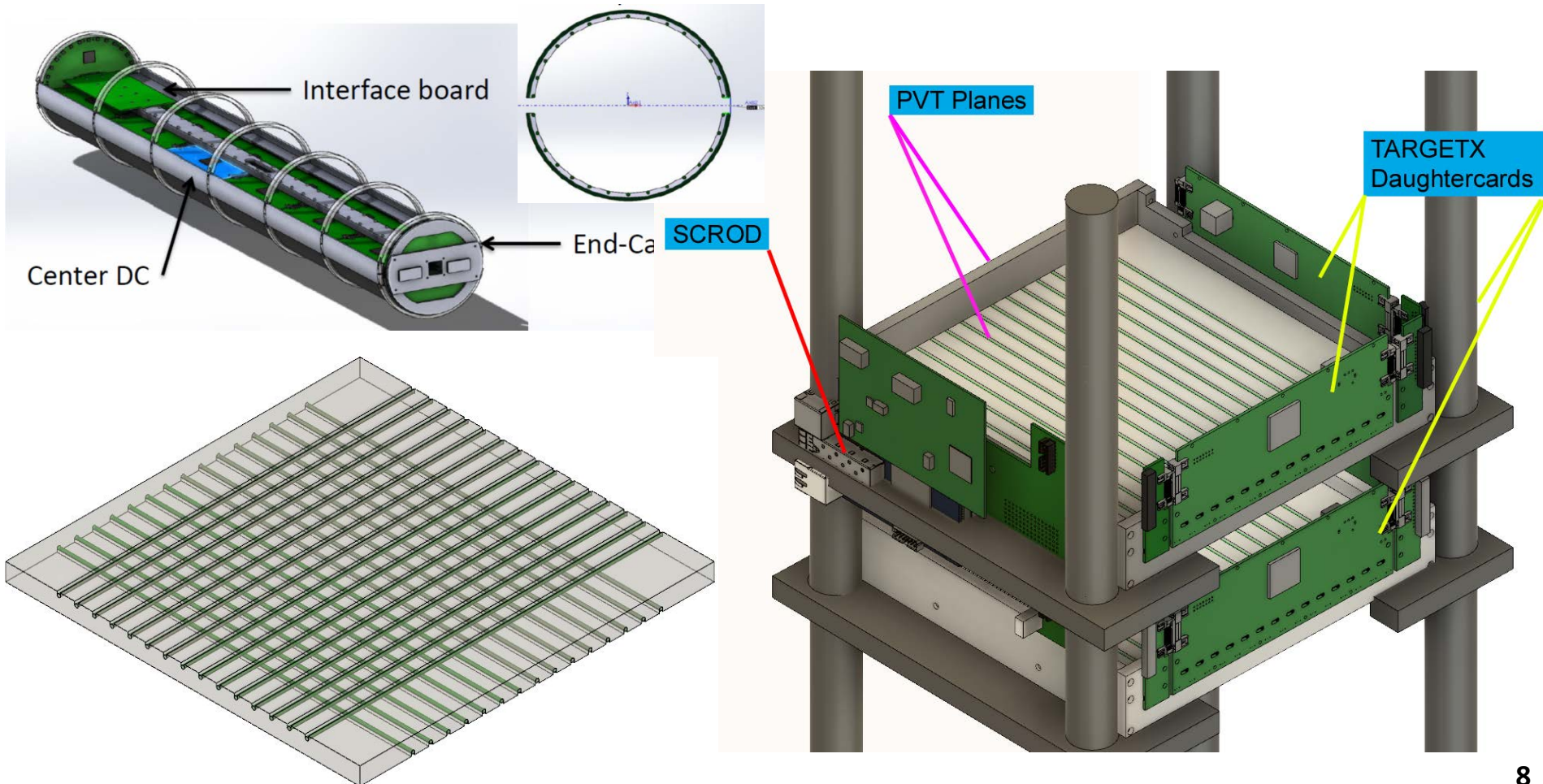
- Re-use Belle Time of Flight fine-mesh PMTs
- Newly fabricated



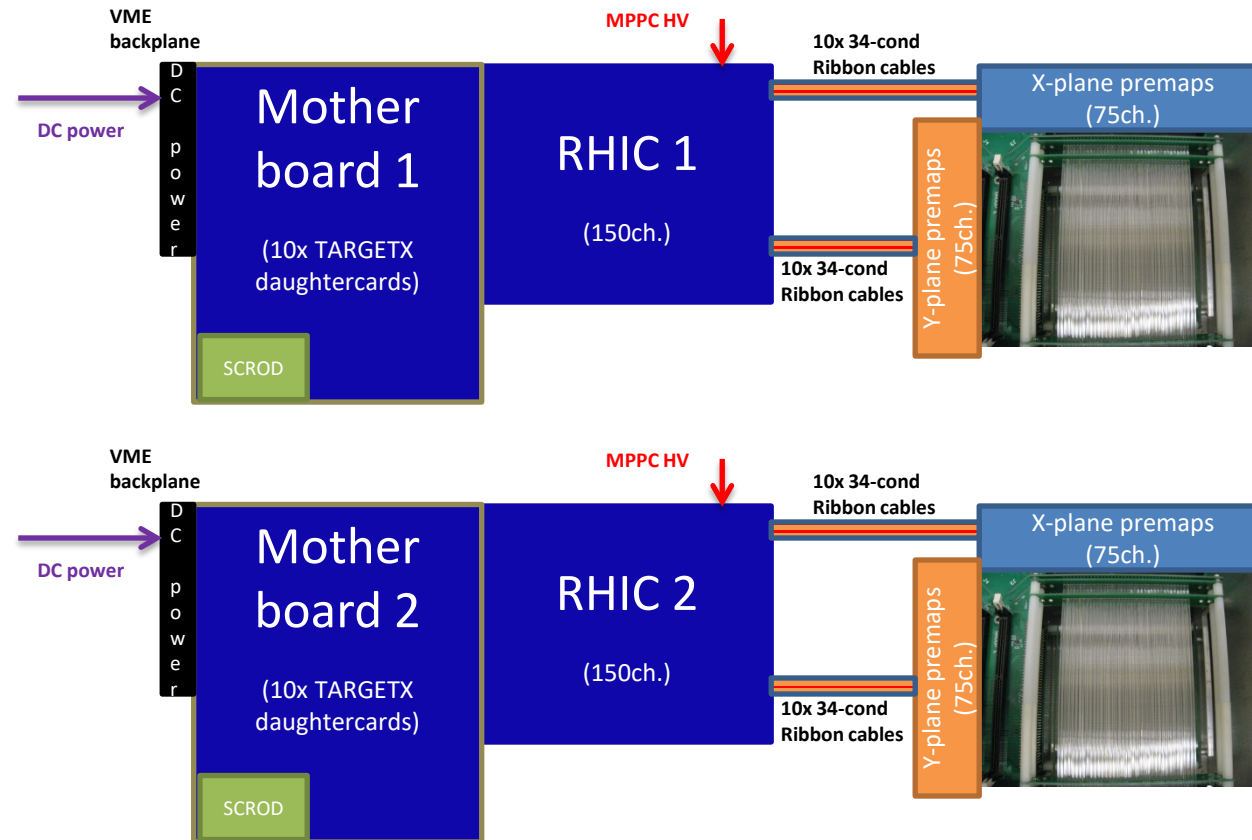
Scint block trackers

Notes:

- Originally prototype for Borehole Muon Detector
- Explore gradiometry in position reconstruction



Scintillating Fiber (Sci-Fi) Trackers



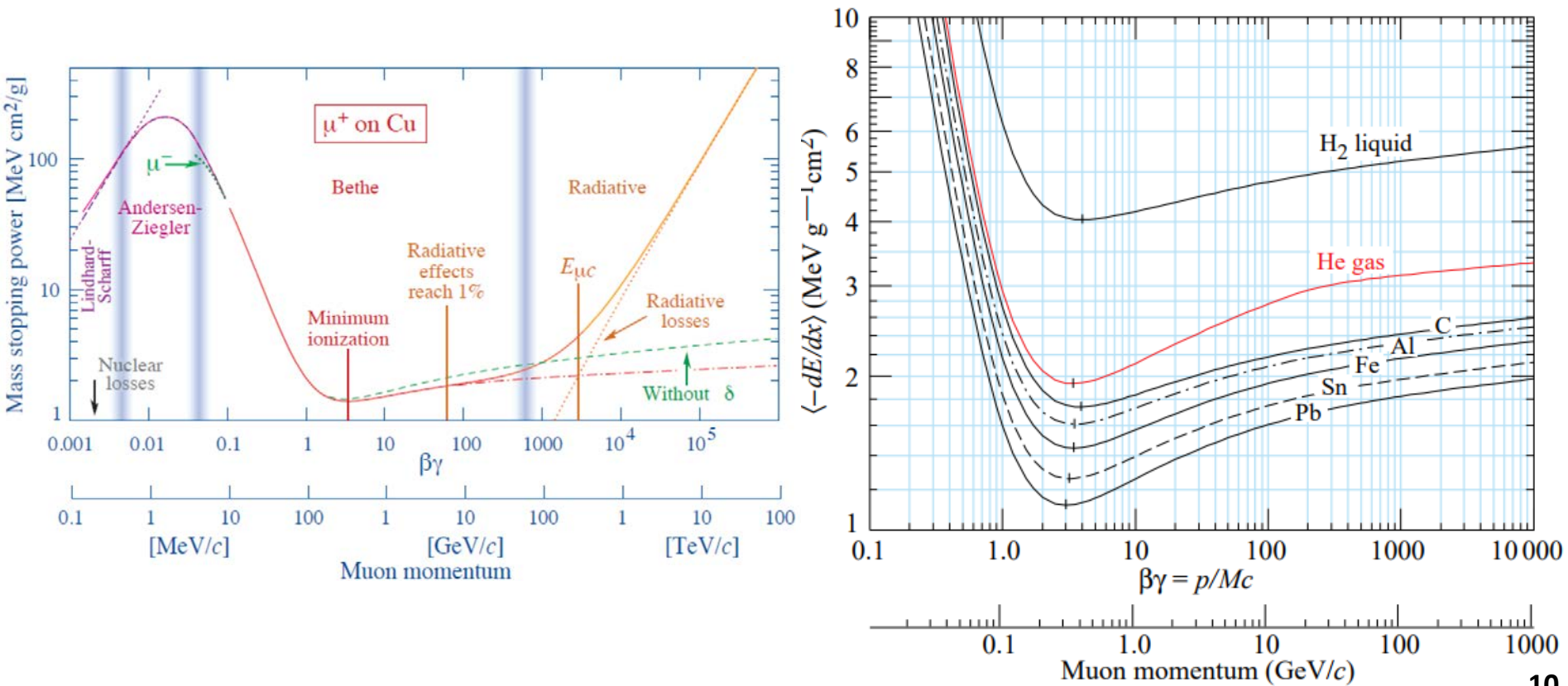
Notes:

- Basically a scaled down version of Belle II KLM
- 4cm x 1cm strips → fibers
- Cables! (Chris Ketter)

Calorimeter

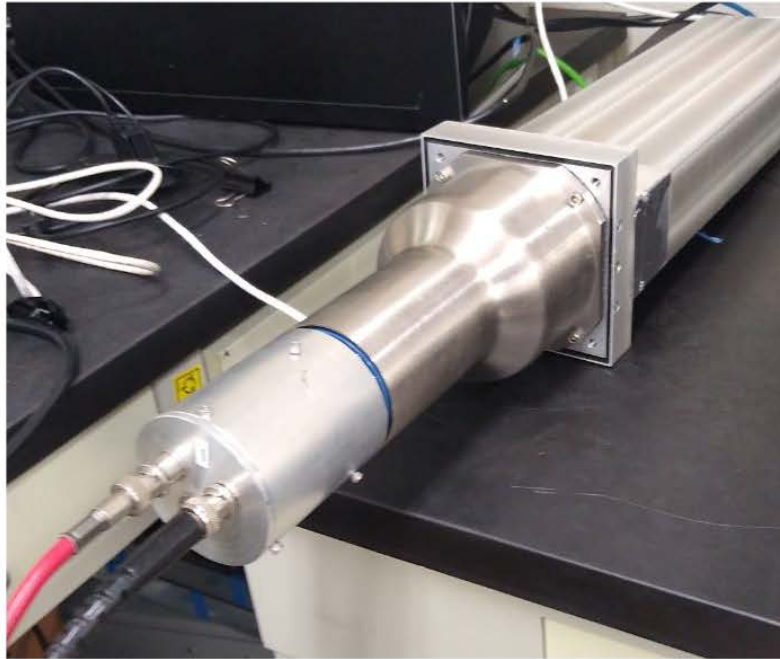
Note:

- Limited space for a magnet (see upgrade slide later)
- Use dE/dx to reject low-p muons, relativistic rise for high-p tag
- Useful to have shower and bremsstrahlung detection



Calorimeter (1 of 6)

- HV = 1000 V



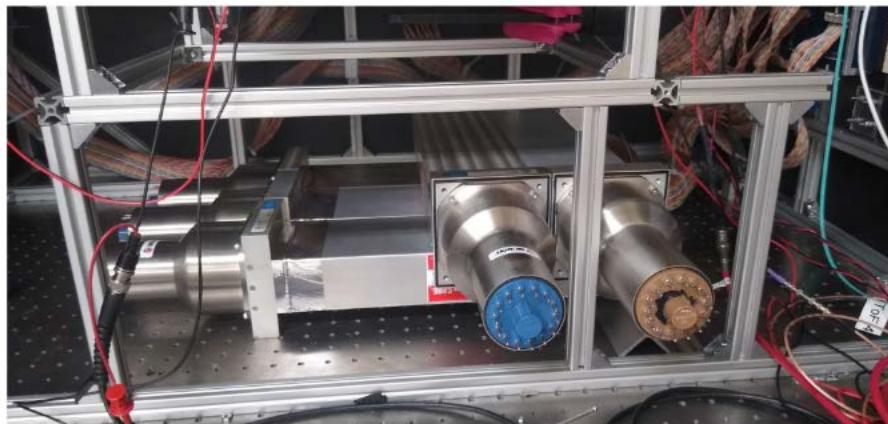
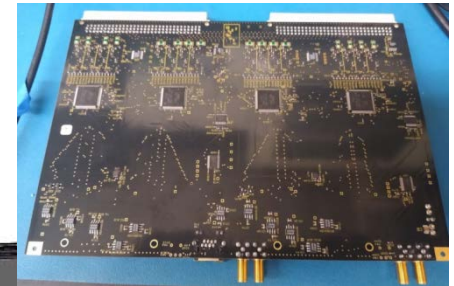
St. Gobain s600-8565 NaI counters

Scintillator	Light yield (photons/keV)	Light output (%) of NaI(Tl) bialkali pmt	Temperature coefficient of light output (%/°C) 25°C to 50°C	1/e Decay time (ns) (10-3μs)	Wavelength of maximum emission γm (nm)	Refractive index at γm	Thickness to stop 50% of 662 keV photons (cm)	Thermal expansion (°/C) x 10 ⁻⁶	Cleavage plane	Hardness (Mho)	Density g/cm ³	Hygroscopic	Comments
NaI(Tl)	38	100	-0.3	250	415	1.85	2.5	47.4	<100>	2	3.67	yes	General purpose, good energy resolution

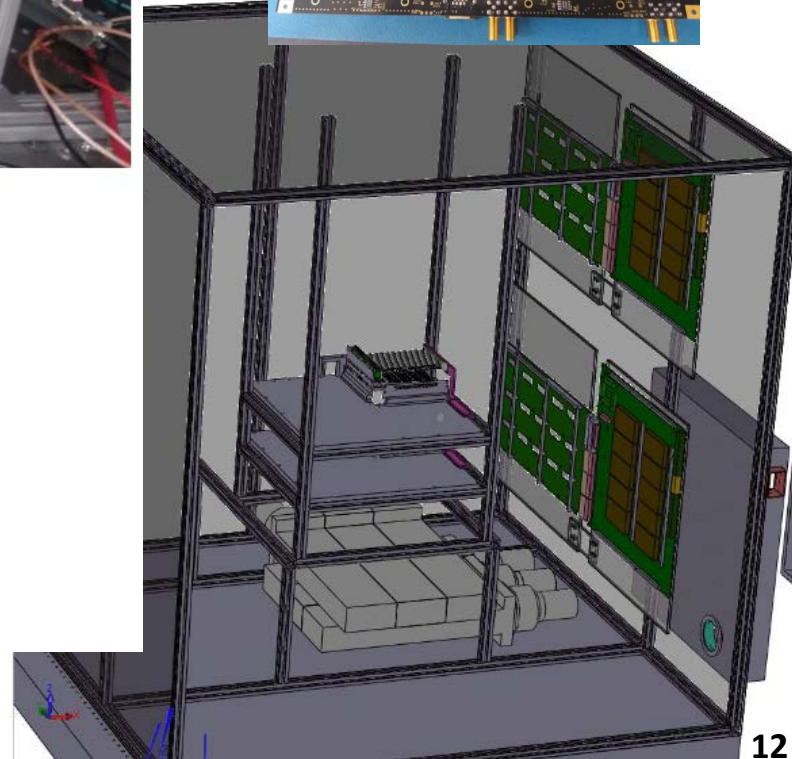
Calorimeter Configuration

- **Nal Calorimeter**

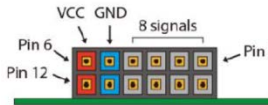
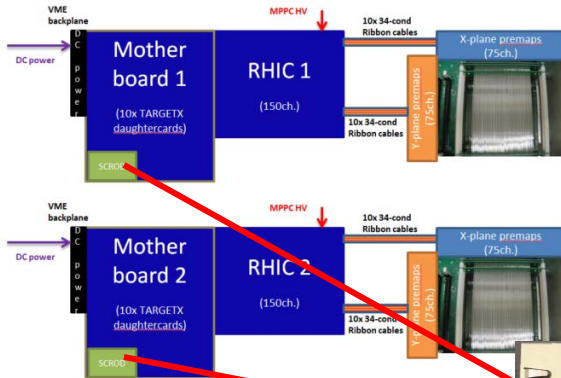
- 6U VME board (WATCHMAN)



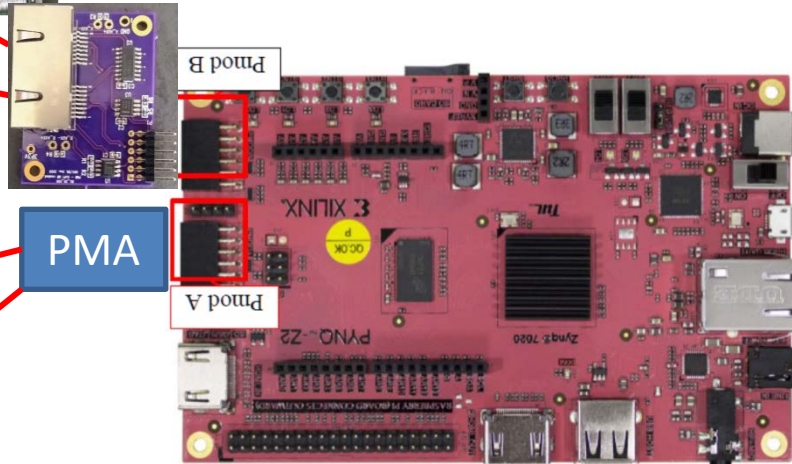
Salvador Ventura



Trigger Overview

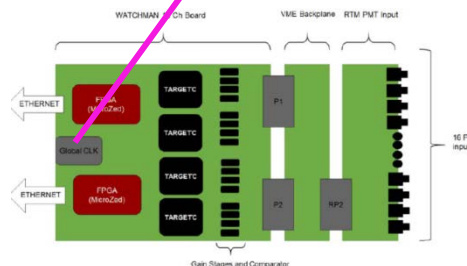


EUDAQ machine



PMA

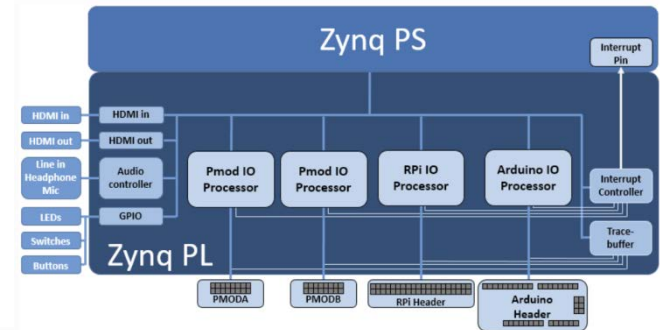
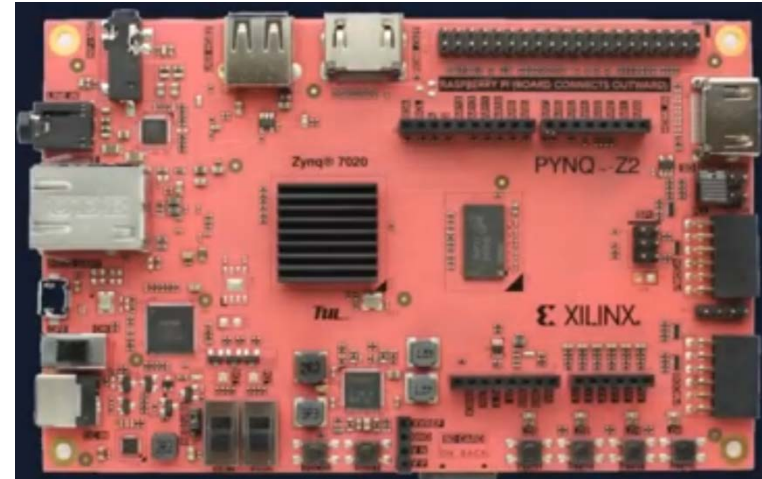
Trigger/
Precision timing
card (TX, LAB4D)



Python productivity for Zynq (Pynq)

- **Pynq architecture**

- Python Zynq (PYNQ) Jupyter Notebook
- Other languages/kernels available
- Hardware (PL) overlays
- SD card for filesystem, DDR3 RAM
- Proper (Arm-9 dual-core), with hardware assist
- HDMI in/out (object recognition)
- Hardware computation assist (DSPs)



192.168.153.217:9090/tree?

jupyter

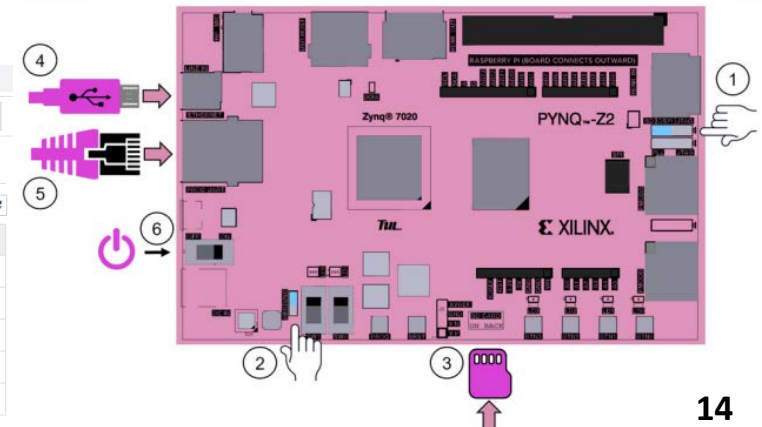
Logout

Files Running Clusters Nbextensions

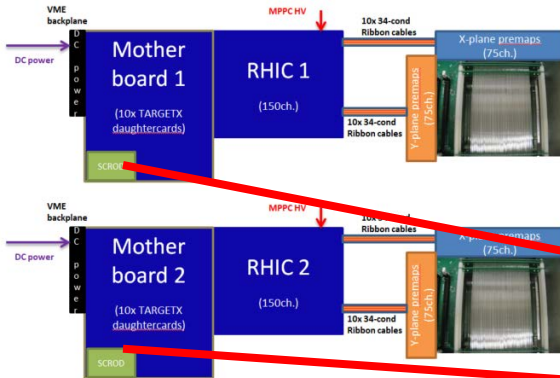
Select items to perform actions on them.

Upload New

	Name	Last Modified
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☐	common	10 months ago
☐	getting_started	10 months ago
☐	logictools	10 months ago
☐	Welcome to Pynq.ipynb	10 months ago

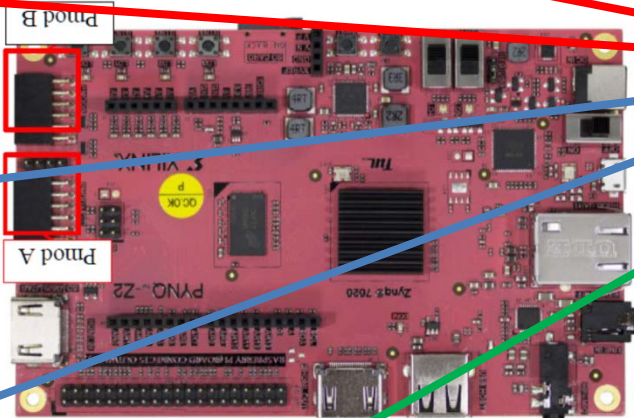


Data Collection Overview



4 SCROD Rev A5 SFP links
1 MicroZed ethernet
1 Zynq ARM ethernet

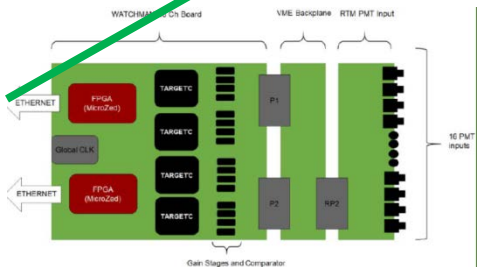
EUDAQ machine



Trigger/
Precision timing
card (TX, LAB4D)

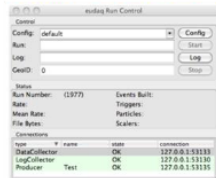
• To be Added

- Pynq (can be done “now”)
- Calorimeter ZedBoard
- Other SCRODs (tracking planes and EIC PID RO)



EUDAQ

Run Control

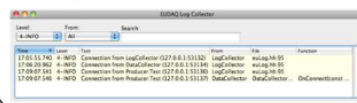


Graphical User interface

Command sender

Status logger

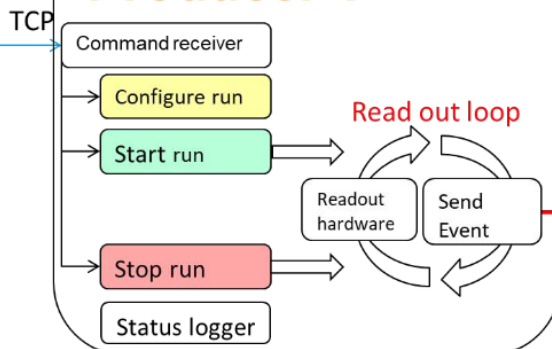
Log Collector



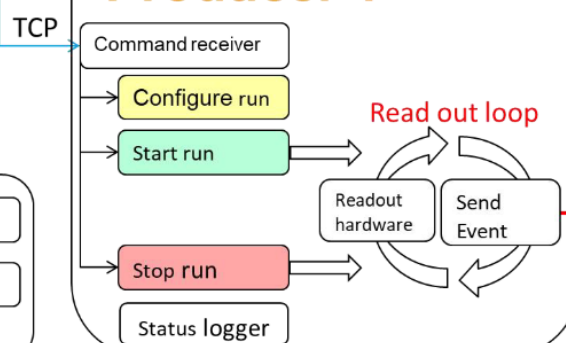
Log receiver

Visualize in GUI

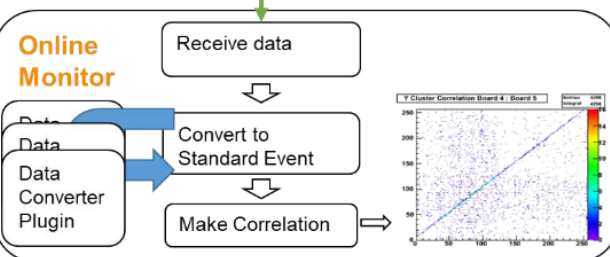
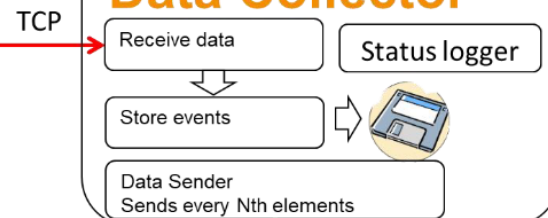
Producer 1



Producer 1

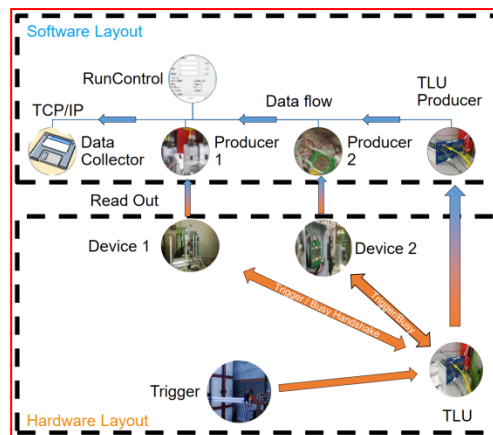


Data Collector

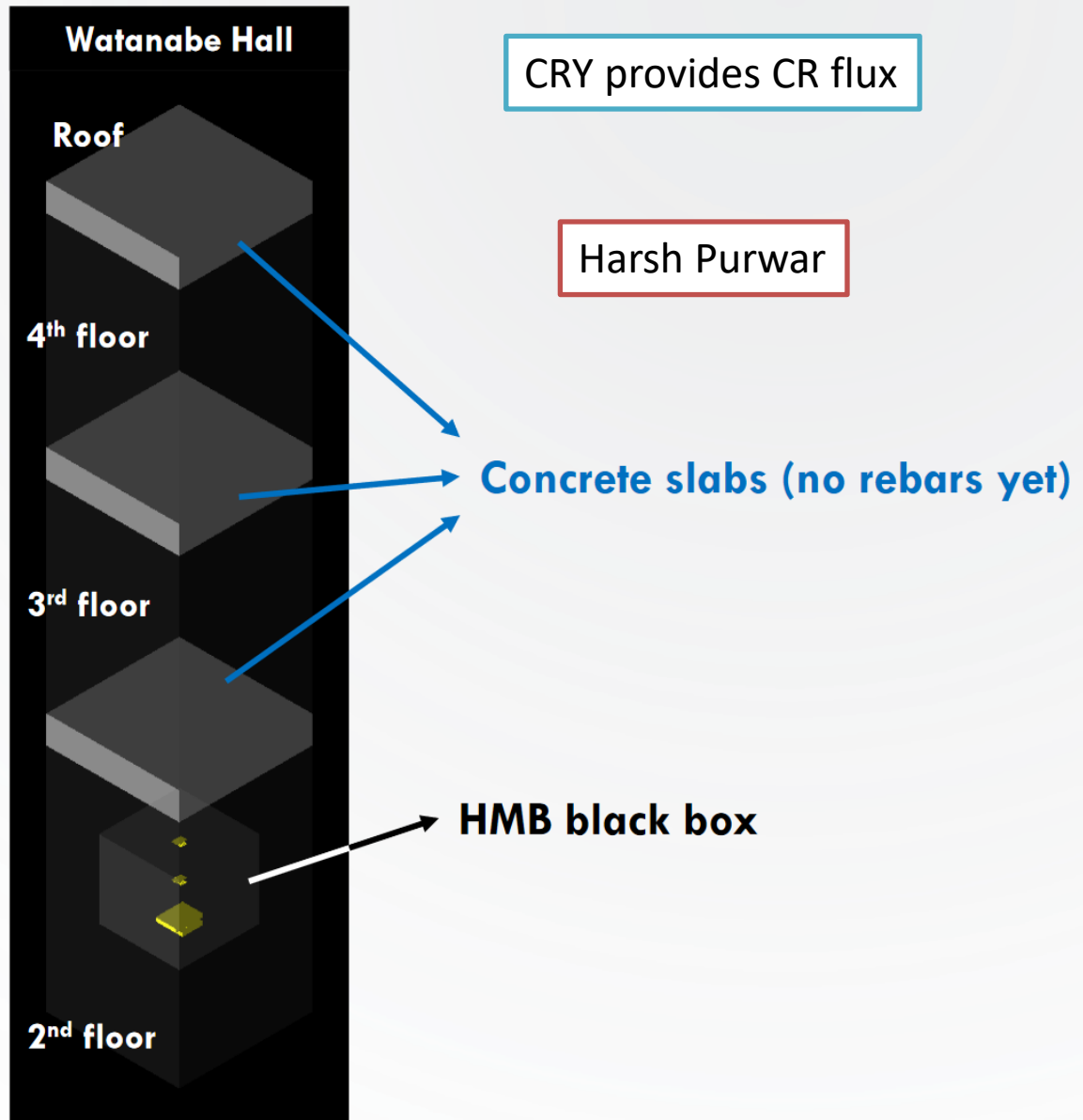


EUDAQ2 – A Flexible Data Acquisition Software Framework for Common Test Beams

Y. Liu^{a,1} M. S. Amjad^b P. Baesso^c D. Cussans^c J. Dreyling-Eschweiler^a R. Ete^a I. Gregor^a
 L. Huth^a A. Irls^d H. Jansen^a K. Krueger^a J. Kvasnicka^{e,a} **R. Peschke^{a,j}** E. Rossi^a
 A. Rummler^g F. Sefkow^a M. Stanitzki^a M. Wing^{b,a} M. Wu^a



GEANT4+CRY simulation



Color codes:

μ^+ : blue

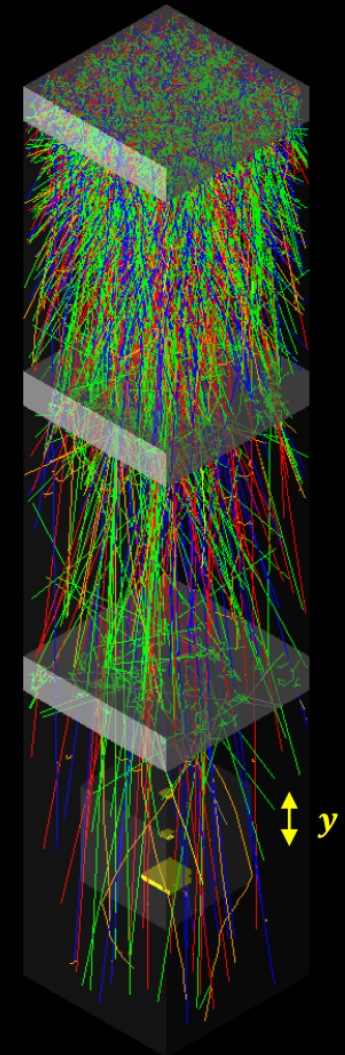
μ^- : red

γ : green

e^+ : yellow

e^- : orange

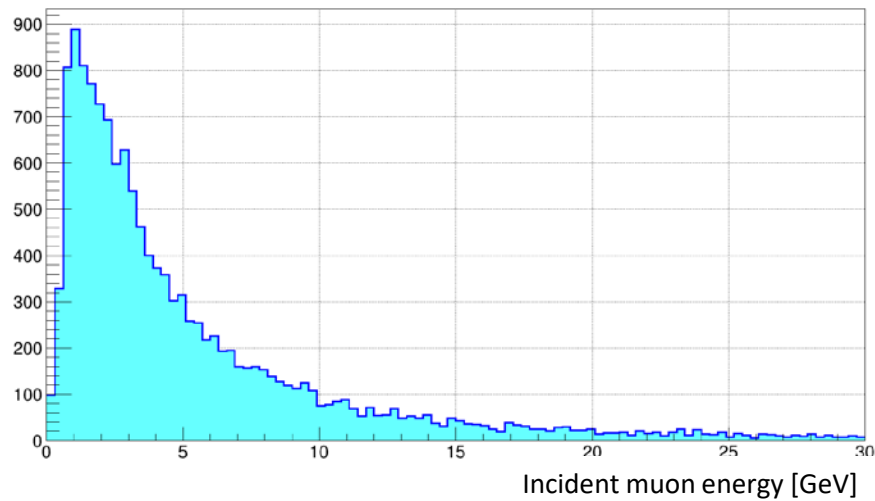
Others: grey



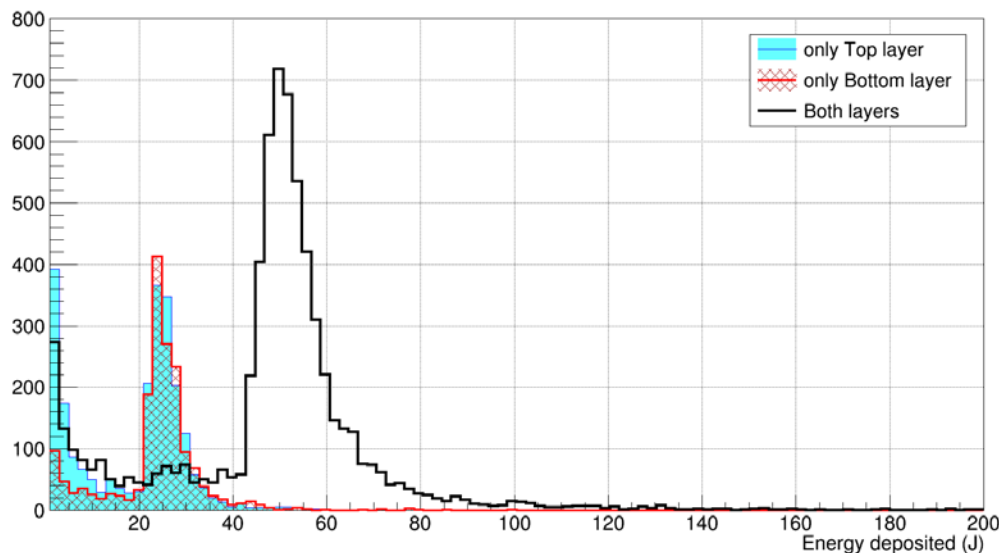
GEANT4+CRY simulation

- Avg. Muon incident rate: 2175 hits per hour (~ 36 hits/min on NaI slab)

Muon energy spectrum

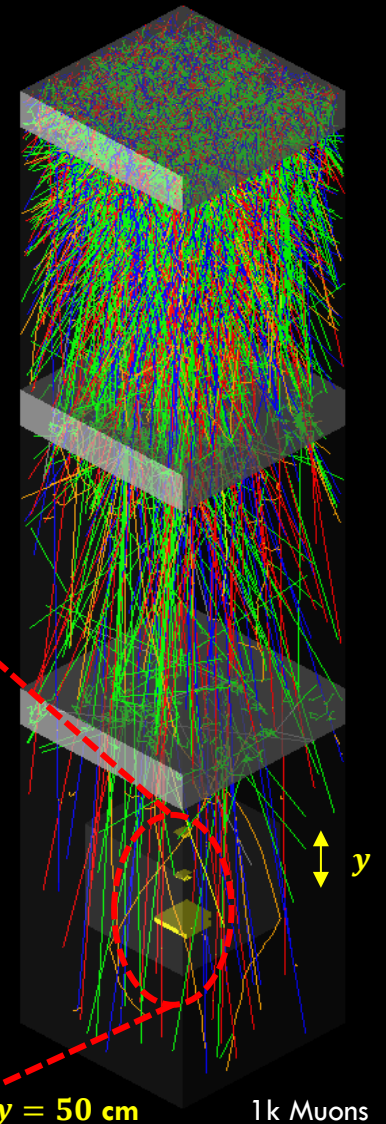
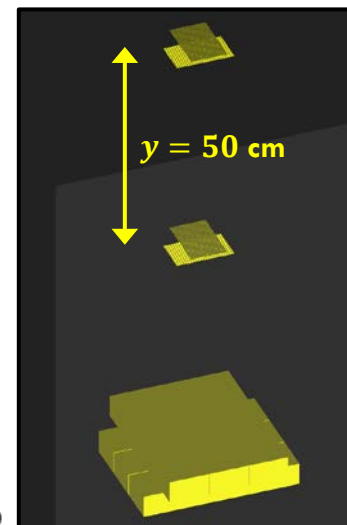


Total energy deposited on HMB calorimeter



Color codes:

μ^+ : blue
 μ^- : red
 γ : green
 e^+ : yellow
 e^- : orange
Others: grey



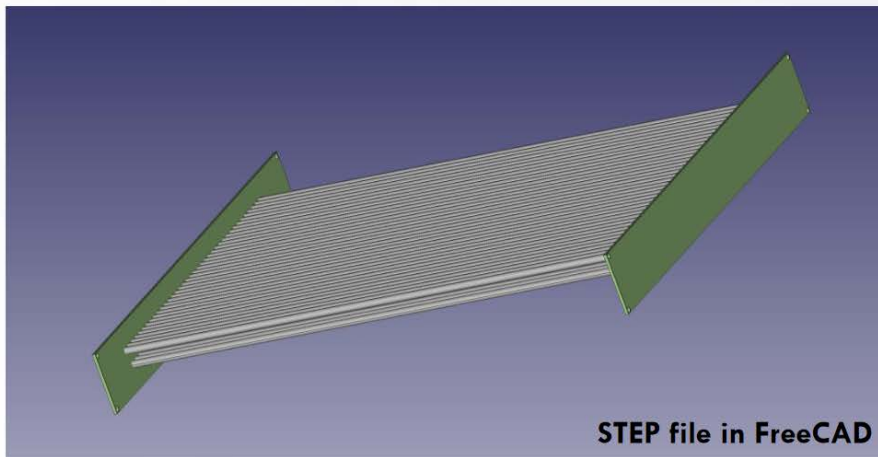
DD4hep

Importing CAD geometry in DD4hep

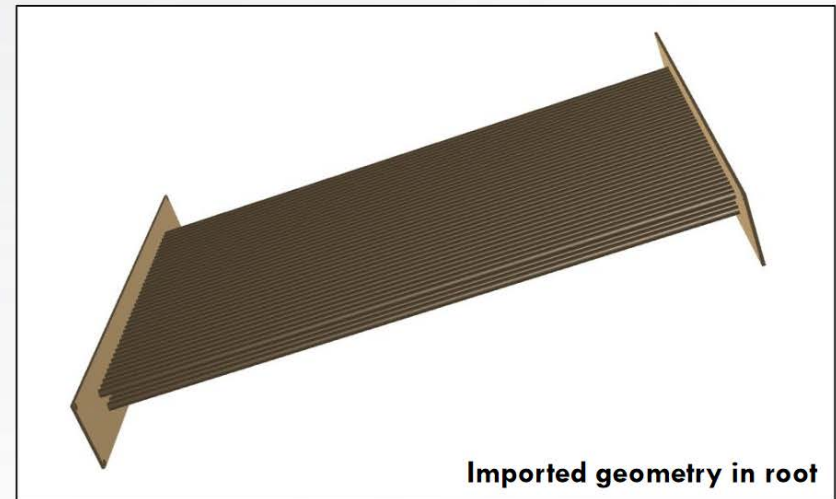
Shivang Tripathi

- Open .STEP file in FreeCAD software and export selected parts to a Collada .dae file.
- Import this .dae file (detector assembly) in DD4hep with DDCAD and then, **root** may be used for visualization.

In FreeCAD (STEP file) → Collada (.dae)



Imported in DD4hep → Visualize with **root**



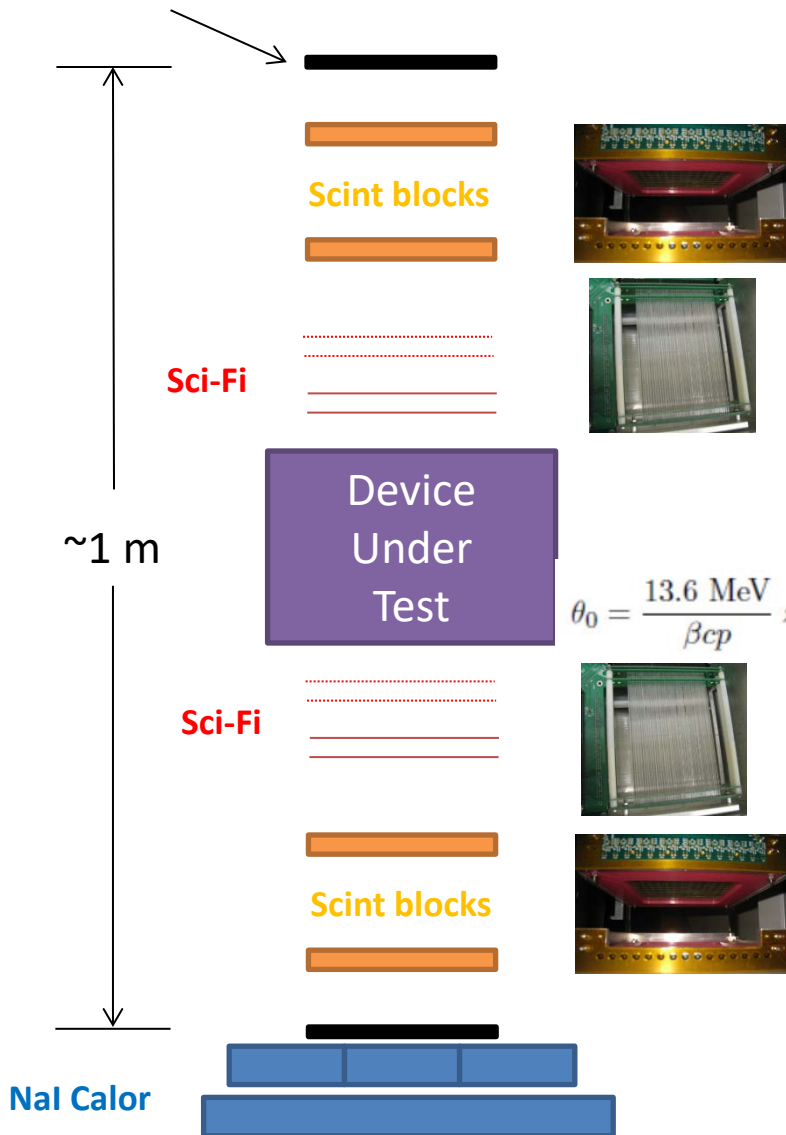
Notes:

- Unified description of mechanics (construction) and simulation

Tracking Resolution Estimates

Trigger paddles

Toy Monte Carlo



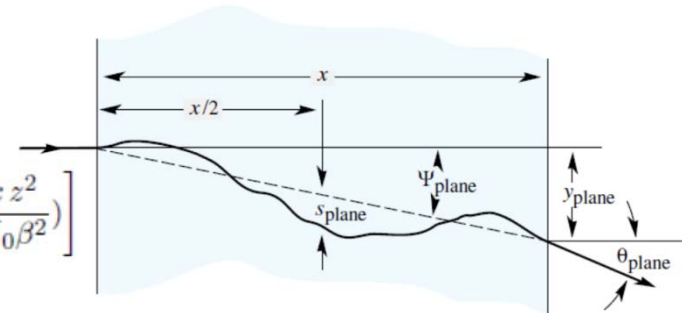
10mm/sqrt(12)

1.25mm/sqrt(12)

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.088 \log_{10} \left(\frac{x z^2}{X_0 \beta^2} \right) \right]$$

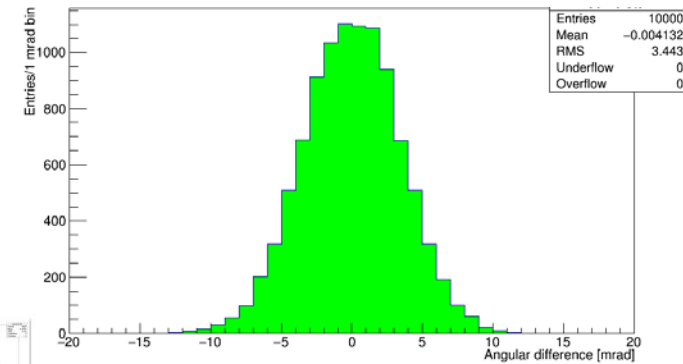
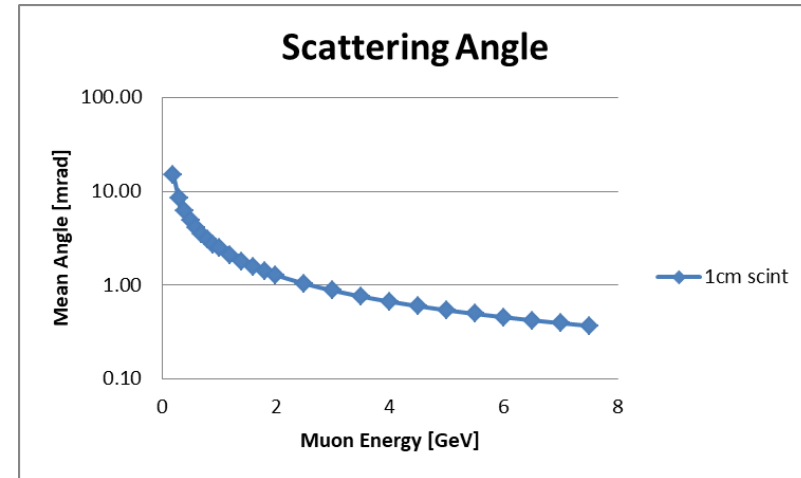
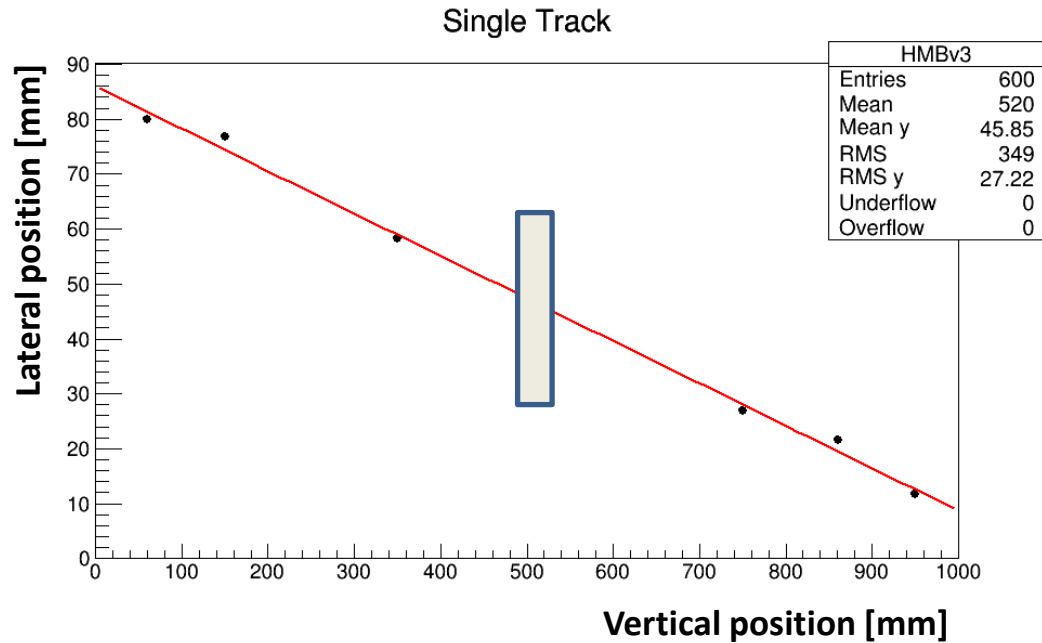
1.25mm/sqrt(12)

10mm/sqrt(12)

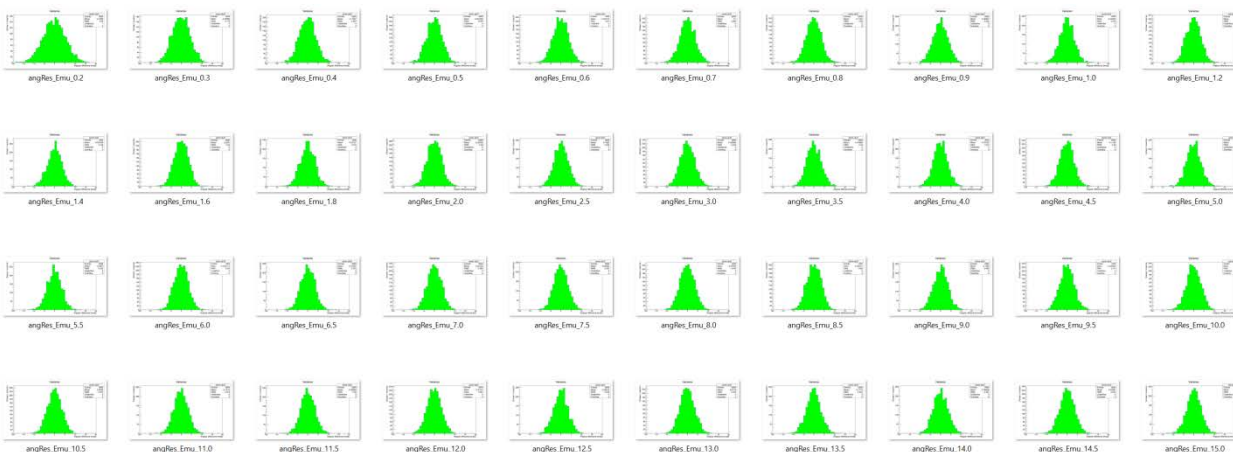


Tracking Resolution Estimates

At reference plane of center of DUT

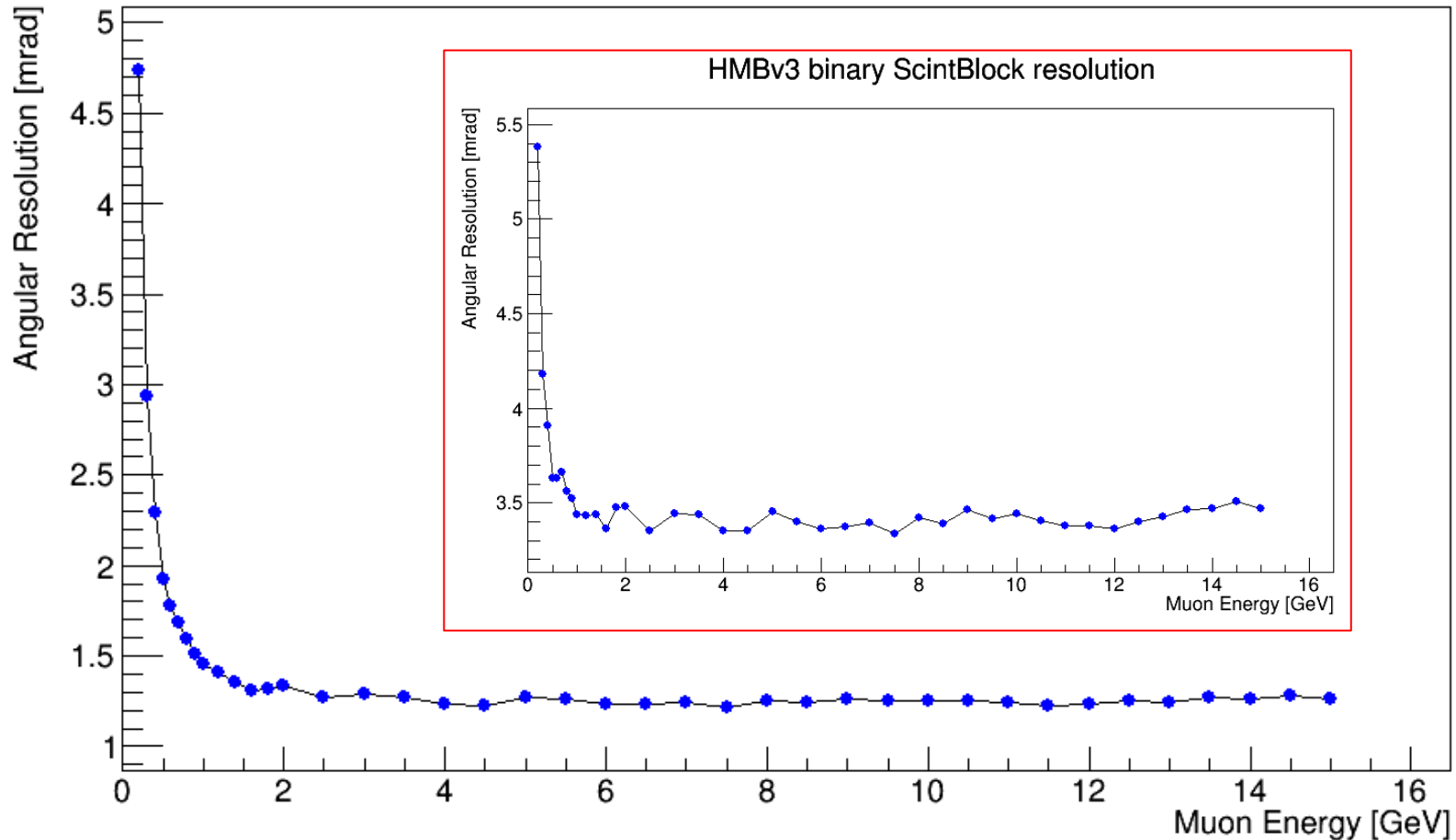


- Typically 3.5 mrad resolution
- Dominated by scint block resolution



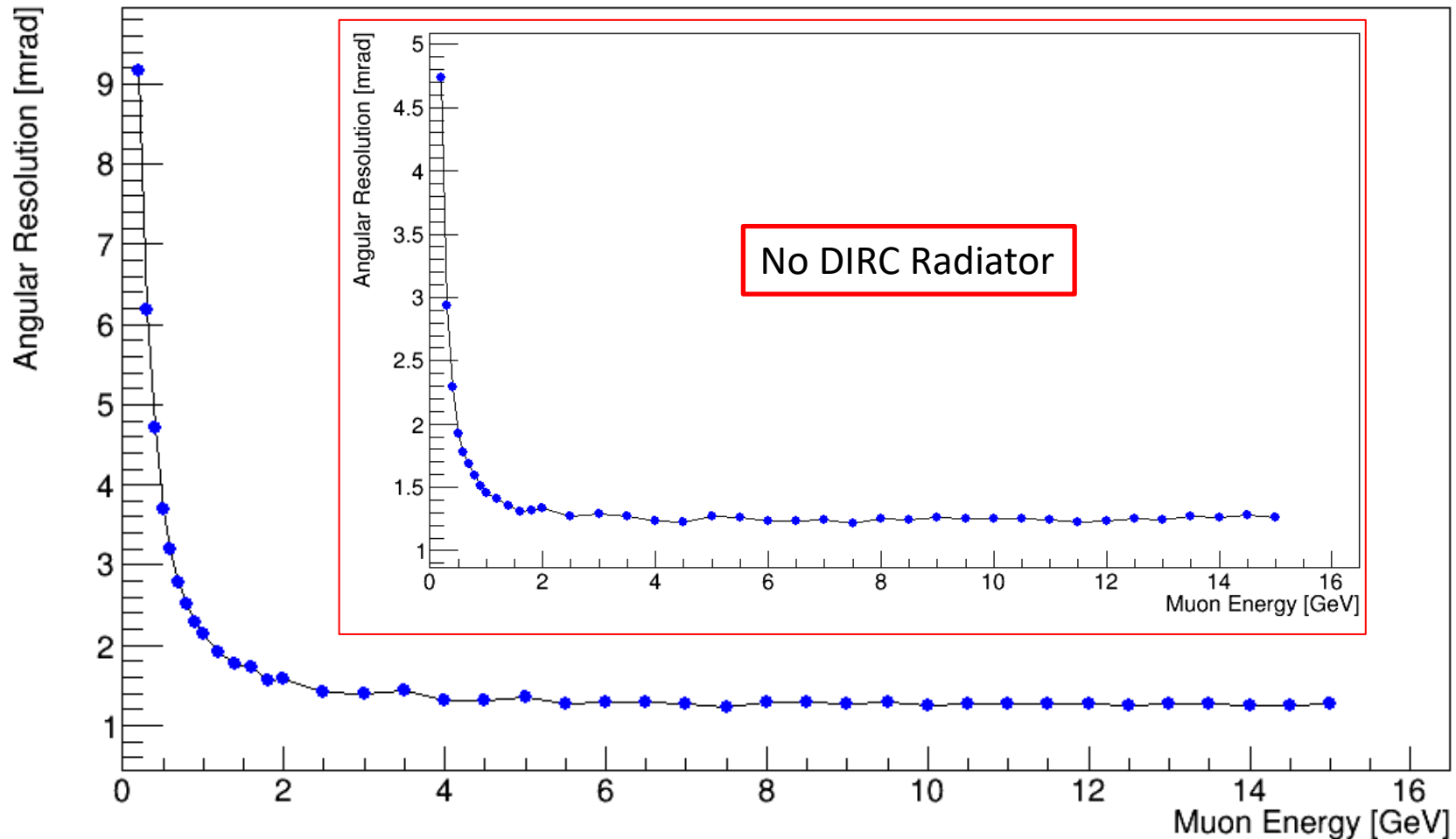
Tracking Resolution Estimates

If can improve from $10\text{mm}/\sqrt{12} \rightarrow 10\text{mm}/10$



Tracking Resolution Estimates

With 17.25 mm thick fused silica radiator at DUT center



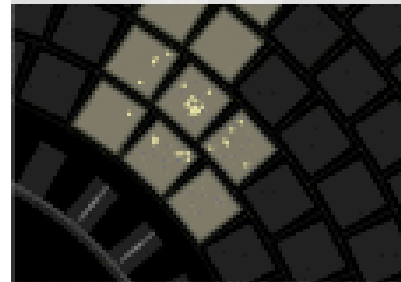
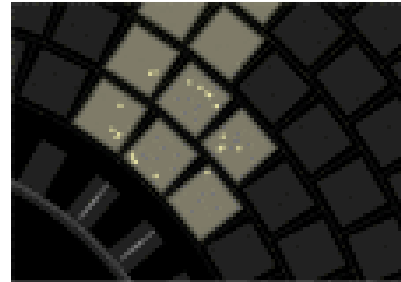
Only 1D, sanity-check of final GEANT result

DUT:

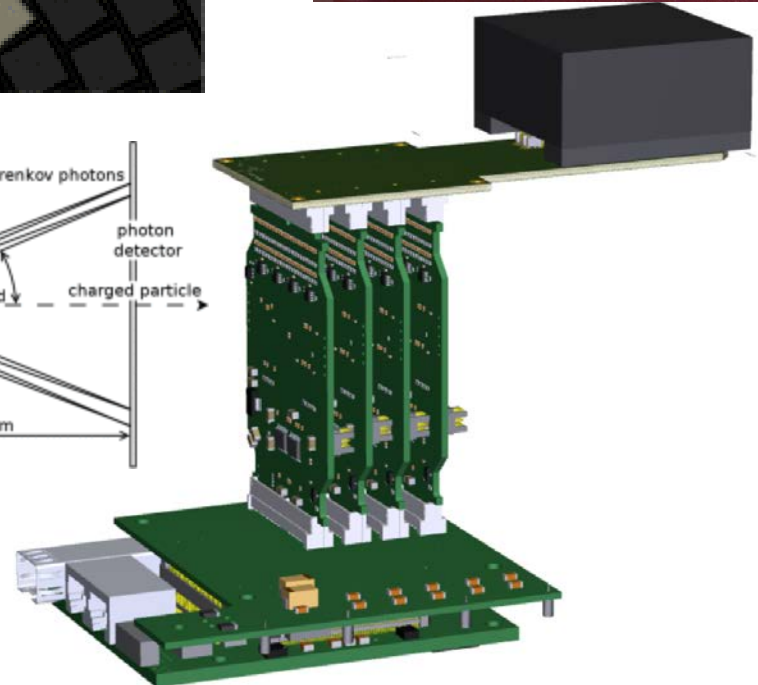
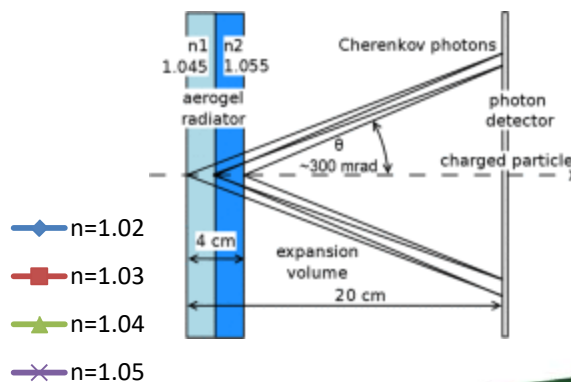
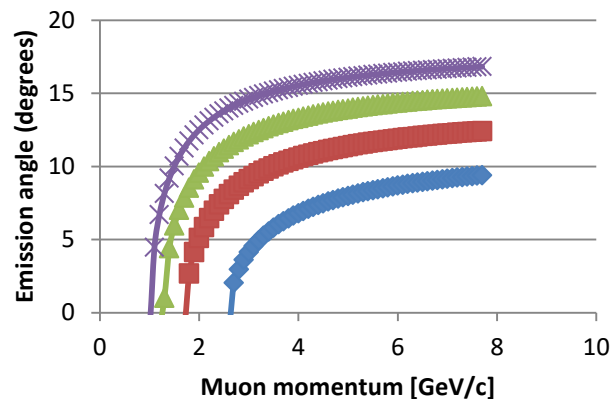
Aerogel Ring Imaging Cherenkov (ARICH)

- **mRICH using ARICH technique**

- Proximity focus
- Can measure ring image to determine muon momentum



Aerogel Radiator

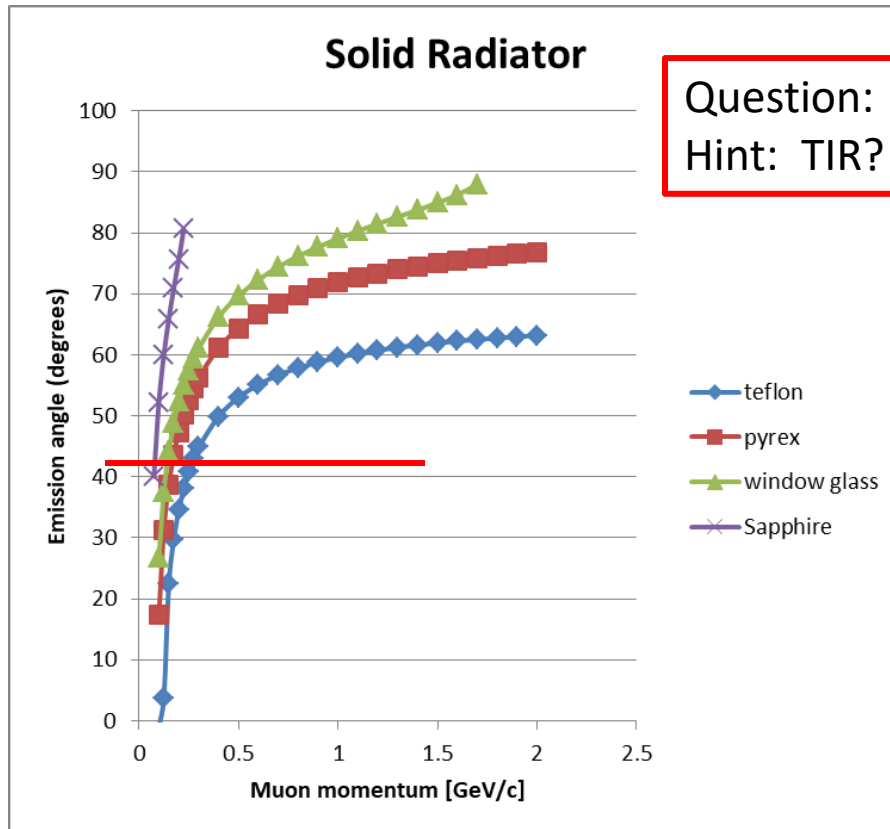


DUT:

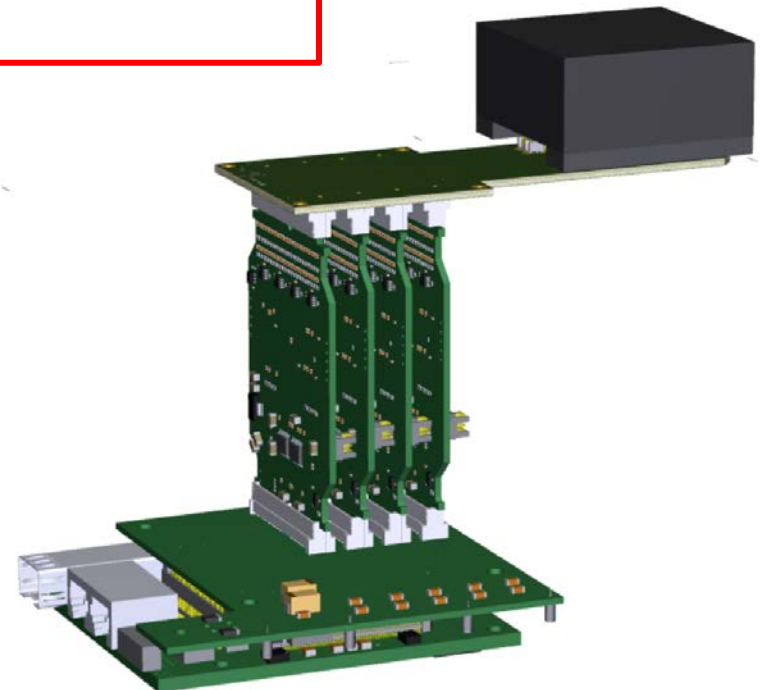
compact Ring Imaging Cherenkov (cRICH)

- **ARICH technique**

- Works well at high p , but many atmospheric muons at lower momentum
- Can make compact if use dense, thin material



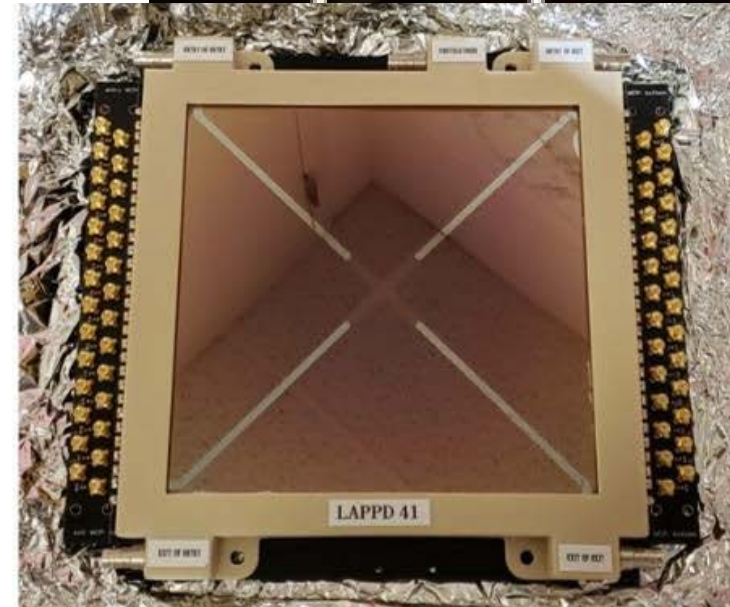
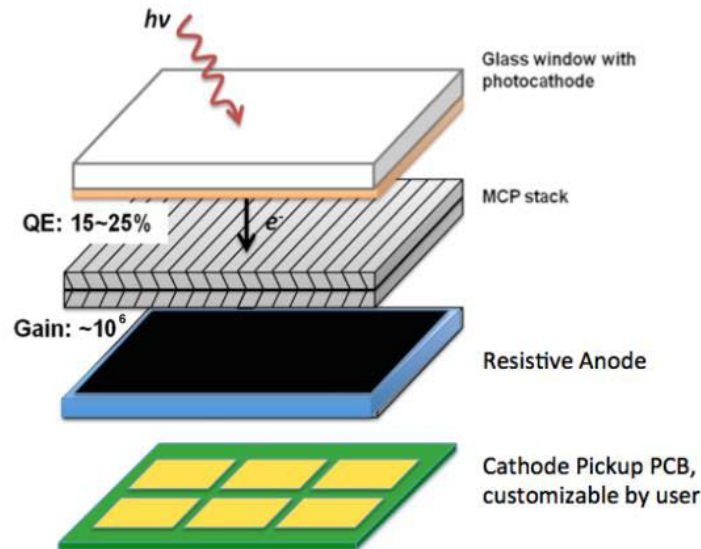
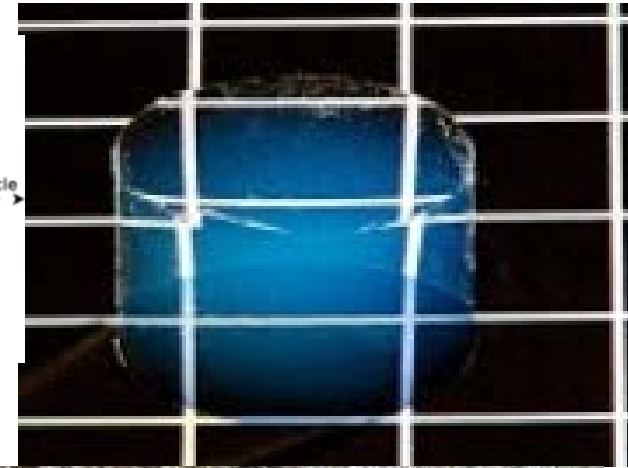
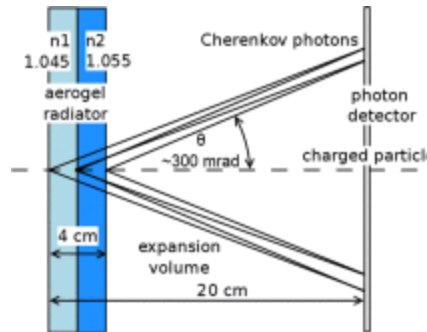
Question: will we see these?
Hint: TIR?



DUT

Large Area Picosecond PhotoDetector (LAPPD)

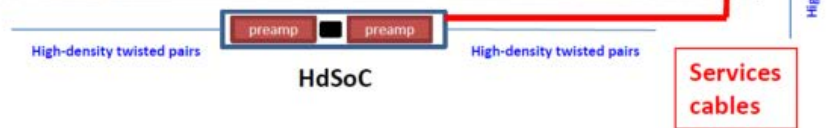
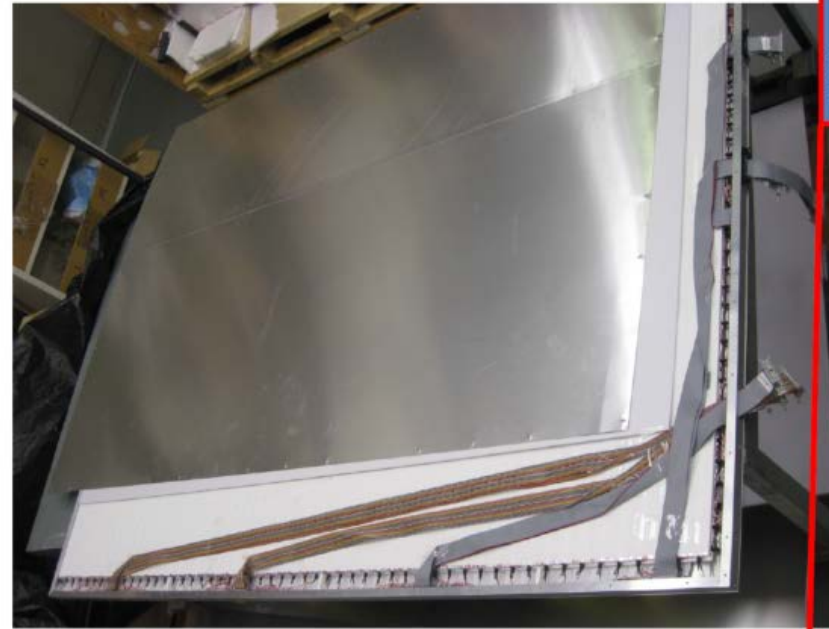
- In addition to laser testing, can also image Cherenkov rings
 - Initially DRS4 readout
 - Transition to AARDVARC readout



HMB v3

Other tests

- Minimize cables, board size



2x CAT-7
Fiber optic
Power (48V?)

7-series FPGA (Zynq?)

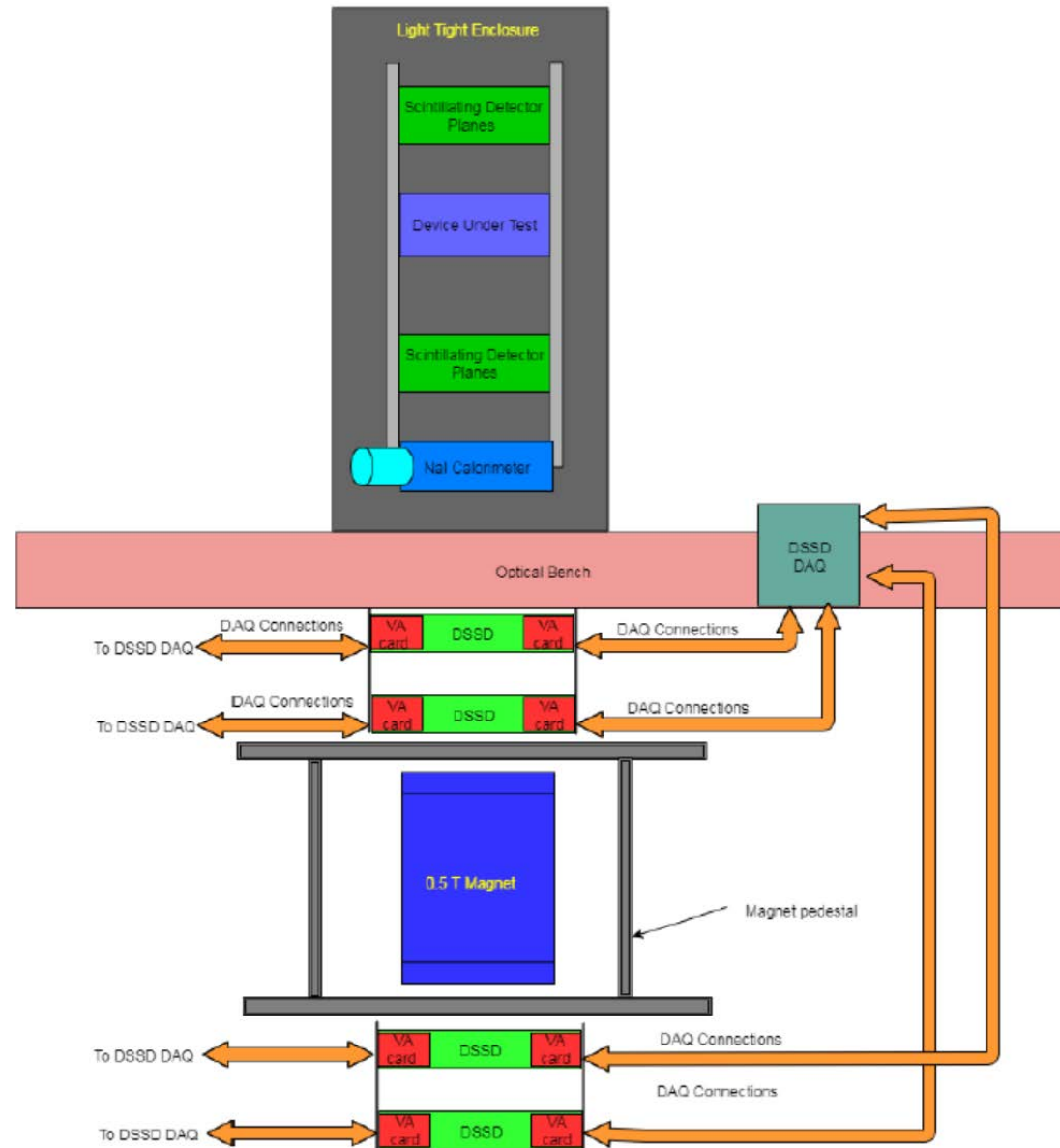
- 2 separate ASIC cards
- #z channels always same; wrap phi channels as needed
- 8 sectors * 15 layers * 2 FW/BW * 2 ASICs = 480 ASICs, ASIC cards
- 240 SCROD

- Timing of long scintillator strips with WLS fibers (KLM scint upgrade)
- mRICH test?
- Spatial/timing resolution comparisons between BMD and SciFi Trackers

HMB v4

- Belle II “2026” upgrades

- Number of beamlines worldwide very limited, resource under great duress
- Want to be *certain* prototype works properly before (or if) doing beamtest
- Improved tracking
- **Silicon strip sensors (Belle I SVD)**
- Permanent magnet to form spectrometer
- Momentum select to mimic K/pi of different velocities



Summary -- Prioritized List

- Nobody working on full-time, **though ...**

- Pynq readout to EUDAQ

- Pynq PMOD-B trigger

- Trigger distribution FW

- ☐ Trigger data format definition (added to spreadsheet)
 ☐ Variants for SCROD and Calor ➔ make the same

- Calorimeter trigger

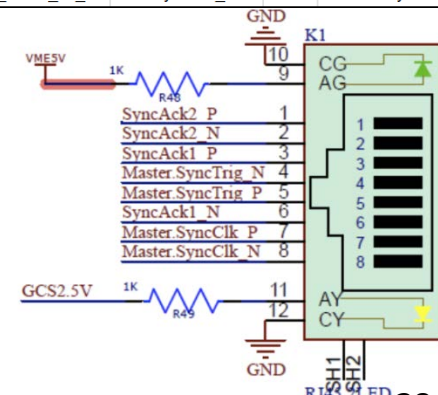
- Use PMOD-B board

- Scint block trigger/readout

- Trigger input card design (with LAB4D readout for Scint paddles) ['final' Calorimeter trigger solution]
- Modify scint plane daughtercards for direct SiPM attach
- Light cones for optical coupling (?)
- Daughtercard firmware (4x window TARGETX)

RJ-45			Pmod B			
Net name	pin #	Net name	Net name	pin #	dir.	src/dest
ACK+	1	ACK_B+	RX+	3	in	Zynq
ACK-	2	ACK_B-	RX-			via RX
TRG+	3	TRG_B+	TX+	1	out	Zynq
RSV-	4	RSV_B-	AUX-			TP
RSV+	5	RSV_B+	AUX+	2	out	Fanout
TRG-	6	TRG_B-	TX-			Zynq
TTDClk+	7	RCLK_B+	SysCLK+	7	out	Clock
TTDClk-	8	RCLK_B-	SysCLK-	8		Fanout

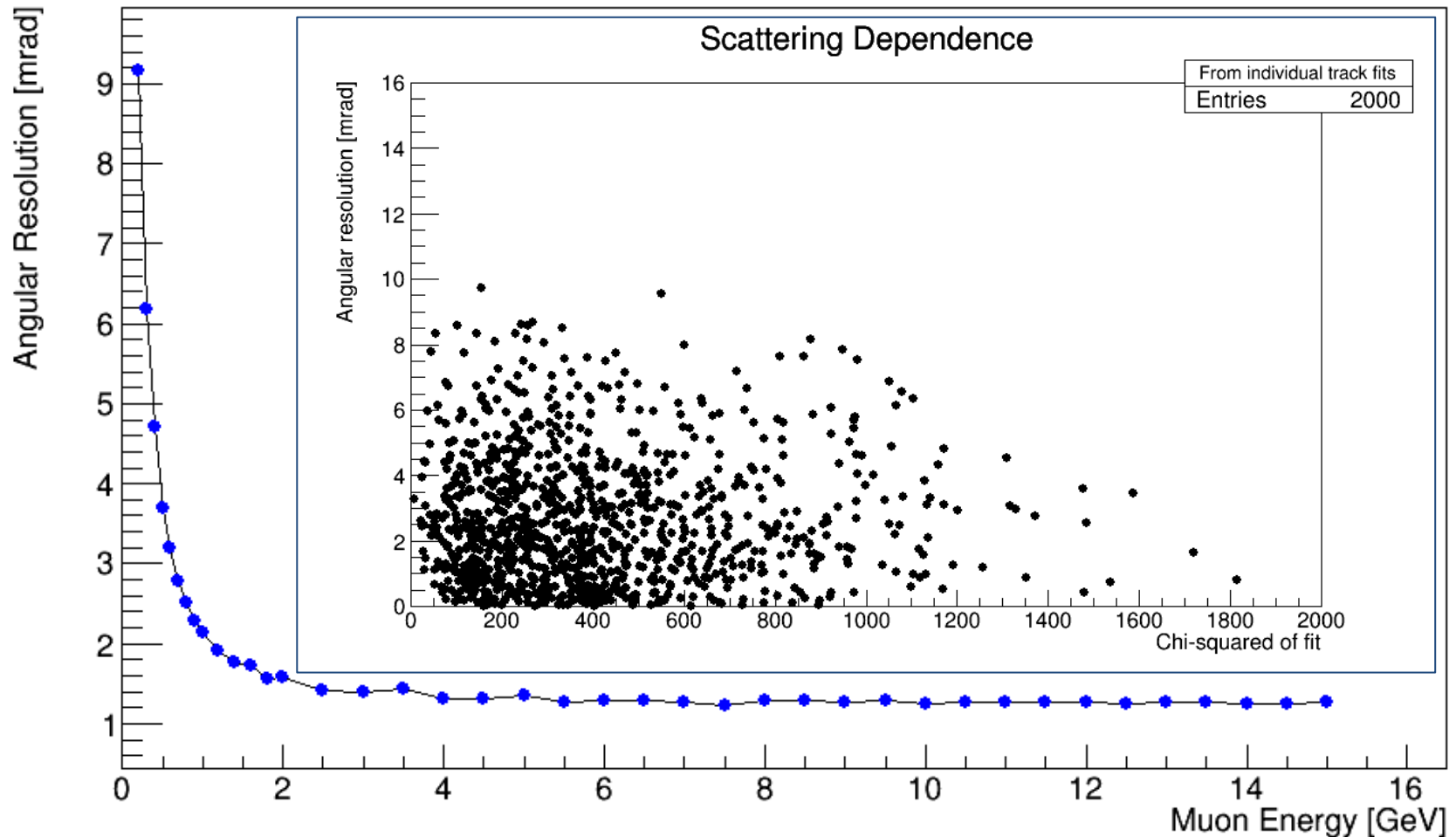
WATCHMAN 6U VME						
ZedBoard 1			RJ-45			
dir	pin #	I/O banking	Net name	pin #	Net name	
		no connect		1	SyncAck2_P	
				2	SyncAck2_N	
out	JX2-43	JX2_LVDS_8_N	SyncAck1_P	3	SyncAck1_P	
in	JX2-55	JX2_LVDS_12_N	1.SyncTrig_N	4	Master.SyncTrig_N	
	JX2-53	JX2_LVDS_12_P	1.SyncTrig_P	5	Master.SyncTrig_P	
out	JX2-41	JX2_LVDS_8_P	SyncAck1_N	6	SyncAck1_N	
in	JX2-49	JX2_LVDS_10_N	1.SyncClk_P	7	Master.SyncClkP	
	JX2-47	JX2_LVDS_10_P	1.SyncClk_N	8	Master.SyncClkN	



Backup

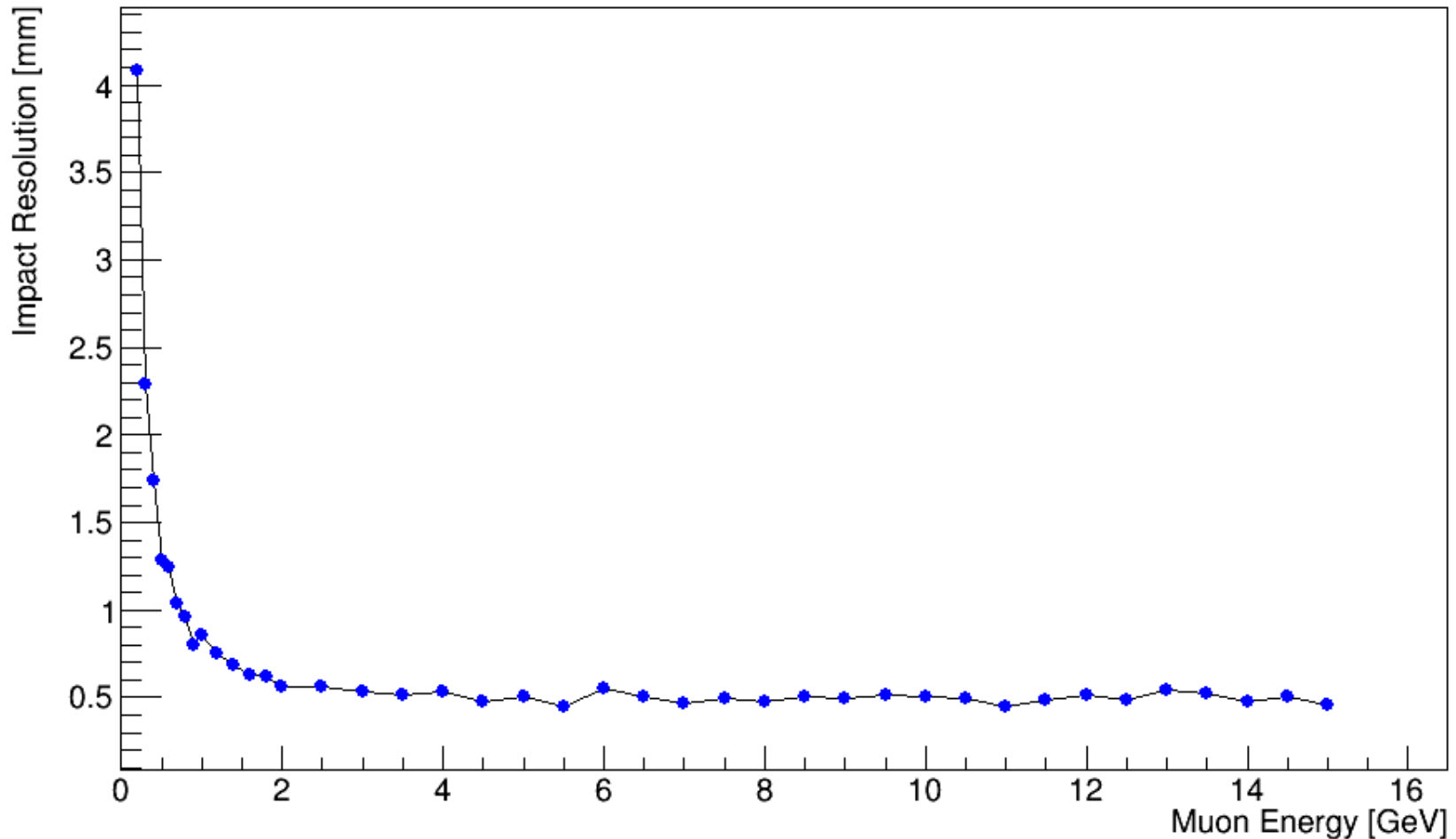
Tracking Resolution Fits

With 17.25 mm thick fused silica radiator at DUT center



Impact Resolution Estimates

While did measurement, could have just related to angle by geometry



HMB 3.1000 power

Scheduled delivery:
Tuesday 9/22/2020 by 5:00 pm



IN TRANSIT

At destination sort facility
HONOLULU, HI

[GET STATUS UPDATES](#)

FROM

THIEF RIVER FALLS, MN US

TO

HONOLULU, HI US

[MANAGE DELIVERY](#) 

Travel History

Shipment Facts

Local Scan Time 

Sunday, 9/20/2020

9:12 pm

HONOLULU, HI

At destination sort facility

[Expand History](#) 

Friday, 9/18/2020

10:52 pm

Shipment information sent to FedEx



Excelsys power
Adjustable 3 – 6 V
40A per module

**Ordered 2 chassis,
5 XG2**

**Repurposed power module
from iTOP prototype**

**Based upon compact DC-
DC**



Nomenclature: HMB 3.abcd

- 1. Version 3. is without semiconductor tracker/magnet (v4)**
 - a. Tracker configuration**
 - b. Calorimeter configuration**
 - c. RICH configuration**
 - d. DUT configuration**

So for example: HMB 3.1000

Will be the first set-up (just 2 existing layer pairs) with KLM Motherboard and pre-amp/cable readout

Will switch to 3.2xxx when scint planes ready (could be 3.2100 or 3.2011 or ... depending upon which other systems ready first)

