Scintillating Crystals

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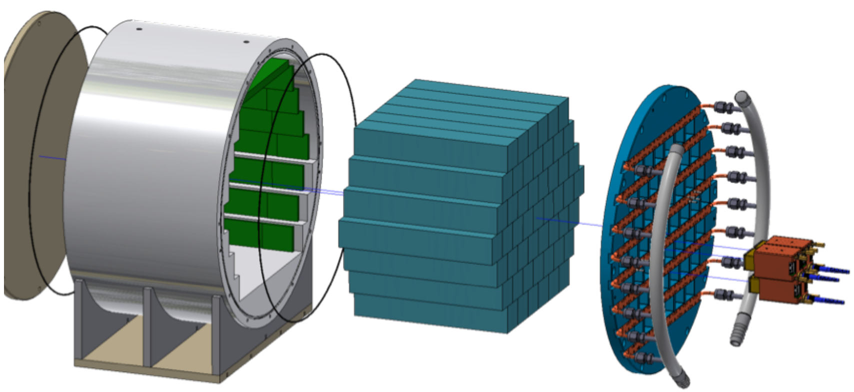
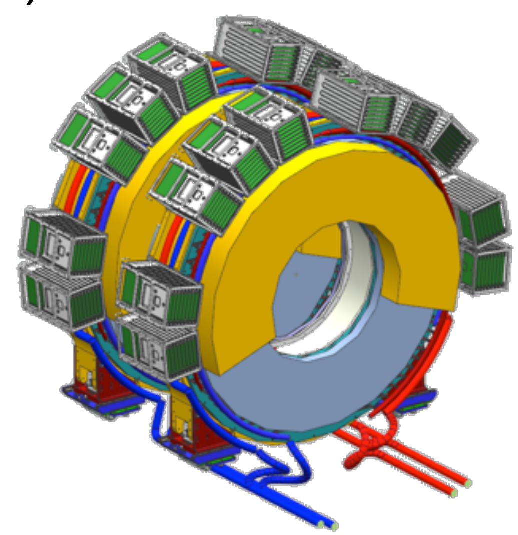




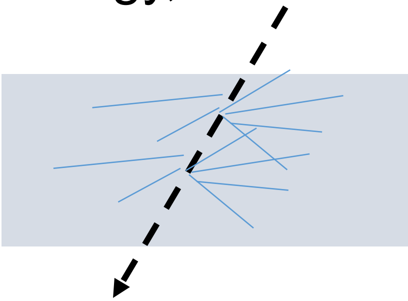
MUSE Outreach Program
University of Rome “Tor Vergata” – 15 May 2017

Outline

- ✗ Scintillator properties
- ✗ Scintillators in High Energy Physics
- ✗ Crystal calorimeters
- ✗ Crystals @ Mu2e
- ✗ Test of pre-production crystals

Scintillators

Basic principle: a charged particle crossing a scintillator loses energy, exciting atoms or molecules of the material

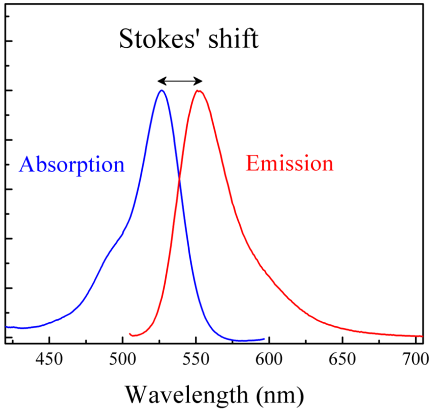


➪ **photon emission** (UV–visible) follows

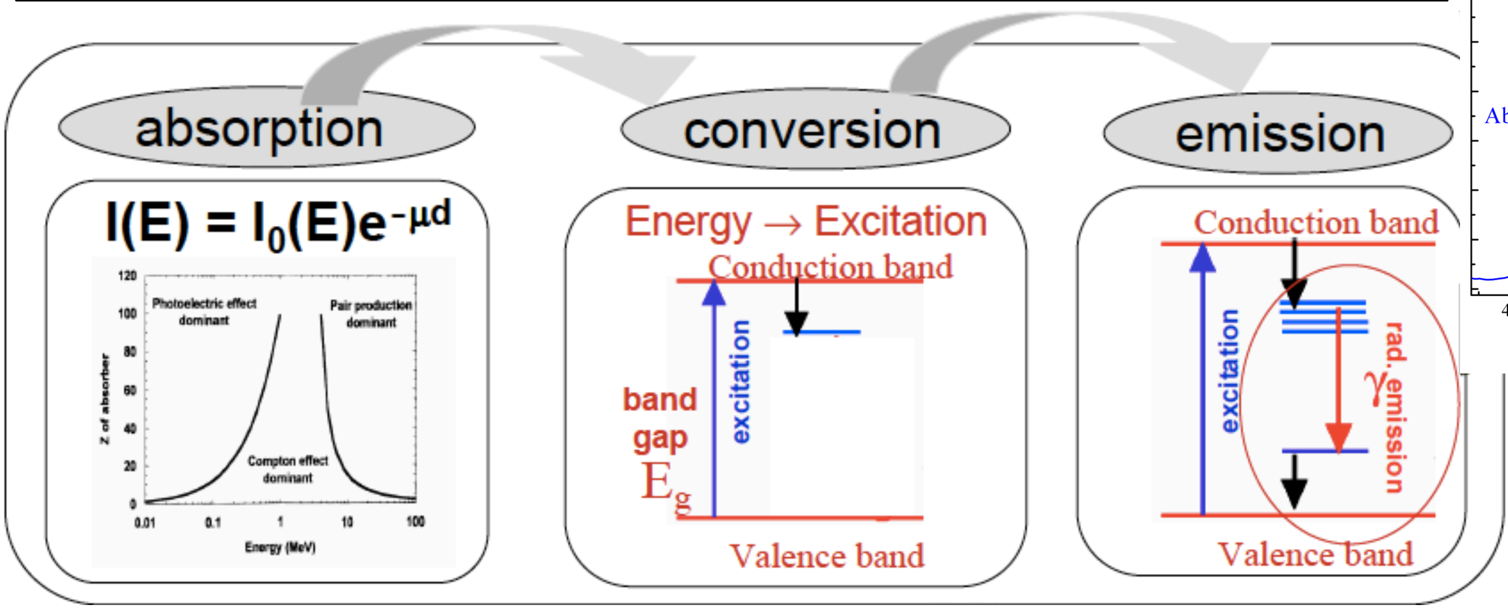
Light emission:

- can be instantaneous, $<10^{-8}$ s, (fluorescence) or delayed, μs to hours, (phosphorescence)
- has an exponential decay time τ_D

Two components (fast and slow) can be simultaneously present



$\lambda_{em} > \lambda_{ex}$



Scintillators: characteristics

Relevant characteristics for particle detection:

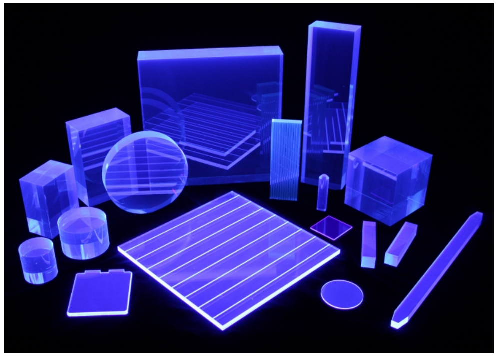
- ✗ Light Yield (LY) number of photons produced for a given absorbed energy
- ✗ Transparency to the emitted radiation
- ✗ Spectral emission compatible with light detectors (photosensors), where light is collected and then converted into electrons via photo-electric effect
- ✗ Linearity
- ✗ Time response

Types of scintillators

Organic scintillators

✗ Complex organic molecules (typically soluted in plastics materials) where UV light is emitted after excitation of molecular levels. Other molecules (wave length shifters) are then added to transfer light into visible radiation

- **Fast emission time** (2.5–10 ns)
- **Low scintillation efficiency** (< 2 k photons / MeV)
- **Low density** (1 g/cm^3)
- Can be easily machined to any shape



Inorganic scintillators

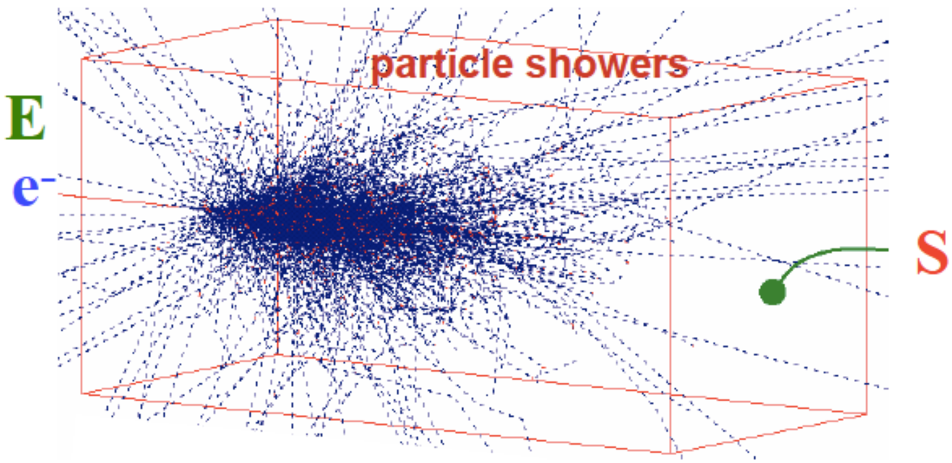
✗ Crystals (alkali, alkaline earth and rare earth), usually doped with impurities uniformly dispersed throughout the crystal lattice

- **High scintillation efficiency** (10-70 k photons / MeV)
- **Slow emission time** (100–600 ns)
- **High density** (4–7 g/cm^3)

Scintillators in High Energy Physics

Scintillators in HEP used to build **calorimeters** ➪ **measure particle energy**

- Which particles? **Stable charged and neutral particles** with sufficient long lifetime ($c\tau$>500 μm): e, μ, π, K, p, n, γ
- How? **Total absorption** (destructive process)



Convert energy **E** of incident particles to a measurable signal **S**:

$$S \propto E$$

ATLAS:
a = 0.1, b = 5×10^{-4}

Why calorimeters?

- **Neutral particle detection**
- **Performance improves with energy**

Calorimeters:	$\frac{\sigma_E}{E} \sim \frac{a}{\sqrt{E}}$	1% @ 100 GeV
Trackers:	$\frac{\sigma_p}{p} \sim bp$	5% @ 100 GeV

Crystal calorimeters

- ✗ Homogeneous: same absorber/active material
- ✗ Electromagnetic Calorimeter (EMC): detection of e.m. showers

Among different types of calorimeters those with scintillating crystals are the most precise in energy measurements

- Excellent energy resolution (over a wide range)
- High detection efficiency for low energy electrons and photons
- Structural compactness:
  - simple building blocks allowing easy mechanical assembly
  - hermetic coverage
  - fine transverse granularity
- Tower structure facilitates event reconstruction
  - straightforward cluster algorithms for energy and position
  - electron/photon identification

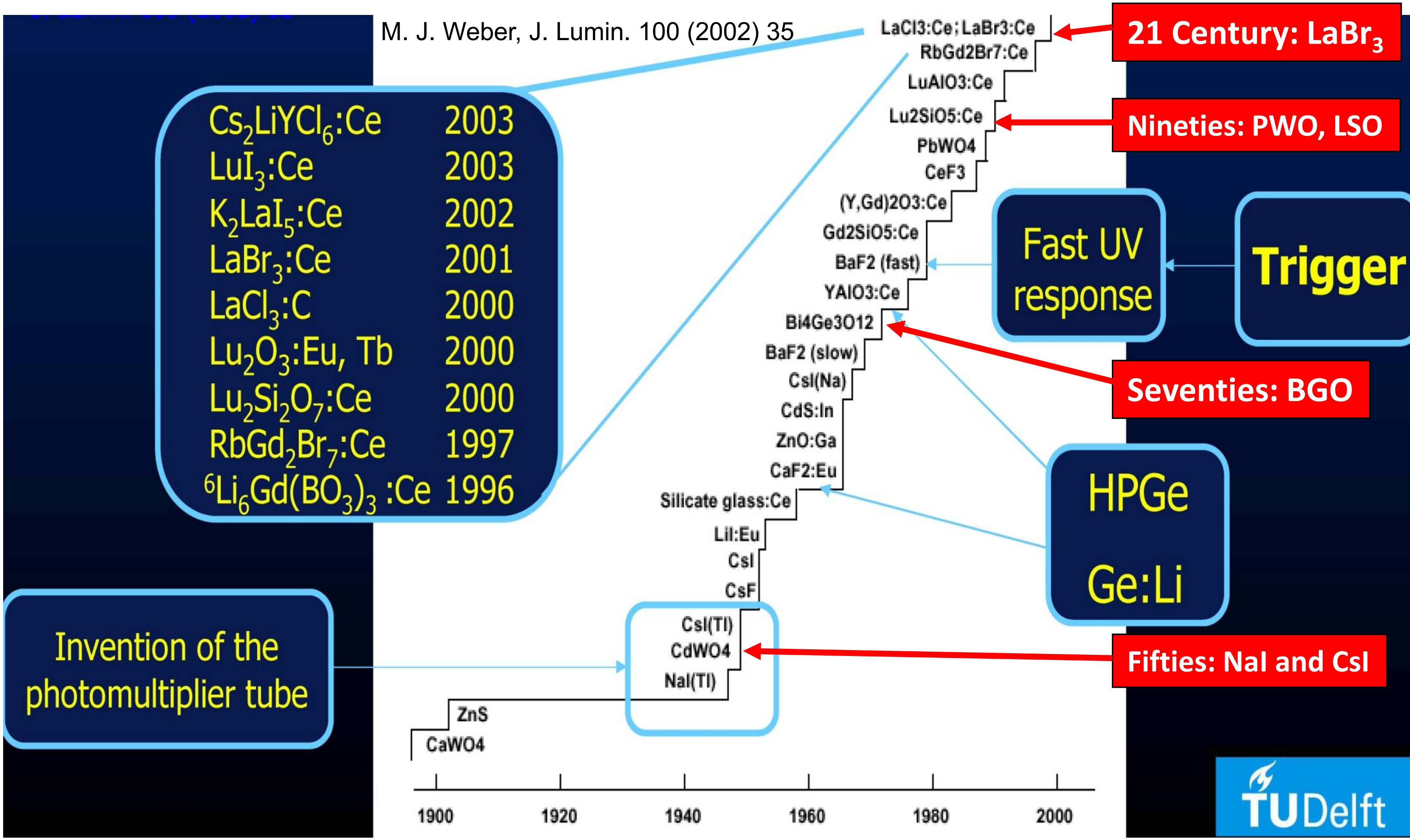
EMC: energy resolution

Precision of the energy measurement (resolution, σ_E/E) in general limited by fluctuations in the shower process

Energy resolution is parametrized as: $$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Stochastic term a → **All statistical effects contribute**
  - ✓ Shower fluctuations
  - ✓ Photoelectron statistics
- Noise term b → **Relevant at low E**
  - ✓ Electronic noise
- Constant term c → **Dominates at high E**
  - ✓ Calibration, leakage

History of inorganic scintillators



- ➢ Discovery and development of new scintillators driven by basic R&D in physics
- ➢ HEP has played a major role in developing new scintillators at an industrial scale and affordable costs (CsI, BGO, PbWO)

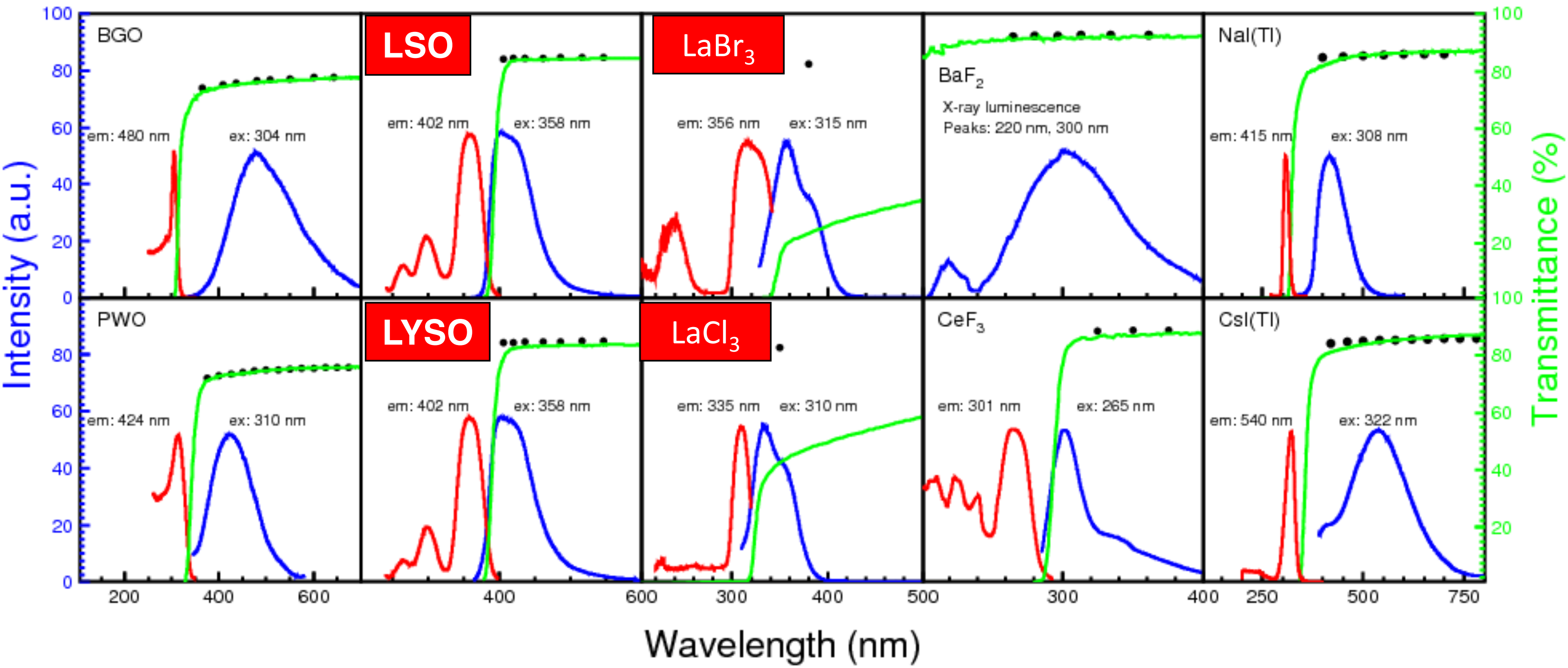
Crystals for HEP

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3
Melting Point (°C)	651	621	621	1280	1050	2050	1123
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20
Hygroscopicity	Yes	Slight	Slight	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] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5

Broad variety of scintillator parameters: relative importance depends on the application

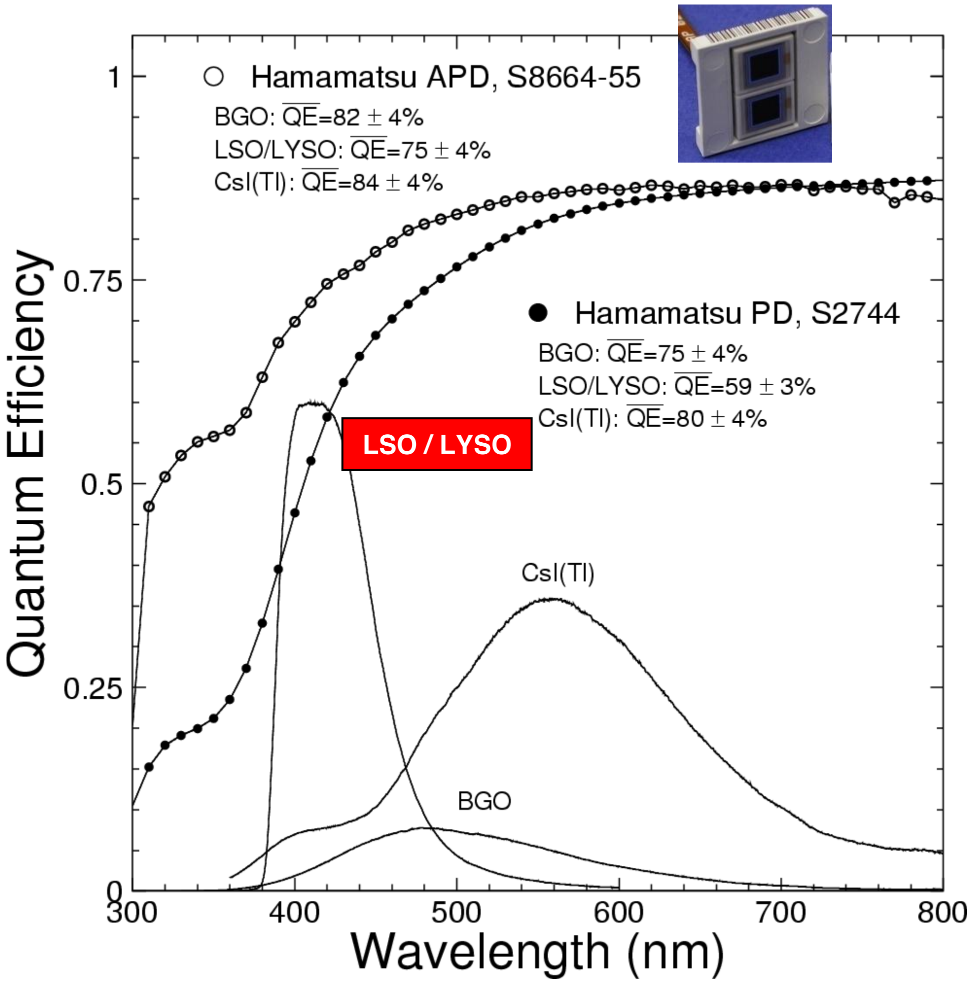
Typical LY of NaI ~ 40000 γ/MeV

Emission spectra

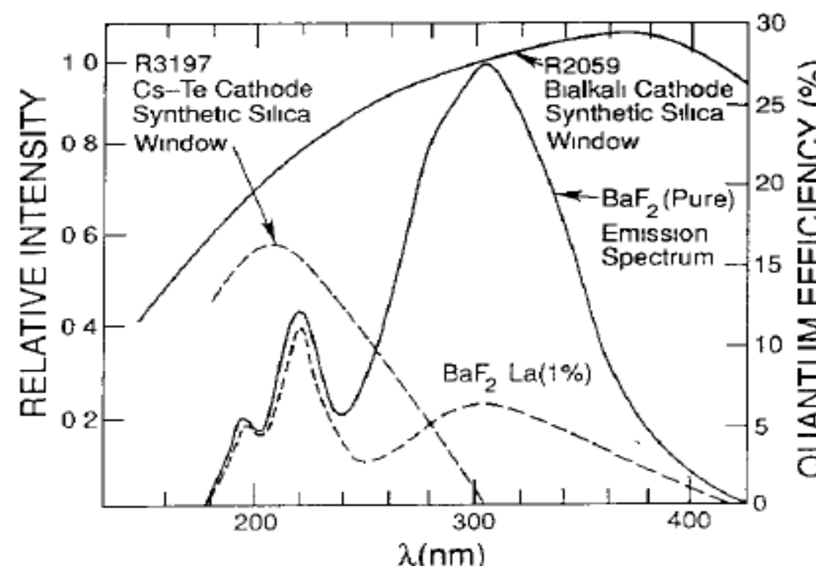


Photosensors

Coupling to Quantum Efficiency of photosensors is essential



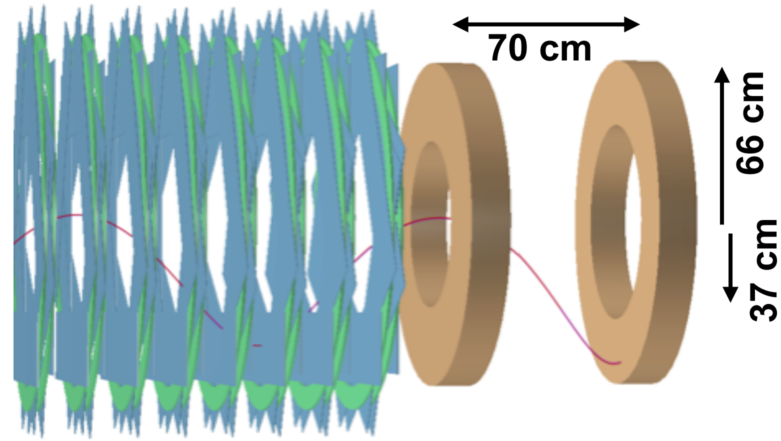
- Crystals with λ > 400 nm well match with standard bi-alcalin PMT and APD
- Pure CsI emits at 315 nm
- BaF_2 fast component at 220 nm



Mu2e: crystal choice

Requirements:

- ✓ $\sigma_E/E = 5\%$ @ E_e=100 MeV
- ✓ $\sigma_T < 500$ ps @ E_e=100 MeV
- ✓ $\sigma_{X,Y} \leq 1$ cm
- ✓ High acceptance for Conversion Electrons
- ✓ B = 1T + vacuum (10^{-4} Torr) operations
- ✓ Radiation hard: 20 krad γ's, 2×10^{11} n/cm^2 per year



Crystal EMC

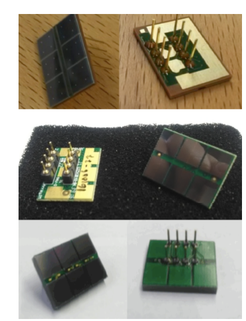
3 different R&D developed:

a. **LYSO + APD**

b. **BaF_2 + SL APD solar blind**

c. **Pure CsI + SiPM UV-extended**

- ➢ 674+674 crystals (34×34×200) mm^3 [10 X_0]
- ➢ 2 UV-ext SiPMs for each crystal 2×3 arrays of (6×6) mm^2 cells



Energy resolution @ low energies

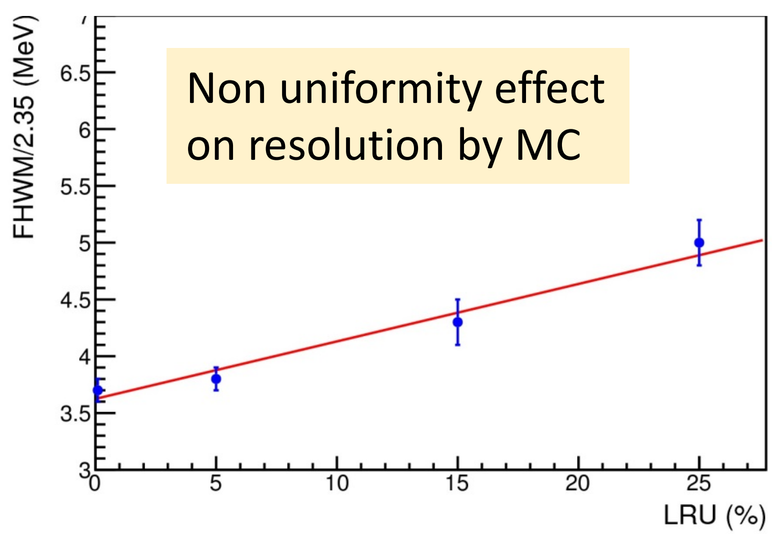
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

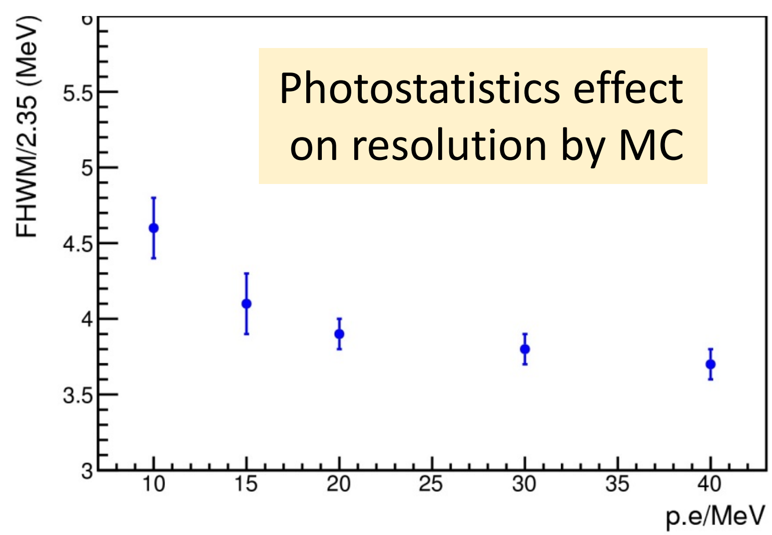
b term, depending mostly on electronics, can be reduced to be negligible also at 100 MeV-1 GeV

- For very bright crystals, LY can be extremely high

ex: LYSO = 2000 p.e./MeV ➪ 0.05% stochastic term resolution expected @ 1 GeV

- In general, other fluctuations (intrinsic contributions) take over
  - ✓ In Mu2e, the most relevant one is the non-uniformity along the z-axis (LRU)
  - ✓ Other examples are non-linearity in response





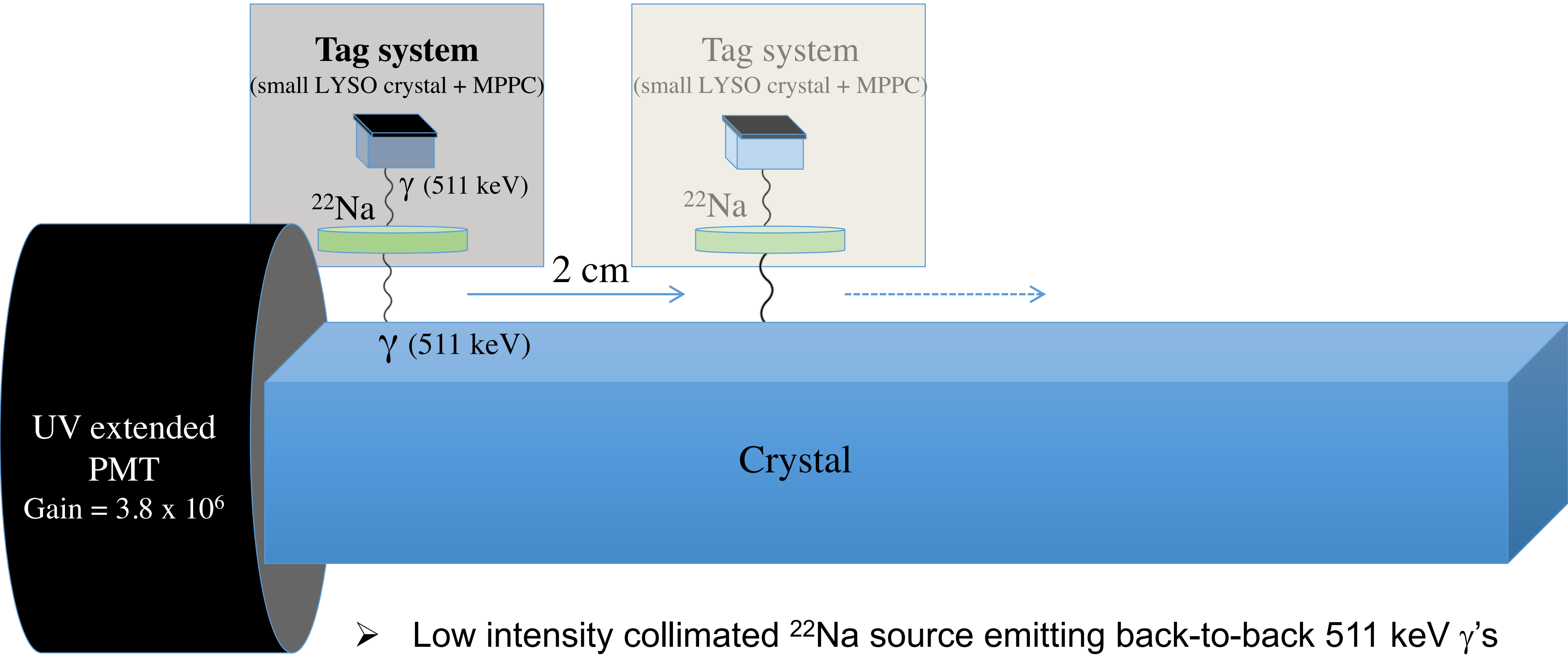
Mu2e pre-production crystals

72 pre-production crystals received from three different vendors

Scintillation properties measured to see if crystals meet requirements:

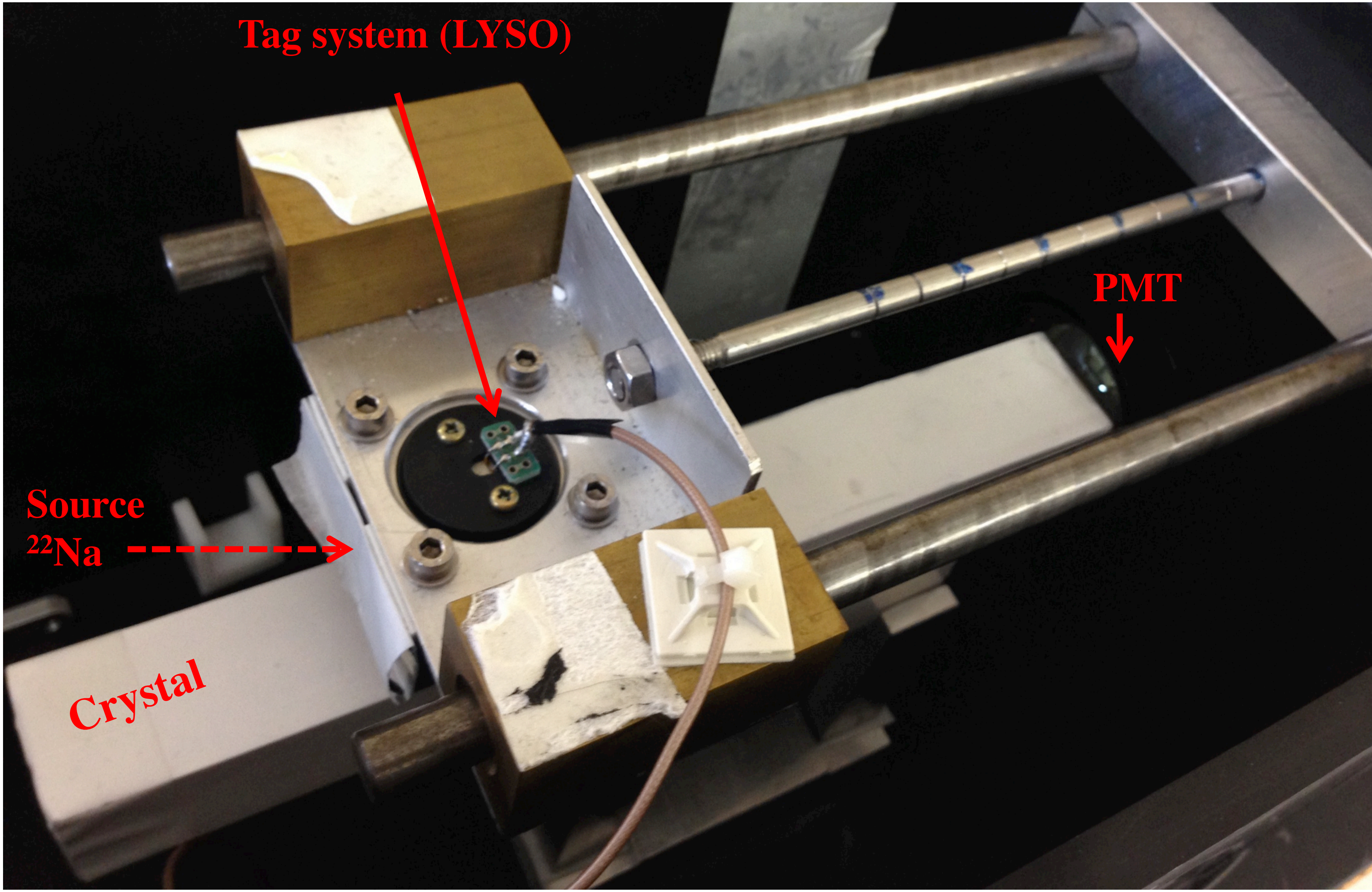
1. Light Output (Np.e./MeV)
2. Response uniformity
3. Fast decay time component

Mu2e crystal test station

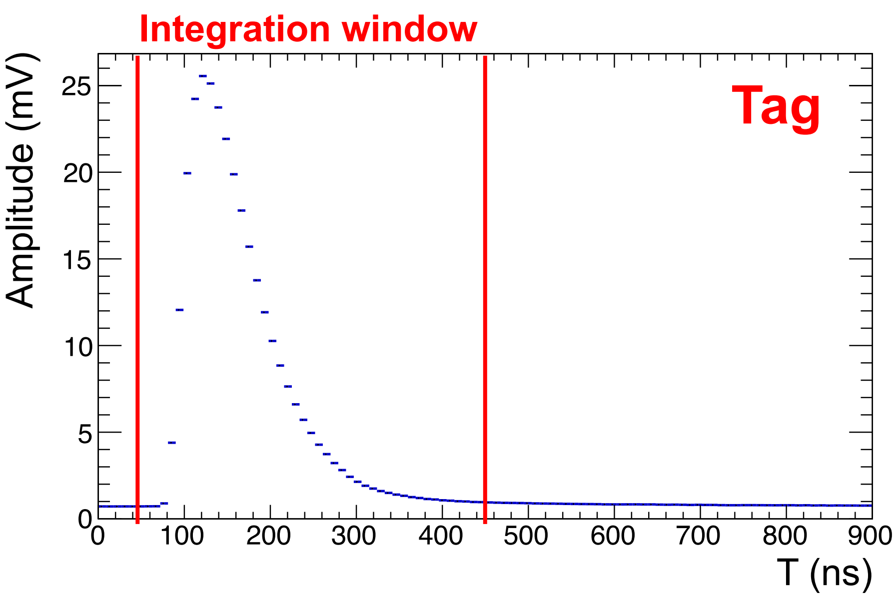


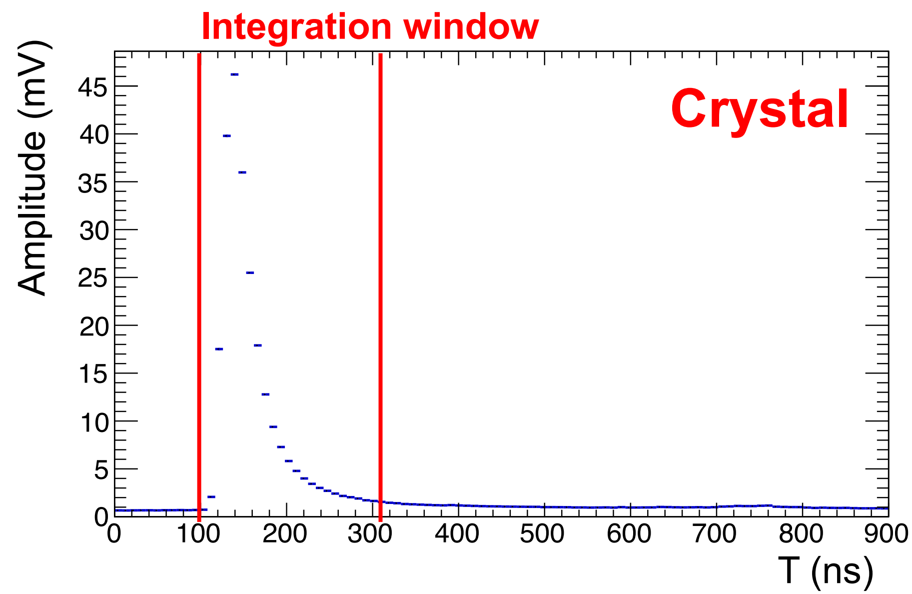
- Low intensity collimated ^{22}Na source emitting back-to-back 511 keV γ's
- Tag: (3×3×10) mm^3 LYSO crystal coupled to (3×3) mm^2 MPPC
- Second photon used to measure pre-production crystals, coupled to 2" UV extended PMT
- Crystals wrapped with 150 μm Tyvek (4173D)
- 8 scan points along the crystal, with 2 cm step

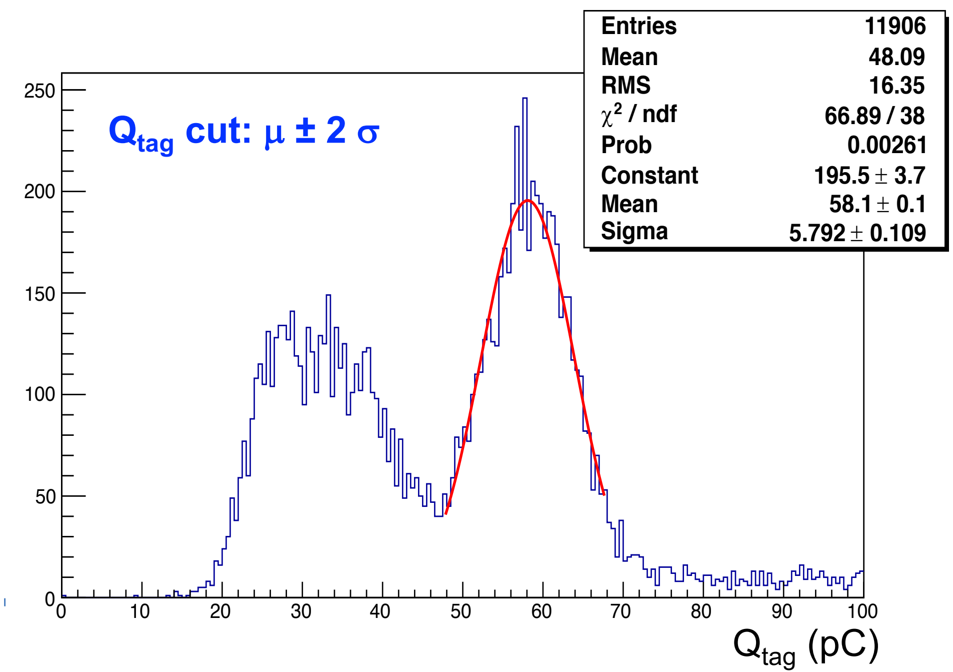
Mu2e crystal test station

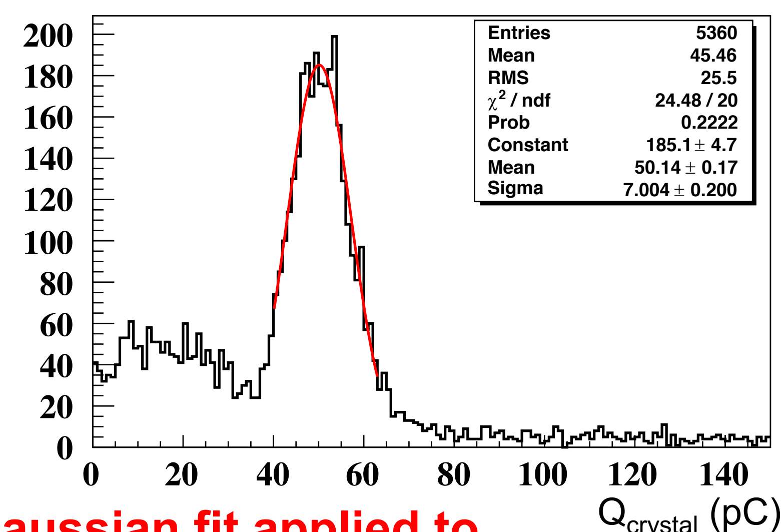


Charge distributions of 511 keV g's









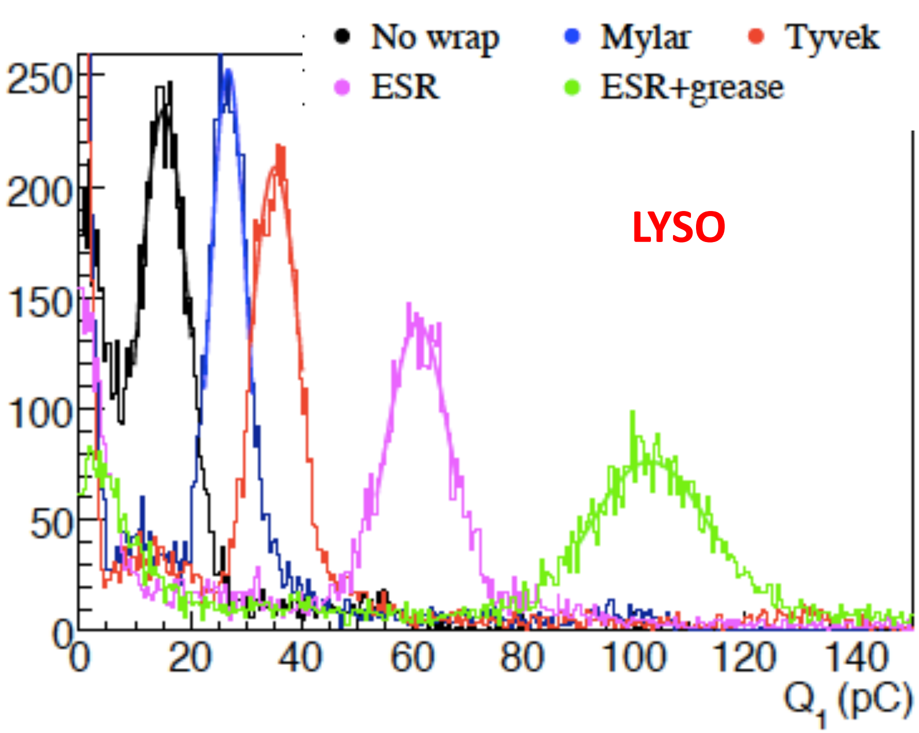
Gaussian fit applied to extract μ/σ for QA tests

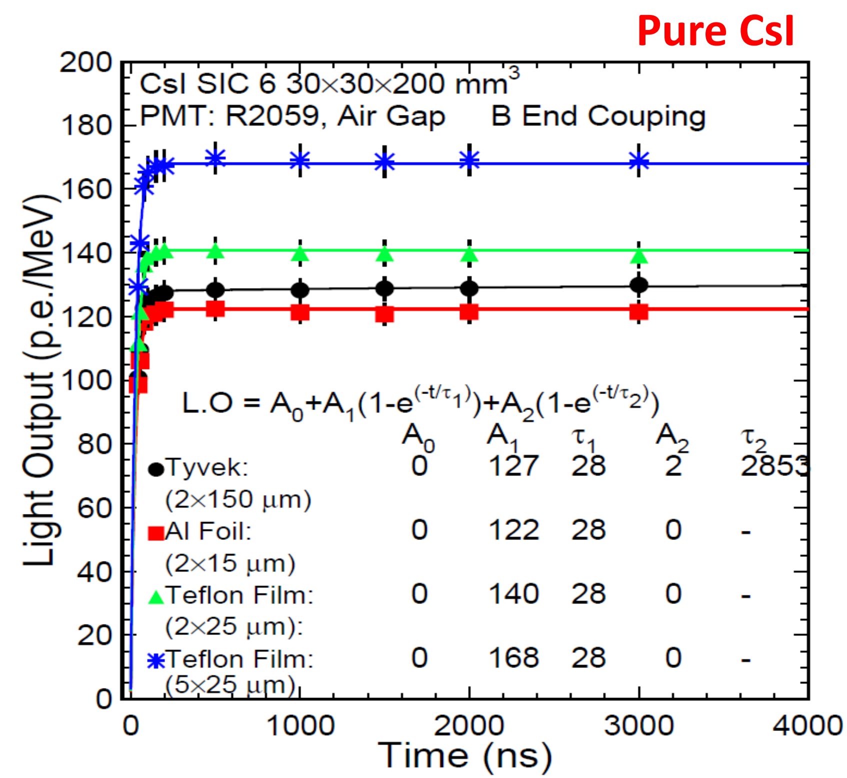
Light Yield evaluation

- ✗ From the charge distributions number of photoelectrons can be extracted:

$$N_{p.e.}/\mathrm{MeV} = \frac{Q}{Q_e \times G_{PMT} \times E_\gamma} = \frac{\mu_Q}{1.6\cdot 10^{-19} \times 3.8\cdot 10^{6} \times 0.511\ \mathrm{MeV}}$$

- ✗ Crystal wrapping enhances light output

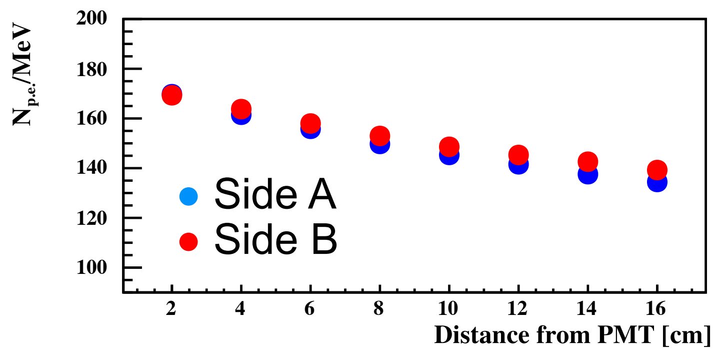


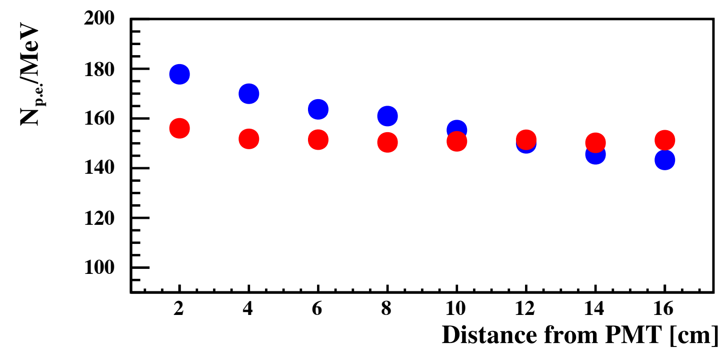


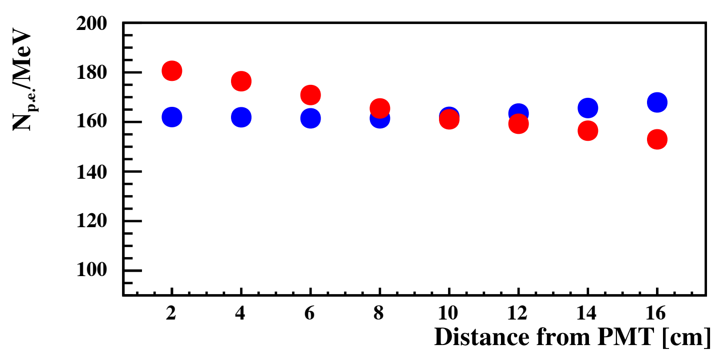
Mu2e requirement: Light Output > 100 $N_{p.e.}$/MeV

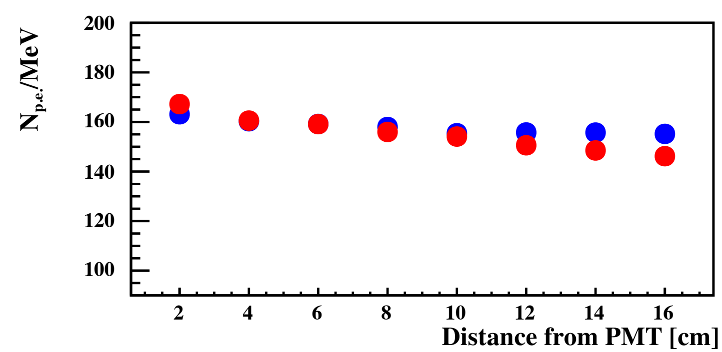
Longitudinal Response Uniformity

- From the dependence of the LY as a function of the source position along the crystal axis, an evaluation of the Longitudinal Response Uniformity (LRU) can be extracted
- Typically, this is done by performing a linear fit to the observed response or by evaluating the RMS of all points









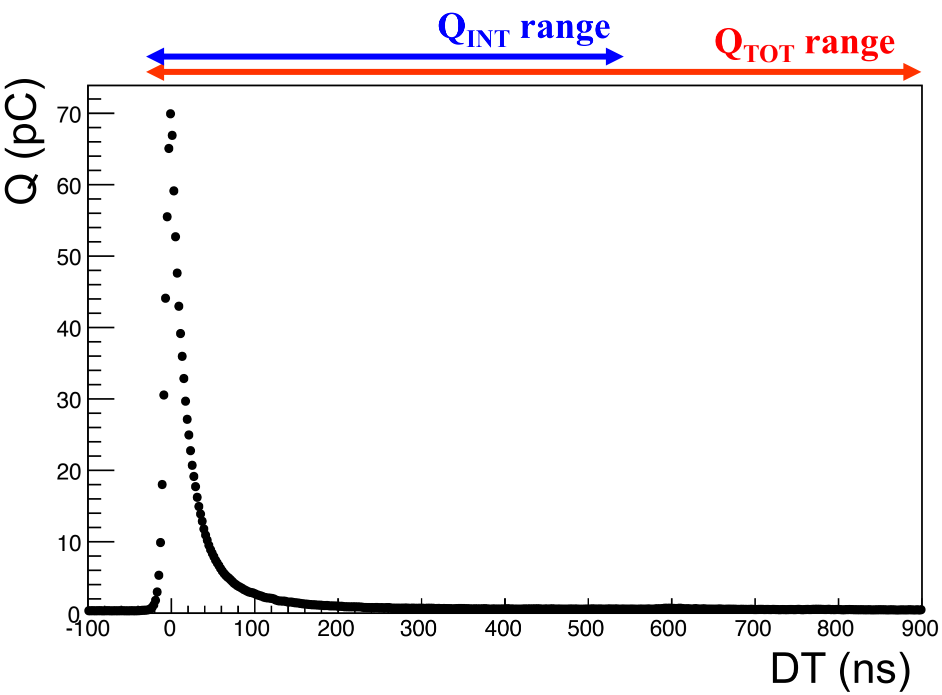
Mu2e requirement:
LRU < 5%

Fast component extraction

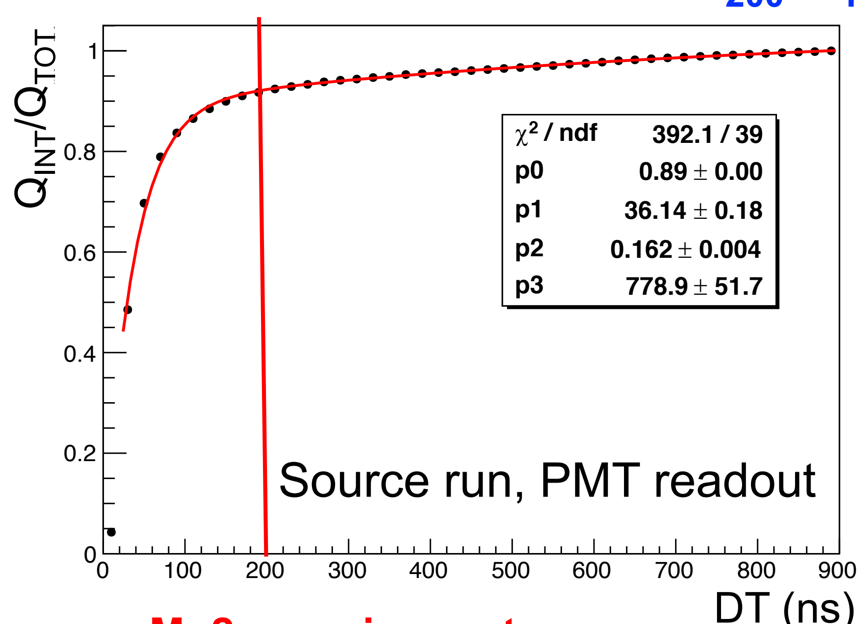
Plot Q_{INT}/Q_{TOT} vs $DT=T-T_{mean}$, with 20 ns bin width, where:

- ➢ T_{mean} is the time corresponding to the peak of the pulse height
- ➢ Q_{INT} is the charge integrated from the start of the signal (DT = –30 ns)
- ➢ Q_{TOT} is the total integrated charge (–30÷900 ns)

Fit with: $$\boldsymbol{P_0(1-exp(-x/P_1)) + P_2(1-exp(-x/P_3))}$$



Fast/Total ratio defined as Q_{200}/Q_{TOT}



Mu2e requirement:
Fast(200ns)/Total(3ns) ratio > 75%

Lab Experience @ LNF

Measurement of scintillation properties for pure CsI crystals