State of the art time resolution in TOF-PET detectors for various crystal sizes and types

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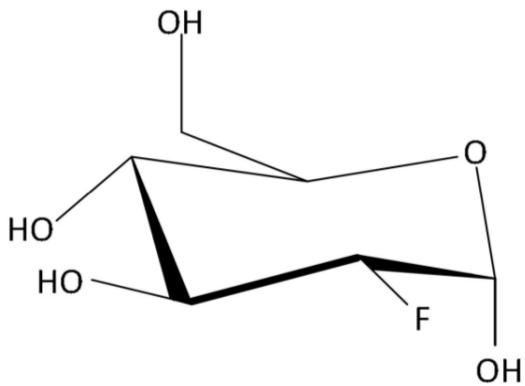
FBK

This work was carried out in the frame of the TICAL ERC Grant 338953, SUBLIMA under Grant 241711 and the Crystal Clear Collaboration

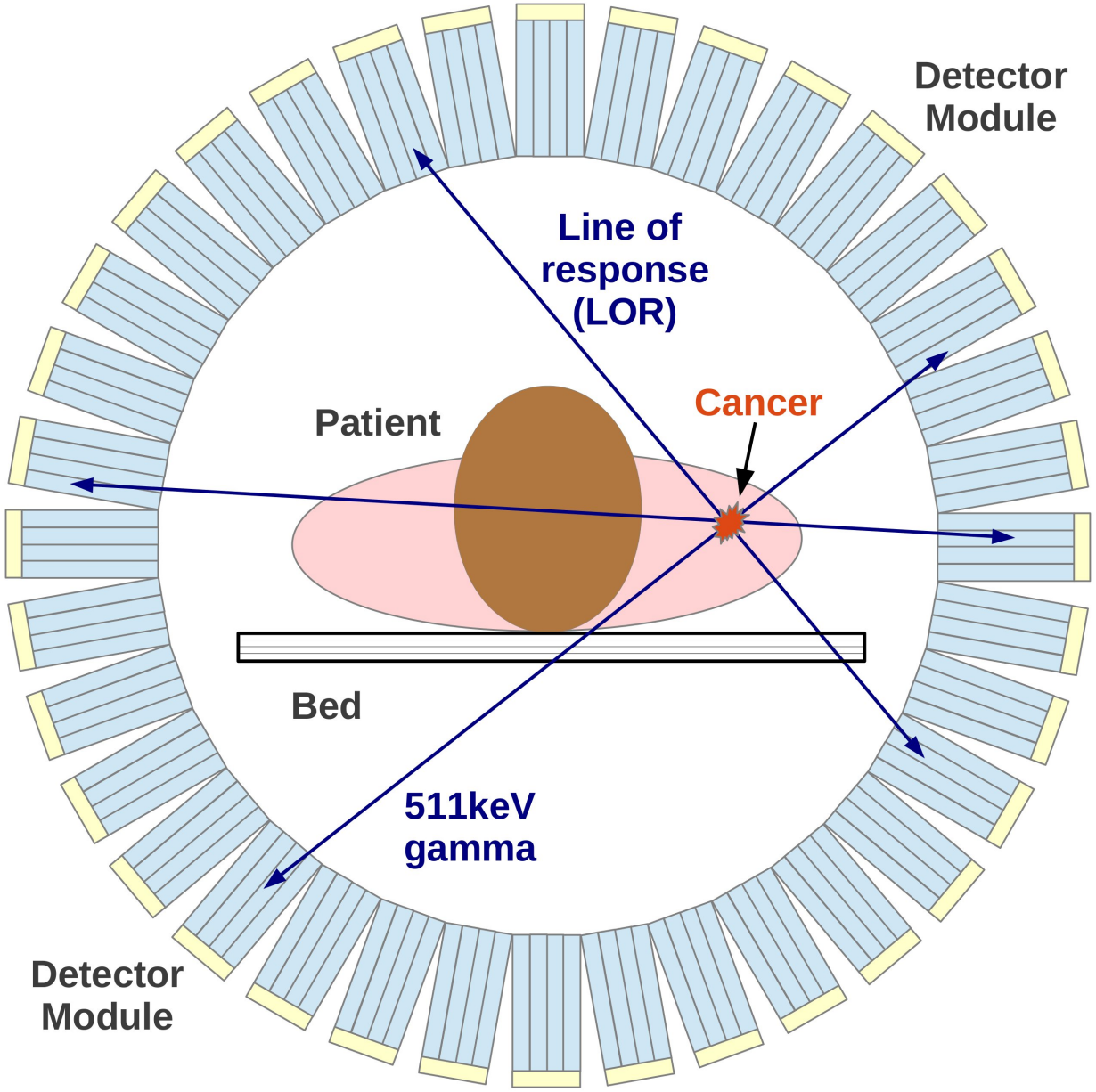
Positron Emission Tomography (PET)

In ^{18}F-Fluorodeoxyglucose (FDG) the radioisotope Fluorine (^{18}F) emits a positron.

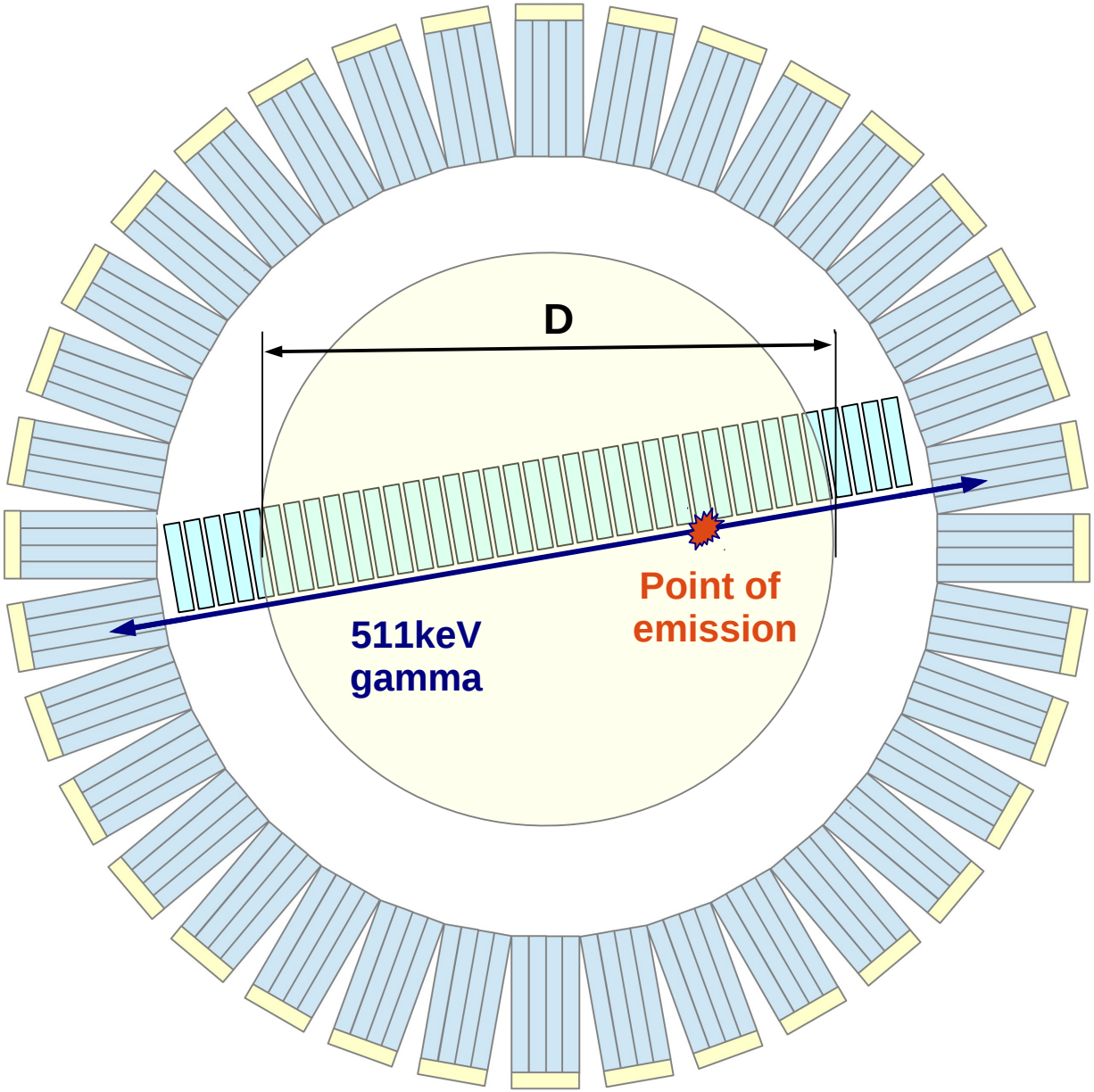


Positron range in FWHM is 0.22mm. Half life of FDG is 110min.

Instead of ^{18}F as well possible: ^{11}C, ^{13}N, ^{15}O, ^{68}Ga, ^{82}Rb

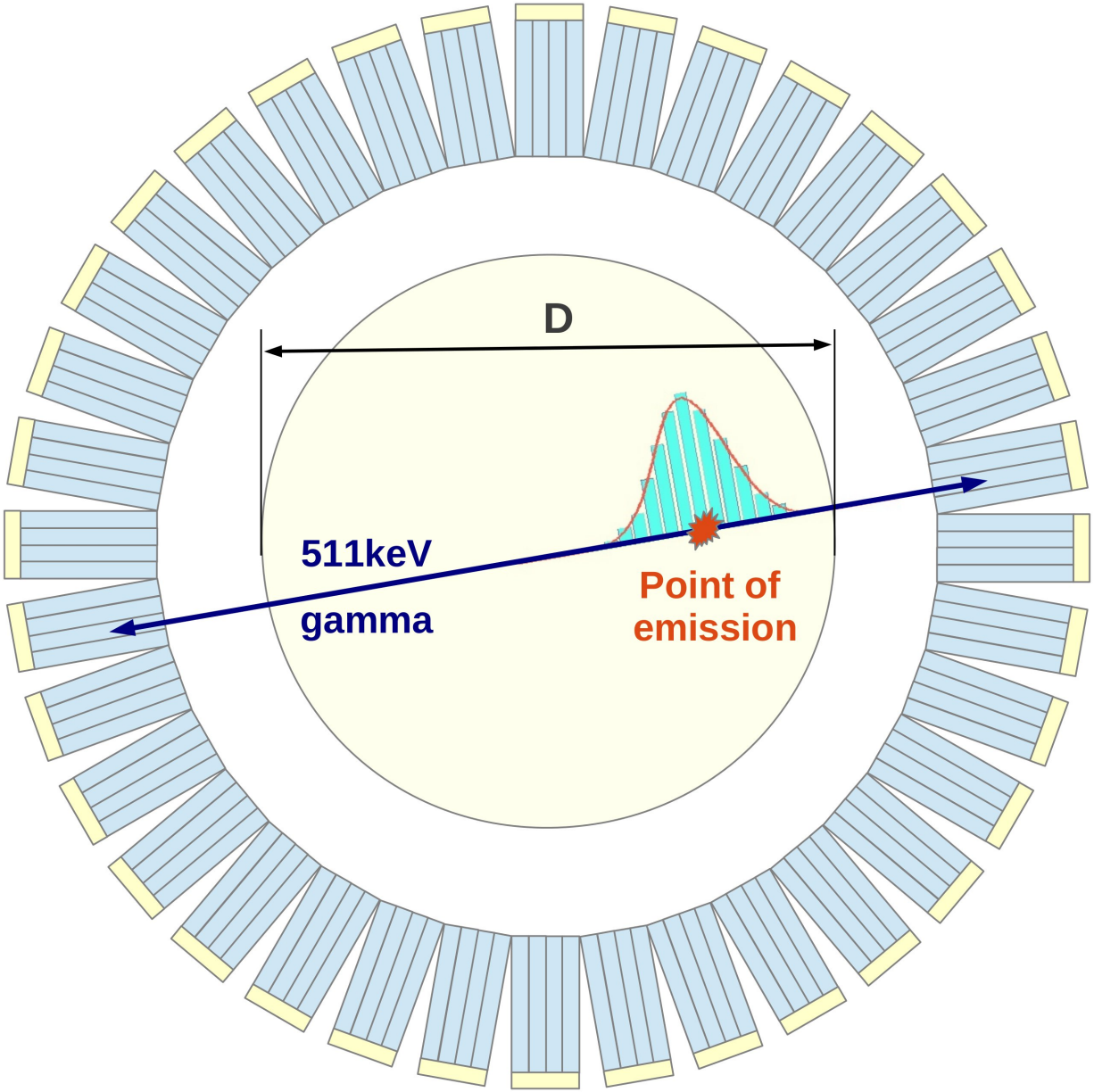


Time of flight in PET



Without timing the positron emission could have happened anywhere along the line of response (LOR).

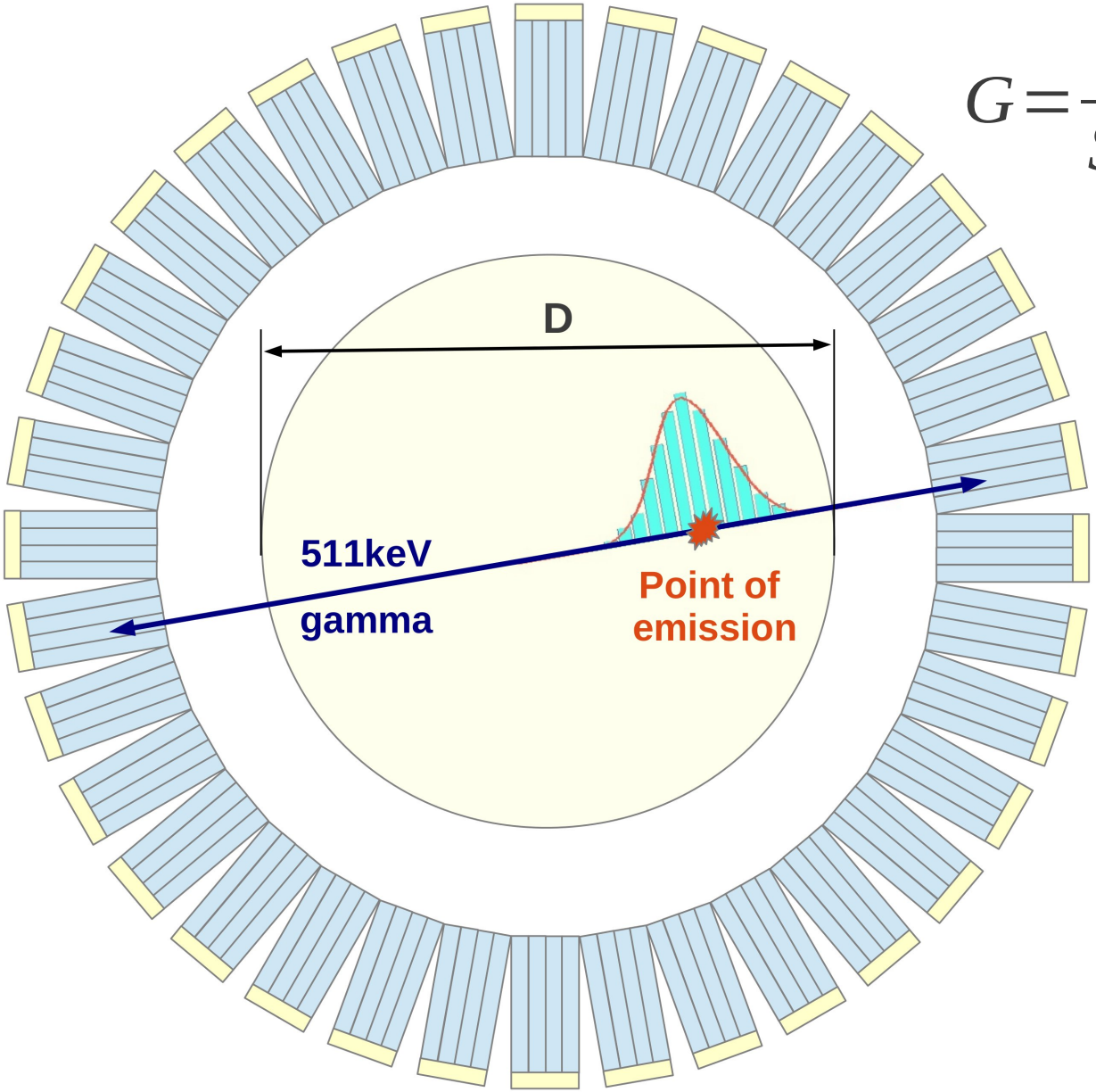
Time of flight in PET



Time of flight can effectively confine the positron emission point.

Timing is determined by the full width at half maximum (FWHM) of the coincidence time resolution (CTR).

Time of flight in PET



$$G = \frac{SNR_{TOF}}{SNR_{non\,TOF}} = \sqrt{\frac{2*D}{c*CTR}}$$

For whole body PET (D=40cm):

CTR=1ns → G=1.6

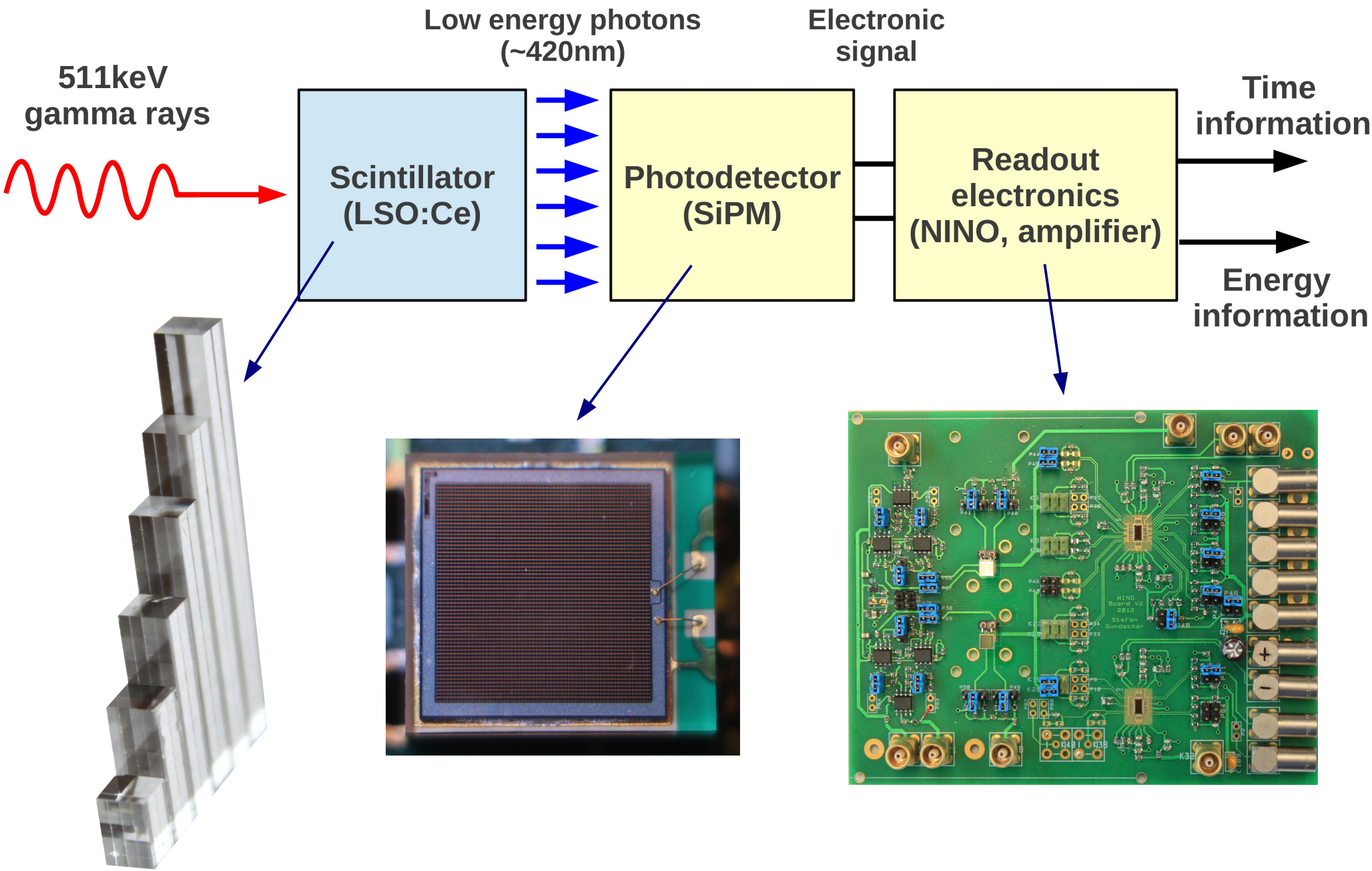
CTR=500ps → G=2.3

CTR=100ps → G=5.2

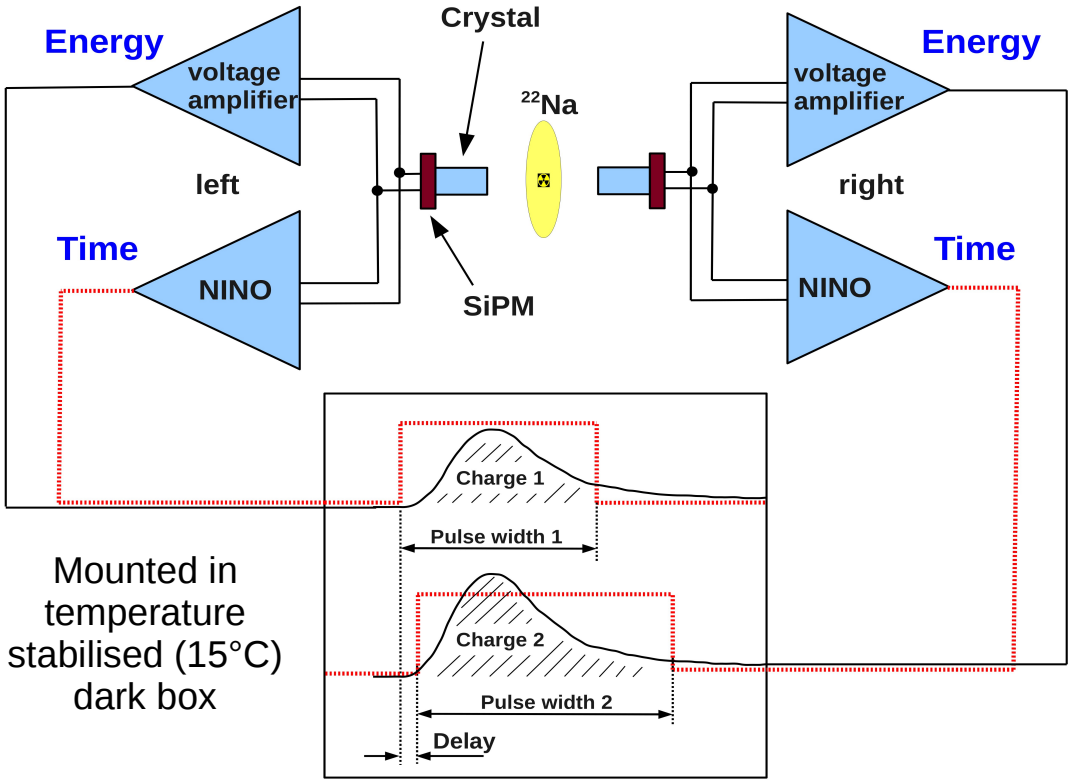
100ps FWHM CTR corresponds to 1.5cm position resolution.

M. Conti, Physica Medica (2009) 25, 1-11

Components of the radiation detector



Coincidence time resolution (CTR) measurements



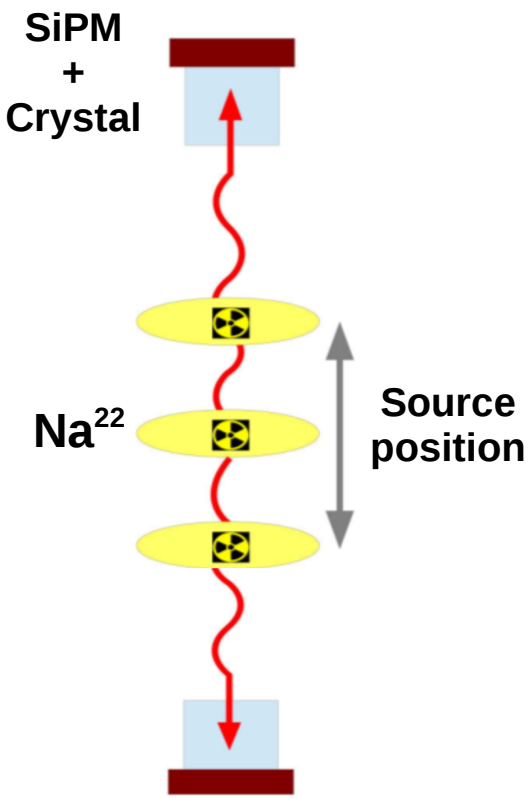
NUV SiPM from FBK: 3x3mm^2, 40um SPAD size, 60% fill factor coupled to 2x2x3mm^3 and 2x2x20mm^3 LSO:Ce codoped 0.4%Ca with Meltmount

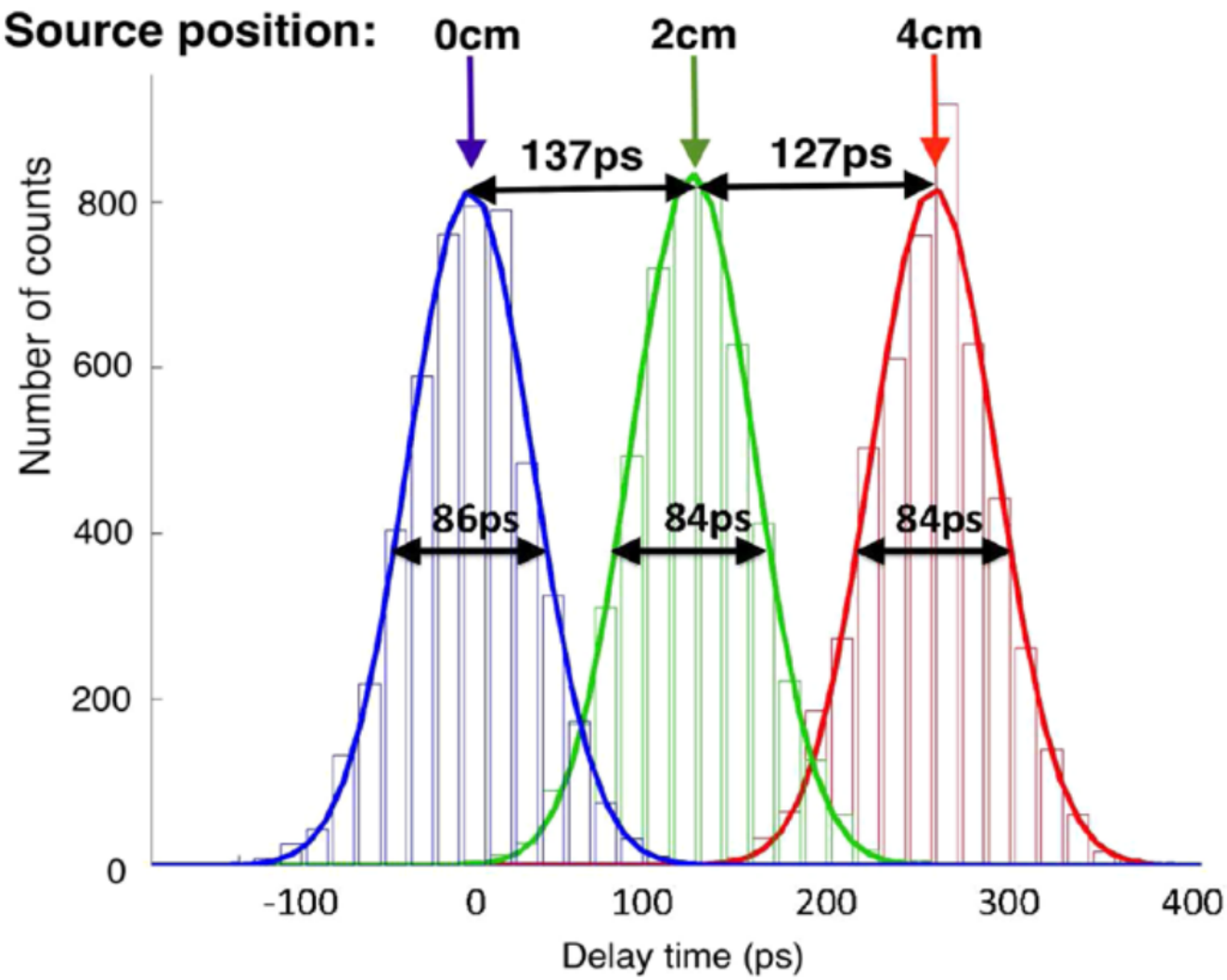
Temperature for measurements stable at 15°C.

S. Gundacker et.al, JINST, August 2013. JINST 8 P07014

FBK NUV (3x3mm^2, 40µm)

Measurements done at CERN with FBK-NUV SiPMs:



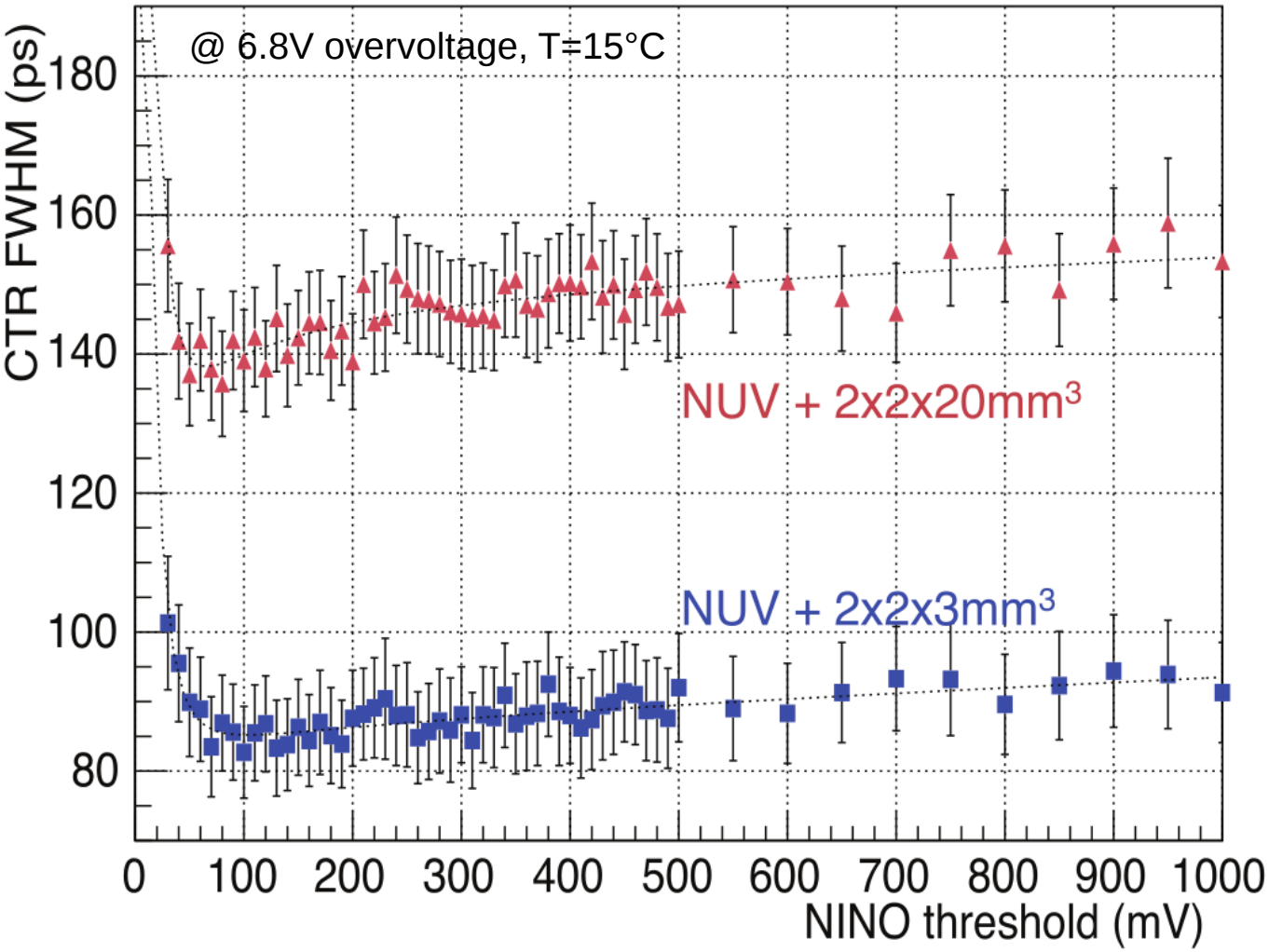


Crystals: 2x2x3mm^3 LSO:Ce codoped 0.4%Ca

M. V. Nemallapudi et.al, Phys. Med. Biol. 60 (2015) 4635

FBK NUV (3x3mm^2, 40µm)

Measurements done at CERN with FBK-NUV SiPMs:



CTR of 140ps FWHM with 20mm long LSO:Ce codoped 0.4%Ca crystal.

CTR of 85ps FWHM with 3mm long LSO:Ce codoped 0.4%Ca crystal.

M. V. Nemallapudi et.al, Phys. Med. Biol. 60 (2015) 4635

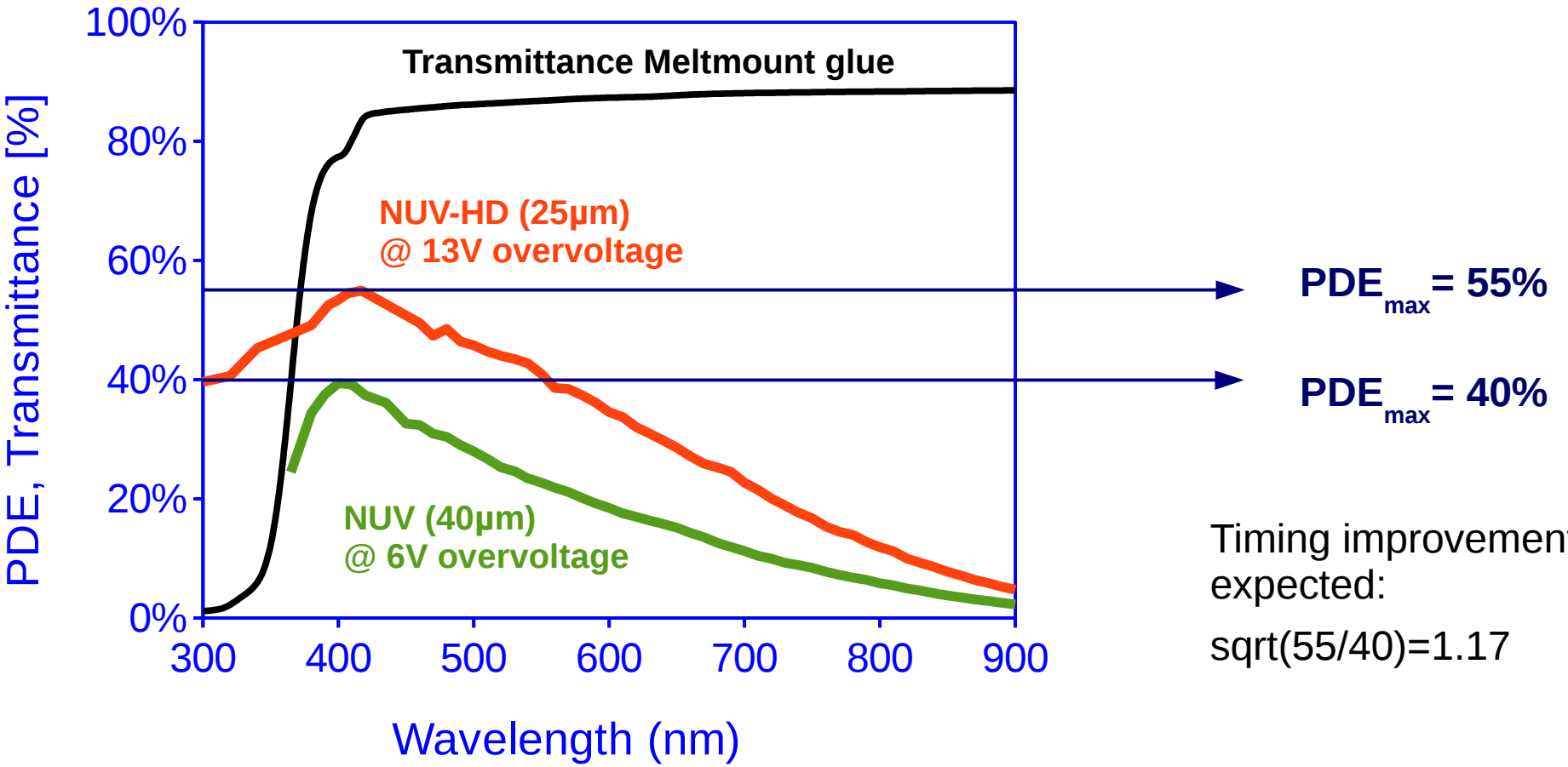
FBK new development:
NUV - high density (HD)
(4x4mm^2, 25µm)

FBK NUV-HD (4x4mm^2, 25µm)

HD (high density)
→ high fill factor and thus higher PDE

Smaller cell size (25µm)
→ higher overvoltage due to less correlated noise and thus higher PDE

Good single photon time resolution of 180ps FWHM despite large 4x4mm^2 area

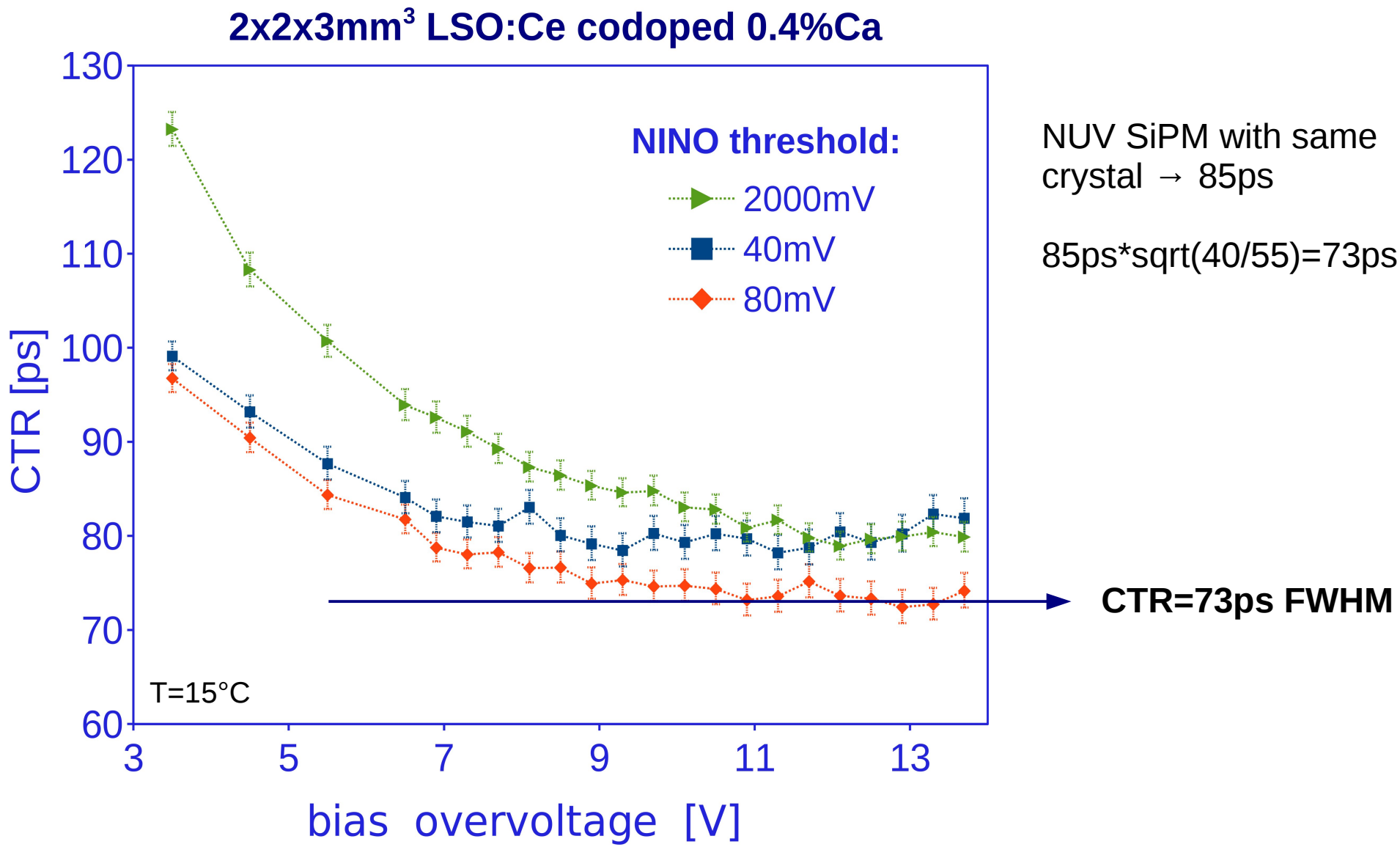


Timing improvement expected:

sqrt(55/40)=1.17

A. Ferri, et.al "100ps coincidence time resolution with LYSO coupled to NUV-HD SiPMs", NSS-MIC, 2015

FBK NUV-HD (4x4mm^2, 25µm)



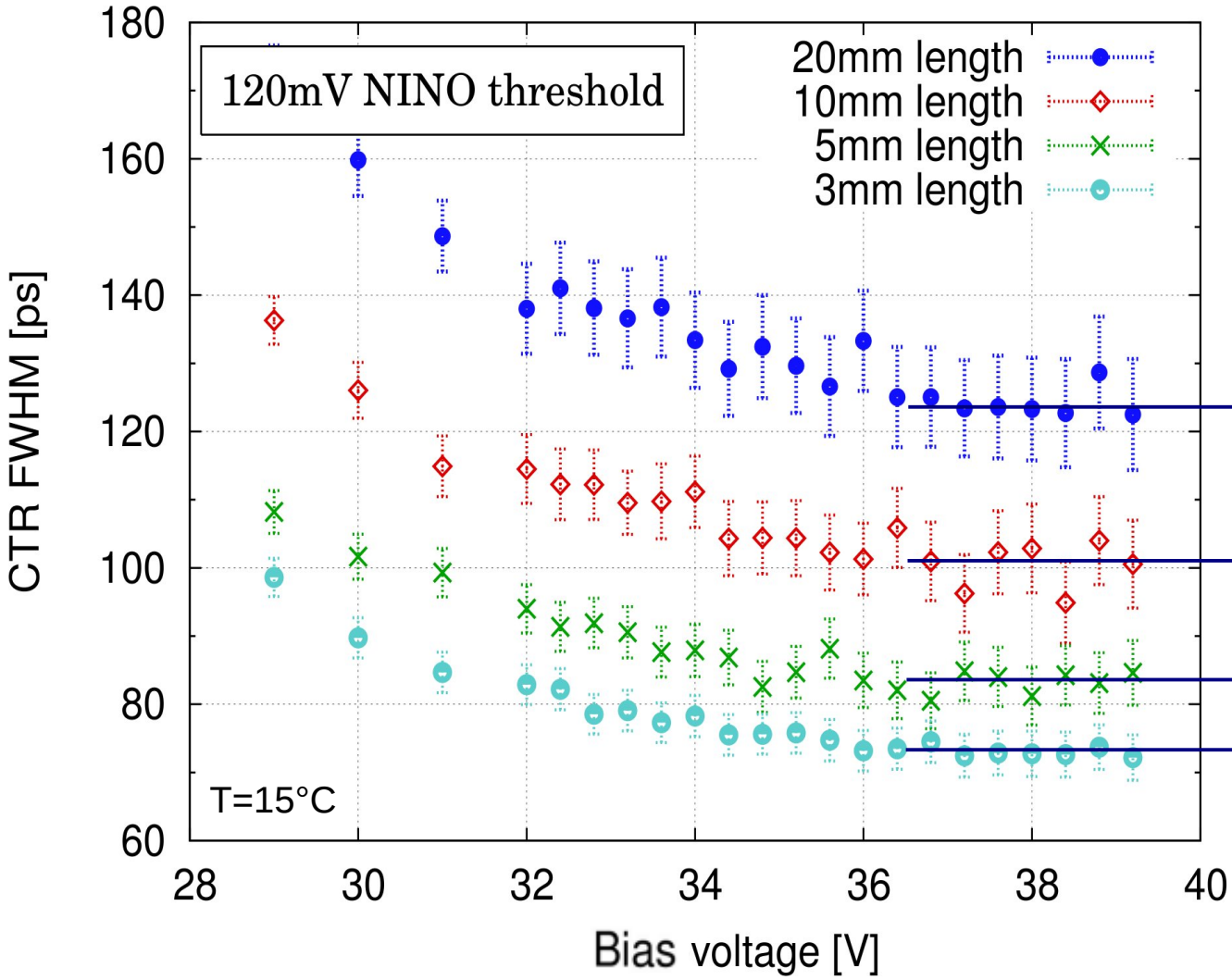
NUV SiPM with same crystal → 85ps

85ps*sqrt(40/55)=73ps

Crystal length influence on the CTR

NUV-HD with various crystal lengths

2x2mm^2 LSO:Ce codoped 0.4% Ca



length: CTR

20mm: 122ps FWHM

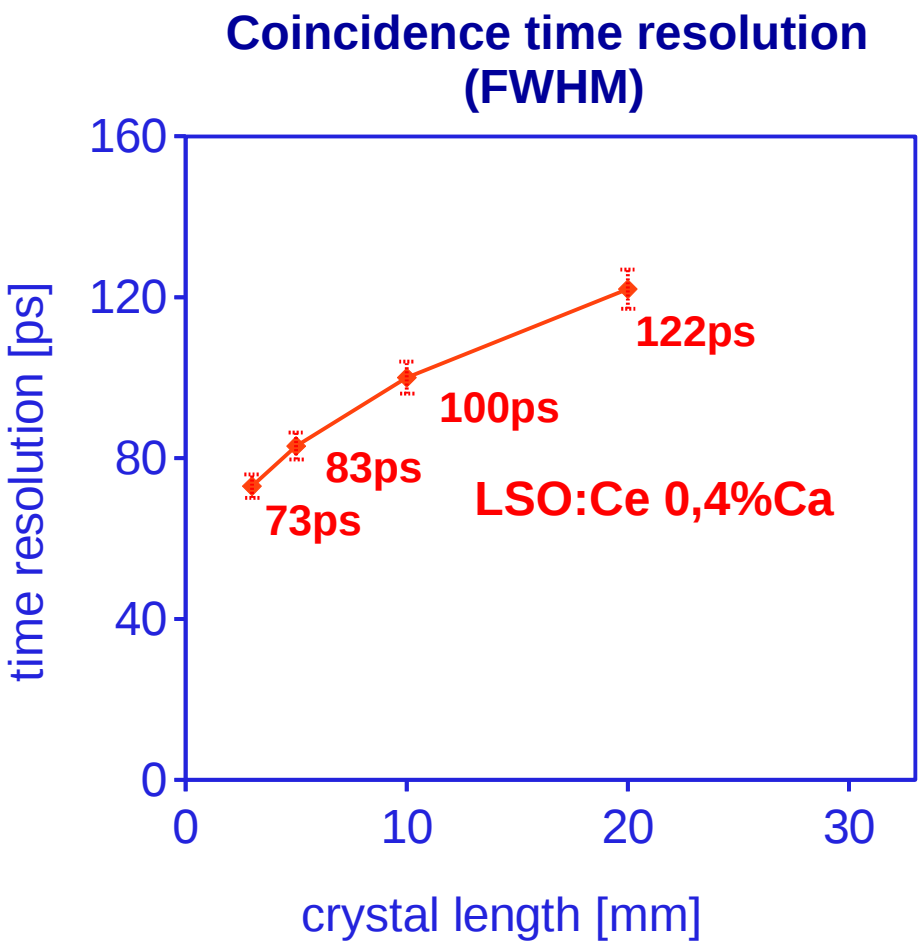
10mm: 100ps FWHM

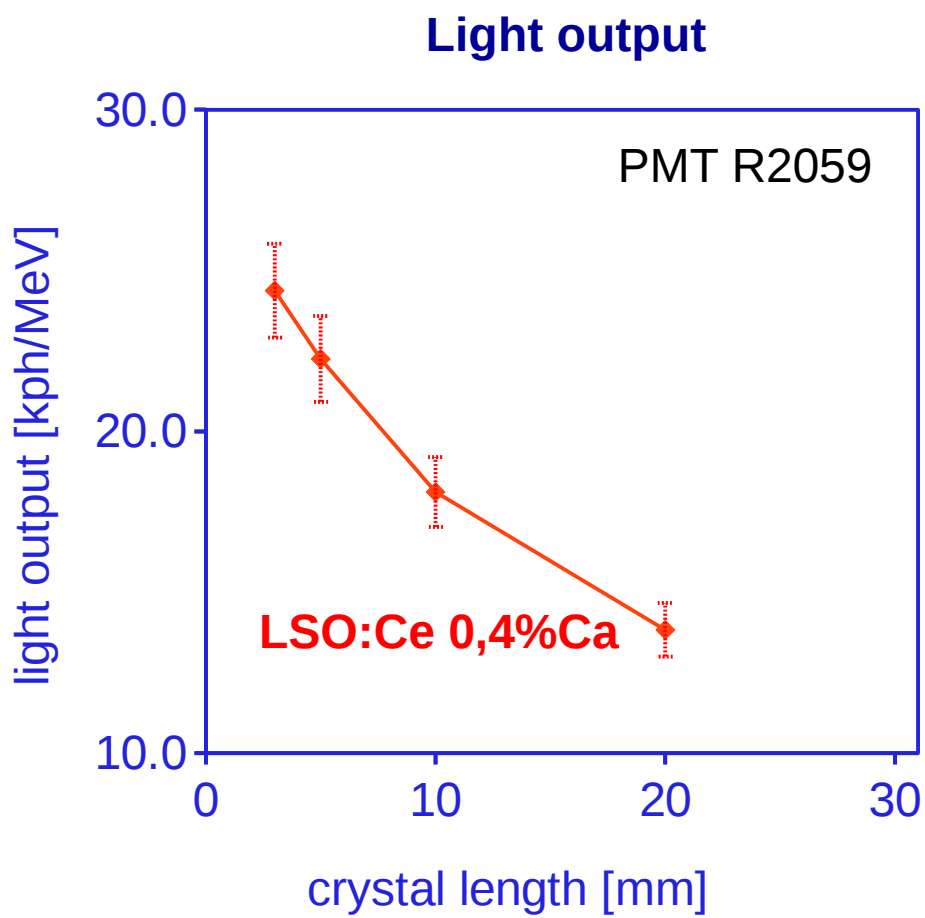
5mm: 83ps FWHM

3mm: 73ps FWHM

Measured with NUV-HD (25µm SPAD size, 4x4mm^2 device size)

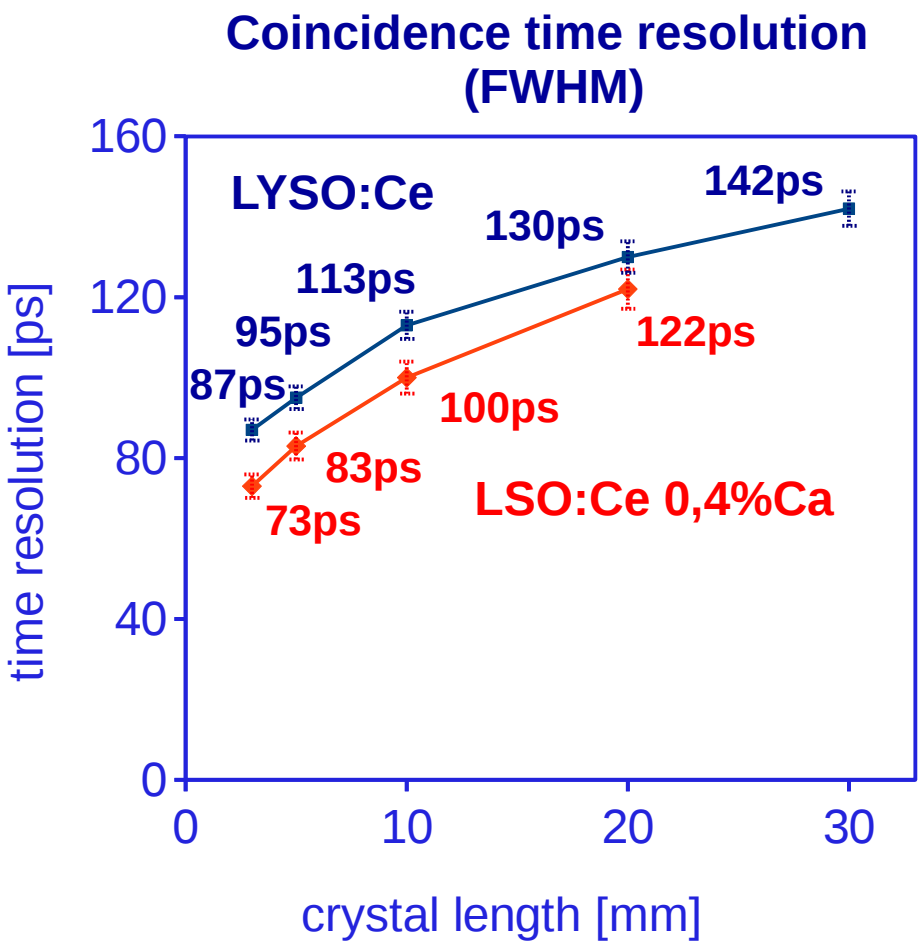
LSO:Ce codoped 0.4% Calcium

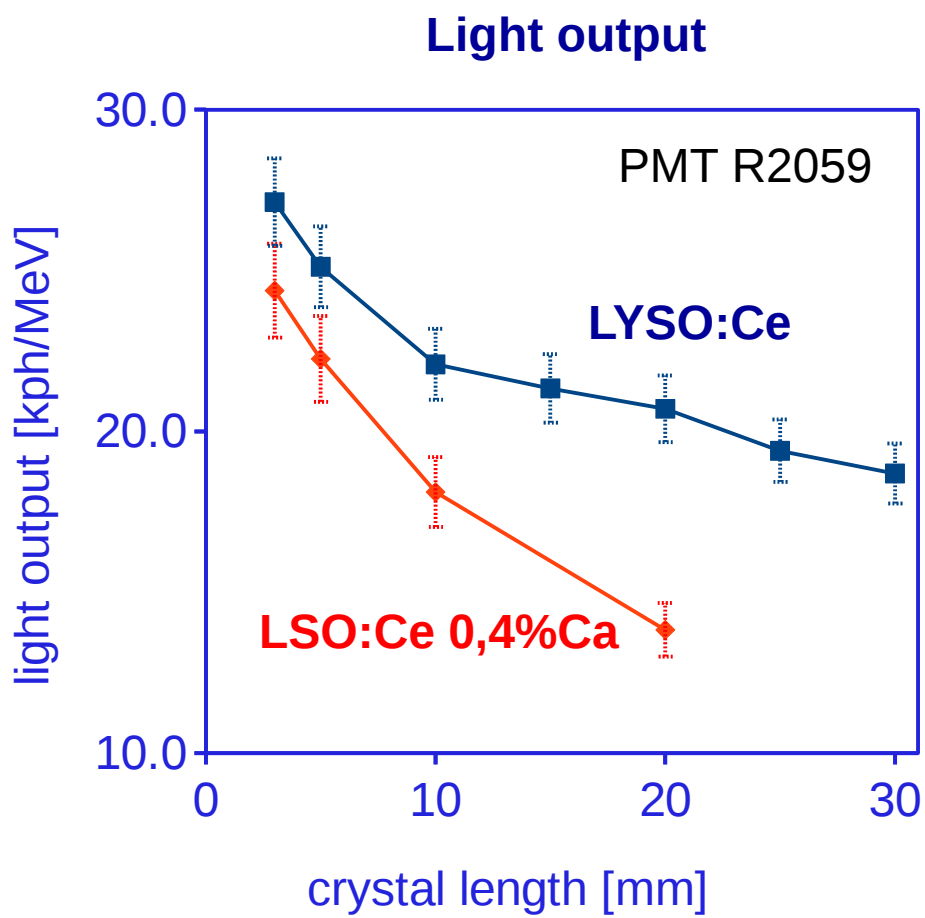




Measured with NUV-HD (25µm SPAD size, 4x4mm^2 device size)
2x2mm^2 crystal cross section, T=15°C

LSO:Ce:Ca versus LYSO:Ce

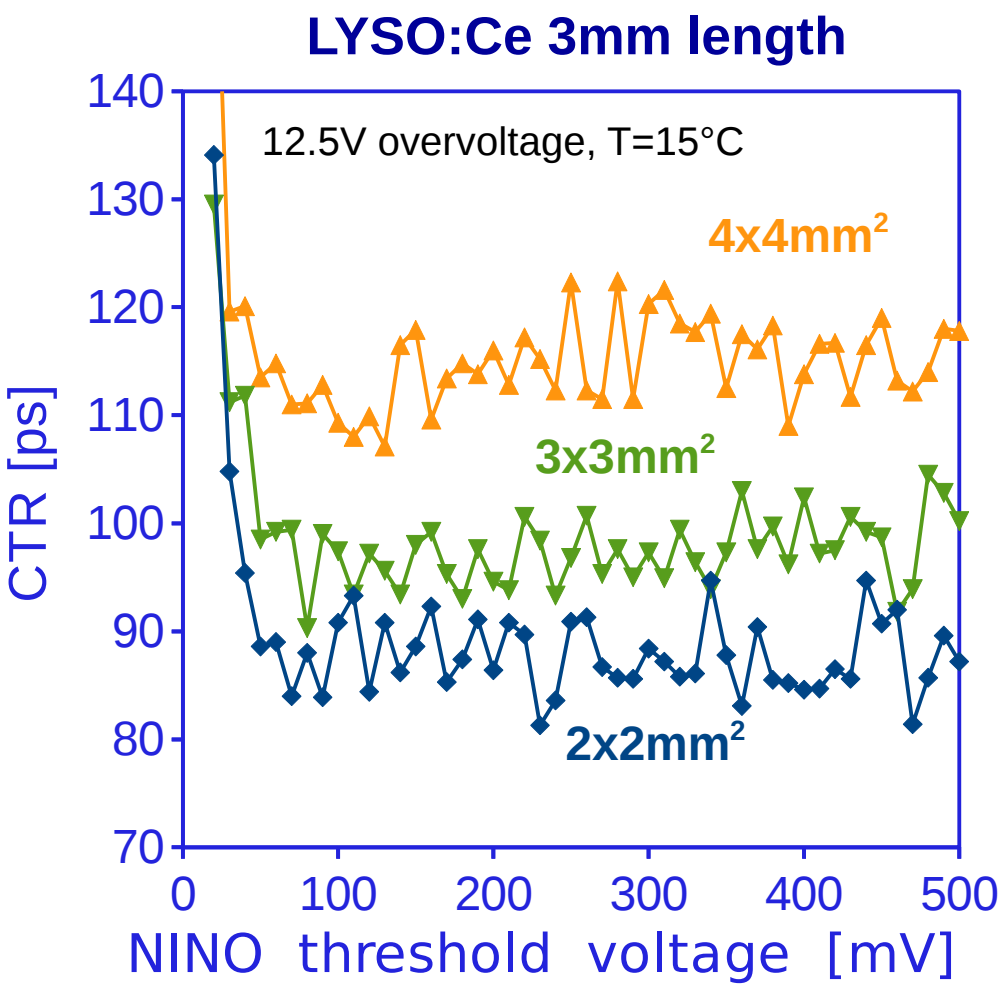


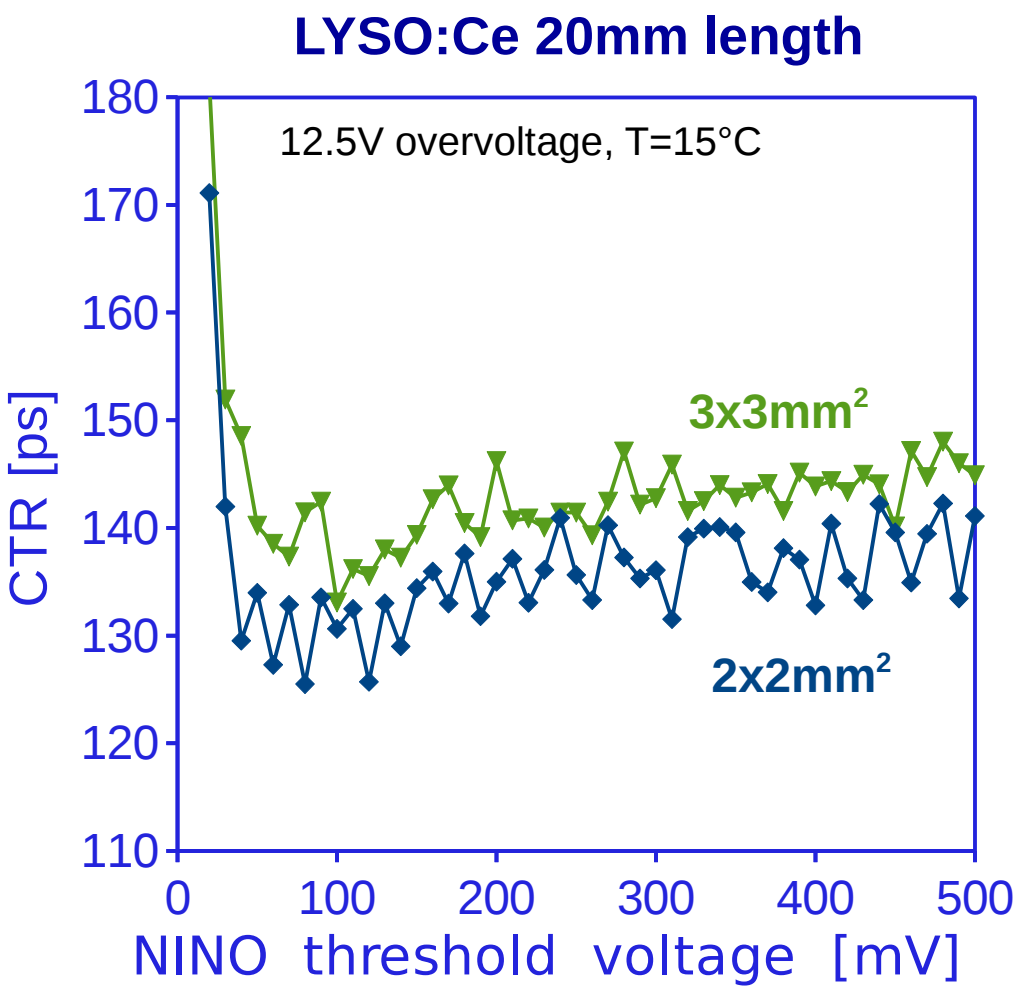


Measured with NUV-HD (25µm SPAD size, 4x4mm^2 device size)
2x2mm^2 crystal cross section, T=15°C

Crystal cross section influence on the CTR

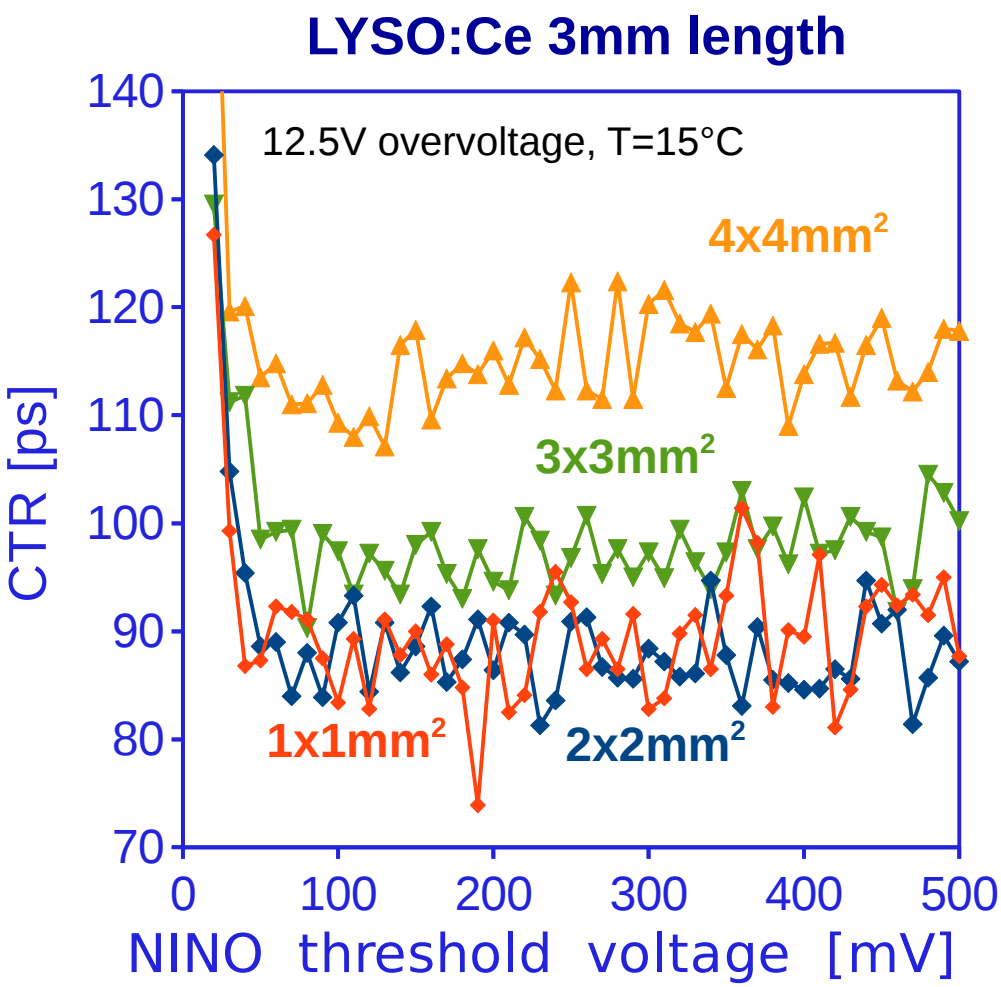
Crystal cross section

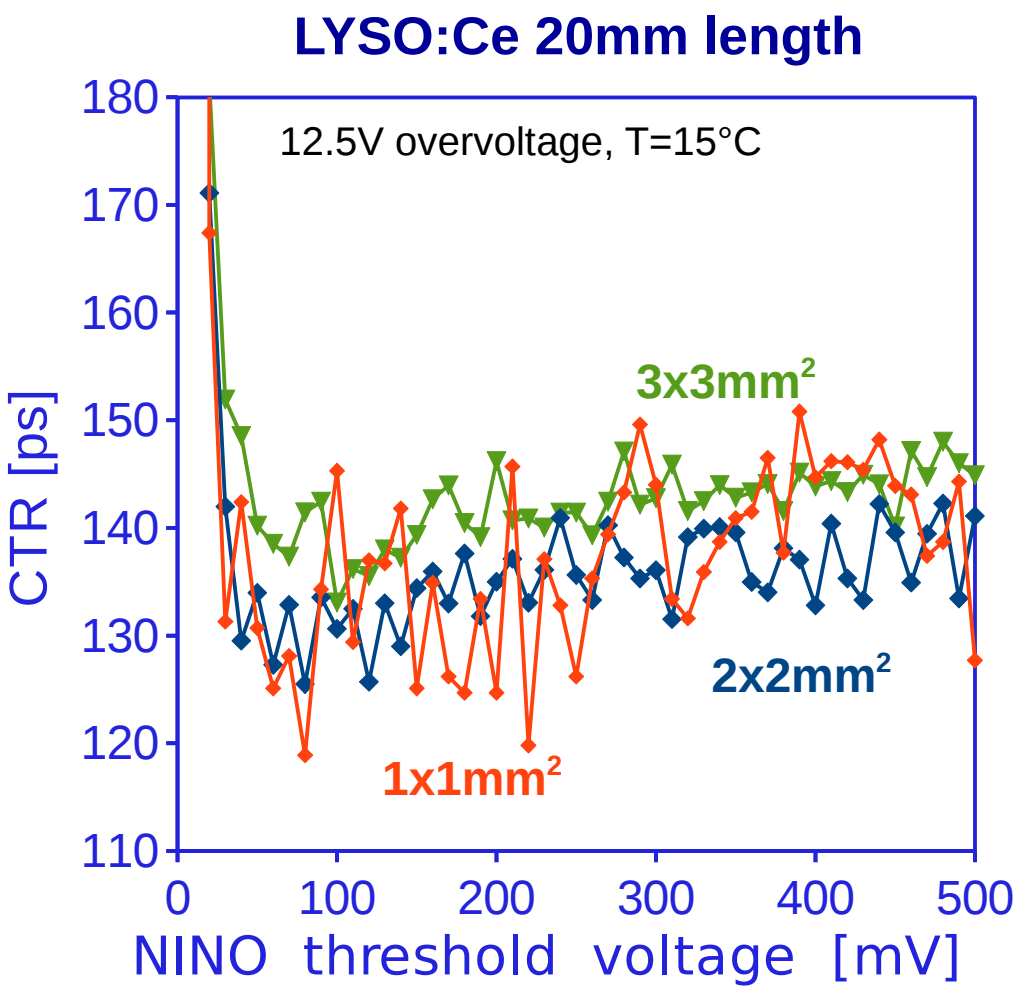




Going from 2x2mm^2 to 3x3mm^2 crystal cross section → ~ 8ps CTR deterioration
4x4mm^2 cross section did not cover whole SiPM (light loss)

Crystal cross section





No CTR difference between 1x1mm^2 and 2x2mm^2 crystal cross section

Confirmation for different lengths and types

LYSO:Ce		crystal length		
		3mm	5mm	20mm
crystal cross section	1x1mm^2	87ps		132ps
	2x2mm^2	87ps	95ps	130ps
	3x3mm^2	95ps	105ps	137ps
	4x4mm^2	111ps		

~ 8ps FWHM

LSO:Ce, 0.2% Ca		crystal length	
		3mm	20mm
crystal section	2x2mm^2	75ps	117ps
	3x3mm^2	82ps	126ps

~ 8ps FWHM

Measured with NUV-HD (25µm SPAD size, 4x4mm^2 device size), T=15°C

Possible reasons for worse CTR with increased crystal area

Possible reasons for increased CTR

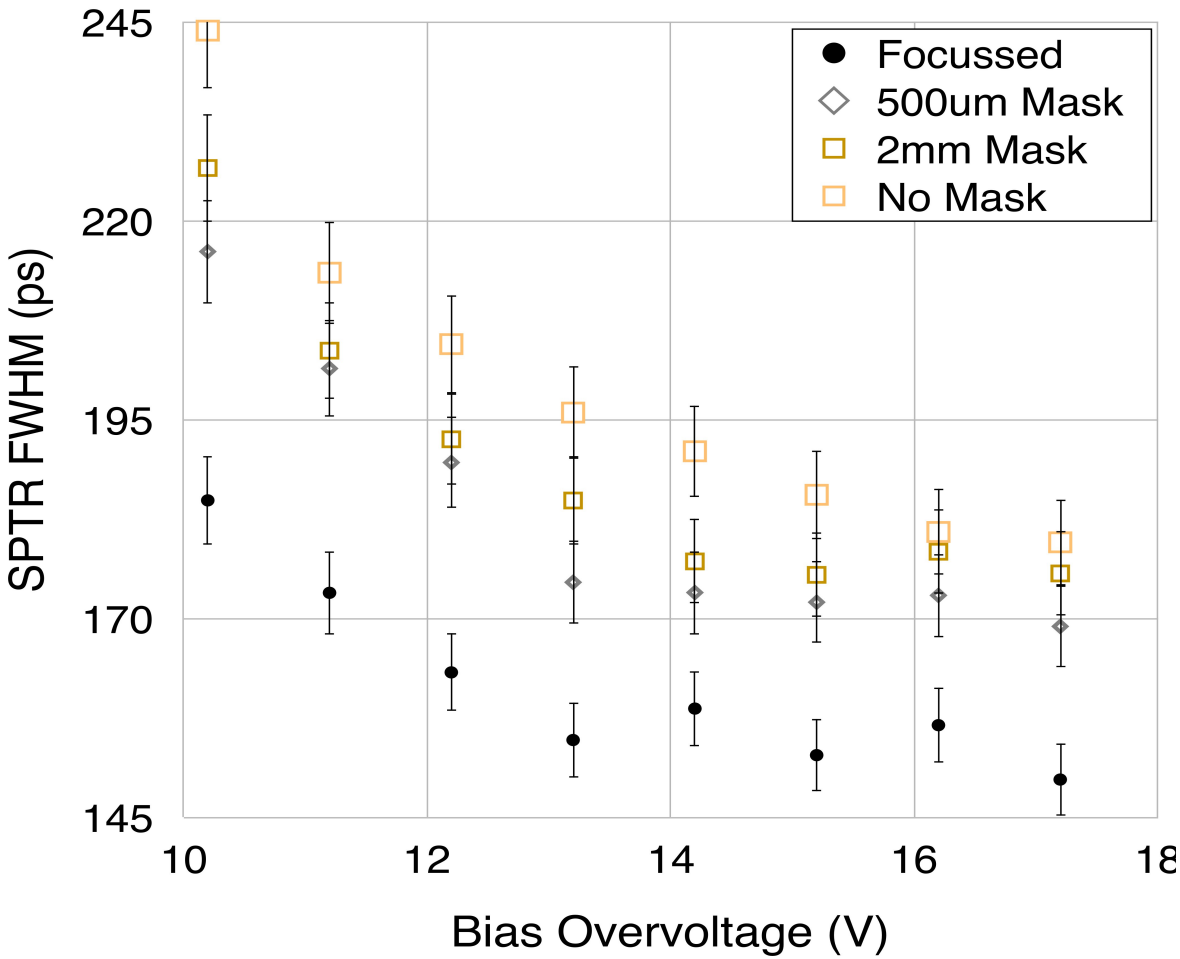
→ SPTR increase due to increased transit time spread with bigger area

→ Light output of crystal could change with section

→ Increased optical crosstalk probability

SPTR NUV-HD with mask

→ Single photon time resolution (SPTR) increase due to increased transit time spread with bigger area



Squared mask in the middle of the SiPM → illumination with defined, smaller area than SiPM size.

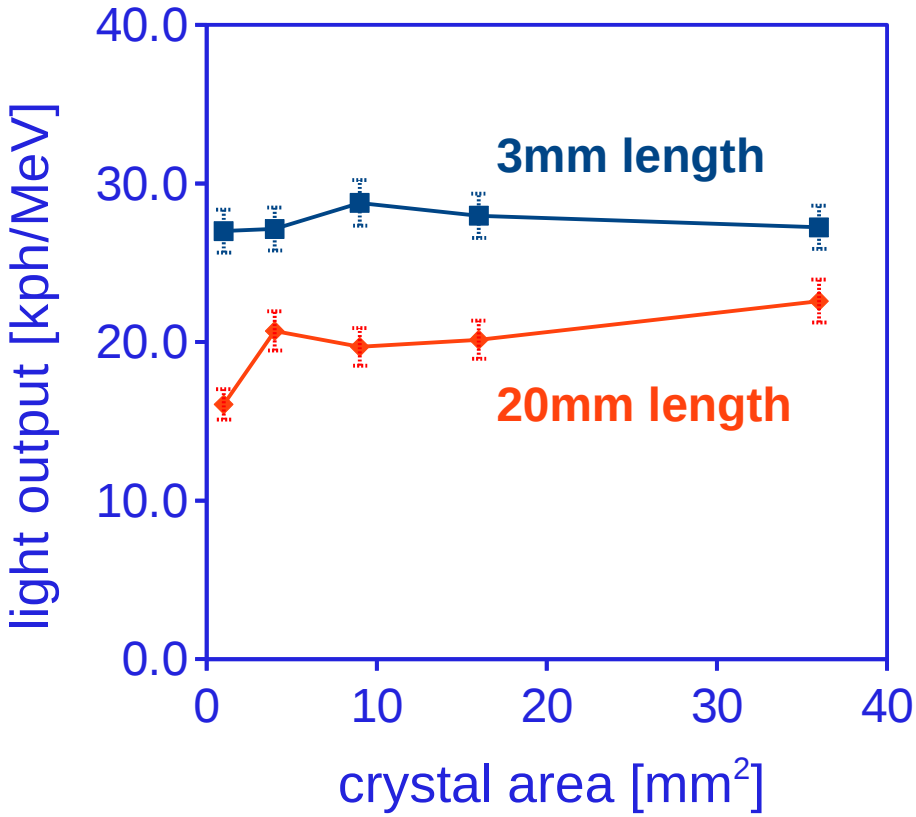
SPTR does not change significantly with different mask sizes.

Measured with NUV-HD (25µm SPAD size, 4x4mm^2 device size), T=15°C

Similar light output for increasing crystal area

→ SPTR increase due to increased transit time spread with bigger area

→ Light output of crystal could change with section



No significant change with crystal area

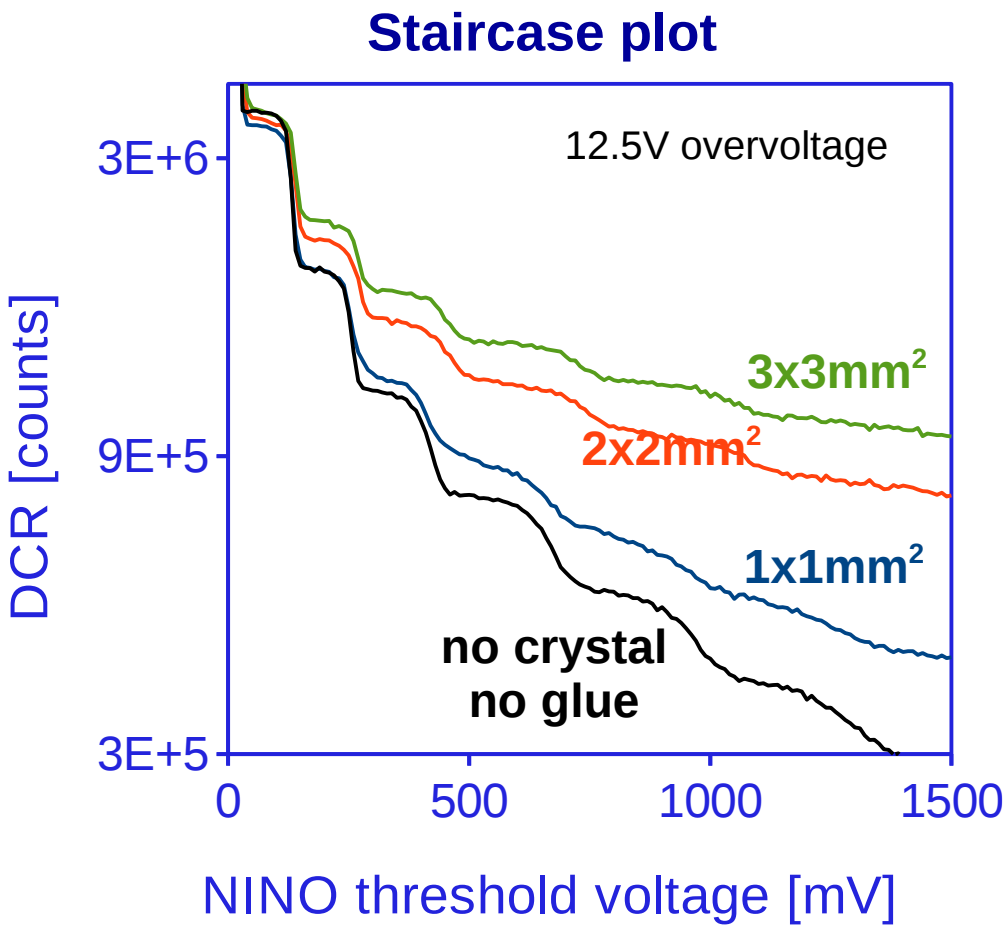
Measured with Hamamatsu PMT R2059

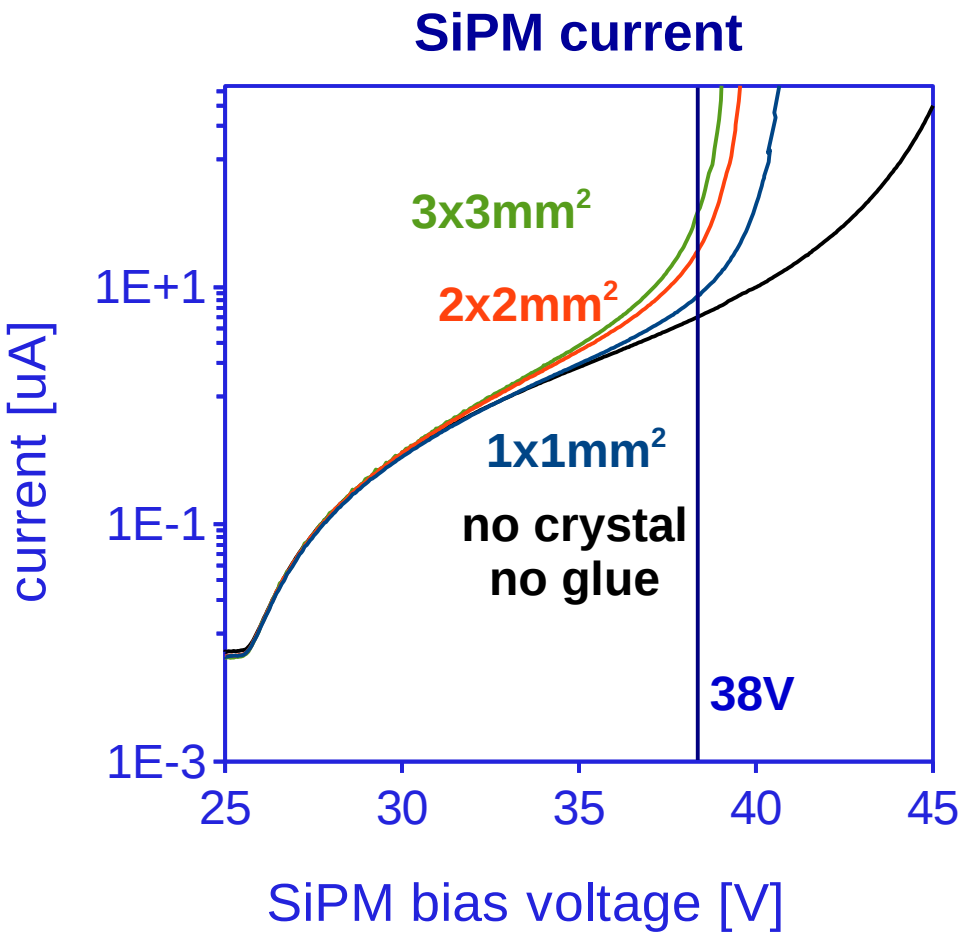
Crosstalk increase with crystal cross section

→ SPTR increase due to increased transit time spread with bigger area

→ Light output of crystal could change with section

→ Increased optical crosstalk probability



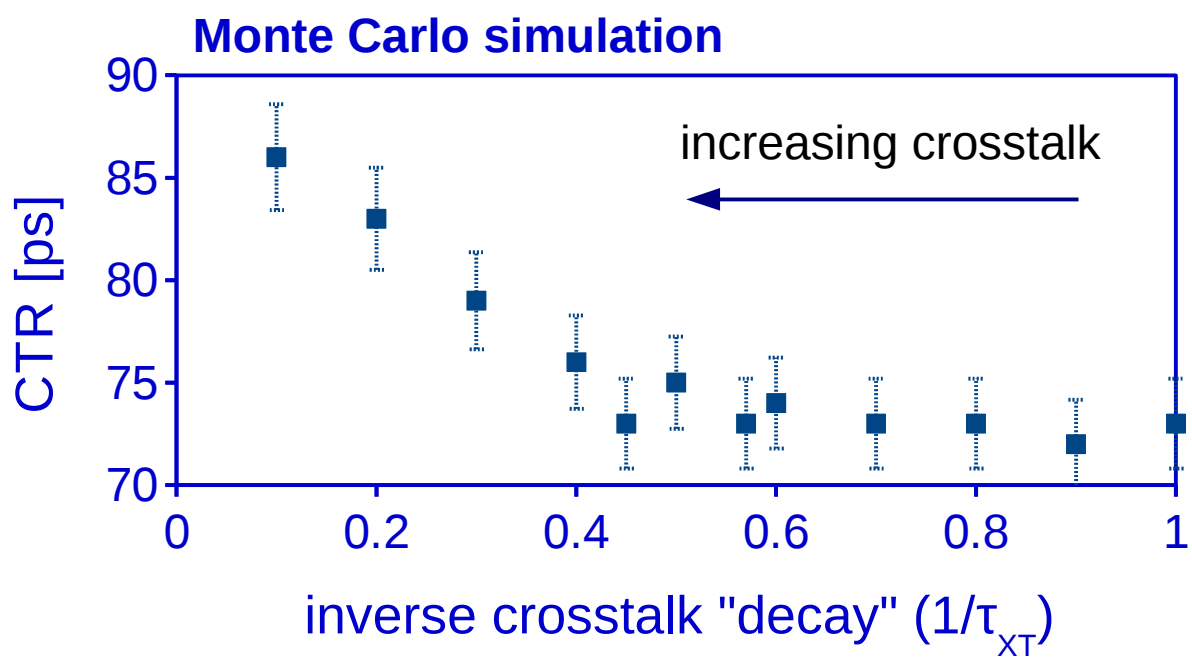


Preliminary test on statistics influence

→ SPTR increase due to increased transit time spread with bigger area

→ Light output of crystal could change with section

→ Increased optical crosstalk probability
- excess noise factor in statistics



$3x3mm^2$: $1/\tau_{XT}$ ~ 0.2-0.3 $2x2mm^2$: $1/\tau_{XT}$ ~ 0.4

i^{th} crosstalk probability given by:

$$P = \exp\left(-i \cdot \frac{1}{\tau_{XT}}\right)$$

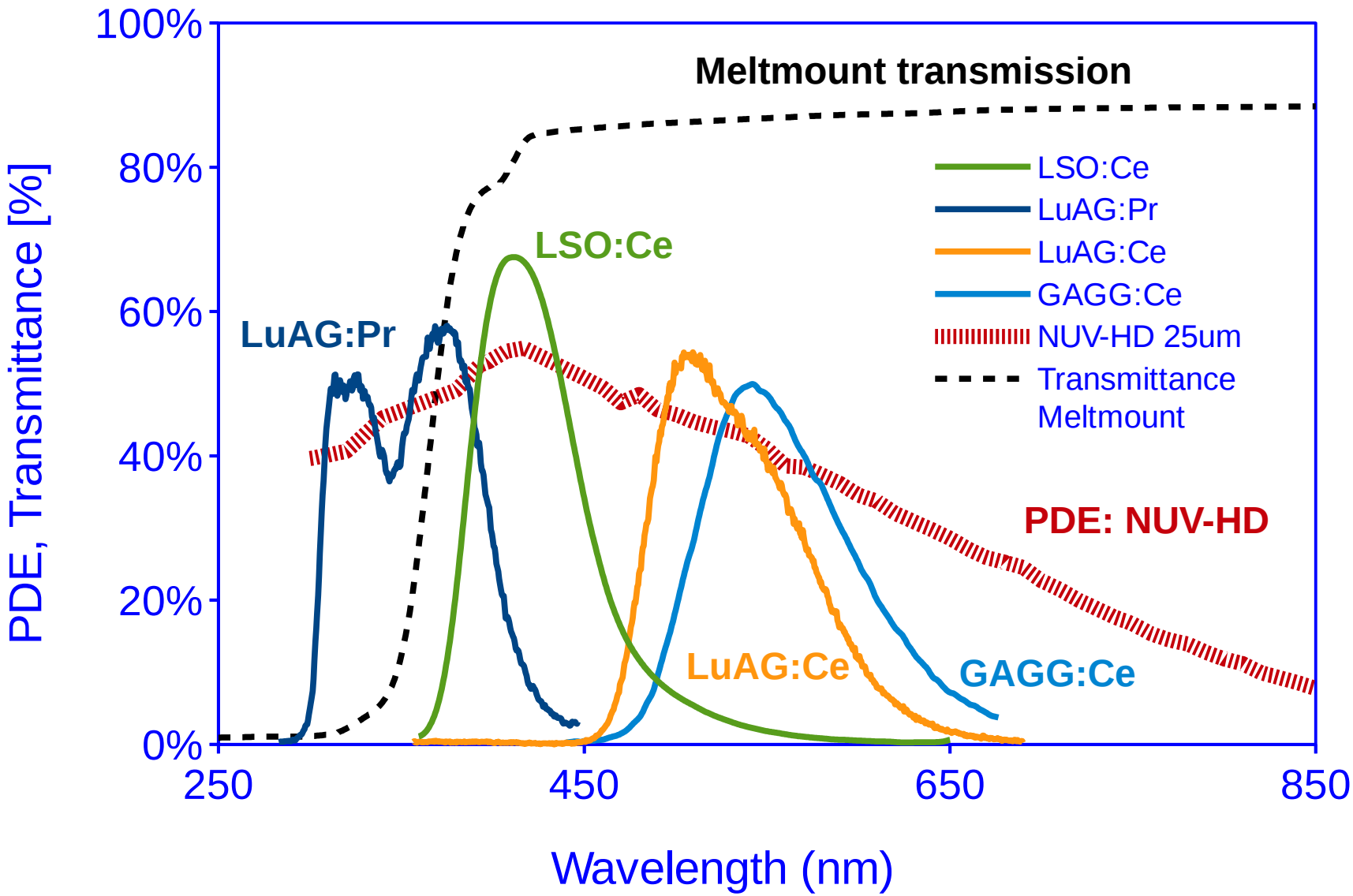
i^{th} crosstalk modelled as Gaussian with:

$$\mu = \mu_0 + SPTR * \sqrt{i}$$
$$\sigma = SPTR * \sqrt{i}$$

time delay and smearing increases

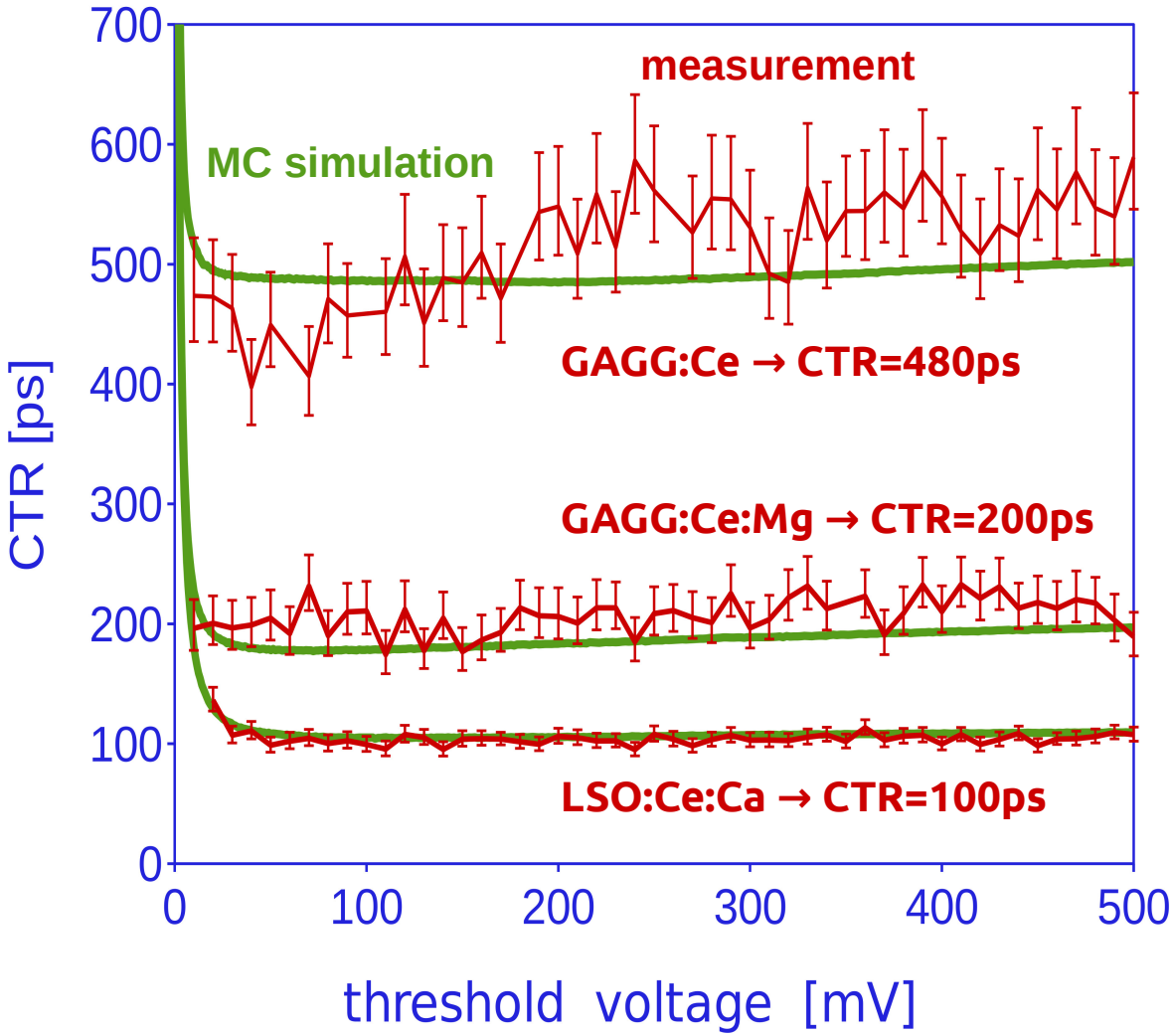
Scintillator material: influence on the CTR

Crystal types tested



GAGG:Ce, GAGG:Ce:Mg and LSO:Ce:Ca

2x2x10mm^3 crystal size, NUV-HD @ 12.5V overvoltage, T=15°C



GAGG:Ce
τ_r=1780ps, τ_{d1}=101ns (65%), τ_{d2}=319ns (35%)
LY=2.12*LY(LSO), PDE(air)=34.2%

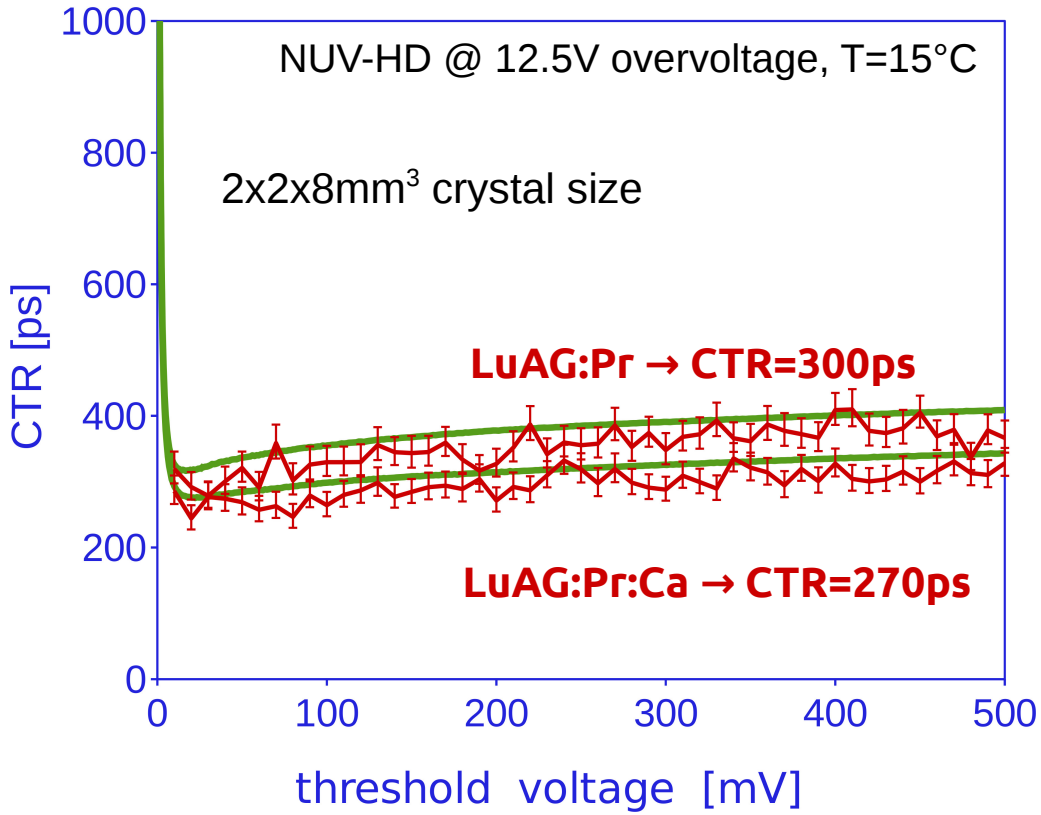
GAGG:Ce codoped Mg
τ_r=54ps, τ_{d1}=56ns (53%), τ_{d2}=225ns (47%)
LY=1.48*LY(LSO), PDE(air)=34.2%

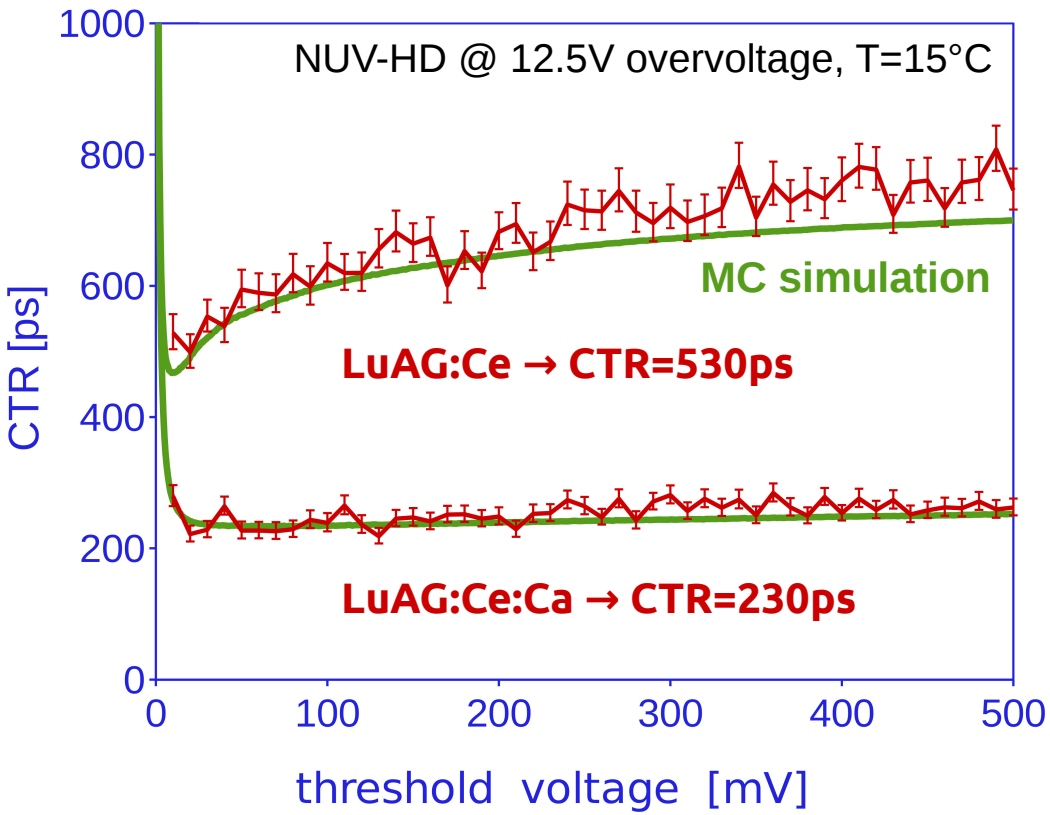
LSO:Ce codoped 0.4%Ca
τ_r=21ps, τ_{d1}=8ns (6%), τ_{d2}=32.6ns (94%)
LY=1*LY(LSO), PDE(air)=42.1%

LYSO:Ce → CTR=113ps

M. T. Lucchini et.a. "Effect of Mg^{2+} ions co-doping on timing performance and radiation tolerance of Cerium doped $Gd_3Al_2Ga_3O_{12}$ crystals", NIMA, Available online 11 February 2016, accepted and in press

LuAG:Pr and LuAG:Ce





	τ_r	τ_{d1}(%)	τ_{d2}(%)	τ_{d3}(%)	LY / LY(LSO)	PDE (air)	Cherenkov / scintillation (detected)
LuAG:Pr	251ps	22ns (52%)	787ns (48%)	–	70%	17.7%	0.2%
LuAG:Pr:Ca	117ps	21ns (49%)	712ns (51%)	–	70%	17.7%	0.21%
LuAG:Ce	535ps	70ns (44%)	1063ns (56%)	–	72%	36.5%	0.06%
LuAG:Ce:Ca	158ps	20ns (12%)	60ns (62%)	822ns (26%)	76%	36.5%	–

S. Gundacker, et.al "Measurement of intrinsic rise times for various L(Y)SO and LuAG scintillators with a general study of prompt photons to achieve 10ps in TOF-PET", IOP PMB, in press

2x2x5mm^3 LSO:Ce 0.4% Ca, coupled to NUV-HD (4x4mm^2, 25µm) in testbeam with 150GeV muons

Timing layer for high luminosity

Future high luminosity colliders demand strategies for event pile-up.

One possibility, calorimeter with timing layer
(time resolution in the order of 20ps sigma needed):

–) 2x2x5mm^2 LSO:Ce codoped 0.4%Ca crystal
give **83ps FWHM CTR in lab with 511keV**.

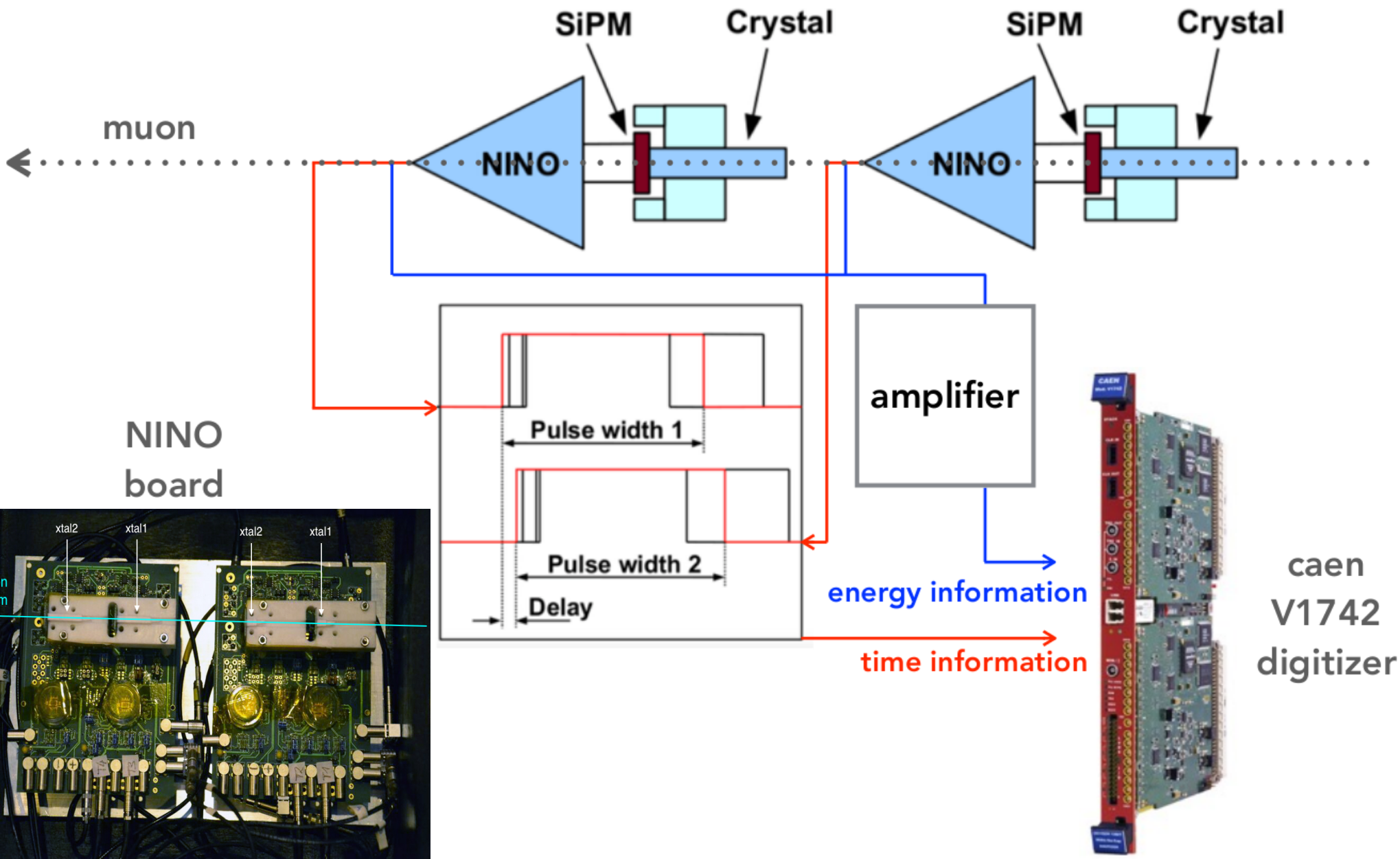
–) Minimum ionizing particle deposits ~1MeV/mm

→ **27ps FWHM CTR expected** in testbeam
with minimum ionizing particles {83 ps / √(5 MeV / 511 keV)}

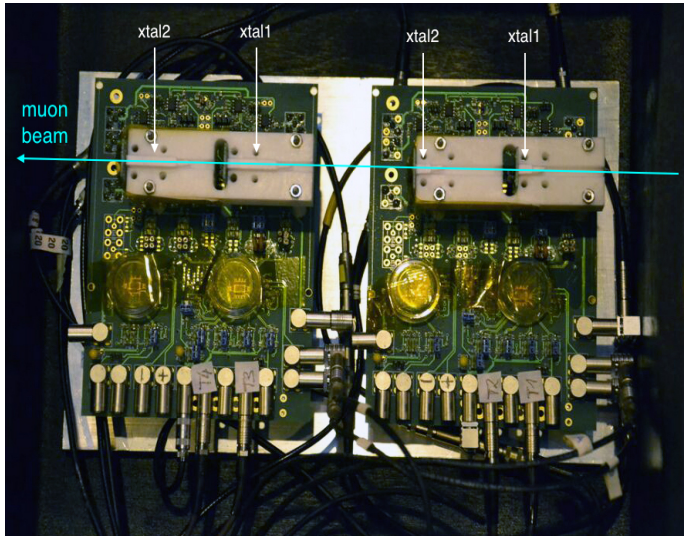
or in sigma single time resolution: 27ps/3.33=8ps

–) timing achievable with 100% detection efficiency

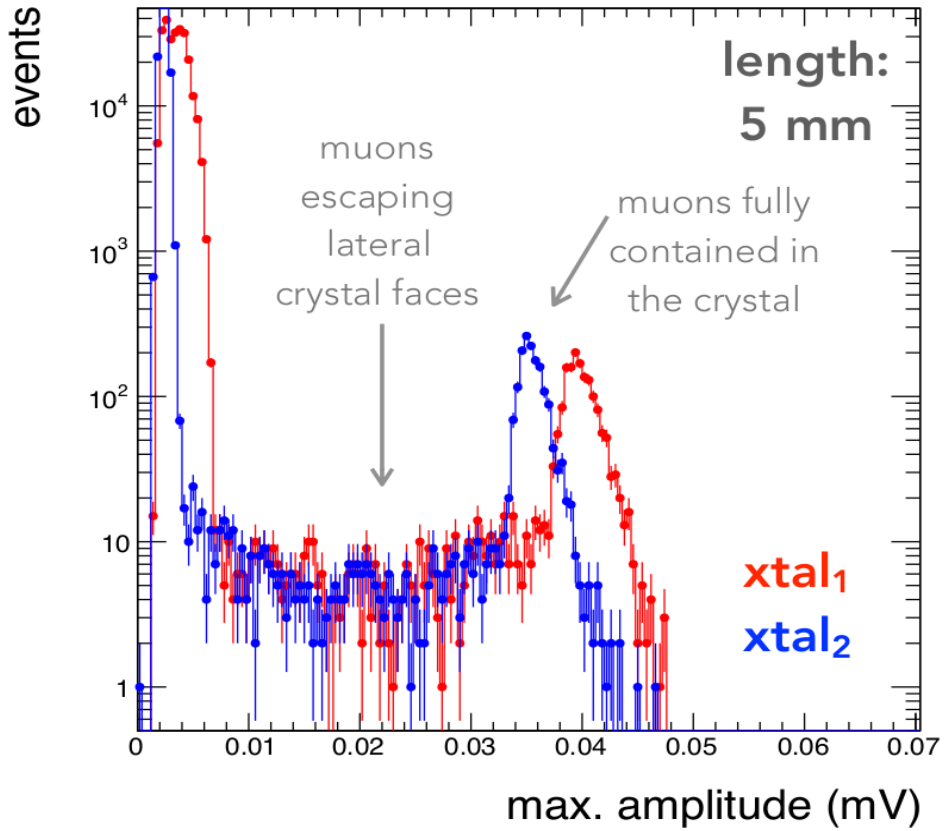
Testbeam setup in H2 (CERN)

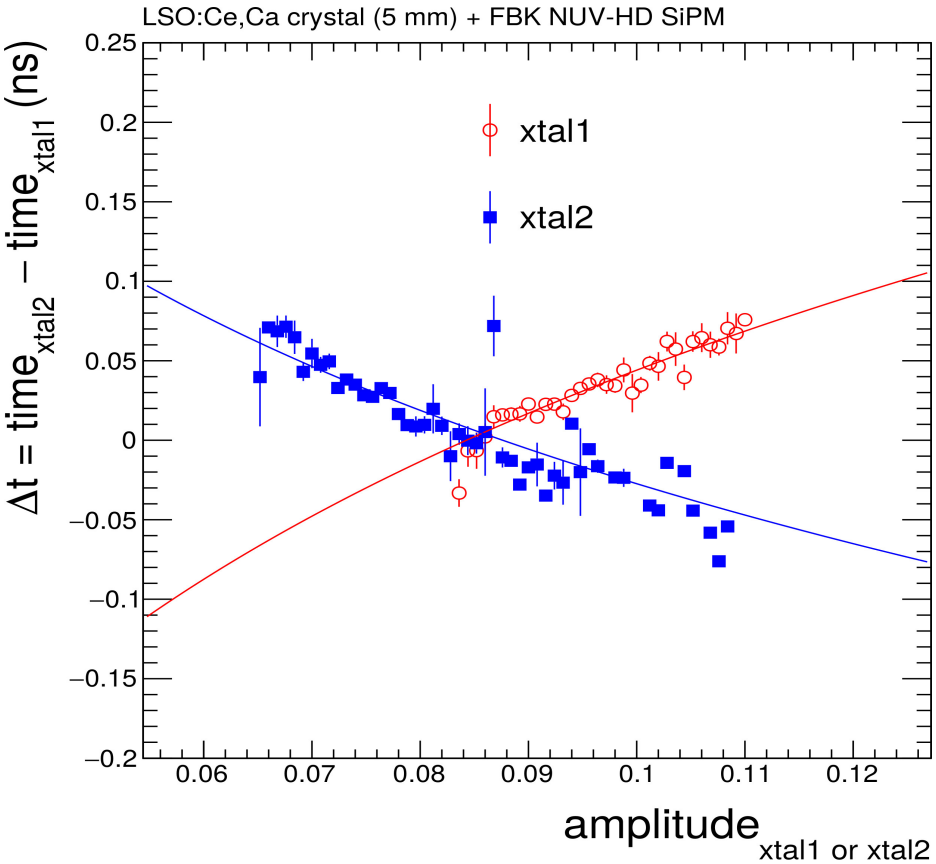


NINO
board



Time walk correction





Non-negligible landau fluctuations

Small beam divergence and misalignment

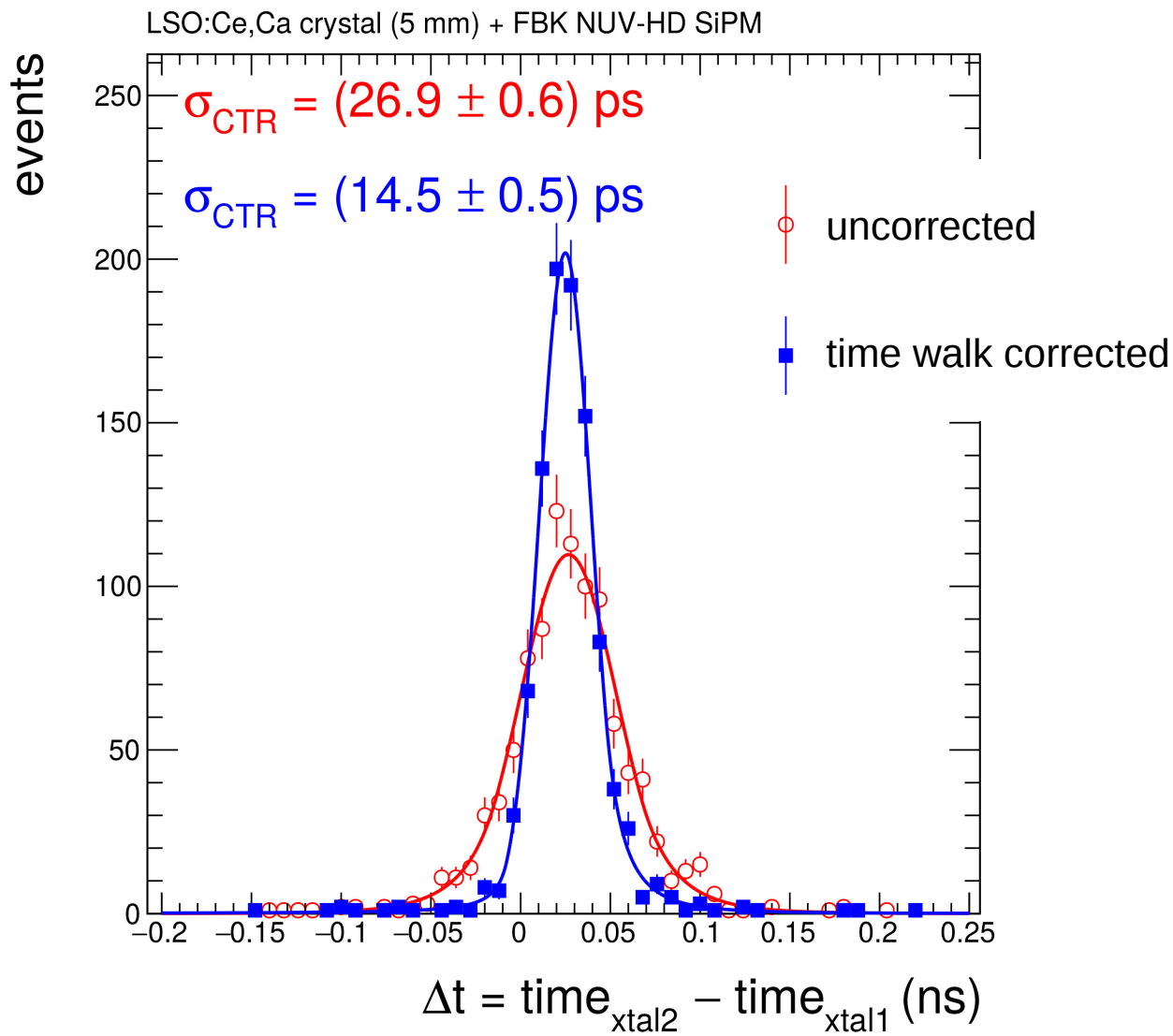
Time walk correction of the landau fluctuations

A. Benaglia et. al. “Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout”, NIMA under review

10ps time resolution with mips

–) We measure
σ_{CTR} ~ 14.5 ps
for 5 mm crystals
(after time-walk correction)

–) This means
σ_{single} ~ 10 ps
(assuming the two crystals equally contribute)



A. Benaglia et. al. "Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout", NIMA under review

Conclusions

- Best CTR of **73ps FWHM for 2x2x3mm^3** and **117ps for 2x2x20mm^3** achieved with LSO:Ce codoped Ca

- Standard **LYSO:Ce achieves 130ps FWHM for 2x2x20mm^3**

- CTR deterioration with larger crystal area starts at 3x3mm^2 and is relativley small (~8ps) --> needs further investigation (6x6mm^2)

- Codoping with Ca or Mg improves scintillation decay- and rise-time, and thus timing significantly.

- **Test-beam results** showed results of **10ps (sigma)** (33ps FWHM CTR) with minimum ionizing particles and 5mm long crystals

Questions?

S. Gundacker, A. Benaglia, M. T. Lucchini,
M.V. Nemallapudi, K. Pauwels, E. Auffray and P. Lecoq
CERN

F. Acerbi, A. Ferri, A. Gola, G. Paternoster, C. Piemonte
FBK

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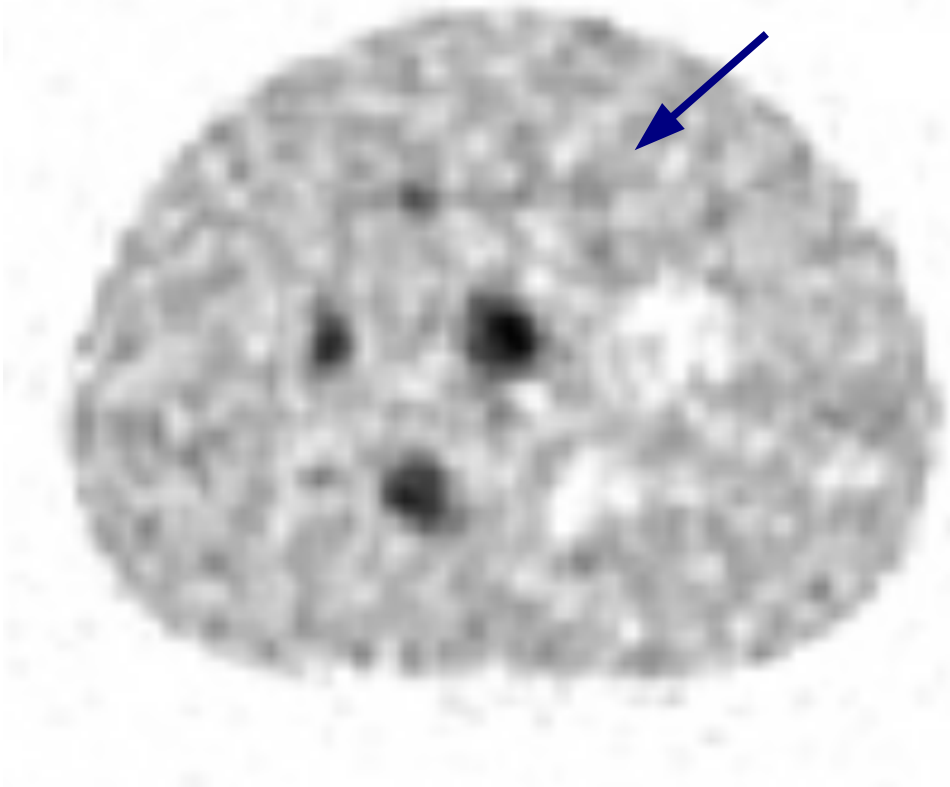
Backup slides

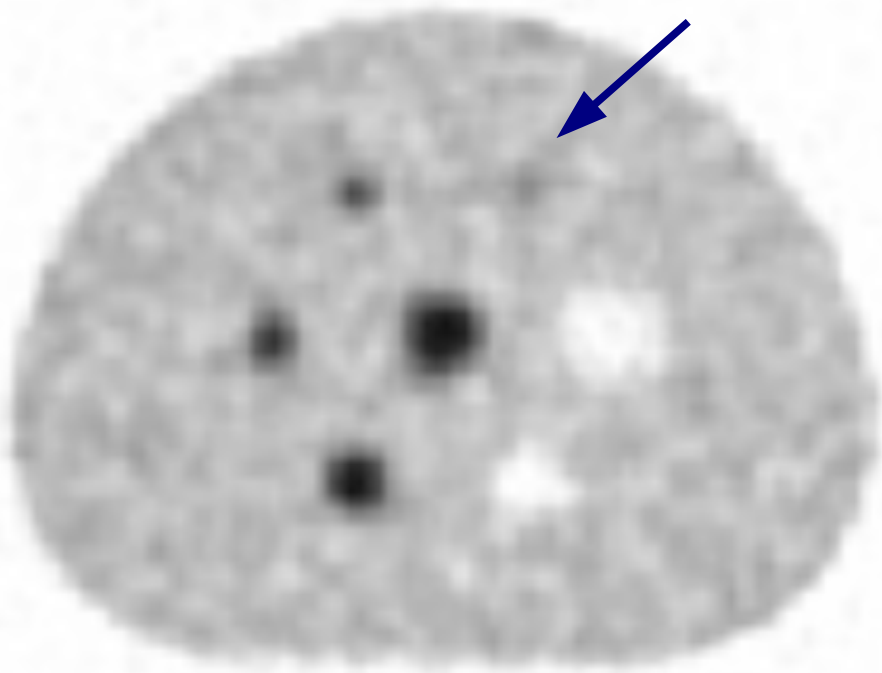
"Tachyon" TOF-PET with 314ps

Single-ring Lutetium Oxyorthosilicate (LSO) based camera designed to obtain significantly better timing resolution than the ~550ps found in present commercial TOF cameras. Incorporating the 314ps TOF reduces the standard deviation of the contrast by a factor of about 2.3.

No timing information is incorporated in the reconstruction

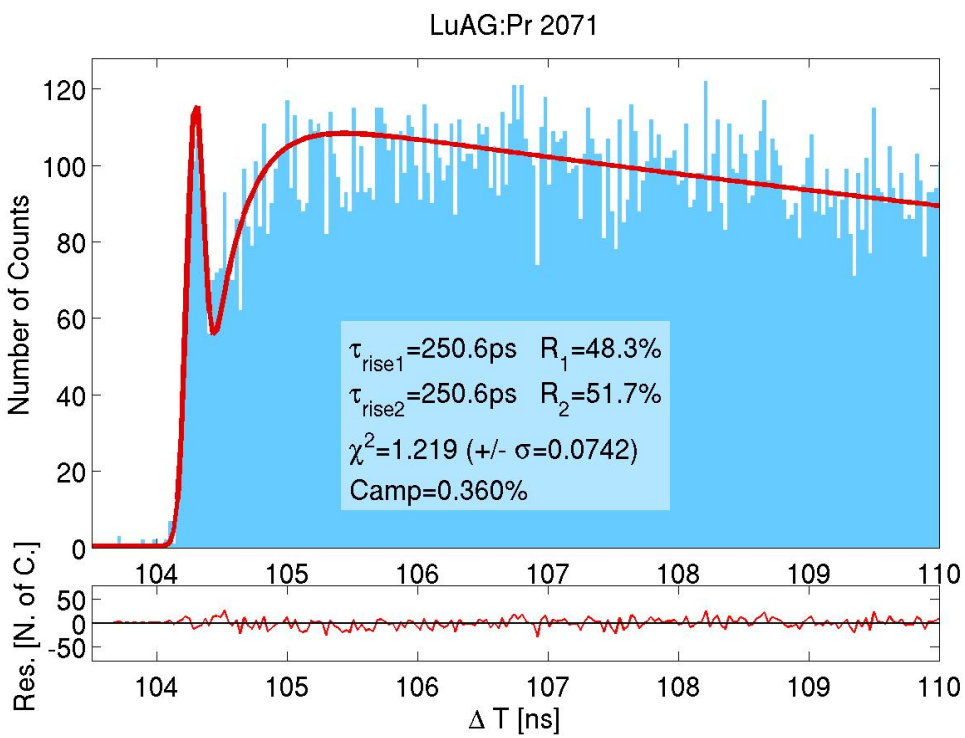


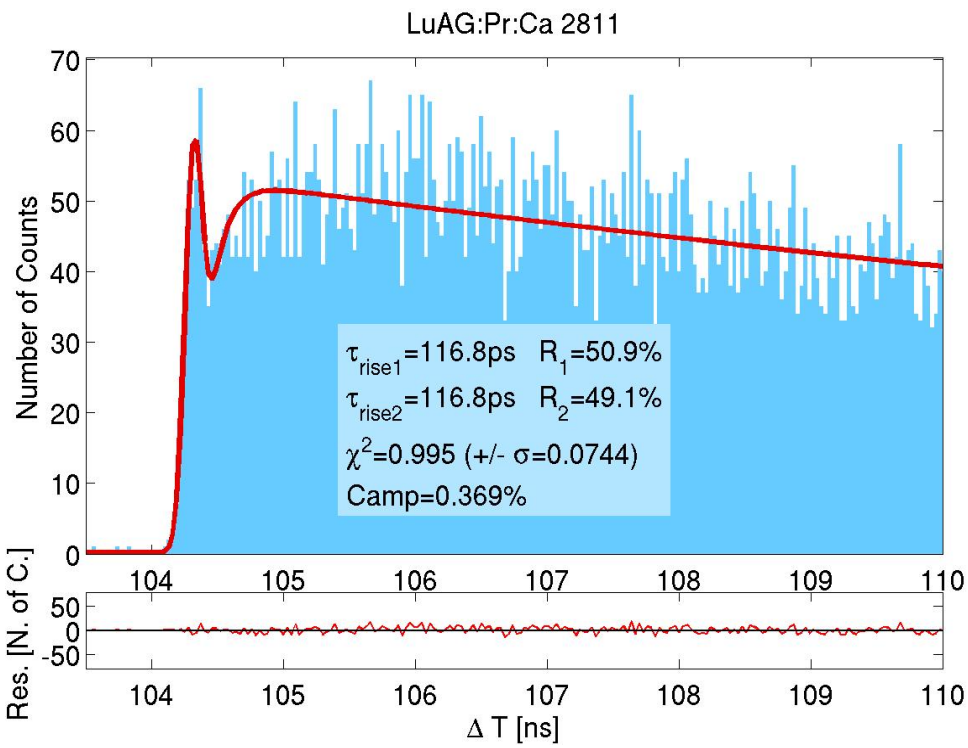
CTR of 314ps FWHM is incorporated in the reconstruction



Q. Peng et. al. “Performance of the Tachyon Time-of-Flight PET Camera”

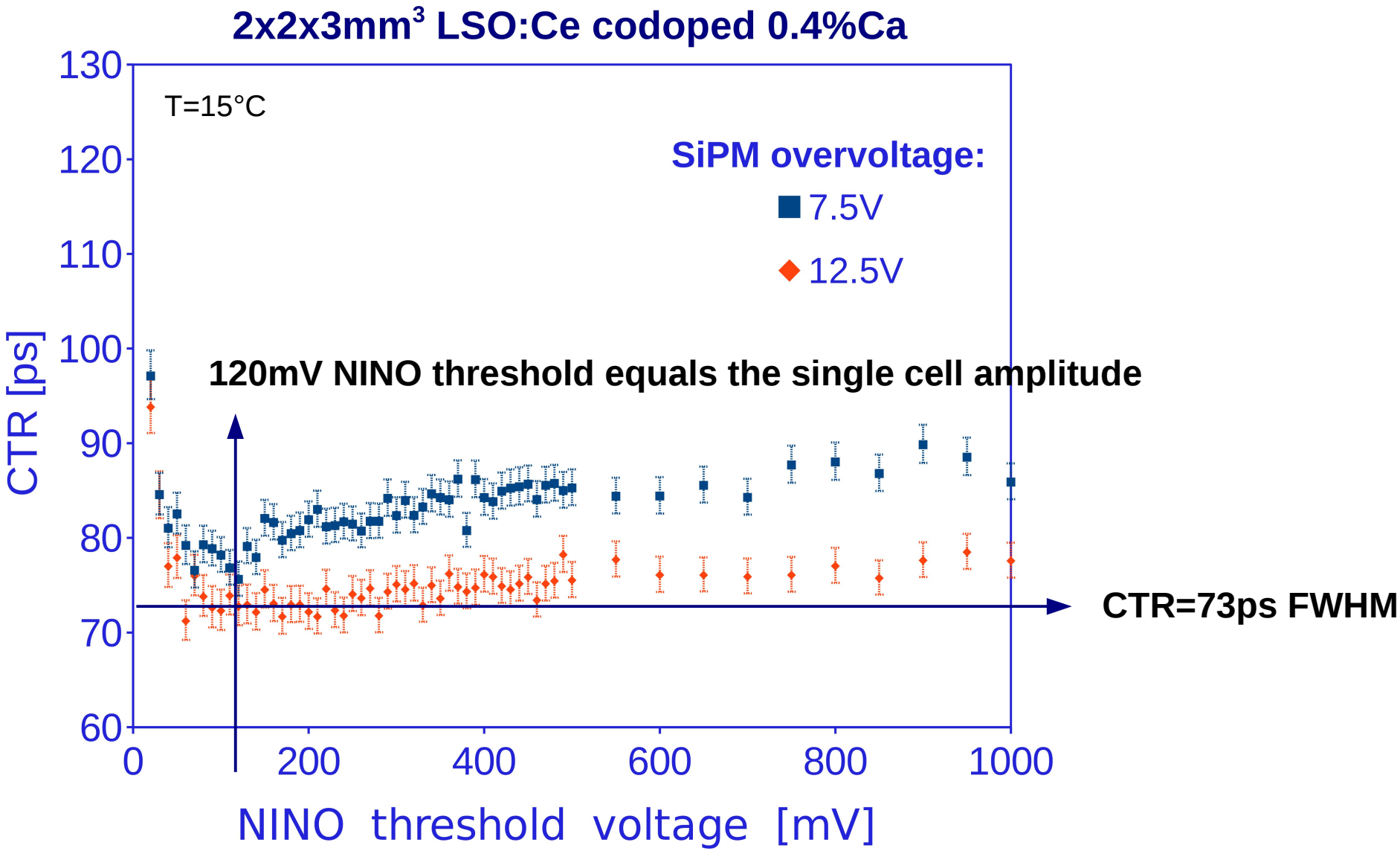
Measured Cherenkov yield in LuAG:Pr





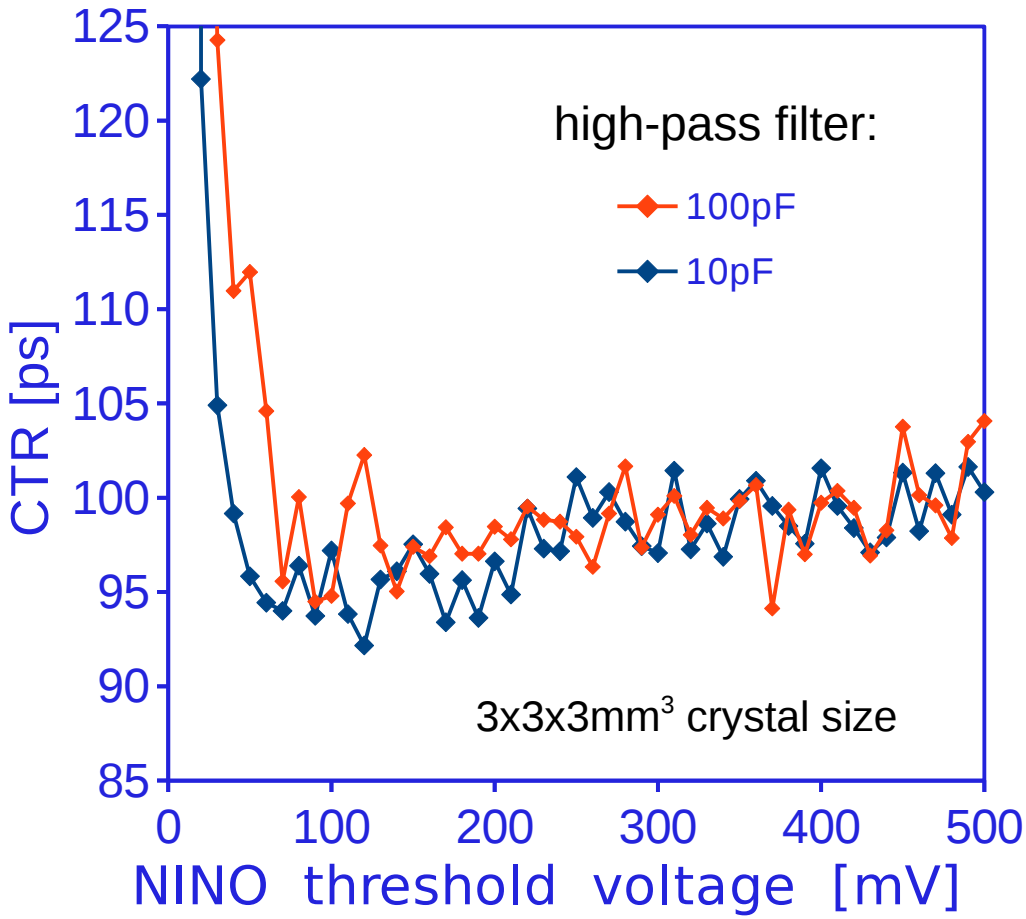
S. Gundacker, et.al "Measurement of intrinsic rise times for various L(Y)SO and LuAG scintillators with a general study of prompt photons to achieve 10ps in TOF-PET", IOP PMB, in press

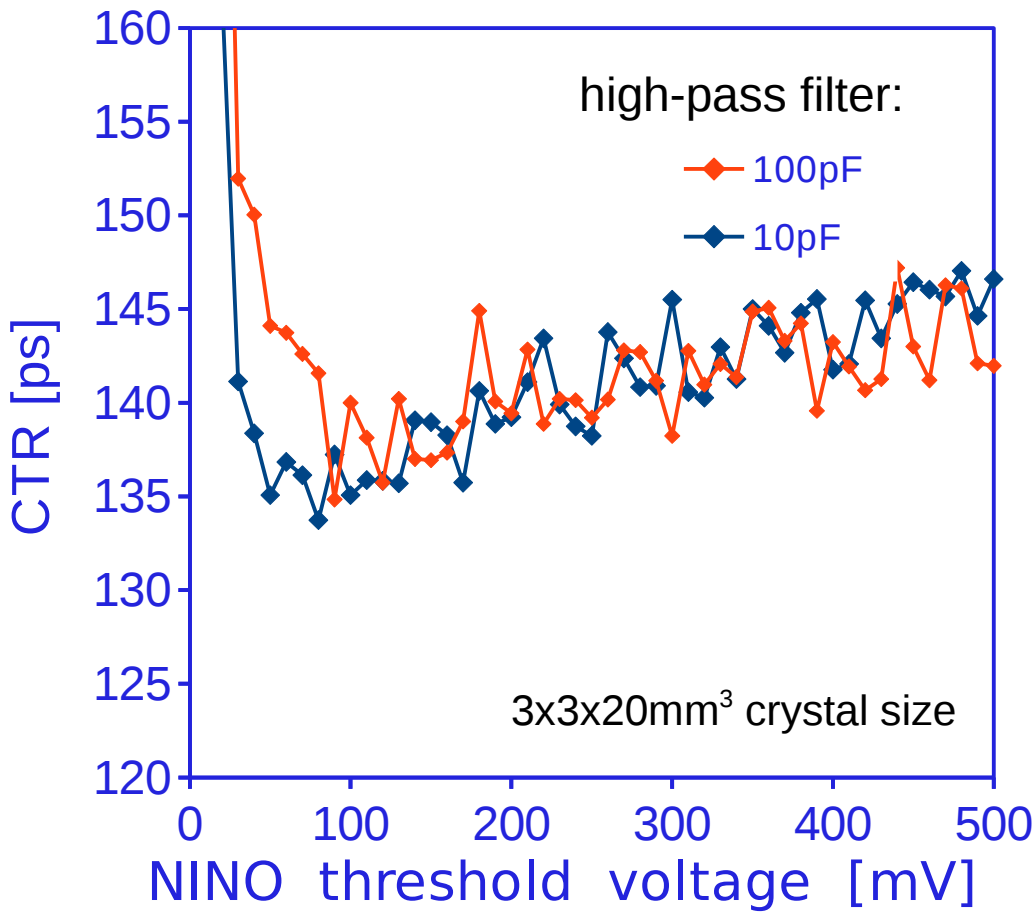
FBK NUV-HD (4x4mm^2, 25µm)



Baseline-shift "filtering"

→ Increased crosstalk probability:
- more baseline noise and thus time pick-up jitter

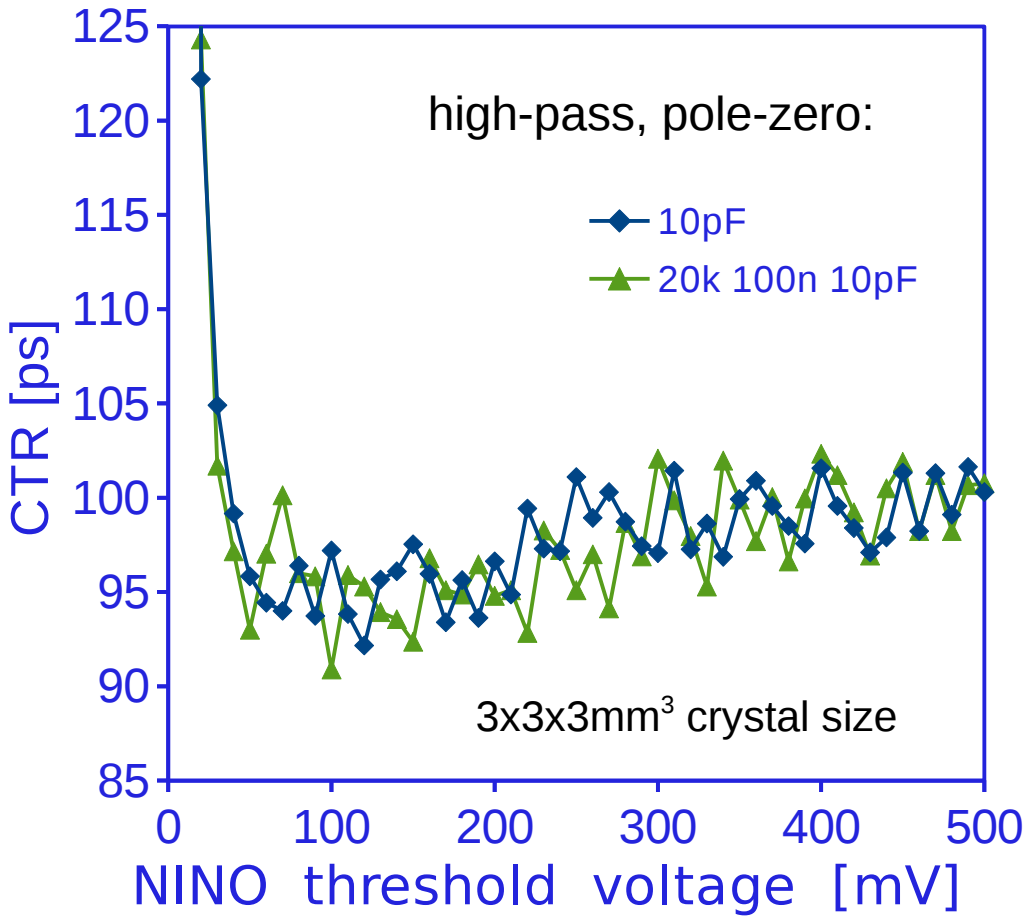


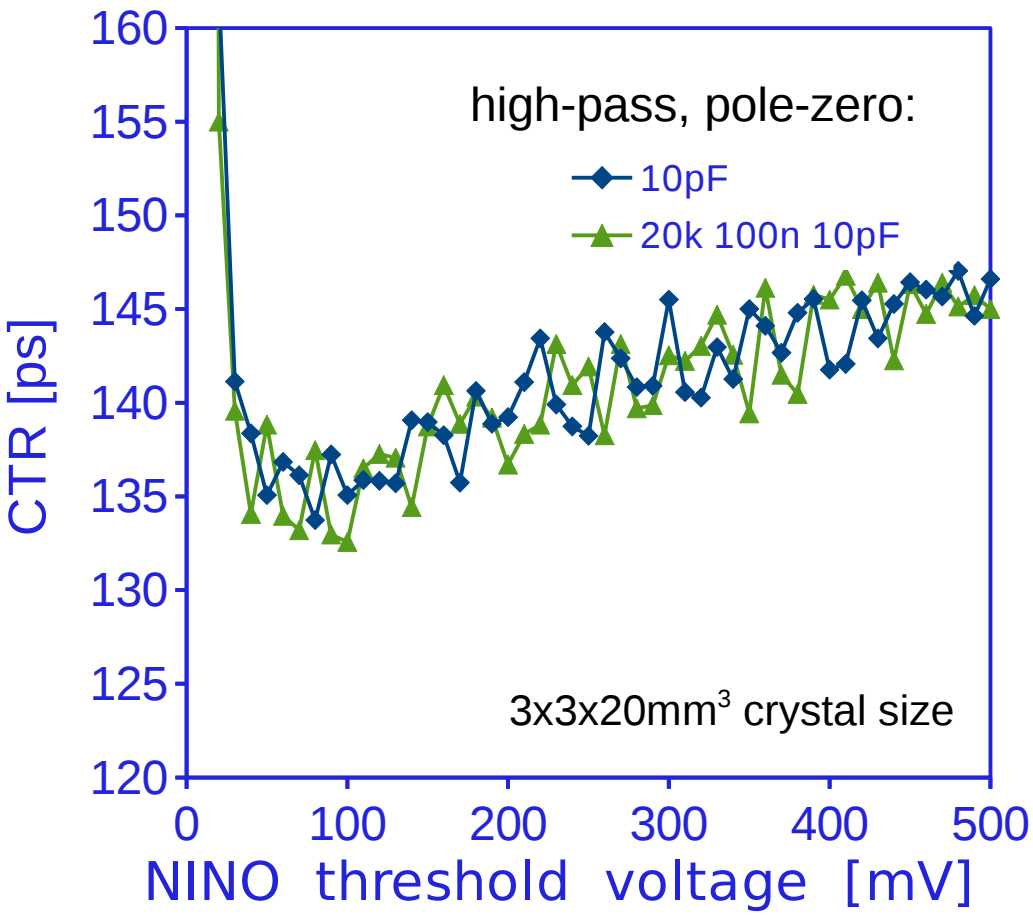


Measured at 12.5V SiPM overvoltage, T=15°C

Baseline-shift "filtering"

→ Increased crosstalk probability:
- more baseline noise and thus time pick-up jitter

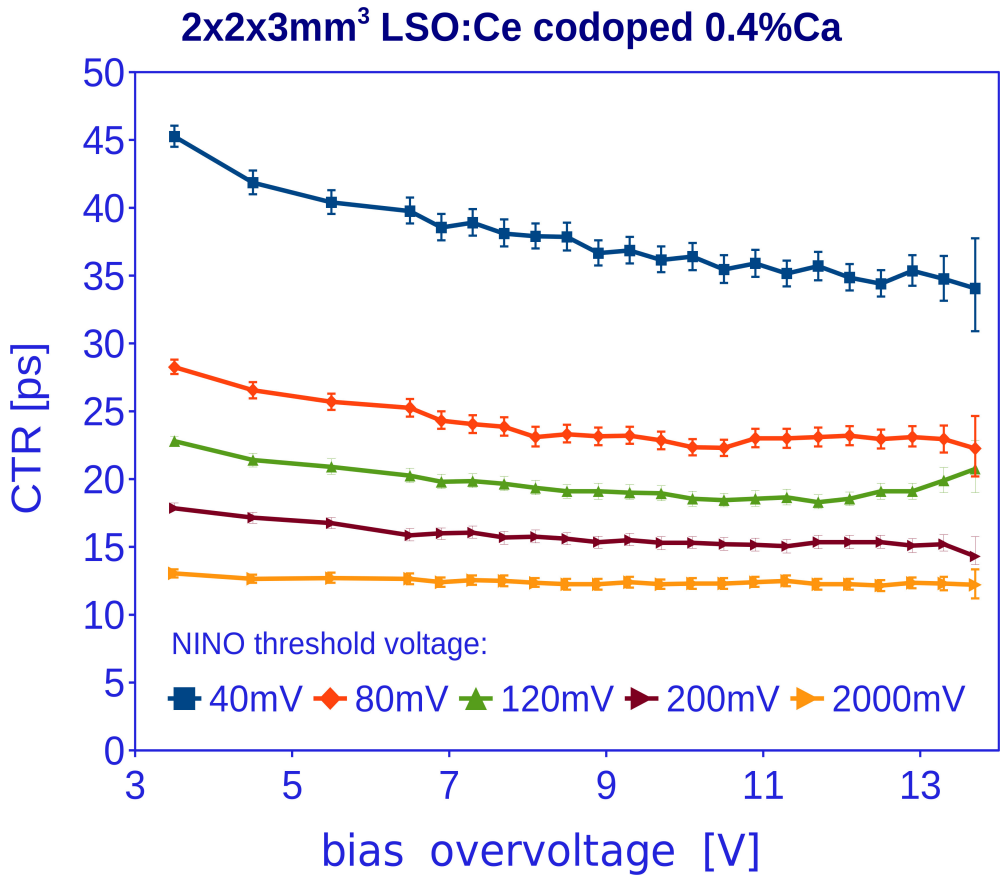


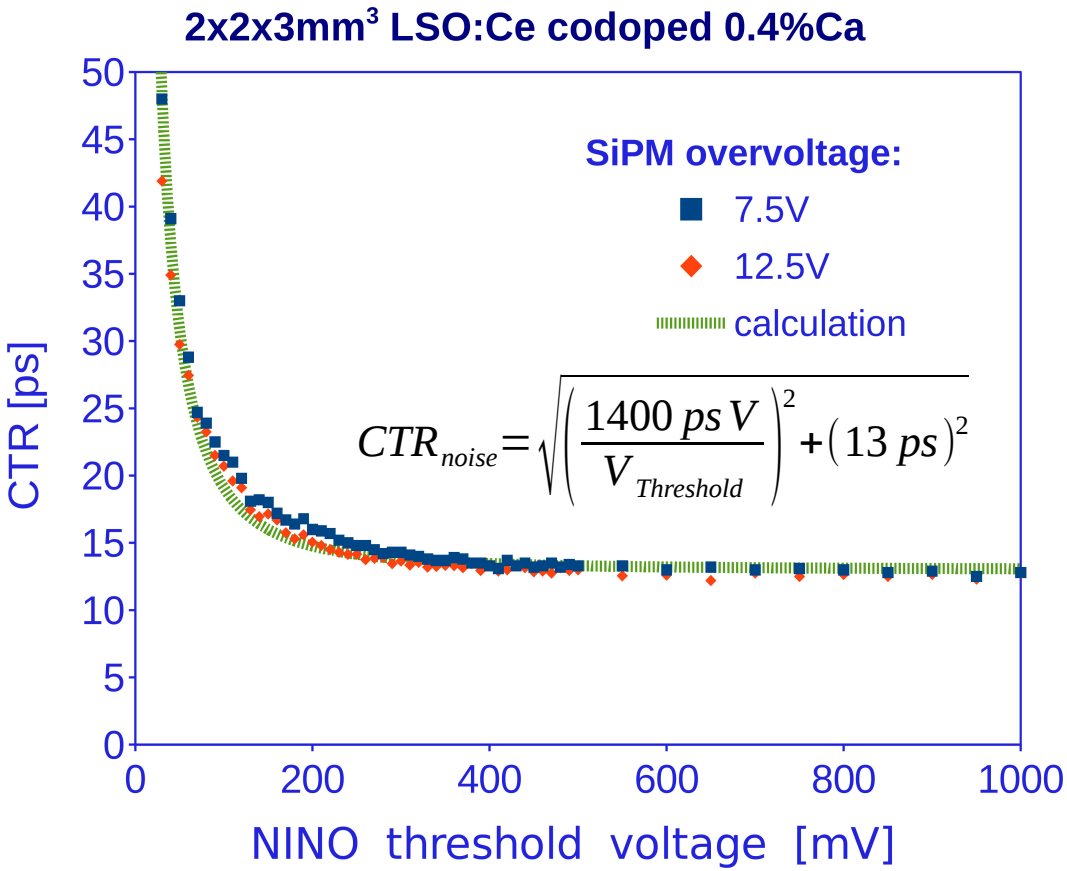


More refined filtering (pole-zero) does not improve CTR anymore (optimized already)

"Intrinsic" CTR performance of the setup

Signal from one crystal + SiPM was split into 2 NINO input channels





$$CTR_{noise} = \frac{\sigma_{noise}}{dV_{SiPM\,signal}/dt}$$

$$V_{SiPM\,signal} \propto \sum_{i=1}^{N} (t - D_i) \left(\frac{dV}{dt}\right)_{single\,cell}$$

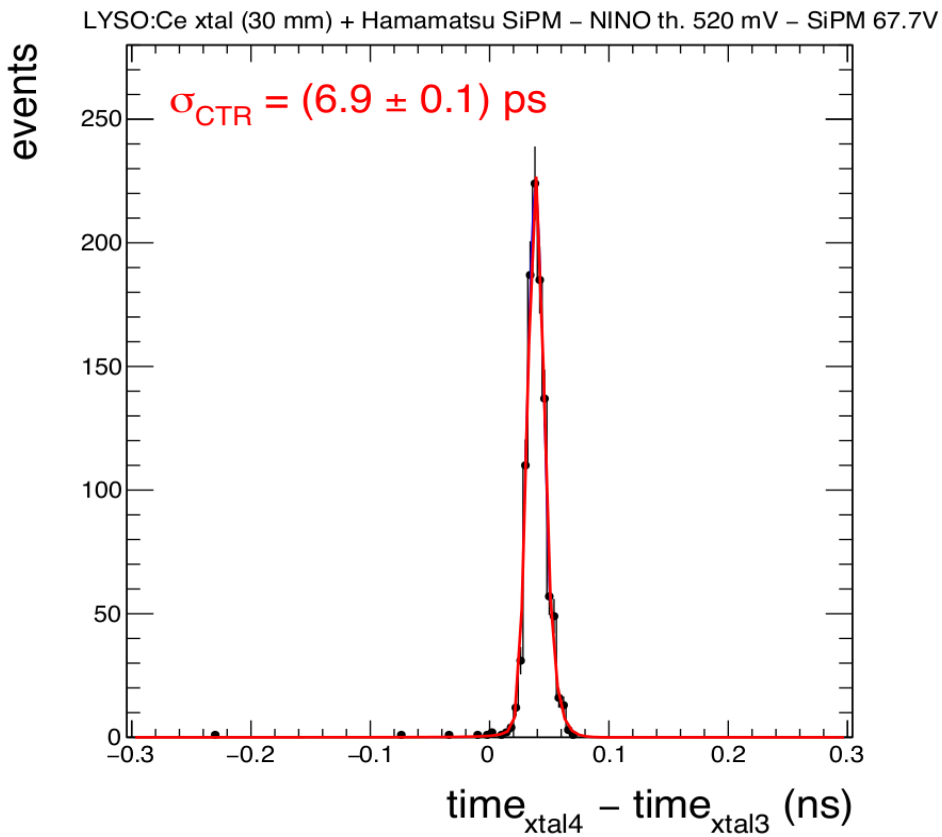
–) 13ps noise floor defined by Oscilloscope

–) dV/dt proportional to number of photoelectrons

Data acquisition: time resolution

–) Signal from one crystal + SiPM was split into 2 NINO input channels

–) Gives the time resolution of the Caen digitizer (acqusition)



Measured ~7 ps of intrinsic resolution in coincidence, sets the limit only due to data acquisition.

=> **5ps sigma of single channel**

5*3.33 = 17ps FWHM CTR, agrees with 511keV measurements in lab.

A. Benaglia et. al. “Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout”, NIMA under review