Advanced Optical Instrumentation for Ultra-compact, Radiation Hard EM Calorimetry

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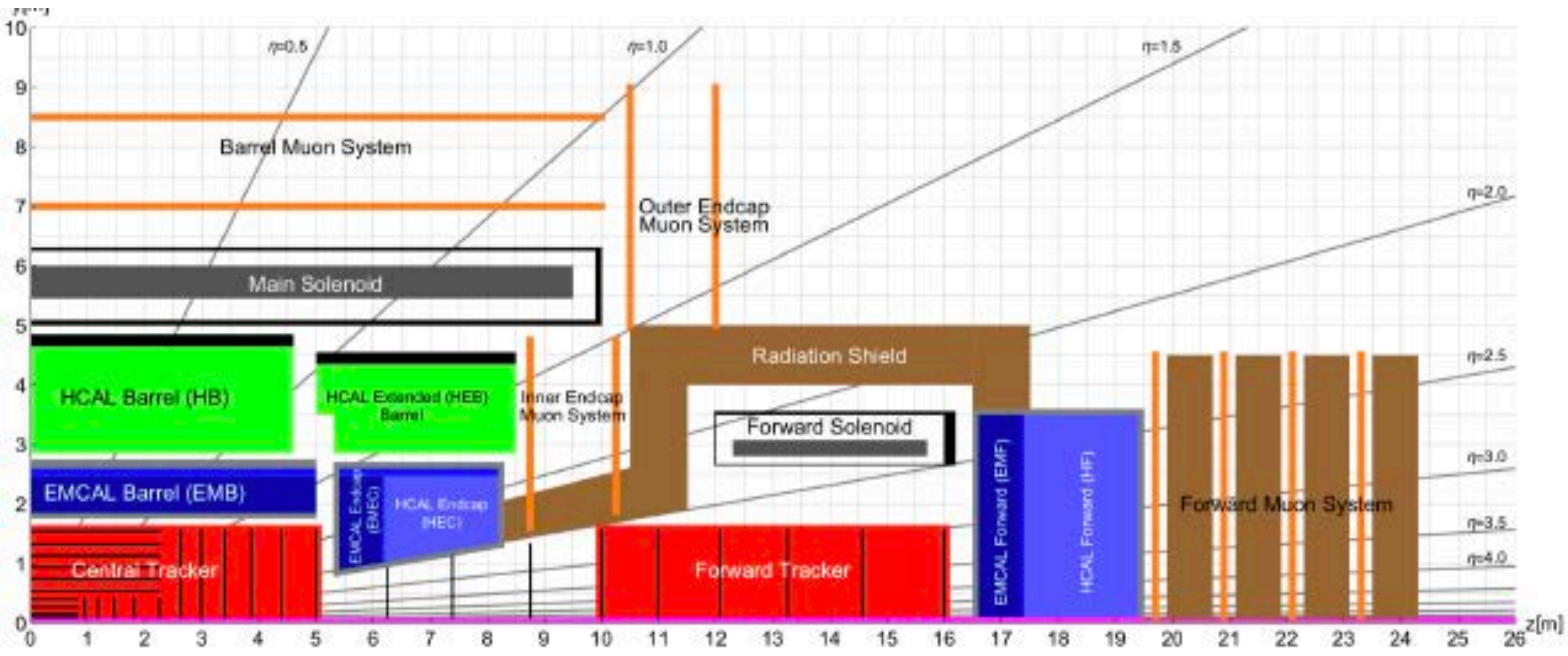
Topics in this presentation:

- The FCC calorimetry environment (next two slides) taken from:

  M. Aleksa, et al, Calorimeters for the FCC-hh,

  CERN-FCC-PHYS-2019-0003, 23 December 2019.

- The R&D interests of this LOI group, in pursuit of potential EM calorimetry and other options relevant to the FCC-hh environment.



	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	$\lvert z \rvert < 5$	$\lvert\eta\rvert < 1.67$	0.1	5
EMEC	0.82–0.96	2.7	$5.3 < \lvert z \rvert < 6.05$	$1.48 < \lvert\eta\rvert < 2.50$	1	30
EMF	0.062–0.065	3.6	$16.5 < \lvert z \rvert < 17.15$	$2.26 < \lvert\eta\rvert < 6.0$	5000	5000
HB	2.85	4.89	$\lvert z \rvert < 4.6$	$\lvert\eta\rvert < 1.26$	0.006	0.3
HEB	2.85	4.59	$4.5 < \lvert z \rvert < 8.3$	$0.94 < \lvert\eta\rvert < 1.81$	0.008	0.3
HEC	0.96-1.32	2.7	$6.05 < \lvert z \rvert < 8.3$	$1.59 < \lvert\eta\rvert < 2.50$	1	20
HF	0.065–0.077	3.6	$17.15 < \lvert z \rvert < 19.5$	$2.29 < \lvert\eta\rvert < 6.0$	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.

From M. Aleksa, et al, op cit

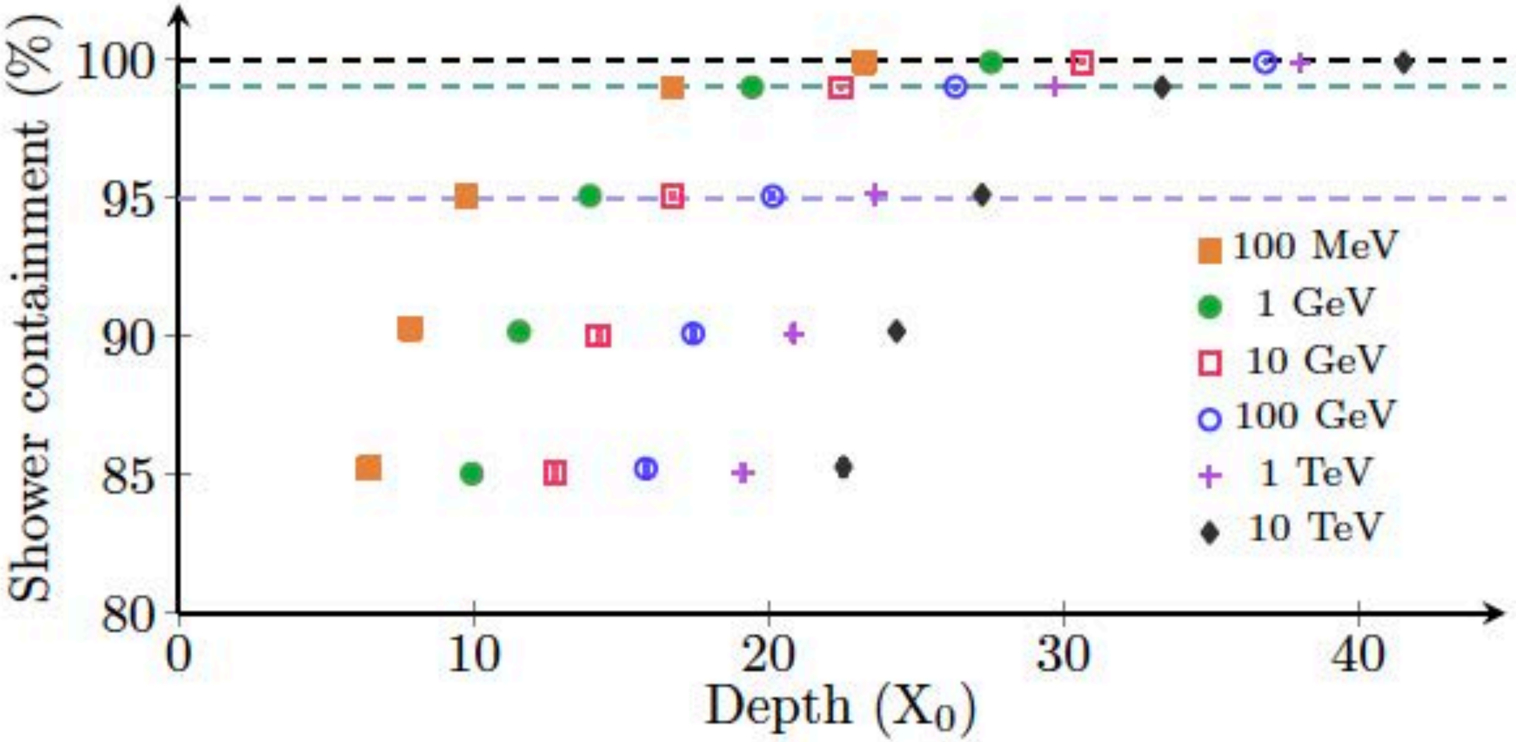


Figure 4: Dependence of the electron shower containment on the calorimeter depth expressed in the radiation lengths. The horizontal lines correspond to the shower containment of 95%, 99% and 100% respectively.

From M. Aleksa, et al, op cit

EM Calorimetry

Desirable Features

- Very Compact Dimensions
- Excellent energy resolution
- High efficiency
- Fast response
- Triggerability
- Good shower position

Challenges

- Radiation Environment
  - Ionization dose
  - Proton fluence
  - Neutron fluence
- Transverse Uniformity
- Longitudinal Uniformity
- Event pileup

EM Calorimetry Approach

- Objectives
  - Energy Resolution: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.3/E \oplus 0.7\%$ up to $|\eta| < 4$.
  - Fast response.
  - Good performance under FCC-hh operating conditions
- Technique - Sampling Calorimetry
  1. Use of dense materials to minimize transverse size and depth
     - Maintaining the Molière Radius as small as possible
     - Modular material with depth ~ 30 X_o but ~ 1 λ
  2. Use of radiation resistant materials and elements
     - Active elements including crystal/ceramic scintillators and waveshifters
     - Optical transfer elements
     - Geiger mode pixelated photosensors
  3. Use of optical techniques for fast signal collection
     - Keeping optical paths as short as possible

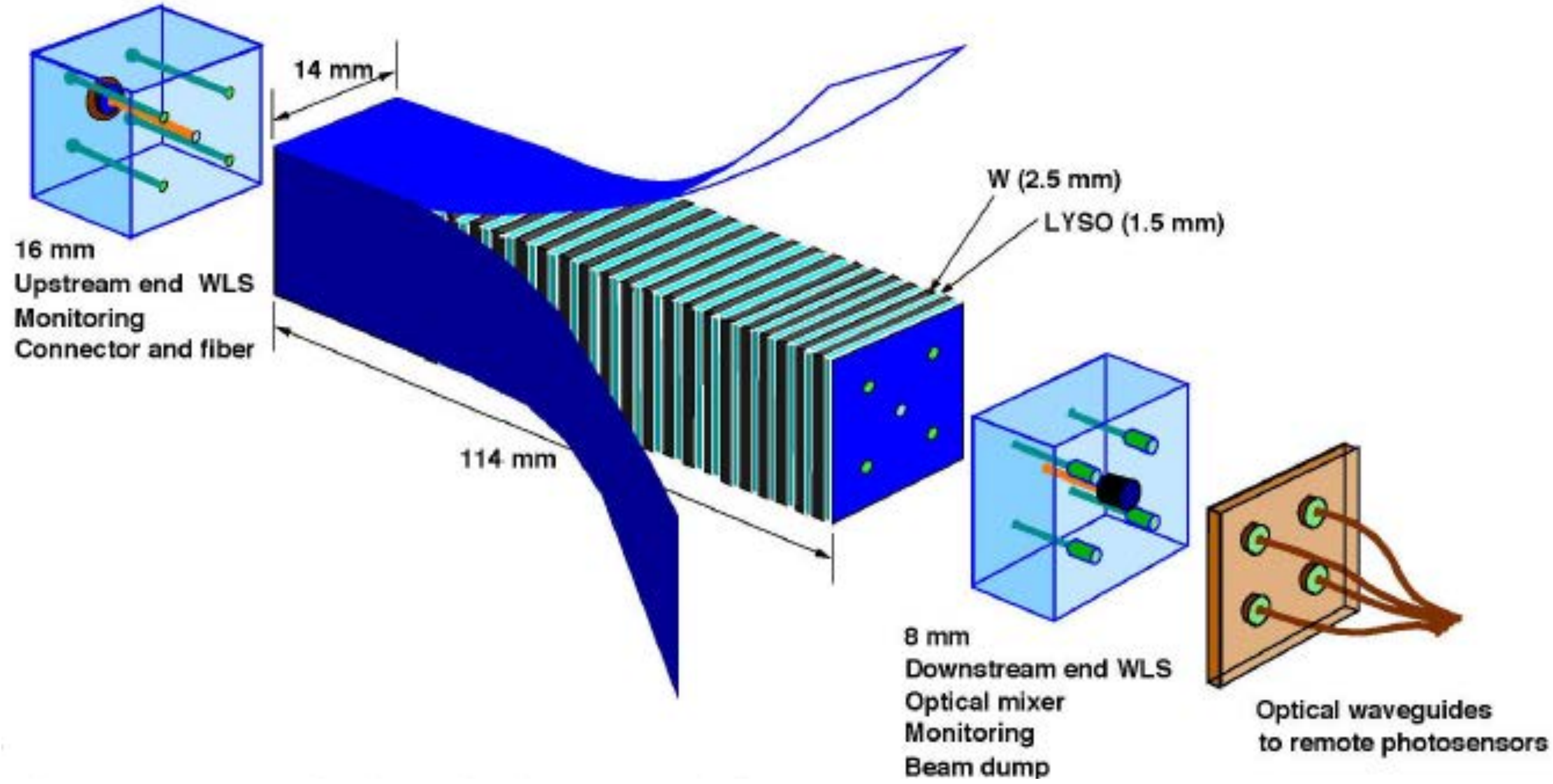
A W/LYSO:Ce optical EM calorimetry module

29 Layers LYSO:Ce (1.5mm thickness)
28 Layers W (2.5mm thickness)

Dimensions 14mm x 14mm x 114mm
Depth 25 X_o and < 1 λ

The left hand end points in the direction of the IP of the experiment.

A sampling EM Calorimetry module considered for HL-LHC operation.



LYSO:Ce comparison with $PbWO_4$

	W/LYSO(Ce)	$PbWO_4$
Length (mm)	114	220
Transverse size (mm)	14	28.6
Average Molière Radius (mm)	13.7	21
Average Radiation Length X_o(mm)	5.1	8.9
Crystal Light Yield (relative to NaI = 100)	85	0.3
Emission Wavelength	420	425
Decay time (ns)	40	25
Light Output (p.e./MeV)	6-8	2
Temp Dependence (%/C)	-0.2	-2.2

Scintillation materials under investigation…

1. Inorganic scintillation crystals and ceramics are the preferred approach because of material density and light efficiency.
   - LYSO, LuAG, GGAG, GYAG, GLuAG…
   - Ce 3+, Pr 3+ doping and also Ca co-doping.
   - Rad hardness of LYSO studied up to 300Mrad ionization dose and neutrons up to 9×10^{15} n_{eq}/cm^2 and protons up to 8×10^{15} p/cm^2.
   - Currently LYSO + SiPM are the key elements of the CMS BTL.
2. Some novel scintillating ceramics such as LuAG:Ce have a better radiation hardness than LYSO.
3. Variously other options such as glass plates with $CsPbX_3$ (where X = Cl, Br, I or Cl/Br or Br/I) quantum dots with tunable wavelengths.

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 1[st] 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

Wavelength shifters and optical transmission elements under investigation…

- If photosensors cannot be positioned proximately to the scintillator, efficient and fast waveshifting of the scintillation light and light transfer to remotely placed photosensors is needed.

- WLS materials specialized to different scintillators
  - To shift 420-425nm to 490-500nm
    - WLS dyes DSB1 and DSF1
    - Fast decay time and high efficiency
  - To shift 350-380nm to 530-560nm
    - WLS dyes based on hydroxyflavones
    - Rapid decay time, good efficiency and very long path length light transmission
  - To shift 520nm to longer wavelengths
    - WLS dyes under study including quantum dots

- Optical transmission elements
  - Capillaries – sealed and liquid WLS filled thick-walled quartz structures
    - Studied to 250Mrad ionization dose and up to 10^{15} p/cm^2.
  - Solid fiber materials, including quartz
  - Novel optical transmission elements such as photonic fibers

Photosensor development

- SiPM Technology
  - Pixelated Geiger-mode devices with high photo efficiency across a broad spectral range.
  - Particularly effective for longer wavelength light detection.
  - Already impactful for light detection of:
    - CMS BTL - LYSO emission (420nm)
    - CMS HCAL - Y11 emission (500nm)
    - In our R&D:
      - DSB1 emission (490nm)
      - LuAG:Ce (520nm)
      - Hydroxyflavone emissions (530-560nm)
  - Intention is to exploit and further the development of localized cooling of the SiPM to reduce noise and extend performance lifetime
  - Continue the development of small pixel devices (5-7μm) for efficiency and response time.

Photosensor development

- Larger Band-gap Technologies
  - Hold promise for operation in very high radiation environments, but it is still rather early days in this R&D in spite of several device versions produced.
  - GaInP pixelated devices have been fabricated so significant progress there.
  - Individual photon counting seen, similar to SiPM.
  - Device optimization needed to reduce surface currents seen in the latest version.

  - Challenge here is the lack (currently) of a broad commercial market to help drive development.   Needs an interested and engaged commercial fabrication house to proceed more effectively.

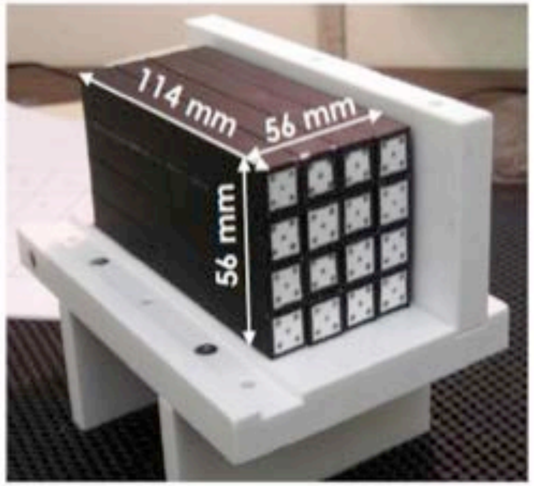
Testing

- Beam tests of modular structures
  - Components
  - Individual modules
  - Modular arrays
- Irradiations of device elements and components
  - Scintillators
  - Waveshifting elements
  - Photosensors

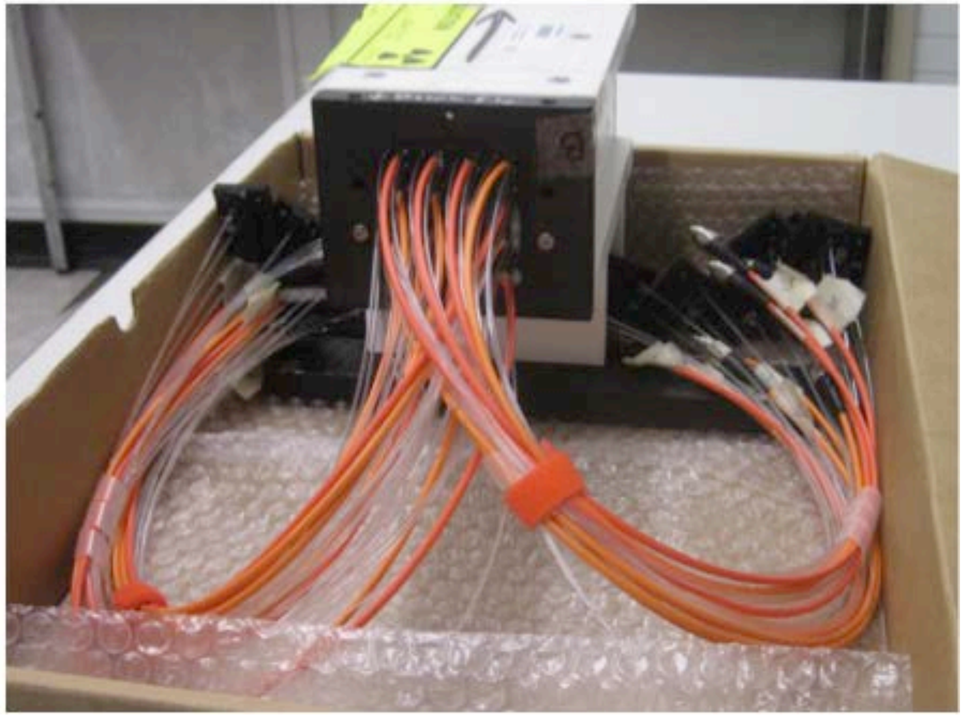
A 4x4 array of W/LYSO:Ce with DSB1 WLS Capillaries

Beam Test
Caltech, Iowa
Notre Dame
Virginia

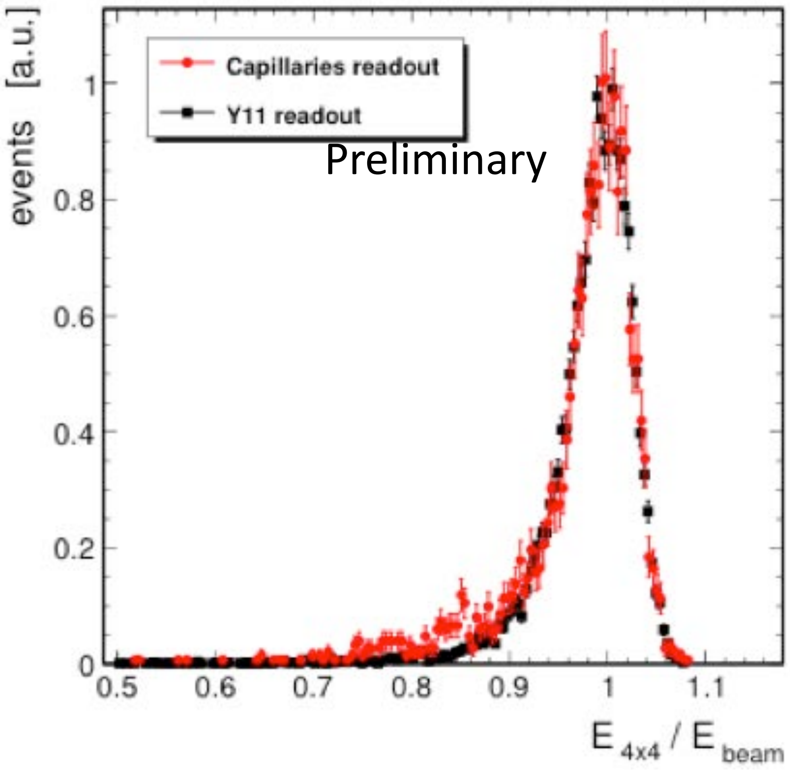
Array tested at CERN H4 and performance compared with earlier measurements using Y11 WLS fibers.



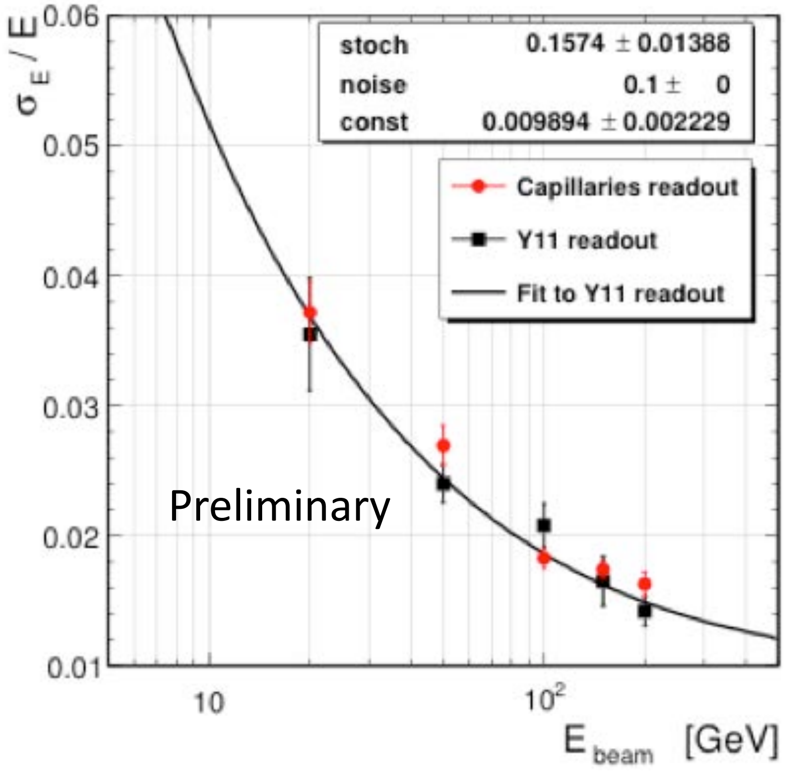
BEAM



Energy Resolution of the compact 4x4 array of W/LYSO modules.



Measured 4x4 energy compared to th
e CERN H4 beam energy for
100 GeV electrons.



Energy resolution vs electron
beam energy. CERN H4.

Summary

- R&D to develop highly efficient, compact and rad hard EM calorimetry elements.
- Applications are broad.
  - Hadronic calorimetry
  - Forward calorimetry
  - Scintillation detection over compact and larger areas
  - Timing applications
- Applications to other research fields.

- <u>Acknowledgement and thanks</u>: Work supported by the DOE/OHEP Instrumentation Research program and the NSF Division of Physics