Inorganic Scintillators for Future High Energy Physics Experiments

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Presented by Ren-Yuan Zhu, Caltech, in the Calor 2024 conference, Tsukuba, Japa

Why Inorganic Scintillators?

arXiv: 2203.06731 and arXiv: 2203.06788

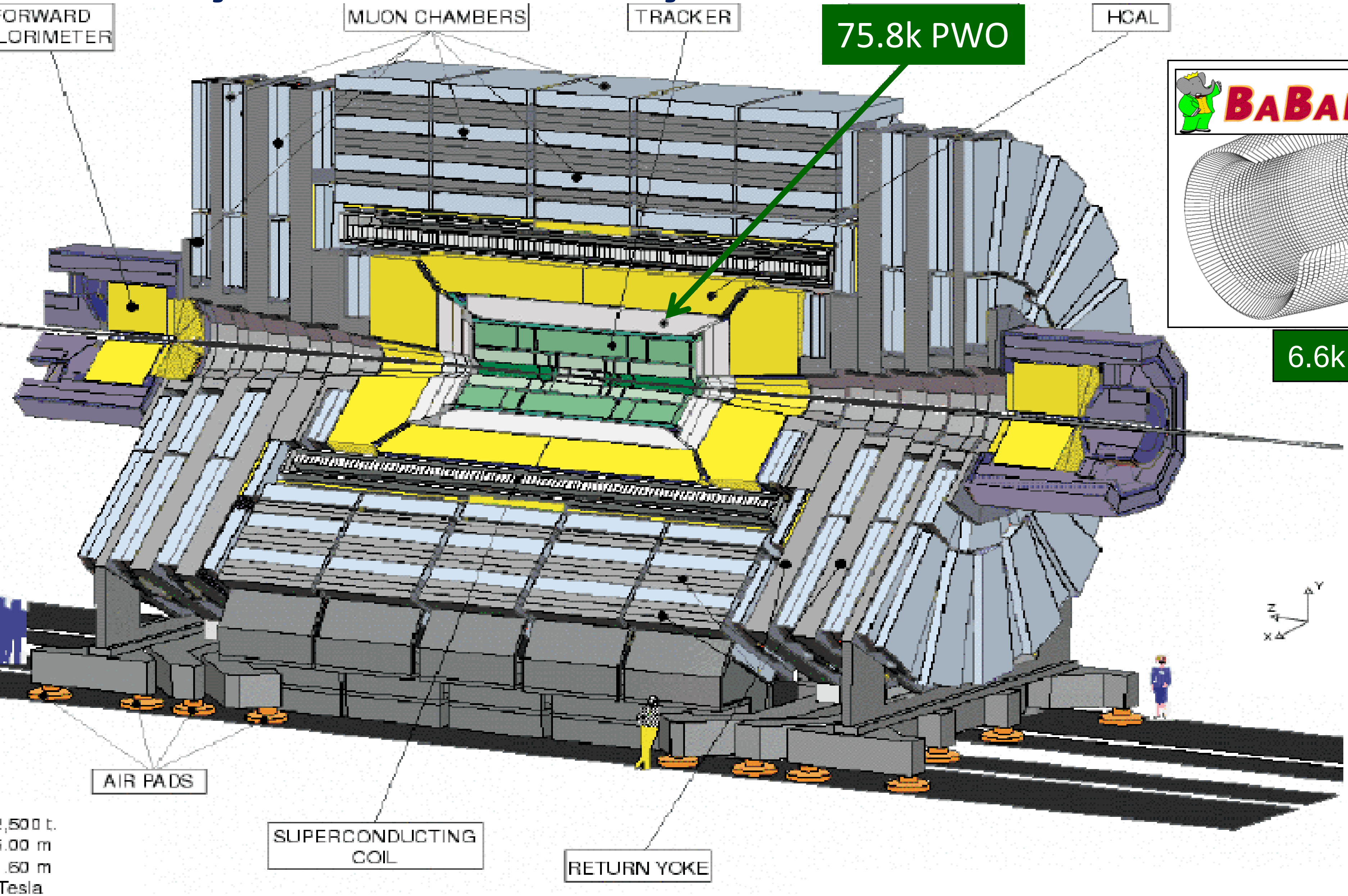
- **Precision e/γ enhance physics discovery potential.**
- **Performance of total absorption ECAL is well understood for e/γ and jets:**
  - **Energy resolution achieved:** $2\%/\sqrt{E} \oplus 1\%$
  - **Position resolution: sub-mm can be achieved;**
  - **Good identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout: C/S light or S/L gate.**
- **On-going Development in Caltech Crystal Lab:**
  - **Rad-hard LYSO:Ce crystals and LuAG:Ce ceramics (RADiCAL) for HL-LHC and FCC-hh;**
  - **Ultrafast BaF_2:Y and Lu_2O_3:Yb for future ultrafast calorimetry and time of flight;**
  - **Cost-effective ABS and DSB glasses for Higgs factory (CalVision) and HHCAL.**

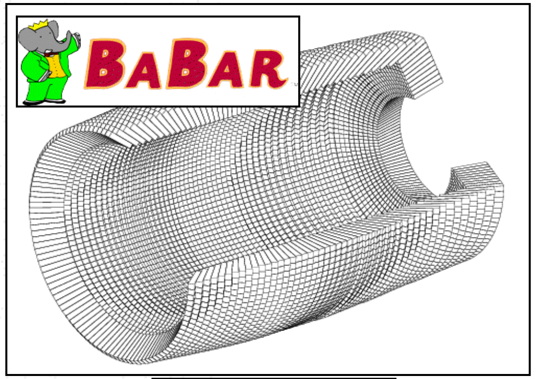
Crystals Used in HEP Calorimeters

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	BGO	LYSO:Ce	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index[a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence[b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	-
Decay Time[b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	-
Light Yield[b,c] (photons/MeV)	38,000	63,000	1,400 420	13,680 1,560	8,000	32,000	114 40	-
d(LY)/dT[b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	-
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV Mu2e	TAPS Mu2e-II	L3 BELLE	COMET CMS BTL PIONEER	CMS ALICE PANDA ePIC	A4 G-2

a. at emission peak; b. up/low row: slow/fast component; c. with QE of readout device taken out.

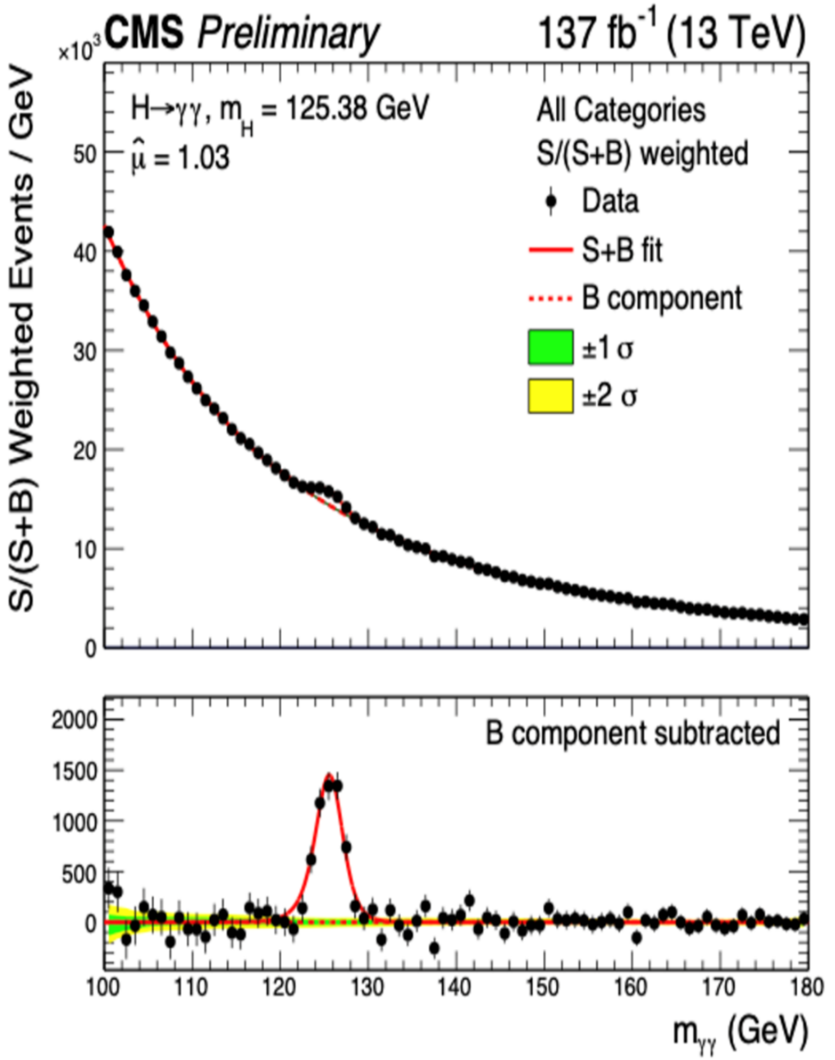
L3 BGO, BaBar CsI, CMS PWO ECAL

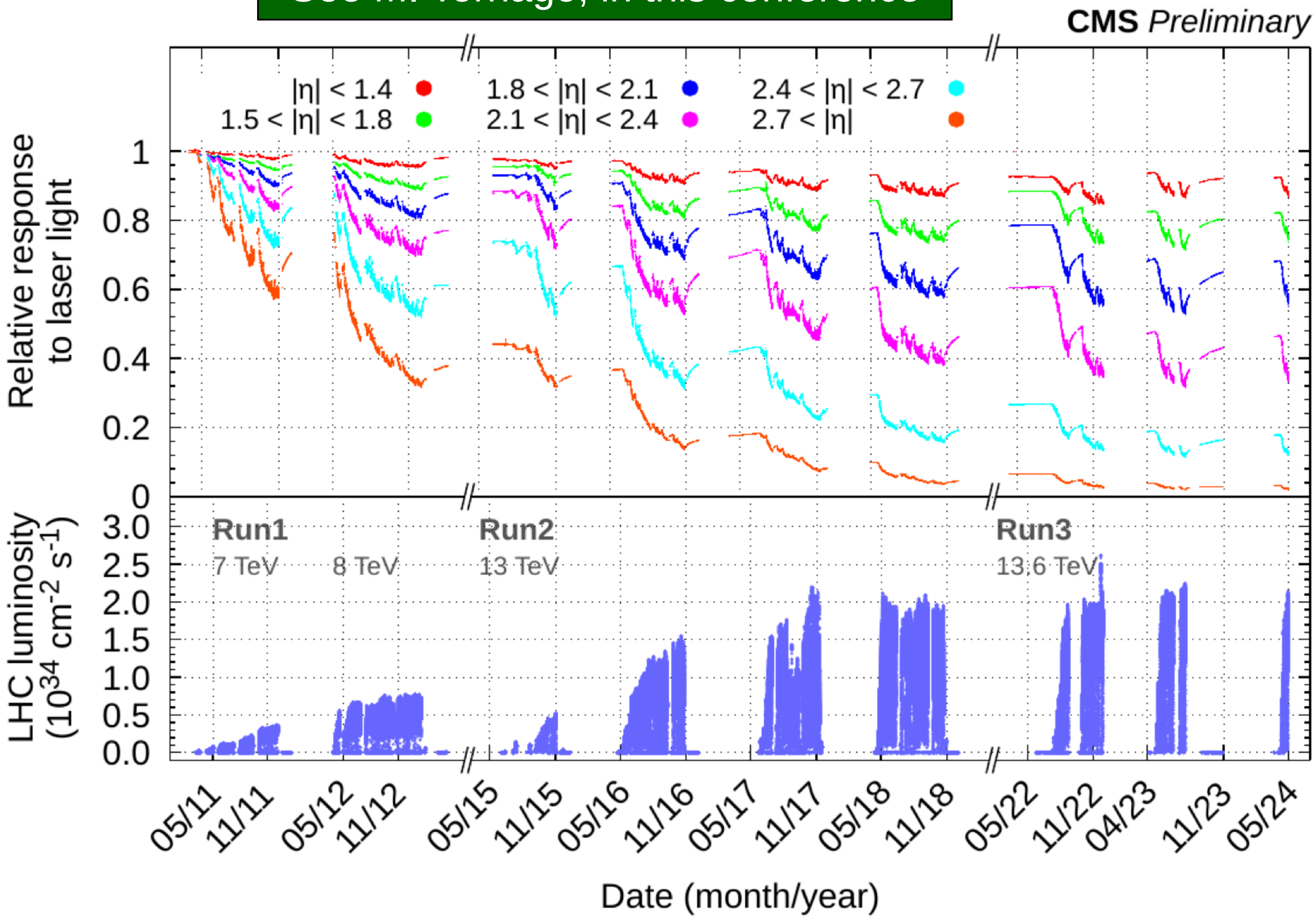




CMS H -> γγ and PWO Damage

See M. Tornago, in this conference



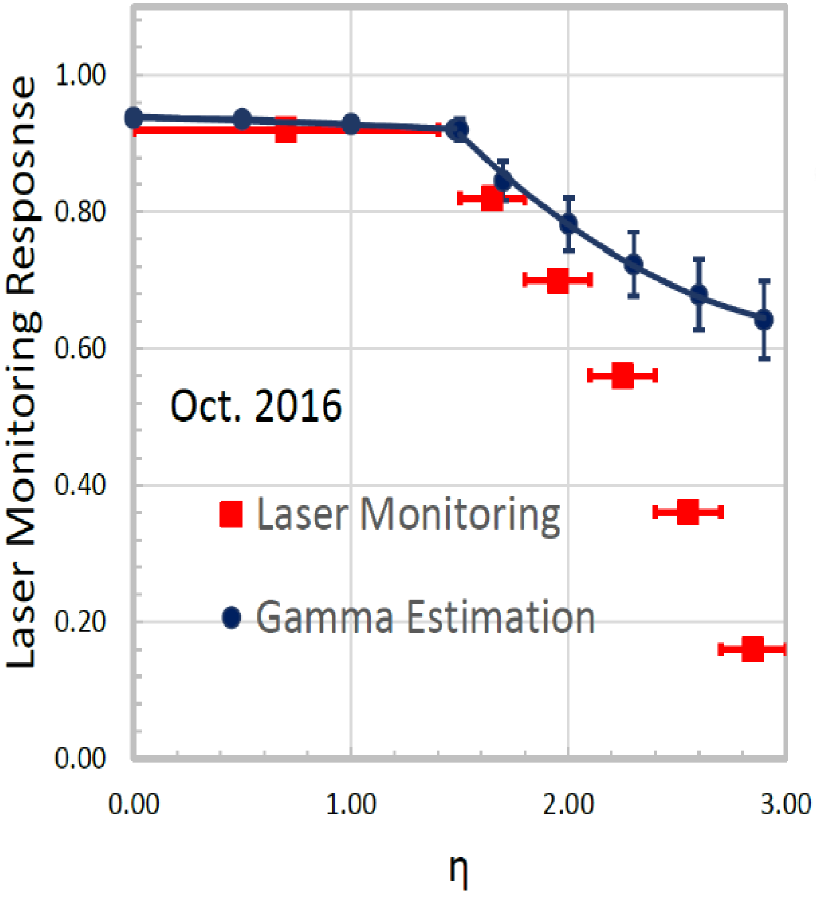


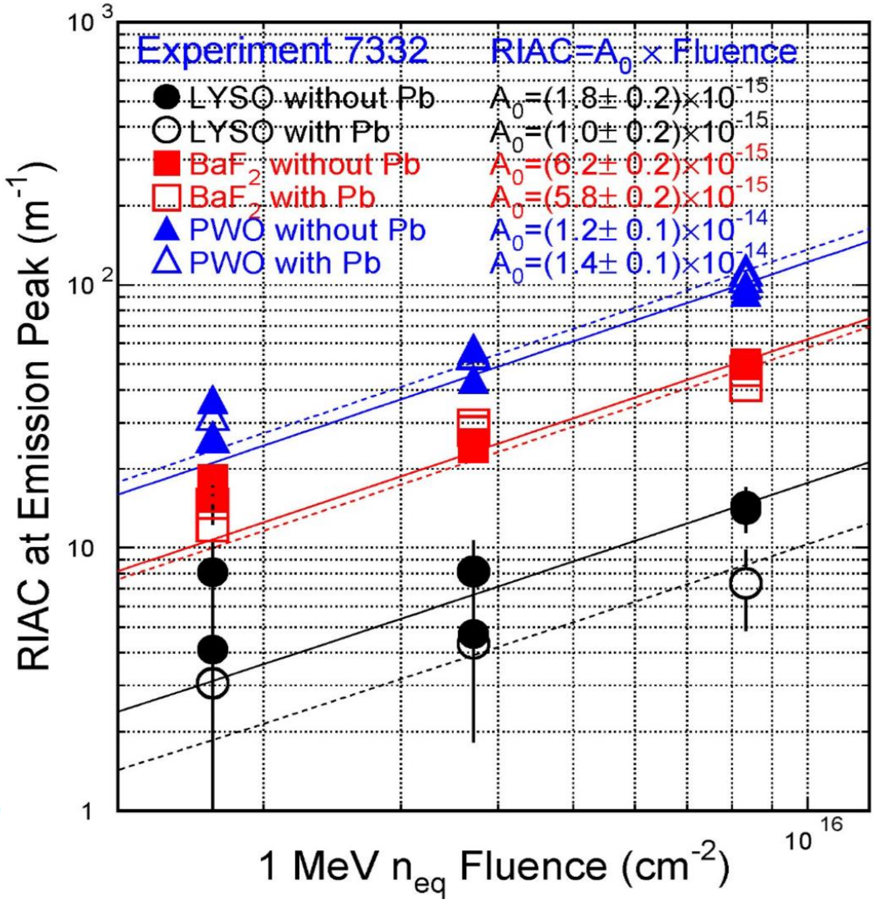
PWO damage caused by ionization dose and hadrons

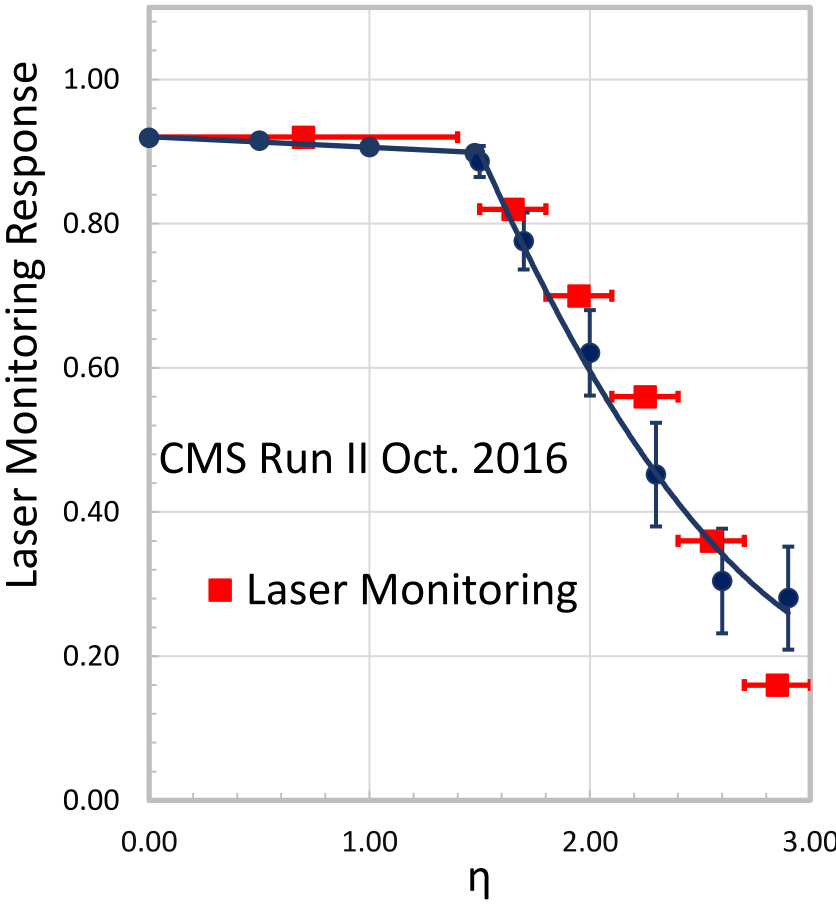
PWO Damage by Ionization & Neutrons

RIAC in PWO = $1.4 \times 10^{-14} \times$ 1 MeV n_{eq} Fluence

γ-ray and hadron induced absorption explains CMS PWO monitoring data
http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf & Trans. NS. 67 (2020) 1086-1092







DOE Basic Research Needs Study
Priority Research Directions for Calorimetry

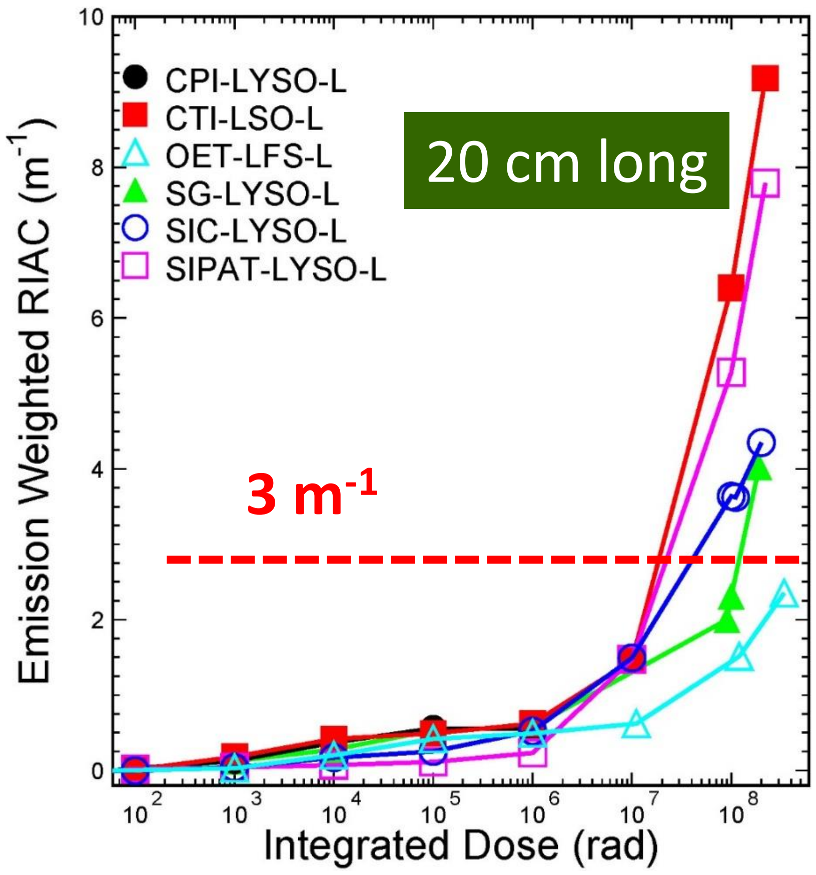
- Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements;
- Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments;
- Develop ultrafast media to improve background rejection in calorimeters and particle identication detectors.

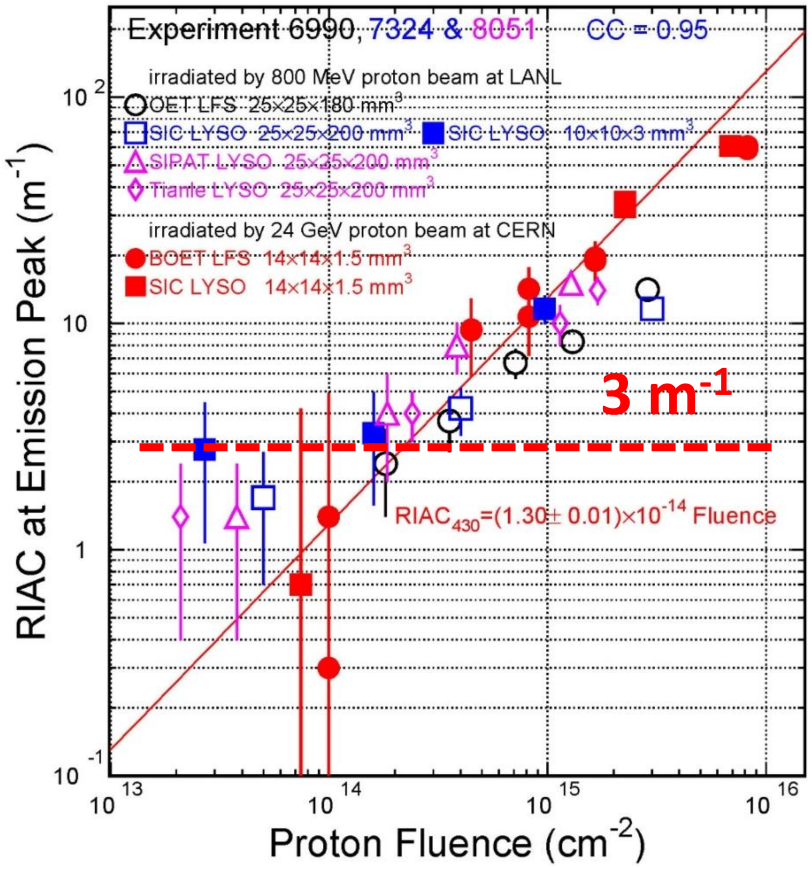
DOE 2019: https://www.osti.gov/servlets/purl/1659761
ECFA 2021: https://cds.cern.ch/record/2784893
Snowmass 2021: https://arxiv.org/abs/2209.14111
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators

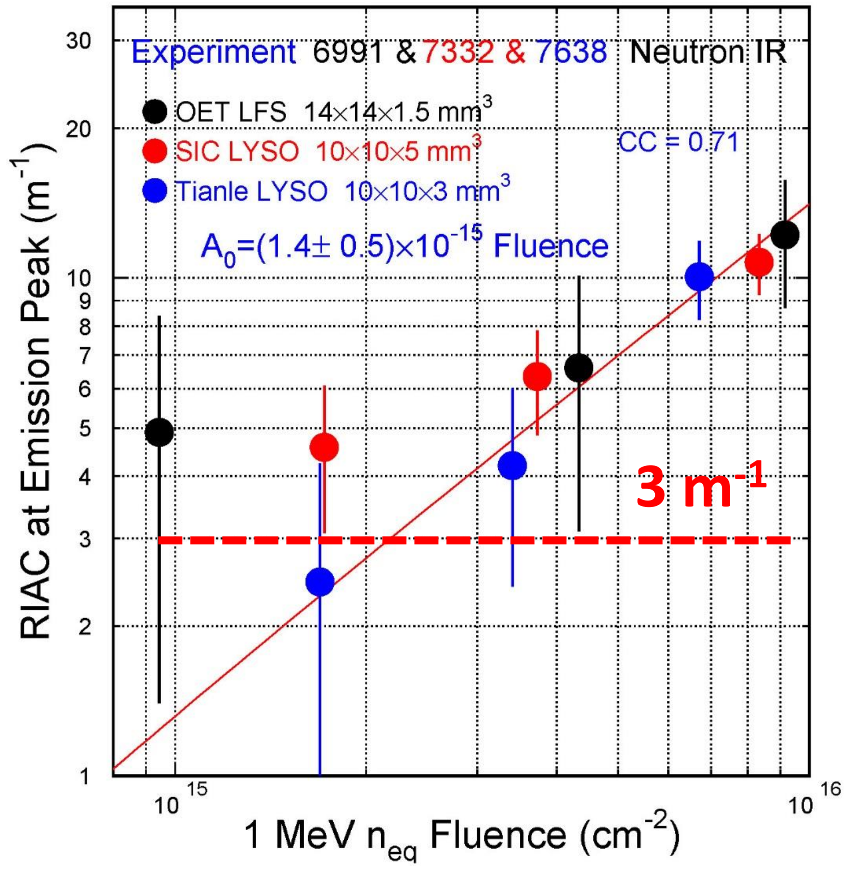
LYSO:Ce Radiation Hardness

IEEE TNS 63 (2016) 612-619

CMS BTL LYSO spec: RIAC < 3 m^{-1} after 4.8 Mrad, 2.5 x 10^{13} p/cm^2 and 3.2 x 10^{14} n_{eq}/cm^2







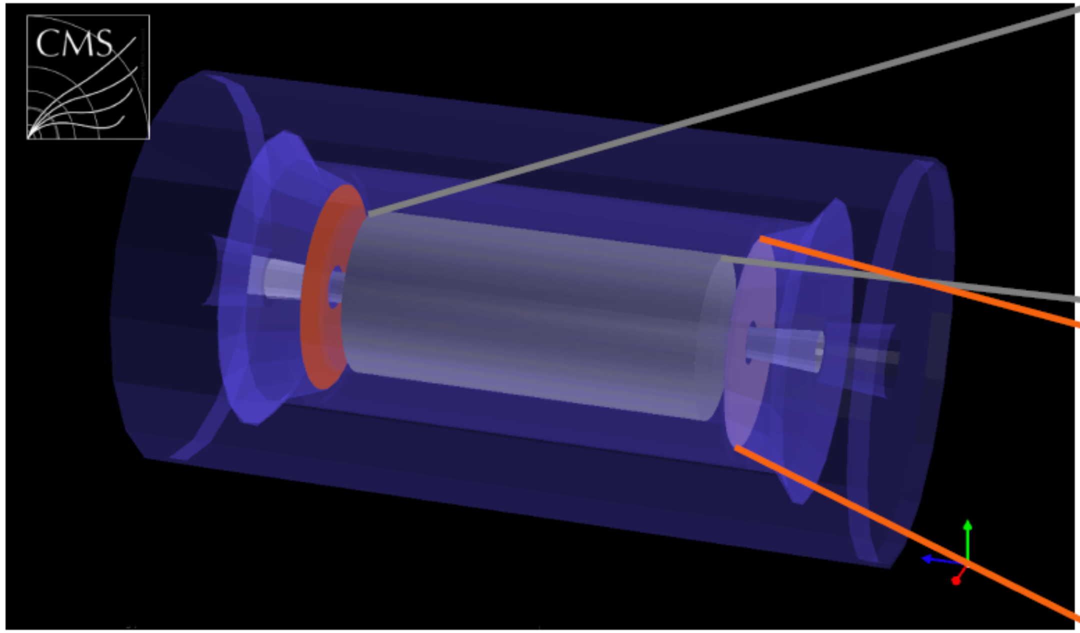
Damage induced by protons is larger than that from neutrons because of ionization energy loss in addition to displacement and nuclear breakup

LYSO:Ce for CMS MIP Timing Detector

MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

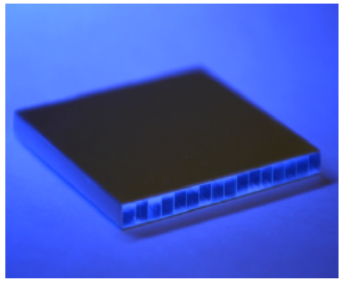
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

Ultrafast inorganic scintillators would help to break the pico-second time barrier



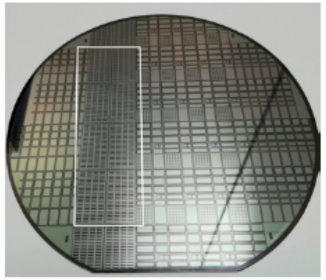
BTL: LYSO bars + SiPM read-out

- TK / ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2



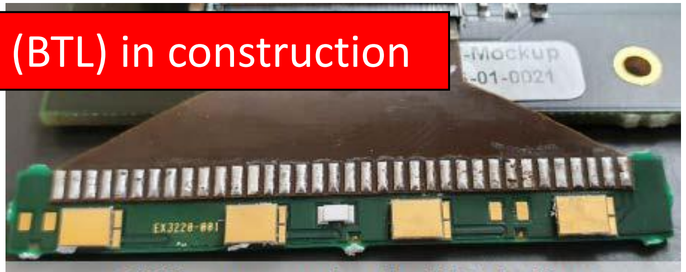
ETL: Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



LYSO + SiPM with Thermal Electric Cooler (TEC) for CMS Barrel Timing Layer (BTL) in construction

SiPM array prototypes from FBK

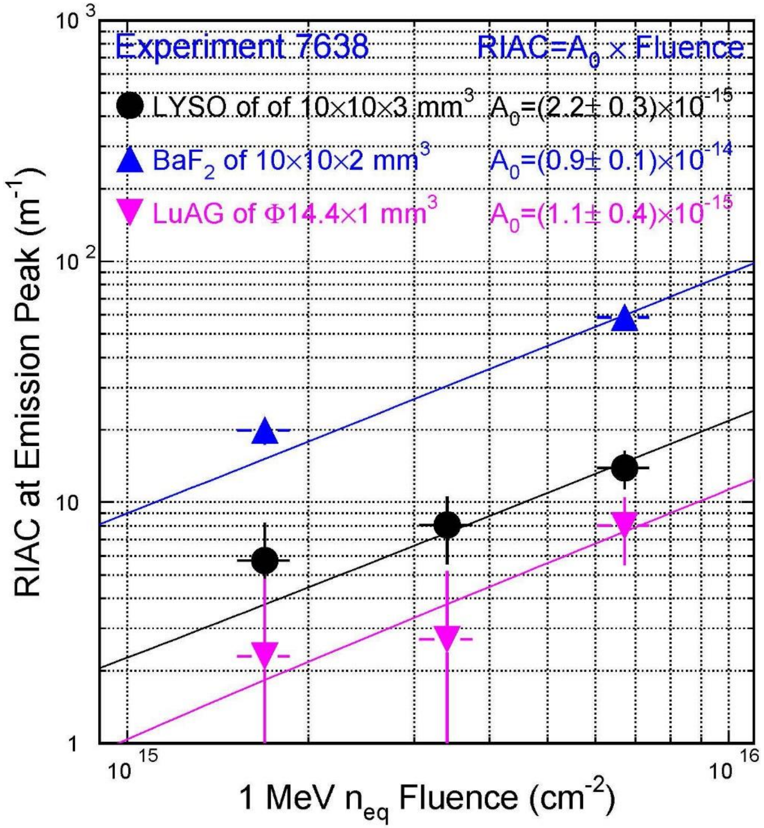


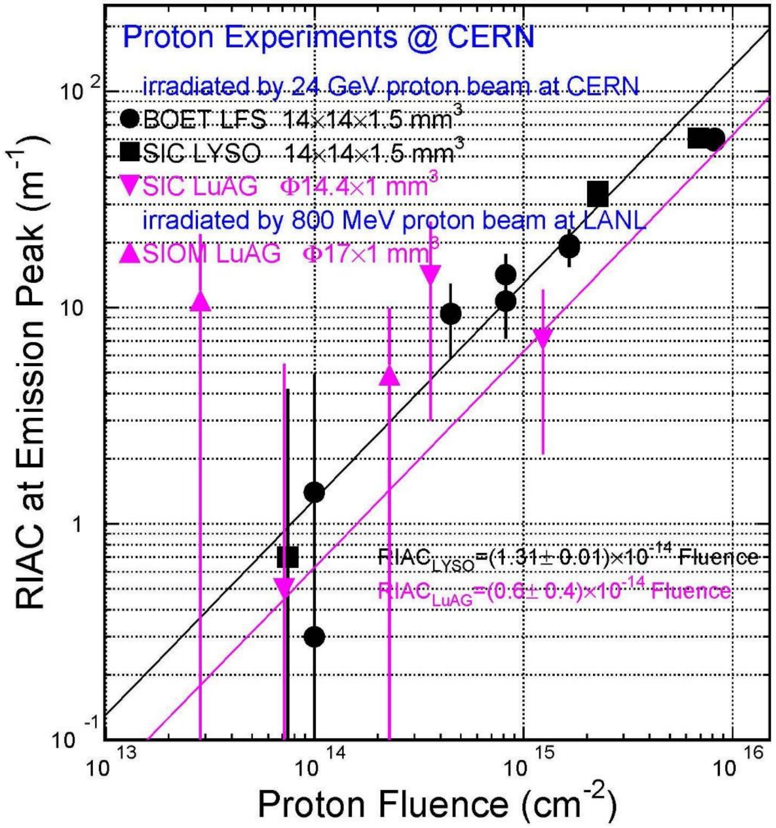
SiPM arrays mockup for TECs testing

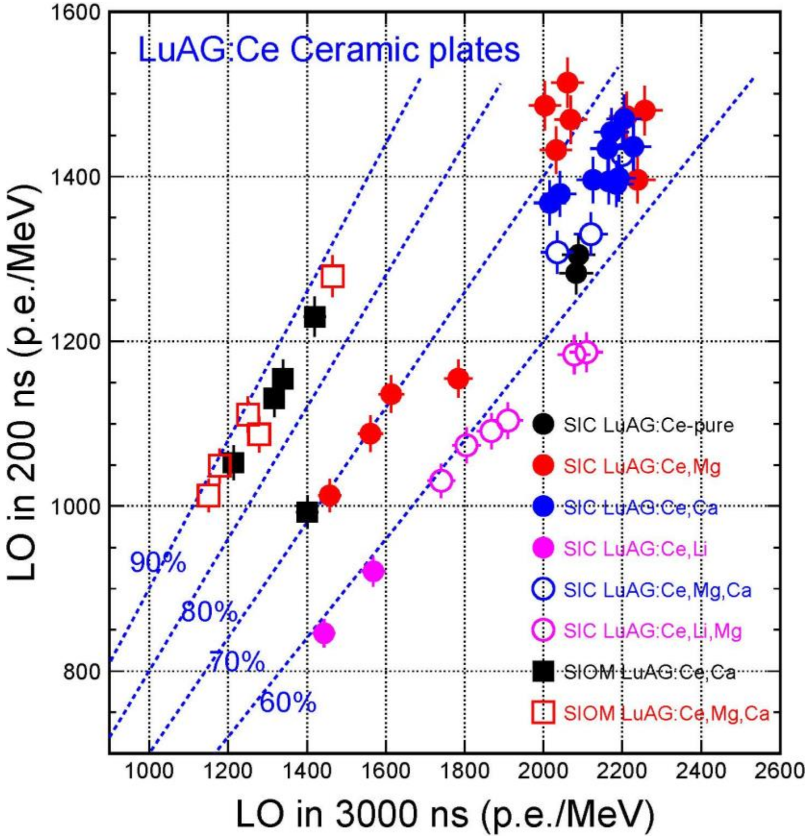
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

LuAG:Ce ceramics show a factor of two smaller RIAC values than LYSO:Ce up to 6.7$\times 10^{15}$ n_{eq}/cm^2 and 1.2$\times 10^{15}$ p/cm^2, promising for FCC-hh

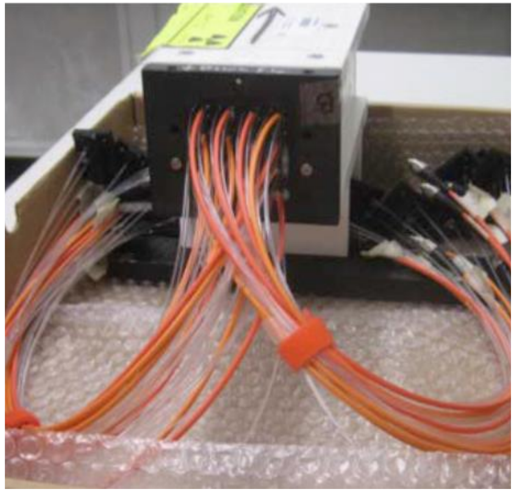


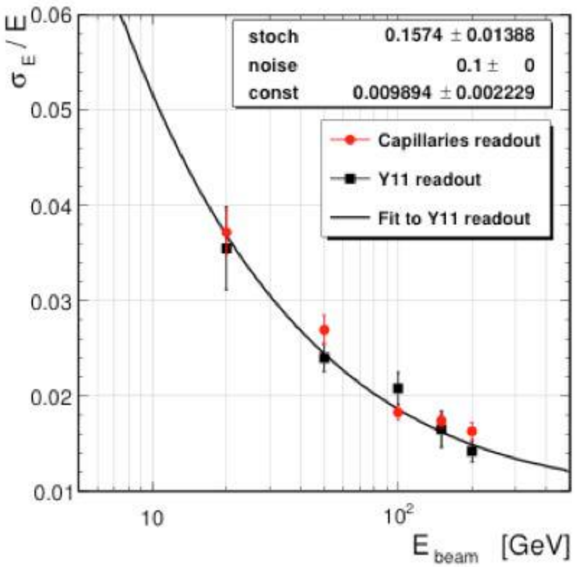




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

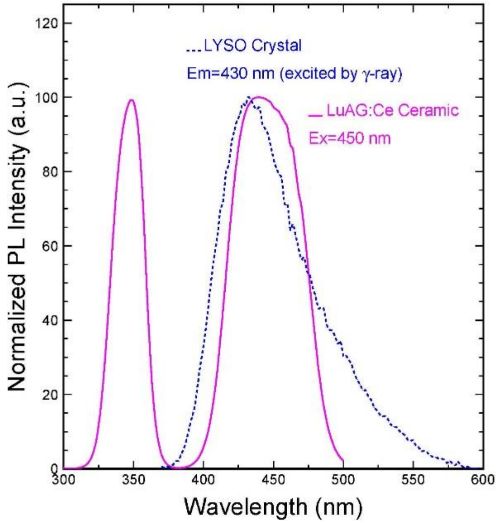
RADiCAL: LYSO/LuAG Shashlik ECAL

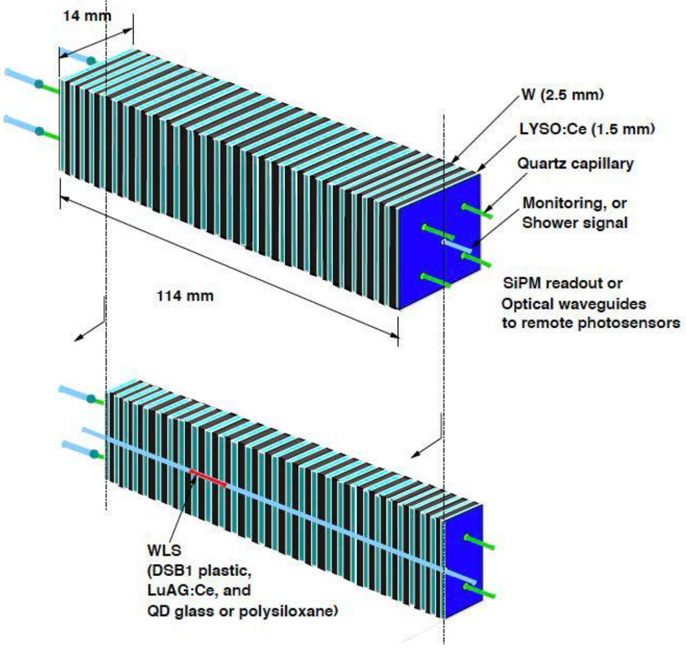


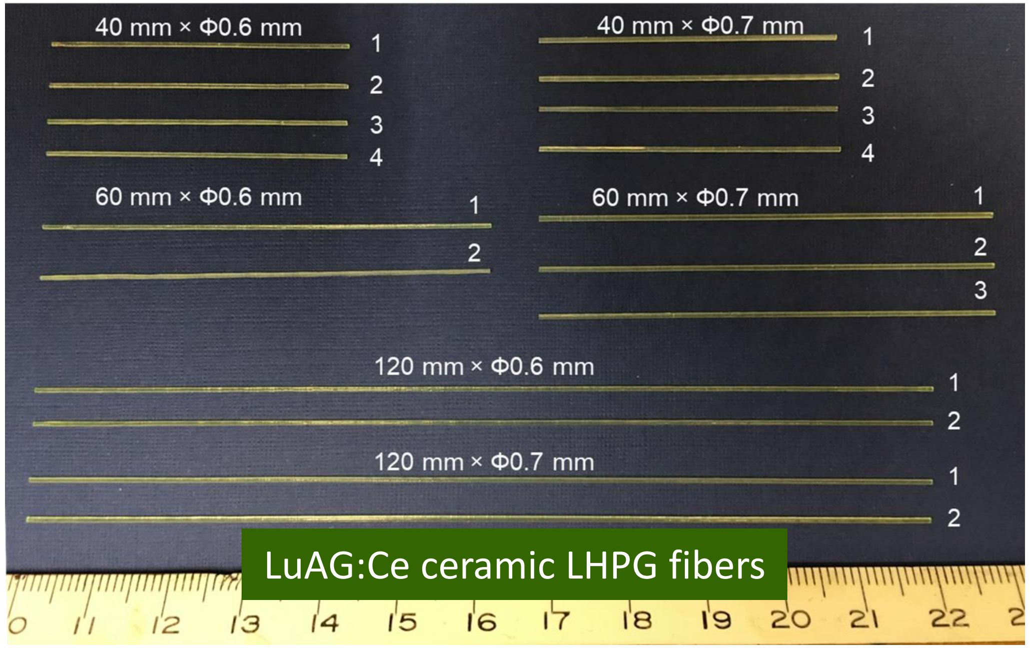


arXiv: 2203.12806
See RADiCAL Talk

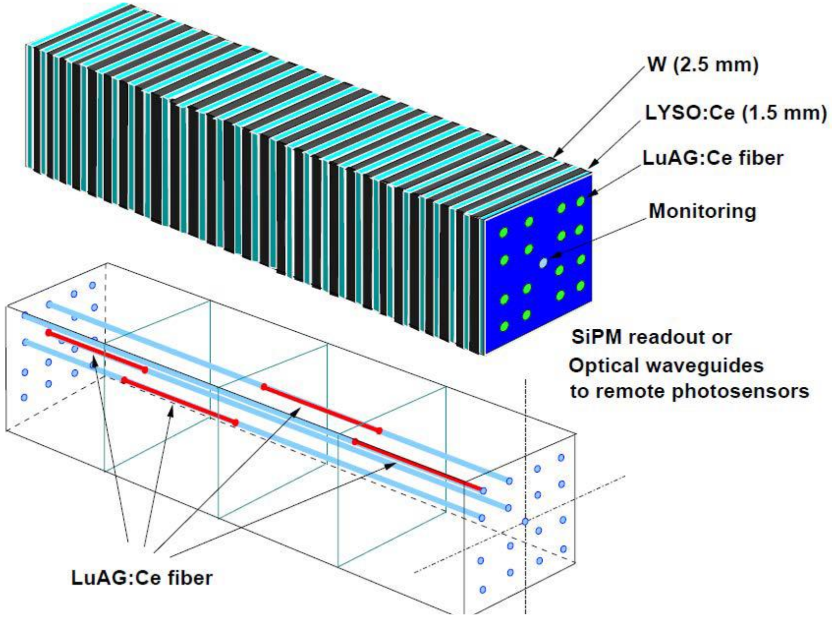
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission







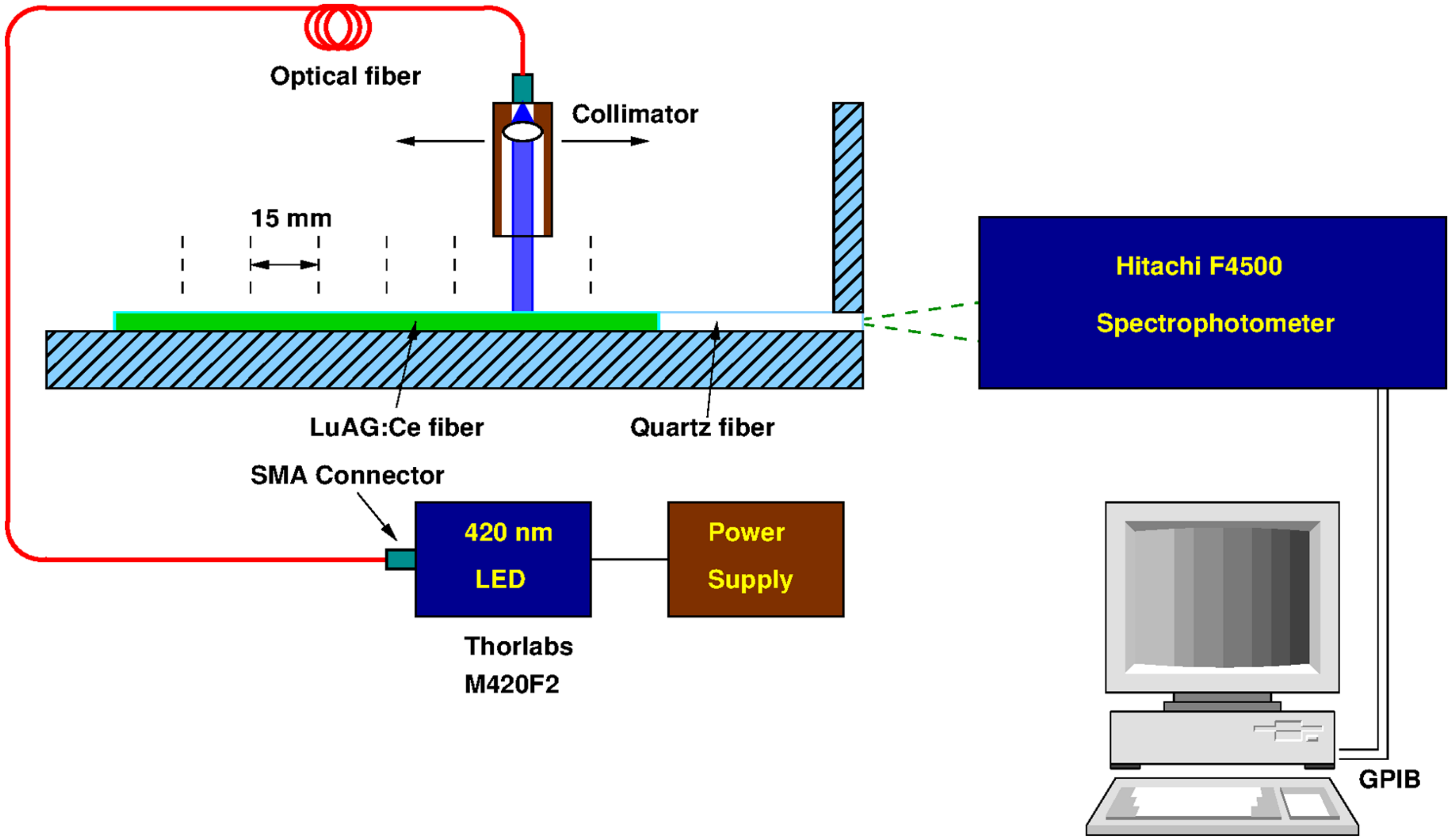
LuAG:Ce ceramic LHPG fibers

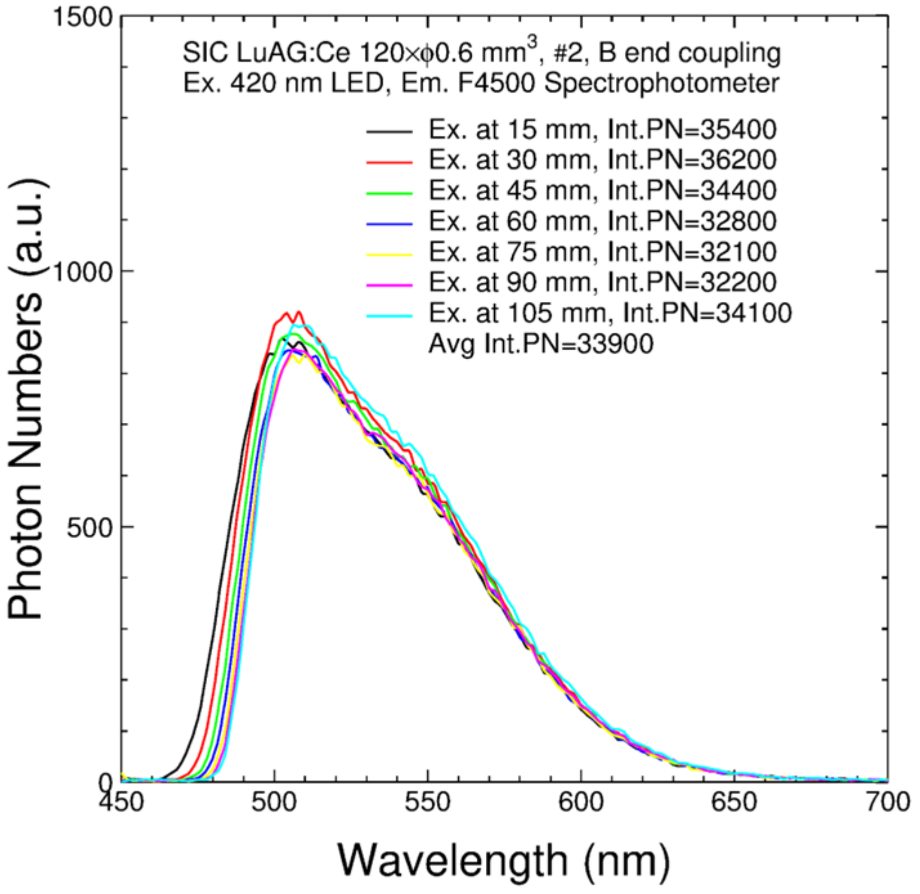


Light Output and Response Uniformity

10.1109/NSS/MIC44867.2021.9875908

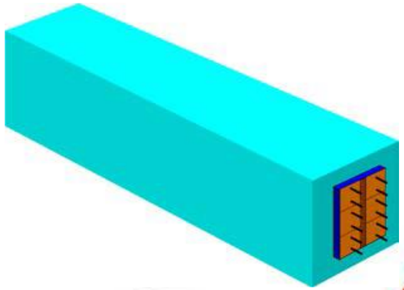
Excellent longitudinal uniformity observed for a Φ0.6 ×120 mm^3 LuAG:Ce ceramic excited by a 420 nm LED at different location, with a solid coupling to a quartz fiber, mimicking its application in RADiCAL





Ultrafast BaF_2:Y Calorimeter for Mu2e-II

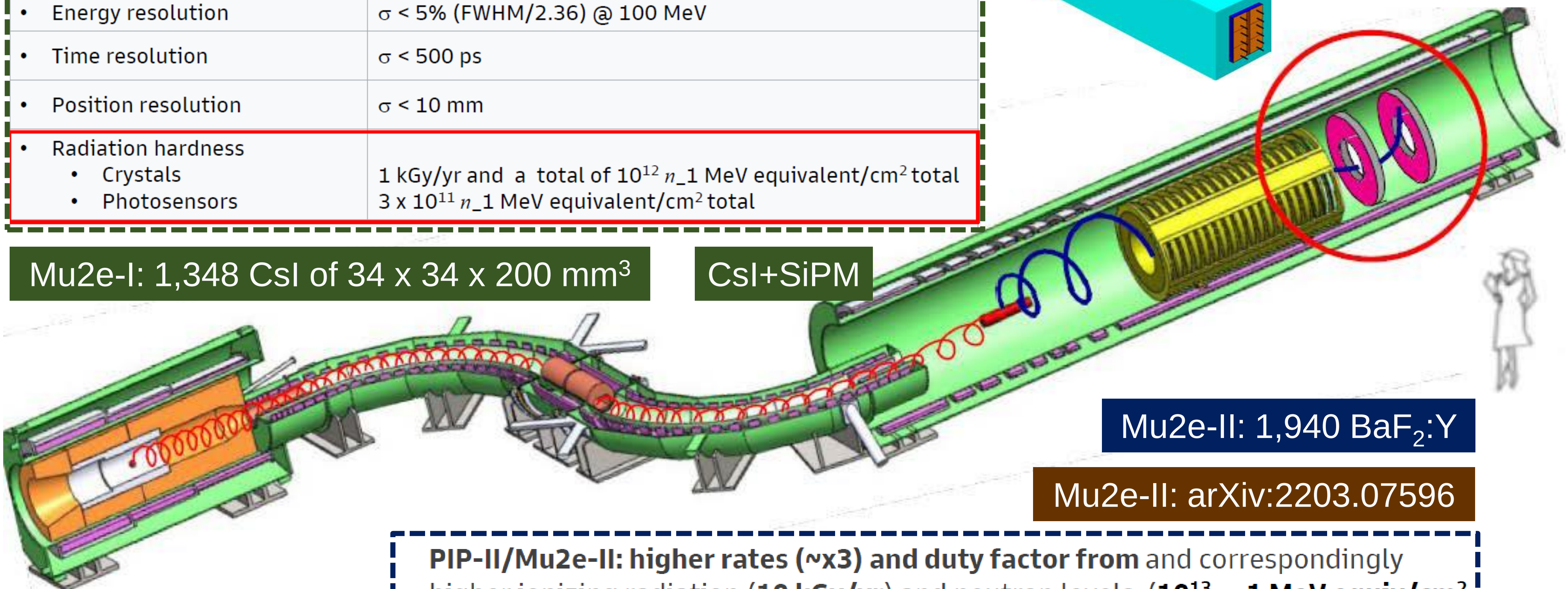
Use ultrafast material to mitigate pile-up



• Energy resolution	σ < 5% (FWHM/2.36) @ 100 MeV
• Time resolution	σ < 500 ps
• Position resolution	σ < 10 mm
• Radiation hardness • Crystals • Photosensors	 1 kGy/yr and a total of 10^{12} n_1 MeV equivalent/cm^2 total 3 x 10^{11} n_1 MeV equivalent/cm^2 total

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm^3

CsI+SiPM



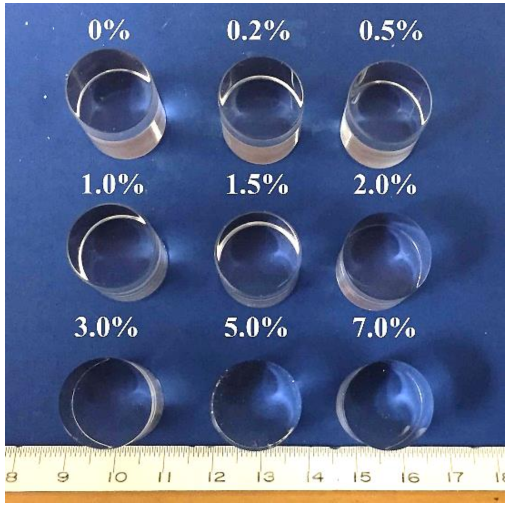
Mu2e-II: 1,940 BaF_2:Y

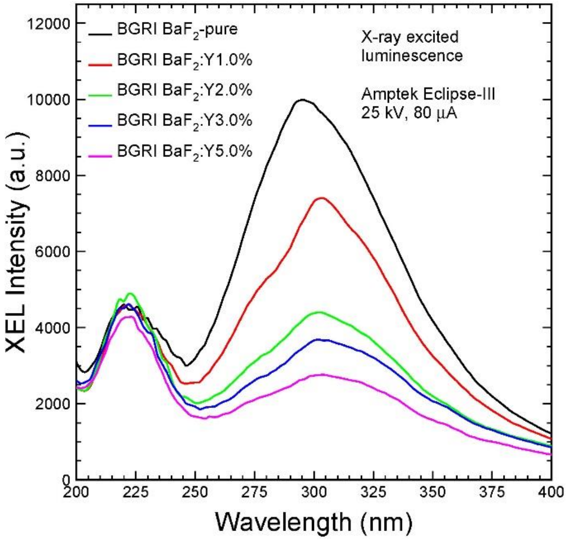
Mu2e-II: arXiv:2203.07596

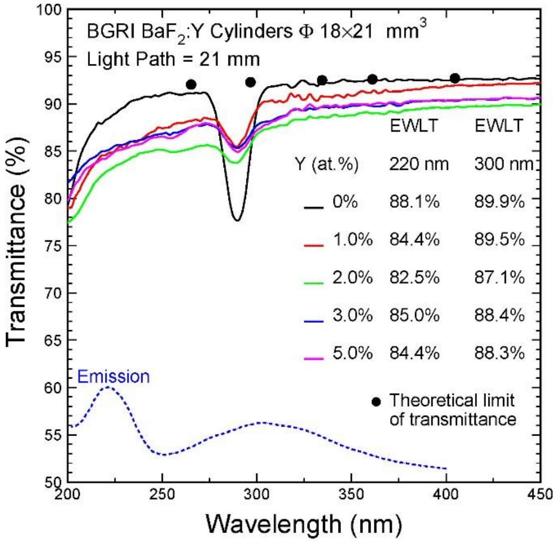
PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

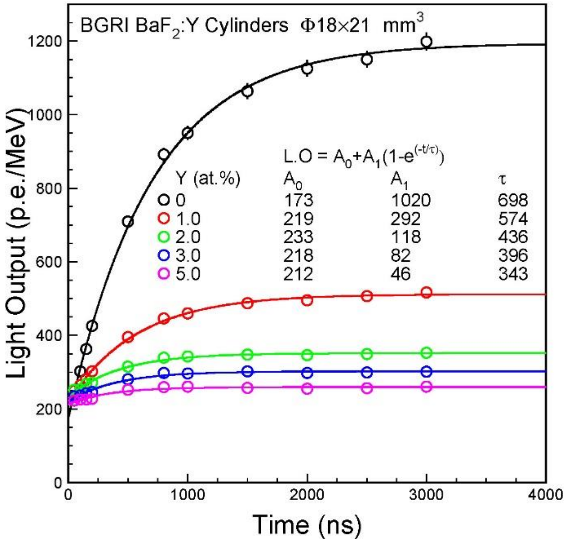
BaF_2:Y for Calorimetry & Imaging

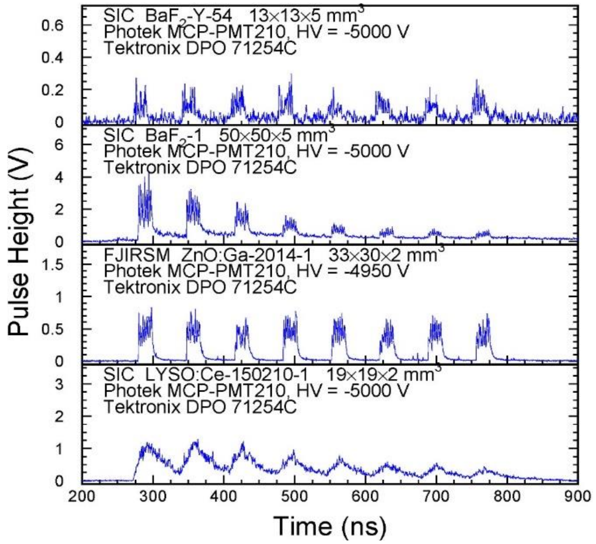
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

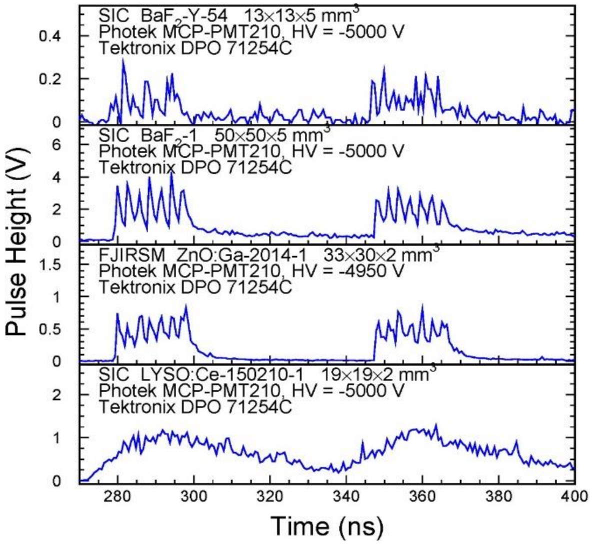


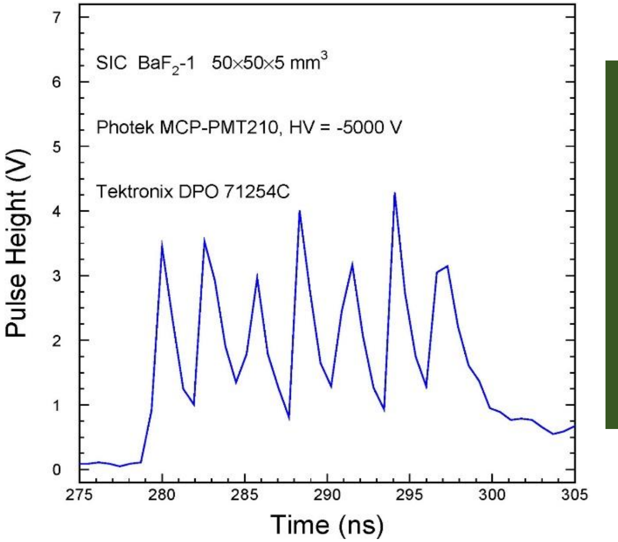












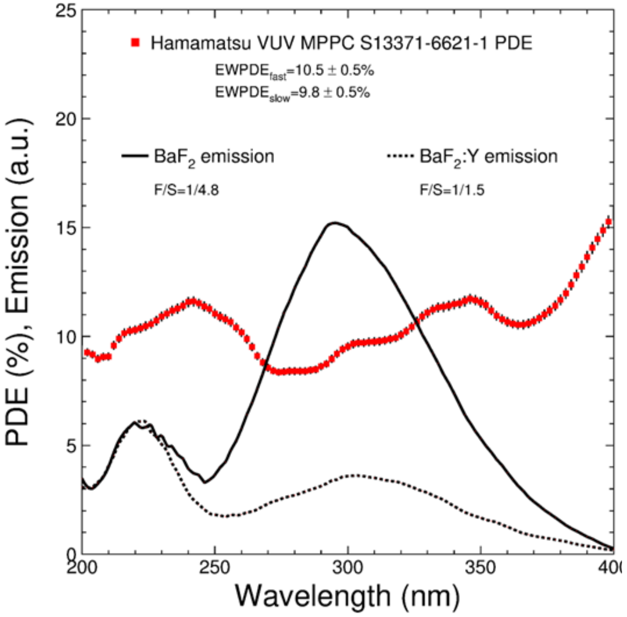
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

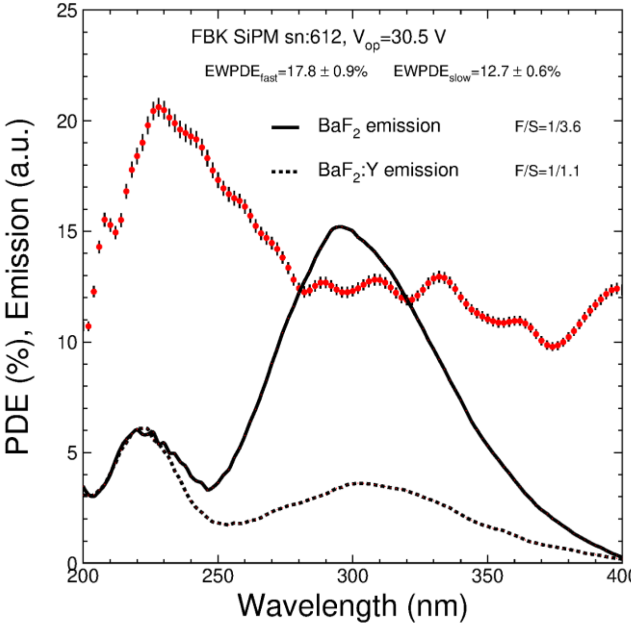
PDE of UV SiPM for BaF_2 and BaF_2:Y

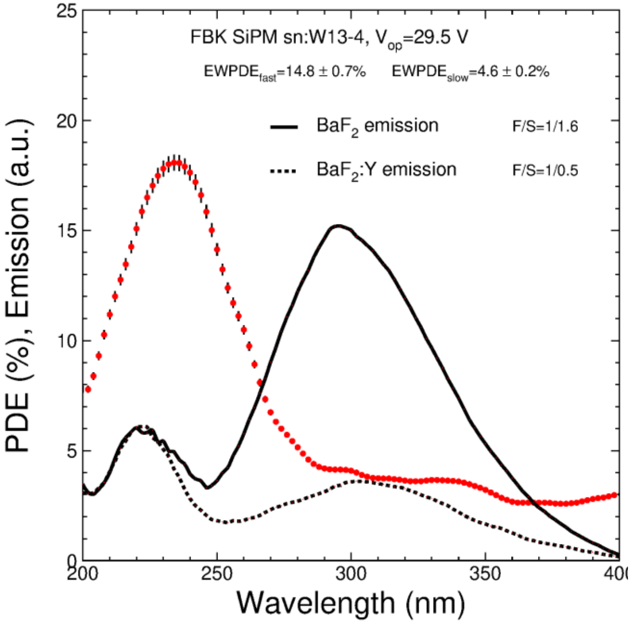
IEEE TNS **69** (2022) 958-964

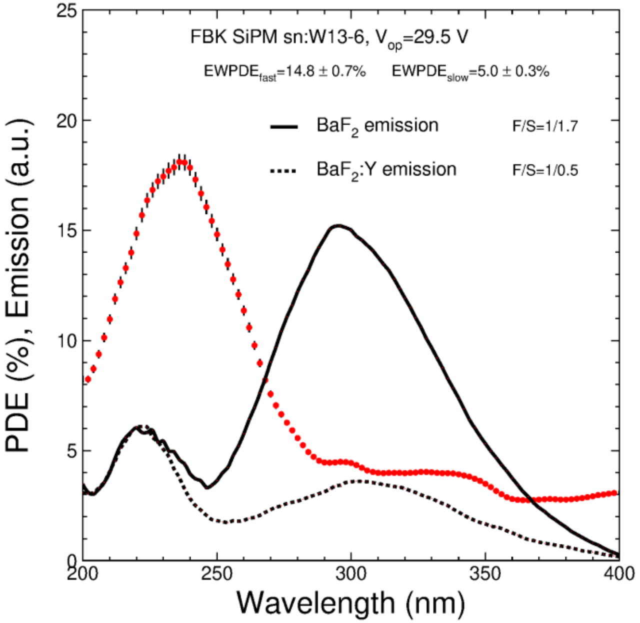
Photodetector	$EWPDE_{fast}$ (%)	$EWPDE_{slow}$ (%)	Relative F/S_{BaF}	Relative $F/S_{BaF:Y}$
Hamamatsu MPPC	10.5	9.8	1/4.8	1/1.5
FBK SiPM 2021	17.8	12.7	1/3.6	1/1.1
FBK SiPM 2023-1	14.8	4.6	1/1.6	1/0.5
FBK SiPM 2023-2	14.8	5.0	1/1.7	1/0.5

γ-ray induced readout noise is reduced by BaF_2:Y slow suppression & solar-blind PDE



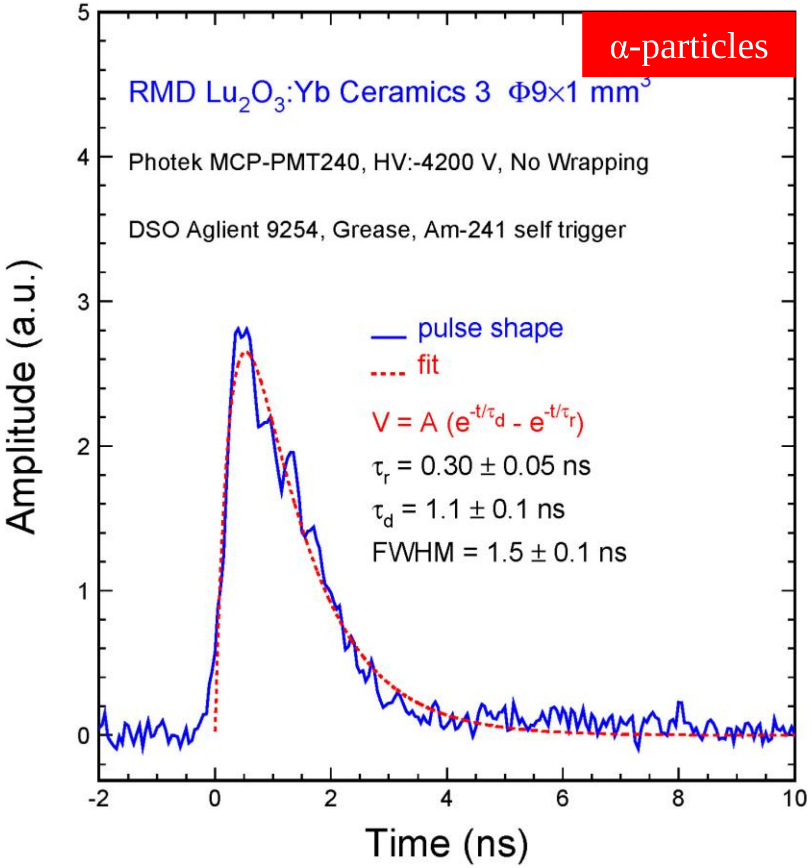


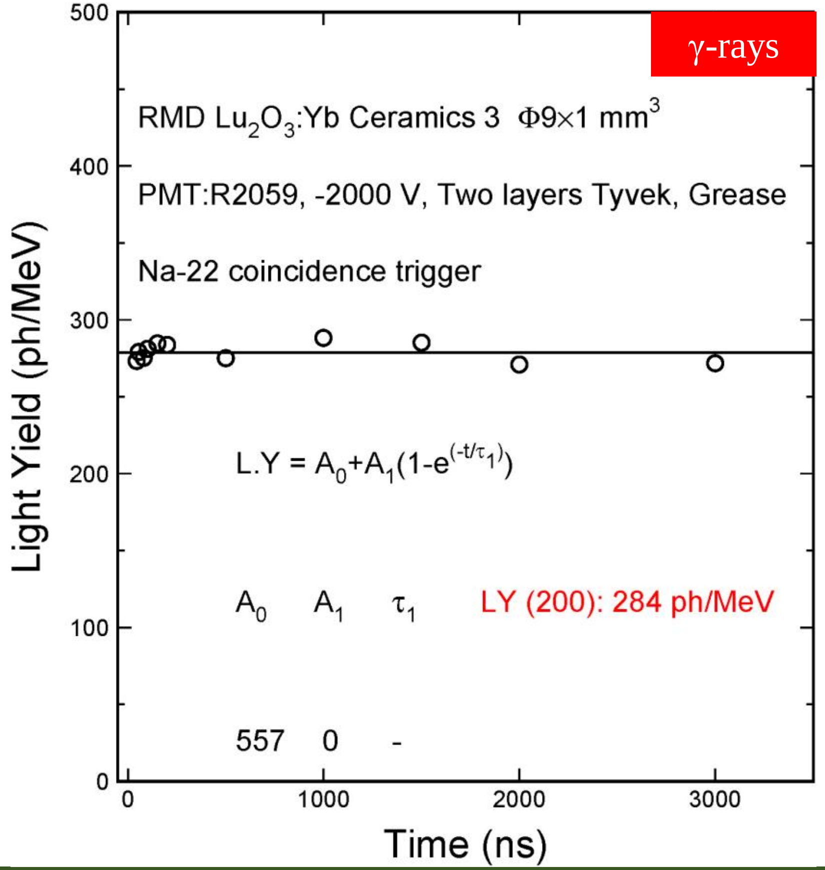


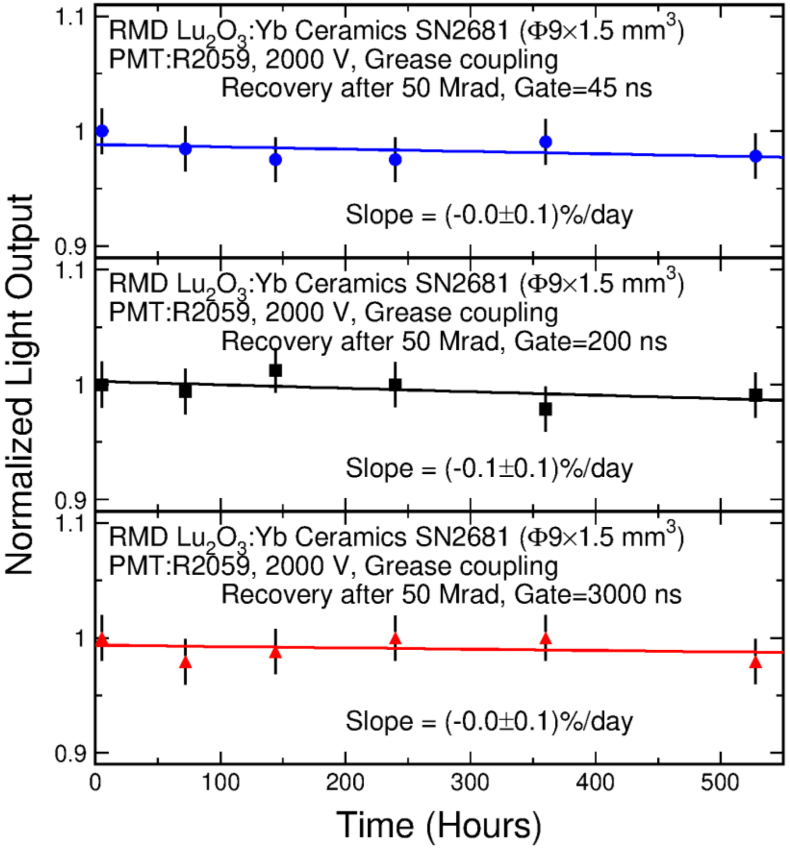


Novel Lu_2O_3:Yb Ceramics

Presented in the NSS2022 conference https://www.its.caltech.edu/~rzhu/talks/NSS22_N21-03.pdf





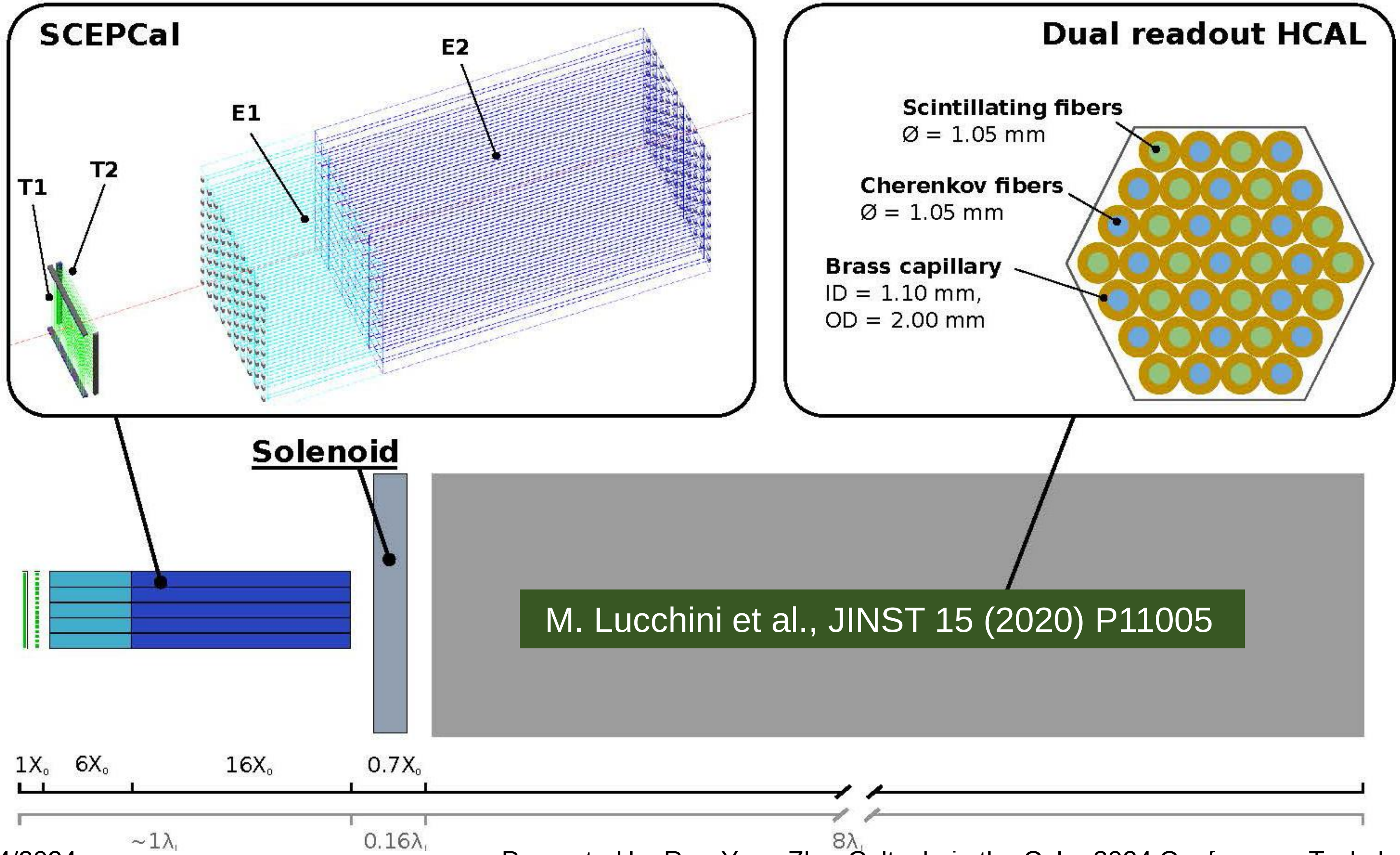


Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

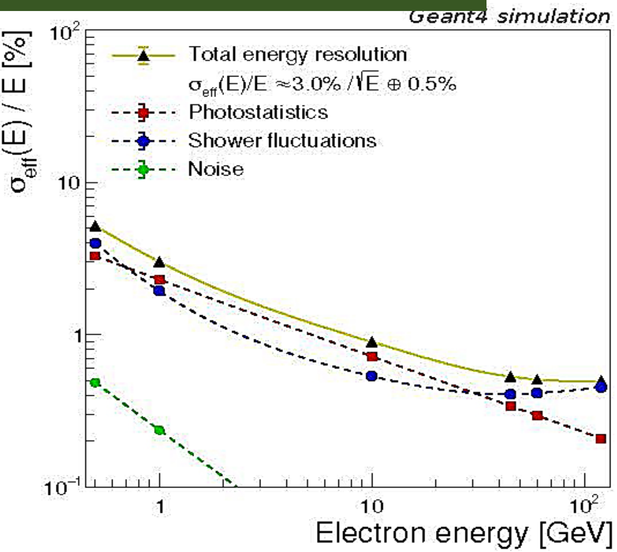
CalVision: Segmented Crystal ECAL

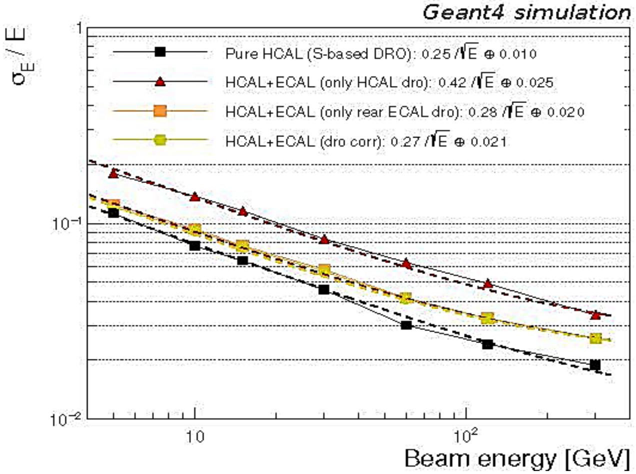
See R. Hiroski in This Conference

Followed by the IDEA DR HCAL, aiming at both EM and jet resolution

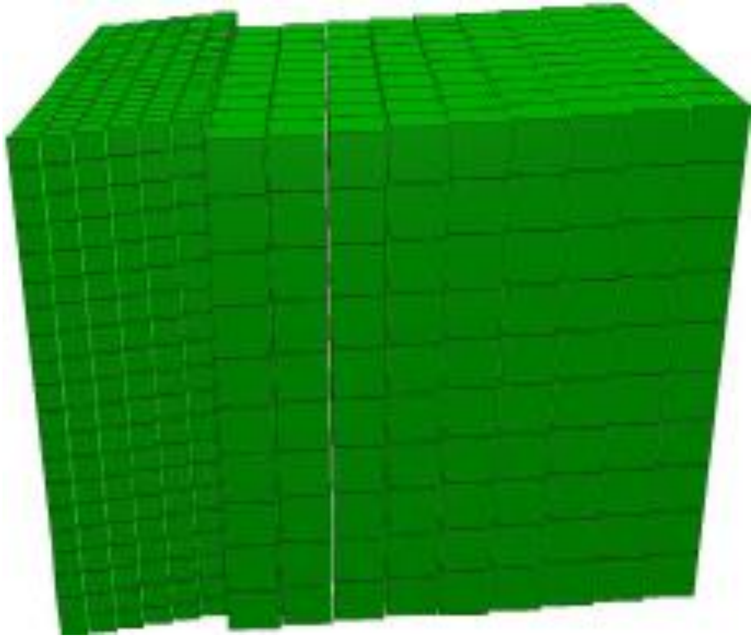


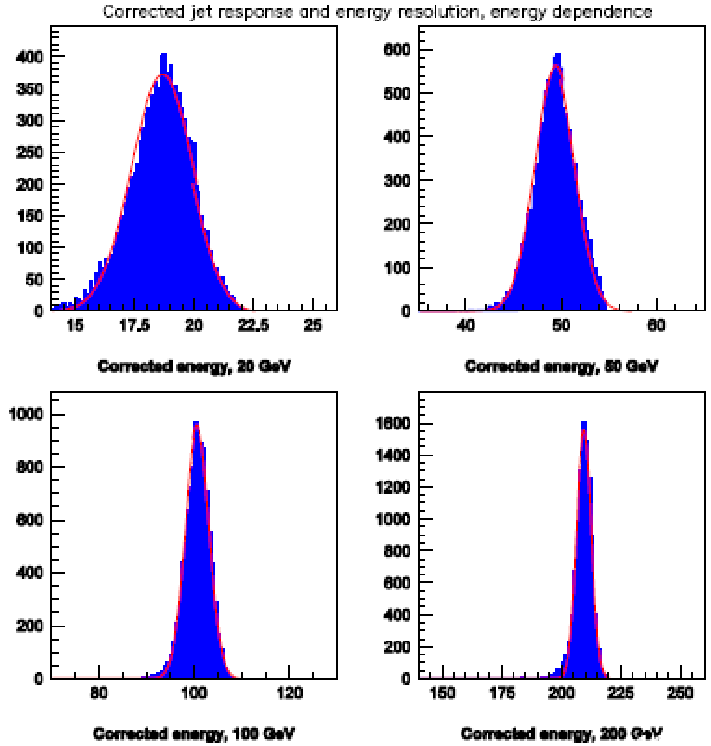
M. Lucchini et al., JINST 15 (2020) P11005



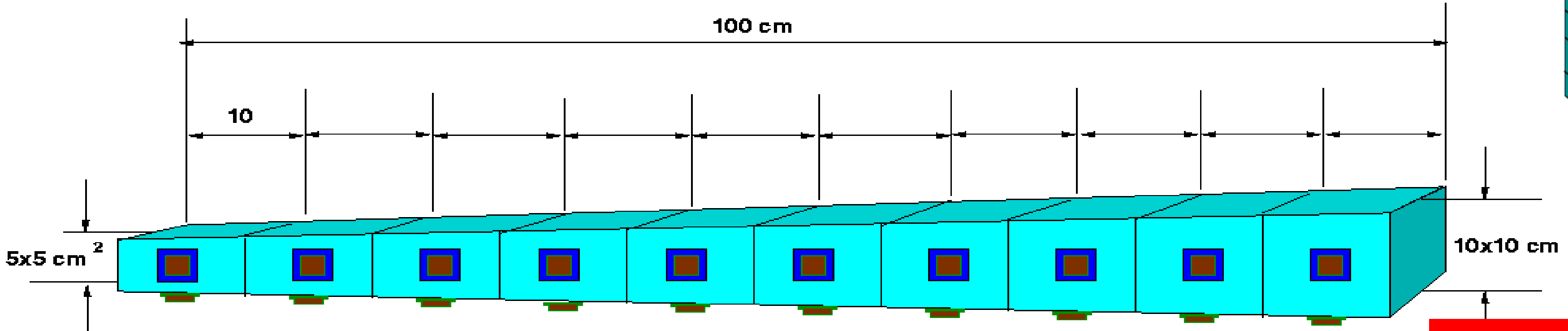


The HHCAL Concept

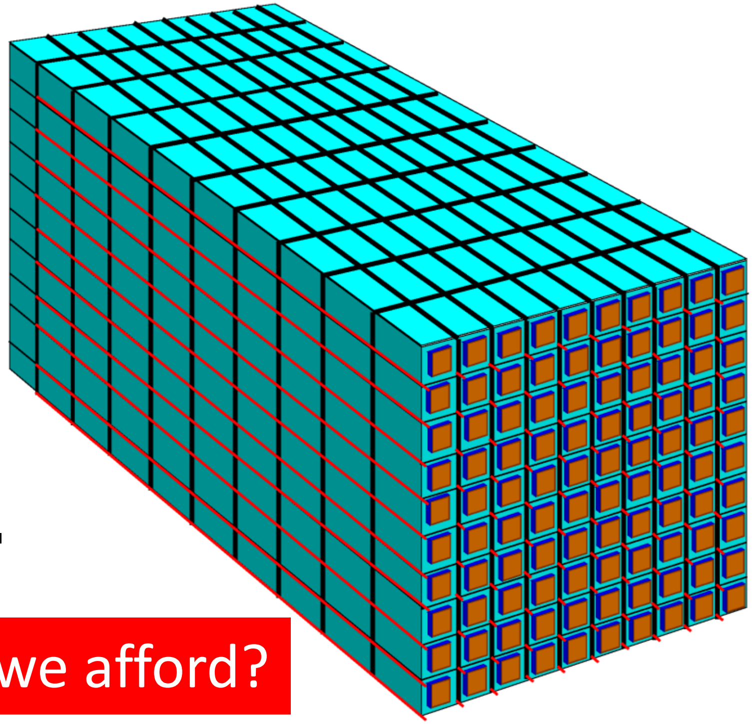




A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al.*, IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.
M. Demarteau, 2021 CPAD Workshop

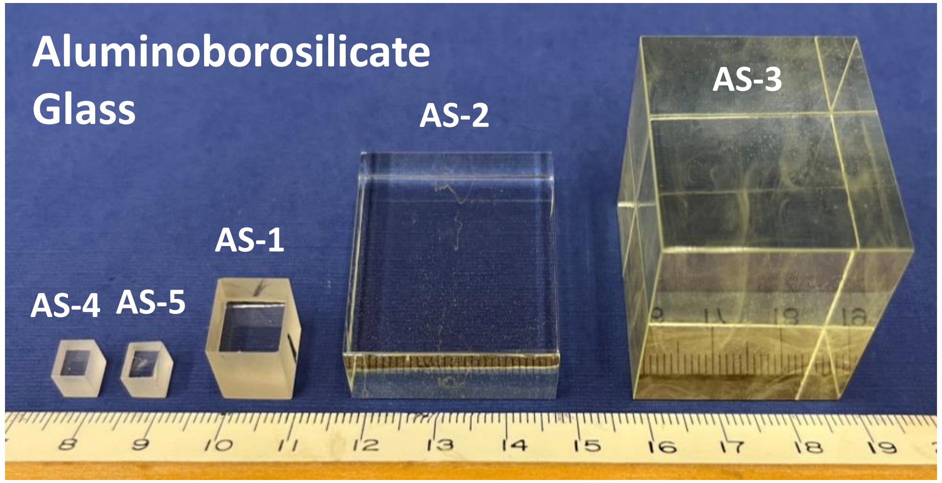


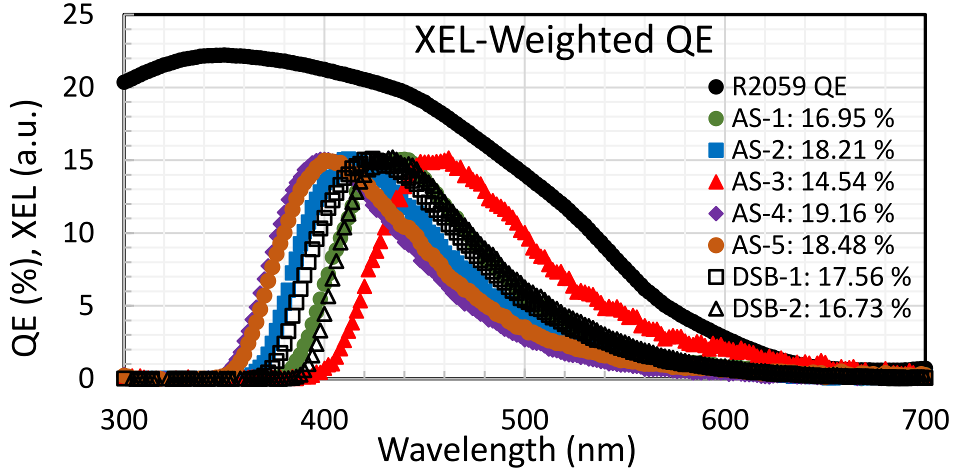
R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

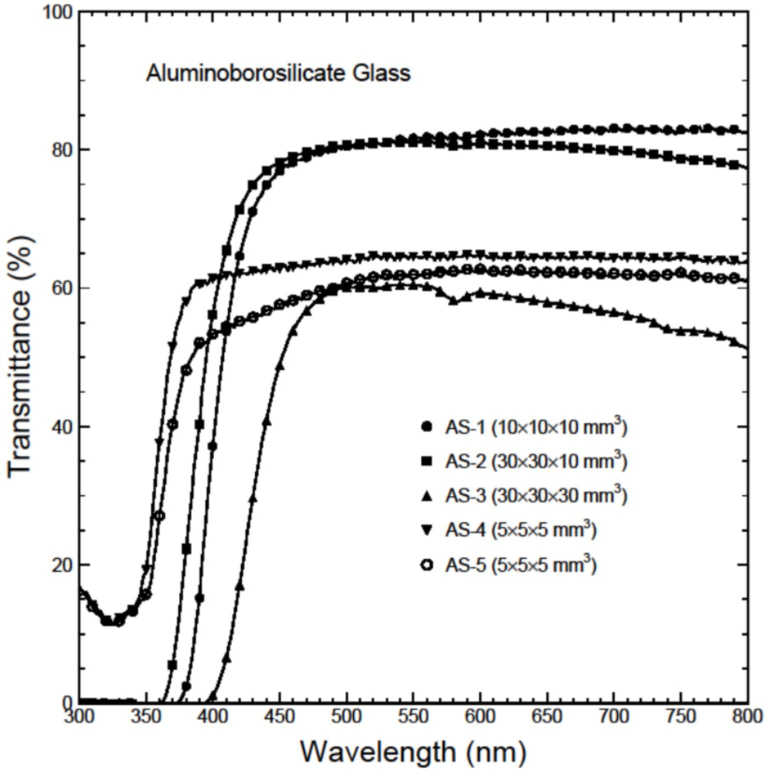


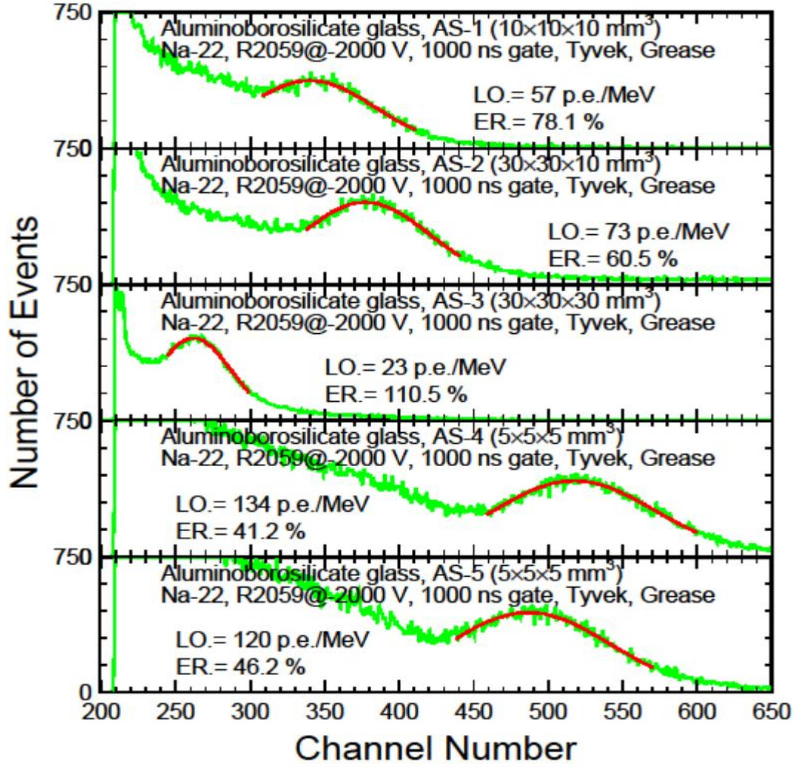
Can we afford?

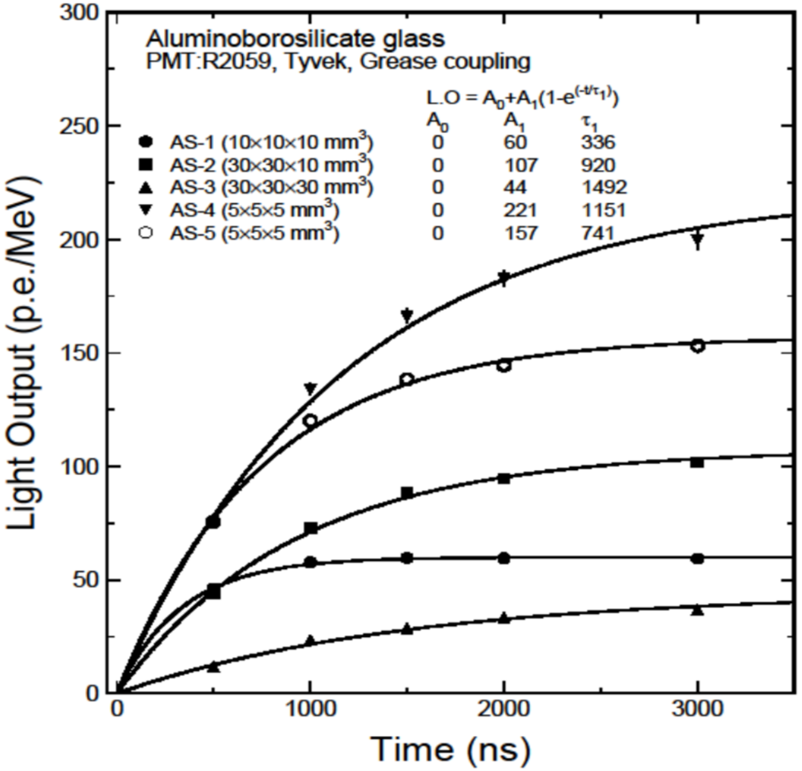
ABS (B_2O_3–SiO_2–Al_2O_3–Gd_2O_3–Ce_2O_3) Glass





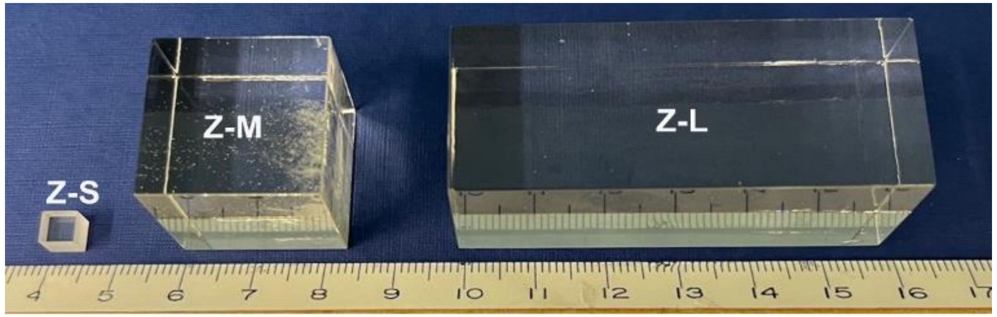


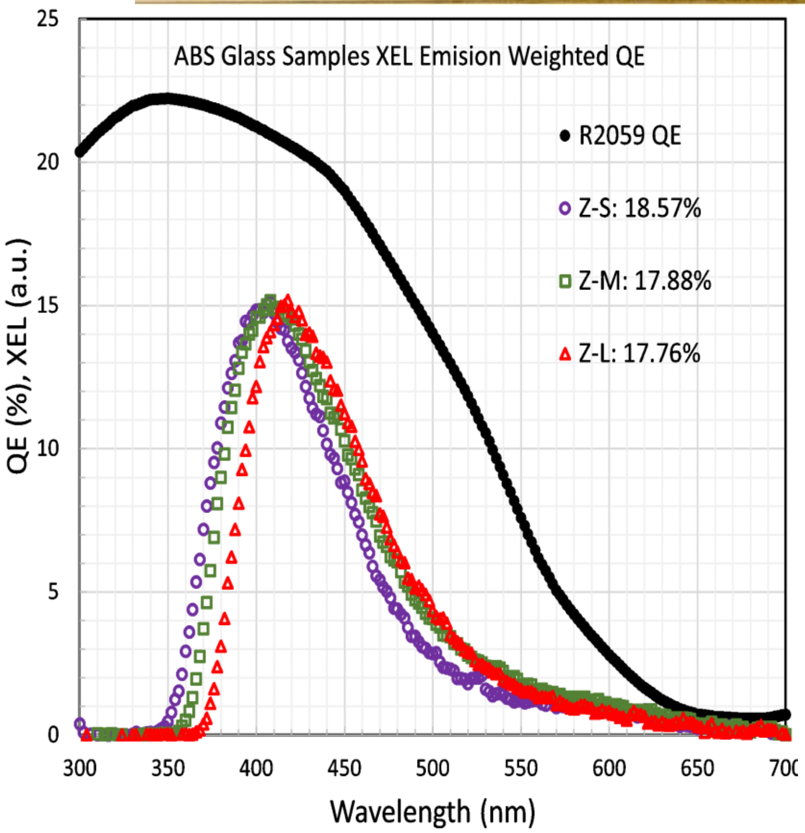


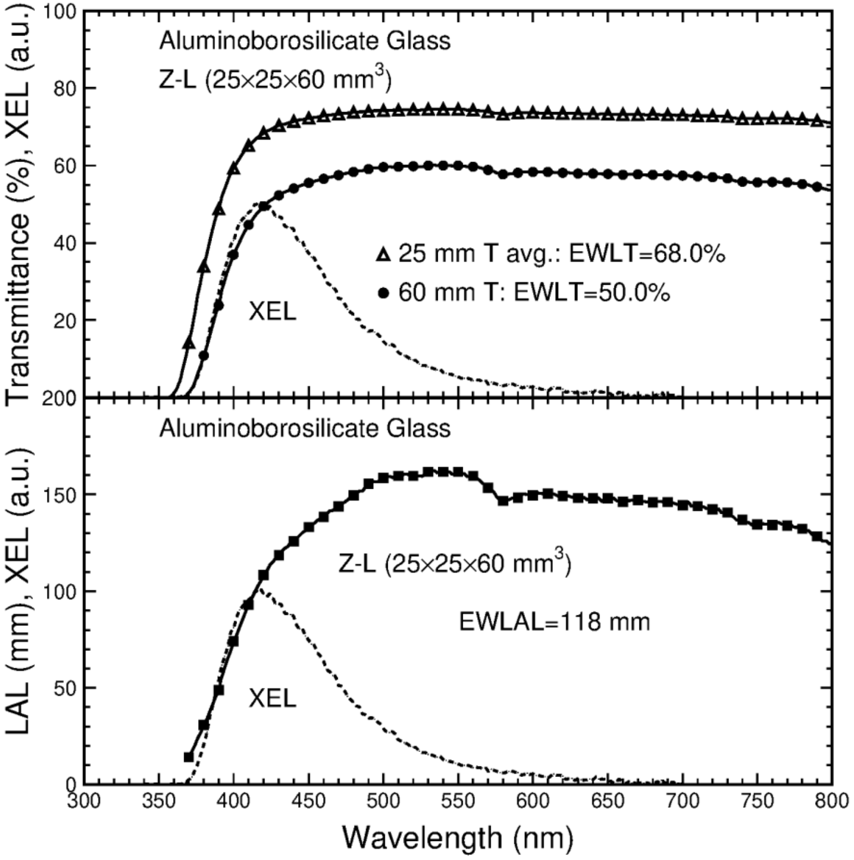


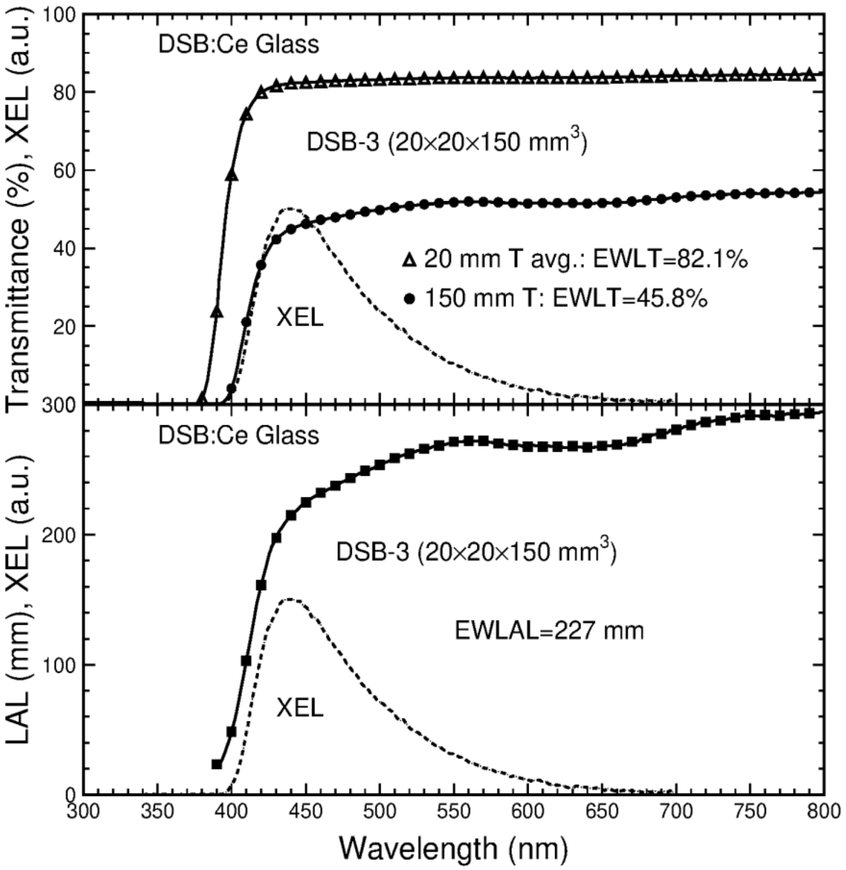
Large Size ABS and DSB Samples

See talks on glass scintillators in this conference









Inorganic Scintillators for HHCAL

Presented in the 9/14/2023 CalVision meeting all samples measured at Caltech

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO:Ce Glass	DSB:Ce Glass	ABS:Ce Glass
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	4.3	6.0
Melting point (℃)	1050	1030	1123	824	608	2040	980[7]	1550	?
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	2.58	1.56
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.90	3.24	2.49
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	30.9	24.2
Z_{eff} value	71.5	73.8	73.6	76.7	74.7	11.1	41.4	49.5	56.6
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	6.1	8.0
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	420	400
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	?	?	?
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	1,360	1,150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	500	740
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	0.3	?
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	2.0	2.0	<1

Summary

The HL-LHC and FCC-hh require fast and radiation hard inorganic scintillators.

RADiCAL proposes an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter with LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals. R&D is on-going to suppress slow components in LuAG:Ce.

Mu2e-II considers ultrafast BaF_2:Y calorimeter. R&D is on radiation hardness of BaF_2:Y and solar-blind SiPM. Industry is developing ultrafast Lu_2O_3:Yb ceramics.

CalVision proposes a dual readout longitudinally segmented crystal ECAL combined with the IDEA HCAL promising excellent EM and Hadronic resolutions for the proposed lepton Higgs factory.

Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. Novel cost-effective heavy scintillating glass is under development.

R&D on calorimetry is being integrated in ECFA DRD6 WP3 and CPAD RDC9

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