Progresses of Inorganic Scintillators for Future HEP Calorimeters

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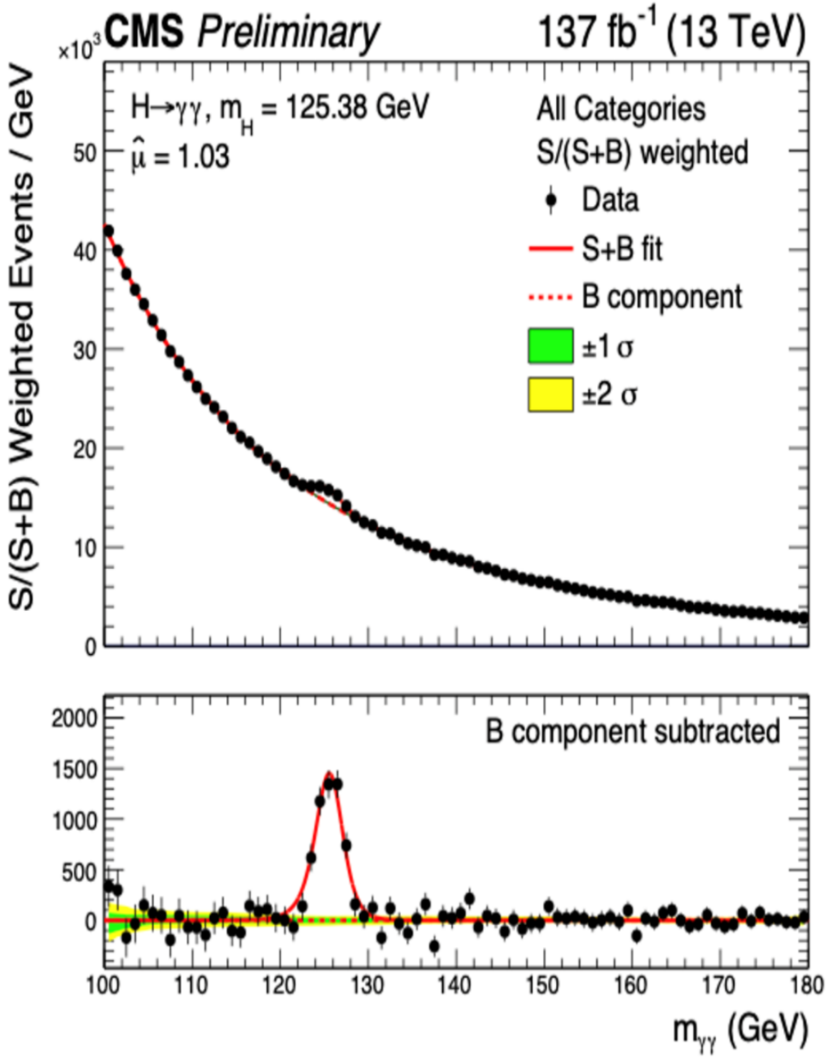
2019 DOE Basic Research Needs Study Priority Research Directions for Calorimetry

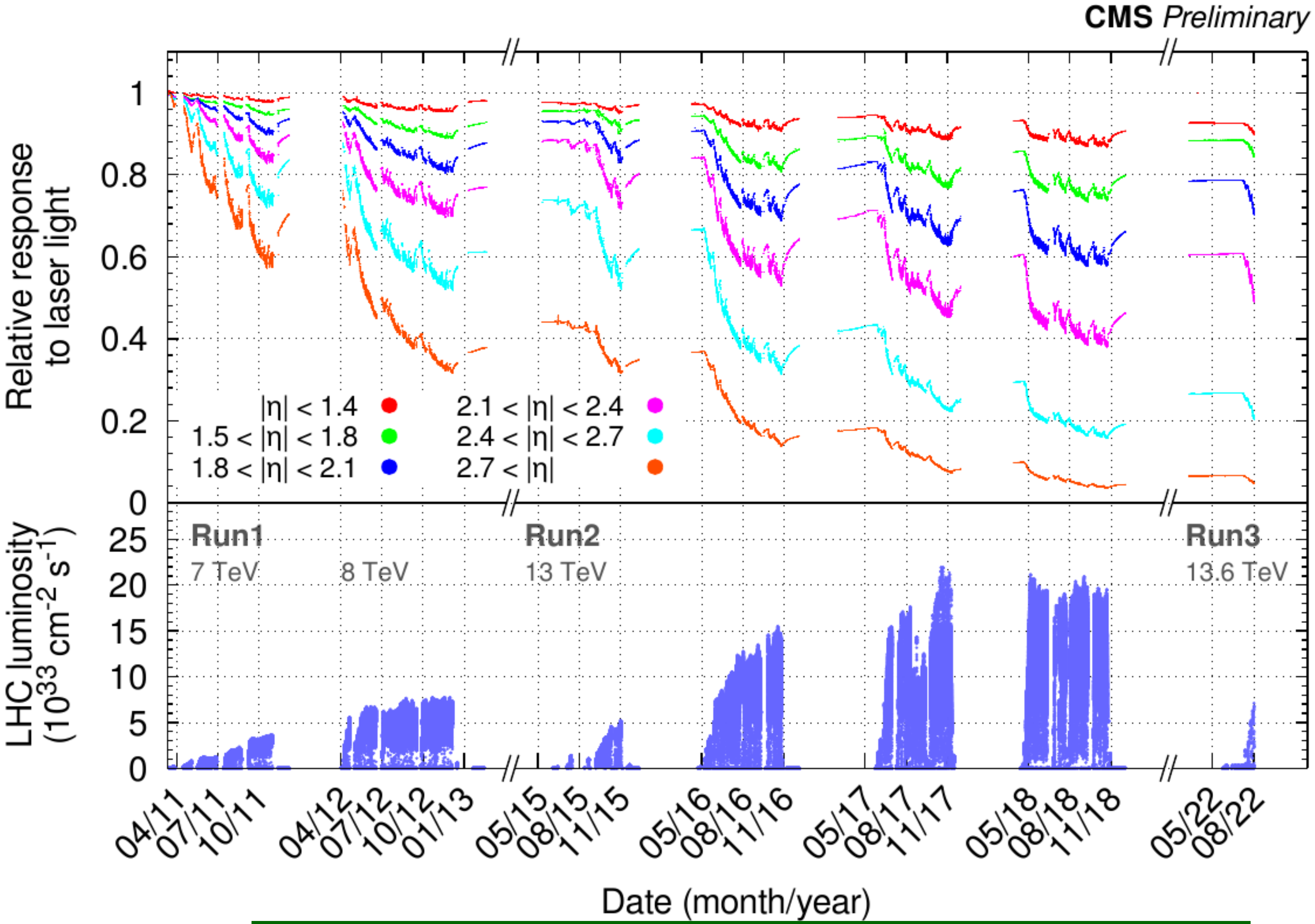
- Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements;
- Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments;
- Develop ultrafast media to improve background rejection in calorimeters and particle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

CMS H -> γγ and PWO Damage

T. Dimova, TIPP2023, light monitoring data





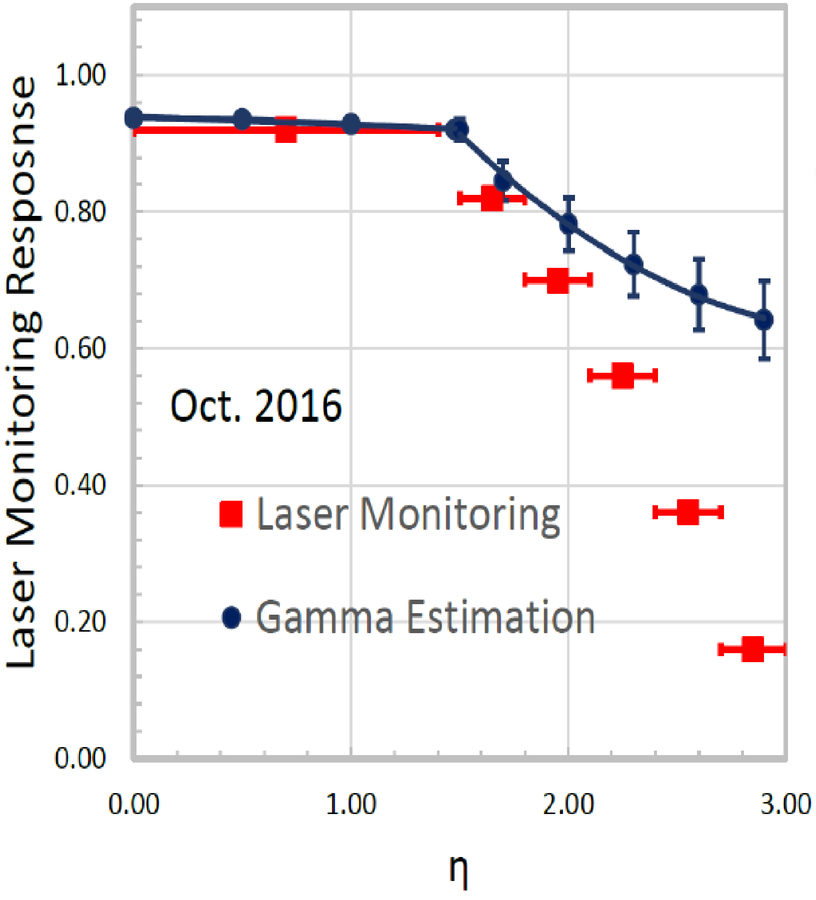
PWO damage due to ionization dose and hadrons

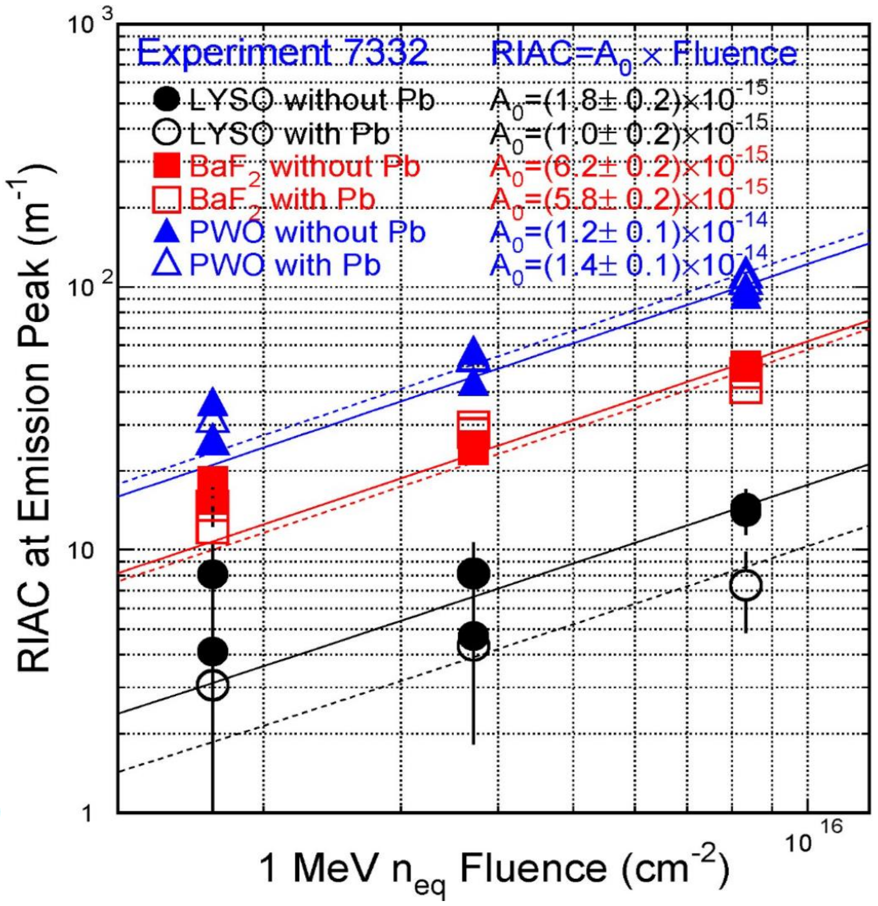
PWO Damage by Ionization & Neutrons

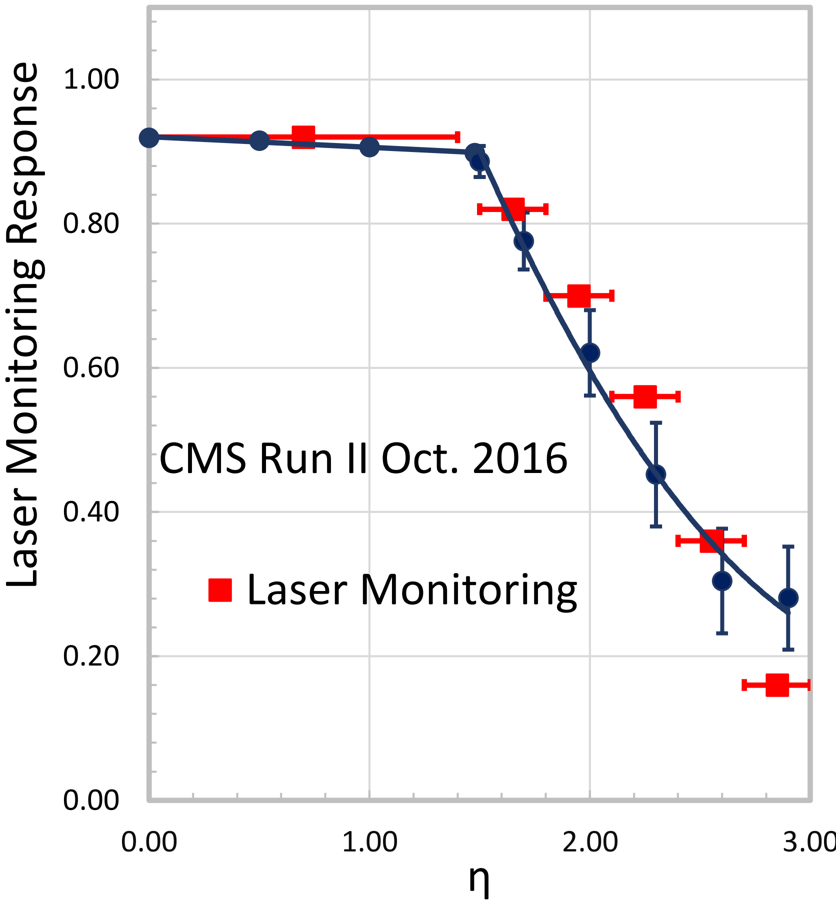
RIAC in PWO = $1.4 \times 10^{-14} \times$ 1 MeV n_{eq} Fluence

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



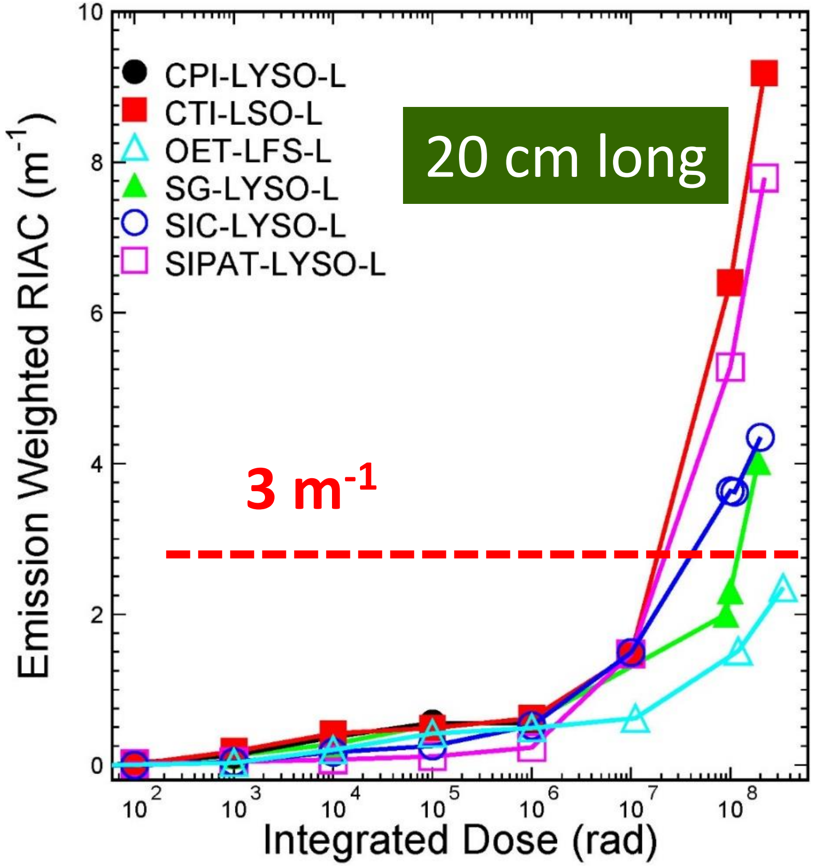


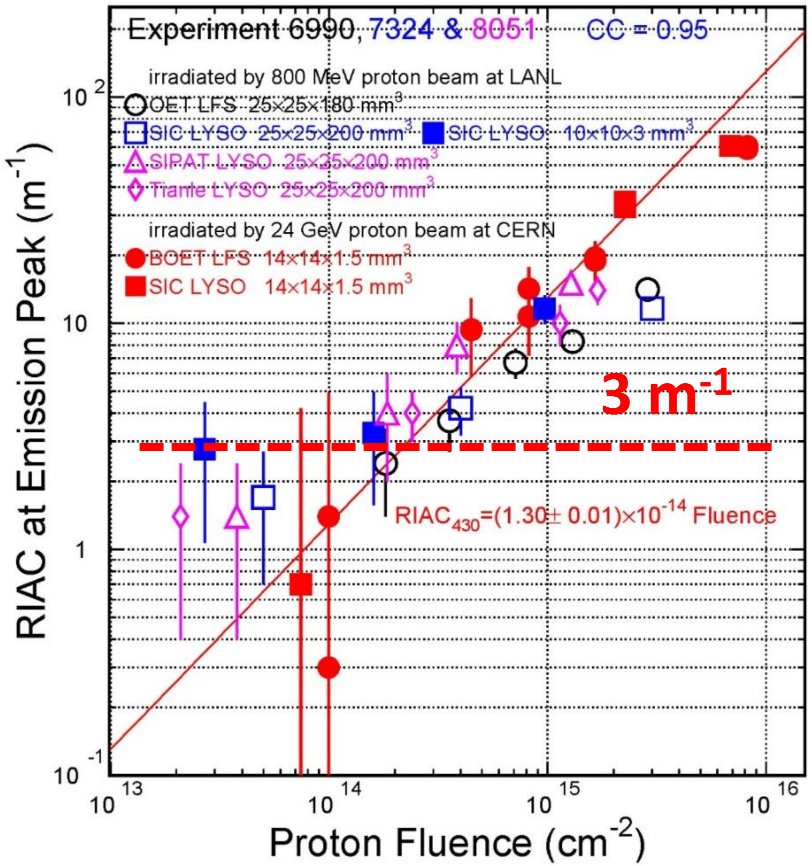


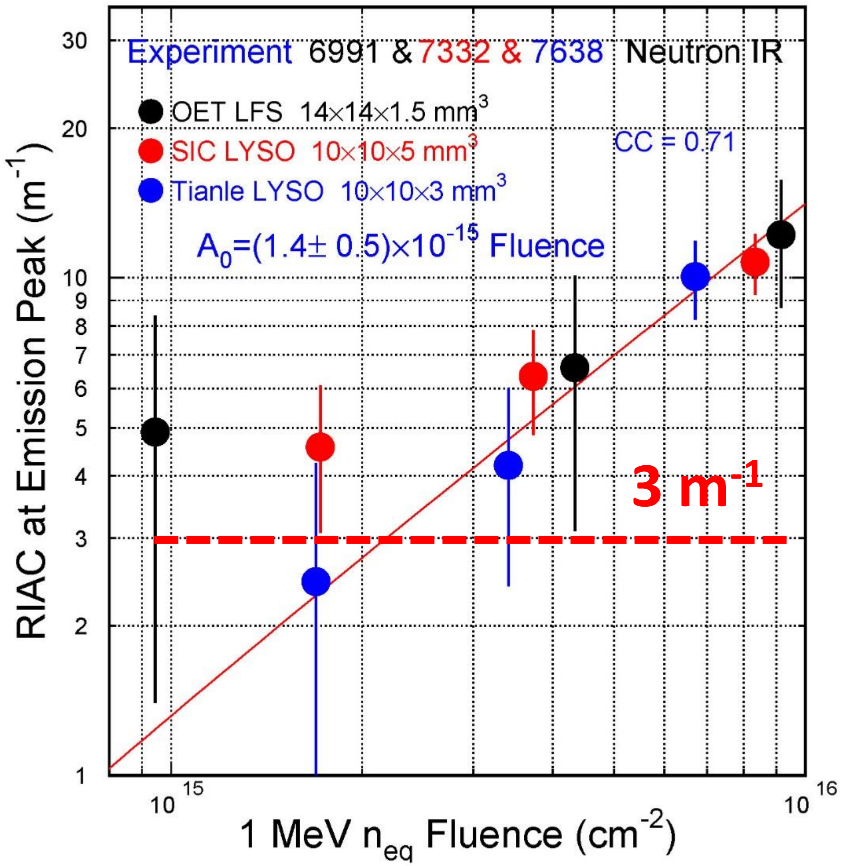
LYSO:Ce Radiation Hardness

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





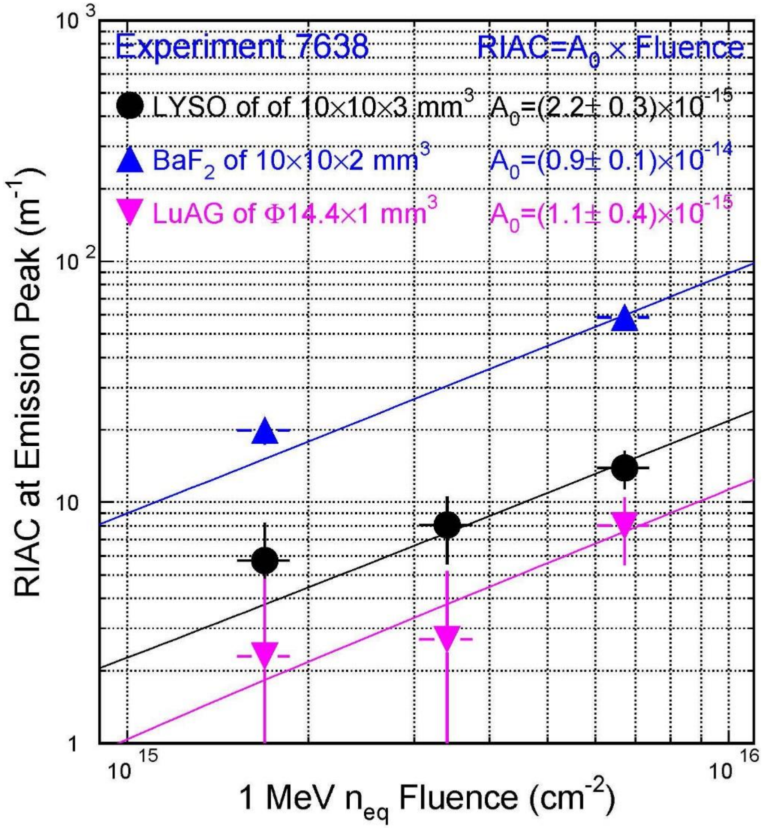


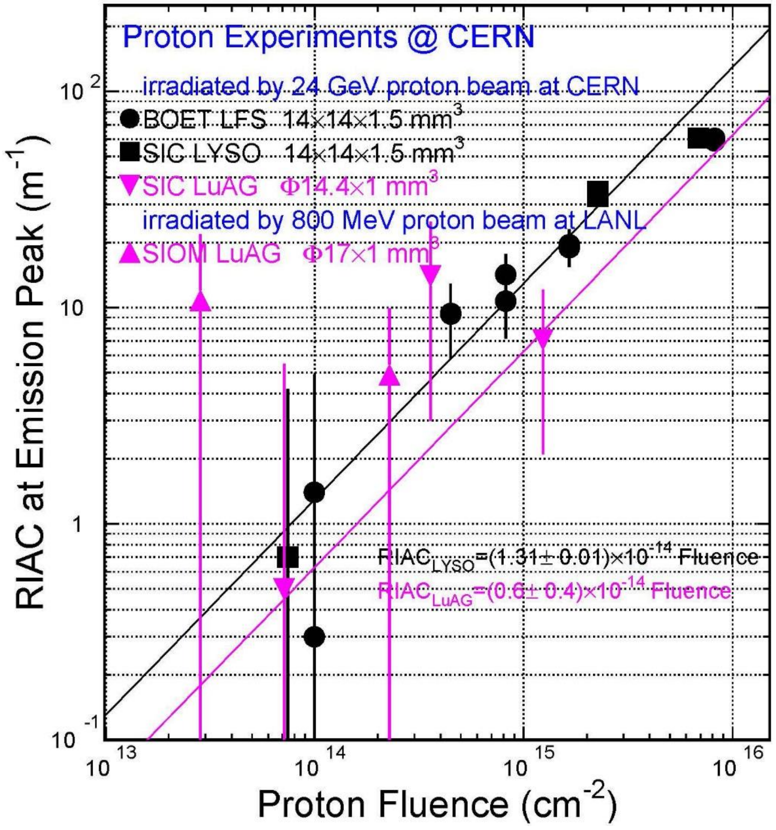
Damage induced by protons is larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

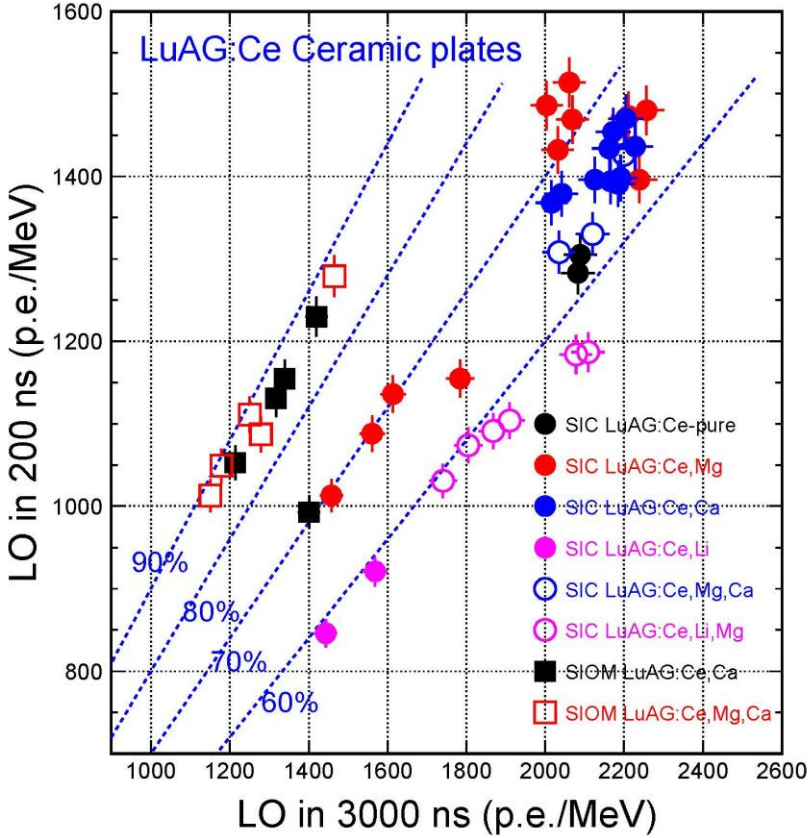
LuAG:Ce Ceramics Radiation Hardness

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

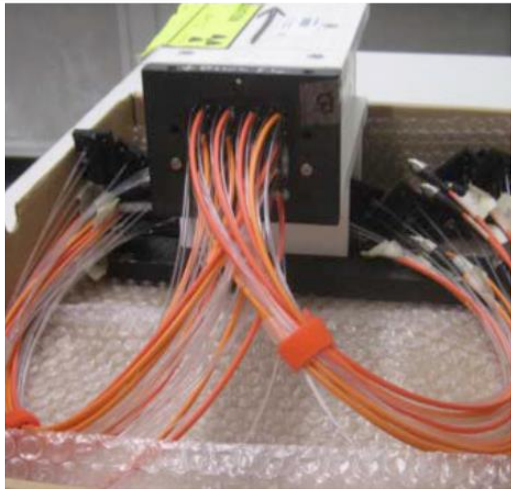


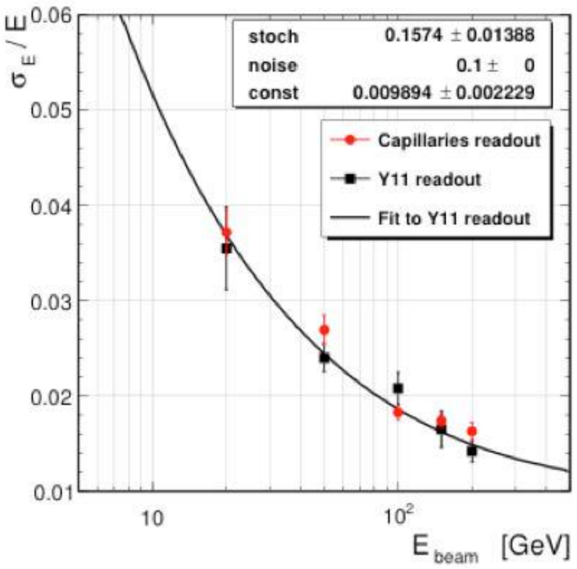




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

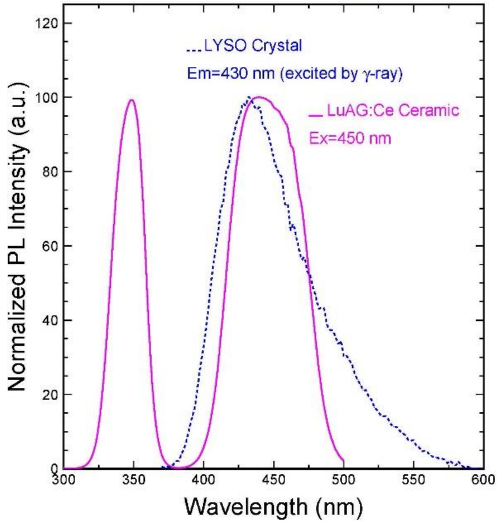
RADiCAL: LYSO/LuAG Shashlik ECAL

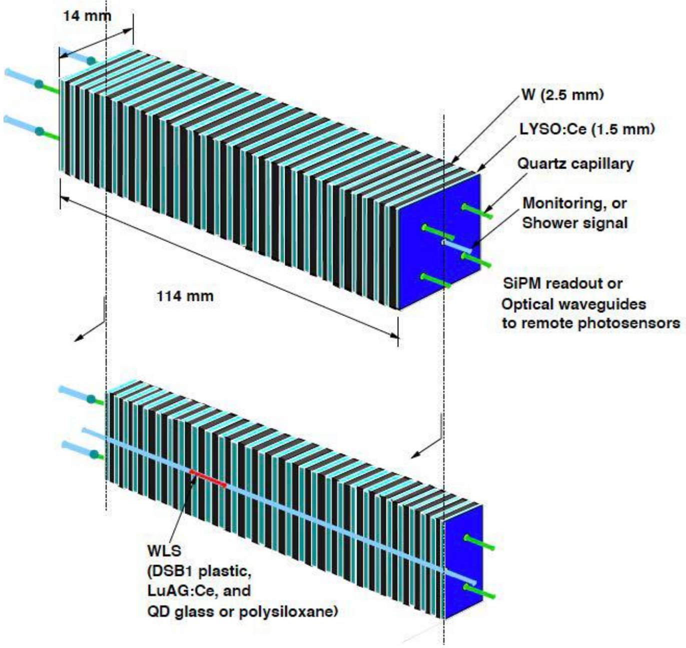


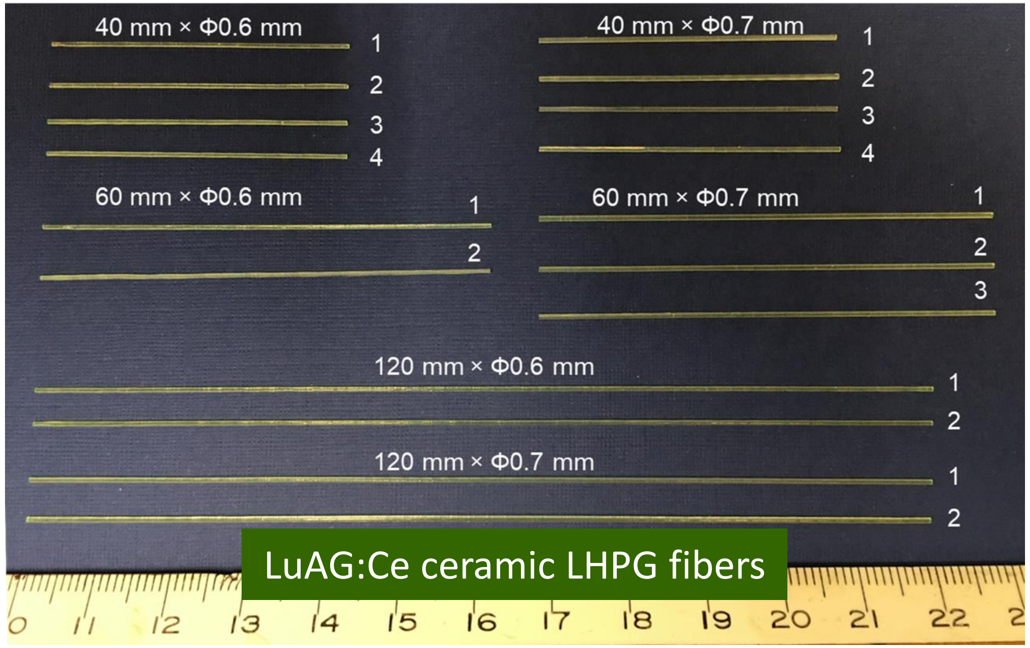


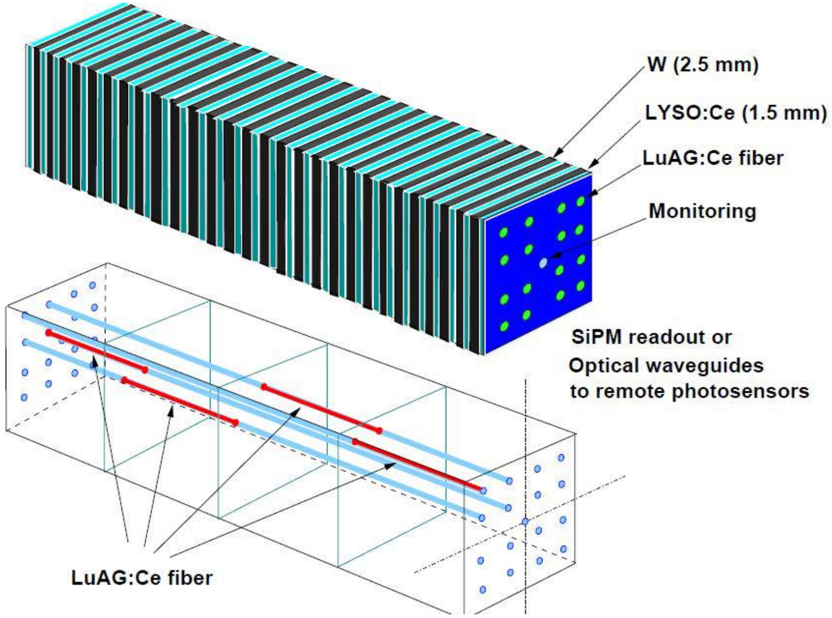
arXiv: 2203.12806, see also
J. Wetzel in this workshop

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





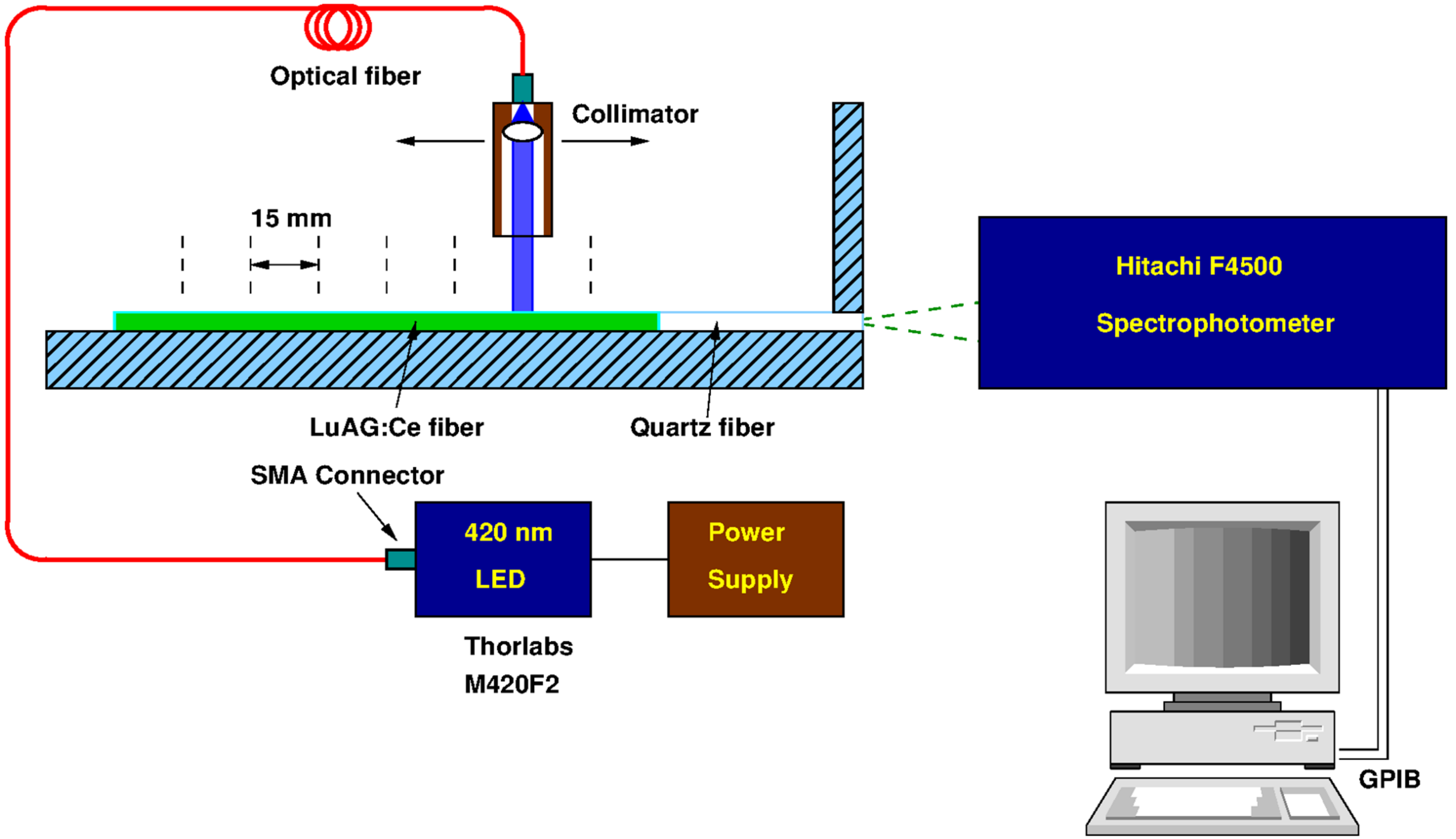


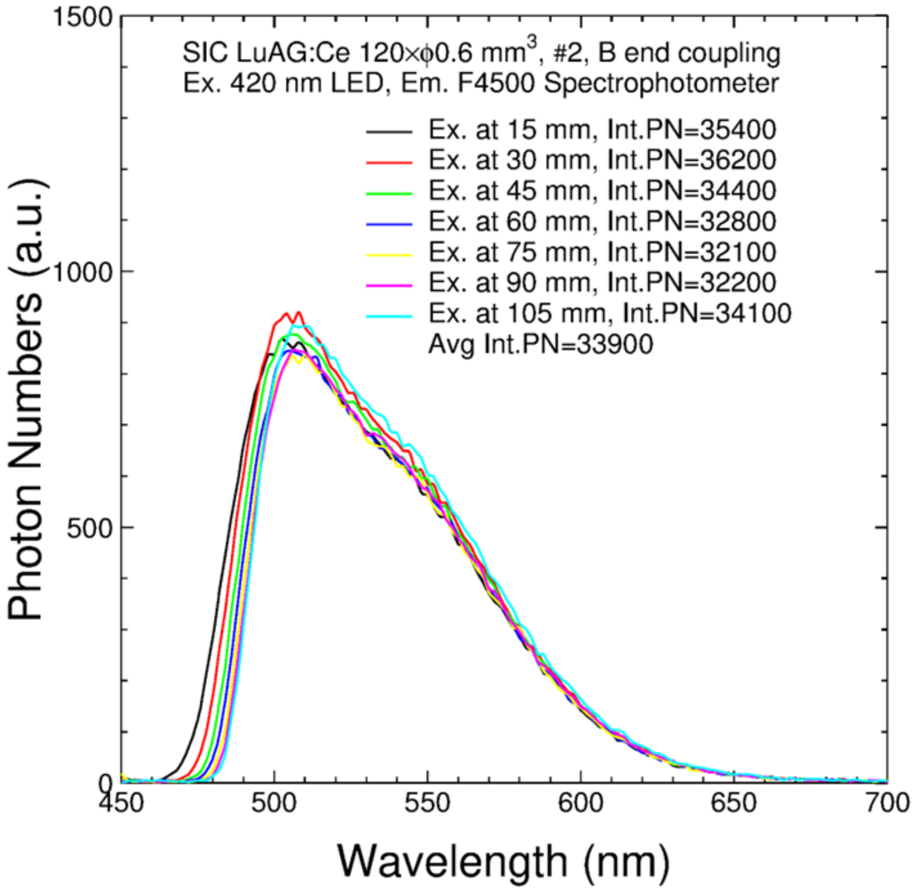


Light Output and Response Uniformity

10.1109/NSS/MIC44867.2021.9875908

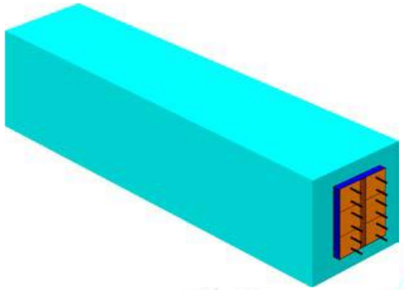
Excellent longitudinal uniformity observed for a Φ0.6 ×120 mm^3 LuAG:Ce ceramic excited by a 420 nm LED at different location, with a solid coupling to a quartz fiber, mimicking its application in RADiCAL





Ultrafast BaF_2:Y Calorimeter for Mu2e-II

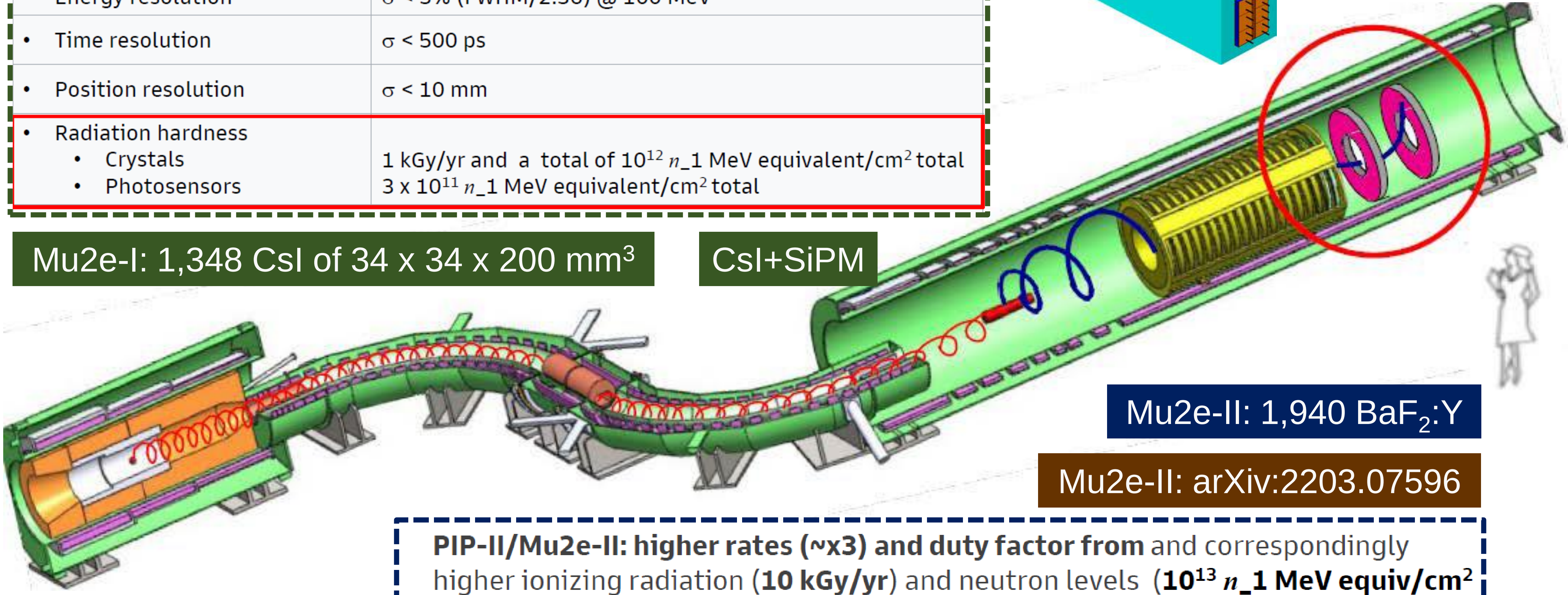
Use ultrafast material to mitigate pile-up



• 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



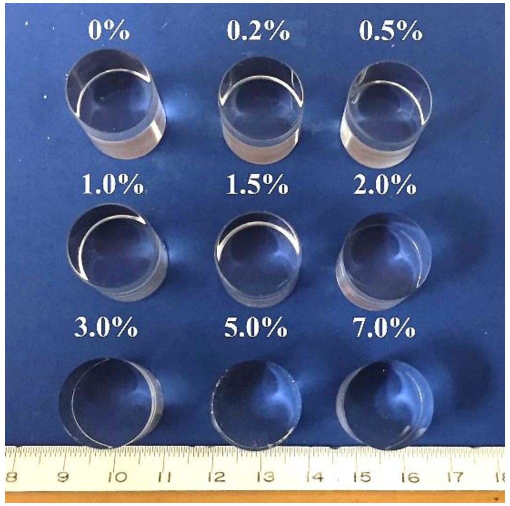
Mu2e-II: 1,940 BaF_2:Y

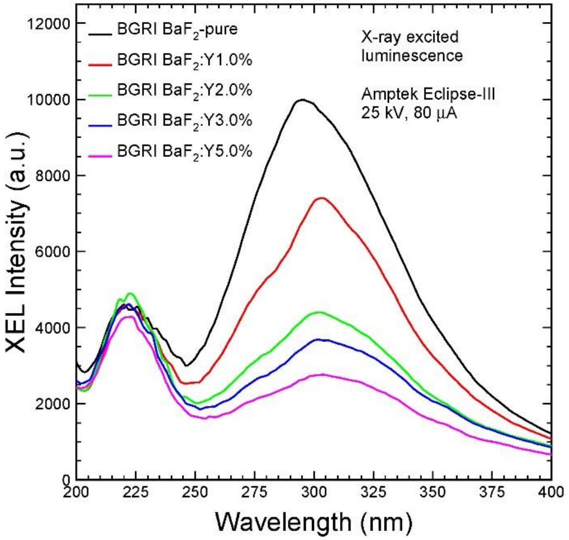
Mu2e-II: arXiv:2203.07596

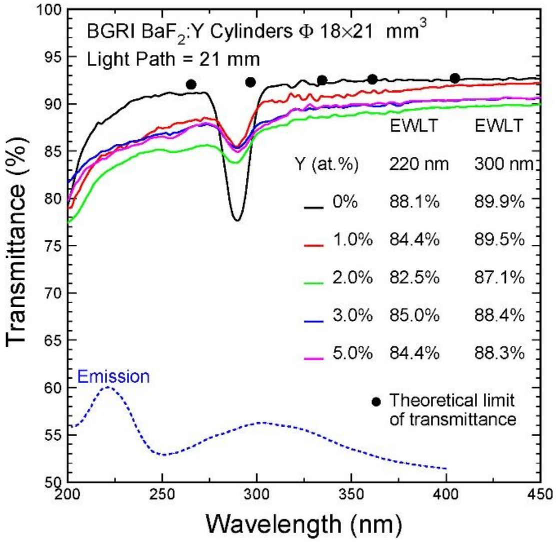
PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

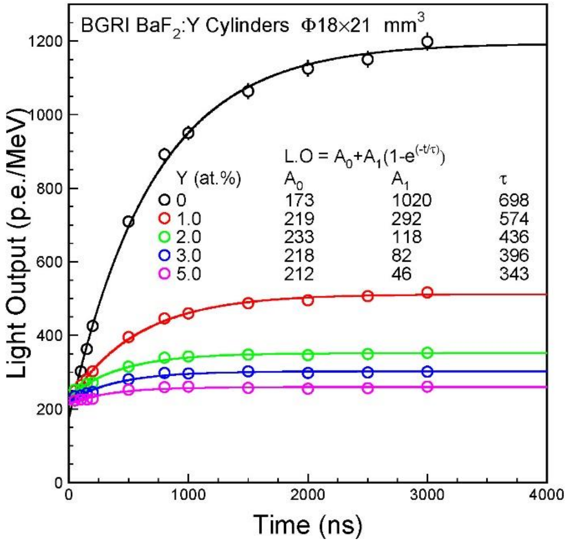
BaF_2:Y for Calorimetry & Imaging

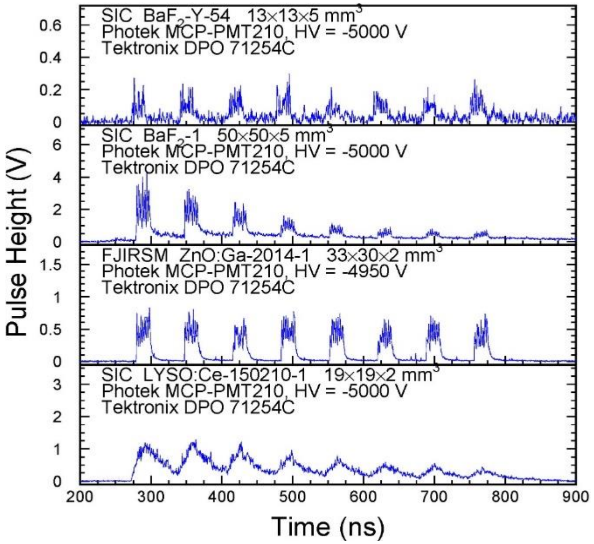
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

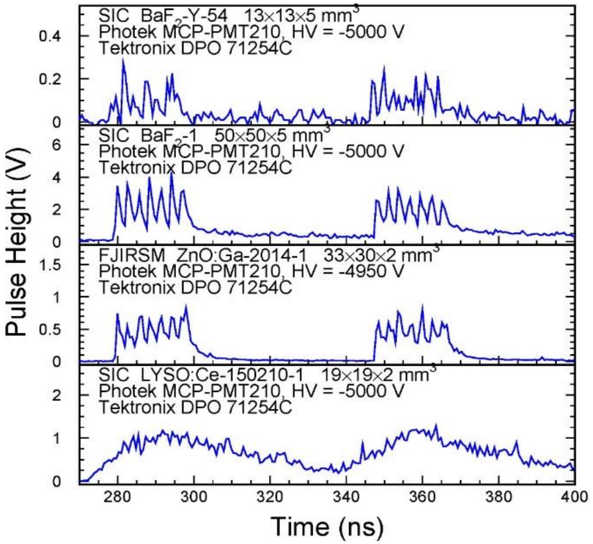


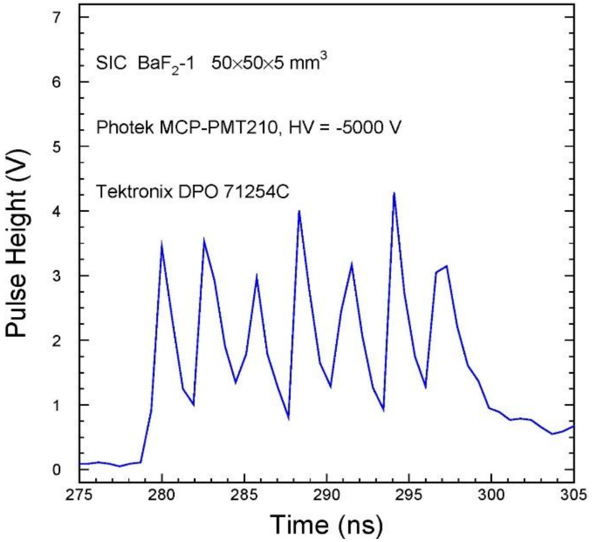












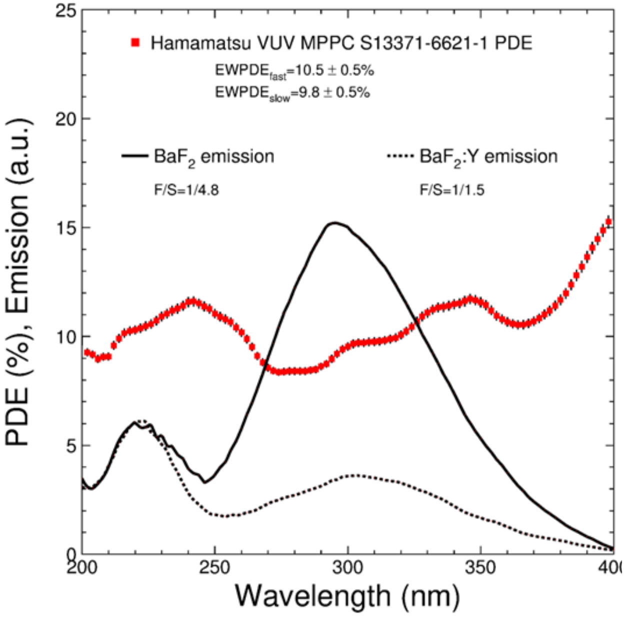
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

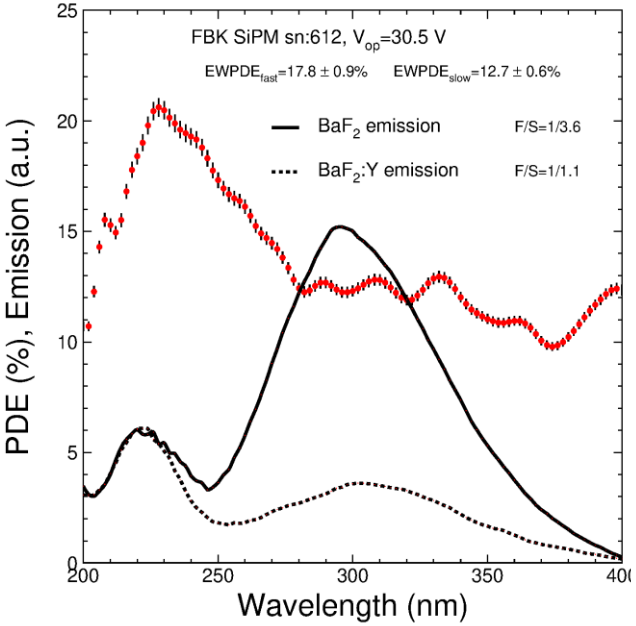
PDE of UV SiPM for BaF_2 and BaF_2:Y

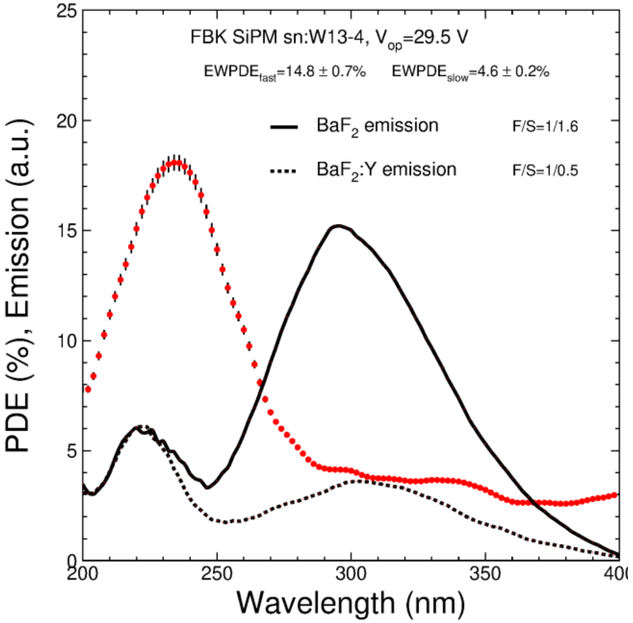
D. Hitlin in this workshop, see also IEEE TNS **69** (2022) 958-964

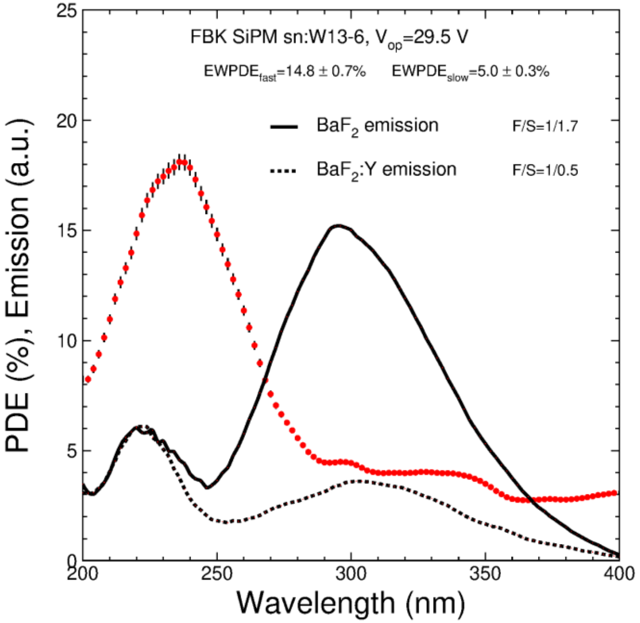
Photodetector	$EWPDE_{fast}$ (%)	$EWPDE_{slow}$ (%)	Relative F/S_{BaF}	Relative $F/S_{BaF:Y}$
Hamamatsu MPPC	10.5	9.8	1/4.8	1/1.5
FBK SiPM 2021	17.8	12.7	1/3.6	1/1.1
FBK SiPM 2023-1	14.8	4.6	1/1.6	1/0.5
FBK SiPM 2023-2	14.8	5.0	1/1.7	1/0.5

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



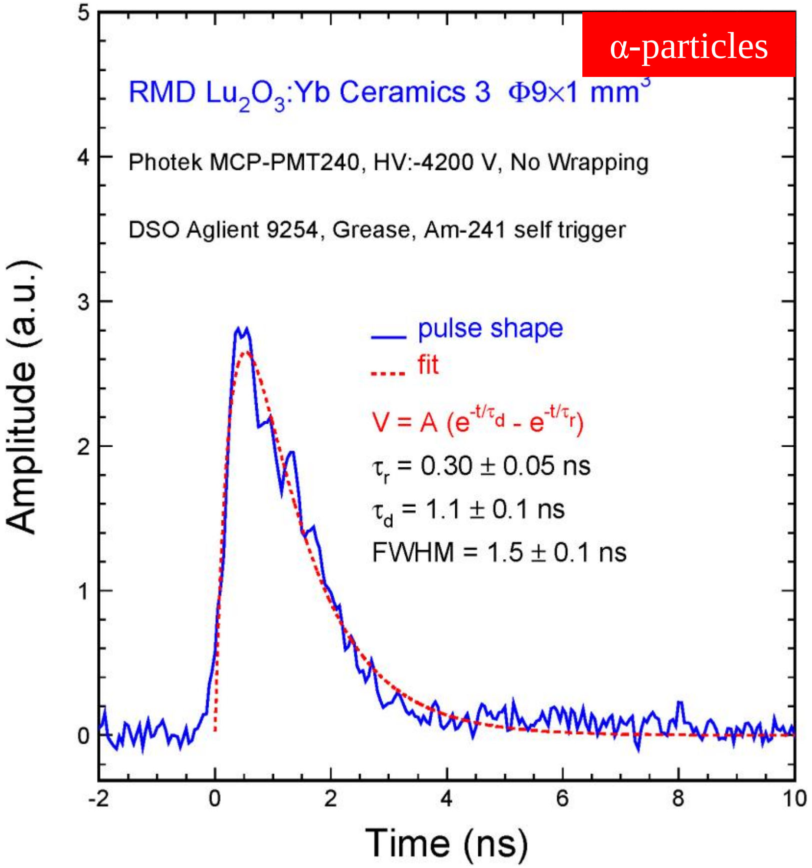


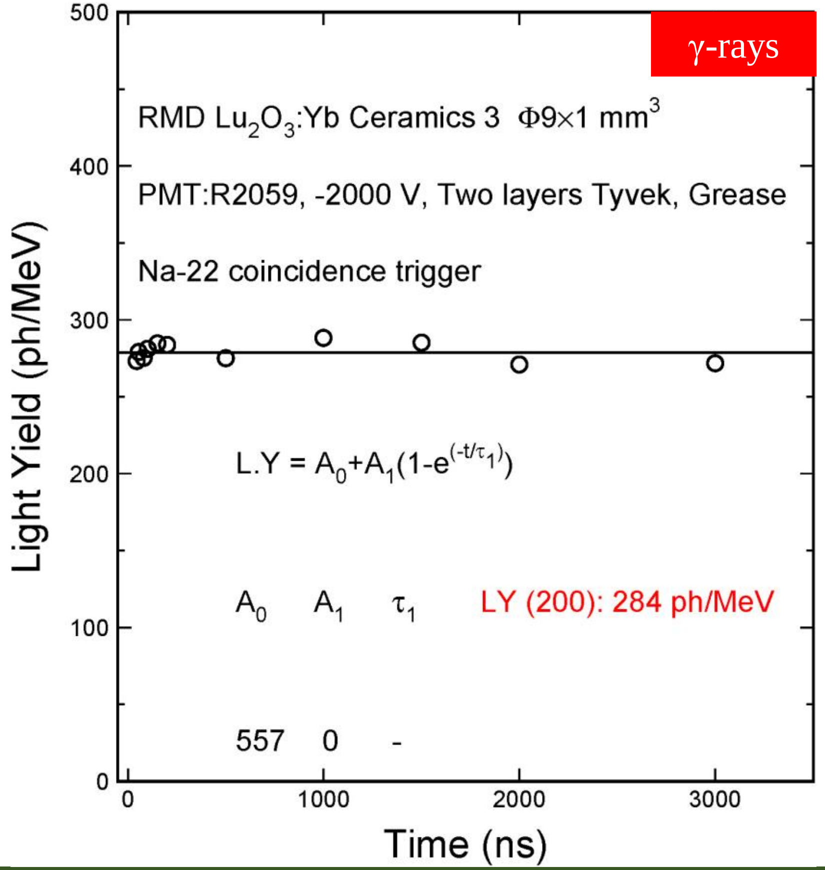


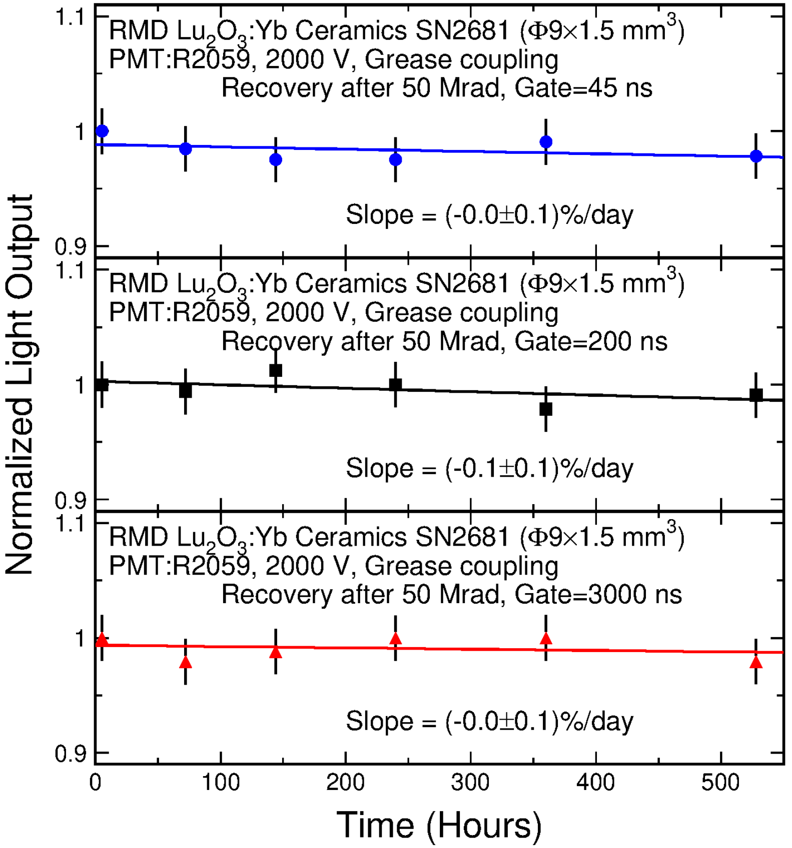


Novel Lu_2O_3:Yb Ceramics

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





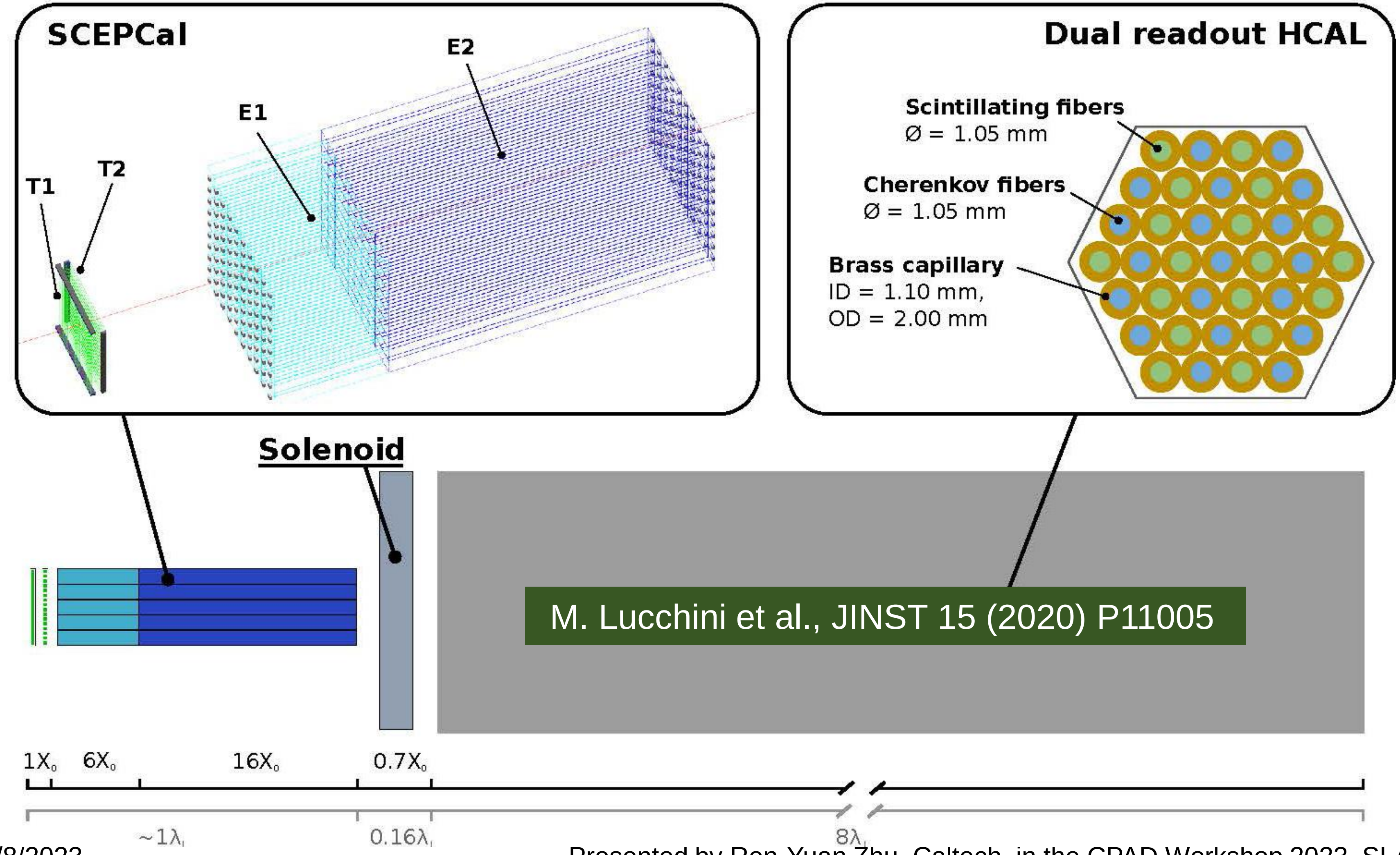


Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

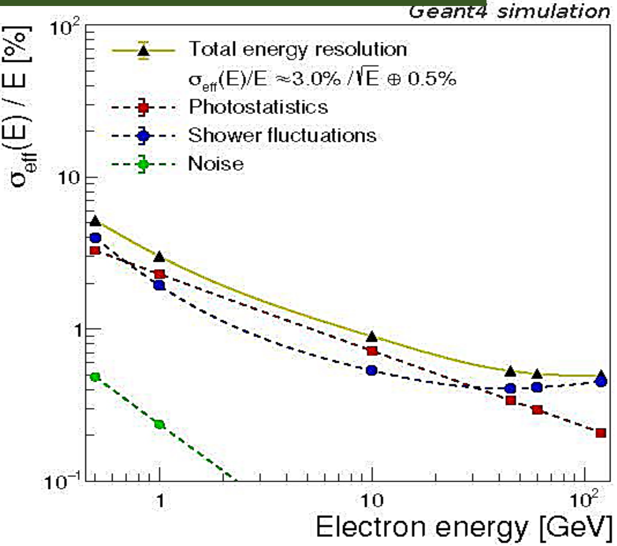
CalVision: Segmented Crystal ECAL

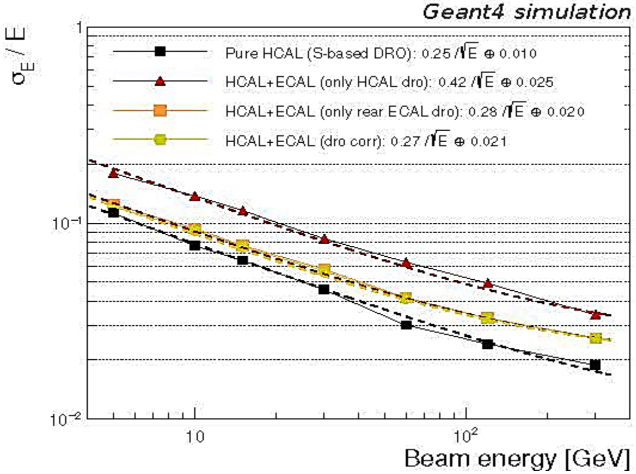
arXiv: 2203.04312, see also R. Hirosky in this Workshop

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

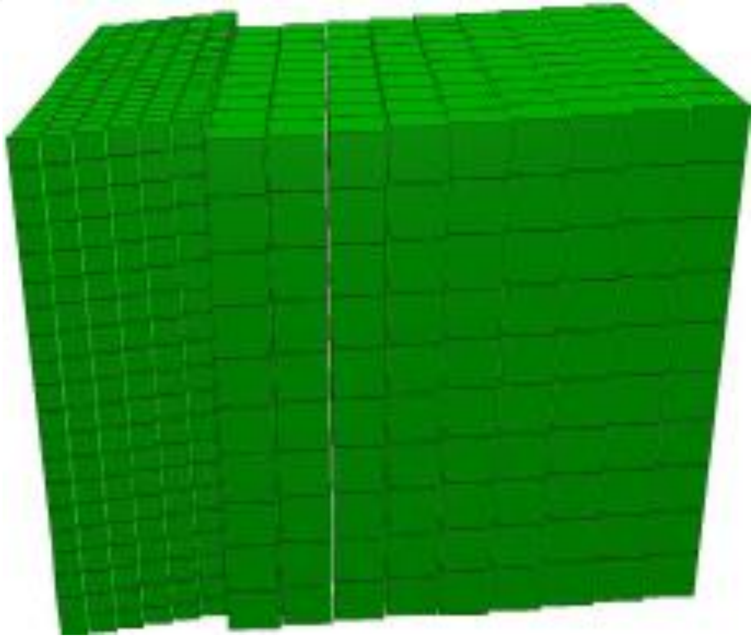


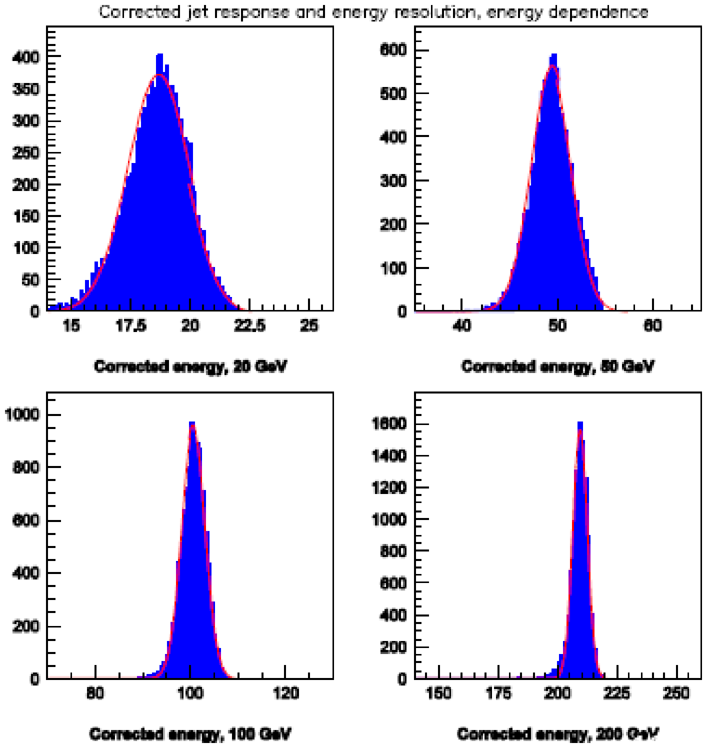
M. Lucchini et al., JINST 15 (2020) P11005



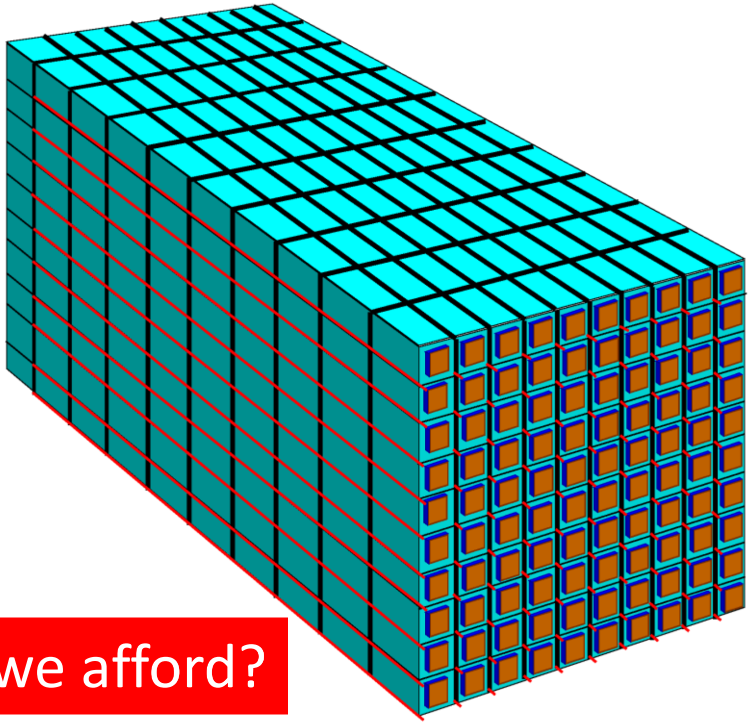


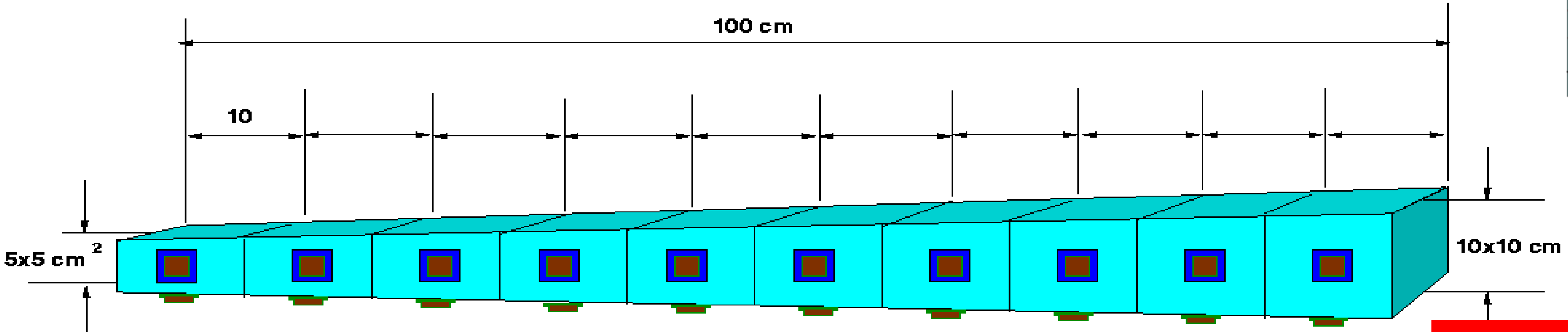
The HHCAL Concept





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

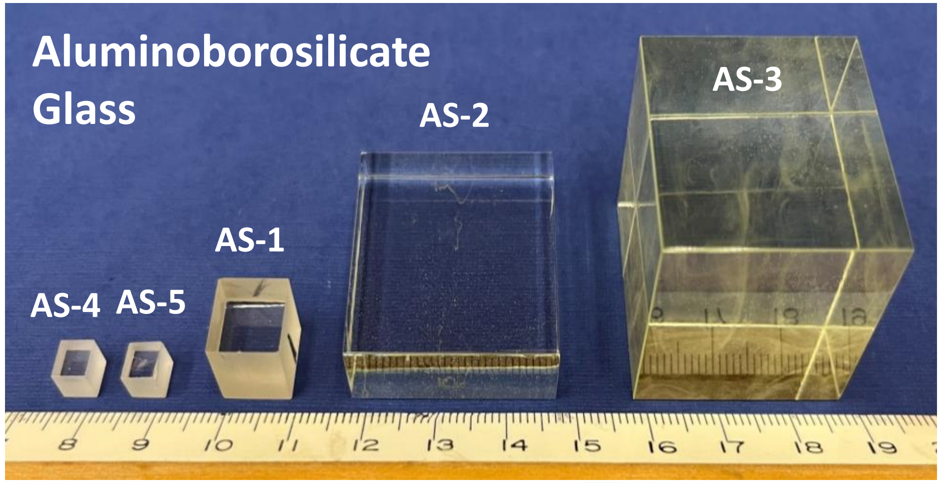


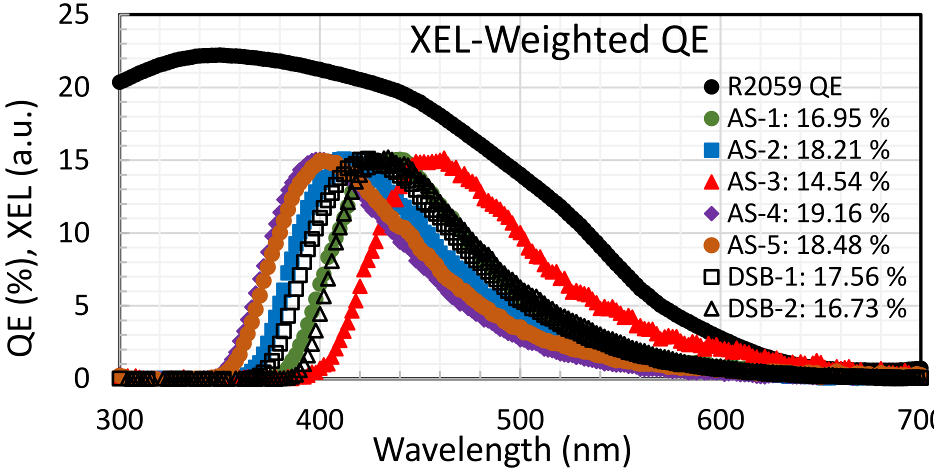


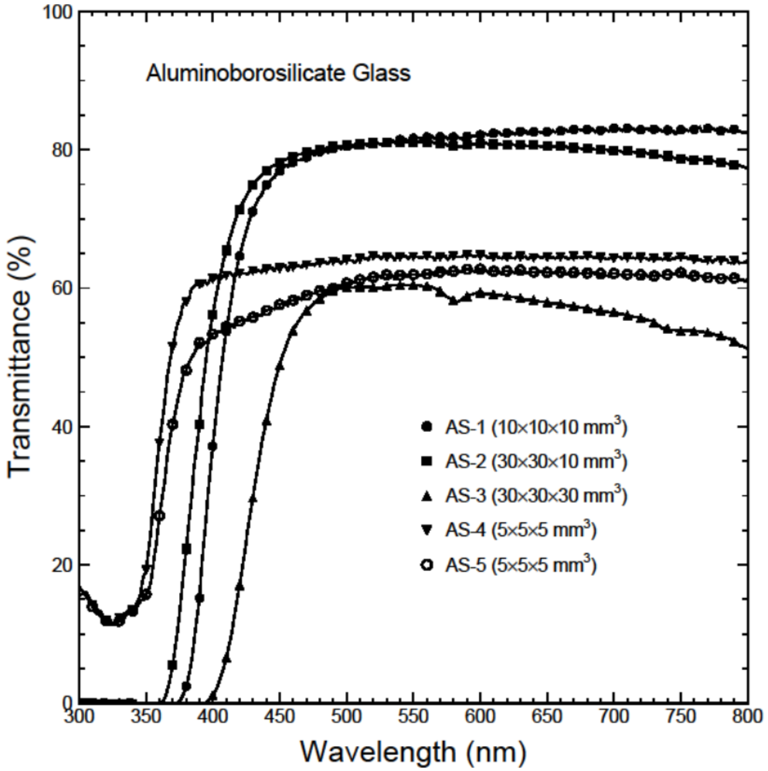
R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

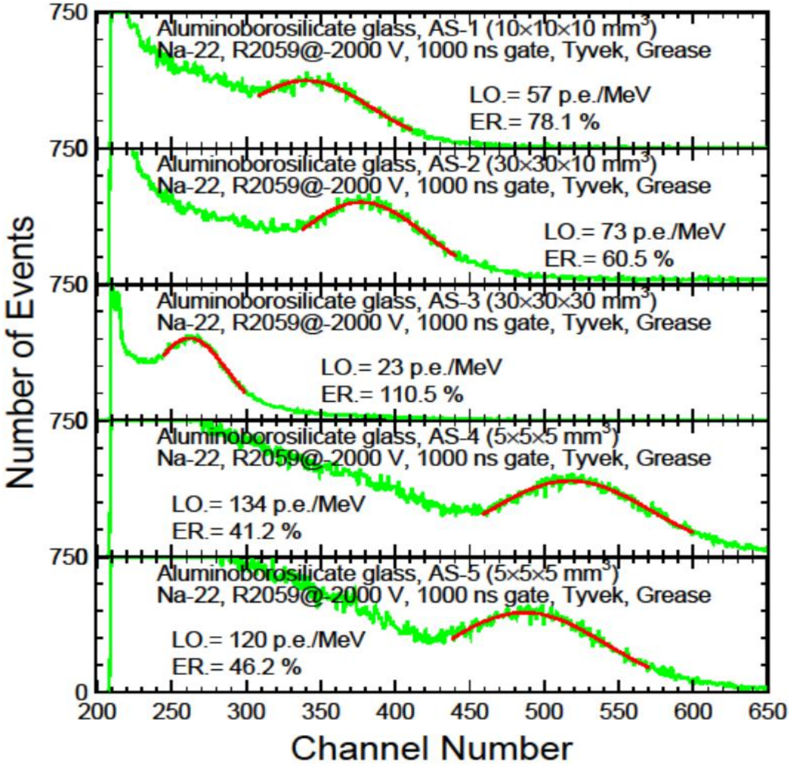
Can we afford?

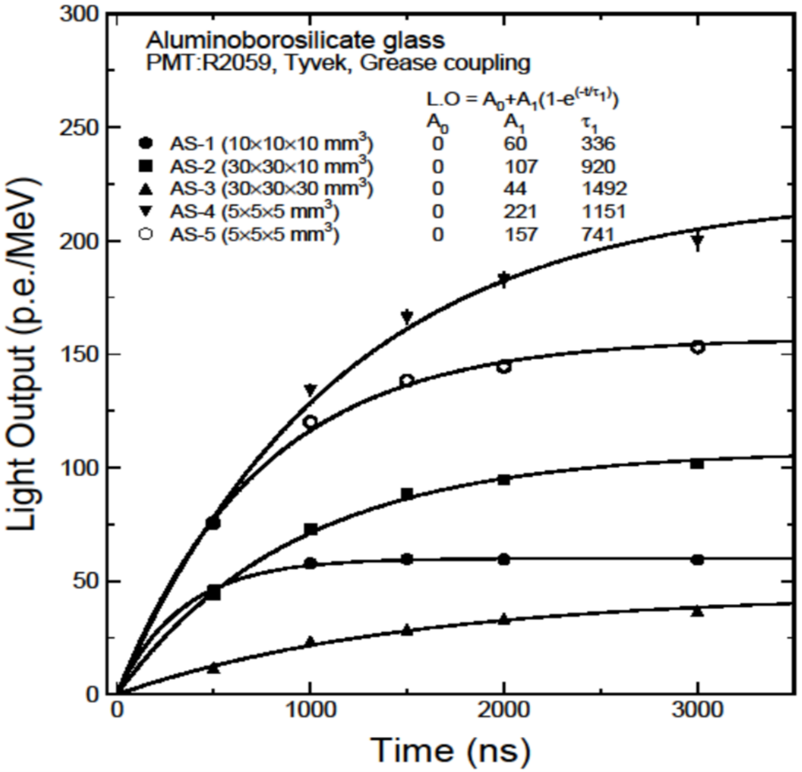
ABS (B_2O_3–SiO_2–Al_2O_3–Gd_2O_3–Ce_2O_3) Glass











Inorganic Scintillators for HHCAL

Presented in 9/14/2023 CalVision meeting All samples measured at Caltech Crystal Lab

	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 scintillator.

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 by industry.

Acknowledgements: DOE HEP Award DE-SC0011925