Fast Crystal Scintillators for Future HEP Experiments

Ren-Yuan Zhu

California Institute of Technology

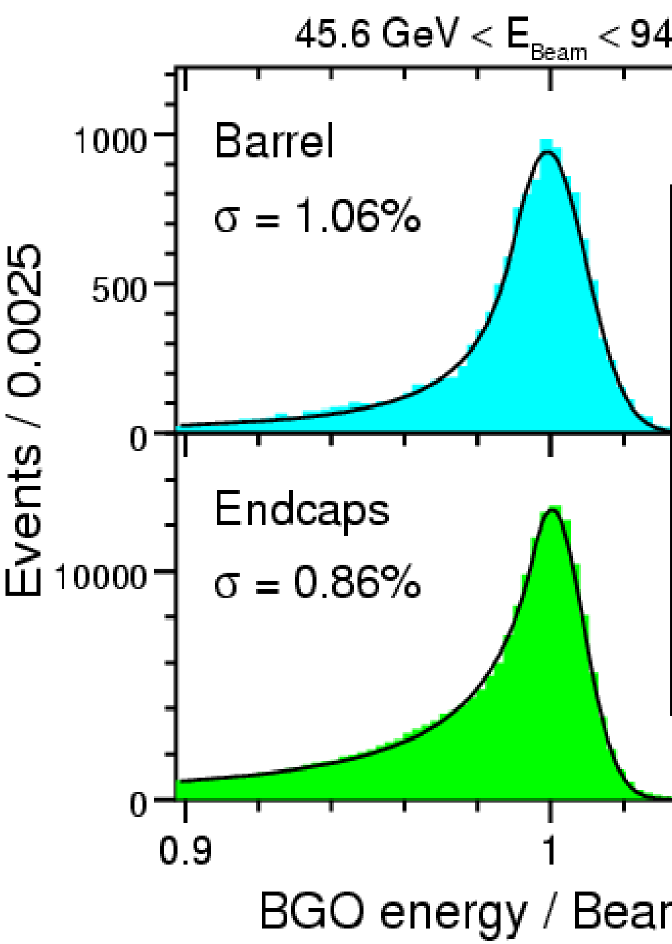
October 3, 2013

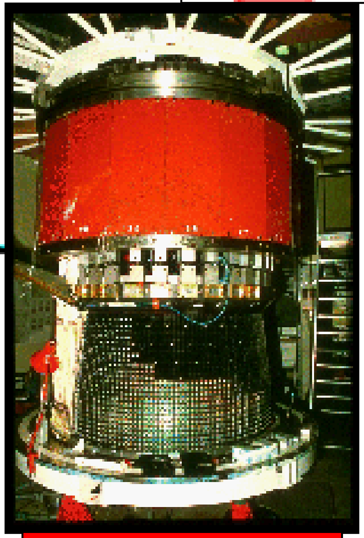
Why Crystal Calorimeter in HEP?

- Precision e/γ measurements enhance physics discovery potential.
- Performance of homogeneous crystal calorimeter for e/γ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good e/γ identification and reconstruction efficiency.
- Challenges at future HEP Experiments:
  - Radiation hard calorimeter for HL-LHC;
  - Good jet mass resolution for ILC/CLIC;
  - **Ultra-fast rate and γ-pointing at the intensity frontier**.

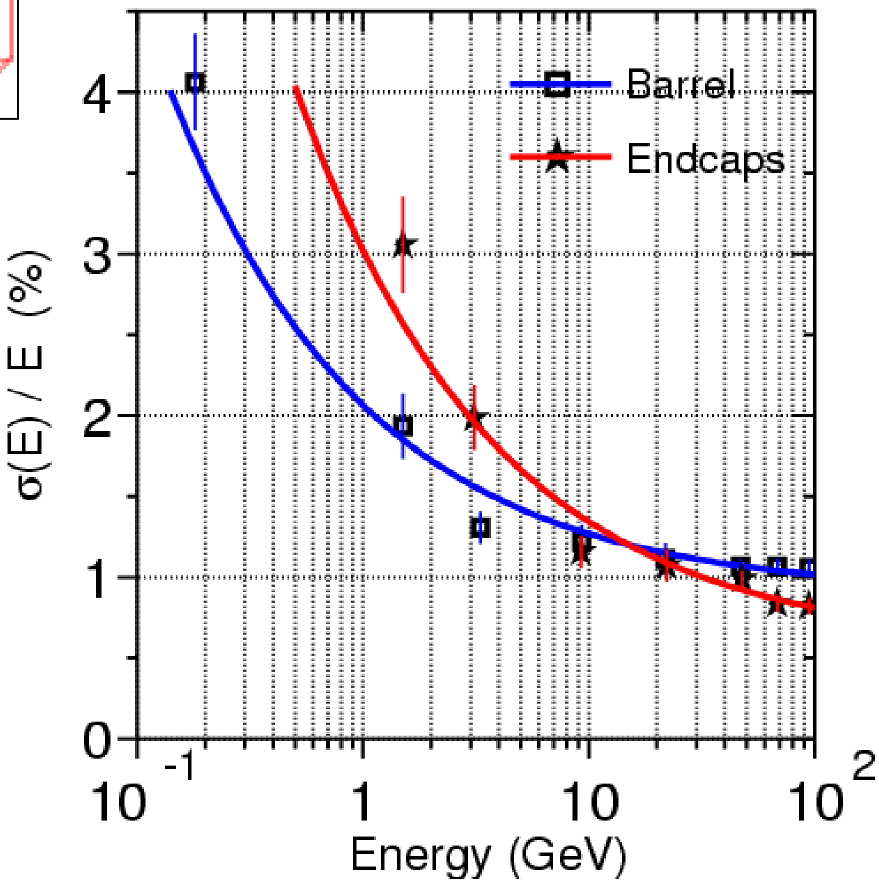
L3 BGO Resolution

Contribution	"Radiative"+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%





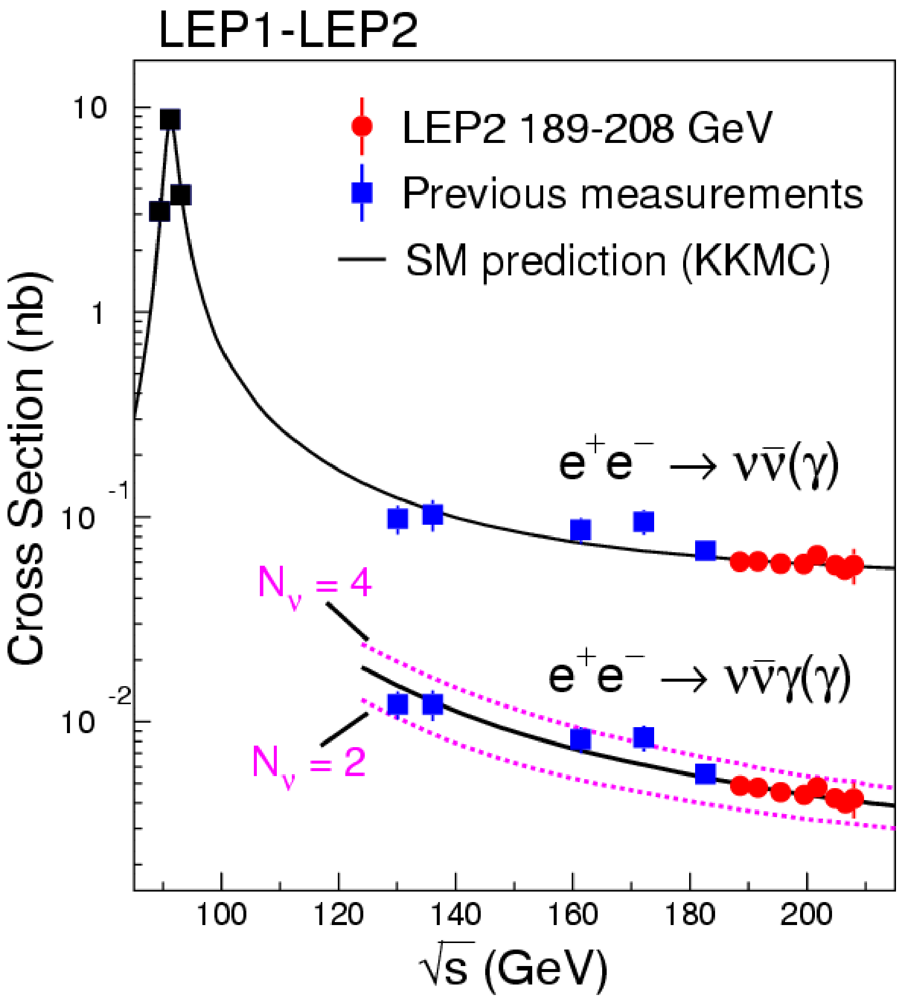
12k BGO



Physics with Crystal Calorimeters (I)

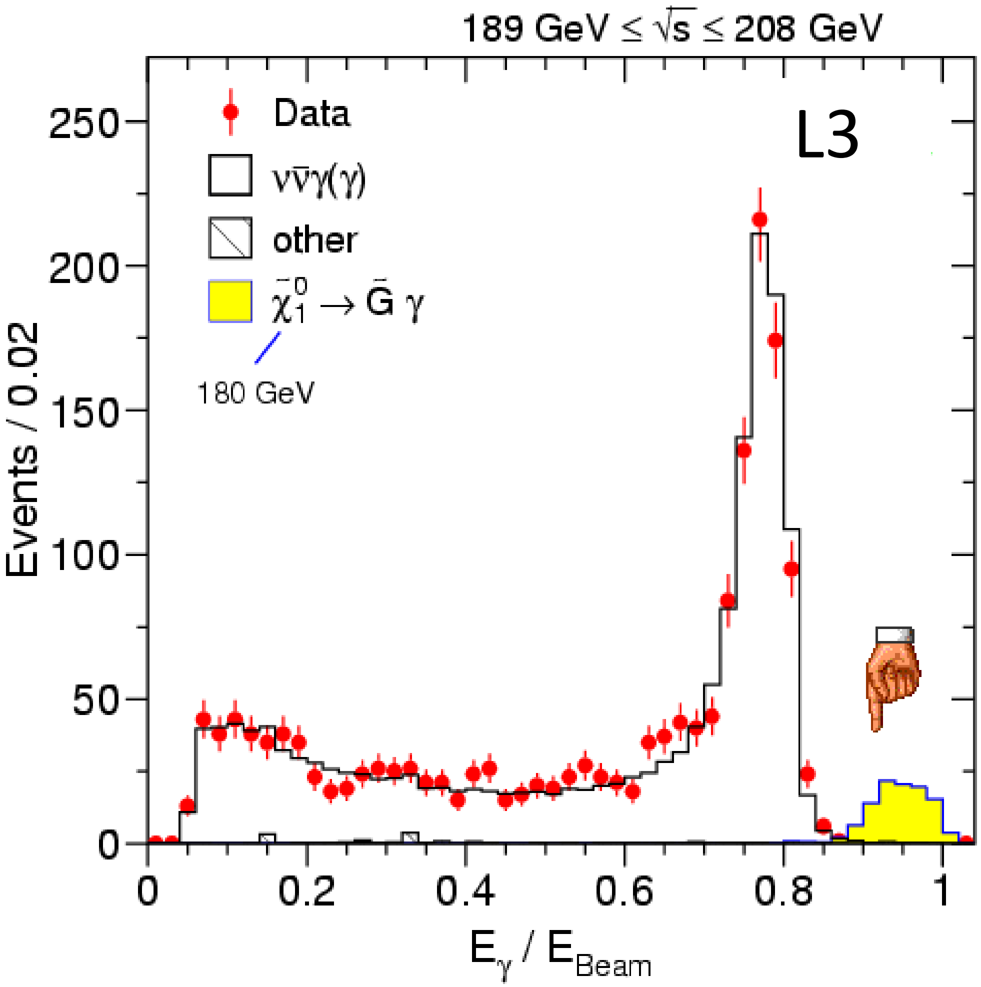
Neutrino Counting in Z Decay

$N_\nu = 2.98 \pm 0.06$



SUSY Breaking with Gravitino

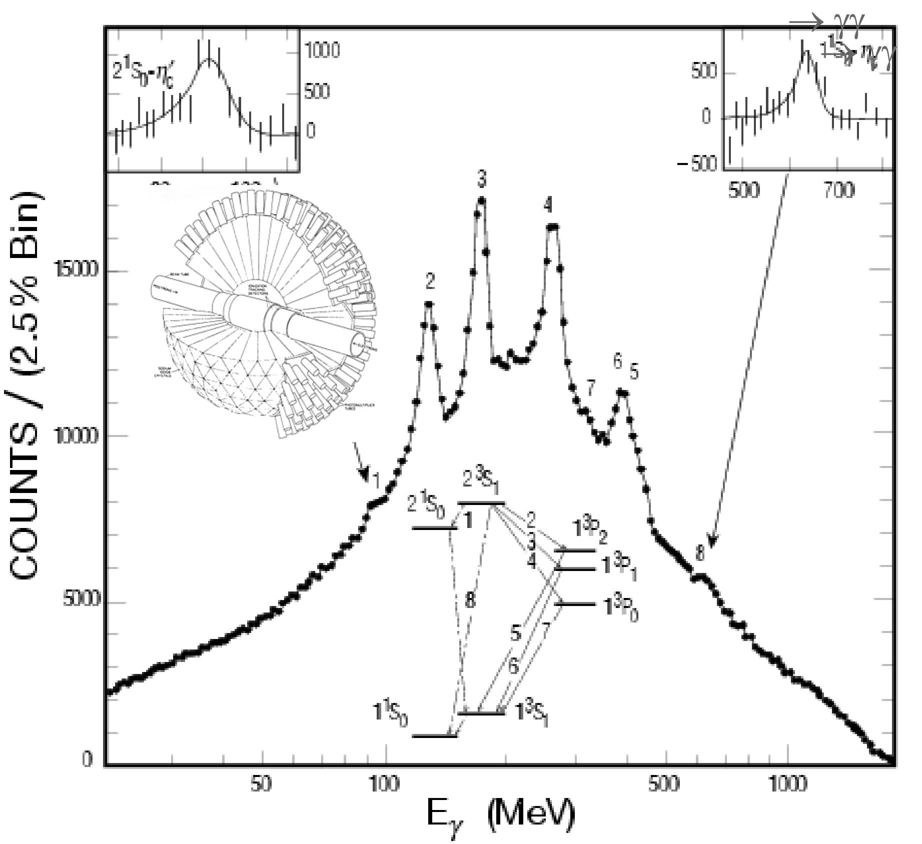
$$e^+e^- \to \tilde{G}\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\gamma$$



Physics with Crystal Calorimeters (II)

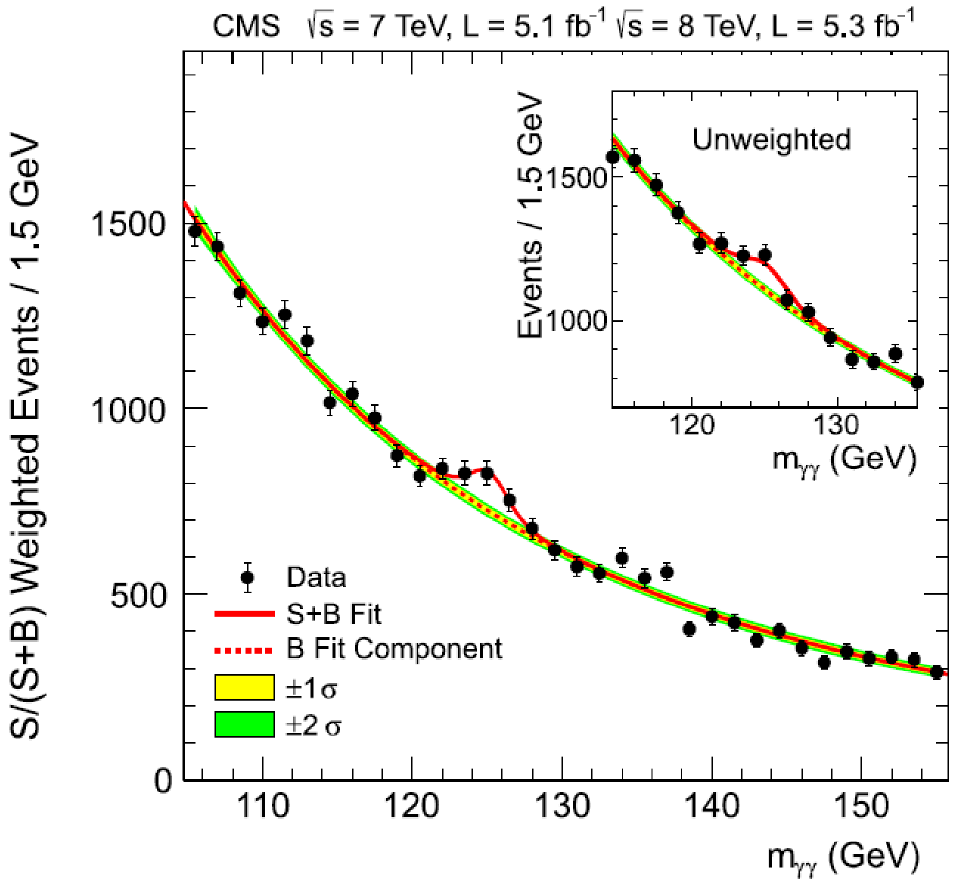
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)

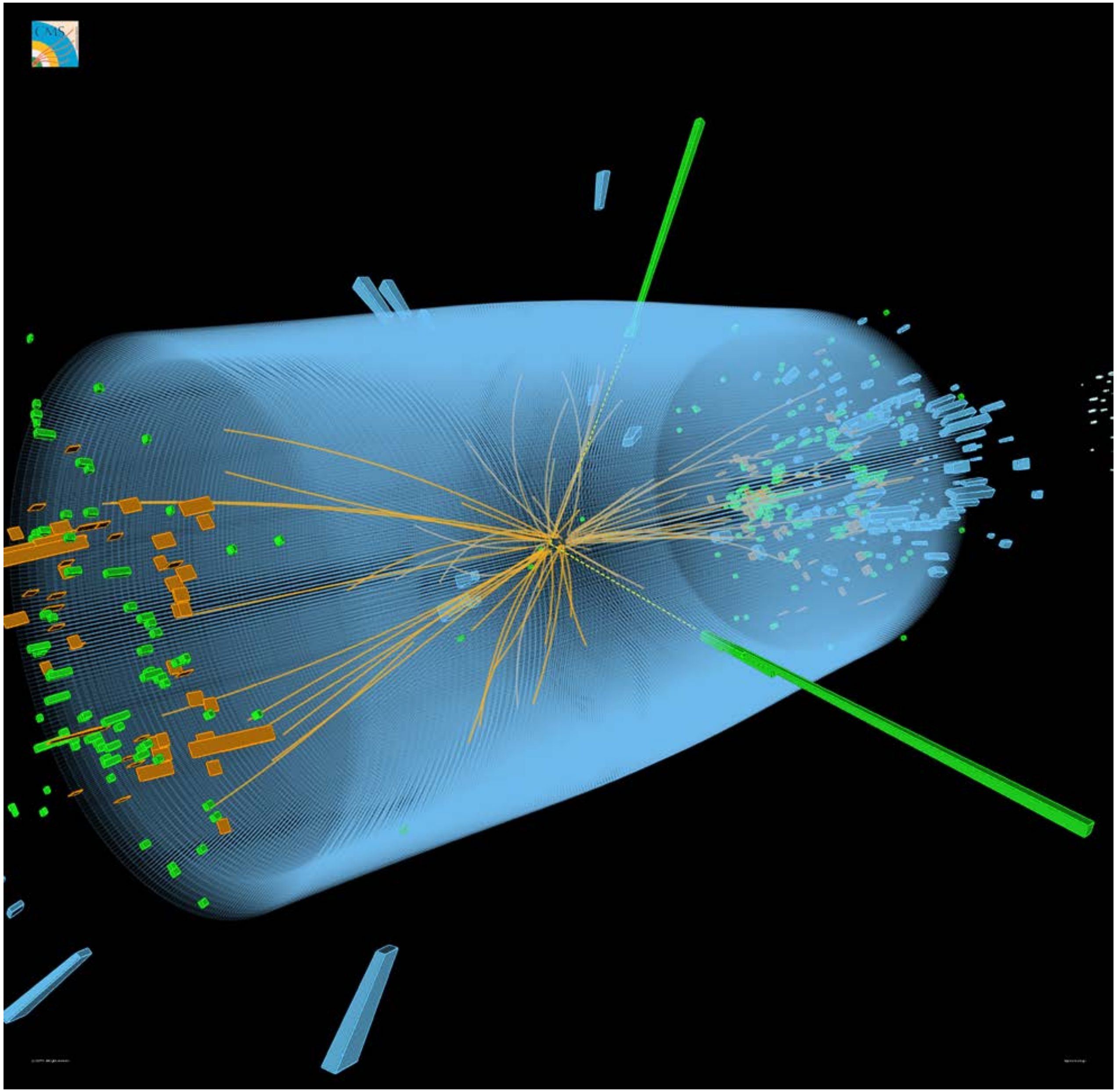


Higgs -> γγ by CMS through reconstructing photon pairs

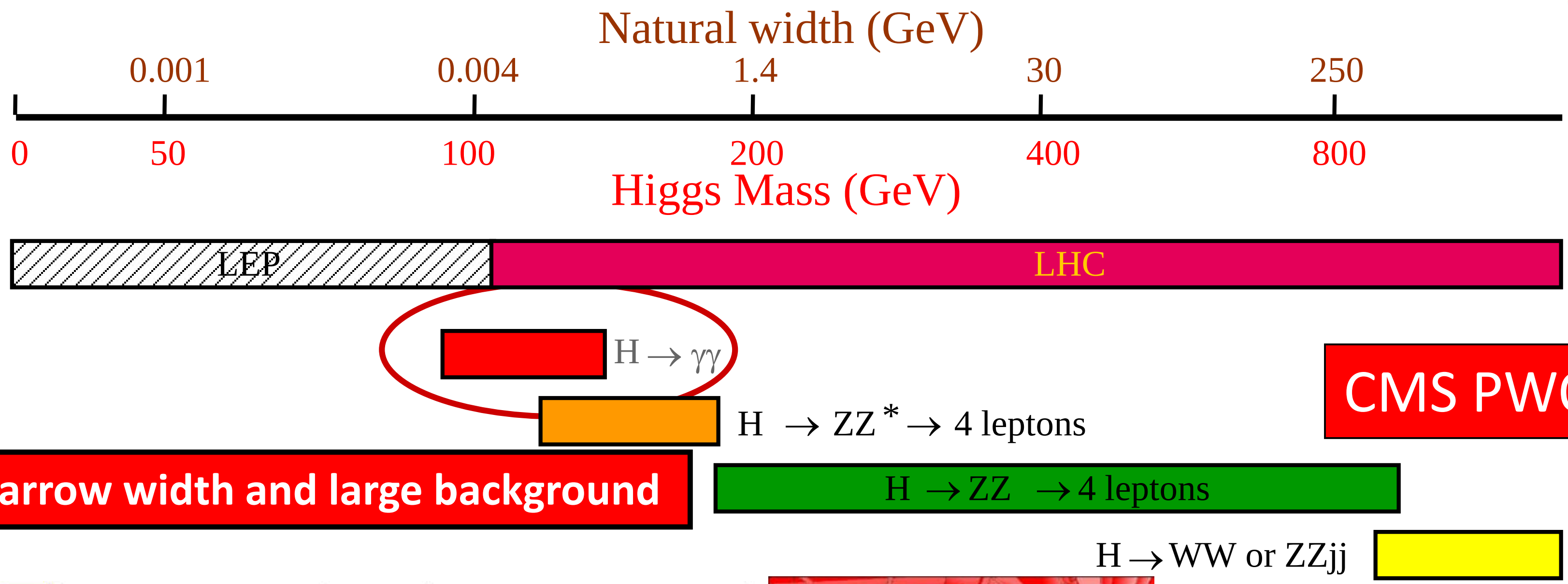
CMS PWO



2013 Nobel Price for Physics?

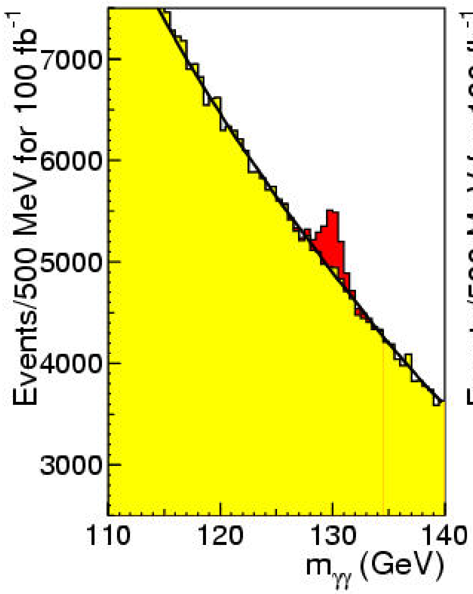


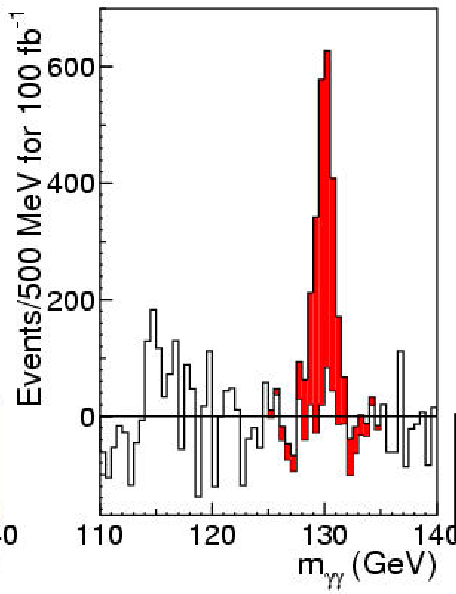
H→γγ Search Needs Precision ECAL

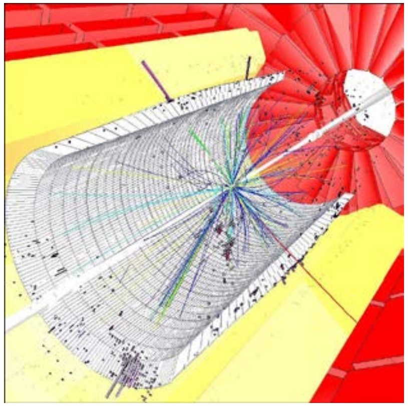


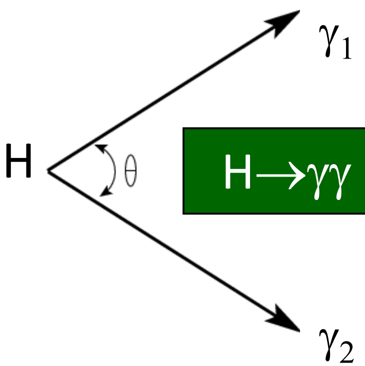
CMS PWO

Narrow width and large background









H→γγ at LHC

$\sigma m / m = 0.5\ [\sigma E_1/E_1 \oplus \sigma E_2/E_2 \oplus \sigma\theta/\tan(\theta/2)]$,
where $\sigma E / E = a/\sqrt{E} \oplus b \oplus c/E$ and E in GeV

Existing Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

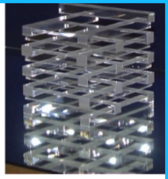
Future crystal calorimeters in HEP:

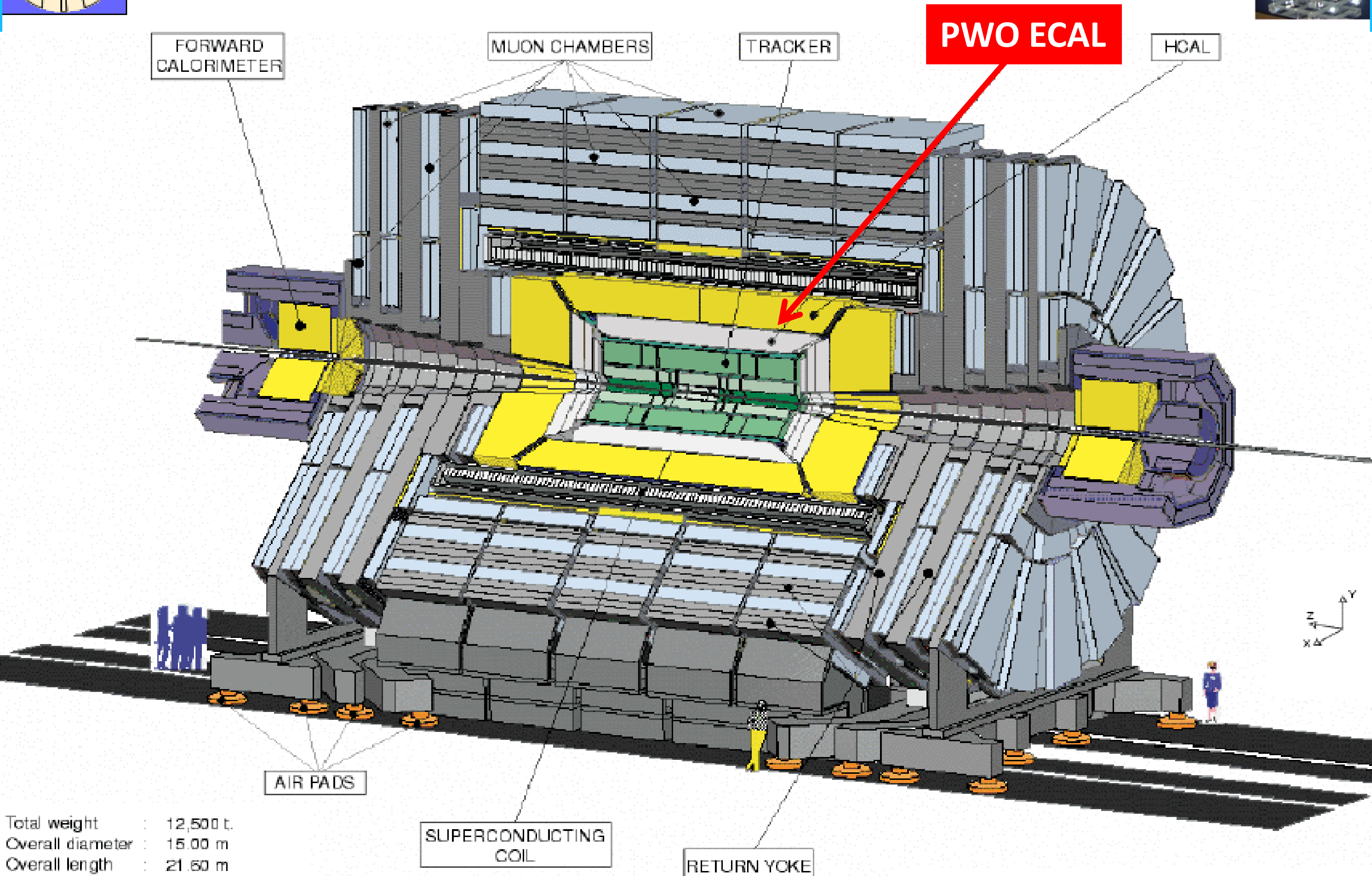
LSO/LYSO for Mu2e, (Super B), and HL-LHC (Sampling)

PbF_2, PbFCl, BSO for Homogeneous HCAL

BaF_2 for fast calorimeters at the intensity frontier

CMS Experiment at LHC

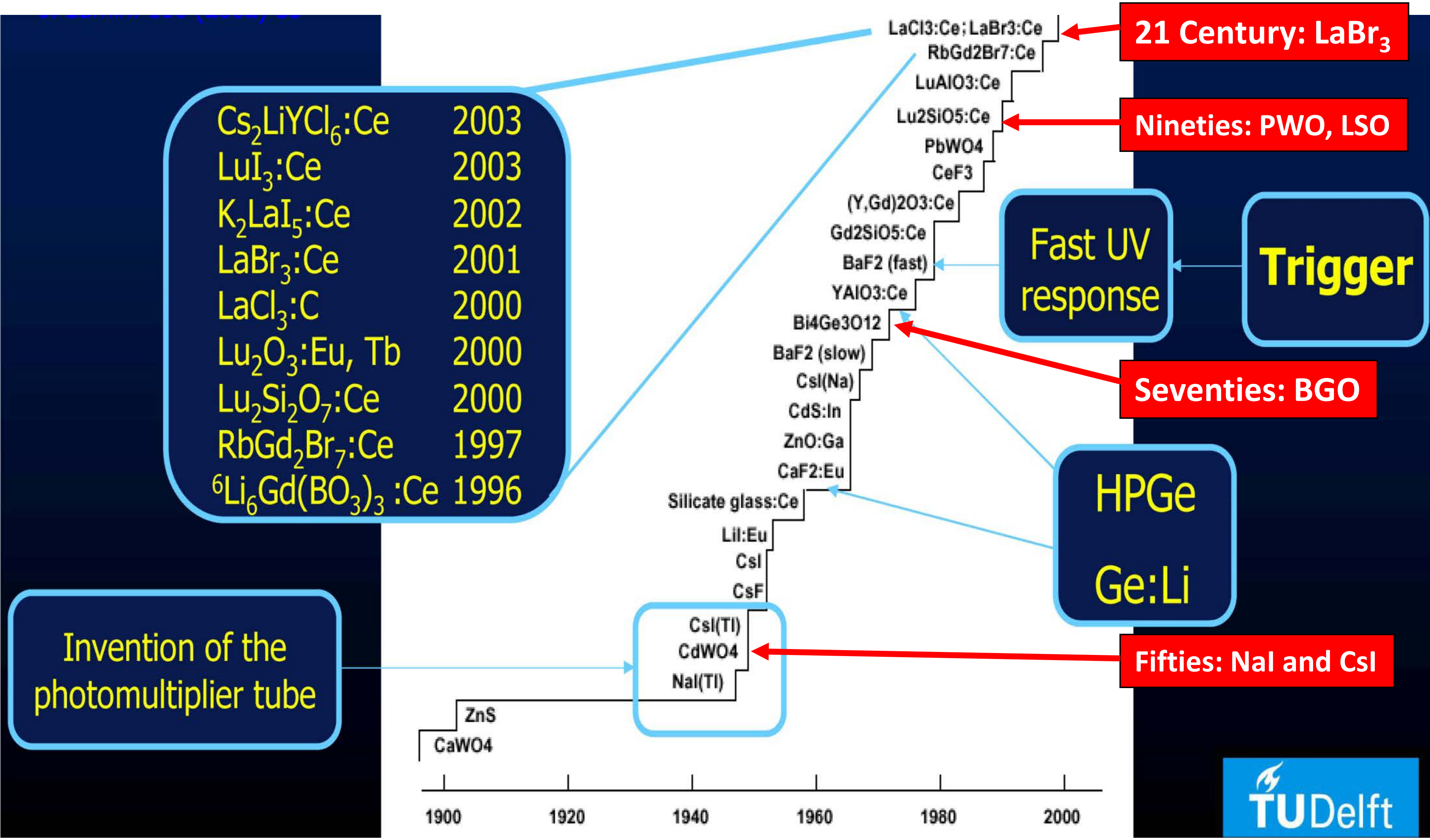




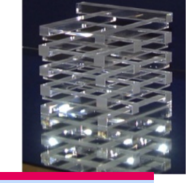
Total weight	:	12,500 t.
Overall diameter	:	15.00 m
Overall length	:	21.60 m
Magnetic field	:	4 Tesla

History of Scintillating Crystals

M.J. Weber, J. Lumin. 100 (2002) 35



Crystals for 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] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1	?
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	(L*) (GEM) TAPS	L3 BELLE	Mu2e (SuperB) HL-LHC?	CMS ALICE PANDA	HHCAL?

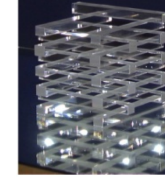
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

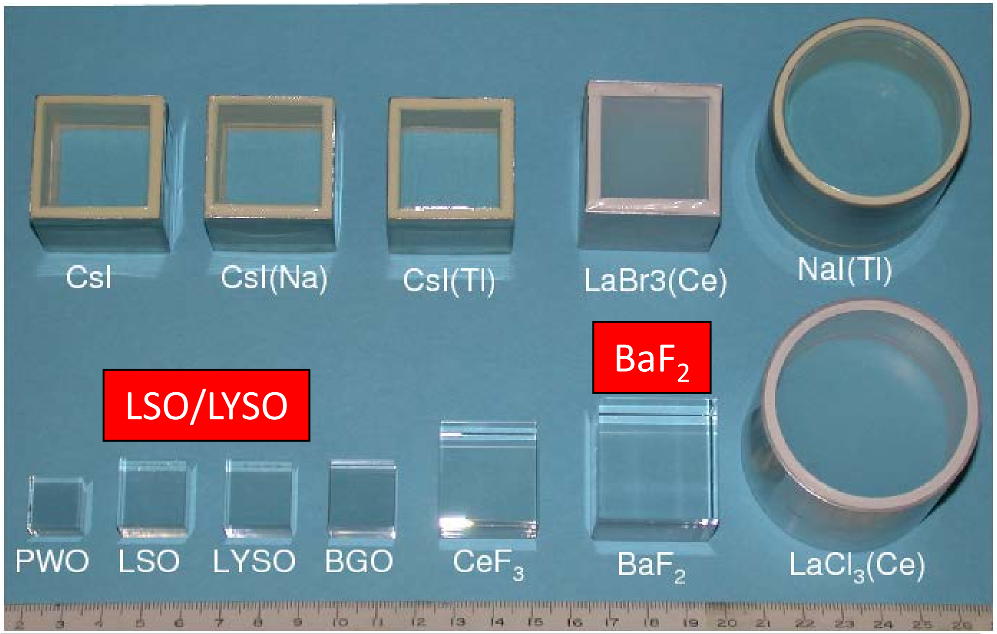
Crystals for Homeland Security

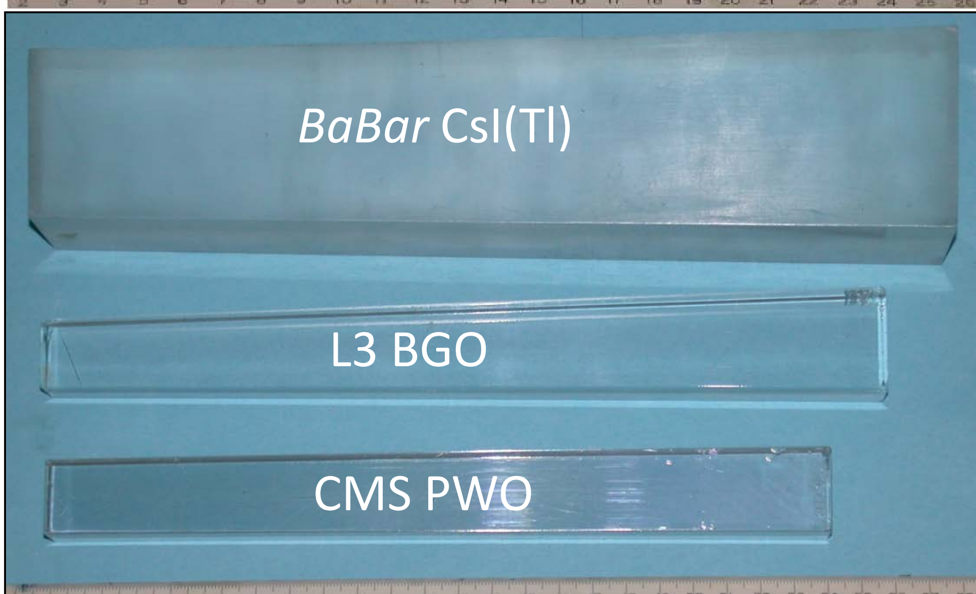
Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	$LaCl_3$(Ce)	SrI_2 (Eu)	$LaBr_3$(Ce)
Density (g/cm^3)	3.67	4.51	4.51	3.86	4.59	5.29
Melting Point (ºC)	651	621	621	859	538	788
Radiation Length (cm)	2.59	1.86	1.86	2.81	1.95	1.88
Molière Radius (cm)	4.13	3.57	3.57	3.71	3.40	2.85
Interaction Length (cm)	42.9	39.3	39.3	37.6	37.0	30.4
Refractive Index [a]	1.85	1.79	1.95	1.9	?	1.9
Hygroscopicity	Yes	Slight	Slight	Yes	Yes	Yes
Luminescence [b] (nm) (at peak)	410	550	420	335	435	356
Decay Time [b] (ns)	245	1220	690	570 24	1100	20
Light Yield [b,c] (%)	100	165	88	13 42	221	130
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	0.4	0.1	?	0.2

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

Crystal Density: Radiation Length







1.5 X_0 Samples:

Hygroscopic: Sealed

Surfaces: Polished

Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

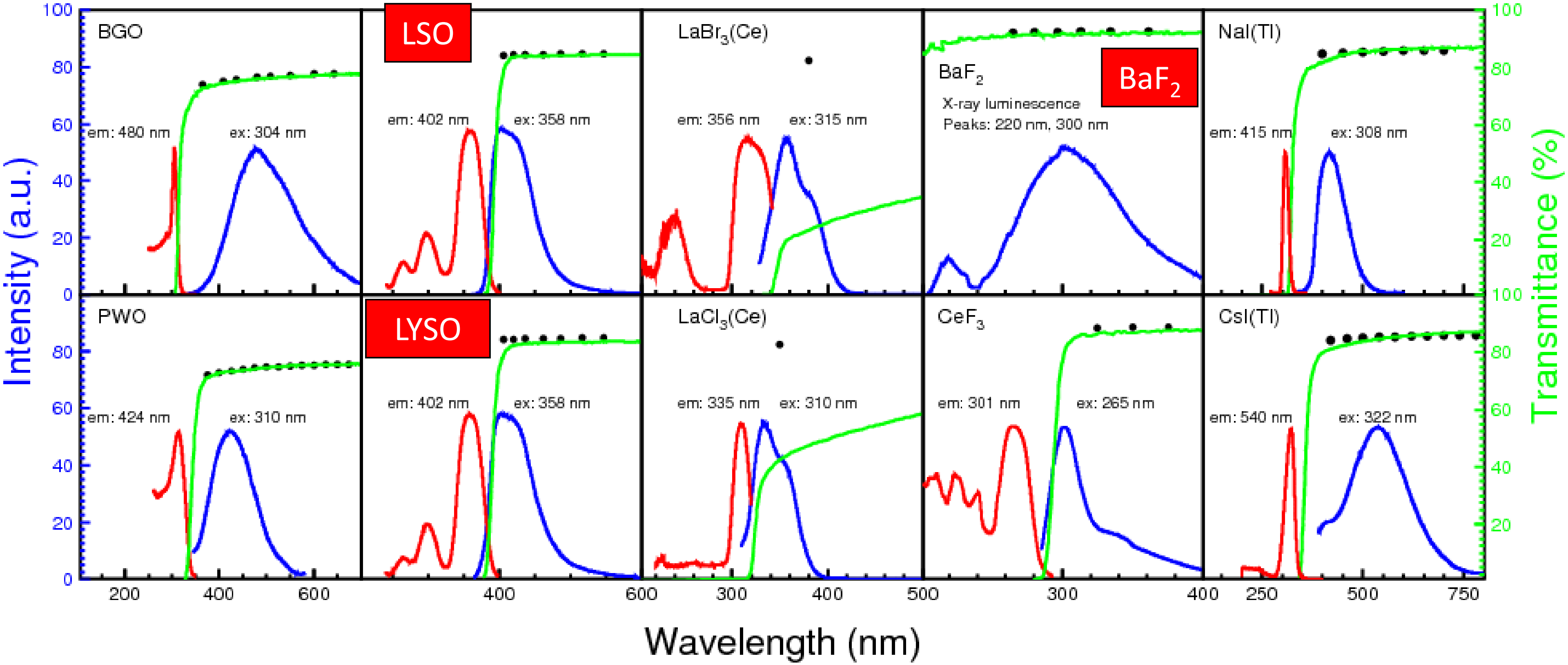
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

$$T_s = (1-R)^2 + R^2(1-R)^2 + \ldots = (1-R)/(1+R), \text{ with}$$

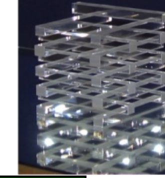
$$R = \frac{(n_{crystal} - n_{air})^2}{(n_{crystal} + n_{air})^2}.$$

Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



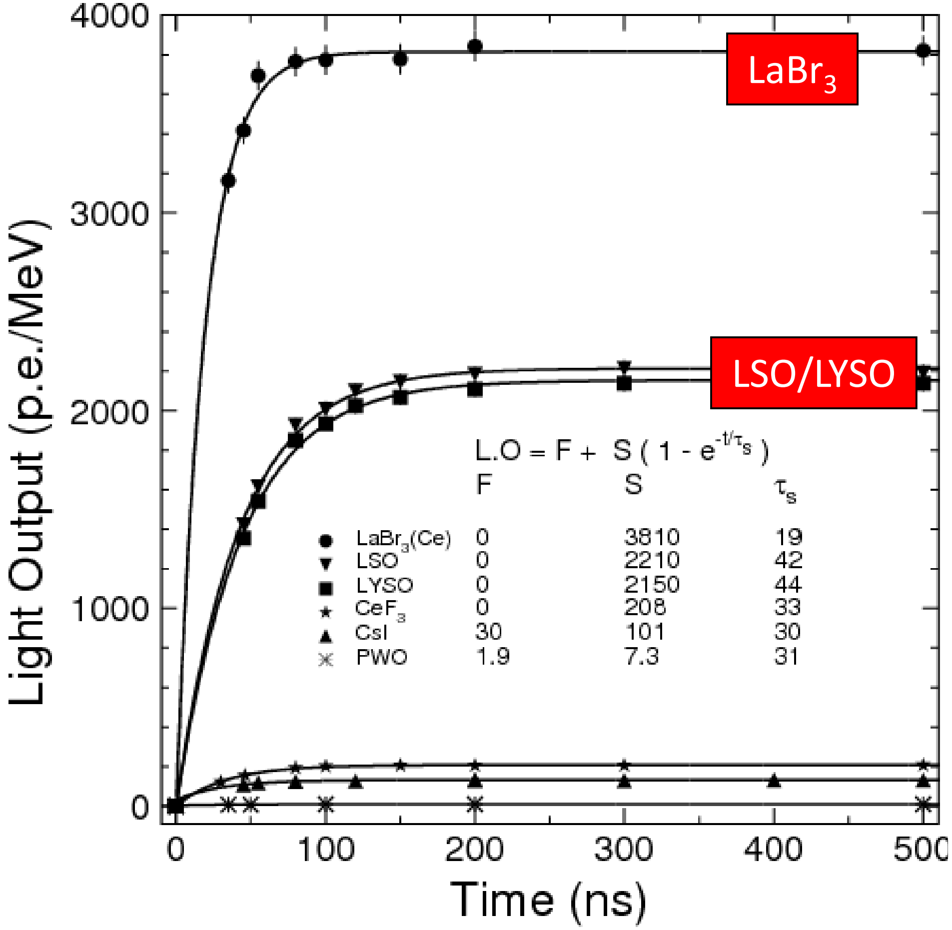
No Self-absorption: BGO, PWO, BaF_2, NaI(Tl) and CsI(Tl)

Light Output & Decay Kinetics

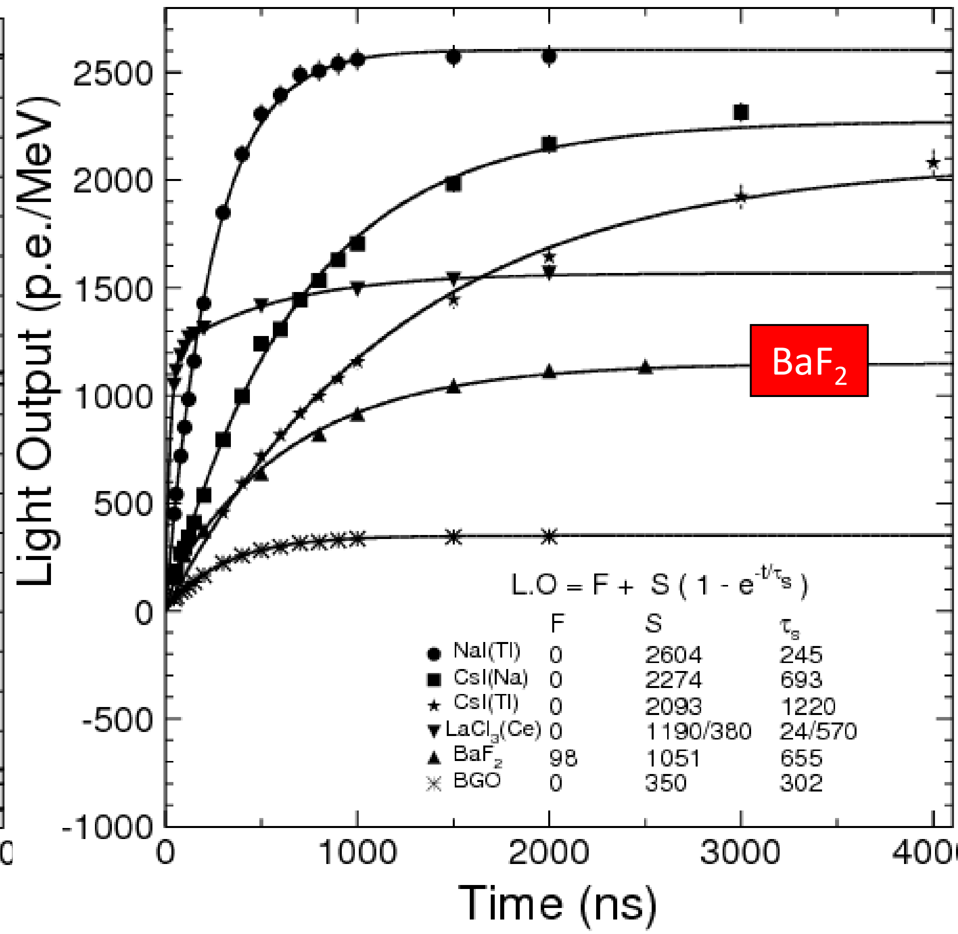


Measured with Philips XP2254B PMT (multi-alkali cathode)
p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

Fast Crystal Scintillators

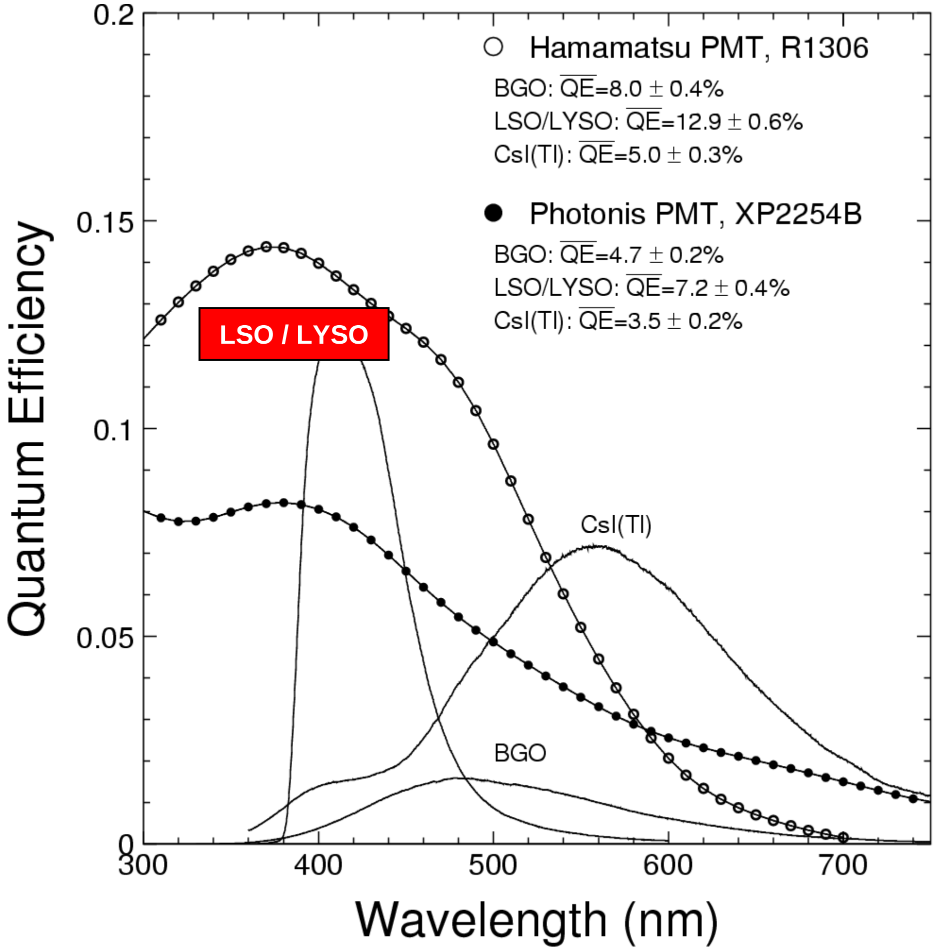


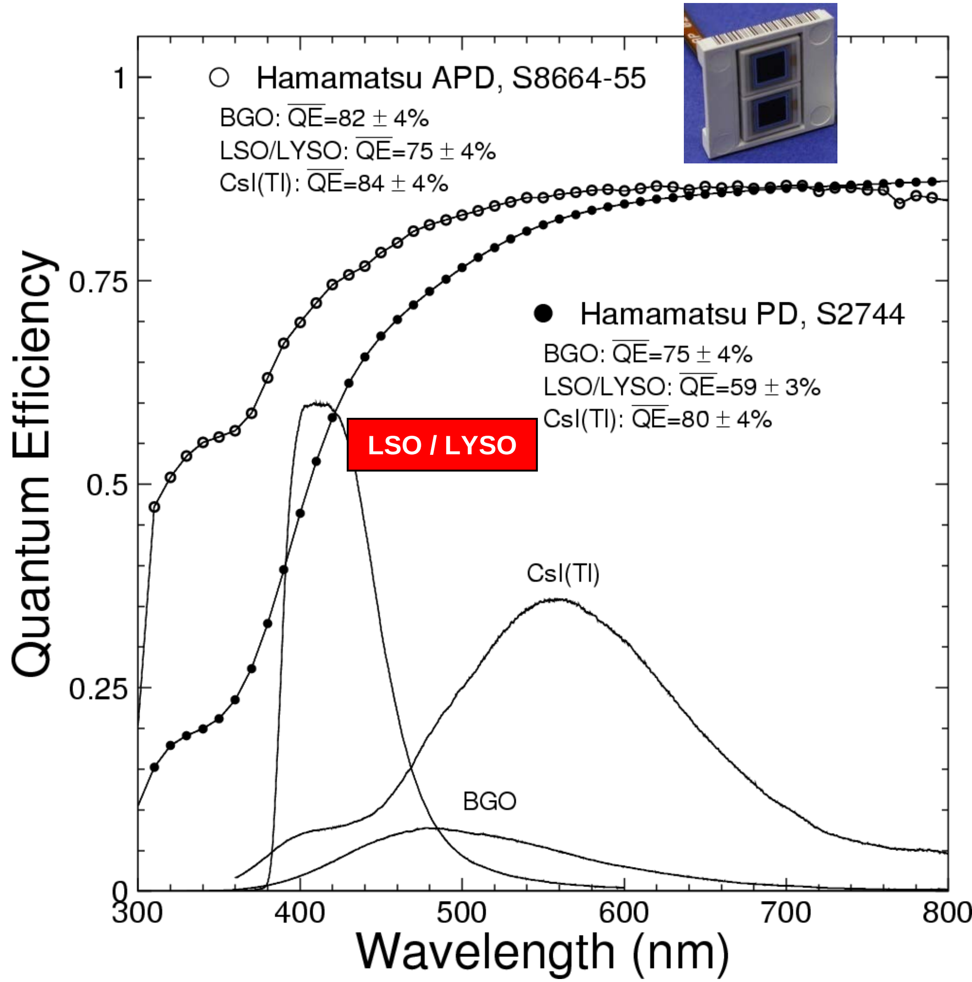
Slow Crystal Scintillators



Emission Weighted QE

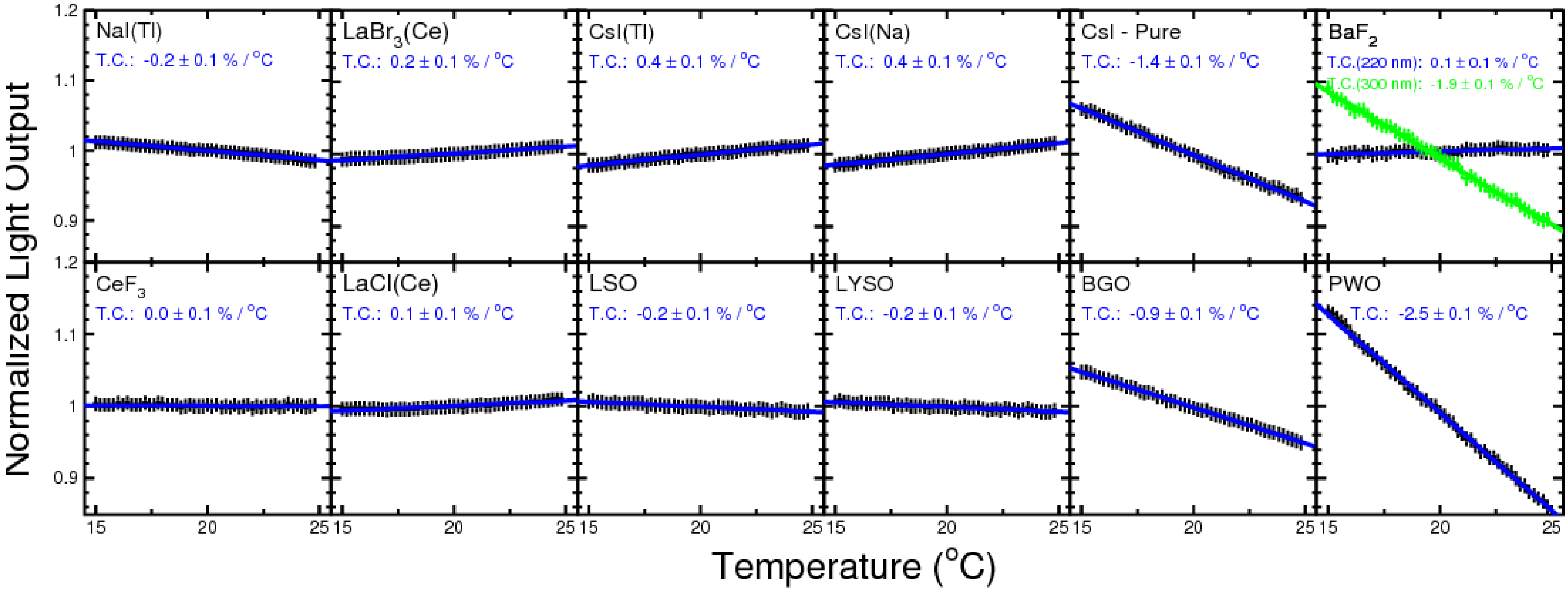
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





L.O. Temperature Coefficient

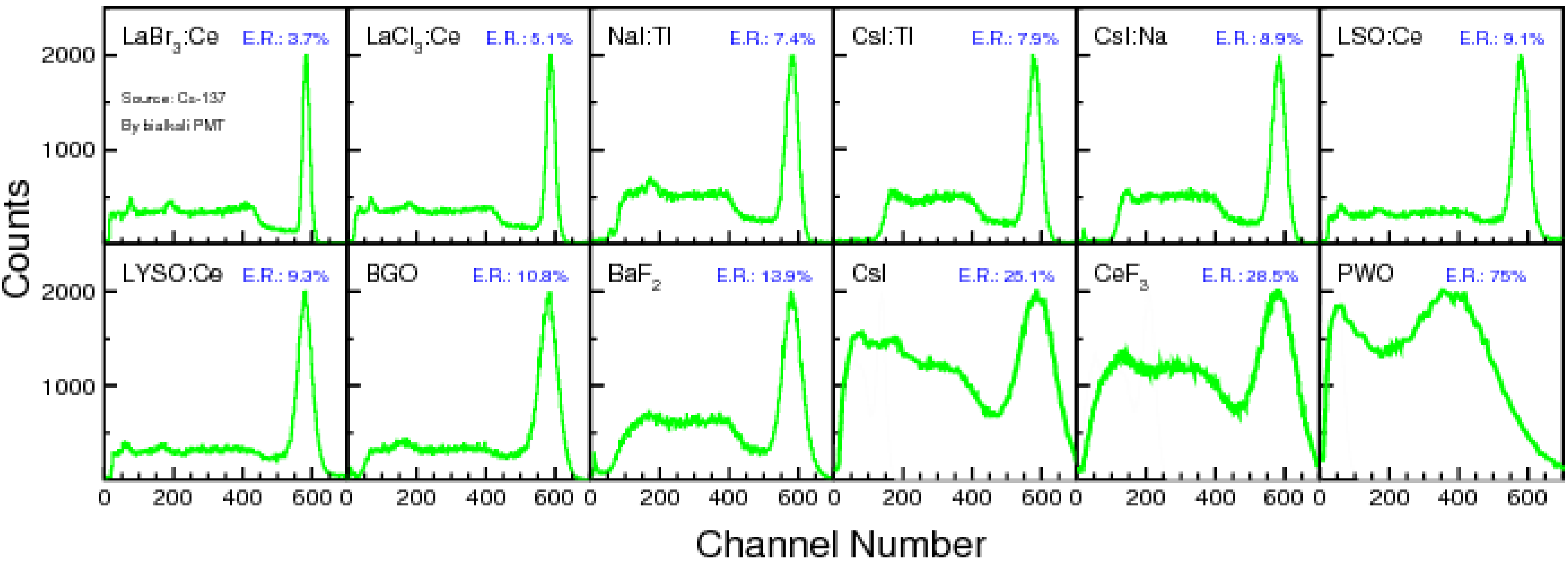
Temperature Range: 15 - 25ºC



Large coefficient: CsI, BGO, slow component of BaF_2 and PWO

^{137}Cs FWHM Energy Resolution

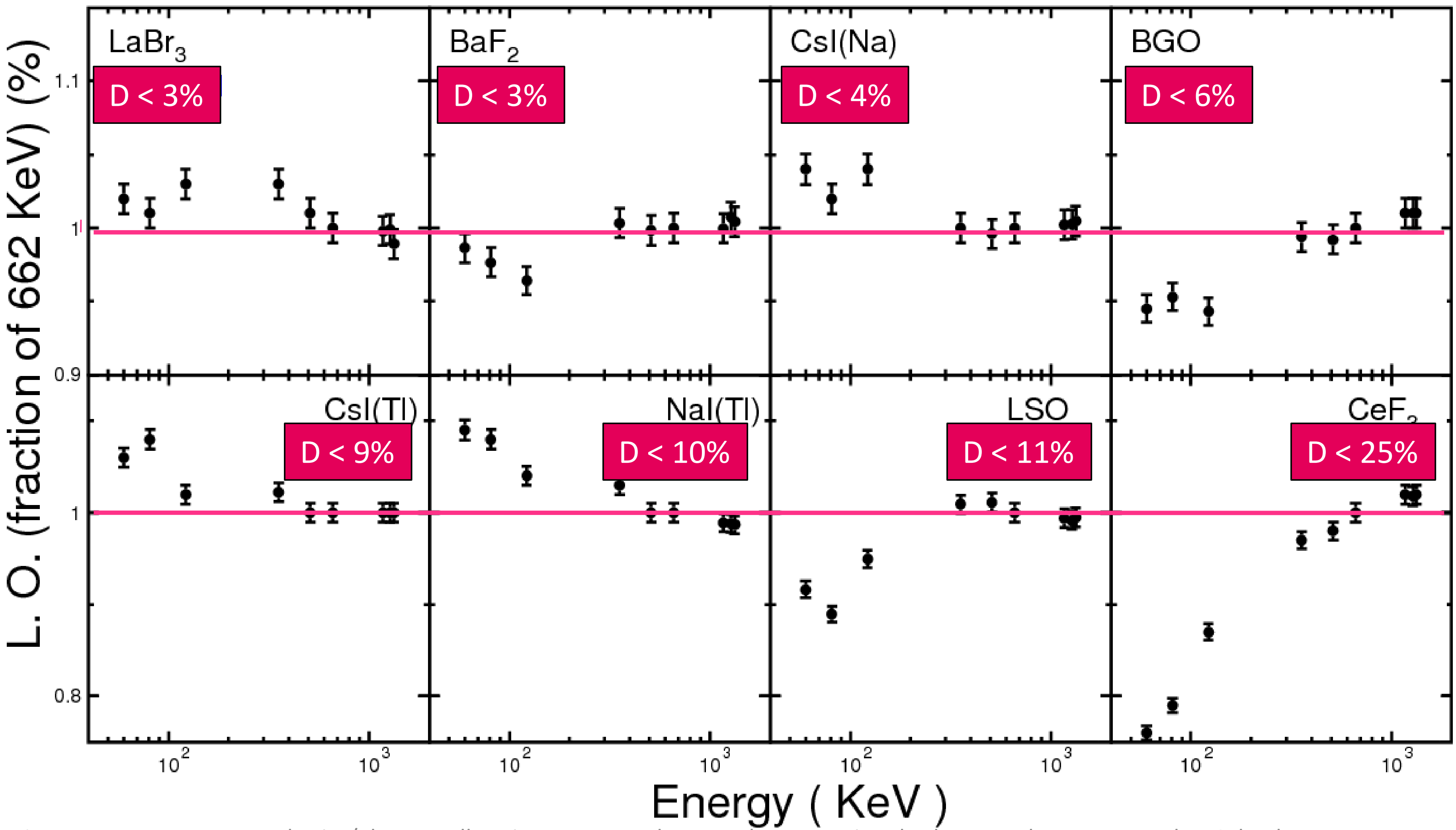
3% to 80% measured with Hamamatsu R1306 PMT with bi-alkali cathode



2% resolution and proportionality are important for γ–ray spectroscopy between 10 keV to 2 MeV

Low Energy Non Proportionality

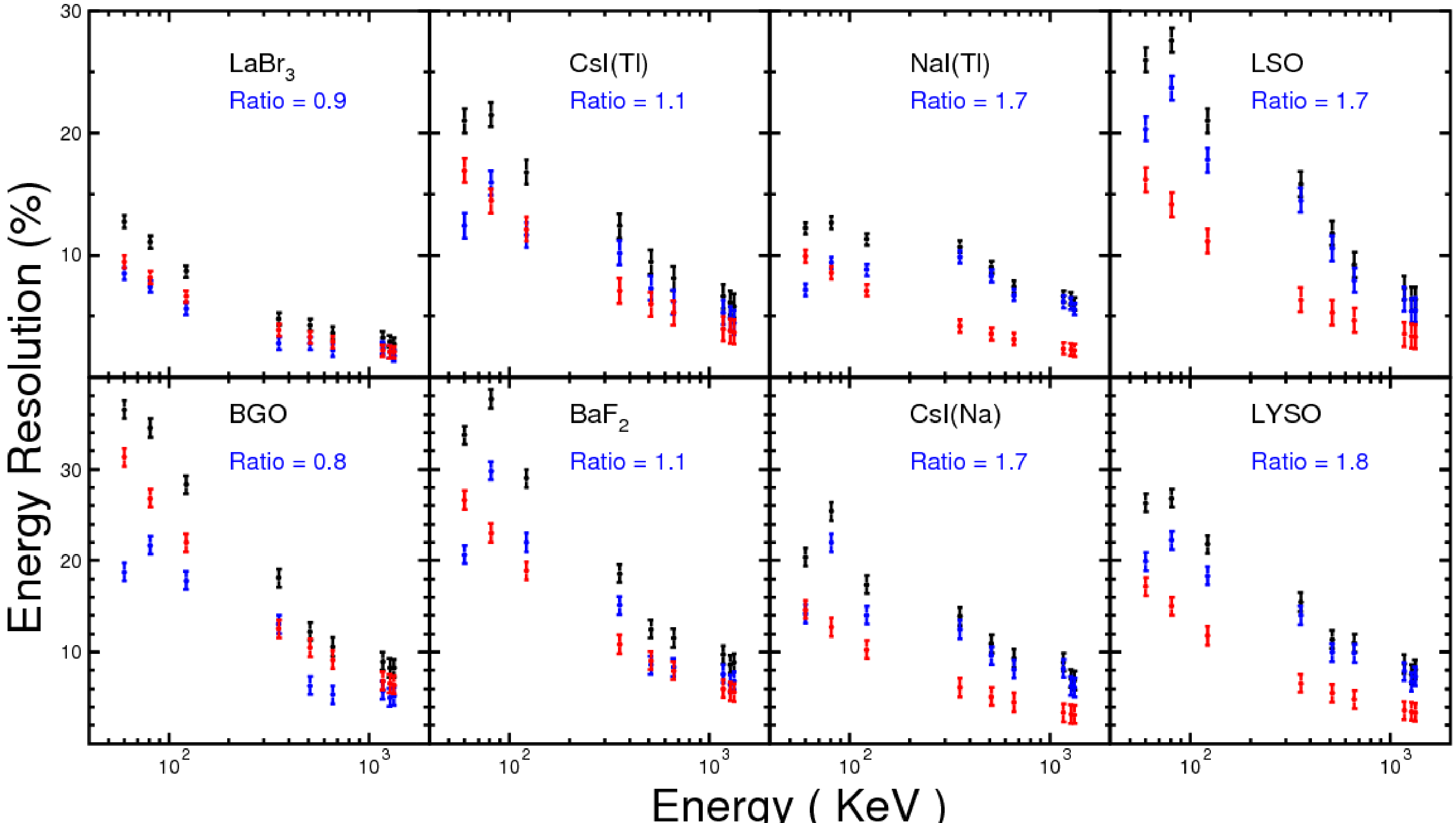
D: deviation from linearity: 60 keV to 1.3 MeV
Good Crystals: $LaBr_3$, BaF_2, CsI(Na) and BGO



Statistical & Intrinsic Resolutions

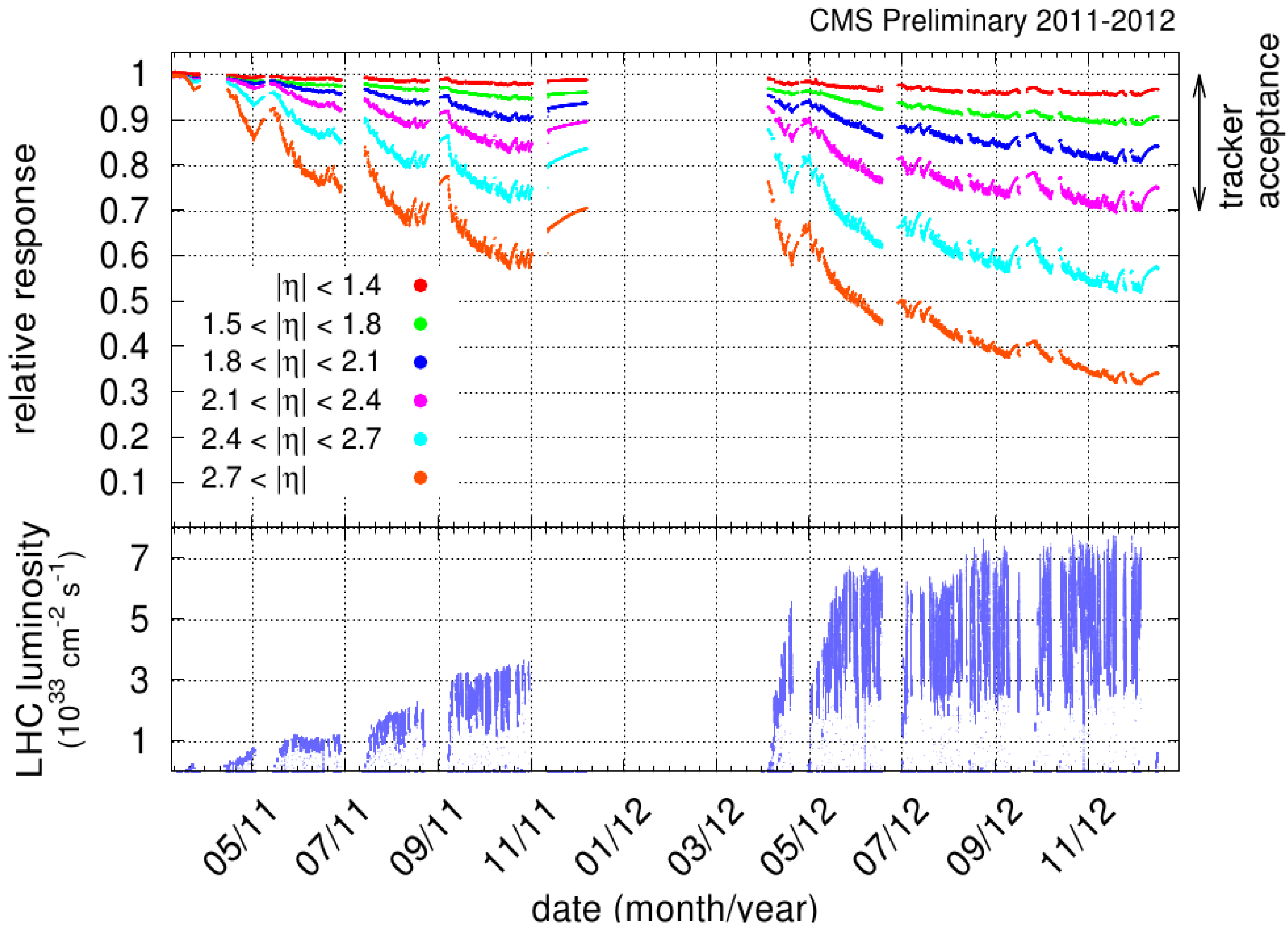
$\sigma^2 = \sigma^2_{intrinsic} + \sigma^2_{statistical}$, ratio = $\sigma_{intrinsic} / \sigma_{statistical}$

Good crystals: BGO and $LaBr_3$



CMS PWO Monitoring Response

The observed degradation is well understood



Dose Rate Dependent EM Damage

IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

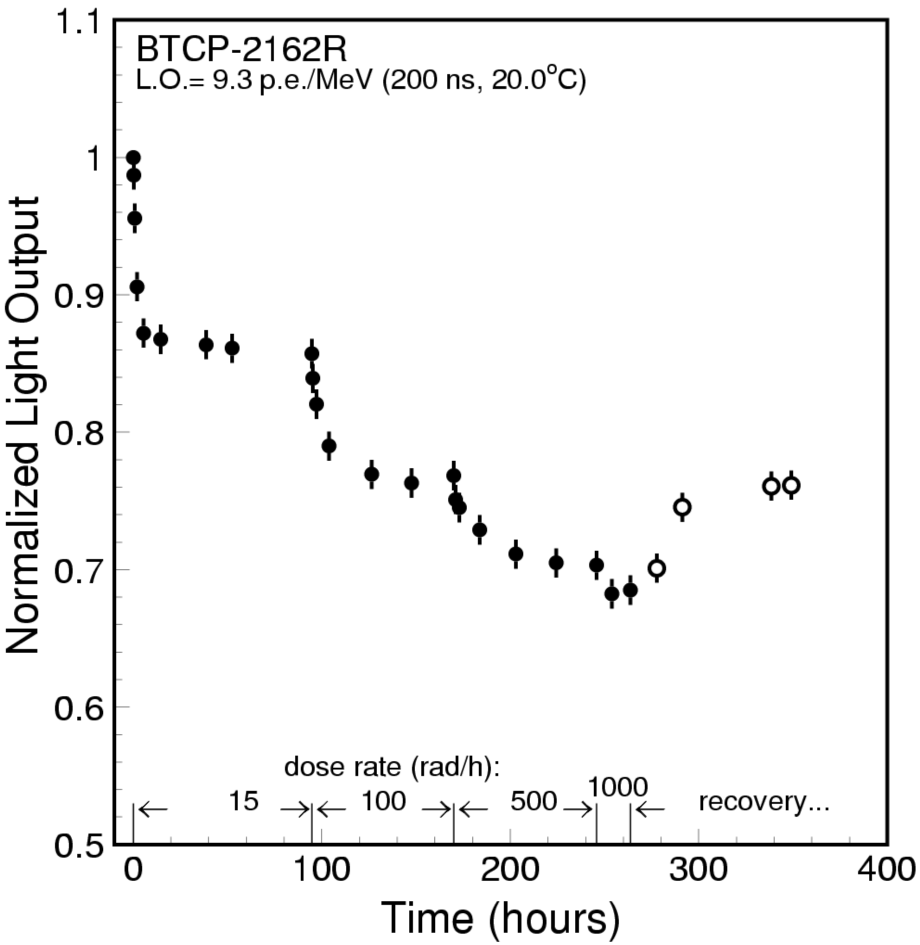
The LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

$$dD = \sum_{i=1}^{n}\{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

$$D = \sum_{i=1}^{n}\{\frac{b_i R D_i^{all}}{a_i + b_i R}\,[1 - e^{-(a_i+b_iR)t}] + D_i^0 e^{-(a_i+b_iR)t}\}$$

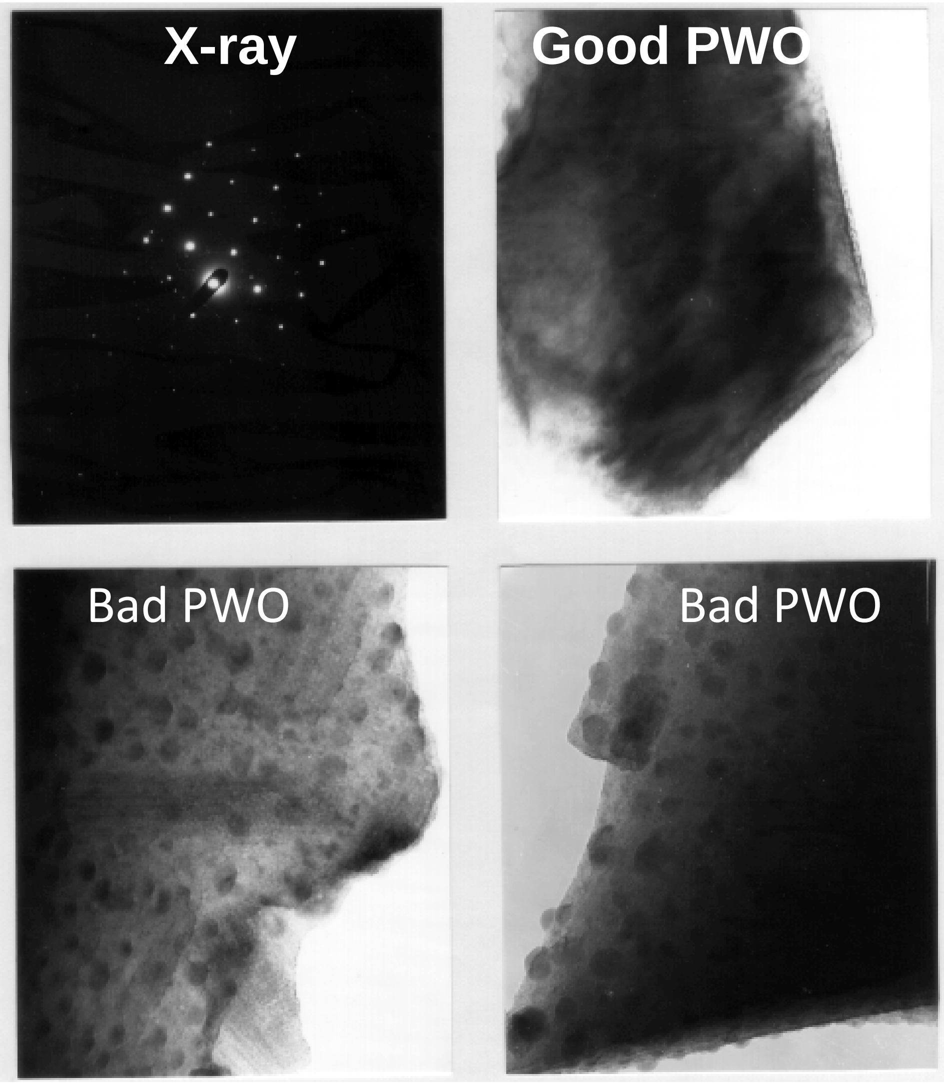
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

$$D_{eq} = \sum_{i=1}^{n}\frac{b_i R D_i^{all}}{a_i + b_i R}$$



Oxygen Vacancies Identified by TEM/EDS

TOPCON-002B scope, 200 kV, 10 uA, 5 to10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis



NIM A413 (1998) 297

Atomic Fraction (%) in $PbWO_4$

As Grown Sample

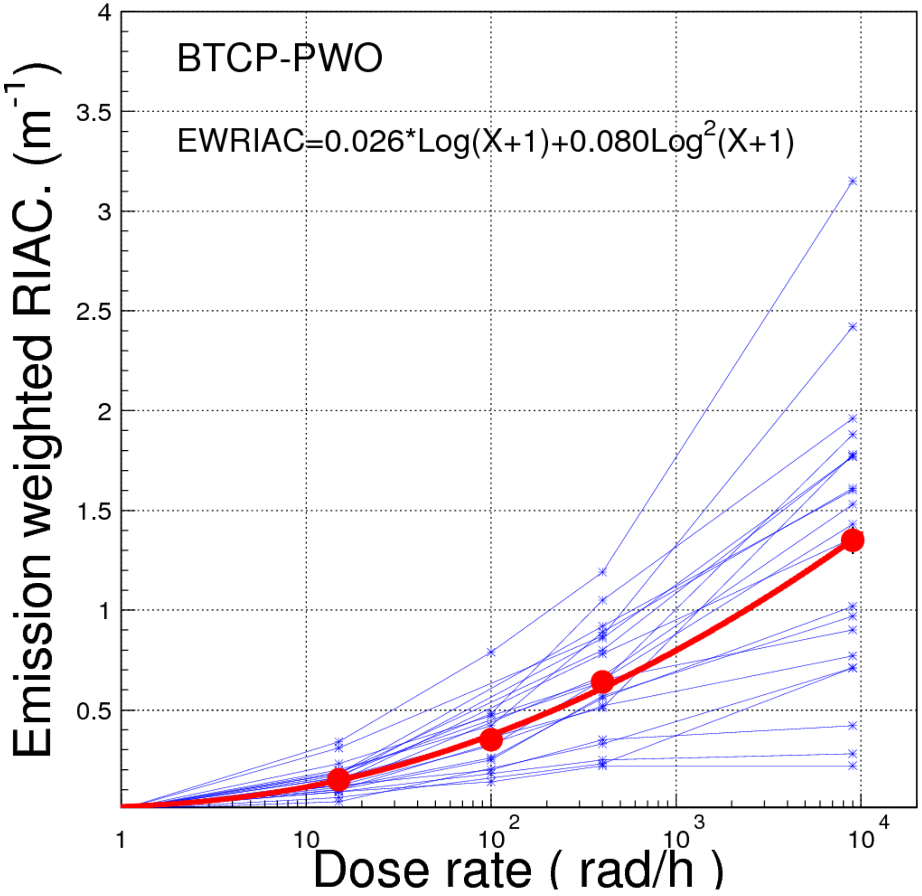
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

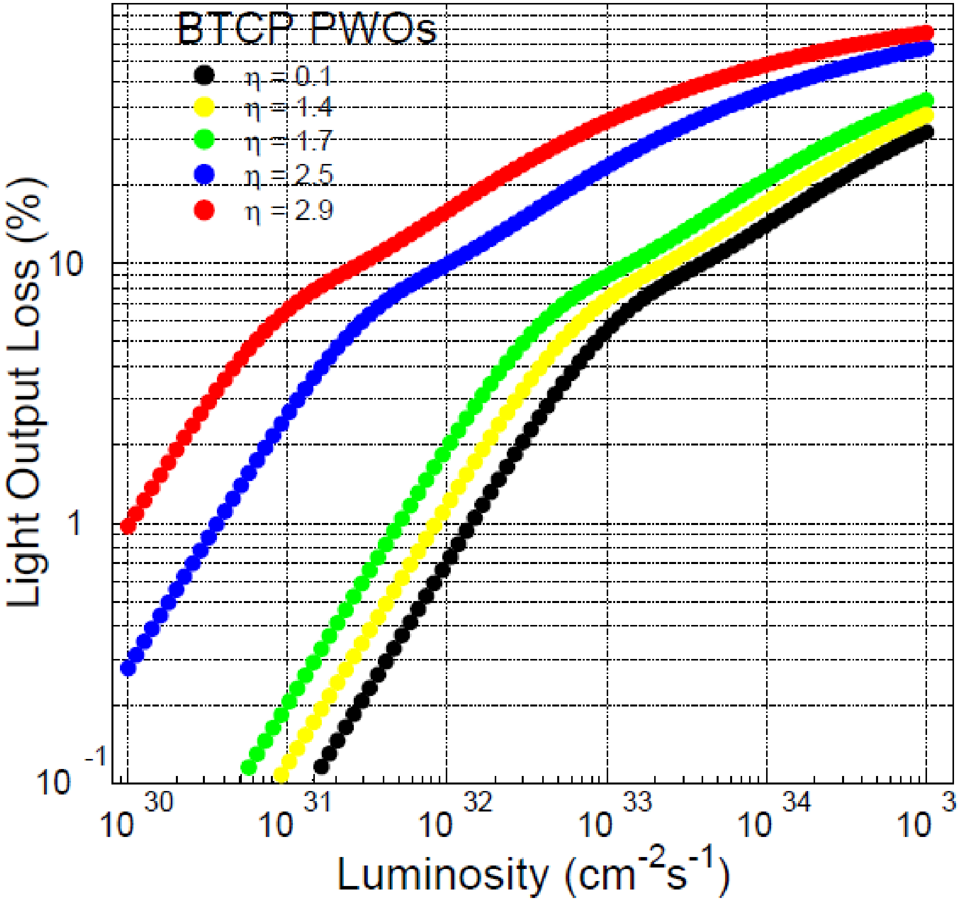
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Prediction of PWO Radiation Damage

IEEE Trans. Nucl. Sci. NS-51 1777 (2004)



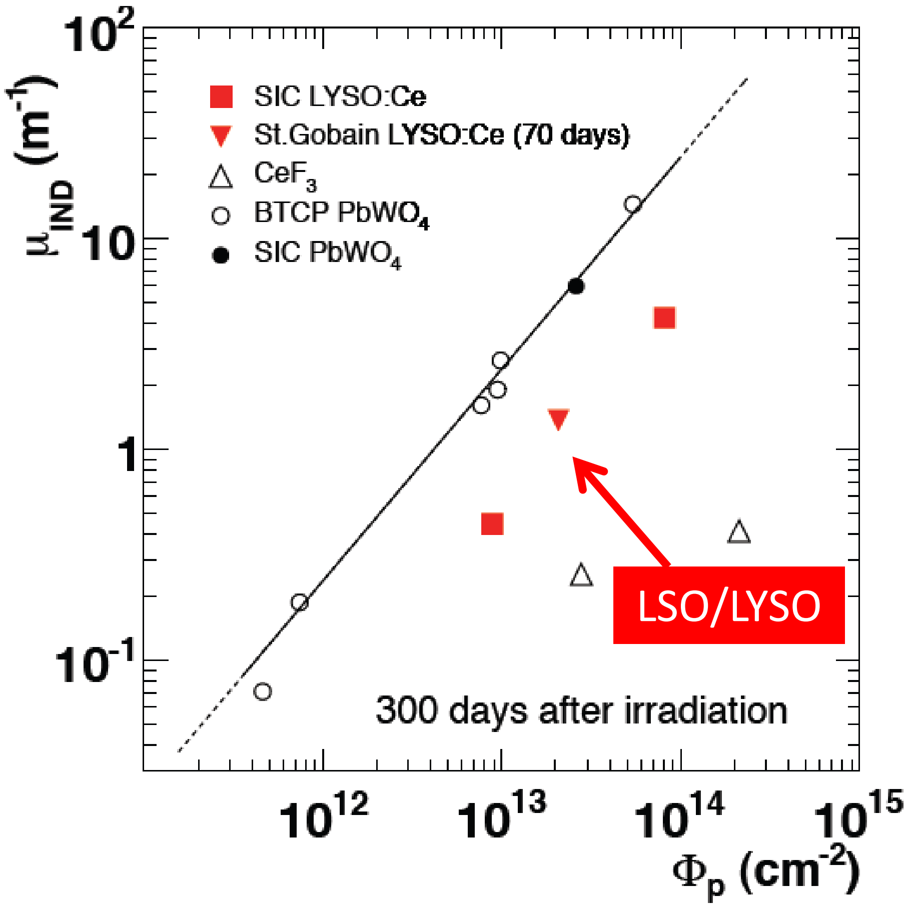
Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 12/10/2010



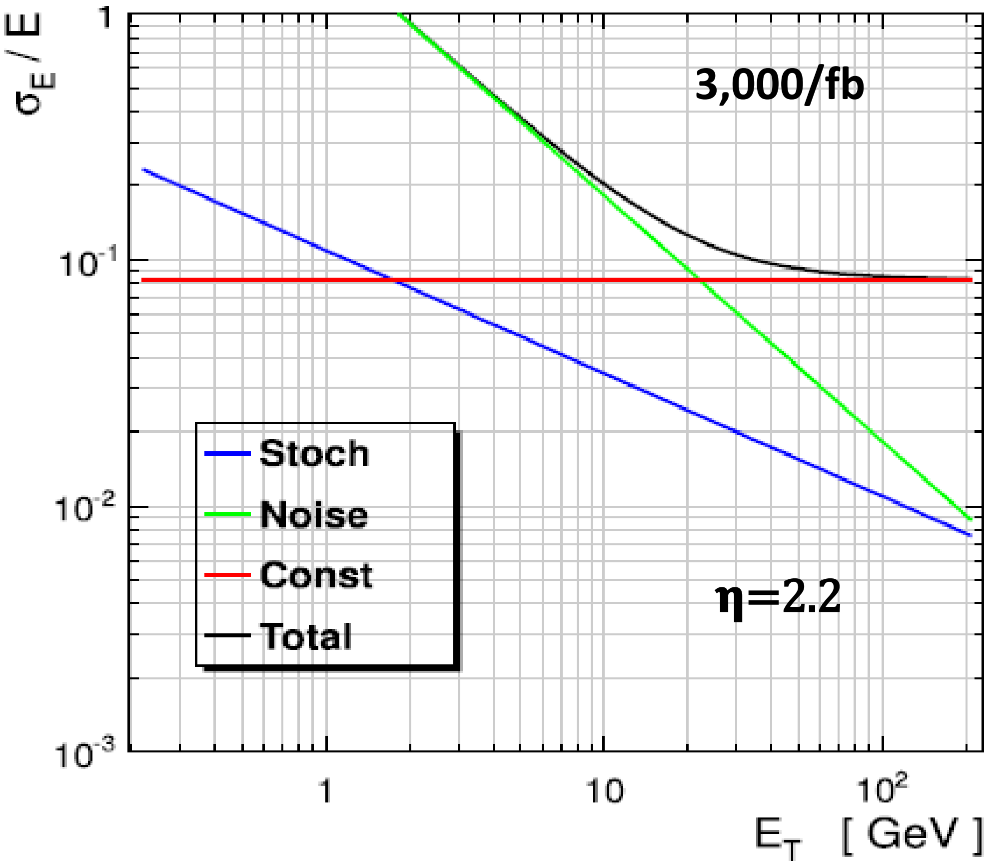
Predicted EM dose induced damage agrees well with the LHC data
In addition, there is cumulative hadron induced damage in PWO

Proton Induced Damage

G. Dissertori et al., IEEE NSS11, NP-5 S-228



Expected resolution @ $\eta = 2.2$

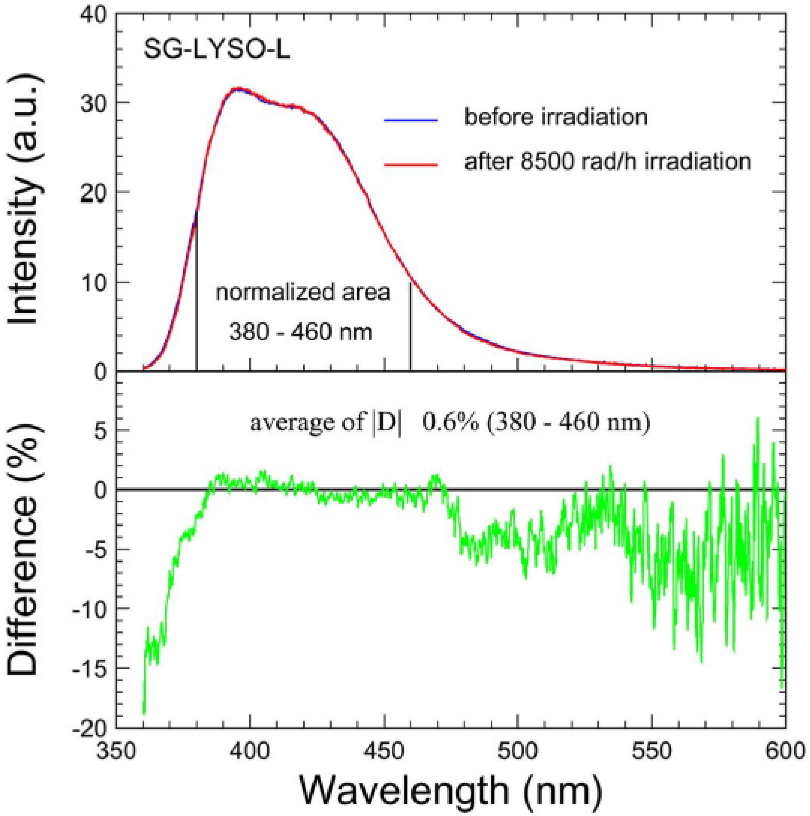


The proton induced absorption in LYSO is 1/5 of PWO

Damage may also be reduced by short light path

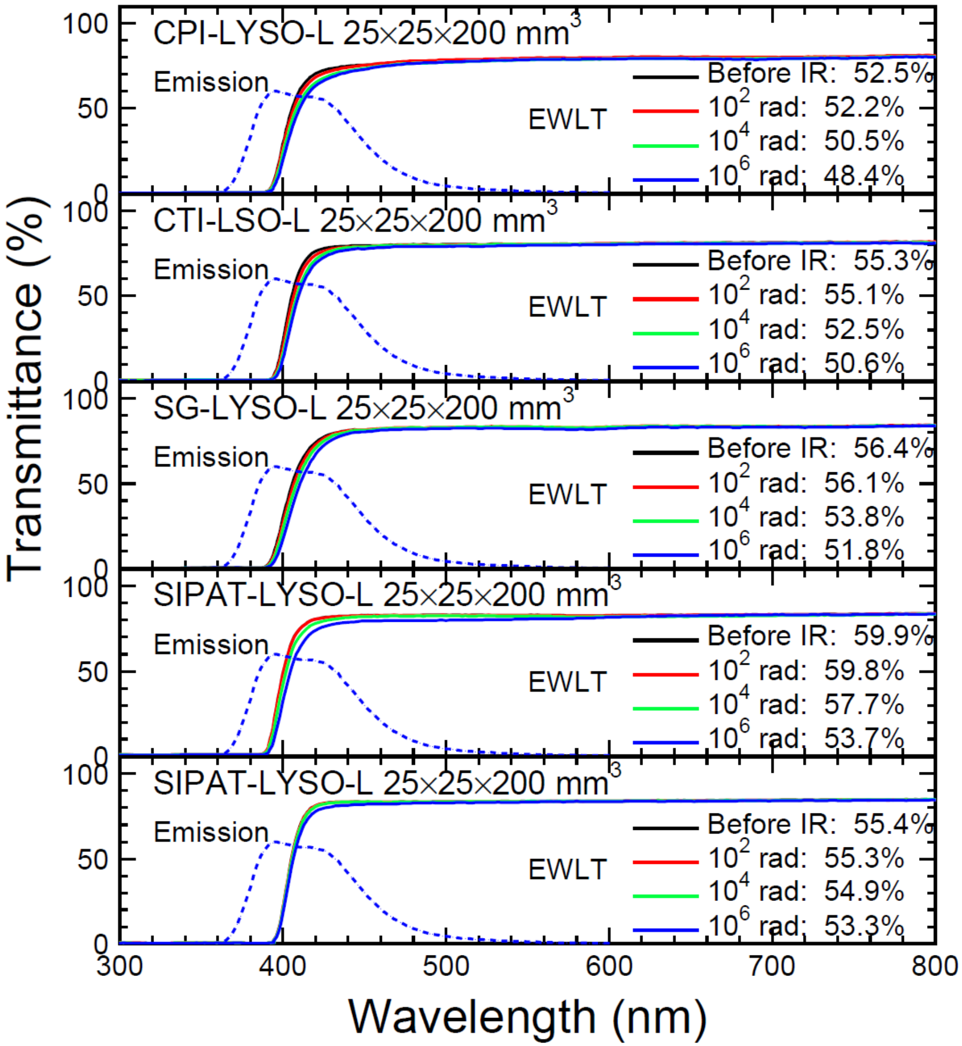
Bright, Fast & Rad Hard LSO/LYSO

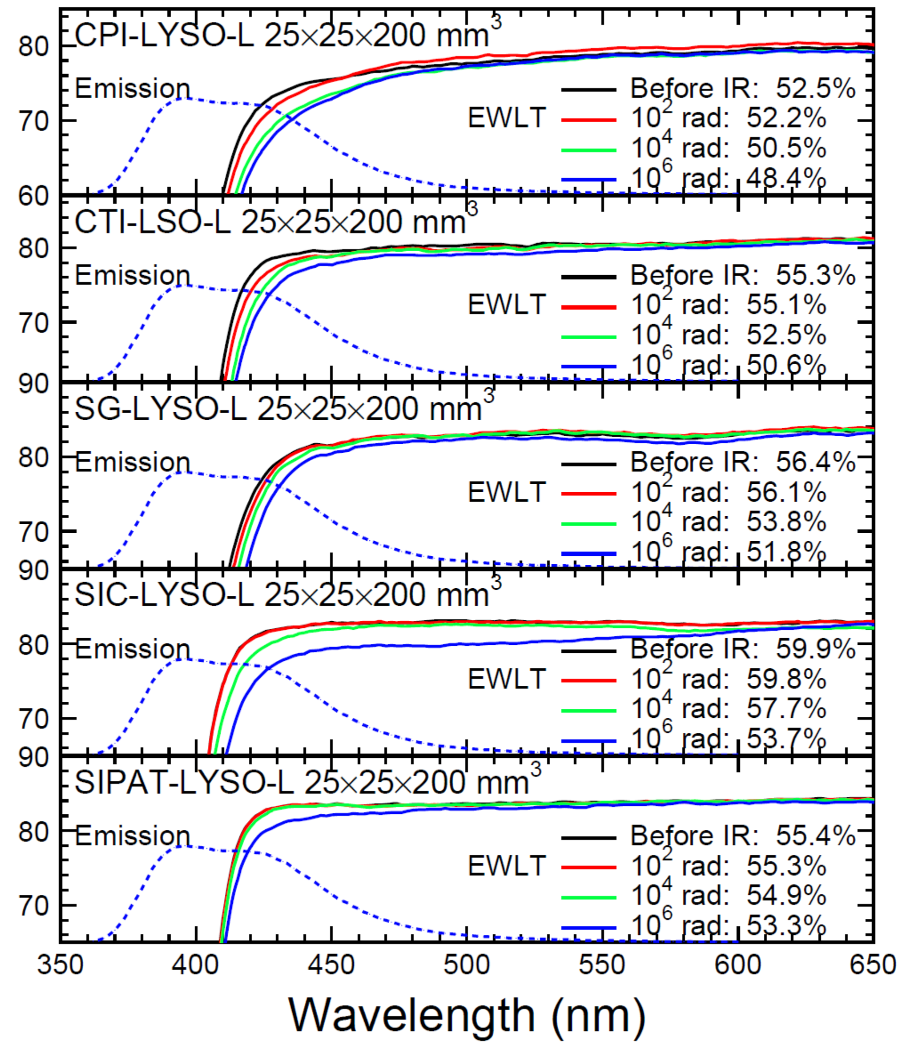
LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface. The material is widely used in the medical industry. Existing mass production capability would help in crystal cost control.



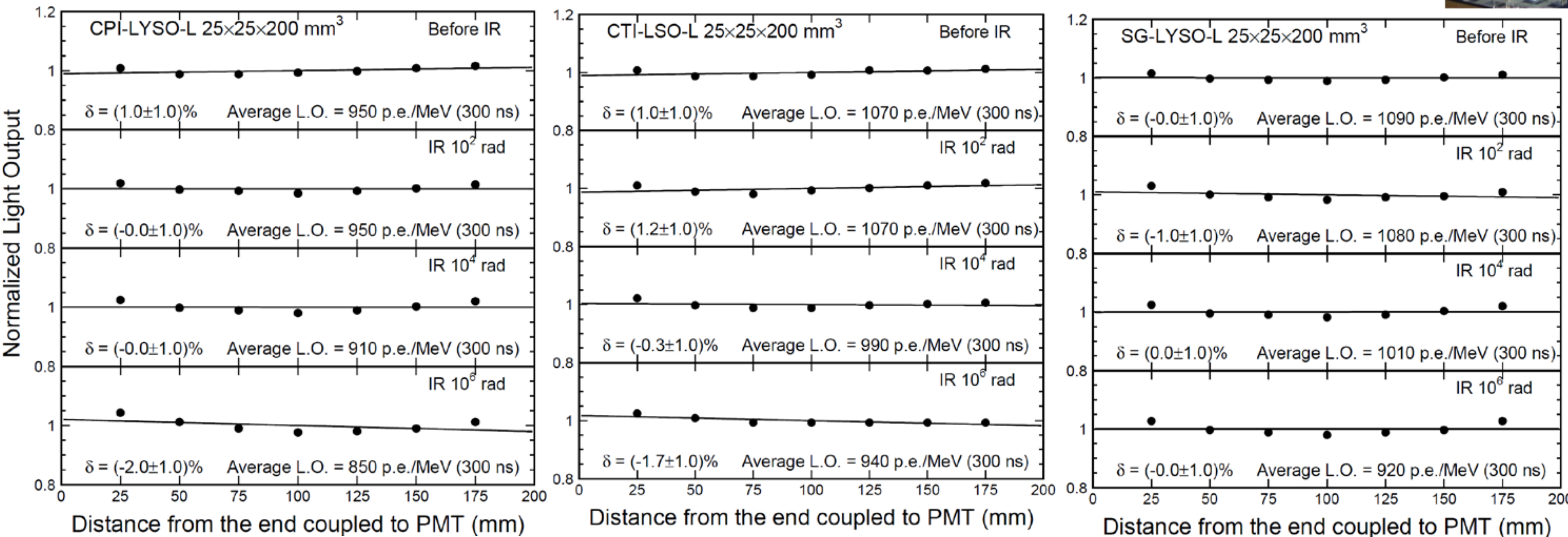
Excellent Radiation Hardness in LT

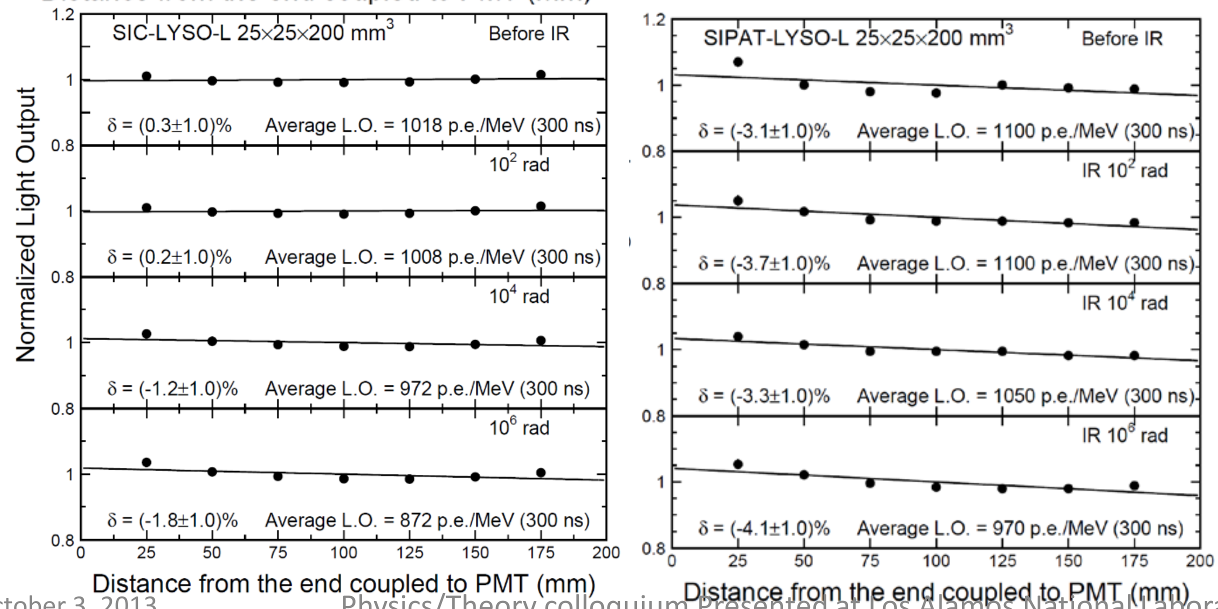
Consistent & Small Damage in LT → Larger variation @ shorter λ





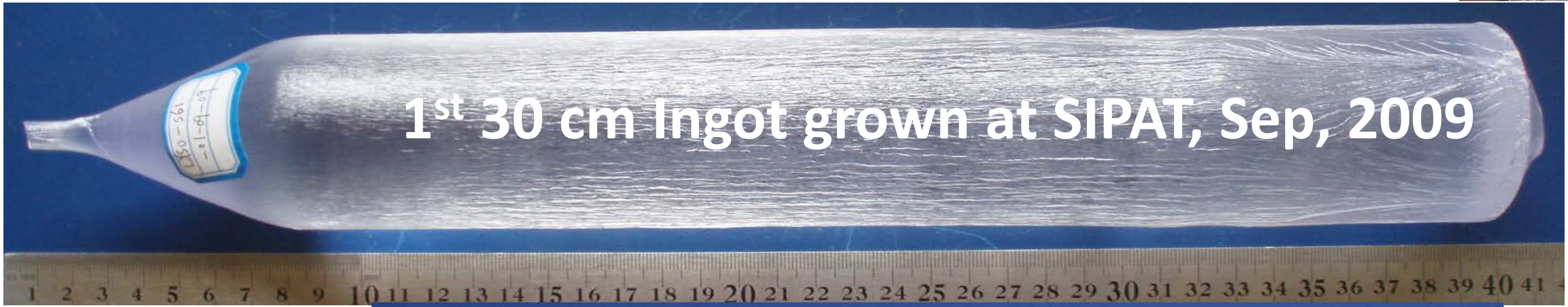
Excellent Radiation Hardness in LO

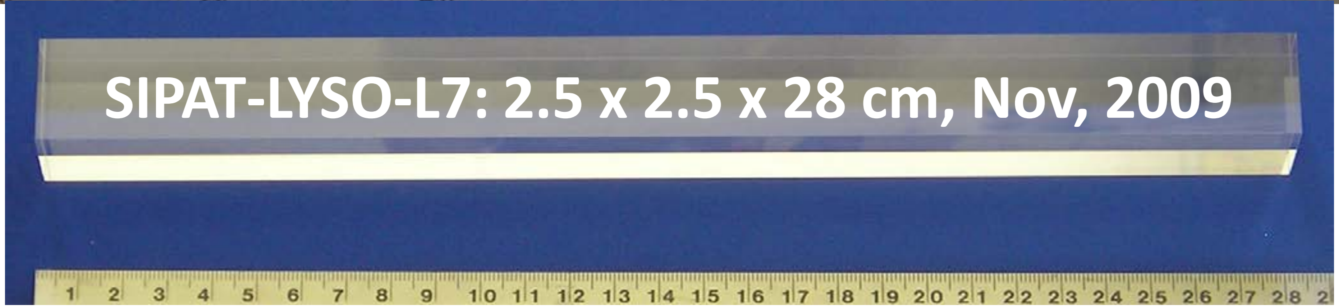


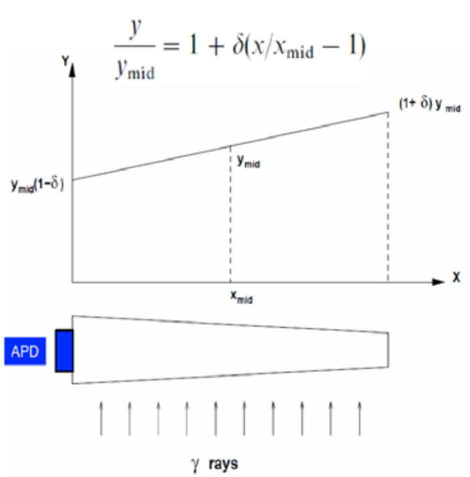


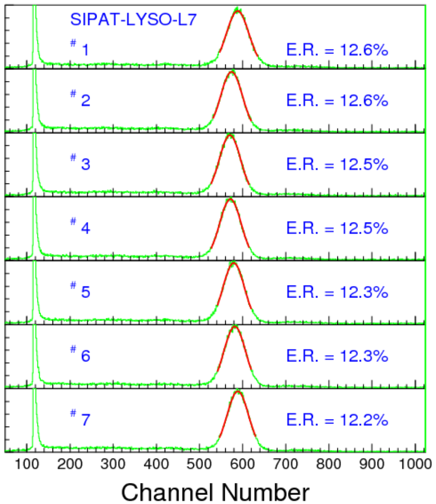
About 12% LO loss observed after 1 Mrad irradiation in all samples with LRU maintained. It can be corrected by light monitoring.

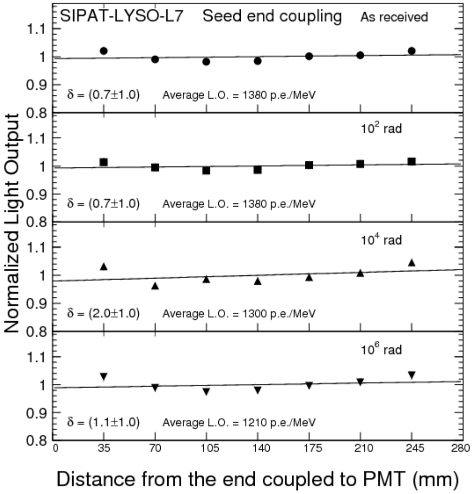
28 cm Long LYSO Under γ-Rays

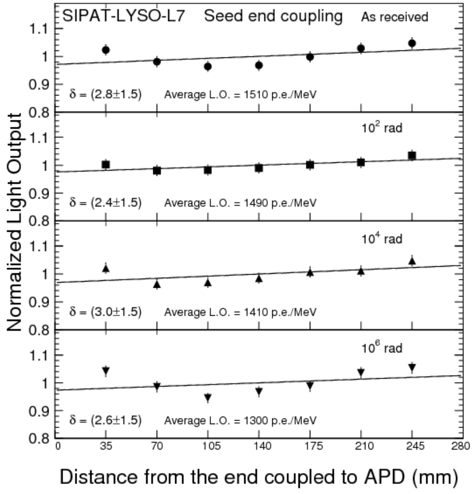






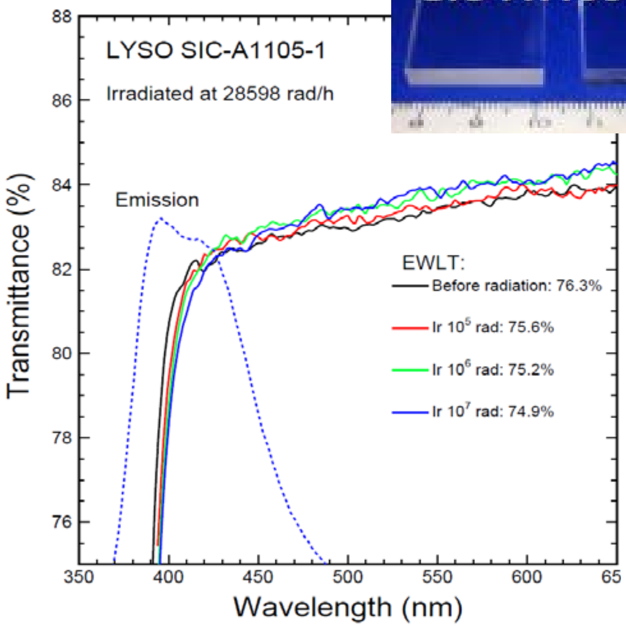


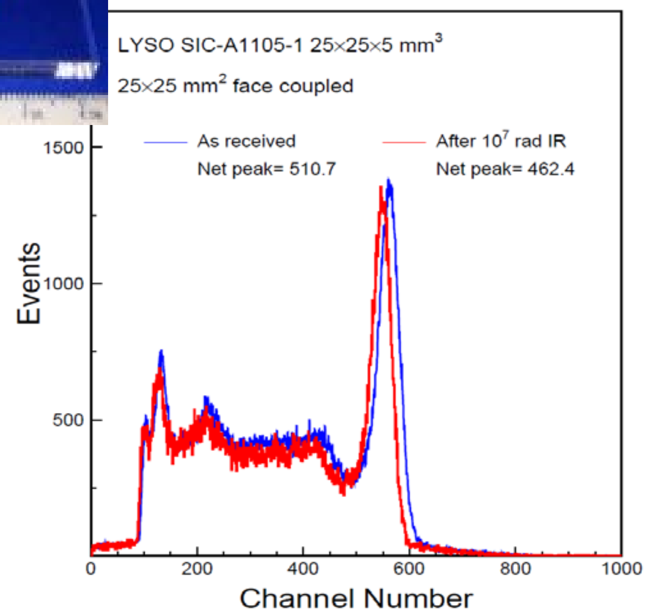


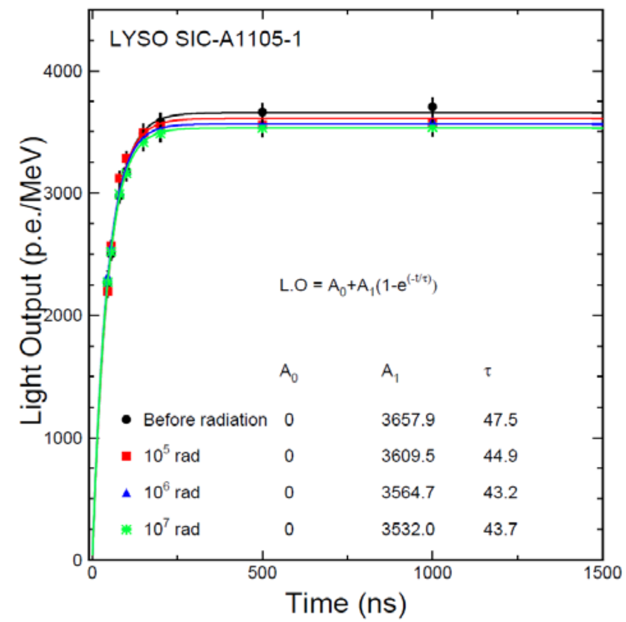


Damage in 25x25x5 mm LYSO Plates

Two 5 mm thick LYSO plates went through γ-ray irradiation to 10 Mrad with degradation in both EWLT and LO less than 10%.







Samples	EWLT (%)	L.O. (p.e./MeV)	EWLT loss (%)			L.O. loss (%)		
			10^5 rad	10^6 rad	10^7 rad	10^5 rad	10^6 rad	10^7 rad
SIC-A1105-1	76.3	3657.9	0.9	1.4	1.8	1.3	2.5	3.4
SIC-A1105-2	77.2	3846.1	2.3	2.5	2.6	4.4	7.7	9.1

Mu2e Experiment at Fermilab

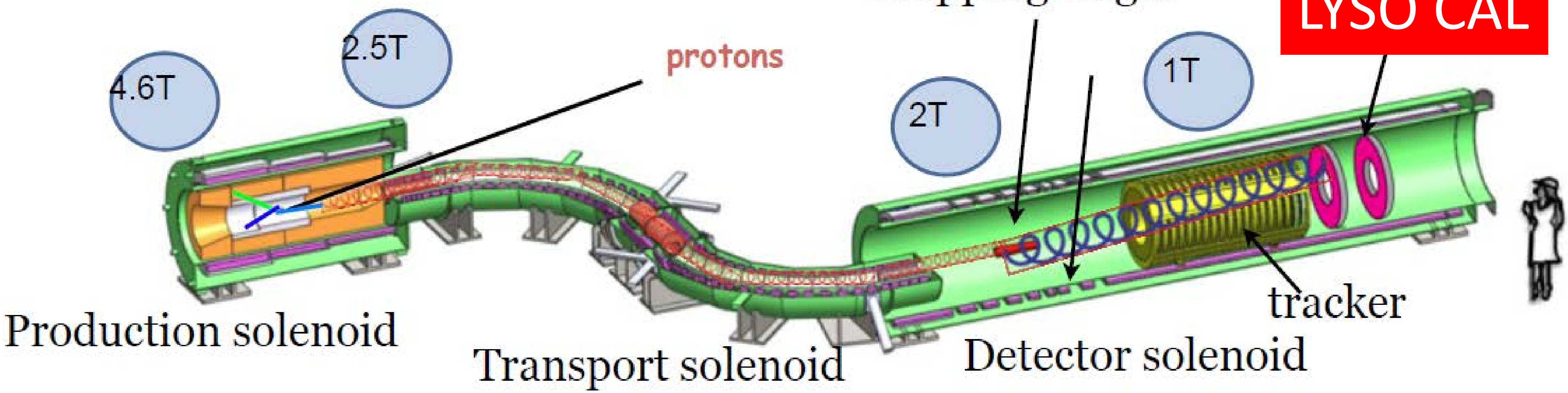
Production Solenoid
- Production target
- Graded field

- Delivers ~ 0.0015 stopped μ^- per incident proton
- 5×10^{10} Hz of stopped muons

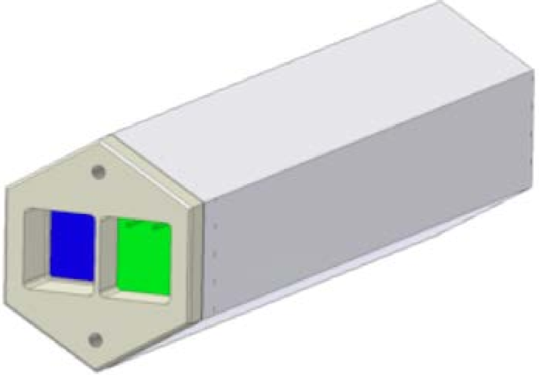
Detector Solenoid
- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to 10^{-4} Torr

Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

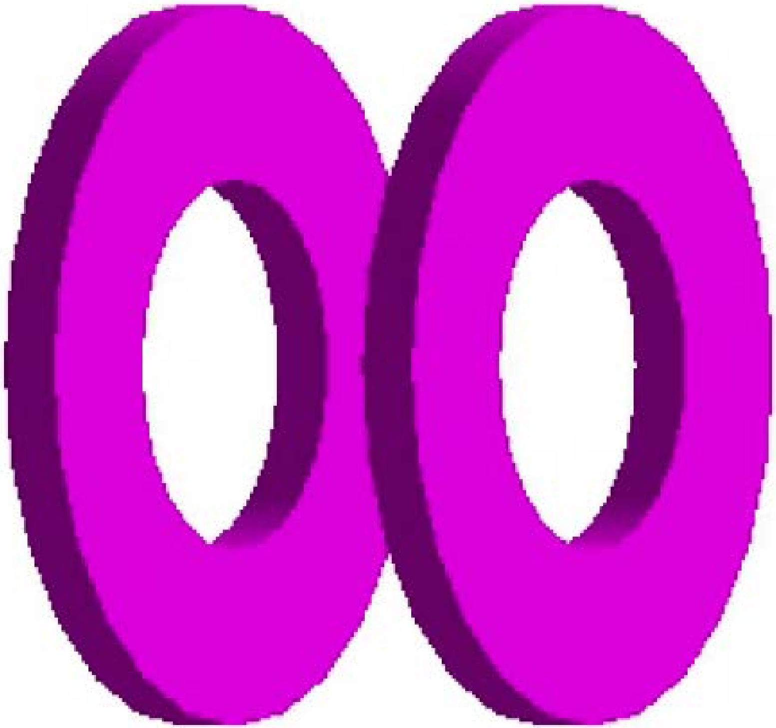
Cosmic Ray Veto not shown

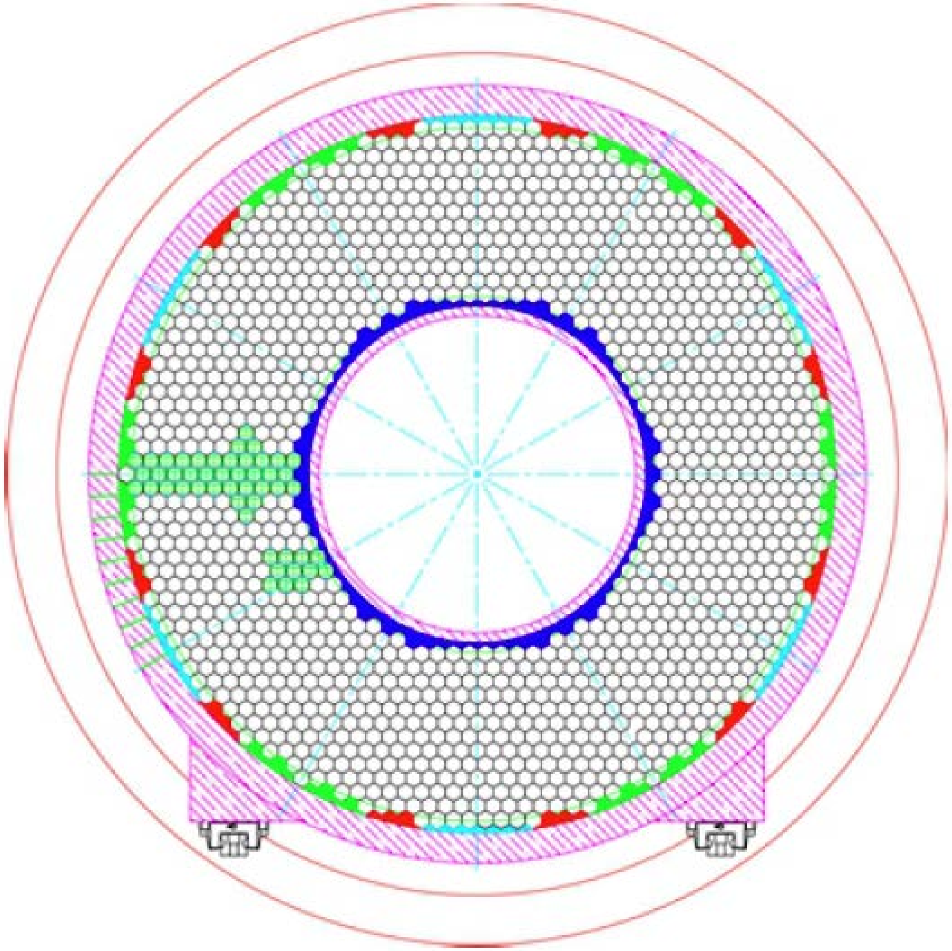


Mu2e LYSO Calorimeter

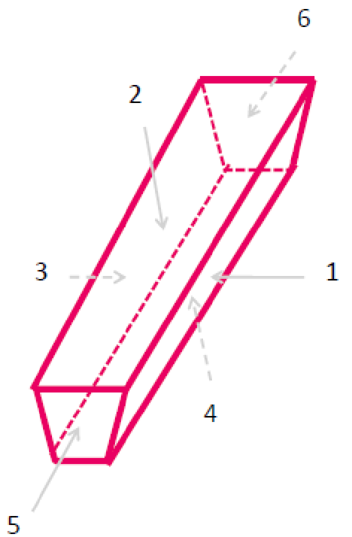


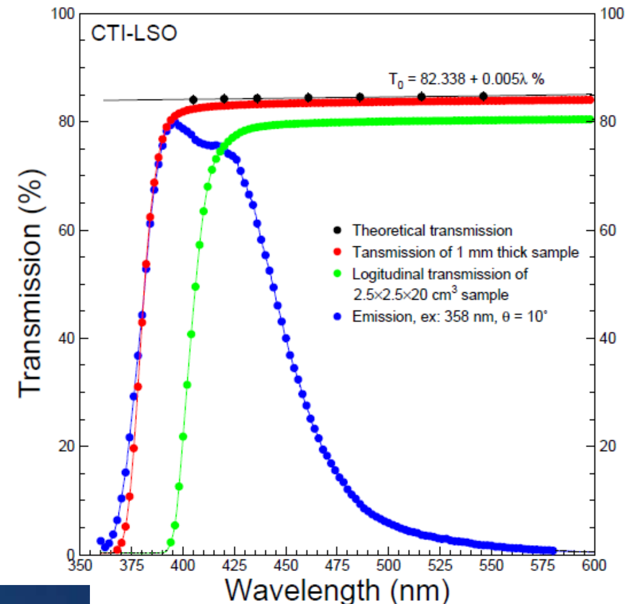
An array of hexagonal LYSO crystals arranged in two disks

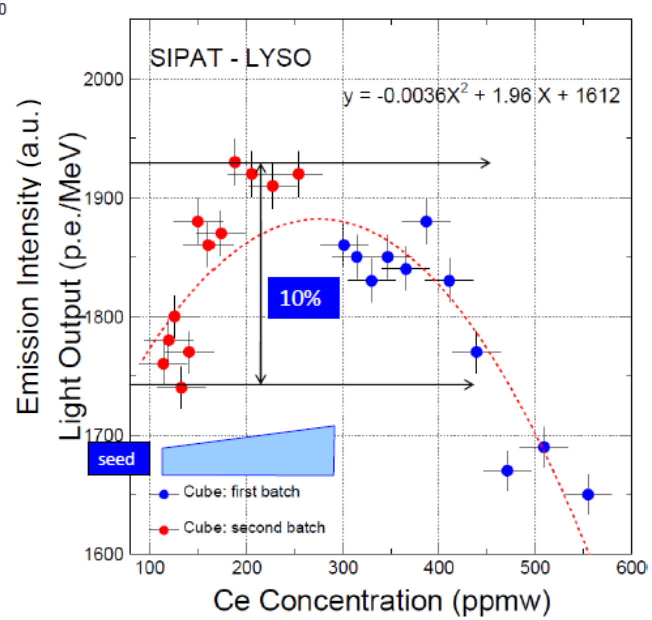


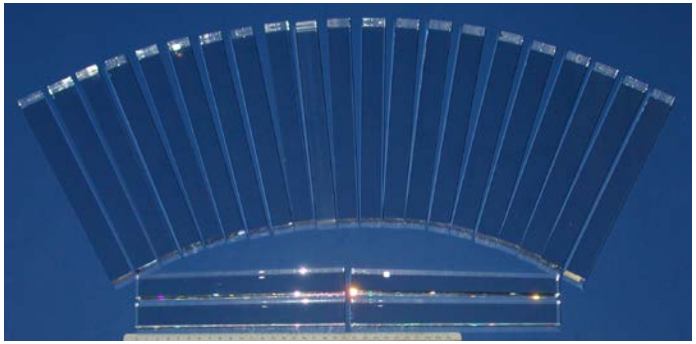


LYSO Light Response Uniformization

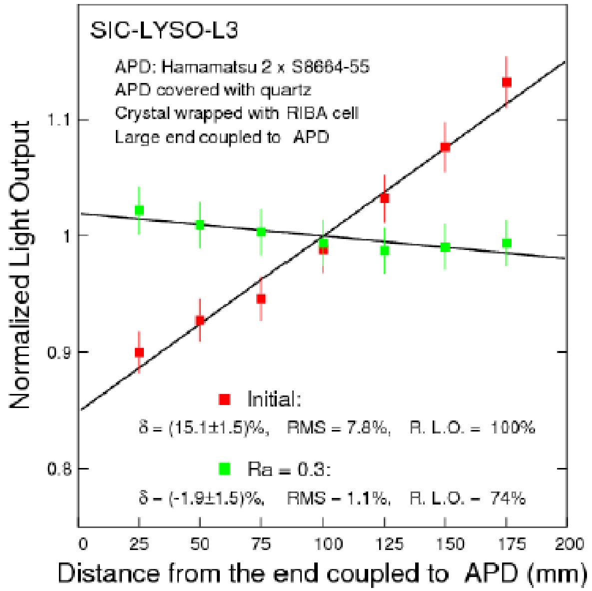


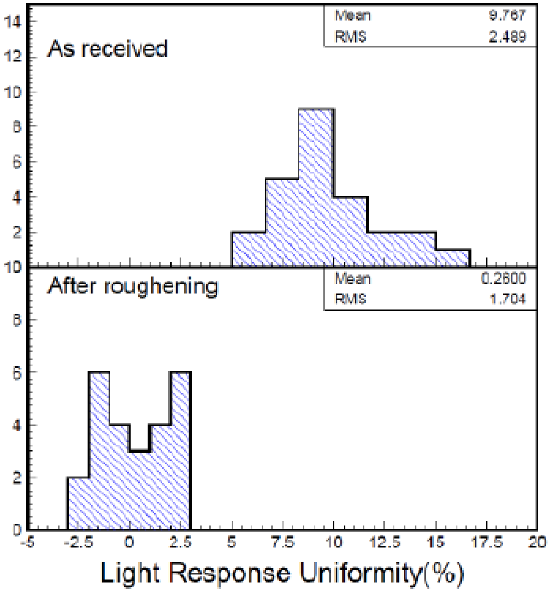






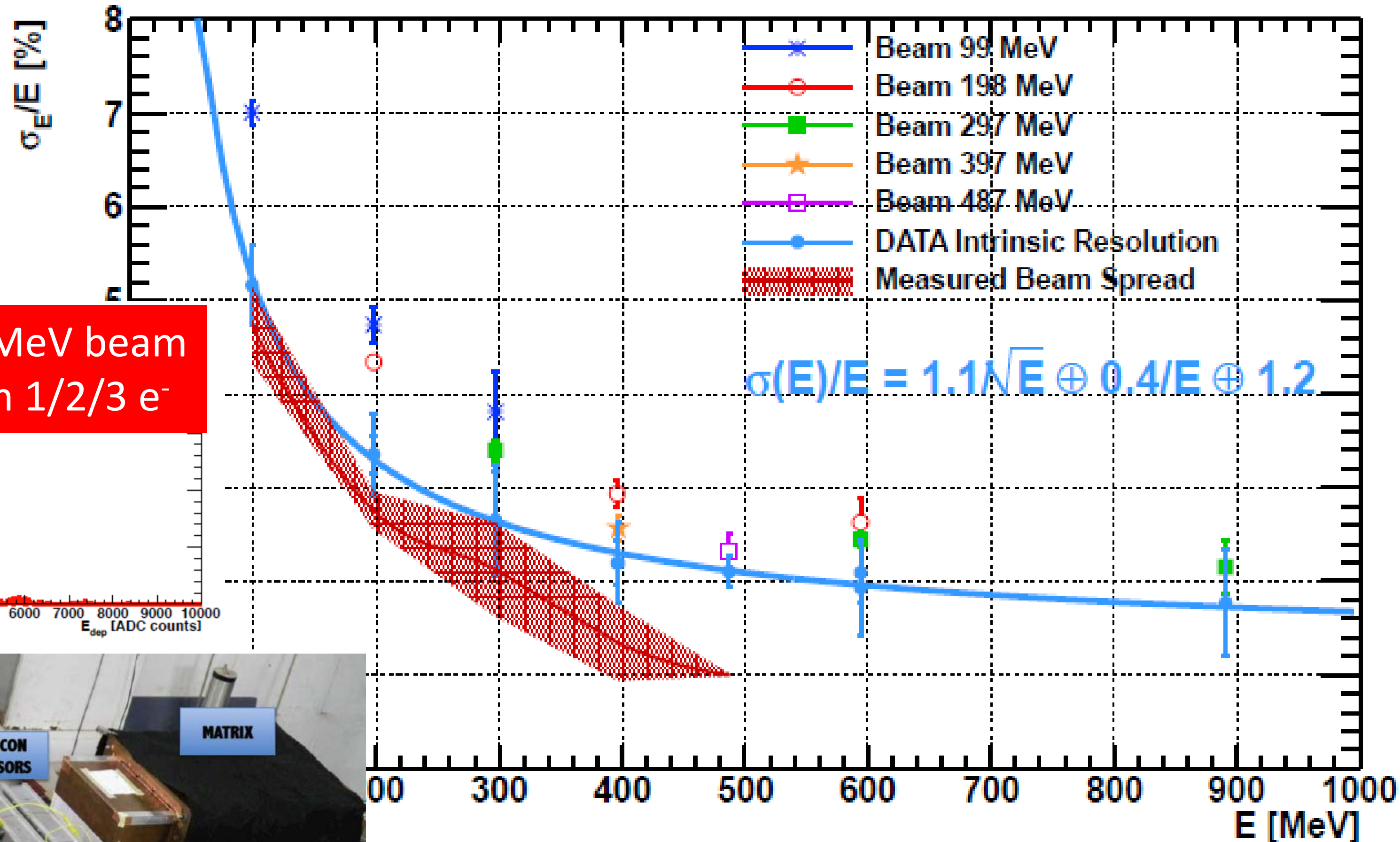
25 LYSO test beam crystals are uniformized to |δ| < 3% by roughening the smallest side surface.

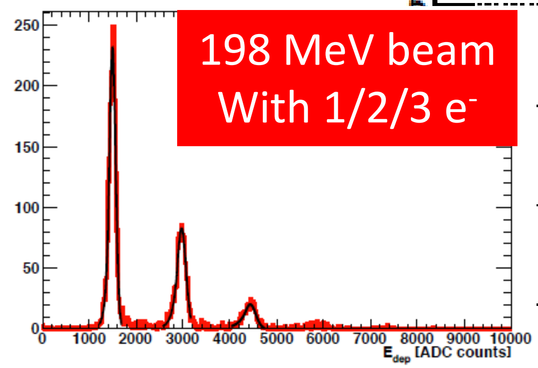


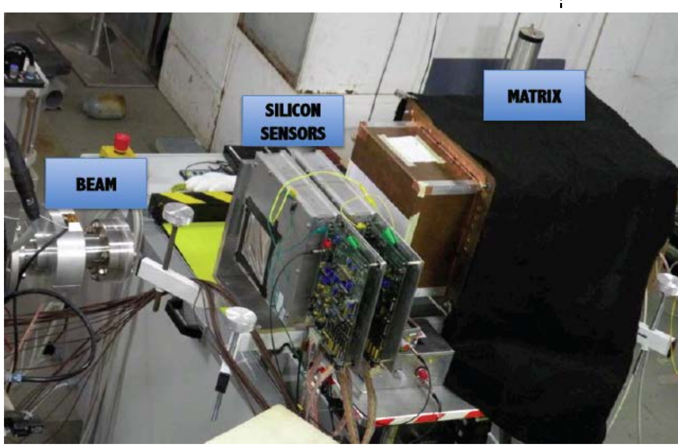


LYSO Test Beam Result

http://iopscience.iop.org/1742-6596/404/1/012065/pdf/1742-6596_404_1_012065.pdf



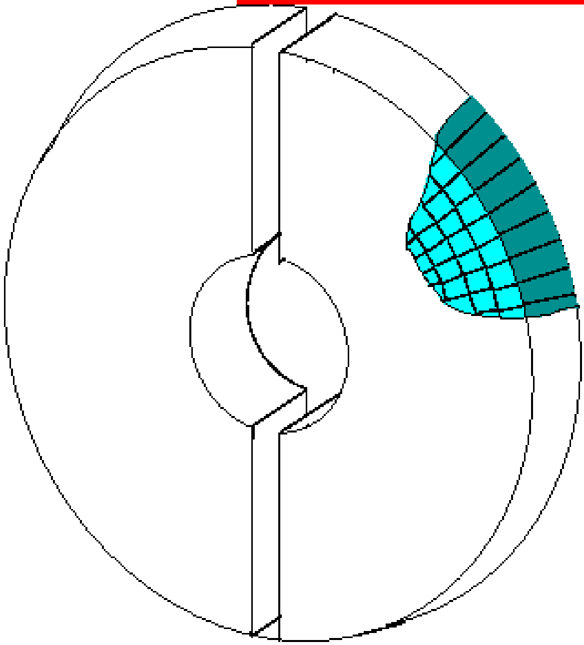


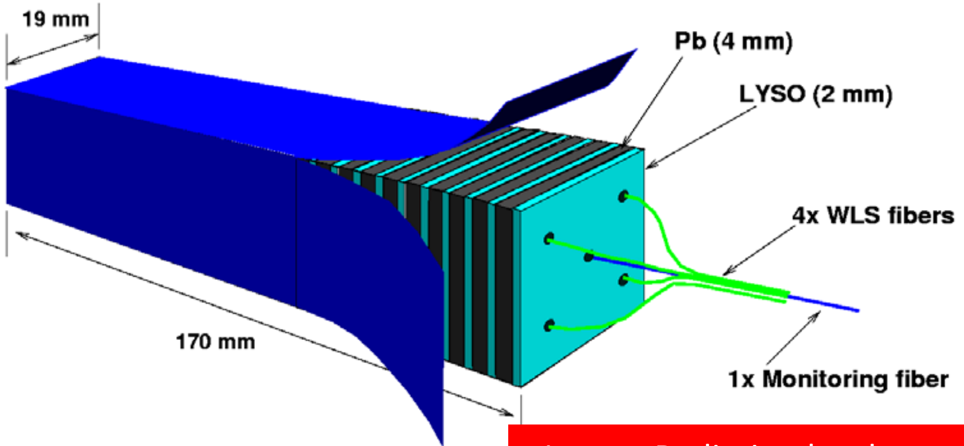


$$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E[GeV]}} \oplus \frac{0.4}{E[GeV]} \oplus 1.2\ \%$$

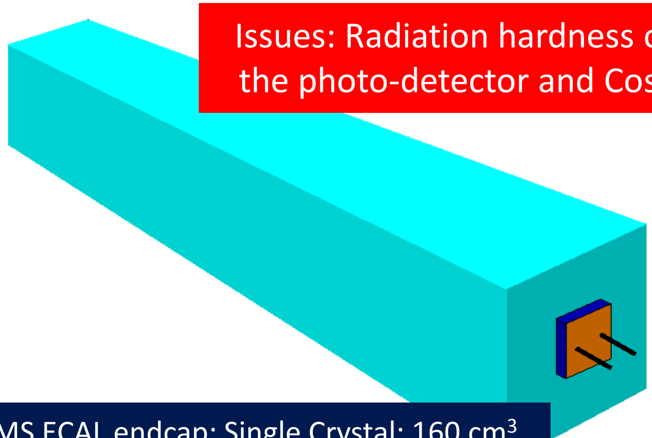
CMS Forward Calorimeter Upgrade

Talk in CMS FCAL Taskforce Meeting at CERN, 6/30/2011



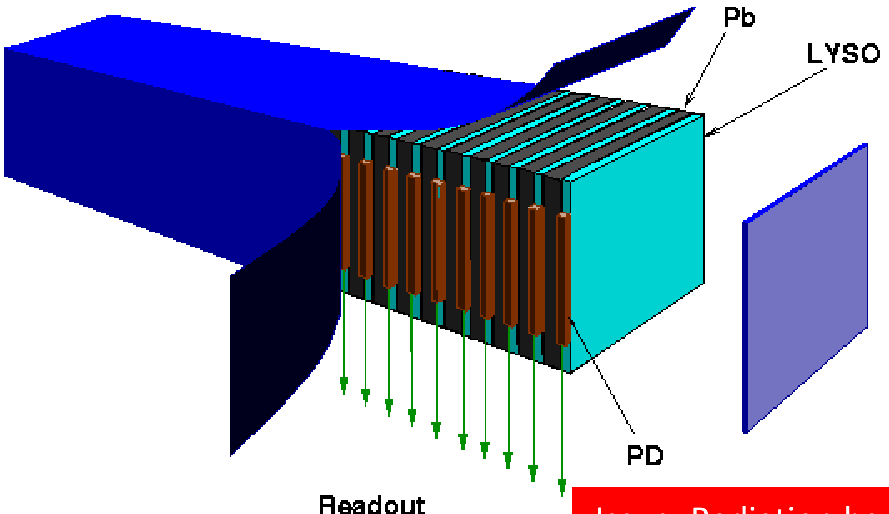


Issues: Radiation hardness of photo-detector and WLS fiber



Issues: Radiation hardness of the photo-detector and Cost

CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 3 m^3
Expected Crystal Cost: ~\$90M@\$30/cc



Crystal Cost: ~\$18M@\$30/cc

Issue: Radiation hardness of the photo-detector

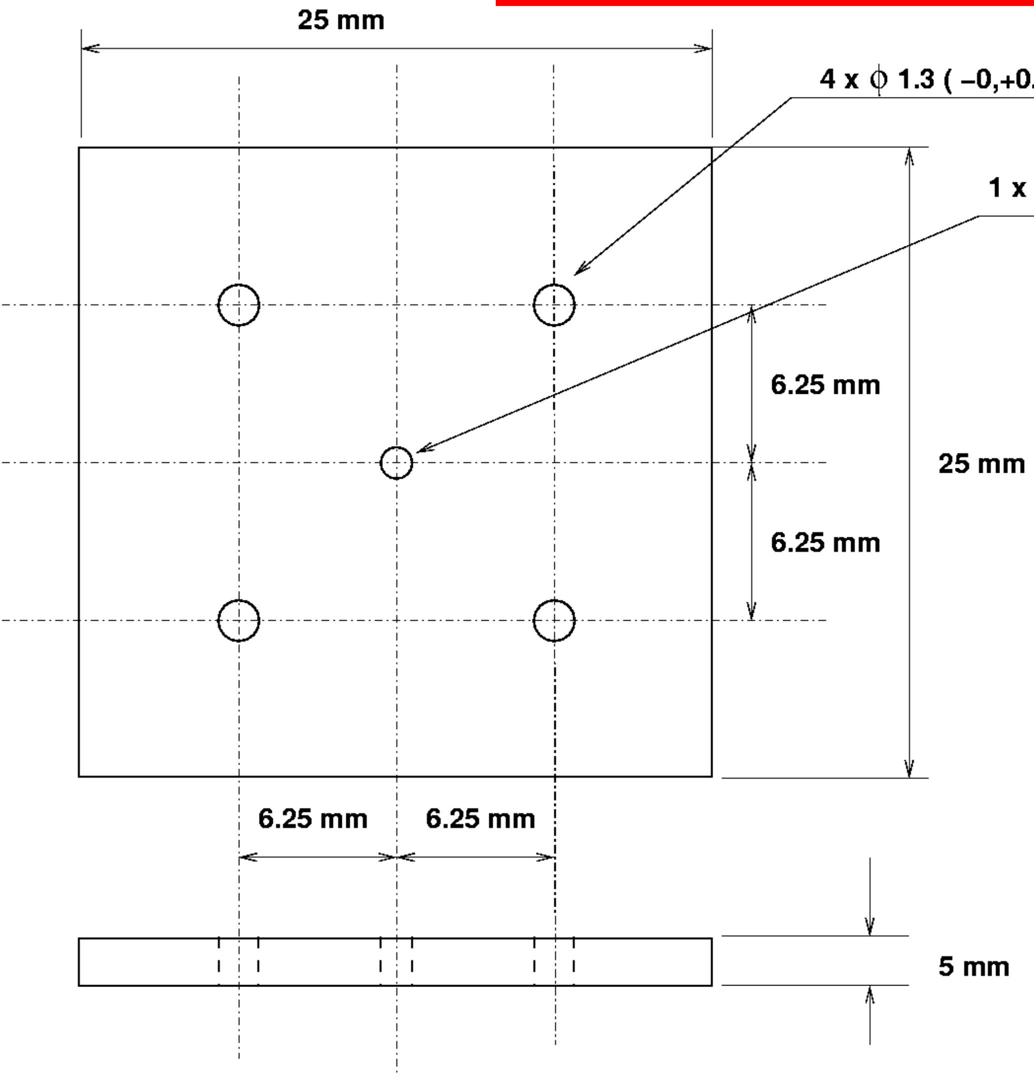
LYSO Based Shashlik Cell Design

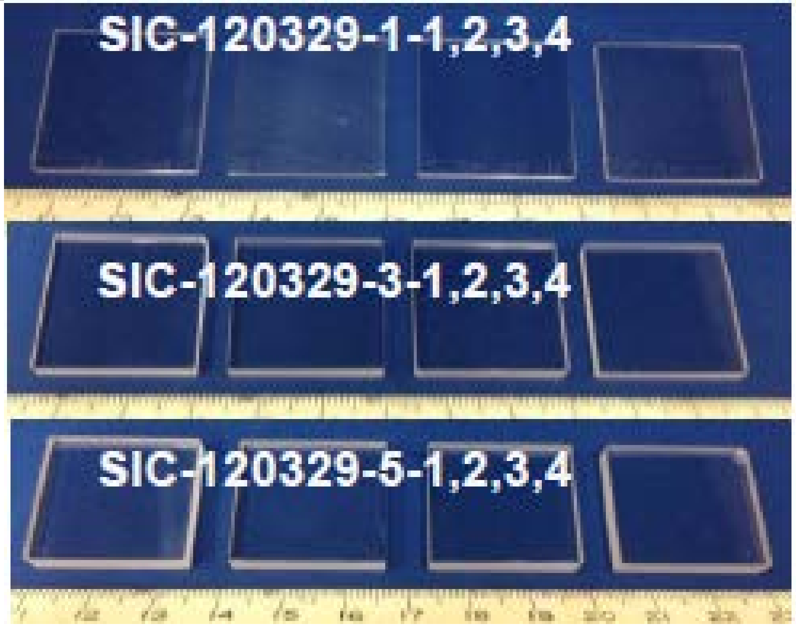
		LHCb	Plan-1	Plan-2
Absorber		Lead (Pb)	Lead (Pb)	Tungsten (W)
	Density (g/cm3)	11.4	11.4	19.3
	Radiation Length (cm)	0.56	0.56	0.35
	Moliere Radius (cm)	1.60	1.60	0.93
	dE/dX (MeV/cm)	12.74	12.74	22.1
	Thickness (mm)	2	4	2.5
	Plates number	66	28	28
Scintillator		BASF-165 Polystyrene (Sc)	LYSO	LYSO
	Density (g/cm3)	1.06	7.4	7.4
	Light Yield (photons/MeV)	5200	30000	30000
	Radiation length (cm)	41.31	1.14	1.14
	Moliere Radius (cm)	9.59	2.07	2.07
	dE/dX (MeV/cm)	2.05	9.55	9.55
	Plate Thickness(mm)	4	**2**	**2**
	Plates number	67	29	29
WLS Fiber		Kurarray Y-11(250)	Kurarray Y-11(250)	Kurarray Y-11(250)
	Diameter (mm)	1.2	1.2	1.2
	Number /Cell	16	4	4
Cell Properties	Total Depth (X0)	24.22	25.09	25.09
	Sampling Fraction (MIPs)	0.25	0.28	0.26
	Total Physical Length (cm)	40	**17**	**12.8**
	Total Sc Length (cm)	26.8	**5.8**	**5.8**
	Absorber Weight Ratio	0.84	0.75	0.76
	Scintillator Weight Ratio	0.16	0.25	0.24
	Average Density (g/cm3)	4.47	10.04	13.91
	Average Radiation Length (cm)	1.65	0.68	0.51
	Average Moliere Radius (cm)	3.6	**1.7**	**1.2**
	Transverse Dimension (cm)	4.1	**1.9**	**1.4**
	Sc-depth/Total-depth in X0	0.0268	**0.2028**	**0.2028**
	WLS Fiber Density (N/cm2)	0.97	**1.06**	**2.07**
MIPs Energy Deposition	Sc plates (MeV)	54.94	55.39	55.39
Light Yield using MIPs	Photon Electrons/GeV	3077	17897	17897
Signal of MIPs	Photon Electrons / MIP	169	**991**	**991**
Module Properties	Energy Resolution (a, %)	8.2	9.0*	9.0*

* Based on the simulation of Zhigang Wang, IHEP, Beijing.

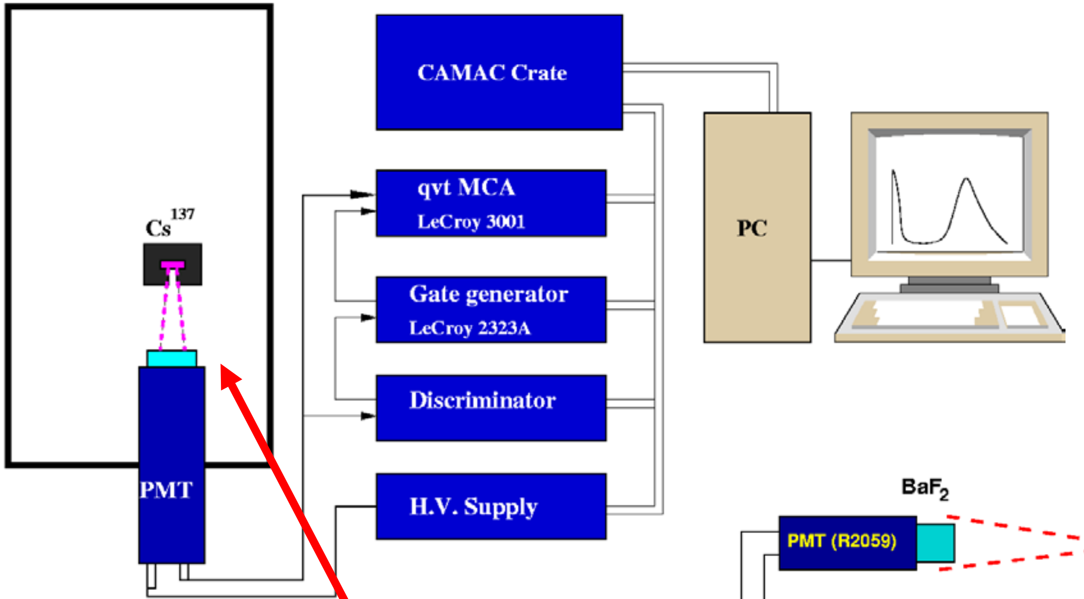
Three LYSO Plates with Holes

25 × 25 × 5, 3 and 1.5 mm^3

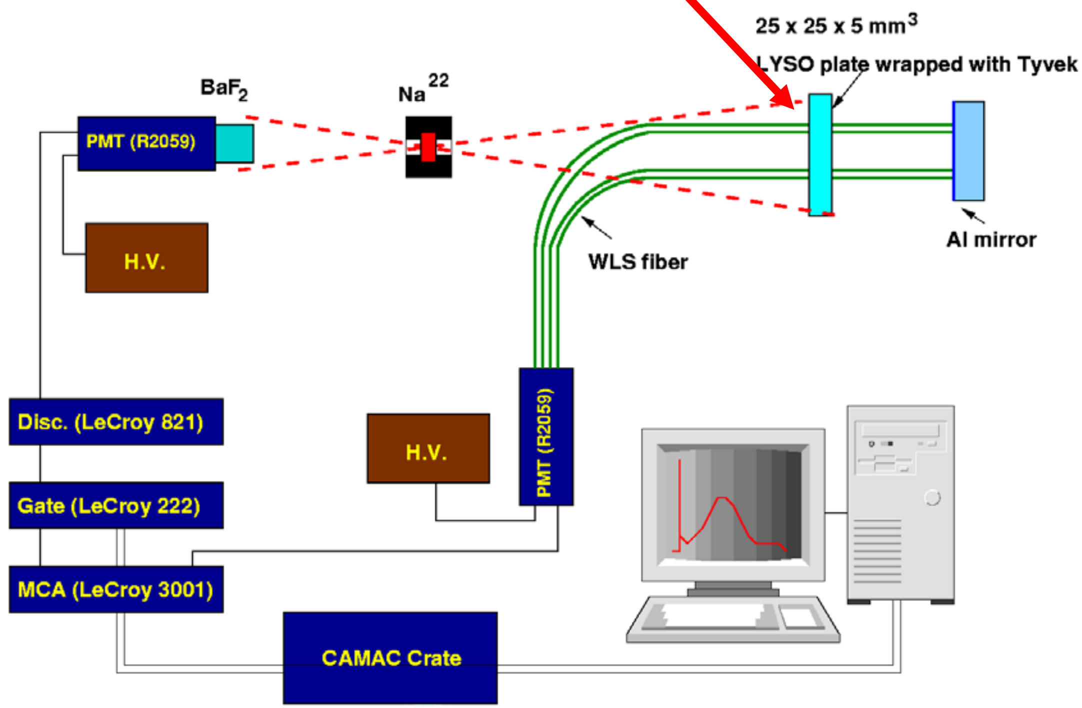




Two Measurement Setups



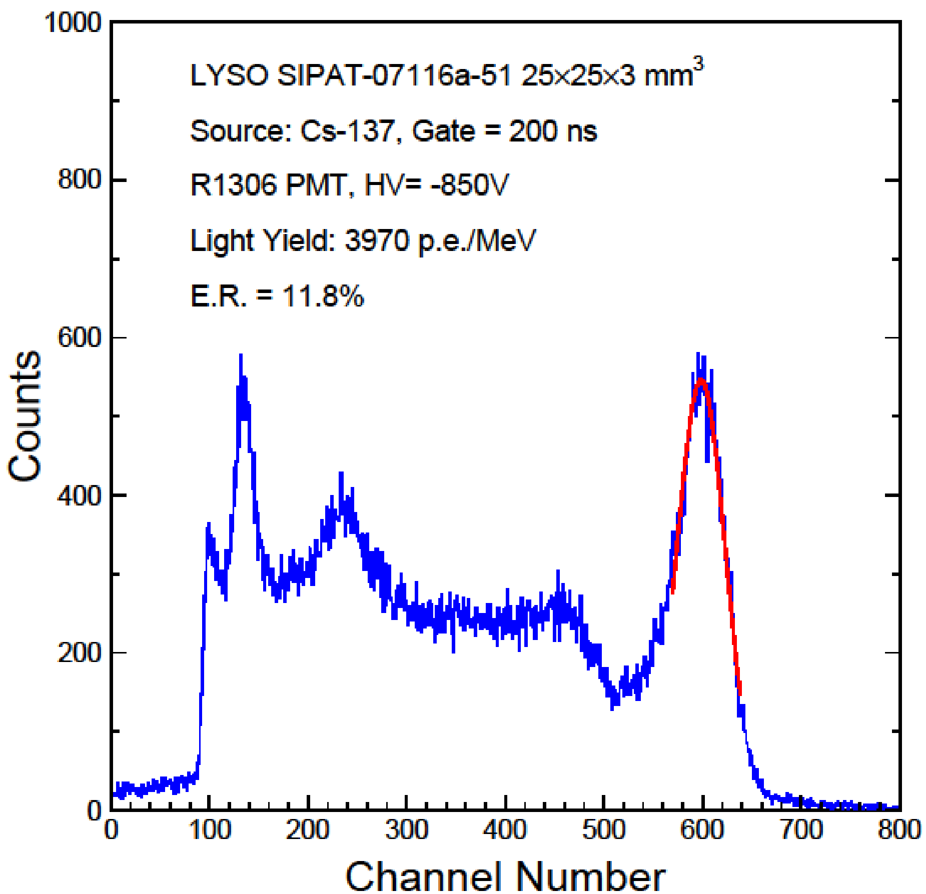
2) LYSO plates with Tyvek wrapping are readout with four Y11 WLS fibers of 40 cm long and a R2059 PMT using a Na-22 γ-ray source and coincidence.



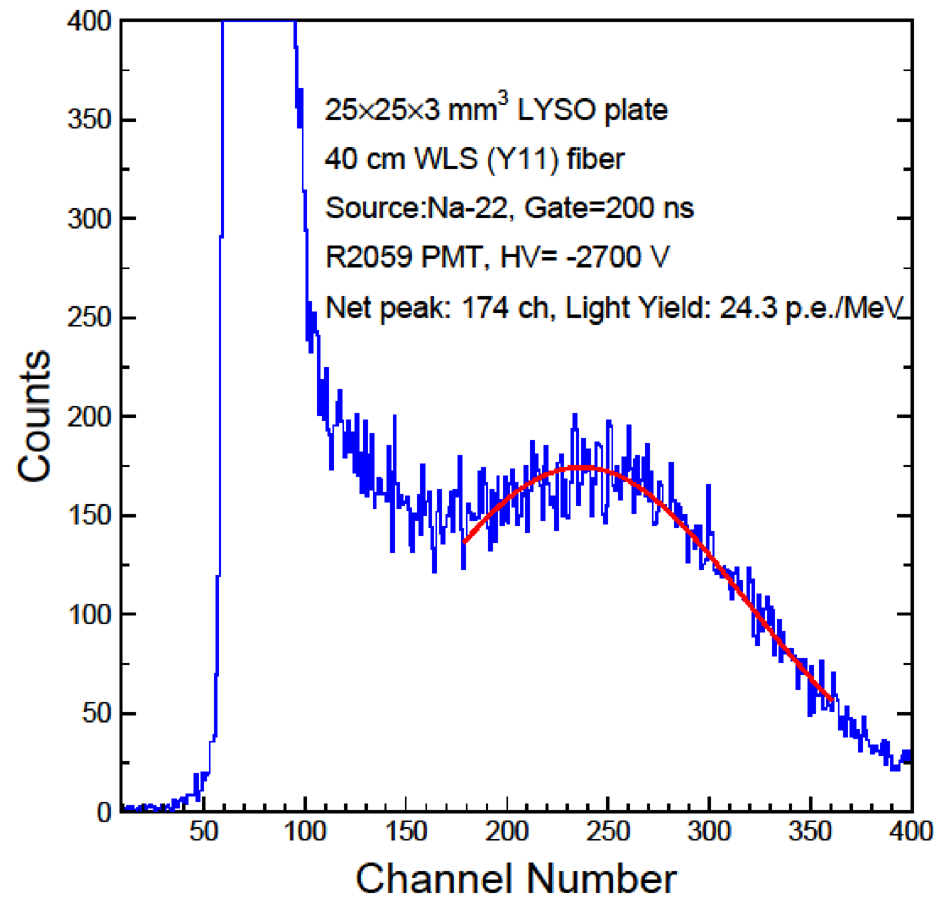
1) LYSO plates with Tyvek wrapping are readout directly by a R1306 PMT using a Cs-137 γ-ray source.

PHS of 3 mm LYSO Plate

LYSO 25 × 25 × 3 mm^3

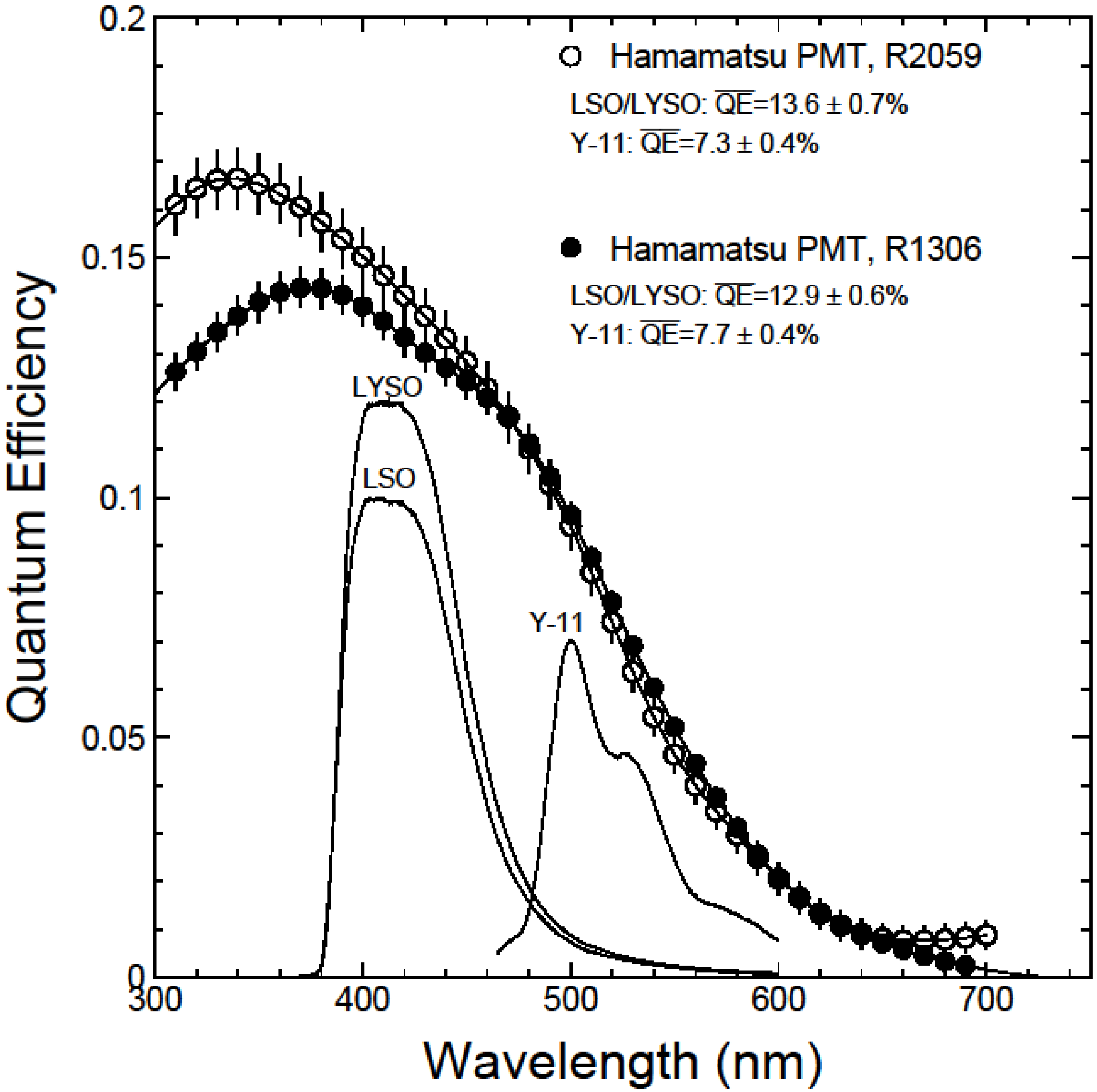


3 mm plate & 4 x 40 cm Y11 fiber



γ-ray peaks are clearly visible

PMT Quantum Efficiency



Light Output (LO) measured in p.e./MeV are converted to Light Yield (LY) in photons/MeV by taking out the QE of the PMT

LY = LO / QE

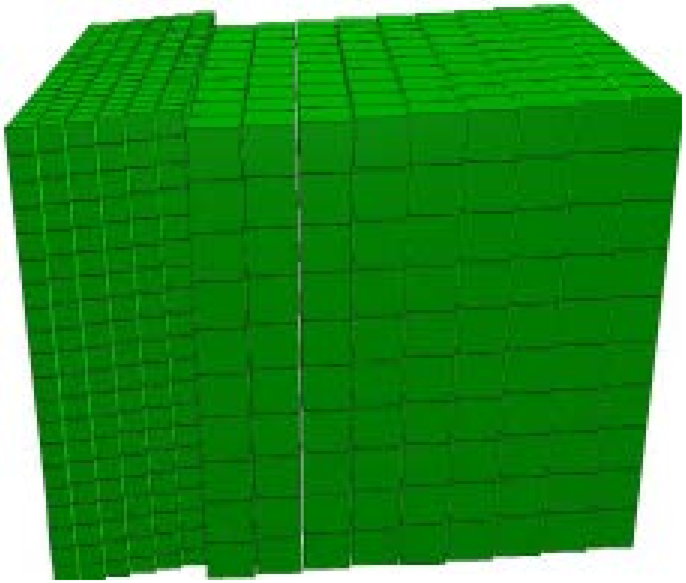
Light Collection Efficiencies

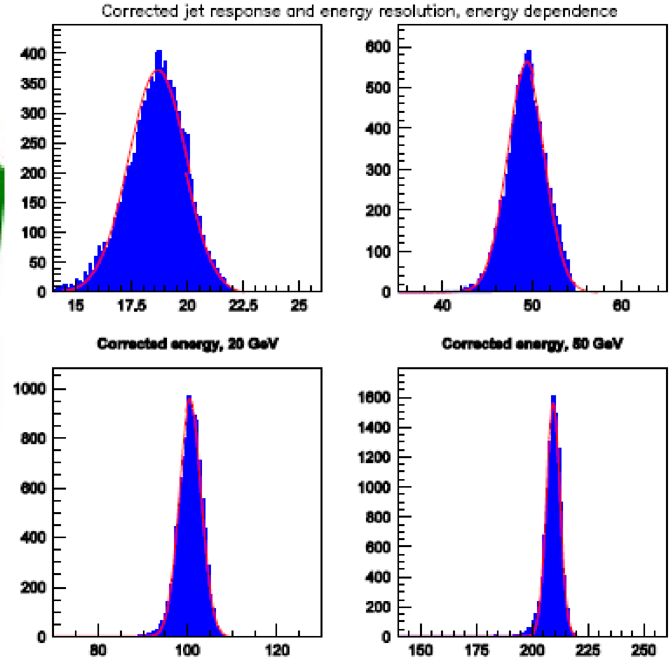
Samples	5 mm LYSO	3 mm LYSO	1.5 mm LYSO	LHCb cell*
LO_1(p.e. /MeV)	3760	3970	4370	
LY_1 (Photons /MeV)	29,150	30,780	33,880	5,200
LO_2 (p.e./MeV)	20.7	24.3	17.9	3.1
LY_2 (Photons /MeV)	479	563	414	
MIP (p.e./55 MeV)	1,140	1,340	990	169
LO_2/LO_1 (%)	0.55	0.61	0.41	
LO_2/LY_1 (%)	0.07	0.08	0.05	0.06
LY_2/LY_1 (%)	1.64	1.83	1.22	

* 2009 J. Phys.: Conf. Ser. 160 012047.

Measured light collection efficiencies consist with the LHCb data

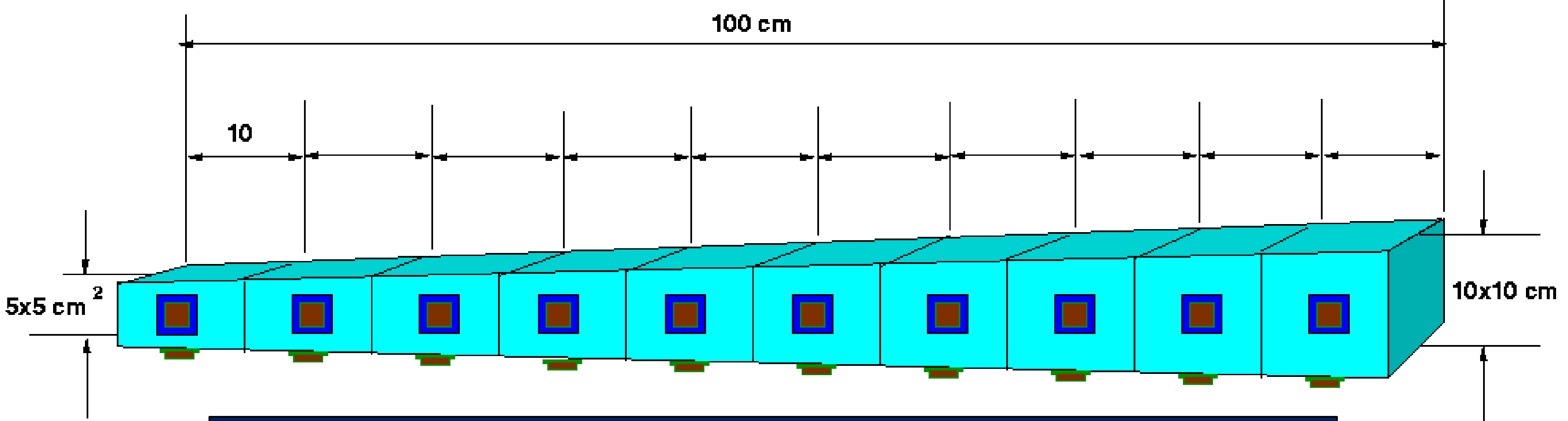
The HHCAL Detector Concept





A. Para, H. Wenzel, and S. McGill, Callor2012: GEANT simulations show a jet energy resolution at a level of 20%/√E after corrections.

Cost !

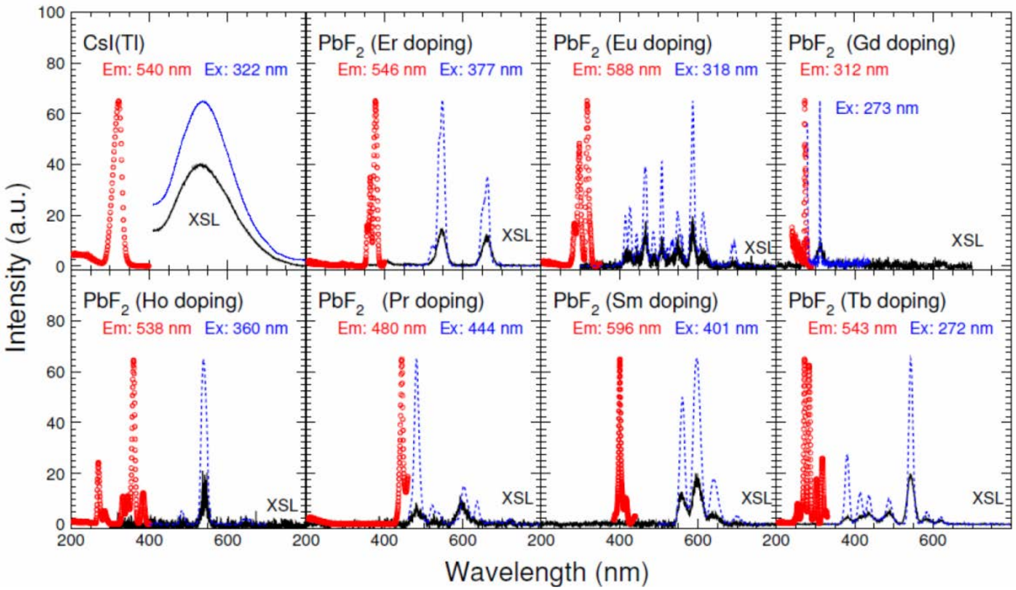


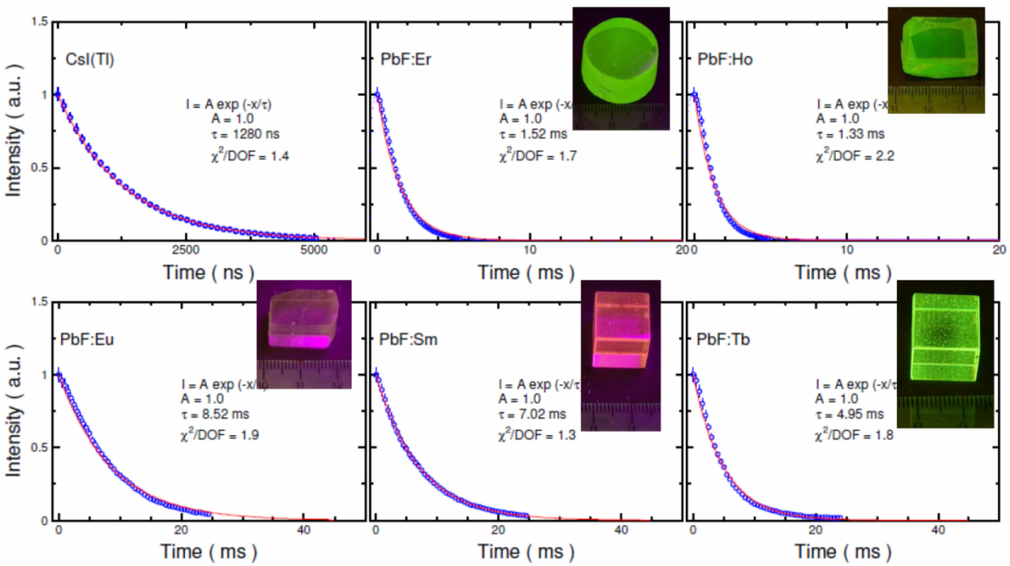
R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

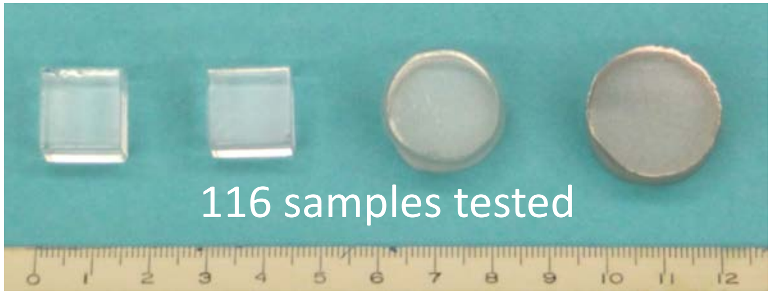
Candidate Crystals for HHCAL

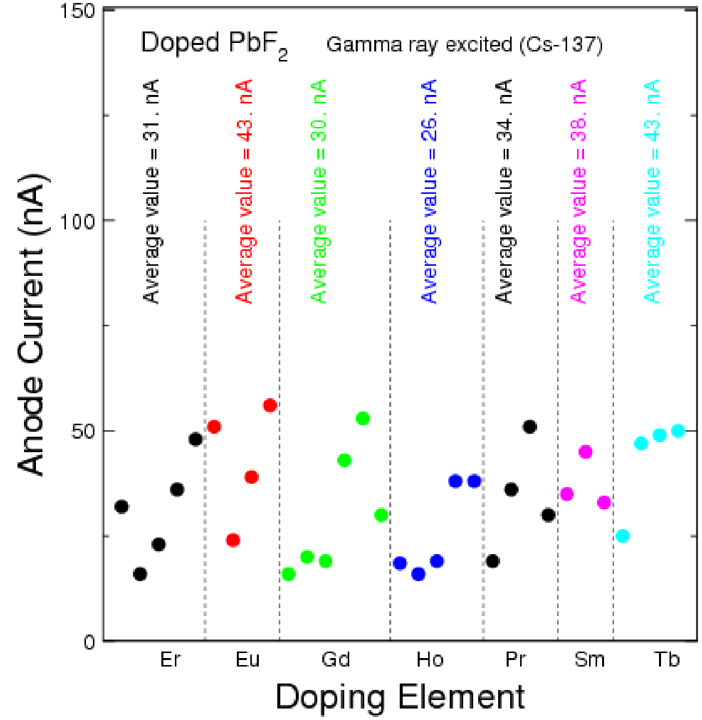
Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbClF	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm^3)	7.13	**8.29**	**7.77**	7.11	6.8
λ_I (cm)	22.8	**20.7**	**21.0**	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	**?**	3	100
λ_{max} (nm)	480	425/420	**?**	400	470
Cut-off λ (nm)	**310**	350	**250**	**280**	**300**
Light Output (%)	100	1.4/0.37	**?**	2	20
Melting point (°C)	**1050**	**1123**	**842**	**608**	**1030**
Raw Material Cost (%)	100	49	**29**	**29**	47

Search for Scintillation in Doped PbF_2



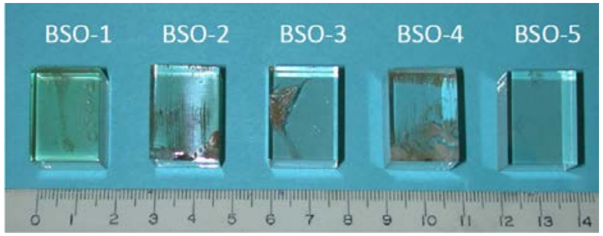


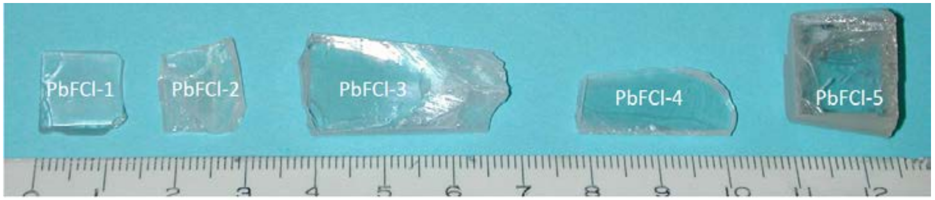




Will look performance at low temperature with the FLS920 fluorescence lifetime spectrometer

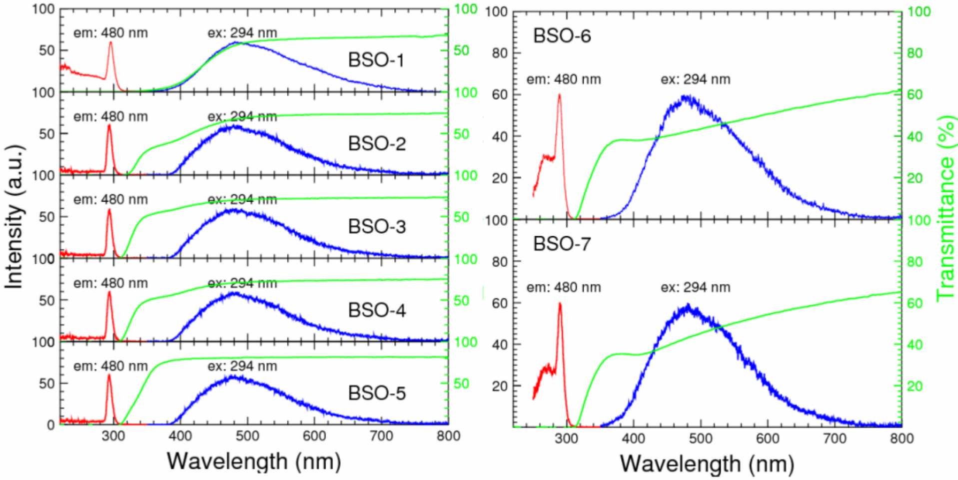
Other Materials: PbFCl & BSO

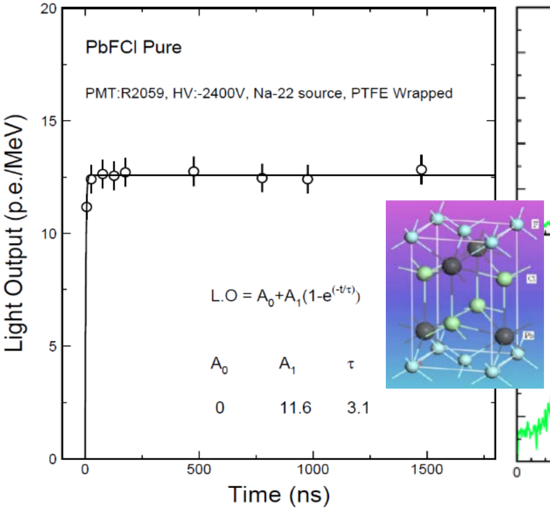


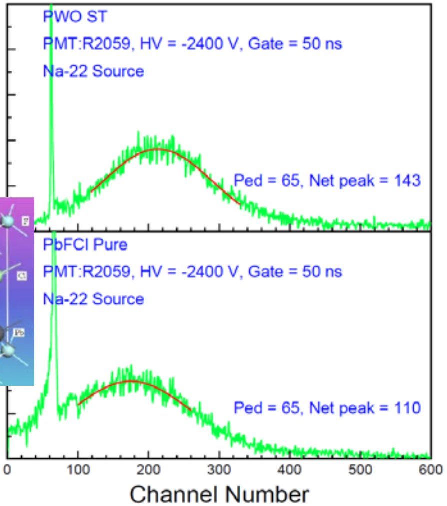


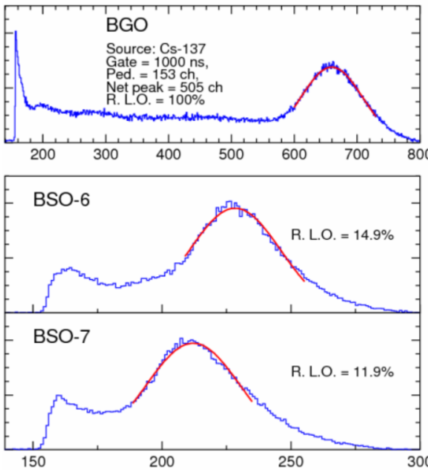
ID	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
Doping	--	Na 0.5at%	--	--	
Dimension (mm)	10x10x2	10x10x2	30x10x5	20x10x3	~10x10x9

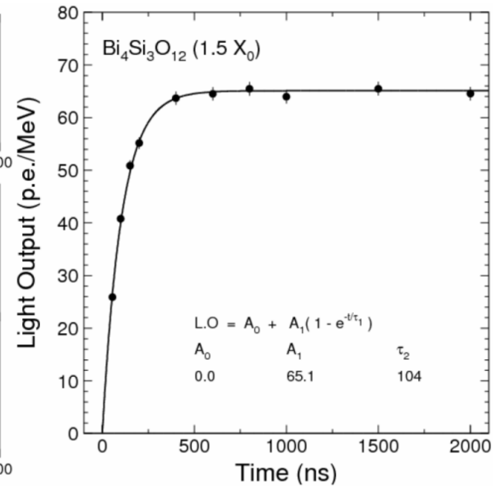
ID	PWO	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
X-luminescence		Peaked @ 420 nm				
L.O. (% PWO)	100	14	64	33	35	31
L.O. (% BGO)	1.8	0.25	1.1	0.59	0.63	0.56











Future Calorimeter at the IF

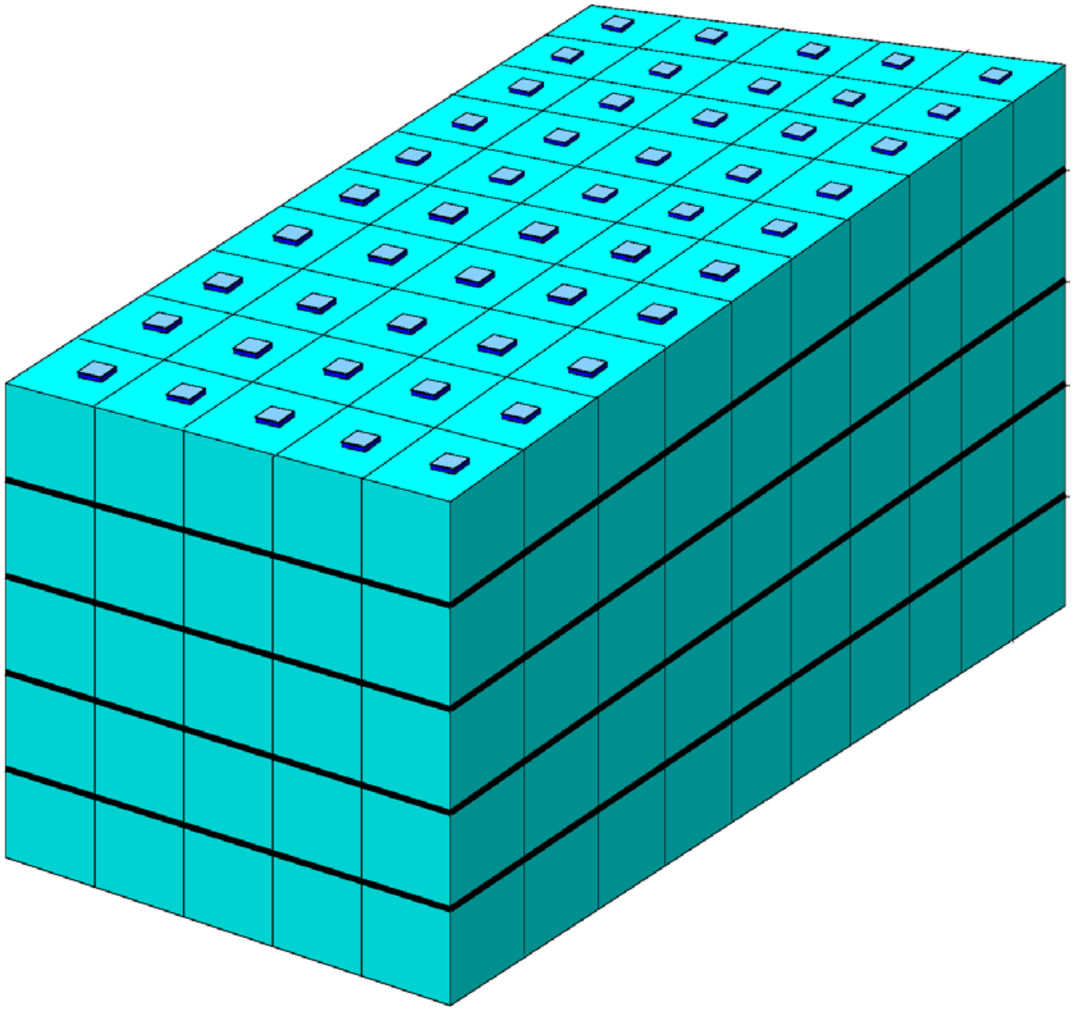
Excellent energy resolution: a total absorption crystal calorimeter.

Good photon pointing for π^0 reconstruction: a longitudinally segmented crystal calorimeter.

A fast calorimeter with ten times rate capability as compared to existing calorimeters: crystals with sub nanosecond scintillation decay time. The figure of merit is the light in the 1^{st} ns.

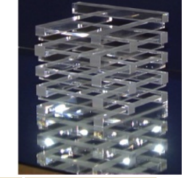
A Long. Segmented Crystal ECAL

With compact readout devices embedded in the detector



May provide needed resolutions for energy, position and photon angle

Fast Scintillator: BaF_2 (ZnO:Ga, PbFCl, YAP:Yb, CuI)



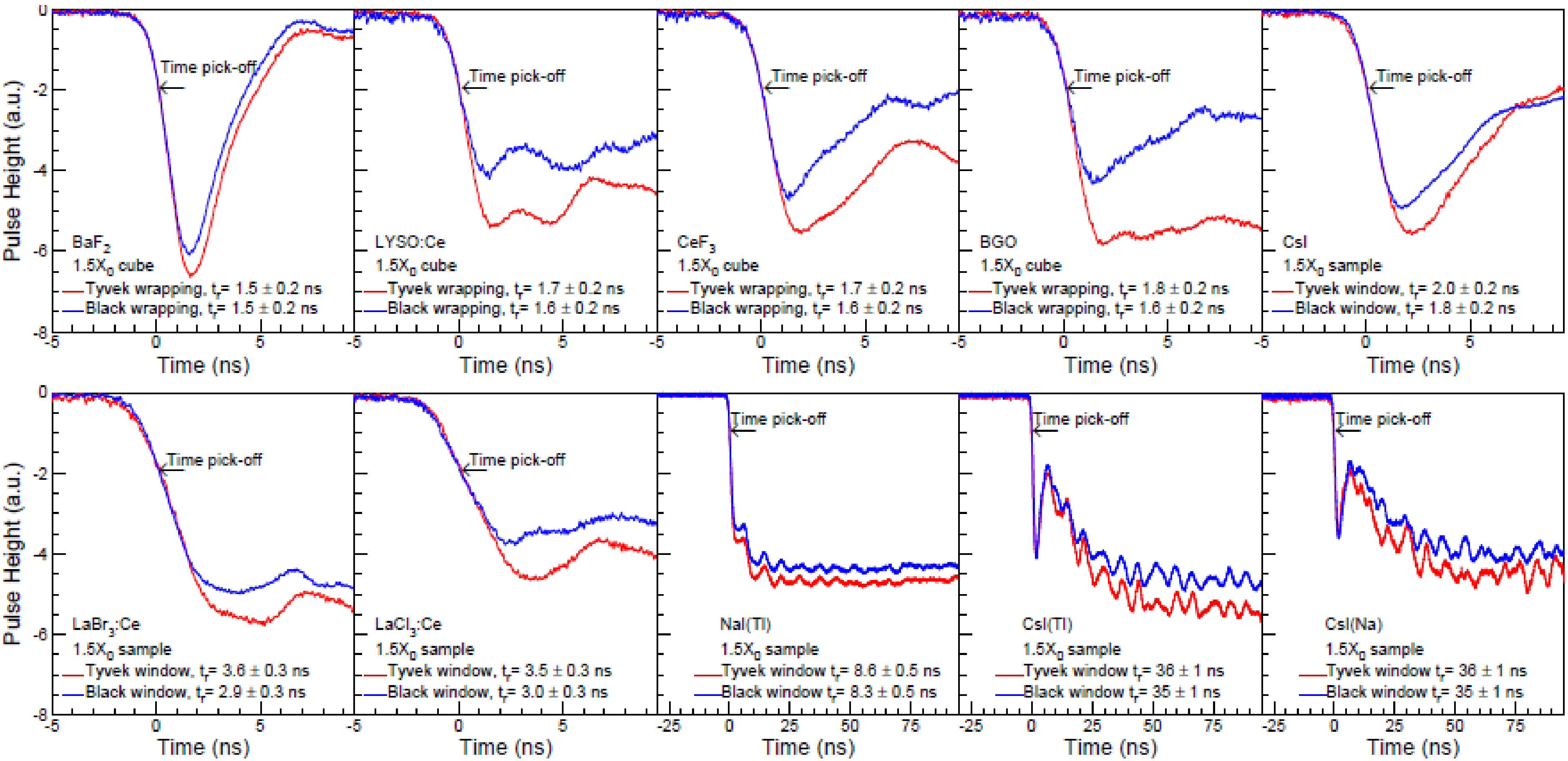
	LYSO:Ce	CsI	BaF_2	CeF_3	$CeBr_3$ [1]	$LaBr_3$:Ce	ZnO:Ga [2]	PbFCl	$Y_{0.55}Yb_{0.45}AlO_3$ [3]	CuI [4]
Density (g/cm^3)	7.40	4.51	4.89	6.16	5.23	5.29	5.67	7.11	6.59	5.61
Melting point (℃)	2050	621	1280	1460	722	783	1975	608	1870	602
Radiation Length (cm)	1.14	1.86	2.03	1.70	1.96	1.88	2.51	1.05	1.67	1.71
Z_{eff}	64.8	54.0	51.6	50.8	45.6	45.6	27.7	75.8	52.6	47.1
dE/dX (MeV/cm)	9.55	5.56	6.52	8.42	6.65	6.90	8.42	8.68	9.27	7.35
Emission Peak[a] (nm)	420	420 310	300 220	340 300	371	356	389	400	350	410
Refractive Index[b]	1.82	1.95	1.50	1.62	1.9	1.9	2.1	2.1	1.96	2.1
Relative Light Yield[a,c]	100	4.2 1.3	42 4.8	8.6	141	153	?	0.5	0.6 ? 2.2 ?	?
LY in 1^{st} ns (photons)	740	100	960	85	2420	2240	?	51	497 ?	?
Decay Time[a] (ns)	40	30 6	650 0.9	30	17	20	<1	3	2.2 <1	<1
d(LY)/dT [a] (%/°C)	-0.2	-1.4	-1.9 0.1	~0	-0.1	0.2	?	?	?	?
40 keV Att. λ (mm)	0.185	0.097	0.106	0.428	0.277	0.131	0.407	0.122	0.245	0.108
40 keV δ 90% (mm)	0.425	0.222	0.244	0.987	0.637	0.301	0.938	0.281	0.564	0.248
40 keV δ 95% (mm)	0.553	0.289	0.317	1.284	0.829	0.392	1.220	0.365	0.734	0.323
40 keV δ 99% (mm)	0.850	0.444	0.488	1.973	1.274	0.602	1.876	0.561	1.128	0.497

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

1) W. Drozdowski et al, ***IEEE TRANS. NUCL. SCI***, VOL.55, (2008) 1391-1396; and Chenliang Li et al, ***Solid State Commun***, Volume 144, Issues 5–6 (2007),220–224.
2) http://scintillator.lbl.gov/; P.J. Simpson et al, NIM A505 (2003) 82-84; and E.D. Bourret-Courchesne et al, NIM A601 (2009) 358-363.
3) M. Nikl et al, Appl. Phys. Lett. 84, 882 (2004).
4) Zu-xu Cai et al, The fluorescence decay time and slow component suppression in CuI single crystal, Talk in SCINT2013, Shanghai.

Rising Time for 1.5 X_0 Samples

Talk in the time resolution workshop at U. Chicago, 4/28/2011: Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns



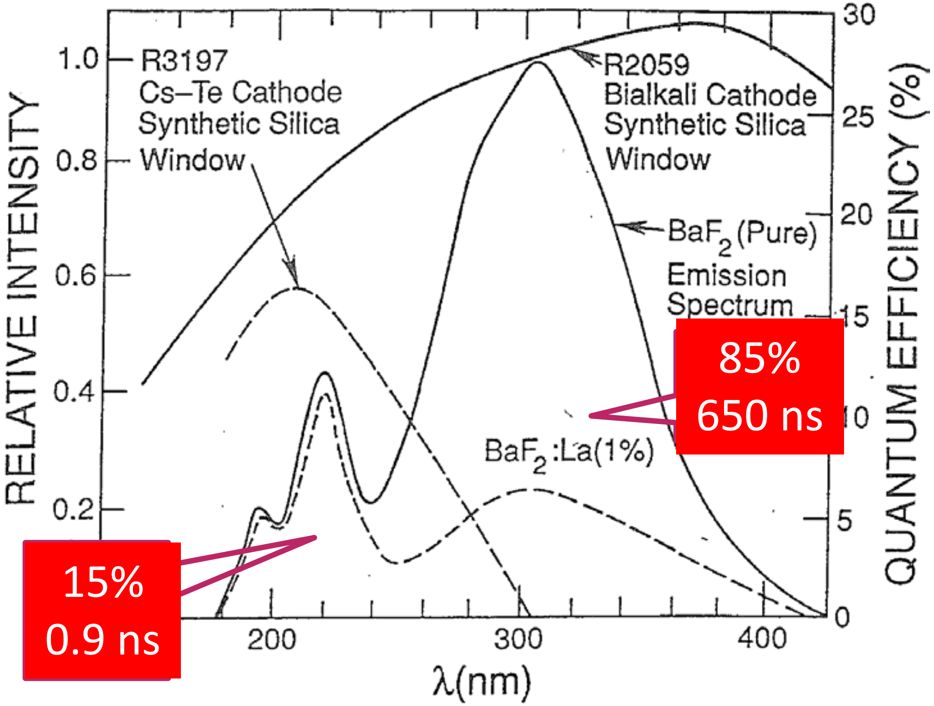
Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.

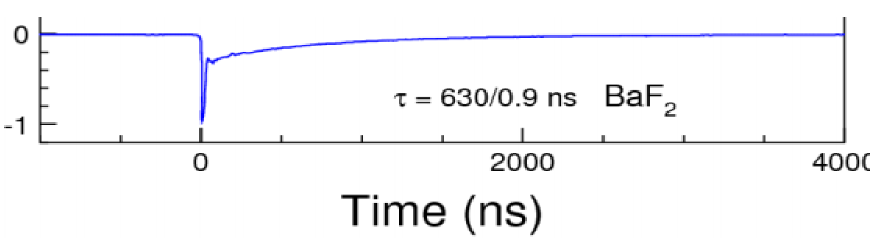
BaF_2 for Very Fast Calorimeter

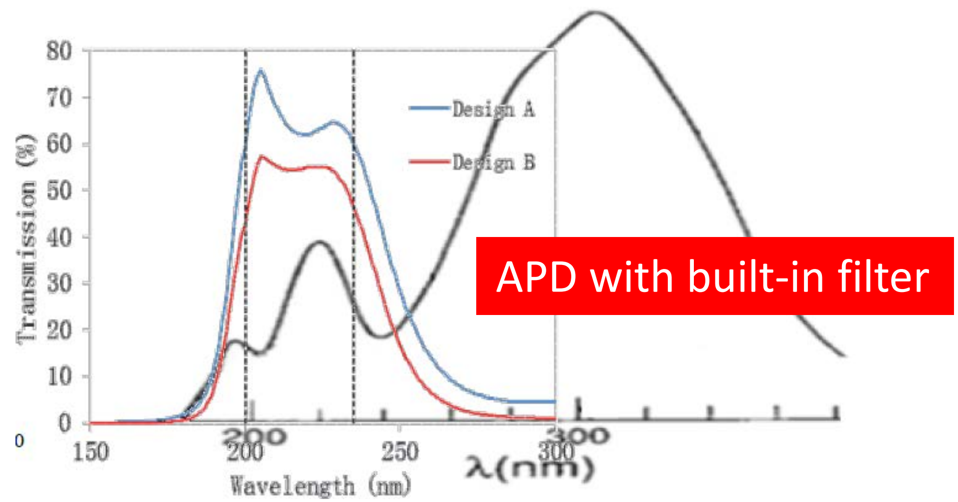
The fast component of BaF_2 crystals at 220 nm has a sub-ns decay time.

The slow component at 300 nm may be reduced by selective doping, such as La.

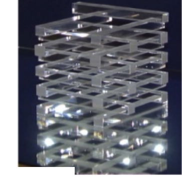
Spectroscopic selection of fast component may be achieved with solar blind photo-detectors or filters.

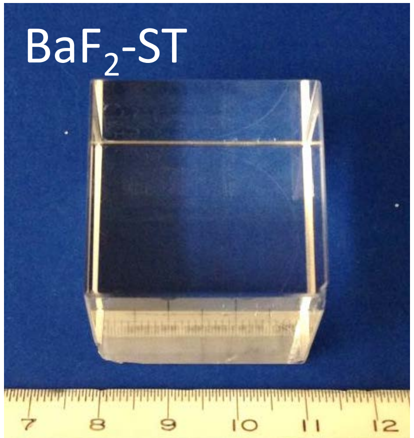




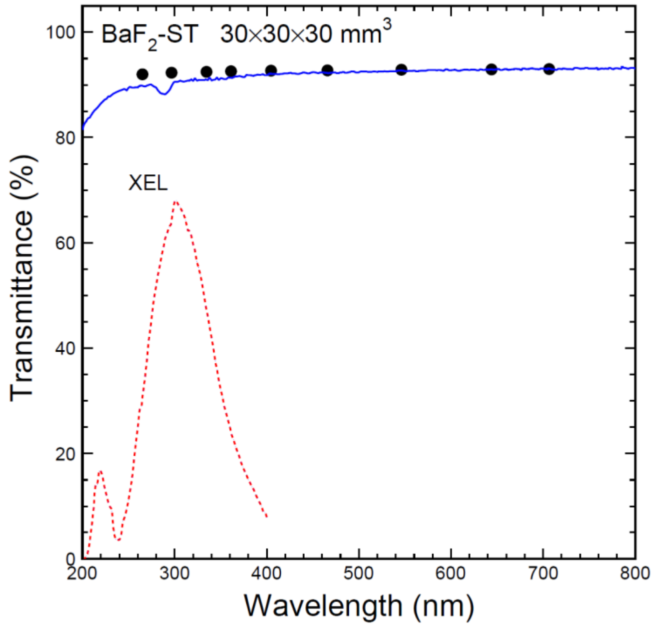


BaF_2

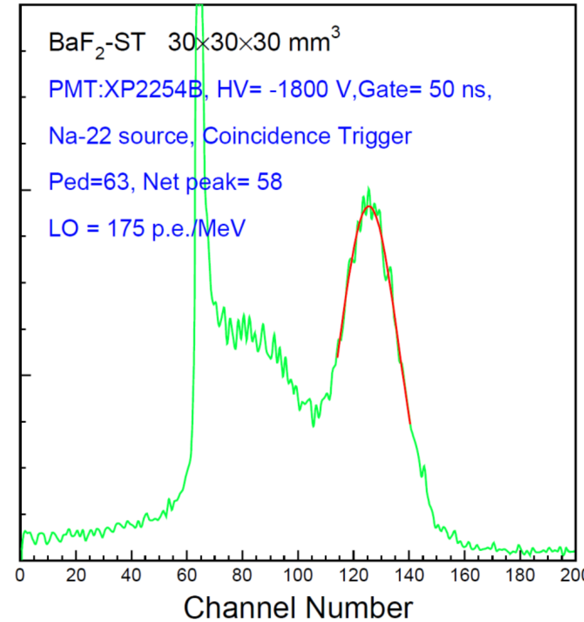




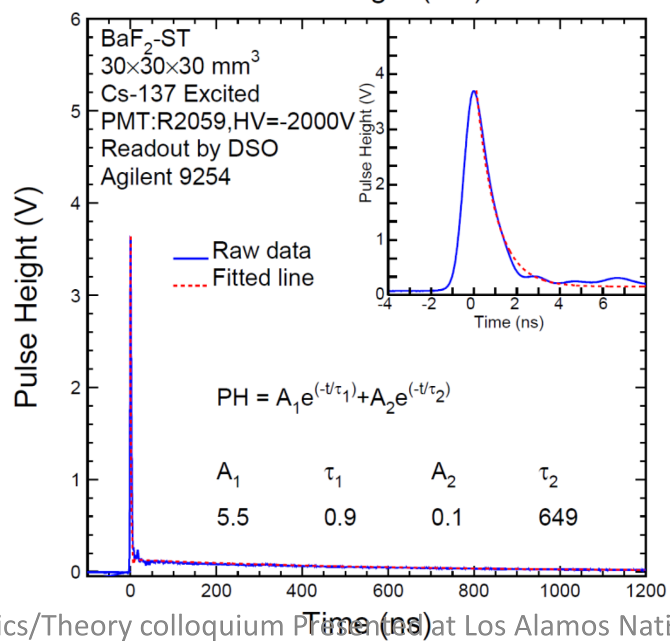
BaF2-ST
7
8
9
10
11
12



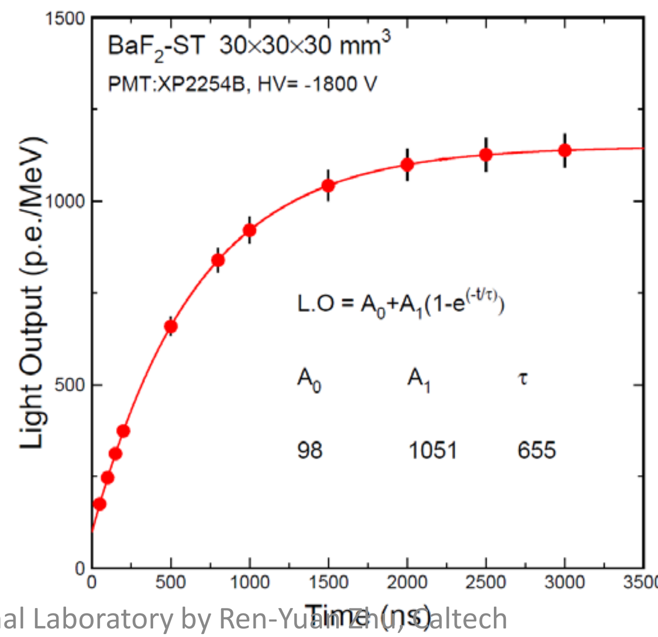
BaF2-ST 30×30×30 mm3
XEL
Transmittance (%)
Wavelength (nm)
0
20
40
60
80
100
200
300
400
500
600
700
800



BaF2-ST 30×30×30 mm3
PMT:XP2254B, HV= -1800 V,Gate= 50 ns,
Na-22 source, Coincidence Trigger
Ped=63, Net peak= 58
LO = 175 p.e./MeV
Channel Number
0
20
40
60
80
100
120
140
160
180
200



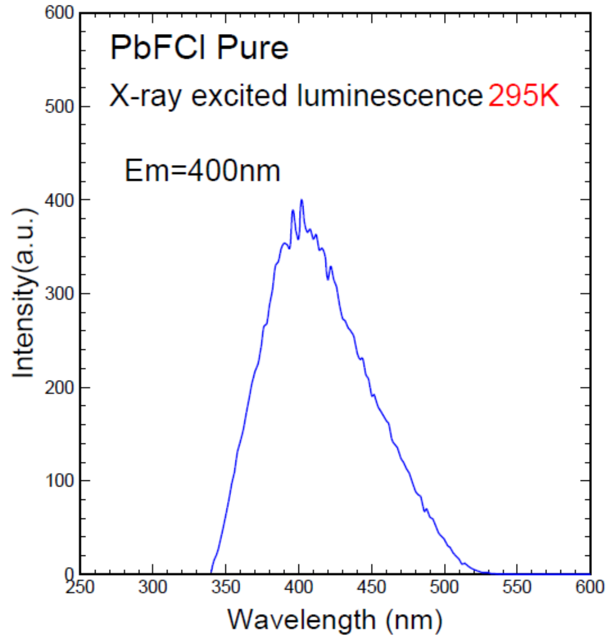
BaF2-ST
30×30×30 mm3
Cs-137 Excited
PMT:R2059,HV=-2000V
Readout by DSO
Agilent 9254
Raw data
Fitted line
PH = A1e(-t/τ1)+A2e(-t/τ2)
A1
τ1
A2
τ2
5.5
0.9
0.1
649
Pulse Height (V)
Time (ns)
Pulse Height (V)
Time (ns)
0
1
2
3
4
5
6
0
200
400
600
800
1000
1200
-4
-2
0
2
4
6

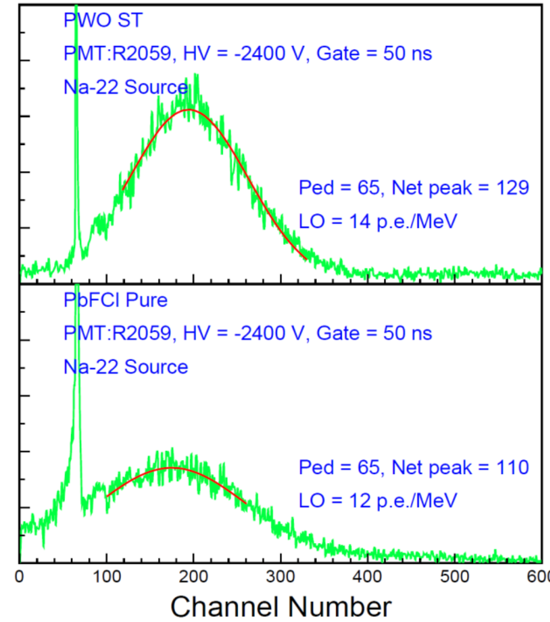


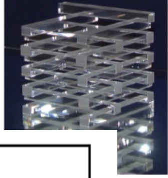
BaF2-ST 30×30×30 mm3
PMT:XP2254B, HV= -1800 V
L.O = A0+A1(1-e(-t/τ))
A0
A1
τ
98
1051
655
Light Output (p.e./MeV)
Time (ns)
0
500
1000
1500
0
500
1000
1500
2000
2500
3000
3500

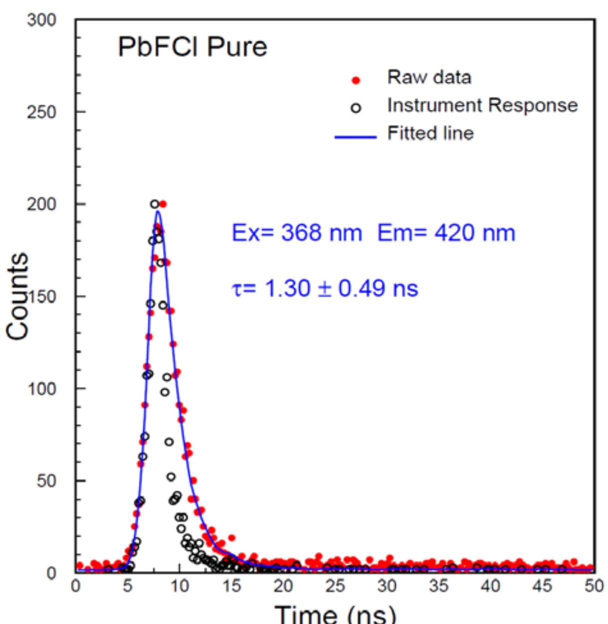
PbFCl

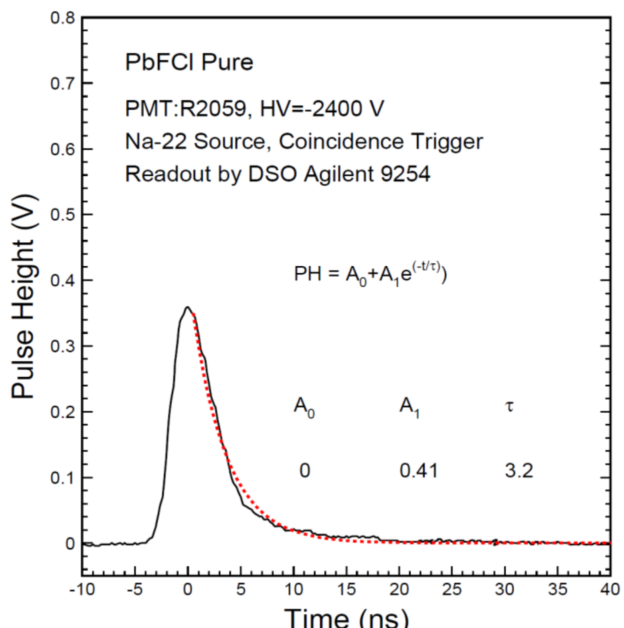

PbFCl Pure
7
8
9
10

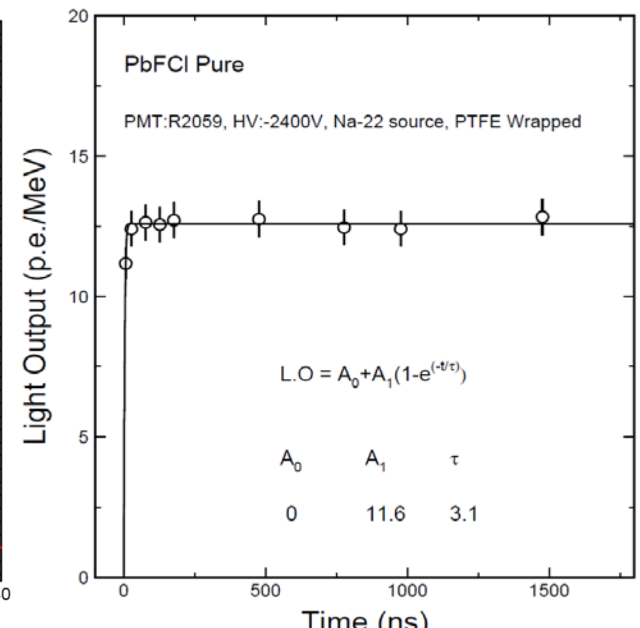

PbFCl Pure
X-ray excited luminescence 295K
Em=400nm
Intensity(a.u.)
Wavelength (nm)
0
100
200
300
400
500
600
250
300
350
400
450
500
550
600


PWO ST
PMT:R2059, HV = -2400 V, Gate = 50 ns
Na-22 Source
Ped = 65, Net peak = 129
LO = 14 p.e./MeV
PbFCl Pure
PMT:R2059, HV = -2400 V, Gate = 50 ns
Na-22 Source
Ped = 65, Net peak = 110
LO = 12 p.e./MeV
0
100
200
300
400
500
600
Channel Number




PbFCl Pure
Raw data
Instrument Response
Fitted line
Ex= 368 nm Em= 420 nm
τ= 1.30 ± 0.49 ns
Counts
Time (ns)
0
50
100
150
200
250
300
0
5
10
15
20
25
30
35
40
45
50


PbFCl Pure
PMT:R2059, HV=-2400 V
Na-22 Source, Coincidence Trigger
Readout by DSO Agilent 9254
PH = A0+A1e(-t/τ)
A0
A1
τ
0
0.41
3.2
Pulse Height (V)
Time (ns)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
-10
-5
0
5
10
15
20
25
30
35
40


PbFCl Pure
PMT:R2059, HV:-2400V, Na-22 source, PTFE Wrapped
L.O = A0+A1(1-e(-t/τ))
A0
A1
τ
0
11.6
3.1
Light Output (p.e./MeV)
Time (ns)
0
5
10
15
20
0
500
1000
1500

$YAlO_3$:Yb

Fast (0.87/2.2 ns) scintillation found in YAP:Yb with low light output

M. Nikl et al, Appl. Phys. Lett., Vol. 84, No. 6,

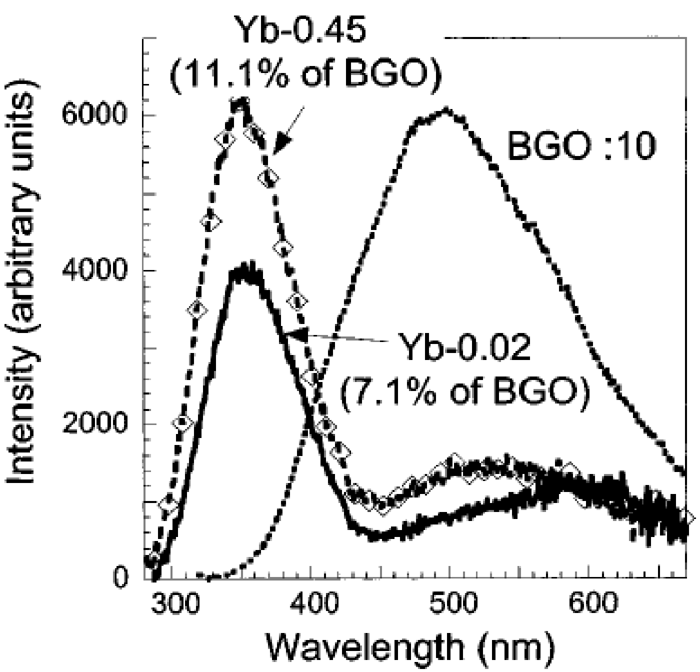


FIG. 1. Radioluminescence of Yb:YAP and BGO at RT. Excitation by x-ray tube, 35 kV, 15 mA. Quantitative comparison with respect to BGO is provided by the calculation of spectra integrals.

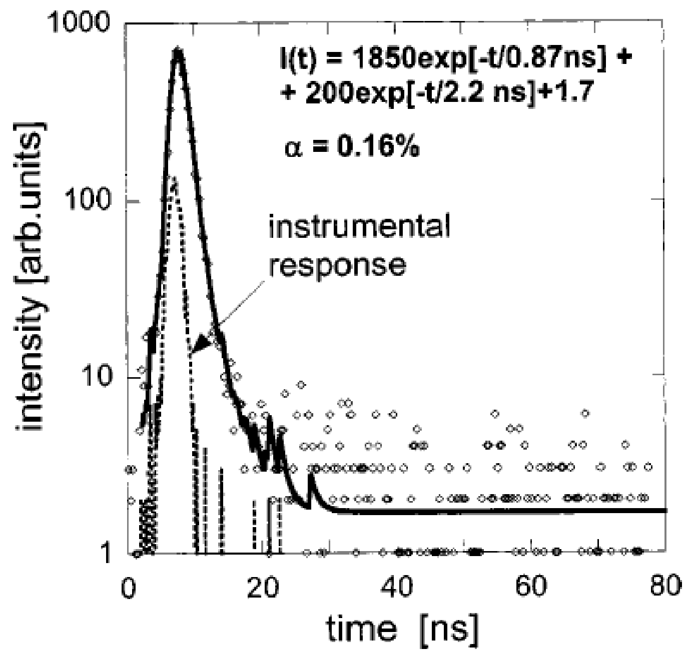
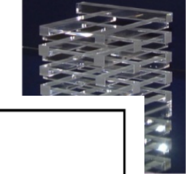
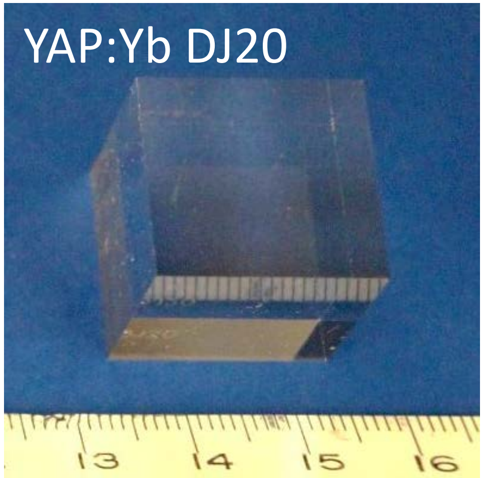
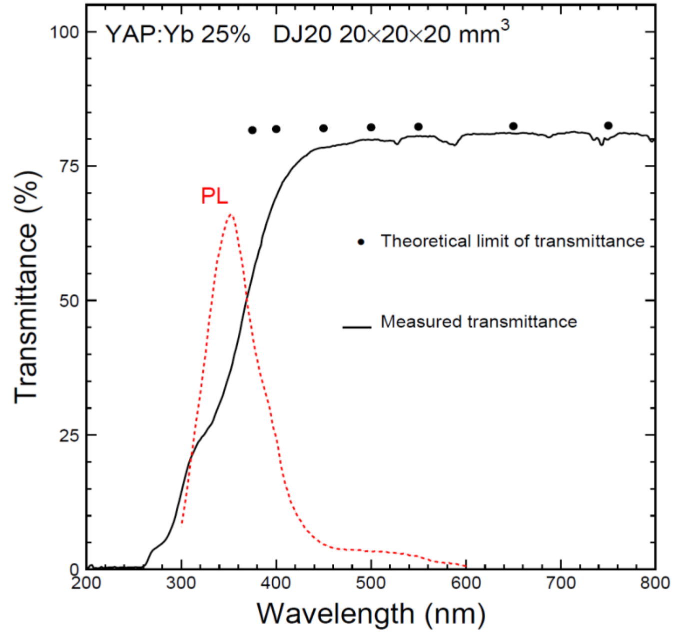


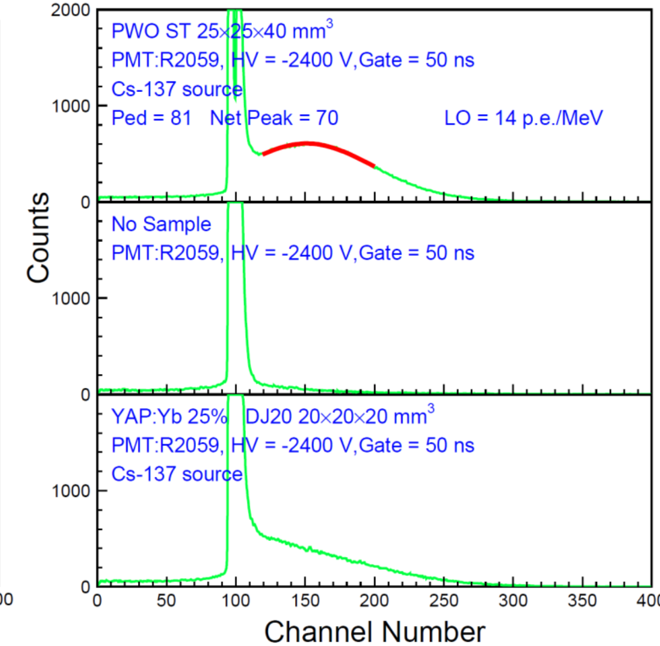
FIG. 3. Scintillation decay of Yb-0.45 at room temperature. Excitation by 511 keV photons of ^{22}Na radioisotope, spectrally unresolved. The two-exponential approximation is given by a solid line: convolution of the two-exponential function in the figure with the instrumental response given by a dashed line. The coefficient alpha related to the relative amplitude of the superslow components calculated according Ref. 12 is also given.

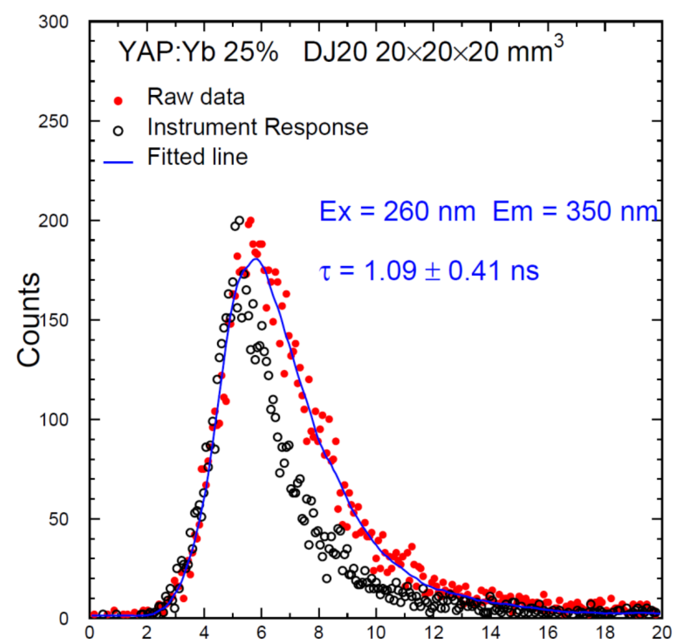
YAP:Yb

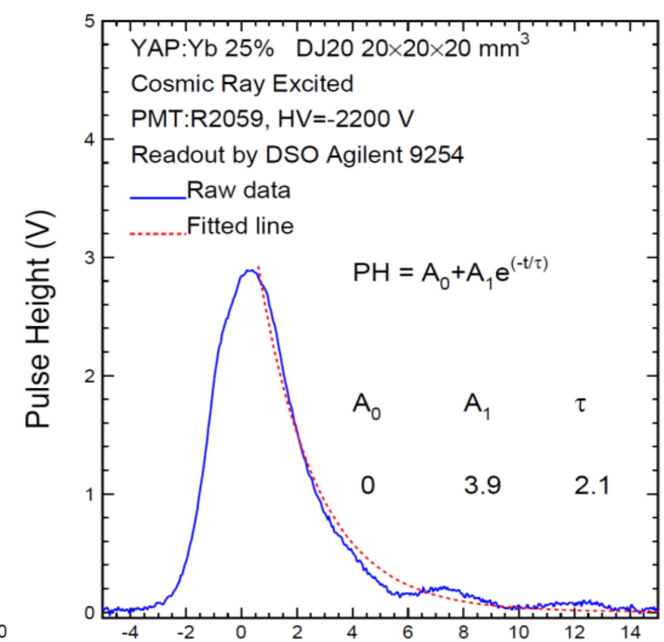



YAP:Yb DJ20
13
14
15
16


YAP:Yb 25% DJ20 20×20×20 mm3
PL
Theoretical limit of transmittance
Measured transmittance
Transmittance (%)
Wavelength (nm)
0
25
50
75
100
200
300
400
500
600
700
800


PWO ST 25×25×40 mm3
PMT:R2059, HV = -2400 V,Gate = 50 ns
Cs-137 source
Ped = 81 Net Peak = 70
LO = 14 p.e./MeV
No Sample
PMT:R2059, HV = -2400 V,Gate = 50 ns
YAP:Yb 25% DJ20 20×20×20 mm3
PMT:R2059, HV = -2400 V,Gate = 50 ns
Cs-137 source
Counts
Channel Number
0
1000
2000
50
100
150
200
250
300
350
400


YAP:Yb 25% DJ20 20×20×20 mm3
Raw data
Instrument Response
Fitted line
Ex = 260 nm Em = 350 nm
τ = 1.09 ± 0.41 ns
Counts
Time (ns)
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16
18
20


YAP:Yb 25% DJ20 20×20×20 mm3
Cosmic Ray Excited
PMT:R2059, HV=-2200 V
Readout by DSO Agilent 9254
Raw data
Fitted line
PH = A0+A1e(-t/τ)
A0
A1
τ
0
3.9
2.1
Pulse Height (V)
Time (ns)
0
1
2
3
4
5
-4
-2
2
4
6
8
10
12
14

Summary

- Precision ECAL with good e/γ resolution may be built for CMS forward calorimeter upgrade at the HL-LHC by using blight, fast and rad hard LYSO crystals.
- Homogeneous hadron calorimeter with good jet mass resolution may be built for future lepton colliders by reading both Cherenkov and scintillation light for PbF_2, PbFCl and BSO.
- Crystal calorimeters with more than ten times faster rate/timing capability may be built for future HEP experiments at the intensity frontier by using the sub-ns decay time of BaF_2.
- Investigations on novel fast crystal scintillators, such as PbFCl, YAP:Yb, ZnO:Ga and CuI, may play important role for future HEP experiments.