Inorganic Scintillators for Future HEP Experiments

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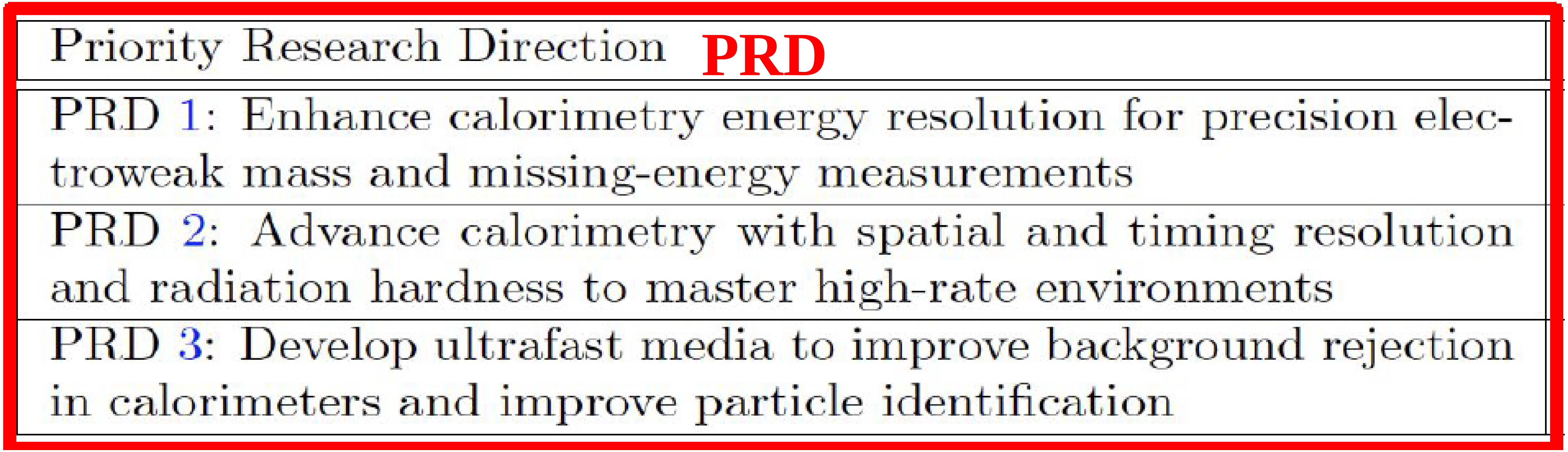
2019 DOE Basic Research Needs Study on Instrumentation for Calorimetry



Priority Research Direction **PRD**
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

Snowmass 2022 White Paper “Materials for Future Calorimeters”
arXiv 2203.07154, or https://doi.org/10.48550/2203.07154
Fast/ultrafast, radiation hard and cost-effective active material

Inorganic Scintillators

2022 IEEE NSS MIC RTSD

- **Precision photons and electrons enhance physics discovery potential.**
- **Crystal performance is well understood:**
  - **The best possible energy resolution and position resolution;**
  - **Good e/γ identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout,: C/S or F/S gate.**
- **Challenges at future HEP Experiments:**
  - **Fast and radiation hard scintillators for the HL-LHC and FCC-hh;**
  - **Ultrafast scintillators to break ps timing barrier & Mu2e-II ECAL;**
  - **Cost-effective crystals for the proposed Higgs factory.**
- **Inorganic scintillators at Caltech Crystal Lab:**
  - **Radiation hard LYSO:Ce and LuAG:Ce ceramics;**
  - **Ultrafast BaF_2:Y crystals and Lu_2O_3:Yb ceramics (N17-2);**
  - **BGO, BSO & PWO crystals and heavy scintillating glasses.**

arXiv: 2203.06731 and arXiv: 2203.06788

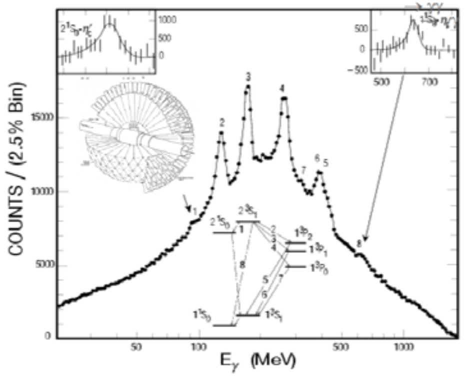
Crystal ECAL Physics

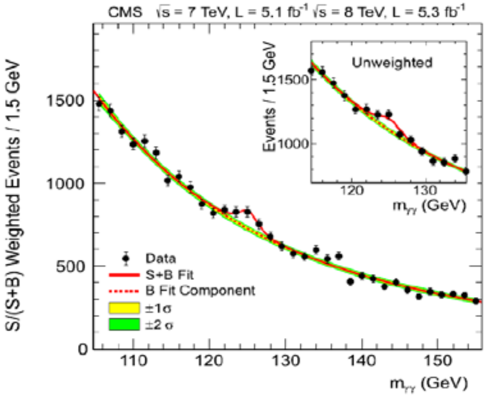
Charmonium system observed by CB through Inclusive photons

Higgs -> γγ by CMS through reconstructing photon pairs

CB NaI(Tl)

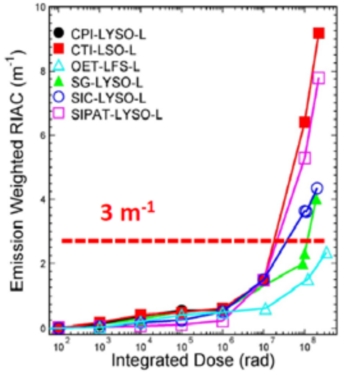
CMS PWO



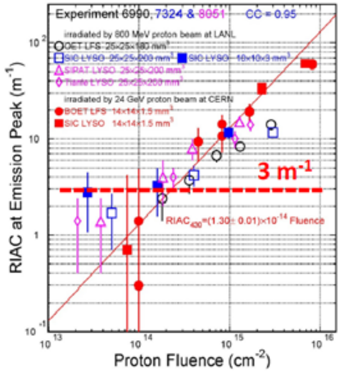


LYSO:Ce Crystals for CMS BTL

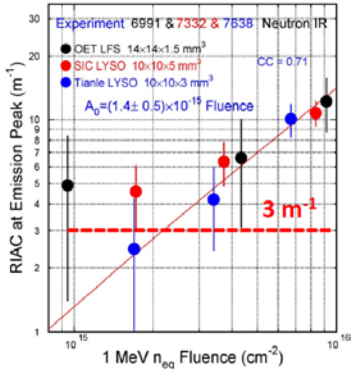
NIM A **824** (2016) 726-728



IEEE TNS **64** (2017) 665-672 , **65** (2018) 1018-1024



IEEE TNS **67** (2020) 1086-1092



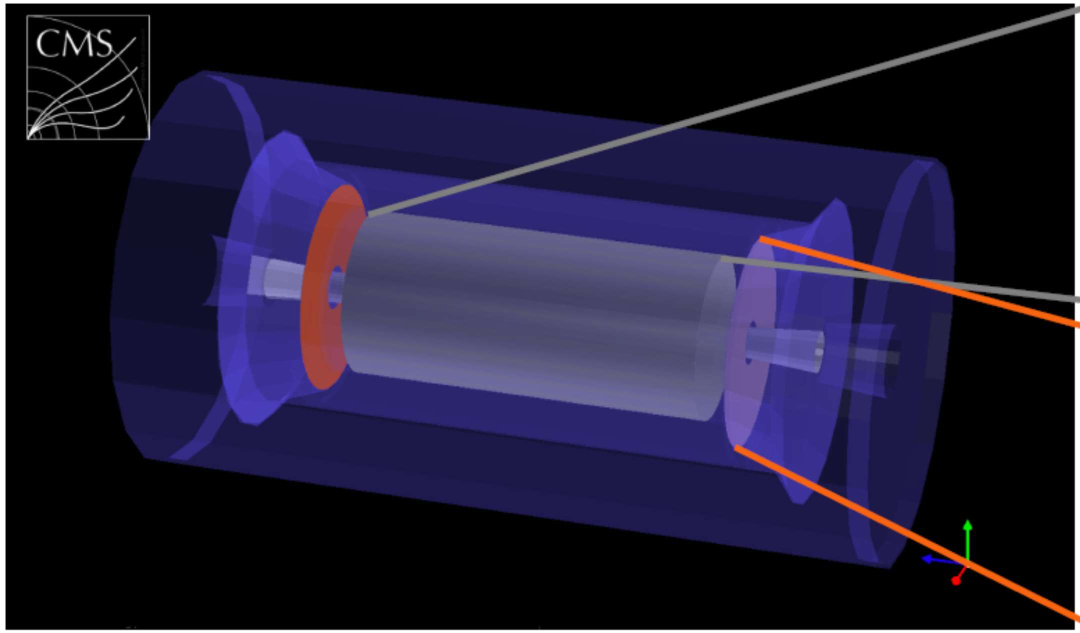
Crystals damaged by both proton and neutron. Damage by proton is larger than that from neutrons because of ionization energy loss in addition to displacement and nuclear breakup

LYSO:Ce for CMS MIP Timing Detector

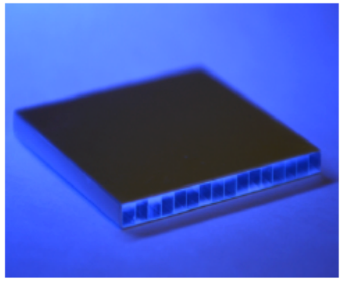
MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

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

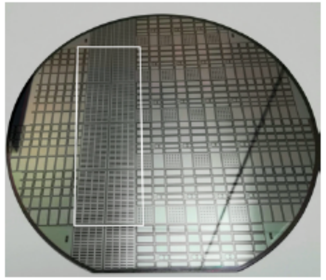
Ultrafast inorganic scintillators would help to break the pico-second time barrier



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

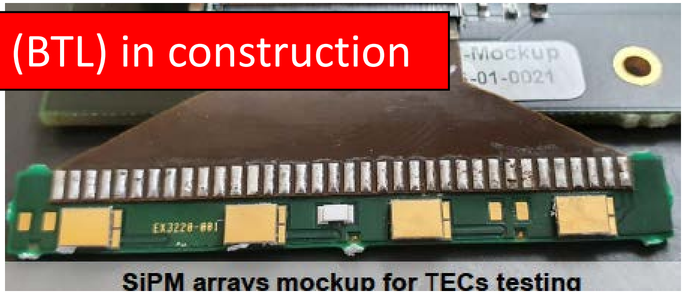


ETL: Si with internal gain (LGAD)
- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



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

Expected Radiation for CMS MTD

CMS BTL/EMEC: 4.8/68 Mrad, 2.5/21×10^{13} p/cm^2 & 3.2/24×10^{14} n_{eq}/cm^2

CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux ($cm^{-2}s^{-1}$)	Proton (cm^{-2})	p Flux ($cm^{-2}s^{-1}$)	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5E+14	2.8E+06	2.2E+13	2.4E+05	2.7	108
Barrel	1.15	2.7E+14	3.0E+06	2.4E+13	2.6E+05	3.8	150
Barrel	**1.45**	**2.9E+14**	**3.2E+06**	**2.5E+13**	**2.8E+05**	**4.8**	**192**
Endcap	1.60	2.3E+14	2.5E+06	2.0E+13	2.2E+05	2.9	114
Endcap	2.00	4.5E+14	5.0E+06	3.9E+13	4.4E+05	7.5	300
Endcap	2.50	1.1E+15	1.3E+07	9.9E+13	1.1E+06	26	1020
Endcap	**3.00**	**2.4E+15**	**2.7E+07**	**2.1E+14**	**2.3E+06**	**68**	**2700**

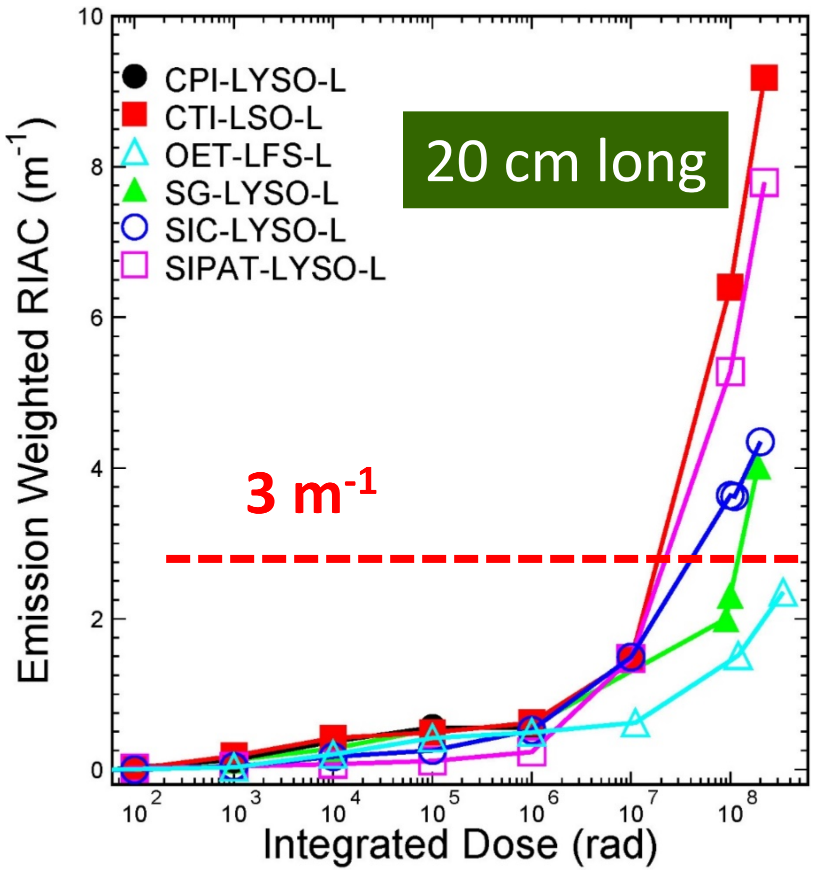
Much higher at FCC-hh: up to 0.1/500 Grad and 3/500 x10^{16} n_{eq}/cm^2 at EMEC/EMF

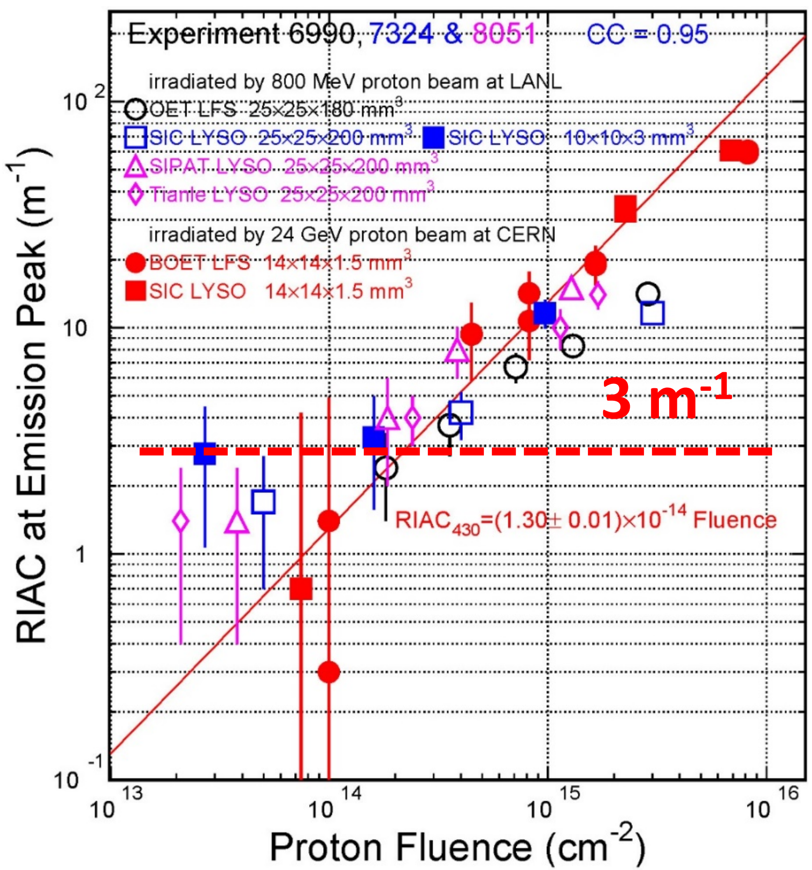
Aleksa *et al.,* Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019

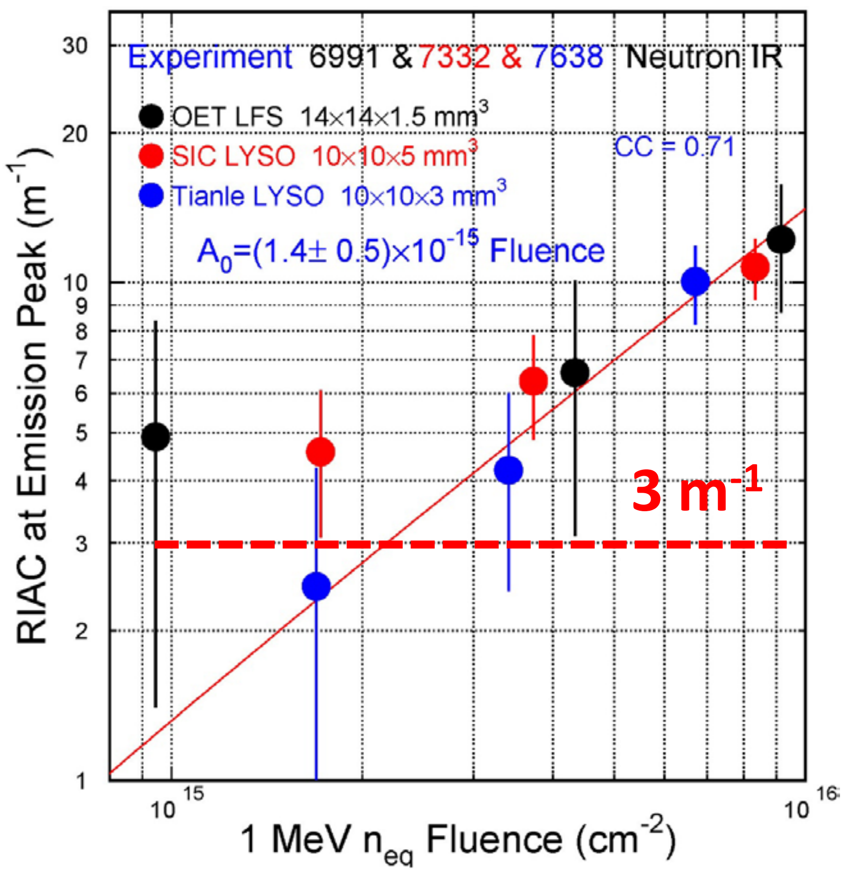
LYSO:Ce Radiation Hardness

IEEE TNS 63 (2016) 612-619

CMS 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







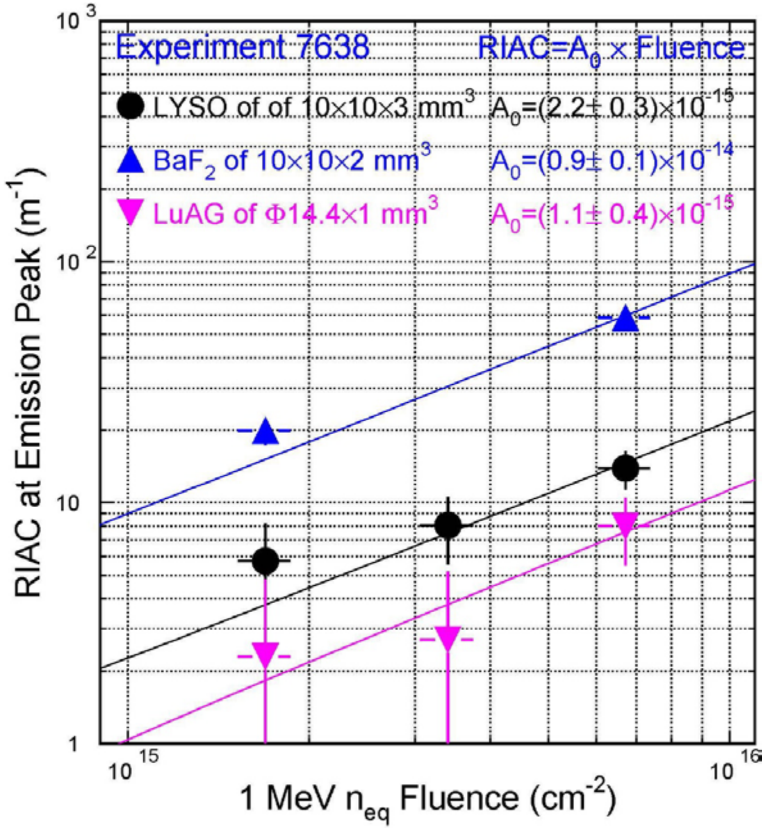
Damage induced by protons larger than that from neutrons

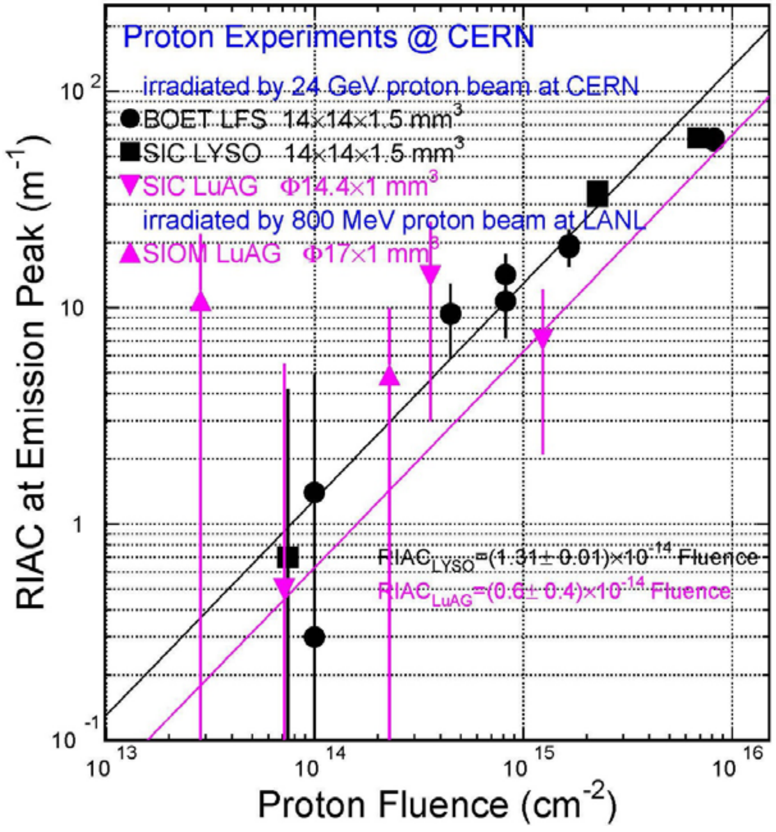
Due to ionization energy loss in addition to displacement and nuclear breakup

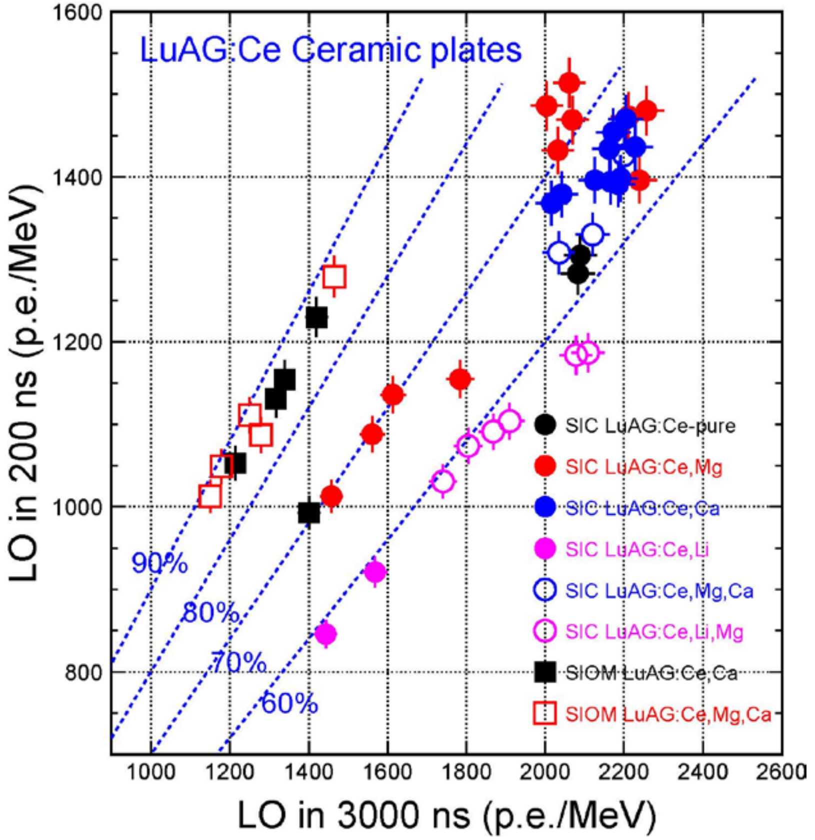
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

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

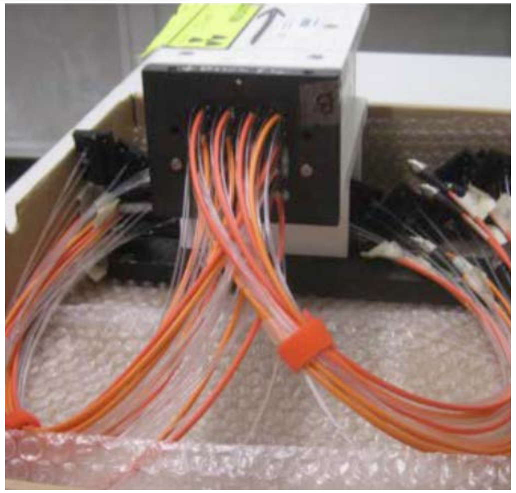


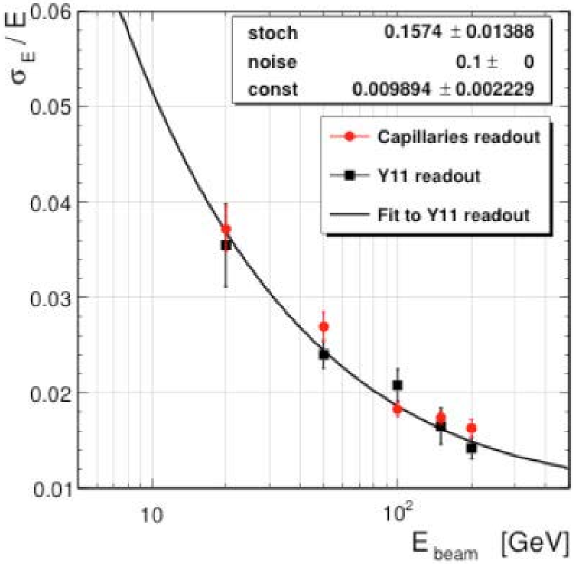




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

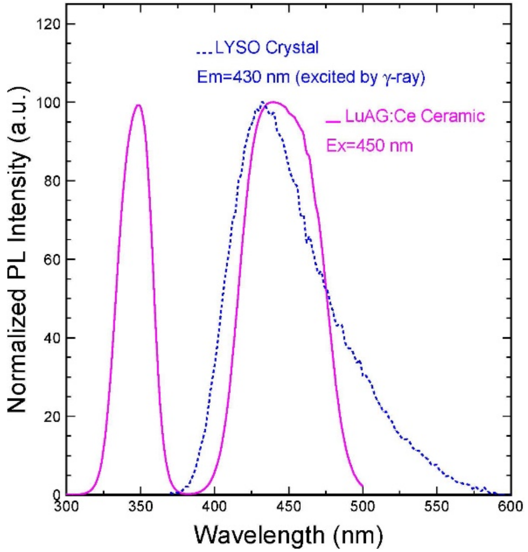
RADiCAL: LYSO/LuAG Shashlik CAL

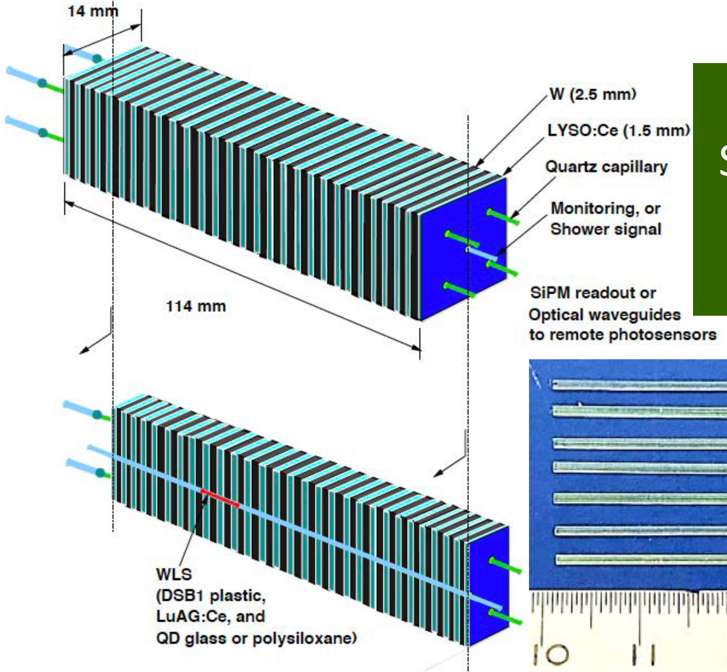




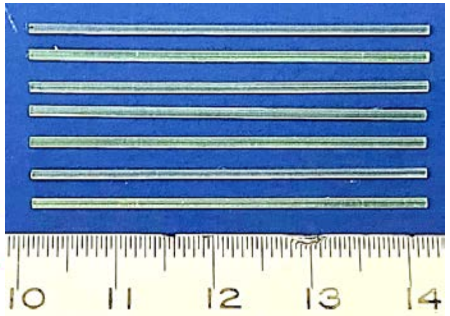
arXiv: 2203.12806 (N35-6)

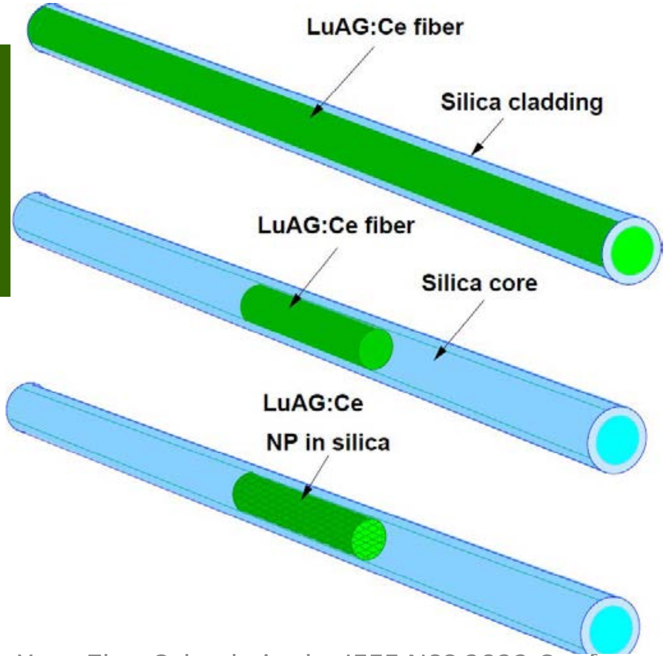
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission

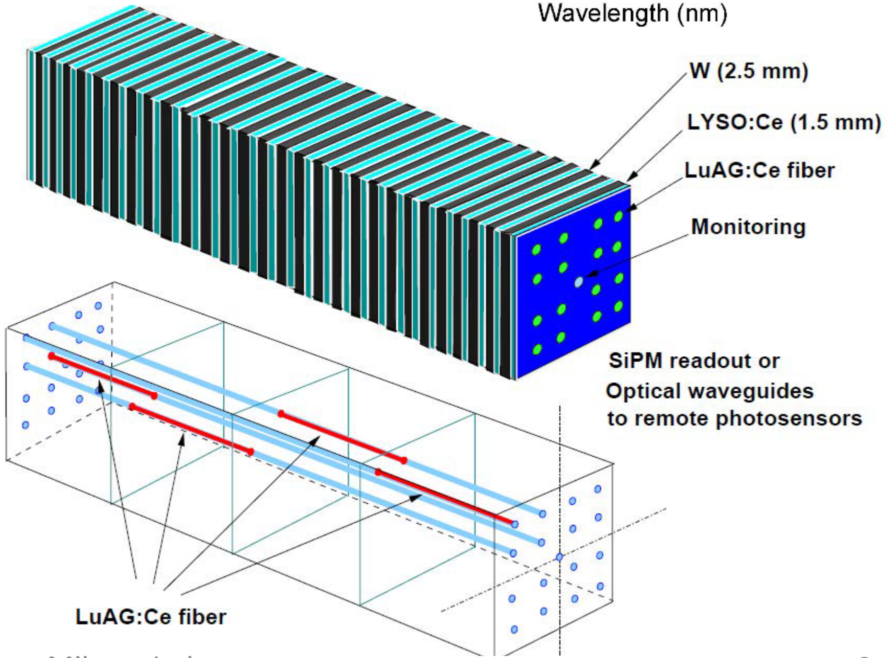




Φ1x40 mm
SIC LuAG:Ce
ceramic
LHPG fibers







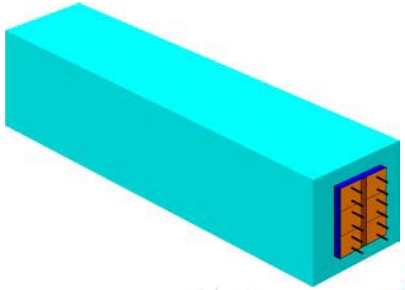
Mu2e-II BaF_2:Y Calorimeter

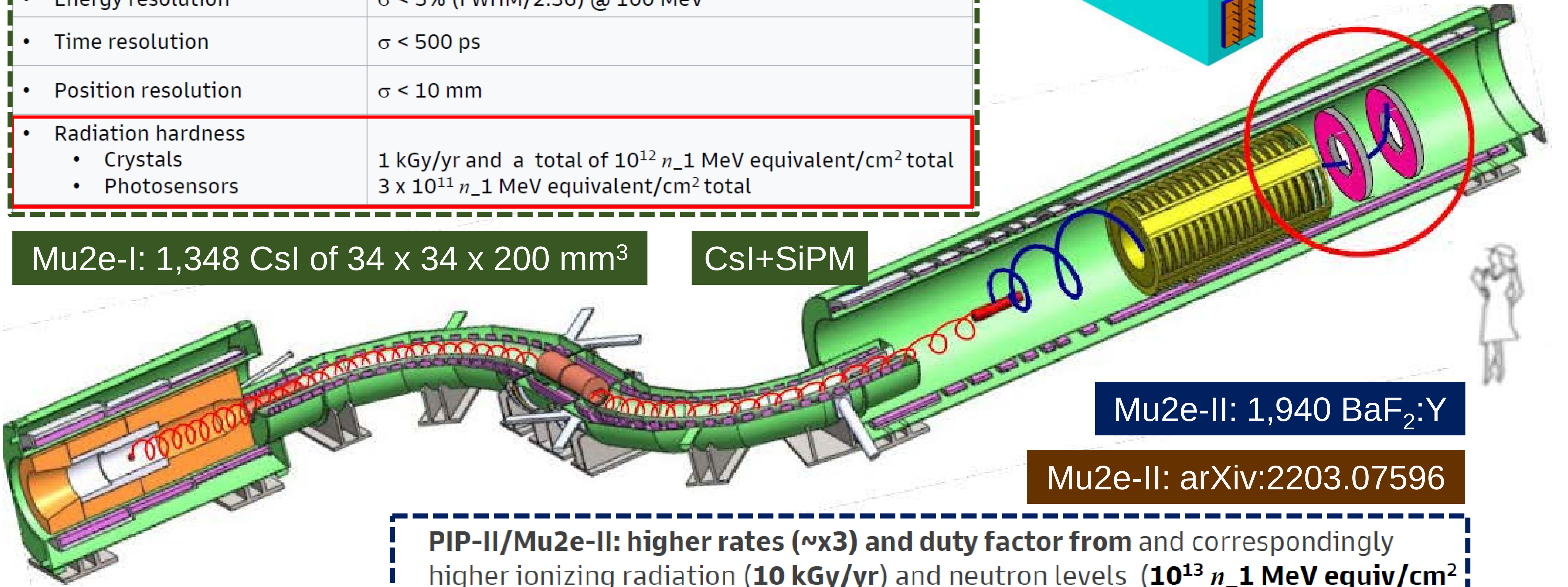
Use ultrafast material to mitigate pile-up

• Energy resolution	$\sigma < 5\%$ (FWHM/2.36) @ 100 MeV
• Time resolution	$\sigma < 500$ ps
• Position resolution	$\sigma < 10$ 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





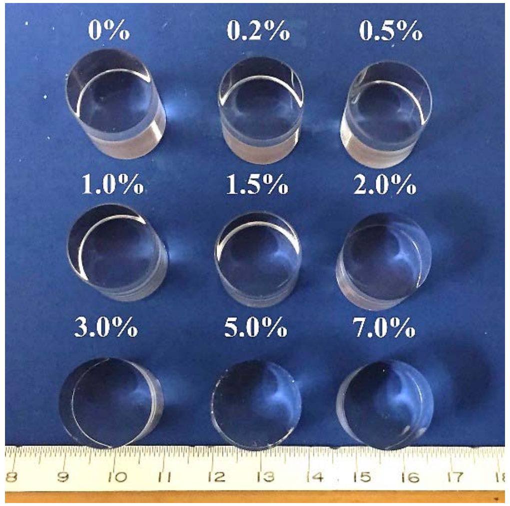
Mu2e-II: 1,940 BaF_2:Y

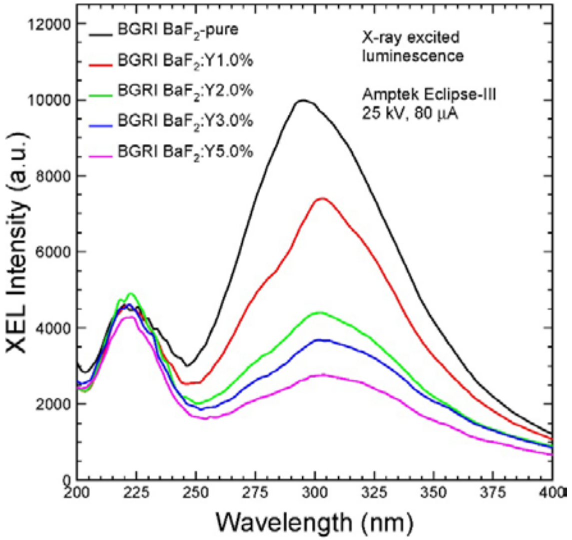
Mu2e-II: arXiv:2203.07596

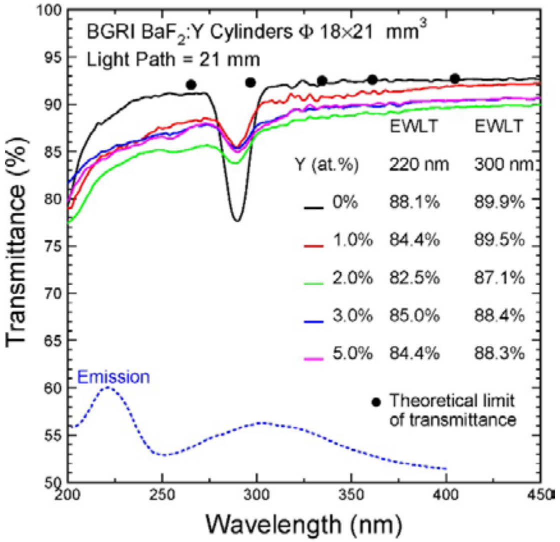
PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

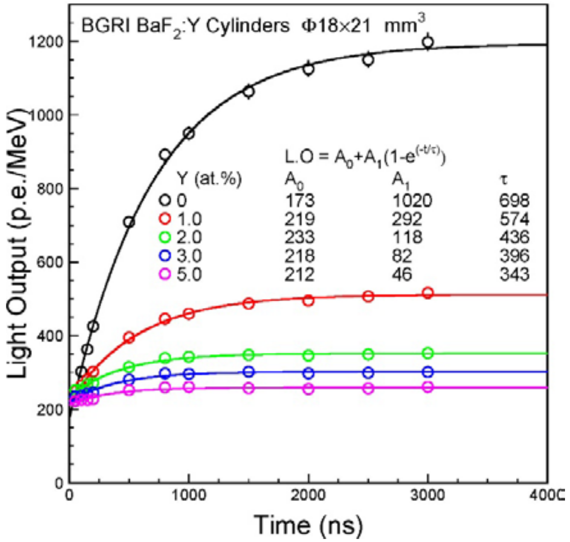
BaF$_2$:Y for Ultrafast Calorimetry

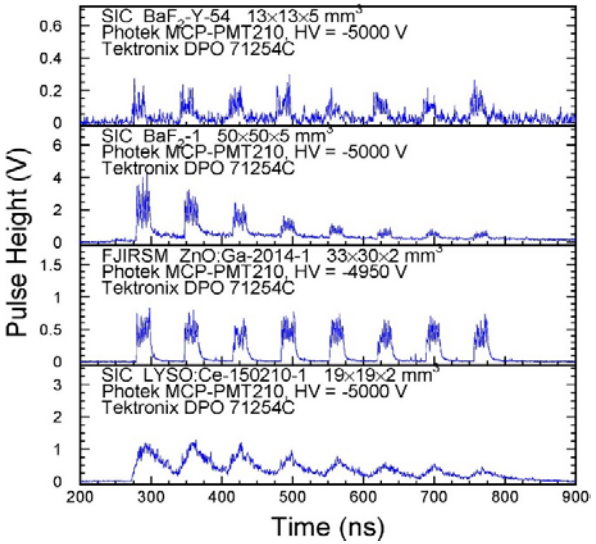
Increased F/S ratio observed in BGRI BaF$_2$:Y crystals: Proc. SPIE 10392 (2017)

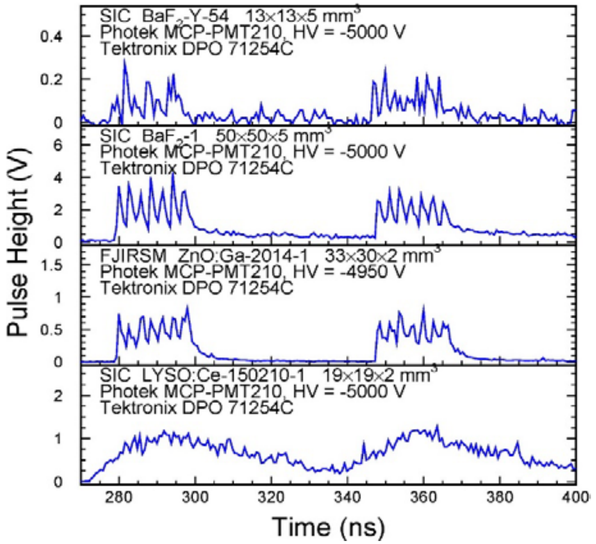


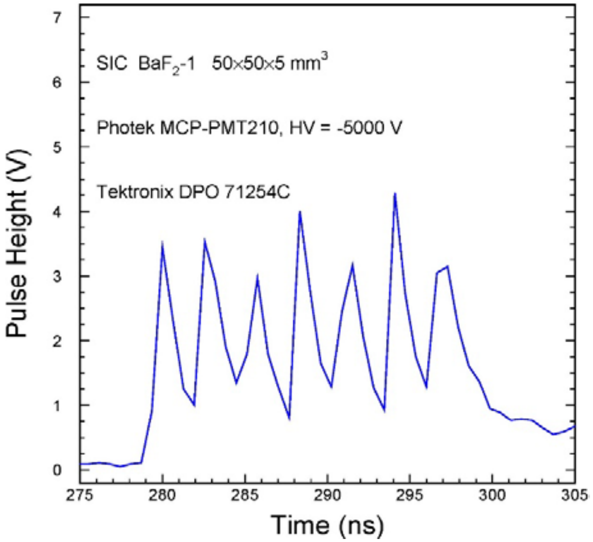












X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF$_2$:Y and BaF$_2$ crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

Fast and Ultrafast Inorganic Scintillators

arXiv: 2203.06788

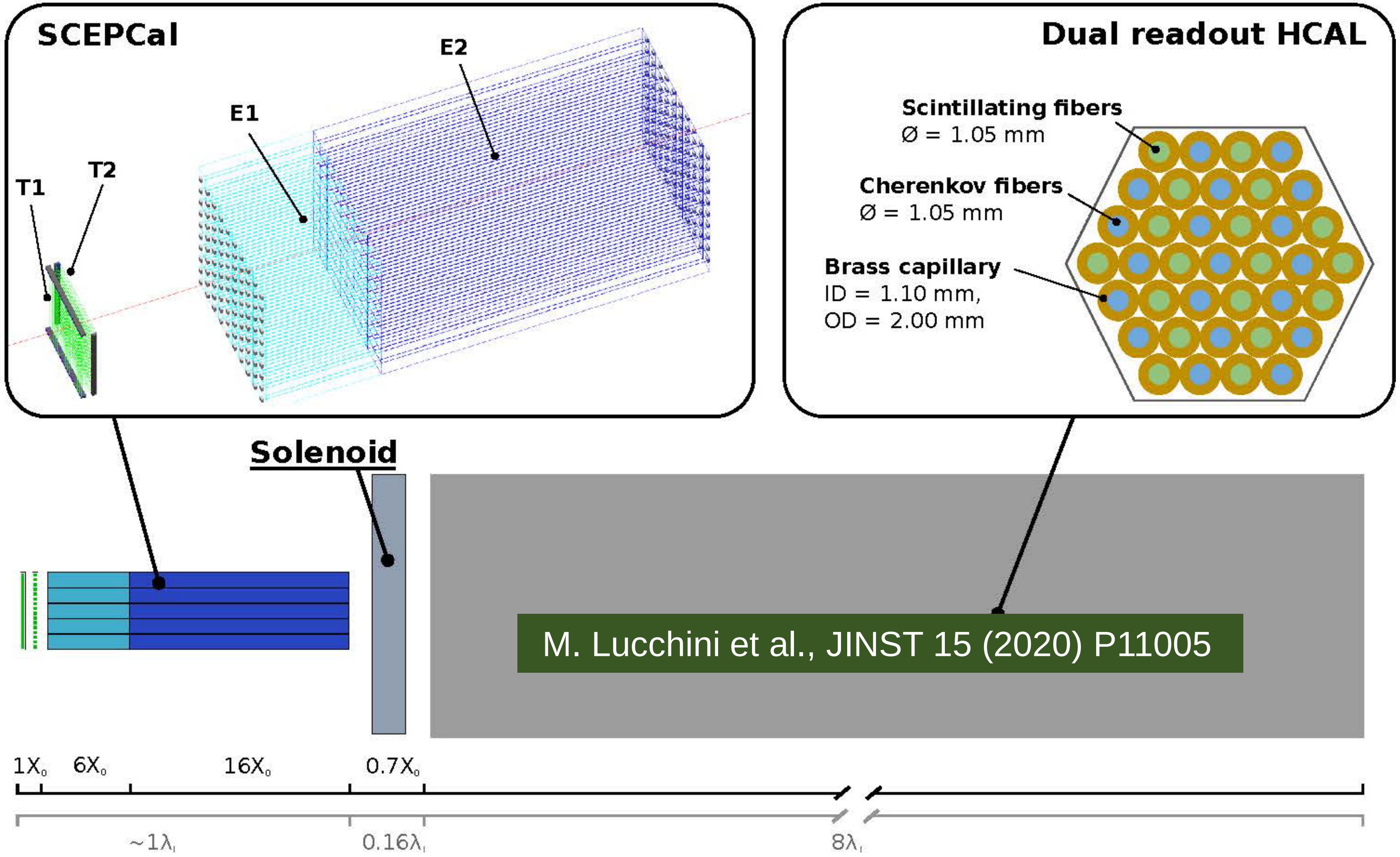
	BaF_2	BaF_2:Y	Lu_2O_3:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	9.42	5.35	4.56	5.67	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	2490	1870	1940	1975	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	0.81	2.59	3.53	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.

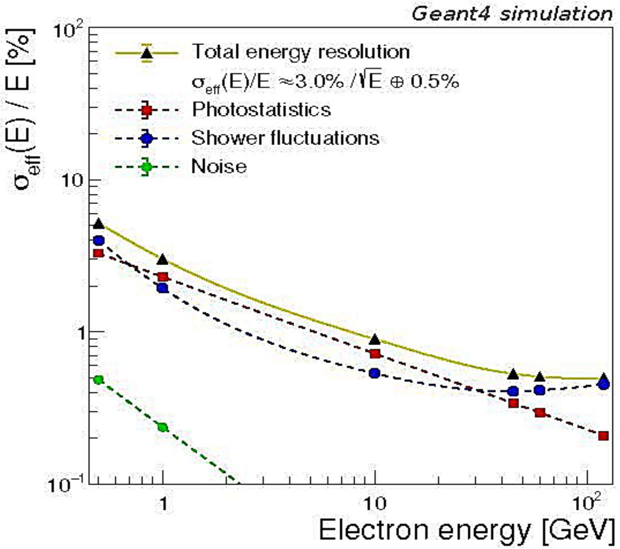
CalVision: Longitudinally Segmented Crystal ECAL

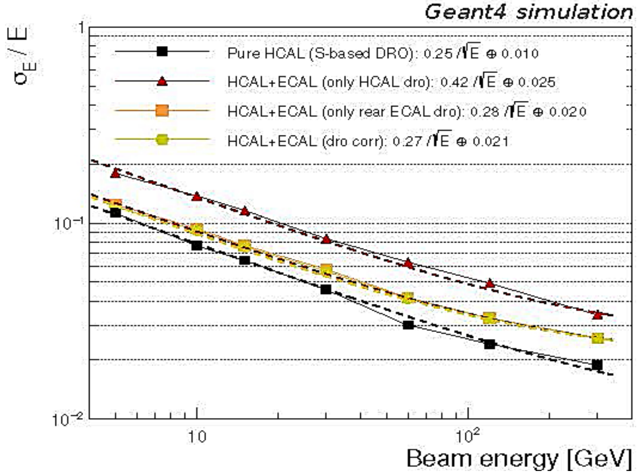
arXiv: 2203.04312

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

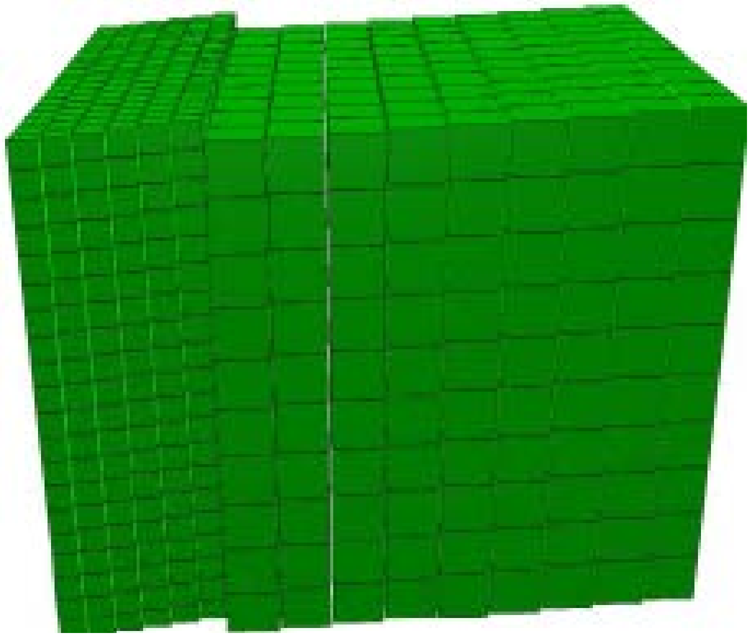


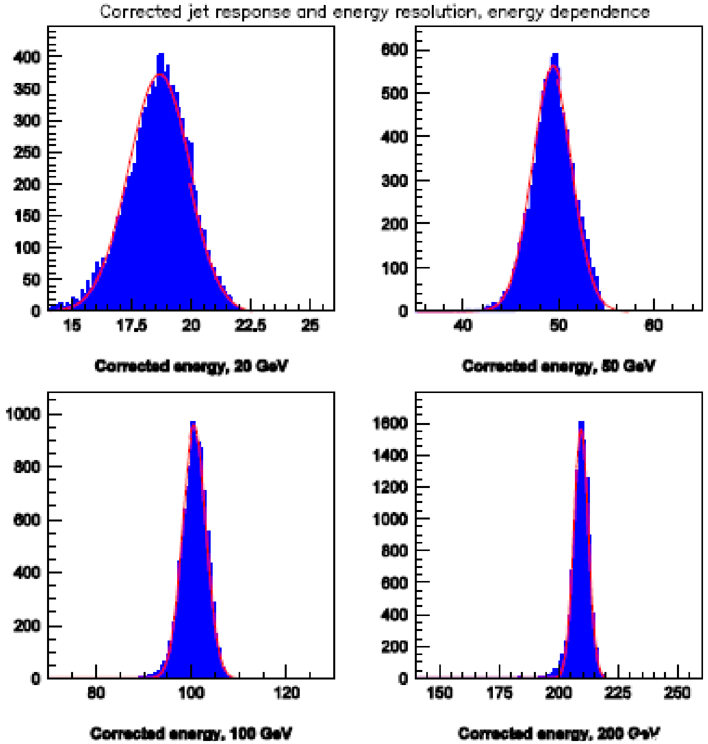
M. Lucchini et al., JINST 15 (2020) P11005





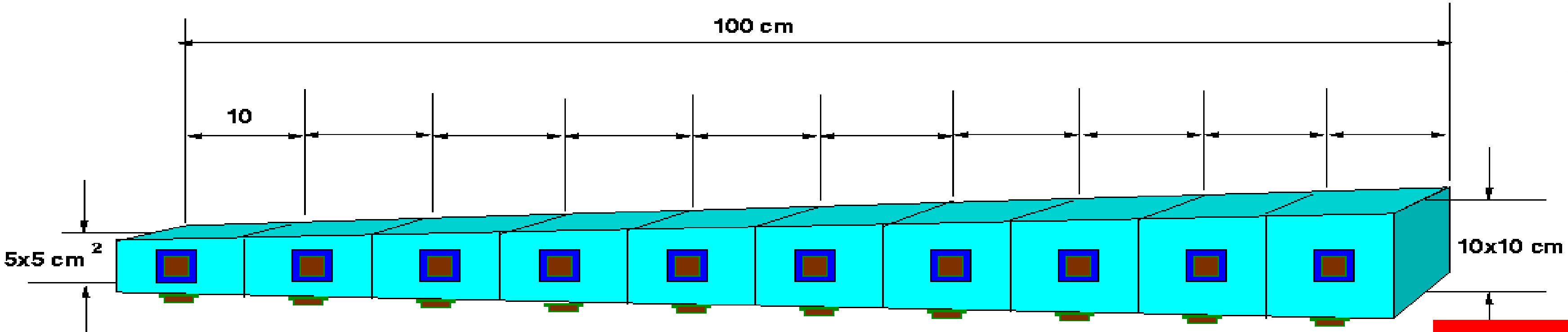
The **HHCAL** Concept



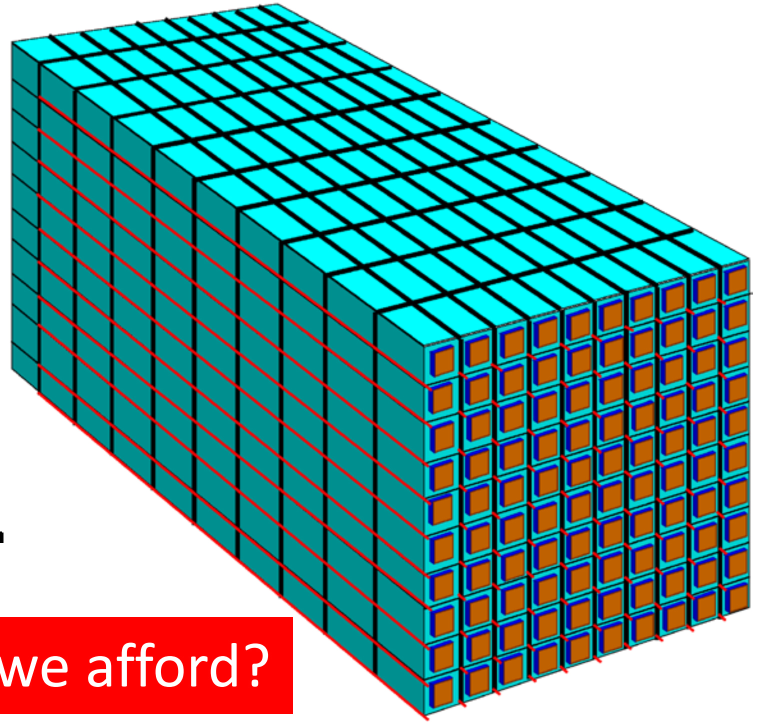


A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al.*, IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.

M. Demarteau, 2021 CPAD Workshop



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



Can we afford?

Inorganic Scintillators for HHCAL

arXiv.2203.06788

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire :Ti	AFO Glass	DSB:Ce Glass[1]	BGS Glass[2]	ABS Glass[3]	DSB:Ce,Gd Glass[4,5]	HFG Glass[6]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	4.2	4.53	4.7 - 5.4[d]	5.95
Melting point (℃)	1050	1030	1123	824	608	2040	980[7]	1420[8]	1550	?	1420[8]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	2.62	2.41	2.14	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.90	3.52	3.33	3.09	2.56	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	31.8	28.8	24.2	23.2
Z_{eff} value	71.5	73.8	73.6	76.7	74.7	11.1	41.4	42.9	49.6	51.9	47.2	55.7
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	5.90	6.42	7.68	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	440	430	396	440 460	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	\	\	\	1.50
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	~500	2,500	800	1,300	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	400 90	1200 260	120, 400 50	25 8
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	-0.04	0.3	?	?	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	?	2.0	2.0	?	2.0	?

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C) with PMT QE taken out.
d. Gd loaded.

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Summary

The HL-LHC and FCC-hh require fast and radiation hard inorganic scintillator. The **RADiCAL** concept uses LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals for an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter. R&D is on-going to suppress the slow components in LuAG:Ce.

An ultrafast BaF_2:Y calorimeter is proposed for **Mu2e-II**. R&D is on-going to investigate radiation hardness of large size BaF_2:Y crystals.

A longitudinally segmented **Calvision** crystal ECAL with dual readout combined with the IDEA HCAL promises excellent EM and Hadronic resolutions for the proposed Higgs factory.

Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. Crucial R&D is needed for cost-effective mass-produced inorganic scintillators

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