Progress of Inorganic Scintillators for Future HEP Experiments

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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 FCC-hh;**
  - **Ultrafast BaF_2:Y and Lu_2O_3:Yb: Ultrafast calorimetry and time of flight;**
  - **Cost-effective ABS and DSB glasses: CalVision for FCC-ee and HHCAL.**

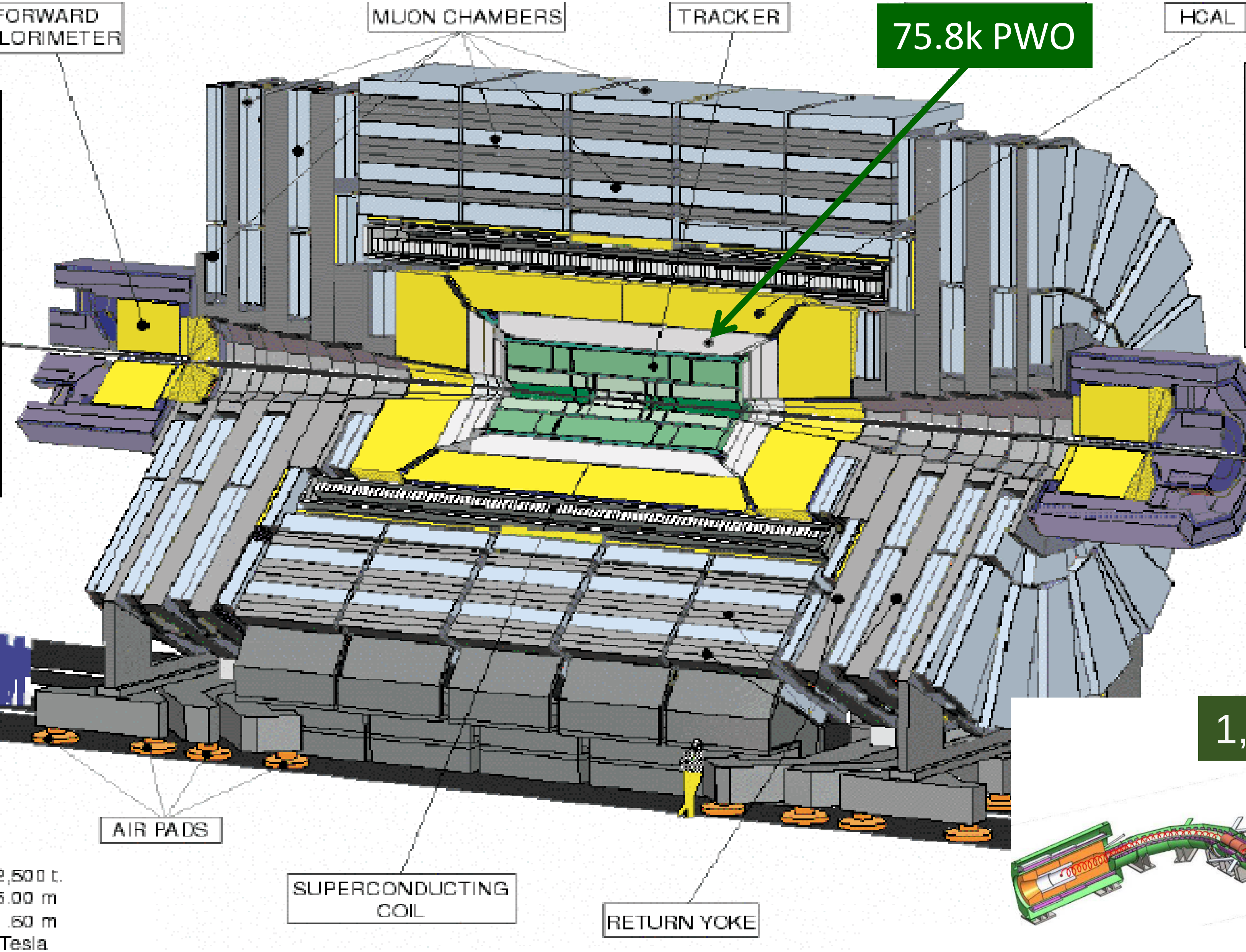
Crystals Used in HEP Calorimeters

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

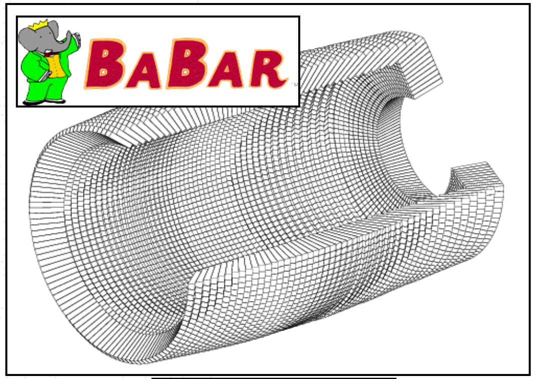
a. at emission peak; b. up/low row: slow/fast component; c. with QE of readout device taken out.

L3 BGO, BaBar CsI:Tl, CMS PWO and Mu2e CsI

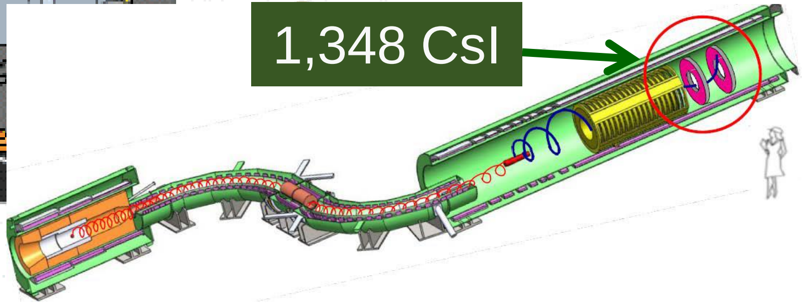
11.4k BGO



75.8k PWO

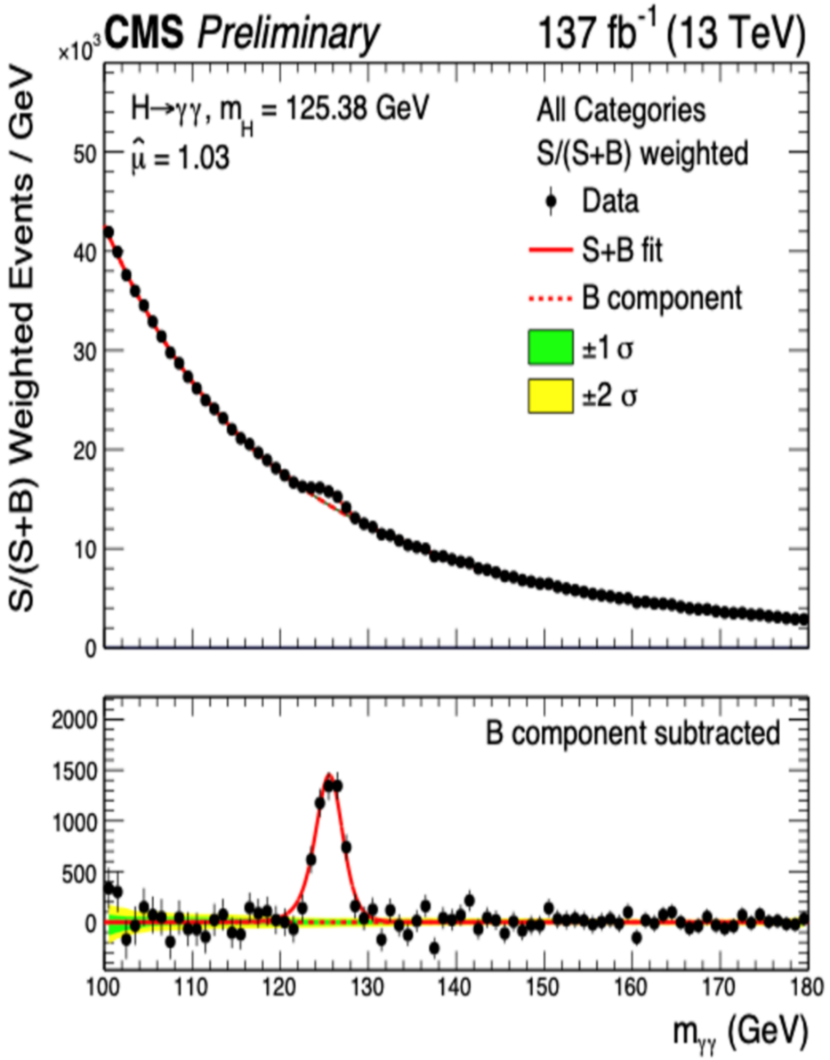


6.6k CsI:Tl

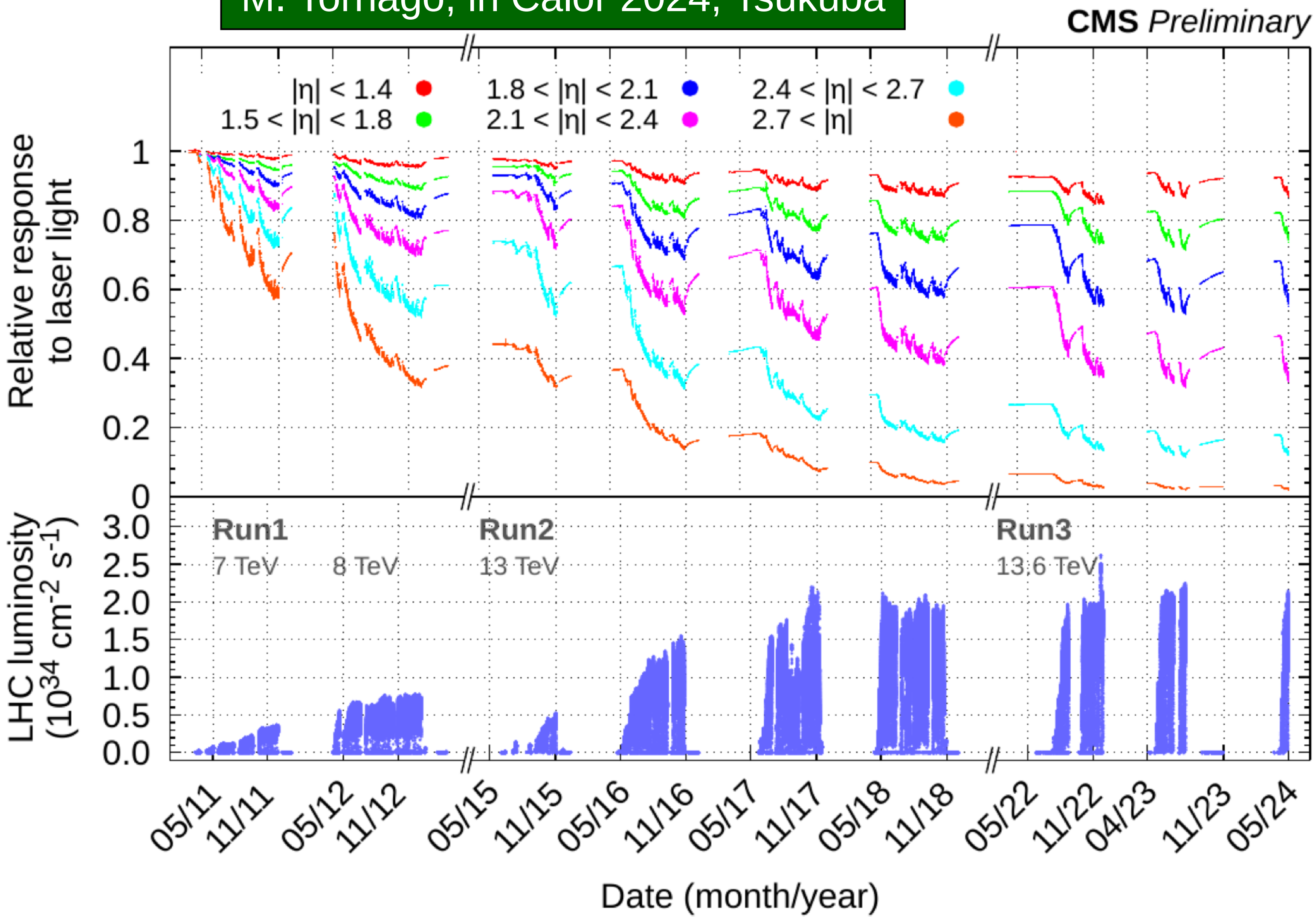


1,348 CsI

CMS H -> γγ and PWO Damage



M. Tornago, in Calor 2024, Tsukuba



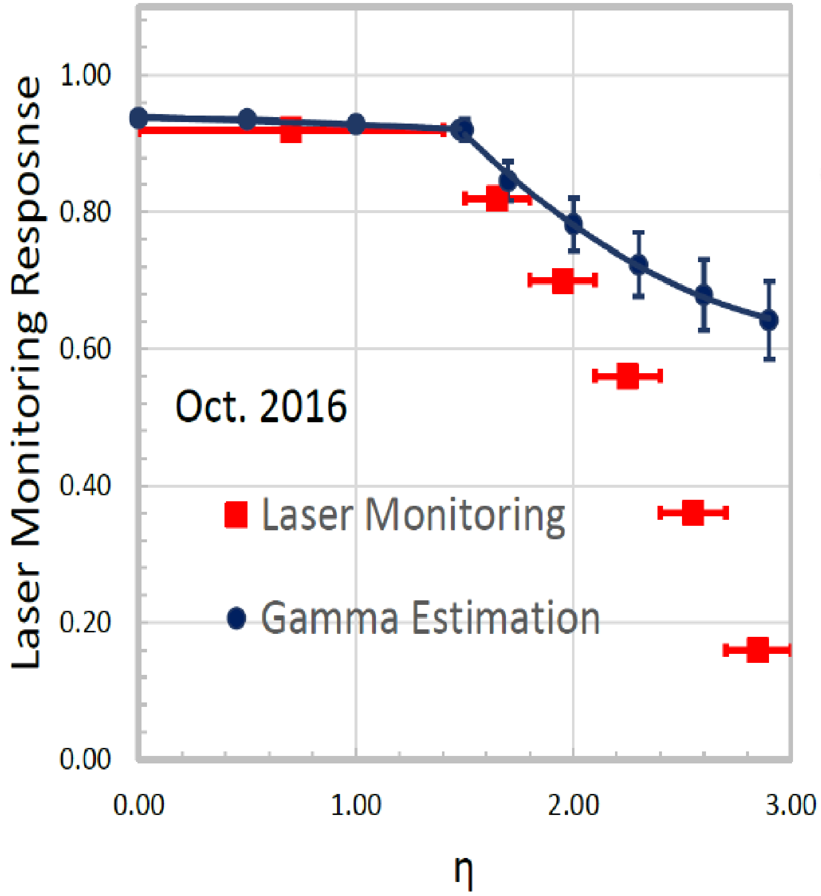
PWO damage caused by ionization dose and hadrons

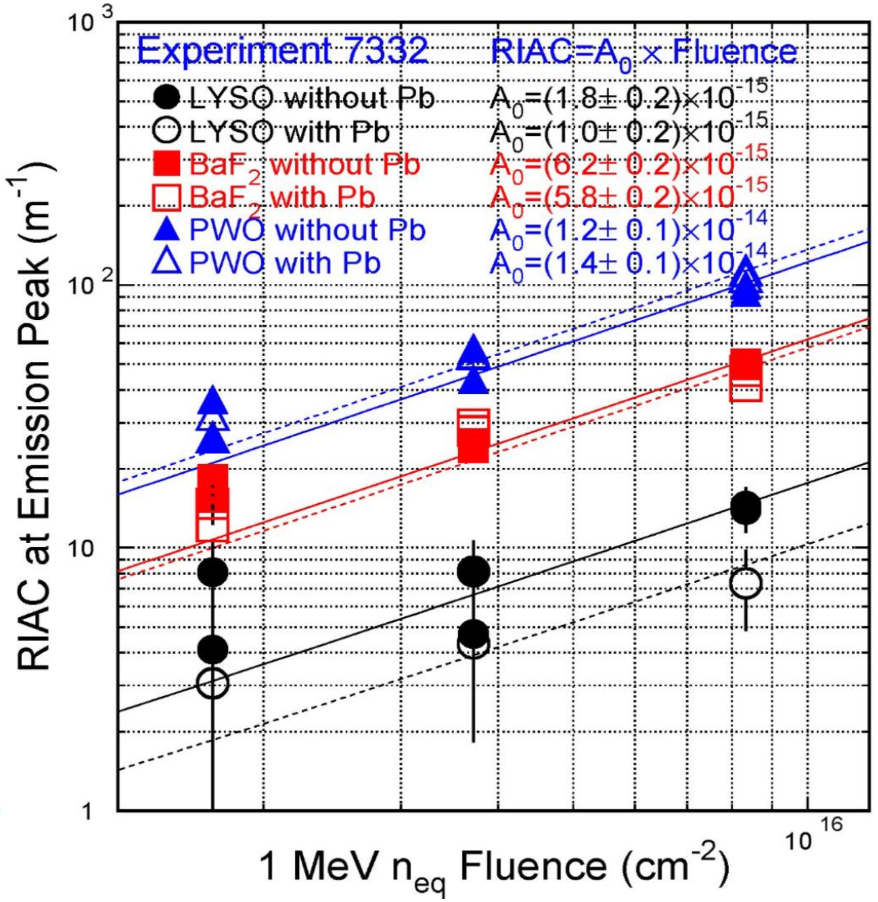
PWO Damage by Ionization & Neutrons

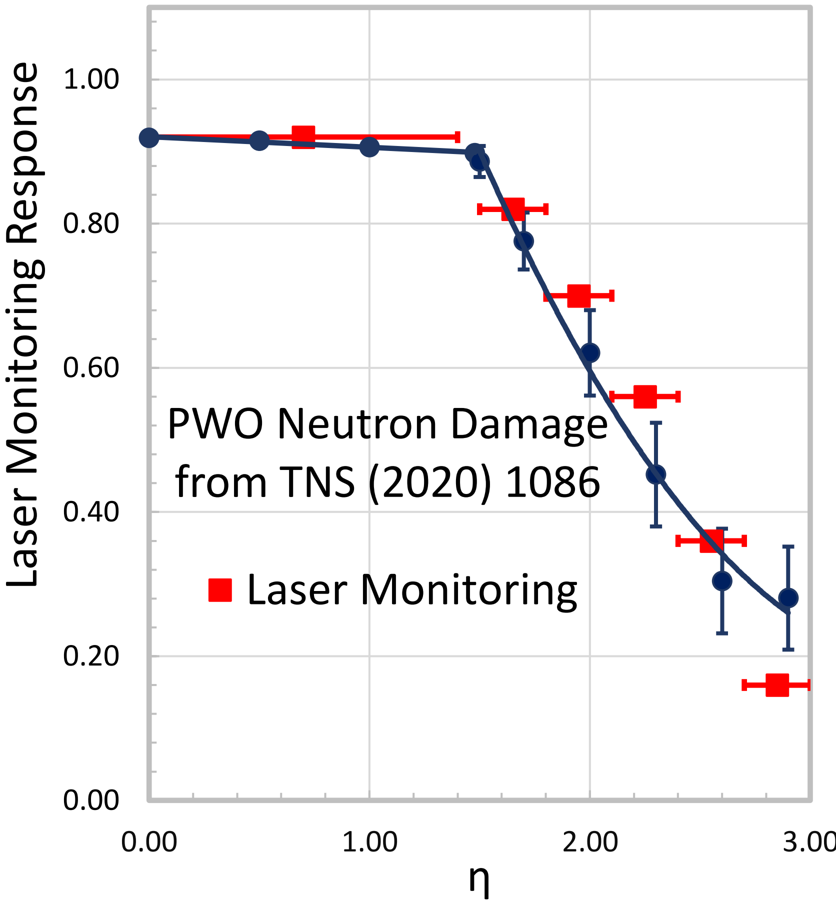
RIAC in PWO = $1.4 \times 10^{-14} \times$ 1 MeV n_{eq} Fluence

γ-ray and neutron induced absorption explains CMS PWO monitoring data

Trans. NS. 67 (2020) 1086-1092 & http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf



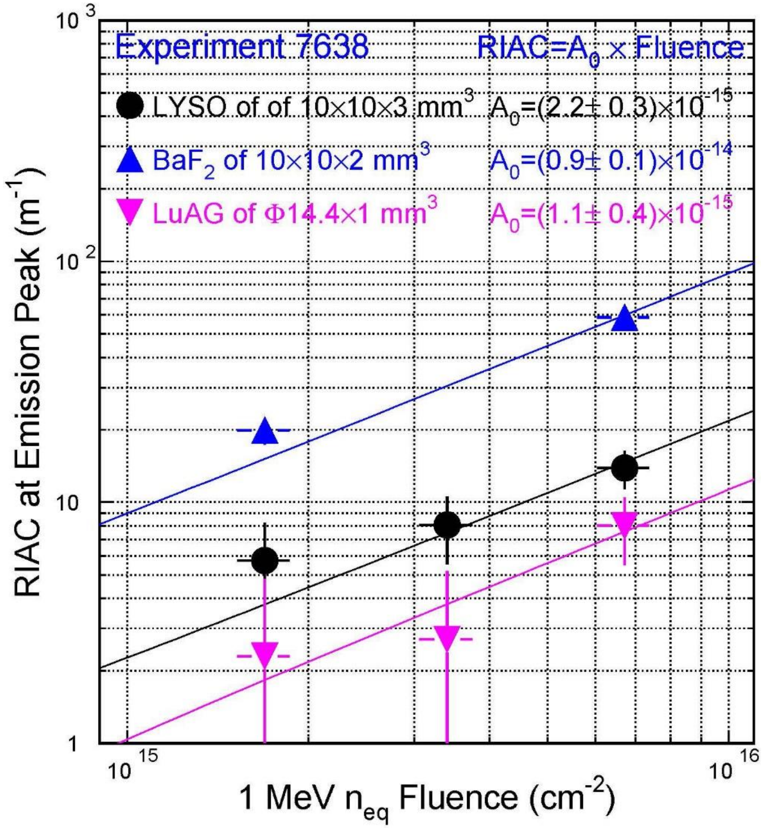


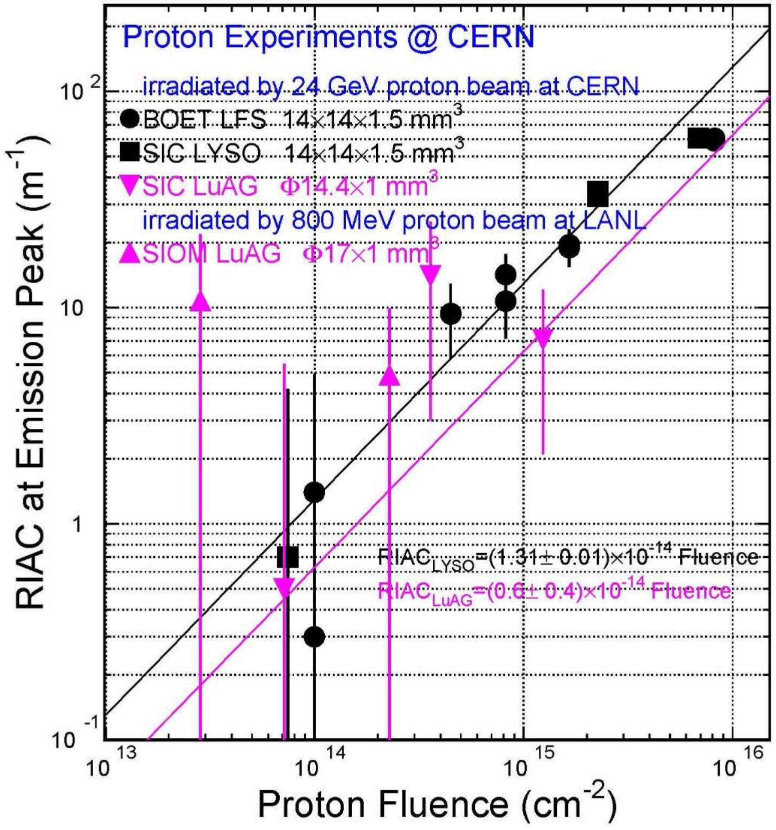


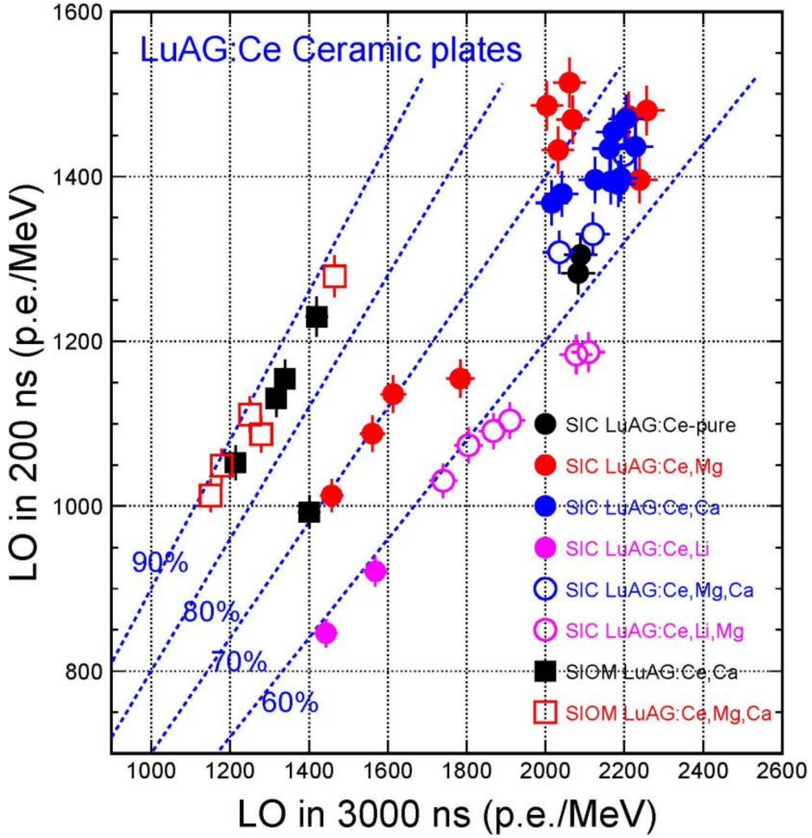
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

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

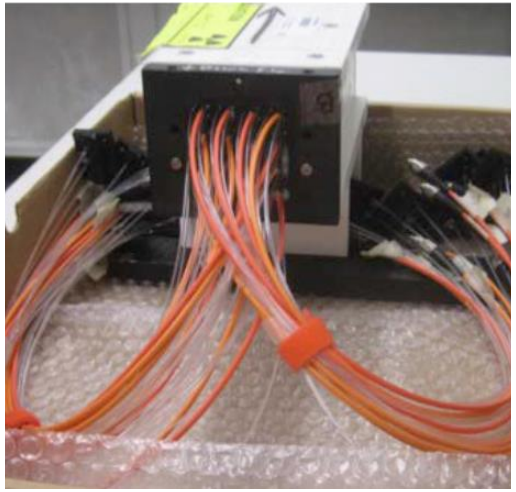


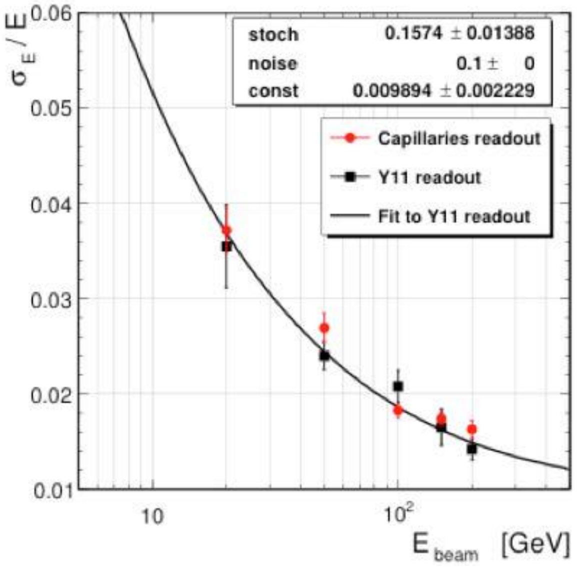




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

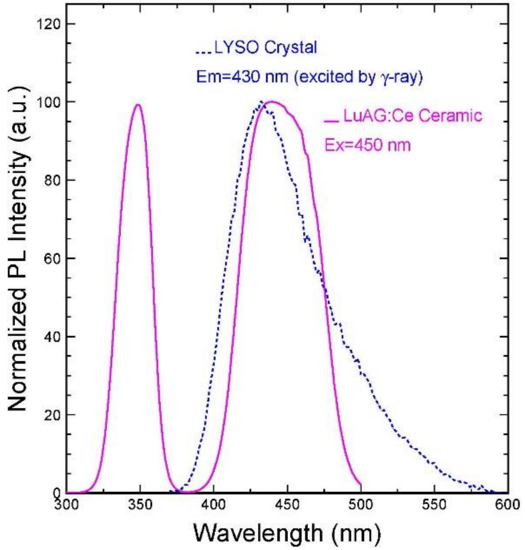
RADiCAL: LYSO/LuAG Shashlik ECAL



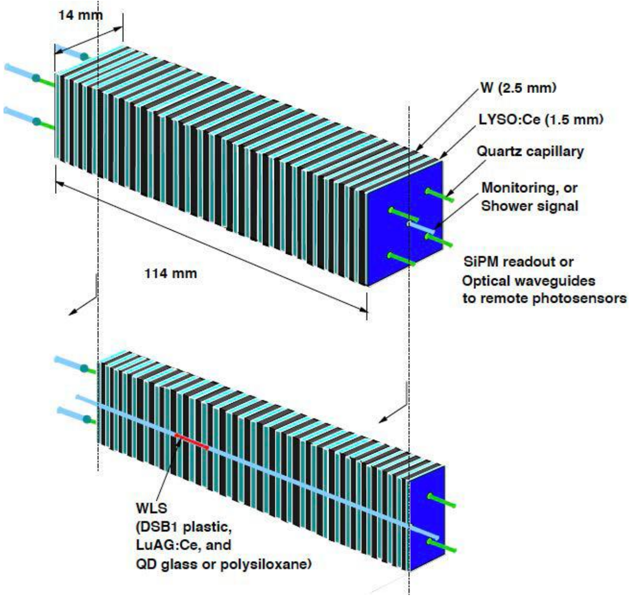


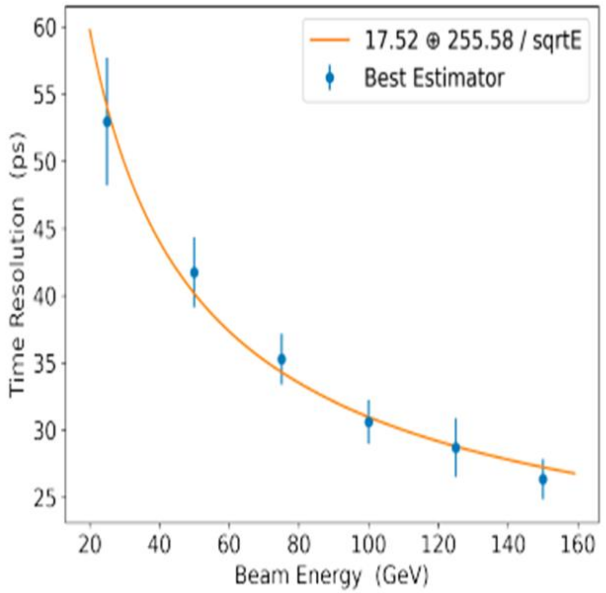
arXiv: 2203.12806

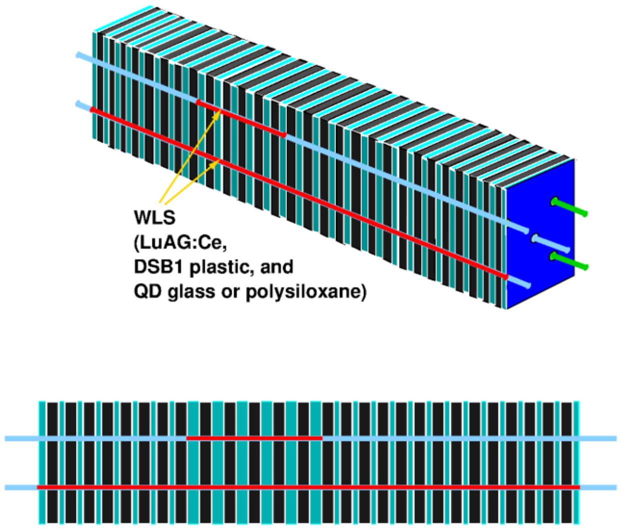
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission

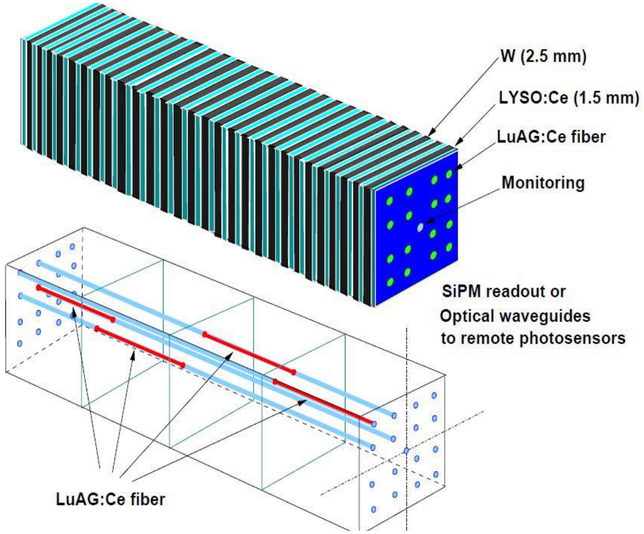


LuAG:Ce fibers



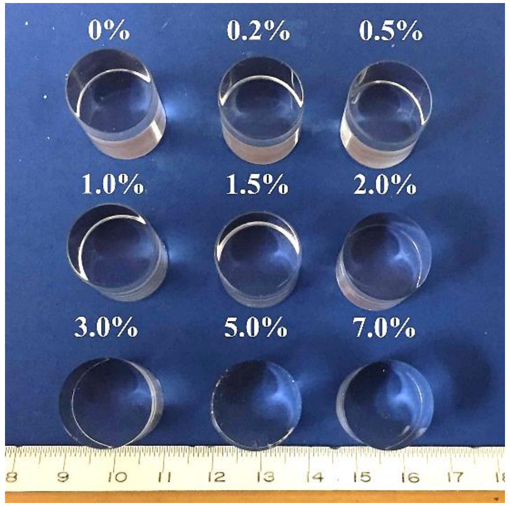


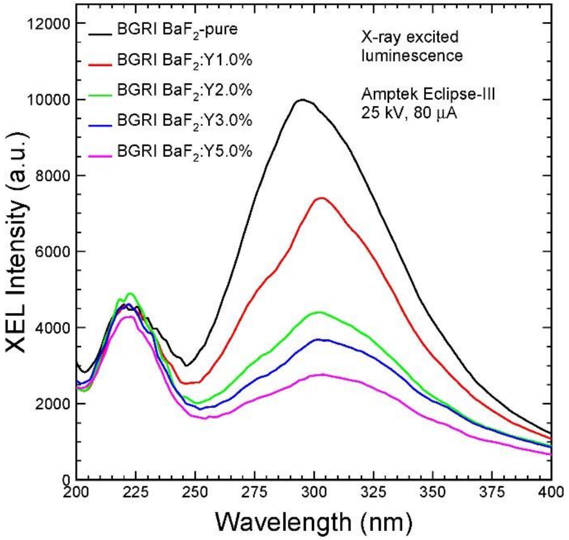


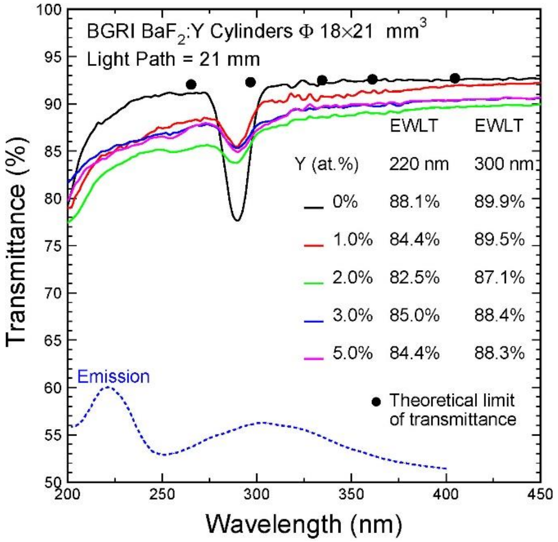


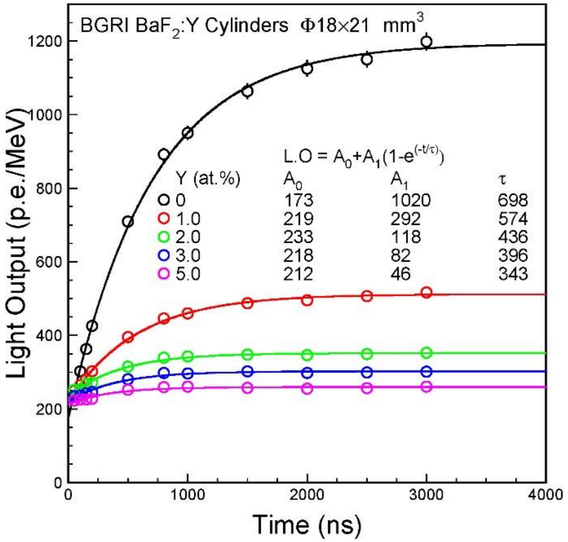
BaF_2:Y Ultrafast Calorimetry & Imaging

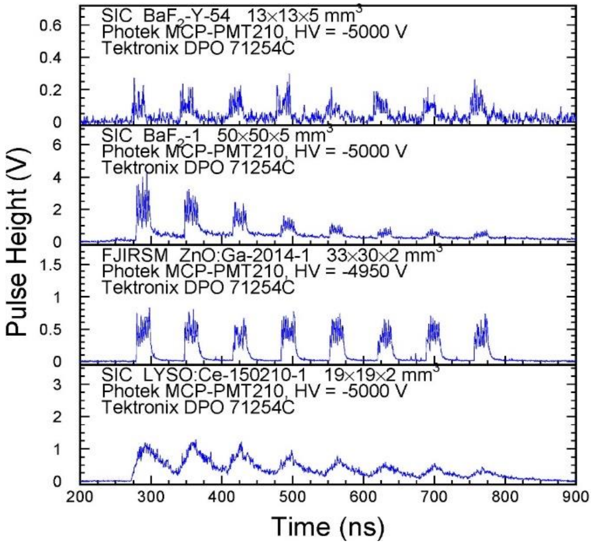
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

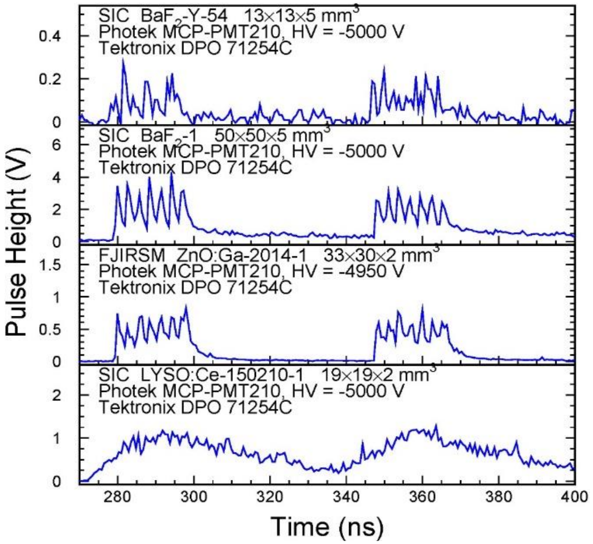


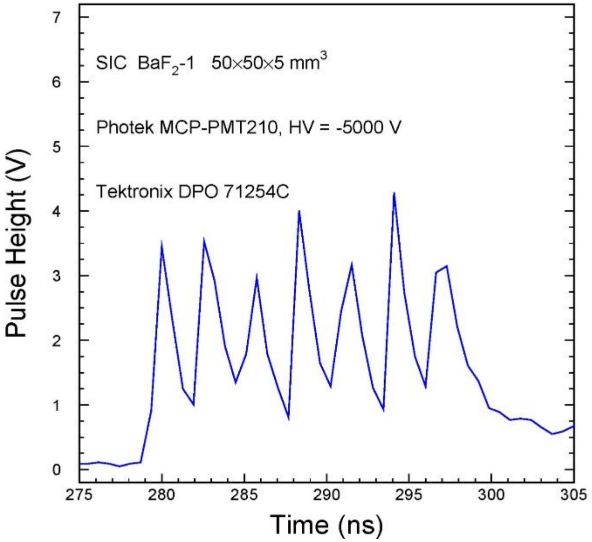








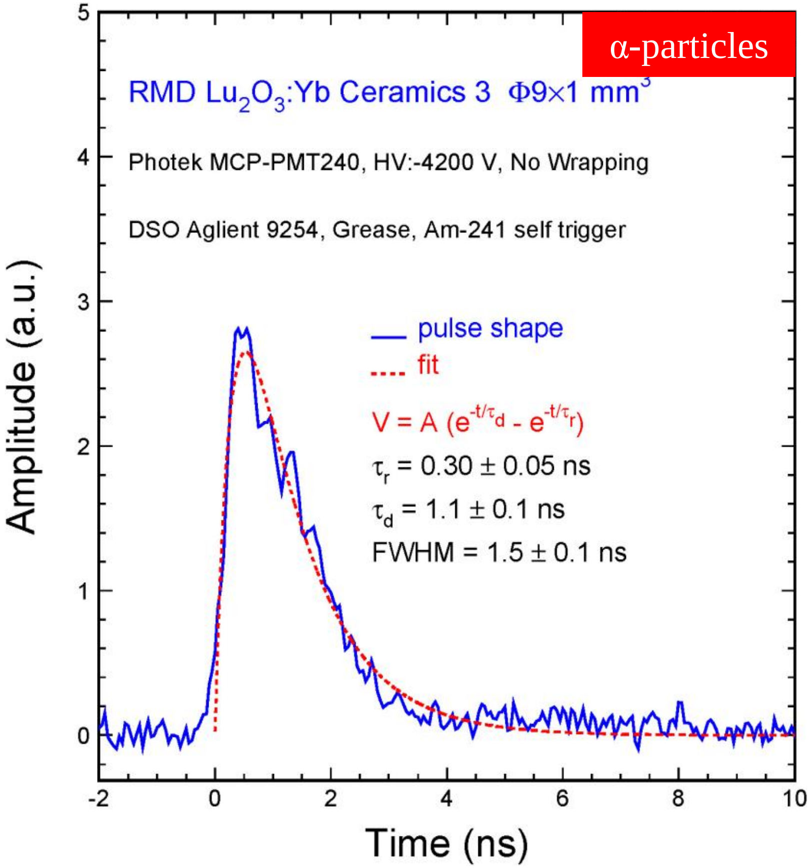


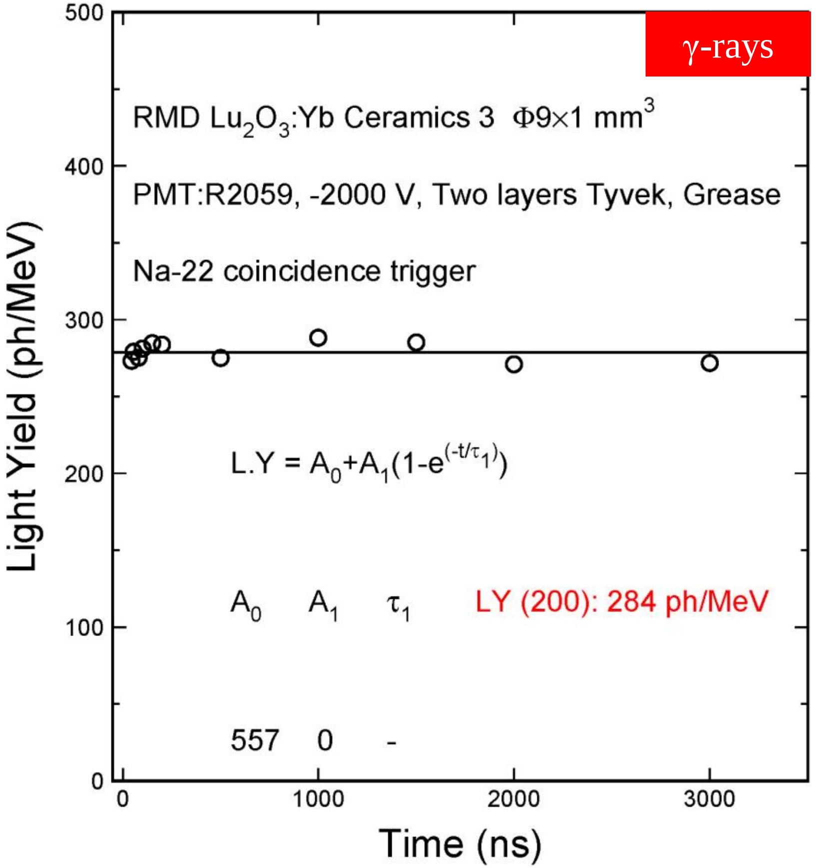


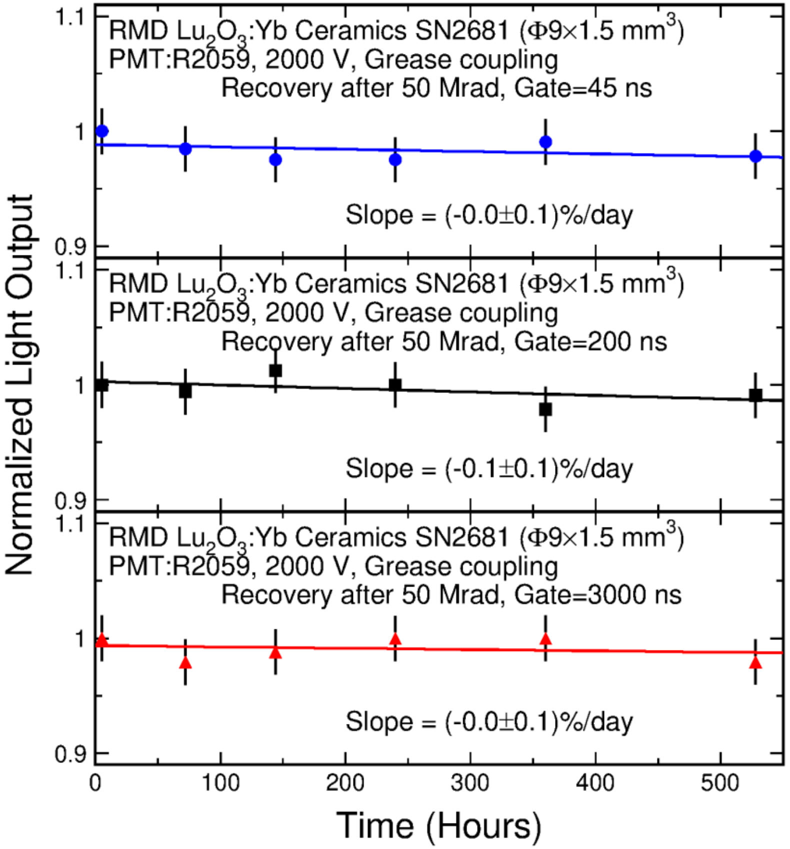
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

Novel Lu_2O_3:Yb Ceramics

Instruments 2022, 6(4), 67 and IEEE NSS 2022/2023 Conference Record





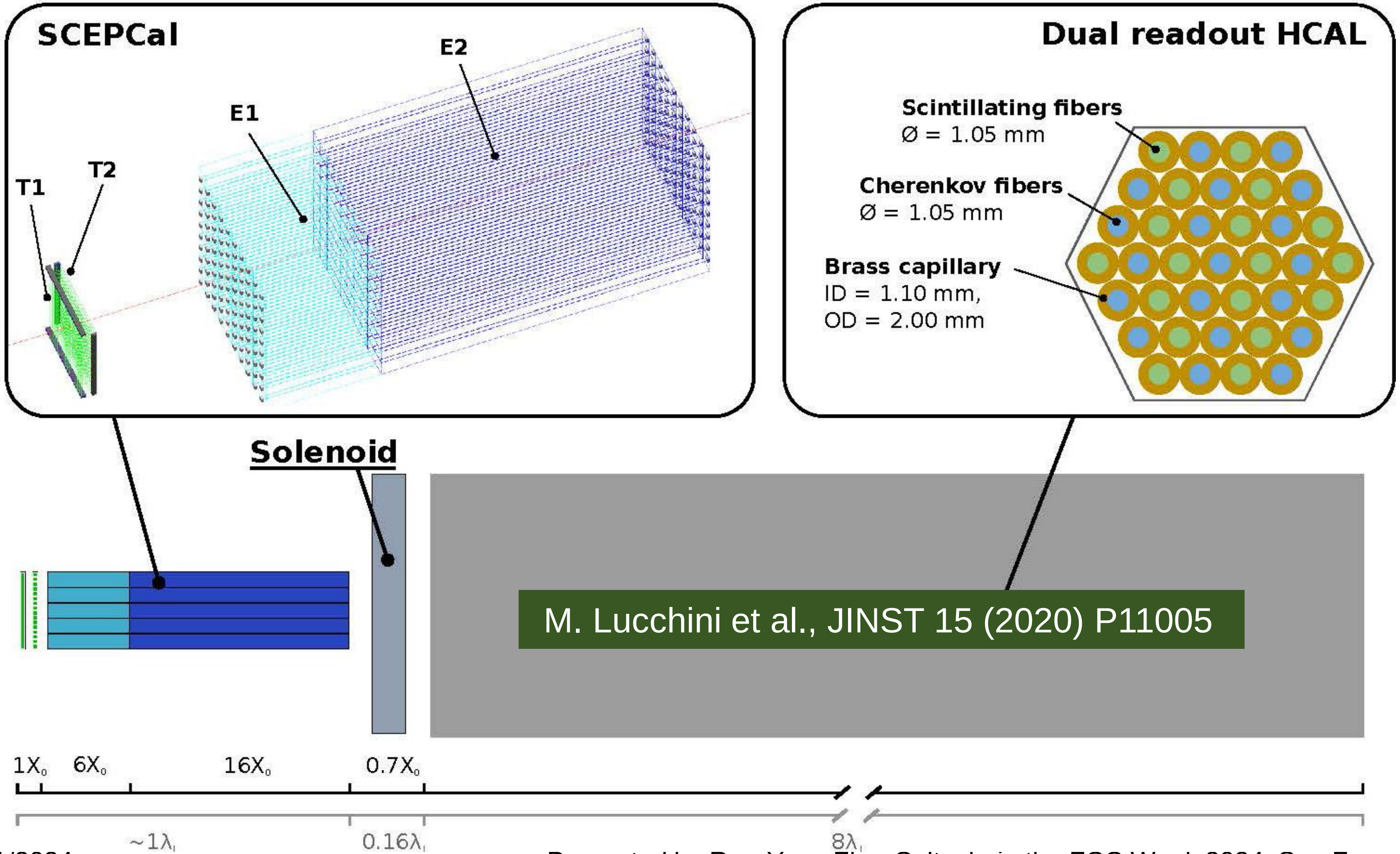


Lu_2O_3:Yb ceramic of 9.4 g/cc shows ultrafast decay of **1.1 ns** with no slow component

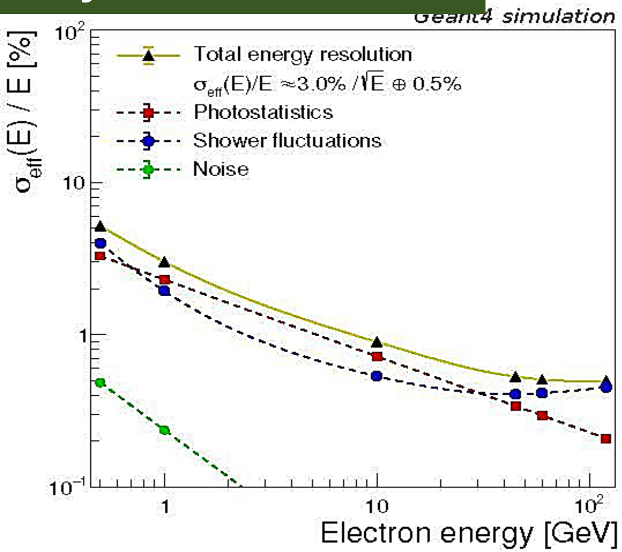
CalVision: Segmented Crystal ECAL

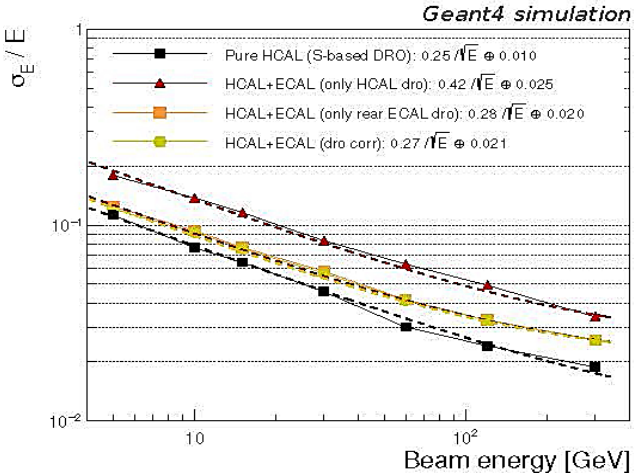
See S. Eno in this Session

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

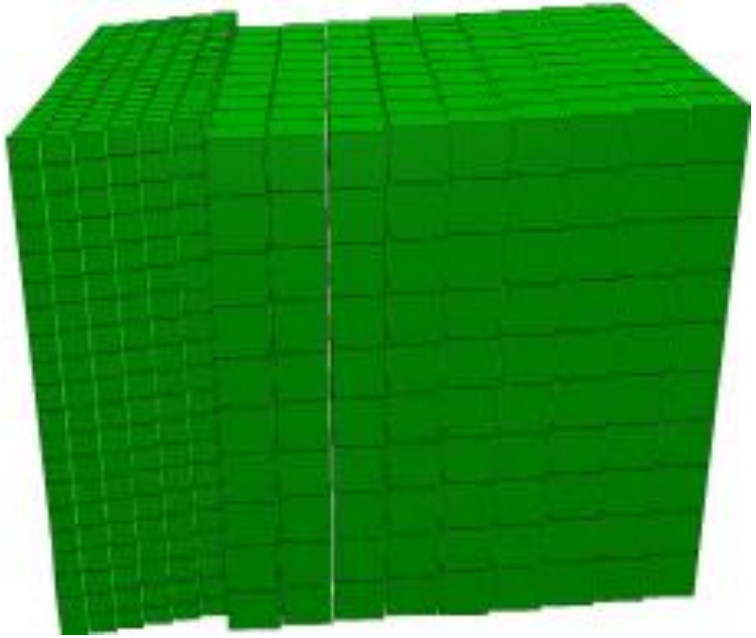


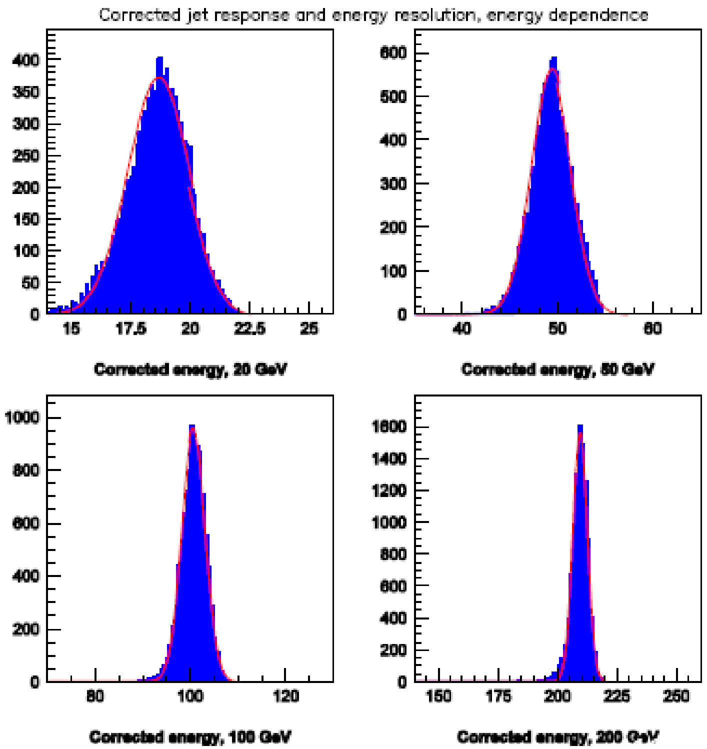
M. Lucchini et al., JINST 15 (2020) P11005



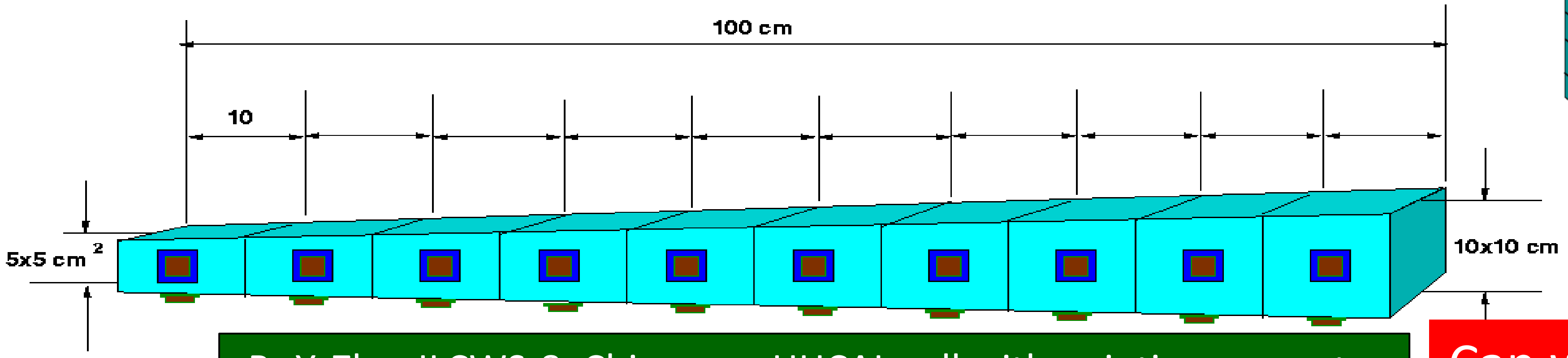


The HHCAL Concept



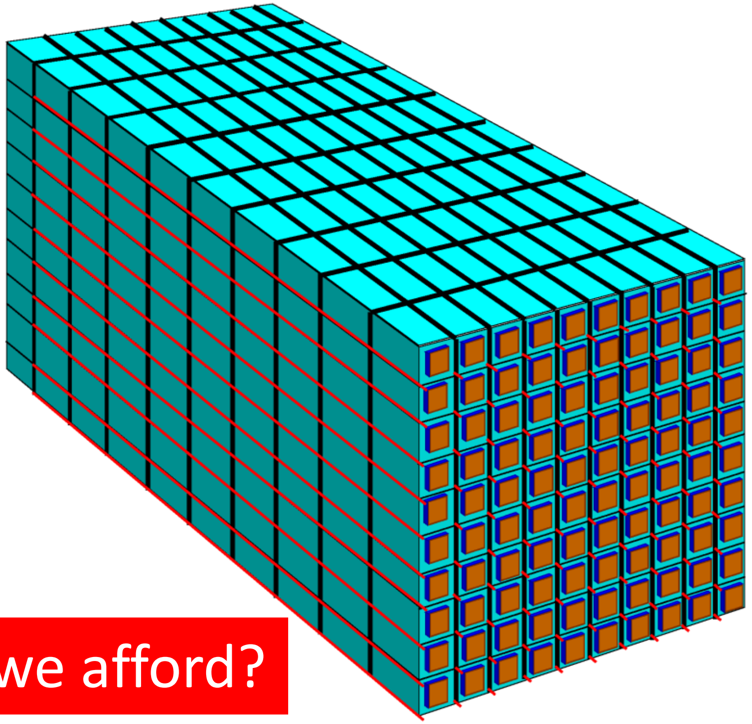


A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and
A. Benaglia *et al.*, IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.
M. Demarteau, 2021 CPAD Workshop



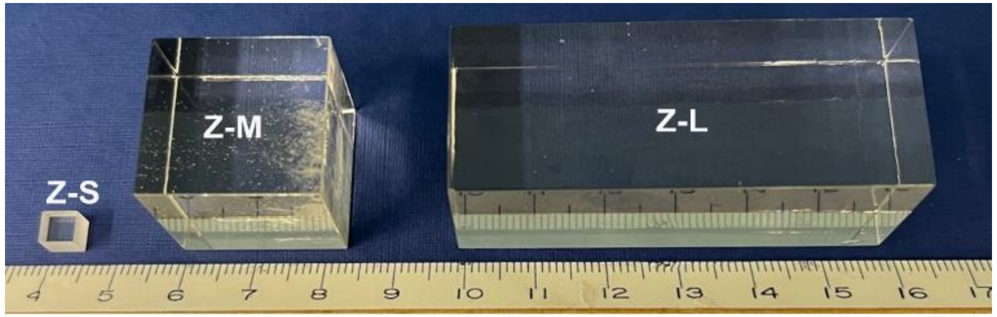
R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

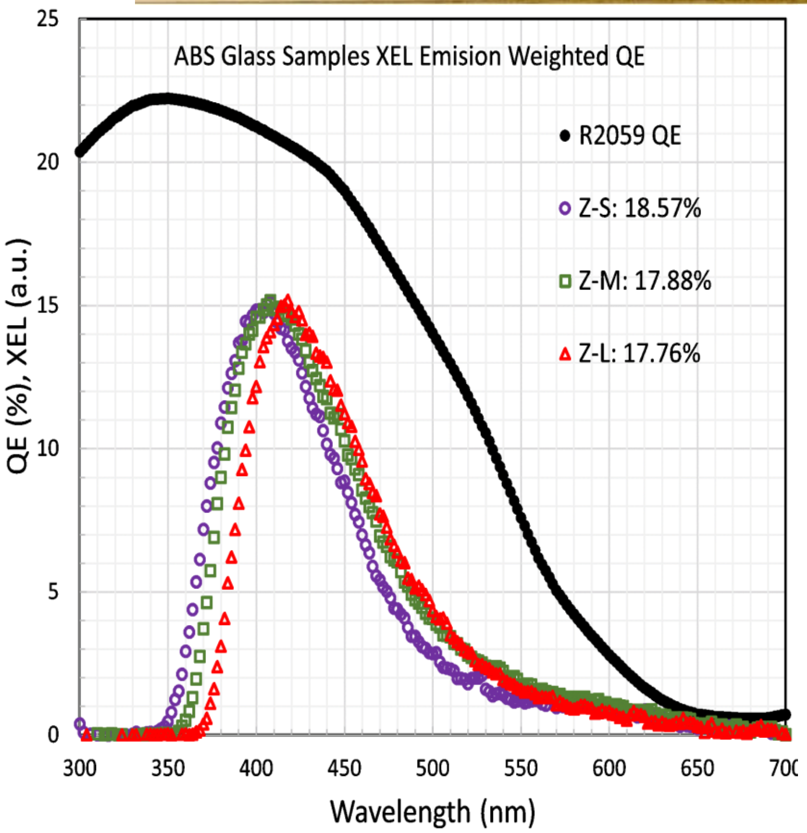
Can we afford?

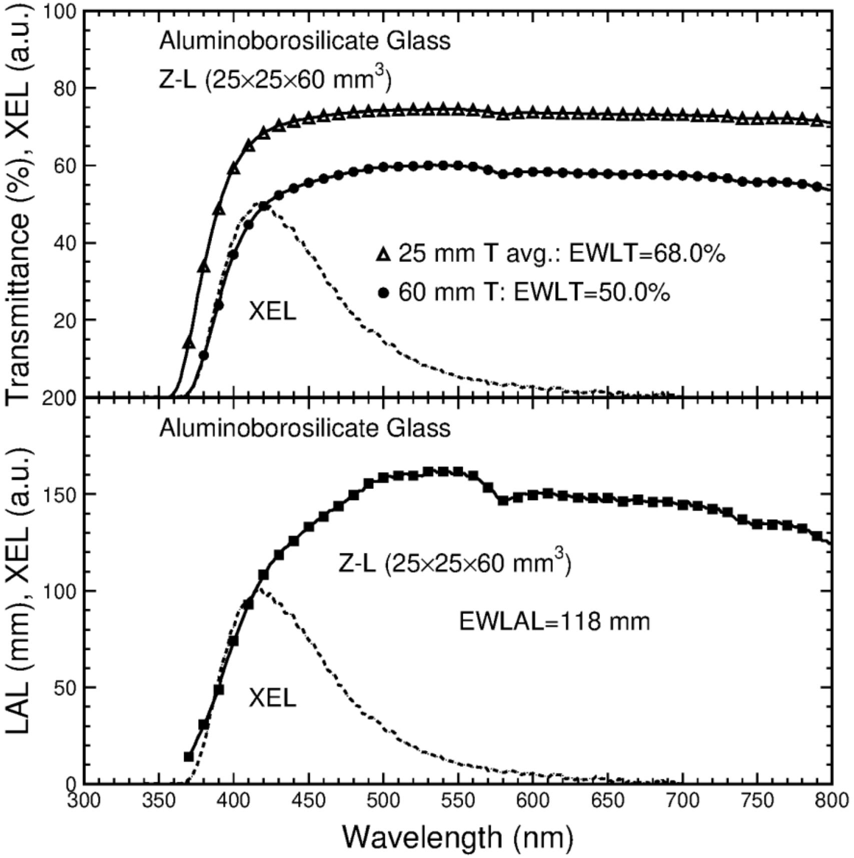


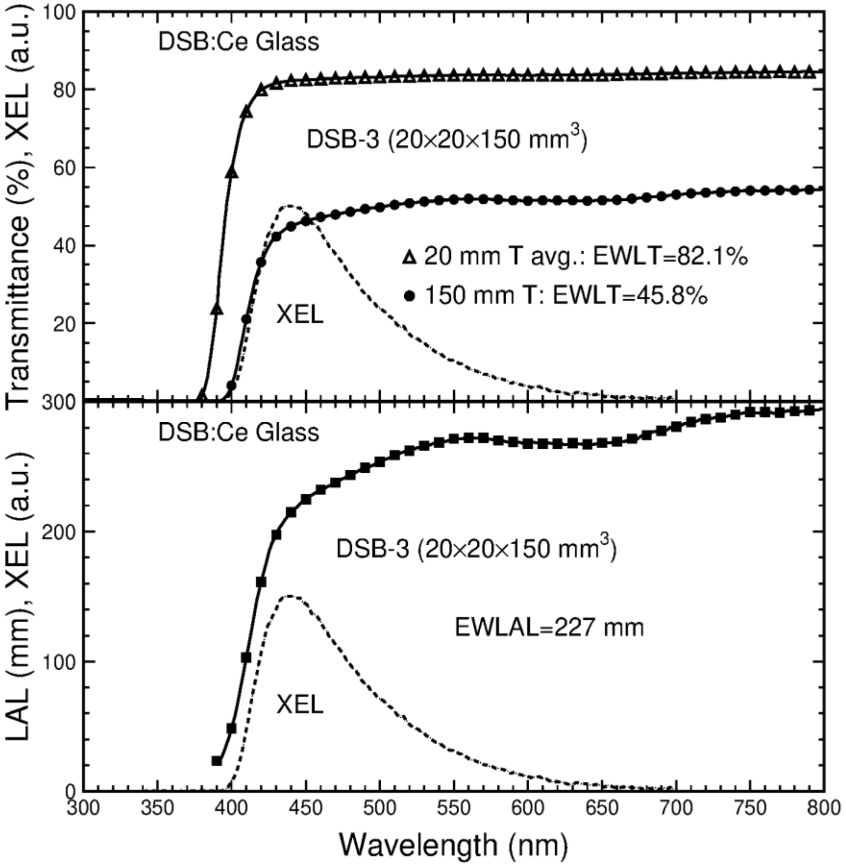
Large Size ABS and DSB Glass

See talks on glass scintillators in Calor2024, Tsukuba









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 inorganic scintillators is integrated in ECFA DRD6 WP3 and CPAD RDC9

Acknowledgements: DOE HEP Award DE-SC0011925 and DE-SC0024094

Fast and Ultrafast Inorganic Scintillators

arXiv: 2203.06788

	BaF_2	BaF_2:Y	Lu_2O_3:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	9.42	5.35	4.56	5.67	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	2490	1870	1940	1975	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	0.81	2.59	3.53	2.51	2.51	1.14	1.45	2.59	1.63	1.37	3.10
R_M (cm)	3.1	3.1	1.72	2.45	2.76	2.28	2.20	2.07	2.15	2.45	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	18.1	23.1	25.2	22.2	20.9	20.9	20.6	23.1	21.5	19.5	27.8
Z_{eff}	51.0	51.0	67.3	32.8	29.3	27.7	27.8	63.7	58.7	32.8	50.6	57.1	32.8
dE/dX (MeV/cm)	6.52	6.52	11.6	7.91	7.01	8.34	8.82	9.55	9.22	7.91	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	370	350	350	380	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.0	1.96	1.87	2.1	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	0.95	0.19[d]	0.36[d]	2.6[d] 4.0[d]	6.5 0.5	100	35[e] 48[e]	9 32	190	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	280	57[d]	110[d]	2,000[d]	2,100	30,000	25,000[e]	12,000	58,000	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	1.1[d]	1.1[d]	1.8[d]	3.0[d] 1.0[d]	110 5.3	40	820 50	191 25	570 130	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	170	34[d]	46[d]	980[d]	43	740	240	391	400	125	318
LY in 1st ns /Total LY (%)	9.0	64	60	60	43	49	2.0	2.5	1.2	3.3	0.7	1.4	1.3
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.127	0.314	0.439	0.407	0.394	0.185	0.251	0.314	0.319	0.214	0.334

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by Alpha particles; [e] 0.3 Mg at% co-doping; [f] $Lu_{0.7}Y_{0.3}AlO_3$:Ce.

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