Usage of long axially oriented crystals in PET developments: timing and axial resolutions

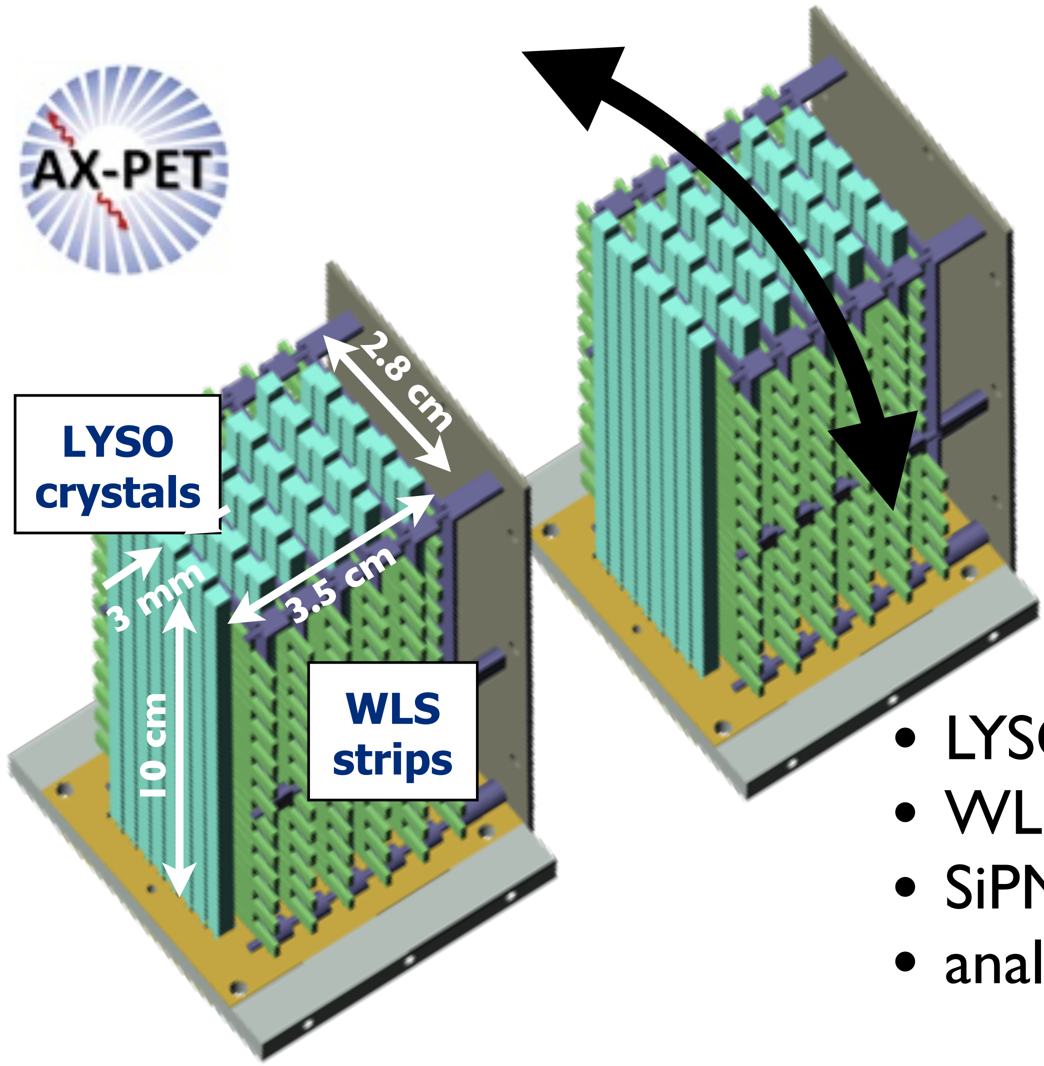
II Symposium on Positron Emission Tomography

September 21st - 24th 2014, Jagiellonian University, Kraków, Poland

Chiara Casella - ETH Zurich

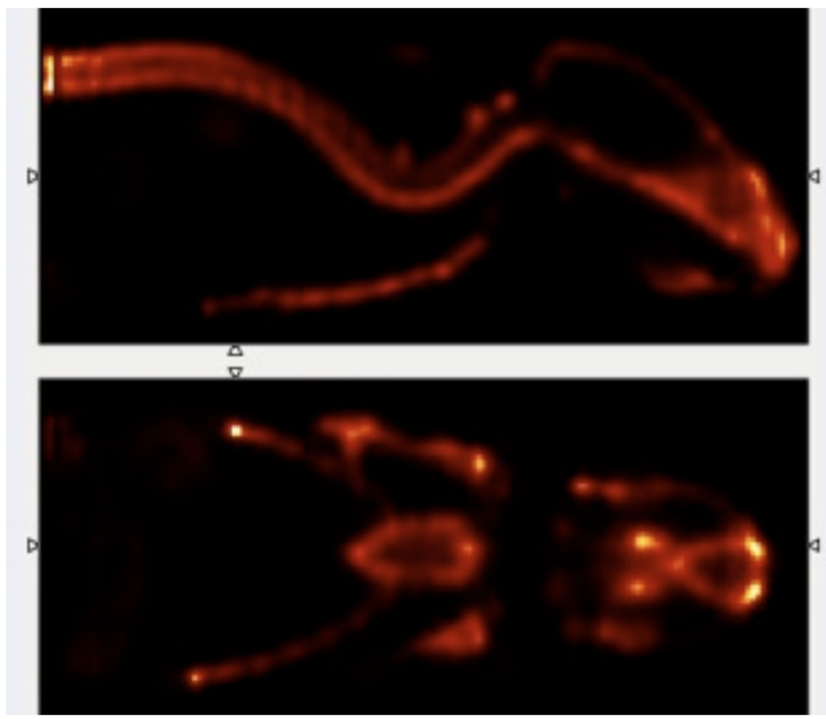
Kracow, 22.09.2014

Usage of long axially oriented crystals



from AX-PET demonstrator
see talk from P. Solevi

- LYSO crystals (10cm long)
- WLS strips
- SiPM (both for xtals and WLS)
- analogue readout



Question1 : is there a TOF potential in an AX-PET like device?

Chiara Casella (ETHZ), Matthieu Heller (CERN), Christian Joram (CERN), Thomas Schneider (CERN),

Question2 : are there possible alternatives to the WLS strips for the definition of the axial coordinate?

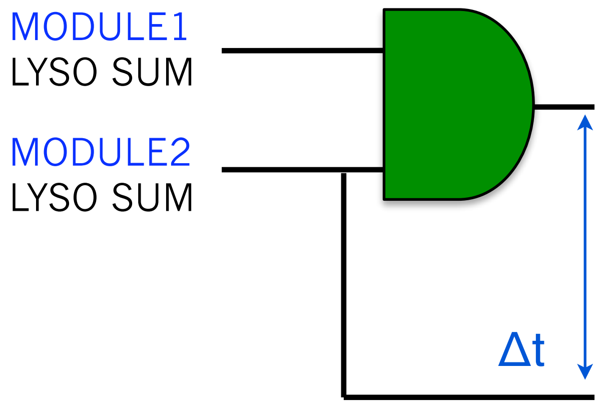
Chiara Casella (ETHZ), Matthieu Heller (CERN), Oliver Holme (ETHZ), Christian Joram (CERN)

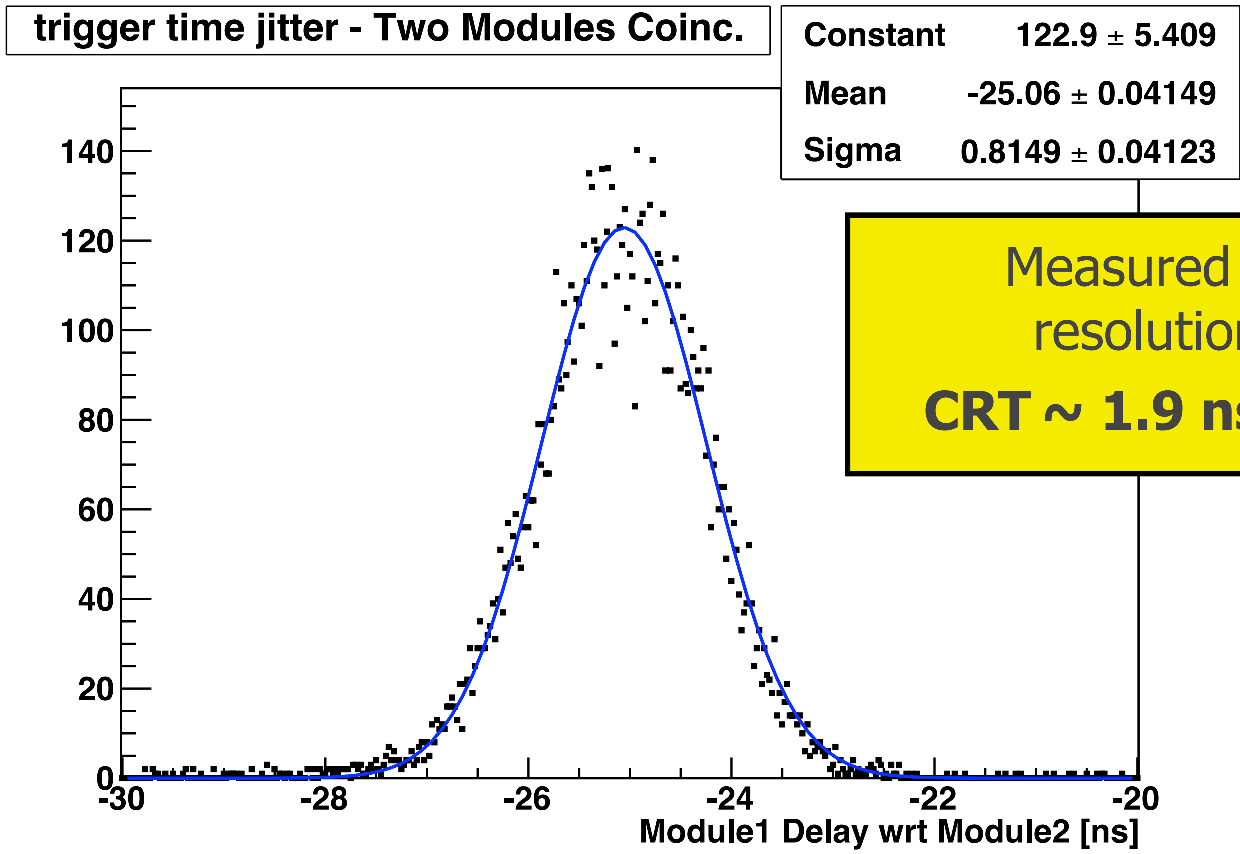
AX-TOF-PET ?

- **no timing information available** in the AX-PET readout (fully analogue readout chain)

measurement from the scope
[Lecroy Waverunner LT584 L 1GHz]

delay of coincidence wrt Mod2





Measured time resolutions :
CRT ~ 1.9 ns FWHM

modest TOF potential in the original AX-PET layout (but anyhow not foreseen in the electronics)

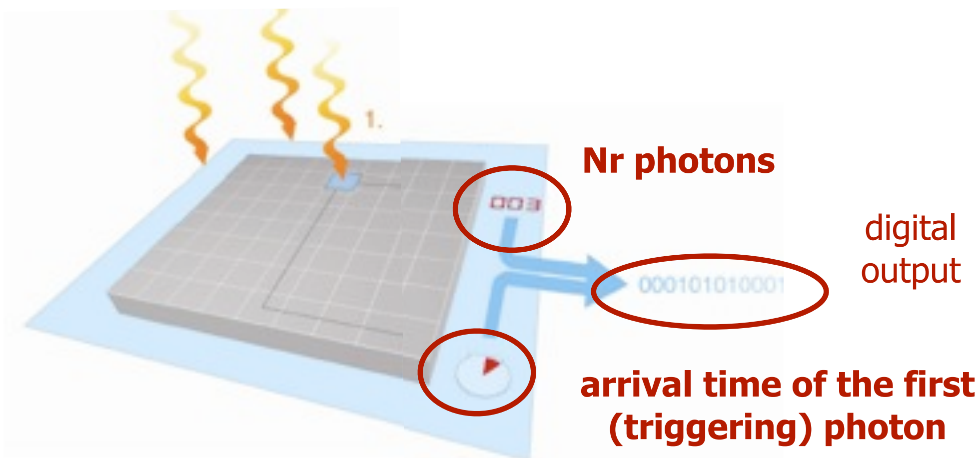
- for a TOF extension of the AX-PET :

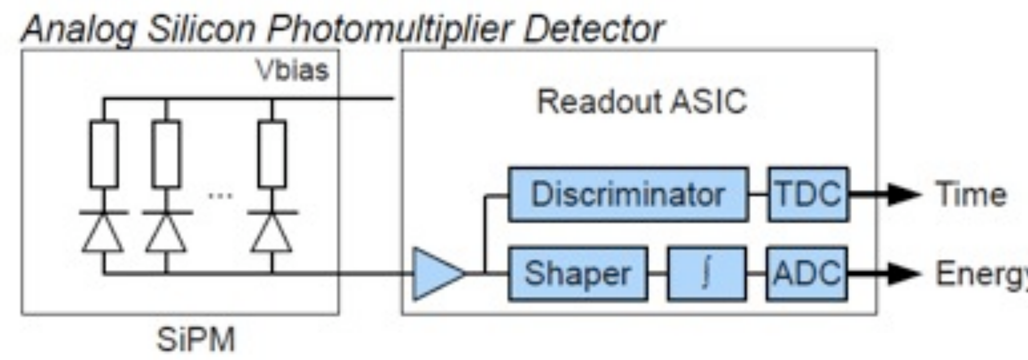
  timing information is needed with high timing resolution (~ few 100s ps)

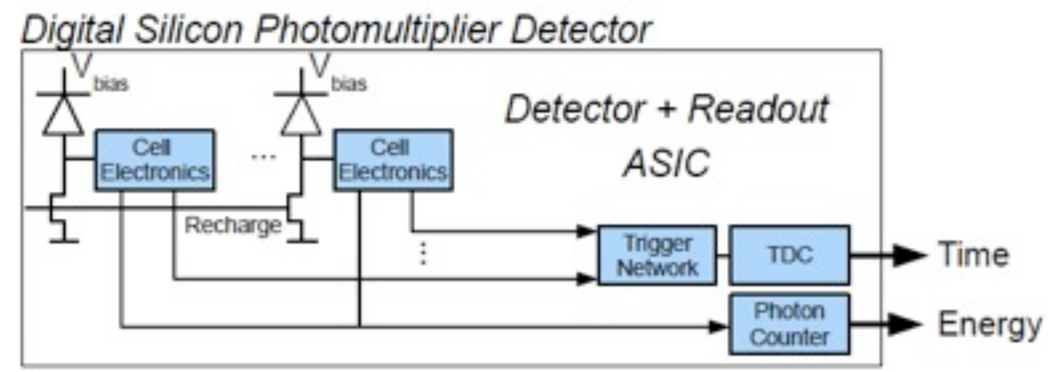
state of the art *full-systems* TOF-PET (clinical) :
e.g. Philips Vereos PET/CT => CRT (coincidence time resolution) ~ 350 ps FWHM

dSiPM : Digital SiPM (Philips)

- fully digital implementation of SiPM
- electronics on the same Si substrate as for the sensor
- on-board TDC (19.5 ps resolution)

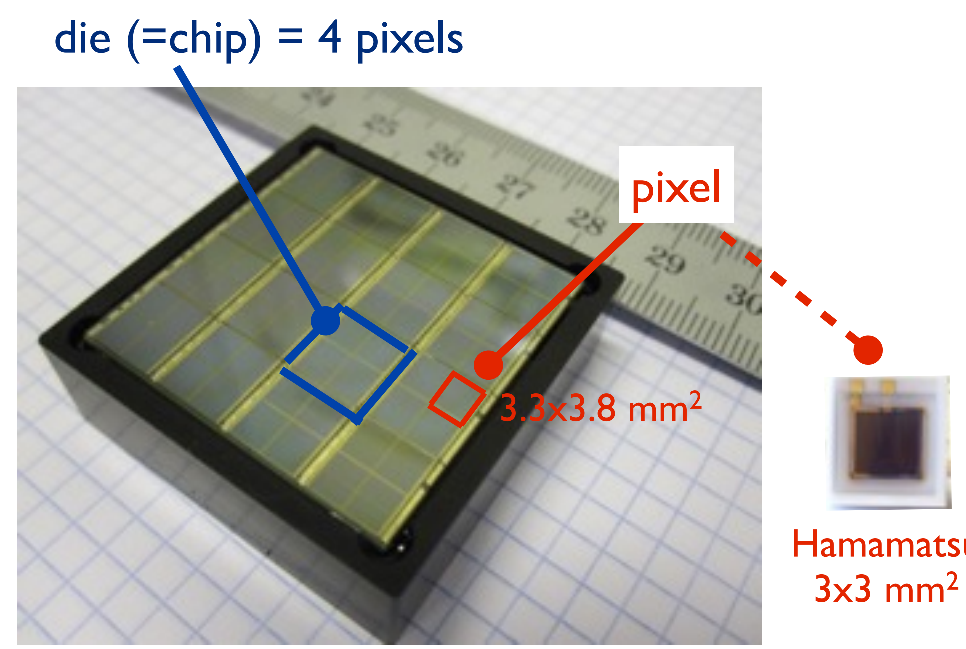






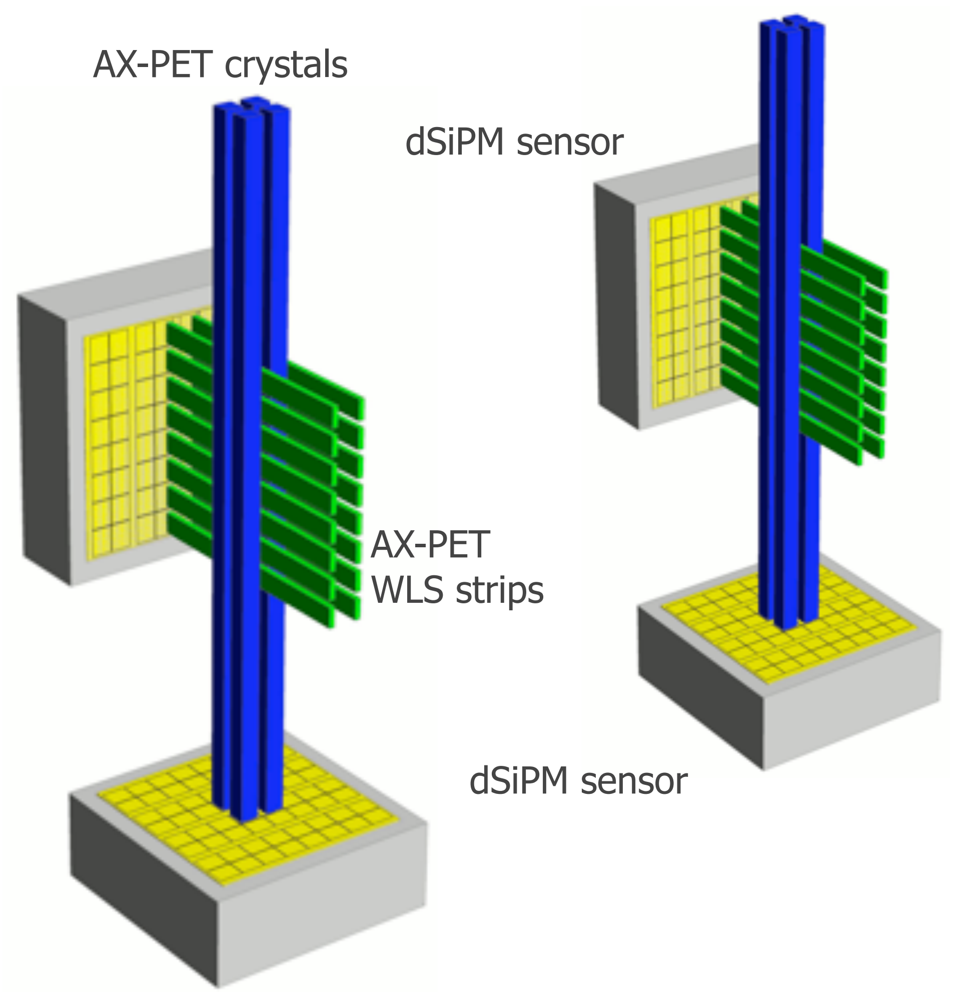
interest of dSiPM for PET applications :

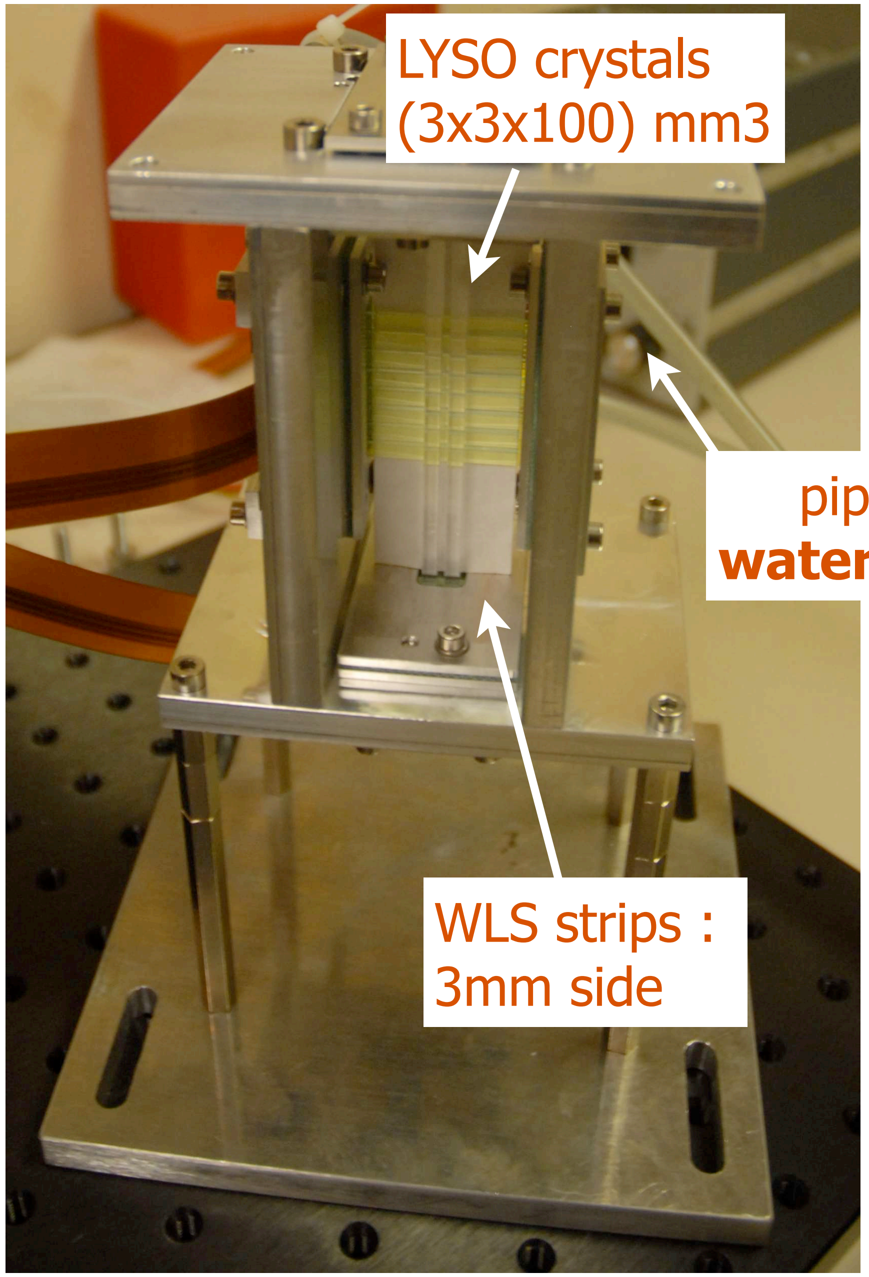
- **High resolution timing information** => TOF-PET
- **Integration** (bias supply included, amplifier, TDC, photon counter)
- **Compactness**
- Early digitization of the output => **Low noise**
- Digital => **Temperature and gain stability less critical** wrt analogue
- Fast active quenching => no Afterpulses.
- Possibility to disable individual cells => **Reduction in the dark count rate** (but lower PDE)
- MRI compatible

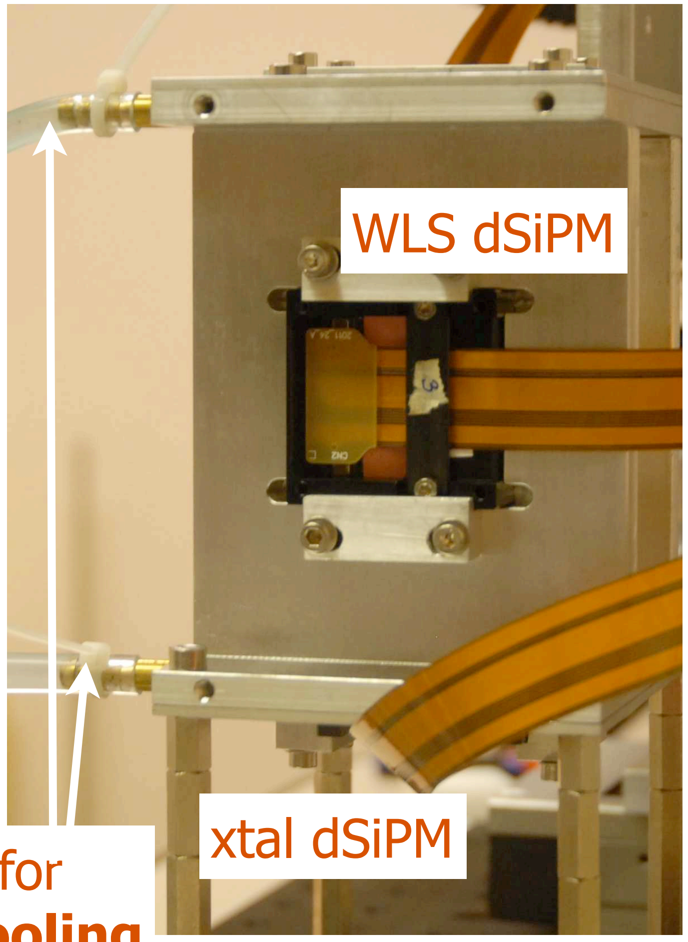


AX-PET small scale modules with dSiPM

- **two "digital" small-scale modules**
- **identical detector elements as AX-PET coupled to dSiPM**
- reduced Nr channels [2 Layers; 2 LYSO and 8 WLS / layer]

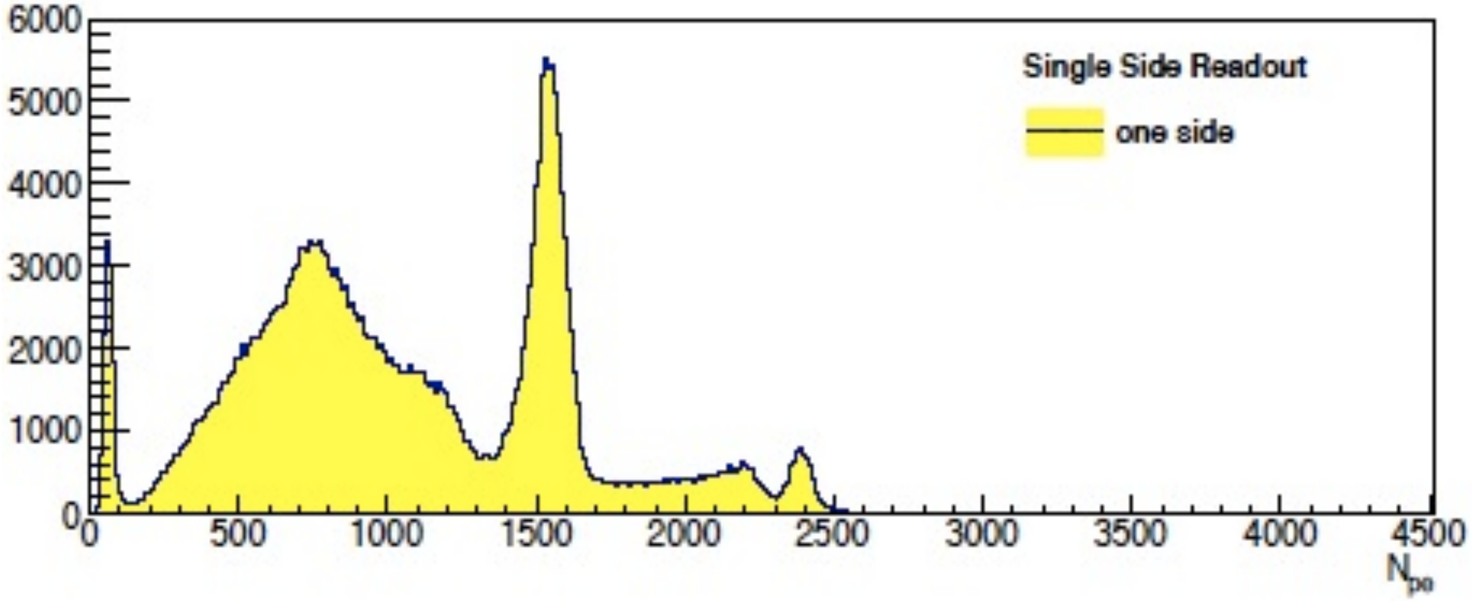




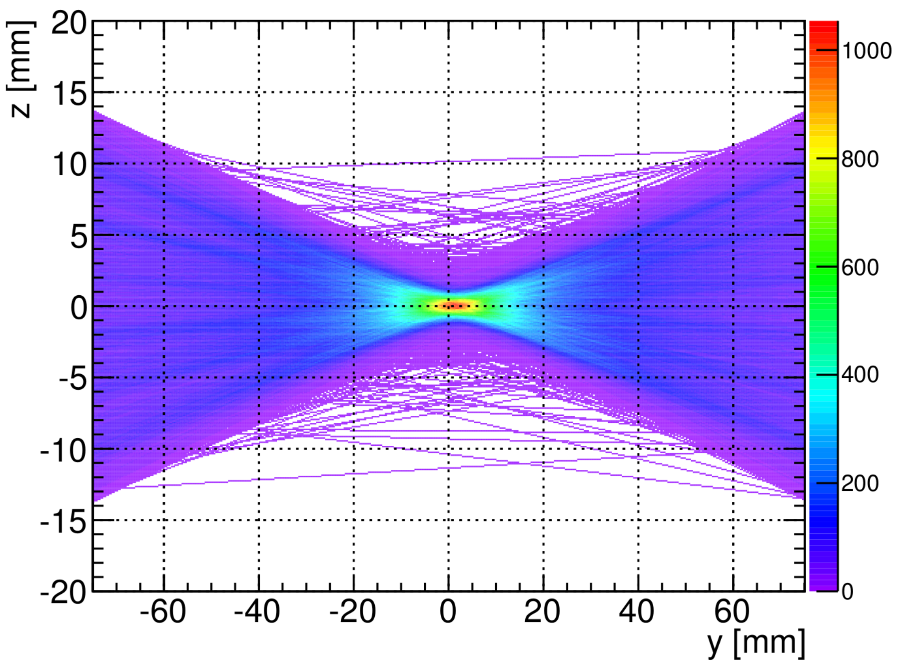


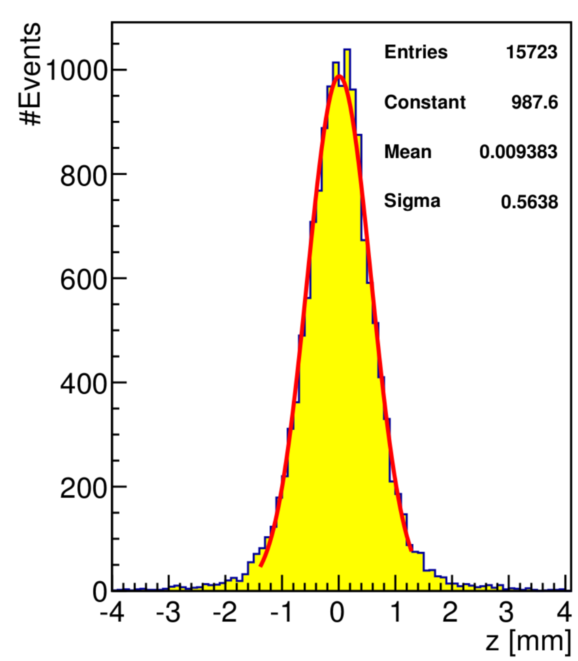
dSiPM AX-PET modules: Performance

Light yield spectrum - no coincidence

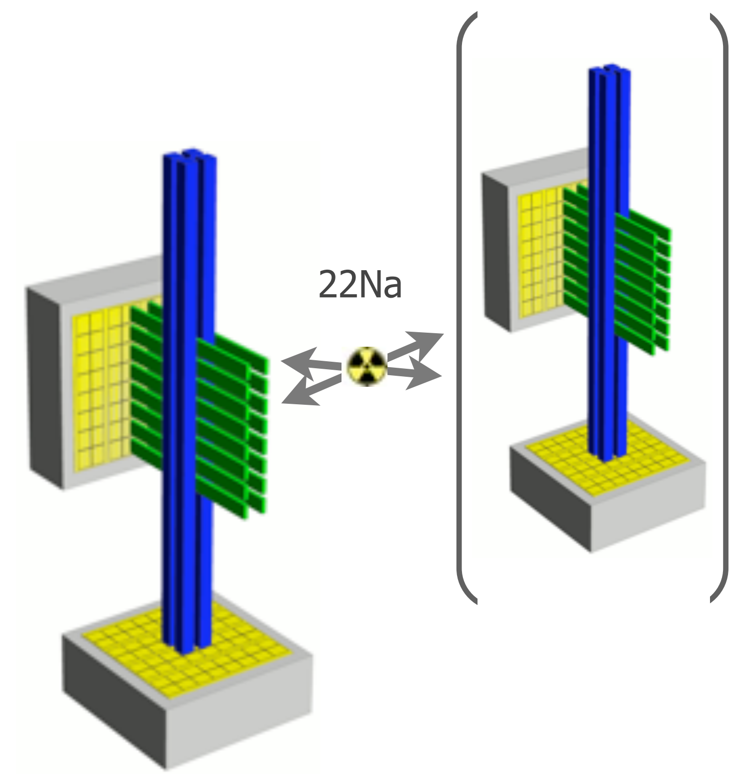


Confocal plane reconstruction - in coincidence





22Na source characterization measurements
(both individually and in coincidence)



Results of the characterization measurements:

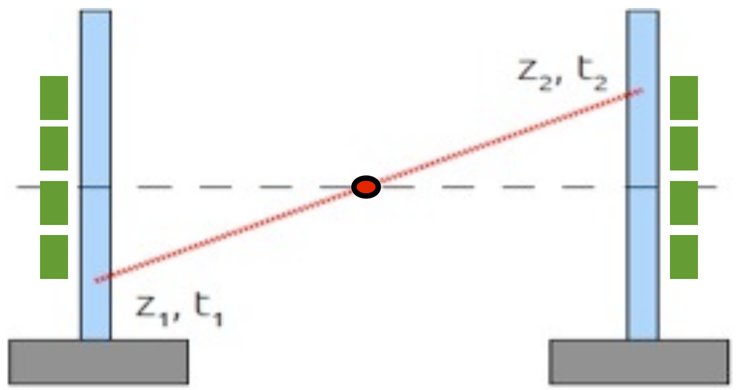
- **Light yield : ~ 1500 pe** (at 511 keV)
- **ΔE/E ~ 14%** @511 keV (after en.calibr.)
- **R_z ~ 1.22 mm**, FWHM (**in coincidence**)
- **$R_{z\,,\,mod}$ ~ 1.71 mm**, FWHM

achieved performance are perfectly comparable with the AX-PET results

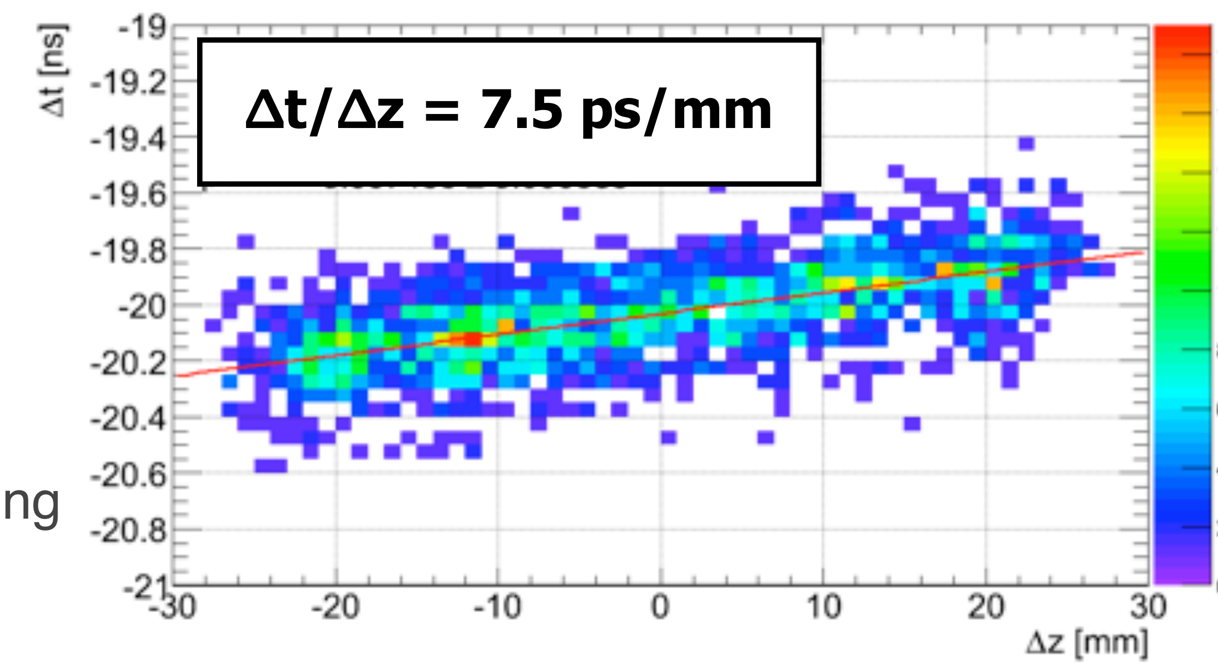
(dSiPM as alternative photodetector)

dSiPM AX-PET: Timing performance

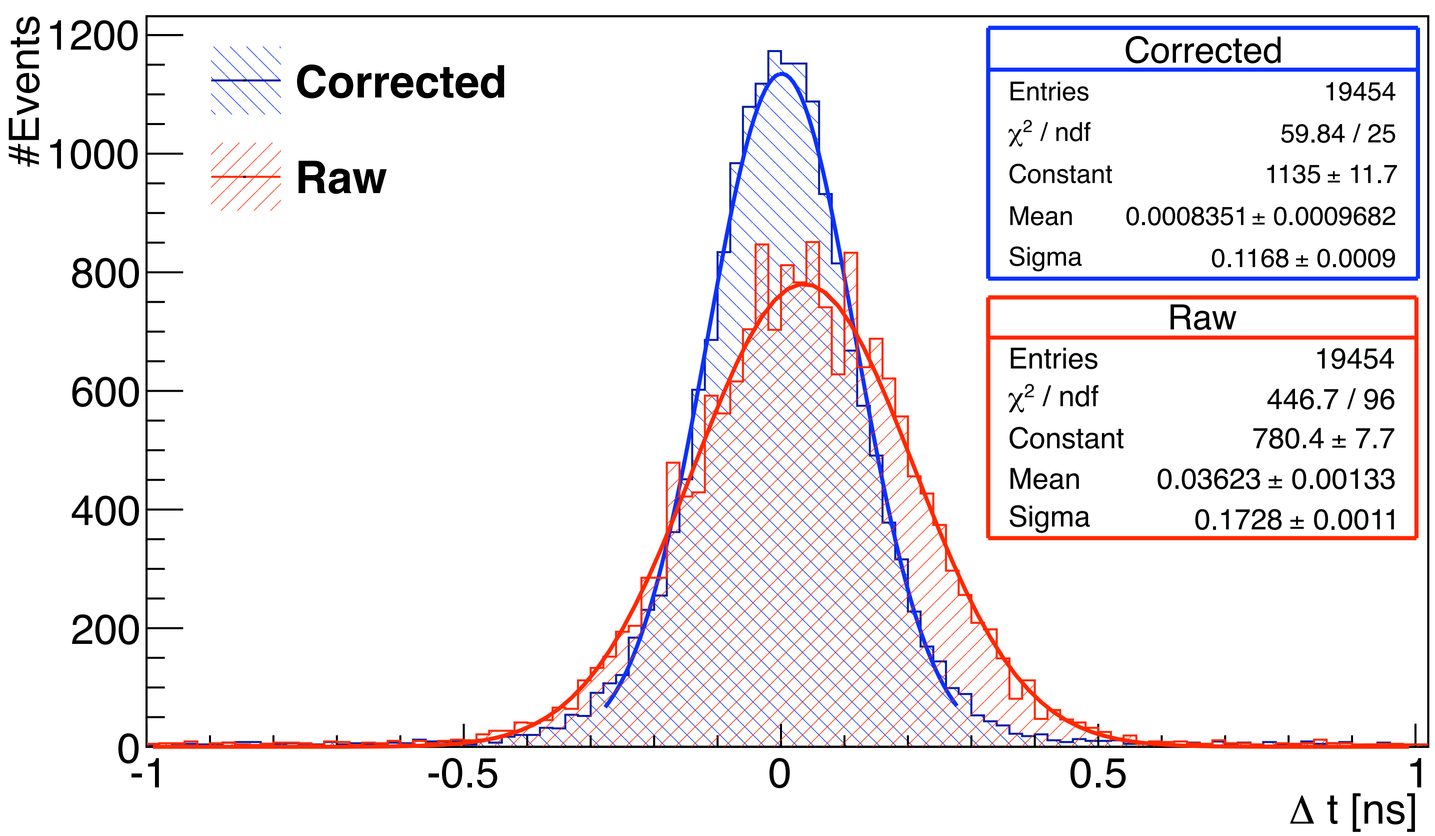
dSiPM as alternative photodetector : **TIMING is the added value !**



10 cm long => **significant path-length dependence** of timing
Need to correct by the axial coordinate



COINCIDENCE RESOLVING TIME



not corrected for axial coord.
(but geometrically constrained in the central part of the crystals)

CRT ~ 406 ps FWHM

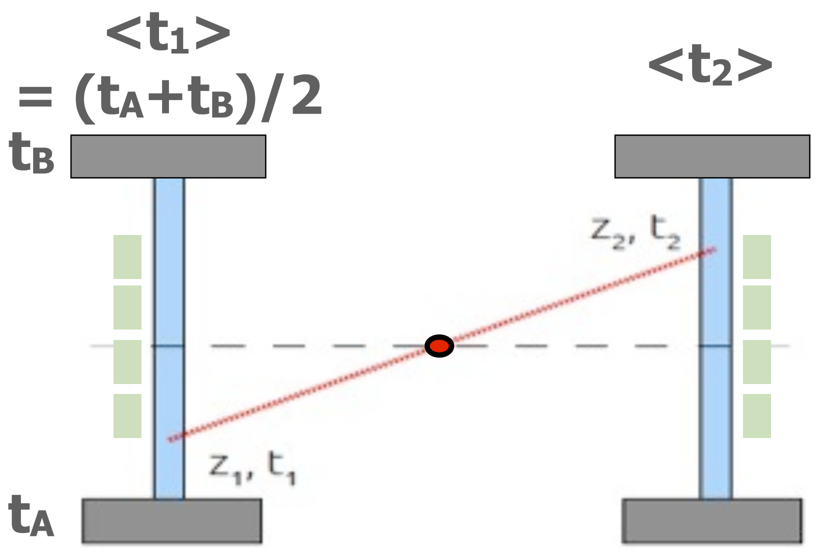
module t_res ~ 287 ps FWHM

corrected for axial coord.
(using information from the WLS)

CRT ~ 269 ps FWHM

module t_res ~ 190 ps FWHM

dSiPM AX-PET: Timing, Dual side readout



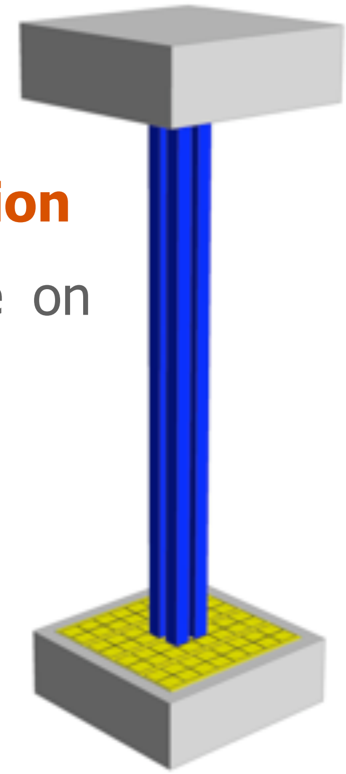
[WLS left in place, not readout]

Improving the path-lenght dependence by introducing

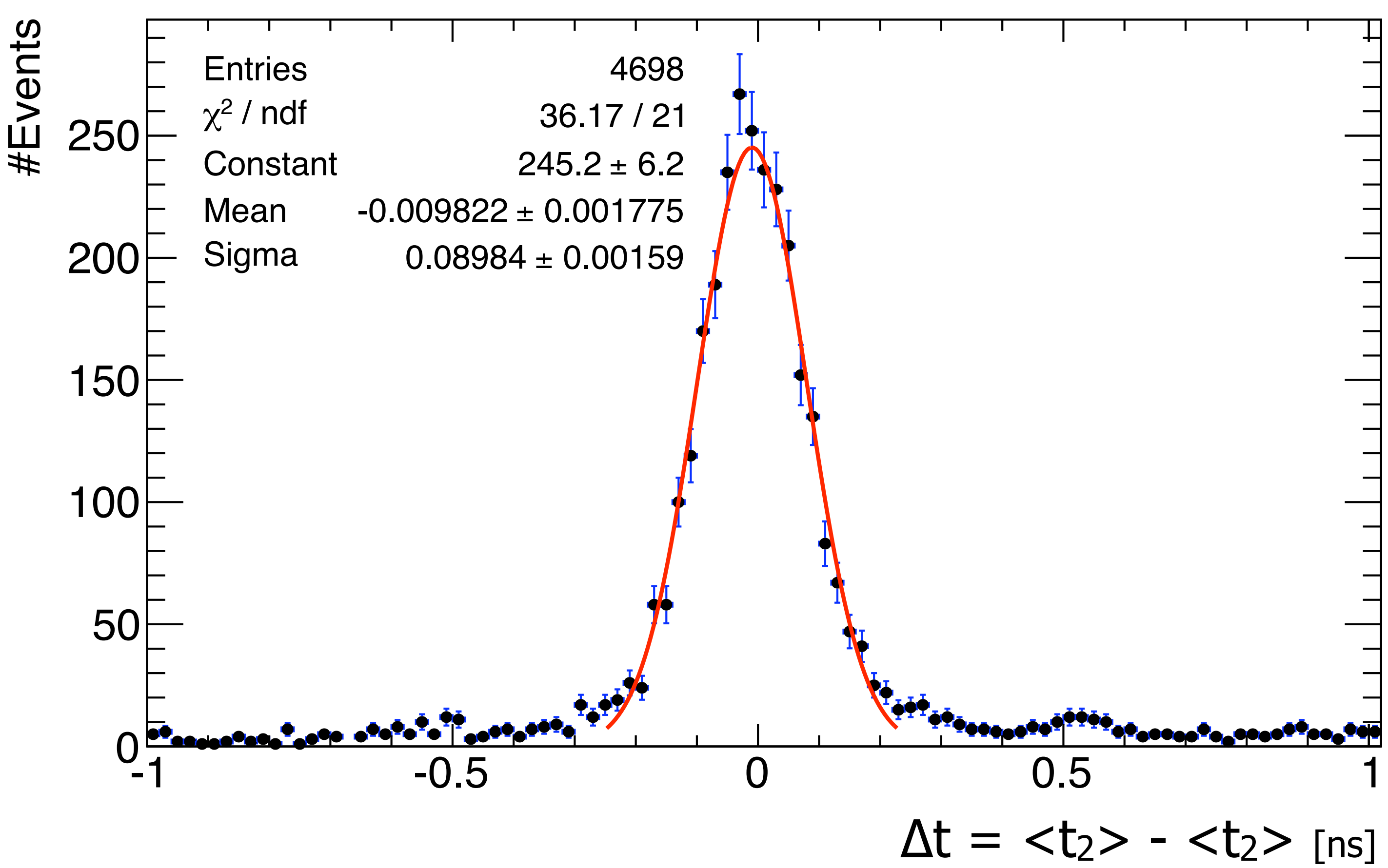
DUAL SIDED READOUT => Average timing definition

By definition corrects for the path length dependence on the axial coordinate.

Extension to the full 10cm lenght of the crystals



COINCIDENCE RESOLVING TIME



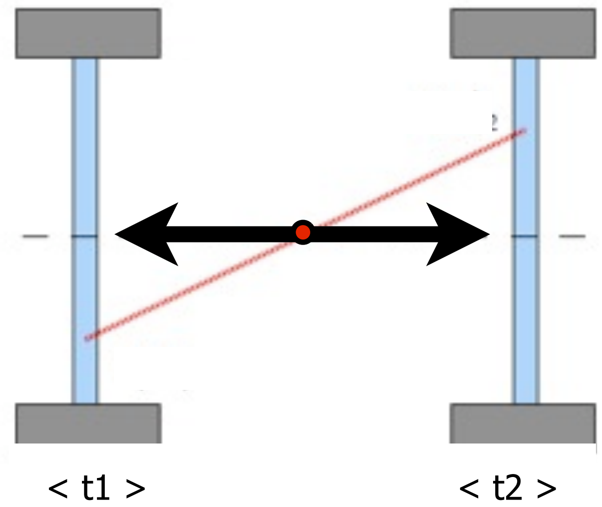
corrected for axial coordinate using the average timing

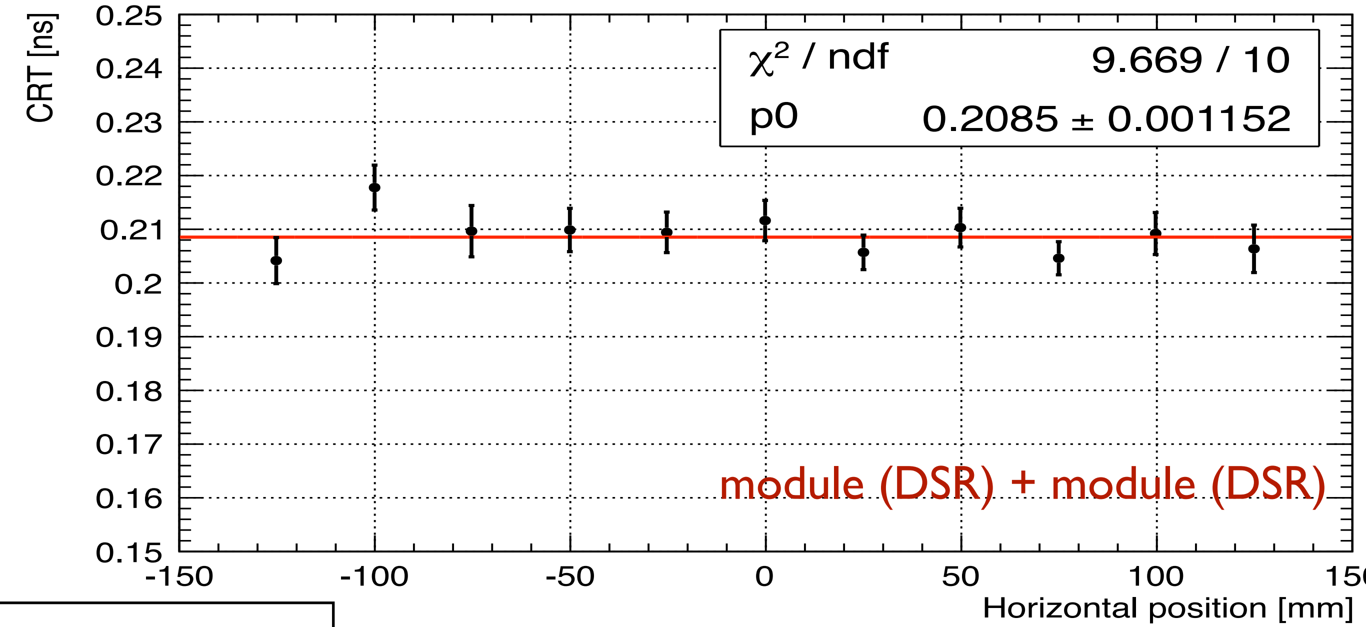
CRT ~ 211 ps FWHM

module t_res ~ 149 ps FWHM

dSiPM AX-PET: Timing, Dual side readout

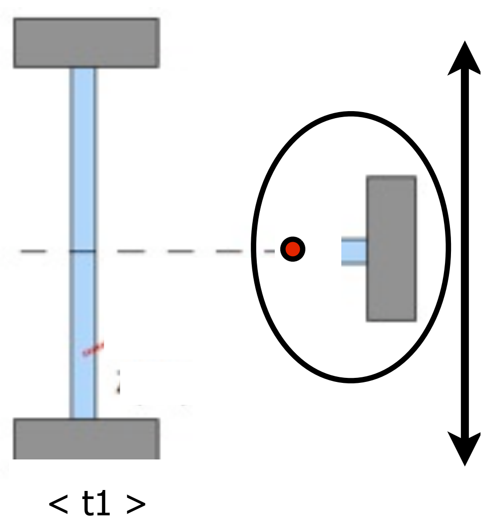
HORIZONTAL scan

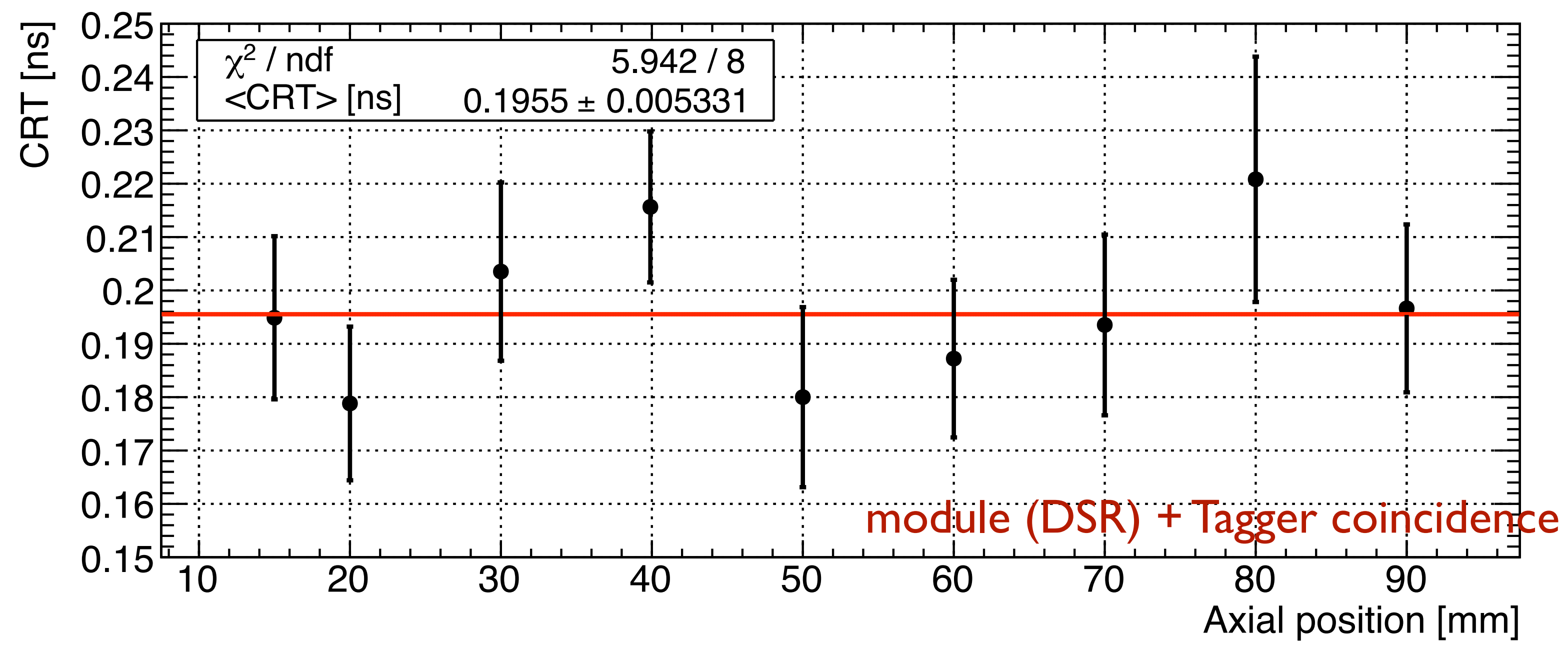




independent on the horizontal position along the FOV

AXIAL scan





independent on axial coordinate

Very good CRT demonstrated. Uniform along the FOV.

Usage of long axially oriented crystals

Question1 : is there a TOF potential in an AX-PET like device?

Christian Joram (CERN), Matthieu Heller (CERN), Thomas Schneider (CERN), Chiara Casella (ETHZ)

yes!

an **axial geometry is perfectly compatible with TOF** applications

need to introduce **correction for the path length dependence**

(either correcting for the axial coordinate or - more powerful - using *dual side readout with average time*)

a proper photosensors + proper readout system is needed

our result with **dSiPM, dual sided readout:**

CRT ~ 210 ps FWHM, uniform all along the field of view

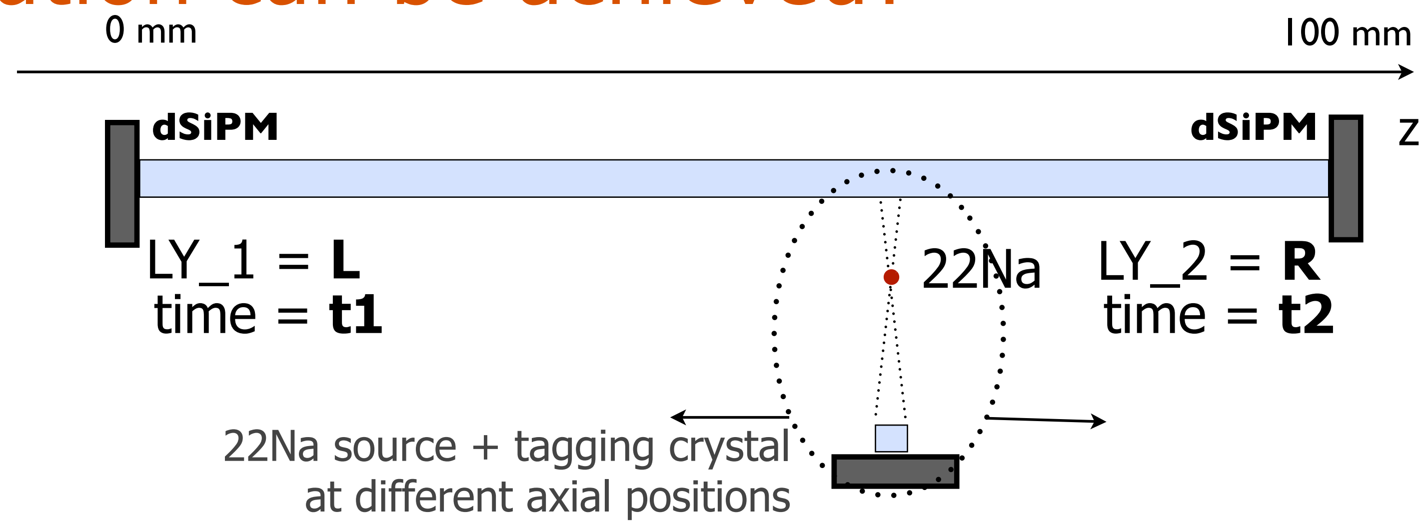
NIM A 736 (2014) 161-168

"A high resolution TOF-PET concept with axial geometry and SiPM readout"

Usage of long axially oriented crystals

Question2 : are there possible alternatives to the WLS strips for the definition of the axial coordinate?

which spatial resolution can be achieved?



- **dSiPM dual sided readout crystals**

- timing difference technique

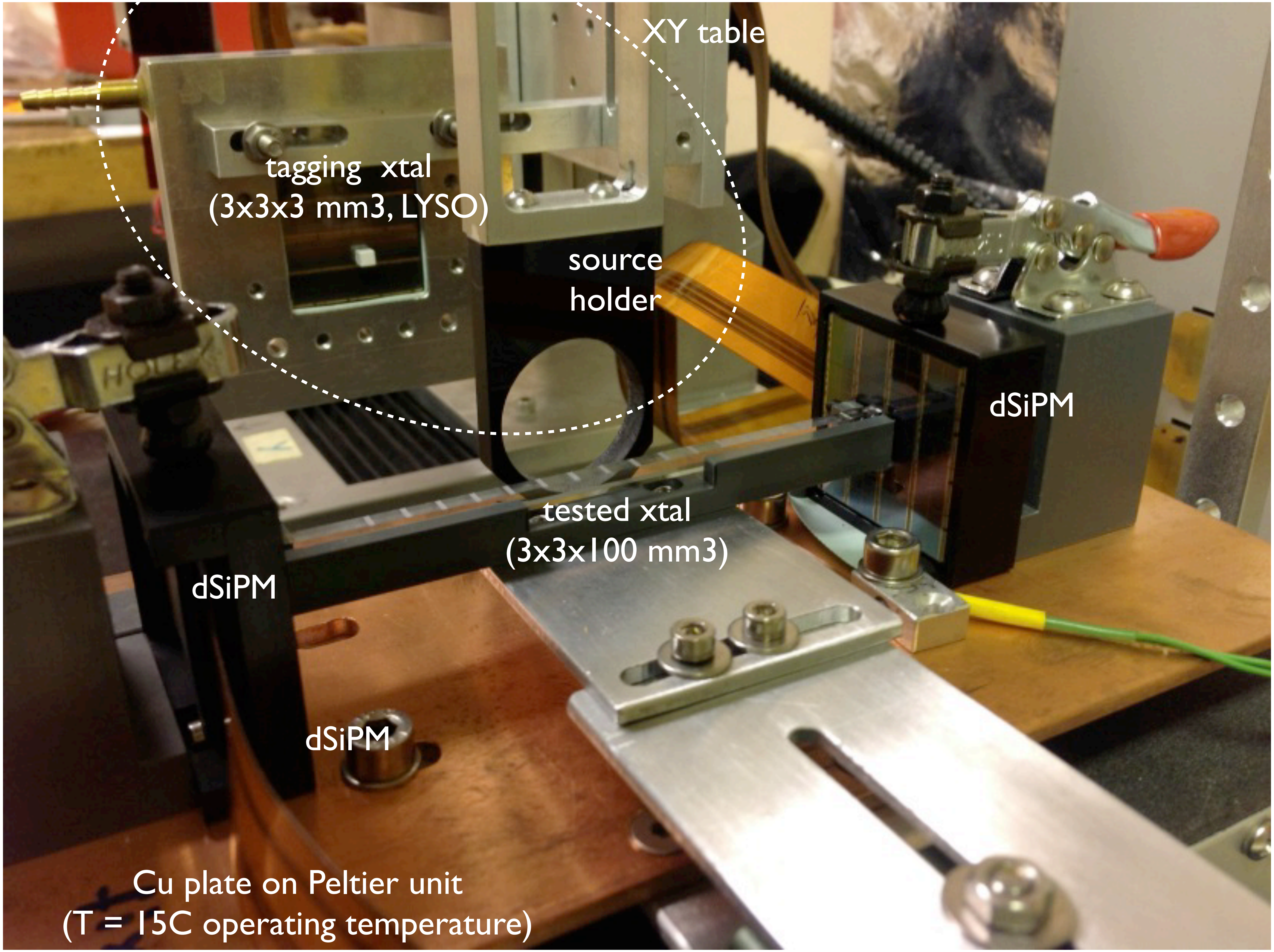
  $\Delta t/\Delta z$ = 15 ps/mm (7.5 ps/mm x2 for dual side)
  too high time resolution required
  not (yet) within reach - EXCLUDED

- light sharing technique

  "contrast" function : **(R-L)/(R+L)**

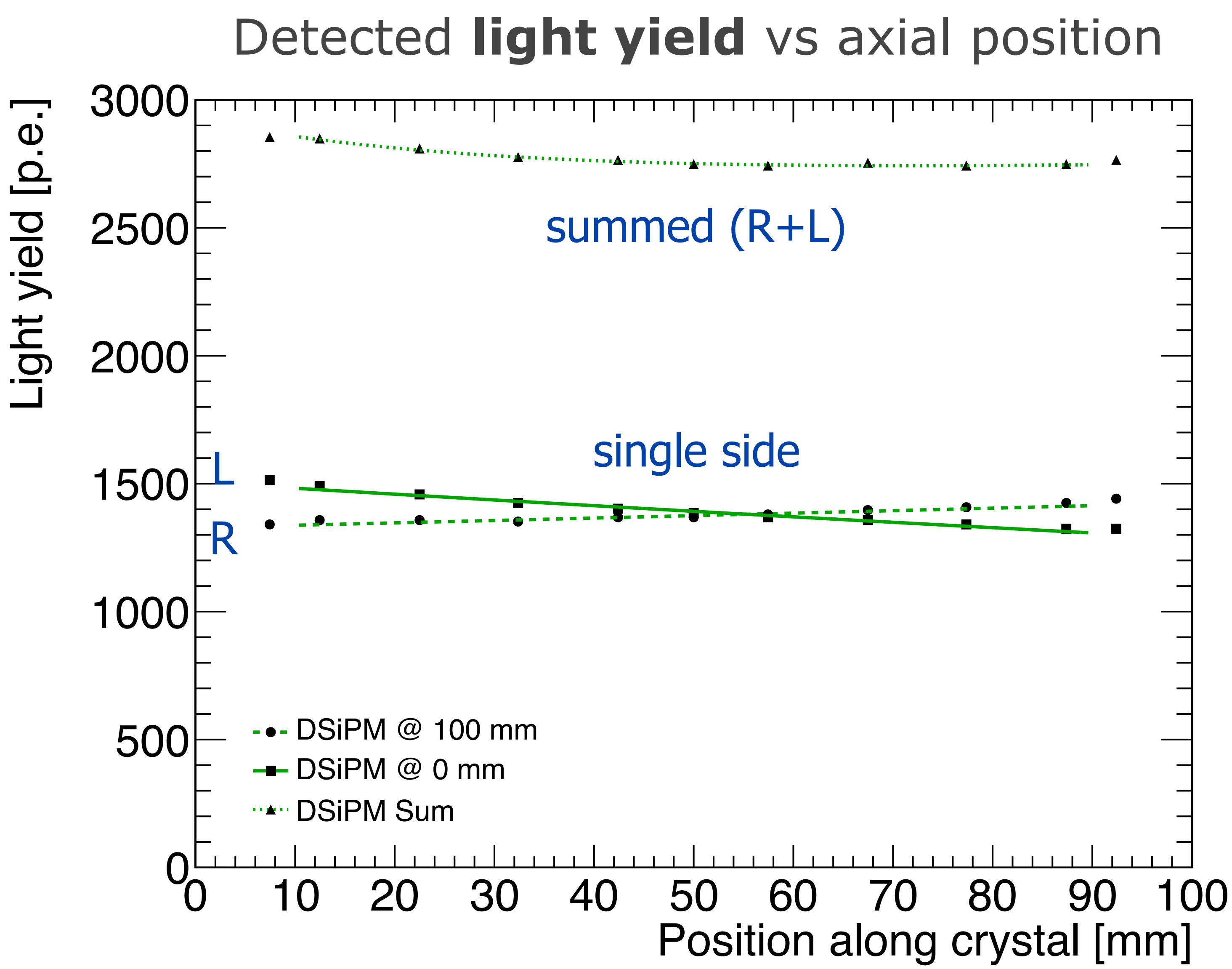
- original idea of the axial PET (HPD-PET)
  J.Seguinot et al, "Il Nuovo Cimento" C29(04), 2006
- also inspired by recent work from University of Manitoba (group A. Goertzen)
  F. ur-Rehman et al, 2011 IEEE. doi:10.1109/NSSMIC.2011.6153681

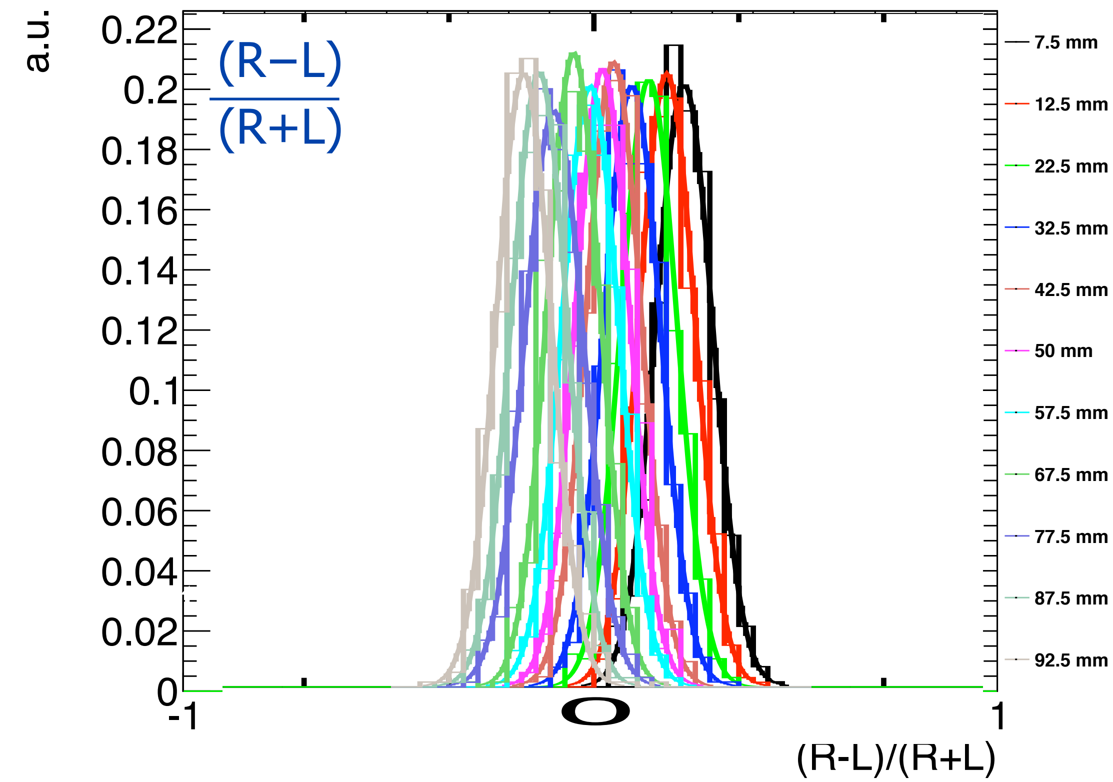
Setup

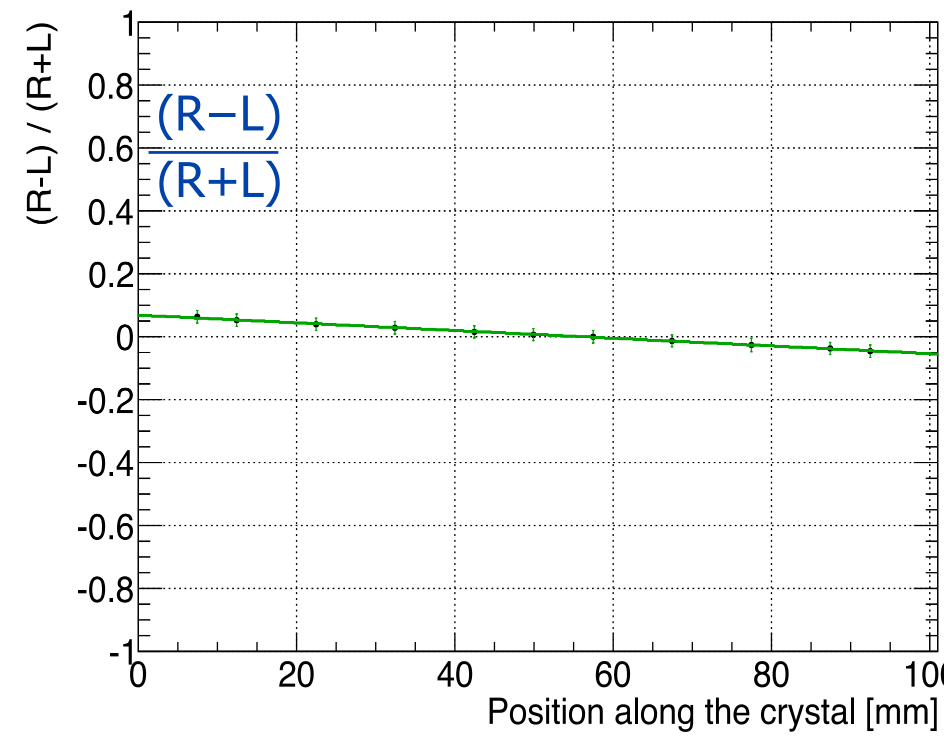

XY table
tagging xtal
(3x3x3 mm3, LYSO)
source
holder
dSiPM
tested xtal
(3x3x100 mm3)
dSiPM
dSiPM
Cu plate on Peltier unit
(T = 15C operating temperature)

Axial coordinate from light sharing

- **The method doesn't work for AX-PET standard crystals**
- **Not enough discriminating power in the contrast function**







AX-PET untreated crystal
(polished from manufacturer)
$\lambda_{optical}$ ~ 400 mm

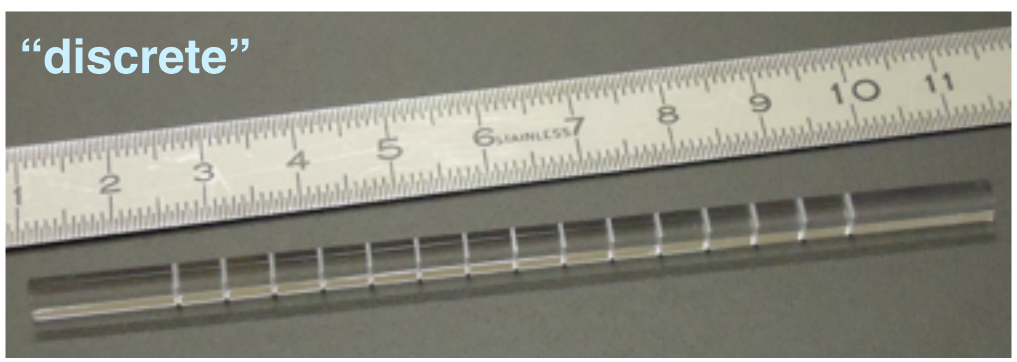
Destroying crystals…

Need to : - increase differences in the light yields L vs R
- artificially decrease $\lambda_{optical}$
- keep sufficiently high light yields

Empirical approach:

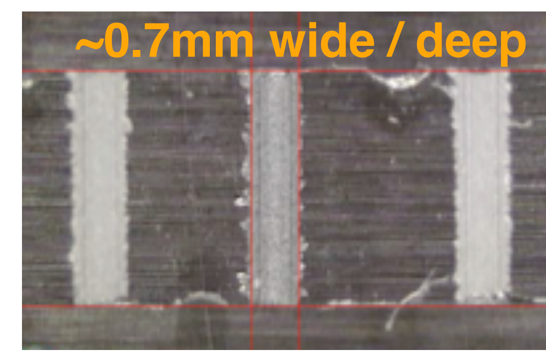
Destroying crystals :

- depolished 1 face, 2 faces (depolishing powder, grade 800)
- mechanical CNC etching (diamond tool), 1 face, 2 faces, 4 faces



5 mm pitch, four faces identical

5 mm pitch, four faces staggered



@CERN DT division:
T. Schneider
M. Van Stenis
C. David

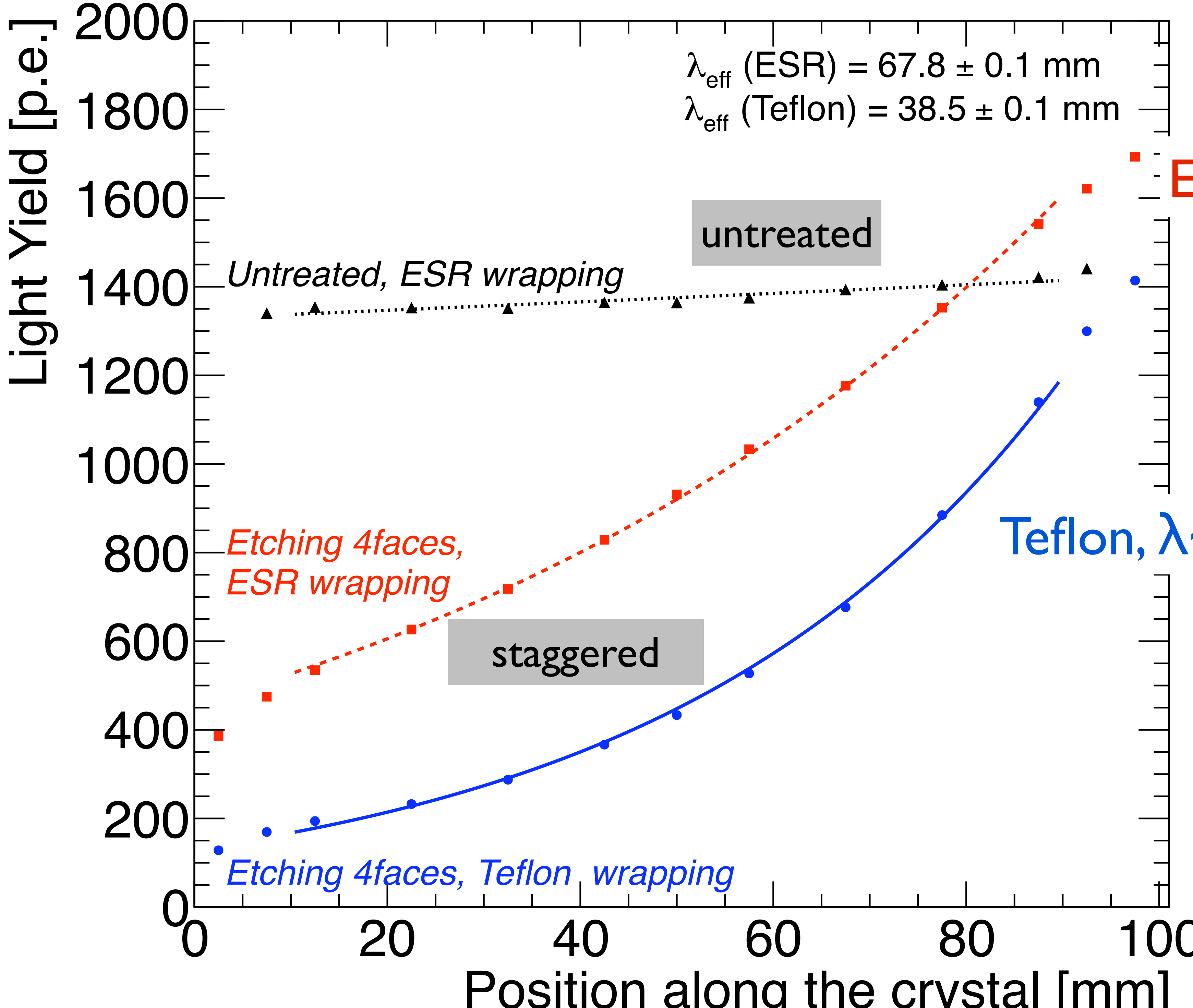
Wrapping (to partly recover the losses in light yield)

- teflon
- ESR (Enhanced Specular Reflector, 3M)
- (TiO2 painting on untreated crystals)

Light yield for surface treated crystal

Detected **light yield** vs axial position (one side only)

100 mm long crystal



ESR, λ~70mm, LY[0] ~ 2000

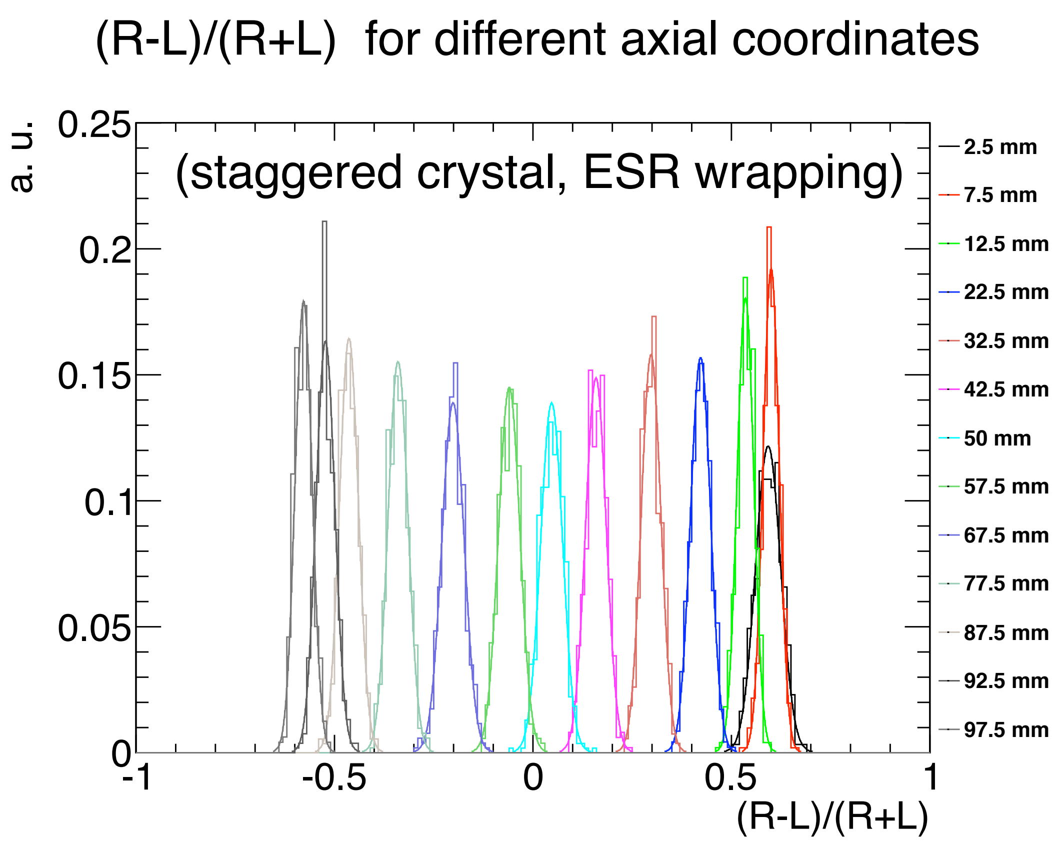
Teflon, λ~40mm, LY[0] ~ 1500

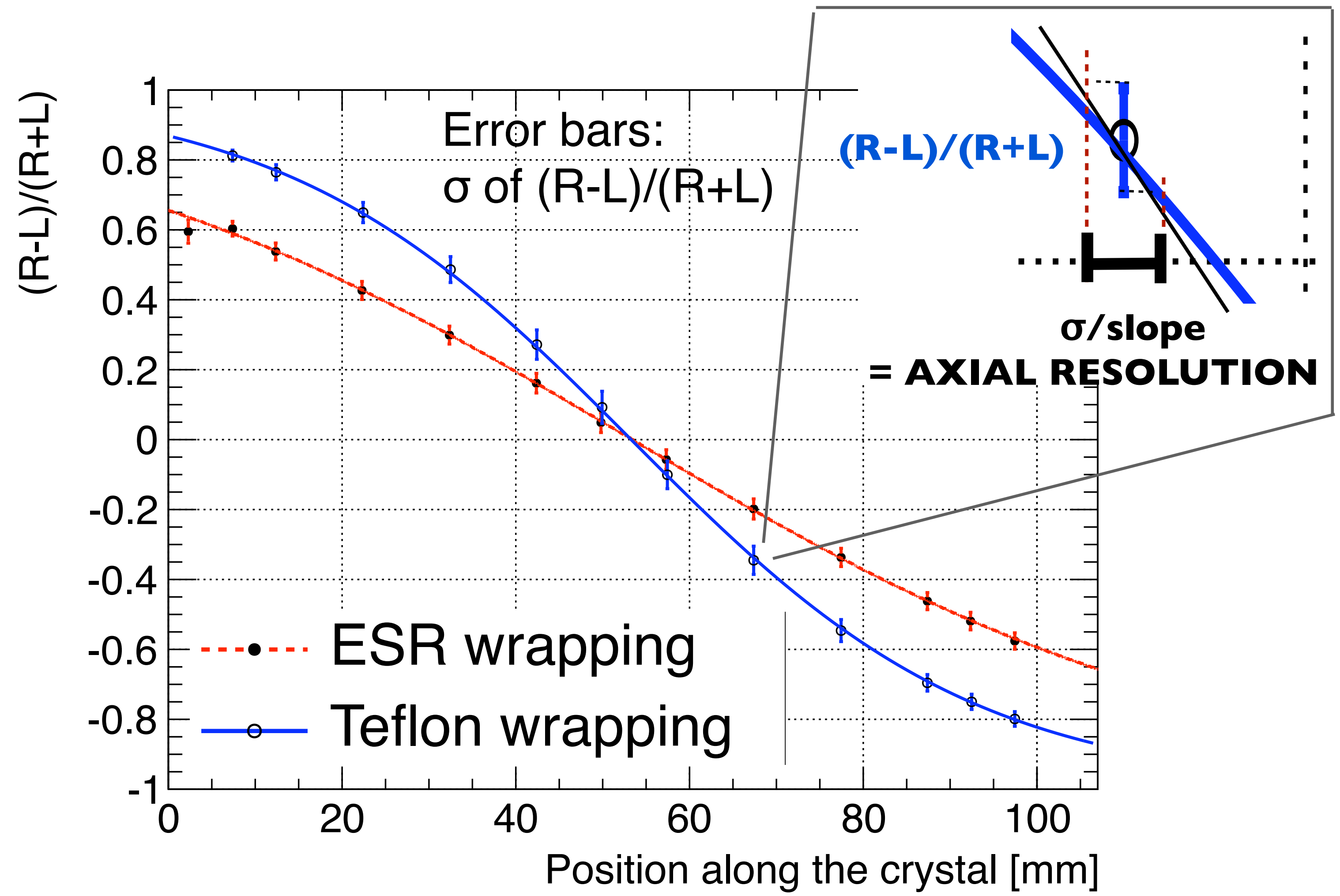
staggered pattern

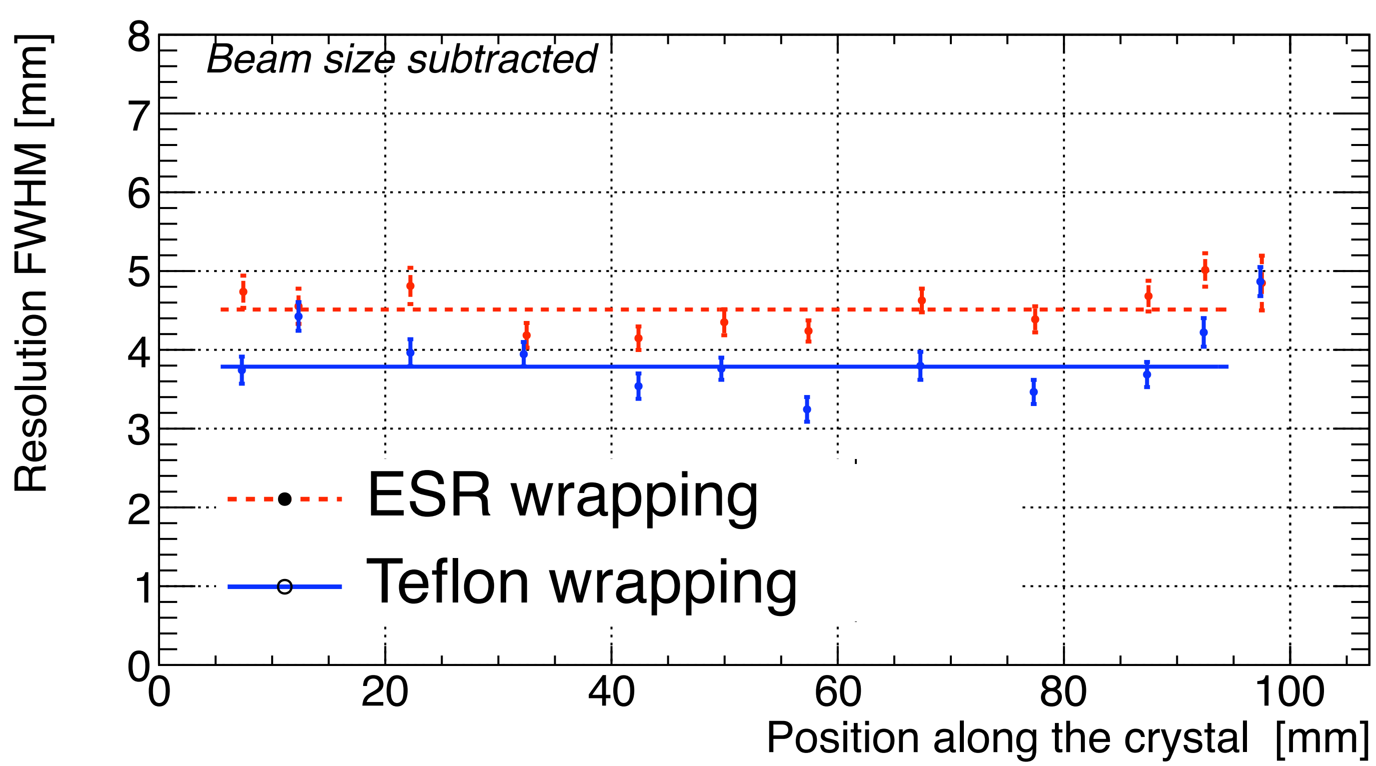
representative of the general results

Axial resolution without WLS

(staggered pattern)
(100 mm long xtal)





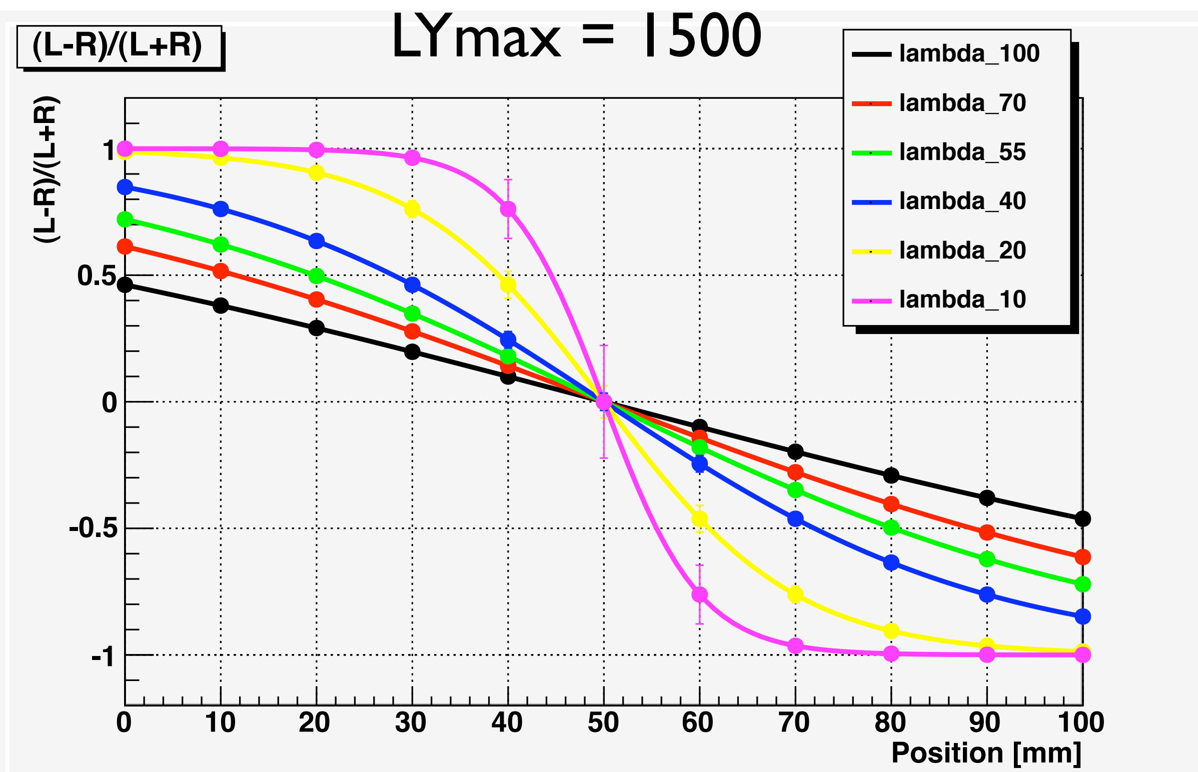


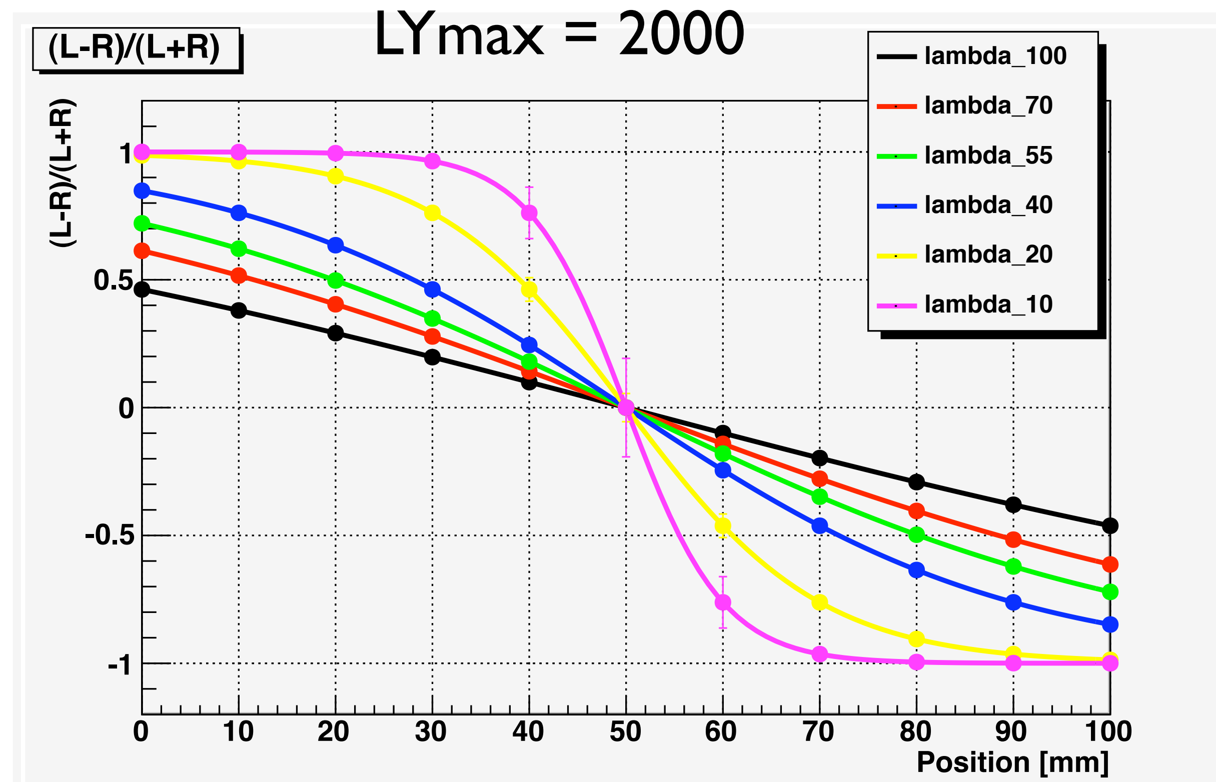
Measured axial resolution without WLS:
dual sided readout on treated crystals
light sharing technique

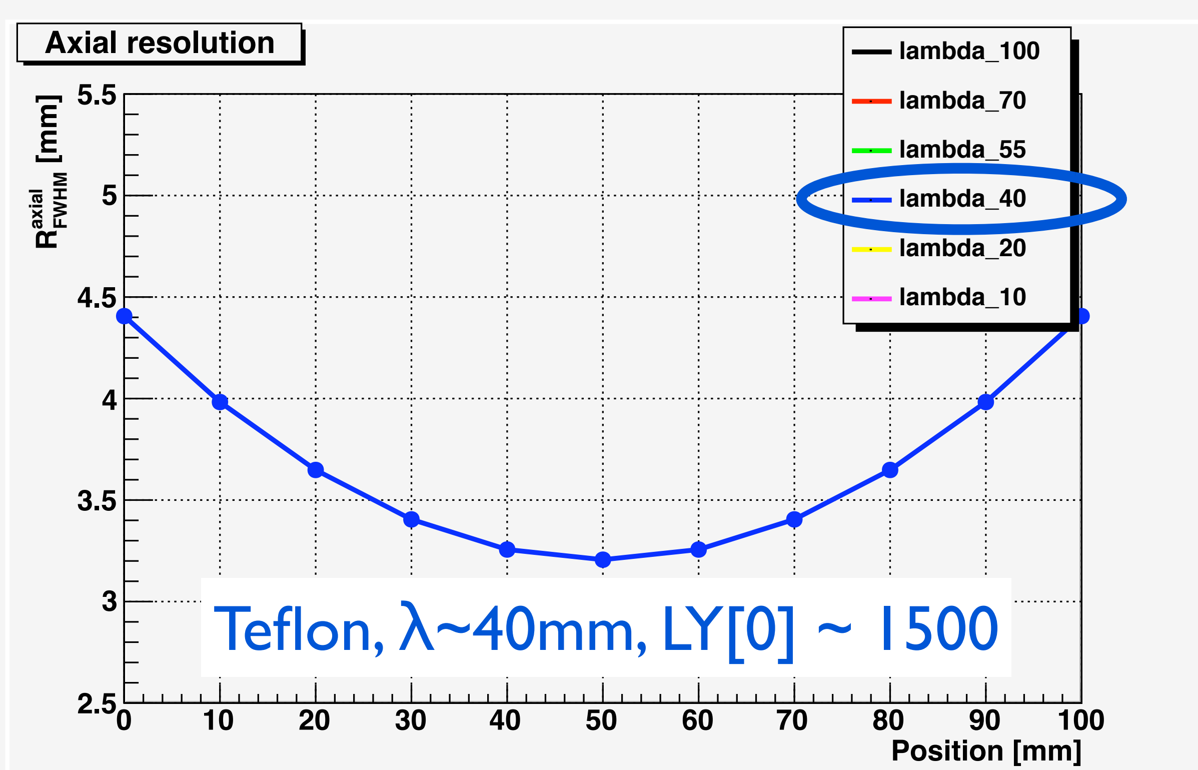
<R_FWHM> = (4.4 ± 0.1) mm
<R_FWHM> = (3.7 ± 0.1) mm

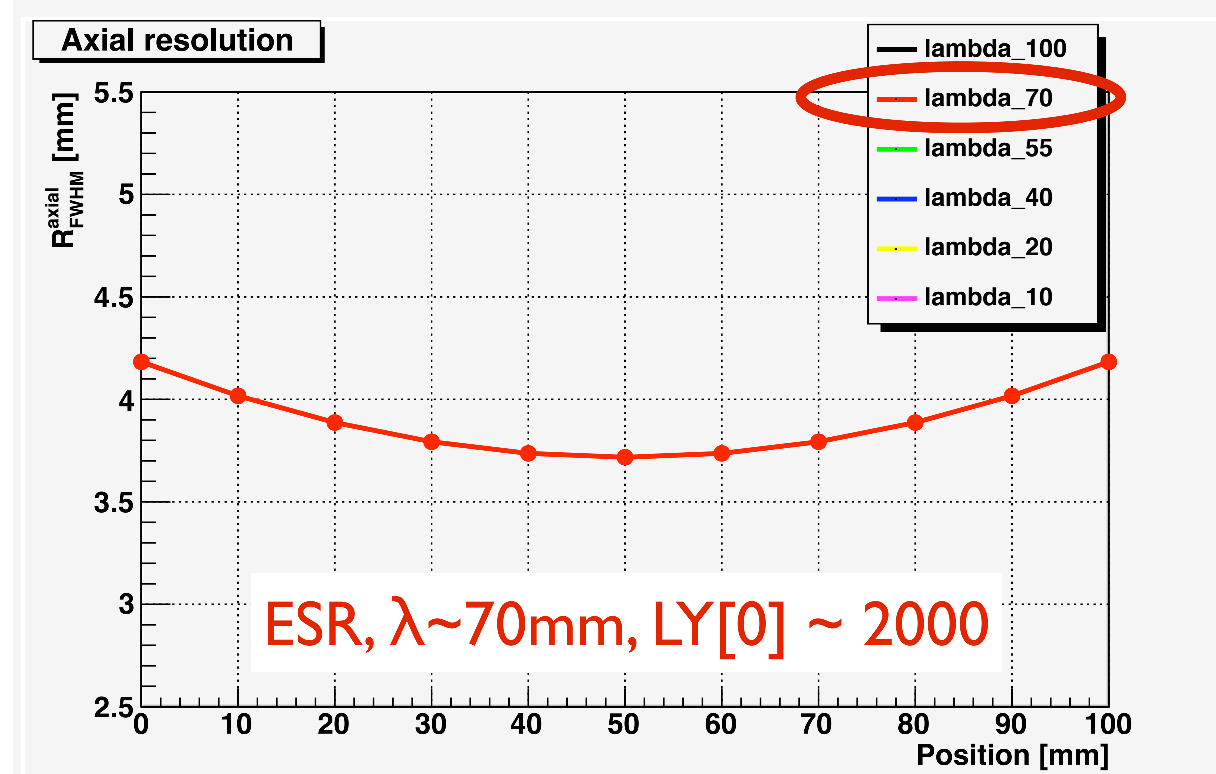
Poisson-based statistical model

The achieved results agree with expectation from a Poisson statistics applied on simple exponential description of the light yield





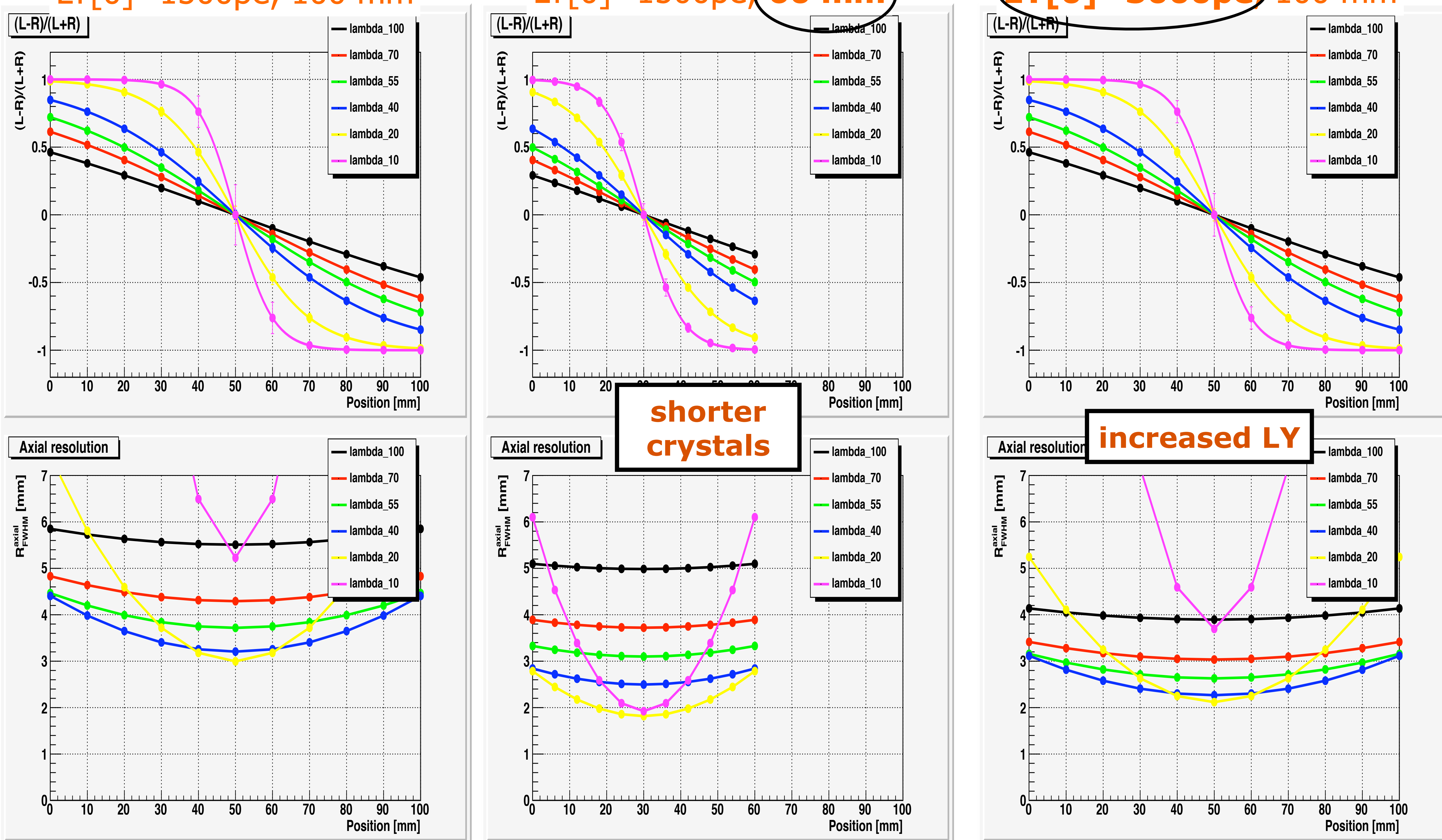




Are higher spatial resolutions possible?

According to Poisson statistical models

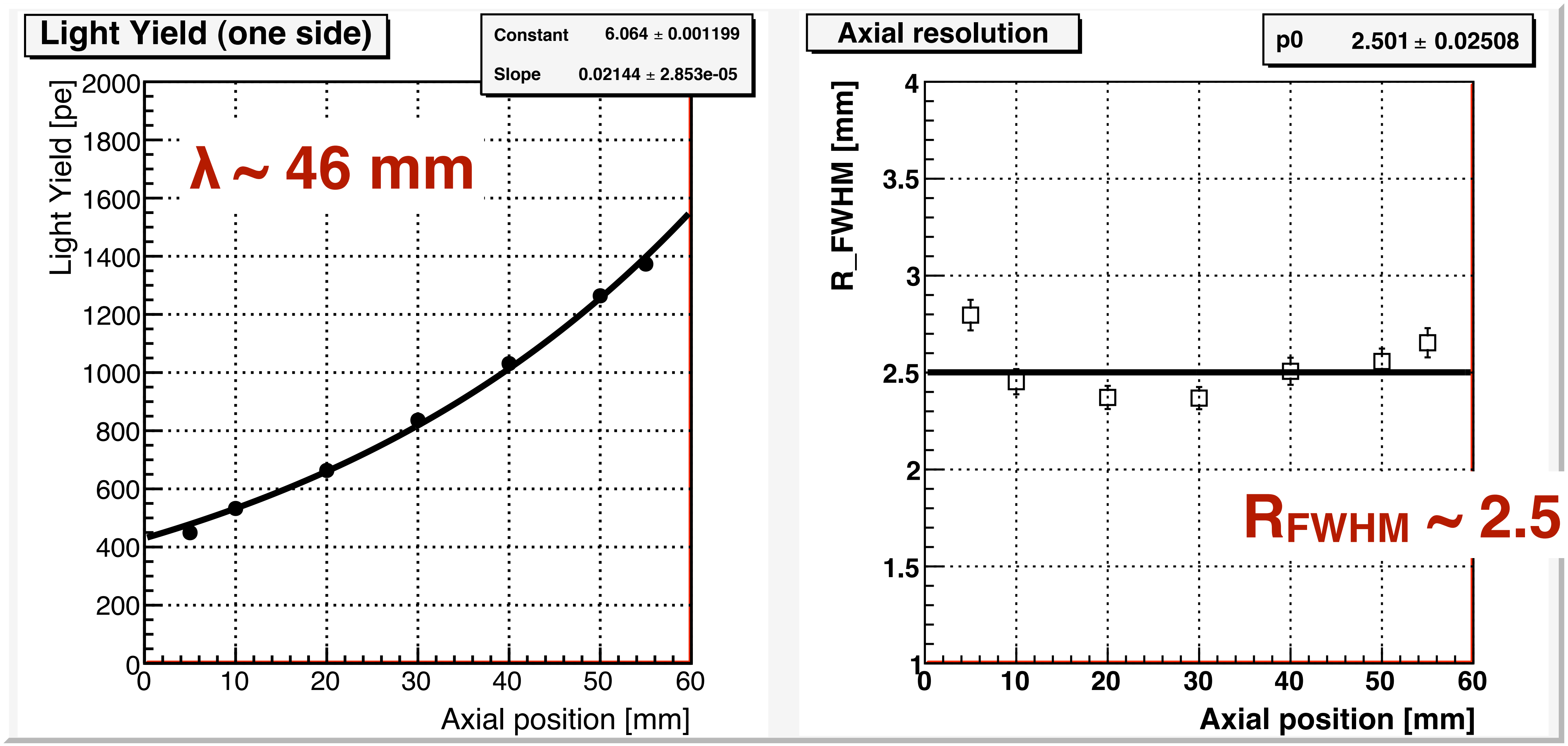
LY[0]=1500pe, 100 mm | LY[0]=1500pe, **60 mm** | **LY[0]=3000pe**, 100 mm



Axial resolution without WLS, 60 mm crystal

- **60 mm long crystal** [before: 100 mm]
- mechanical etching, 3mm pitch [before: 5 mm pitch]
- staggered 4 faces
- **Teflon wrapped**

results with **60 mm long** LYSO crystals !

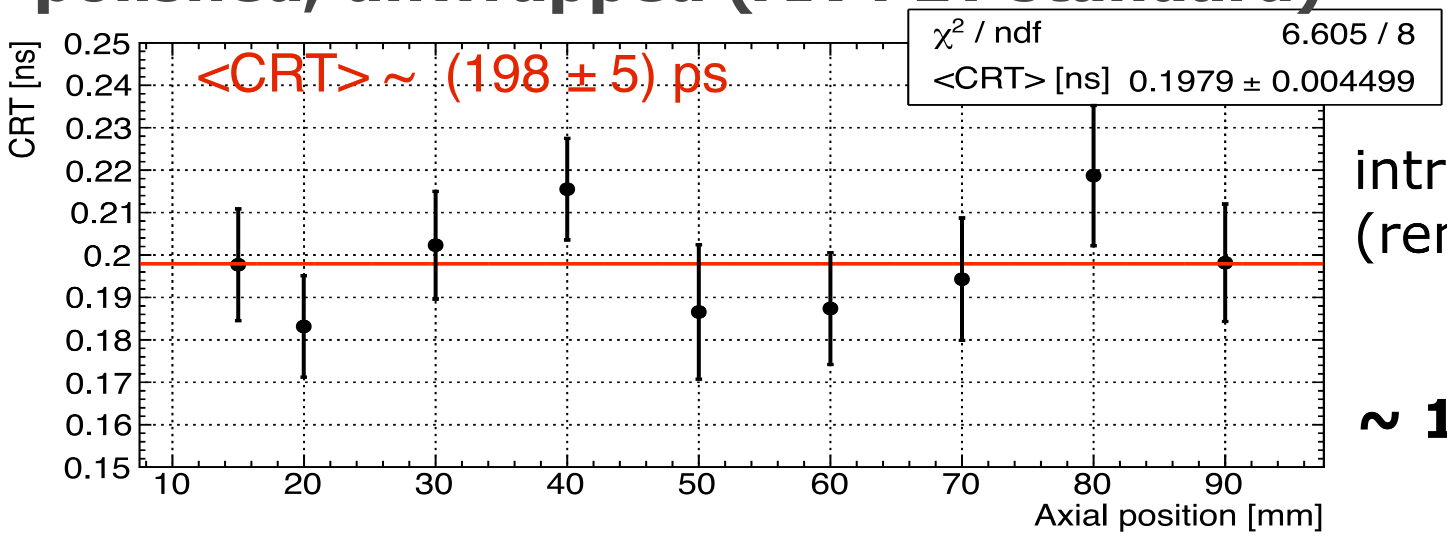


Resolutions approaching the ones of AX-PET with WLS strips

AX-PET => R_{FWHM} ~ 1.9 mm / dSiPM AX-PET small scale => R_{FWHM} ~ 1.7 mm

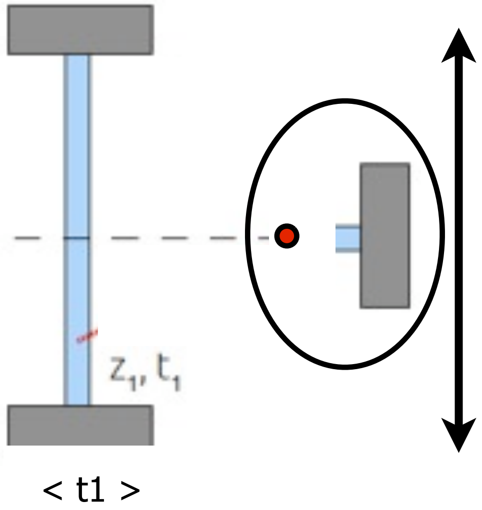
Timing performance of treated crystals

polished, unwrapped (AX-PET standard)



intrinsic time res
(removing tag contr)

~ 149 ps FWHM



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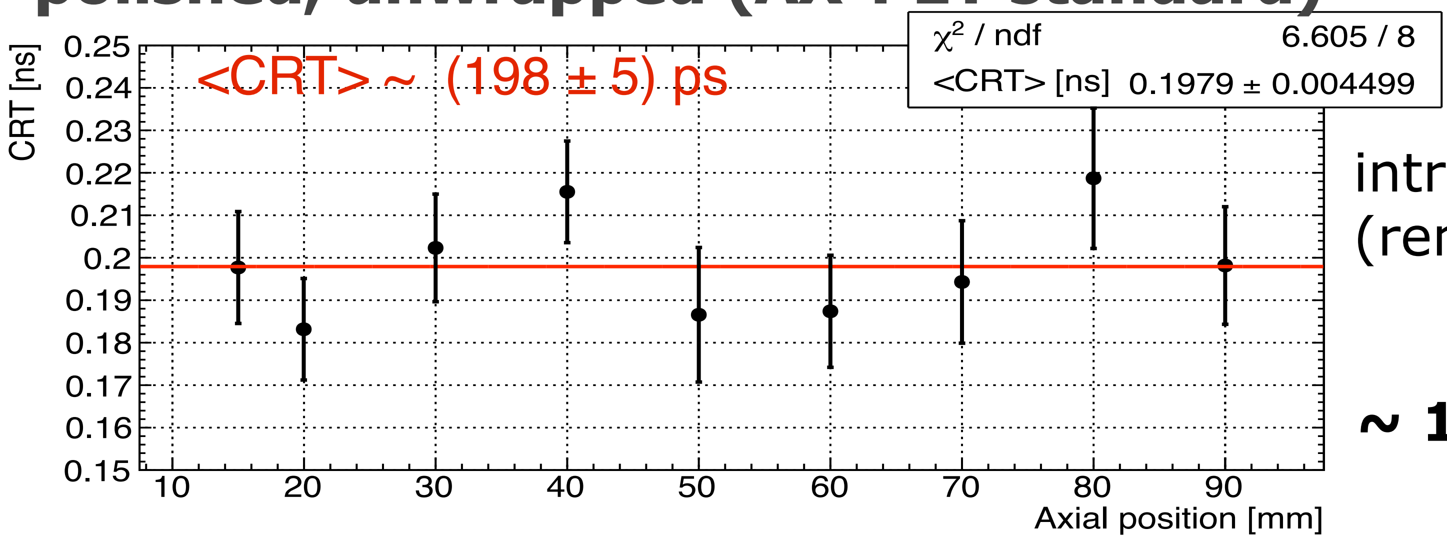

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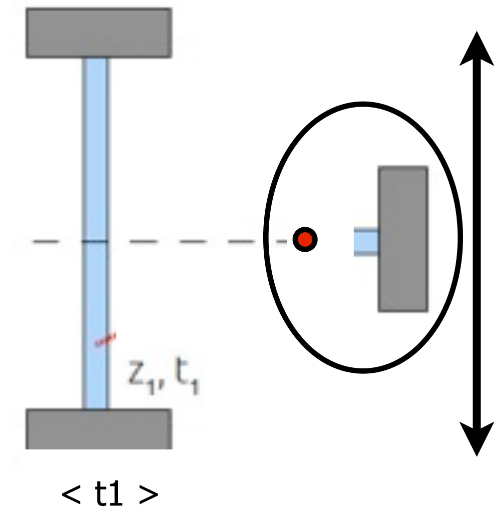
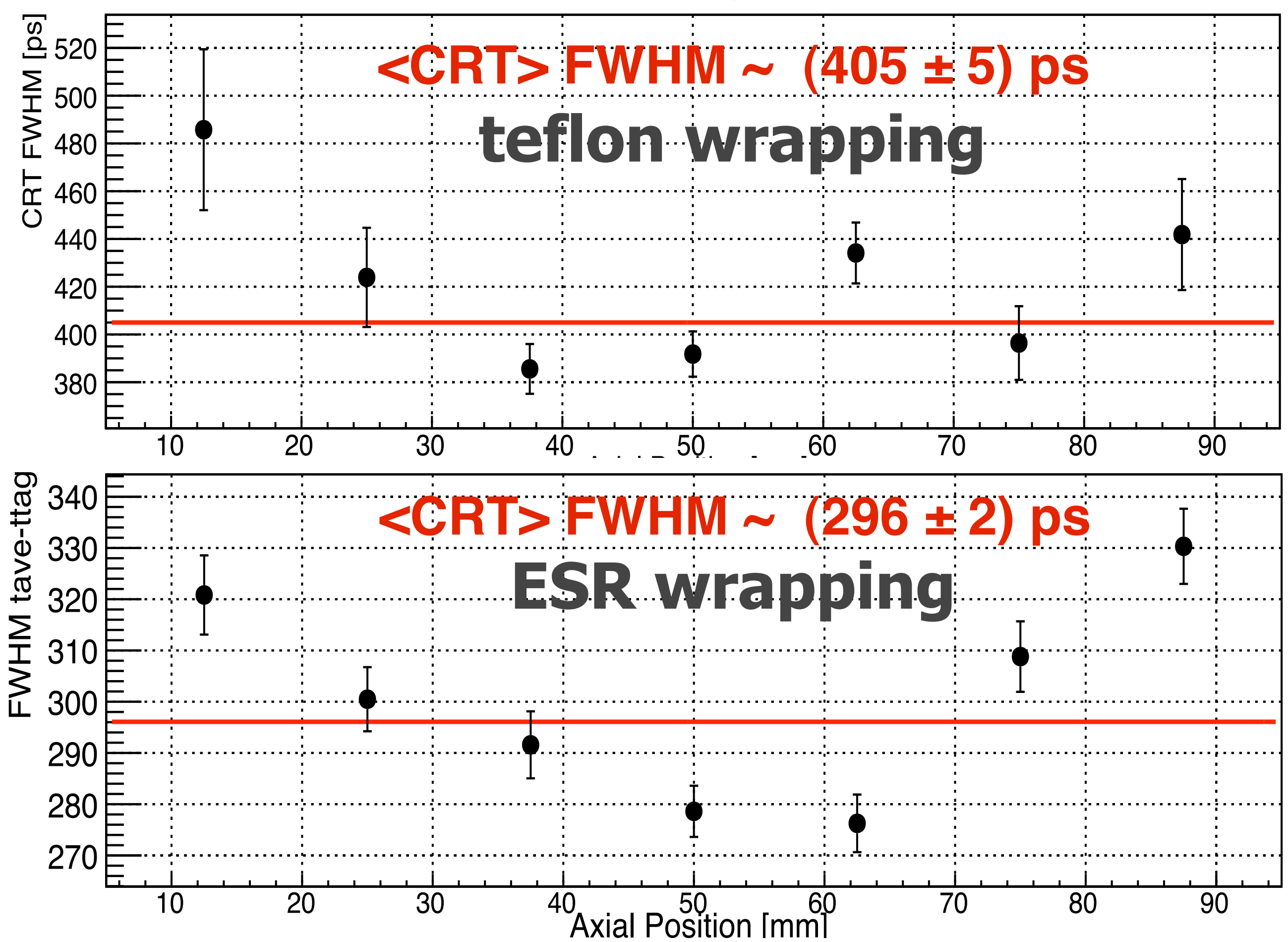


treated crystal (4f - aligned)

100 mm long crystal



~ 383 ps FWHM

deterioration of the absolute timing resolution
and
non uniformity in the axial direction

~ 266 ps FWHM

Usage of long axially oriented crystals

Question2 : are there possible alternatives to the WLS strips for the definition of the axial coordinate?

yes!

Method : **Dual side readout** and **light sharing technique** ((L-R)/(L+R))

need to “destroy” the crystals (reducing the attenuation length, keeping the highest possible light yield)

100mm crystals, mechanical etching, teflon / ESR wrapping => **Rz ~ 4.0 mm FWHM**

60 mm crystals, mechanical etching, teflon / ESR wrapping => **Rz ~ 2.5 mm FWHM**

destroyed crystal => compromize on the timing resolution wrt untreated crystals

with **CRT ~ 400 - 300 ps (not uniform)**

Usage of long axially oriented crystals beyond AX-PET

AX-TOF-PET

(dual side readout
&
average timing introduction)

AX-PET without WLS strips :

- not competitive in spatial resolution with the WLS strips solution
- compact, simple, few nr of channels
- only crystals in the sensitive volume (PET/MRI?)
- room for improvement
  (e.g. shorter crystals ?)
  (e.g. higher LY, higher PDE...)
  (e.g. improved timing [$\Delta t/\Delta x \sim 15$ ps/mm] with no need of destroing the crystals ...)

Usage of long axially oriented crystals beyond AX-PET

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(dual side readout
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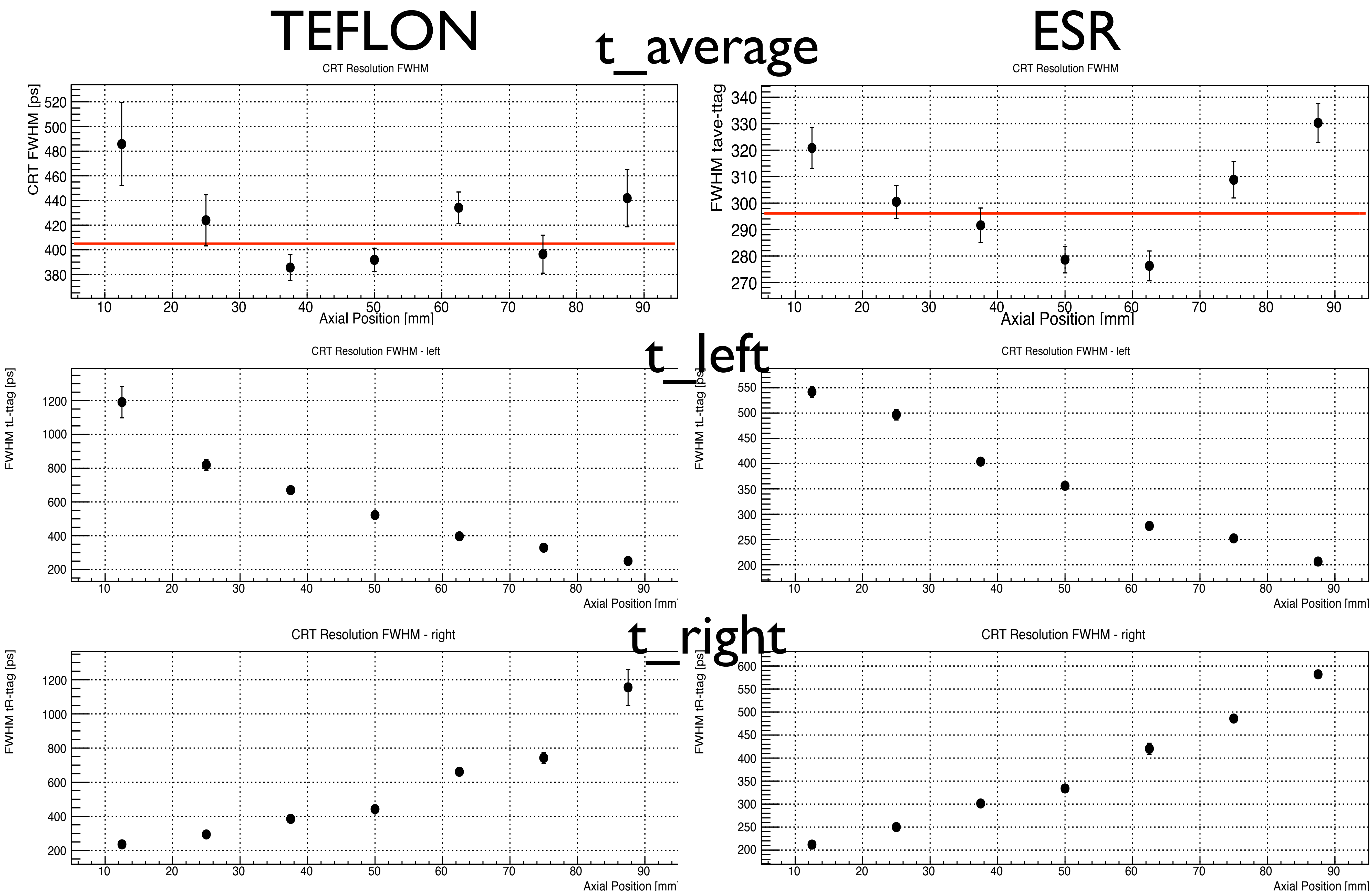
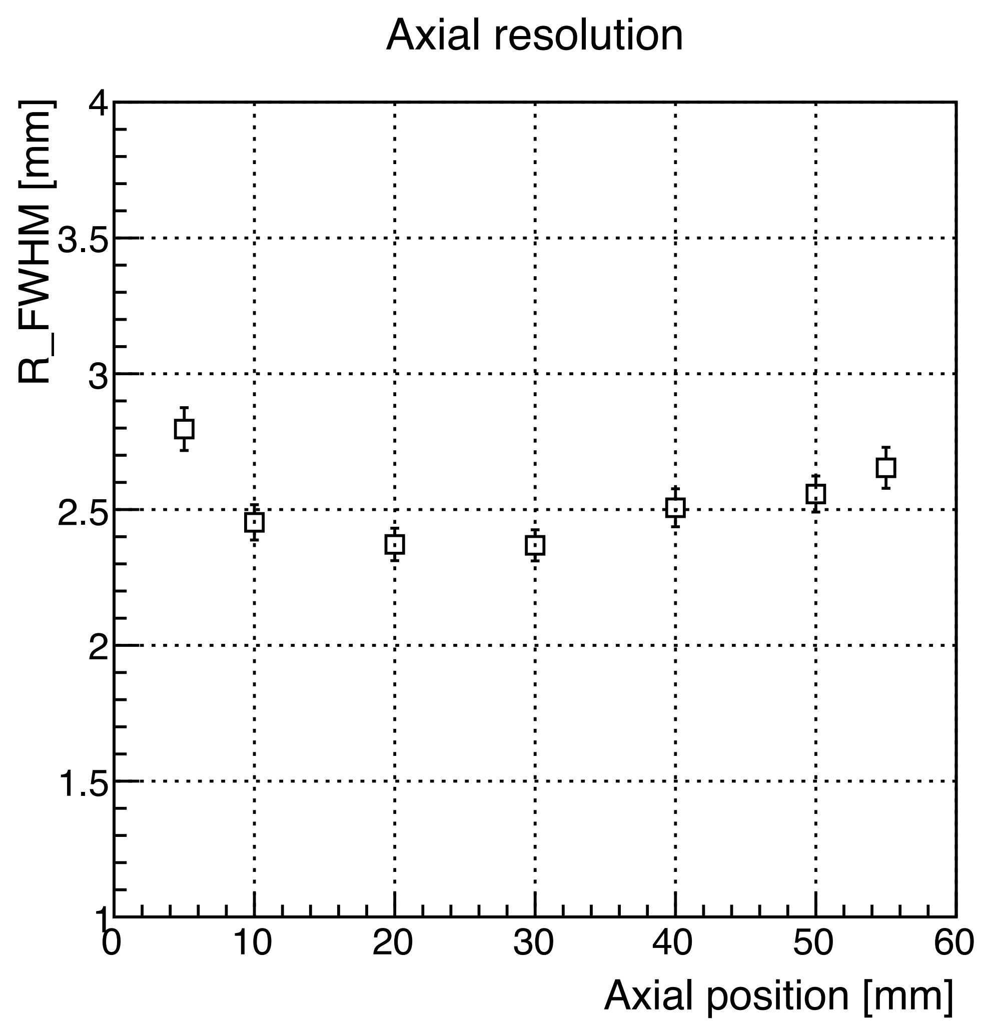
T H A N X f o r t h e a t t e n t i o n !

treated crystal (4f - aligned)



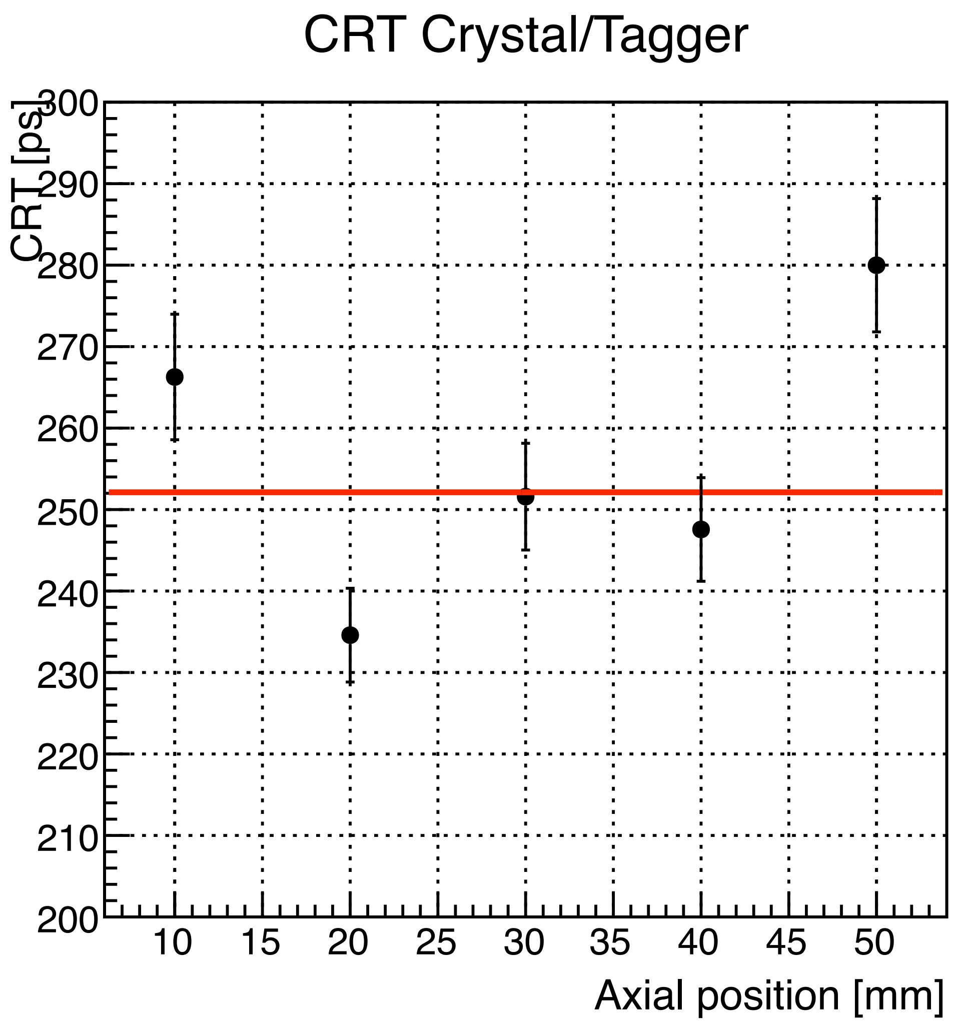
Additional test: 60 mm long LYSO crystals

axial resolution



R_{FWHM} ~ 2.5 mm

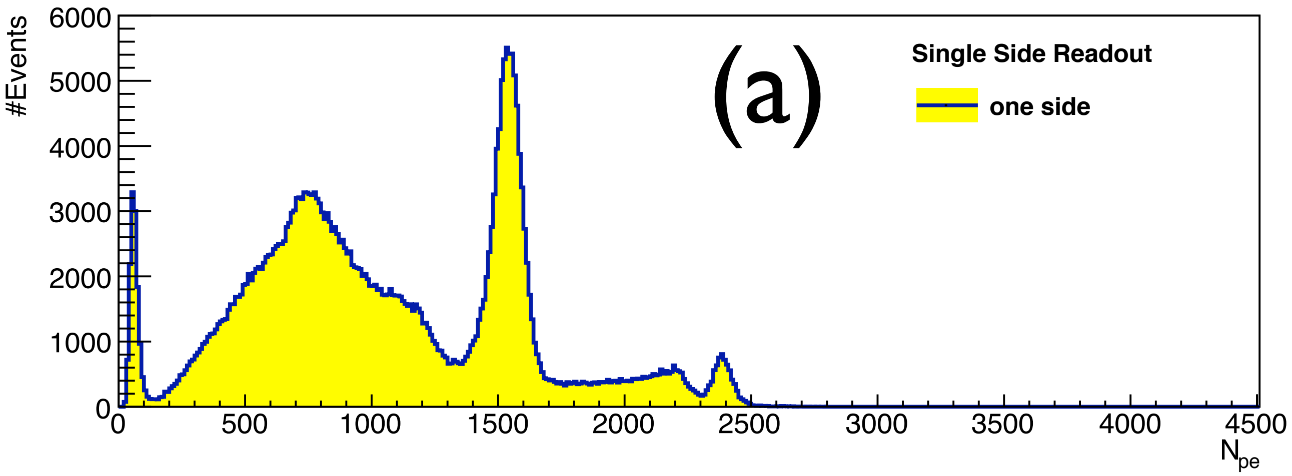
timing performance

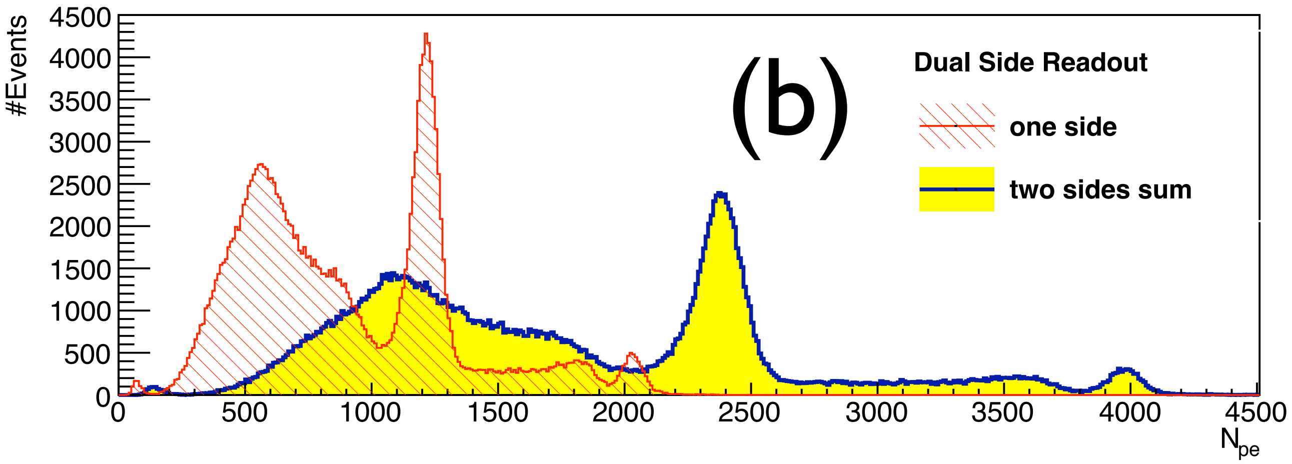


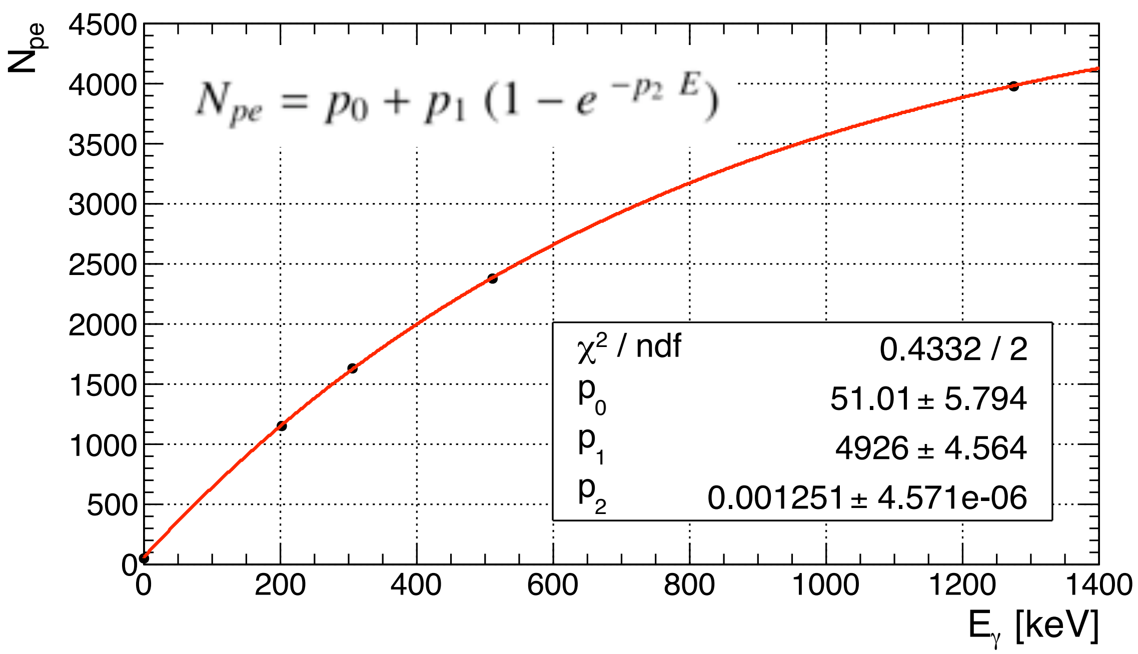
CRT ~ 250 ps FWM
$R_{intrinsic}$ ~ 215 ps

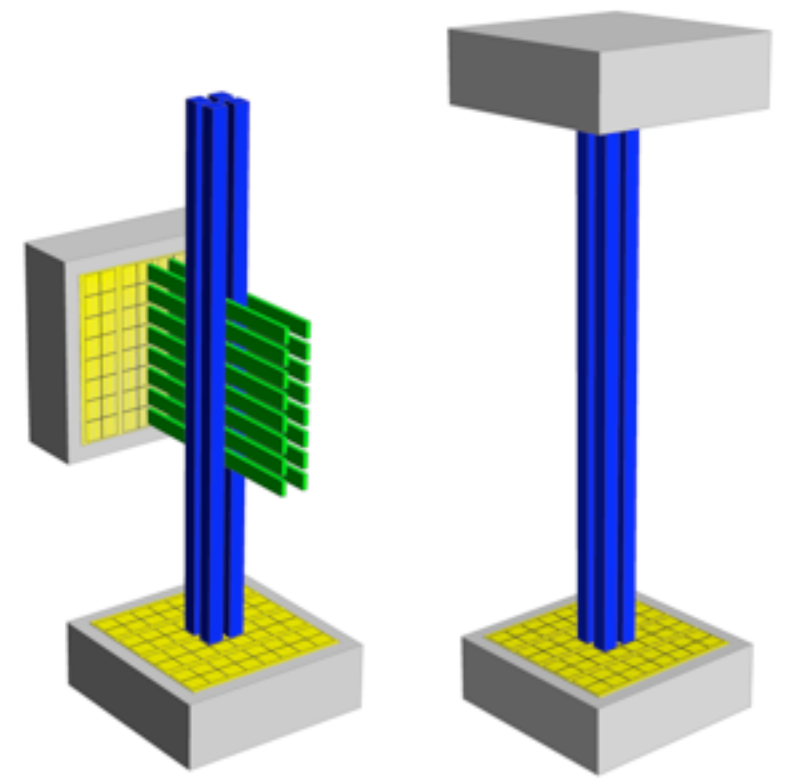
very promising results (axial resolution/timing) with **60 mm long** LYSO xtals

“digital AX-PET modules” : light yield









(a) (b)

Light yield (averaged over 8 crystals):

(a) LY = (1326 ± 118) pe

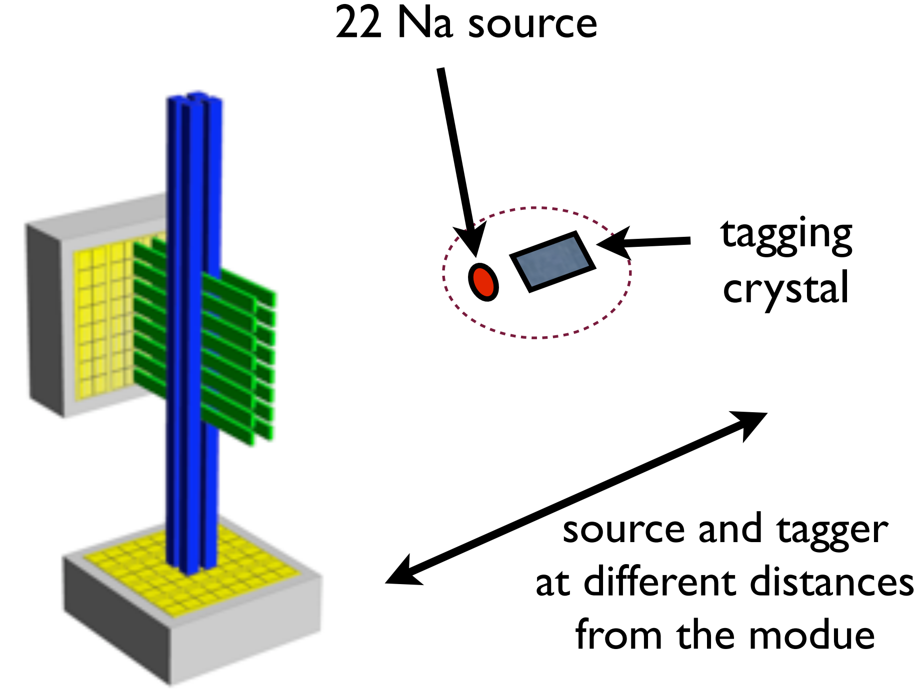
(b) LY = (2159 ± 93) pe

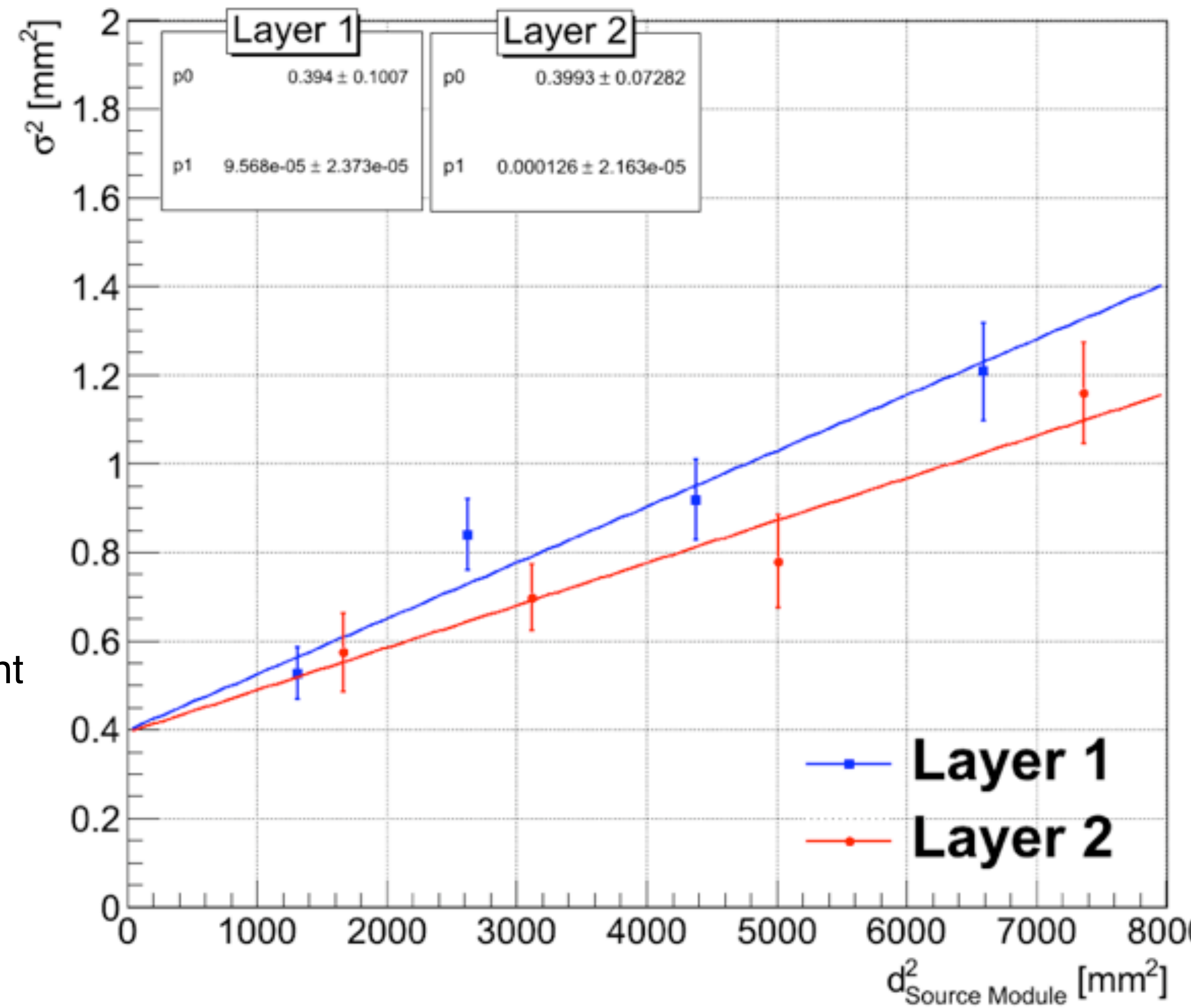
Energy resolution (after energy calibration):

(a) ΔE/E ~ 14.2 %

(b) ΔE/E ~ 12.6 %

"digital AX-PET modules" : axial resolution (1/2)

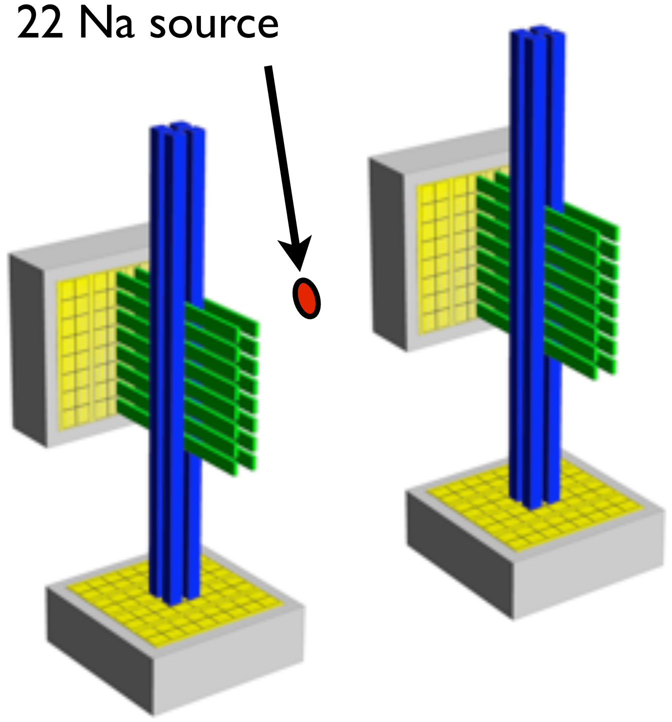


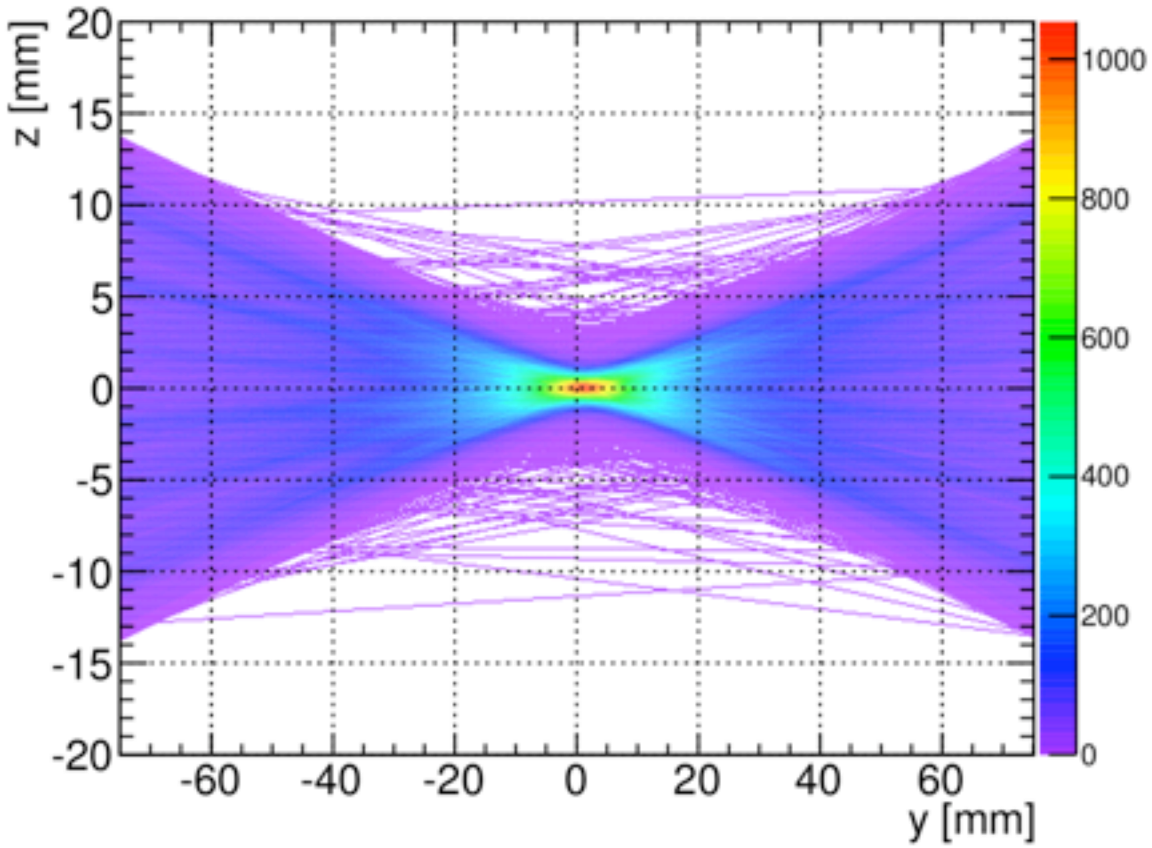


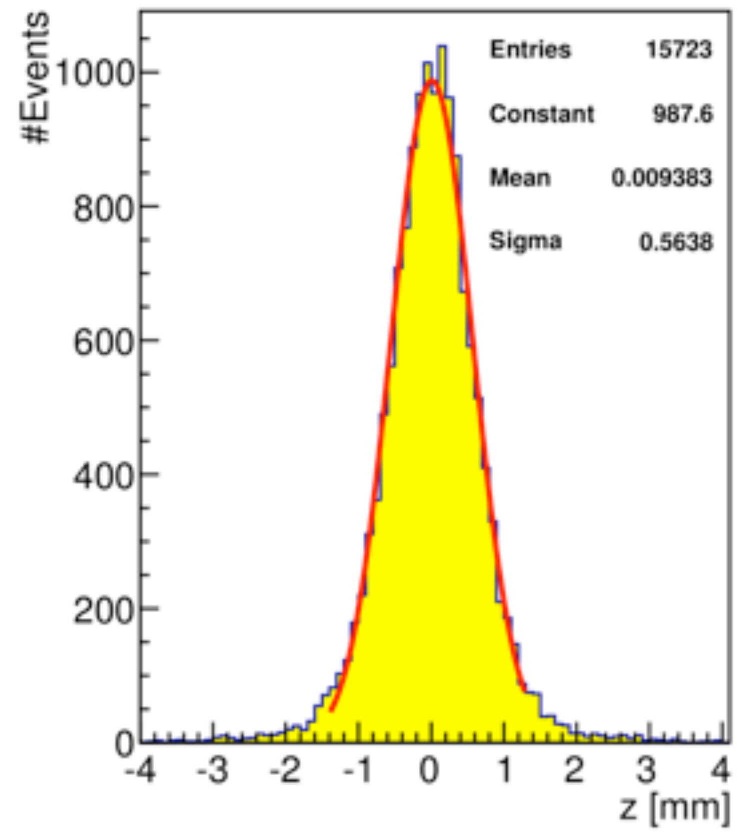
- 22Na source (diam = 0.250 mm)
- Measure reconstructed beam size at different distances
- Extrapolate to zero distance (non colinearity and beam divergence suppressed)
- Positron annihilation physics (i.e. range) subtracted
- Source size subtracted (negligible)

=> Module axial resolution ~ 1.57 mm FWHM

"digital AX-PET modules" : axial resolution (2/2)







Two modules coincidence, 22Na source

Draw LOW => Confocal plane reconstruction => R_meas

$$R_{intr} = \sqrt{R_{meas}^2 - R_\rho^2 - R_{180}^2}$$

limits to the achievable spatial resolution in a PET system, due to the **physics of positron emission** :

positron range : $R_\rho^2 = [\ 0.54 \text{ mm }]^2$

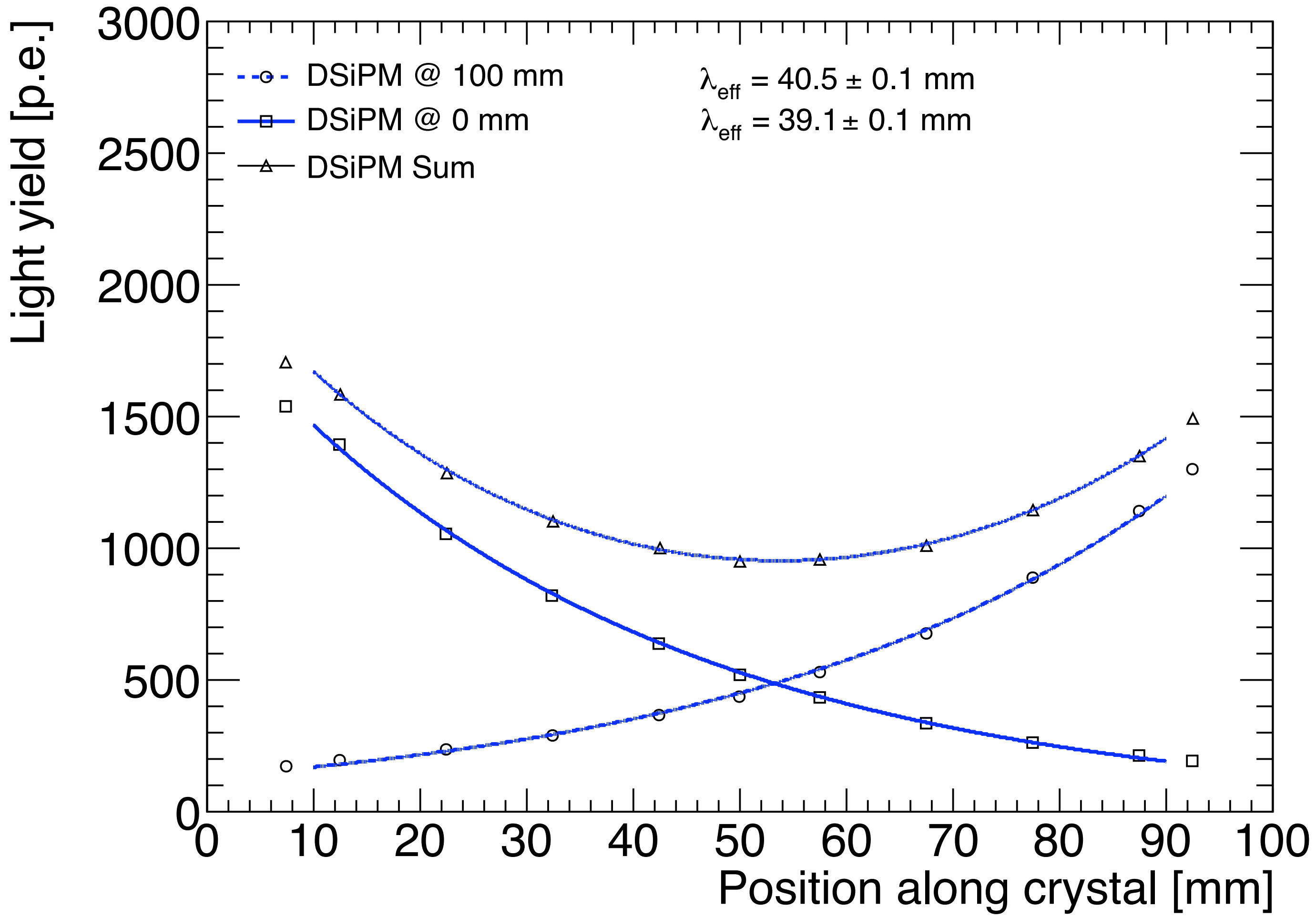
non collinearity : $R_{180}^2 = [\ 0.0022 \text{ x Diameter }]^2 = [\ 0.33 \text{ mm }]^2$

=> COINCIDENCE axial resolution ~ 1.21 mm FWHM

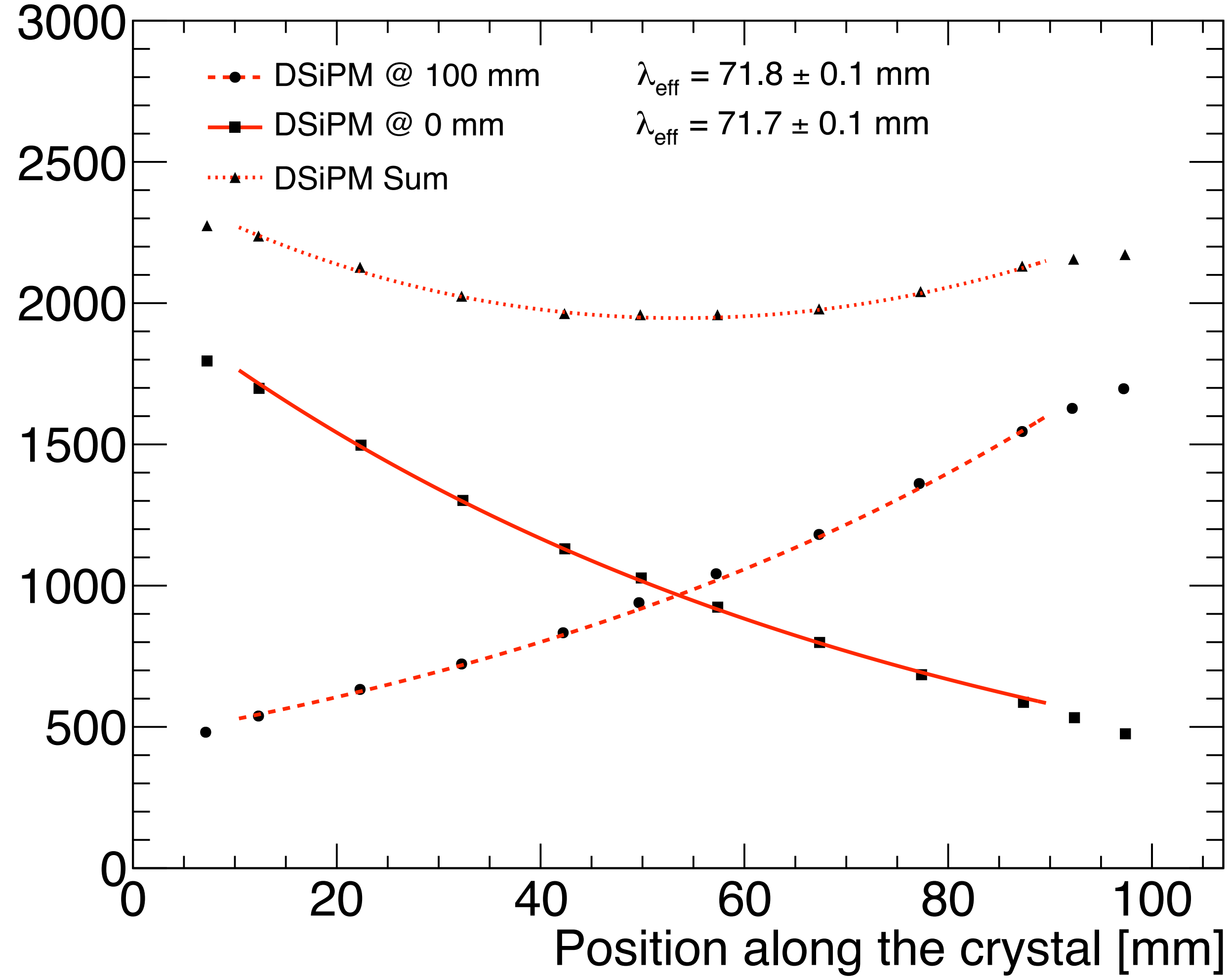
=> MODULE axial resolution = 1.21 x √2 ~ 1.71 mm FWHM

Teflon vs ESR wrapping

TEFLON



ESR



ESR : higher light yield

=> better ΔE/E

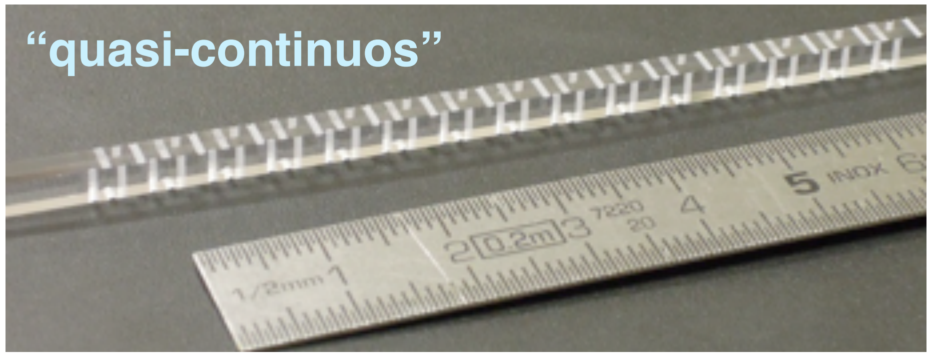
=> better timing performance

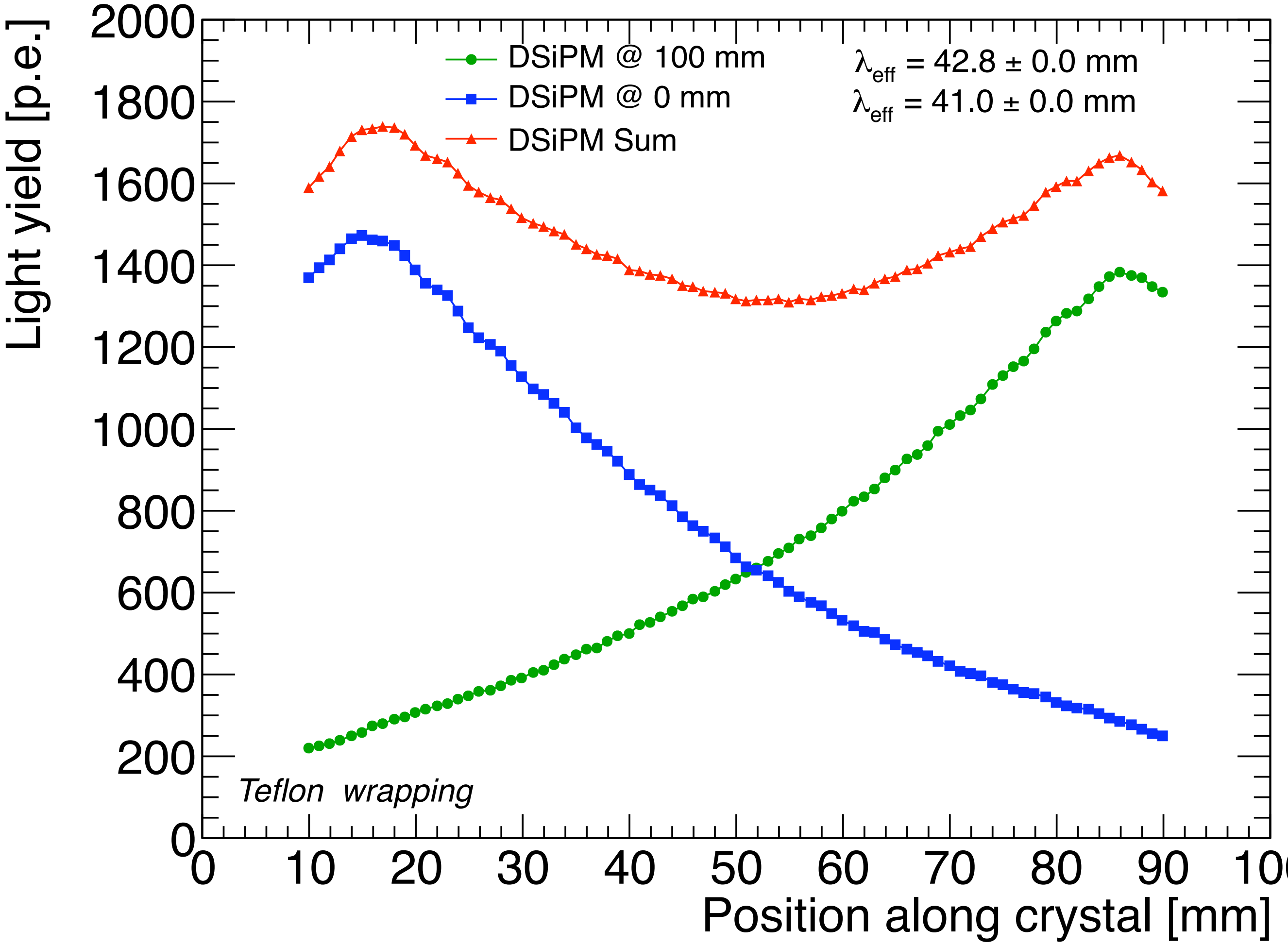
Teflon: smaller effective attenuation length

=> higher slope in (L-R)/(L+R)

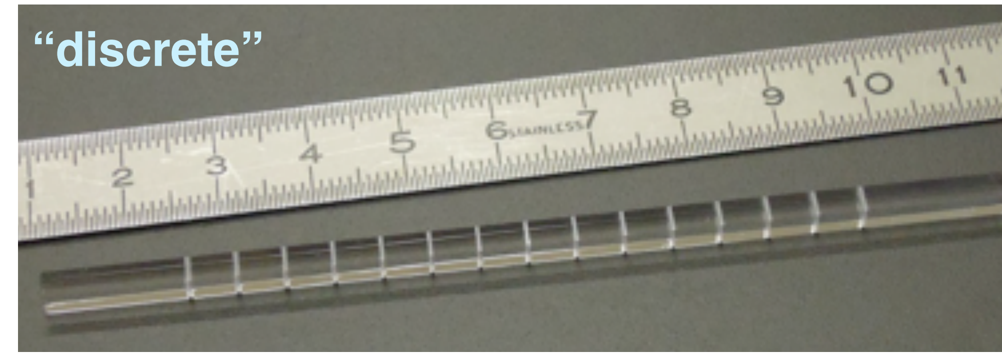
=> better spatial resolution (although in principle less uniform)

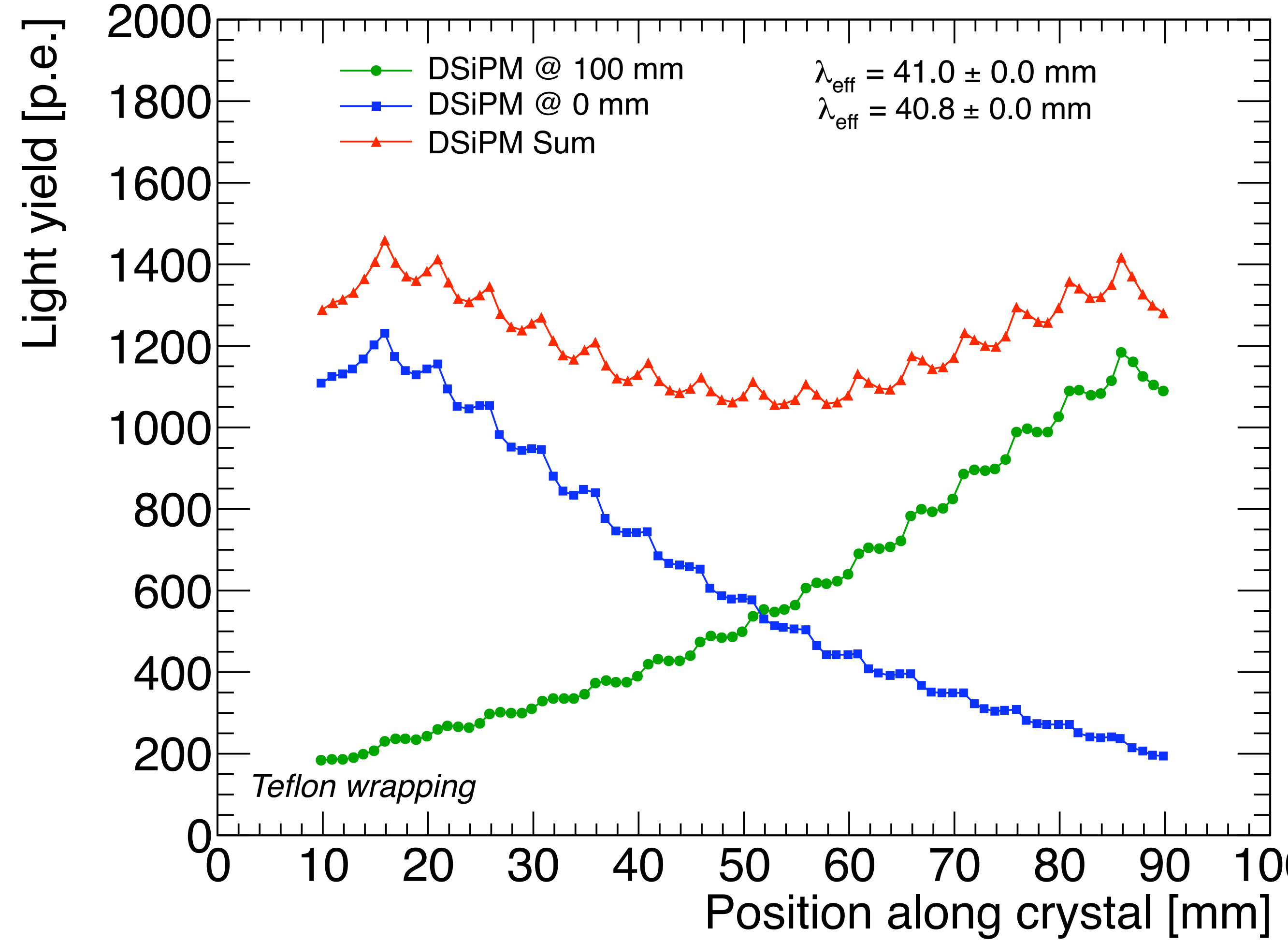
Staggered vs Aligned Pattern





5 mm pitch, four faces staggered

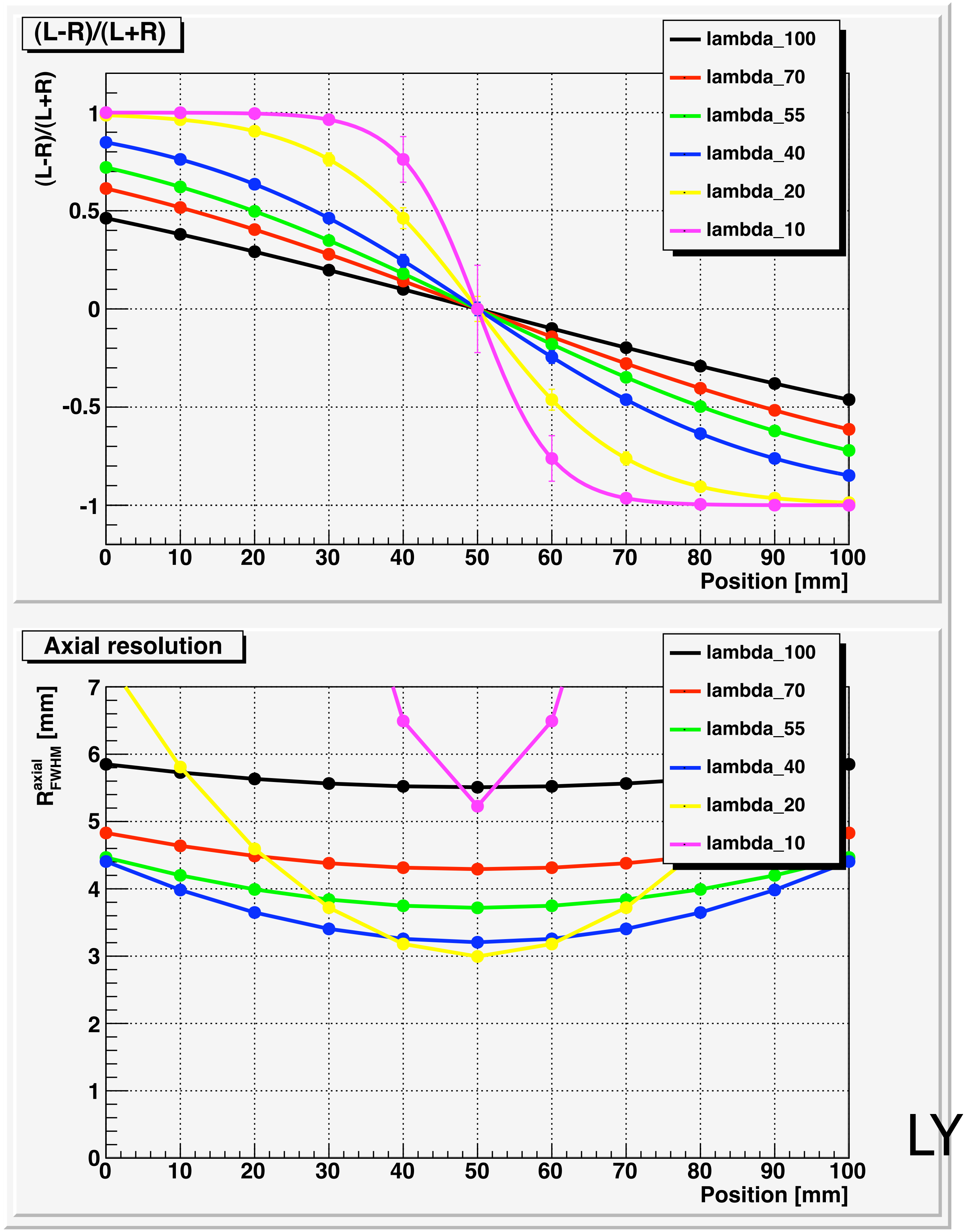




5 mm pitch, four faces identical

staggered is preferred because of uniformity !

Axial Resolution: Toy MC



ASSUMPTION :
Poisson statistics

$L \pm \sigma_L$; $\sigma_L = \sqrt{L}$

$R \pm \sigma_R$; $\sigma_R = \sqrt{R}$

$f = (L-R) / (L+R)$

σ_f : from error propagation

Light yield LY[0] defines the size of the error bars => Resolution

LY[0] = 1500