



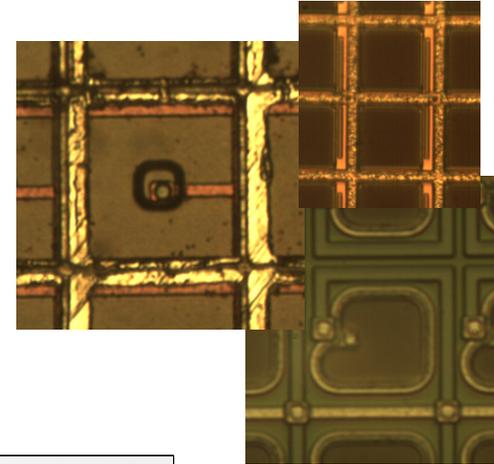
Analysis of the Response of Silicon Photomultipliers to Optical Light Fields

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Outline

- Main Features of SiPMs
- Characterization Protocol
- Experimental Setup
- Theoretical Model
 - Detection
 - Dark Count Rate
 - Optical Cross-Talk
- Data Analysis
 - Self-Consistent
 - Multi-fit
- Applications to Fluorescence Fluctuation Spectroscopy
- Conclusions



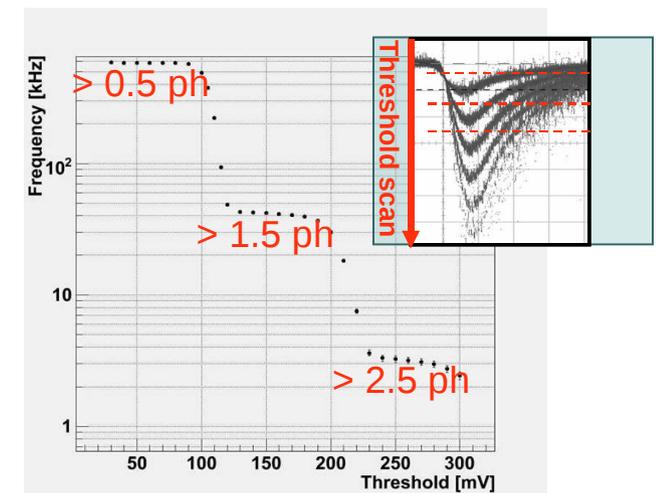
SiPMs: Main Features

Array of parallel diodes
Common output
Avalanche Mode

High Gain
High Photon number resolution
High speed ($T_{\text{fall}} \sim 50 \text{ ns}$)
Low dead time

Producer	Area (mm ²)	Pixel size (μm)	No. cells	V _{working}	DCR	GAIN	PDE (%) (peak λ)
SensL	3 x 3	20 x 20	8640	30	~4 MHz	10 ⁶	10
Hamamatsu	1 x 1	100 x 100	100	77	~0.4 MHz	2 x 10 ⁶	65
CPTA	1 x 1	30 x 30	500	24	~3 MHz	10 ⁶	30

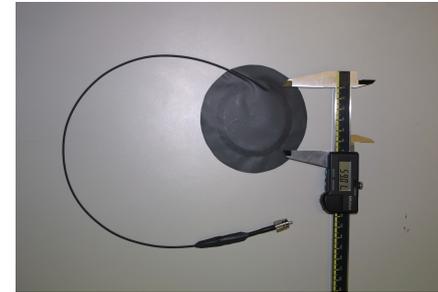
High Dark Count Rate (DCR): 100 kHz – 5 MHz
High optical cross-talk (X_T): up to 40%



Some Application in RAPSODI

Real time dosimetry in mammography

Sensitivity
High dynamic range



Illicit radioactive material detector

Low flux sensitivity
Stability vs Environmental Condition variations



Radon detector

Close to Zero Dark Count
Stability vs Environmental Condition variations



Need for Characterization

Within RAPSODI

I-V measurements (leakage current, quenching resistor, breakdown voltage)

Noise measurements (vs over voltage and vs temperature):

dark counting rate (DCR) vs bias voltage

optical cross-talk (DCR vs threshold)

linearity & dynamic range

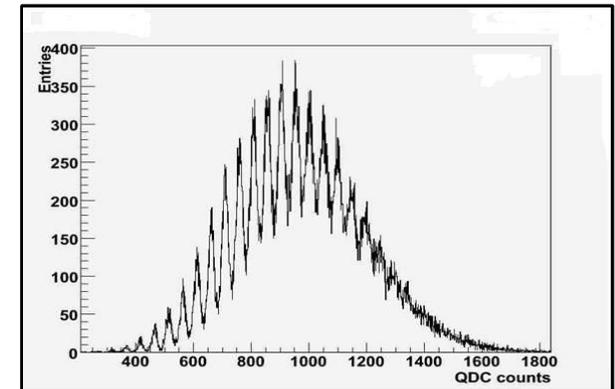
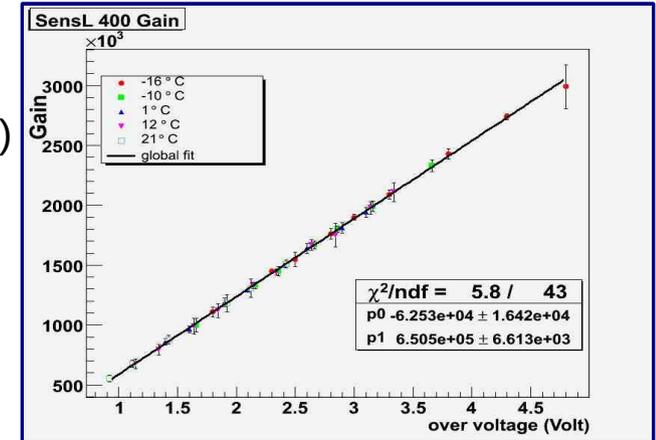
Spectral response (PDE vs λ , PDE vs temperature)

Analysis of (Poissonian photon) **spectrum** (vs temperature)

resolution power (how many photons can I distinguish?) & gain

working point optimization (at low and large flux)

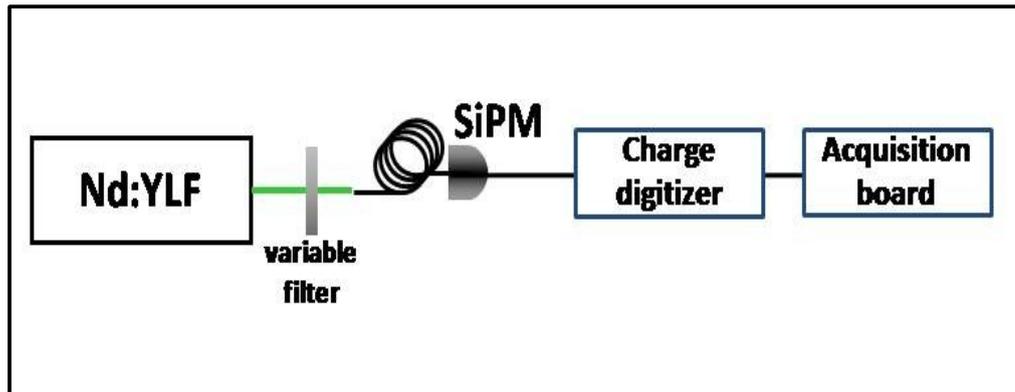
optical cross-talk (deviations from the Poissonian distribution)



M. Bondani, A. Allevi, A. Agliati, A. Andreoni "Self-consistent characterization of light statistics", J. Mod. Opt. 56, 226-231 (2009)

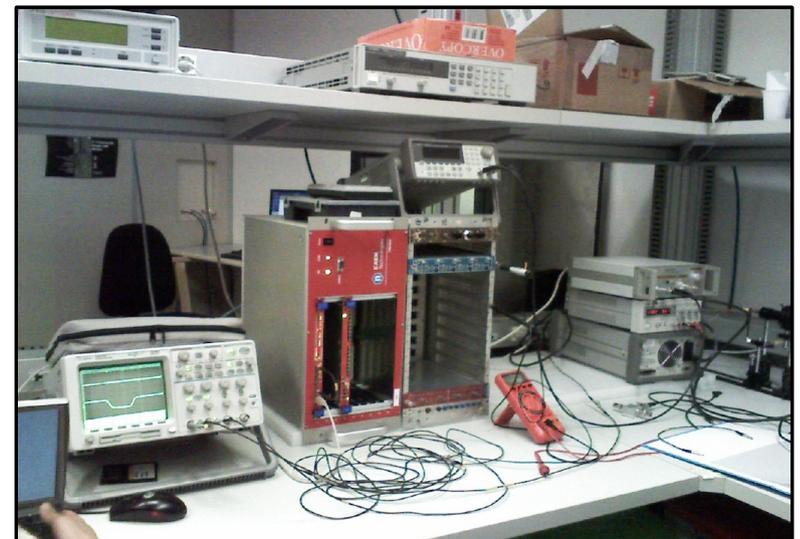
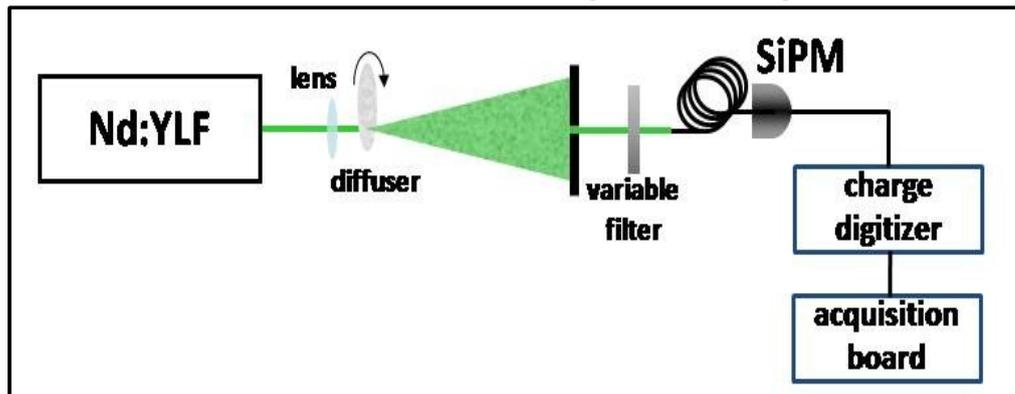
Experimental Setup

Poissonian Light Setup



Nd:YLF mode-locked laser amplified at 500 Hz - pulse duration 5.4 ps second-harmonics (523 nm)
Hamamatsu MPPC S10362 11 100C
General Purpose Amplifier (GPA)
USB-VME Bridge CAEN
V171816ch QDC CAEN V792N
Pulse Generator Agilent 33250A [50 MHz]

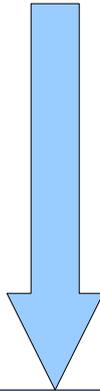
Thermal-like Light Setup



The Model

What we Measure:
Geiger – Müller Avalanches

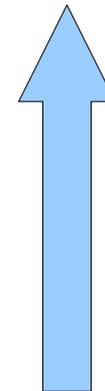
generated by:



Detection of impinging photons
Thermally Generated (DCR)
Optical Cross-Talk



What we Want:
Light Field Statistics



Model the contributions
parameters

Modeling the response: Detection

$P_{n,ph}$ - statistics of the light field

$P_{m,el}$ - distribution of avalanches triggered by impinging photons

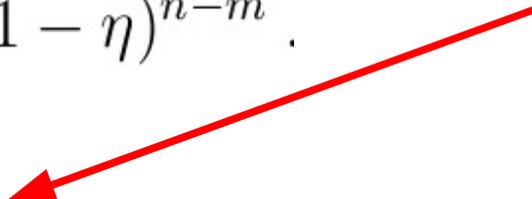
$$P_{m,el} = \sum_{n=m}^{\infty} B_{m,n}(\eta) P_{n,ph} .$$

$$B_{m,n}(\eta) = \binom{n}{m} \eta^m (1 - \eta)^{n-m} .$$

η - PDE

m_{el} expect. value of triggered cells

key parameter!



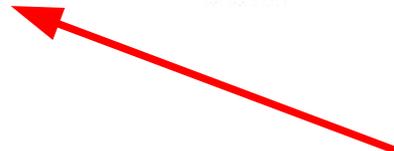
Modeling the response: DCR

DCR modeled as a poissonian event during the integration time

$$P_{m,dc} = \frac{\bar{m}_{dc}^m}{m!} e^{-\bar{m}_{dc}}$$

$$\bar{m}_{dc} = \nu_{dc} \times t_{gate}$$

key parameter!



The distribution of the avalanches is now given by the convolution

$$P_{m,el+dc} = \sum_{k=0}^m P_{k,dc} P_{m-k,el}$$

Modeling the response: Cross-talk

Avalanche triggering in neighbour cells by other avalanches had been modeled with a bernoullian-like process:

$$C_{k,m}(\epsilon) = \binom{m}{k-m} \epsilon^{k-m} (1-\epsilon)^{2m-k}$$

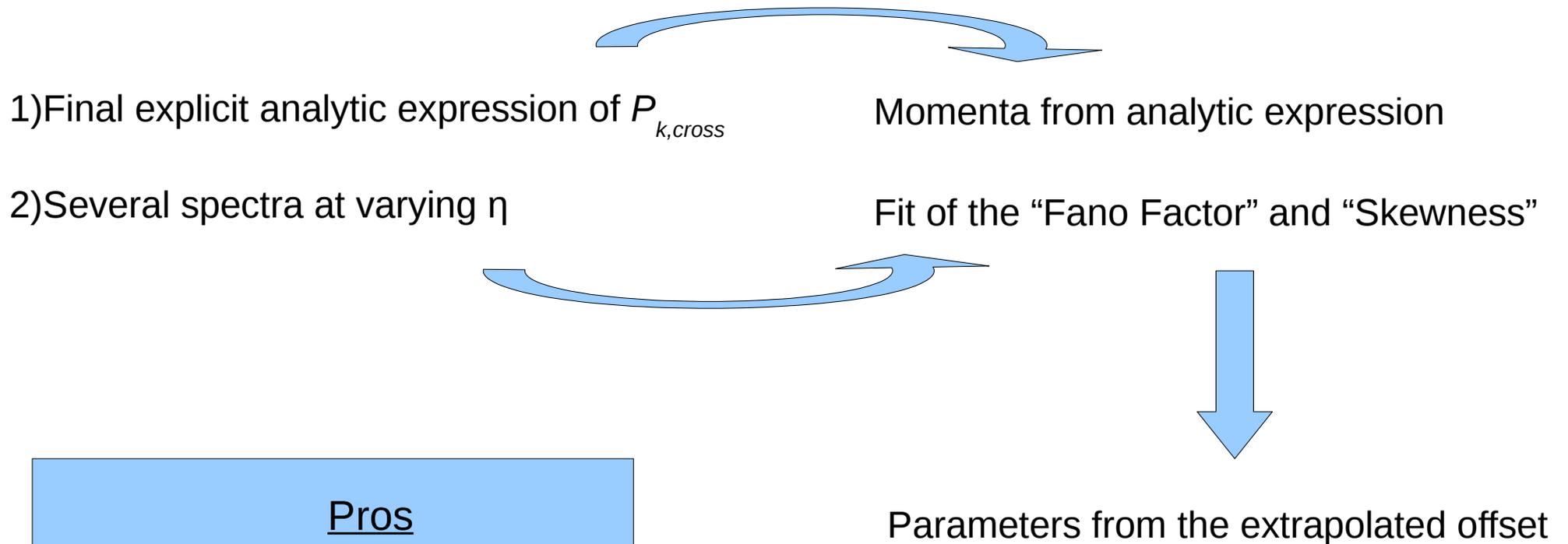

and the distribution of avalanches becomes

key parameter!

$$P_{k,\text{cross}} = \sum_{m=0}^k C_{k,m}(\epsilon) P_{m,\text{el+dc}}$$

X_T a cascade phenomenon: more than one stage

Self-Consistent Approach: Outlook



Pros

Not limited by peak resolution
Self-Consistent

Cons

Several acquisitions
Explicit analytic expression to calculate momenta

Multi-fit Analysis: Outlook

1) Multi-peak fit of spectrum



Peak Areas

2) Fit of curve of $P_{k,cross}$



Parameters

Pros

No need to several spectra acquisition

$P_{k,cross}$ no need to be explicit analytic expression

Cons

Limited to peak resolving spectra

Resolved peaks greater than free parameters of $P_{k,cross}$

Multi-peak fit procedure

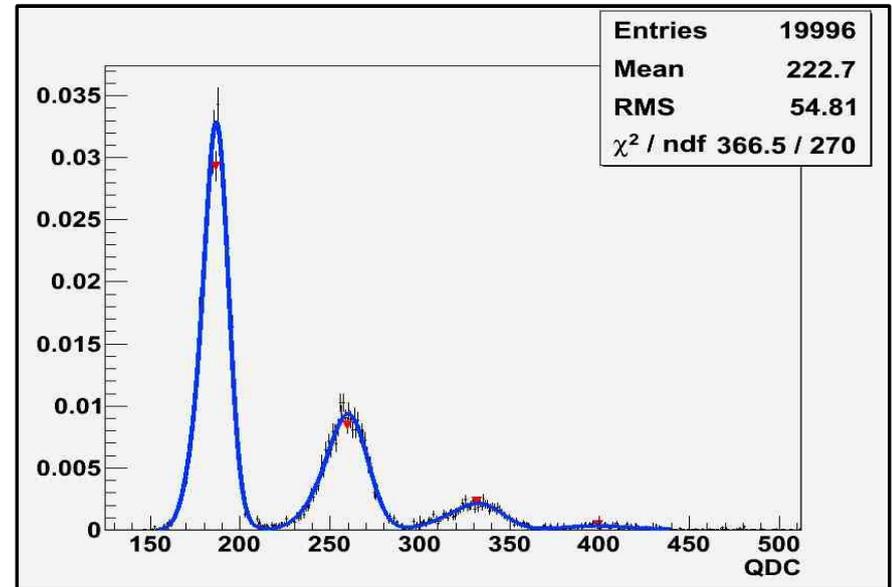
Total area of spectrum normalized

Multi-peak fit performed

Each peak described by a Gauss-Hermite Function

$$GH = N e^{-w^2/2} \left(1 + {}^3hH_3(w) + {}^4hH_4(w) \right)$$

$$w = \frac{x - \bar{x}}{\sigma}$$



Peak areas A calculated from fit parameters

$$A = N \sigma (\sqrt{2\pi} + {}^4h)$$

Moreover: gain calculated from fitted peak-to-peak distance

Results: Poissonian Light

$P_{m,el}$ is poissonian
 $P_{m,dc}$ is poissonian

↓

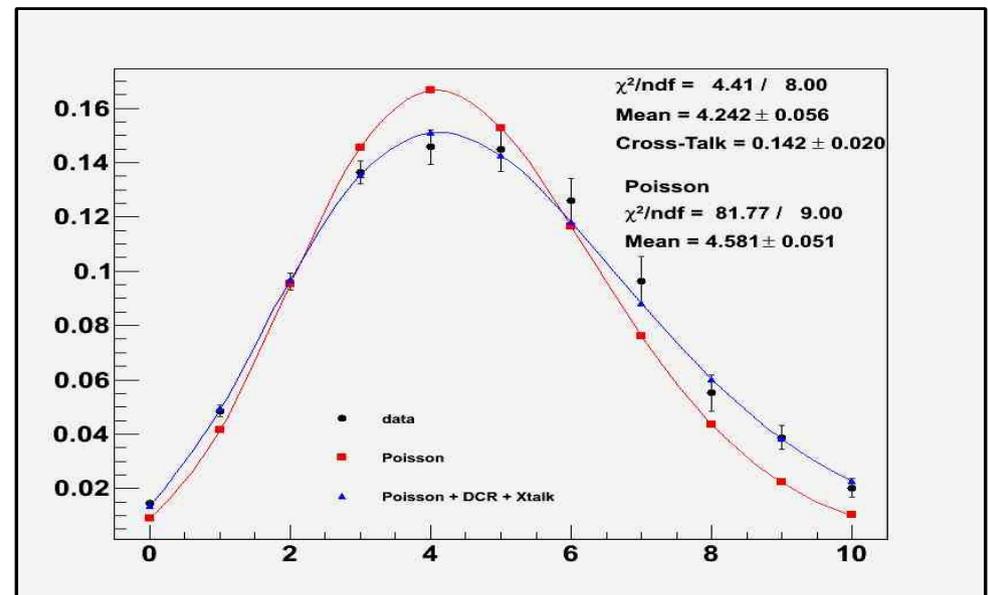
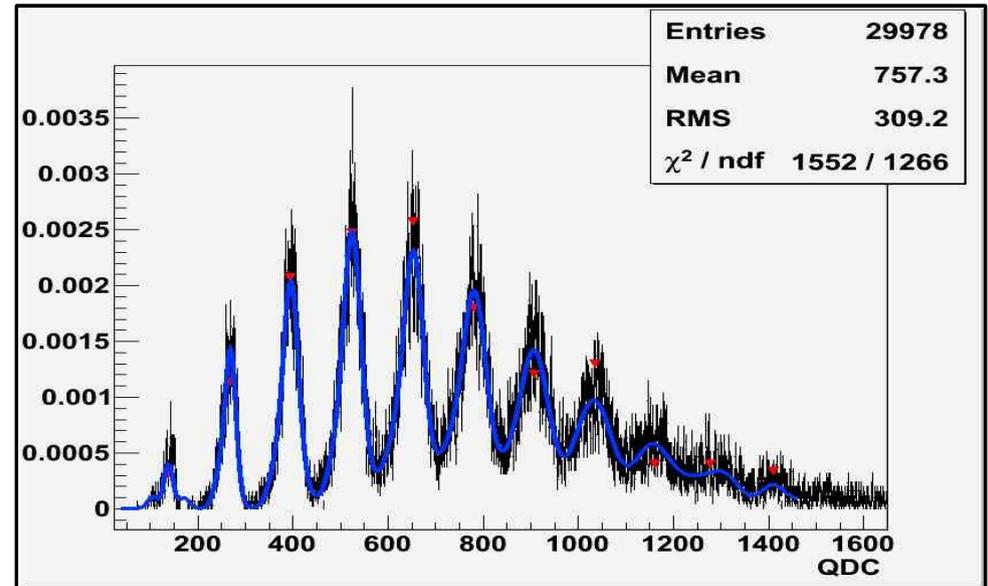
$P_{k,el+dc}$ is poissonian too

Three free parameters:

$$\rightarrow m_{el+dc} = m_{el} + m_{dc}$$

$$\rightarrow X_T$$

→ Prefactor



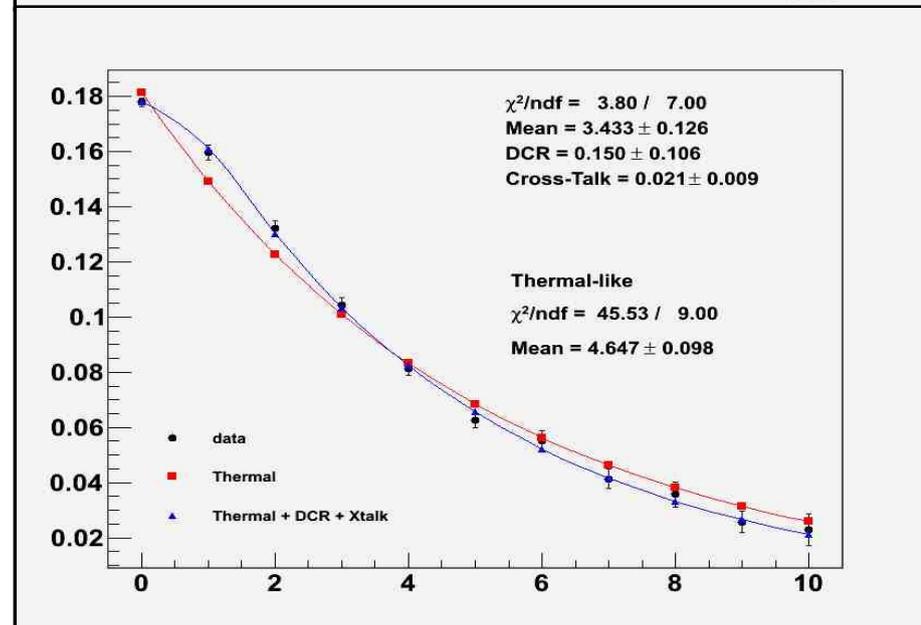
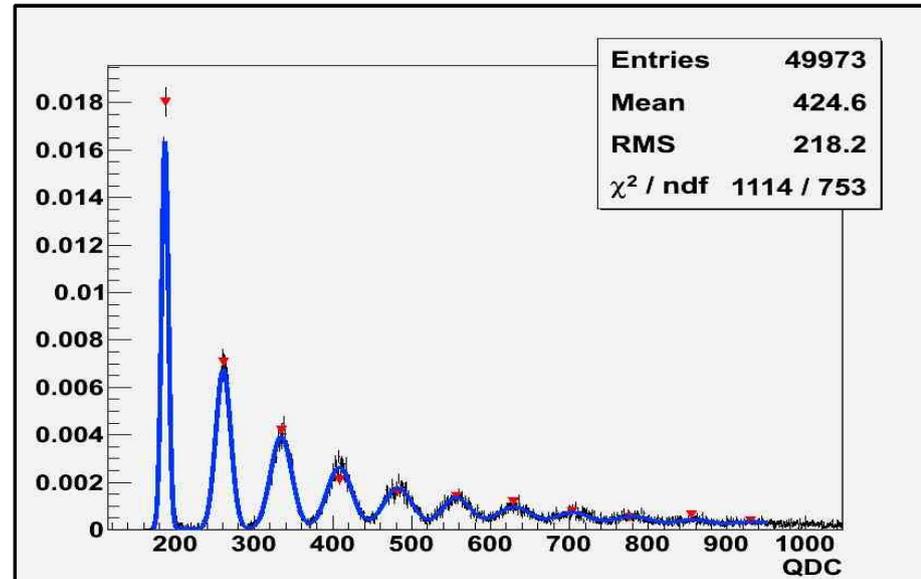
Results: Thermal-like Light

Probability distribution of single mode thermal light is described by

$$P_{m,el} = \frac{\bar{m}_{el}^m}{(\bar{m}_{el} + 1)^{m+1}}$$

Four free parameters:

- m_{el}
- m_{dc}
- X_T
- Prefactor



Cui Prodest?

Example: *Photon Counting Histogram* techniques

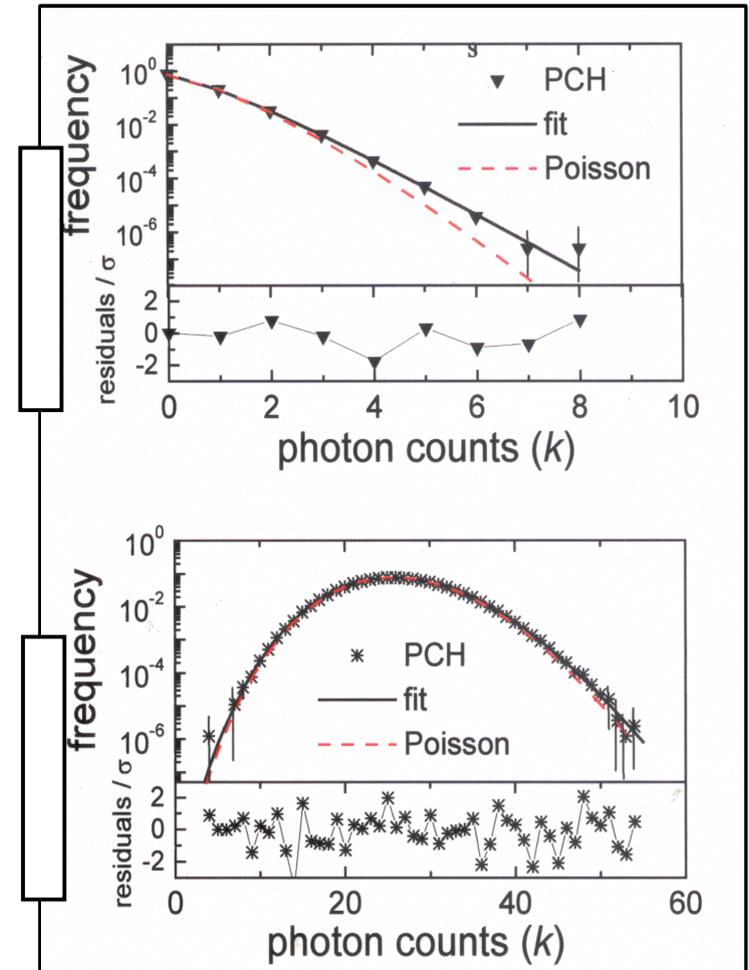
Acquisition of spectra of fluorophore emission

Physical parameter obtained from measure of
deviation from poissonian distribution

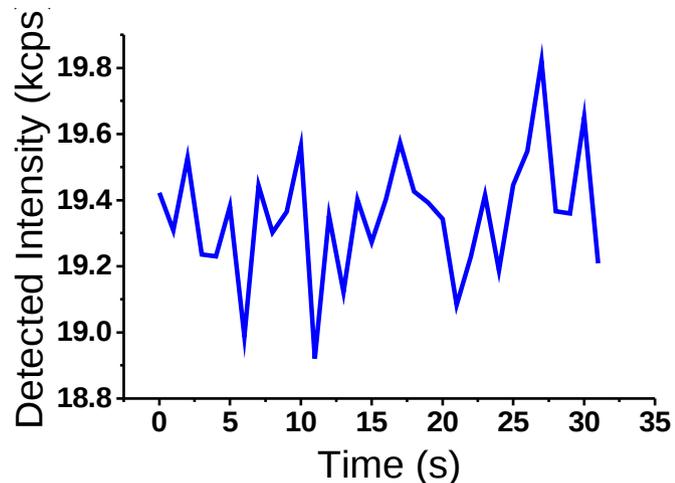
Diffusing Particles in an Inhomogeneous
Excitation Beam
Particle Number Fluctuations
Multiple Species
Detector Noise

$$p(k) = PCH(\epsilon, \langle N \rangle)$$

knowledge of other sources of deviation
needed!!!



Why PCH with SiPMs?

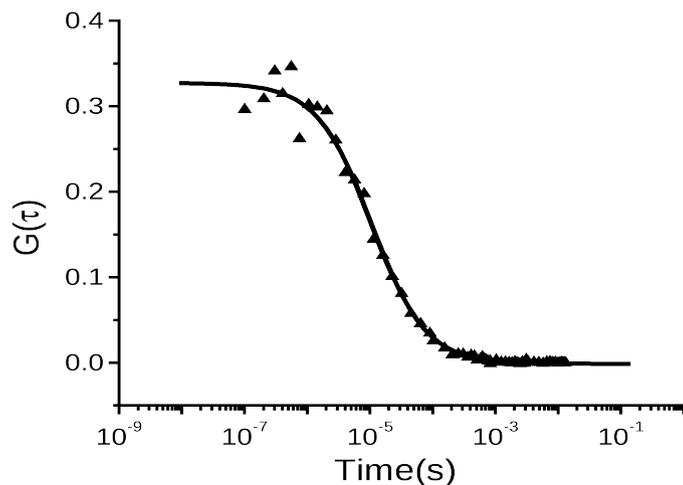


In *Fluorescence Correlation Spectroscopy*

measure “pulse-by-pulse” fluorophore emission
time correlation of emission



Use same data to perform both
PCH & FCS!!



$$G(\tau) = \frac{\langle \delta F(t) \delta F(t + \tau) \rangle}{\langle F(t) \rangle^2} \quad G(0) = \frac{\text{Variance}}{\langle N \rangle^2} = \frac{1}{\langle N \rangle}$$

Proof of Principle

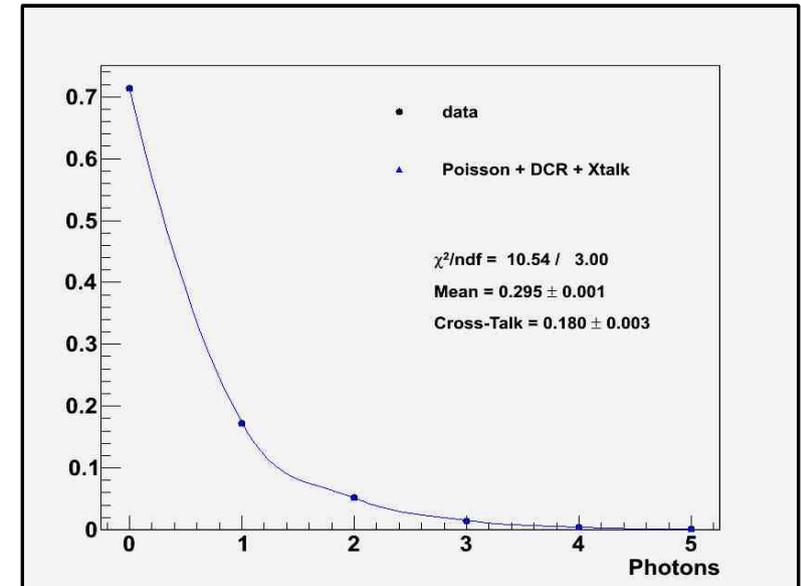
PicoQuant PDL 800-B: 10 Hz – 80 MHz

*Hamamatsu MPPC S10362 11 100C
Pulse Amplification Board from SensL*

USB-VME Bridge CAEN

V171816ch QDC CAEN V792N

Best result: ~10 MHz
Pile-up problems



- Commissioning confocal microscope setup
- Performing standard tests with SPADs



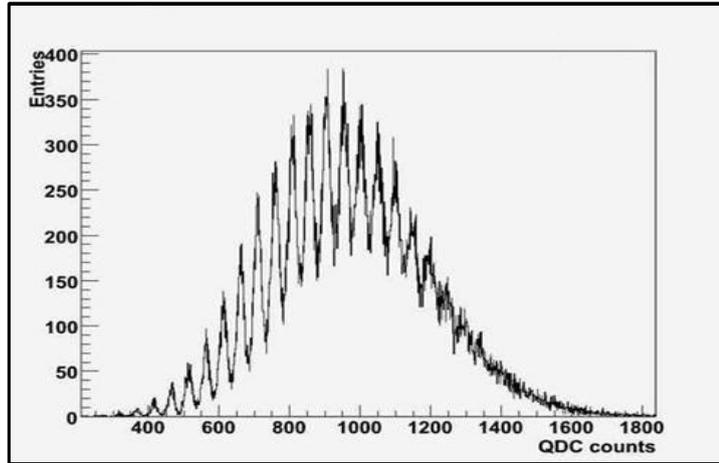
Sampling at lower frequency
and/or
Change Acquisition chain
(Waveform Digitizer)

Conclusions

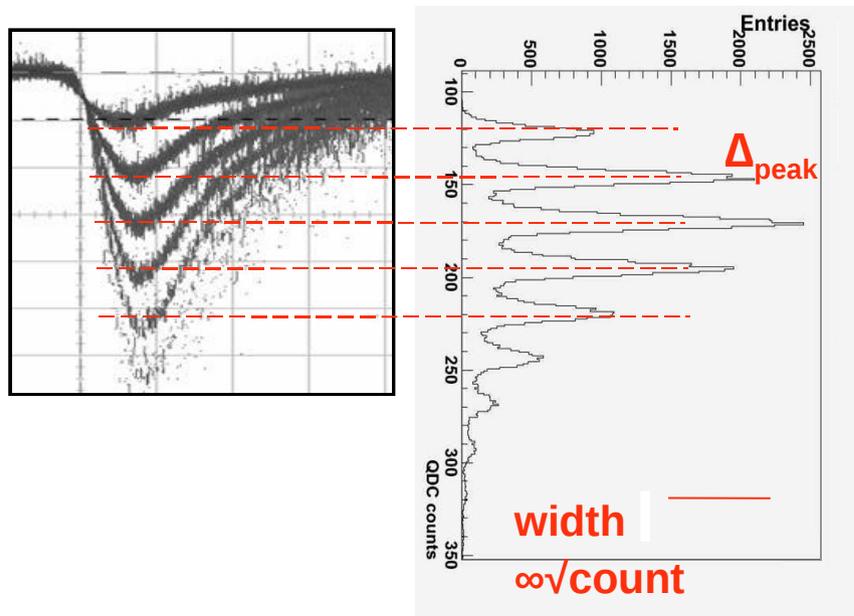
- Provided a mathematical model for cross-talk and DCR effects;
- Developed a procedure to analyzed data taking these contributions into account;
- Tested the model
 - Poissonian light
 - Thermal-like light
- *Full description of Self-Consistent Method in upcoming paper!*
- Example of possible applications of the procedure to FFS
 - Proof-of-Principle for the “pulse-by-pulse” acquisition
 - Commissioning of the PCH setup

Backup Slides

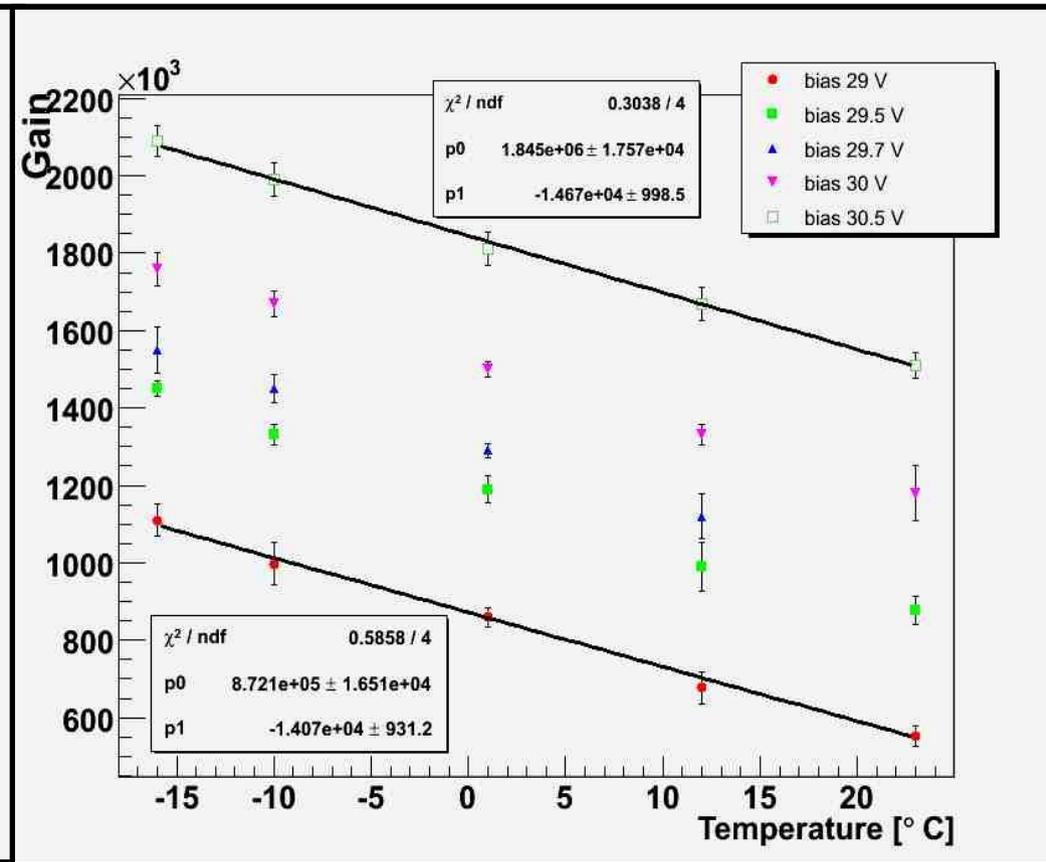
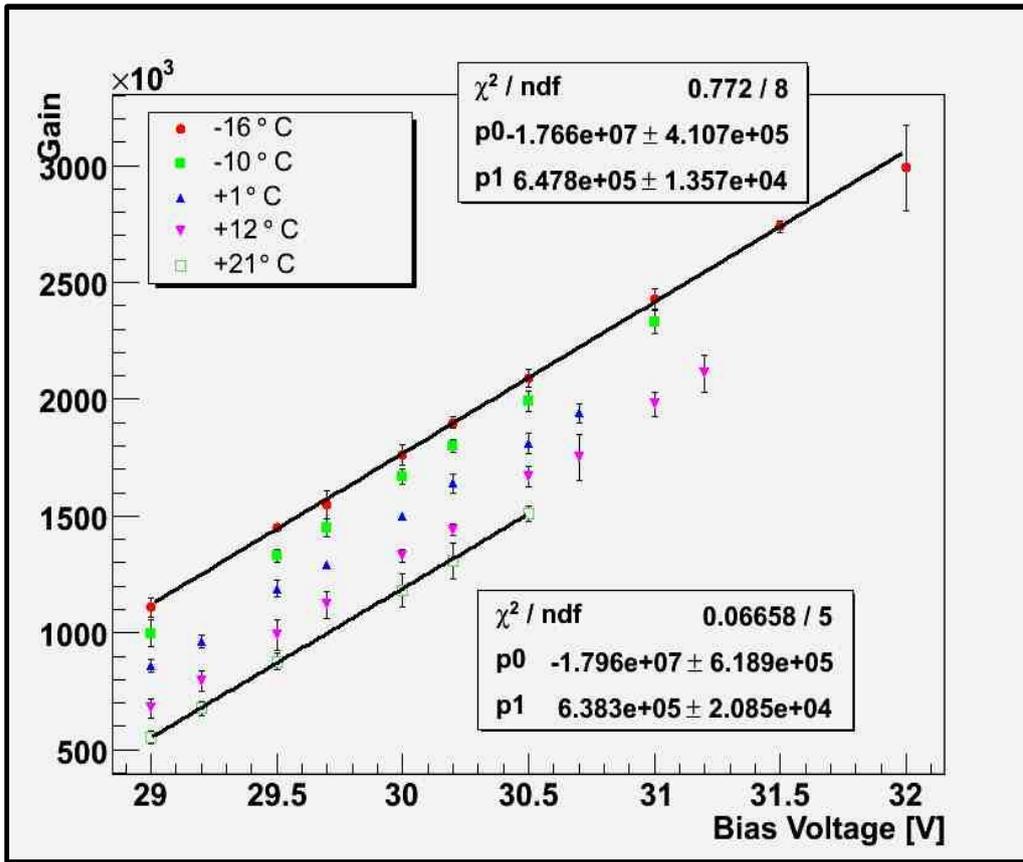
Gain



~38 picchi a temperatura ambiente



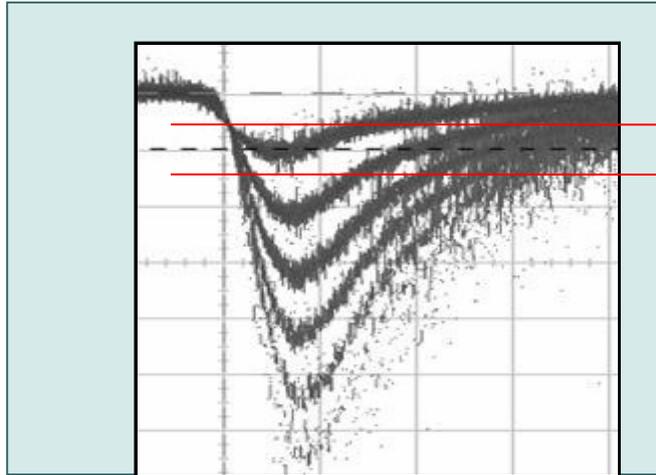
$$G = \Delta_{PP} \frac{Q/QDC}{e^-AMP}$$



$$\frac{dV}{dT} = - \frac{dG}{dT} \frac{1}{\frac{dG}{dV}}$$

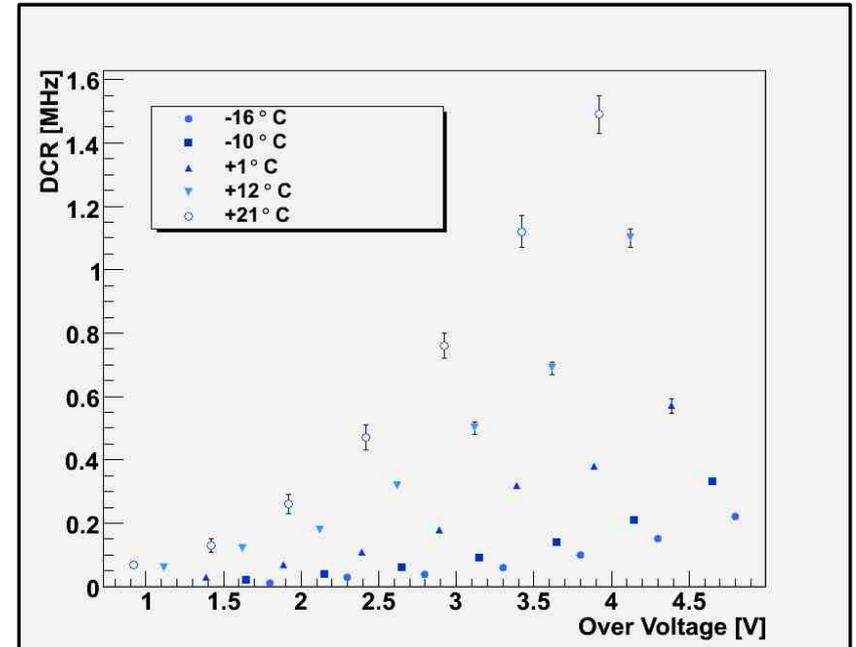
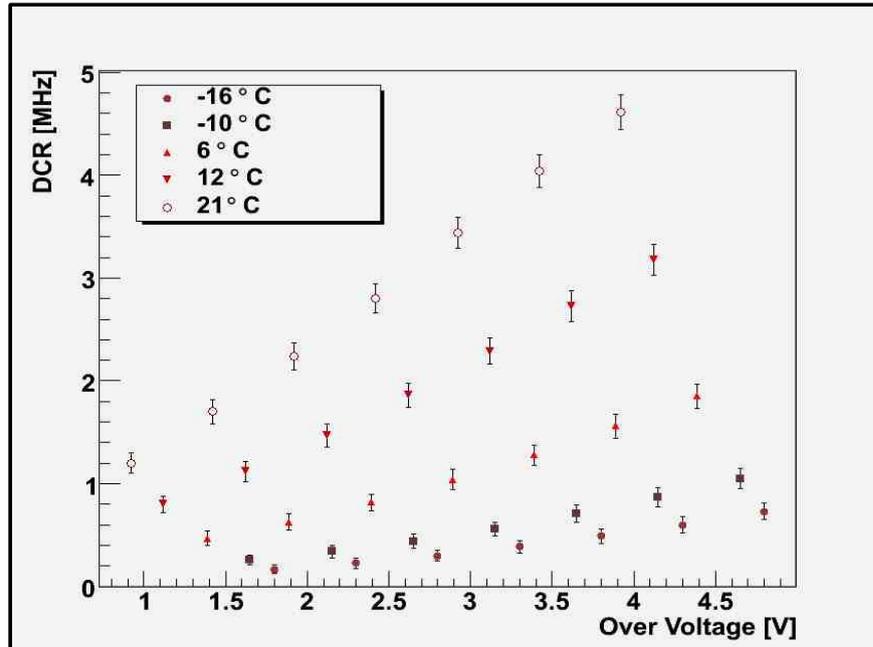
- SensL 8640 cells: 23.2 mV/°C ± 1.4 mV/°C
- SensL 1144 cells : 23.6 mV/°C ± 0.9 mV/°C

Dark Count Rate



Soglia a "0.5 fotoni"

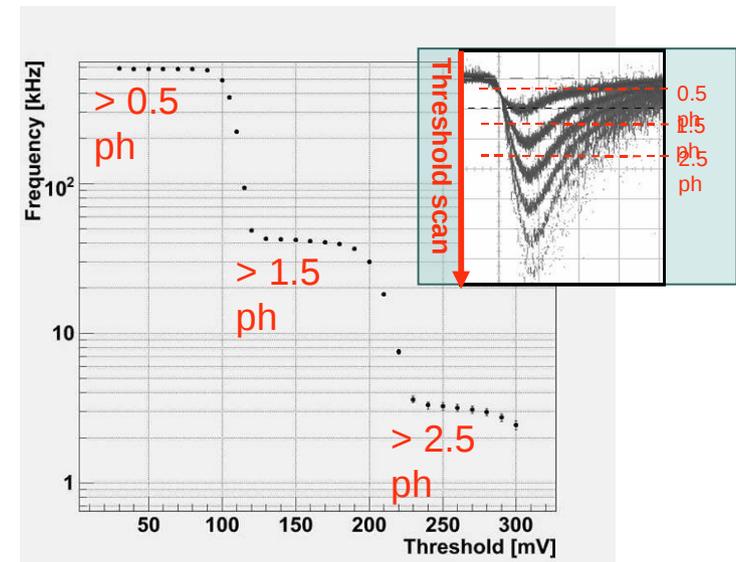
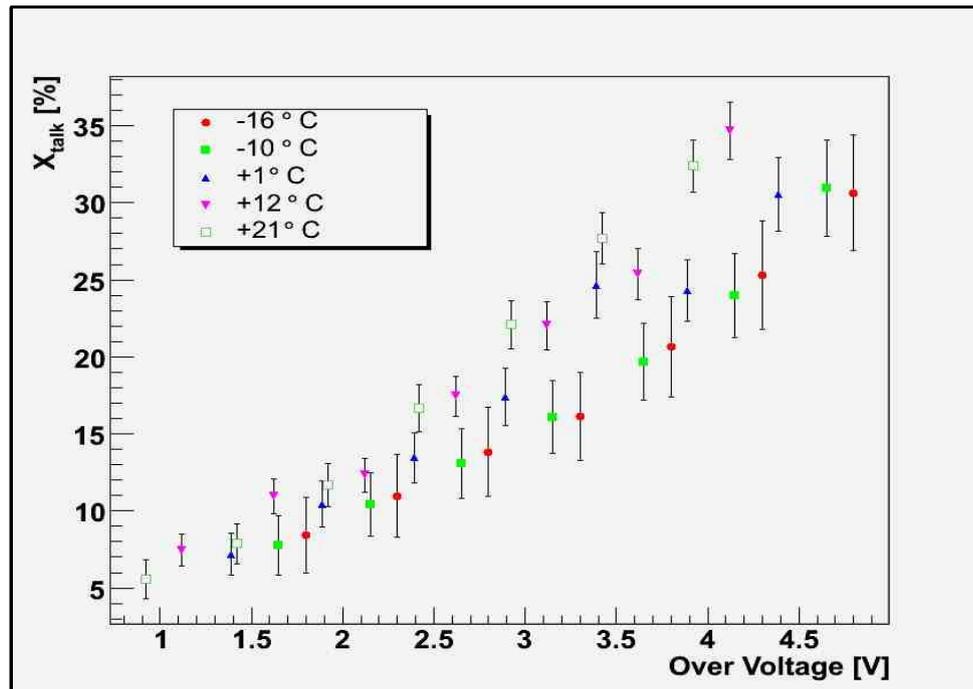
Soglia a "1.5 fotoni"



Optical Cross Talk

X_{talk} : probabilita` che una valanga causi un'altra valanga in una cella vicina

calcoliamo:
$$X_{\text{Talk}} = \frac{\text{DCR}(1.5\text{ph})}{\text{DCR}(0.5\text{ph})}$$

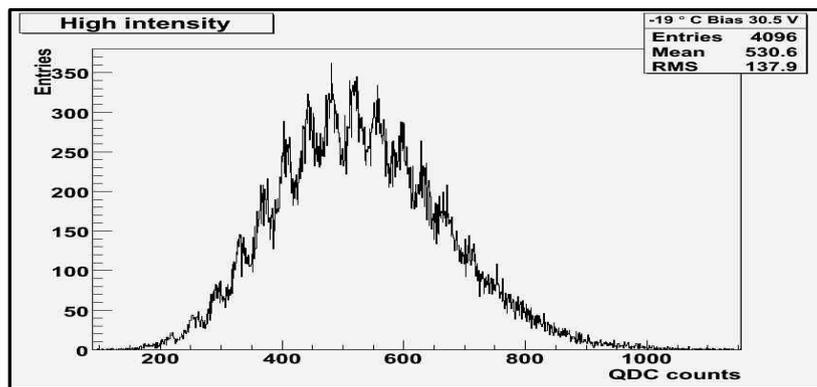


X_{talk} non mostra dipendenze significative dalla Temperatura

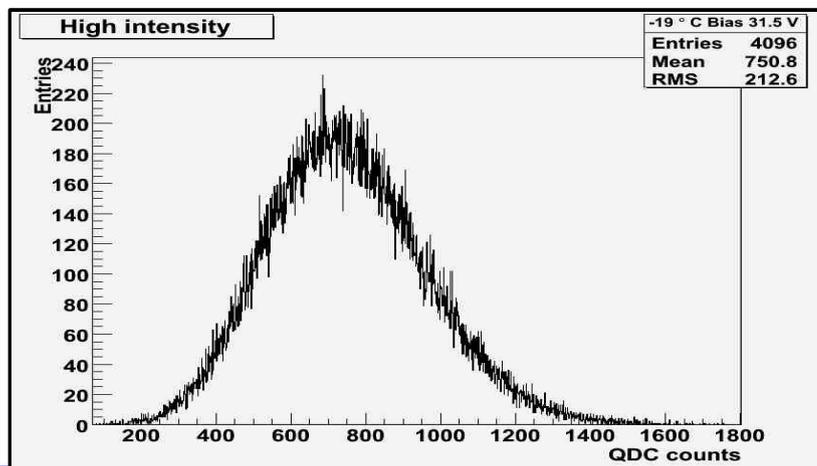
Photo-Detection Efficiency

$$PDE = FF \times QE(\lambda) \times P_{GM}(V)$$

Misurazioni ad alto flusso F, fissato



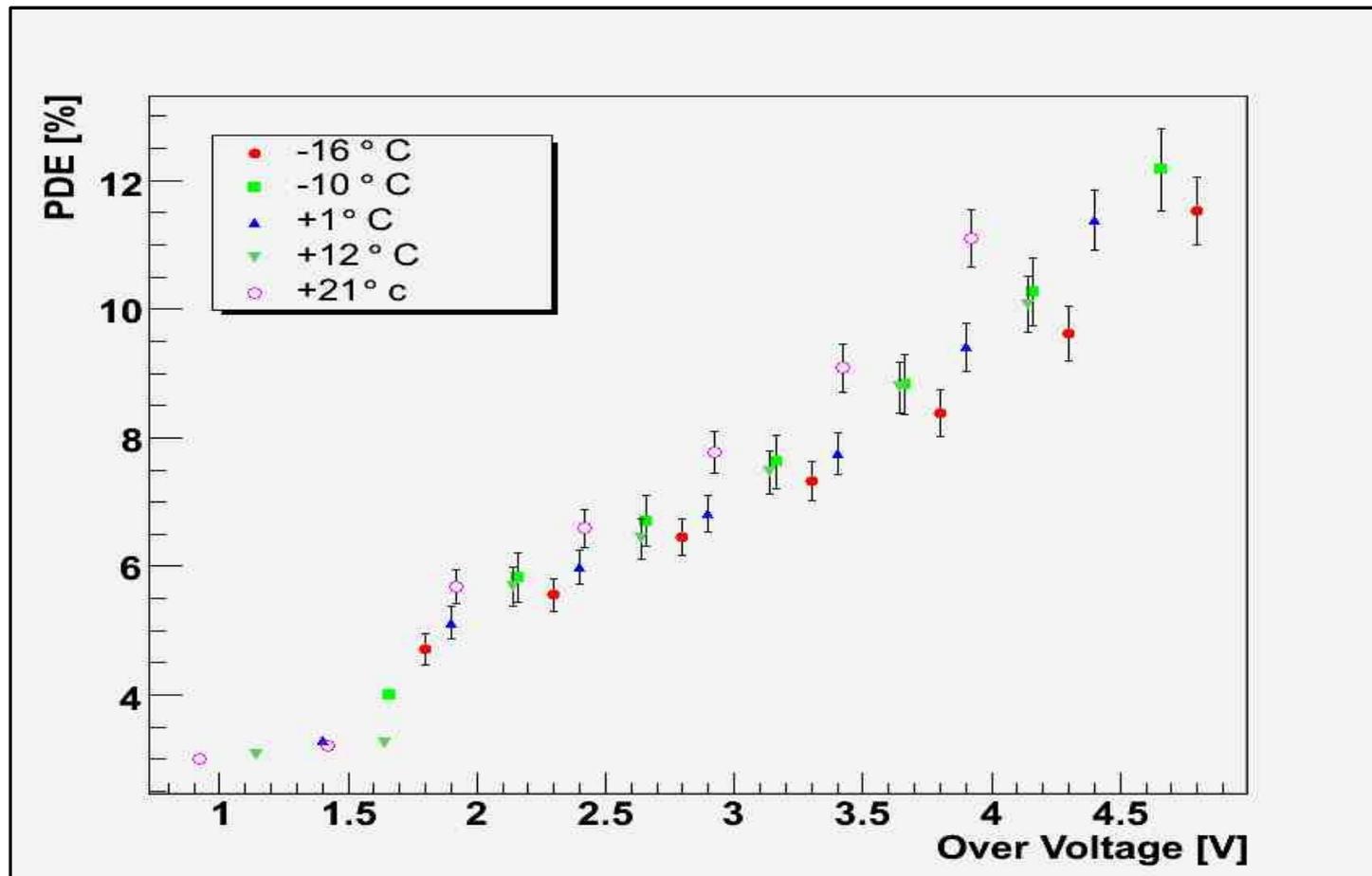
$$PDE = \frac{\langle n \rangle_{meas}}{F}$$



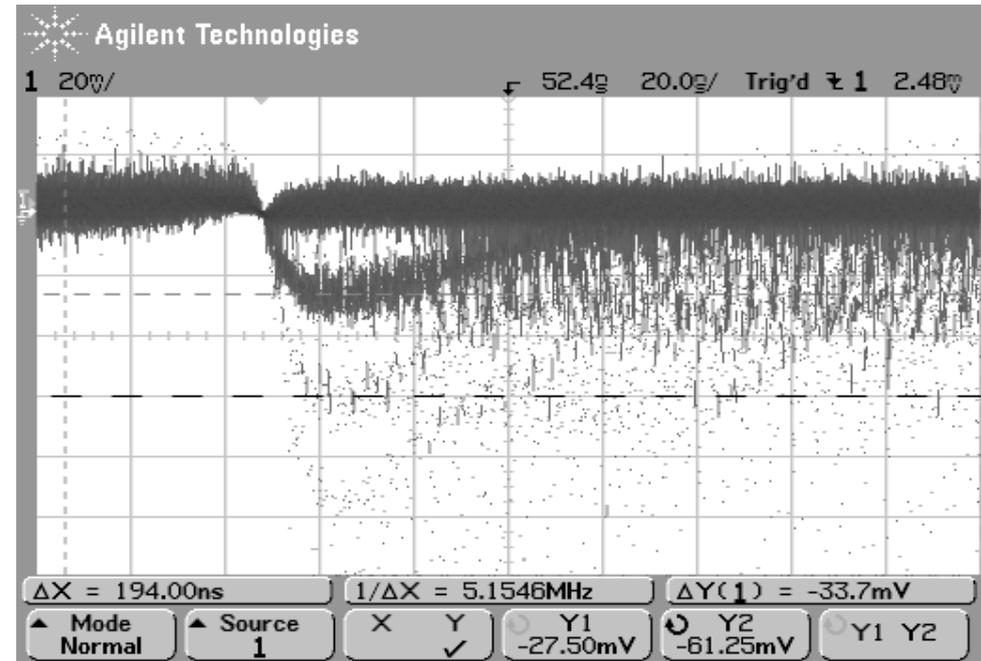
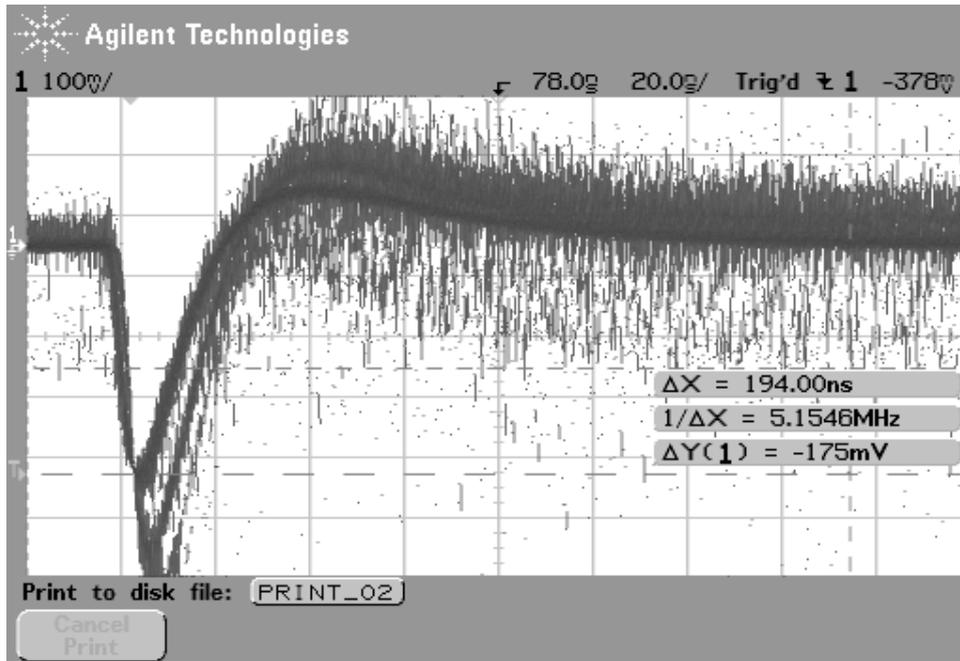
$$PDE = (QDC_{mean} - QDC_{ped}) \frac{Q/QDC}{e^{-AMP}} \frac{1}{G \times F}$$

Correction to PDE

$$\langle n \rangle_{meas} = \langle n \rangle_0 (1 + X_{Talk}) \quad \longrightarrow \quad PDE_{corr} = \frac{PDE}{(1 + X_{talk})}$$



Overshoot



→ the overshoot is inducing a twofold unpleasant effect:

- having to integrate for time windows in excess of 200 ns, it reduces the integrated signal
- in case of DCR at the multi-MHz (~ 8 MHz at 0.5 p.e. threshold) level, it piles up with an effective baseline shift, making the discrimination difficult (minimum discriminator threshold 30 mV)

→ the price to pay using the transimpedance ampli is a reduction of the gain by a factor 5