G-APD Photon detection efficiency

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Outline

- Motivation
- Measurements Setup
- Samples
- Fitting Procedureses
- Results
- Conclusions

- The results presented are preliminary.

Motivation

- Multi-pixel Geiger-mode photodiodes (G-APDs) used in calorimetric detectors.The crucial point is:
- **The Photon Detection Efficiency**

Every detector can only convert a certain percentage of incident photons to signals. This overall efficiency is dependent on factors such as the surface reflection, fill factor, quantum efficiency and amplification probability. It is depending from λ.

$$\mathrm{PDE} = \mathrm{QE} \times \epsilon_{\mathrm{geom}} \times \epsilon_{\mathrm{Geiger}}$$

QE is the quantum efficiency of G-APD function of the wavelenght

ϵ_{geom} is geometrical factor $\epsilon_{\mathrm{Geiger}}$ is the probability to trigger a Geiger

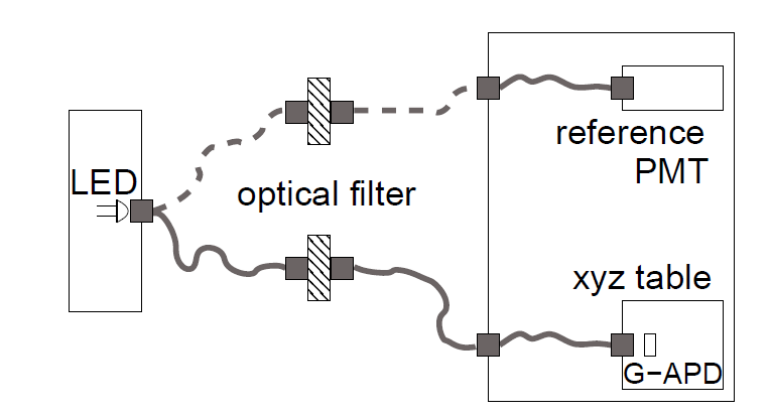
- Comparison in same experimental conditions of various samples from different manufactures

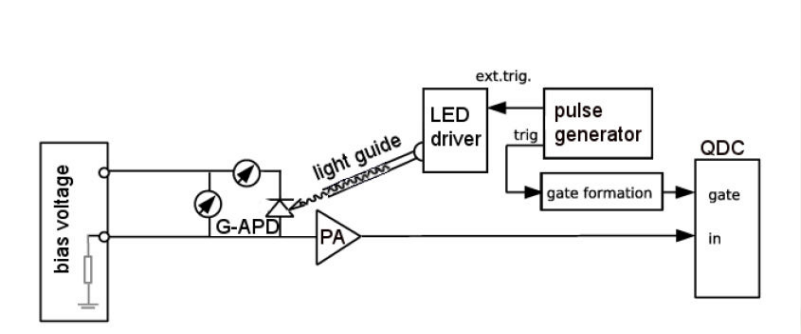
Terms

- **Fill factor**. The percentage of detector's surface area which is sensitive to photons
- **Crosstalk.** With multiple avalanche regions on a single device one avalanche process may create photons that trigger another cell.The result is a pulse with doubled amplitude
- **After-pulsing**. When the quenching does not completly drain all the charges in the sensitive area the cell will fire again a short time after the original pulse. This is caused by so-called charge-traps in the avalanche region, which capture single charges and release them again after a while.

Measurement Set up

Thermalized box
($\Delta T \sim 0.1^0C$)



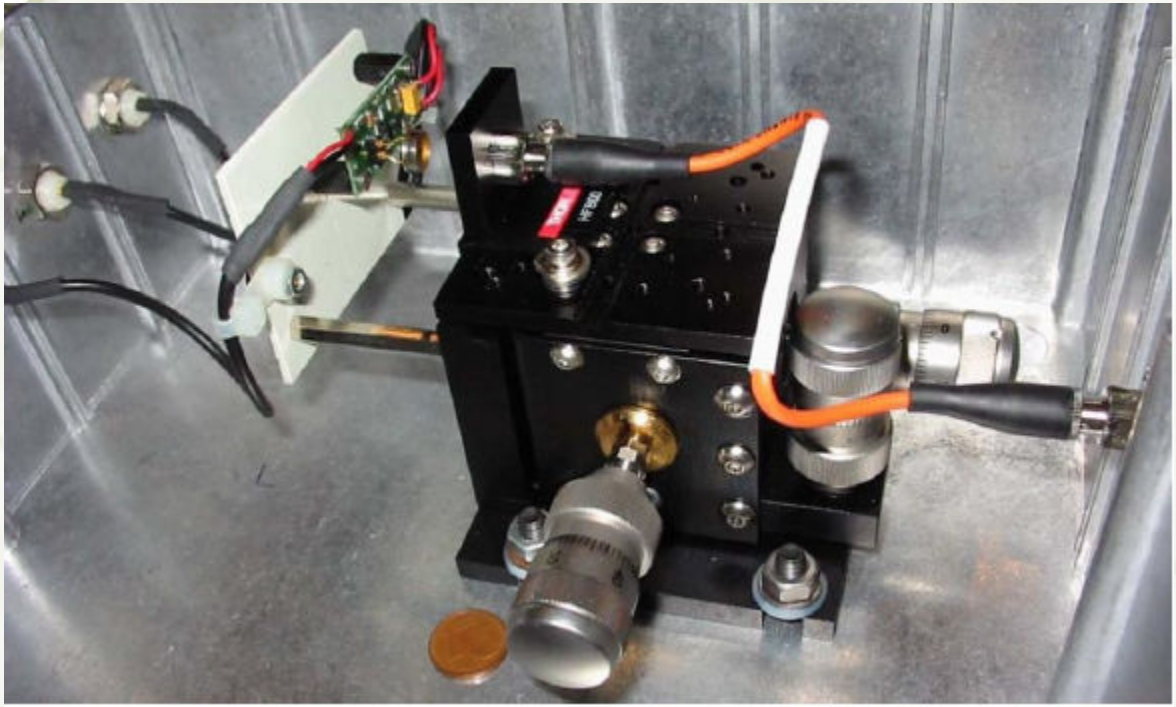


- **Reference PMT**

HAMAMTSU H5783P calibrated efficiency for λ =380-650nm

- **Filters** FWHM ± 3nm.
- **Optical Fibers:** 50 μm core
- **OpticalConnectors**: superFC/PC
- To estimate and correct for different optic coupling and **reconnection systematic error** other measurements with crossed fibers are also done

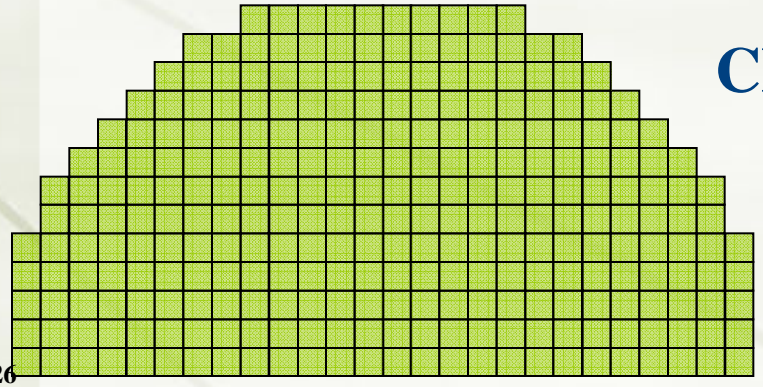
Measurement Setup



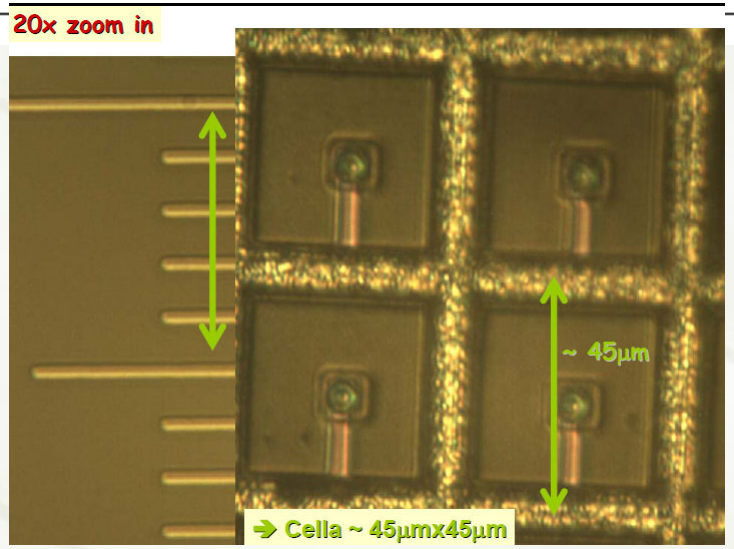
Samples

TABLE II. – *[1] Sample kindly proved from Prof.M.Danilov,[2]Sentistive area octaganal shape, [3]Sample kindly provided from Dott.C. Piemonte(Fondazione Bruno Keller)*

Sample	Type	Photosensive area $[mm^2]$	Number of pixel	Pixel pitch $[\mu m]$
HAMAMATSU	S10362-11-025U	1x1	1600	25x25
CPTA[1]	143	1.028[2]	556	43x43
IRST[3]	2007 prod	1x1	400	50x50



CPTA



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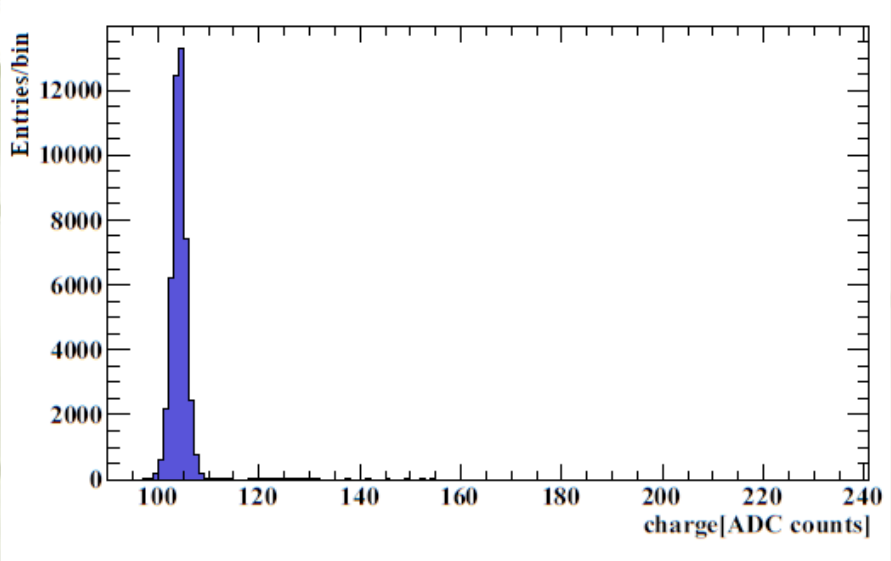
Eugeny Tarkosky

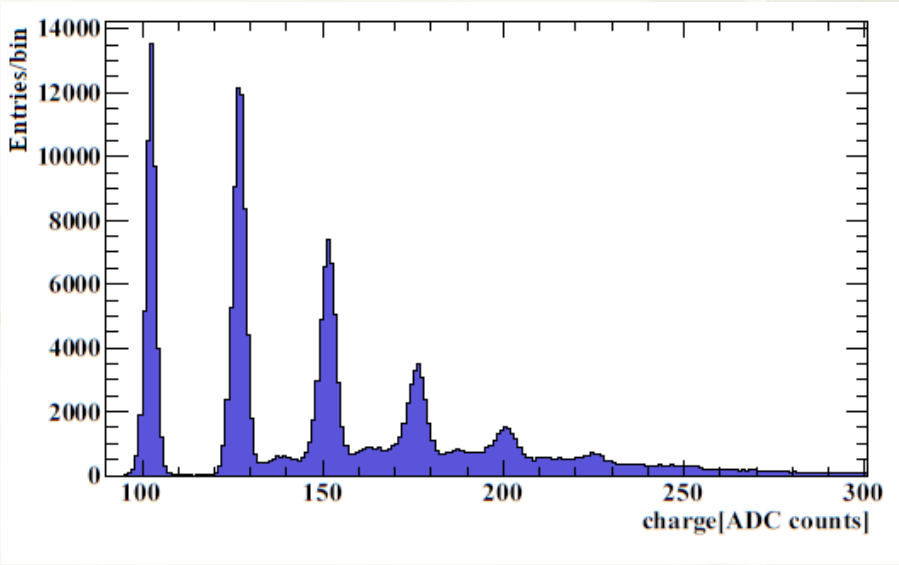
MPPC S10362-11-025U Hamamatsu

λ=450nm

pedestal



signal



Wavelenghths

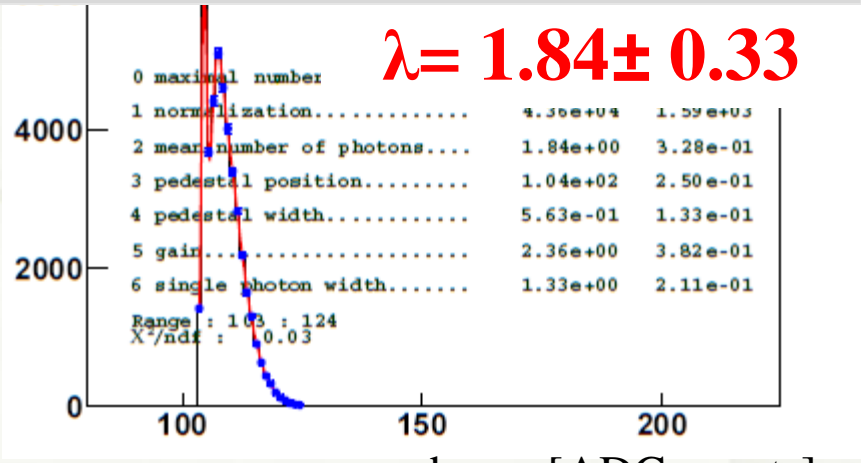
TABLE I. – *Efficiency of reference detector PMT-based photosensor H5783P. Values provided on the used device as provided from the manifacture Hamamatsu[1]. Efficiency values used[2].*

λ (nm)	$\epsilon^{ref}_{\text{peak}}$[1] [%]	$\text{FWHM}_{\text{filter}}$ (nm)	$\text{FWHM}_{\text{source}}$ (nm)	$\epsilon^{ref}_{\text{evaluated}}$ [%]
380	23.46		$\pm$ 8	$22.98\ ^{-0.21}_{-0.05}$
400	22.69		$\pm$ 13	$22.75\ ^{+0.46}_{-0.10}$
450	20.33	$\pm$ 3		$20.33\ ^{+0.27}_{-0.28}$
500	15.45	$\pm$ 3		$15.45\ ^{+0.32}_{-0.68}$
565			$\pm$ 30	$5.30\ ^{+2.37}_{-2.63}$
600	2.30	$\pm$ 3		$2.30\ ^{+0.19}_{-0.19}$
650	0.28	$\pm$ 3		$0.28\ ^{+0.05}_{-0.04}$

Fit Procedure: Reference

Direct measurement, no amplification

wavelenght 450nm



$$N(x) = N \times \sum_n (\text{Gauss}(x, \mu_n, \sigma_n) \times \text{Poisson}(n, \lambda)),$$

$$\text{const} \times e^{-\lambda} \sum_n (\lambda^n/n!\ 1/\sigma_n \exp\{-(x-\mu_n)^2/(2\sigma_n)^2\})$$

$\mu_n = \mu_0 + n \times g$

x is the charge in ADC counts

n is the number of photons detected

λ is the mean number of the detected photons

gain g in units of ADC counts

$\sigma_n^2 = \sigma_0^2 + n \times \sigma_1^2$

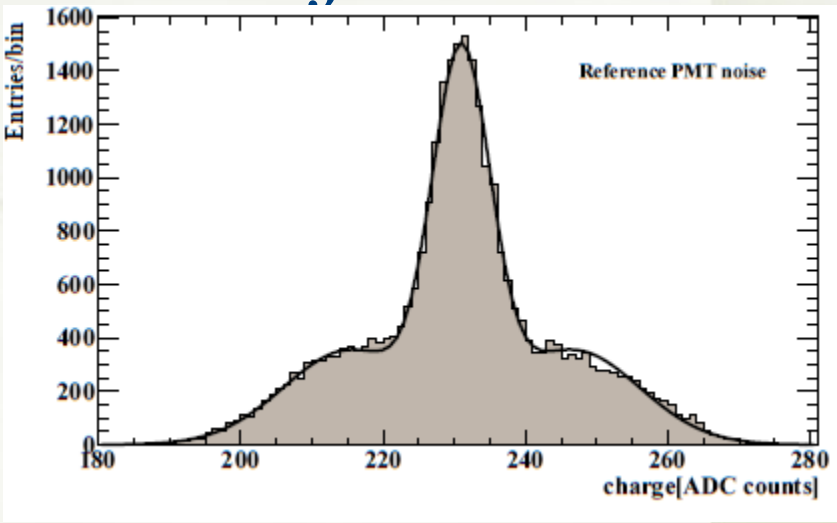
n detected photons electronic noise (σ_0) signal fluctuation (σ_1)

Single photon width

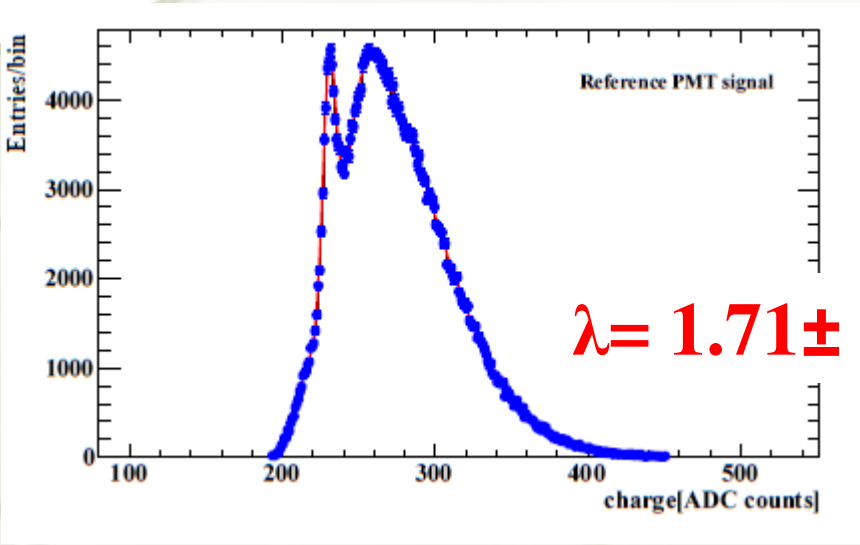
Due to ADC resolution → **signal ampification**

Fit Procedure : Reference

- Reference PMT



$$Noise(x) = G_1(x-\delta/2)+G_0(x)+G_1(x+\delta/2)$$



$\lambda = 1.71 \pm 0.02$

ORTEC NIM amplifier

$N(x)=N \times Noise \times Poisson(n,\lambda)$

wavelenght 450nm

PMT $\varepsilon^{ref}_{evaluated} = 20.33^{+0.27}_{-0.28}\%$

Fit Procedure: Silicon PhotoMultipliers

- Ideal case

$$N(x) = N \times \sum_n \left(\mathrm{Gauss}(\mathrm{x}, \mu_\mathrm{n}, \sigma_\mathrm{n}) \times \mathrm{Poisson}(\mathrm{n}, \lambda)\right),$$

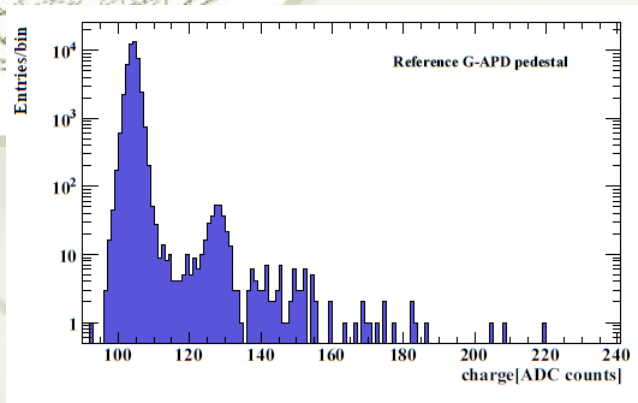
- Real situation
- Termogeneration
- After-Pulse
- Cross-talk

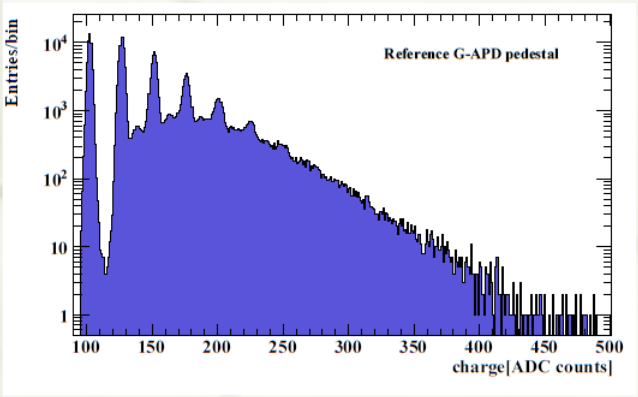
G-APD reponse:

$$A = G \times N_\gamma \times \mathrm{PDE} \times (1+\varepsilon) \times (1+AP)$$

gain

Fit Procedure: Silicon PhotoMultipliers



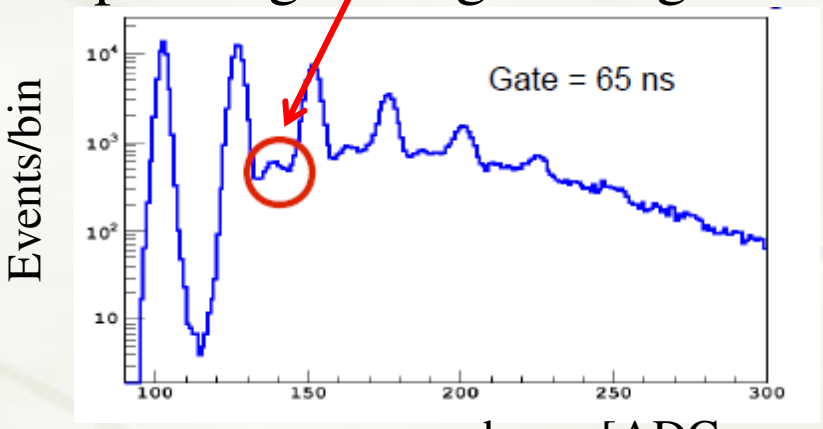


- Hamamatsu MPPC:

S10362-11-025U G ~3.4 10^5

- AfterPulse

depending from gate lenght



After Pulses

Residual distribution after a substraction of best-fitted ideal gaussians from the signal spectrum

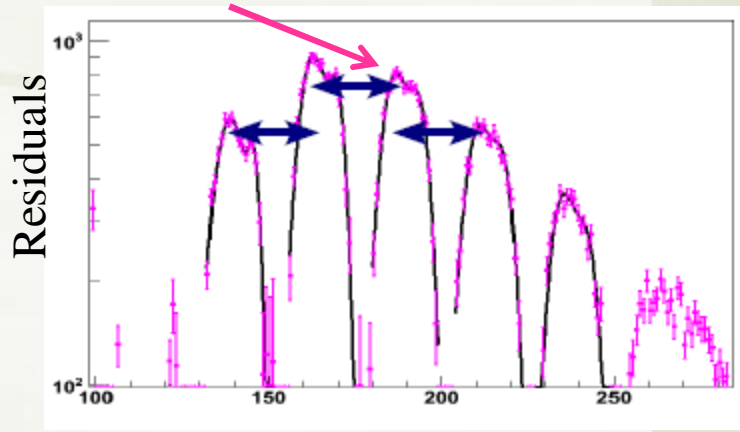
- $P_i^{\mathrm{noAP}} = P_i^0 \times (1 - P_{\mathrm{AP}})^i$

P_i^0 is probability to get initially i cells fired

P_{AP} is a probability to get an AP

- $P_i^{\mathrm{AP}} = 1 - P_i^{\mathrm{noAP}} = P_i^0 \times (1 - (1 - P_{\mathrm{AP}})^i)$

- $P_i^{AP} = P_i^{AP1} + P_i^{AP2} = P_i^0 \times [1-(1-P_{AP})^i] \times [(1-P_{AP})^j] + P_i^0 \times [1-(1-P_{AP})^i] \times [1-(1-P_{AP})^j],\ j \geq 1$



Double gaussian approximation for the after –pulse contribution

$\delta_{1,2}$ distance from gaussian simulating AP from main peak

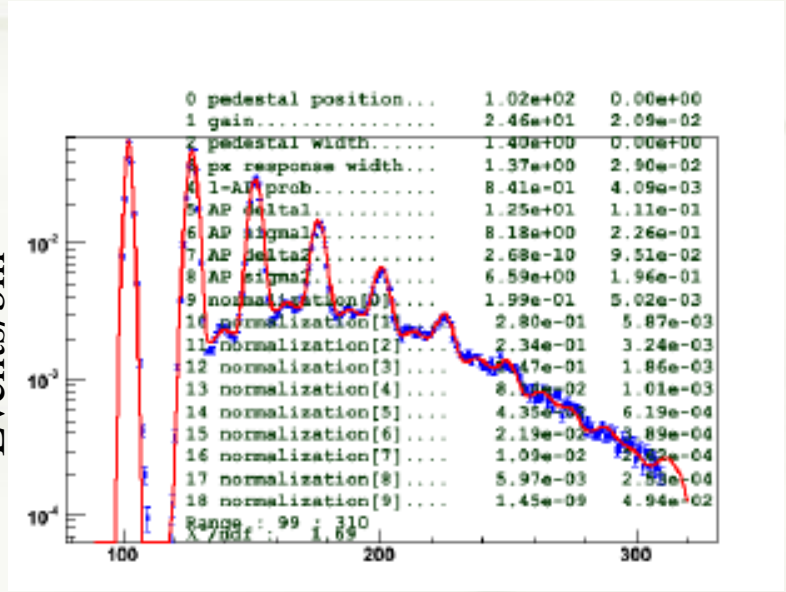
$$P(x) = P_i^{\mathrm{noAP}} \times G(\mu_i, \sigma_i) + P_i^{\mathrm{AP1}} \times G(\mu_i + \delta_1, \sigma_1) + P_i^{\mathrm{AP2}} \times G(\mu_i + \delta_2, \sigma_2)$$

After Pulse fit

Fit Procedure yelds:

- Probability to get i cells fired.
- After Pulse probability:

AP ~ 15% (65 ns gate)



charge [ADC counts]

Cross talk

- In ideal case without cross-talk the value of P^0_i are distributed according Poisson statistics

Peak 0 - from P(0)

Peak 1 - from P(1) without xtalk:

X $P(1)\times(1-\varepsilon)$

Peak 2 - from P(2) without xtalk and P(1) with 1xtalk

X X→X

X $P(2)\times(1-\varepsilon)^2+P(1)\times\varepsilon\times(1-\varepsilon)$

Peak 3 – from P(3), P(2) and P(1)

X X→X X X→X→X

X X X→X

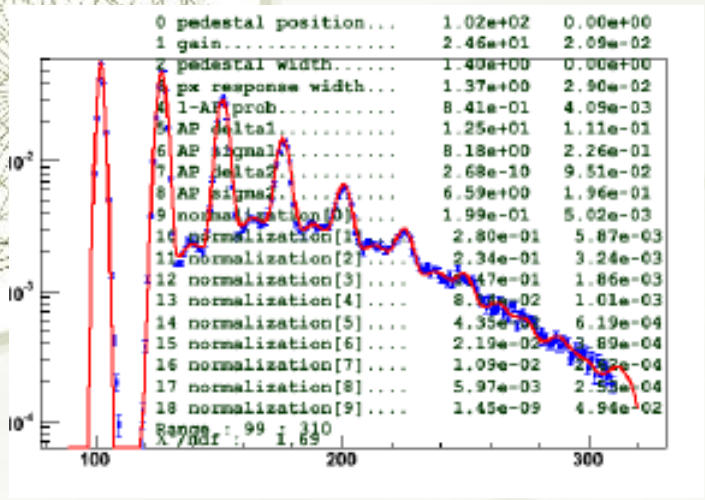
X $P(3)\times(1-\varepsilon)^3+2\times P(2)\times(1-\varepsilon)^2\times\varepsilon+P(1)\times\varepsilon^2\times(1-\varepsilon)$

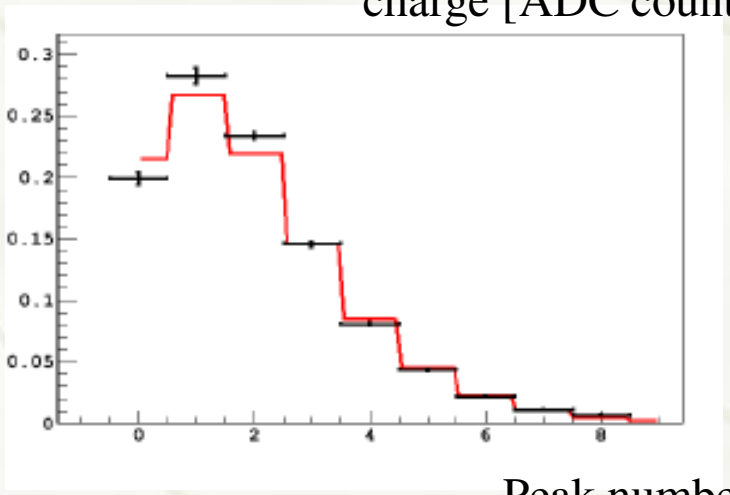
$$\sum_{j=0}^{i} P_j^0 (1-\varepsilon)^j \varepsilon^{i-j} B(i-1, j-1),$$

$B(i-1, j-1)$

Binomial coeff.

Cross talk fit





- $N_\gamma = 1.55 \pm 0.02$
- Xtalk $= 0.20 \pm 0.01$
- 1-AP $= 0.84 \pm 0.01$

Probability to observe i fired cells obtained from signal fit

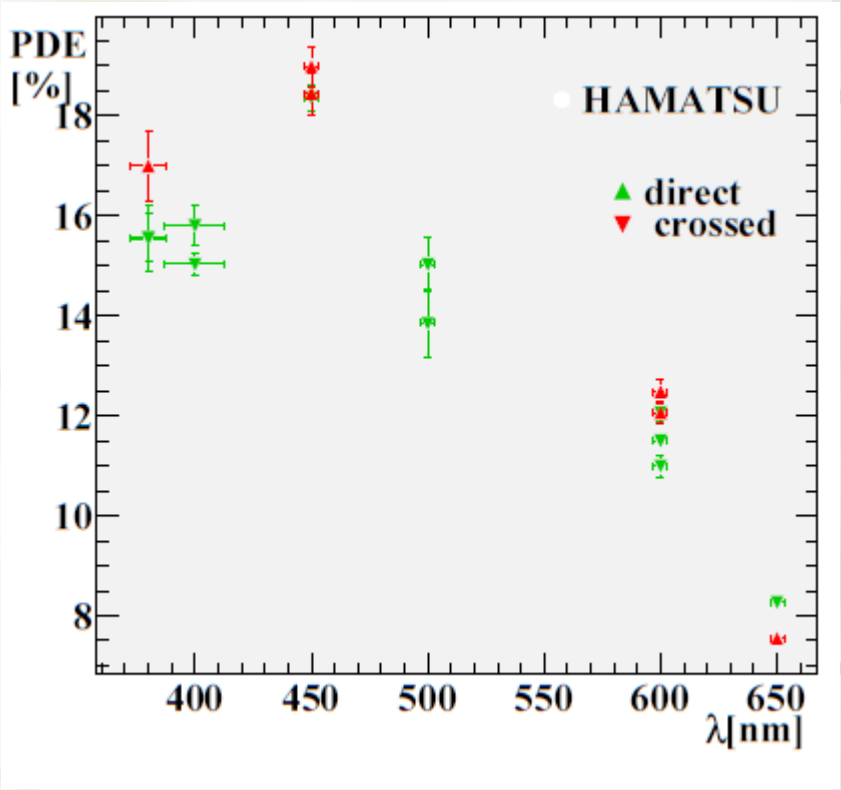
Exercise:

$N_\gamma^{PMT} \approx 1.71/0.2033 = 8.4$

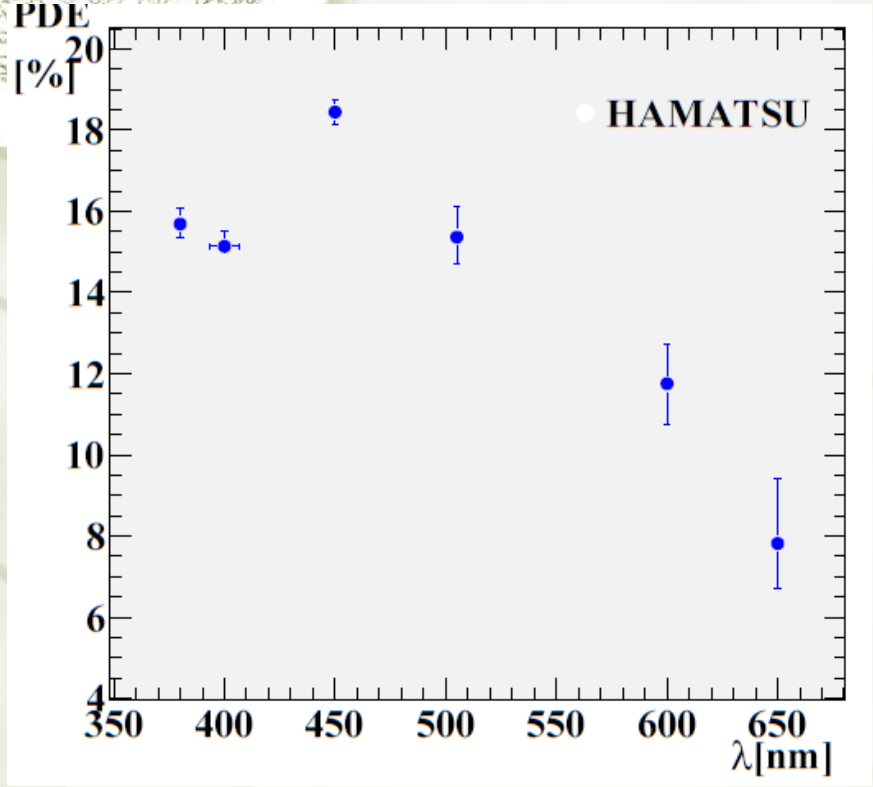
PDE$= N_\gamma / N_\gamma^{PMT} \approx$ **18%**

Optical contact

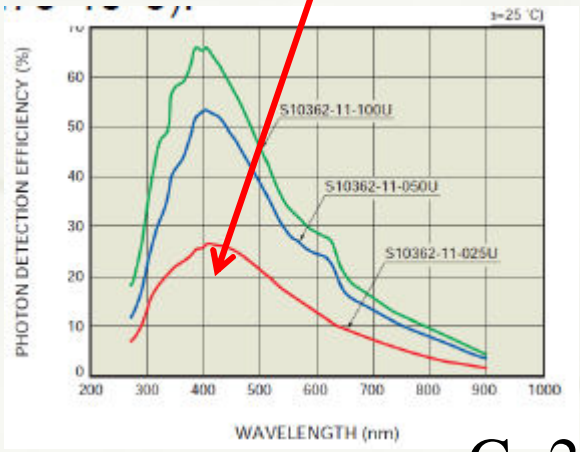
- A source of systematics is the optical contact
- The absolute error is ~1%



Photon detection results



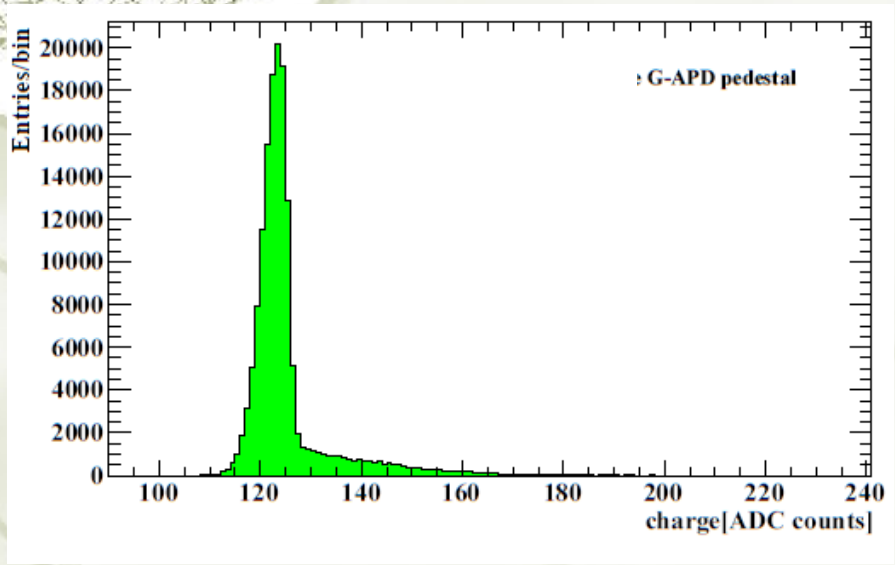
S10362-11-025U MPPC
Hamamatsu

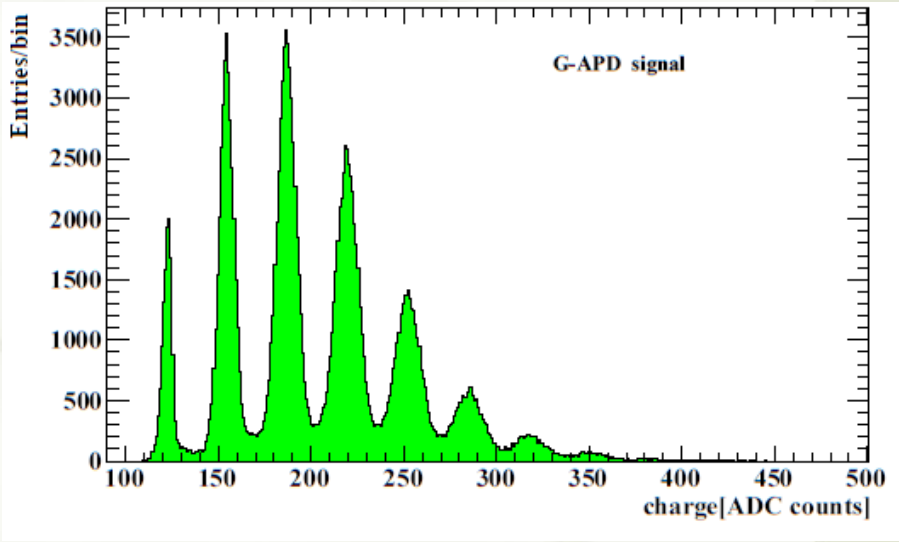


G~2.75 *10^5
Including AP and xtalk

CPTA

λ=600nm



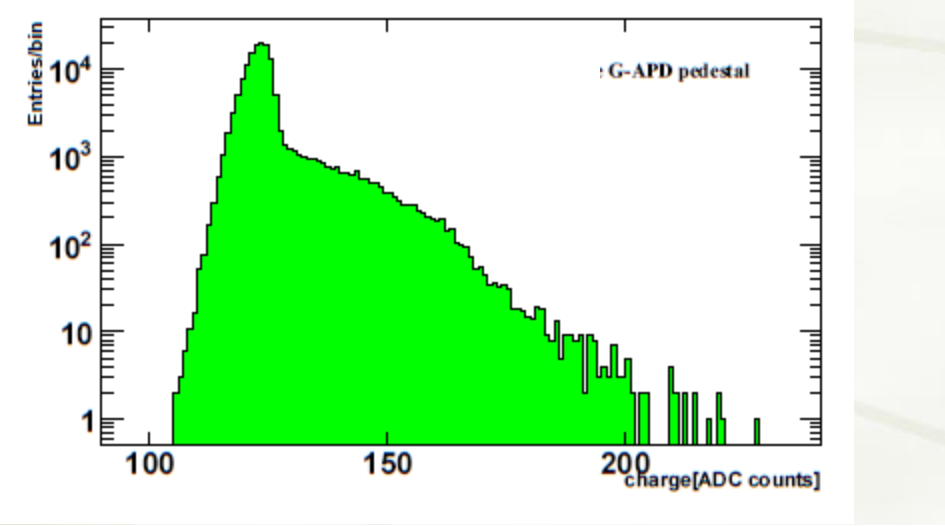


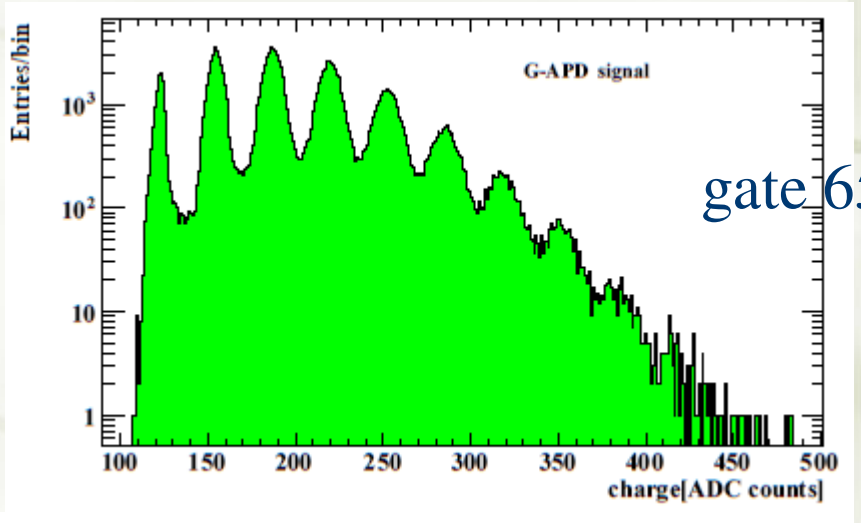
CPTA 2009

noise

signal

G ~4.7 *10^5





gate 65ns

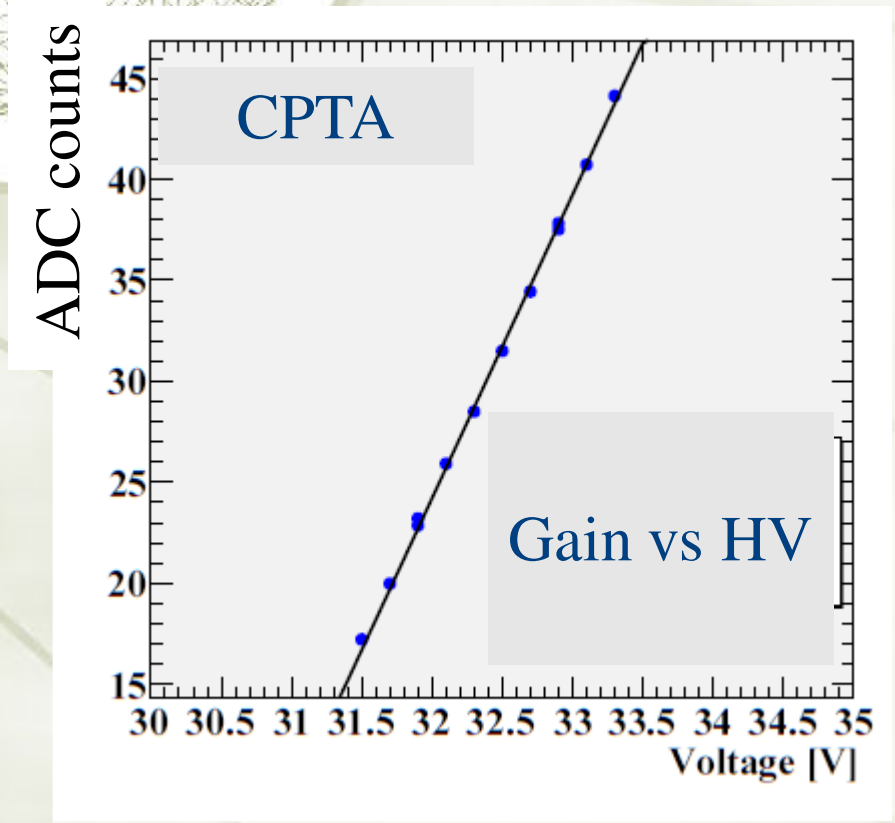
$$N(x) = N \times \sum_n (\mathrm{Gauss}(\mathrm{x}, \mu_\mathrm{n}, \sigma_\mathrm{n}) \times \mathrm{Poisson}(\mathrm{n}, \lambda))$$

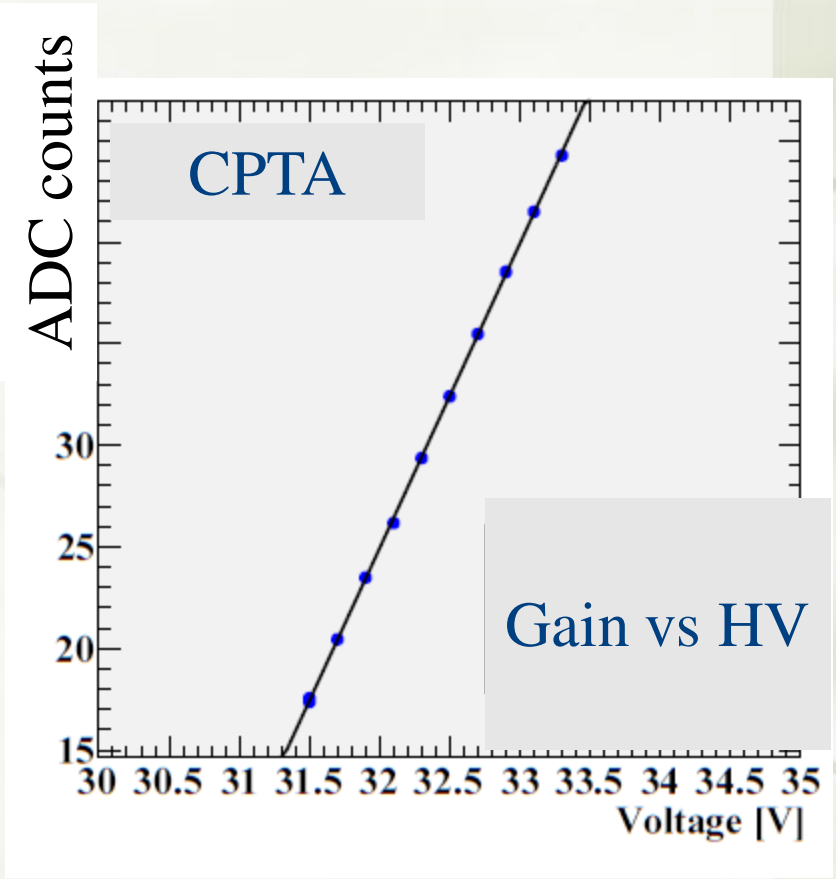
const x $e^{-\lambda} \sum_n (\lambda^n/n!\ 1/\sigma_n \exp\{-(x-\mu_n)^2/(2\sigma_n)^2\})$

Real situation:

- Termogeneration → ~ 30% our timing
- After-pulsing→minor compared to Termogener.
- Cross-talk →much lower than Hamamatsu

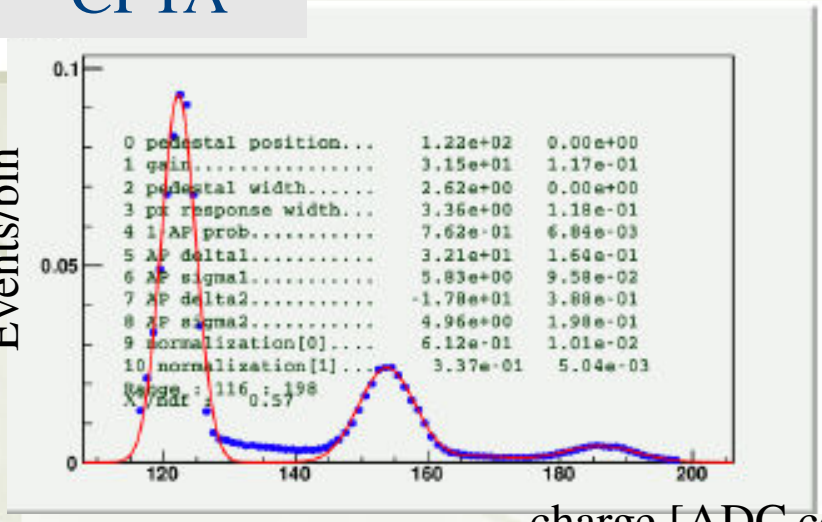
Gain vs HV


CPTA
Gain vs HV
ADC counts
45
40
35
30
25
20
15
30 30.5 31 31.5 32 32.5 33 33.5 34 34.5 35
Voltage [V]


CPTA
Gain vs HV
ADC counts
30
25
20
15
30 30.5 31 31.5 32 32.5 33 33.5 34 34.5 35
Voltage [V]

PDE CPTA

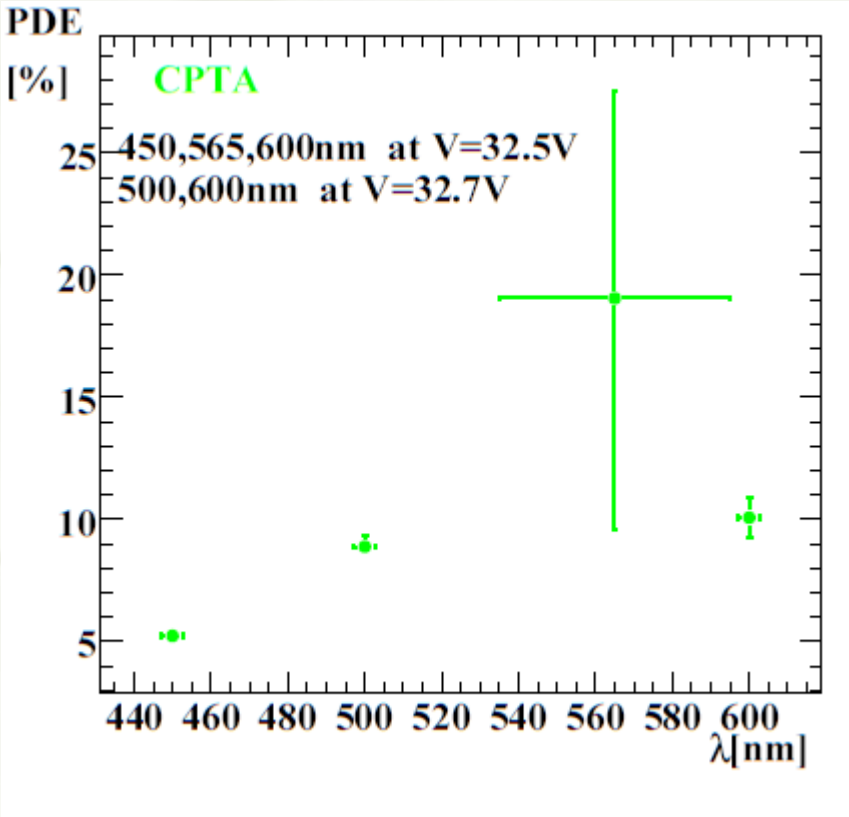
CPTA



Preliminary results

- Ignoring Thermogeneration contribution.
- AP considered as a correction term taking in account AP and TG
- **Low crosstalk value**
- No sensitivity to crosstalk in the fit

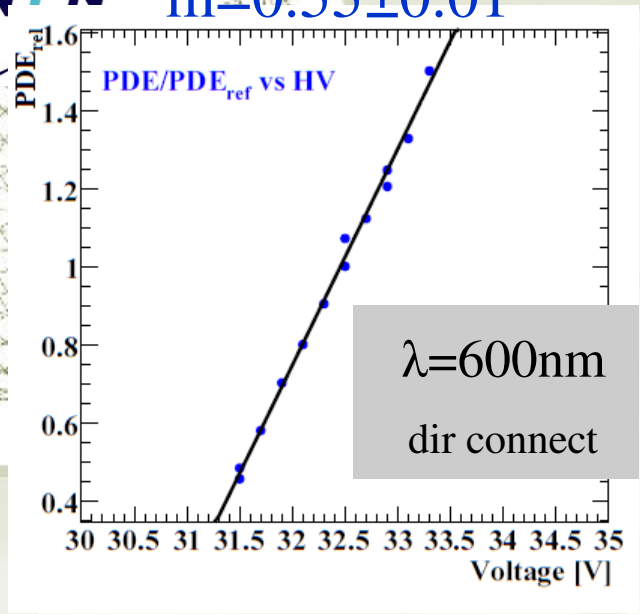
PDE CPTA



- Similar results extrapolating all point at 32.5V

PDE vs HV

m=0.55±0.01



As test:

at **32.7V**

PDE extrap ~ 10.14 ±0.08 %

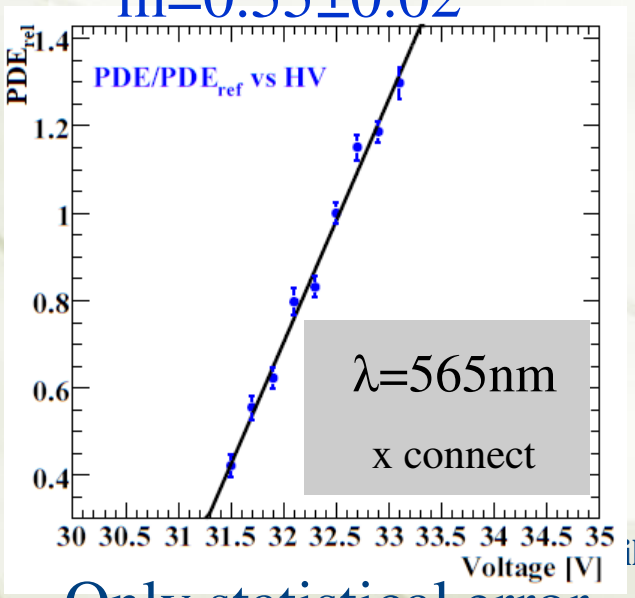
PDE meas=10.07±0.09 %

Not included error on wavelenght

PDE extrap[%]

32.7V ,32.5 V

m=0.55±0.02



- **565nm**

21.15 ±0.23

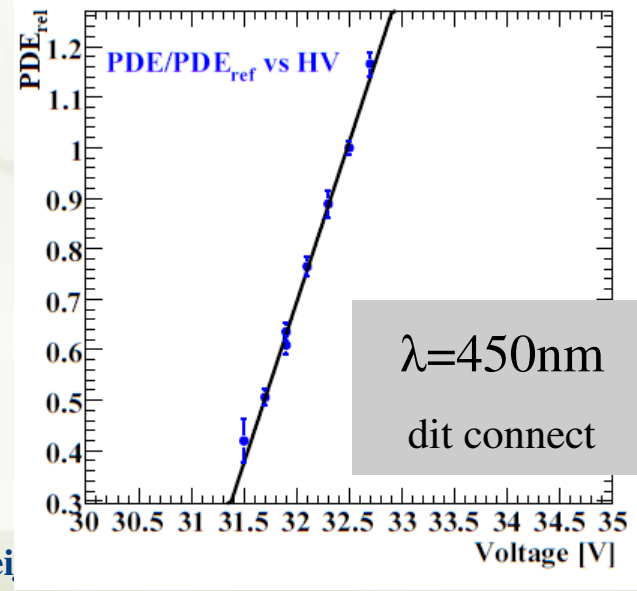
19.05 ±0.22

- **450nm**

5.90 ± 0.05

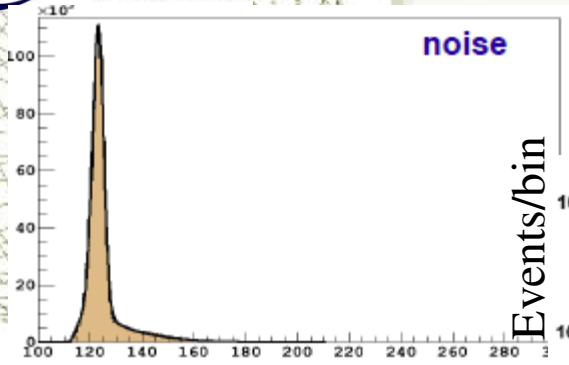
5.23±0.05

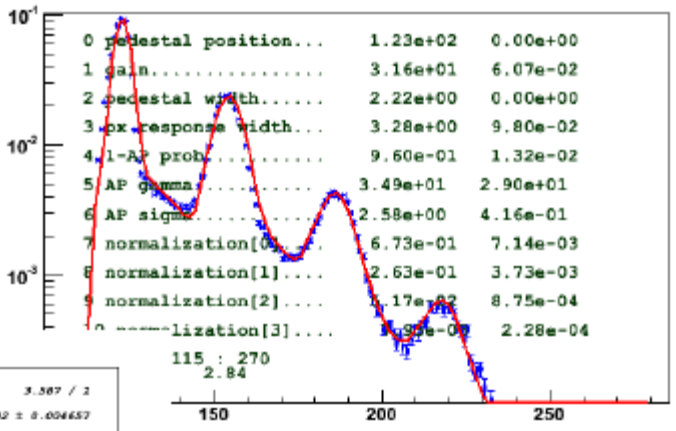
m=0.64±0.02

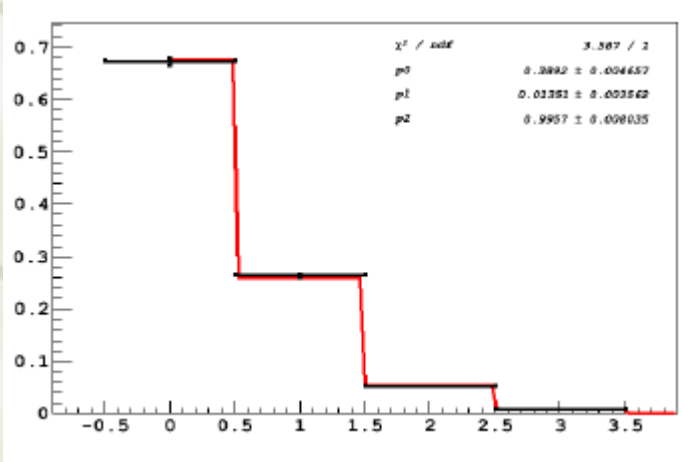


Only statistical error

CPTA Crosstalk







Average x-talk

~ 1.7%

- Thermogeneration taken in account
- Asymmetric shape AP

$(dP/dx \sim (G-x)^{\gamma})$

$\gamma = 1/(\alpha\,\tau - 1)$

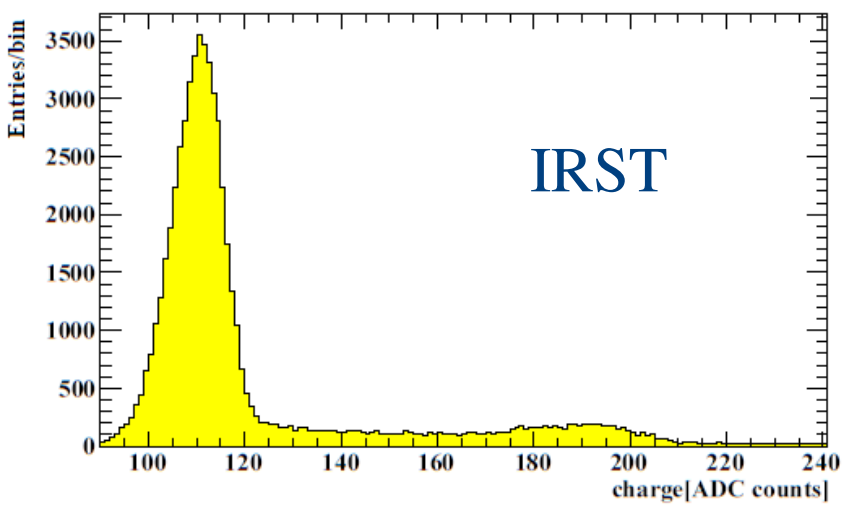
τ trap life time

α recovery time

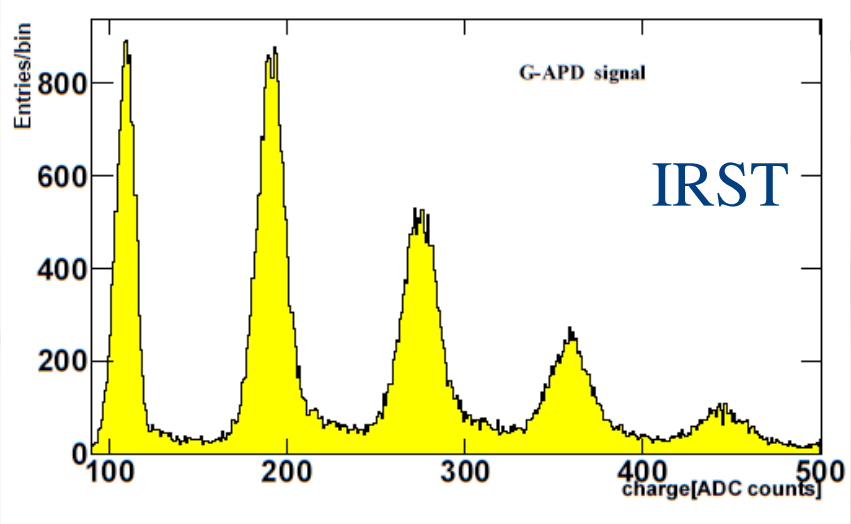
IRST

λ=600nm

Pedestal



Signal



Different light intensity of CPTA sample

Peculiar specimen

Conclusion

- Estimation of PDE based on LED response measurements on Hamatsu and CPTA G-APD.
- Fit procedure including individual AP and cross talk
- Systematic error:
- **Different fibers** for reference and test detector.Neglegible
- **Reconnection of fibers**. Weighted mean over several mesaurements after reconnection
- **Fit procedure**: weighted mean over serveral mesaurements for different light intensities
- Possible improvement of fit procedure