Scintillation studies for The Axial 3-D PET Concept HPD-PET project implemented by Wave Length Shifter Strip Hodoscope

HPD-PET --> AX-PET

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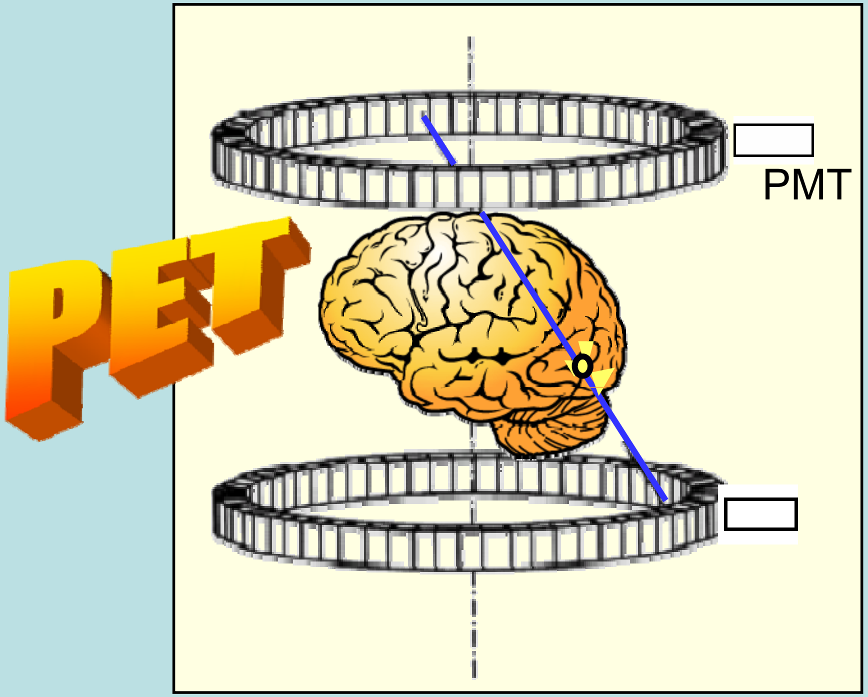
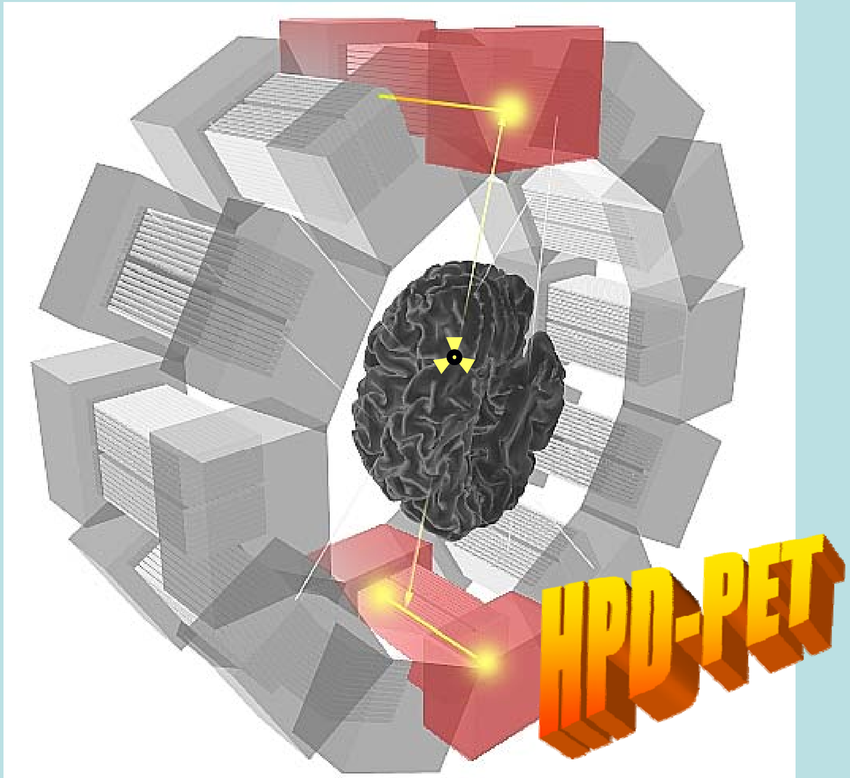
The 3D PET cameras

Standard radial **PET** concept



Many rings of
crystal–photodetector blocks
radially displaced
Lc =1.5-3cm

the axial **HPD-PET** concept



Arrays of long (Lc~10-20 cm) crystal bars
read out at both sides by segmented HPDs

Concept made possible by CERN development of rectangular segmented 5'' HPDs
with integrated self-triggering electronics

ADVANTAGES OF THE AXIAL HPD-PET CONCEPT

High Granularity → exact reconstruction of the γ interaction point (no parallax error)

- x,y from fired scintillator
  σ(x,y) = 3.2 mm/√12= 0.92 mm
  Δx,Δy (FWHM) = 2.2 mm

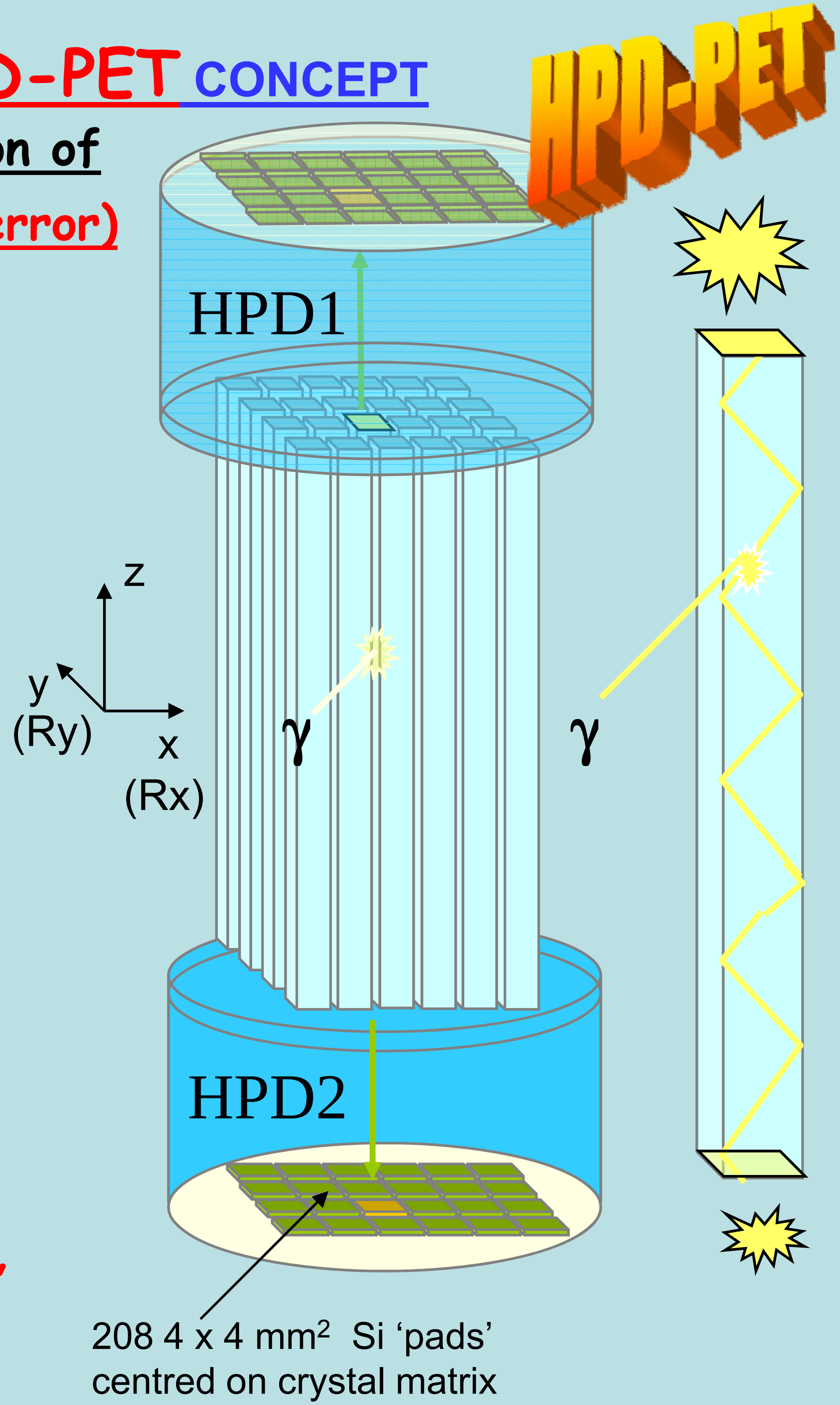
- z (DOI) from the ratio of the photoelectrons detected at the two crystal ends
  σ(z) linked to the scint. choice

Reduced # of photodet., scint., electr.
→ **(12 module PET: only 24 HPDs)**

No limit to module radial dimension
→ **higher efficiency**

Double scatt. events in one module (Compton-photoel) reconstruction
→ **higher efficiency**

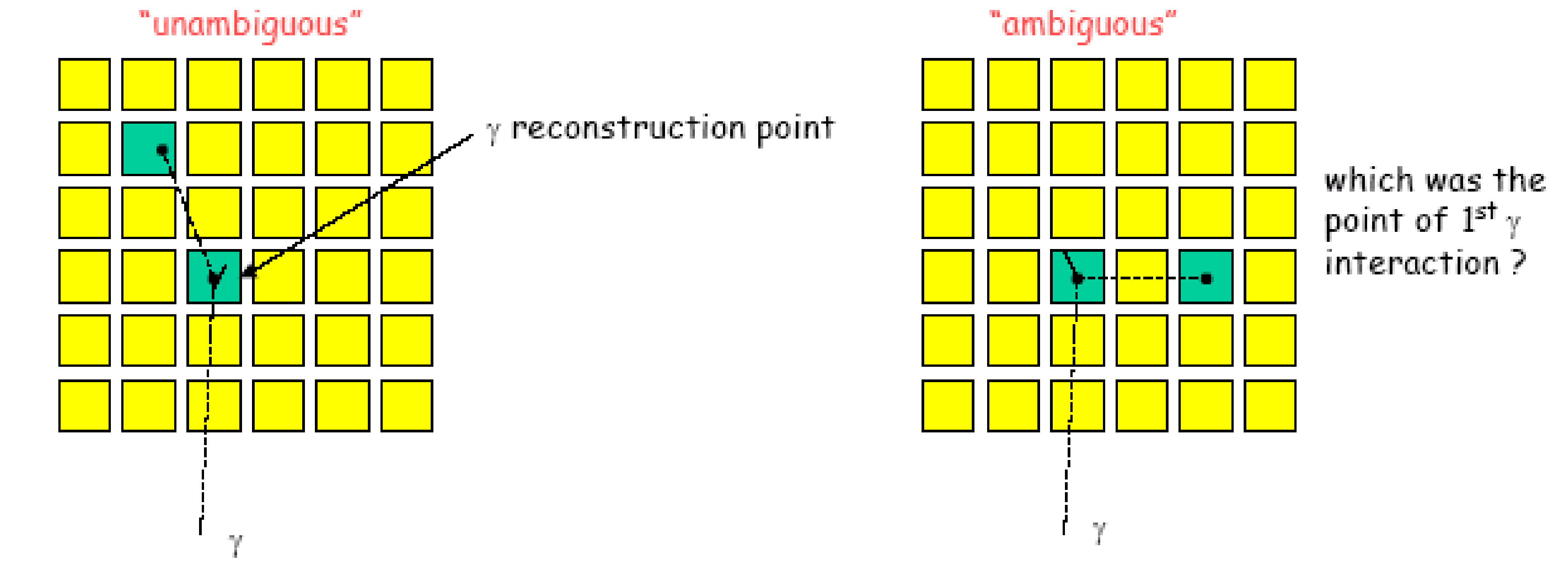
J. Séguinot et al.,Nuovo Cimento C, 29 (2006)429-463



2) ADVANTAGES OF THE AXIAL HPD-PET CONCEPT

possibility to reconstruct the int. point of part of γ's that suffers a double (Compton + photoelectric) event in the same module

COMPTON + PHOTOELECTRIC events-



- Select only events in which Compton scattering happens in forward hemisphere
- Restrict to Compton angle $10° \leq \theta \leq 60°$
- Ask for energy deposit in first interaction $E \leq 170$ keV

~ 25% Compton events (50 keV [energy cut] < E < 170 keV) followed by a photoelectric one in the same module can unambiguously be reconstructed

→ **detection efficiency increases but spatial resolution worsens**

Inorganic Scintillation crystals

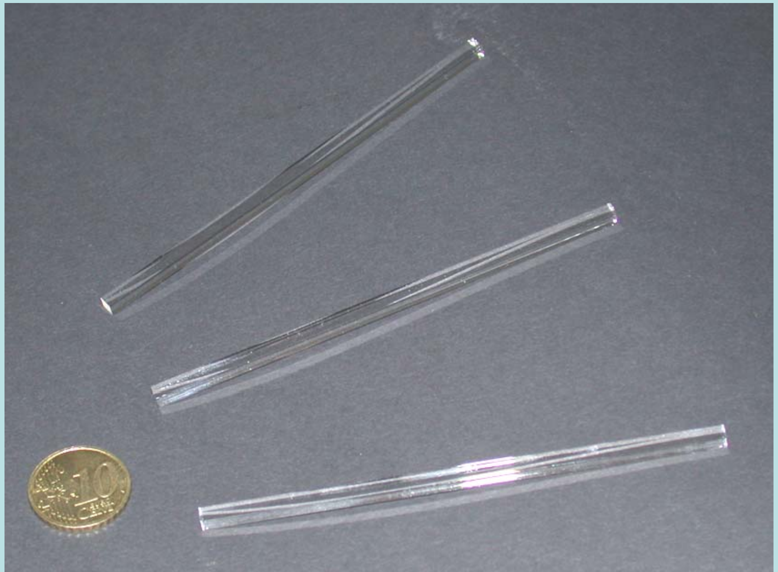
- Criteria to be taken into account: light yield, absorption length, photo fraction, self absorption, decay time, availability, machinability, price.

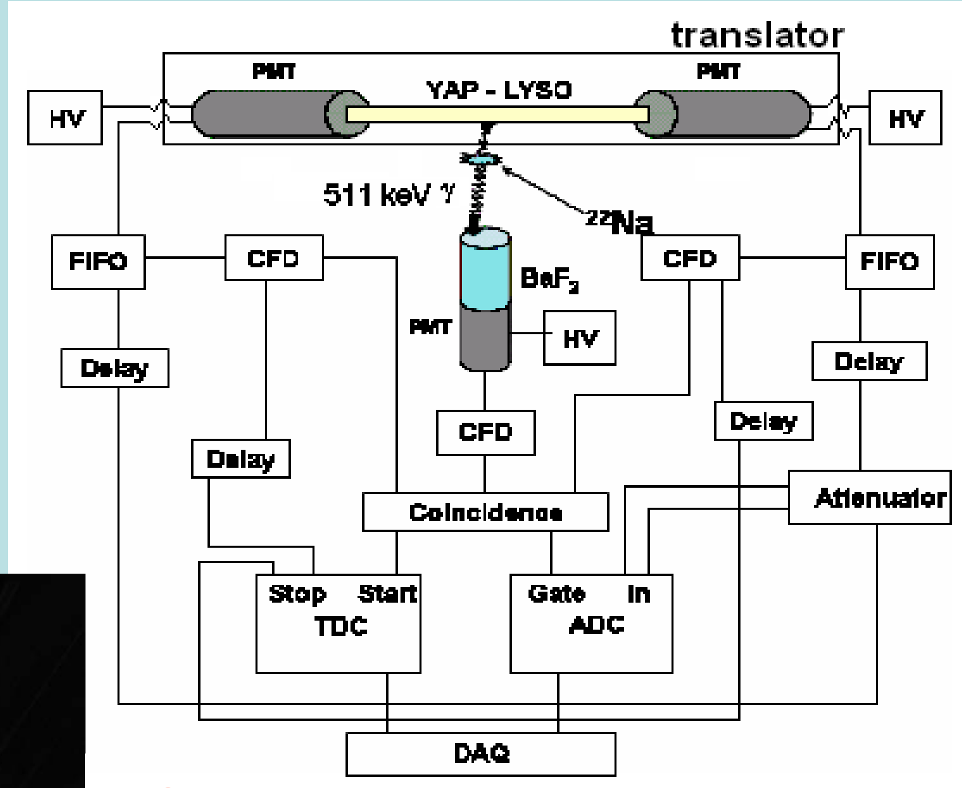
	YAP:Ce	LSO:Ce	LuAP:Ce	$LaBr_3$:Ce	BGO
Density **ρ** (g/cm^3)	5.55	7.4	8.34	5.3	7.13
Effective atomic charge Z	32	66	65	46.9	75
Scintillation light output (photons / MeV)	18000	23000	~10000	~61000	~9000
wavelength λmax of max. emission (nm)	370	420	370	356	480
Refractive index n at λmax	1.94	1.82	1.95	~1.88	~2.15
Bulk light abs. length λbulk (cm) at λmax	~20	~40			
Principal decay time (ns)	27	40	18	30+5	300
Mean γ atten. length λa at 511keV (mm)	22.4	11.5	10.5	~20	~11.6
Photo fraction at 511 keV (%)	4,5	32.5	30.5	15	41.5
Energy resolution (FWHM) at 663 keV	4.5	8		2.9	

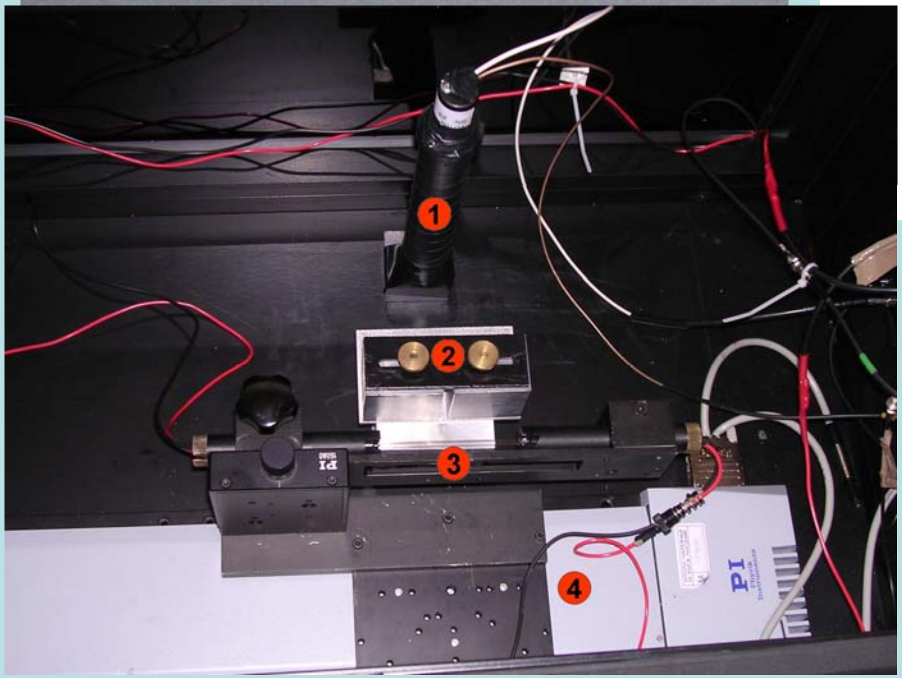
⇧

LSO (LYSO) is the most interesting crystal scintillator :
fast (40 ns), short att. length (~12mm) at 511keV, high photofraction (32%), not hygroscopic, but high energy resolution (8% FWHM)

PROOF of the HPD-PET CONCEPT with YAP and LYSO crystals and PMTs







❶ BaF_2 (used with a ^{22}Na source)

❷ Pb collimator Pb + source

❸ YAP (Preciosa Co)
LYSO (Photonic Materials)
($3.2 \times 3.2 \times 100$ mm^3)
PMT H3164-10 (Φ=8mm, 1250 V)

❹ linear translator M-511(Phys.Instrum.)

Lc, λ_{eff}, No: KEY PARAMETERS OF THE HPD-PET CONCEPT

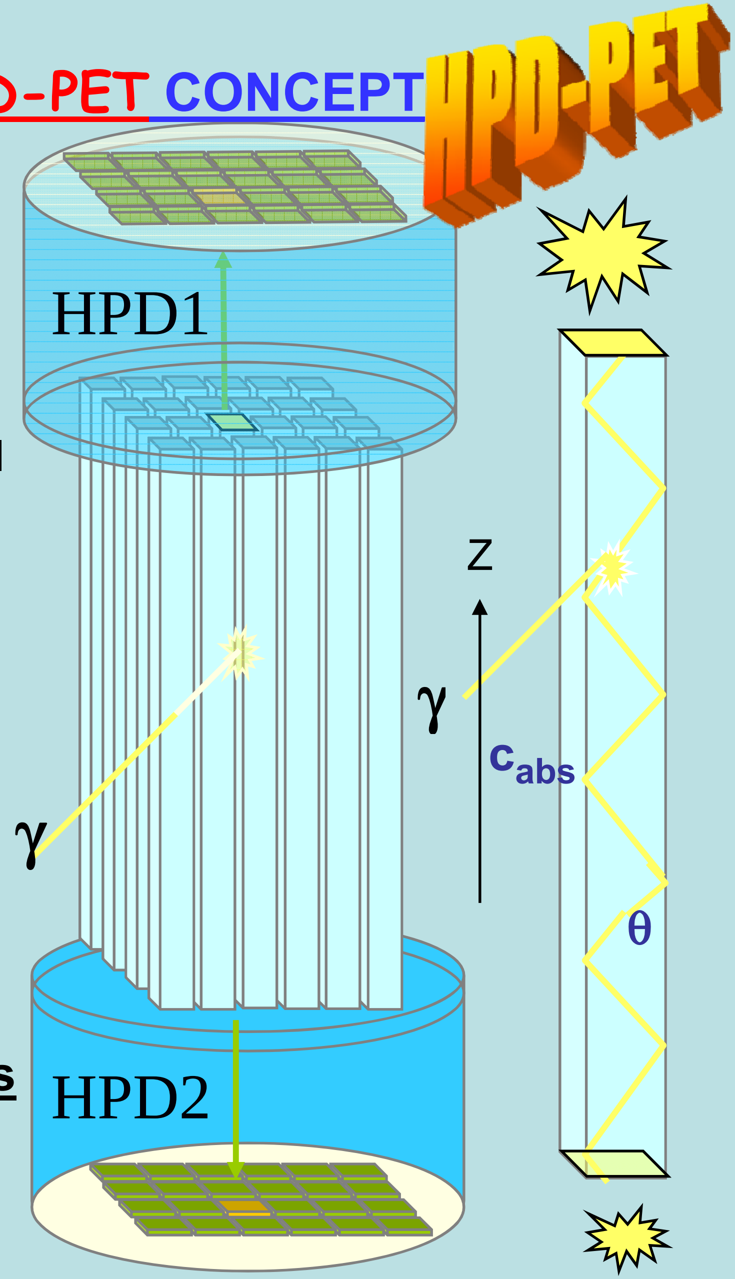
- **Lc: crystal length**
- **λ_{eff}: attenuation length of scint. photons**
  $1/\lambda_{eff} = 1/(\lambda_{bulk}{}^{*} \cos\theta) + c'/(c_{abs})$
- **No: light yield, p.e.'s (511keV γ) in a Lc~0 crystal**
  (n_{ph}/keV, sci.ph.transport, q.e. & wind. of photodet.)

σ_z, σ_E/E, σ_t : (only statistical)

$$N_1 = \frac{N_0}{2}\exp\left(\frac{-z}{\lambda_{eff}}\right), \quad N_2 = \frac{N_0}{2}\exp\left(\frac{-(L_C - z)}{\lambda_{eff}}\right), \quad N_{pe}(z) = N_1 + N_2.$$

$$z = \frac{1}{2}\left(\lambda_{eff}\ln\frac{N_1}{N_2} + L_C\right), \quad \sigma_z = \frac{\sqrt{ENF}\lambda_{eff}}{\sqrt{2N_o}}\left(\exp\frac{z}{\lambda_{eff}} + \exp\frac{L_C - z}{\lambda_{eff}}\right)^{1/2},$$

$$\frac{\sigma_E}{E} = \sqrt{\frac{ENF}{N_{pe}}} \oplus \mathrm{Rint}, \quad \sigma_T = \frac{c}{\sqrt{N_{pe}}},$$



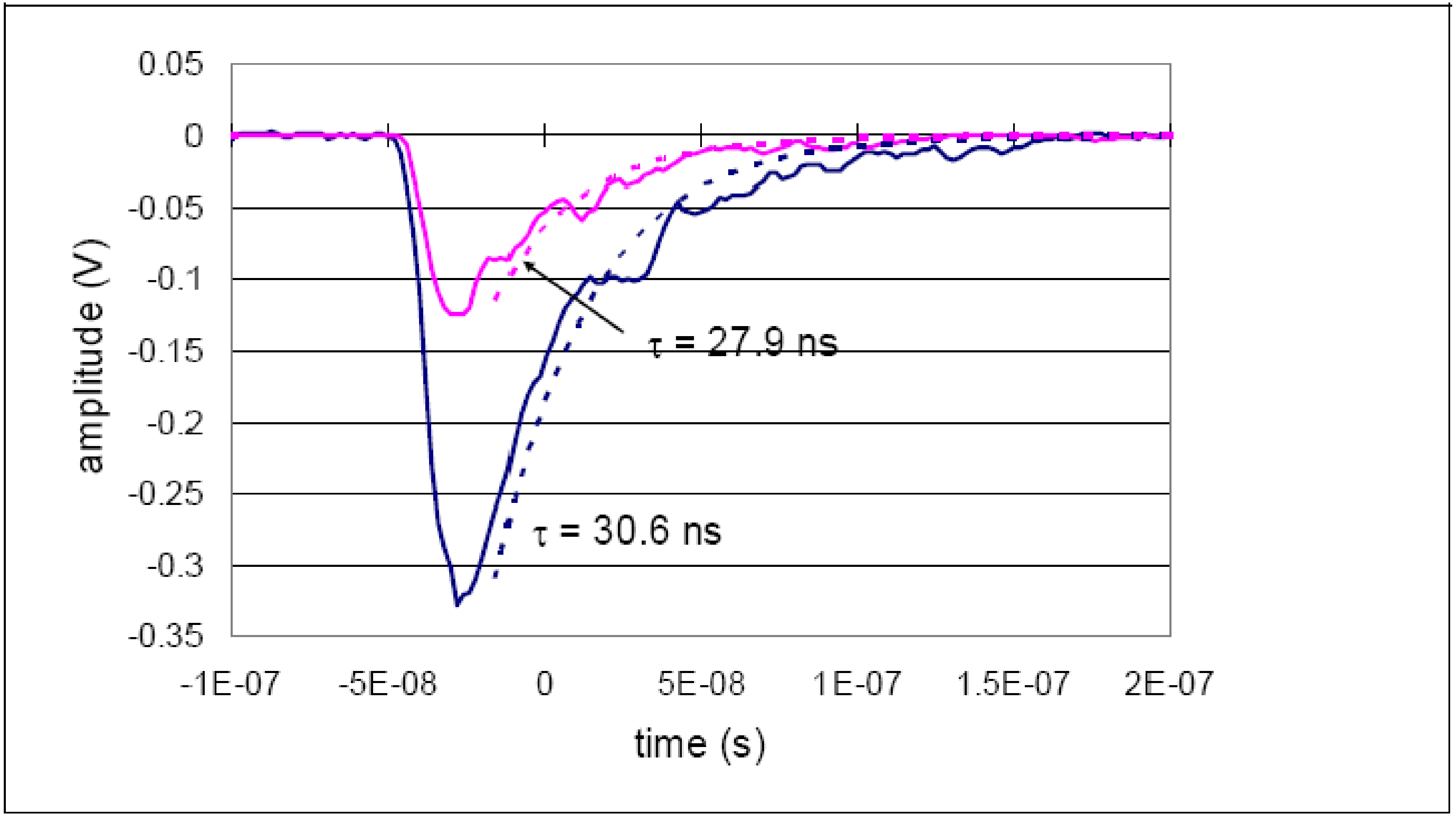
a) **crystal axial length (Lc) worsens all resolutions**
   limit of Lc: 10 ~ 15 cm

b) **light yield (No) improves all resolutions**

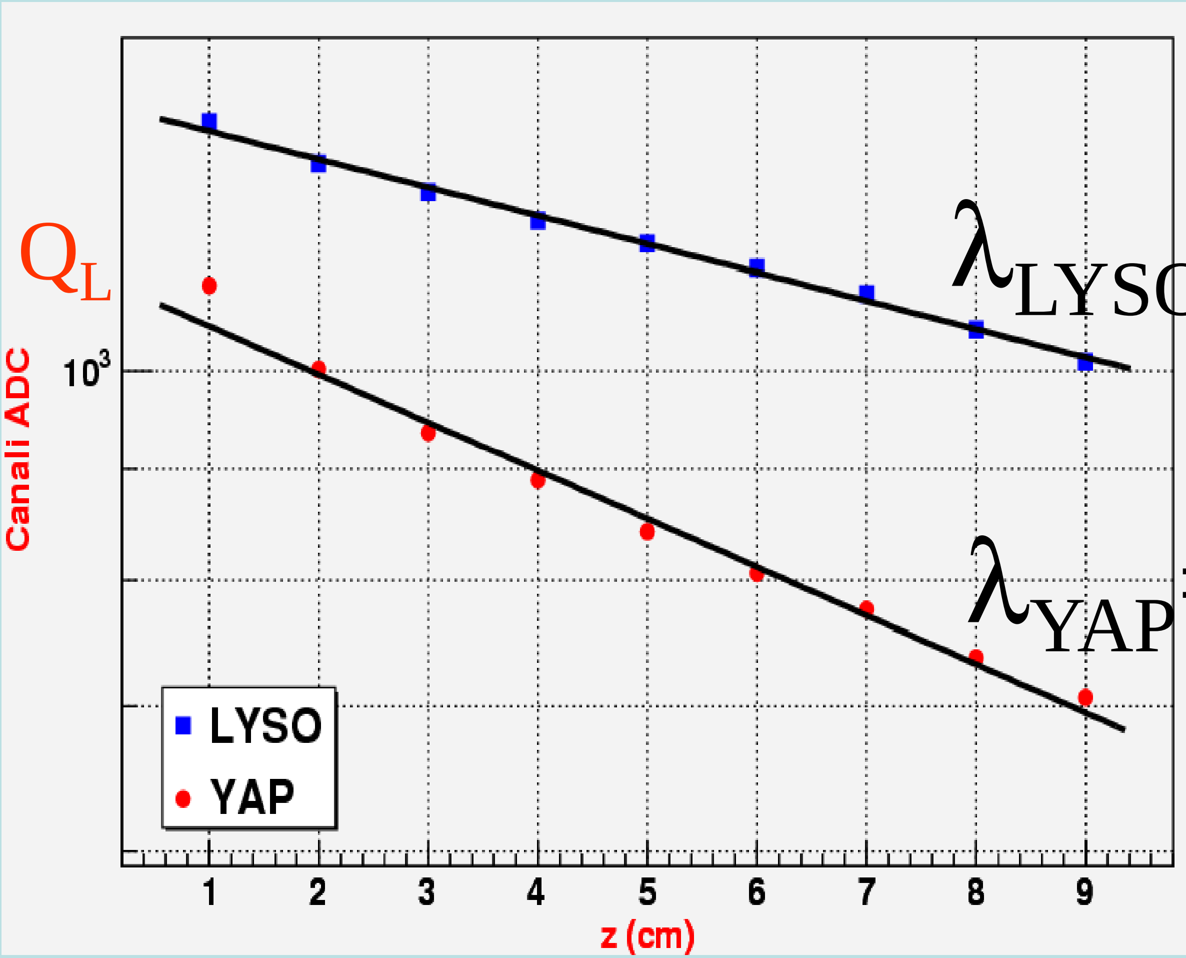
c) **contrasting effects of λ_{eff} on σ_z & σ_E/E, σ_t**

→ **optimize λ_{eff} value by wrapping or coating the crystal lateral surface**

Typical pulses from LYSO bars



λ_{eff} in polished 3x3x100 mm^3 YAP-LYSO



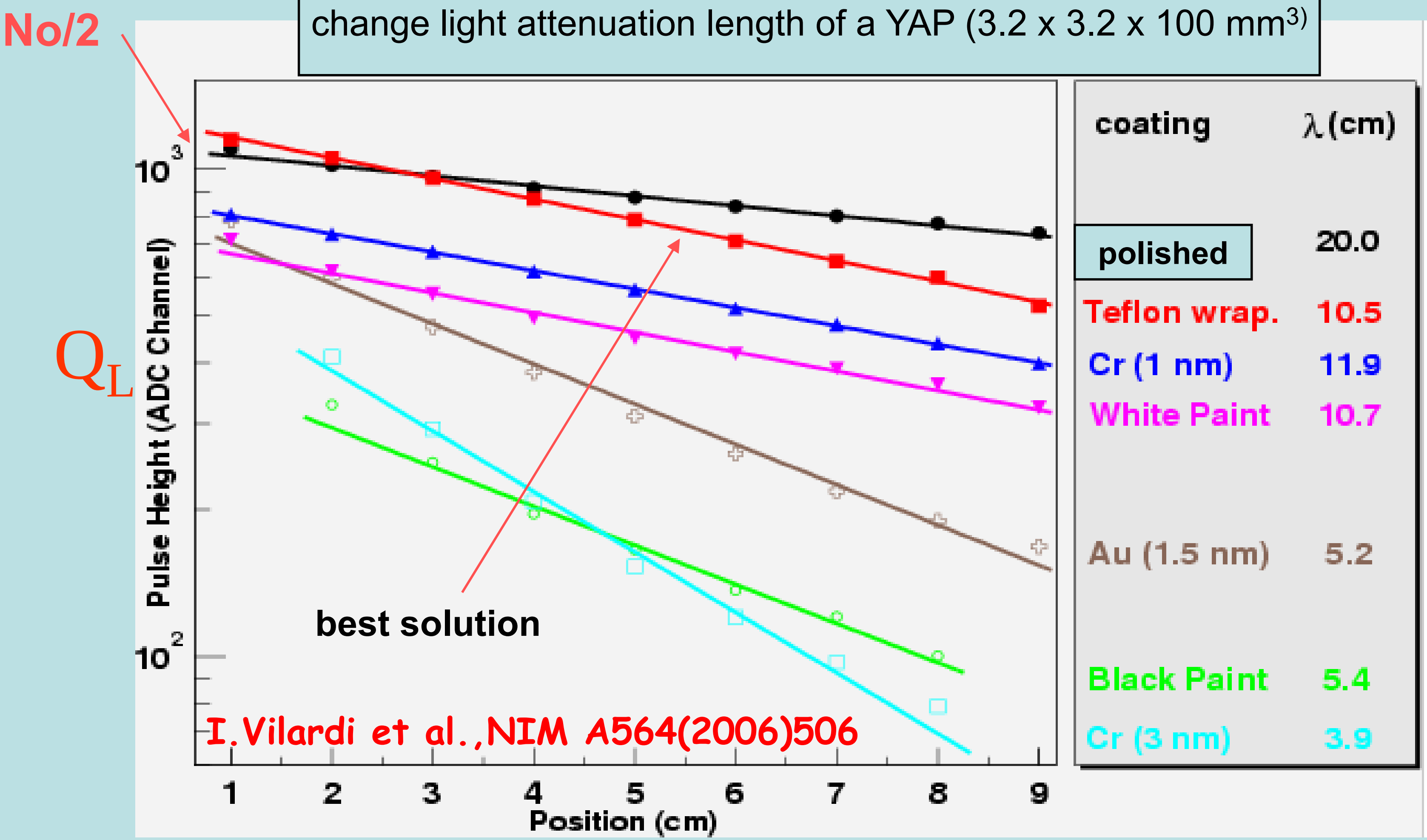
Q_L

$\lambda_{LYSO} = 42.6 \pm 0.9$ cm

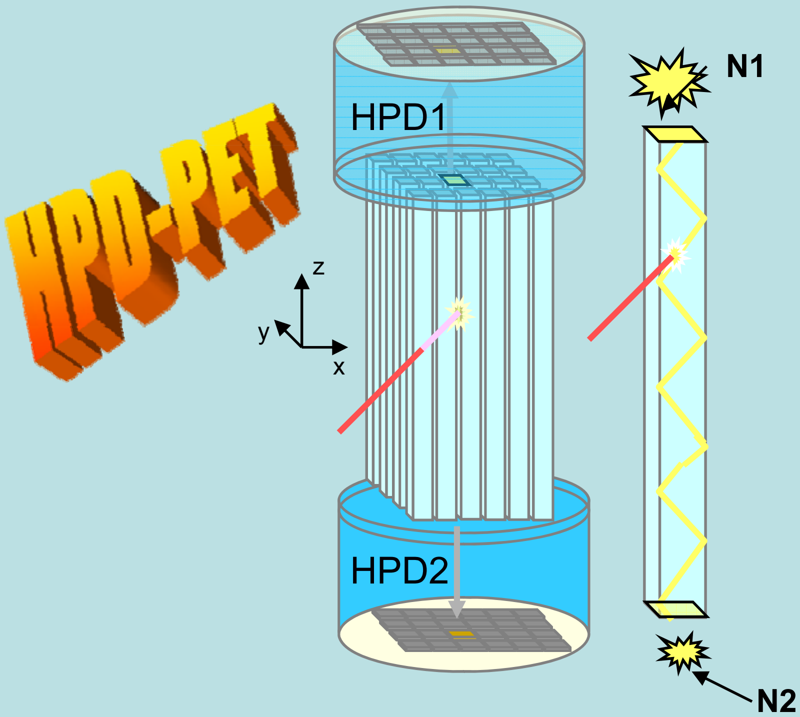
$\lambda_{YAP} = 20.8 \pm 0.4$ cm

- LYSO more transparent (higher λ_{eff}) than YAP
- too high λ-eff values (poor σ_z) both for LYSO and YAP

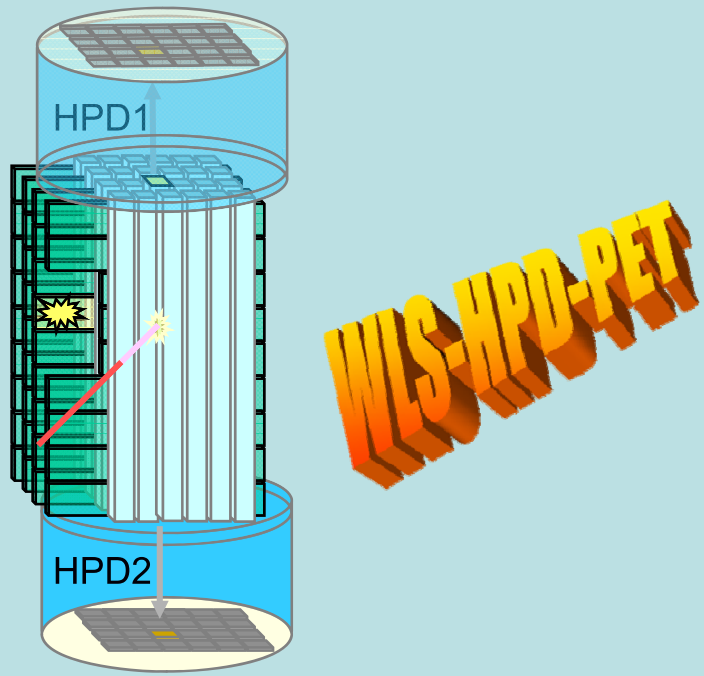
Crystal wrappings or metal-coatings change light attenuation length of a YAP (3.2 x 3.2 x 100 mm³)



- at z=0 Q(teflon) > Q(polished): slight increase of No
- λ (polished) / λ(teflon) = 1.9
- possibility to tune λ-eff value with metal coatings
- metal coating reduces No



HPD-PET concept



New WLS-HPD-PET concept

(proposed by D.Schinzel)

WLS strip width w = 3 mm, $\sigma_z \leq$ w/√12 =0.9 mm

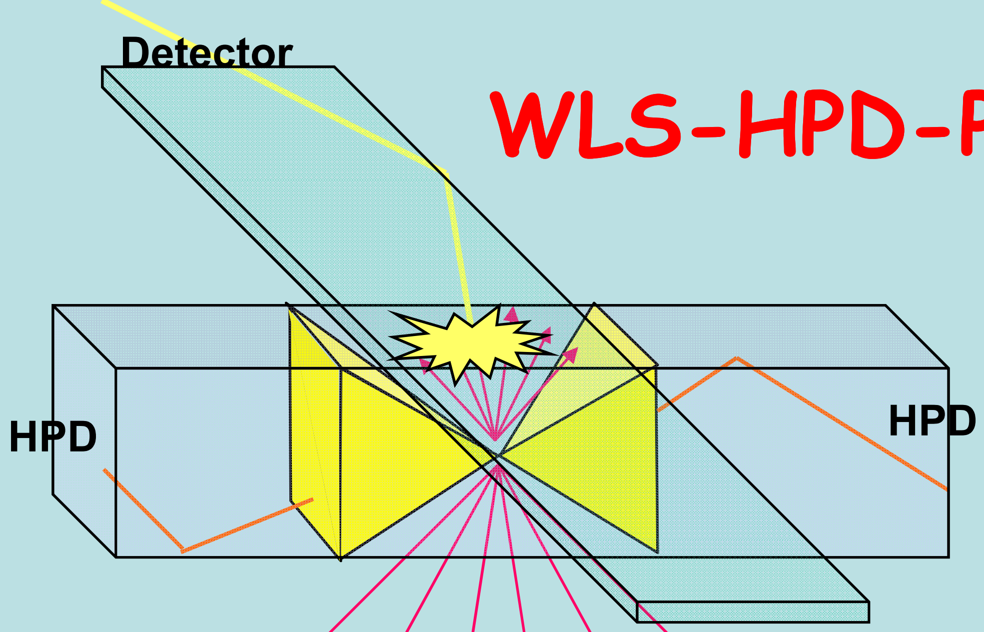
crystal	λeff(cm)	σ_z(mm)	σ_E/E (%)
YAP polish	21	10	4
YAP coated	8	4	6
LYSO polish	42	18	7
LYSO coated	8	5	10

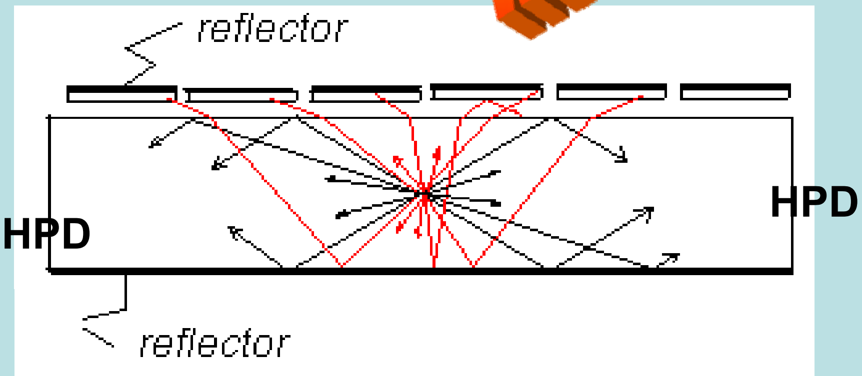
λeff(cm)	σ_z(mm)	σ_E/E (%)
21	1	4
42	1	7

A. Braem et al.,NIM A580(2007)1513

WLS-HPD-PET concept

WLS-HPD-PET





$$N_{pe} = Y \cdot \frac{d\Omega}{4\pi} \cdot \frac{1}{4} \cdot \varepsilon_{fluor} \cdot \varepsilon_{trans} \cdot \varepsilon_{\det}$$

$$Y = 32000 \ / \ \mathrm{MeV} \quad (\mathrm{LYSO})$$

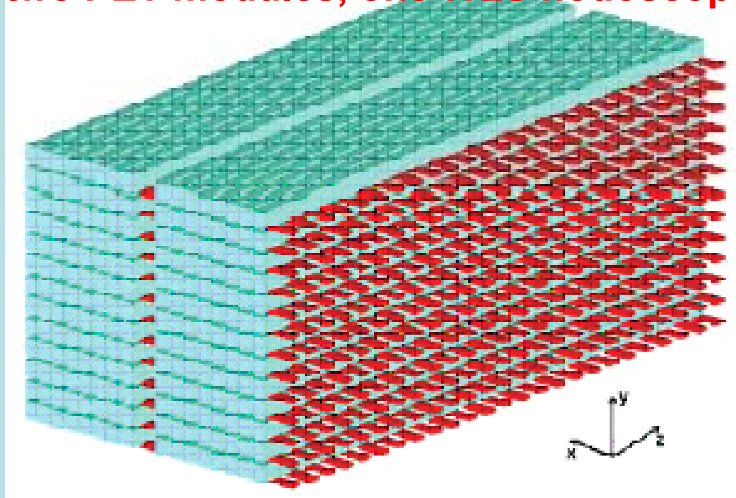
$$\varepsilon_{fluor} = 0.8$$

$$\varepsilon_{trans} = 0.5$$

$$\varepsilon_{\det} = 0.15 \ \ (@ \ 490 \ nm)$$

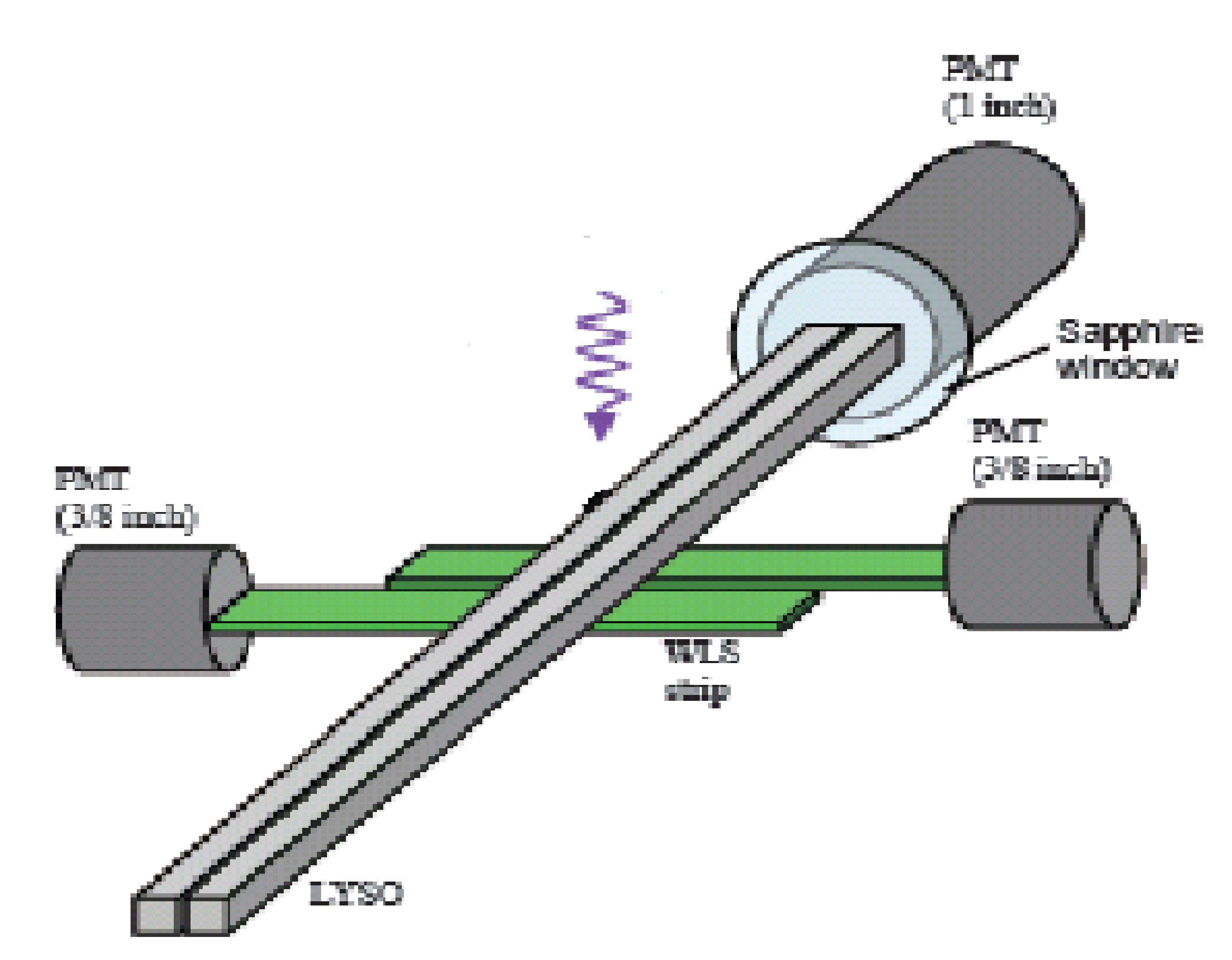
$$N_{pe} = 46 \ \ (@ \ 511 \ keV) \quad \rightarrow \quad \boxed{\varepsilon_{\gamma} \approx 1}$$

two PET modules, one WLS hodoscope

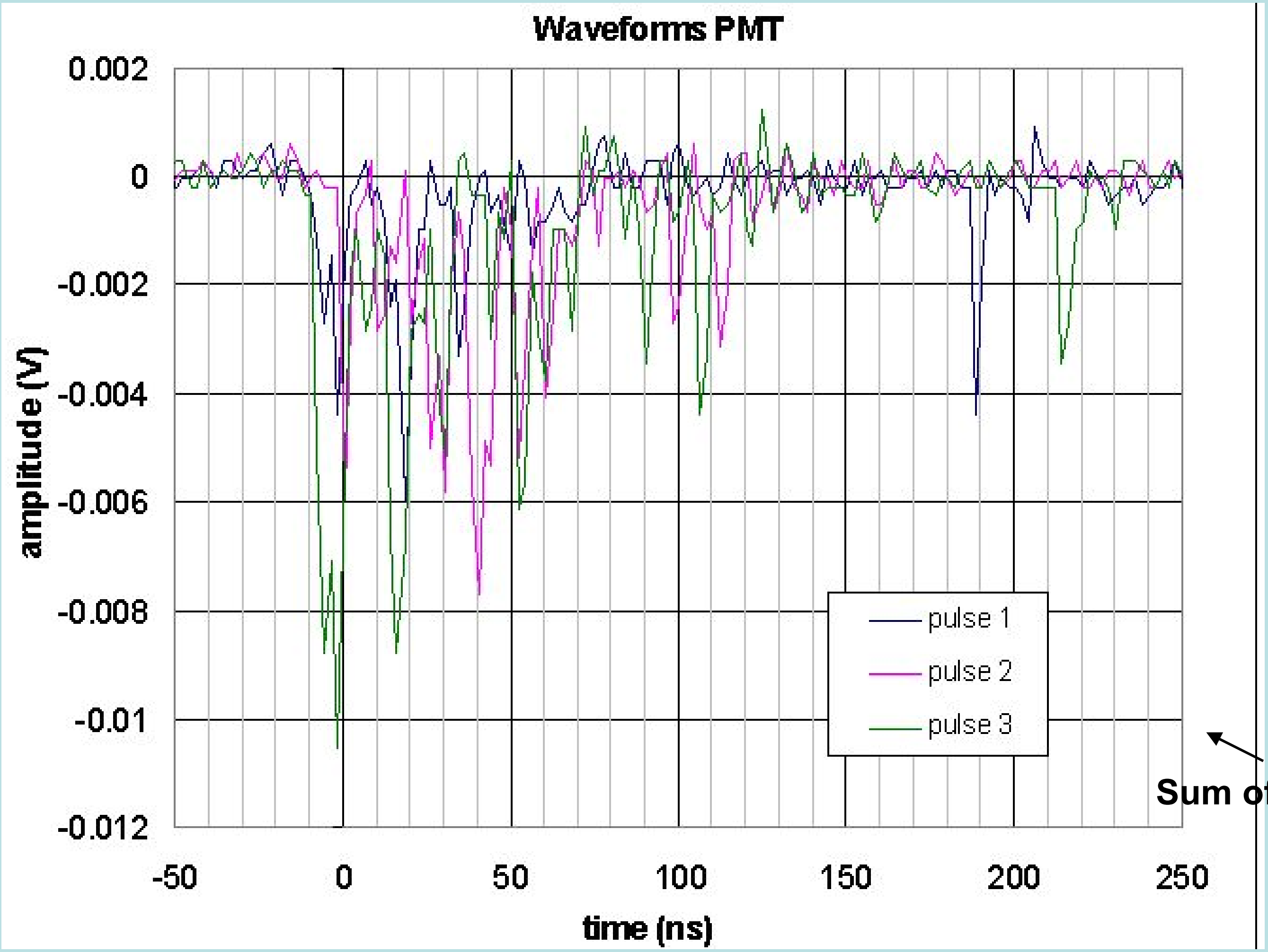


SETUP for WLS-HPD-PET Test

LYSO + 2WLS readout by PMTs



Typical pulses from WLS strips bars

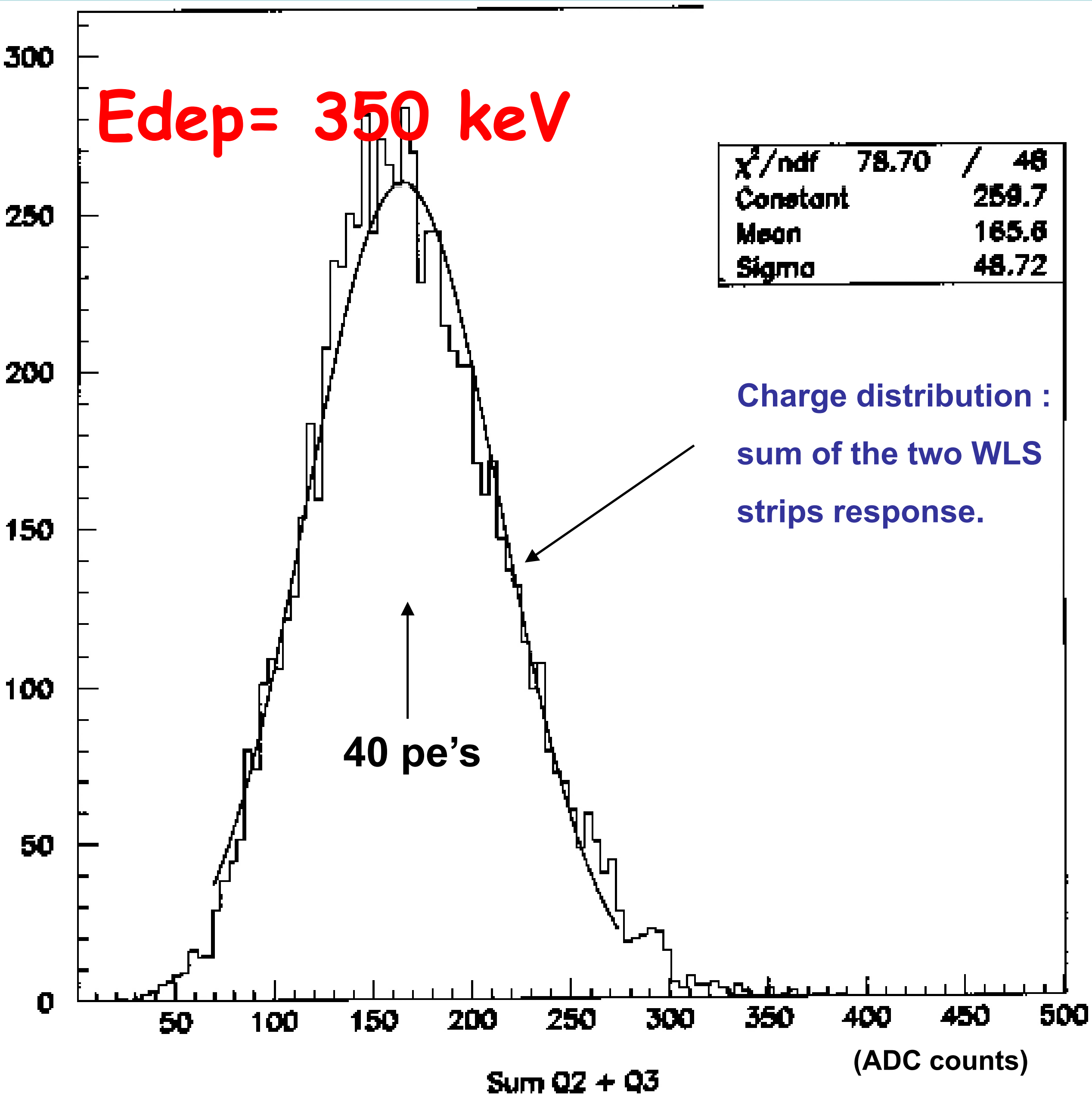


τ_{WLS} =10 ns

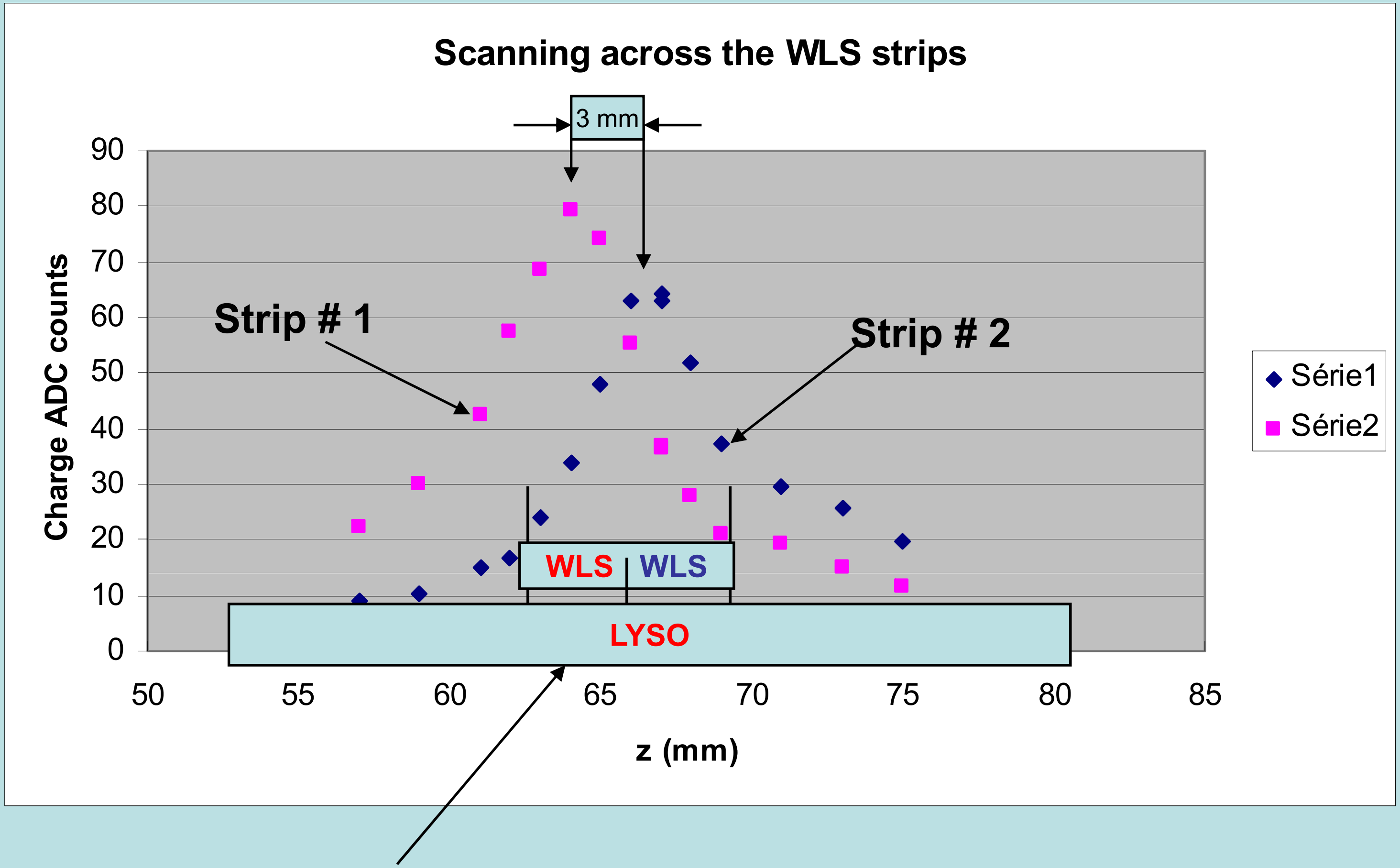
τ_{LYSO} =30 ns

Sum of channels 1 and 2

charge distribution of the sum of two WLS



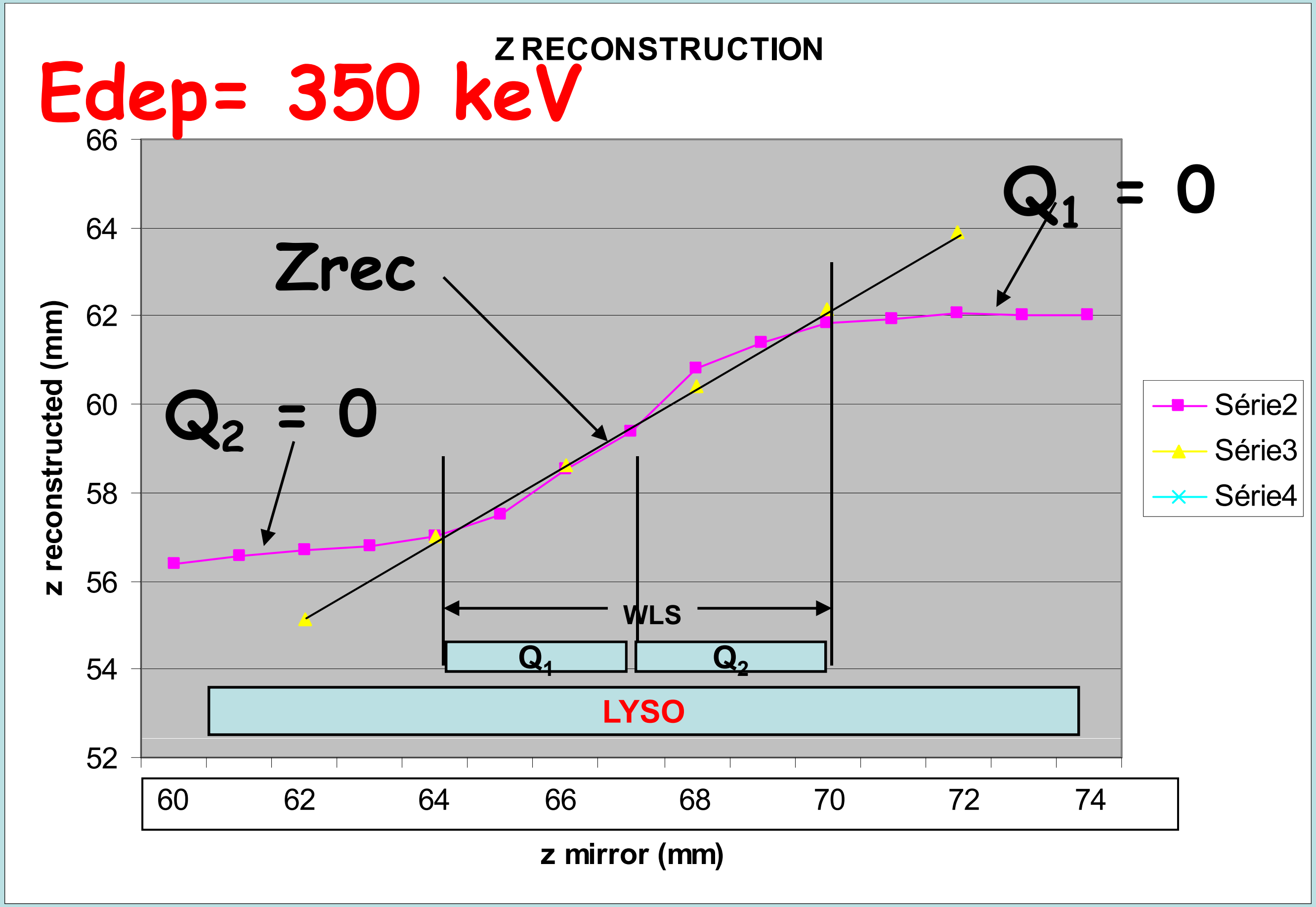
charges on 2 LYSO bars



at z = 64 mm (centre of strip #1)

65% of charge on strip #1, 35% on strip#2

Scintillation position (DoI) reconstruction

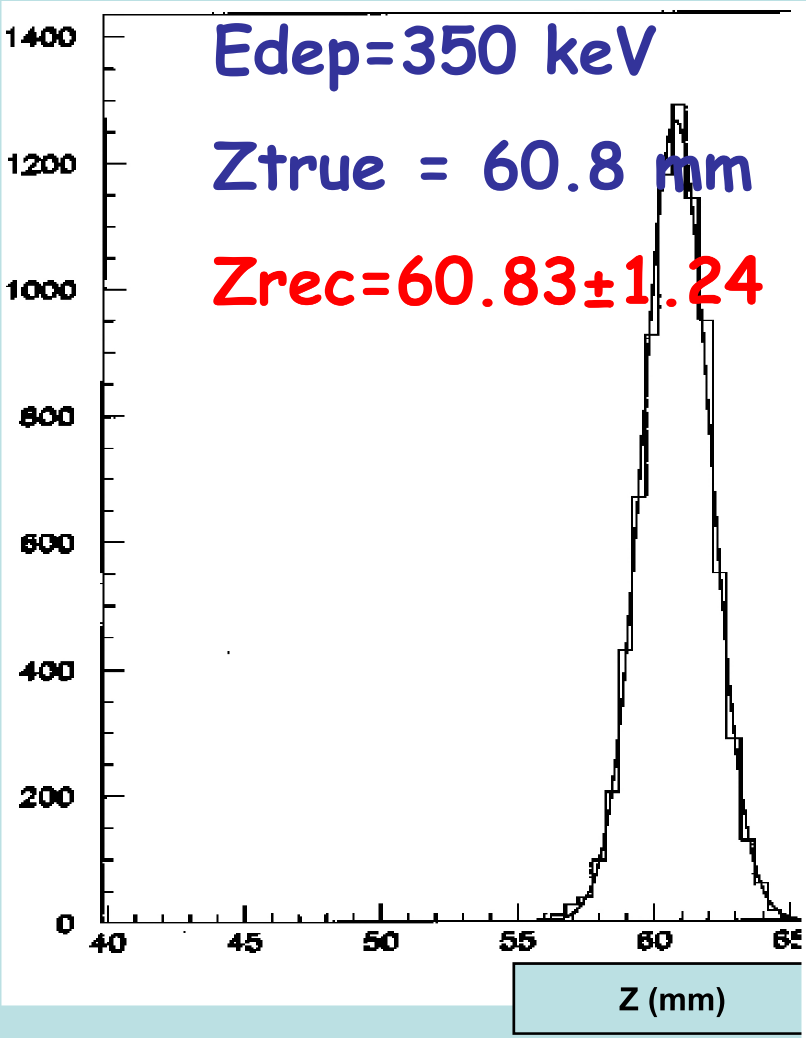


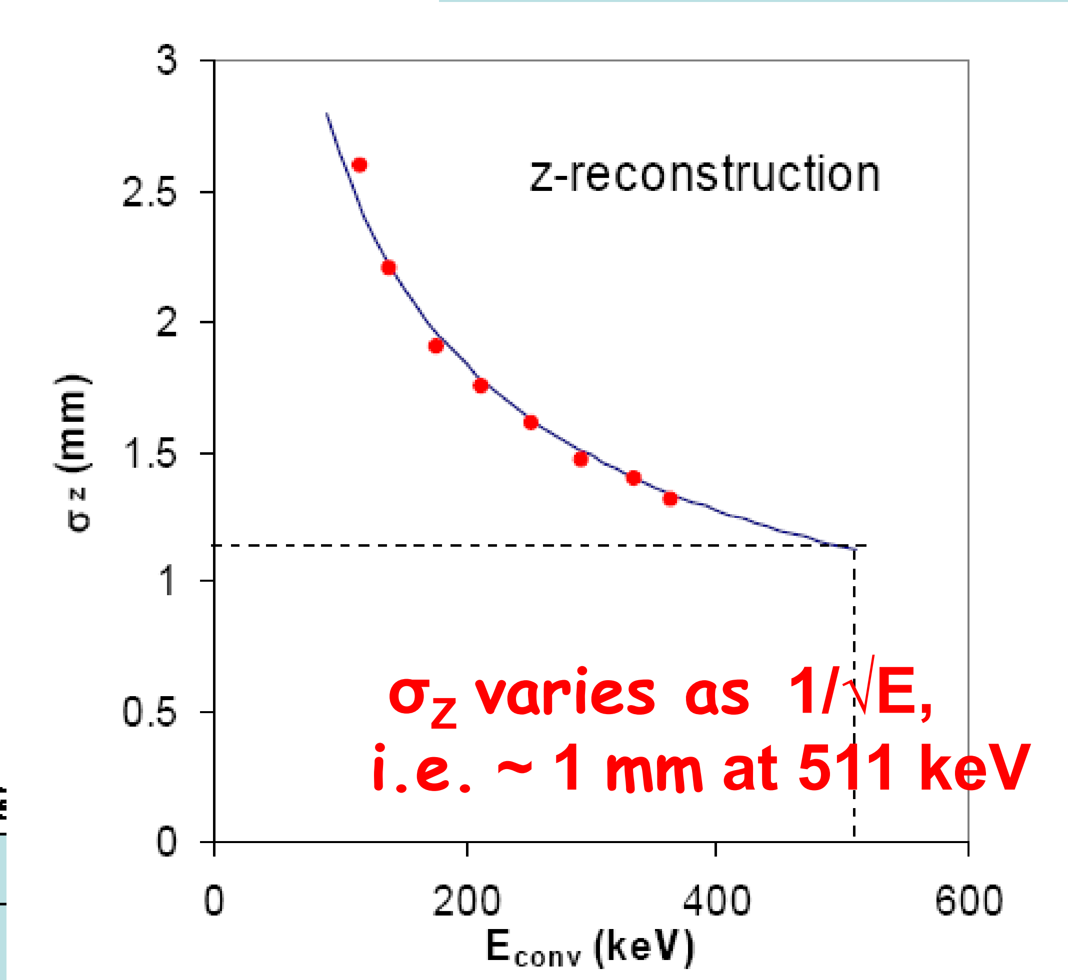
$$Z_{rec} = c + m\,(Q_2 - Q_1) / (Q_2 + Q_1)$$

m = 0.9 (# 1) is due to a different det.eff. of the two WLS strips.

c = constant

Zrec distribution from two WLS charges





From our publication in Il Nuovo Cimento Vol. 29 C,N. 4

FWHM values

Comparison of reconstruction resolution (FWHM values): HRRT data vs. HPD–PET simulation. In the simulations a crystal length of 150 mm was assumed. All values correspond to the central plane (z=0).

	Transaxial resolution $R_x(=R_y)$ (mm)		Axial resolution R_z (mm)		Mean volumetric resolution $R_V = R_x \times R_y \times R_z$ (mm^3)
	x=0; y=0	x=100; y=0	x=0; y=0	x=100; y=0	
HRRT data, span 9	2.35	2.75	2.5	3.6	20
HRRT data, span 3	2.35	2.75	2.5	2.8	18
HPD-PET LSO	1.85	2.35	5.78	6.33	26
HPD-PET $LaBr_3$	1.59	2.13	3.43	3.57	11.8
WLS-HPD-PET LYSO	**~ 2.2**	**~ 2.2**	**2.1**		**~ 9 mm^3**

This is ~ physical limit

due to positron range and gamma acolinearity