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Characterization of radiation-degraded SiPM with unresolved pulse height spectrum

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[d] CERN CMS collaboration

Content

- Motivation:
  - Unresolved photoelectron spectra are not very exotic
  - SiPM characterization methods are not determined to find

  Gain, number of primary photoelectrons Npe, ENF/probability of crosstalk CT

- Statistics of correlated events as a key of the problem:

Branching Poisson process and Generalized Poisson distribution

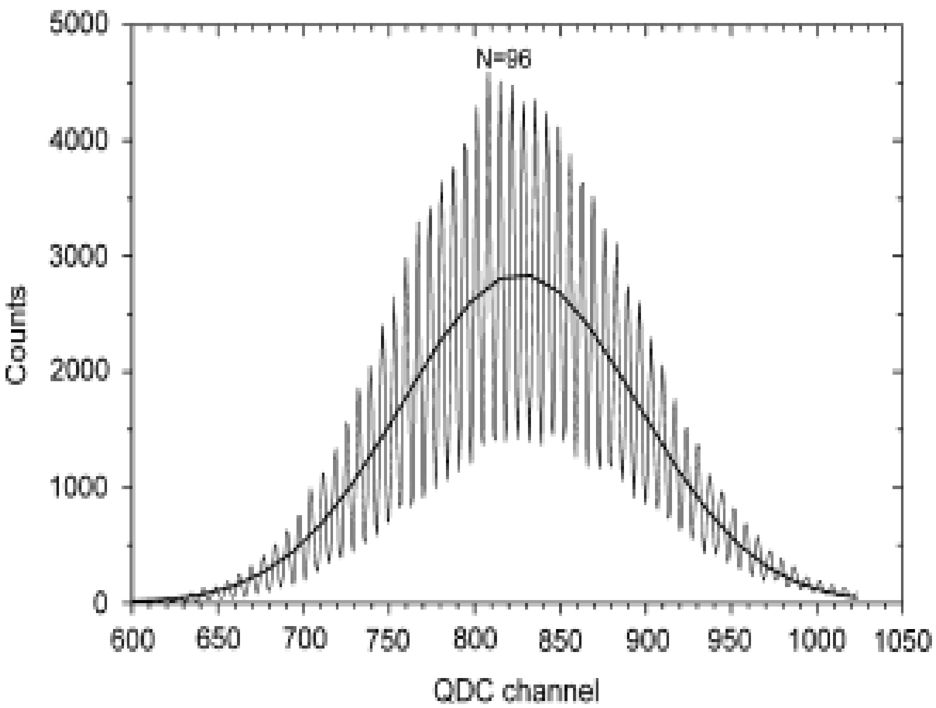
  - Model and its verification results
  - CERN CMS SiPM characterization by Generalized Poisson

- Resolving unresolved by Effective Gain (Fano factor)

- Summary

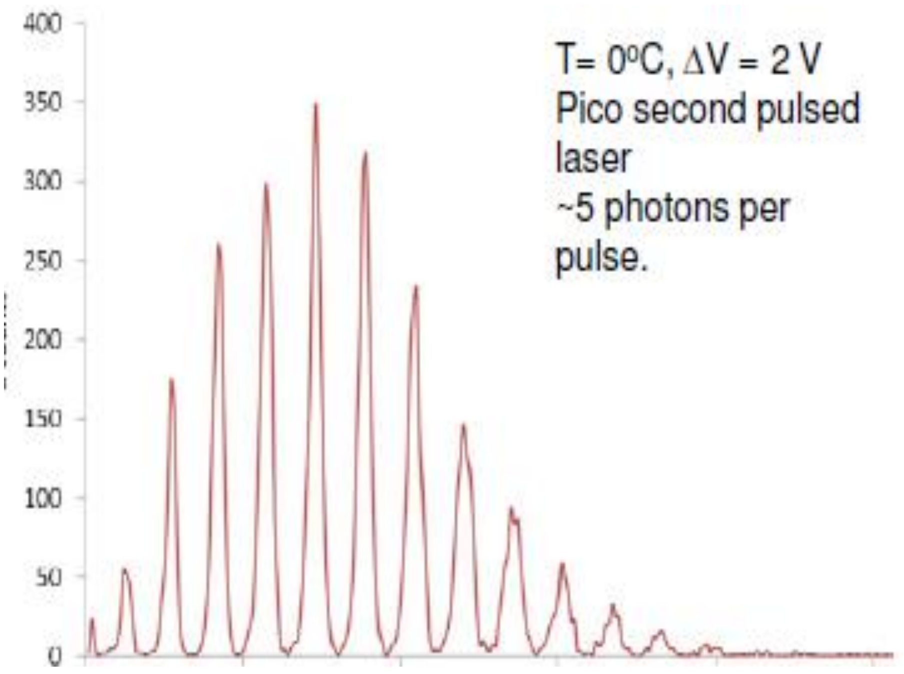
SiPM: photon number resolving detector

SiPM (MEPhI / Pulsar)



R. Mirzoyan et al., NDIP, 2008

SiPM (Excelitas)



A. Barlow and J. Schilz, CERN, 2011

- Why we are concerned about unresolved SiPM spectra?

Resolved spectrum = known Npe & Gain

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If the spectrum peaks are visible => Gain

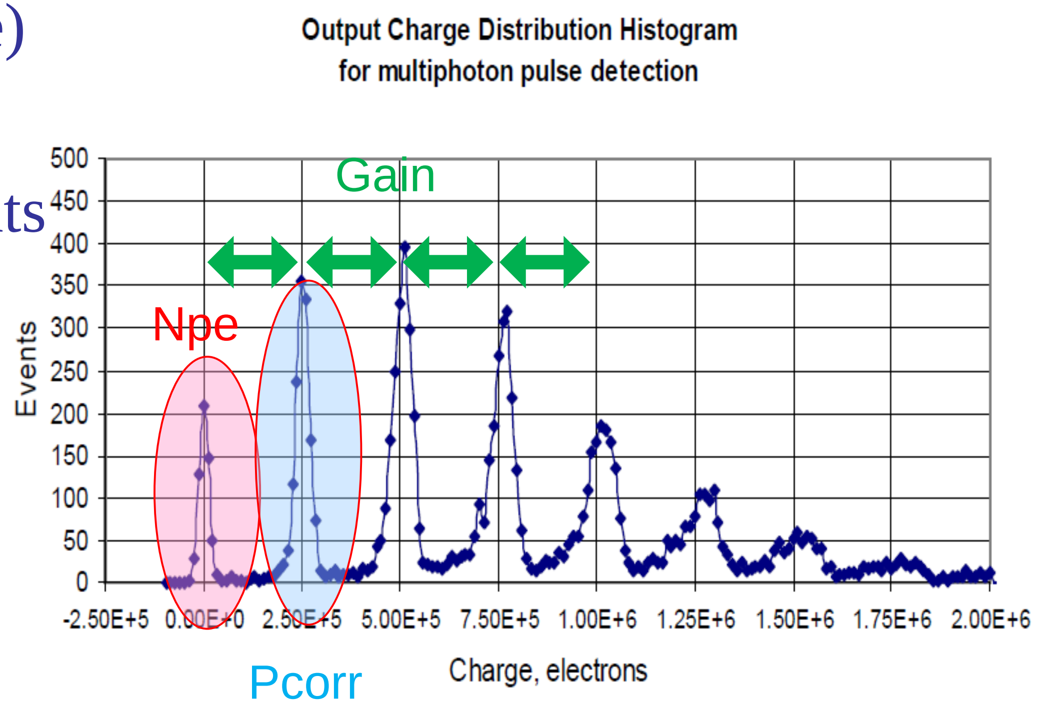
If the zero-peak N(0) is determined and

if Poisson light is assumed => Npe

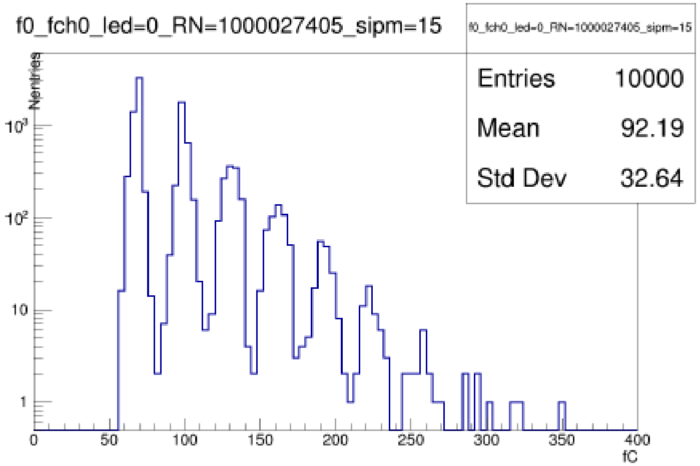
Pr(0) = N(0)/Ntot = exp(-Npe)

Probability of correlated events Pcorr could be defined by deviation from Poisson:

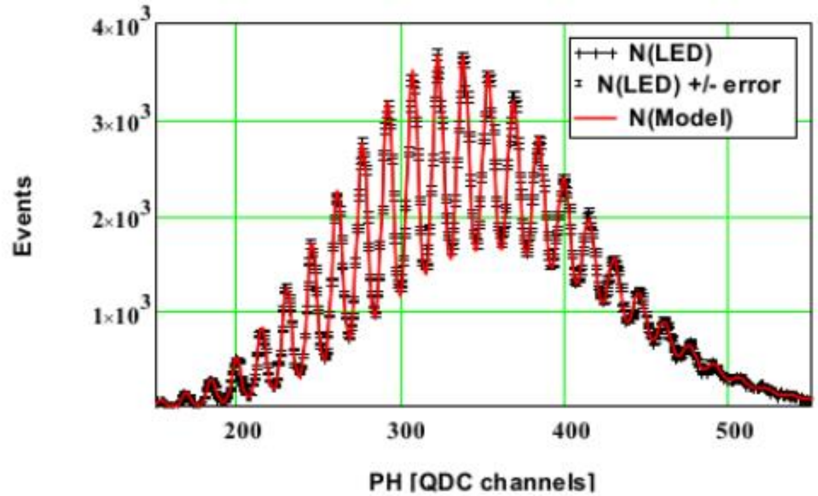
$$P(N=1) = P_{poisson}(N=1)\cdot\left(1-P_{corr}\right)$$



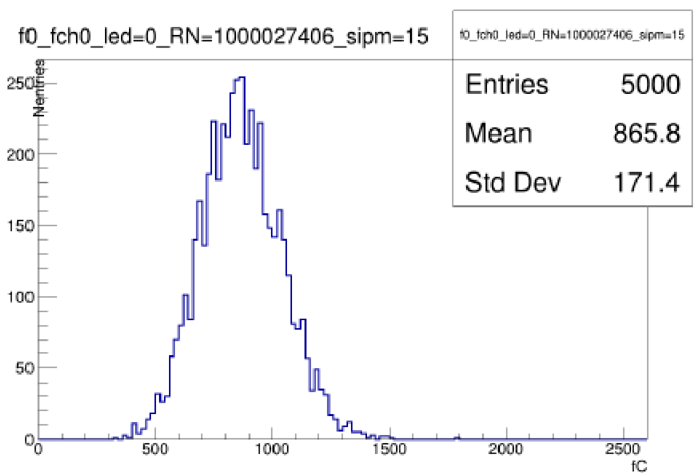
1. Large signal detection



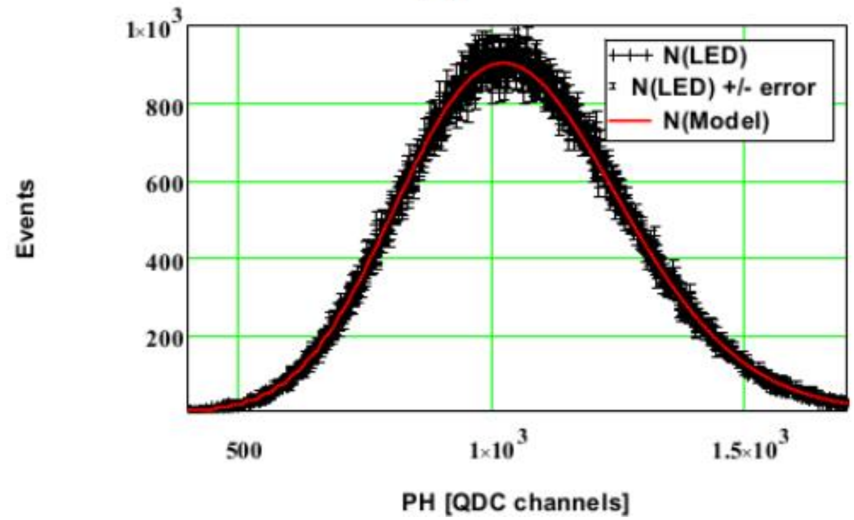
Low intensity LED spectrum



(b)



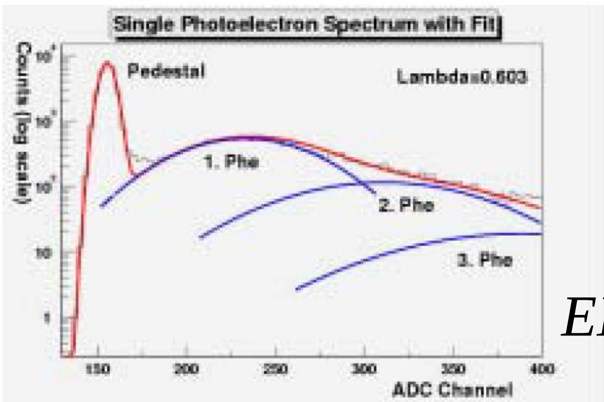
High intensity LED spectrum Pavel



P. Parygin et al., CMS meeting, Varna 2017

V. Chmill et al., NIMA 2017

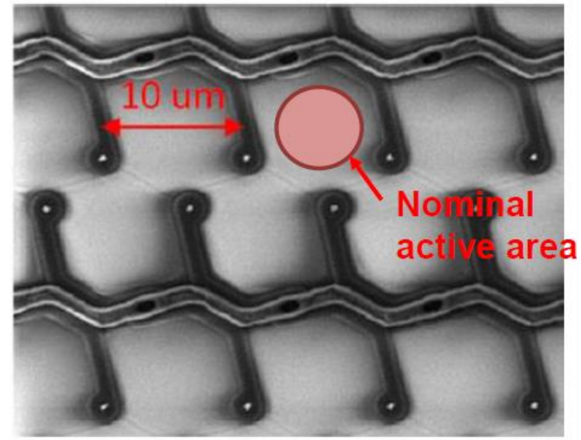
- Excess Noise Factor (ENF) is a measure of SNR degradation due to multiplication process with random gain



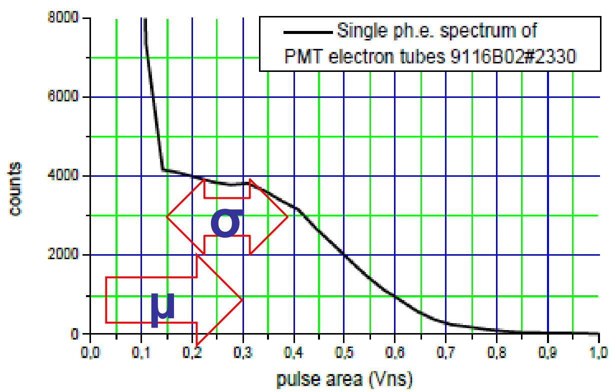
C. Hsu et al, PMT Characterization for MAGIC II Telescope, ICRS 2007

$$ENF_{Gain} = 1 + \frac{\sigma^2_{Gain}}{\overline{Gain}^2}$$

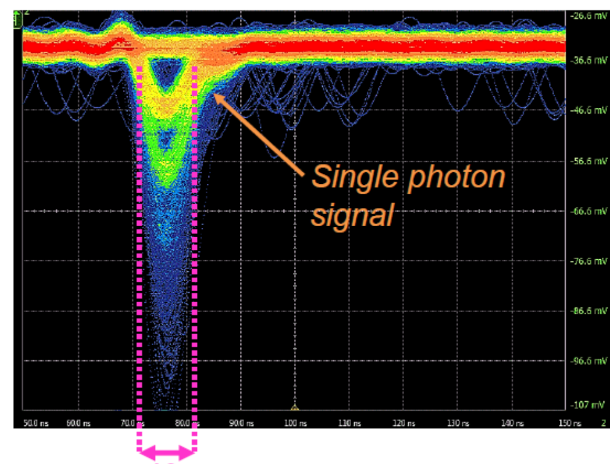
$$\overline{Gain}_{SiPM} = C \cdot (V - Vbr)$$



7.5 µm cell

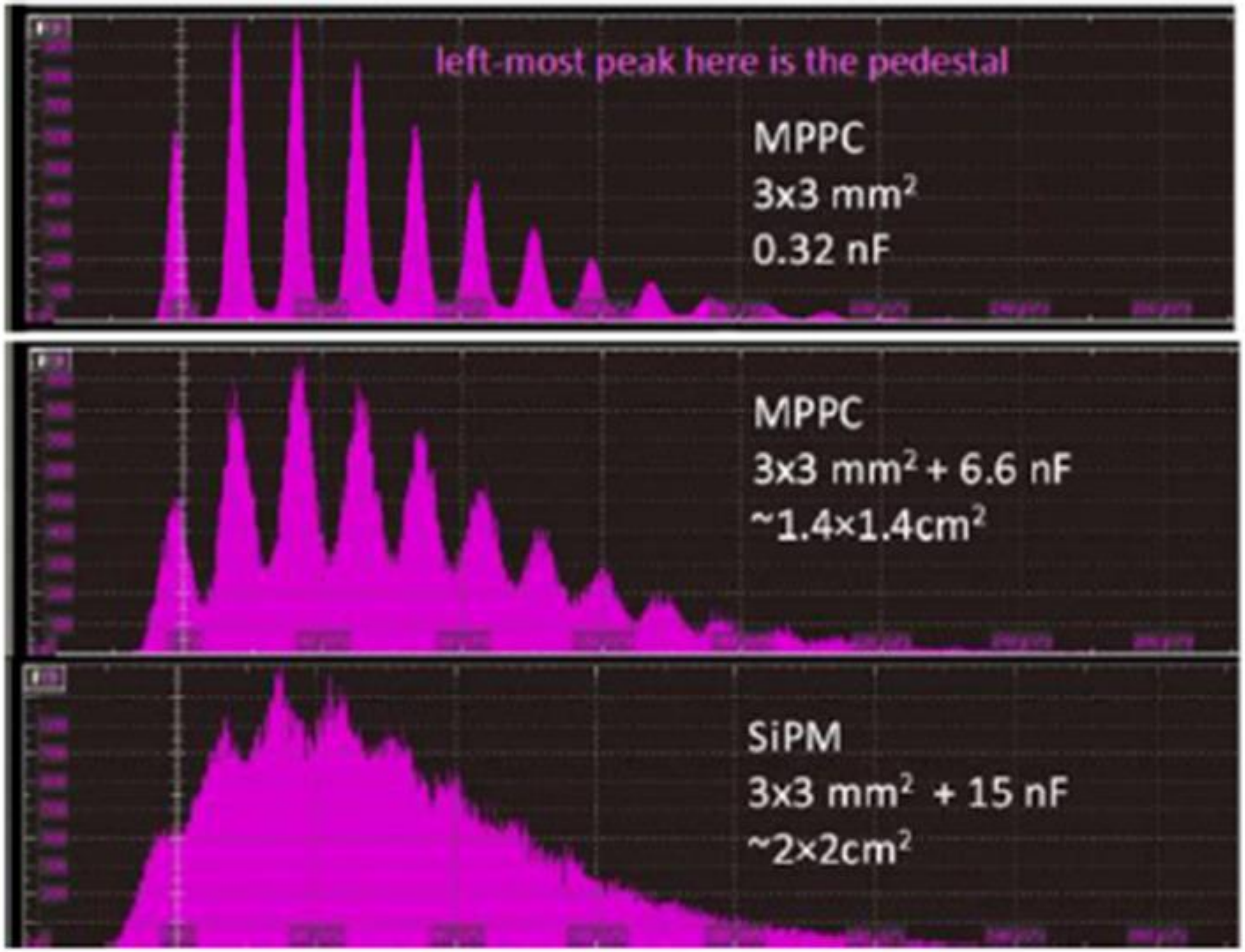


R. Mirzoyan: SER of low gain PMT for MAGIC (Gain ~2·10^4)



F.Acerbi, FBK UHD SiPM, 2017

3. Large area / High noise

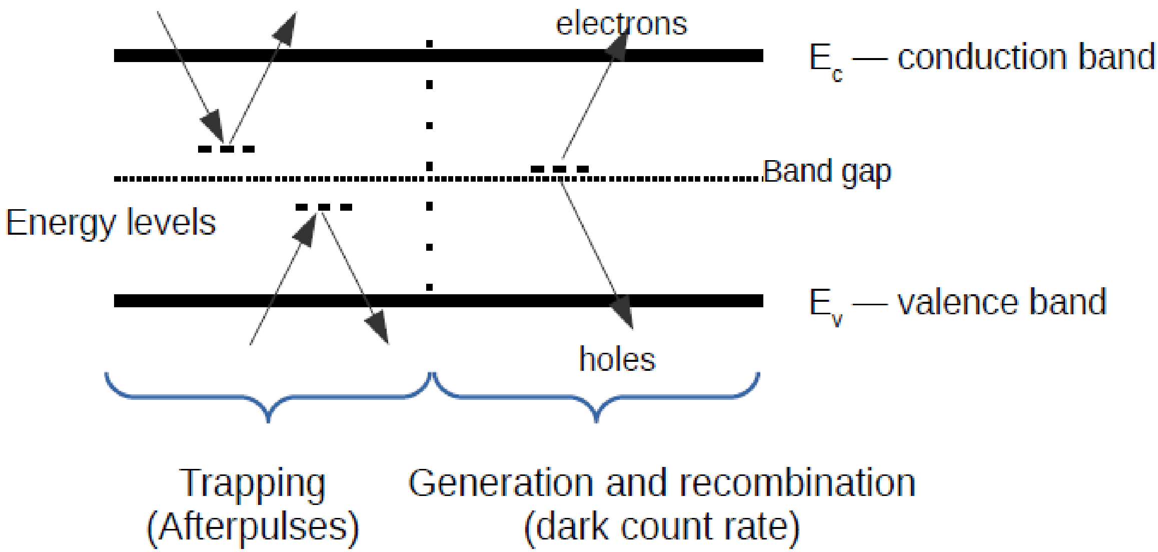


G. Visser (Indiana Univ.)

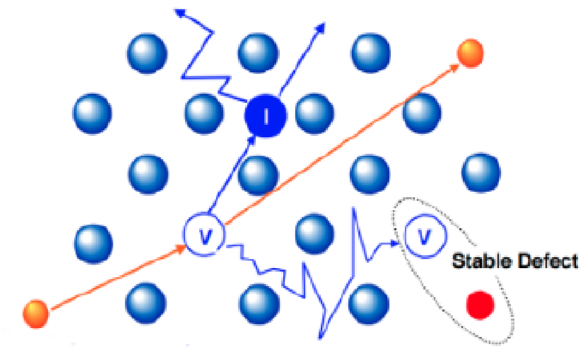
Large area SiPM (imitation by external Capacitance)

4. Radiation damage of SiPM

Energy levels of radiation defects in bandgap:



Formation of defects:



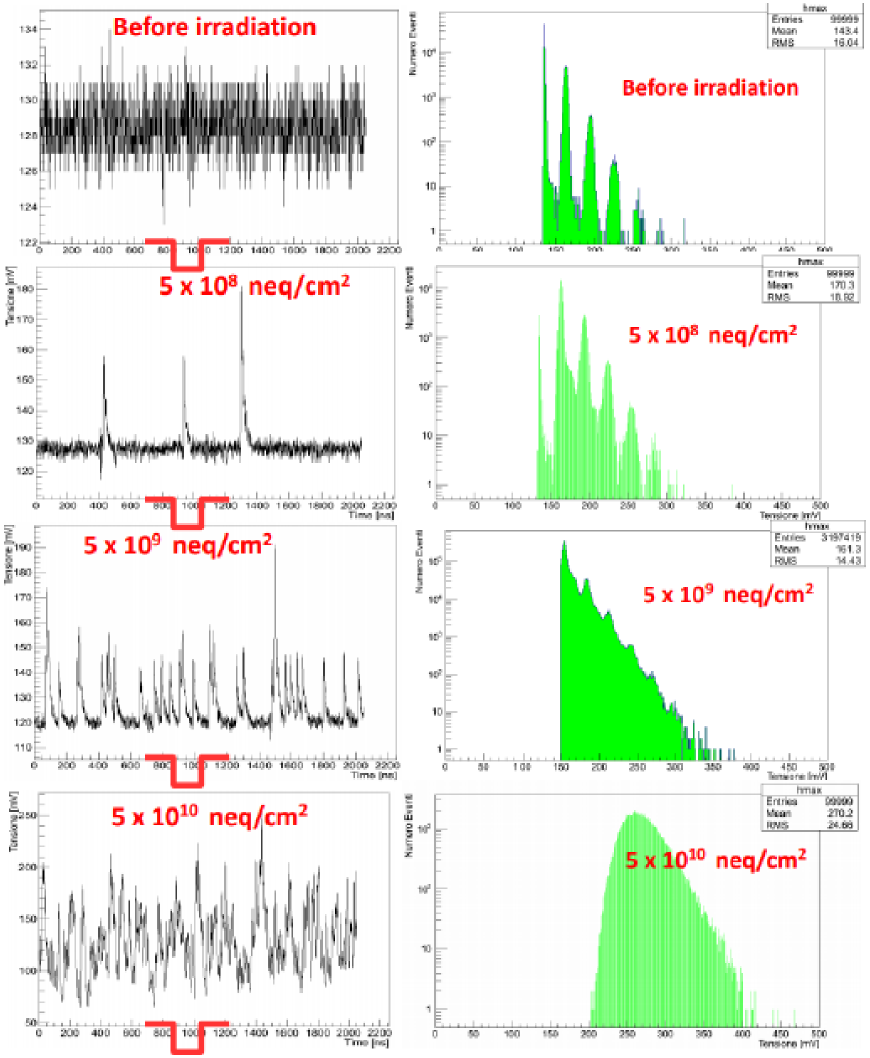
Radiation defects produce energy levels in bandgap. These levels may work as trap levels or generation-recombination levels:

- Trapping levels can capture electrons or holes during avalanche and release them later. This can cause additional avalanche and additional firing of cells;
- Generation and recombination levels provide probability to generate a pair of free hole and electron (generation process) or eliminate electron and hole captured from conducted and valence bands.

Afterpulsing will increase total number of correlated events.

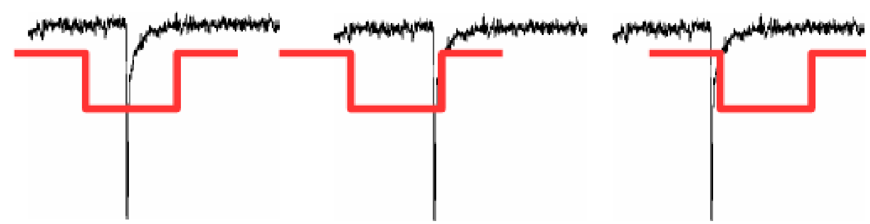
Pavel Parygin, Varna, 30th August 2017 5

4. Radiation damage / High DCR / Night Sky



1x1 mm^2, 50 um pixel size

Partially integrated pulses cause blurring of spectrs.
Increase of DCR will increase degradation of spectra.



Expected fluences in HCAL in Phase 1 upgrade:

- HE — up to 10^{11} neq/cm^2;
- HF — up to 10^{12} neq/cm^2;

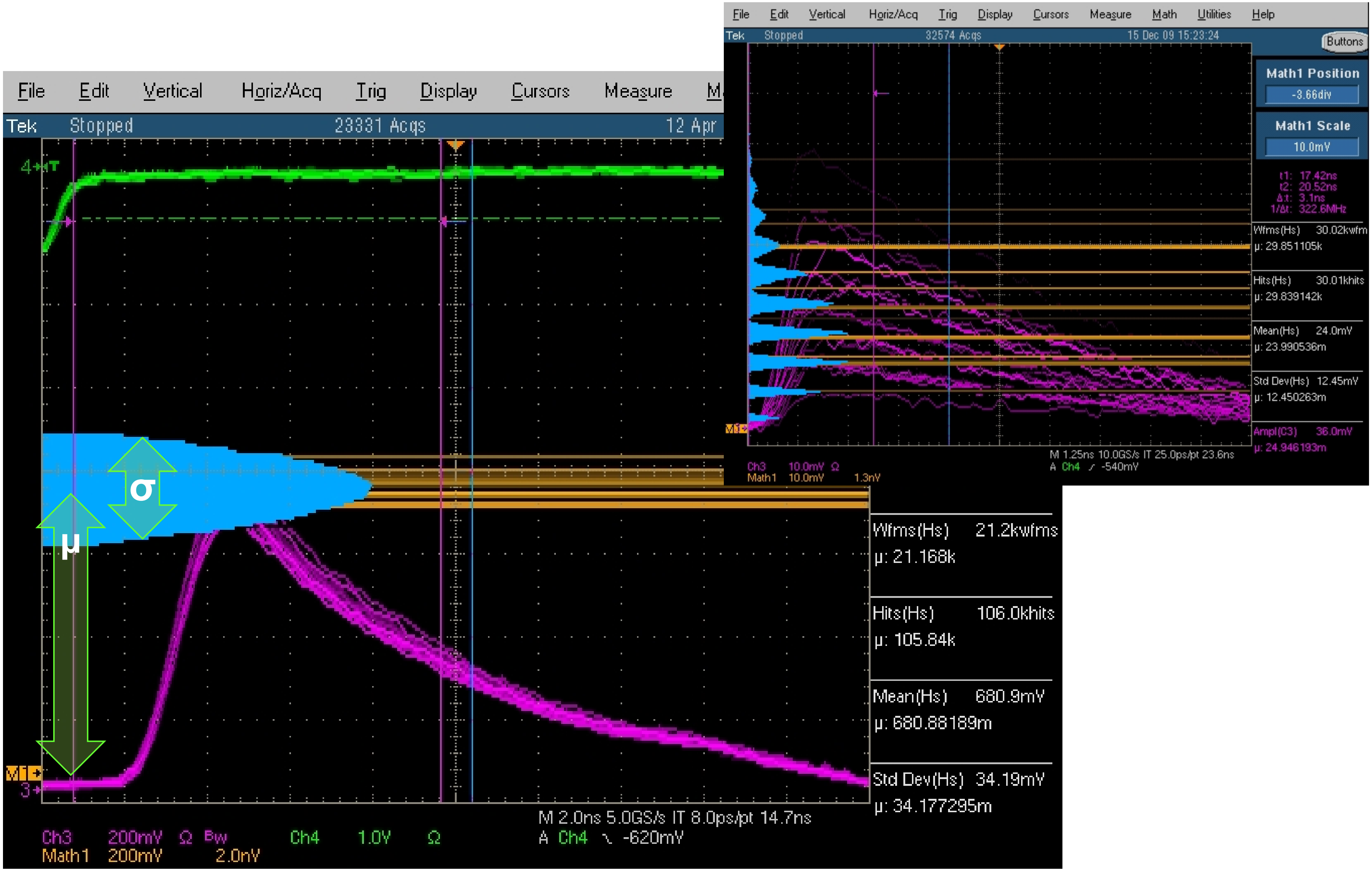
For HGCAL expected fluence is up to $5{*}10^{13}$ neq/cm^2.

Increasing of DCR leads to loss of SPE peaks.

Pavel Parygin, Varna, 30th August 2017

Wander Baldini, TIPP 2014 Amsterdam, June 2-6 2014

What we can do with unresolved spectrum?



SiPM response: Mean and StdDev with correlated events (CT & AP)

N_{pe}, Gain, ENF, $Mean_{Corr}$ - unknown

Mean & Var = $StdDev^2$ - measured

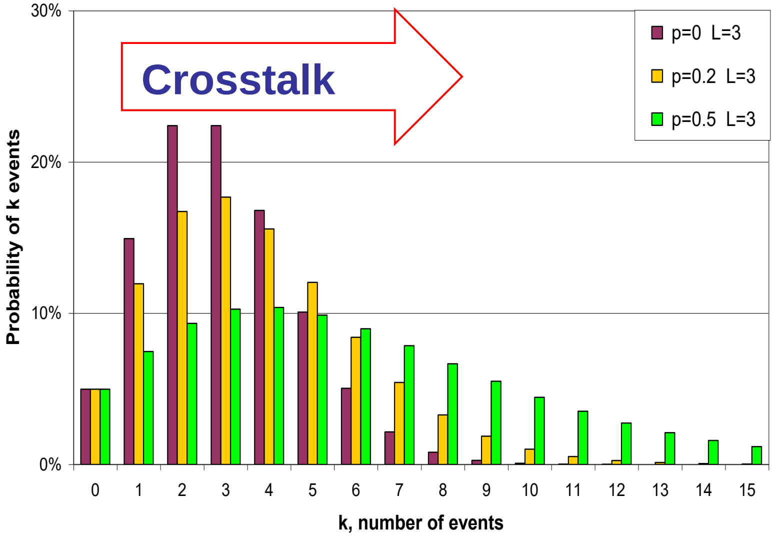
$$Mean_{OUT} = N_{pe} \cdot (1+\mu_{Corr}) \cdot Gain$$

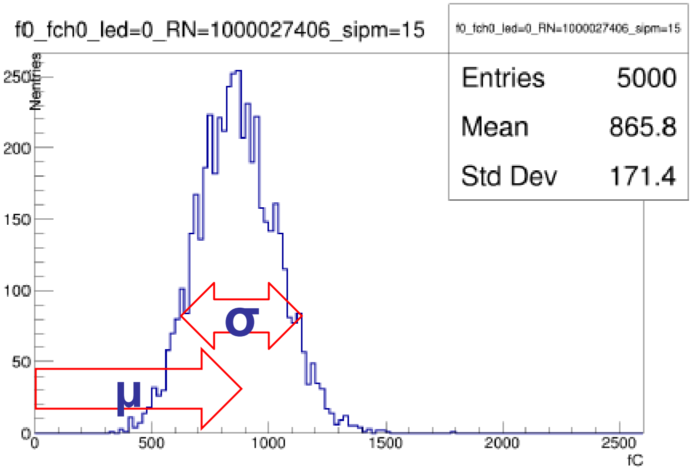
$$Var_{OUT} = N_{pe} \cdot (1+\mu_{Corr})^2 \cdot Gain^2 \cdot ENF$$

or

$$RES_{OUT} = \frac{StdDev_{OUT}}{Mean_{OUT}} = \sqrt{\frac{ENF}{N_{pe}}}$$

$$Fano_{OUT} = \frac{Var_{OUT}}{Mean_{OUT}} = Gain \cdot (1+\mu_{Corr}) \cdot ENF$$





High intensity LED spectrum

Pavel

P. Parygin et al., CMS meeting, Varna 2017

Unresolved spectrum =

= unresolved unknowns =>

Statistics of CT & AP to be determined

Statistics of correlated events (CT & AP)

- Probability distribution of number of correlated events N
  - Initiated by single primary event (photoelectron, dark electron)
  - Initiated by random (Poissonian) primary events
- Mean number of correlated events μ_{corr}
- StdDev of correlated events σ_{corr}
- ENF of correlated events

$$ENF_{Corr} = 1 + \frac{\sigma_{Corr}^2}{\mu_{Corr}^2}$$

Correlated avalanche events: SiPM crosstalk (CT) & afterpulsing (AP)

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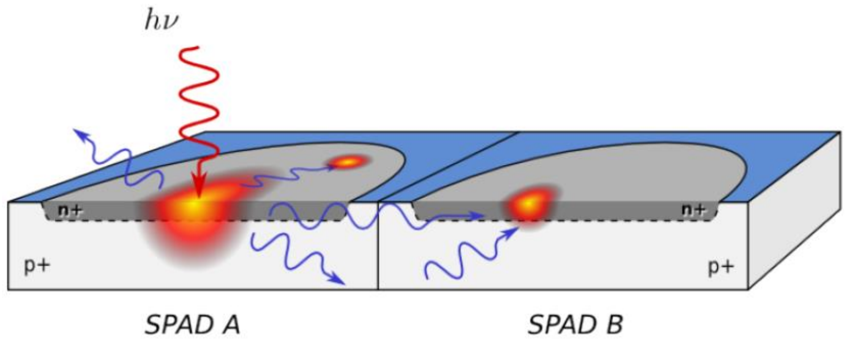
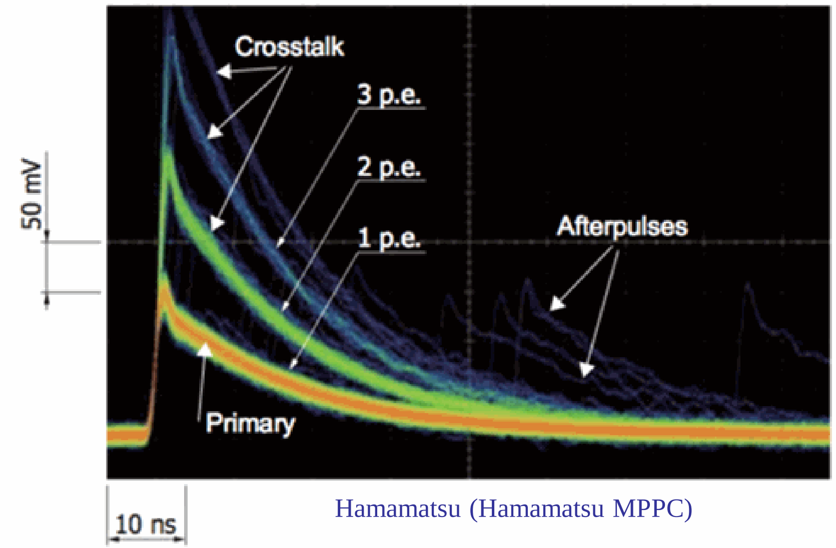
Hot carrier photon emission = CT

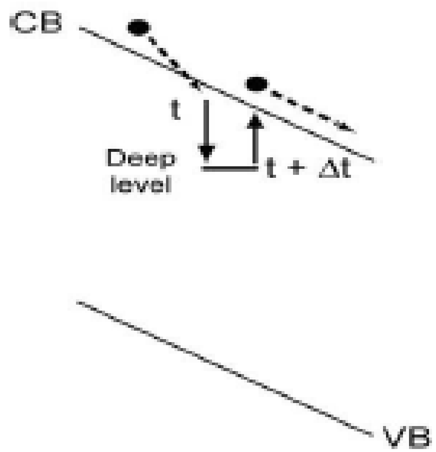


A. Lacaita et al., IEEE TED, 1993

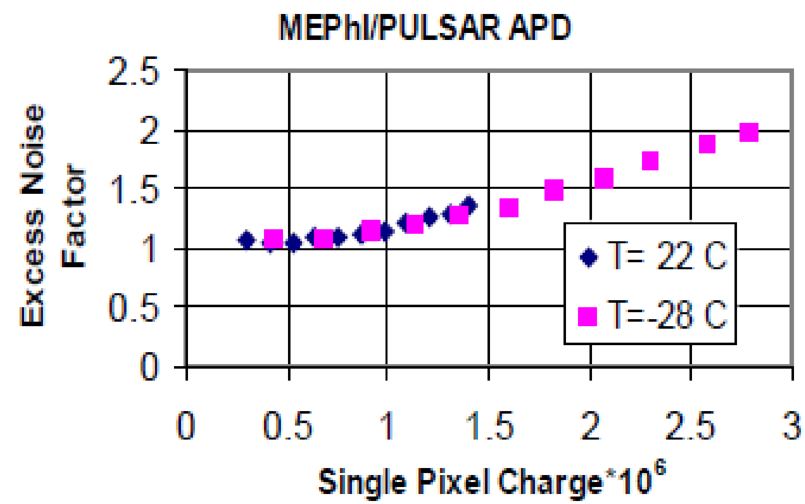


Hamamatsu (Hamamatsu MPPC)

Trapping-detrapping of carriers = AP

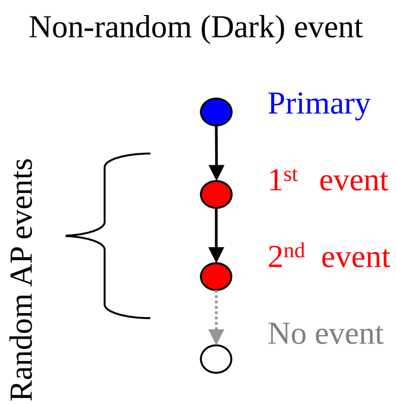
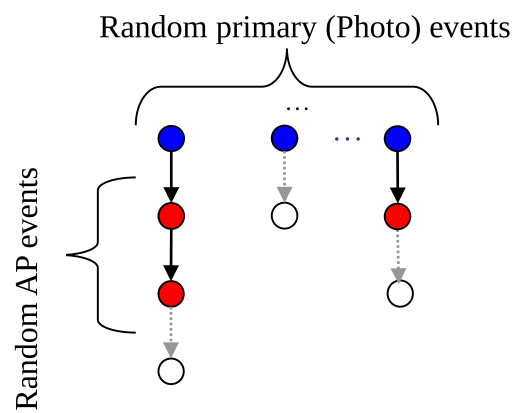
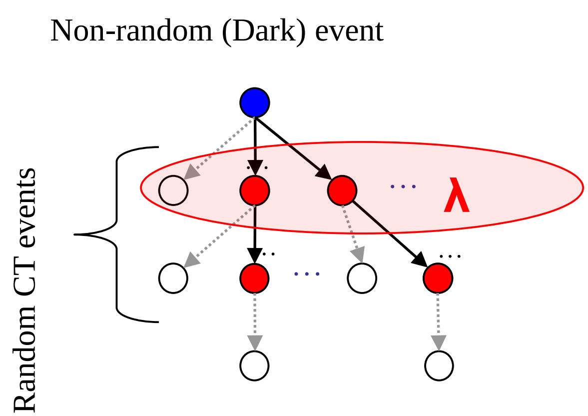
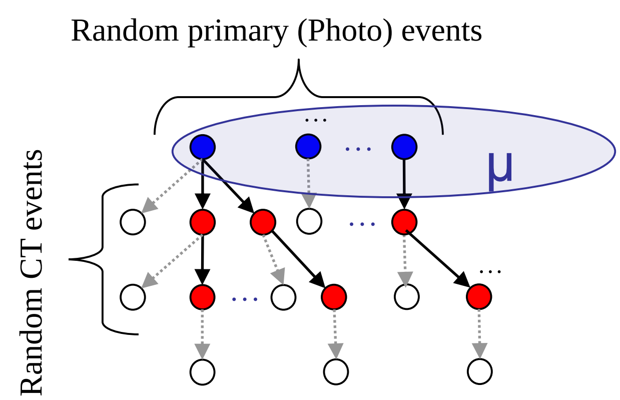


CT is a main contribution to ENF in SiPM



Yu. Musienko, NDIP, 2005

Correlated stochastic processes of CT & AP

Process Models	Single primary event N≡1 e.g. SiPM dark electron spectrum	Poisson number of primaries <N>=μ e.g. SiPM photoelectron spectrum
Geometric Chain Process		
Branching Poisson Process		

S. Vinogradov, IEEE NSS/MIC 2009, TNS 2011, NDIP 2011, NIMA 2012

Correlated process models

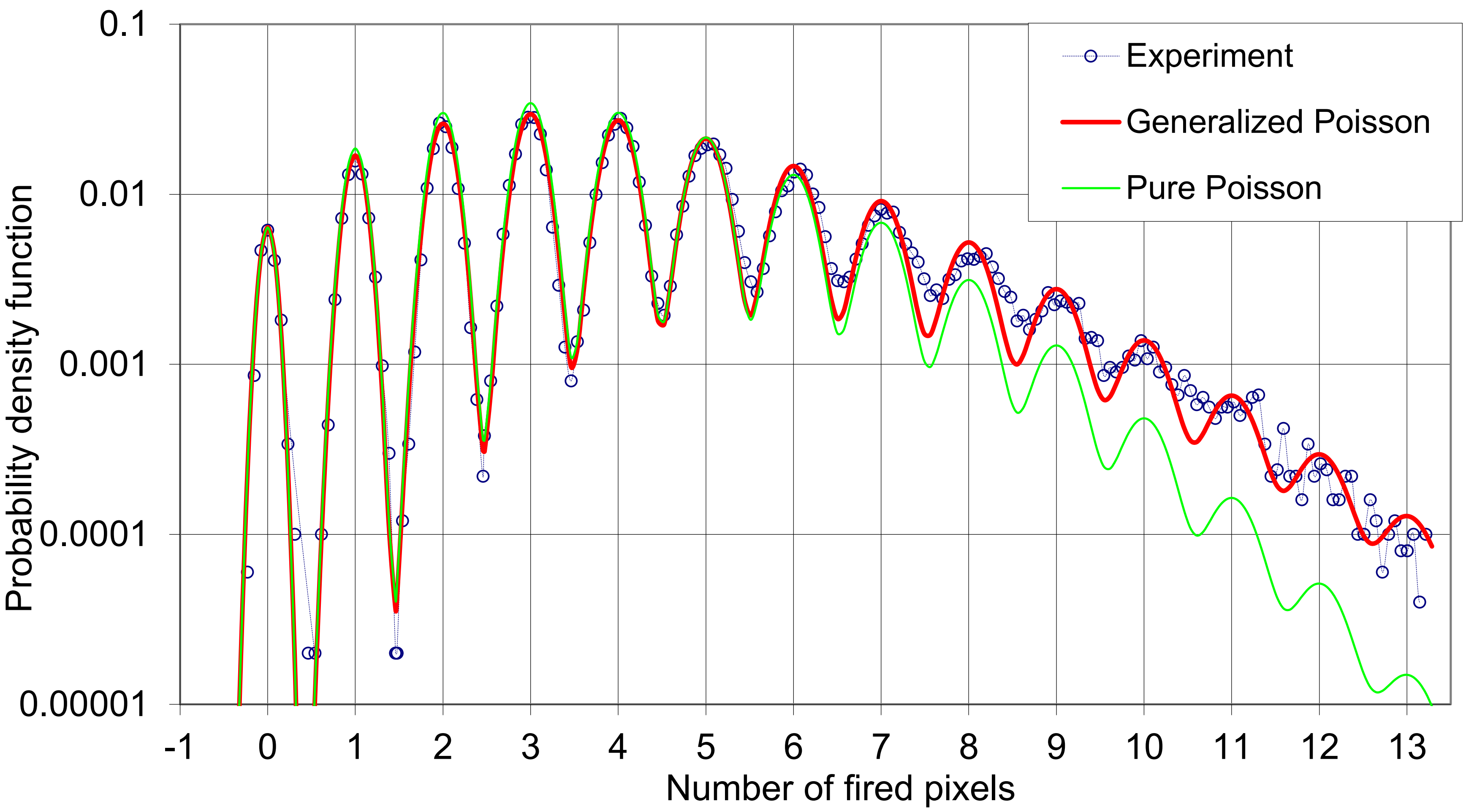
Results	**Geometric chain process**		**Branching Poisson process**	
Primary event distribution	Non-random single ($N\equiv1$)	Poisson (μ)	Non-random single ($N\equiv1$)	Poisson (μ)
Total event distribution	Geometric (p)	Compound Poisson (μ, p)	Borel (λ)	Generalized Poisson (μ, λ)
$P(X=k)$	$p^{k-1}\cdot(1-p)$	Ref. [1]	$\frac{(\lambda\cdot k)^{k-1}\cdot\exp(-k\cdot\lambda)}{k!}$	$\frac{\mu\cdot(\mu+\lambda\cdot k)^{k-1}\cdot\exp(-\mu-k\cdot\lambda)}{k!}$
$E[X]$	$\frac{1}{1-p}$	$\frac{\mu}{1-p}$	$\frac{1}{1-\lambda}$	$\frac{\mu}{1-\lambda}$
$Var[X]$	$\frac{p}{(1-p)^2}$	$\frac{\mu\cdot(1+p)}{(1-p)^2}$	$\frac{\lambda}{(1-\lambda)^3}$	$\frac{\mu}{(1-\lambda)^3}$
ENF	$1+p$		$\frac{1}{1-\lambda}\approx1+p+\frac{3}{2}p^2+o(p^3)\ldots$	

[1] S. Vinogradov et al., NSS/MIC 2009

λ is a mean number of successors in one branch generation

S. Vinogradov, IEEE NSS/MIC 2009, TNS 2011, NDIP 2011, NIMA 2012

Generalized Poisson (branching CT) model



A few photon detection spectrum of Hamamatsu MPPC (S. Vinogradov, NDIP-2011, SPIE-2012)

FBK results on Generalized Poisson model

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$$\mathrm{ENF} = \frac{1}{(1-\gamma)} = \mathrm{ECF}. \qquad (7)$$

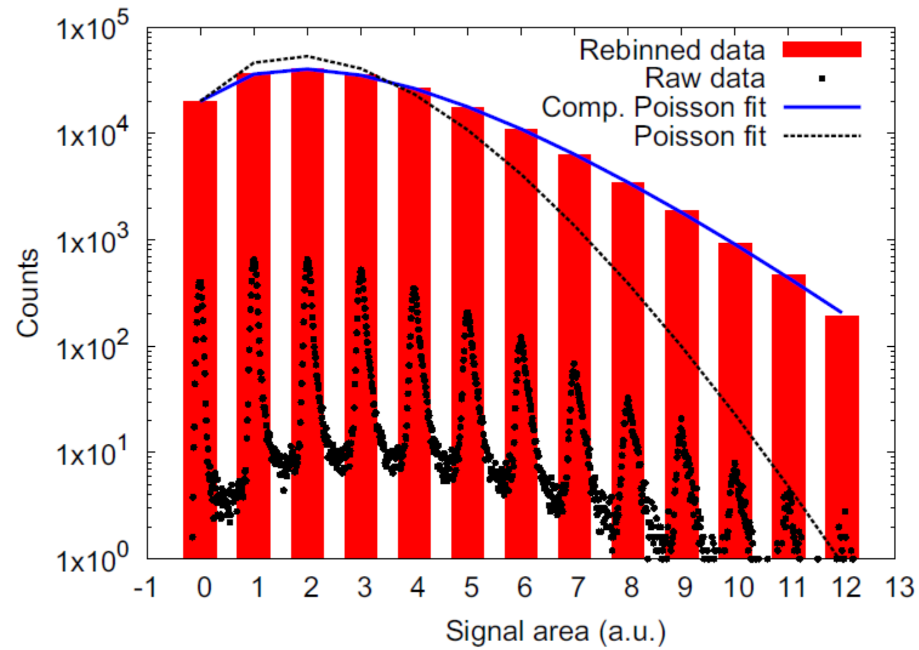

Fig. 8. Histogram of the signal area of a $50 \times 50-\mu\mathrm{m}^2$ RGB SiPM excited with short and faint light pulses. Measurement conditions: $T = 20$ °C; $V_{OV} = 3$ V.

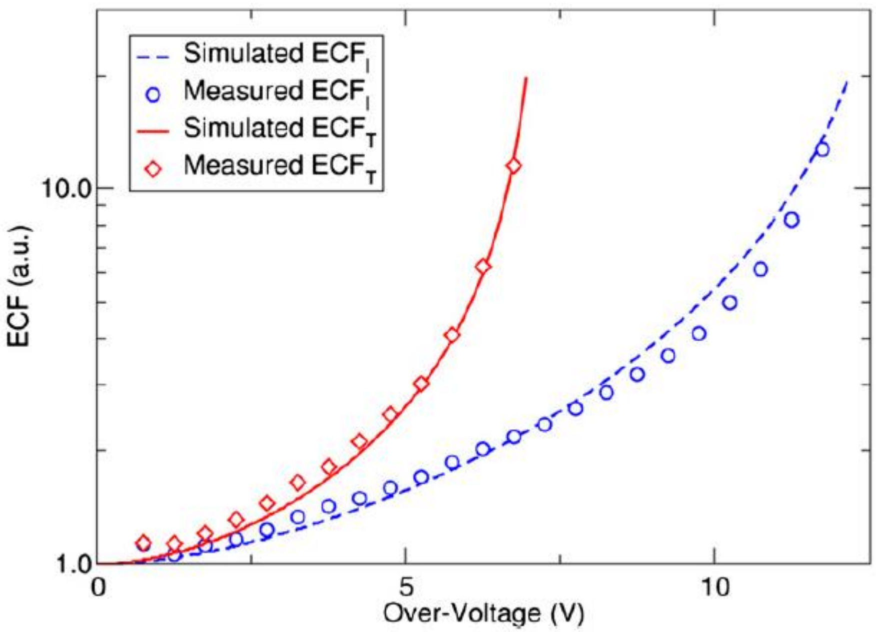

Figure 5. Comparison between the simulated and measured values of ECF for the internal and for the total (internal + external) crosstalk.

A. Gola, A. Ferri, A. Tarolli, N. Zorzi, and C. Piemonte, "SiPM optical crosstalk amplification due to scintillator crystal: effects on timing performance," *Phys. Med. Biol.*, vol. 59, no. 13, p. 3615, 2014.

DESY results on Generalized Poisson

CERN

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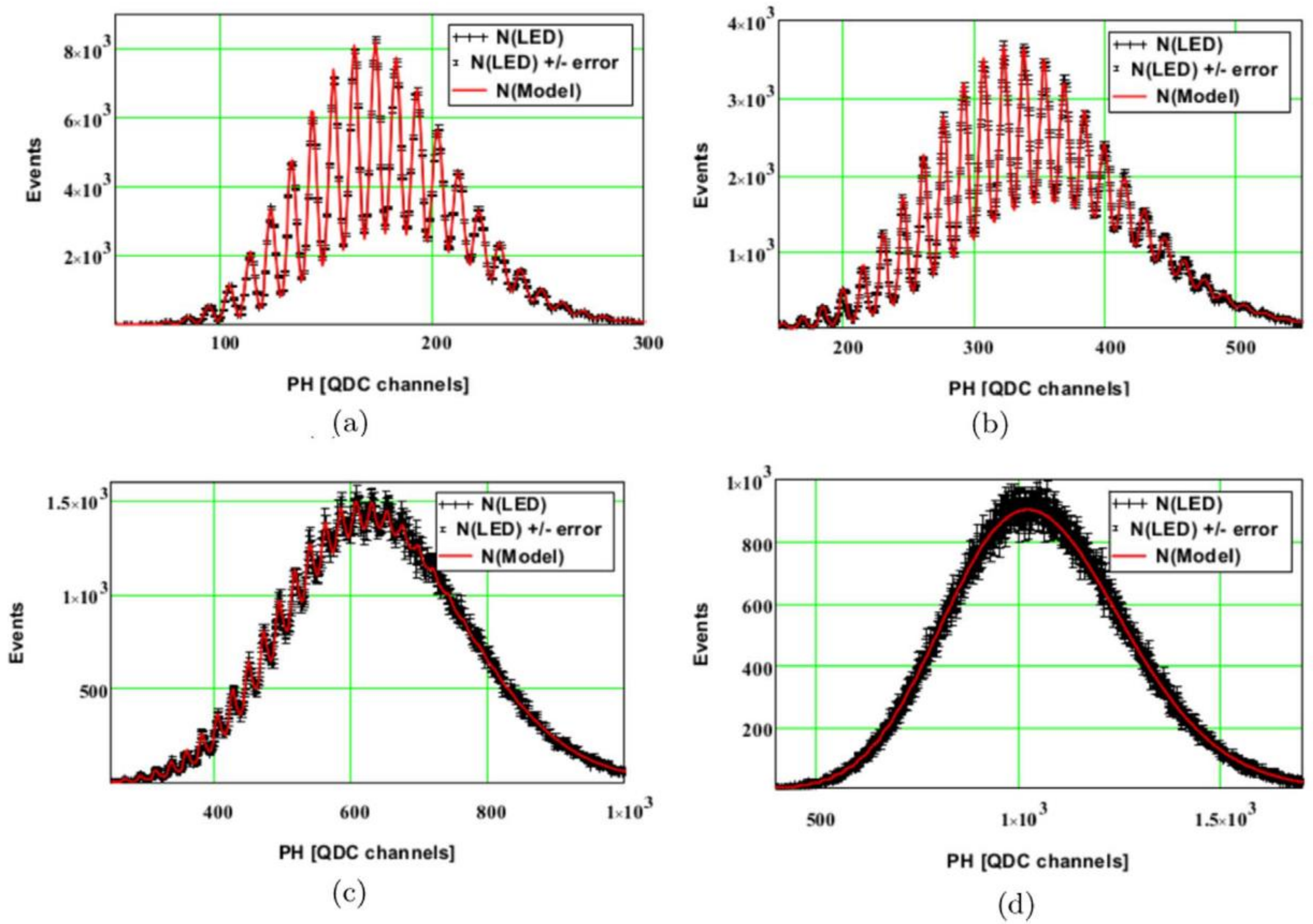
- E. Garutti group @ DESY: V. Chmill et al., NIMA 2017

V. Chmill et al. *Nuclear Instruments and Methods in Physics Research A 854 (2017)*

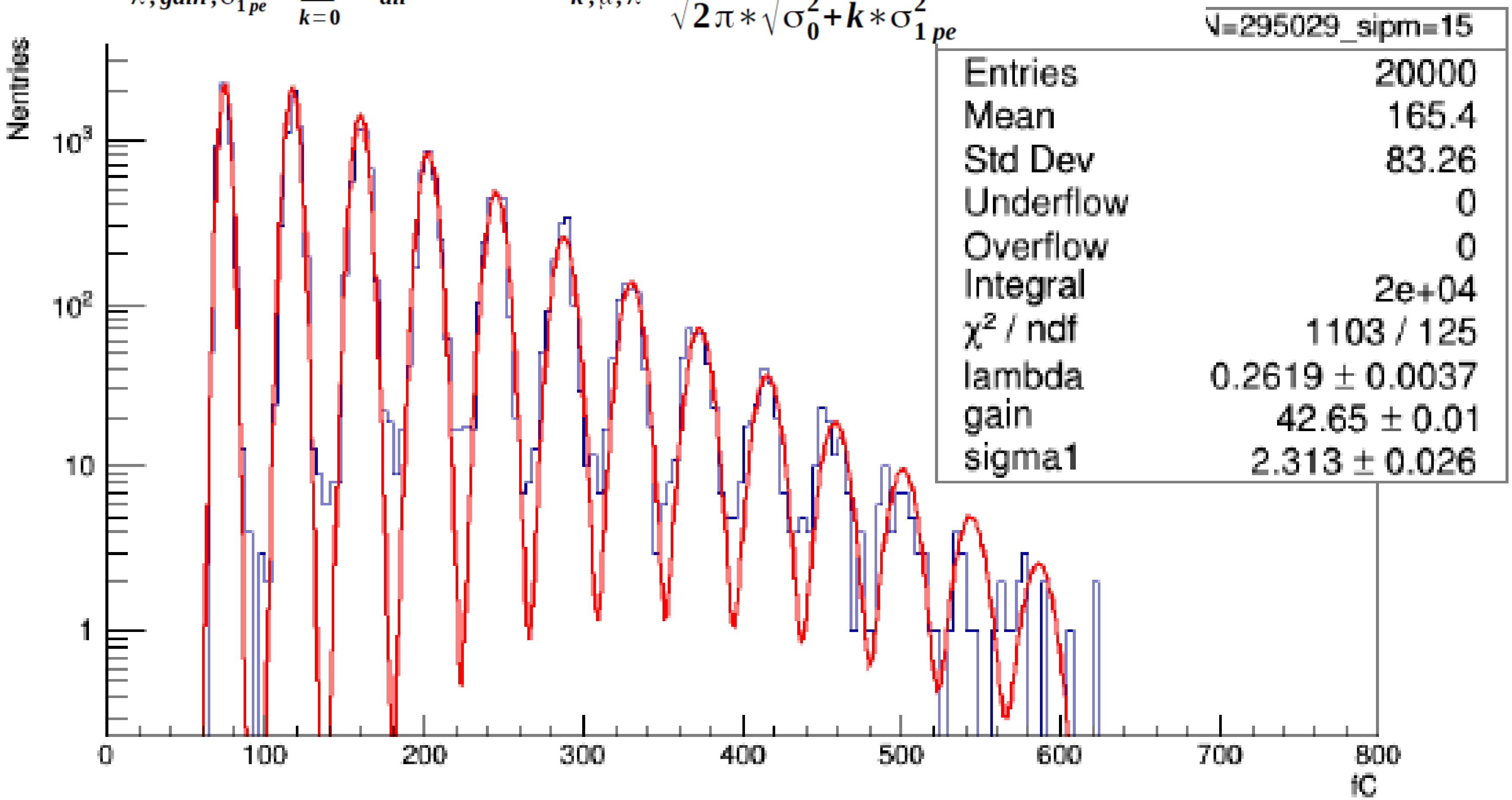


CERN CMS results on Generalized Poisson

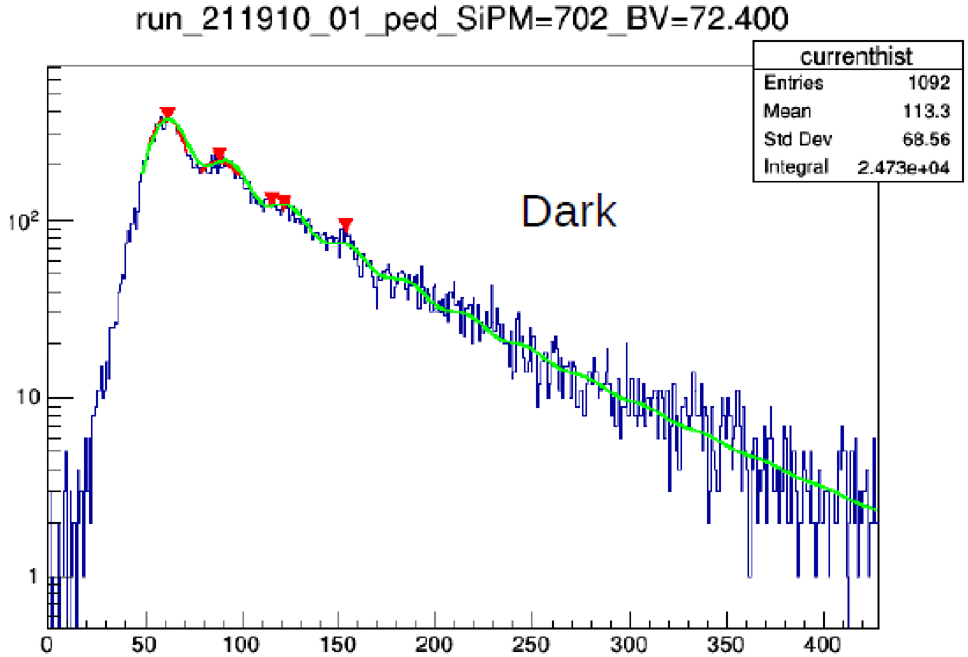
$$G_k(\mu,\lambda)=\frac{\mu*(\mu+k*\lambda)^{k-1}*e^{-(\mu+k*\lambda)}}{k!}$$ – Generalized Poisson

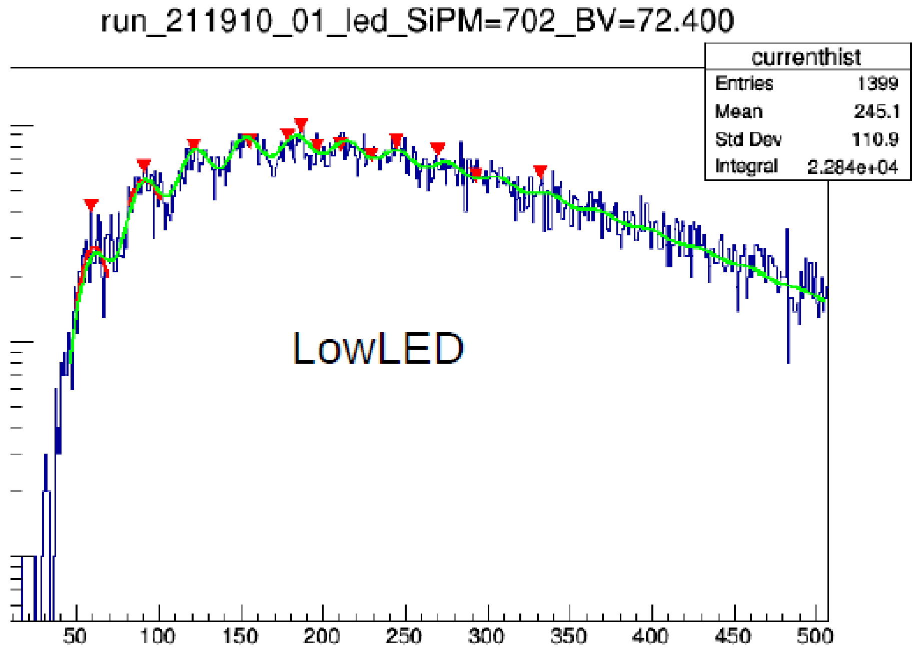
$$G_0(\mu,\lambda)=e^{-\mu}$$ – for 0 peak

$$FF_{\lambda,gain,\sigma_{1pe}}=\sum_{k=0}^{n} N_{all}*BW*GP_{k,\mu,\lambda}*\frac{1}{\sqrt{2\pi*\sqrt{\sigma_0^2+k*\sigma_{1pe}^2}}}\mathrm{e}^{-\frac{(x-(\mu_0+k*gain))^2}{2(\sigma_0^2+k*\sigma_{1pe}^2)}}$$



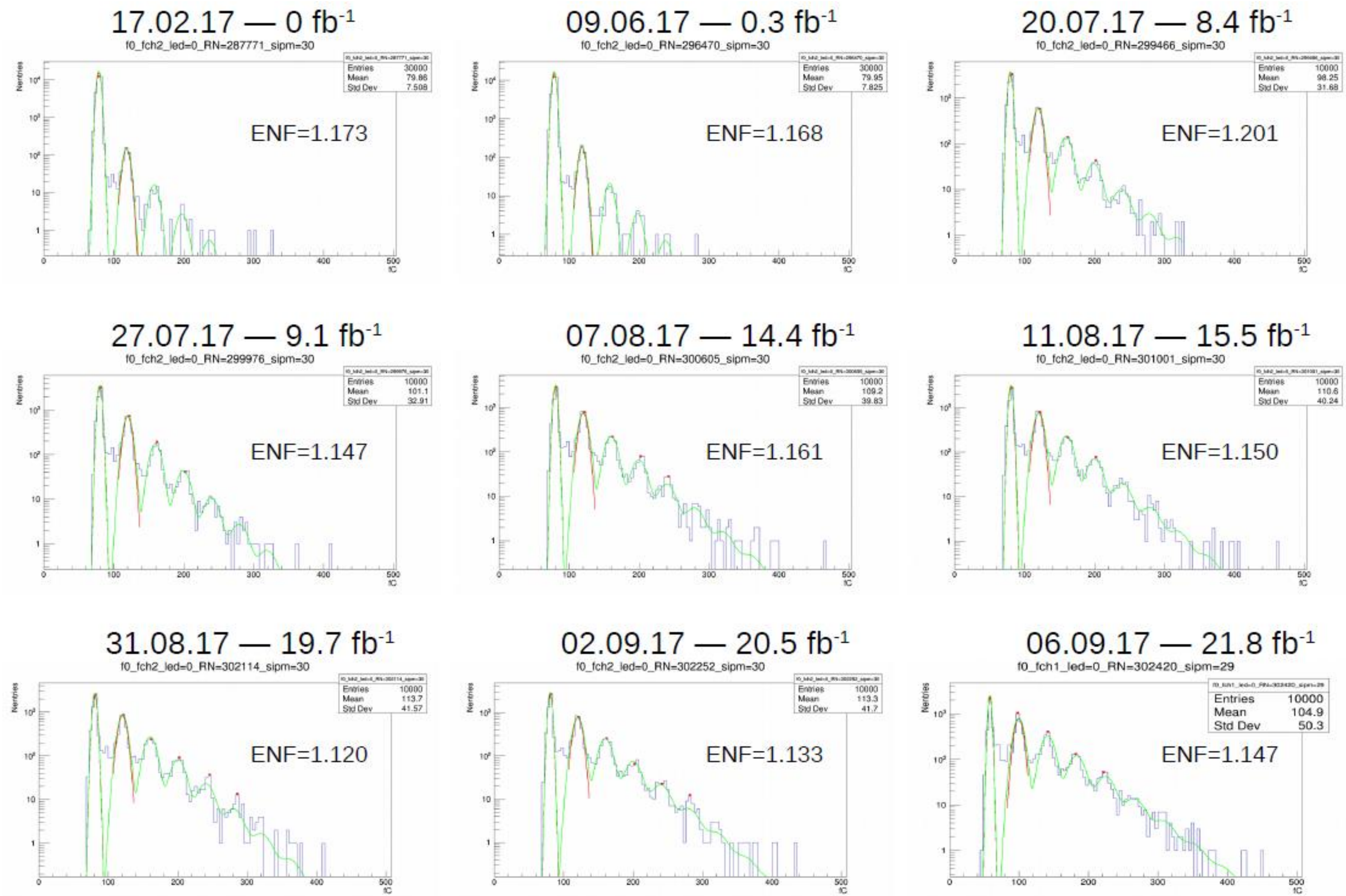
CERN CMS results on Generalized Poisson with blurred spectra due to background light





Pavel Parygin, Varna, 30th August 2017 20

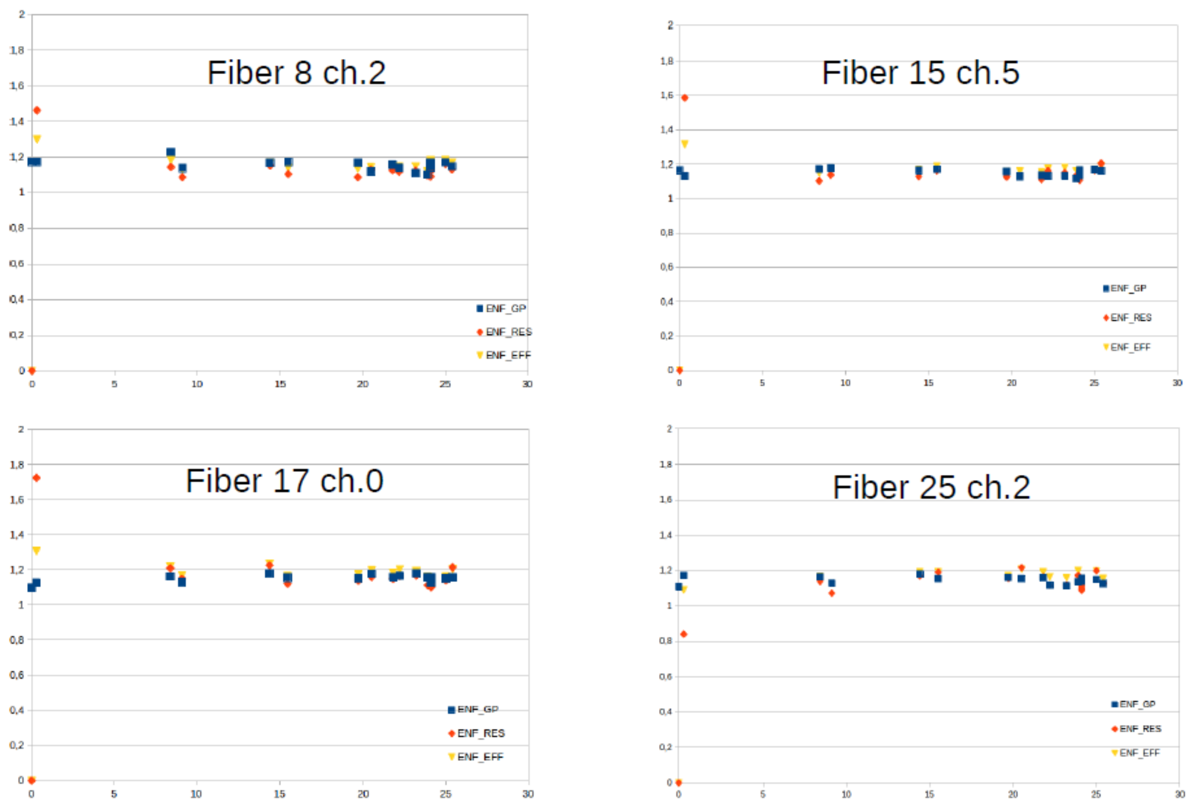
CERN CMS results on Generalized Poisson in a progress of radiation degration



CERN CMS results: ENF is stable and corresponds Generalized Poisson model

Total ENF of SiPM ≈ ENF of CT ($ENF_{Gain} \approx 1.01$)

ENF values calculated by different methods



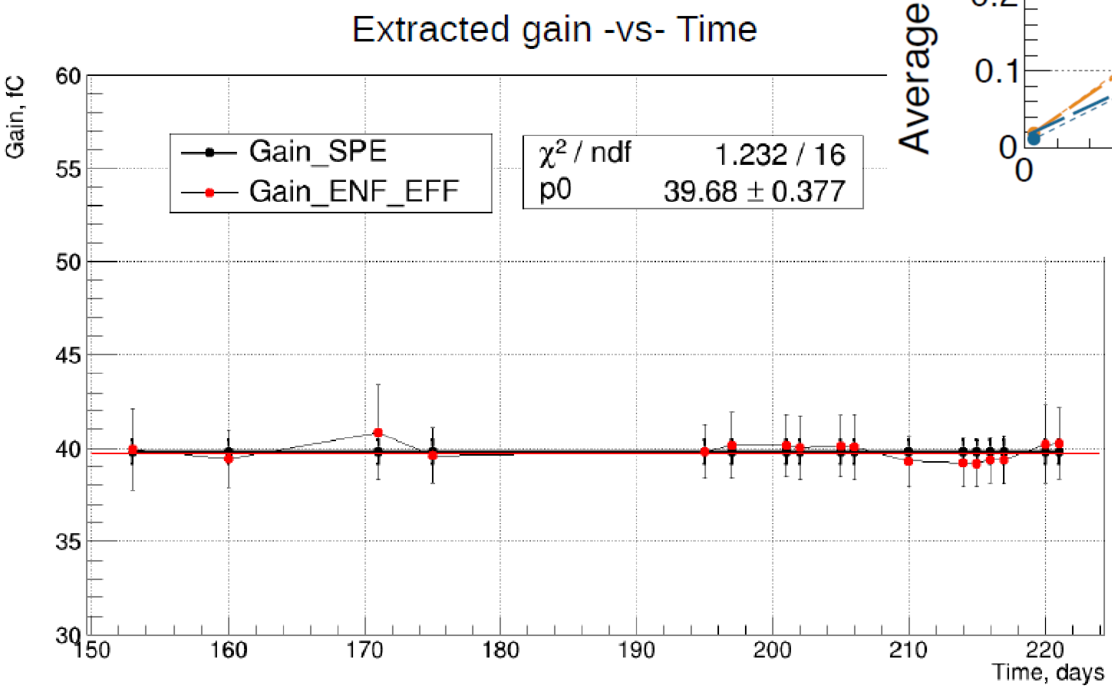
Comparison of the ENF values calculated by 3 methods
plotted with respect to integrated luminosity

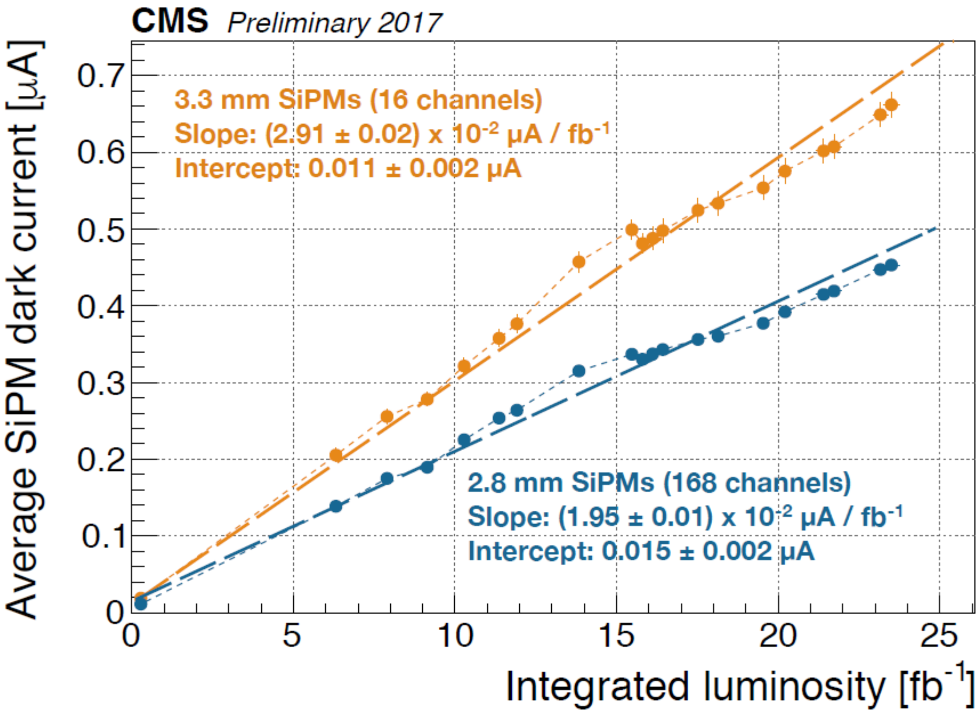
14

Monitoring of Gain during degradation

$$Effective\quad Gain = Fano = \frac{Var_{OUT}}{Mean_{OUT}} = Gain \cdot ENF^2$$

$$\Rightarrow Gain_{ENF} = \frac{Var_{OUT}}{Mean_{OUT}} \cdot \frac{1}{ENF^2}$$





Next question:
How to recognize changes of Gain and/or ENF if something is unstable?

Assumptions based on branching process model of corelated events

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Knowledge on ENF

- Total ENF of SiPM ≈ ENF of CT ($ENF_{Gain} \approx 1.01$)
- CT branching process model:

$$ENF_{CT} = 1 + \mu_{CT} = \frac{1}{1-\lambda} = \frac{1}{1+\ln(1-Pct)} \approx 1 + Pct + \frac{3}{2} Pct^2 \ldots$$

$$\frac{StdDev_{OUT}}{Mean_{OUT}} = \sqrt{\frac{ENF}{N_{pe}}} \quad => N_{ENF} = \frac{Mean_{OUT}{}^2}{Var_{OUT}} \cdot ENF$$

$$\frac{Var_{OUT}}{Mean_{OUT}} = Gain \cdot ENF^2 => Gain_{ENF} = \frac{Var_{OUT}}{Mean_{OUT}} \cdot \frac{1}{ENF^2}$$

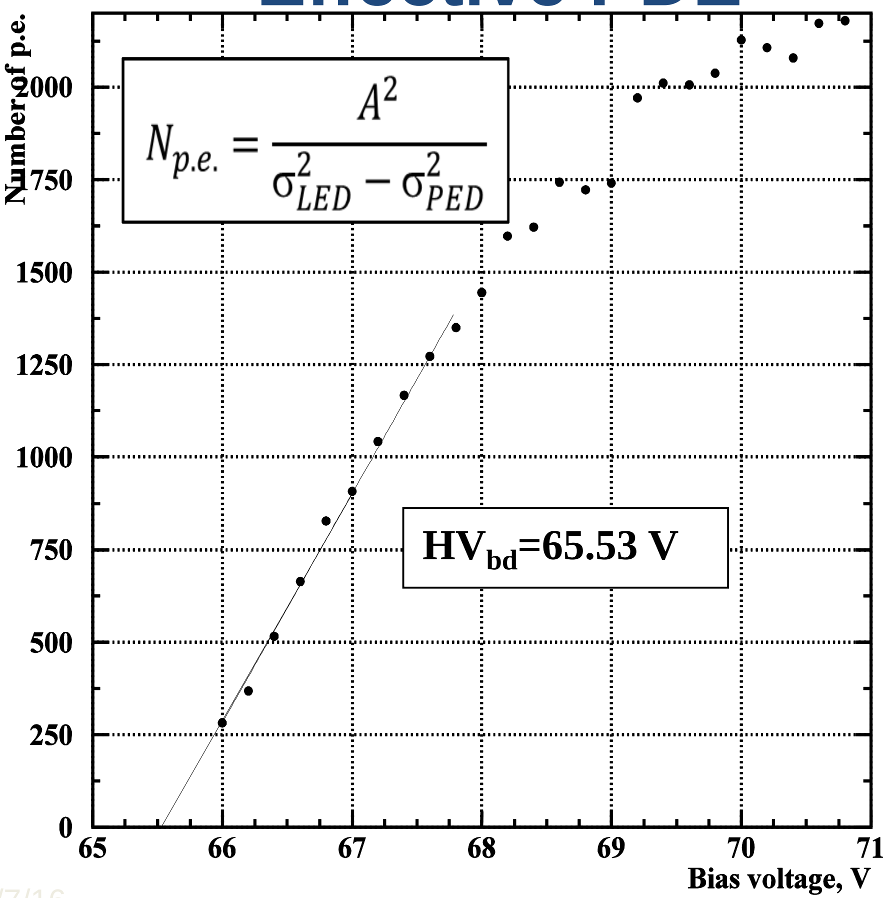
Knowledge on Gain: linearity vs Overvoltage

$$Effective \quad Gain = \frac{Var_{OUT}}{Mean_{OUT}} = Gain \cdot ENF^2 = \frac{C(V - Vbr)}{q} \cdot \left[ENF(V - Vbr)\right]^2$$

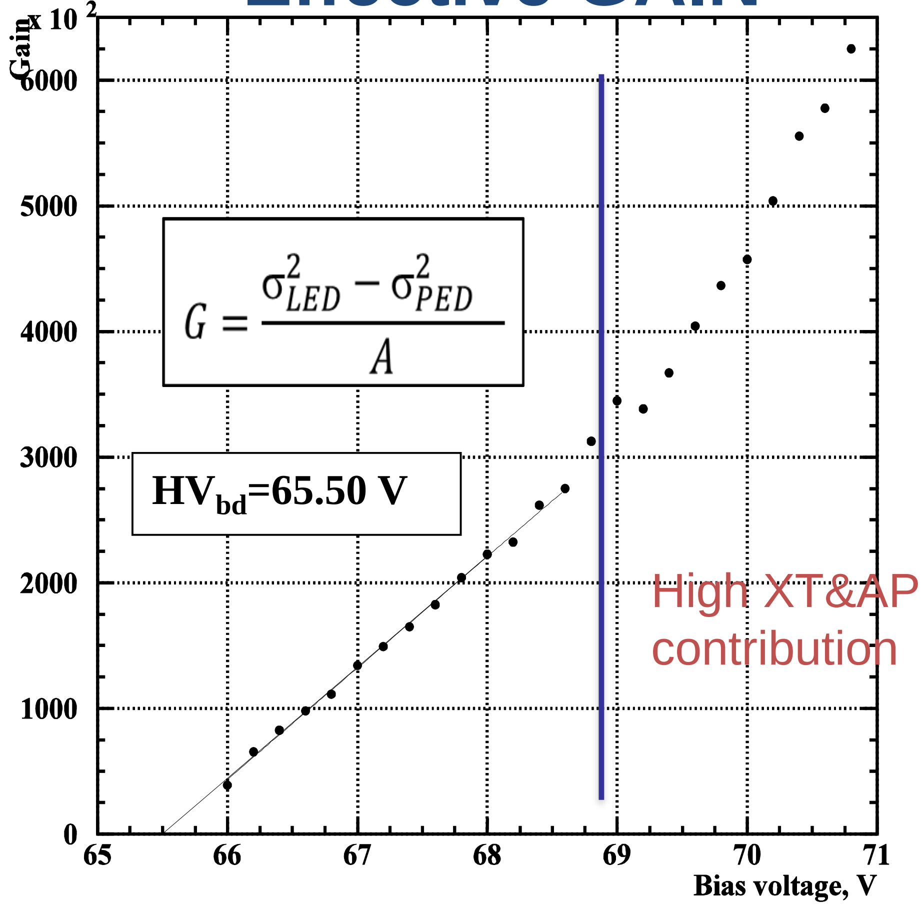
Number of photoelectrons and gain from statistical approach for high intensity LED flashes

This procedure may be applied to SiPM's after irradiation and doesn't require IV measurements

Effective PDE

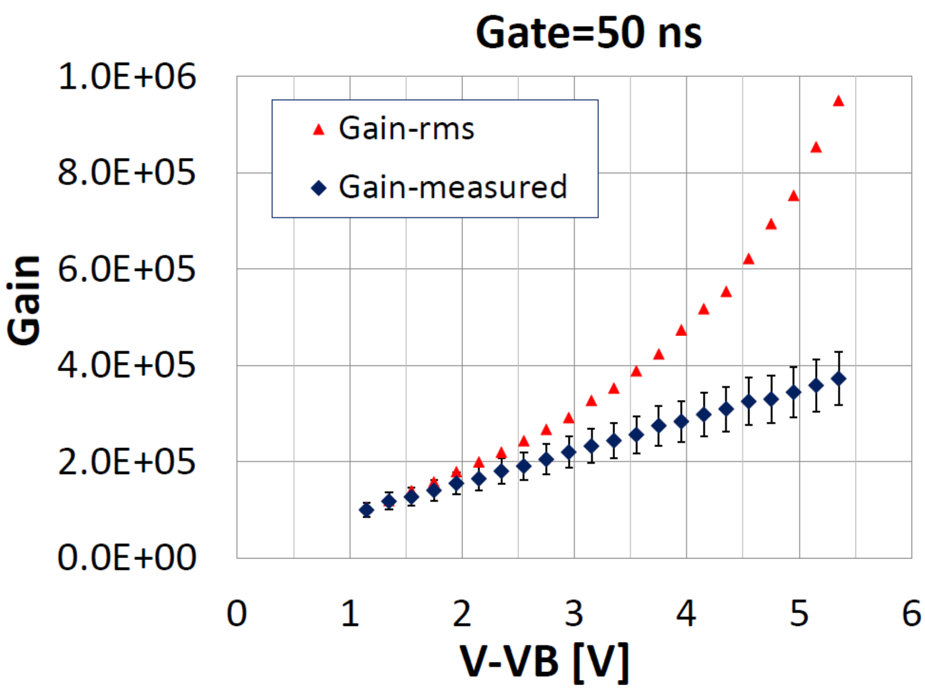


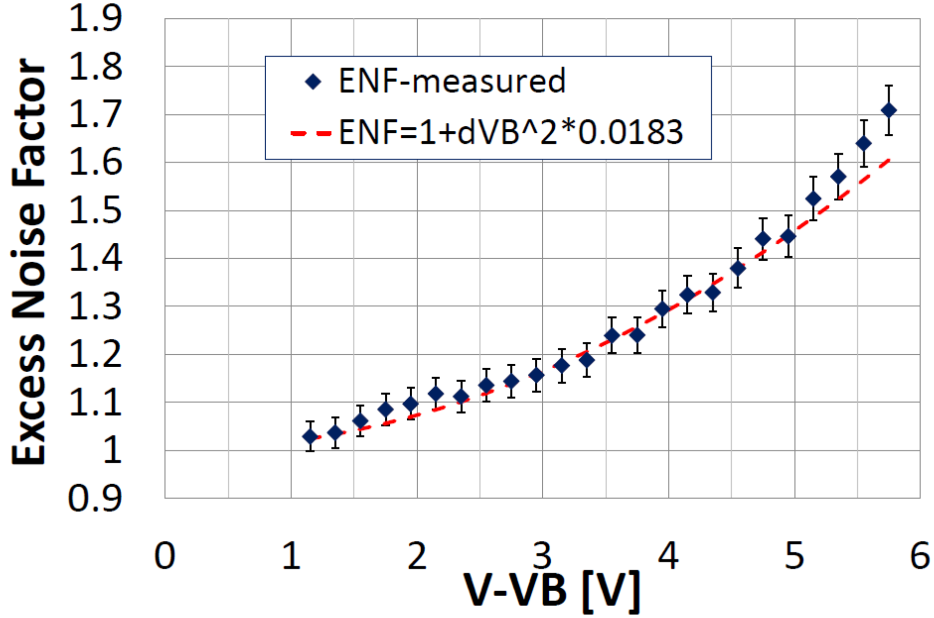
Effective GAIN



Approach is also supported by CMS SiPM results (Yu. Musienko)

- Gain-rms = Effective Gain = Var/Mean





Yu. Musienko, CERN CMS meeting on SiPM, 12-07-2017

Summary

- Unresolved SiPM spectra could be caused by many scenarios
- SiPM characterization in such cases is challenging, but possible
- Characterization is facilitated by Branching Poisson CT model
- Radiation-induced damage of SiPM does not affect CT (ENFct)
- Monitoring of Gain in case of known and stable ENFct is accurate and reliable by Fano factor (Effective gain) = Var/Mean
- True Gain and ENF could be determined from Effective Gain due to linearity of Gain vs Voltage

- We are in progress to advance the GP-based characterization

The end

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Questions?

Sergey.Vinogradov@cern.ch

BACKUP

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Modeling optical crosstalk: formulations

L. Gallego *et al.* JINST 8 (2013) P05010

Analytical expressions for P_1(k) and related parameters

k	4 nearest neighbors	8 nearest neighbors	8 L-connected neighbors	All neighbors
1	$q^4 (= 1-\varepsilon)$	$q^8 (= 1-\varepsilon)$	$q^8 (= 1-\varepsilon)$	$q^{N-1} (= 1-\varepsilon)$
2	$4pq^6$	$8pq^{14}$	$8pq^{14}$	$\binom{N-1}{1} pq^{2(N-2)}$
3	$18p^2q^8$	$12p^2q^{18}[1+2q+4q^2]$	$84p^2q^{20}$	$\binom{N-1}{2} p^2q^{3(N-3)}[1+2q]$
4	$4p^3q^8[1+3q+18q^2]$	$4p^3q^{20}[1+3q +14q^2+30q^3+61q^4 +59q^5+72q^6]$	$24p^3q^{24}[1+3q+38q^2]$	$\binom{N-1}{3} p^3q^{4(N-4)} [1+3q+6q^2+6q^3]$
5	$5p^4q^{10}[8+24q+55q^2]$	$5p^4q^{24}[9+36q+98q^2 +188q^3+310q^4+372q^5 +520q^6+396q^7+341q^8]$	$4p^4q^{30} [180+540q+2521q^2]$	$\binom{N-1}{4} p^4q^{5(N-5)} [1+4q+10q^2+20q^3 +30q^4+36q^5+24q^6]$

p : prob. for 1 neighbor $\quad q$ = 1-p $\quad \varepsilon = P_1(k>1)$ $\quad N$: number pixels of the array

Geometric extrapolation for k > 5

$$P_1(k) \approx P_1(5)\cdot(1-r)^{k-5}$$

$$r = \frac{P_1(5)}{1-\sum_{k=1}^{4} P_1(k)}$$

$$E_1 \approx \sum_{k=1}^{4} k\cdot P_1(k) + P_1(5)\frac{1+4r}{r^2}$$

$$Var_1 \approx \sum_{k=1}^{4} k^2\cdot P_1(k) + P_1(5)\frac{2+7r+16r^2}{r^3} - E_1^2$$

$$ENF = \frac{\sum_{k=1}^{4} k^2\cdot P_1(k) + P_1(5)\frac{2+7r+16r^2}{r^3}}{\left[\sum_{k=1}^{4} k\cdot P_1(k) + P_1(5)\frac{1+4r}{r^2}\right]^2}$$

Erlang distribution (FACT team, 2014)

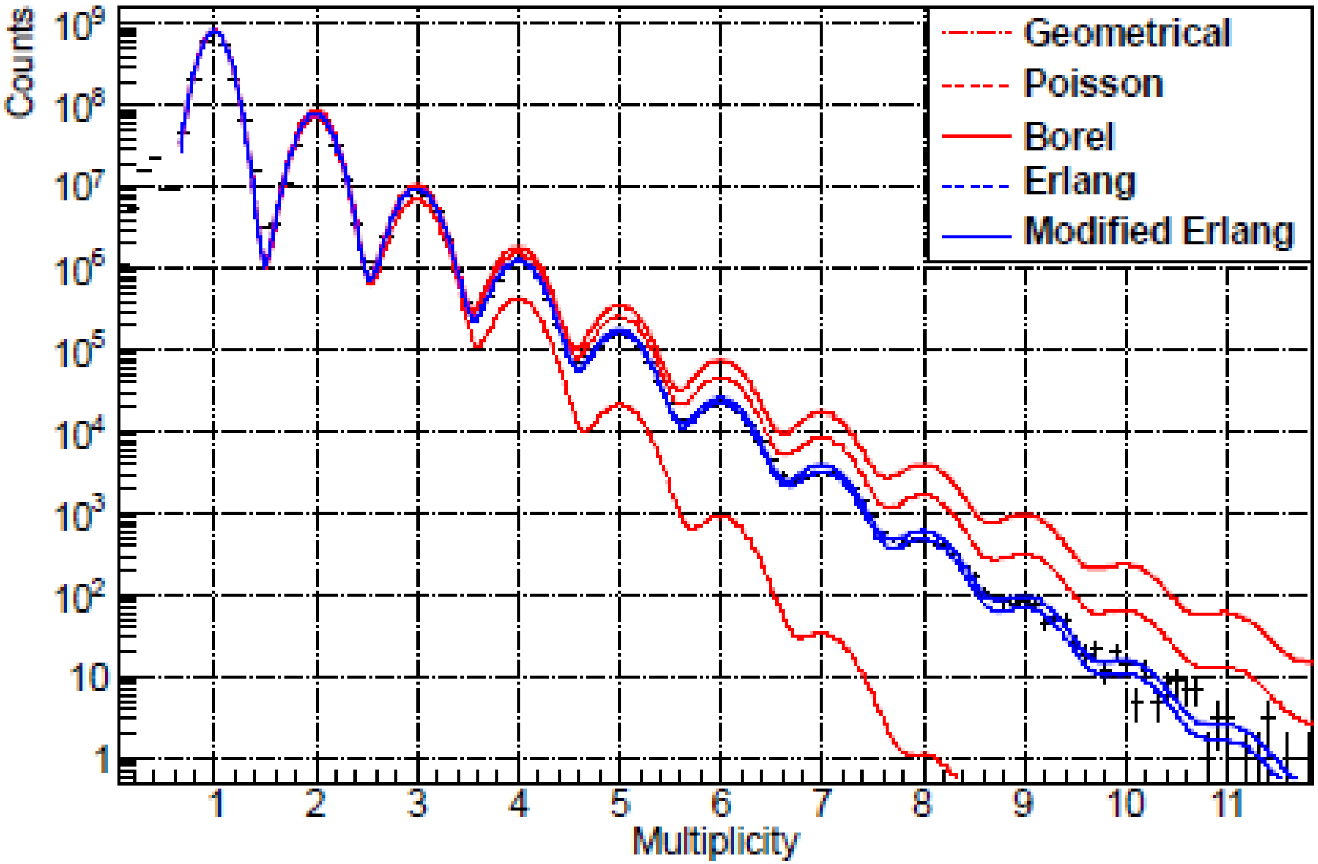
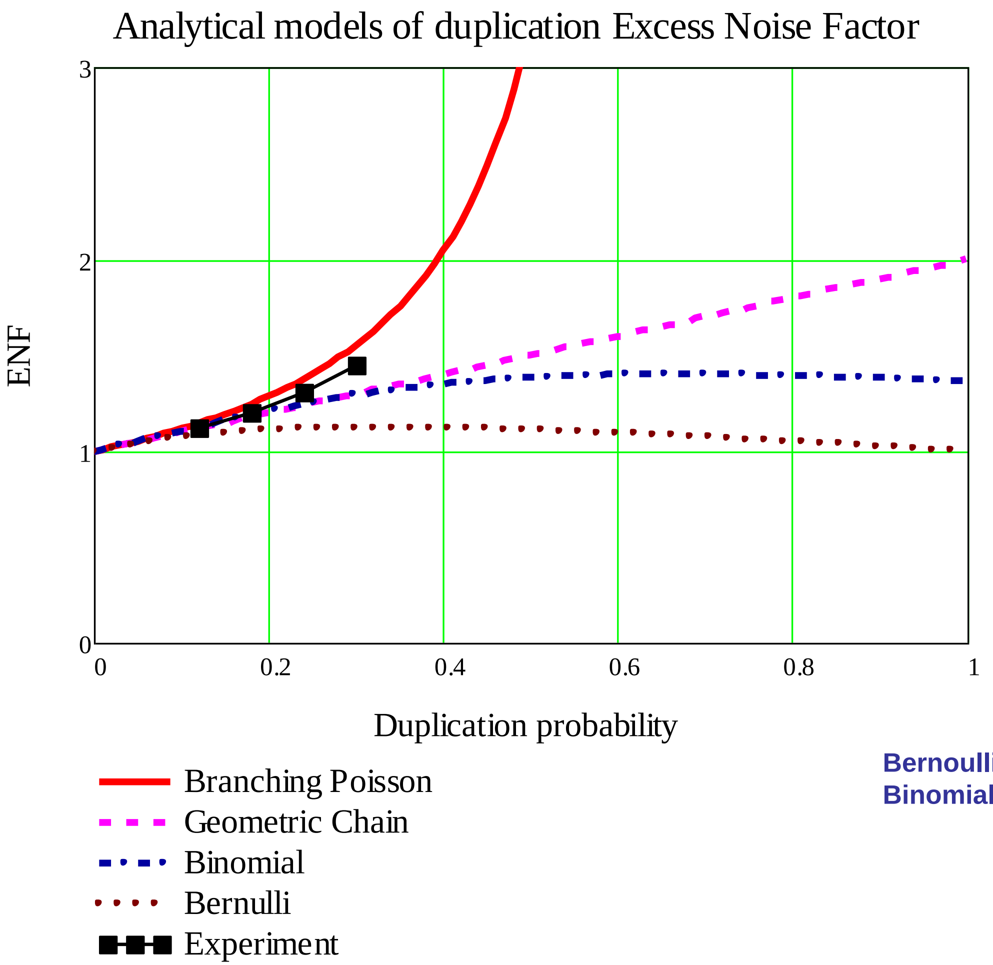
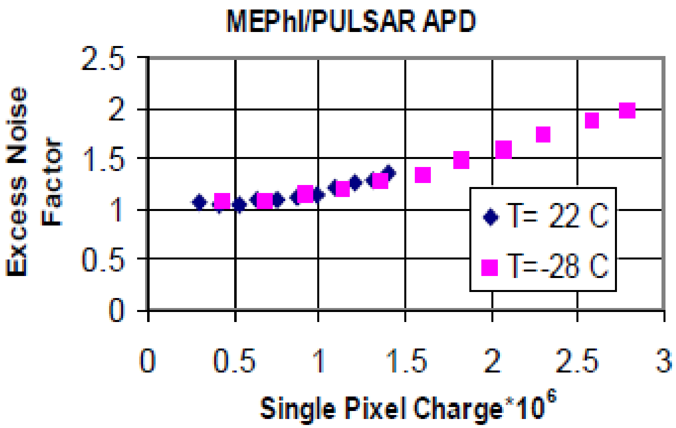


Figure 17. A measured single-p.e. spectrum overlayed with several different distribution function fitted to the data. The pure Poisson distribution significantly underestimates the data, while the Borel distribution clearly overestimates the data. The geometrical distribution by chance gets very close to the data. A good fit is obtained by the Erlang and modified Erlang distribution.

CT ENF models and experiments





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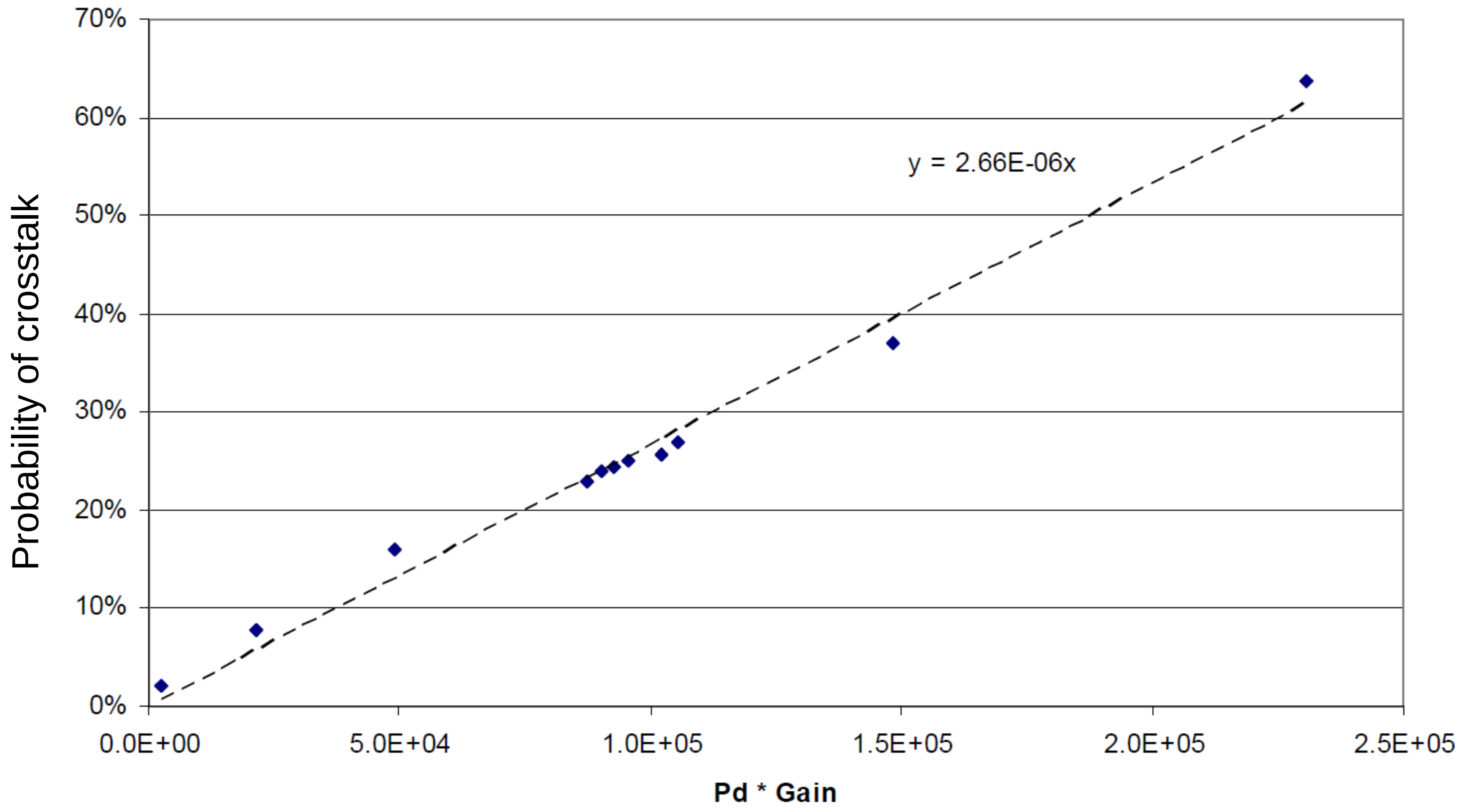
Pct ~ PDE·Gain



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