Study of time and energy resolution of an ultracompact sampling calorimeter (RADiCAL) module at EM shower maximum over the energy range 25 ≤ E ≤ 150 GeV using scintillation and wavelength shifting technology

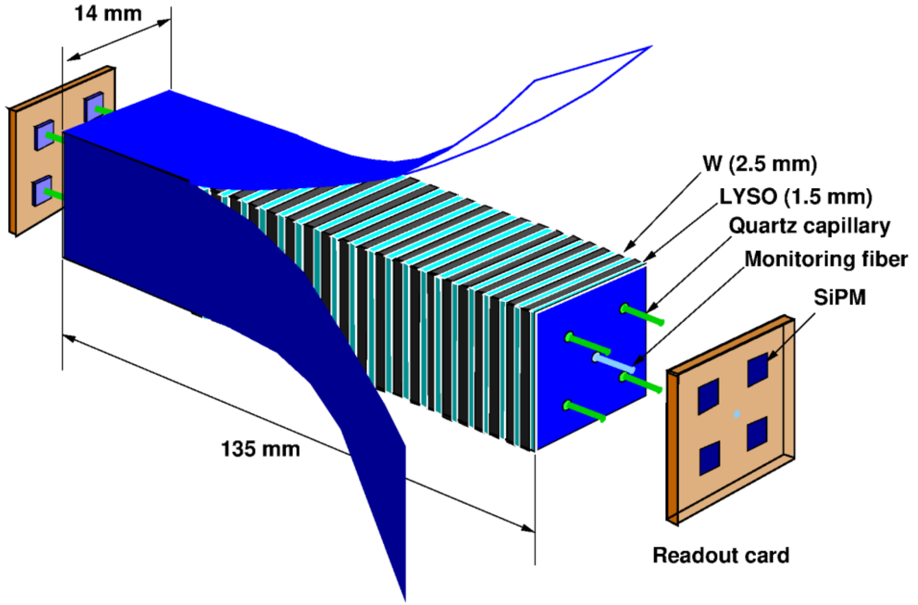
Ren-Yuan Zhu (Caltech) for the RADiCAL Collaboration

Objectives:

1. Develop and test individual ultracompact sampling calorimetry modules to measure for EM showers:
   - Shower timing to σ_t ~ 10ps
   - Energy resolution stochastic term to σ_{E}/E ~ 10%/root(E)
   - Shower position localization to a few mm
2. Fabricate a 3 x 3 array of modules for full EM shower characterization.
3. Develop and test new scintillators, wavelength shifters and optical transmission elements using individual modules and the array.
4. Application: FCC-ee, FCC-hh, Muon Collider, Fixed target and forward physics applications.

Currently under test is a detector module built of 28 W tiles, 29 LYSO:Ce scintillating tiles, and quartz capillaries containing DSB1 or LuAG:Ce WLS and quartz filaments:

Radiation Length 5.4mm, Moliere Radius 13.7mm
SiPM readout - both upstream and downstream



C. Perez-Lara et al, arXiv: 2401.01747, submitted to NIM A

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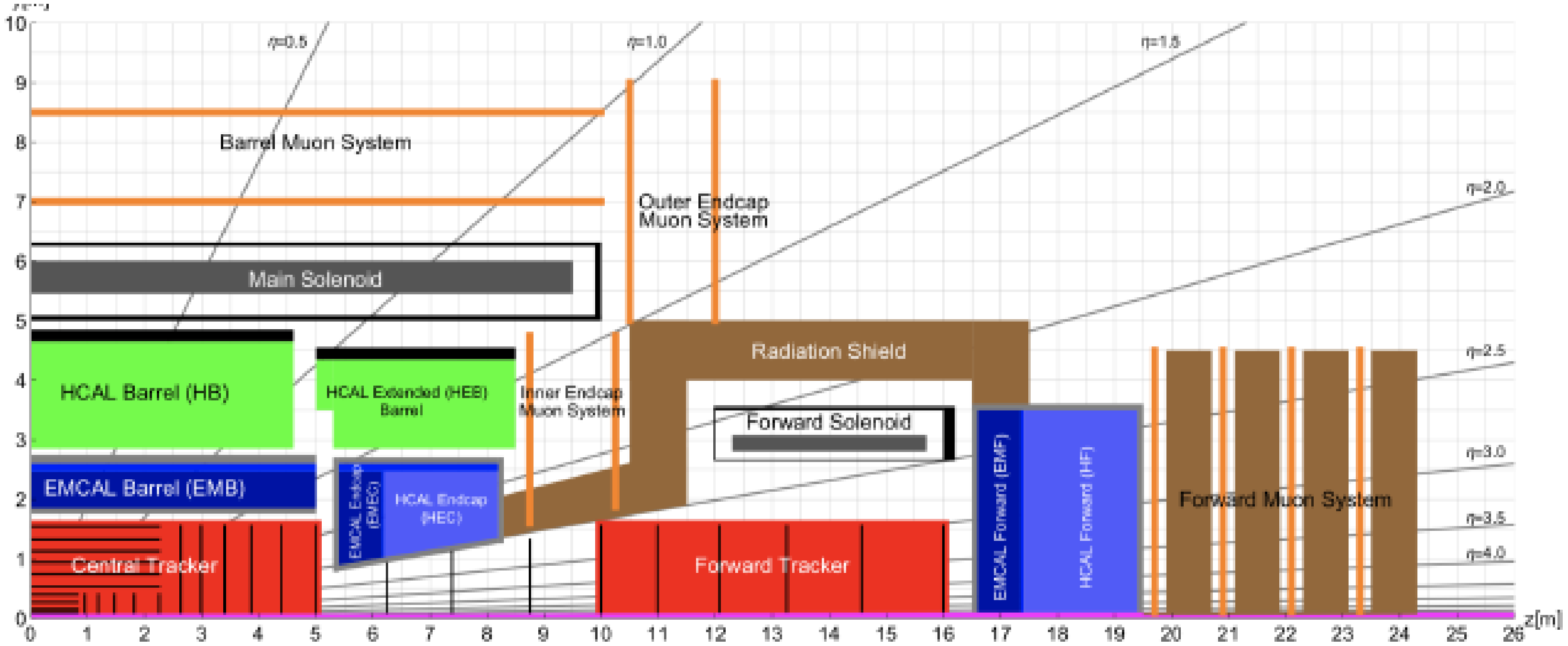
EFCA DRD6 WP3: Optical Calorimetry
CPAD RDC9: Calorimetry



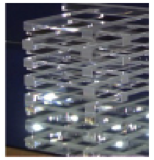
Radiation at FCC-hh

From M. Aleksa, et al, Calorimeters for the FCC-hh, CERN-FCC-PHYS-2019-0003, 23 December 2019.

	R_{min}	R_{max}	z coverage	η coverage	Dose	1 MeV n_{eq} fluence
Unit	m	m	m		MGy	$\times 10^{15}$ cm^{-2}
EMB	1.75	2.75	$\|z\| < 5$	$\|\eta\| < 1.67$	0.1	5
EMEC	0.82–0.96	2.7	$5.3 < \|z\| < 6.05$	$1.48 < \|\eta\| < 2.50$	1	30
EMF	0.062–0.065	3.6	$16.5 < \|z\| < 17.15$	$2.26 < \|\eta\| < 6.0$	5000	5000
HB	2.85	4.89	$\|z\| < 4.6$	$\|\eta\| < 1.26$	0.006	0.3
HEB	2.85	4.59	$4.5 < \|z\| < 8.3$	$0.94 < \|\eta\| < 1.81$	0.008	0.3
HEC	0.96-1.32	2.7	$6.05 < \|z\| < 8.3$	$1.59 < \|\eta\| < 2.50$	1	20
HF	0.065–0.077	3.6	$17.15 < \|z\| < 19.5$	$2.29 < \|\eta\| < 6.0$	5000	5000

Table 1: Dimensions of the envelopes for the calorimeter sub-systems (including some space for services) and the maximum radiation load at inner radii (total ionising dose is estimated for 30 ab^{-1}). The abbreviations used in the first column are explained in the text.

Fast and Ultrafast Inorganic Scintillators



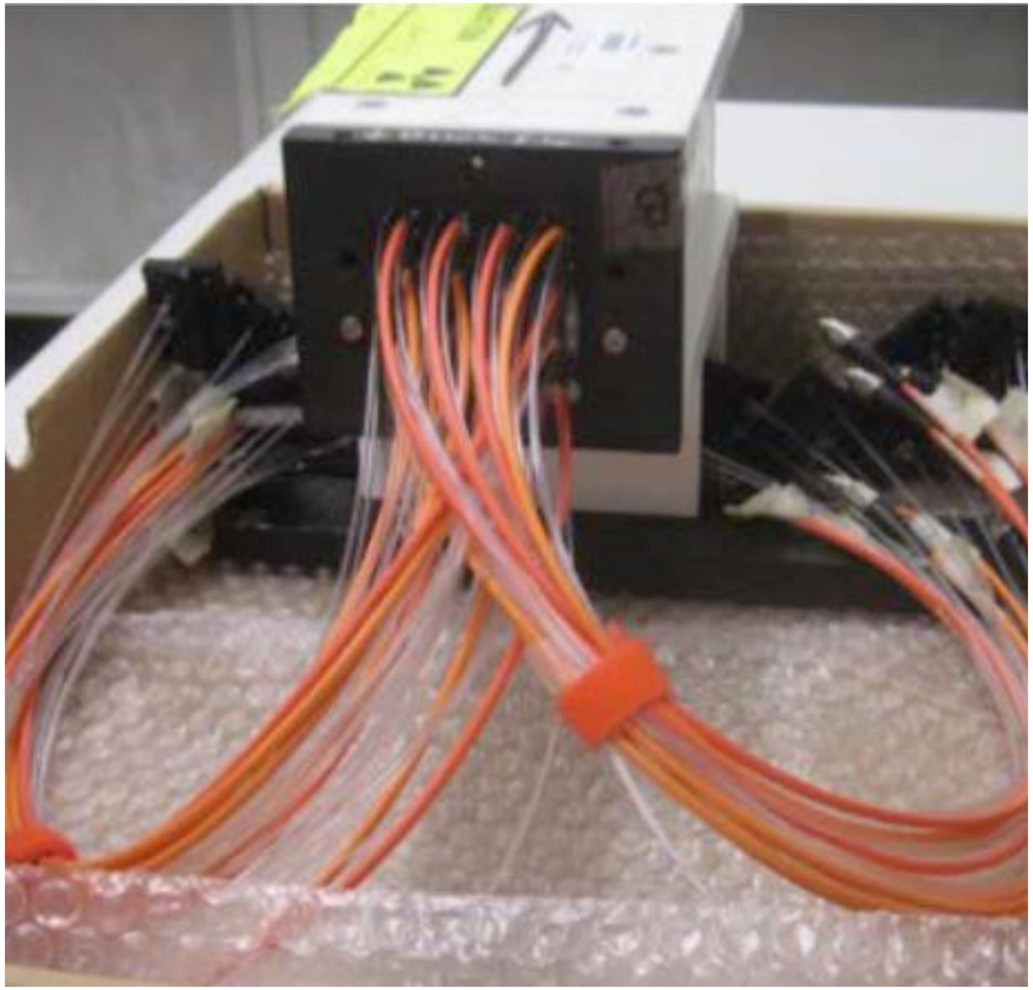
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 <0.6	600 <0.6	<1	1.5	4	148 6	40	820 50	191 25	800 80	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

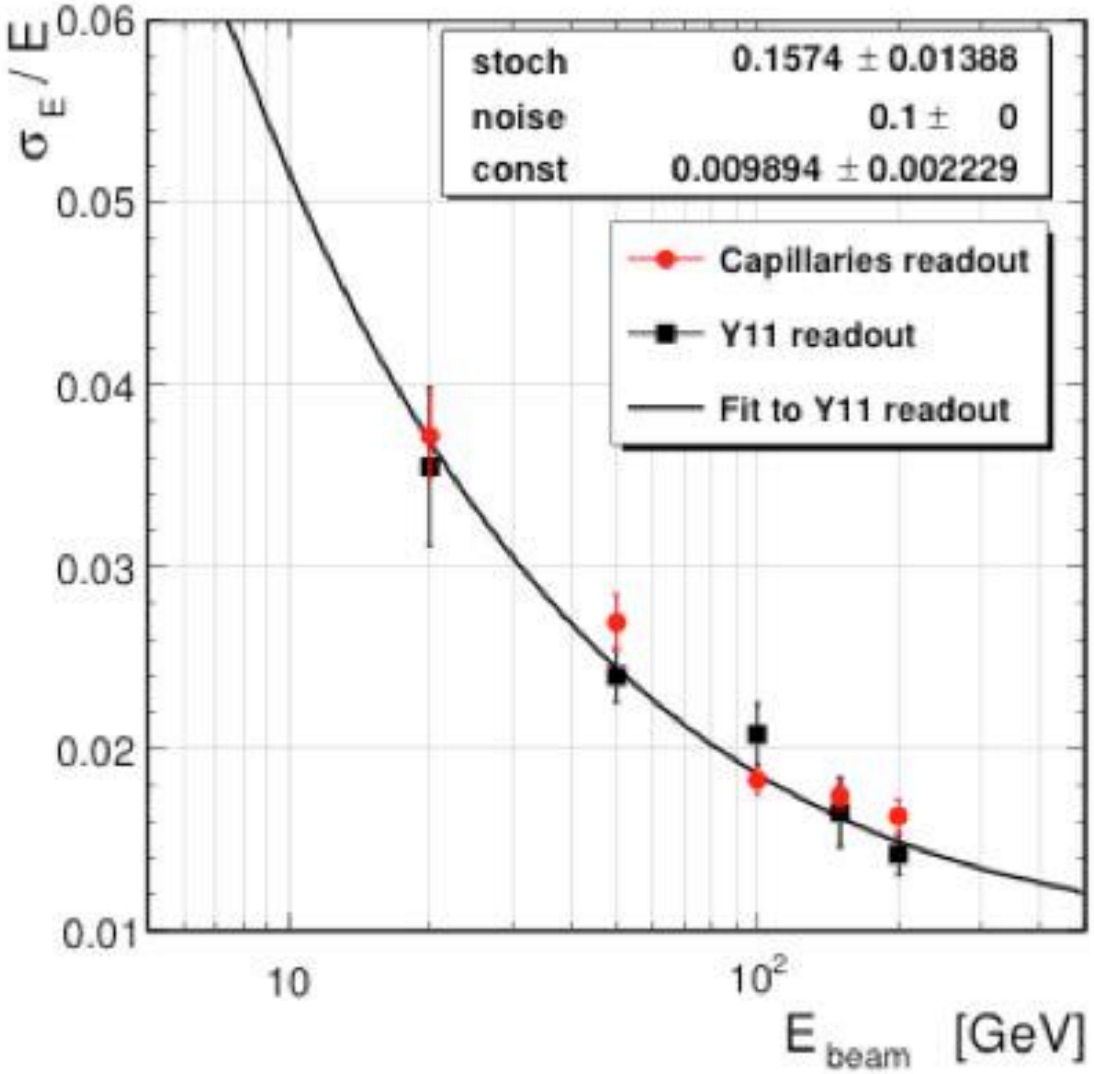
December 8, 2019

Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI

RADiCAL: 4x4 LYSO/WLS Shashlik ECAL Module

arXiv: 2203.12806

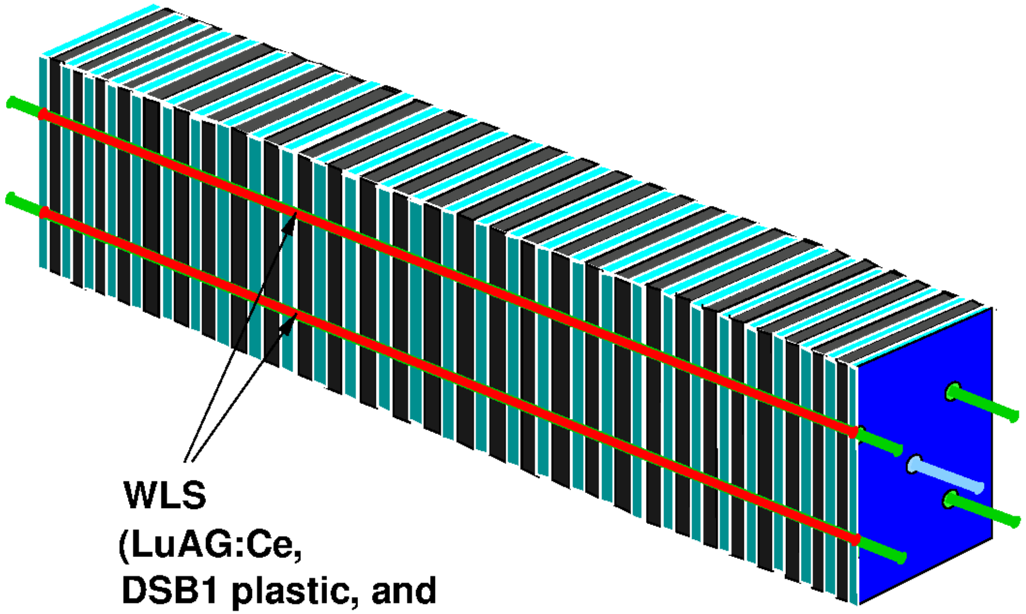




RADiCAL: Wavelength Shifter Configurations

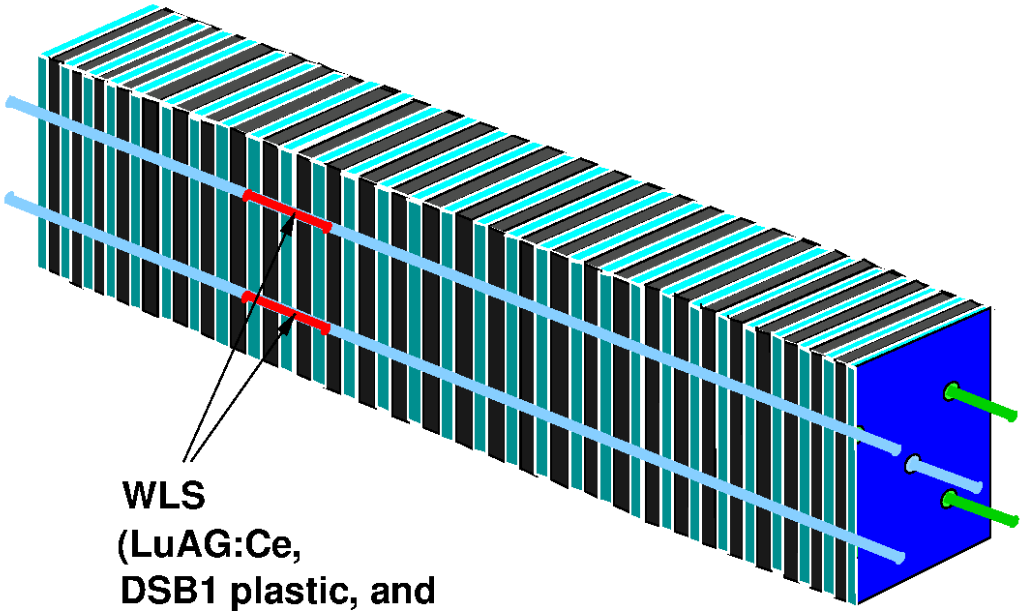
For Full Shower Energy:

WLS filaments extend over the full length of the RADiCAL module

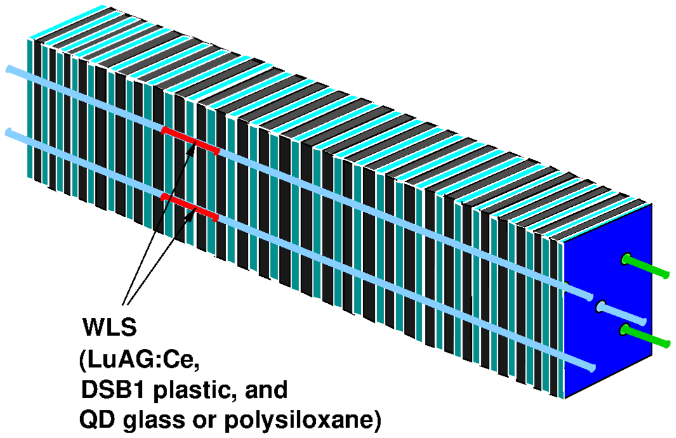


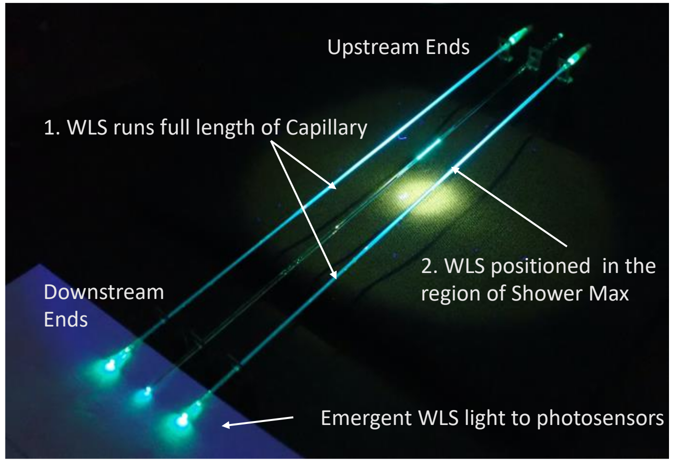
For Timing and Shower Spatial Localization:

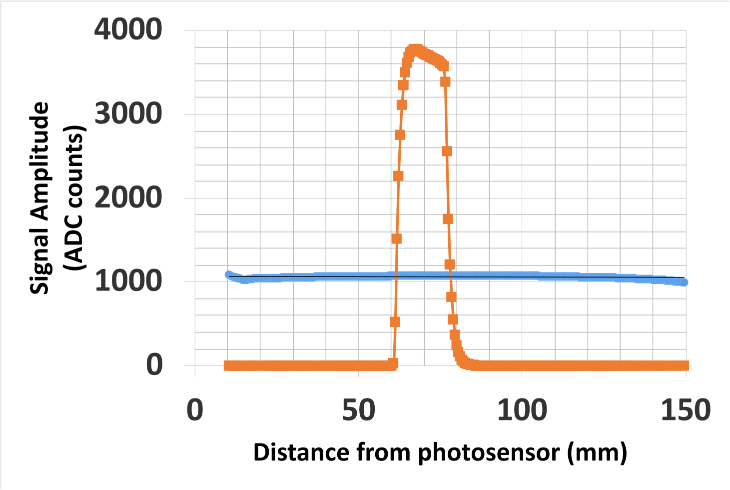
WLS filaments are positioned in the shower max region.



New approach to timing measurement with RADiCAL
Timing from WLS at Shower Max.







Specialized WLS Applications

1. To measure shower energy
   WLS runs the full length
2. To measure timing
   WLS filament at Shower Max
   Remainder of capillary is filled with Quartz Fiber and fused solid.
   Capillary can be read out from both ends.

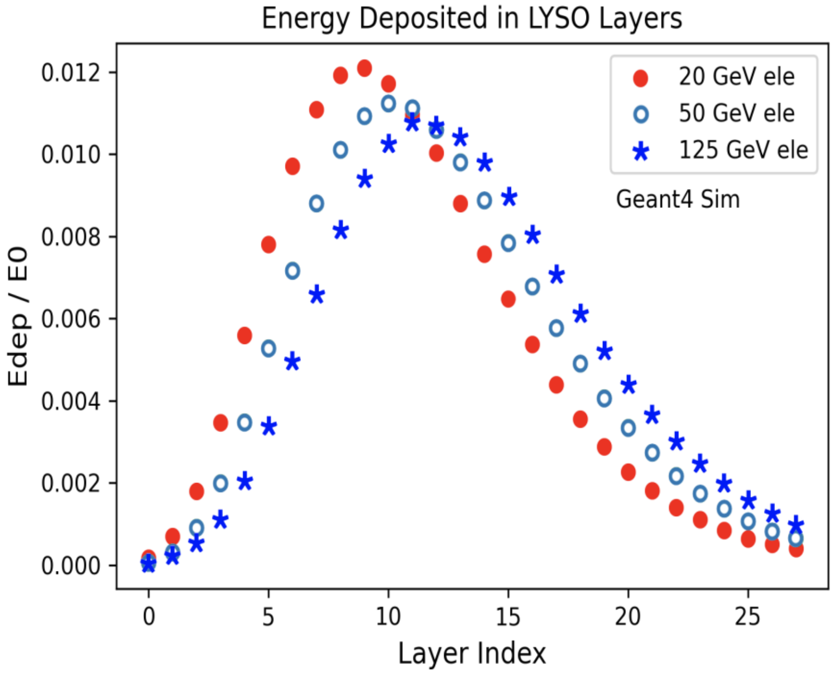
WLS Light Yield as a function of distance from photosensor.

Blue: Energy Capillary
Orange: Timing Capillary

The Benefit of EM Shower Max for Timing and Position:

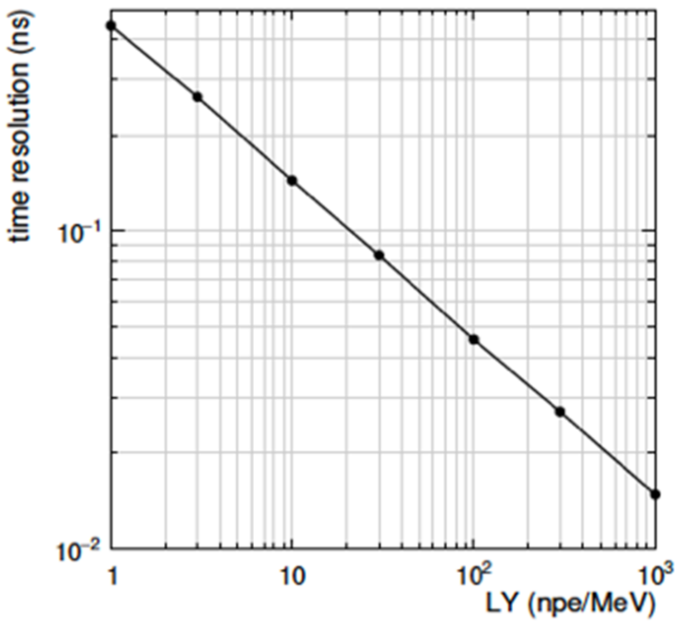
The shower radius is scaled by the radiation length not the Moliere Radius

GEANT4 Simulation of energy deposition in successive LYSO:Ce tiles as a function of beam energy. EM Shower Max moves logarithmically with energy, indicating that WLS filaments positioned in that region will be appropriate over an extensive energy range.



Timing resolution expectation as a function of detected light yield

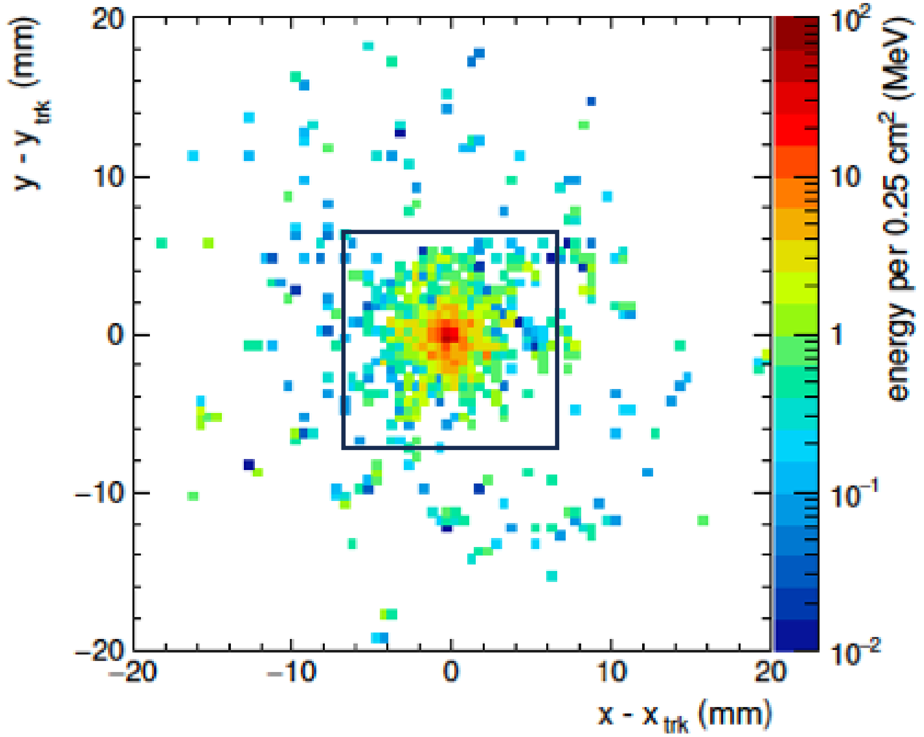
In number of photoelectrons (npe/MeV) at EM Shower Max, from GEANT4 Simulation



Shower profile at EM Shower Max

GEANT4 Simulation for 50 GeV electron with energy detected in DSB1 WLS filament positioned in the shower max region

Note the shower can be fully contained in the module in that region

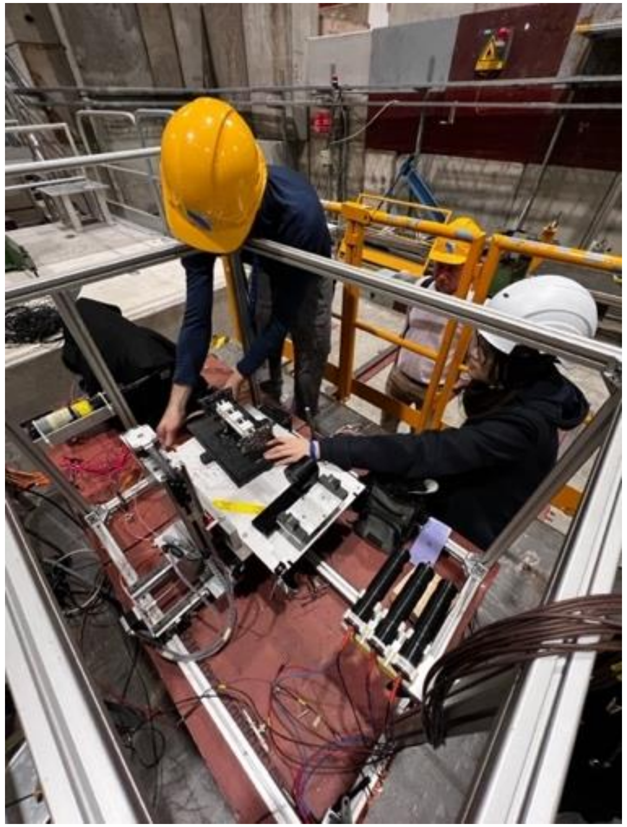


RADiCAL Module Tested in CERN H2 Beamline

May 2023

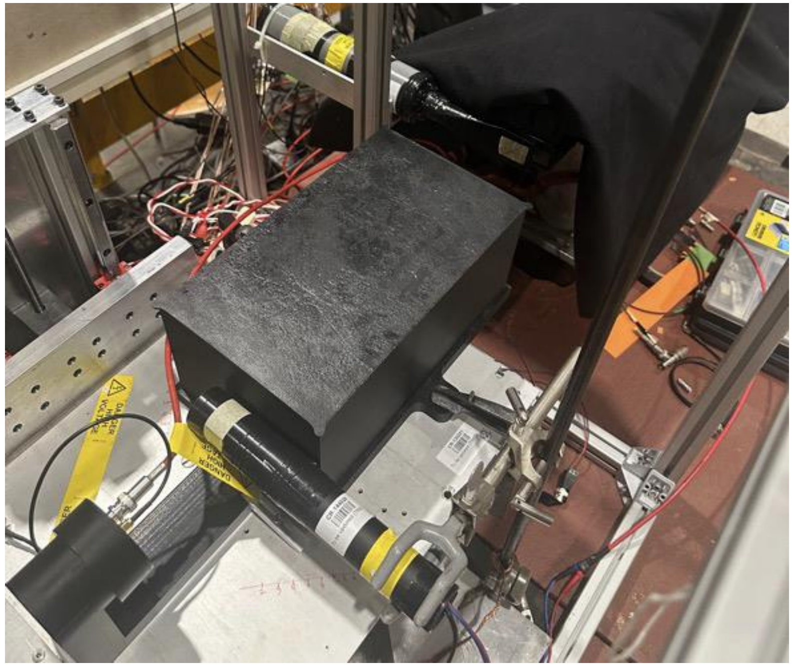
Module Assembly with an MCP PMT tube upstream for timing reference. Beam incident from the left. RADiCAL module is mounted within a DELRIN housing. Readout cards are mounted both upstream and downstream with four SiPM each of low gain and differential high gain amplifiers on each SiPM.

Module installation on the H2/HF lift table

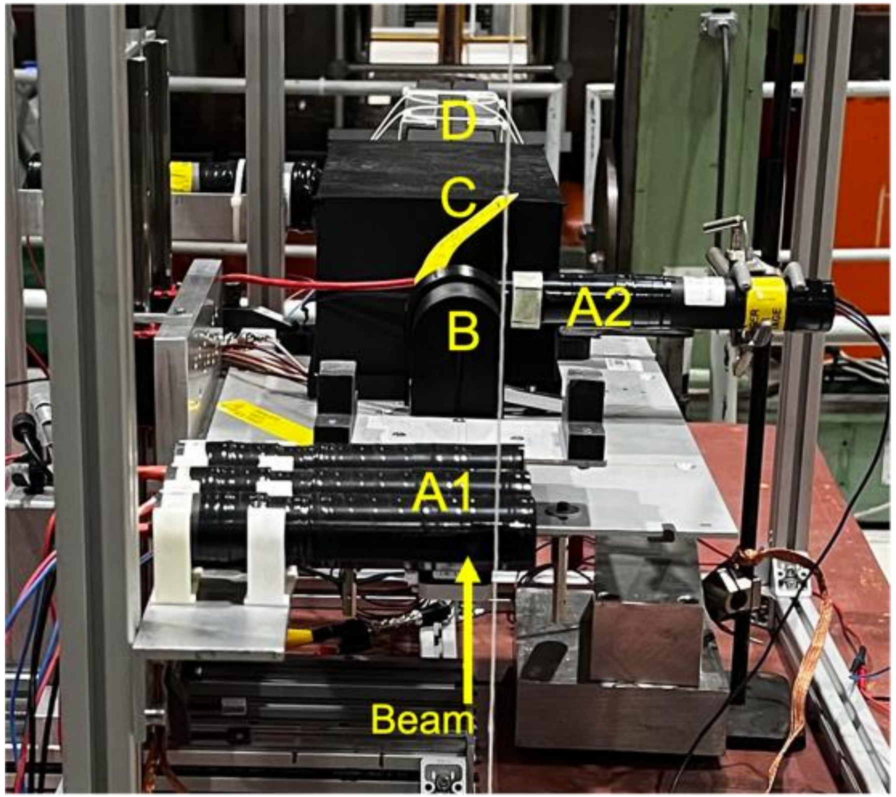


Module placement at CERN H2 Beamline

Module installation on the lift table. Beam enters from lower left. RADiCAL is under the black light tight cover

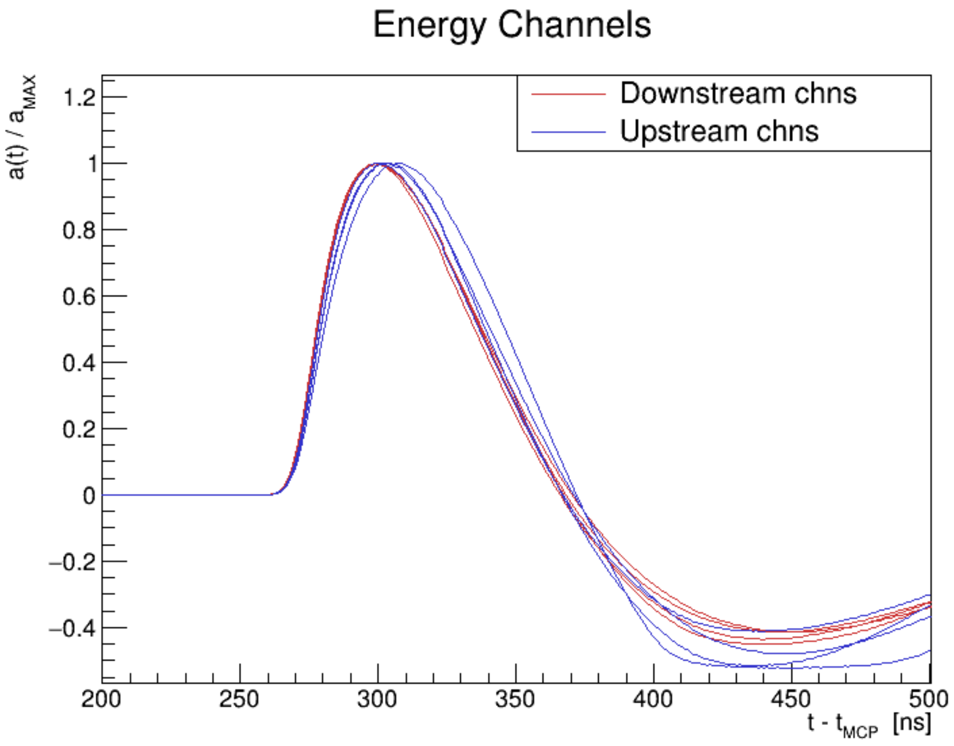


Beam elements: Trigger counters (A1, A2), MCP PMT (B), RADiCAL (C), Pb glass backing calorimeter (D). Upstream Beam Chamber not shown.

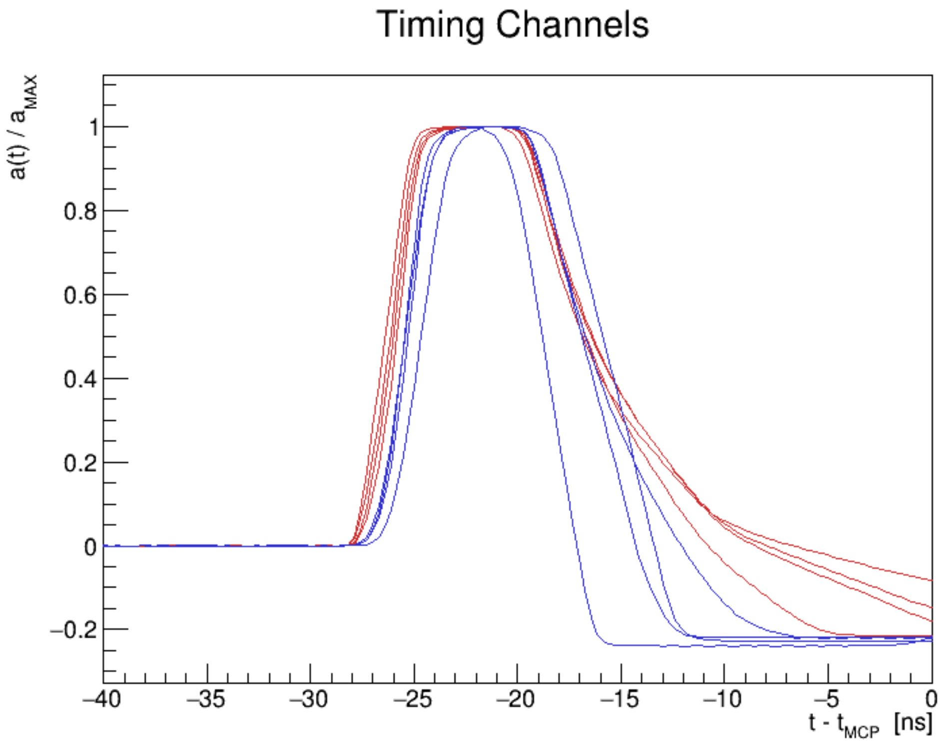


Sample low gain and differential high gain signals from the SiPM.

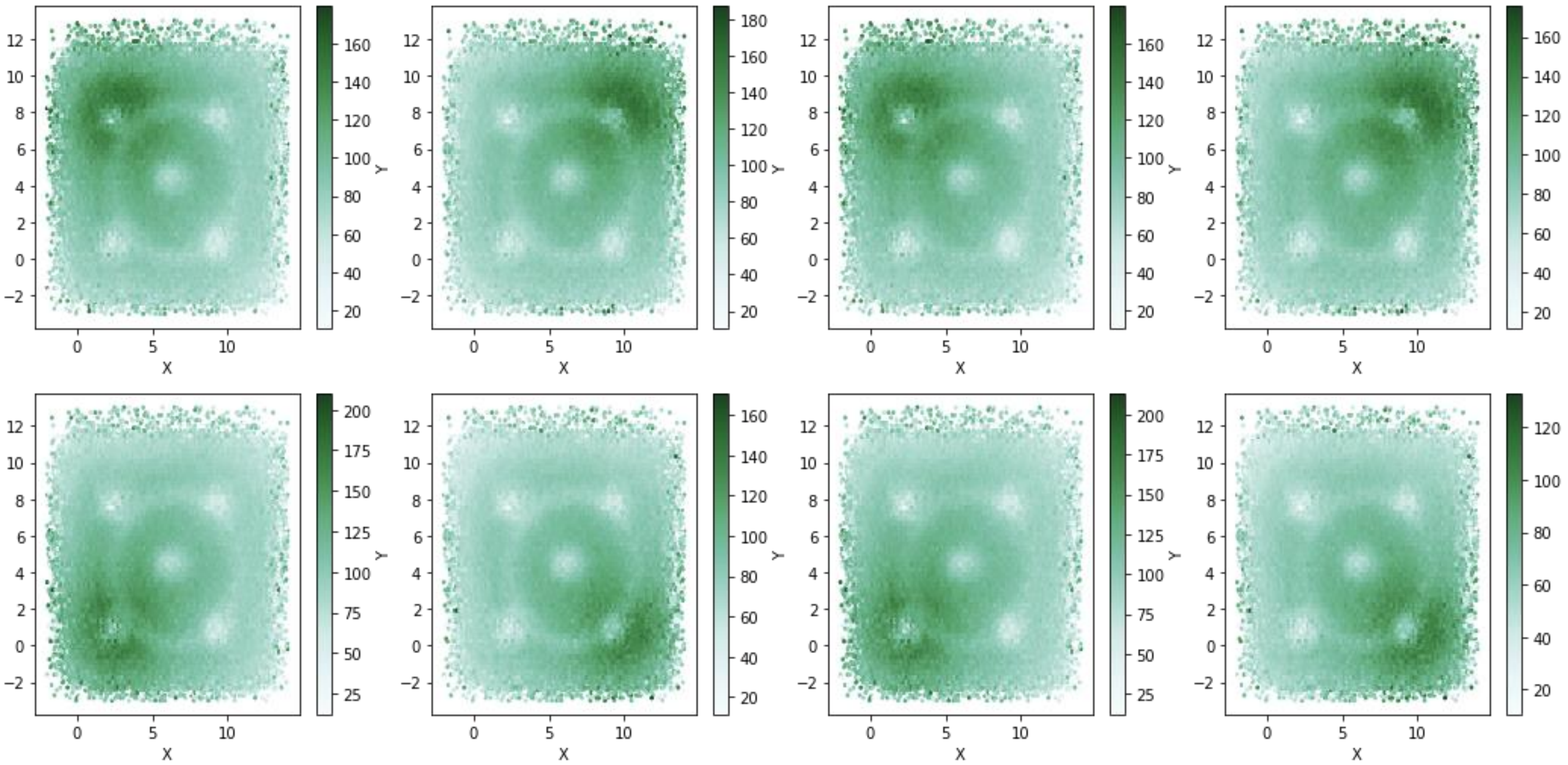
Low gain signals for local energy and position measurement at Shower Max



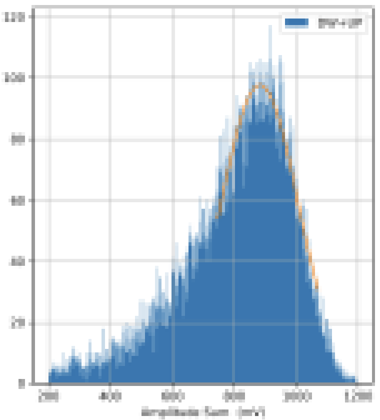
Differential High gain signals for timing with fixed threshold on leading edge.



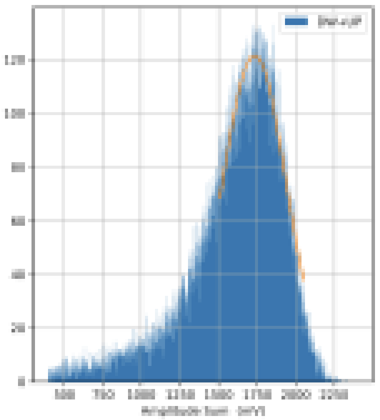
Images of the low-gain response from each SiPM as a function of beam position in the RADiCAL module - specified by the beam chamber.



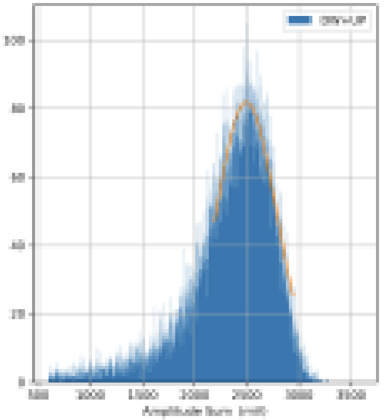
Measured energy in Shower Max region in RADiCAL for various H2 electron beam energies



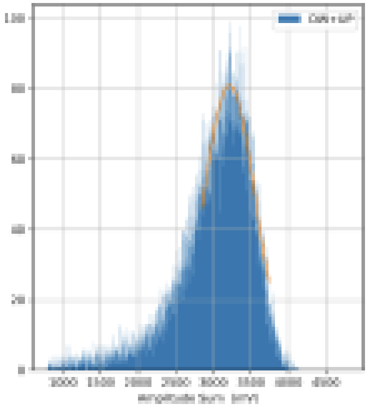
E_{beam} = 25 GeV



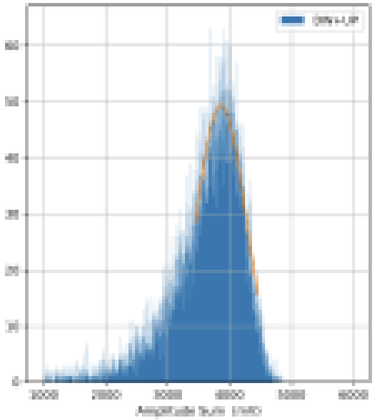
E_{beam} = 50 GeV



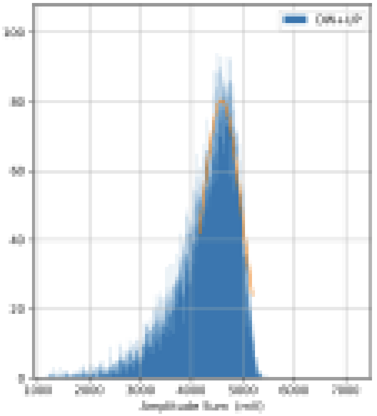
E_{beam} = 75 GeV



E_{beam} = 100 GeV

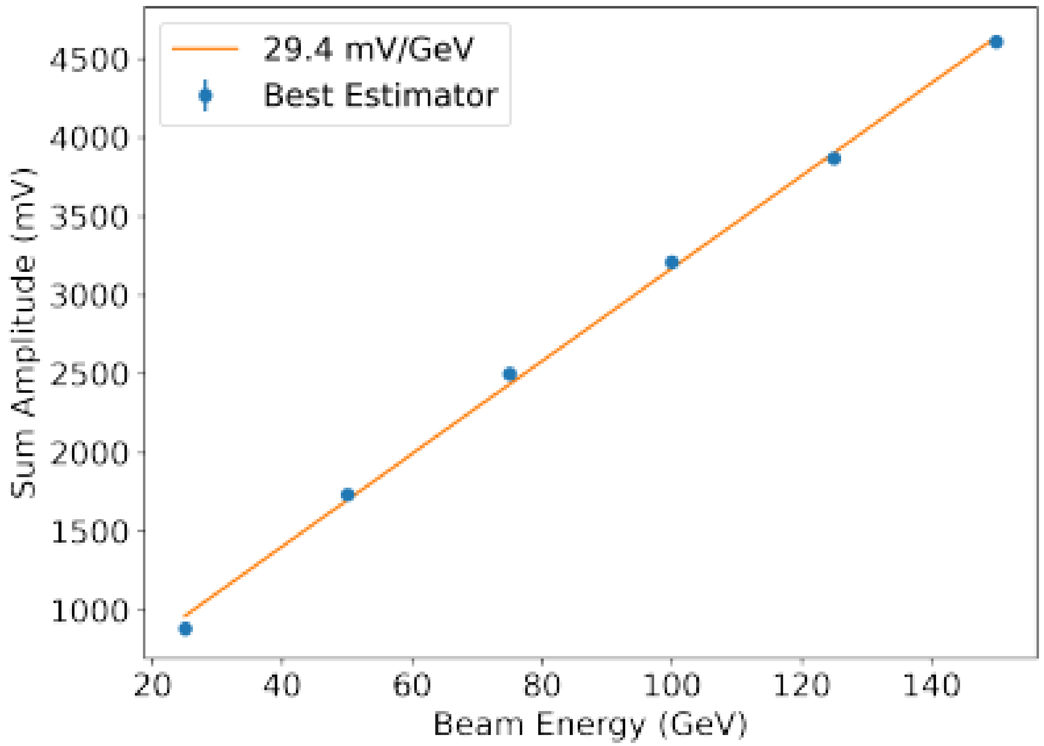


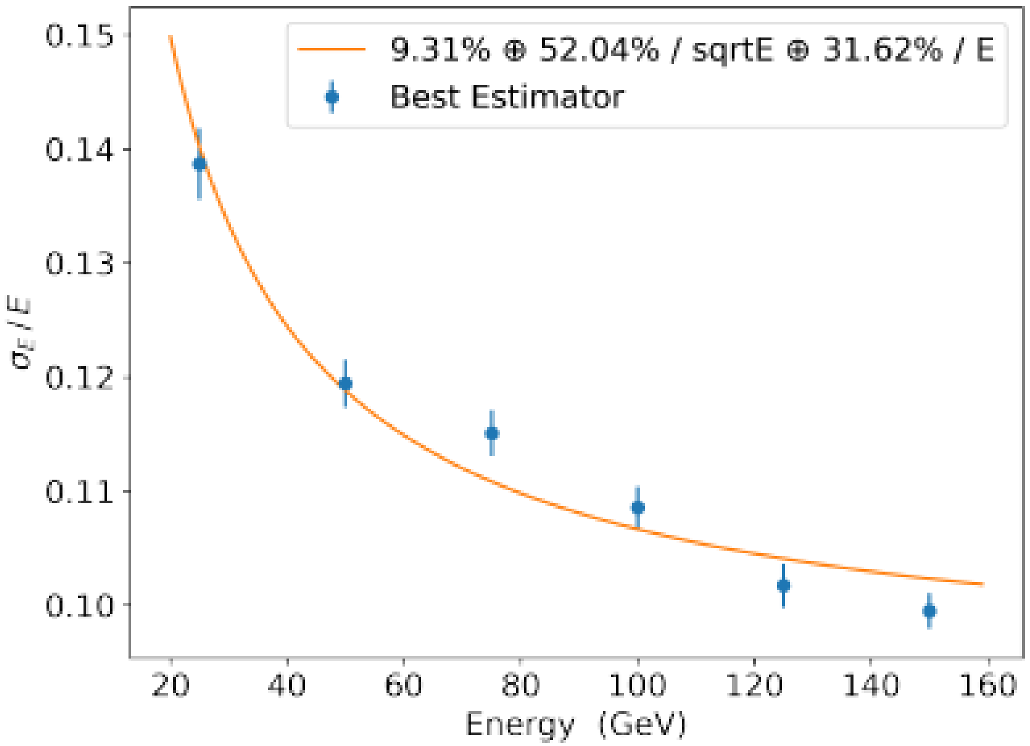
E_{beam} = 125 GeV



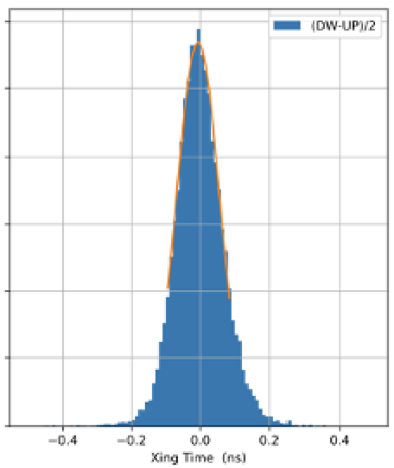
E_{beam} = 150 GeV

Measured energy only from the EM Shower Max region as a function of nominal electron beam energy.

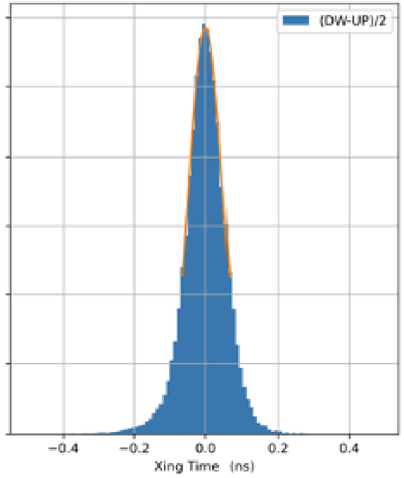




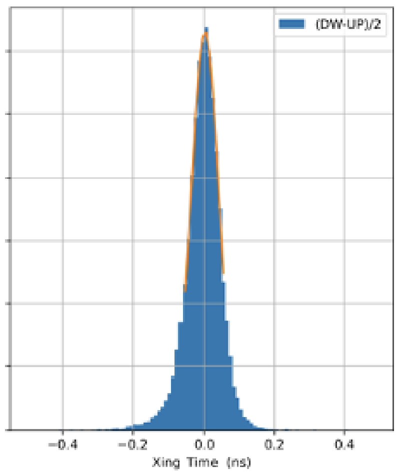
Timing difference between the average times of Downstream and Upstream SiPMs as a function of nominal electron beam energy. Peaks narrow with increasing energy.



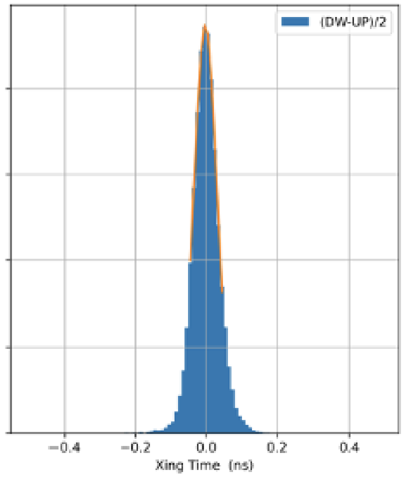
E_{beam} = 25 GeV



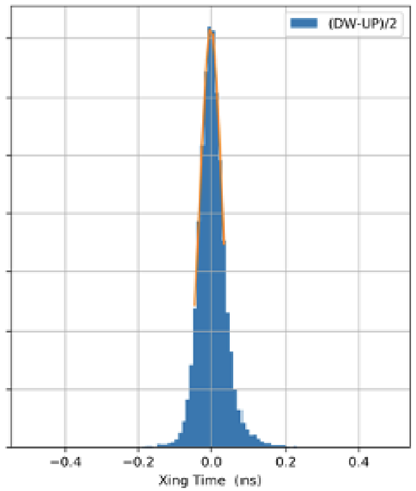
E_{beam} = 50 GeV



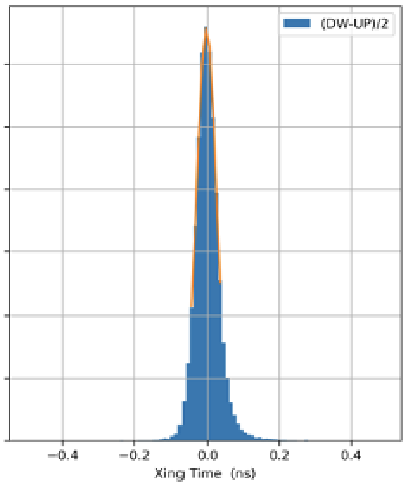
E_{beam} = 75 GeV



E_{beam} = 100 GeV

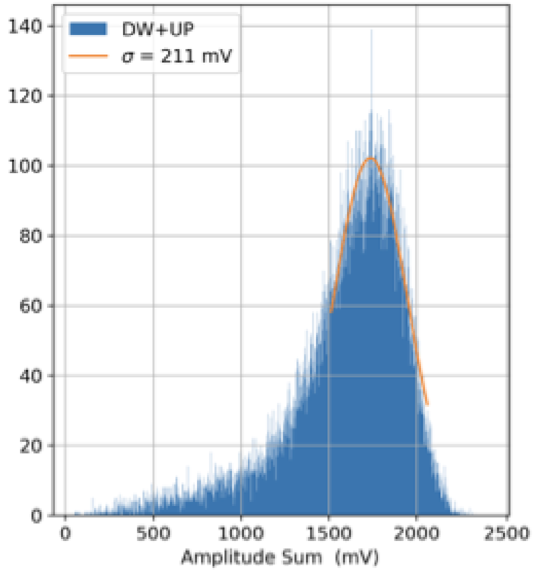


E_{beam} = 125 GeV

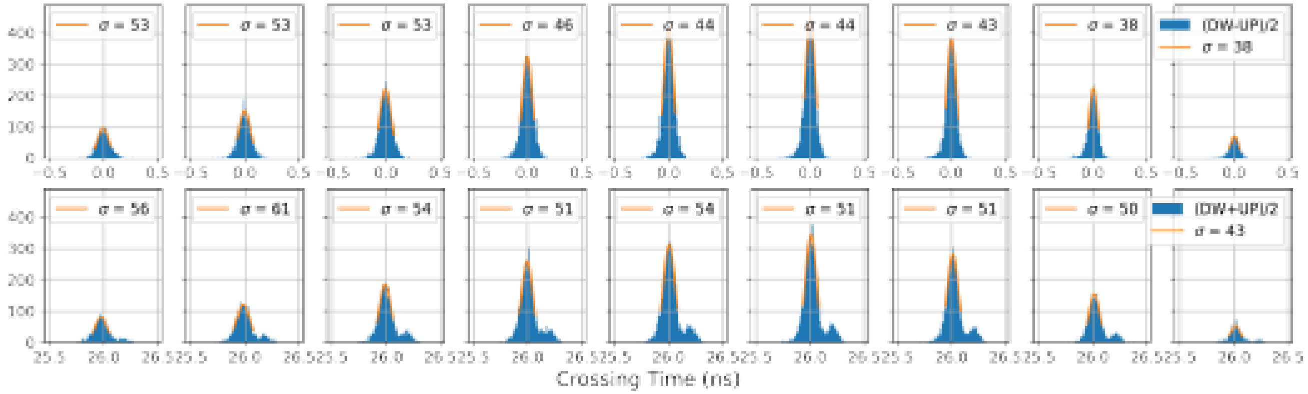


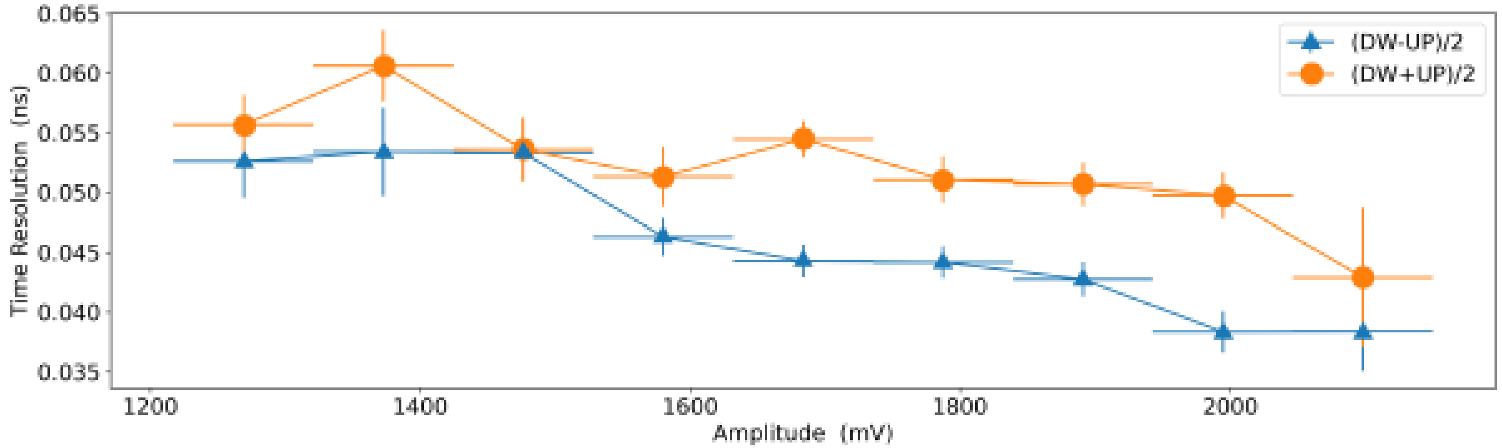
E_{beam} = 150 GeV

Best estimator method for finding timing resolution: Examine timing difference between upstream and downstream SiPM in bins of measured energy. 50 GeV beam example.



E_{beam} = 50 GeV



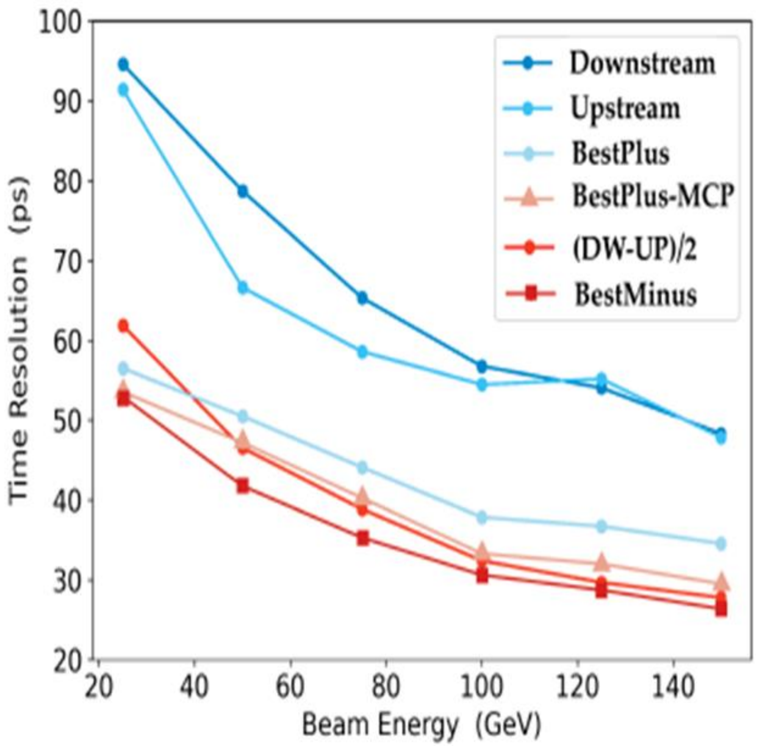


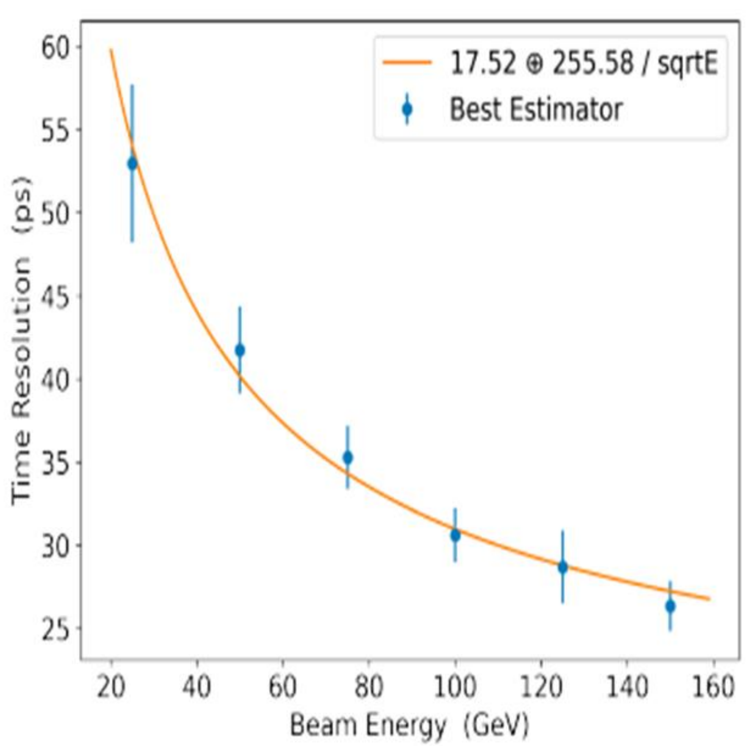
Divide measured low gain energy into nine bins. Plot timing difference for each of the nine bins. Note timing resolution improvement with detected energy amplitude.

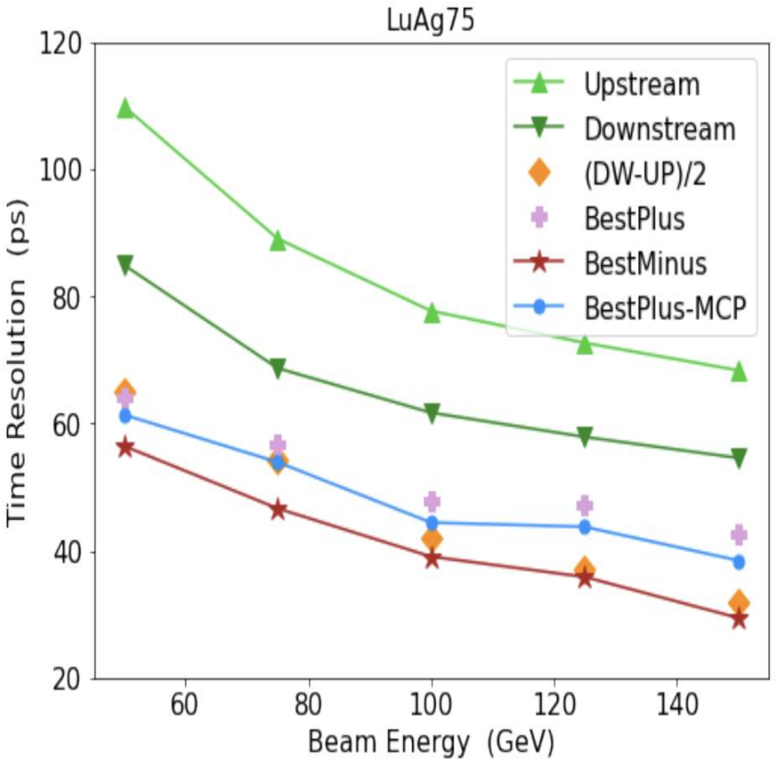
Timing resolution measurement methods and the best estimator of the time resolution (DSB1 and LuAG:Ce)

Detailed analysis of DSB1 WLS for the timing measurement.

Very preliminary analysis of LuAG:Ce WLS for the timing measurement. Work in progress…







RADiCAL Areas of Interest

- Current group member interests/expertise;
  - Inorganic Crystals and Ceramics - Caltech, Istanbul
  - Glass based Scintillators - Coe College, Iowa, Caltech
  - WLS materials - Coe College, Iowa, Notre Dame, Caltech
  - Capillary/Quartz waveguides - Coe College, Notre Dame
  - Modular Structures/Assemblies - Iowa, Coe College
  - Electronics/DAQ - Fermilab, Hofstra, Istanbul, Istanbul Cerrahpasa, Virginia, Yildiz Technical University
  - Photosensors - Virginia, Notre Dame, Fermilab
- Group Participation via:
  - EFCA DRD6 WP3: Optical Calorimetry
  - CPAD RDC9: Calorimetry

Scintillator and Wavelength Shifters

for optimization timing, position and energy

Some examples for study through a variety of methods utilizing RADiCAL modular structure and other methods

Example Scintillator Material (wavelength, type)	**Candidate Matched Wavelength Shifter (wavelength, type)**
LYSO:Ce (420nm) inorganic crystal	DSB1 (495nm) organic filament
LYSO:Ce (420nm) inorganic crystal	LuAG:Ce (510nm) ceramic filament
LuAG: Ce (510 nm) crystal, ceramic	Quantum Dots (580nm) glass or ceramic
LuAG: Pr (310 nm) crystal, ceramic	pTP (350nm) organic filament
CeF_3 (330nm) crystal	pTP (350nm) organic filament
CeF_3 (330nm) crystal	Flavonols (530-560nm) organic filament
Lu_2O_3:Yb (370nm) ceramic	Flavonols (530-560nm) organic filament
BaF_2:Y (220nm, fast component) crystal	Under study

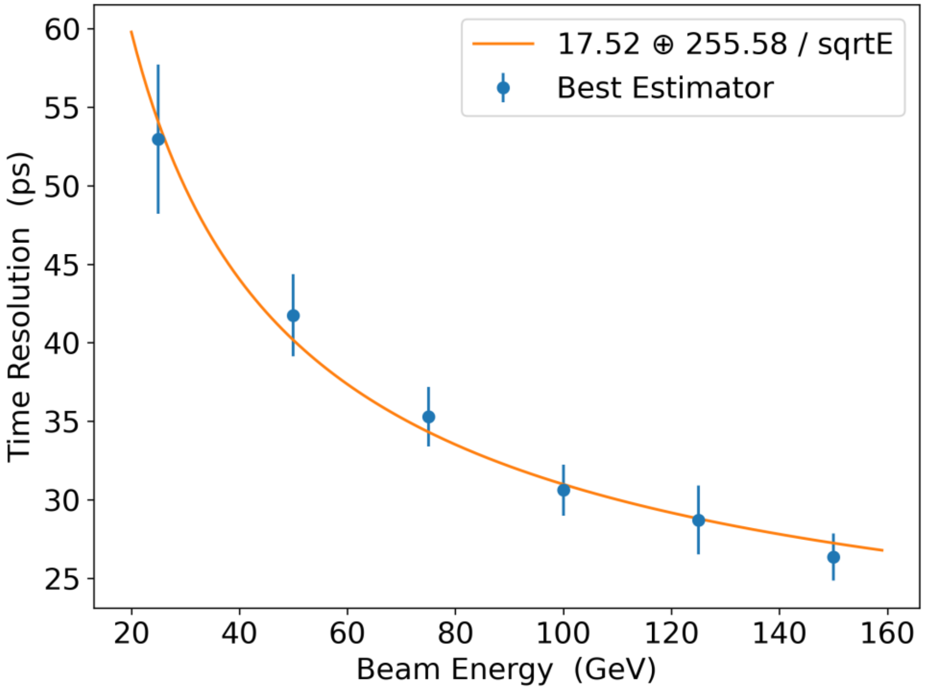
Summary of recent EM shower max timing results:

See: C. Perez-Lara, et al, arXiv:2401.01747, submitted to NIMA

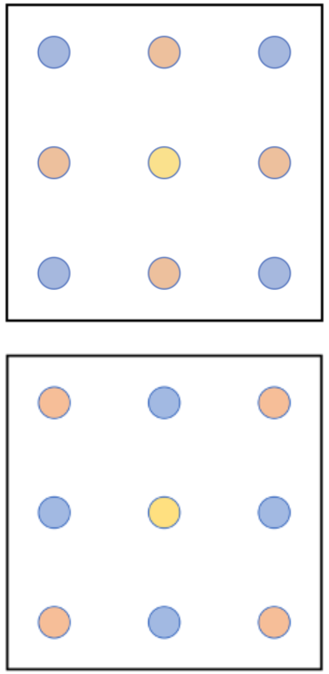
Time resolution vs electron energy

From test run at CERN H2, May 2023

Current estimate of liming time resolution of 17.52 ps at current level of analysis



Ongoing R&D Efforts. Structure for further study: both timing and energy capillaries to reach objectives for timing and energy resolution. Beam testing. Radiation testing.



Blue - Timing

Orange - Energy

Yellow - T or E or depth

Scintillating tile size and thickness

Scintillation materials

Compatible WLS materials

Waveguides/Capillaries

Photosensors

High and Low Gain Amplification

Summary

- RADiCAL R&D to develop highly efficient, ultra-compact and rad hard EM calorimetry elements with precision timing capability.
- Development and testing of modular elements that can provide:
    1. Shower Max timing measurement.
    2. Energy measurement.
    3. EM Shower Position derived from the region of shower max where the shower cross section is confined within a radiation length.
- Potential applications of the technique or components in other areas:
    - Endcap and Forward Calorimetry
    - Timing detectors
    - Scintillation/WLS detection over compact regions

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