An LSO/LYSO Crystal Calorimeter & Jet Measurement for the ILC

Ren-Yuan Zhu

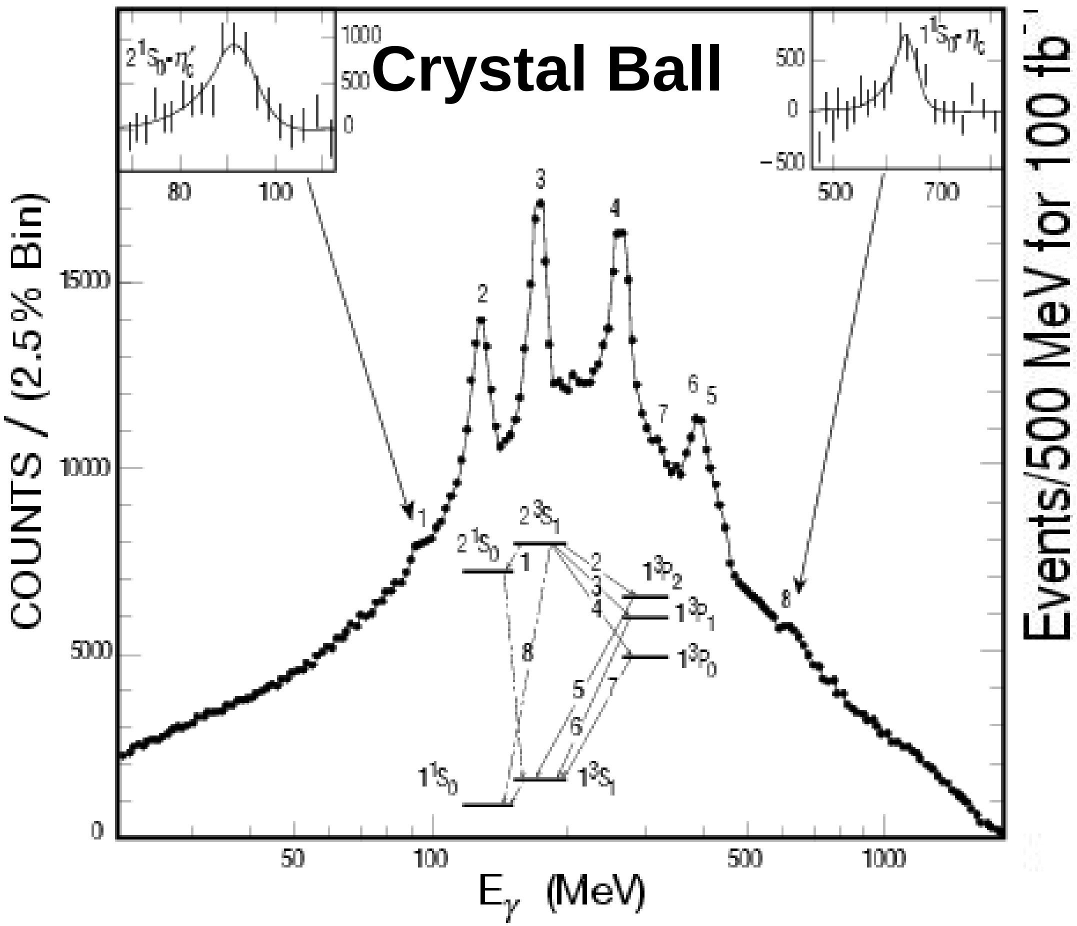
California Institute of Technology

Why a Crystal Calorimeter

- Photons and electrons are fundamental particles in the SM and for new physics.
- Performance of a crystal calorimeter is well understood:
  - The best possible energy resolution, good position and photon angular resolution;
  - Good e/photon identification and reconstruction efficiency;
  - Good missing energy resolutions;
  - Good jet mass resolution.
- Precision e/γ: physics discovery potential.

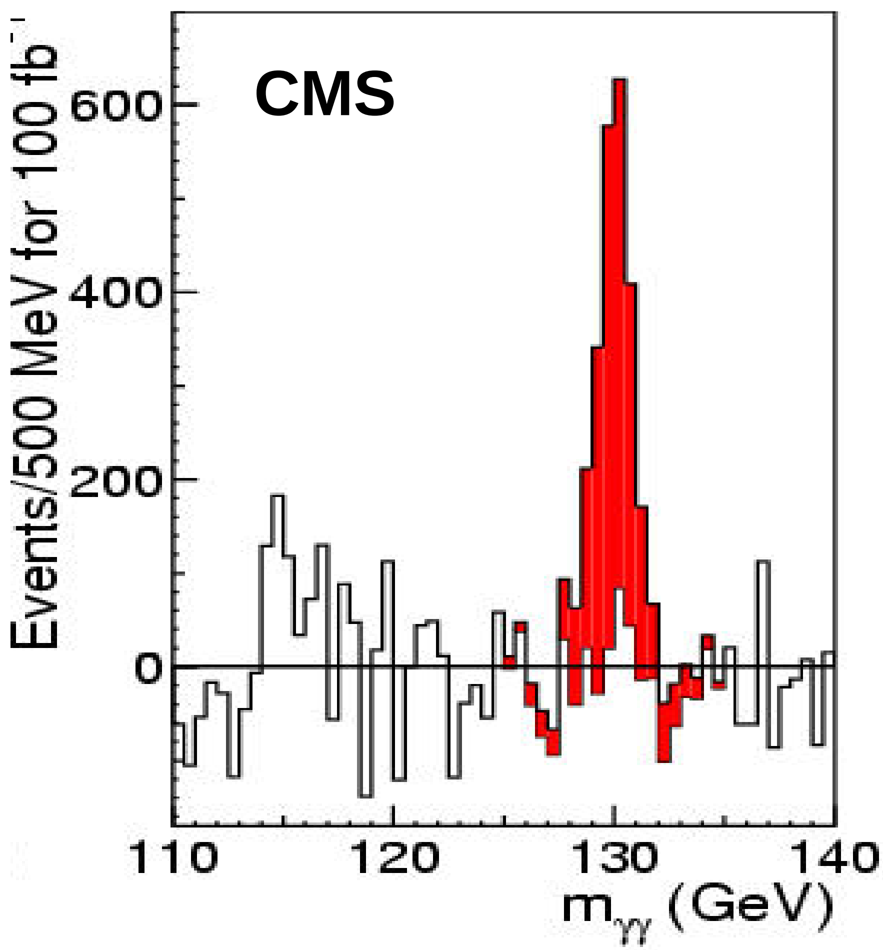
Physics in Crystal Calorimeters

Charmonium System Observed Through Inclusive Photons



Higgs Searches at LHC

$$H \to \gamma\gamma$$



Single & Multi-Photons Physics

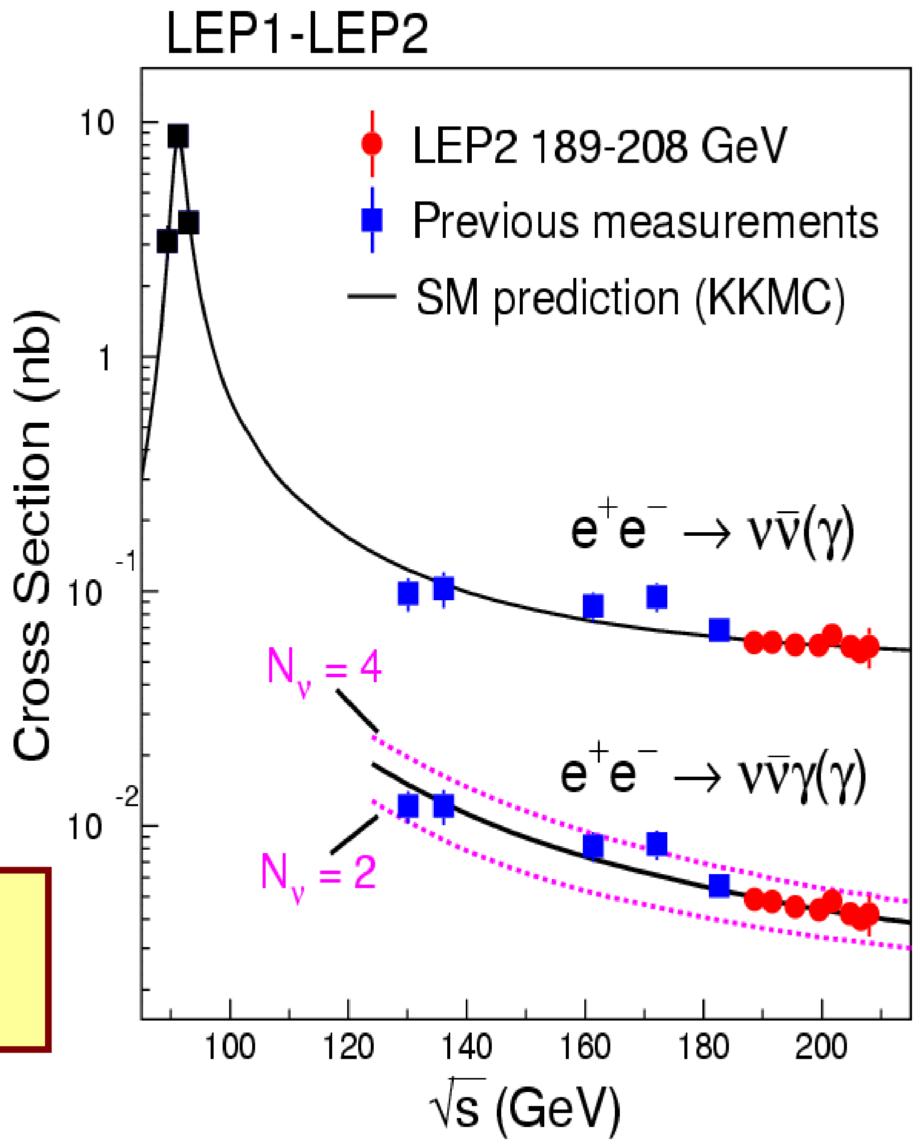
L3 BGO was the best ECAL at LEP
Efficiency ~ 73%
Purity ~ 99%:
Precision: 0.5% (RFQ calibration)
Best sensitivity at LEP

Physics Topics Include:

- Neutrino Production (SM)
- Extra Dimensions and SUSY
- Additional light neutrino flavors
- Anomalous gauge couplings through γ-W and γ-Z vertices

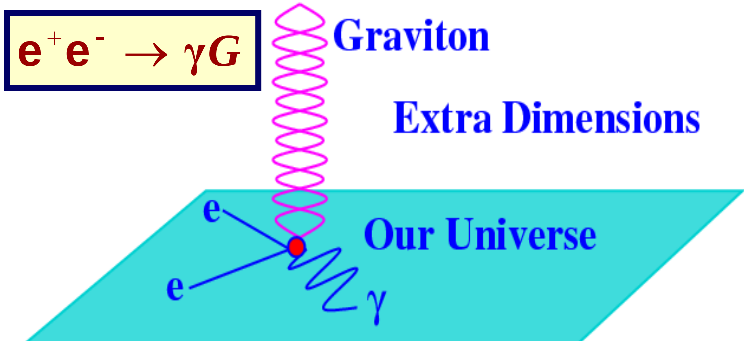
Number of neutrino species
$N_\nu = 2.98 \pm 0.06$

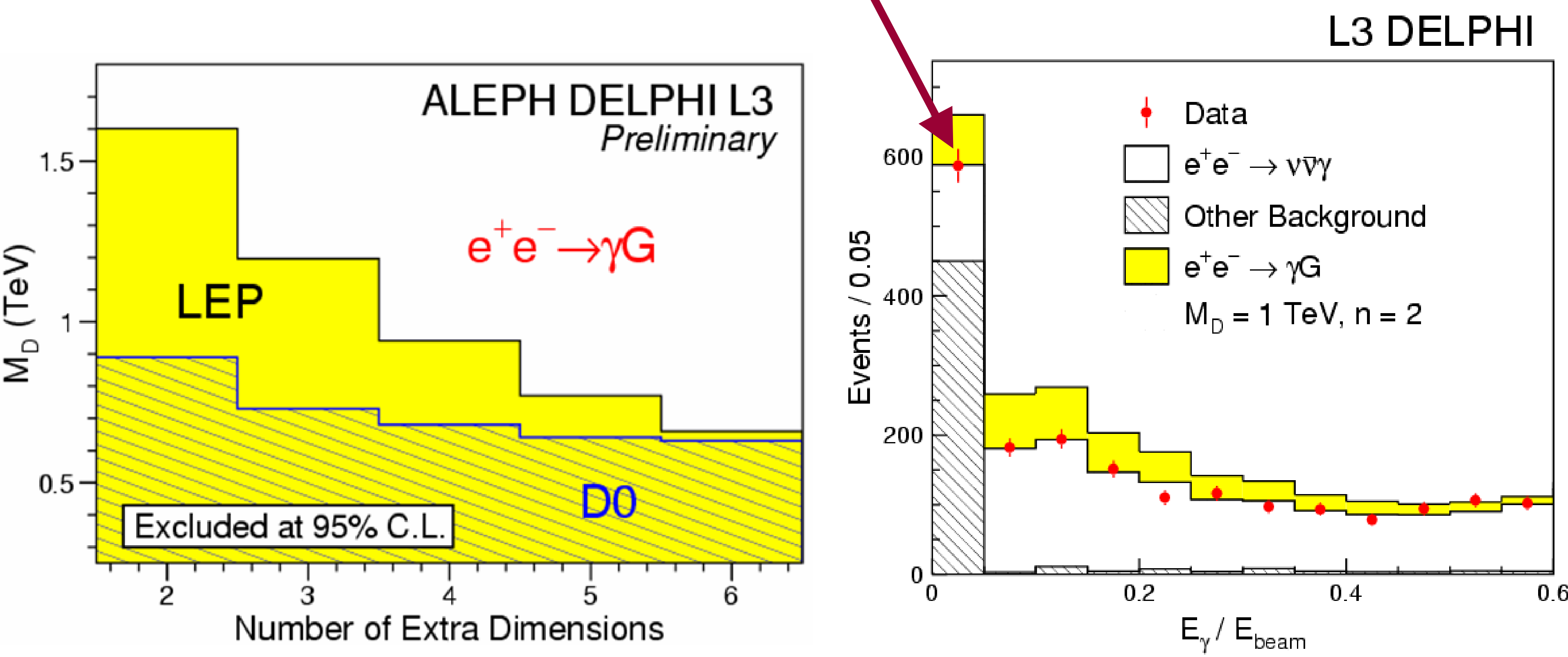
More precise than PDG'04



Extra Dimensions at LEP

- SM particles live on a 3D wall, gravity propagates in extra dimensions
- *Single photon* is the discovery channel
- Low P_t selection increases sensitivity

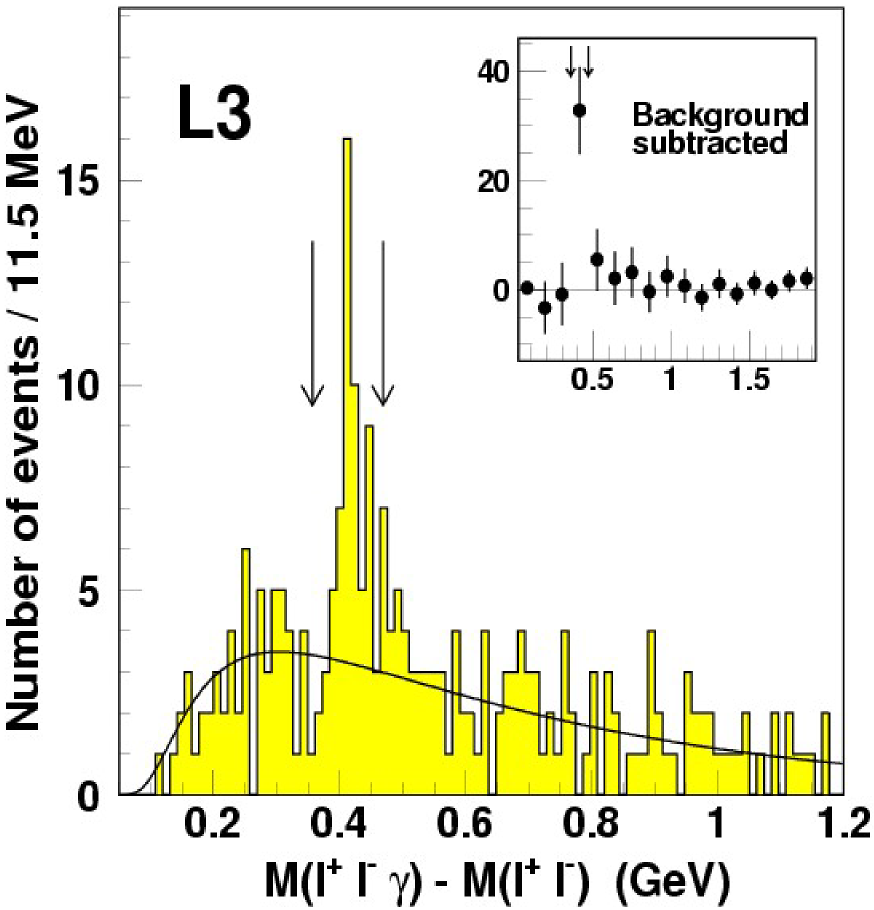




Physics in Crystal Calorimeter

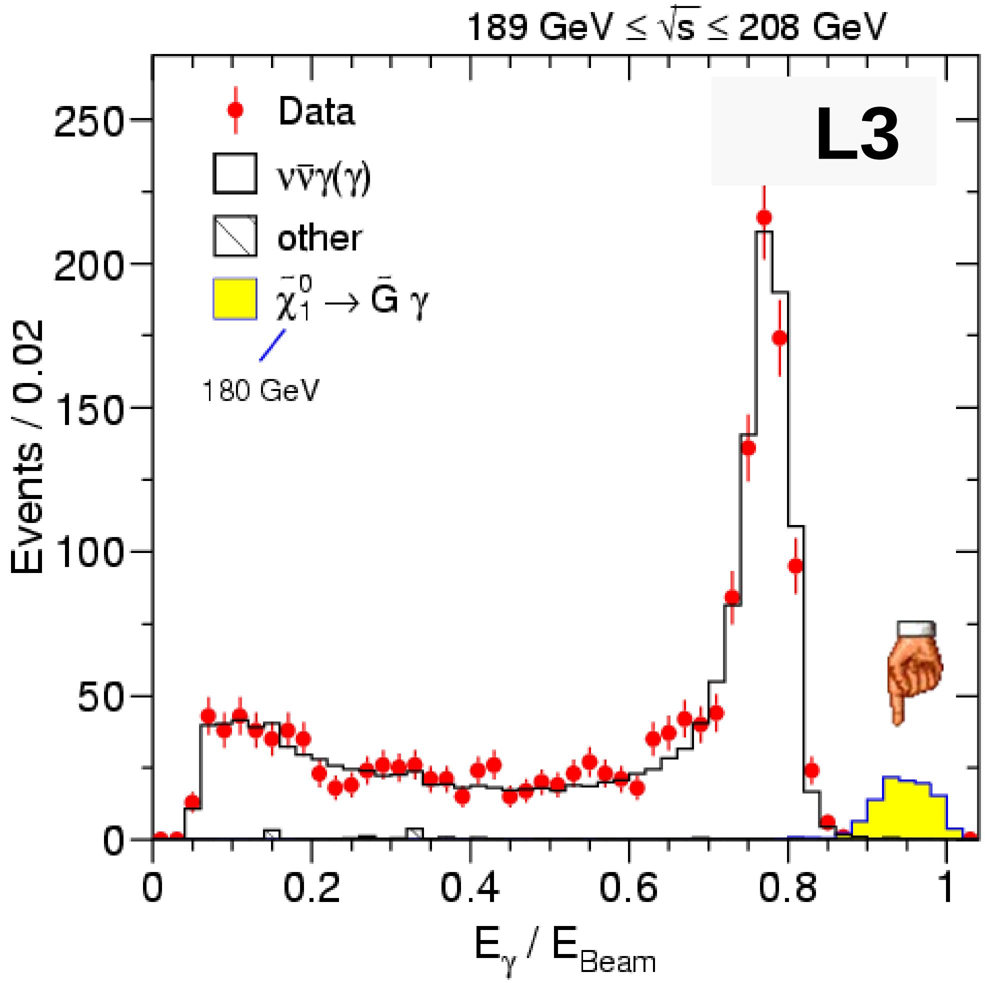
Charmed Meson in Z Decay

$$\chi_{c1} \rightarrow J/\psi\gamma$$

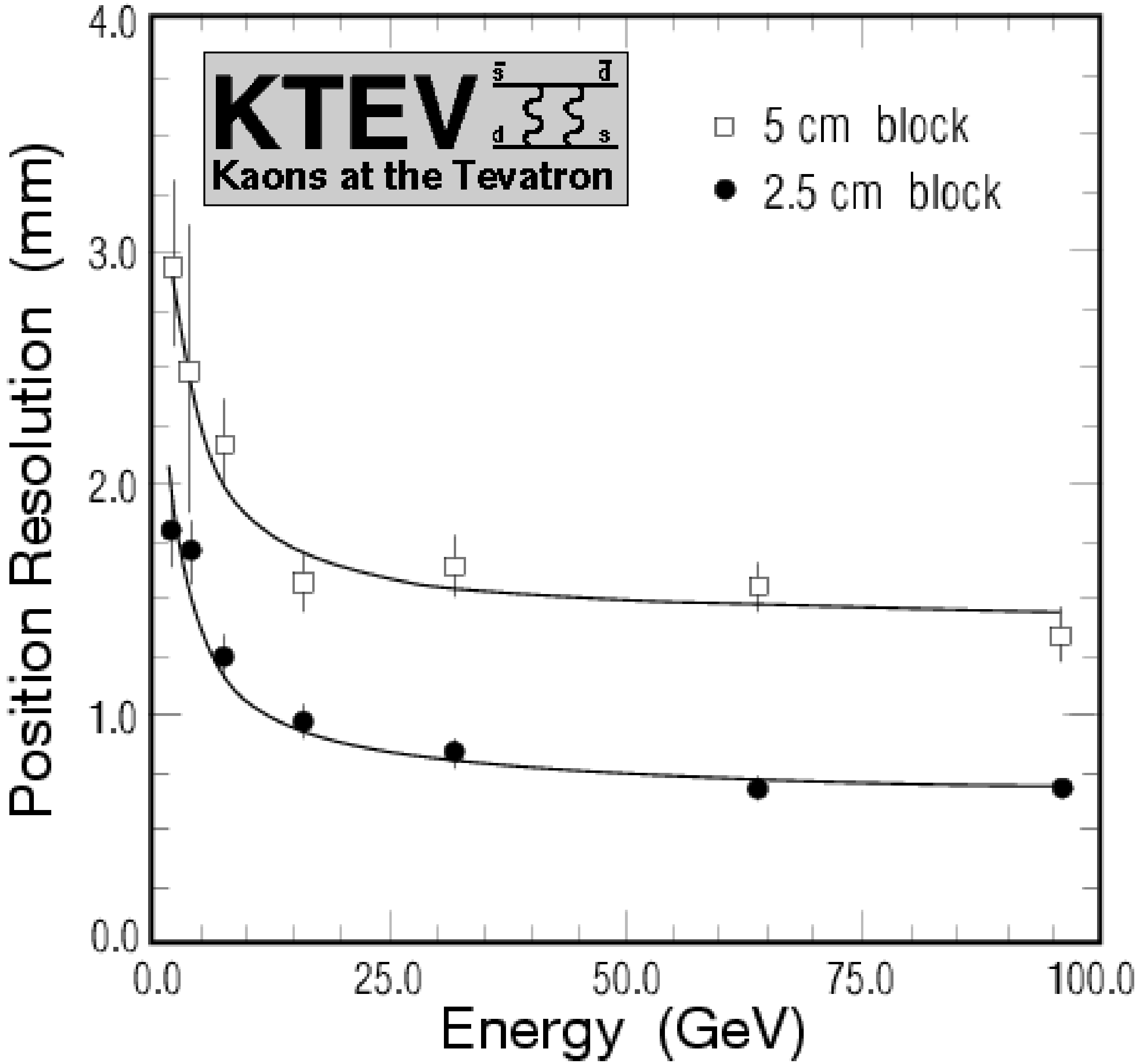


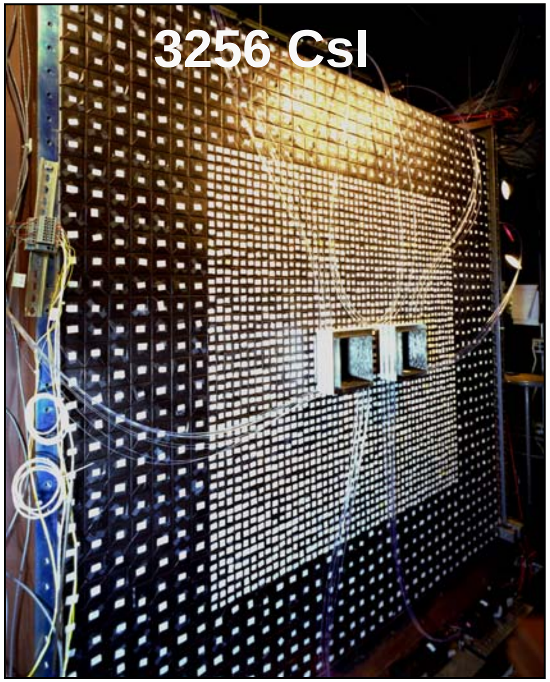
SUSY Breaking with Gravitino

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



KTeV CsI Position Resolution



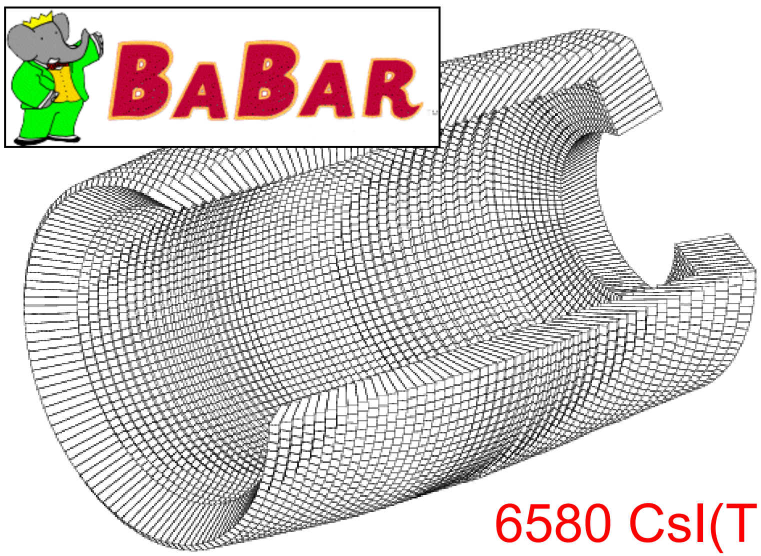


Sub mm position resolution at high energies.

L3 BGO & CMS PWO: 0.3 mm.

BaBar CsI(Tl) Resolution

A crystal calorimeter at low energies

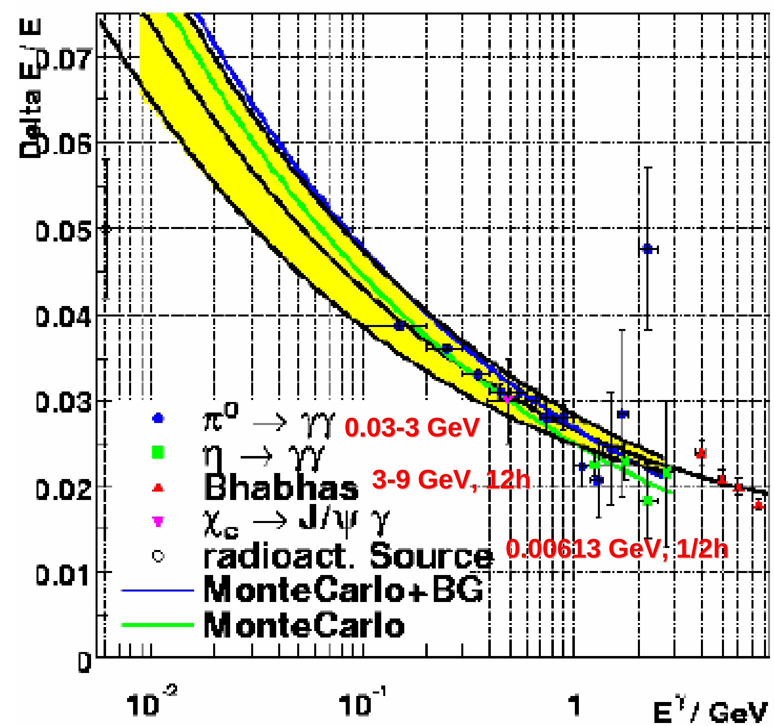


6580 CsI(Tl)

Good light yield of CsI(Tl) provides excellent energy resolution at low energies

Energy resolution

M. Kocian, SLAC, CALOR2002



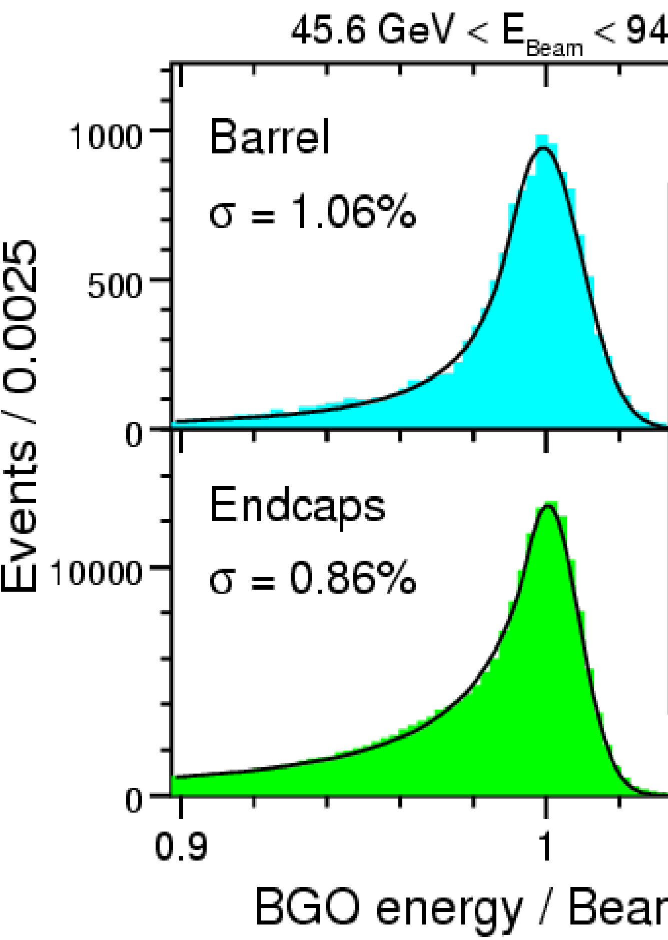
$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

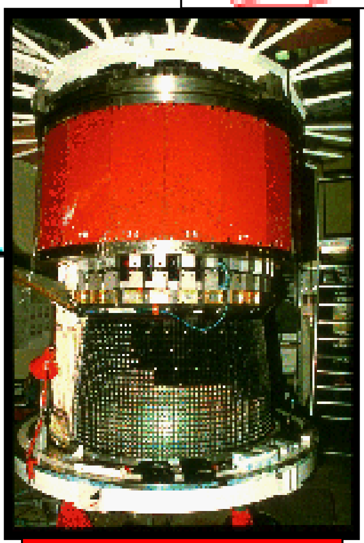
$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

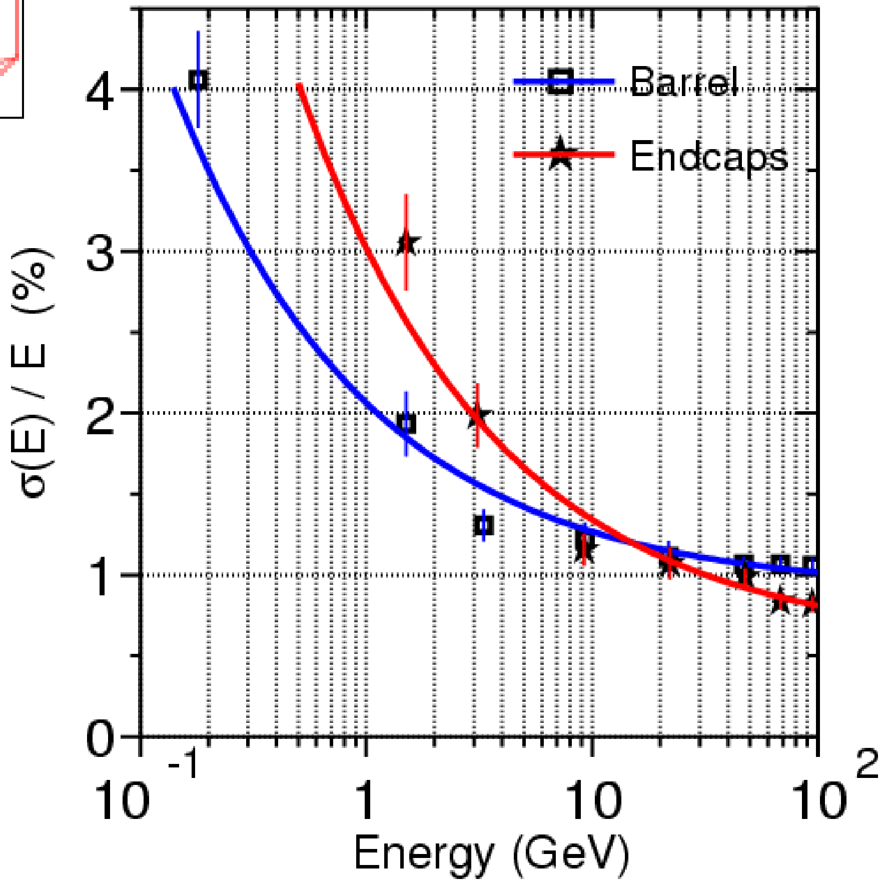
L3 BGO Resolution

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

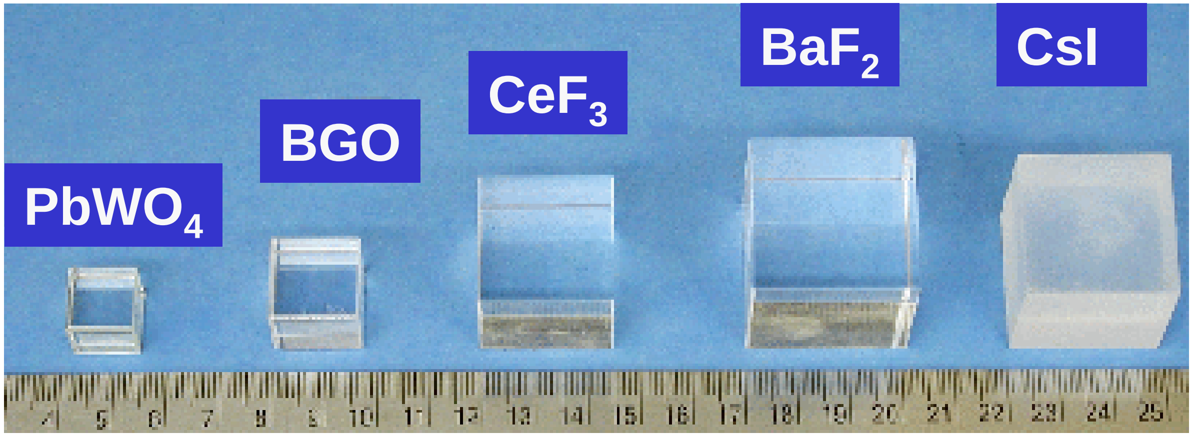




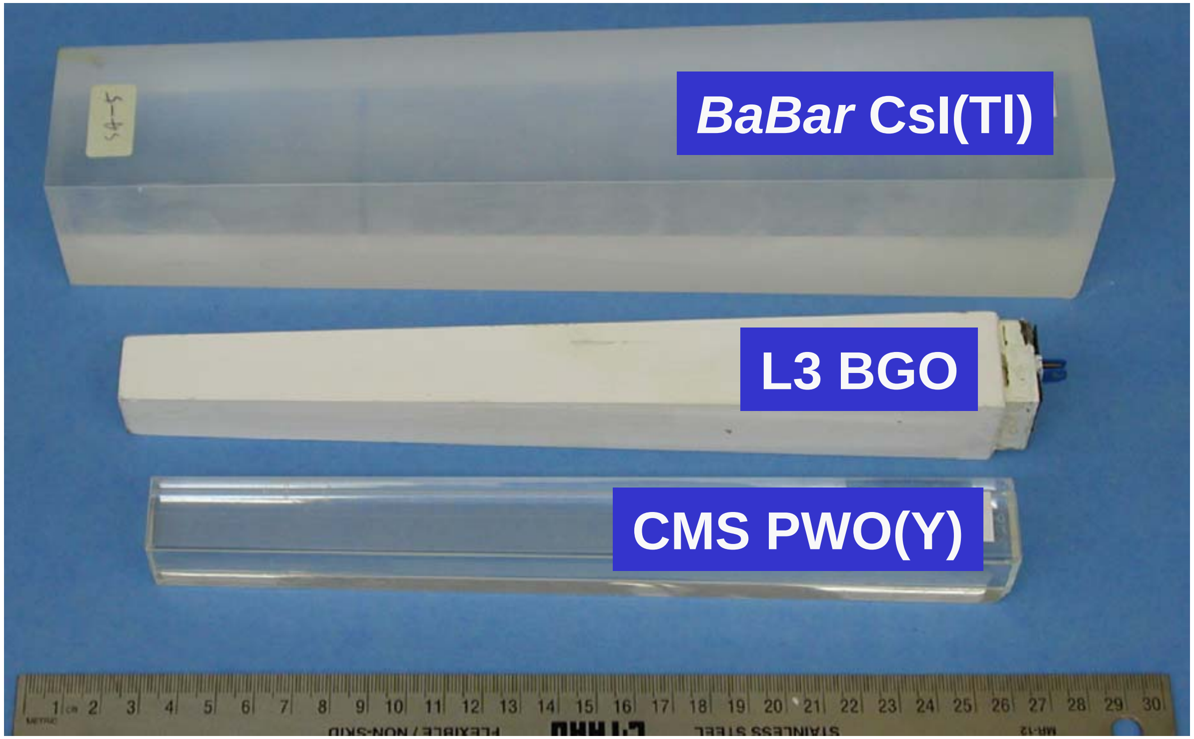
12k BGO



Crystal Density: Radiation Length



1.5 X_0 Cubic



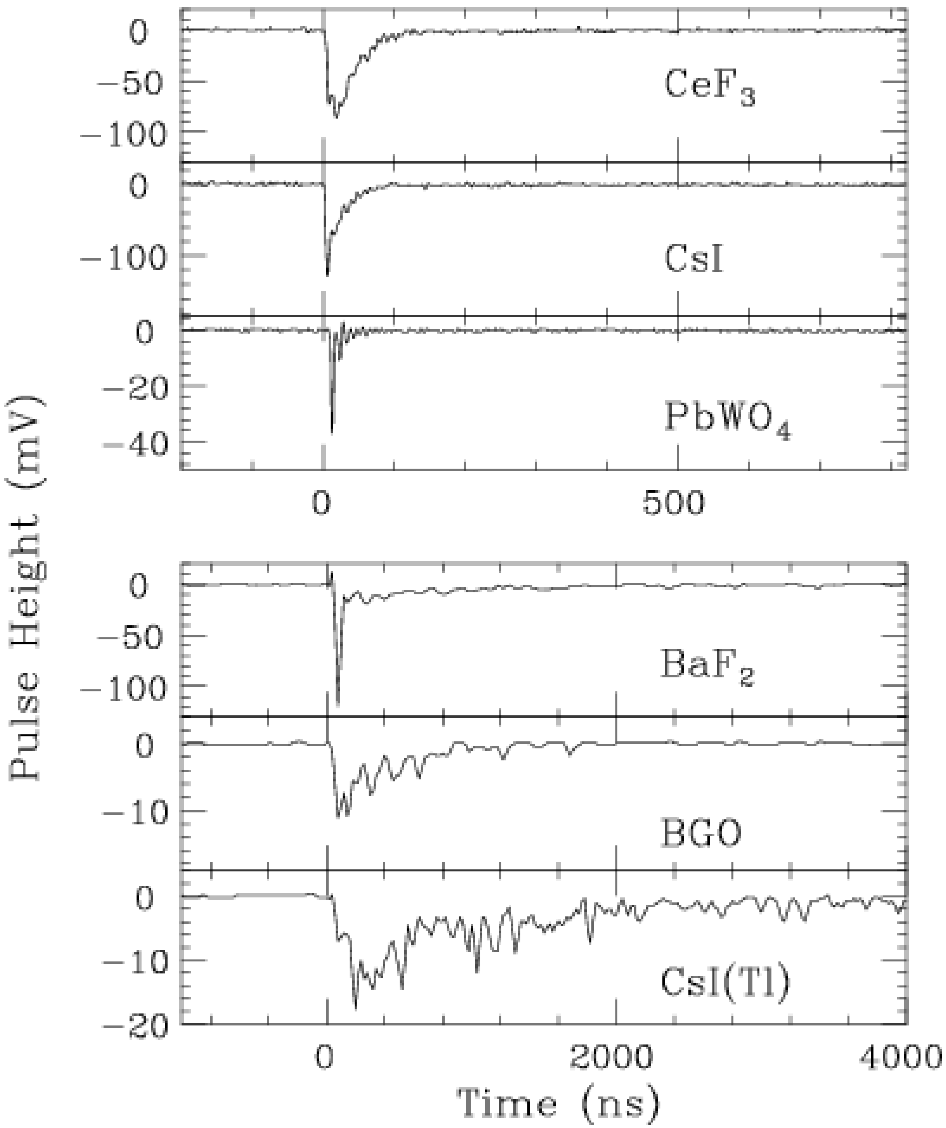
Full Size Samples

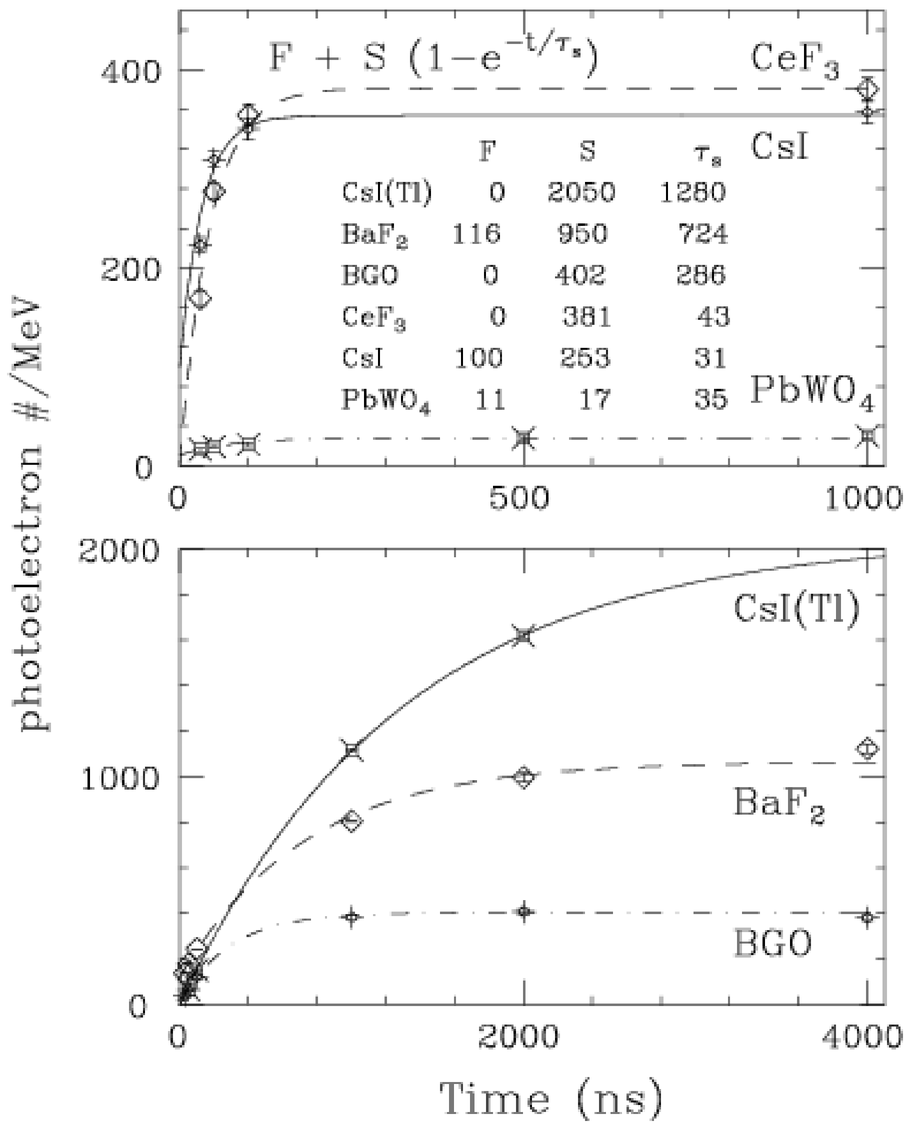
***BaBar* CsI(Tl): 16 X_0**

L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

Crystal Speed: Decay Time





Summary of Crystals for HEP

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$	LSO(Ce)	GSO(Ce)
Density (g/cm³)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (ºC)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	0.9	1.14	1.37
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.3	2.0	2.3	2.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	21.8	18	21	22
Refracti								.85
Hygros								lo
Lumine (at peak								40
Decay Time ^{b} (ns)	230	1300	35 6	630 0.9	300	50 10	40	60
Light Yield ^{b,c} (%)	100	45	5.6 2.3	21 2.7	13	0.1 0.6	75	30
d(LY)/dT ^{b} (%/ ºC)	~0	0.3	-0.6	-2 ~0	-1.6	-1.9	~0	-0.1
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV	TAPS (L*) (GEM)	L3 BELLE PANDA?	CMS ALICE PANDA? (BTeV)…	-	-

LSO/LYSO is a unique crystal with high light output & fast decay time

a. at peak of emission; b. up/low row: slow/fast component; c. measured by PMT of bi-alkali cathode.

LSO/LYSO Mass Production

CTI: LSO

CPI: LYSO

Saint-Gobain LYSO

Additional Capability: SIPAT @ Sichuan, China

Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT)

SIPAT LSO

Quoted Price: 13-15 USD/cc

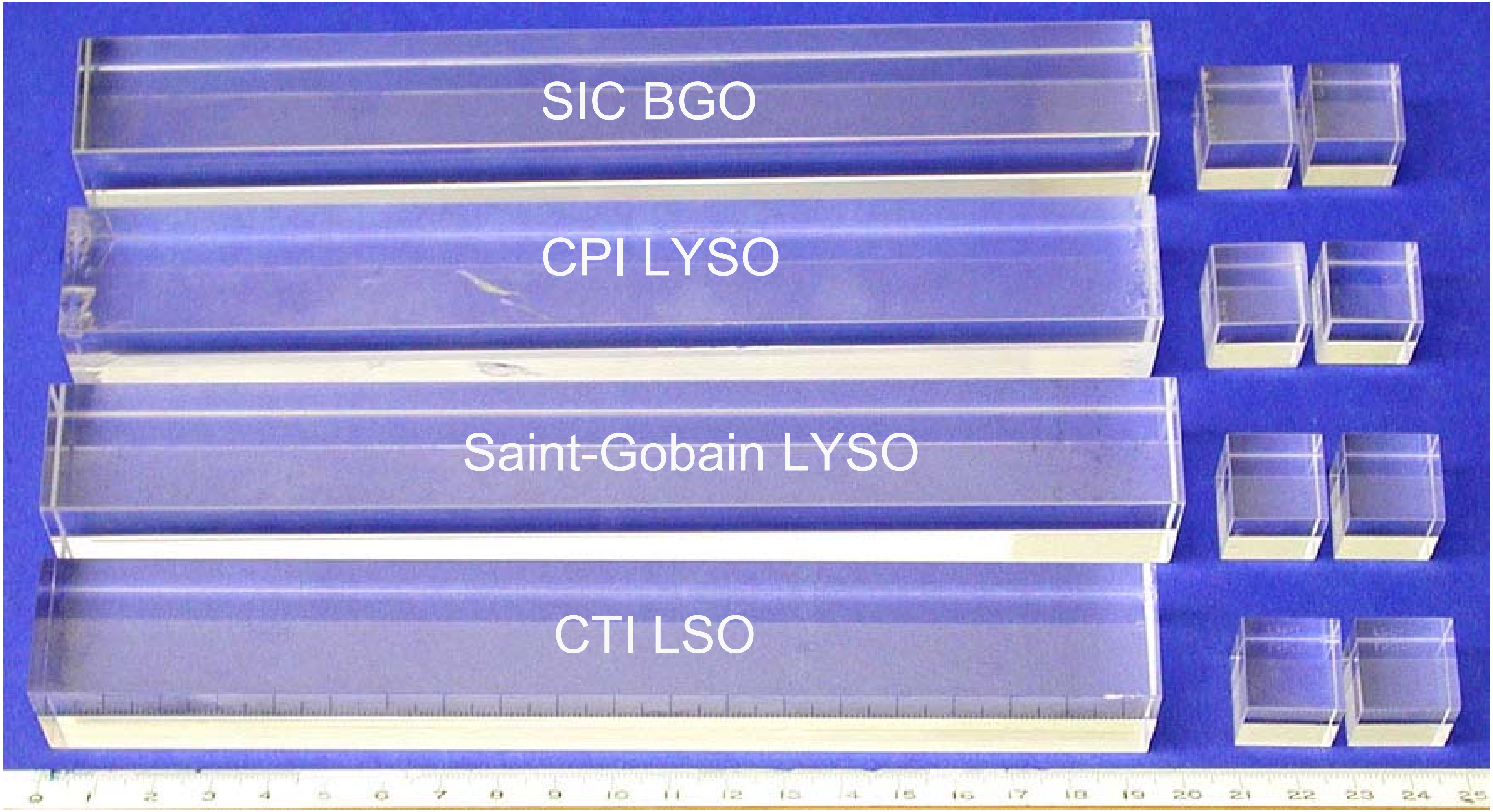
Φ80 x 70

Φ80 x 120

Large size LSO ($Ce:Lu_2SiO_5$) crystals are in production

BGO, LSO & LYSO Samples

Cube: 1.7 X1.7 x 1.7 cm (1.5 X_0)
Bar: 2.5 x 2.5 x 20 cm (18 X_0)



Experiment

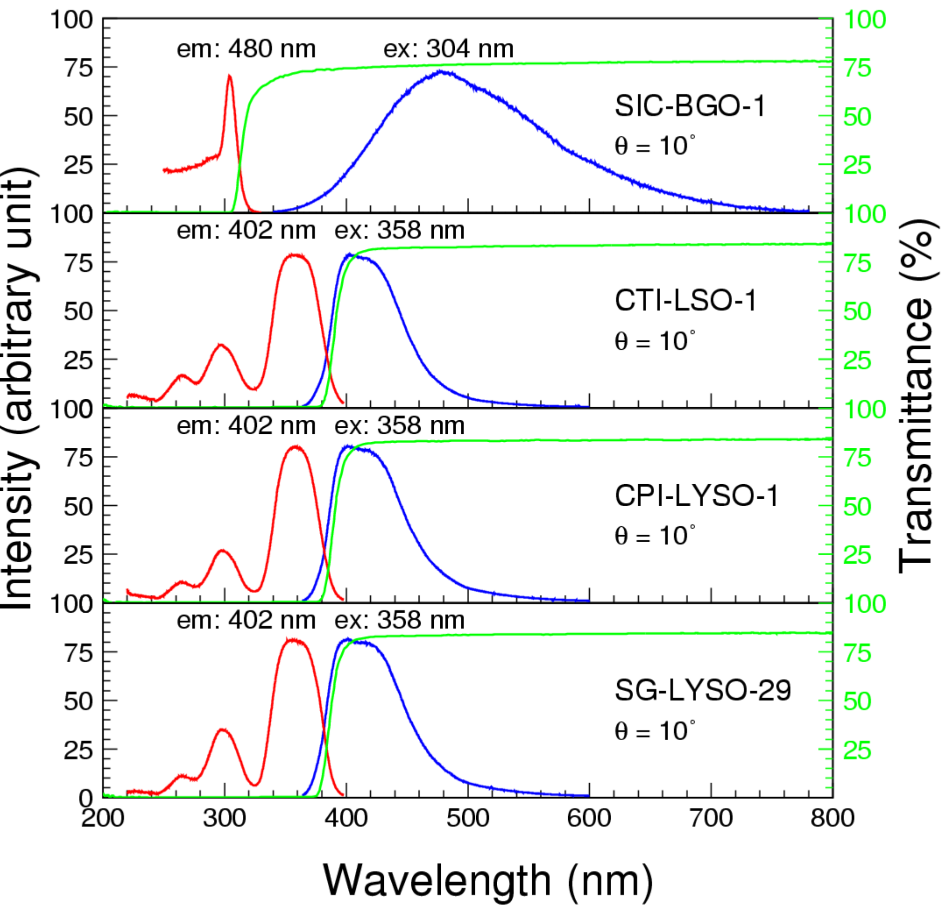
- Without any thermal treatment, all samples went through initial measurement for optical and scintillation properties.
- Properties measured: transmittance, emission and excitation spectra, light output, decay kinetics and light response uniformity.
- Two LYSO long samples went through a series of γ–ray irradiations in steps under 2, 100 and 9k rad/h for 19/24, 19/24 and 22 hours respectively, followed by recovery.
- Light output was measured again for two long LYSO samples two days after ending γ–ray irradiations.

Excitation, Emission & Transmittance

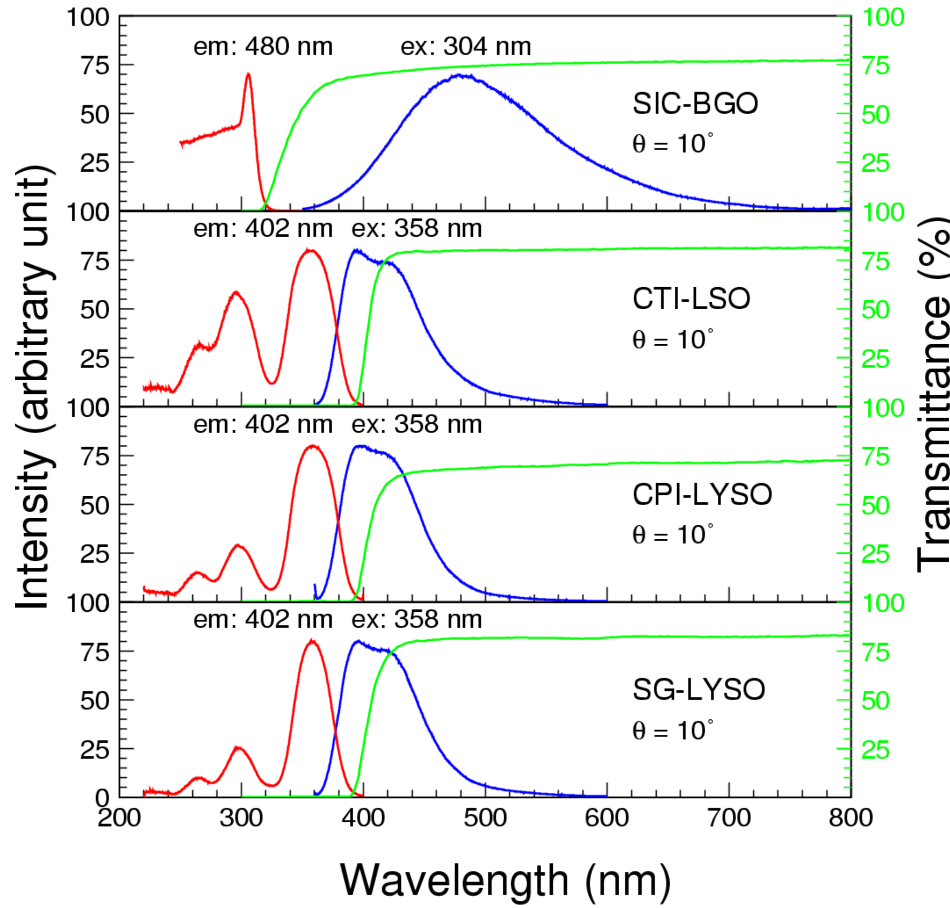
Identical transmittance, emission & excitation spectra

Part of emitted light may be self-absorbed in long samples

1.7 cm Cube



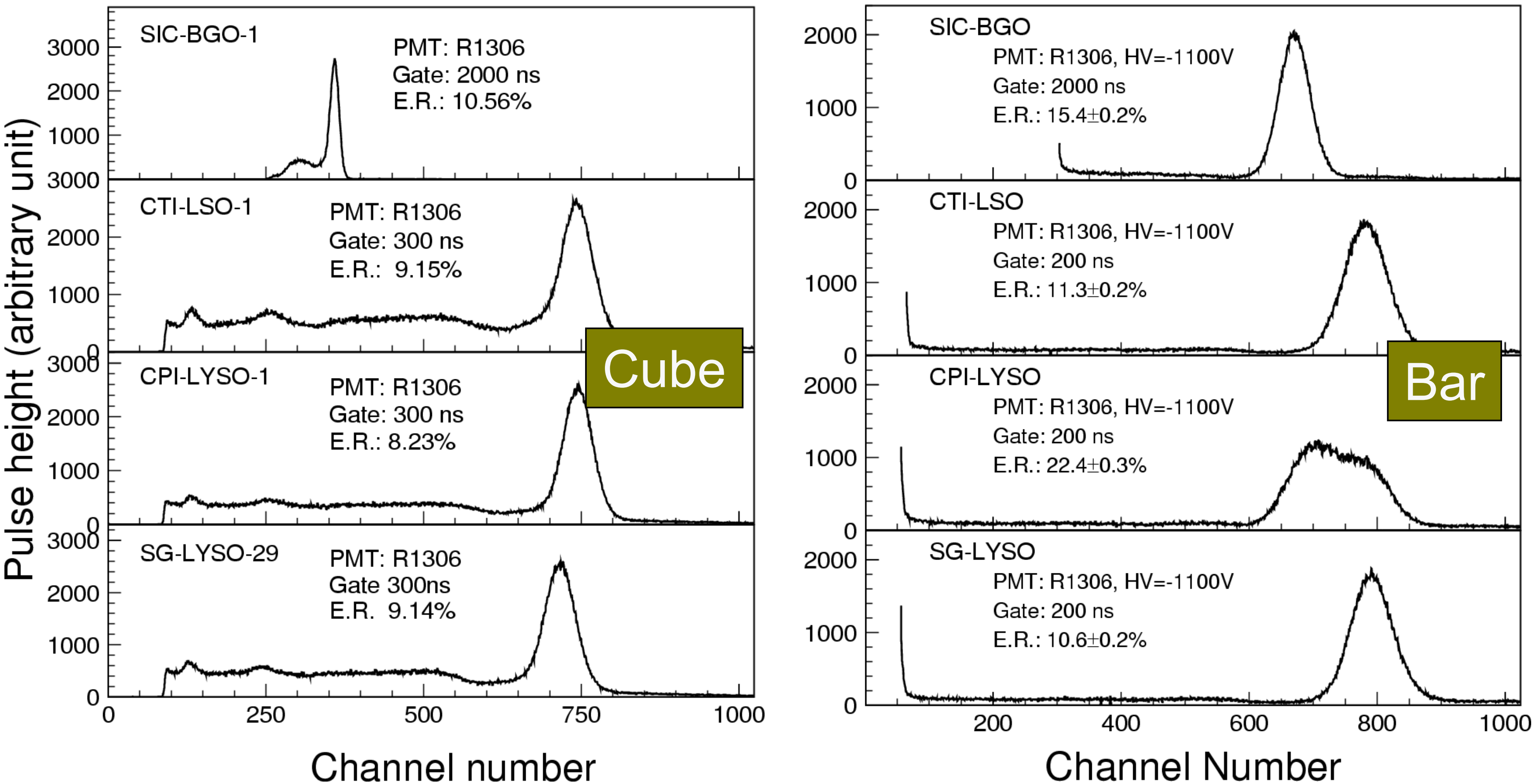
2.5 x 2.5 x 20 cm Bar



^{137}Cs & ^{22}Na Pulse Height Spectra

Cube and bar samples have 8% and 10% FWHM resolution respectively for ^{137}Cs (0.66 MeV) and ^{22}Na source (0.51 MeV)

CPI LYSO bar has double peak because of poor annealing

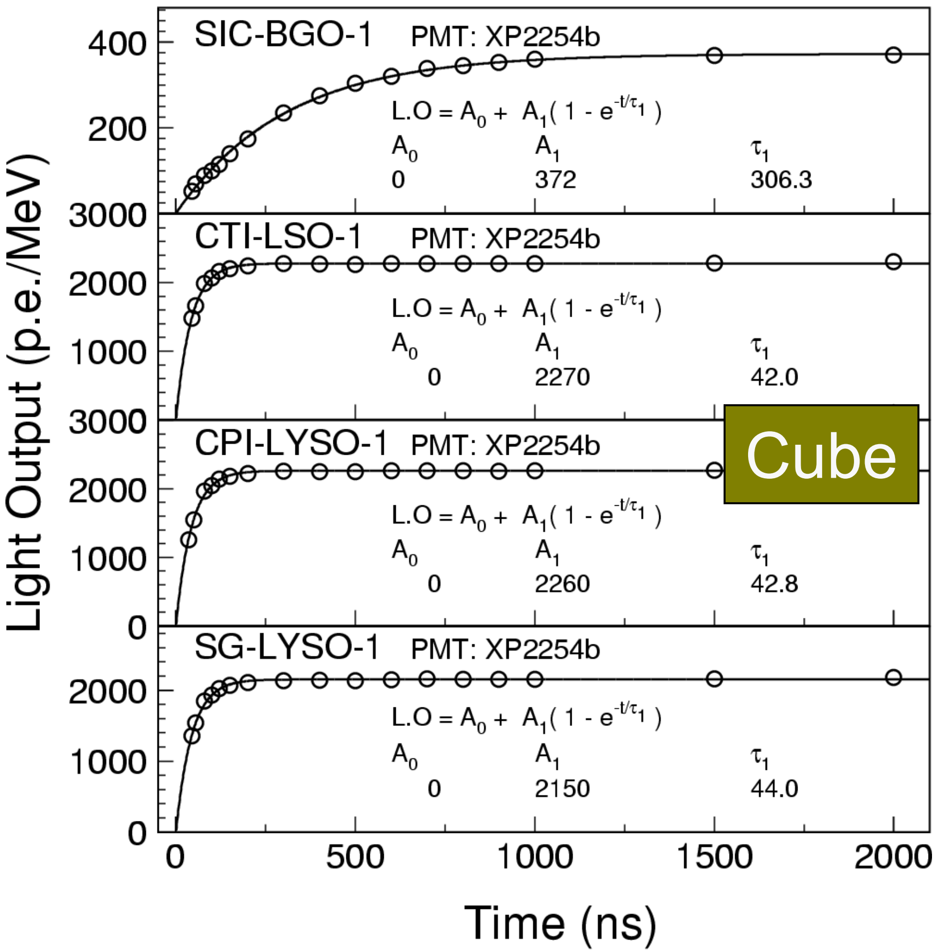


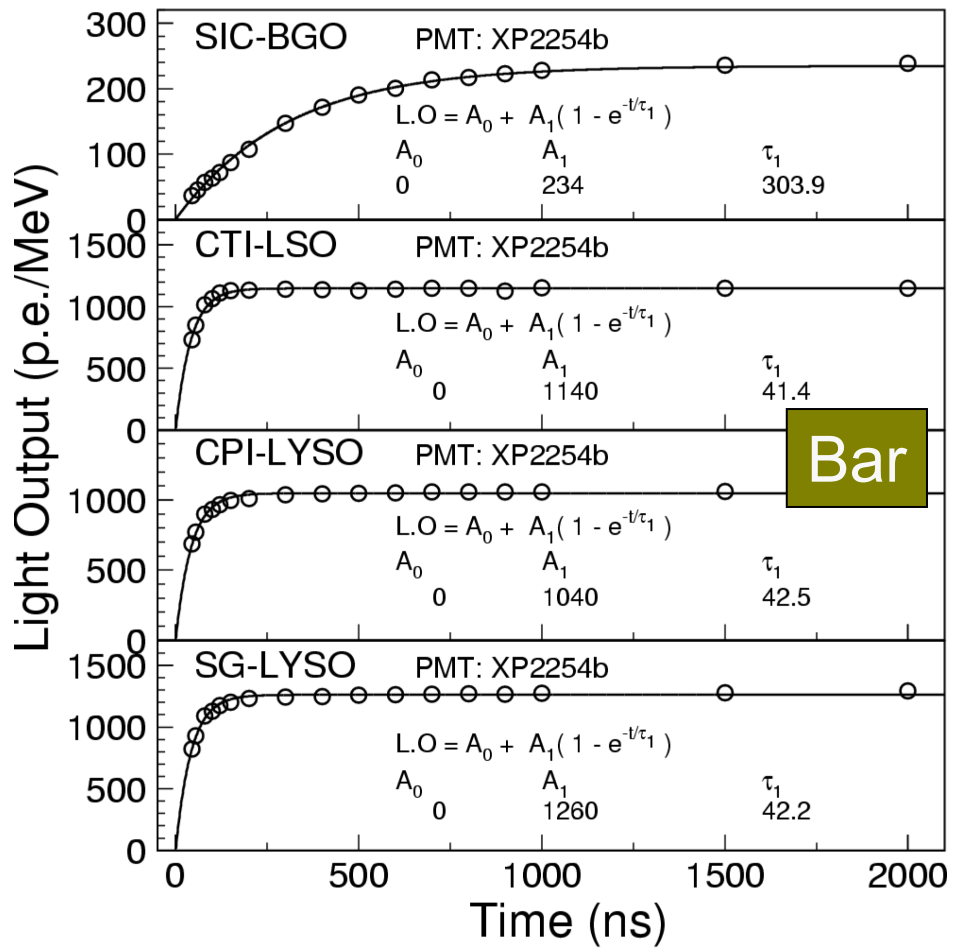
Light Output & Decay Time

LSO/LYSO Light yield: a factor of 6/100 of BGO/PWO

Bar sample has ~50% light of the cube sample

LSO/LYSO decay time: 42 ns compared to 300 ns of BGO

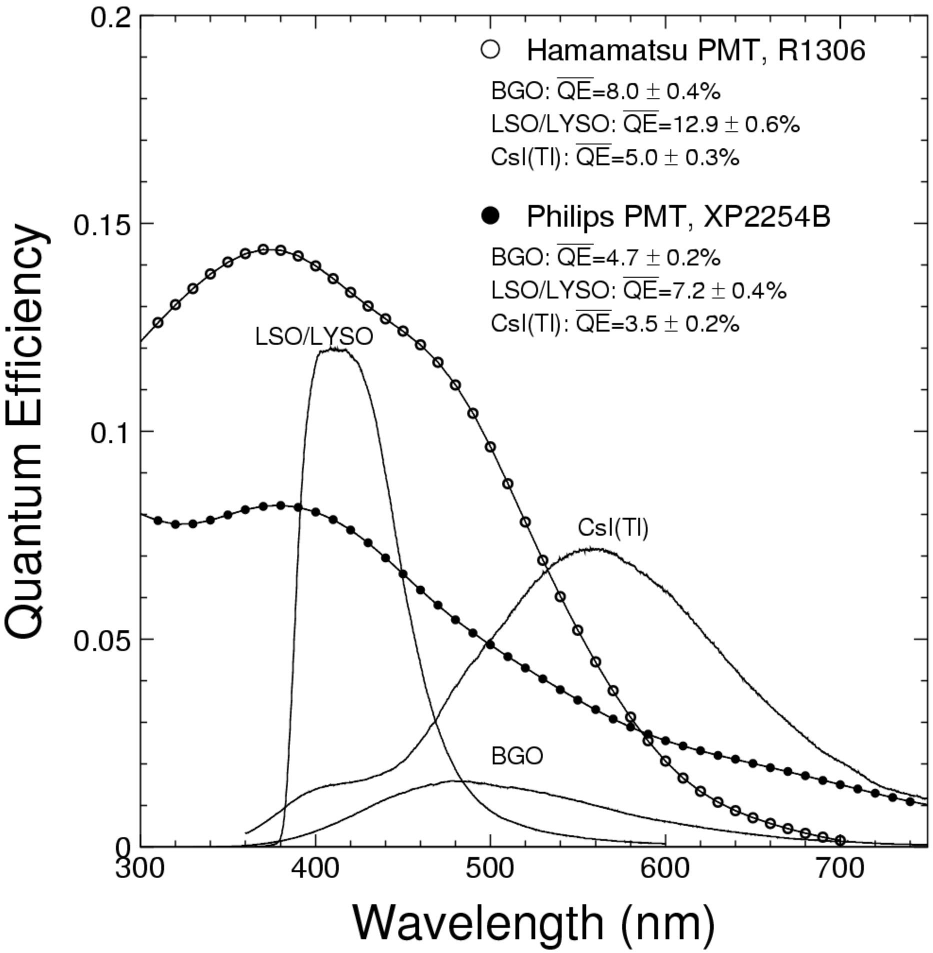


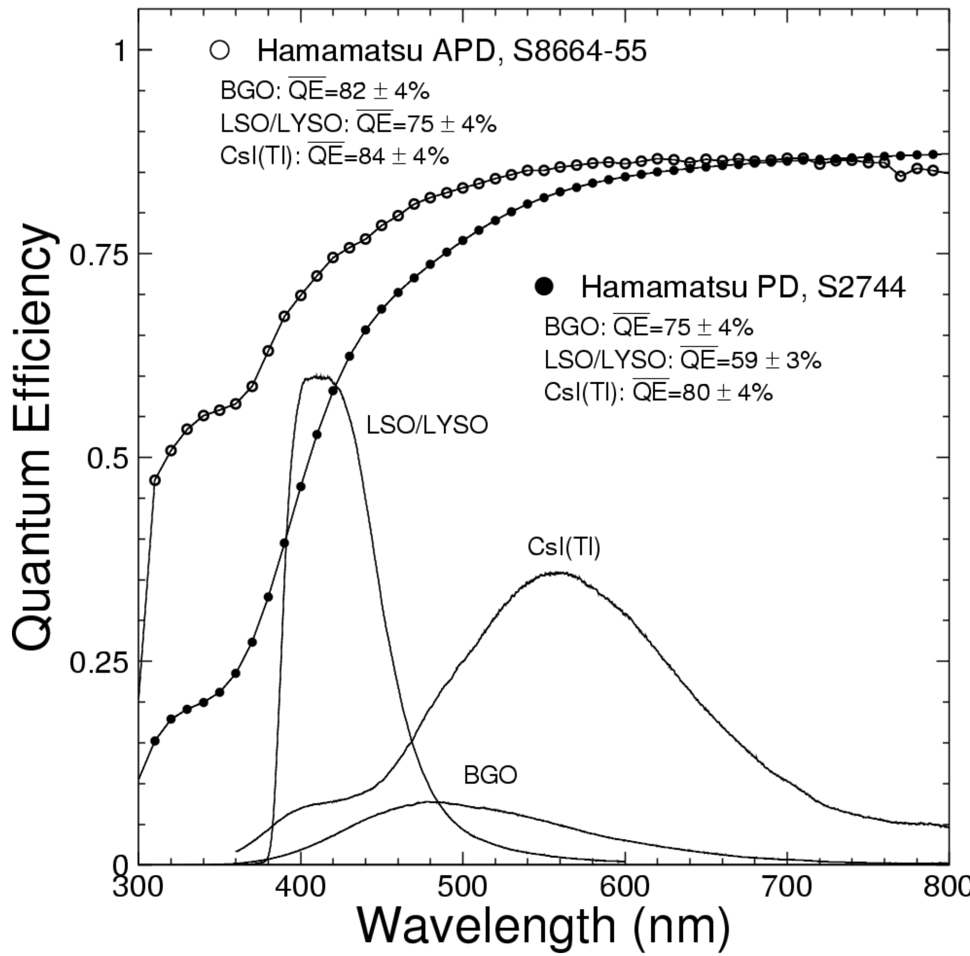


Emission Weighted Q.E.

Taking out PMT QE, LO of LSO/LYSO is 4 times BGO

Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO

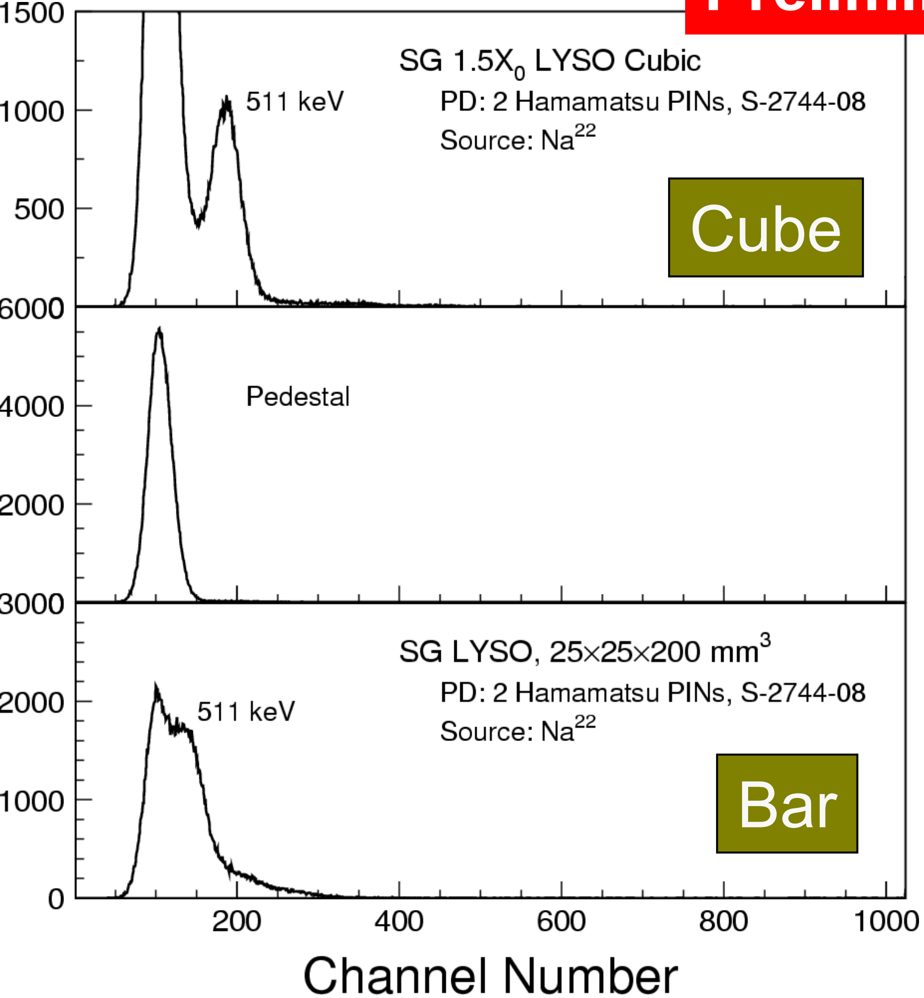


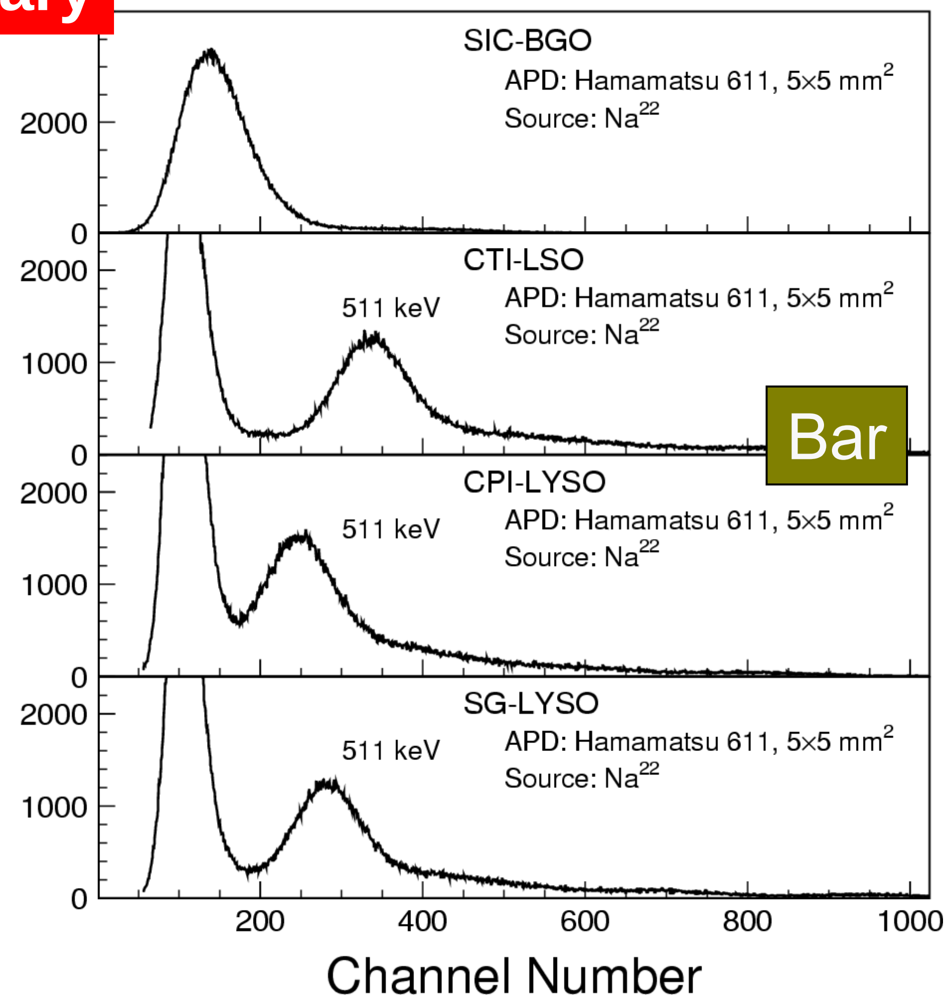


LSO/LYSO with Si Readout

LSO/LYSO bars can be measured in lab by using one S8664-55 APD of 25 mm^2 and 0.51 MeV ^{22}Na source

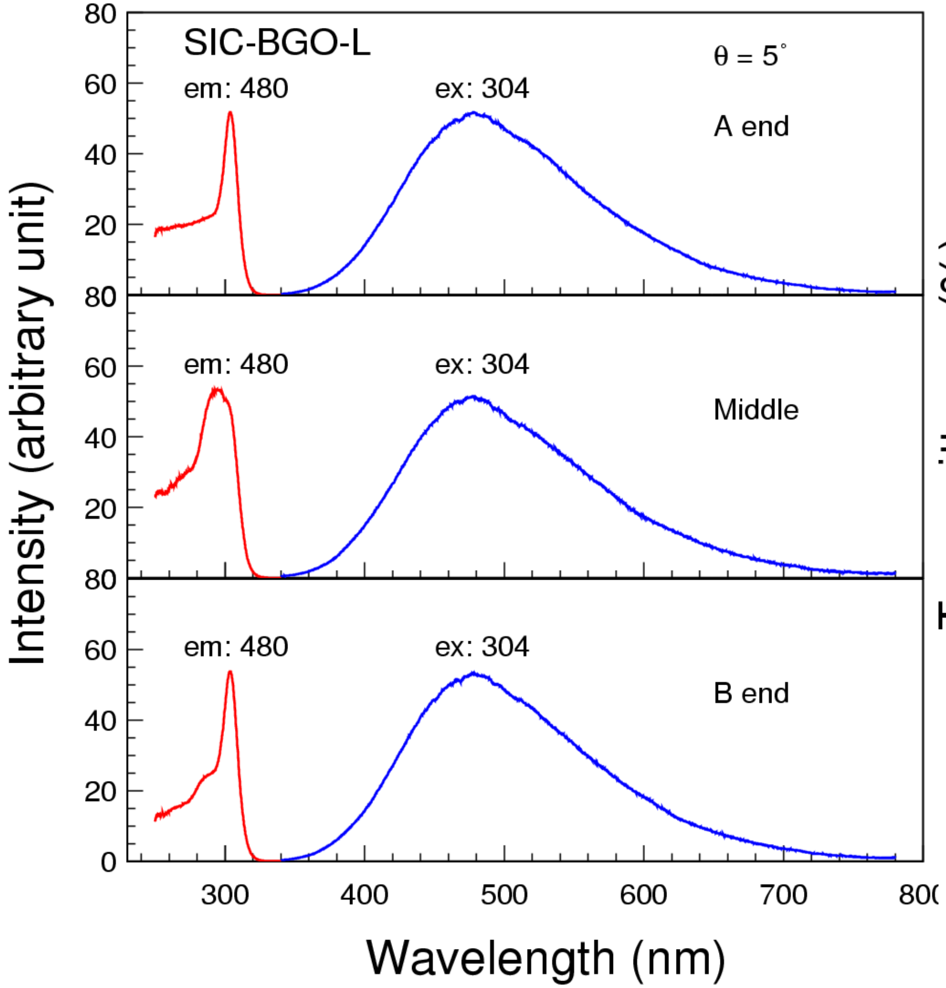
Preliminary

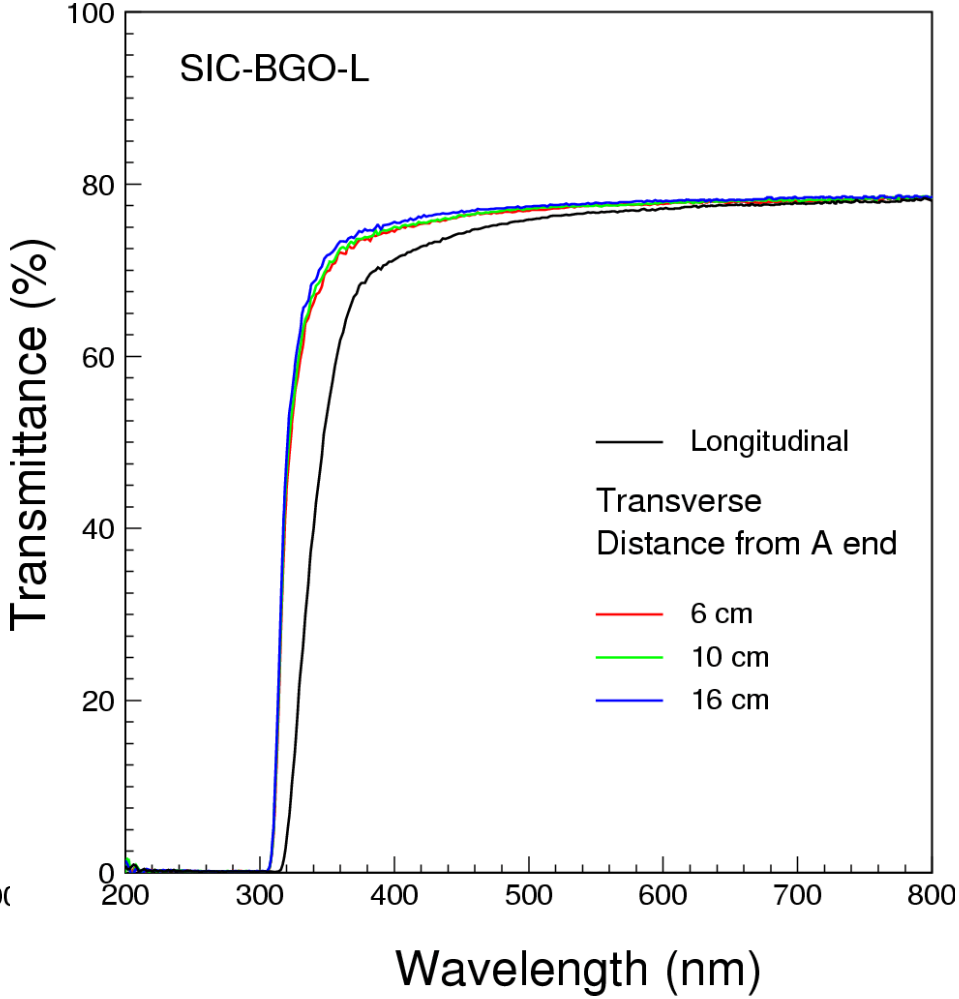




BGO: Longitudinal Uniformity

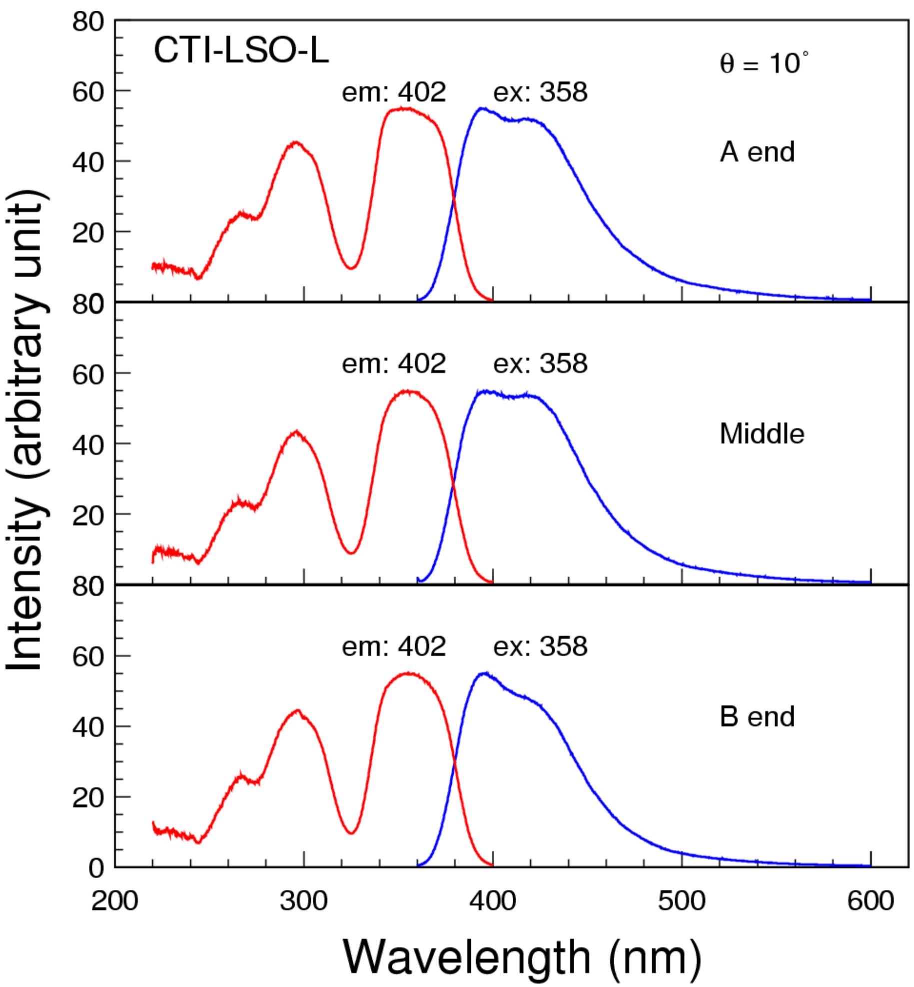
No longitudinal variation in optical properties

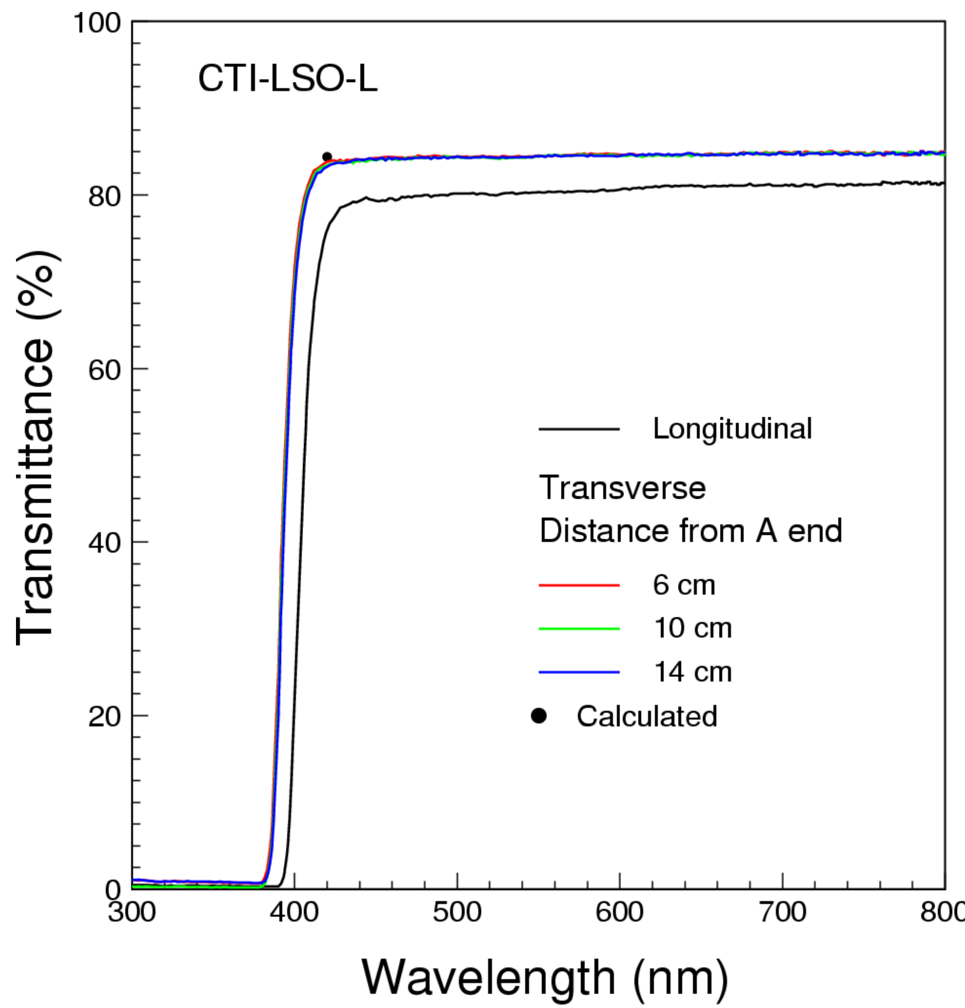




LSO: Longitudinal Uniformity

No longitudinal variation in optical properties
Transverse transmittance approaches theoretical limit

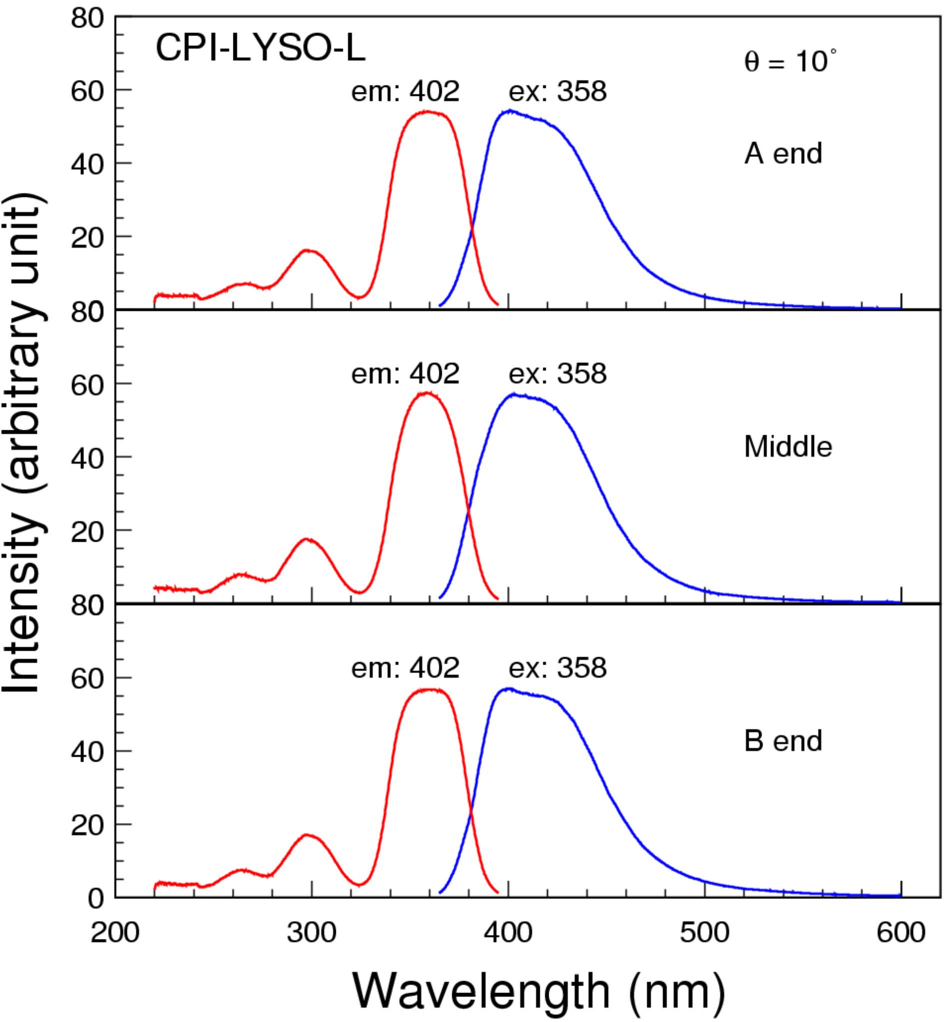


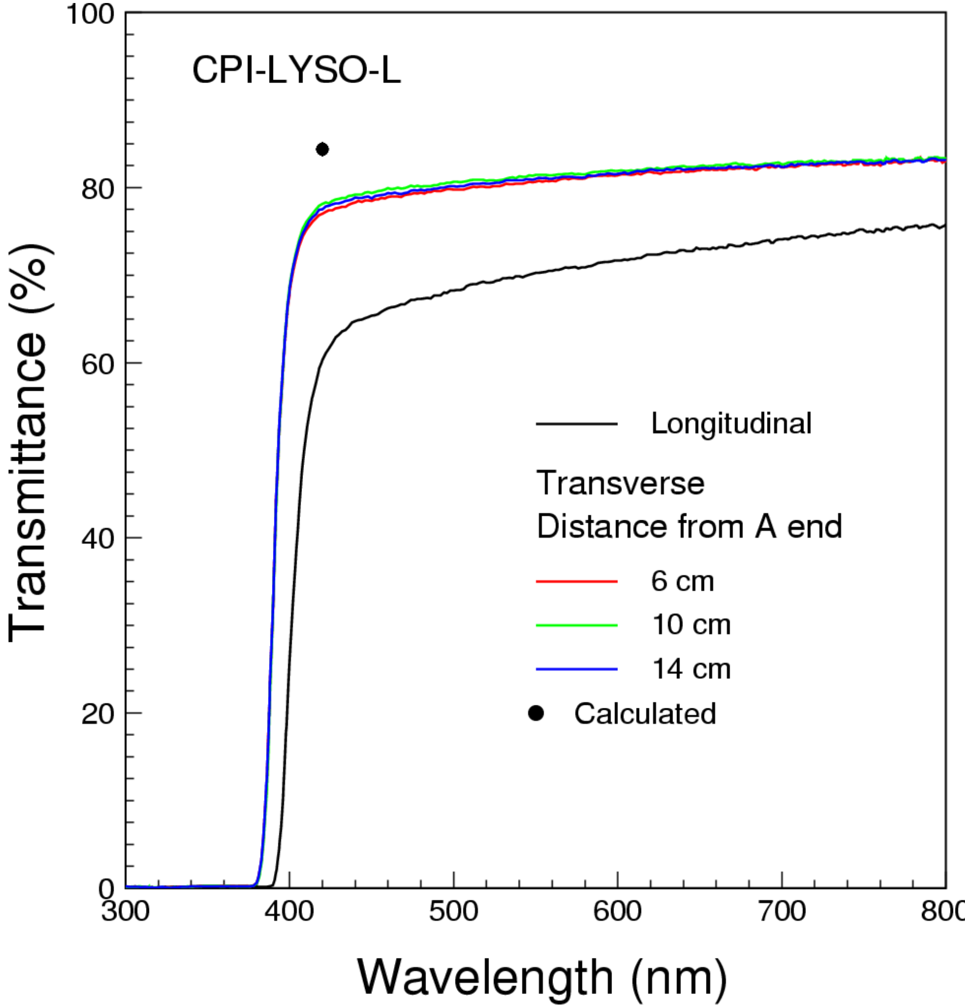


LYSO: Longitudinal Uniformity

No longitudinal variation in optical properties

Poor LT and TT may be caused by poor surface polishing

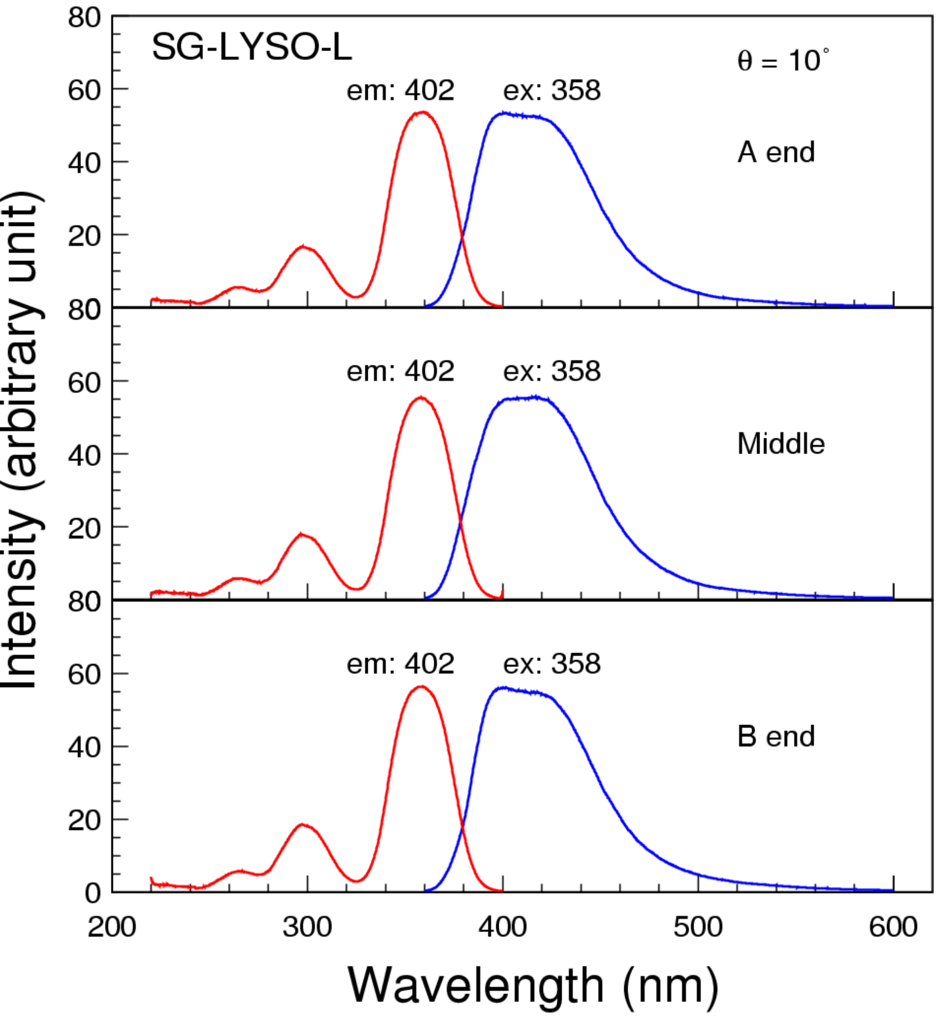


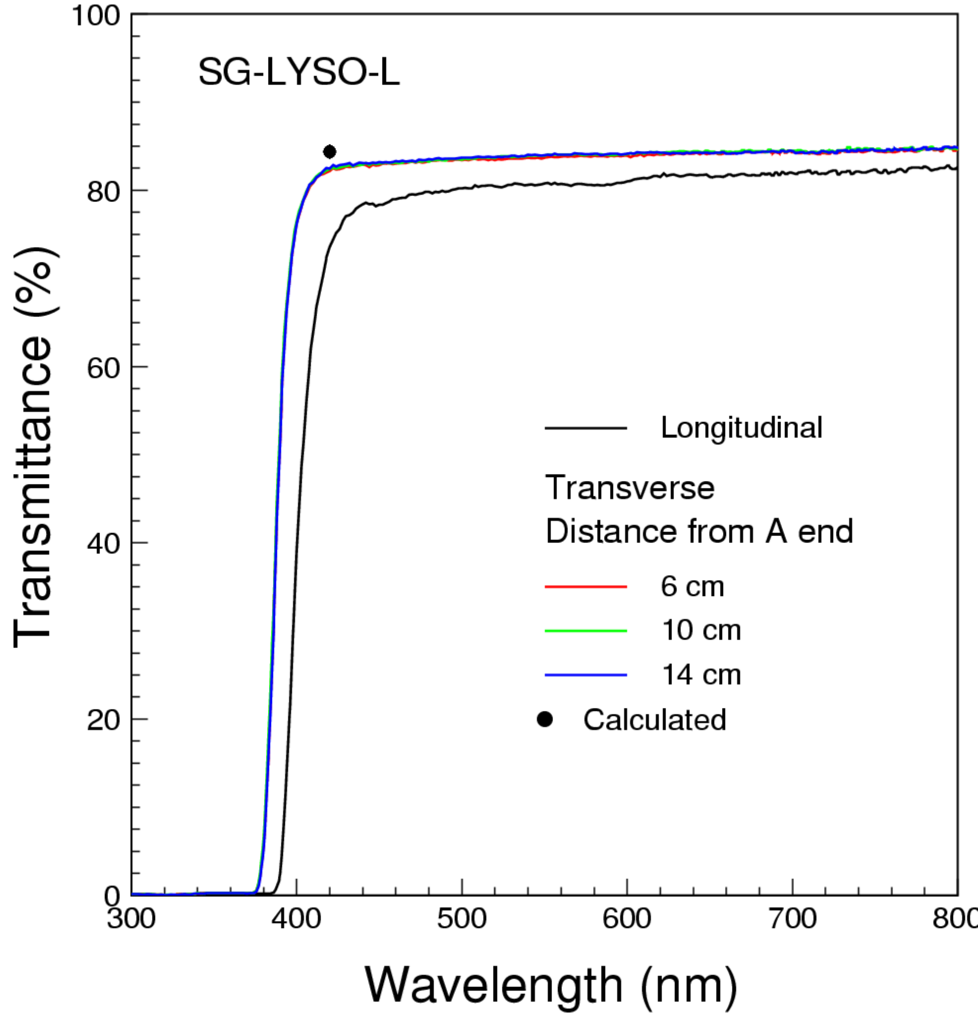


LYSO: Longitudinal Uniformity

No longitudinal variation in optical properties.

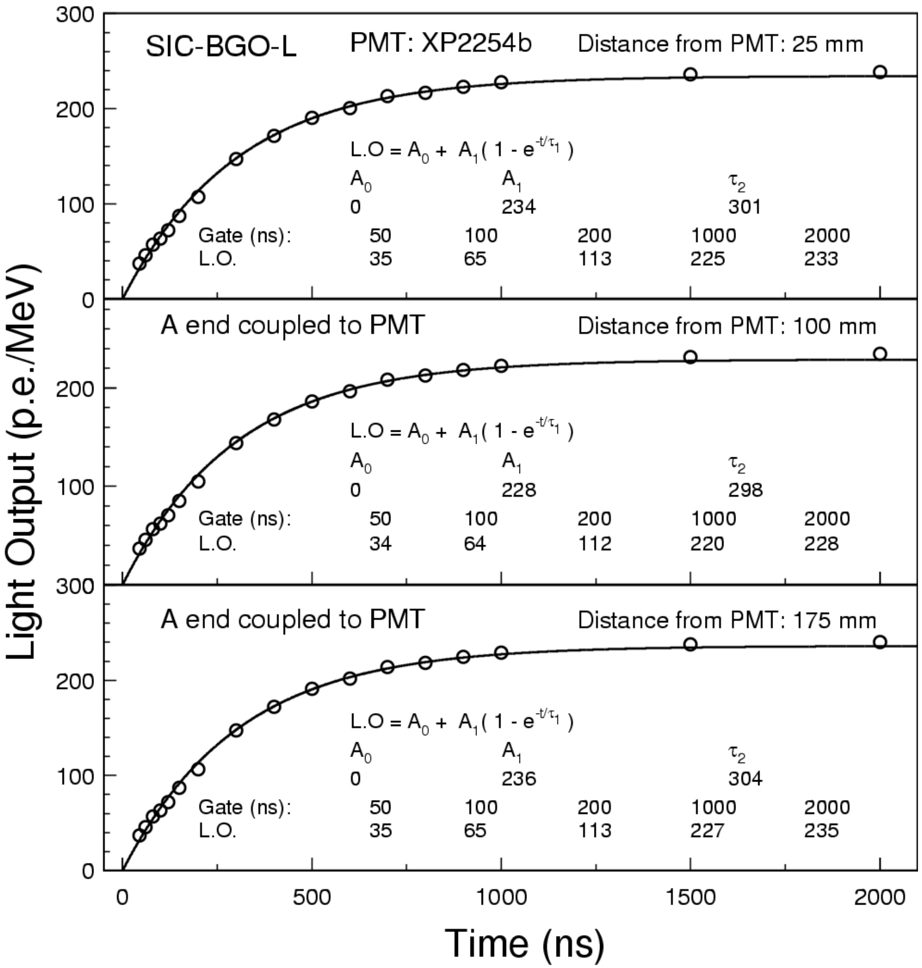
TT approaches theoretical limit, LT shows an absorption band peaked at 580 nm: no effect on emission

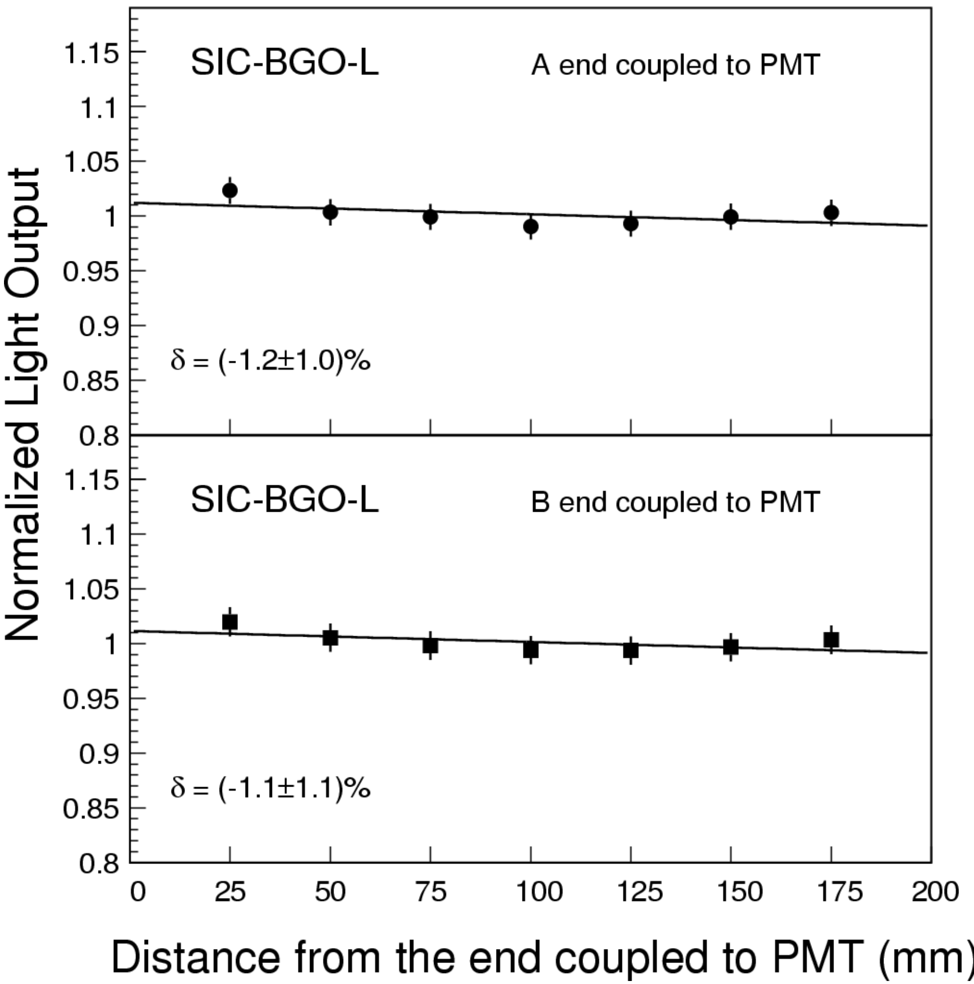




BGO Light Response Uniformity

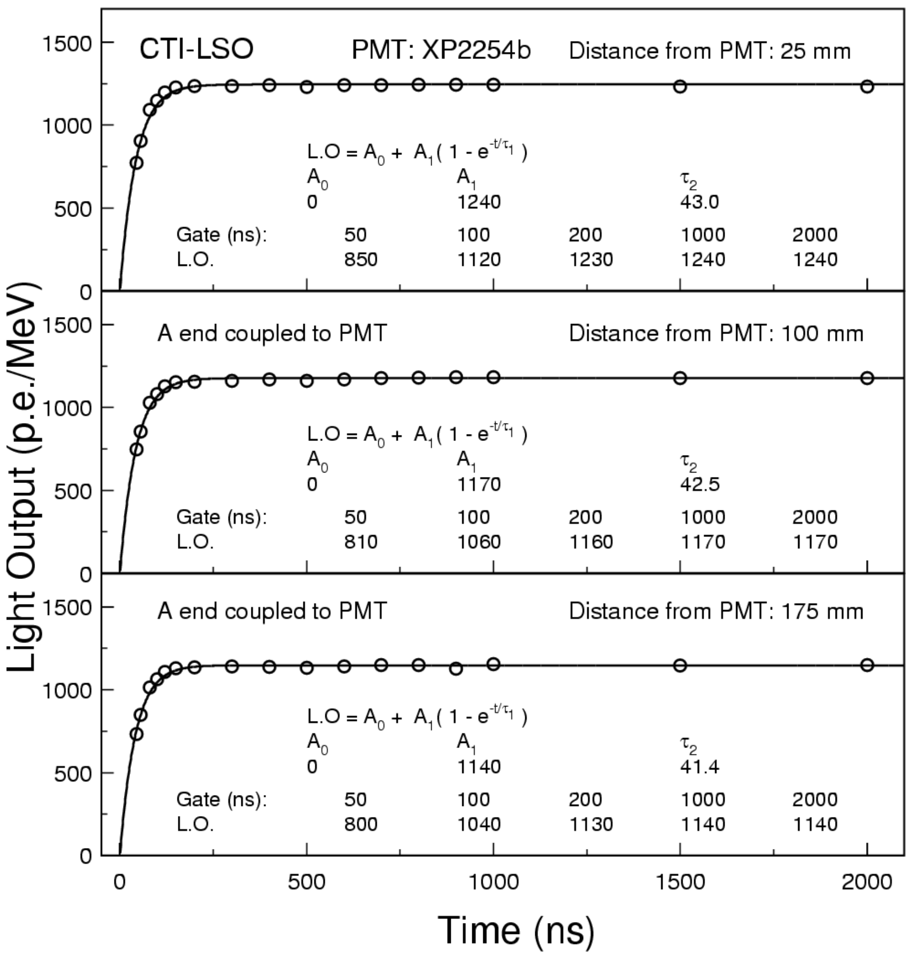
A slight negative slope for both end coupled to the PMT indicating a good longitudinal uniformity

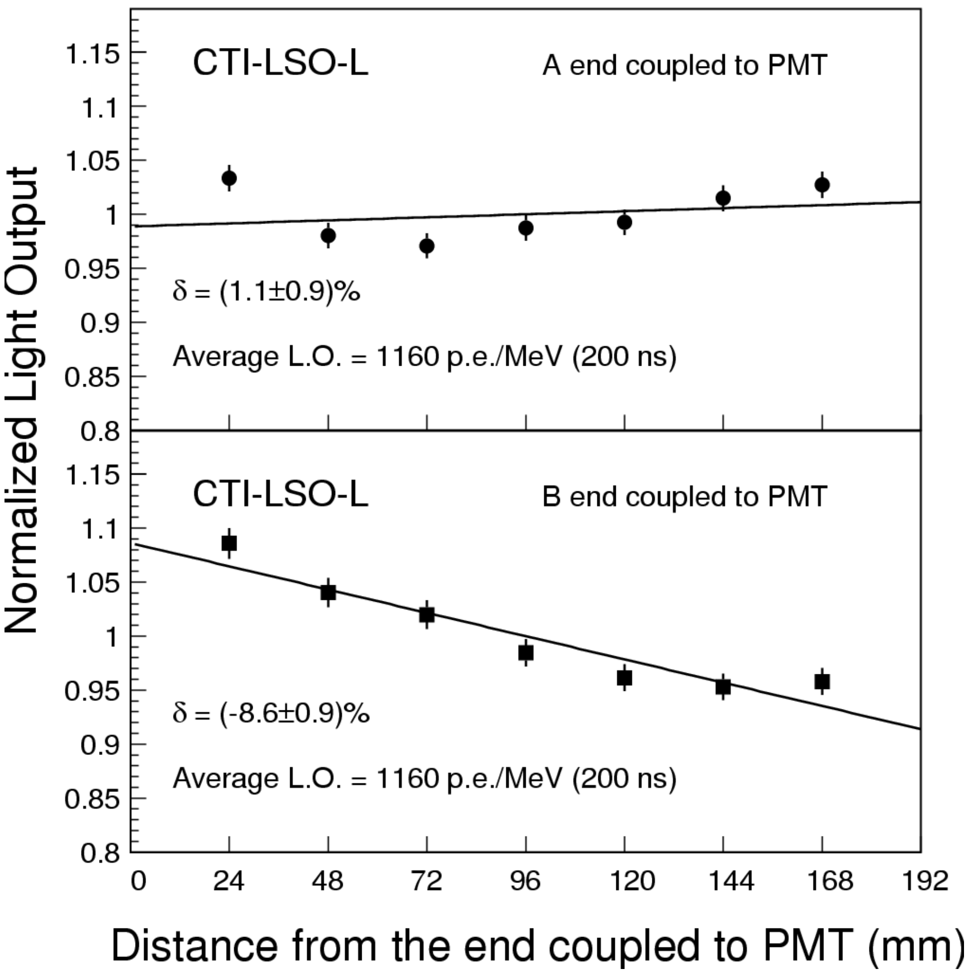




LSO Light Response Uniformity

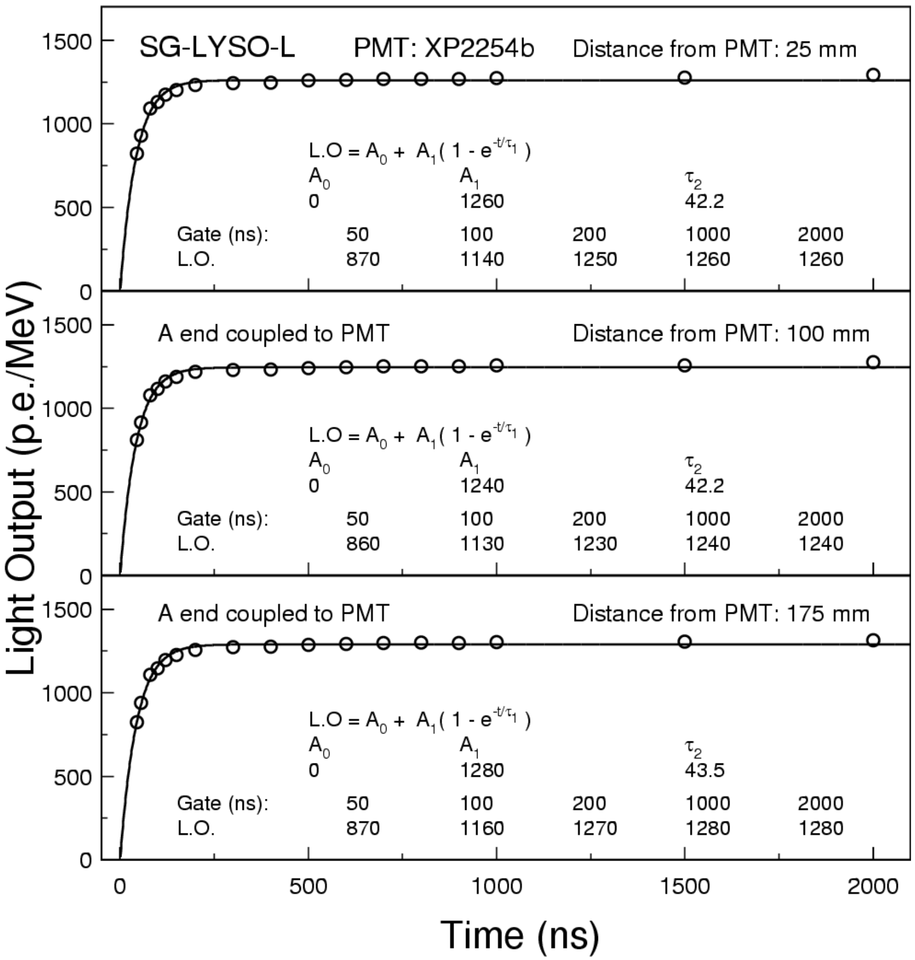
Uniformity depends on which end coupled to the PMT, indicating a not uniform light yield along crystal

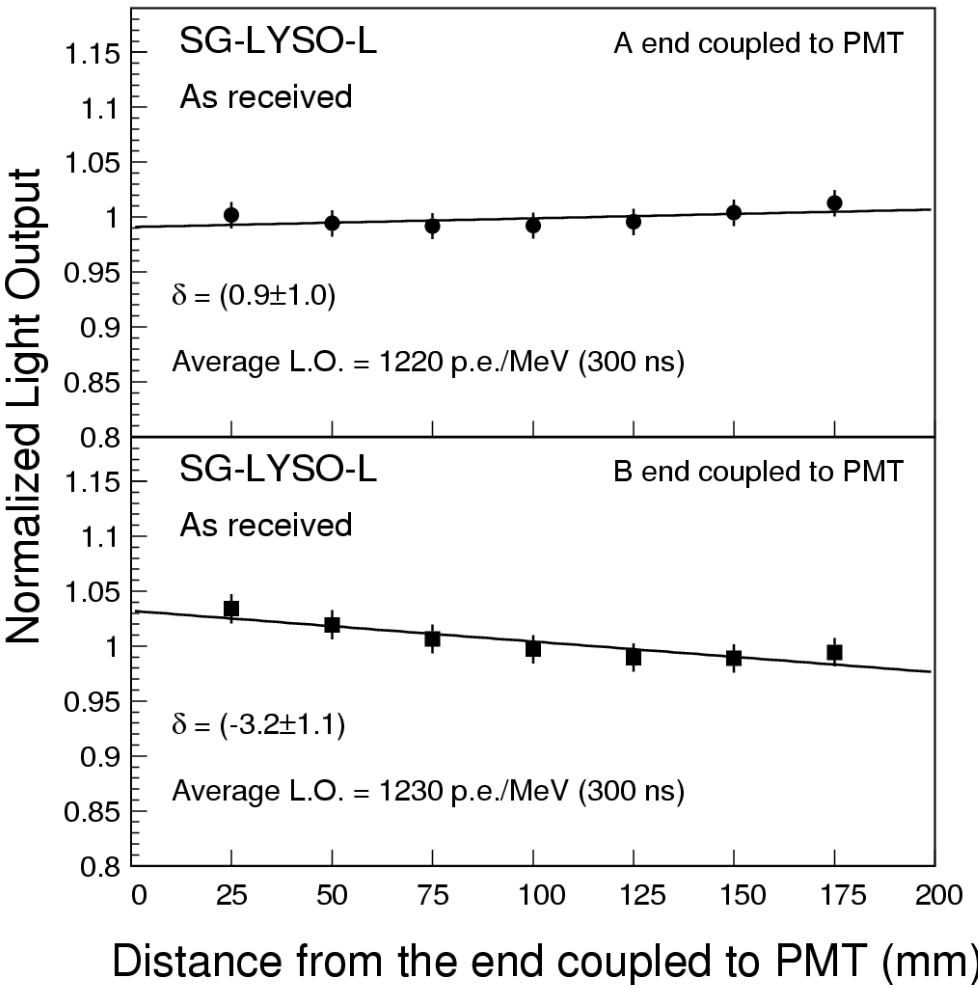




LYSO Light Response Uniformity

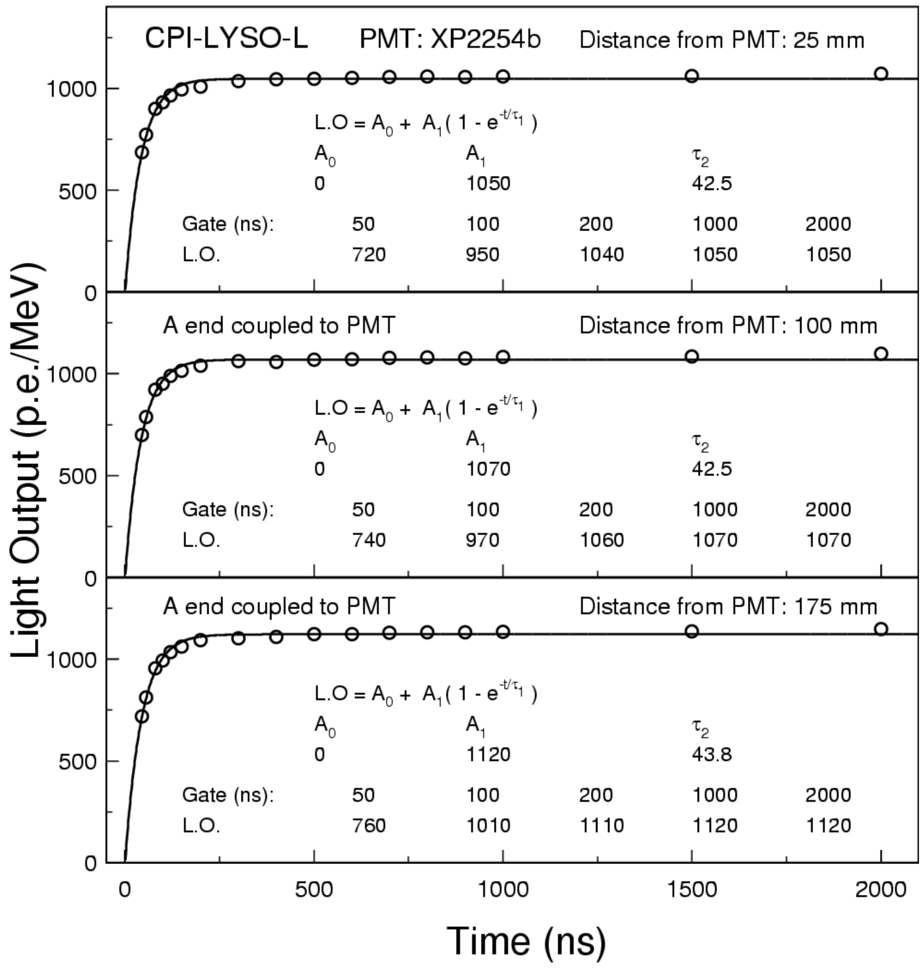
Uniformity depends on which end coupled to the PMT, indicating a not uniform light yield along crystal

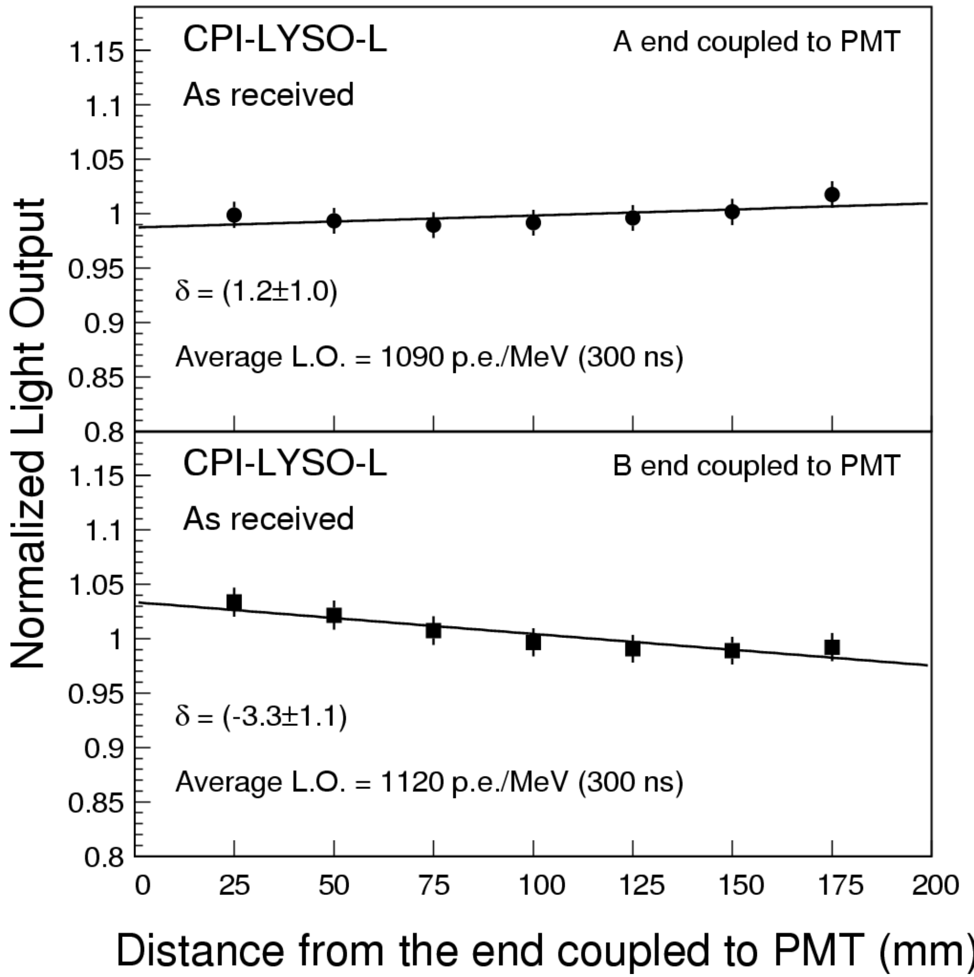




LYSO Light Response Uniformity

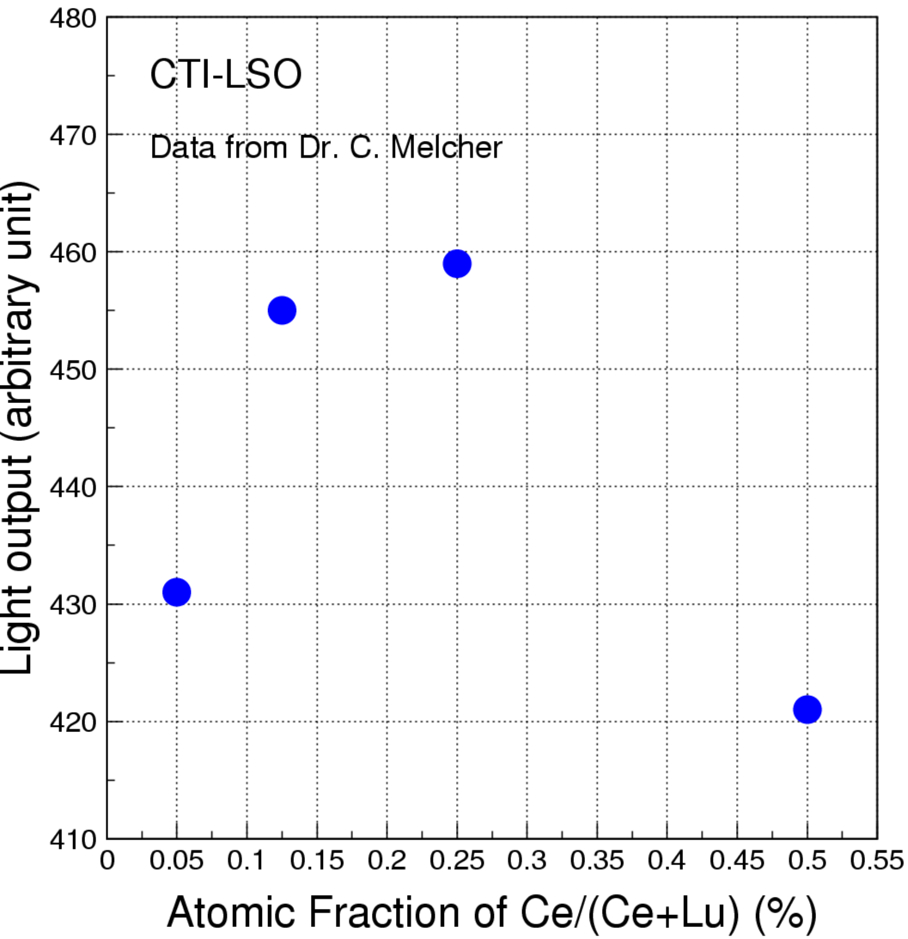
Uniformity depends on which end coupled to the PMT, indicating a not uniform light yield along crystal

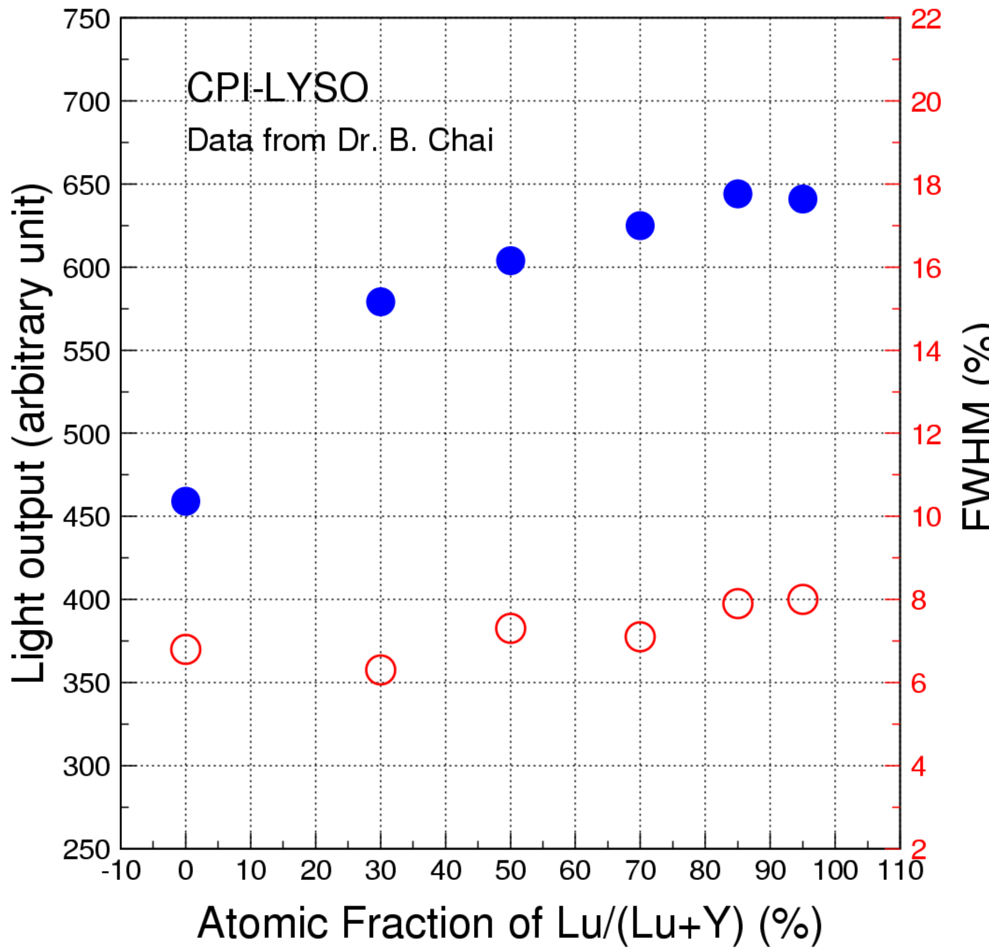




Possible Origin of Non-Uniformity

C. Melcher: LO in LSO is a function of Ce concentration
B. Chai: LO in LYSO is a function of atomic fraction of Yttrium

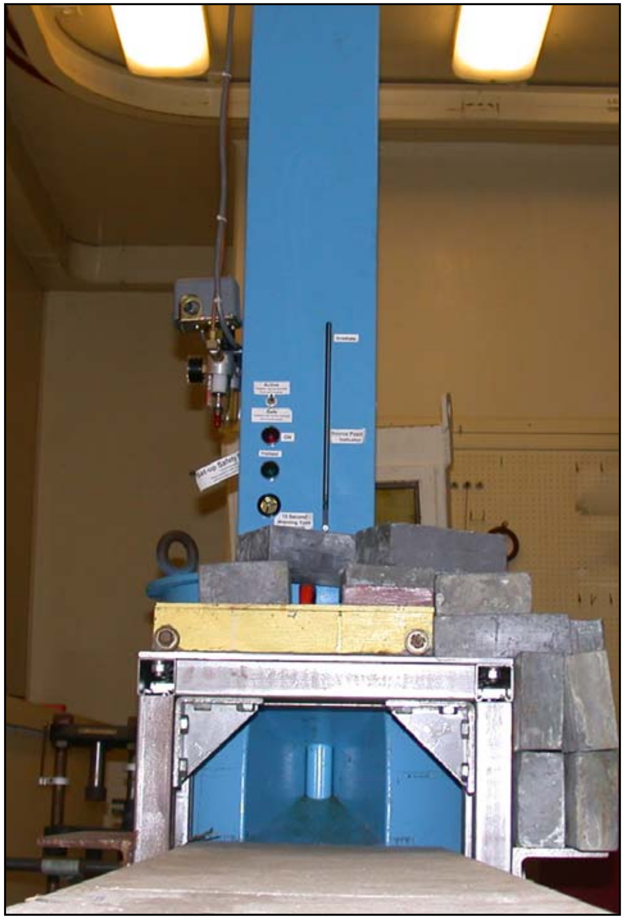




Caltech γ–ray Irradiation Facilities

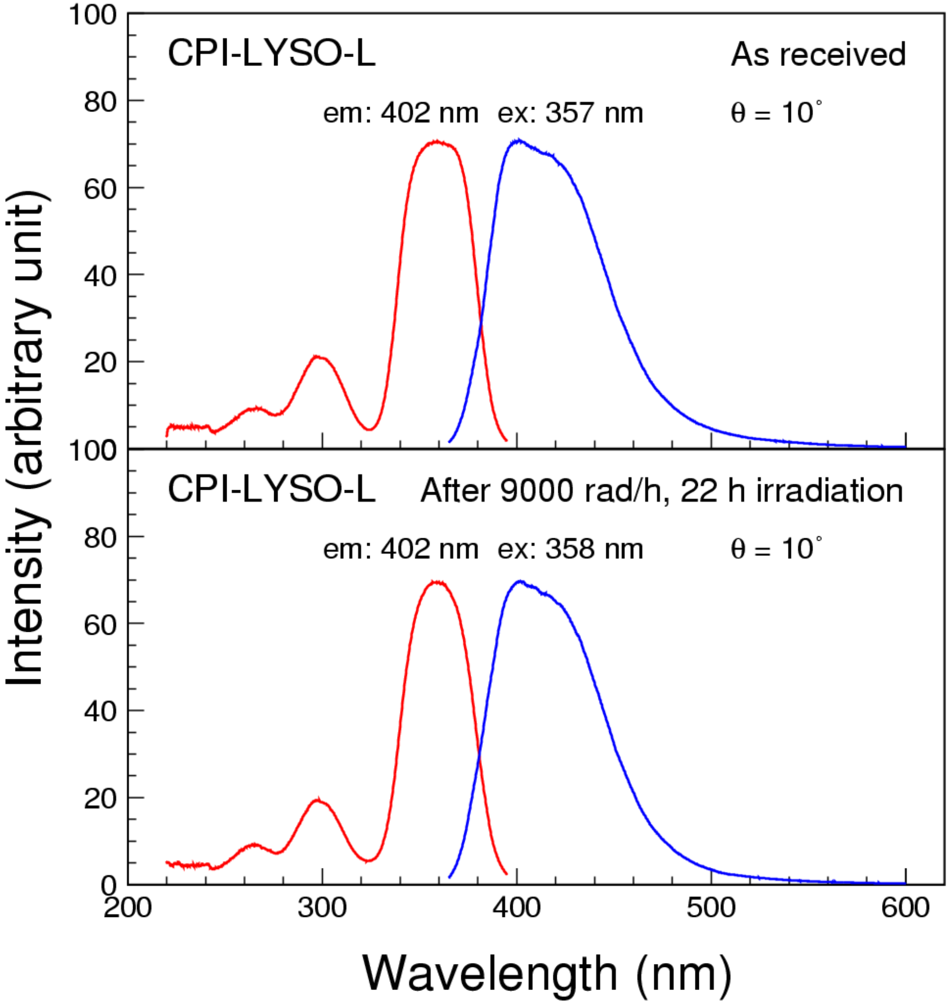
Open 50 curie Co-60 provides 2 & 100 rad/h

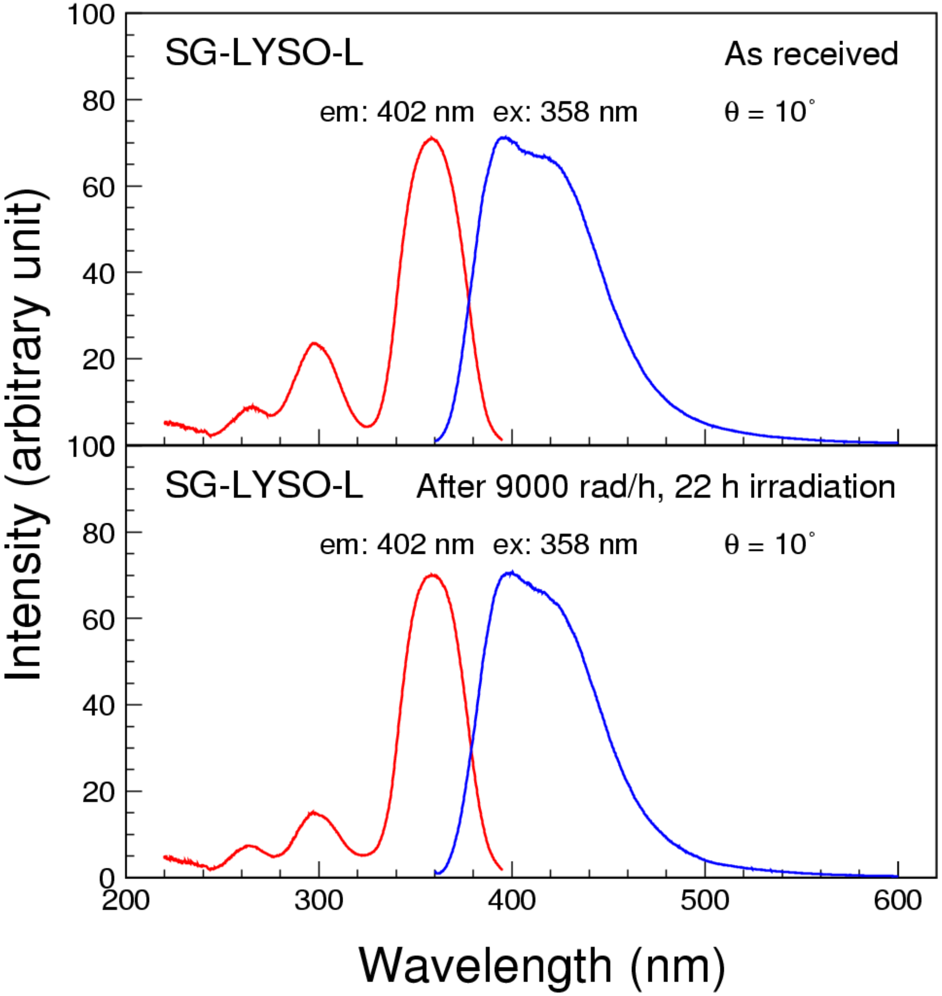
Closed 2,000 curie Cs-137 provides 9k rad/h with 5% uniformity



LYSO Excitation/Emission

No variation in emission & excitation

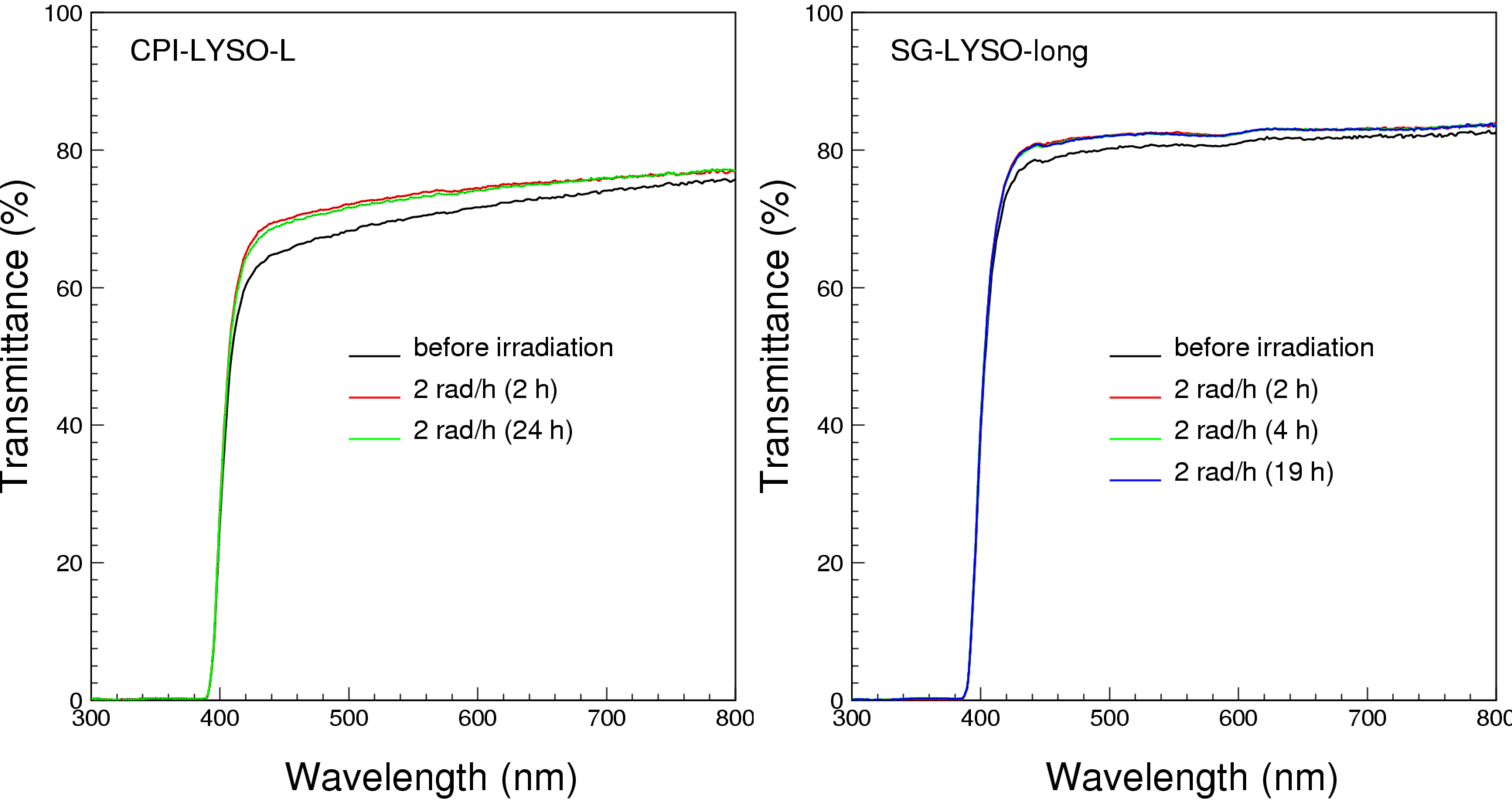




Transmittance Under 2 rad/h

An initial increase under 2 rad/h (need thermal annealing?)

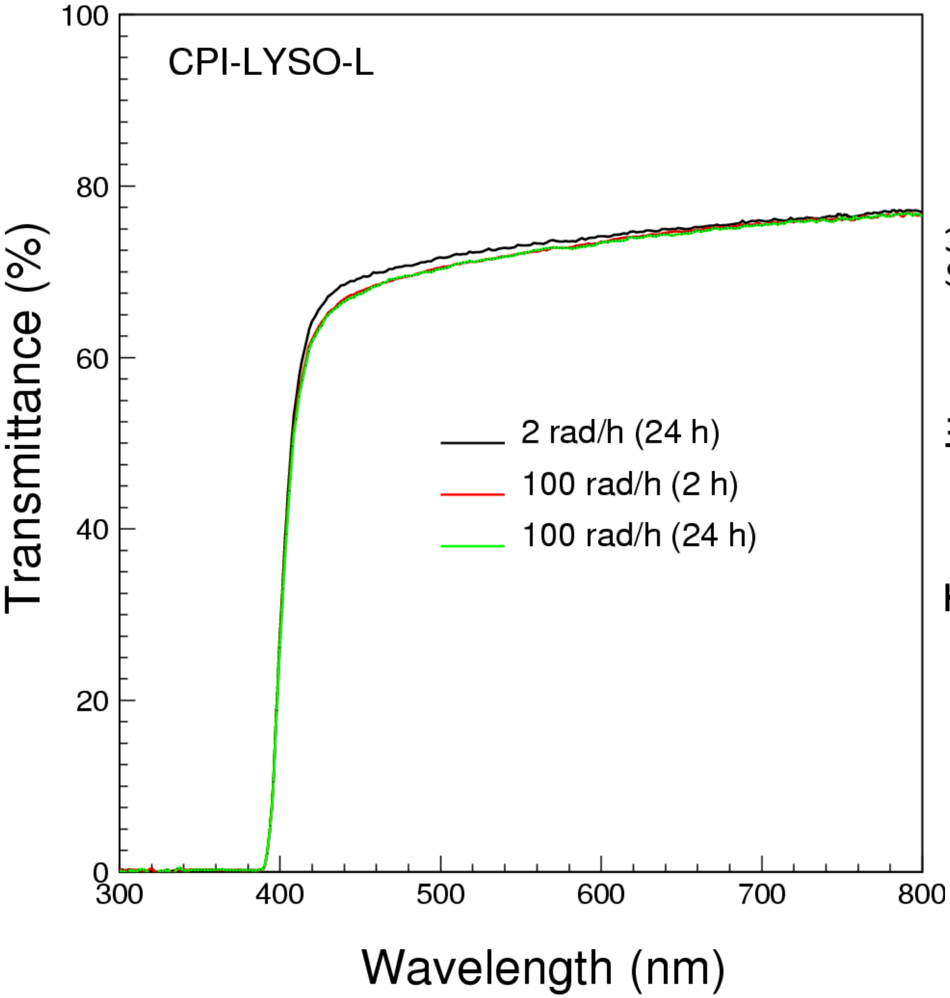
No further variation observed under 2 rad/h

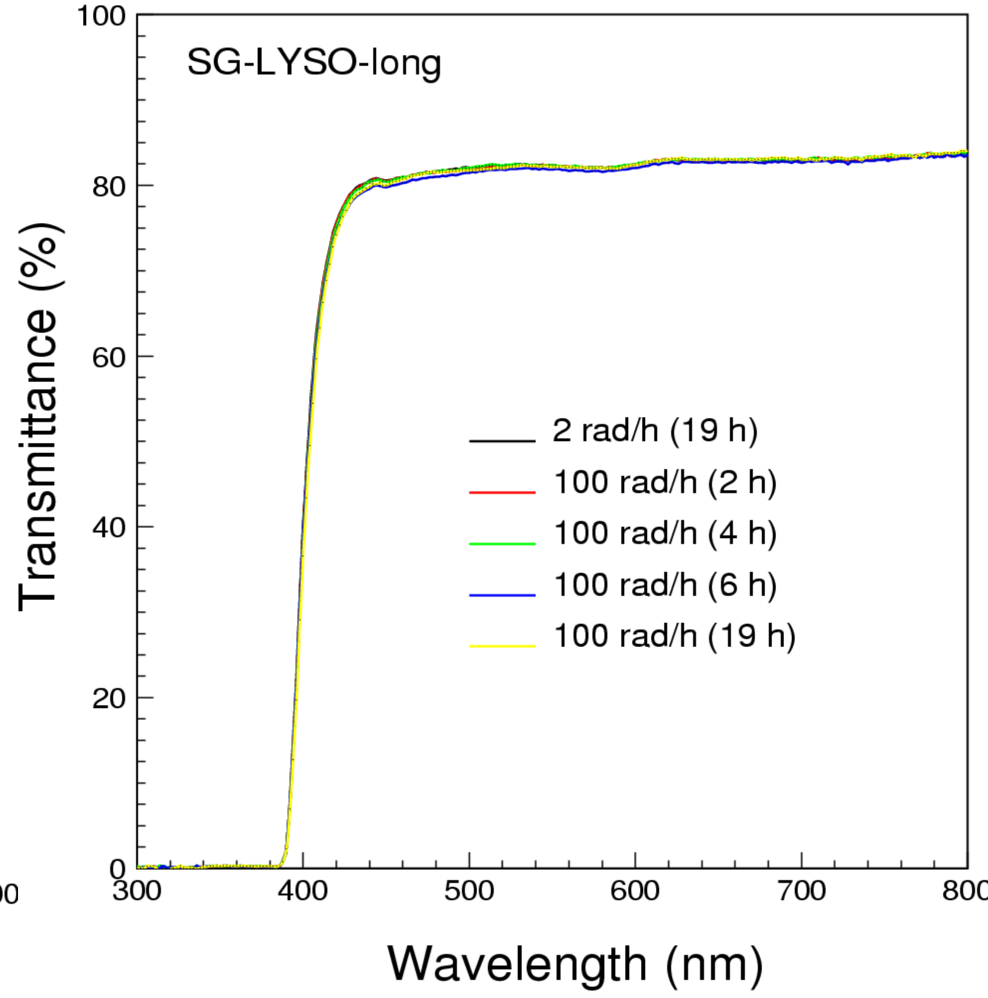


Transmittance Under 100 rad/h

Some indication on initial decrease under 100 rad/h

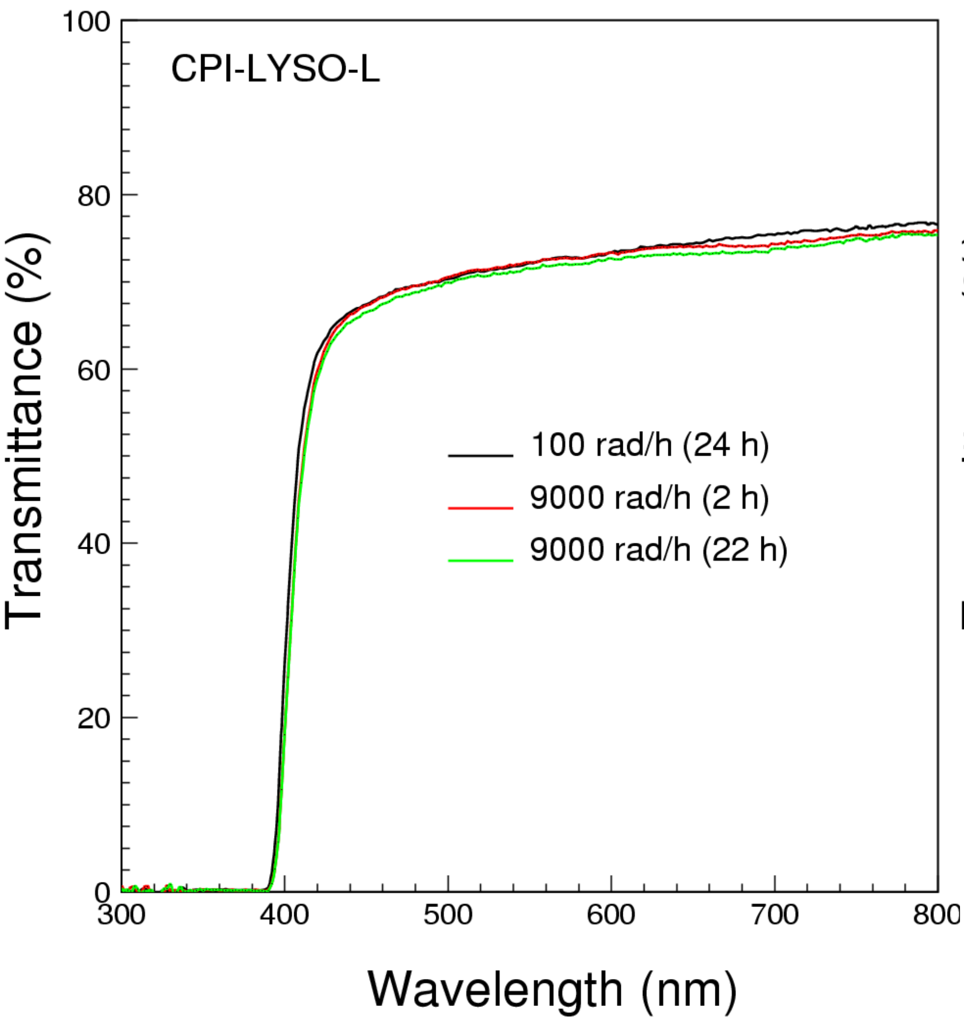
No further variation observed under 100 rad/h

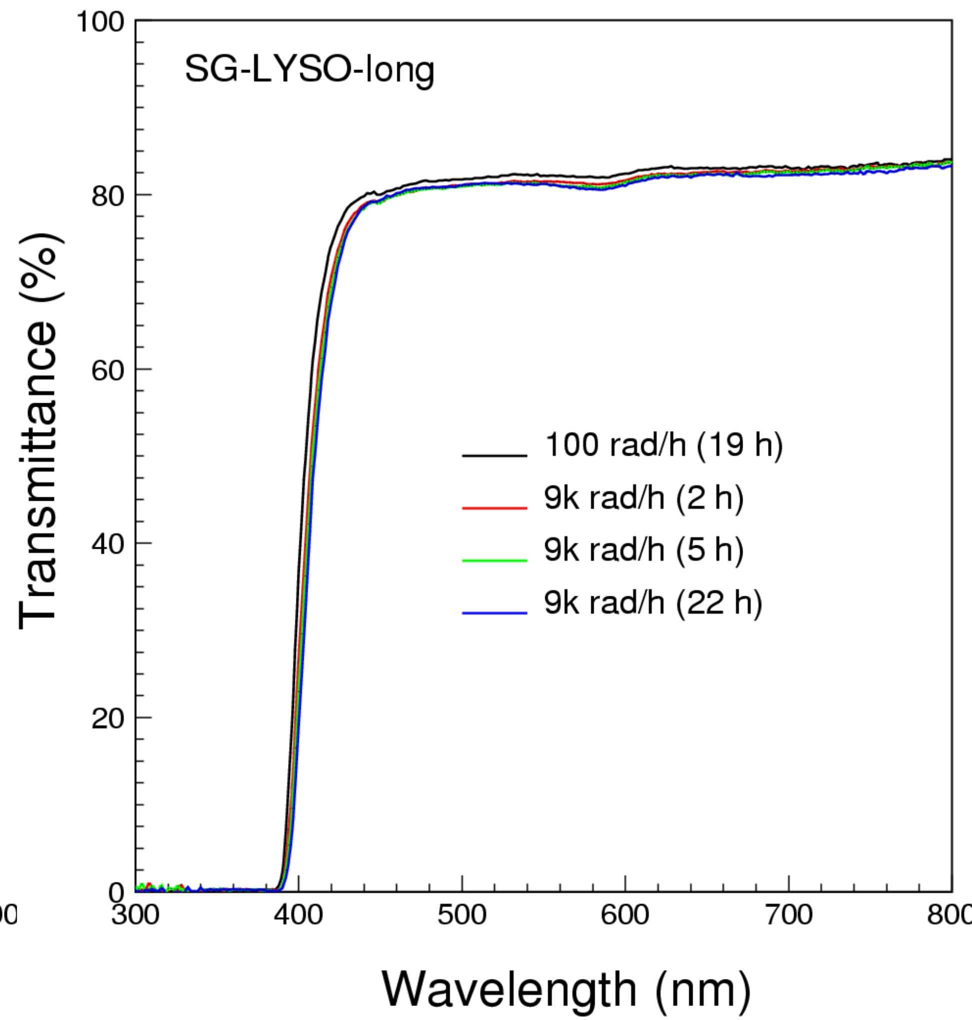




Transmittance Under 9 krad/h

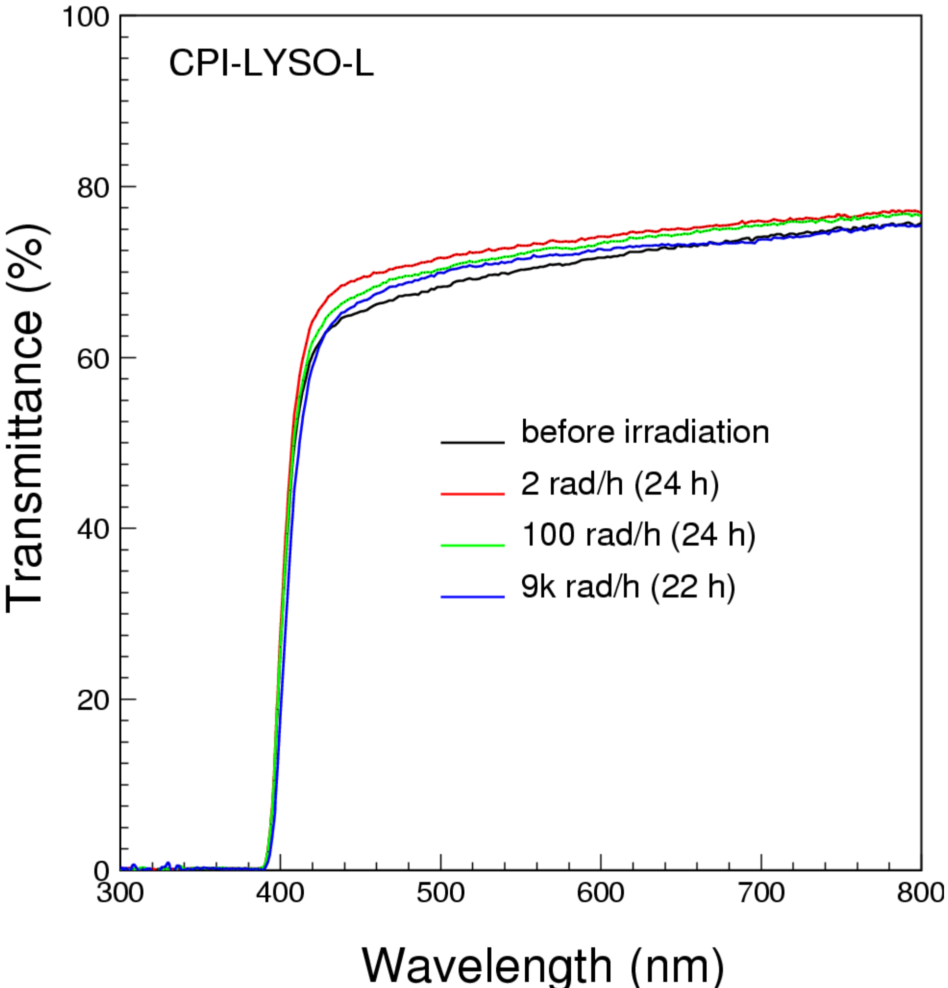
Small variation observed under 9 krad/h

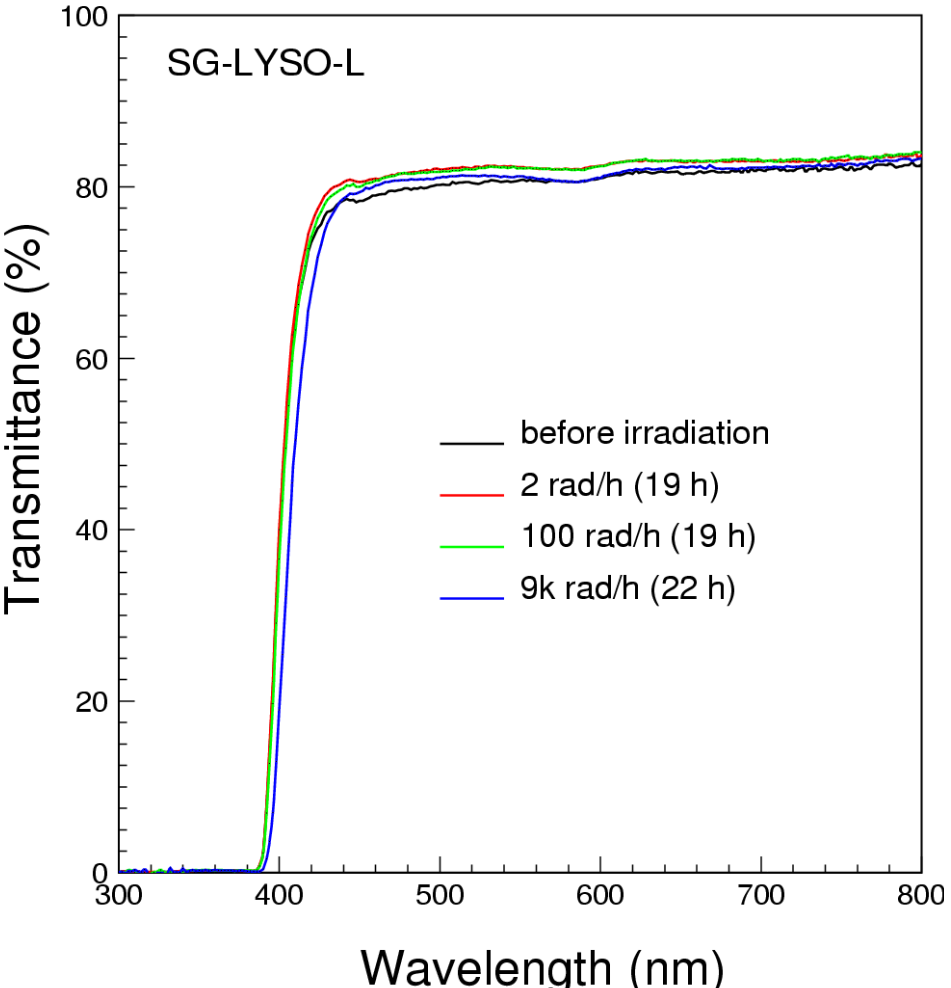




LYSO Longitudinal Transmittance

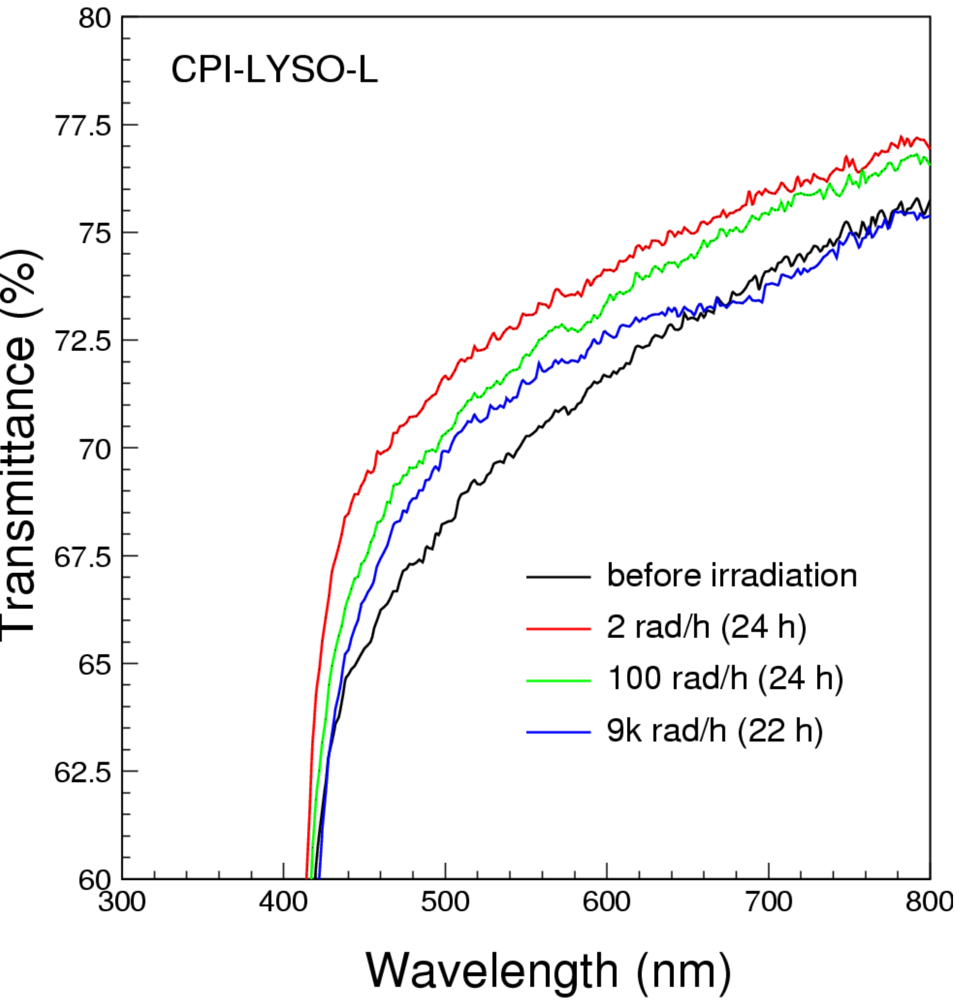
LT@430 nm	Initial	2 rad/h	100 rad/h	9 krad/h
CPI	63.2%	67.1%	64.9%	63.3%
SG	77.1%	79.3%	78.5%	75.7%

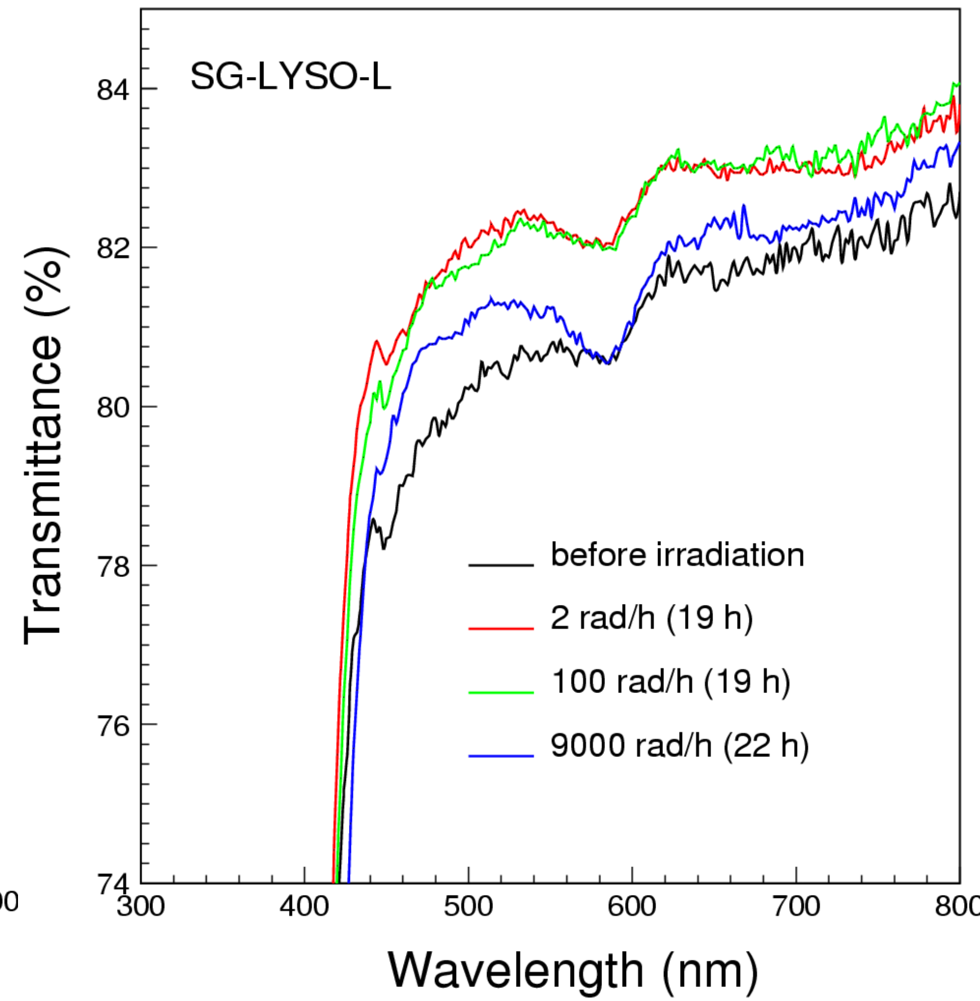




LYSO Transmittance Damage

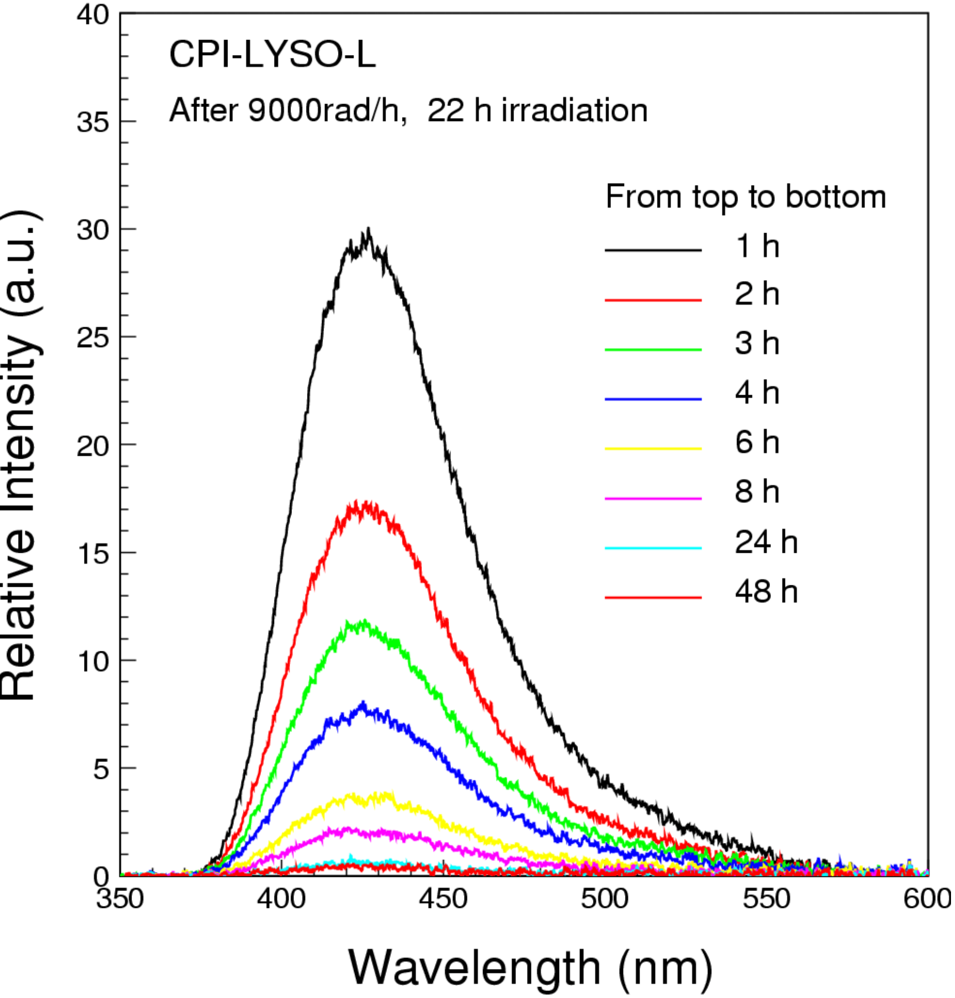
LT @ 430 nm shows 6 and 3% increase under 2 rad/h, followed by 6 and 5% degradation under 9 krad/h for CPI and SG samples respectively

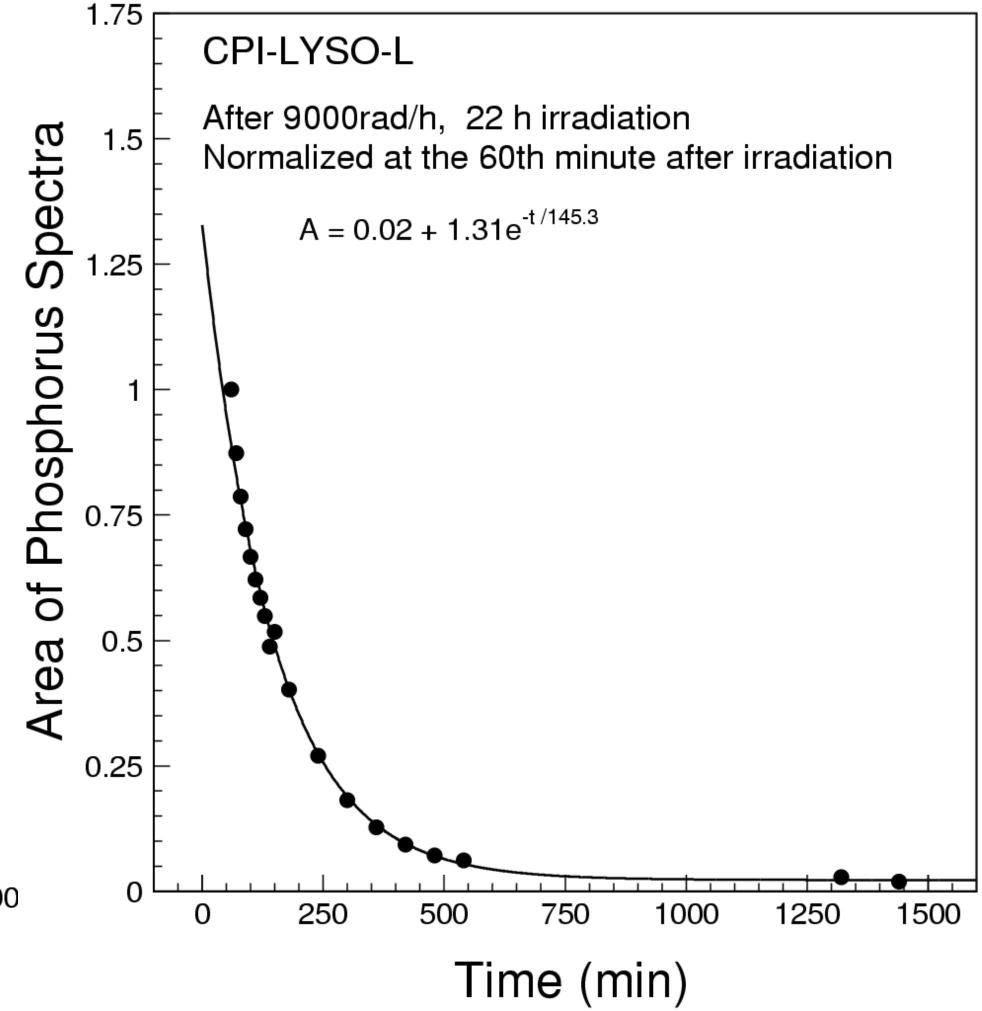




Radiation Induced Phosphorescence

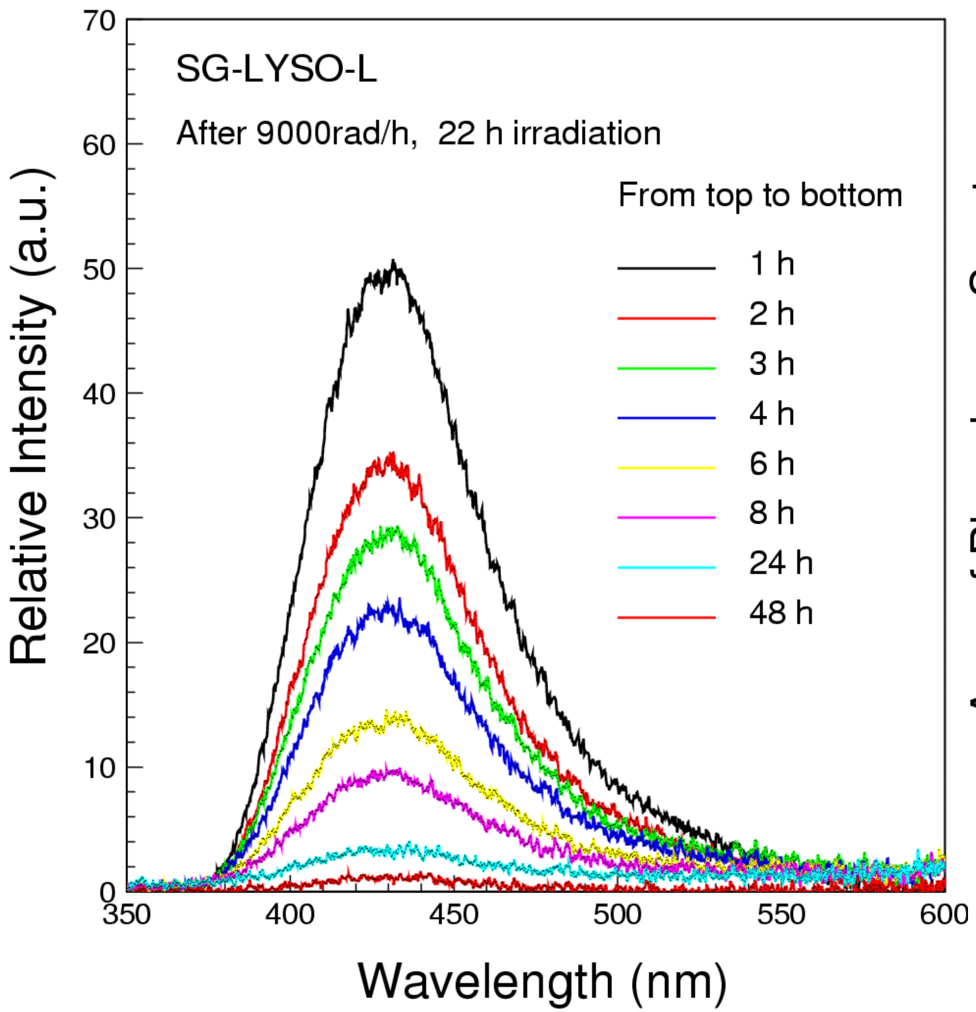
Phosphorescence peaked at 430 nm with decay time constant of 2.5 h observed

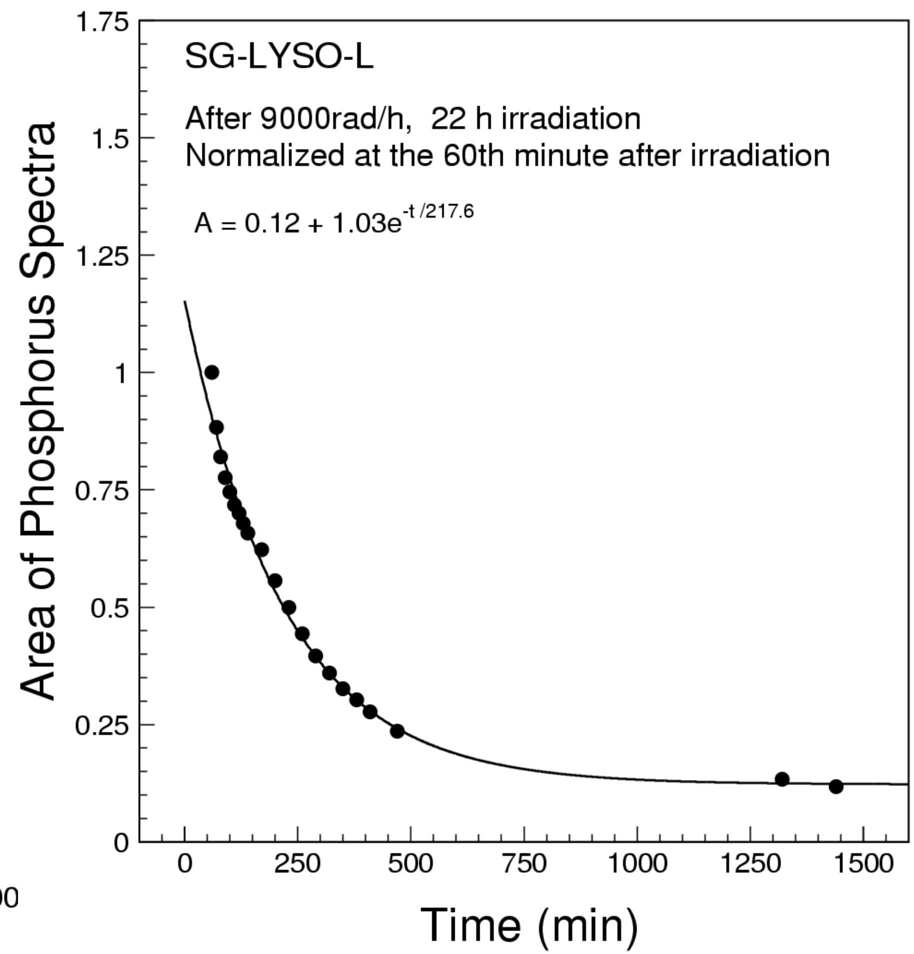




Radiation Induced Phosphorescence

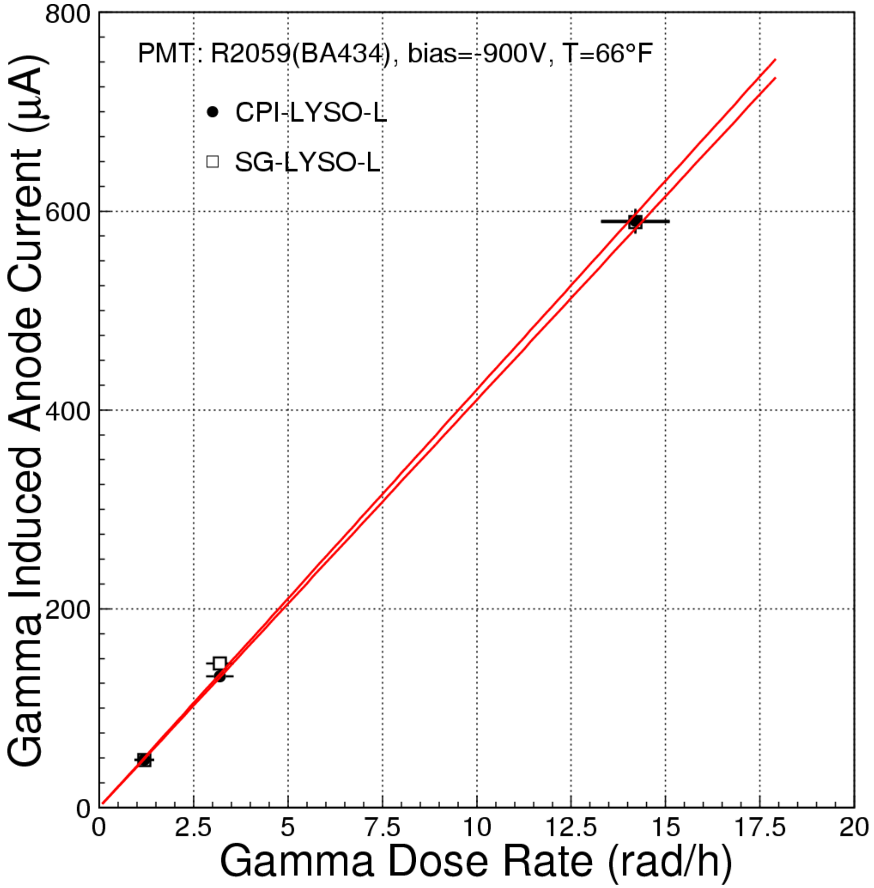
Phosphorescence peaked at 430 nm
with decay time constant of 2 h observed





γ–ray Induced Readout Noise

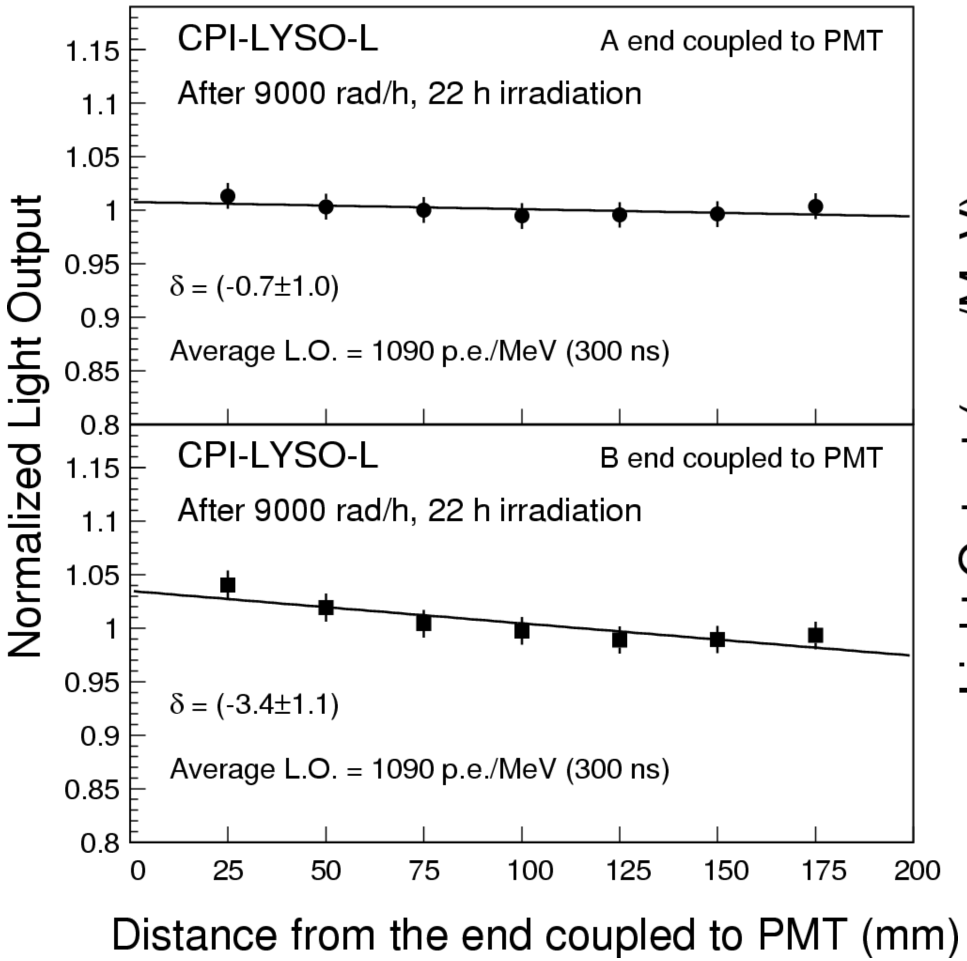
Sample ID	L.Y. p.e./MeV	F μ A/rad/h	$Q_{15\ rad/h}$ p.e.	$Q_{500\ rad/h}$ p.e.	$\sigma_{15\ rad/h}$ MeV	$\sigma_{500\ rad/h}$ MeV
CPI	1,480	41	6.98×10^4	2.33×10^6	0.18	1.03
SG	1,580	42	7.15×10^4	2.38×10^6	0.17	0.97

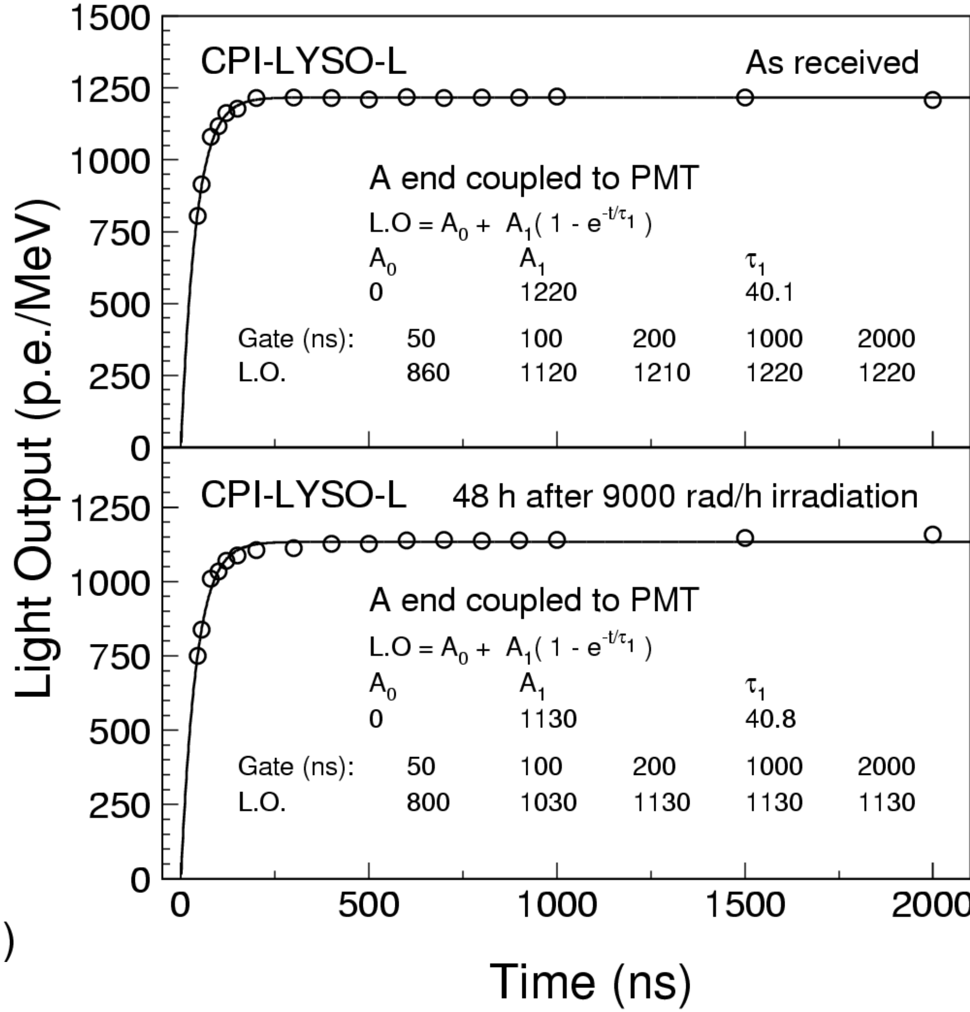


γ–ray induced PMT anode current can be converted to the photoelectron numbers (Q) integrated in 100 ns gate. Its statistical fluctuation contributes to the readout noise (σ).

Radiation Damage in LYSO

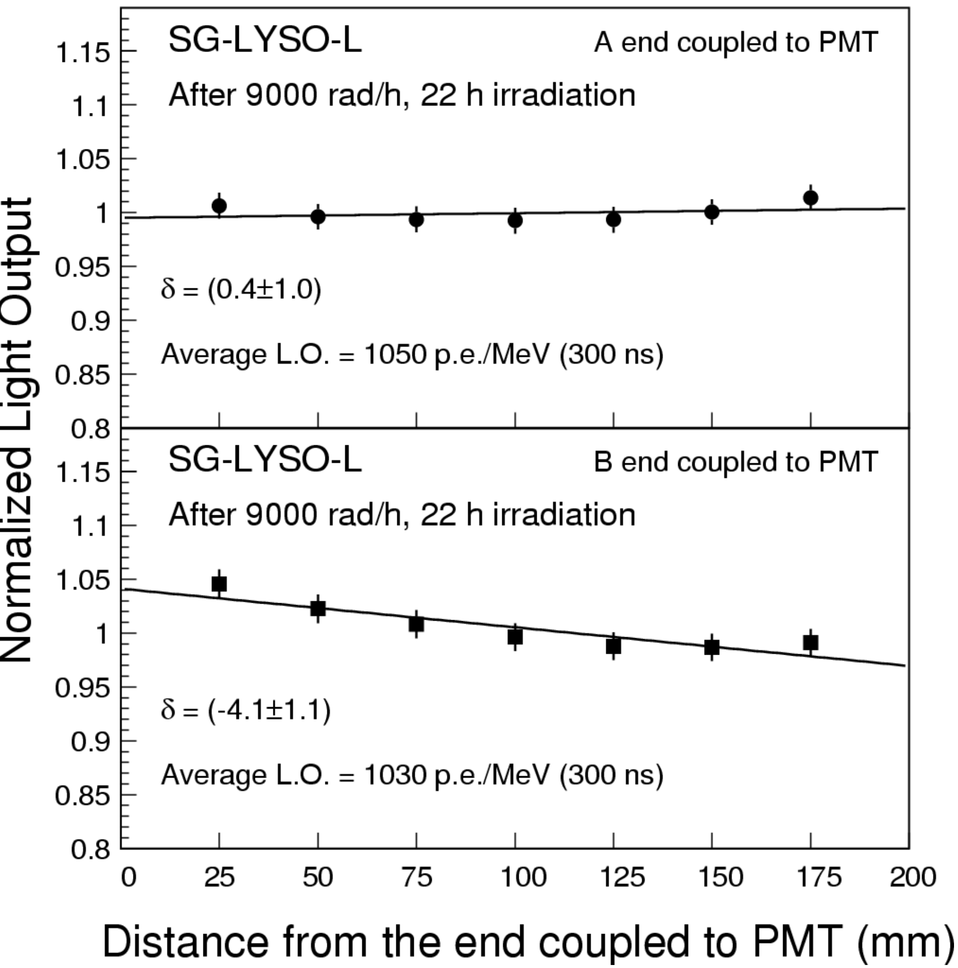
Damages in LRU and LO is small after γ–ray irradiations of 22 h at 9,000 rad/h

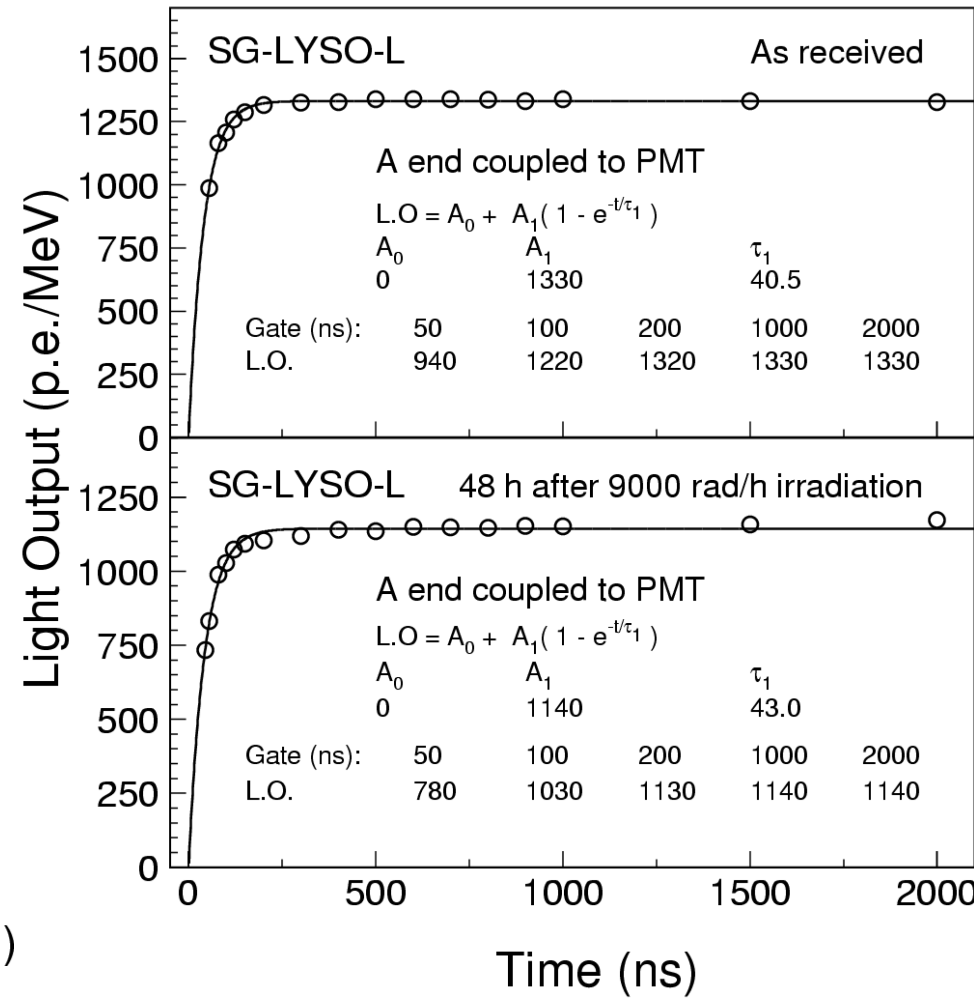




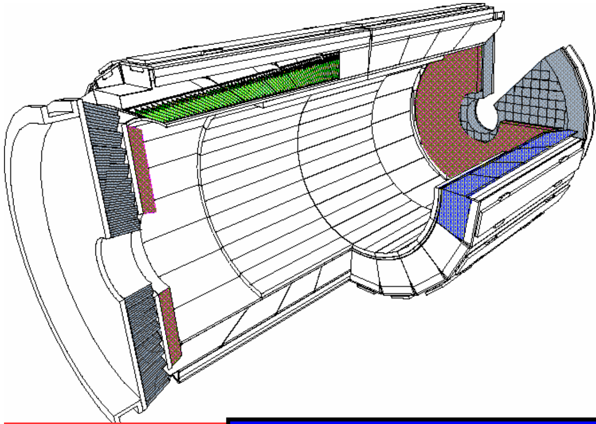
Radiation Damage in LYSO

Damage effect in LRU and LO is small after 22 h γ–ray irradiations at 9,000 rad/h: better than PWO



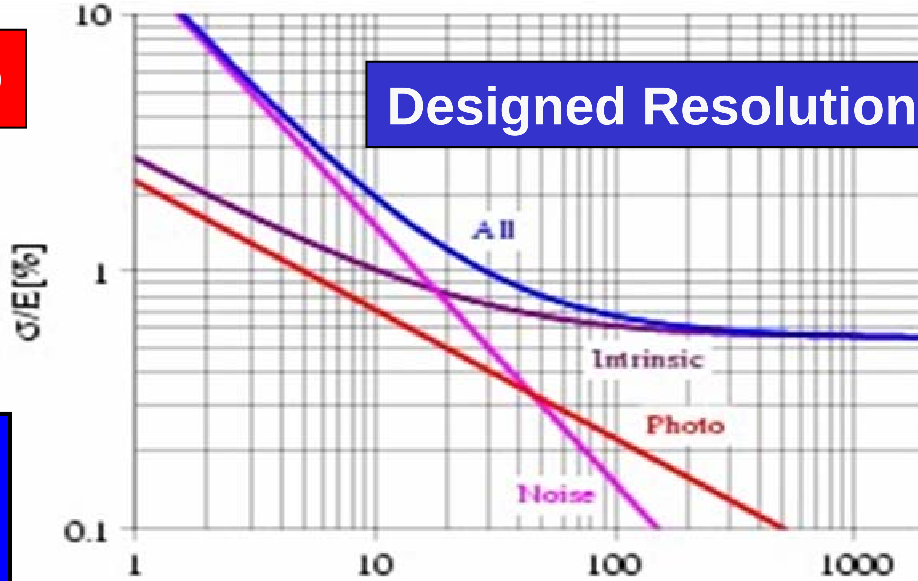


CMS PWO Resolution



77k PWO

Designed Resolution

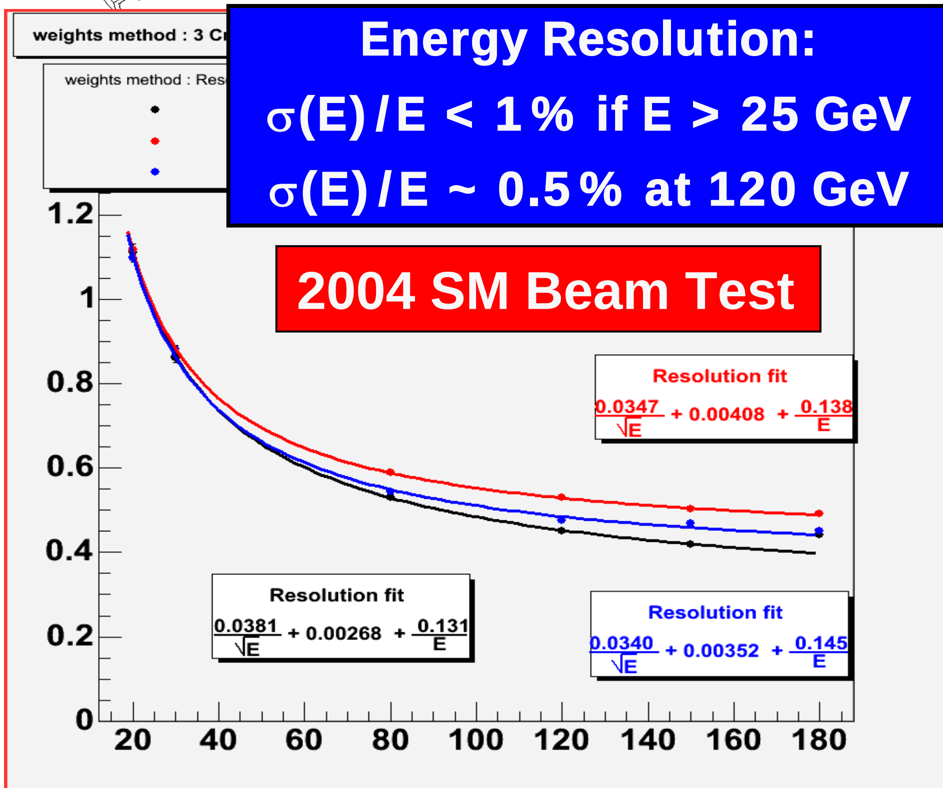


Energy Resolution:

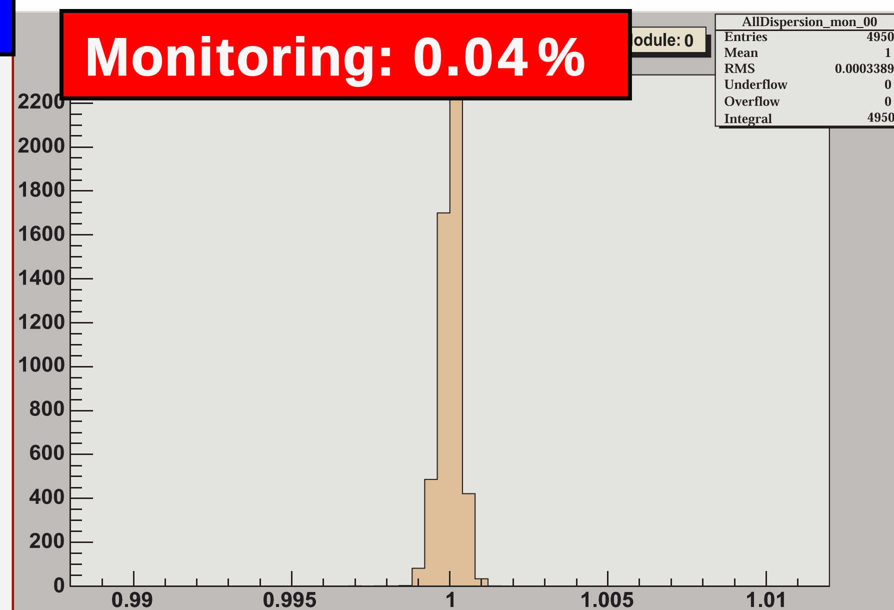
$\sigma(E)/E < 1\%$ if $E > 25$ GeV

$\sigma(E)/E \sim 0.5\%$ at 120 GeV

2004 SM Beam Test



Monitoring: 0.04%



LSO/LYSO ECAL Performance

- A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

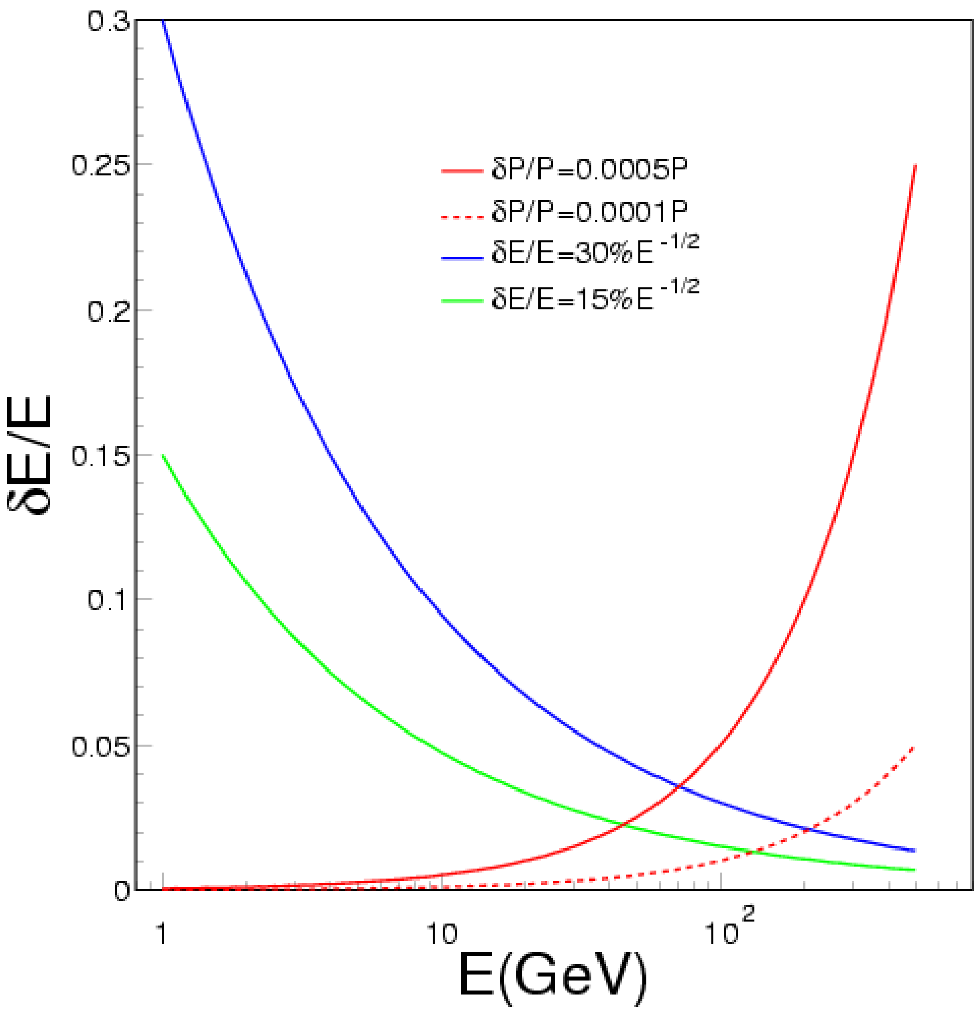
$$2.0\%/\sqrt{E} \oplus 0.5\% \oplus .002/E$$

- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to the CMS PWO ECAL.
- No degradation if ILC energy increases.

Summary: LSO/LYSO ECAL

- Ce doped LSO & LYSO crystals have fast (42 ns) and high (4 X BGO) light output. The light output of 2.5 x 2.5 x 20 cm LSO and LYSO samples, excited by 0.51 MeV γ–ray, can be readout by single APD of 25 mm^2.
- LSO/LYSO has good radiation hardness. The radiation induced phosphorescence in 2.5 x 2.5 x 20 cm LYSO causes ~1 MeV noise @ 500 rad/h.
- An LSO/LYSO crystal calorimeter will provide excellent energy resolution even the beam energy increases, and will produce rich physics with precision electrons and photons at the ILC.

Jet Measurement: Using Tracker



- Jet energy is not well measured by calorimeter, e.g. ZEUS calorimeter.
- Energy of isolated charged cluster may be **replaced** by better measured tracker momentum.
- For overlapping clusters in jets, one has to **subtract** average calorimeter response, leading to **30%** improvement.

Stochastic Term "a" in Jet Resolution

	L3	CDF	ZEUS
Calorimeter	88%	83%	50%
Using Tracker	60%	64%	**35%??**
4C Fit	**23%**		

Jet Energy Measurement

$$E_{jet} = \sum_{i=1}^{n} E_i$$

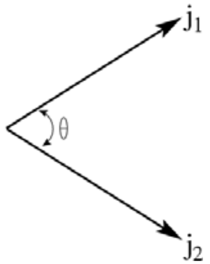
Assuming calorimeter resolution:

$$\frac{\delta E_i}{E_i} = \frac{a}{\sqrt{E_i}} \oplus b$$

Neglecting the constant term b,

$$\frac{\delta E_{jet}}{E_{jet}} = \frac{a}{\sqrt{E_{jet}}}$$

Jet-Jet Mass Measurement



$$M = 2\sqrt{E_1 E_2}\, sin\frac{\theta}{2}$$

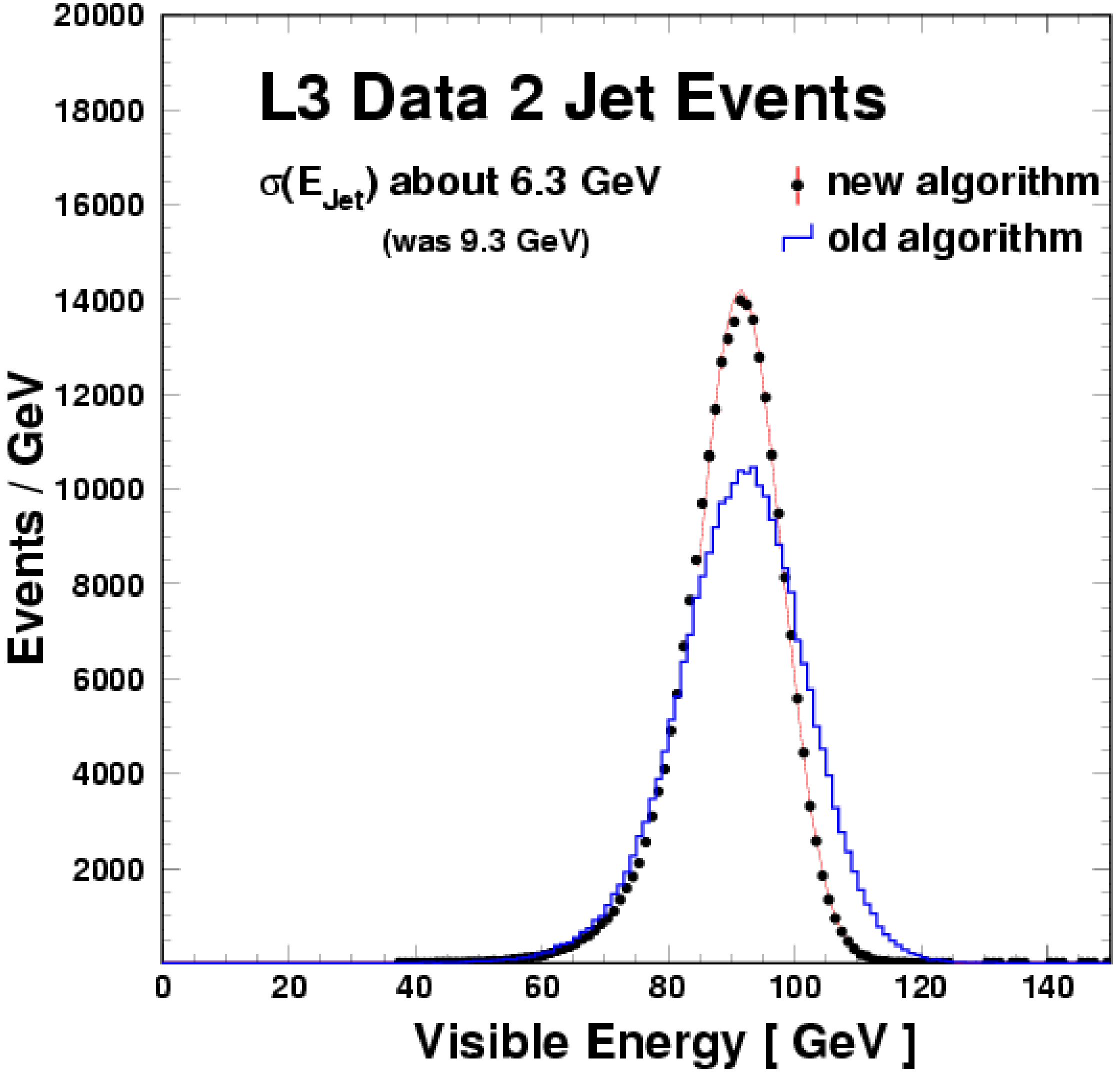
$$\frac{\delta M}{M} = \frac{1}{2}\sqrt{(\frac{\delta E_1}{E_1})^2 + (\frac{\delta E_2}{E_2})^2 + (ctg\frac{\theta}{2}\delta\theta)^2}$$

If $\theta = \pi$ and $E_1 = E_2$,

$$\frac{\delta M}{M} = \frac{a}{\sqrt{M}}$$

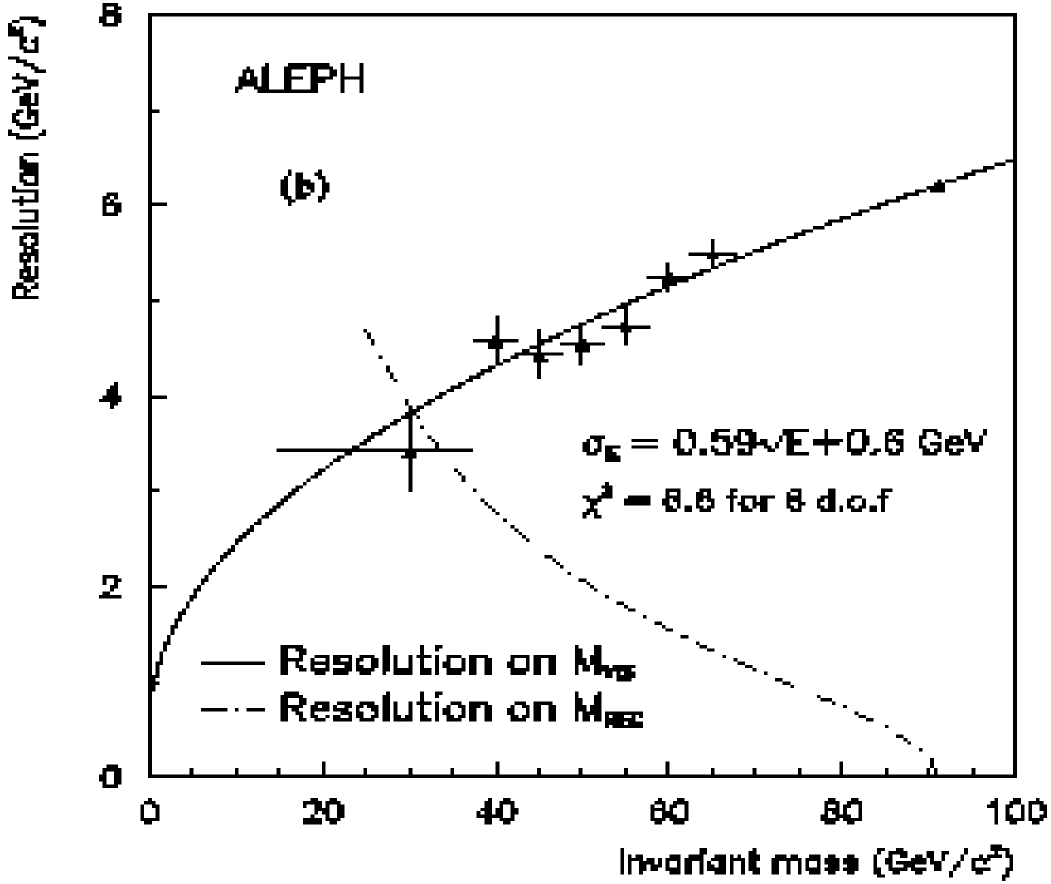
L3 Jet Mass Resolution: Z->qq

Proceedings, Sitges ILC Workshop (1999)

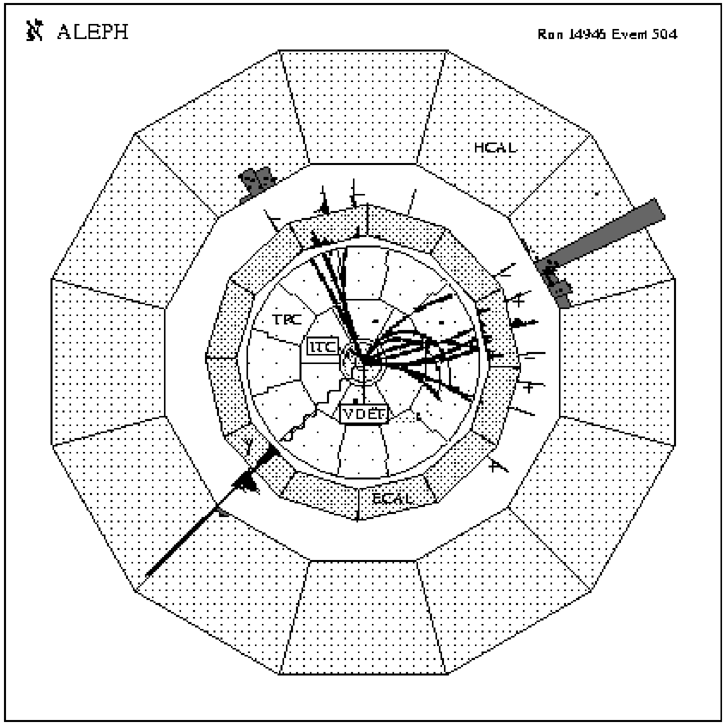


- Measured jet mass resolution: 88%/ √ E
- Using tracker momentum for charged particles: 60%/ √ E
- 30% improvement since calculated energies was subtracted.

ALEPH: Jet Mass Resolution: Z->qqγ



M. Minard, Calor2002



$\sigma(E)=(0.59+-0.03)\sqrt{E}+(0.6+-0.3)$ GeV: 6.3 GeV @ Z

CDF Jet Energy Resolution

Photon + Jets by CDF, using shower maximum (particle ID) and tracker: 25% improvement.

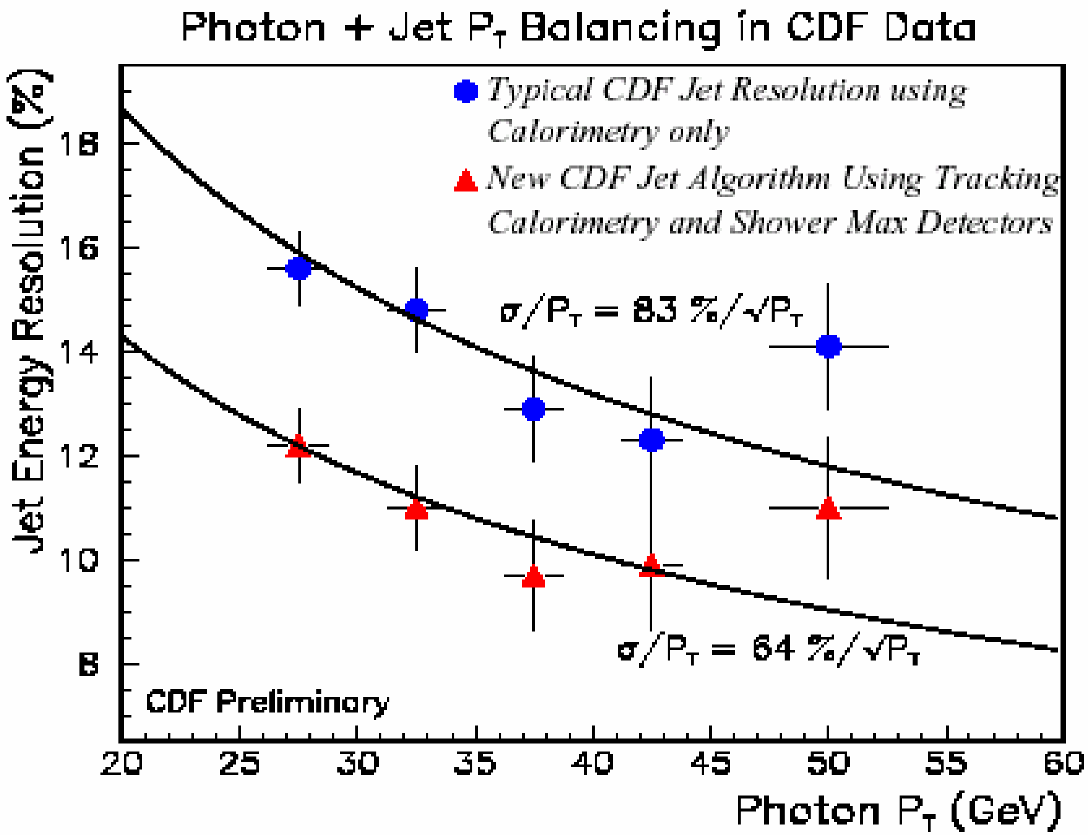


Figure 4: *The central detector resolution σ_D is plotted as a function of P_T^γ for the two methods.*

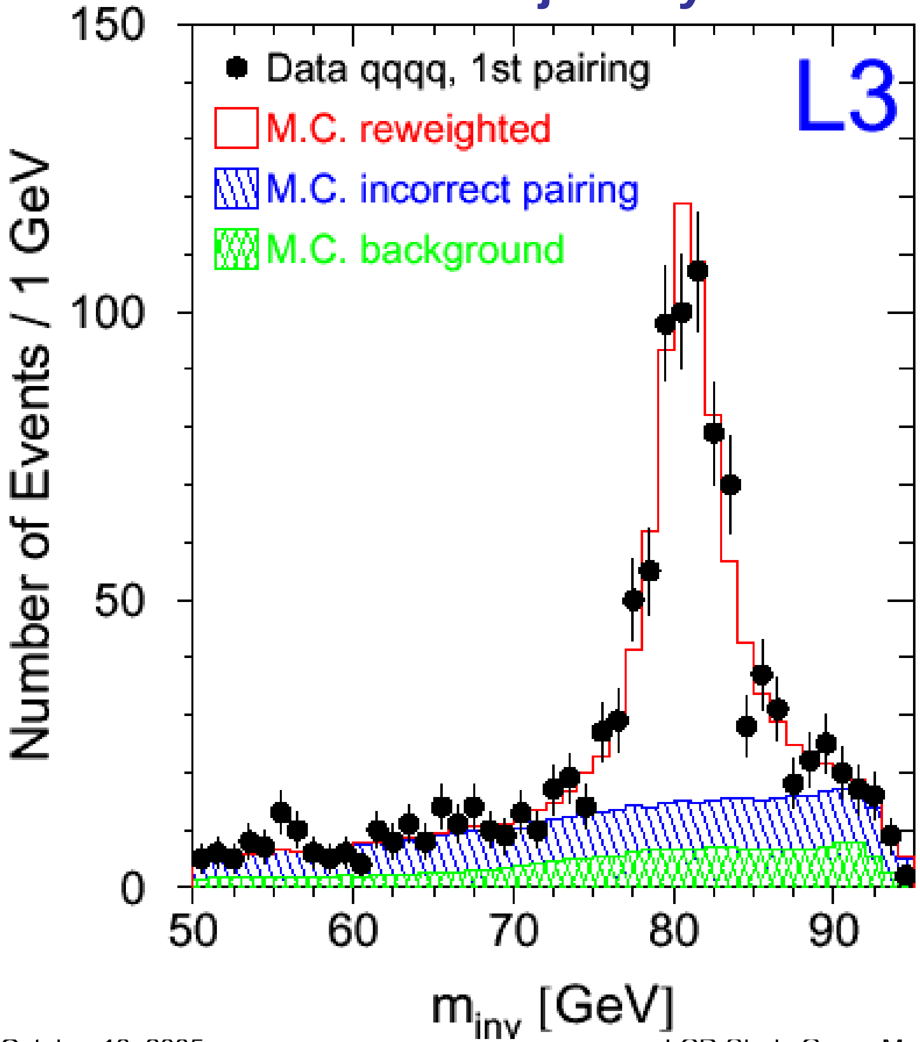
U. Baur et al., Fermilab-Pub-001297, 2000.

The Best Jet Mass Resolution at LEP

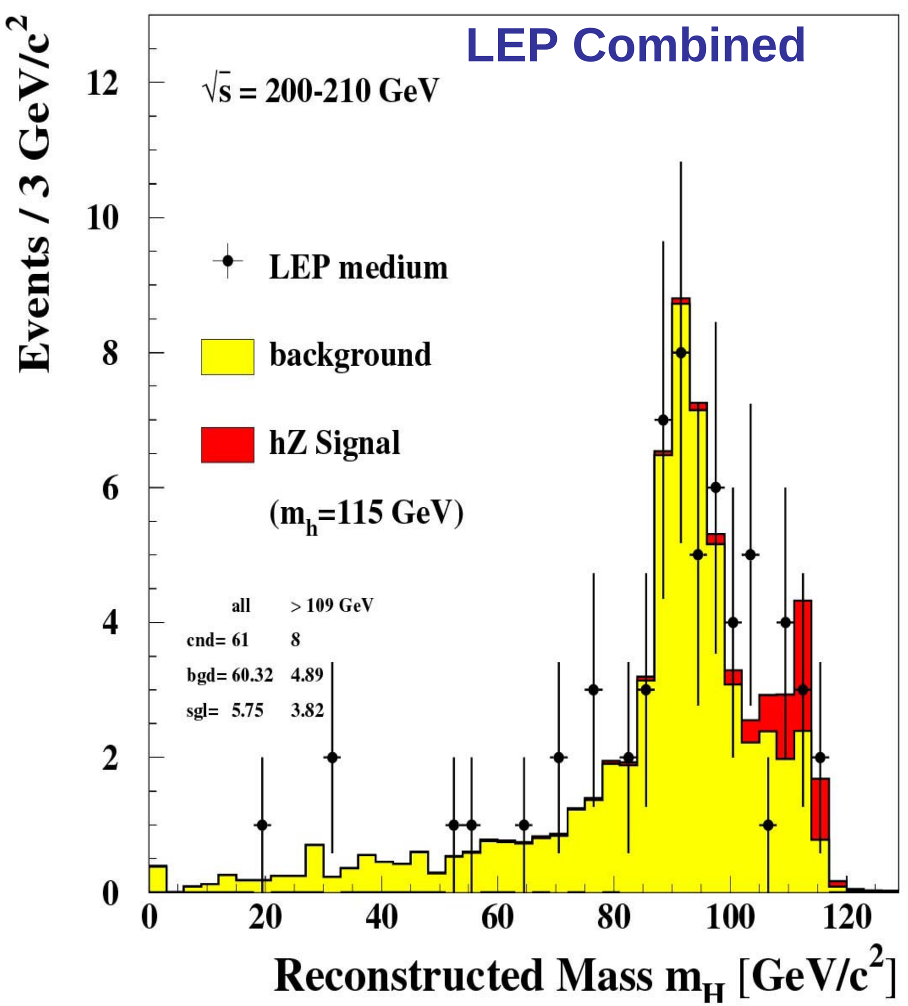
achieved by using jet direction and constrained fit

Proceedings, Jeju ILC Workshop (2002)

W Mass with 2 jets by L3: 3%



Higgs with 2 jets at LEP: 3%



“Theoretical Limit” of the PFA?

V. Morgunov, Paper in Calor2002 Proceedings

E_{jet} consists, in average, 30% γ, 60% charged hadron (c.h.) and 10% neutral hadron (n.h.)

Assuming calorimeter resolutions:

$$\frac{\delta E_\gamma}{E_\gamma} = \frac{11\%}{\sqrt{E_\gamma}} \text{and}$$

$$\frac{\delta E_{n.h}}{E_{n.h}} = \frac{40\%}{\sqrt{E_{n.h}}}.$$

Assuming 100% charged track replacement,

$$\frac{\delta E_{c.h}}{E_{c.h}} = 10^{-4} E_{c.h},$$

which is negligible, modern **energy flow** has

$$\frac{\delta E_{jet}}{E_{jet}} = \frac{\sqrt{0.00363 + 0.016}}{\sqrt{E_{jet}}} = \frac{14\%}{\sqrt{E_{jet}}}.$$

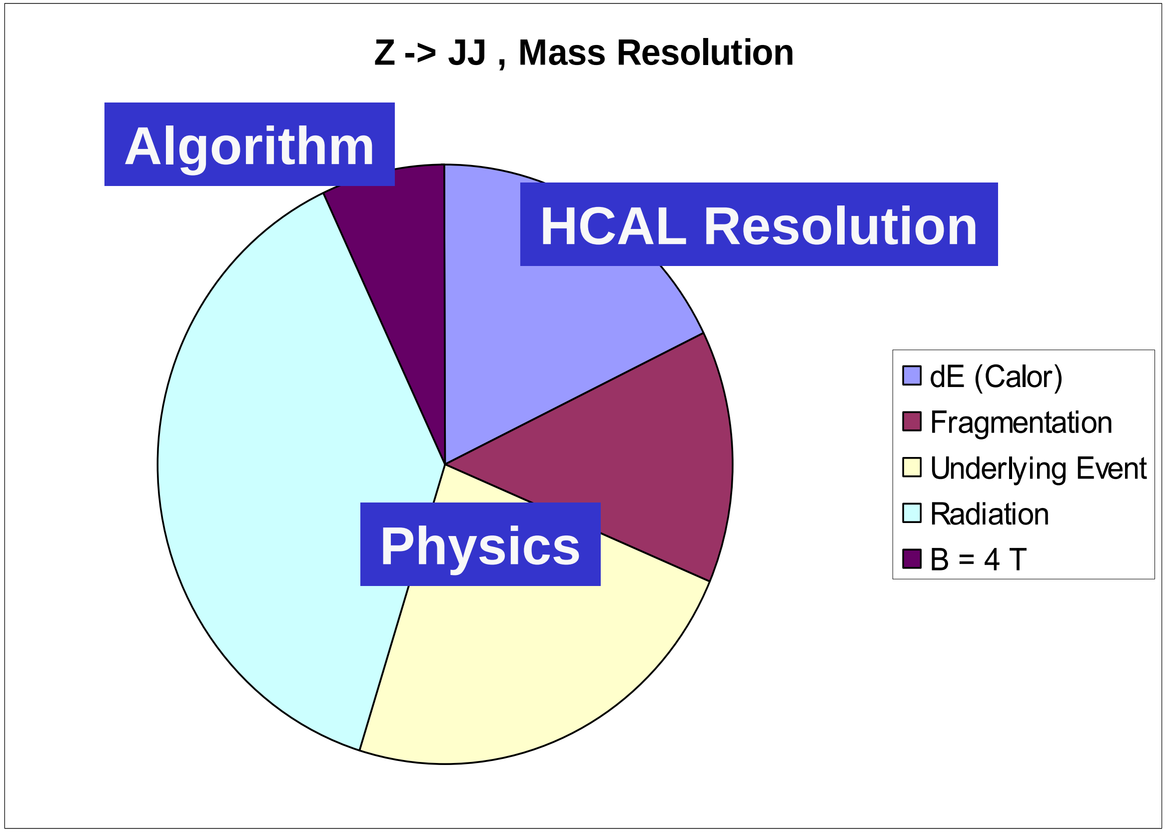
Comments:

- 100% charged track replacement is impossible because of shower overlap.
- Additional uncertainty due to QCD physics and jet definition.
- Particle ID will be worse when jet energy increases.

Jet Mass Resolution in Hadron Collider

D. Green, Paper in Calor2002 Proceedings

- Monte Carlo studies identify the elements contributing to the mass error. Quote low P_T, Z -> JJ. dM/M ~ 13% without FSR.



FSR is the biggest effect. Underlying event is the second largest error (if cone R ~ 0.7). Calorimeter resolution is a minor effect.

Summary: Jet Measurement

- **Using tracker** improves jet energy resolution by 30%. 60% stochastic term has been achieved for all detectors at LEP. With 50% jet energy resolution can the ZEUS calorimeter do 35% without PFA?
- In addition to detector leakage, jet measurement is also limited by physics (QCD and fragmentation) and algorithm (jet definition).
- The **PFA** is not free from above limitations, and its performance can not be parameterized as

$$\mathbf{a}\ \% / \sqrt{E} \oplus \mathbf{b}\ \%$$

since it degrades when jet energy increases.

- 23% jet mass resolution was achieved at LEP by using constrained fit, which is free from all limitations.