Understanding the Timing Performance of Silicon Photomultipliers in Fast Scintillation Detection

S. Seifert[1], R. Vinke[2], H.T. van Dam[1], H. Löhner [2], P. Dendooven[2], F.J. Beekman[1], D.R. Schaart[1]

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Outline

- Introduction, some recent history
- Modeling the timing performance of SiPM-based scintillation detectors
- Results
- Discussion / Conclusions

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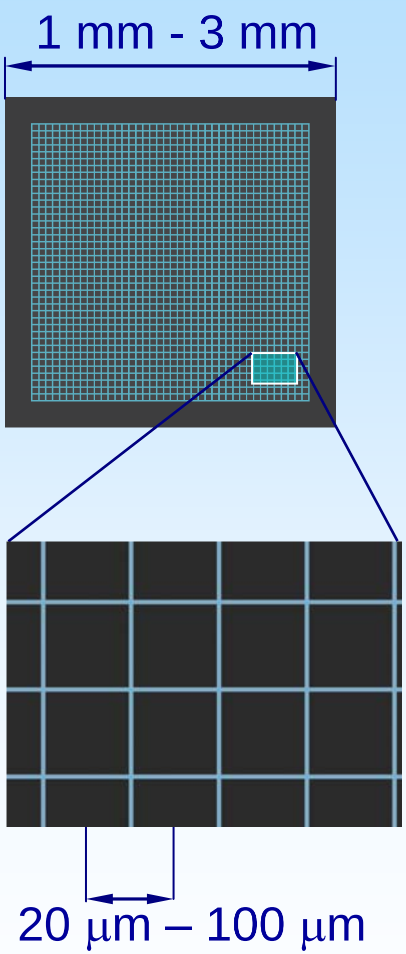
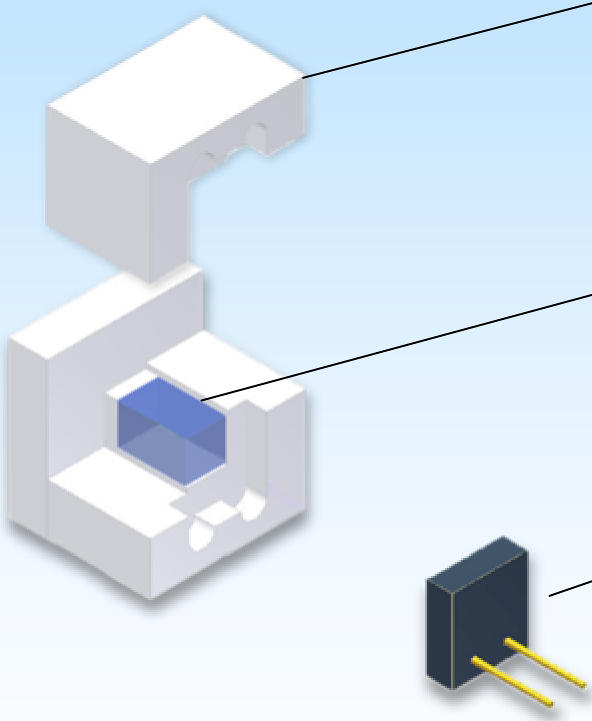
Introduction: Silicon Photomultipliers



- Array of many self quenched Geiger mode APDs (microcells) connected in parallel
- Increasingly interesting as replacement for PMTs:
  - high gain (~10^6)
  - high PDE
  - Insensitive to magnetic fields
  - compact and rugged
  - transparent to γ-photons
  - fast response (ns)

→ The ideal device for accurate timing and TOF PET?

Coincidence Timing Experiment



- Spectralon® reflective enclosure
- 3x3x5 mm^3 $LaBr_3$:Ce5% (Saint Gobain) / 3x3x5 mm^3 LYSO (Crystal Photonics)
- SiPM: Hamamatsu MPPC
  S10362-33-050c

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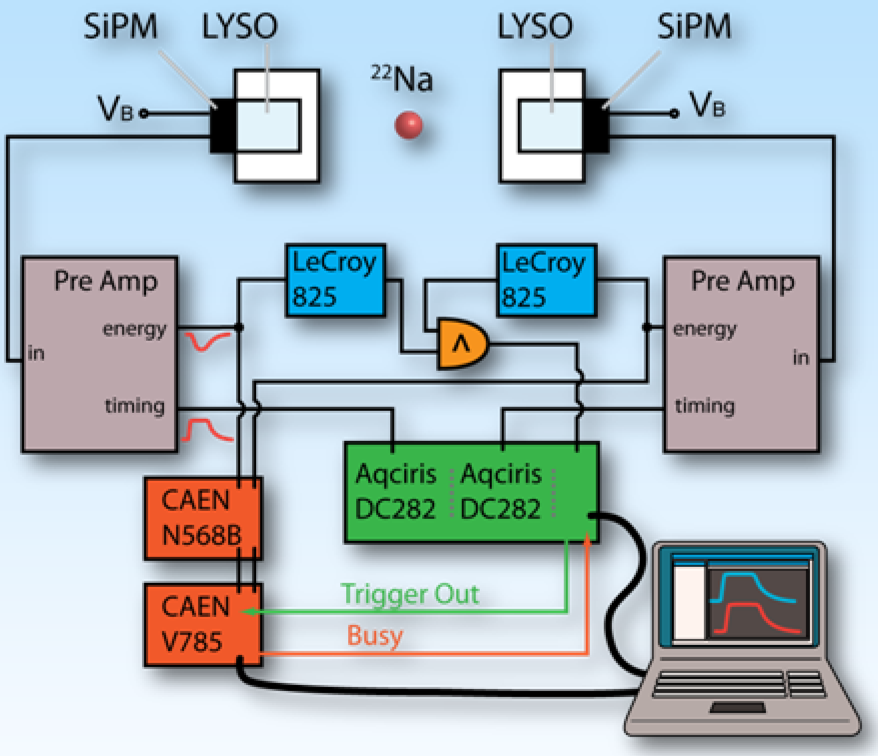
Coincidence Timing Experiment



- SiPM signals are amplified in two separate branches for energy determination and timing
- Energy signals are shaped and fed into peak sensing ADCs
- Timing signals are sampled at 8 GS/s
- In case of a valid coincidence the timing traces are stored and a gate signal is sent to the peak sensing ADCs
- Post processing of timing signals to acquire time stamps (baseline corrected leading edge trigger)

D. R Schaart, et al., Phys. Med. Biol., vol. 55, pp. 179–189, (2010)

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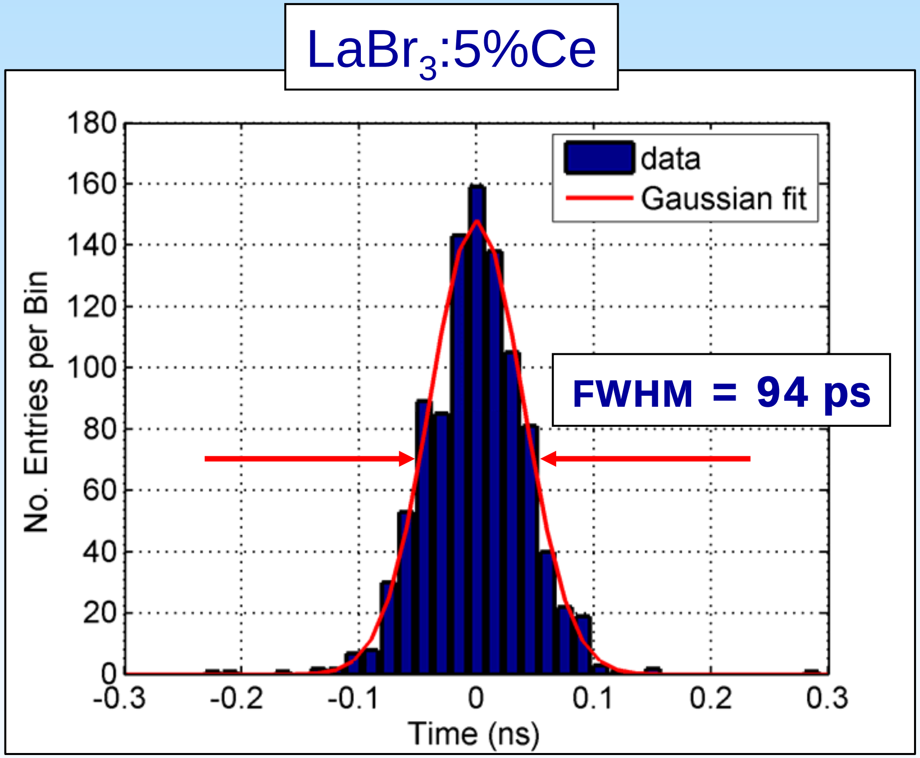
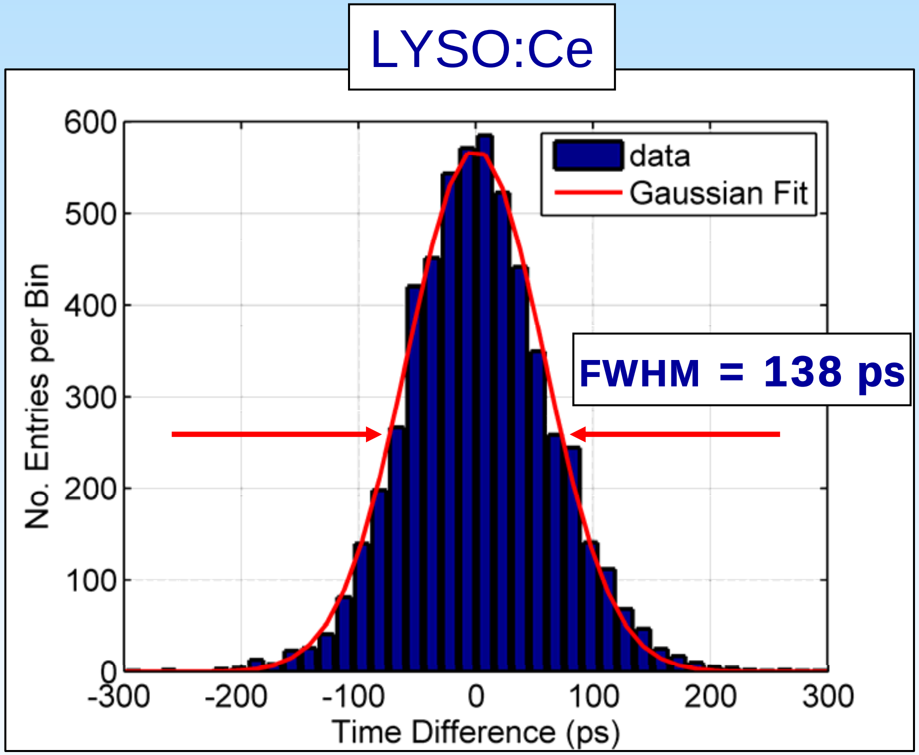
Coincidence Timing Resolution





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- What makes timing with SiPMs so good?
- What are the limiting factors? Can we improve even further?
- What is the influence of Cross Talk on the timing performance

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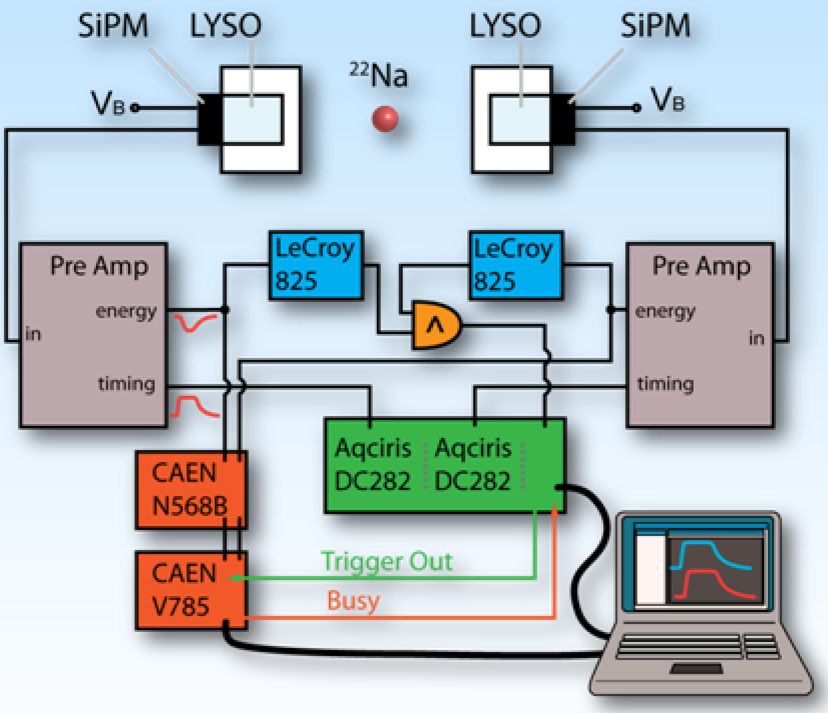
A Comprehensive Timing Model for SiPM-Based Scintillation Detectors



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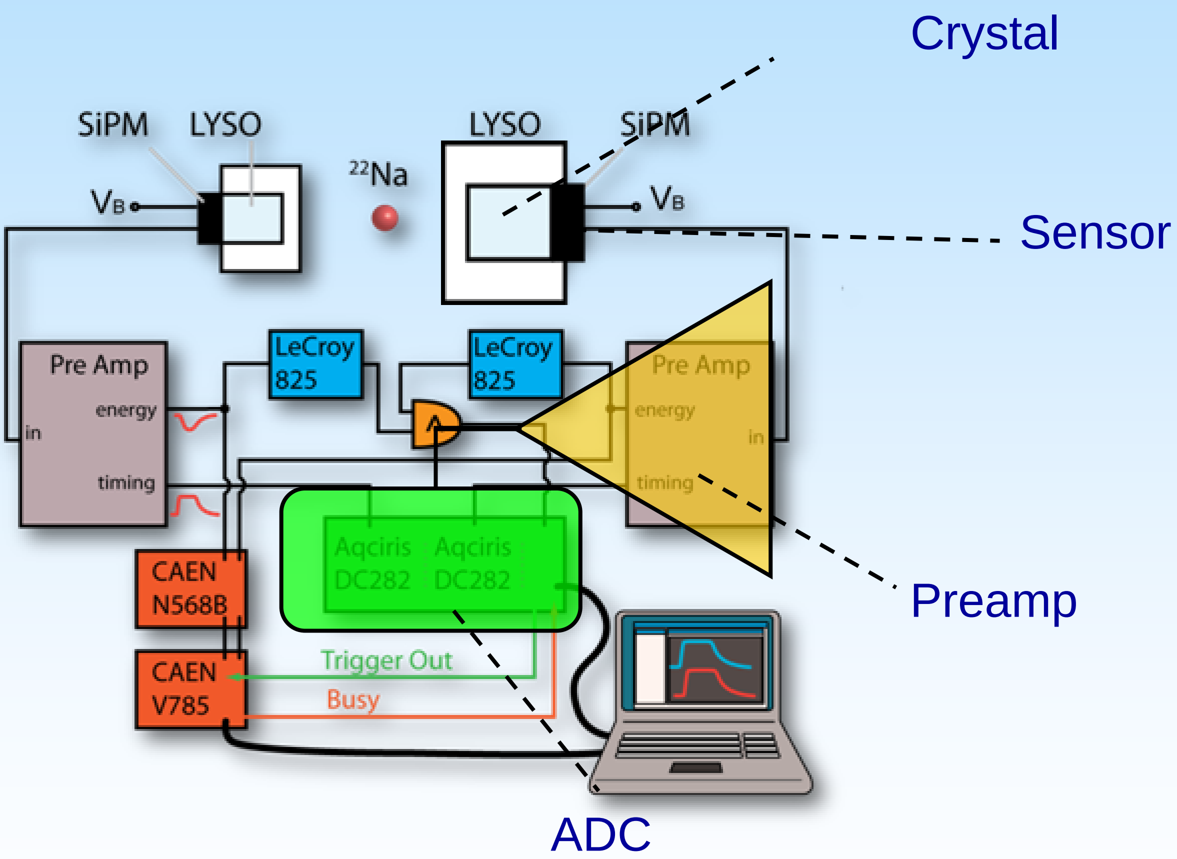

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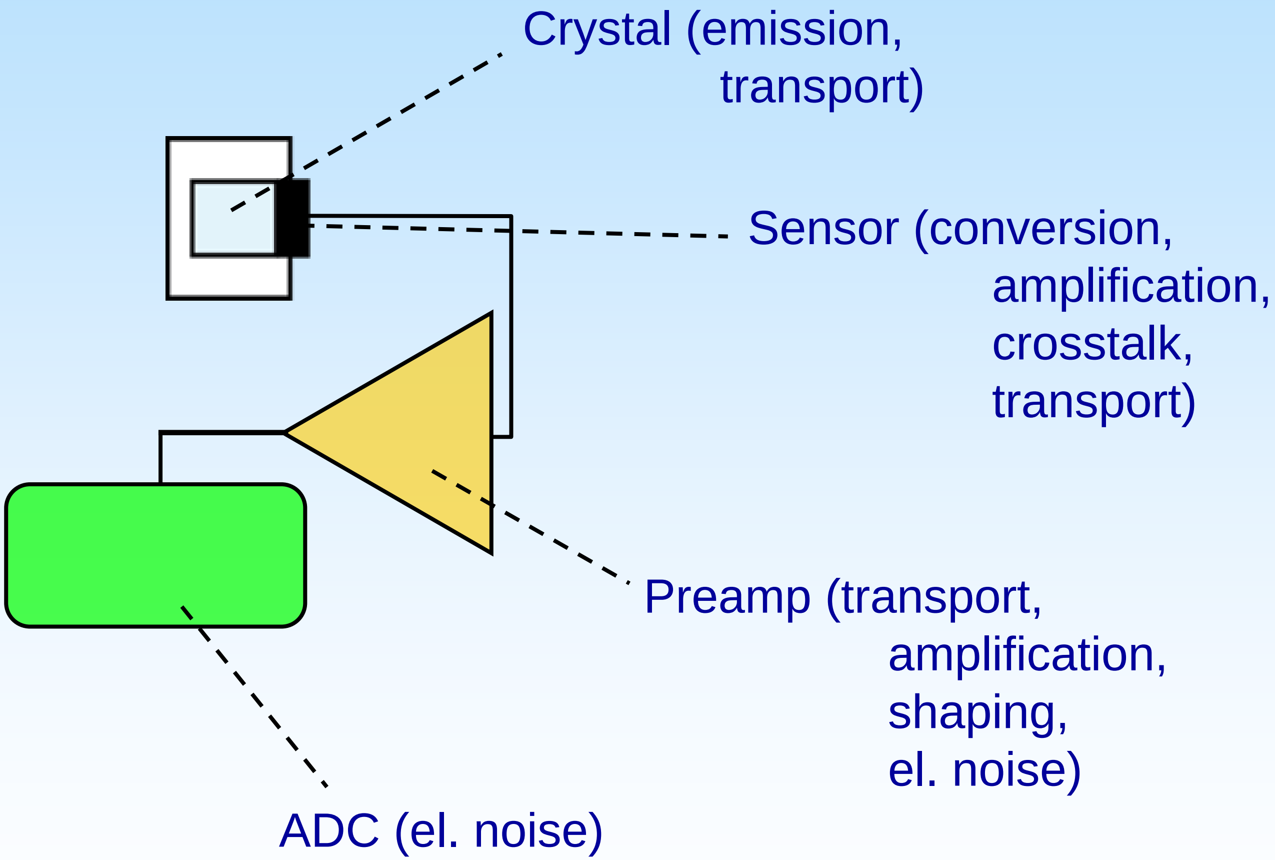
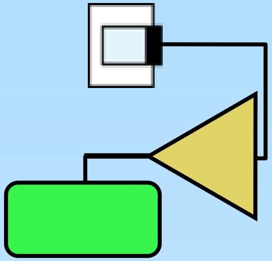
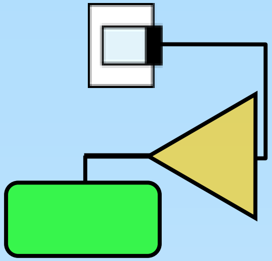


Model Assumptions



- The arrival times of the individual scintillation photons are statistically independent and identically distributed (i.i.d.);
- The corresponding primary triggers are i.i.d.
- The amplitudes of all single cell signals (SCSs) are i.i.d. & SCSs are additive;
- The temporal distributions of crosstalk events with respect to a primary trigger are i.i.d..

Model Assumptions



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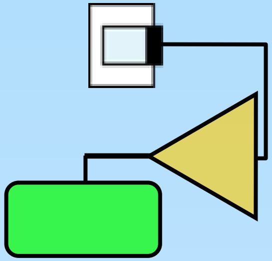
- Emission
- Transport
- Conversion
- Amplification
- Crosstalk
- Transport
- Transport
- Amplification
- Shaping
- El. noise
- El. noise

Model Assumptions



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⇒ SiPM-Scintillation-Signal as a linear combination of Single Photon Signals

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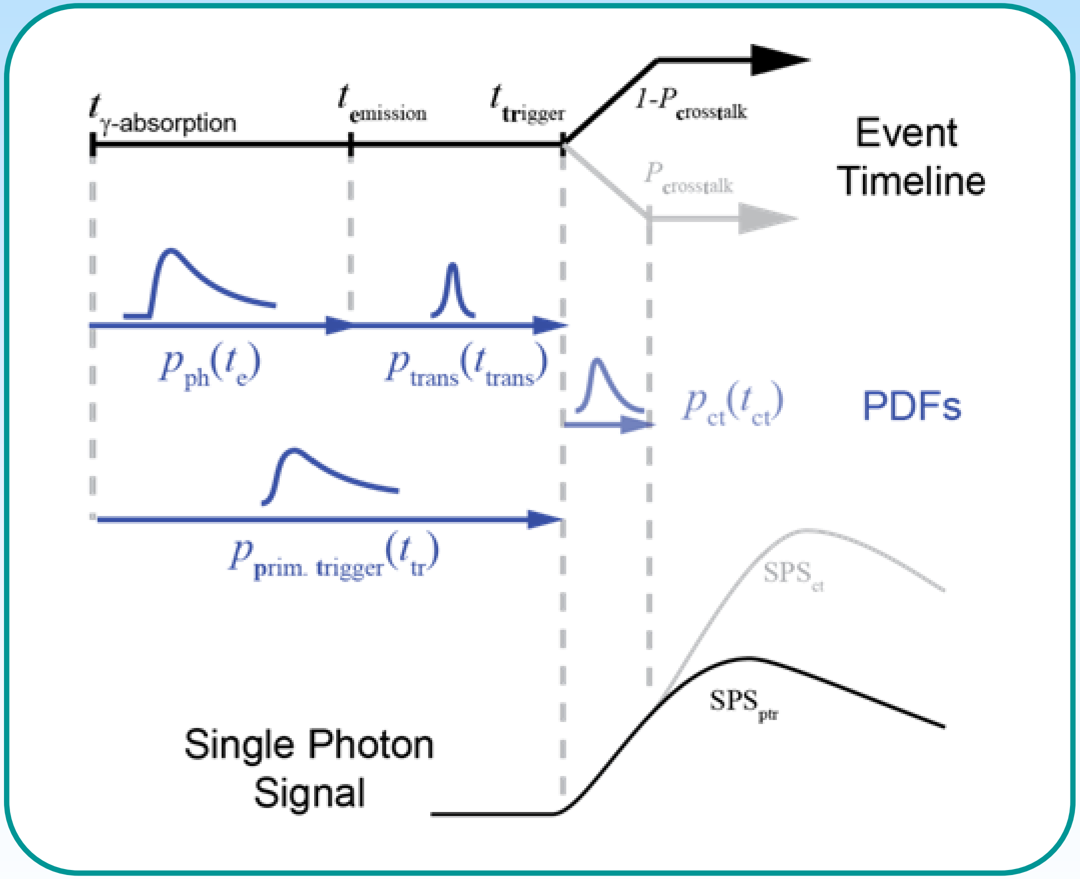
Single Photon Signal



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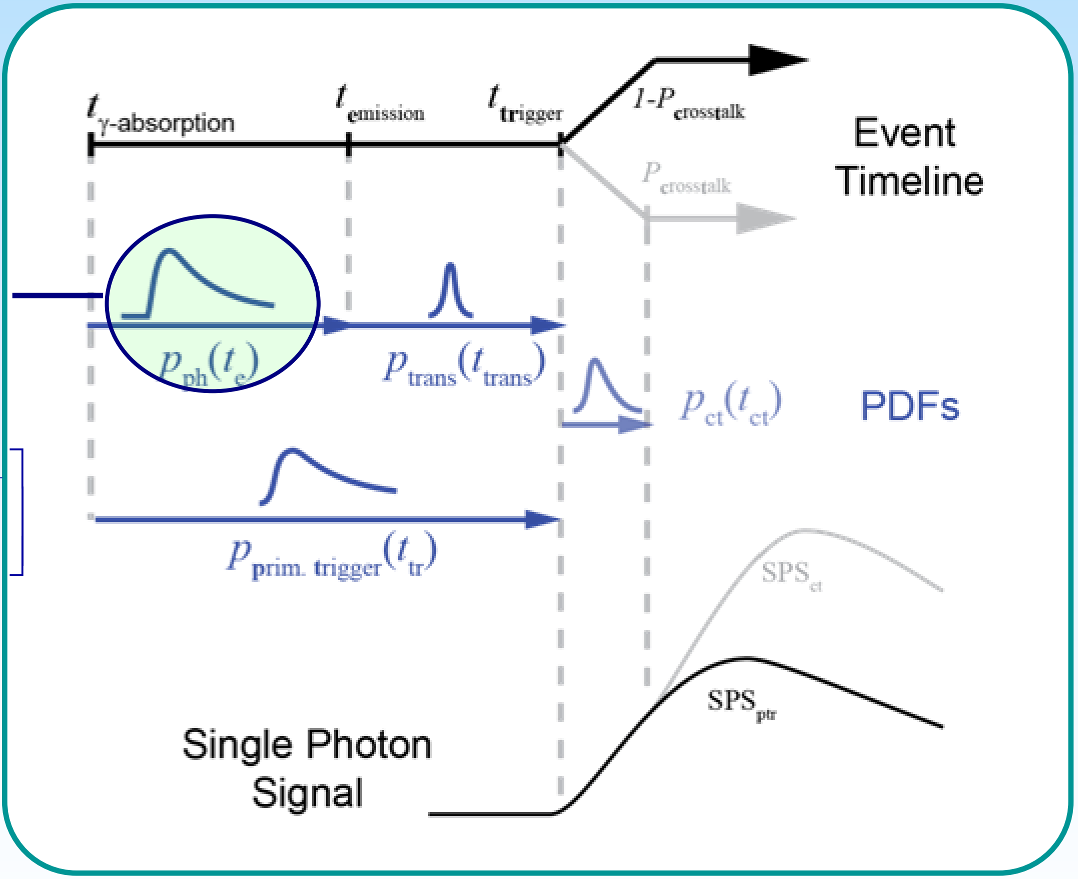
Single Photon Signal

Emission probability distribution

Linear combination of exponentials:

$$\sum_i P_{ec,i} \frac{1}{(\tau_{d,i} - \tau_{r,i})} \left[e^{-\frac{t_{em}}{\tau_{d,i}}} - e^{-\frac{t_{em}}{\tau_{r,i}}} \right]$$



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Single Photon Signal

Emission probability distribution

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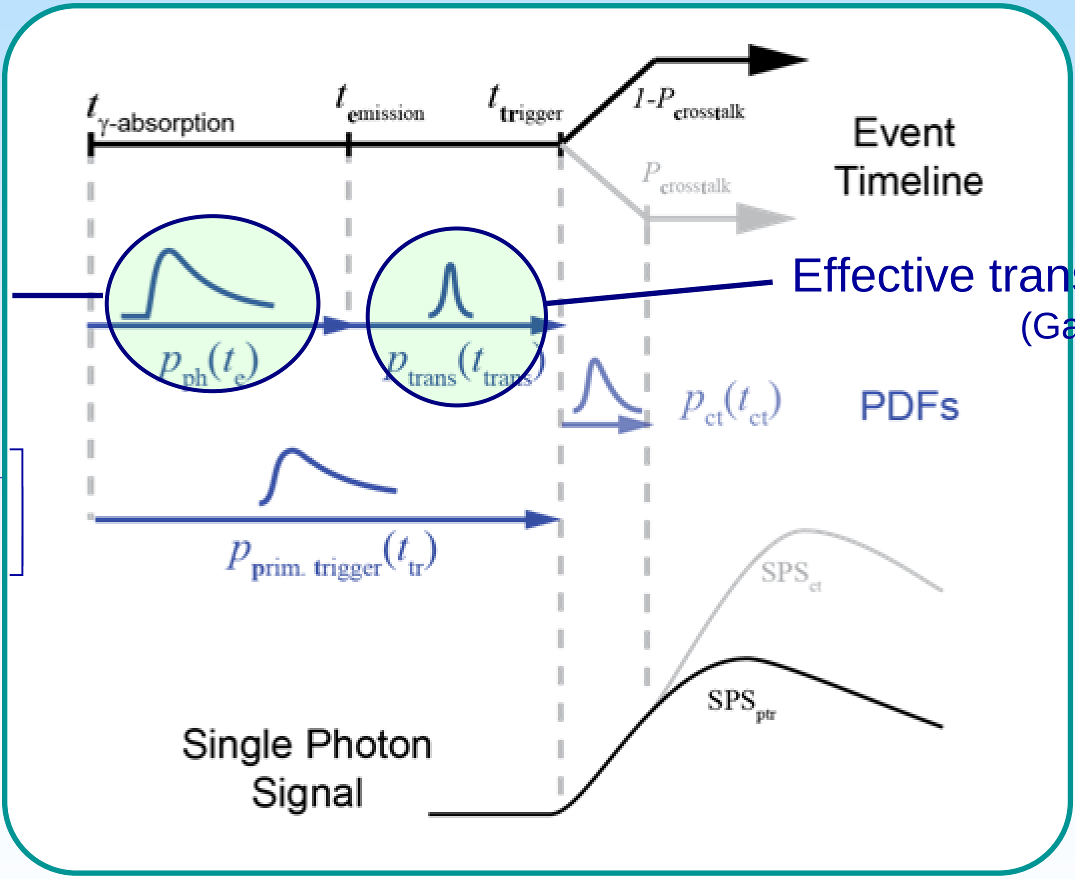
Effective transit time spread (Gaussian Distribution)



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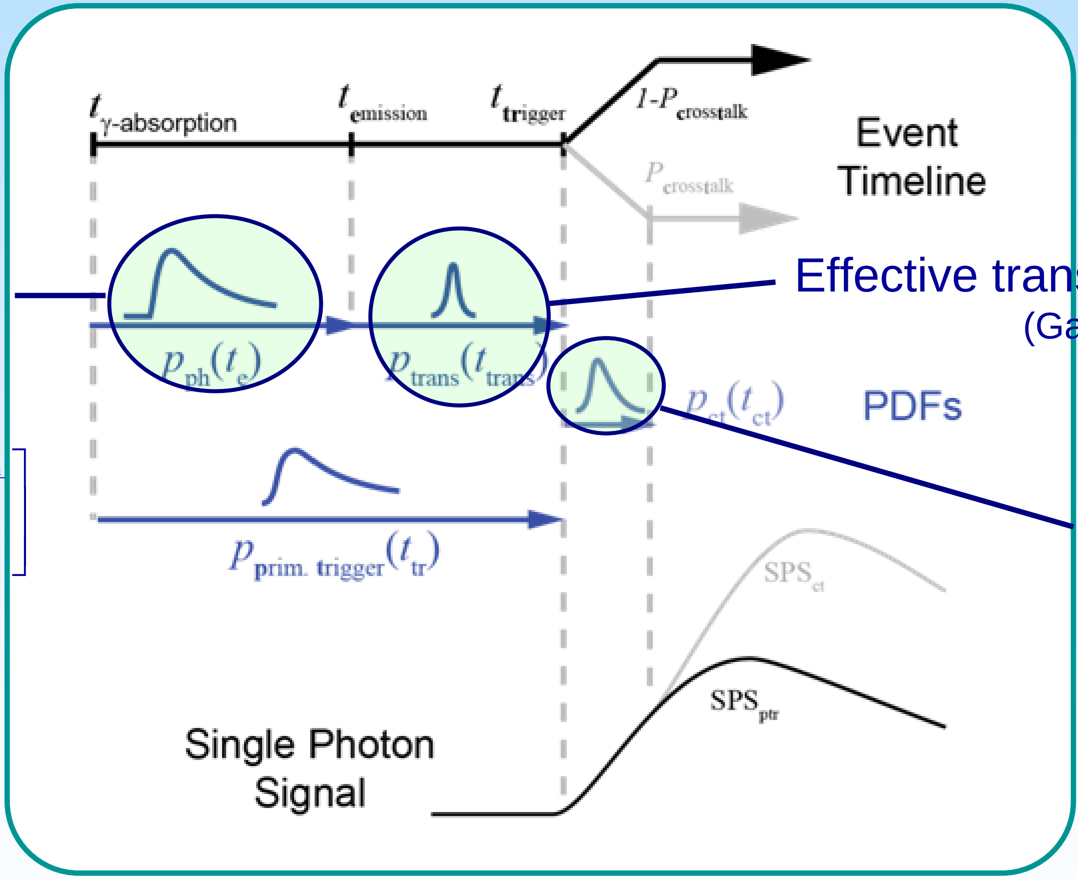
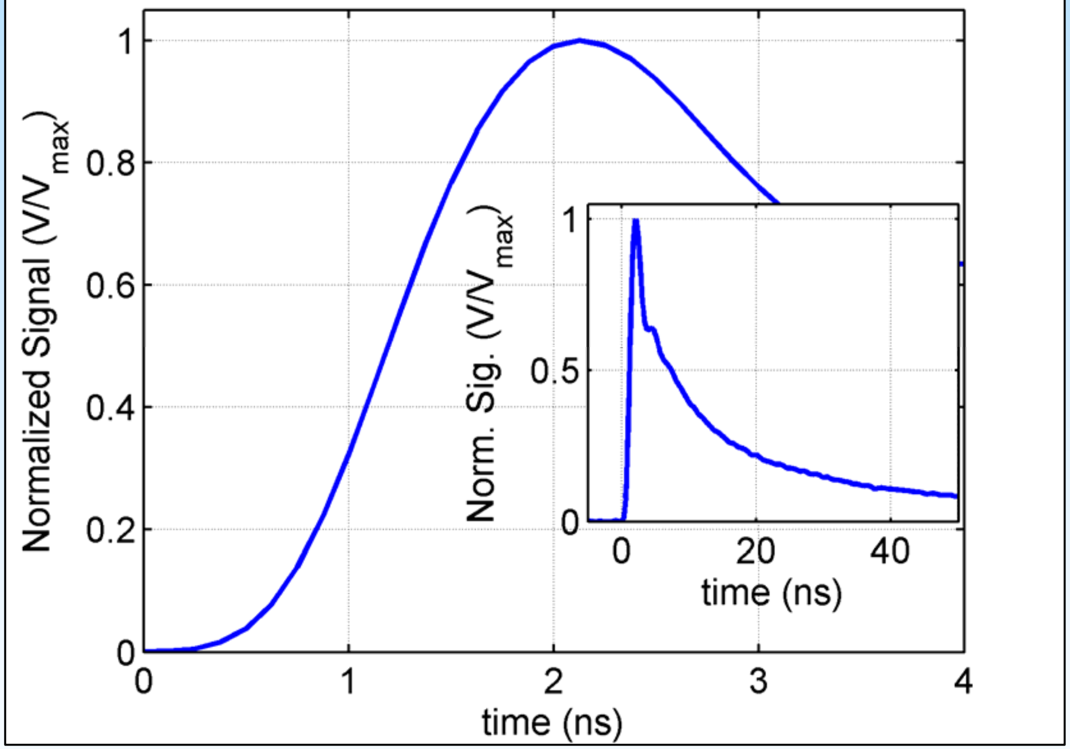


Effective transit time spread
(Gaussian Distribution)

Cross talk distribution
(exponential decay)

Single Photon Signal

Measured average MPPC-single cell signal



Visit: **J. Huizenga, et al., "A fast preamplifier concept for SiPM based time-of-flight PET detectors", poster session IV (Friday)** for amplifier details

Single Photon Signal pdf

↓

Calculate single photon signal expectation value and variance

↓

Calculate summed signal expectation value and variance (incl. Spread in the total number of photons)

↓

Add electronic noise and estimate timing error:

$$\Delta t \approx \frac{\sqrt{\mathrm{var}(V_{sum}) + \sigma_{el}^2}}{\frac{d}{dt}E(V_{sum})}$$

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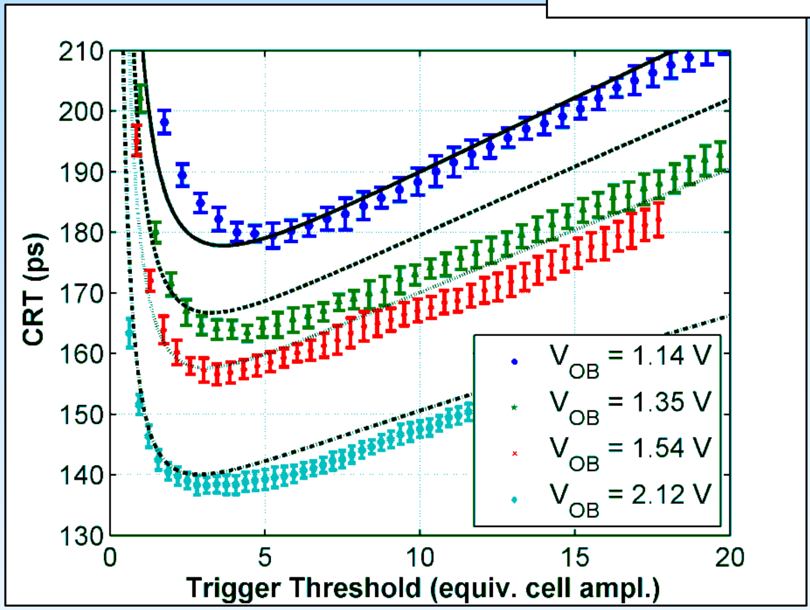
Model input parameters

	V_{ob} (V)	$N_{pt,\,tot}$	a (mV)	σ_a / a	P_{ct}	R_d	C_{tot} (fF)	σ_{el} (mV)	σ_{trans} (ps)
LYSO:Ce	1.14	3300	1.31 ± 0.07	0.12	0.10 ± 0.01	1 kΩ	90	0.31 ± 0.04	139 *
	1.35	3600	1.55 ± 0.06	0.12	0.12 ± 0.01	1 kΩ	90	0.31 ± 0.04	131 *
	1.54	3900	1.77 ± 0.06	0.12	0.14 ± 0.01	1 kΩ	90	0.32 ± 0.04	124 *
	2.12	4700	2.44 ± 0.09	0.12	0.24 ± 0.02	1 kΩ	90	0.36 ± 0.04	120 *
$LaBr_3$:Ce	1.22	5000	1.59 ± 0.07	0.12	0.11 ± 0.01	1 kΩ	90	0.30 ± 0.04	132 *
	1.37	5400	1.78 ± 0.07	0.12	0.14 ± 0.01	1 kΩ	90	0.31 ± 0.04	127 *
	1.54	5700	2.00 ± 0.06	0.12	0.15 ± 0.01	1 kΩ	90	0.30 ± 0.04	124 *
	2.06	6800	2.69 ± 0.09	0.12	0.23 ± 0.02	1 kΩ	90	0.40 ± 0.04	120 *

* 1 mm x 1mm MPPC - Ronzhin, et. al "Tests of timing properties of silicon photomultipliers", *Nucl. Instr. and Meth. A*, vol. 616, pp. 38–44, 2010

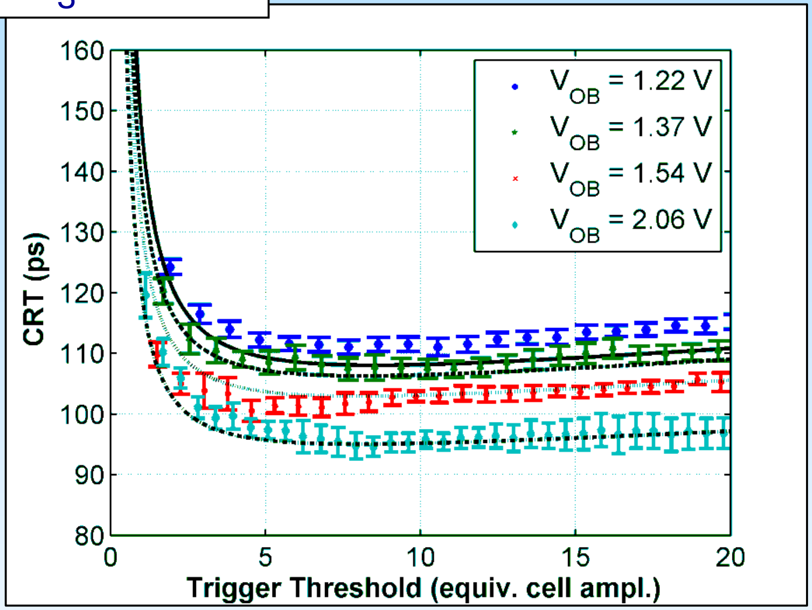
Results: Comparison to Measurements

LYSO:Ce



V_{ob} (V)	PDE	P_{ct}	σ_{trans} (ps)	$\tau_{r,i}$ / $P_{ec,i}$ (ns)	τ_d (ns)
1.14	0.25	0.10	139 *		
↓	↓	↓	↓	0.09	43.8
2.12	0.35	0.24	120 *		

$LaBr_3$:5%Ce



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1.22	0.14	0.11	132 *		
↓	↓	↓	↓	0.37 / 0.8 2.2 / 0.2	15
2.06	0.17	0.23	120 *		

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Results: Model Implications

- Cross talk contribution is small (~5%)
- Contribution of the variance on total number of detected photons (i.e. energy resolution) ~ 2% (due to low threshold values)
- electronic noise contributes little to timing uncertainty (2 % in the case of $LaBr_3$:5%Ce and up to 8% for LYSO:Ce)
- Amplifier bandwidth seems to have little influence (10% worsening of the LYSO timing resolution by reducing the signal bandwidth to 200 MHz by adding an additional low pass filter)

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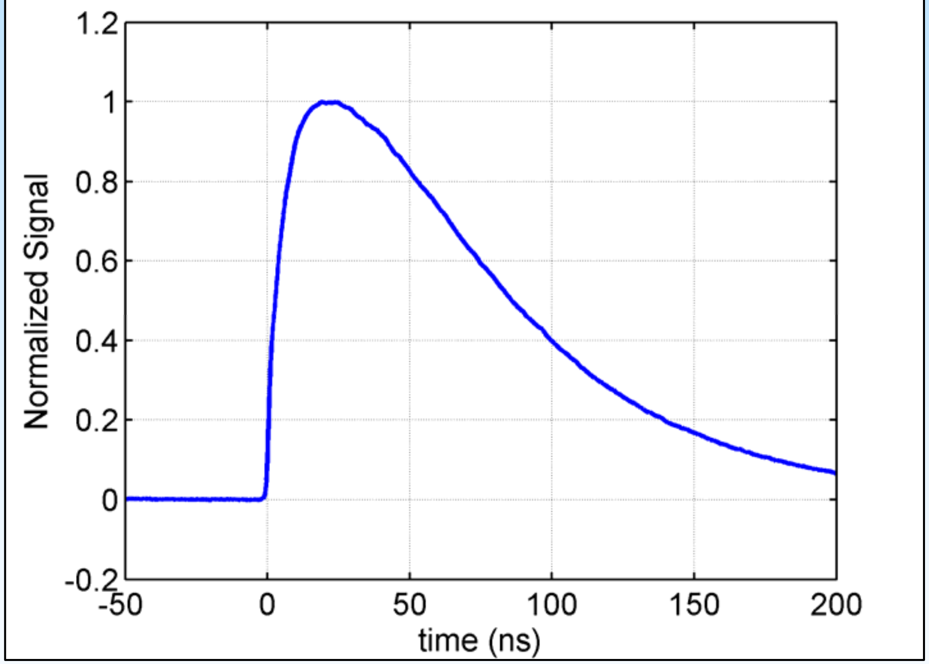
Measured average MPPC-LYSO:Ce scintillation pulse



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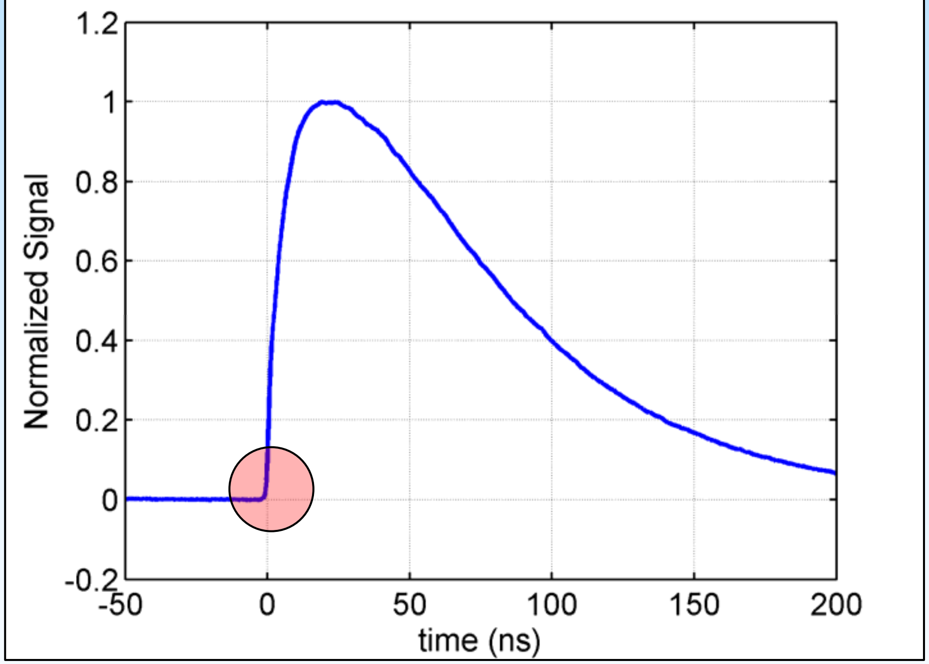

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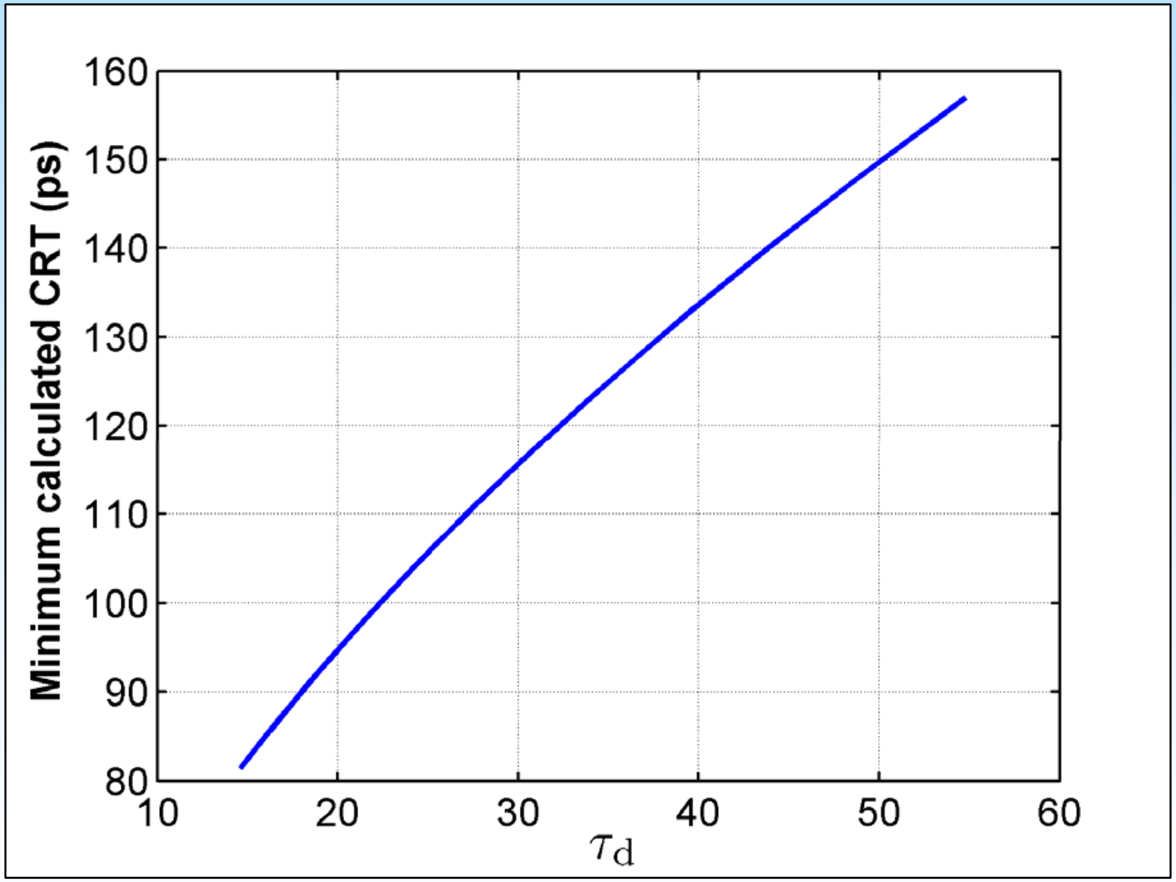
➡ The by far largest contribution arises from primary trigger statistics (photon arrival + TTS)

Results: Model Implications

- All parameters as in MPPC-LYSO:Ce detector at optimum bias voltage



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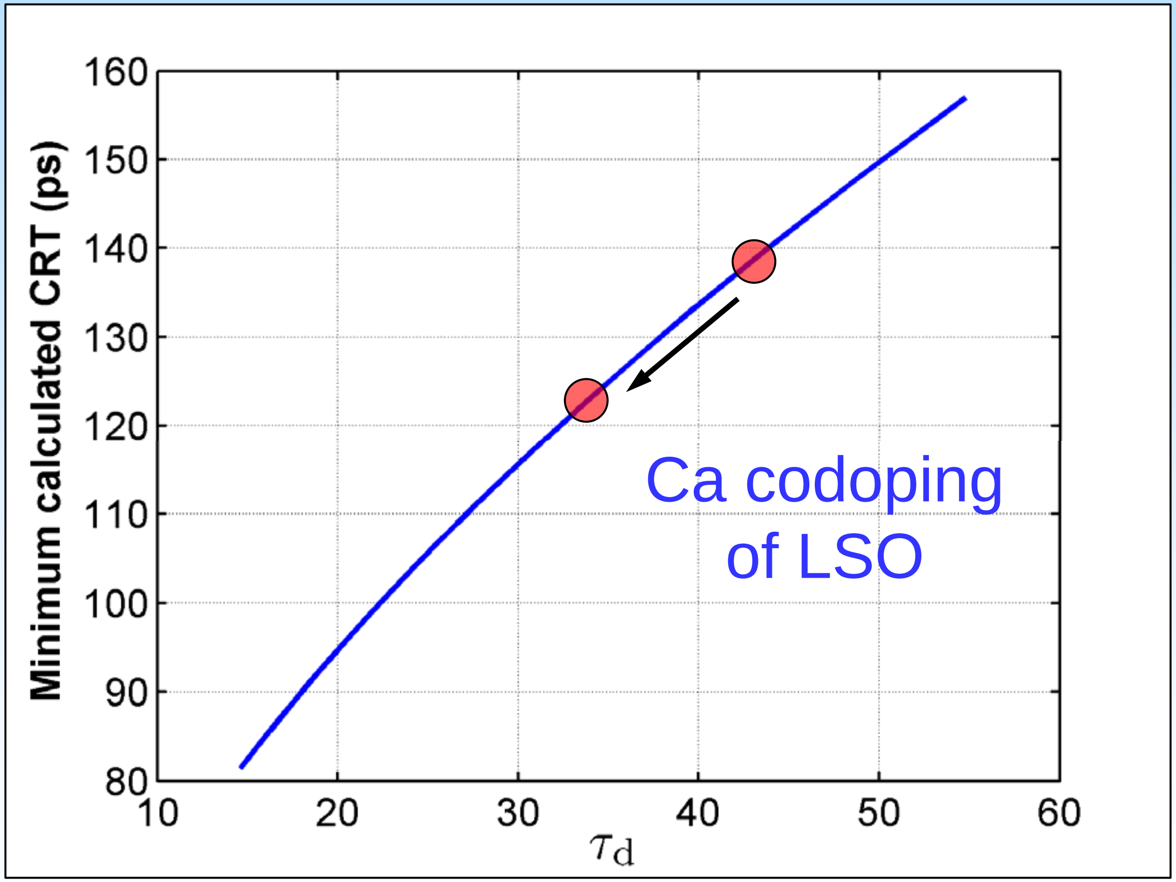
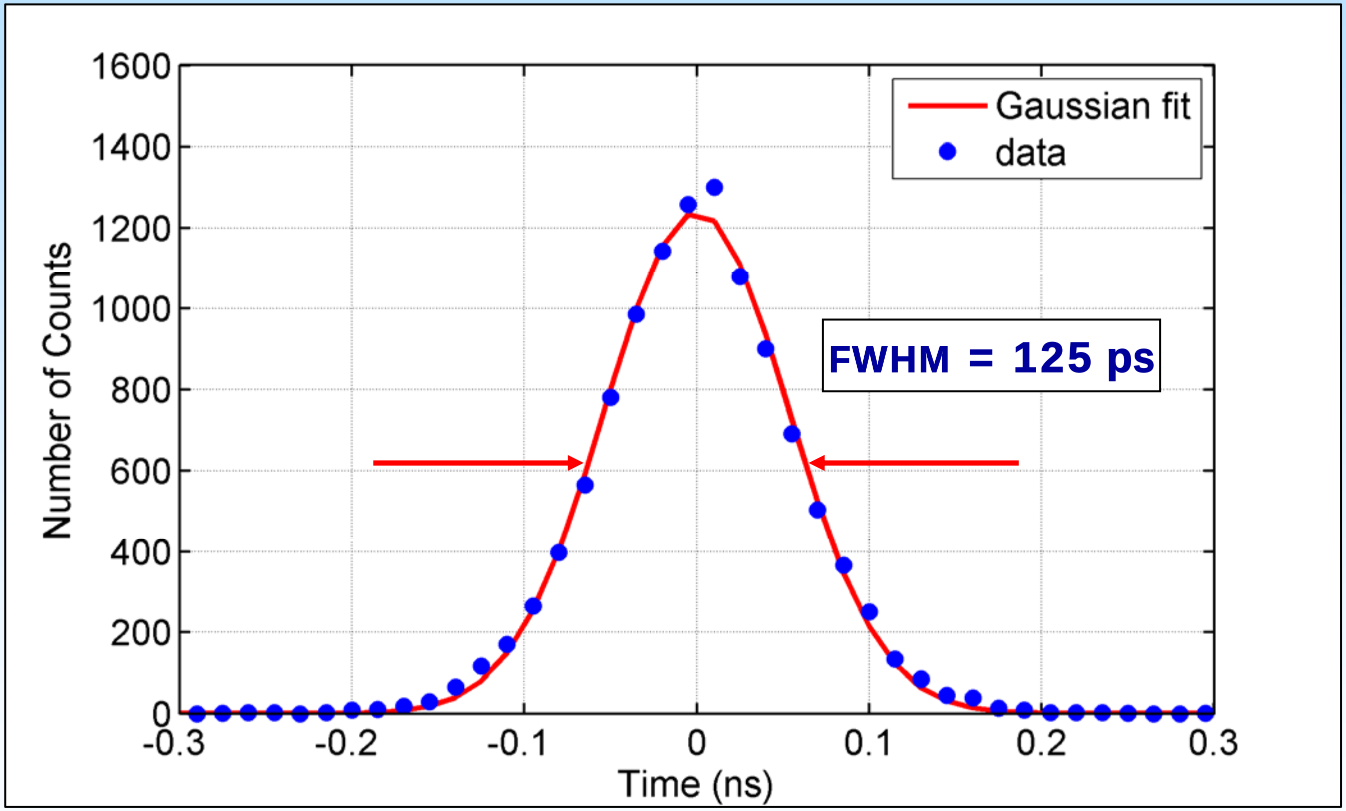


Recent Measurements with LSO:Ce,0.2 % Ca



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Summary

- Cross talk contribution to timing resolution is small
- Contribution of the variance on total number of detected photons (i.e. Energy resolution) ~ 2% (due to low threshold values)
- Optimum (Leading edge) trigger threshold depends on scintillator, transit effective time spread (thus crystal size), PDE, and SiPM electronic response
- Optimum trigger threshold in general at very low values
  - Fast rising edge of the SiPM electronic response is the key to accurate timing.

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Backup

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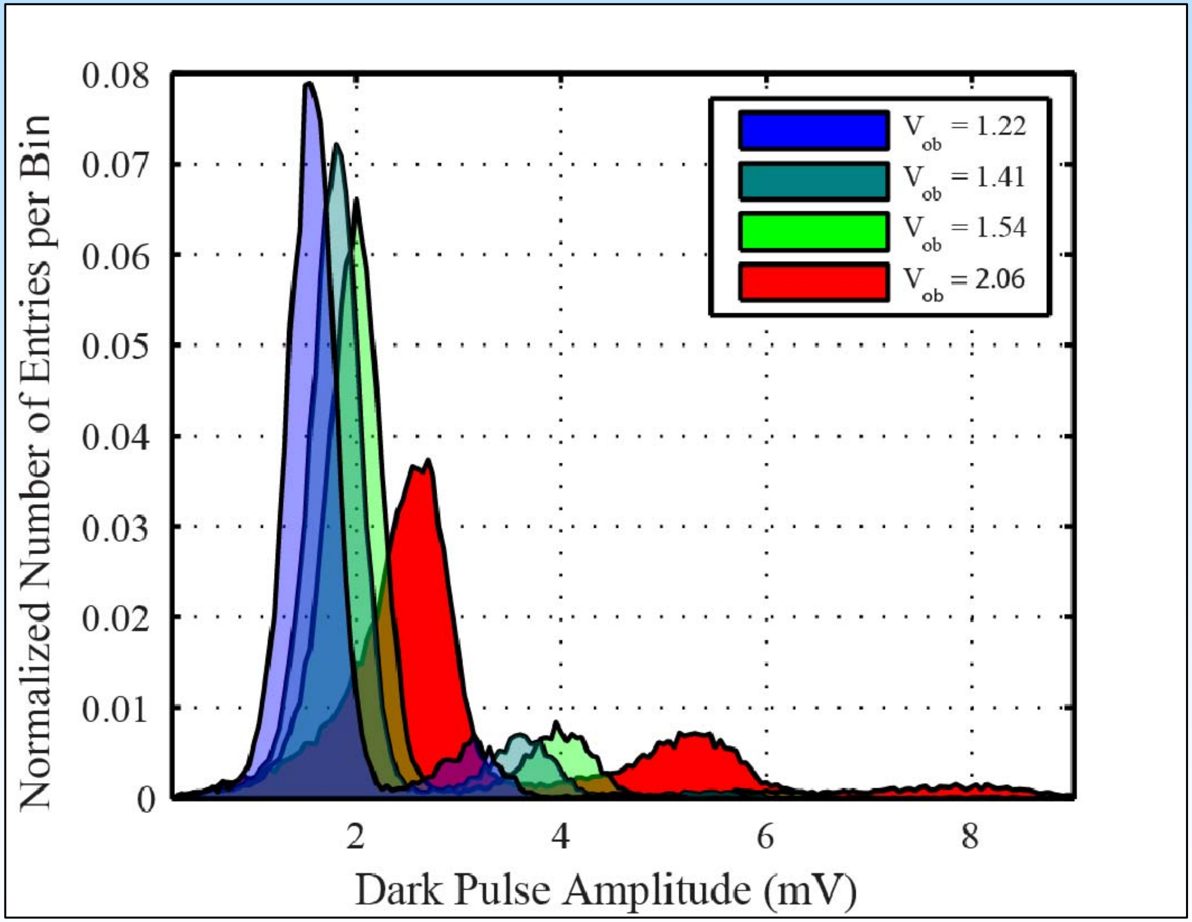
Dark Pulse Amplitude Histogram



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Scintillator Parameters

	$\tau_{r,i}$ / $P_{ec,i}$ (ns)	τ_d (ns)	R_{int} (FWHM at 511keV)
LYSO	0.09 / 1	43.8 ± 0.8	9.0 % *
$LaBr_3$:5%Ce	0.37 / 0.8 2.2 / 0.2	15	3.5 % *

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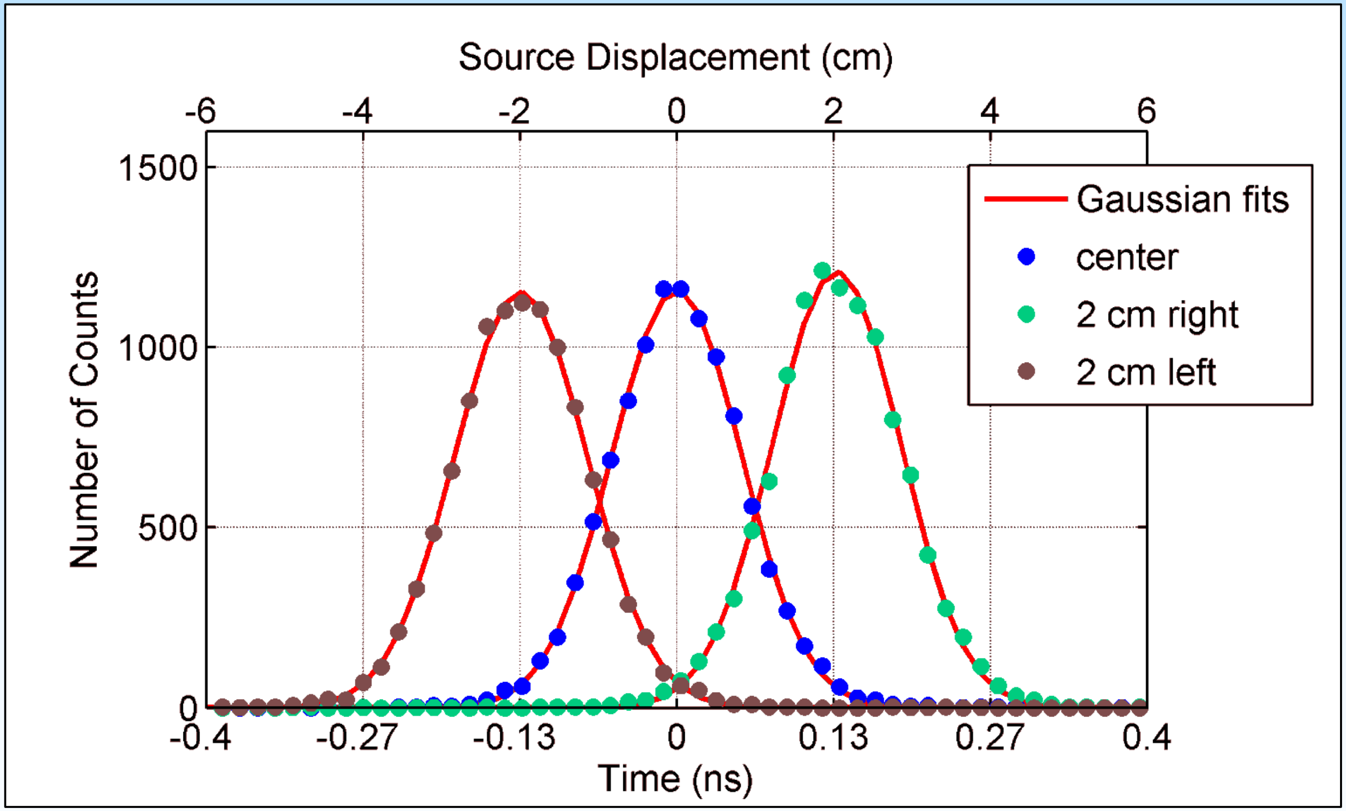

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