12Gev Upgrade.
Silicon Photo Multipliers for Hall-B (CTOF) and Hall-D applications.

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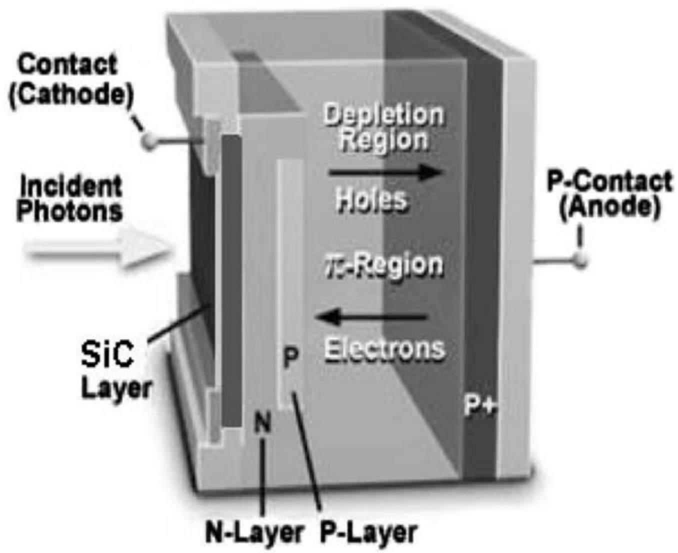
Jlab
I.Tolstukhin
MEPhI

Jul-2011

PRINCIPLE OF OPERATION

1) thin p-type layer
2) thick lightly doped p-layer
3) heavily doped p+ layer.



V. Golovin, V. Saveliev

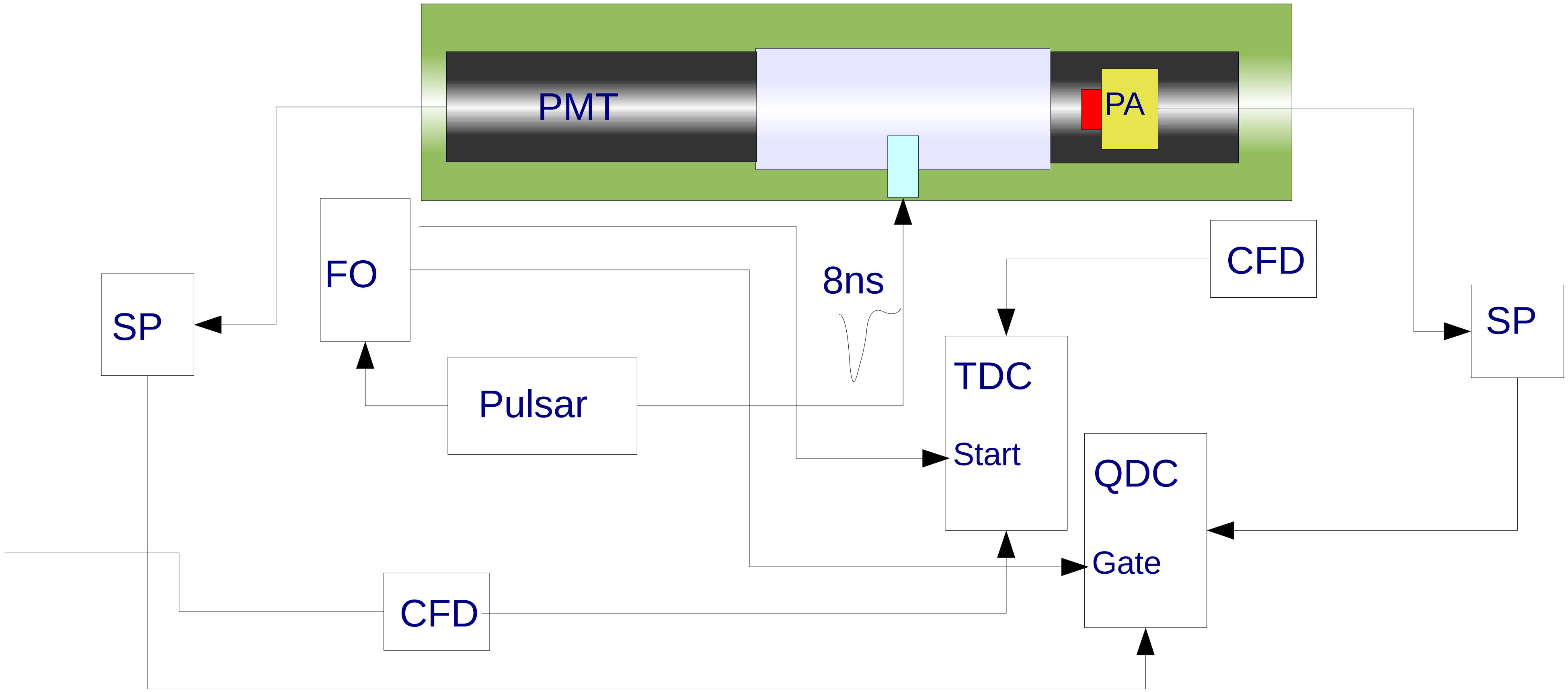
Novel type of avalanche photo detector with Geiger mode operation

Center of Perspective Technology and Apparatus, Moscow, Russia
Obninsk State University of Nuclear Engineering, Obninsk, Russia

Nuclear Instruments and Methods in Physics Research A 518 (2004) 560–564

Test Setup.   R2083 vs. SiPM

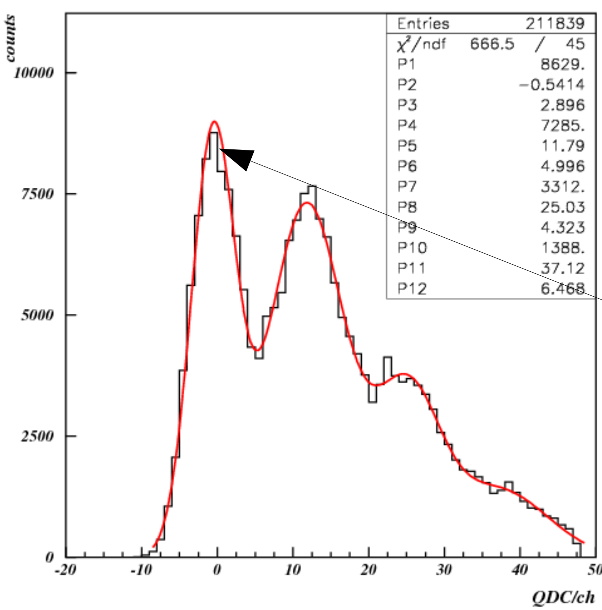
Equal Light to PMT&SiPM



Name	Manufacturer ID	Sens. area / mm^2	Sizes / mm^2
SiPM-1	S10362-33-050C	3x3=9	5.9x6.6
SiPM-3	S10931-050C	1x1=1	5x6
SiPM-16	S11064	16x3x3=144	16.2x17.8
Refer. PMT	R2083	Same (mask)	D=46

SiPM-3 Photon Counting with 470 nm-LED

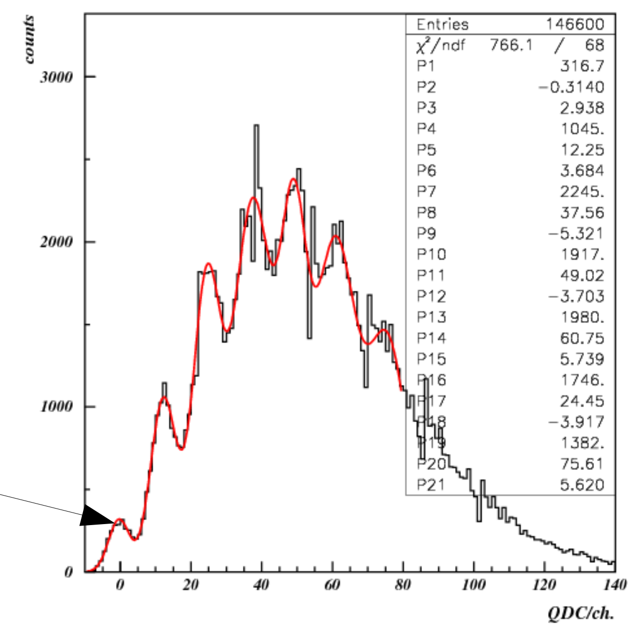
No LED light



QDC counts

pedestal

~4 pixel fired by LED

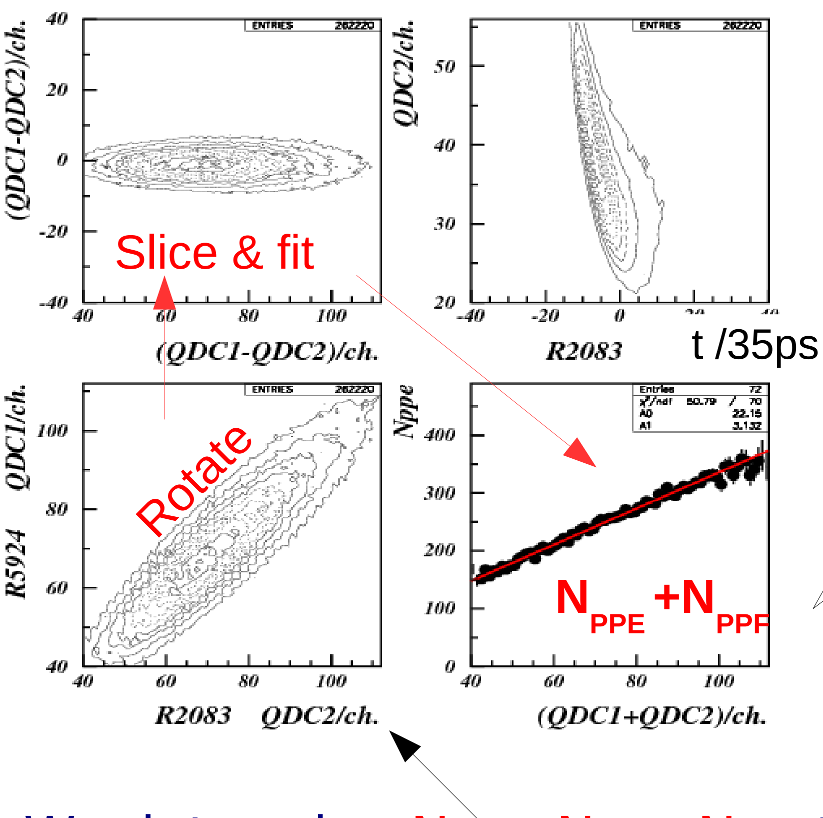


PMT at the opposite side of Bench Setup has been calibrated.

Number of photo electrons. Q-variance measuring method-1.

Time resolution makes no sense without referencing N_{ppe} and N_{ppf}

We determine $N_e = N_{PPE} + N_{PPF}$ from QDC spectra of two PMs.

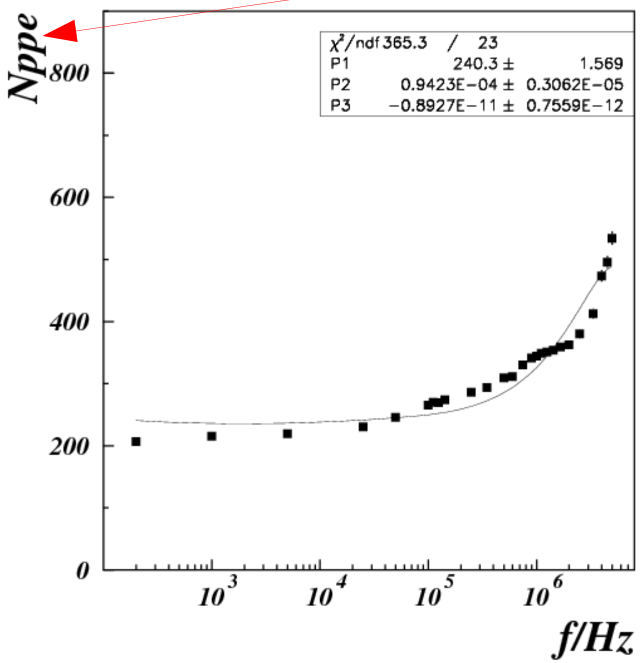


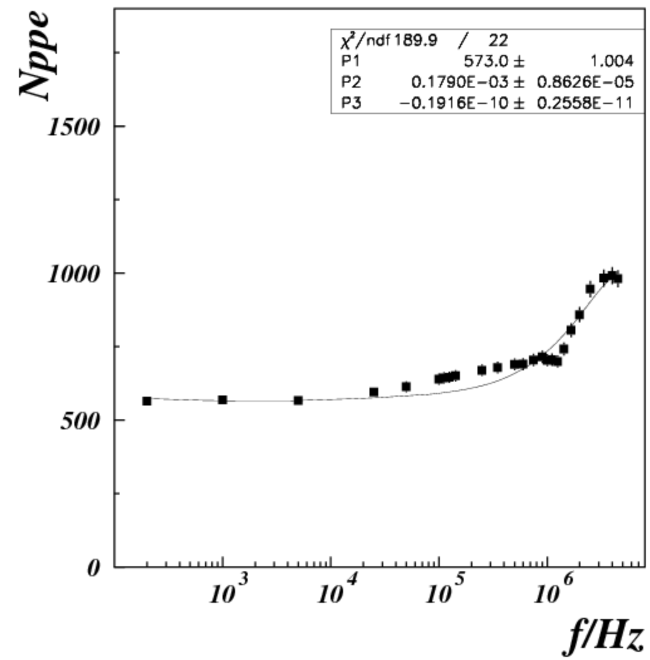
$$N_e = (N_{ppe} + N_{ppf}) = \frac{(Q_1 + Q_2)^2}{var(Q_1 - Q_2)}$$

- We determine $N_e = N_{ppe} + N_{ppf}$ that changes linearly with QDC readout.
- N_{ppe} in the reference PMT may be determined independently .

Number of photo electrons. Measuring method-2

$$\sigma_{R2083} = \sqrt{\frac{\tau_p^2}{N_{ppe}}}, \quad where \quad \tau_p = 2.9\,ns$$





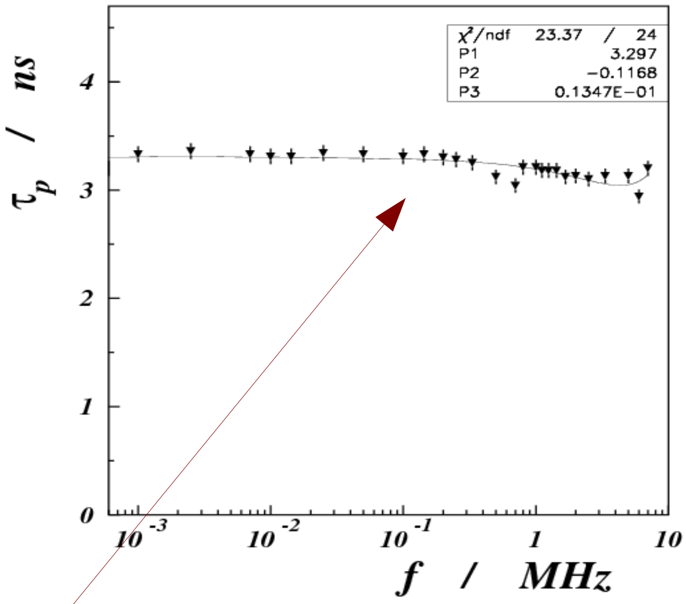
$$N_{ppf} + N_{ppe} = (Q_1 + Q_2)^2 / var(Q_1 - Q_2)$$

$$N_{ppe} = \tau_p^2 / \sigma_{R2083} = 0.17\,N_\gamma$$

- Time resolutions of R2083 **follows Stat. Law with linearly increasing N_γ**
- We determine Quantum efficiency of the SiPM at low rate/flux.

Time resolution of reference PMT.

$$\sigma_{R2083} = \sqrt{\frac{\tau_p^2}{0.5N_e}} \quad vs. \quad \sigma_{R2083} = \sqrt{\frac{\tau_p^2}{N_{ppe}}}; \tau_p - signal\ rise\ time$$



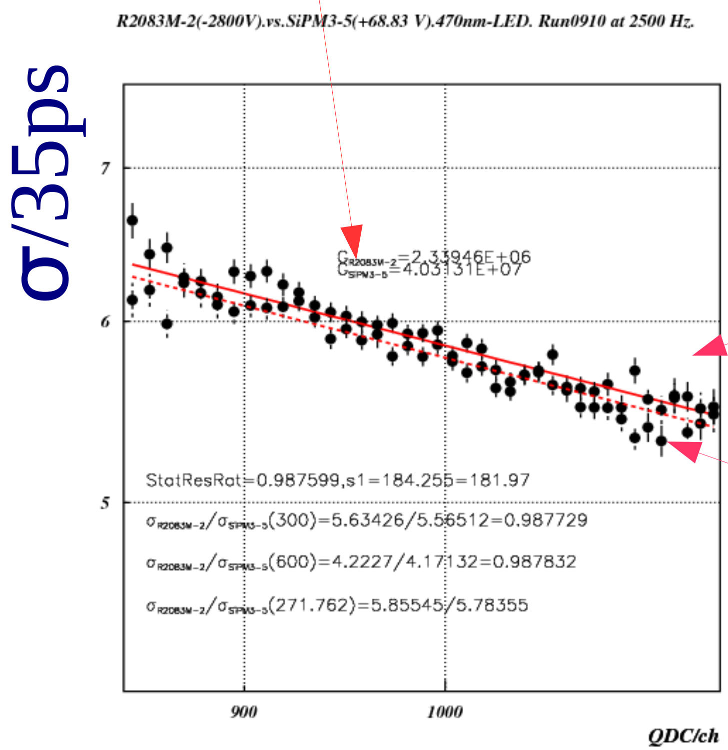
$$N_e = (Q_p + Q_s) N_\gamma$$

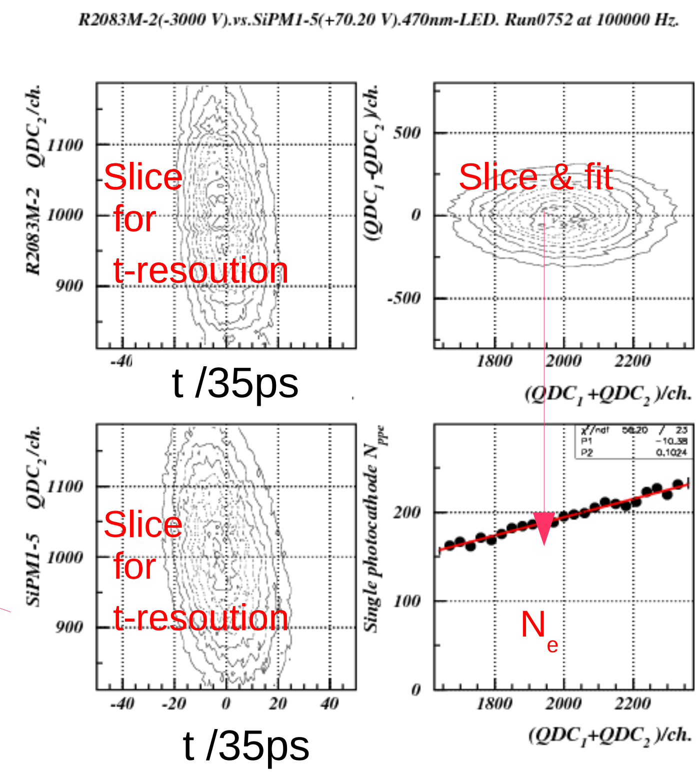
$$\sqrt{\frac{1}{2}\left(1 + \frac{Q_s}{Q_p}\right)} = \frac{\tau_p}{2.9}$$

- Fit parameter τ_p **=3.3 ns.** Stable within ±5% up to 7 MHz.
- The rise signal time is **2.9 ns.** The difference is due to $Q_s > Q_p$=0.17 at 475 nm.
- **Re-normalizing** to N_{ppe} we determine Q_s **= 0.27 ±0.07**

Example. R2083 vs. SiPM3. Time Resolution at Bias Voltage 68.83 V

Fit function: $$\sigma_{PM} = \sqrt{\frac{\sigma_s^2}{N_e/2} + \sigma_e^2} \quad , \quad \sigma_e = 21\,ps$$

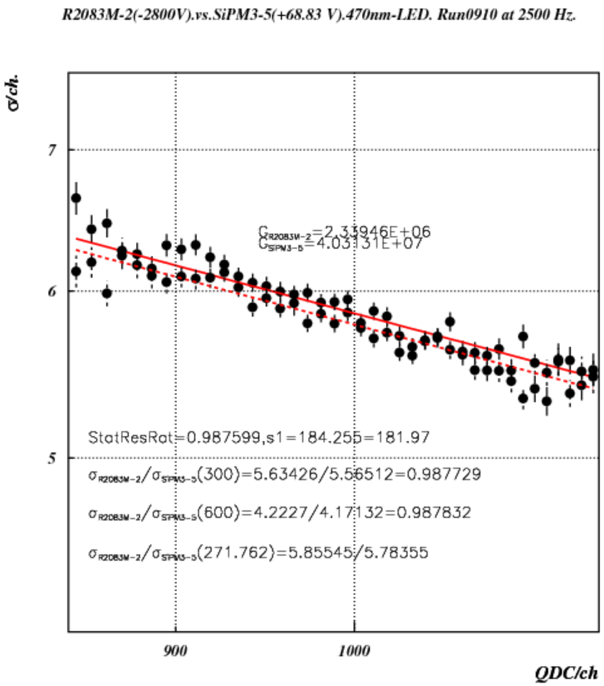




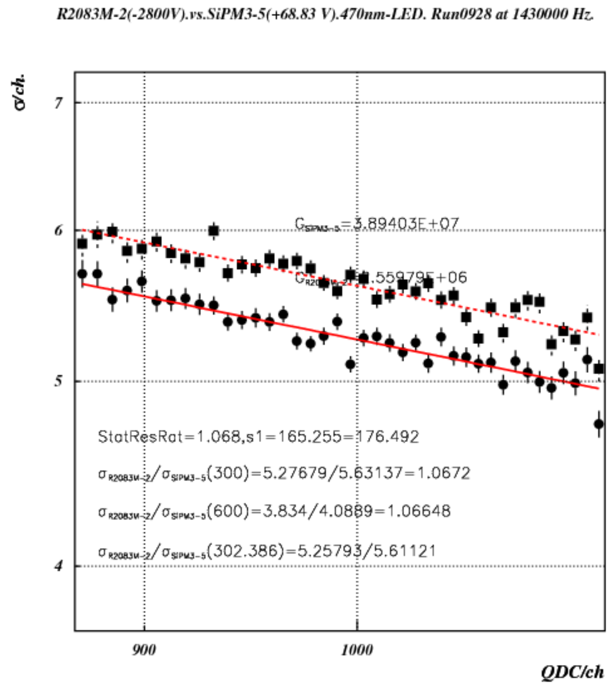
- Time resolutions of both R2083 and SiPM3 **follows the Statistical Law.**
- We determine constant σ_s from each measurement.

Comparative measurements (σ_{R2083} vs. σ_{SiPM3})

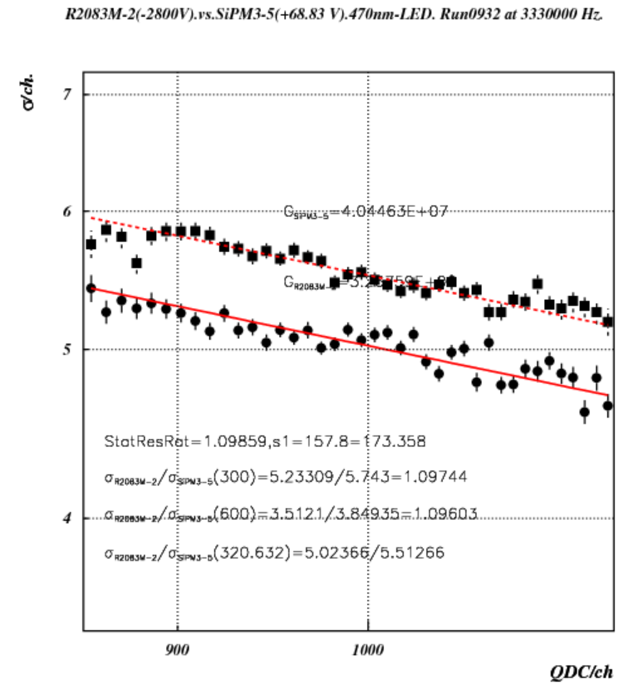
2.5 KHz



1.43 MHz



3.3 MHz



- SiPM resolution is a function of τ, f, and N_γ
- Reasonable parameterization is required

Parameterization (σ_{R2083} vs. σ_{SiPM3})

$$\sigma_{R2083} = \frac{\tau_p}{\sqrt{Q_p N_\gamma}} ,$$

$$\sigma_{SiPM} = \frac{\tau_s}{\sqrt{Q_s(f, N_\gamma) N_\gamma}} ,$$

$$\sigma_{SiPM3} = \alpha \, \sigma_{R2083} \left(\frac{N_{ppe}}{N_{pix}}\right)^{\frac{1}{2}} \left(1 - \exp\left(-\frac{Q_s N_\gamma}{N_{pix}}\right)\right)^{\frac{-1}{2}} \left(1 - \frac{Q_s N_\gamma}{N_{pix}}\right)^{\frac{-t_p f}{2}} .$$

τ_p - measured PMT signal rise time

N_γ - measured number of photons

Q_s - quantum efficiency of SiPM at f -> 0 and $N_{\gamma \to}$ 0

Q_p =0.17 ; Q_s may be estimated

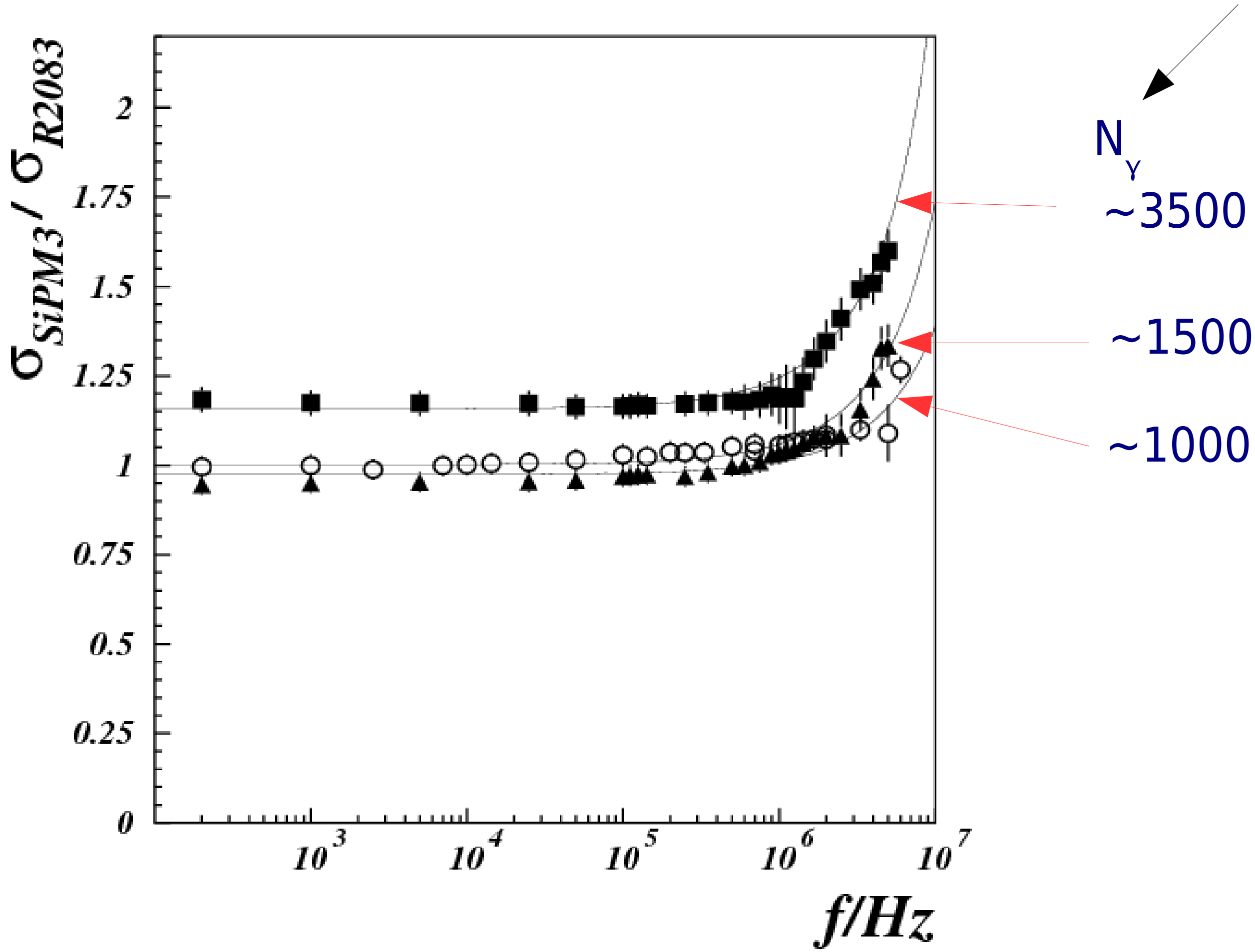
N_{pix} - nominal number of pixels

t_p - unknown pixel dead time

- Our goal is to determine experimentally α, Q_s , and t_p

Comparative measurements of σ_{R2083} vs. σ_{SiPM3}

$$\sigma_{SiPM3} = (1 \pm 0.05)\,\sigma_{R2083}\left(\frac{Q_s N_\gamma}{N_{pix}}\right)^{\frac{1}{2}}\left(1-\exp\left(-\frac{Q_s N_\gamma}{N_{pix}}\right)\right)^{\frac{-1}{2}}\left(1-\frac{Q_s N_\gamma}{N_{pix}}\right)^{\frac{-t_p f}{2}}$$



- Time resolutions of SiPM3 follows the selected parameterization with

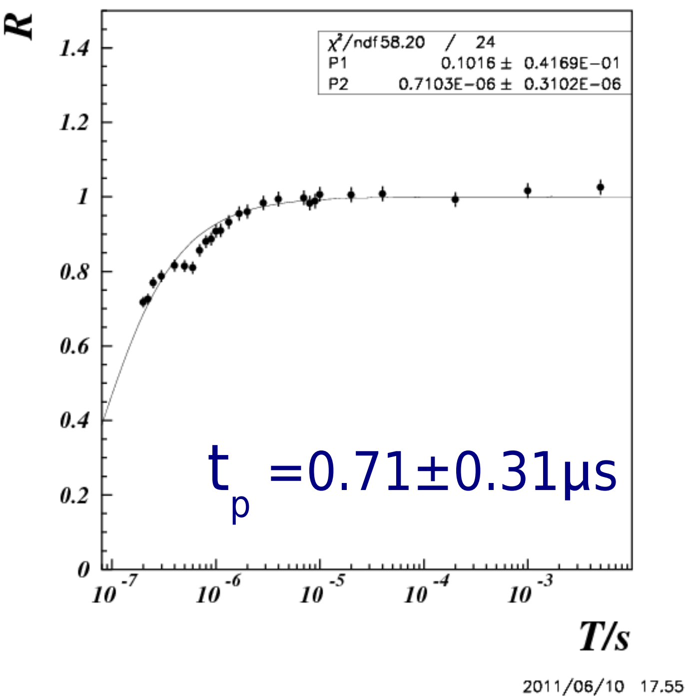
  $t_p = 0.8 \pm 0.3$ μs

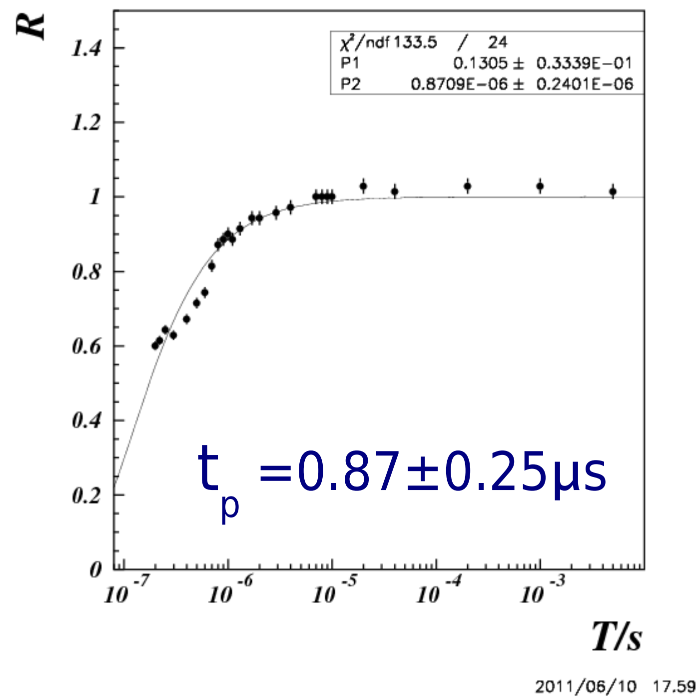
  $Q_s = 0.3 \pm 0.05$ provided $Q_p = 0.17$ at 475 nm

SiPM response function R and SiPM dead time t_p

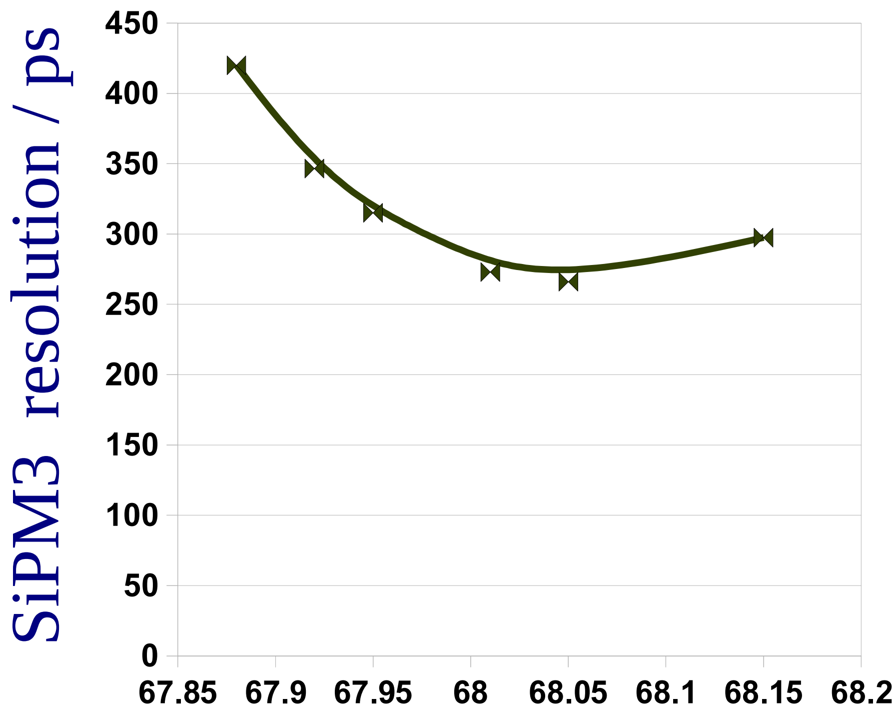
$$R = \left(1 - \frac{N_{ppf}}{N_{pix}}\right)^{\frac{t_p}{T}} \propto \frac{\sigma_p}{\sigma_s}$$

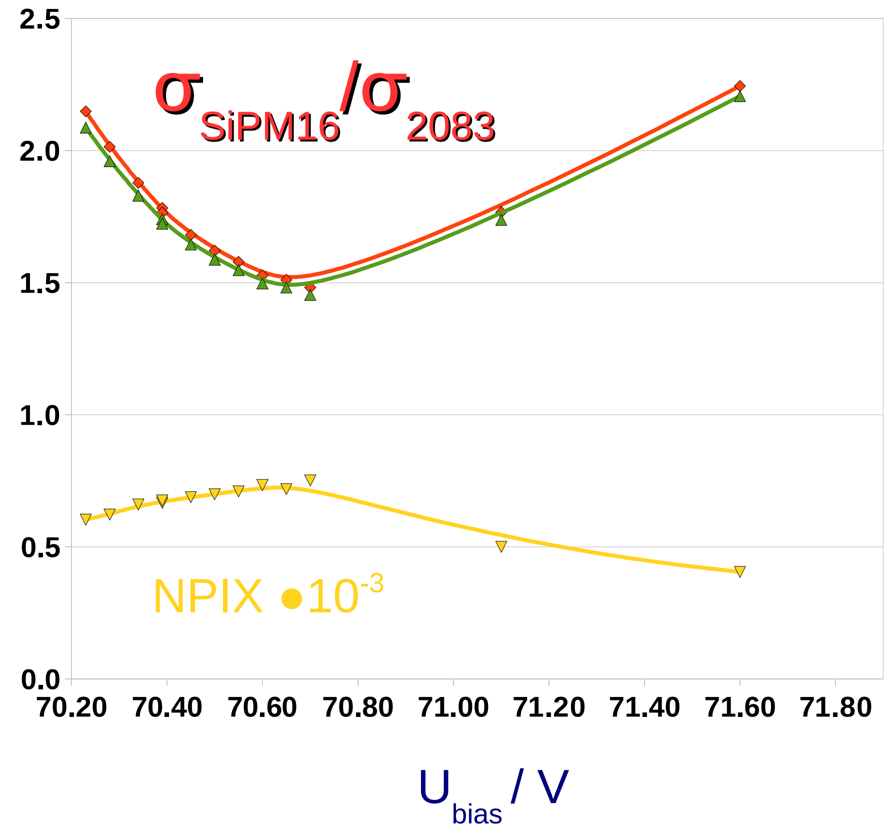
Experimental R is normalized to 1 at low rate





- “ pixel dead time” t_p = 0.8 ±0.3 microsecond.





- The best Time Resolution of SiPM16 at +70.8 V (Nominal +70.39 V)
- Number of fired pixels has a maximum at this bias.
- Pixel dead time will be studied.

Conclusion & Outlook

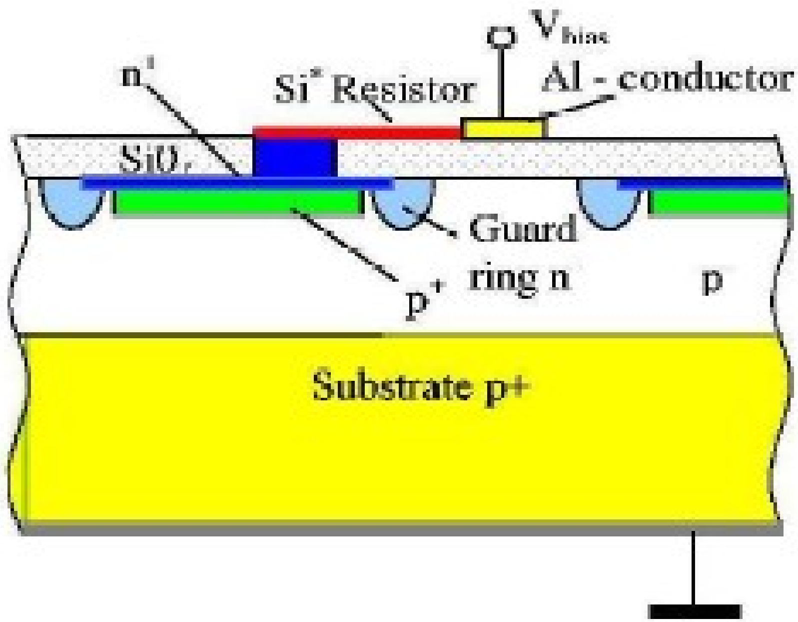
- Resolution of SiPM-1 : ~ 25% better than R2083 (at low rates)
- Resolution of SiPM-3 : ~ same as for R2083
- Resolution of SiPM-16: ~50% worse.
- Quantum efficiency of SiPM: at 475 nm $Q_s = 0.3 \pm 0.05$ (=0.17 for PMT)
- "Pixel dead time" $t_p = (0.8 \pm 0.3) * 10^{-6}$s.
- Resolution of SiPM3 degrades at f > 1MHz due to "pixel dead time" :

$$\sigma_{SiPM3} = (1. \pm 0.05)\,\sigma_{R2083} \left(\frac{N_{ppf}}{N_{pix}}\right)^{\frac{1}{2}} \left(1 - \exp\left(-\frac{N_{ppf}}{N_{pix}}\right)\right)^{-\frac{1}{2}} \left(1 - \frac{N_{ppf}}{N_{pix}}\right)^{-\frac{t_p f}{2}}$$

Plan

- More accurate measurements with lower reference PMT HV(No saturation effects).
- Measurements with identical SiPMs at both sides of the setup.

$d = 1$ mm
$S = 50\times50$ micron
$U_b = 100$ V



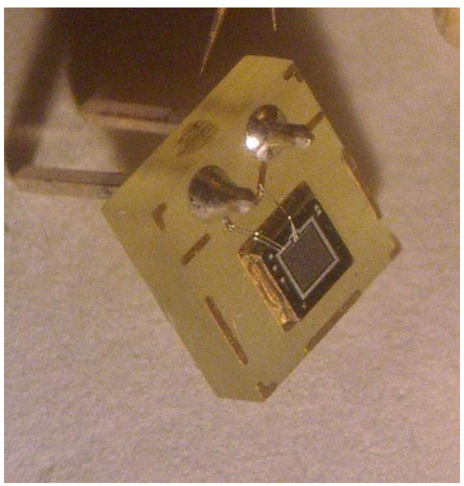
$$Q = CU = \epsilon_0 \epsilon \frac{S}{d} U_b \approx 2\epsilon x 10^4 e$$

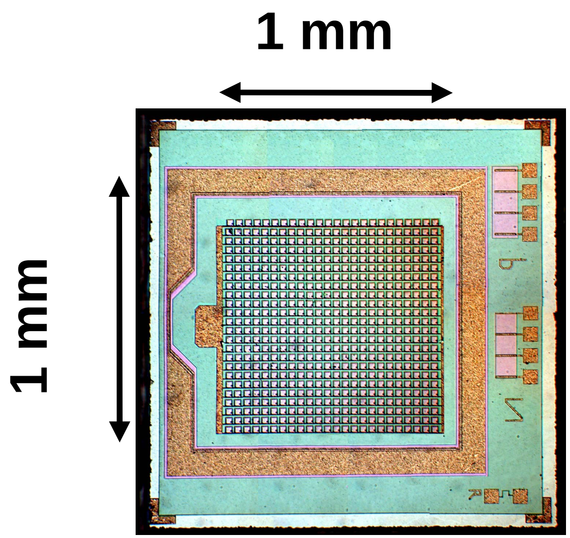
$$v = \mu E \quad ; \qquad 50 < \mu < 500 \quad (\frac{cm^2}{Vs})$$

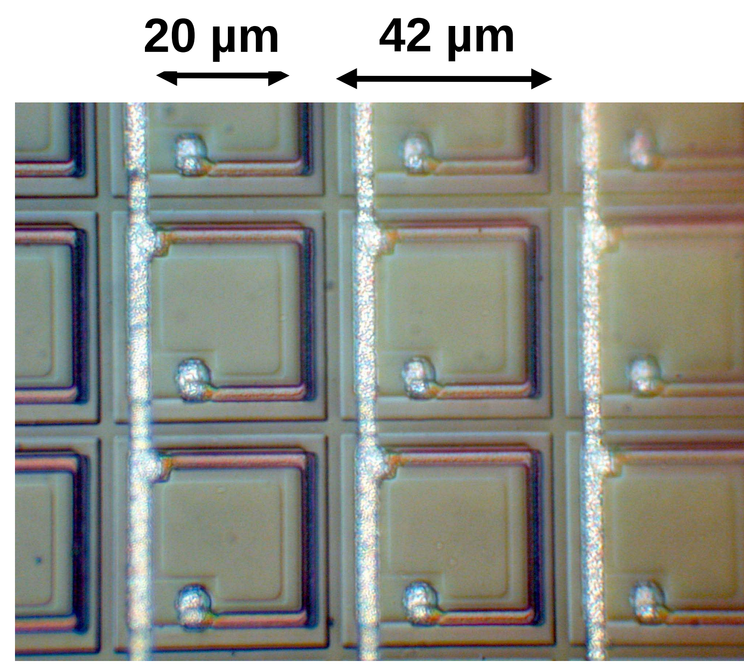
$$\tau_p = \frac{d^2}{\mu U_b} \in (0.2, 2.) \quad (\mu s)$$

- Primary electron may create a p-charge that screens the applied field.
- Hole escape time from the depletion zone may be of 1 microsecond.

First SiPM with 24x24 pixels from MEPhI&PULSAR Enterprise

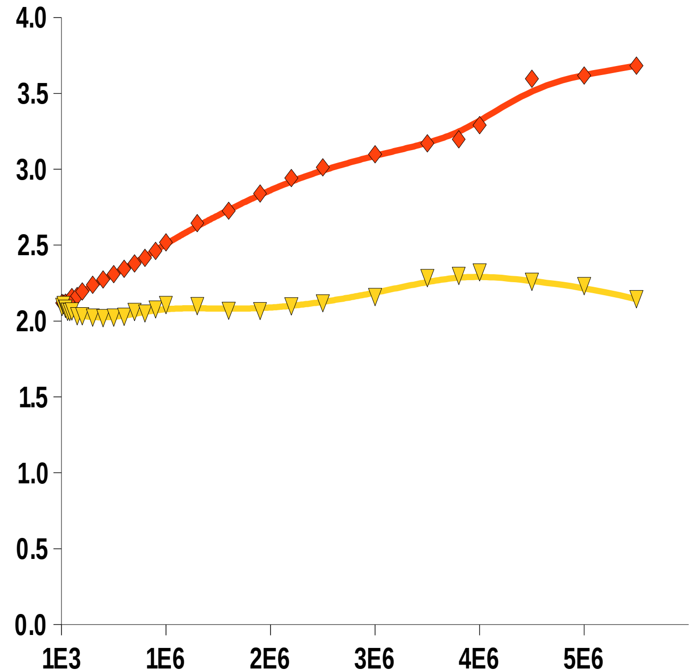






$$\sigma_{SiPM} = \sqrt{\frac{\sigma_s^2}{N} + \sigma_e^2} \quad where \quad \sigma_e = 23\ ps$$

σ_s/ns



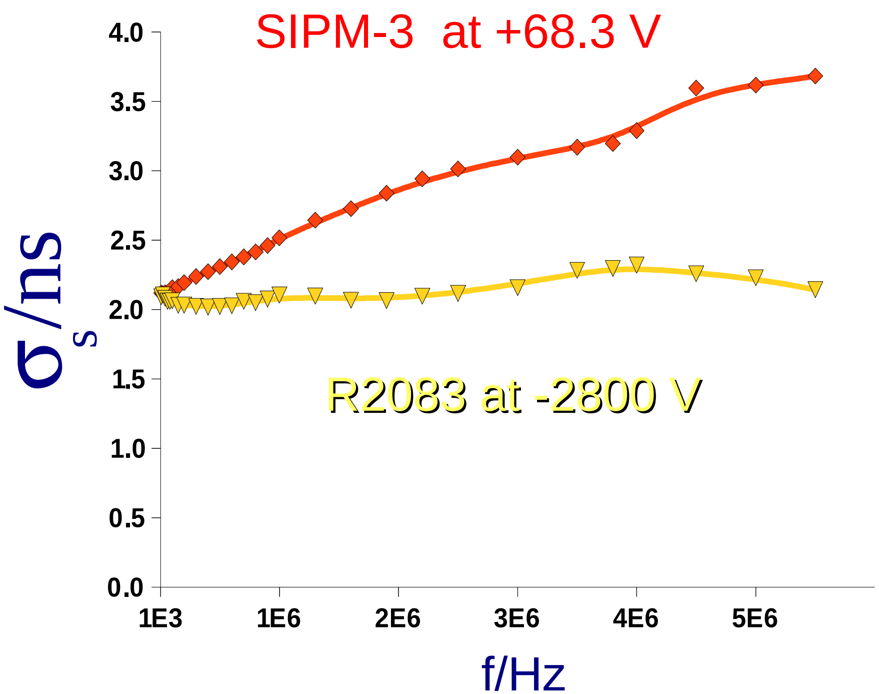
σ/ps

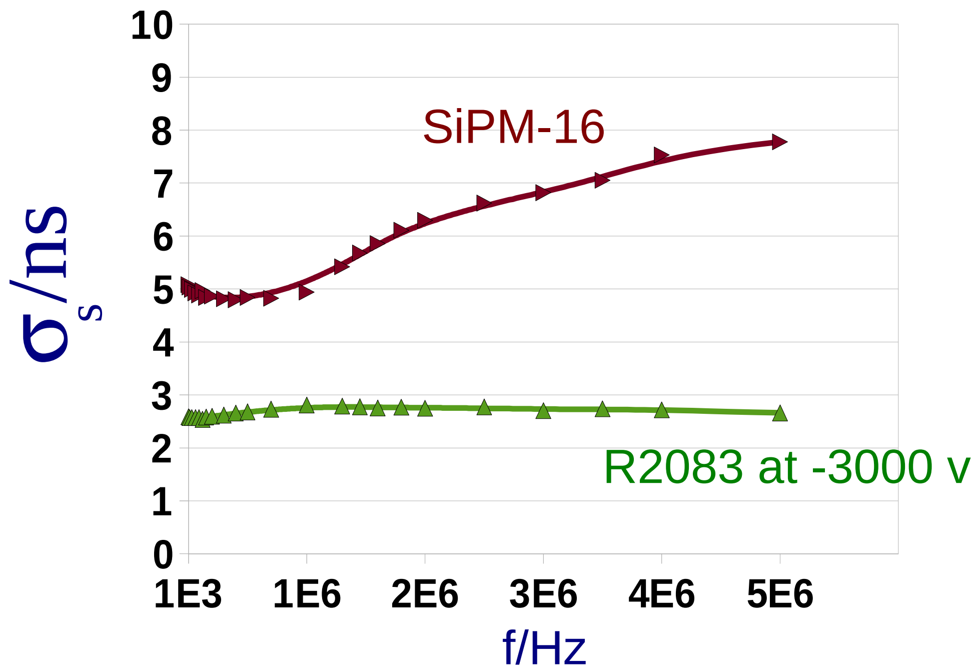
f/Hz

f/Hz

$$\sigma_s = 2.0\,(ns) + (0.25\text{E-}6\, ns)\, f\,(Hz)$$

SiPM Time Resolution vs. Rate





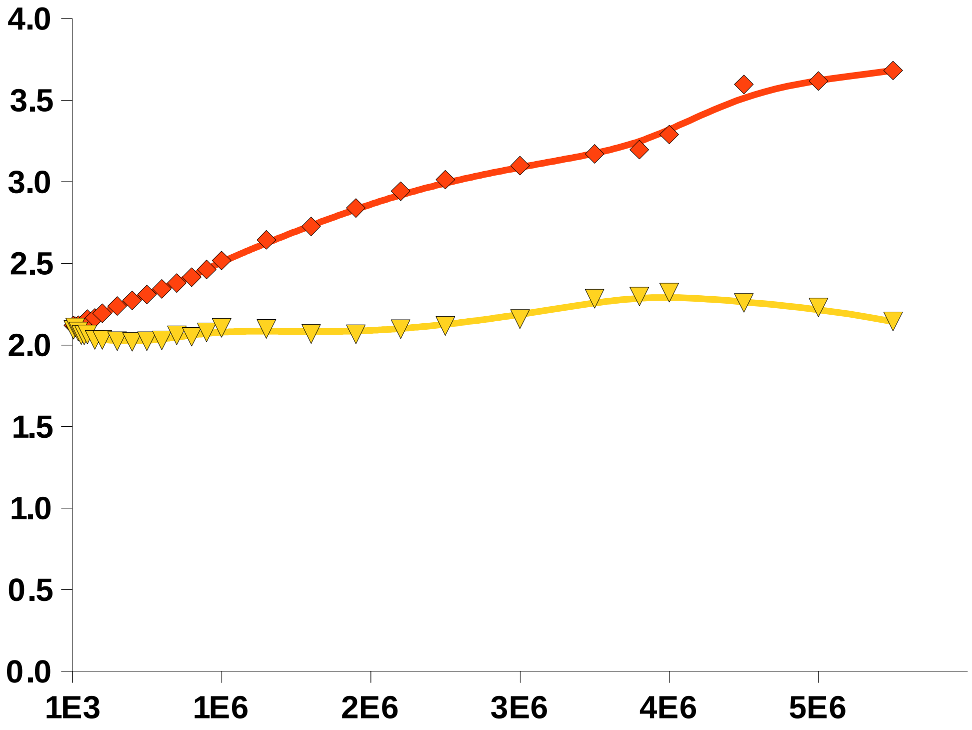
Time Resolution of SiPM may be parametrized as:

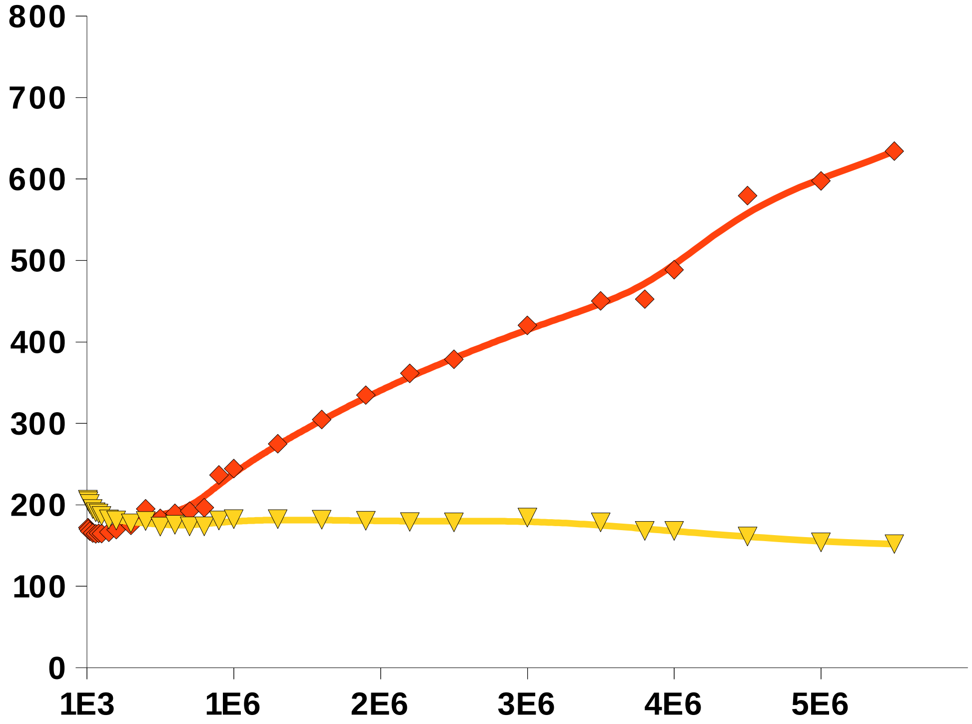
$$\sigma_{PM} = \sqrt{\frac{\sigma_s^2}{N} + \sigma_e^2} \quad where \quad \sigma_e = 23\ ps$$

Here, σ_s is frequency dependent at high rates:

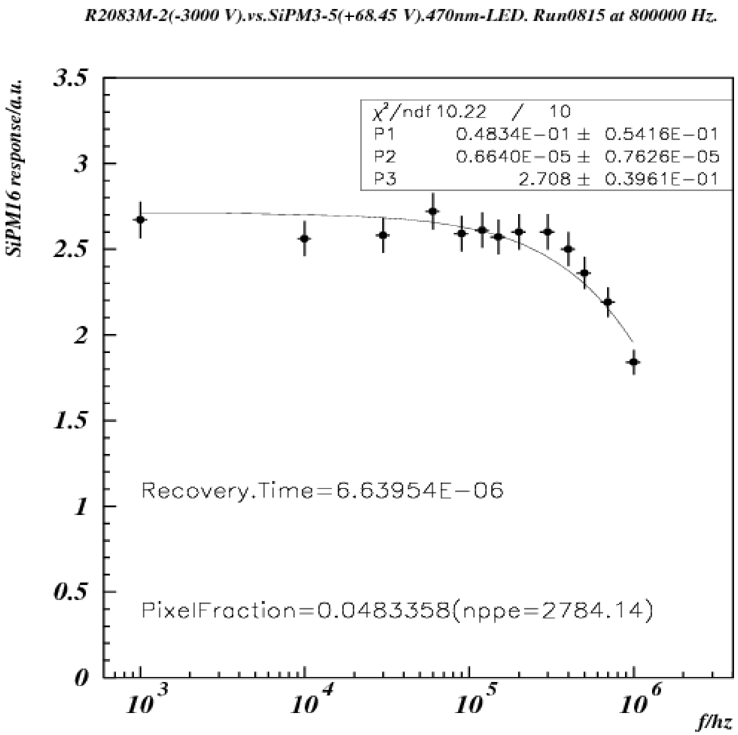
$$SiPM-3: \quad \sigma_s/ns = 2.2 + (0.25E\text{-}6) f$$

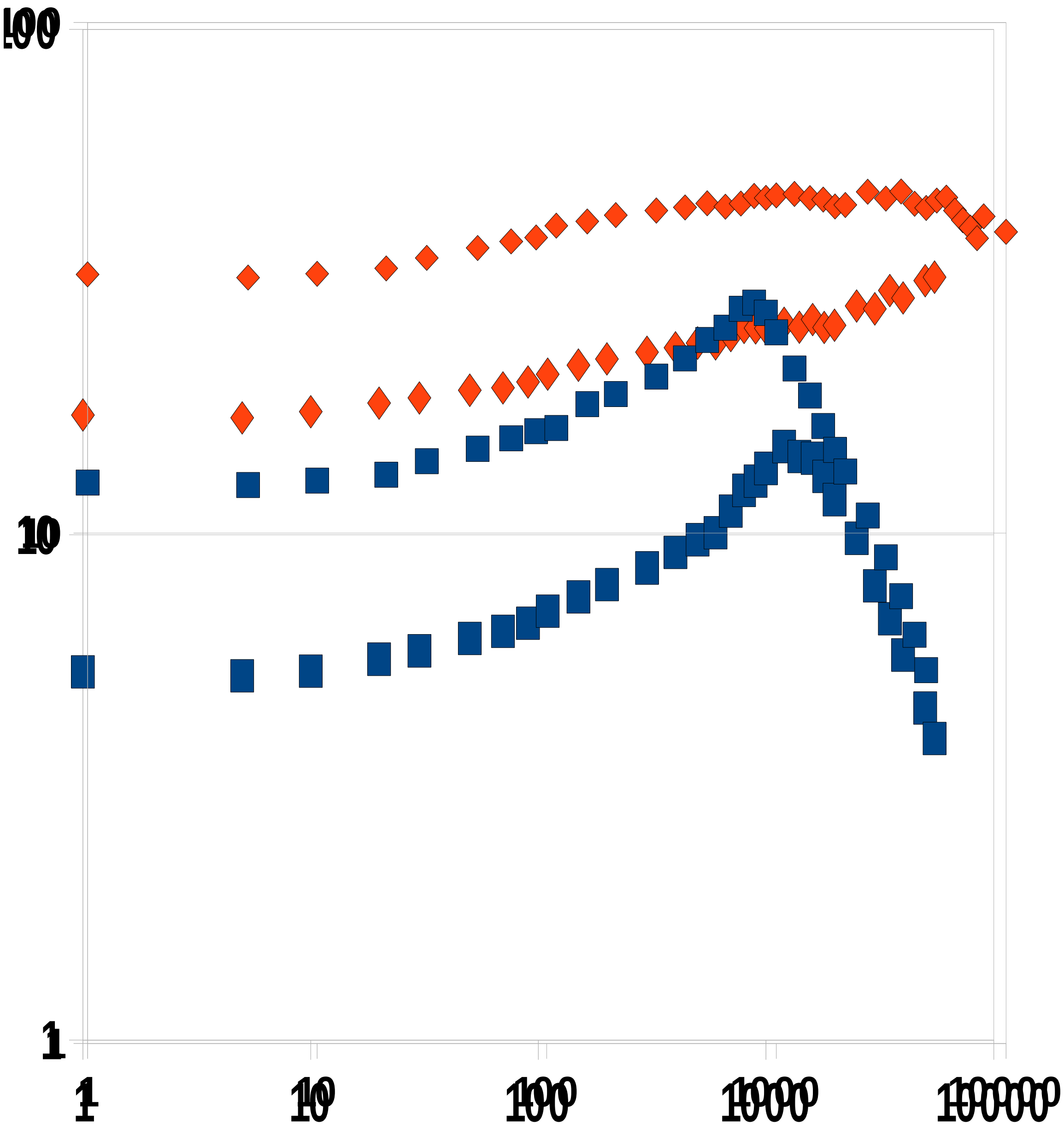
$$SiPM-16: \quad \sigma_s/ns = 5.0 + (0.75E\text{-}6) f$$


4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1E3
1E6
2E6
3E6
4E6
5E6

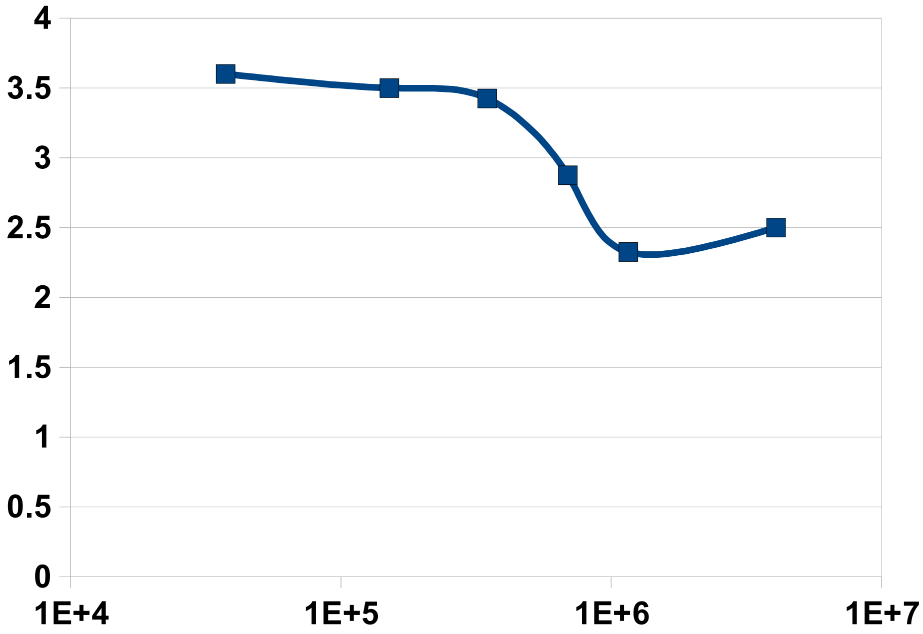

800
700
600
500
400
300
200
100
0
1E3
1E6
2E6
3E6
4E6
5E6

SiPM16 Response vs. Count Rate



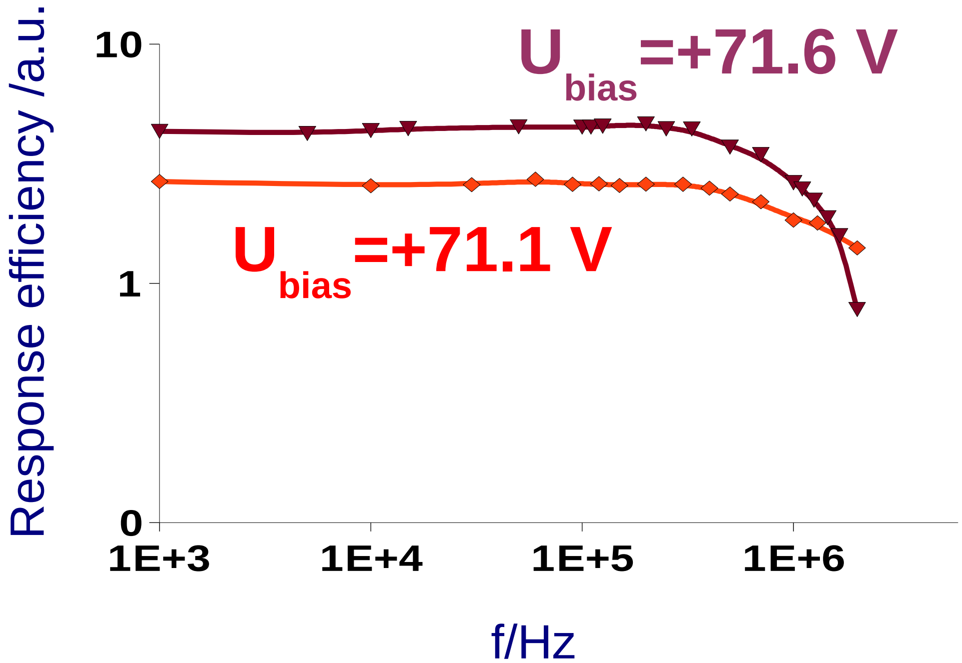


Rate effects in SiPM3 signal amplitude



f / MHz

SiPM-16 Response vs. Bias Voltage

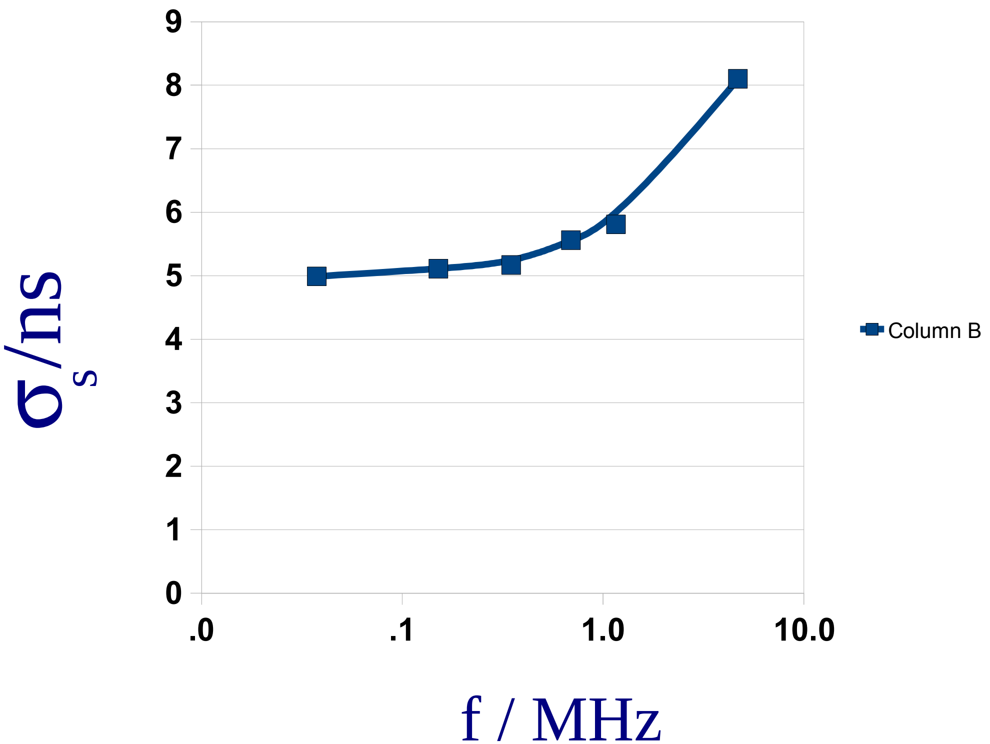


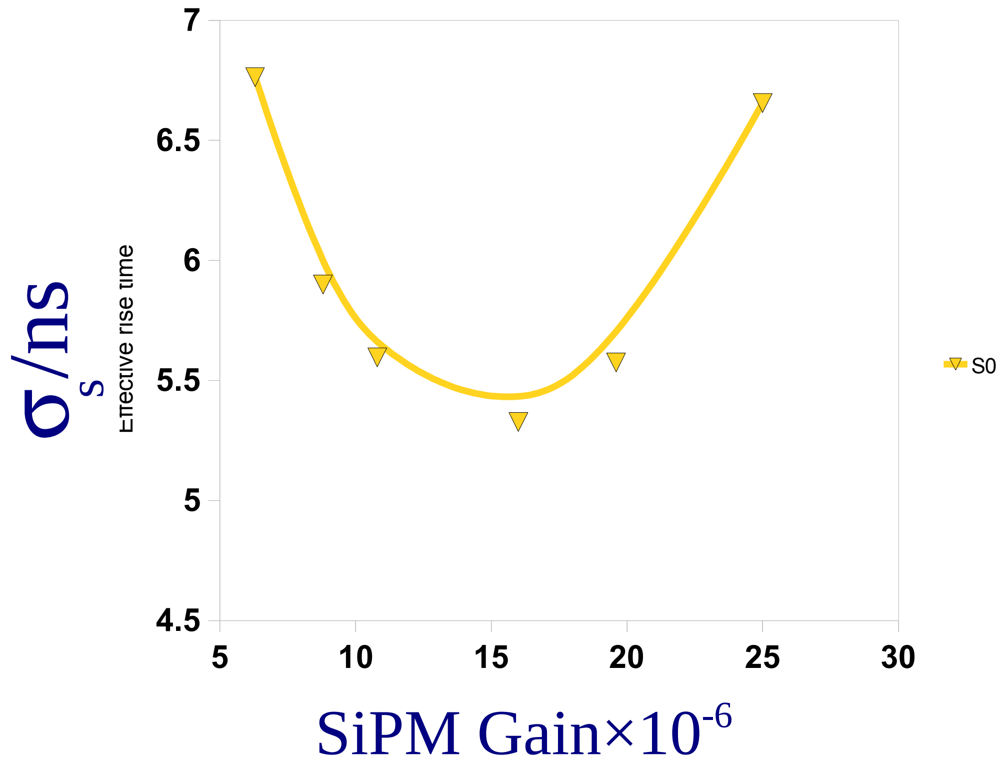
~390 pix

- SIPM-16 response drops after 100 KHz, sooner at higher Gain.
- Manifestation of space-charge effect, similar to regular PMT(?)

SiPM Time Resolution vs. Gain and Count Rate

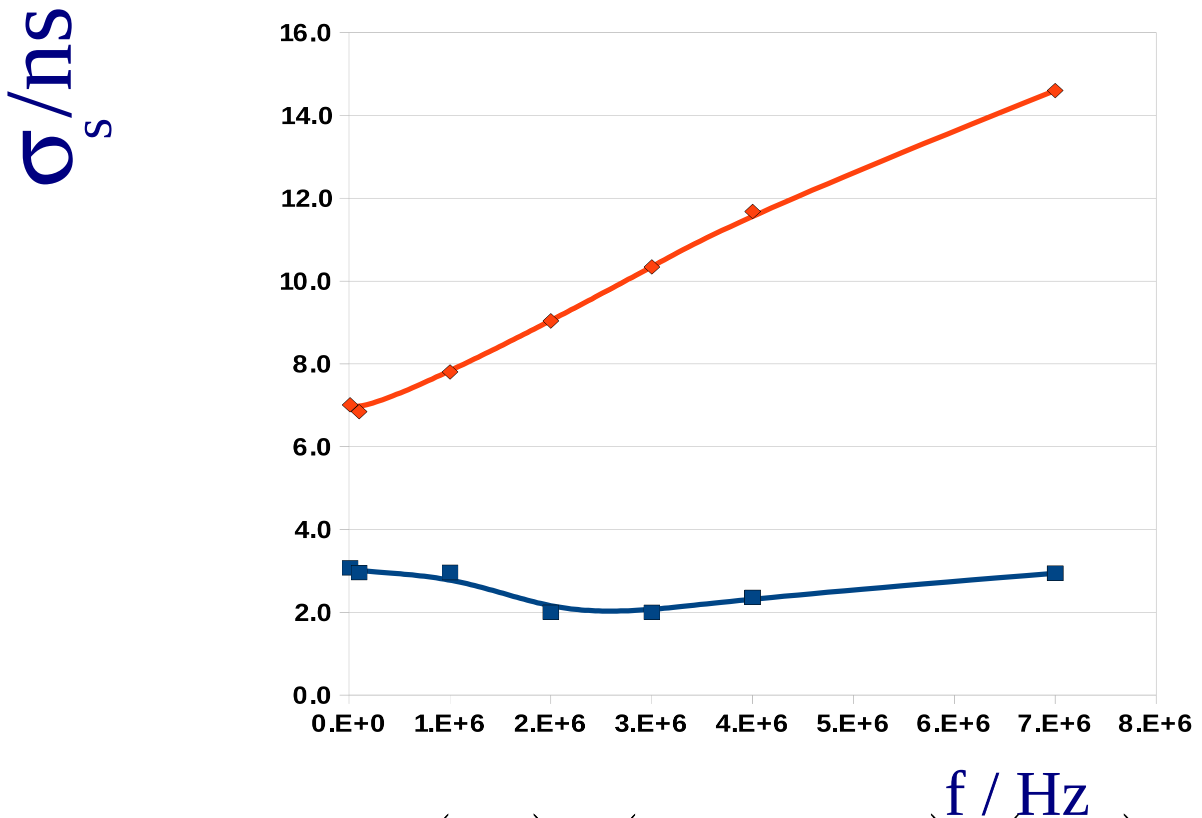
$$\sigma_{SiPM} = \sqrt{\frac{\sigma_s^2}{N} + \sigma_e^2} \qquad where \quad \sigma_e = 23\,ps$$



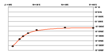
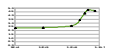
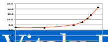


SiPM1 Time Resolution vs. MHz

$$\sigma_{SiPM} = \sqrt{\frac{\sigma_s^2}{N} + \sigma_e^2} \quad \textit{where} \quad \sigma_e = 23\, ps$$



$$\sigma_s = 7.0(ns) + (3.9\text{E-}6\, ns) f (Hz)$$

SiPM3 Time Resolution vs Gain at 1.2 MHz random rate

$$\sigma_{SiPM} = \sqrt{\frac{\sigma_s^2}{N} + \sigma_e^2} \qquad where \quad \sigma_e = 23\,ps$$