GDR Neutrino reunion

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Calibration of the Double Chooz Inner Veto photomultipliers

Gain calibration, monitoring and related topics…

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Introduction

- Decades after their discovery, photomultiplier tubes (PMT) are still commonly used in the fields of particle, astroparticle, high energy and neutrino physics.
- Easy to manufacture in large quantities.
- Low cost instruments.
- Large area of photocathode coverage.
- Stable response in a wide period of time.
- Solid understanding of the way they operate.
- Well developed methods to model their characteristics,
- But still an open and fascinating area of physics research.
- Some examples:
  - Super-Kamiokande III: 11129 PMT.
  - The SNO observatory: 10000 PMT.

In this talk

- I will give a general overview of the PMT functioning.
- A gain calibration interim.
- A “new” model for charge amplification.
- Performance of the model.
- Analysis software.
- Data analysis.

Photon detection

- A flux of photons hits the photocathode.
- Photoelectron (PE) creation via external photoelectric effect.
- Charge collection and focusing to the dynode structure.
- Amplification through electron cascades.
- Signal is measured in the PMT anode.
- The signal is (if required) further amplified by electronics.
- The final detected to specific number of initial incoming photons follows a probability distribution function (PDF).
- An important value of this procedure is the PMT gain.
- Total measured charge: (number of PE)×(gain)
- The knowledge of the gain and its possible changes/drifts are important for the performance of a detector.

A general treatment

- To measure and monitor the photomultiplier gain usual you expose them to low intensity light pulses; single photoelectron (SPE) region.
- Photo-conversion and light collection follow a Poissonian law:

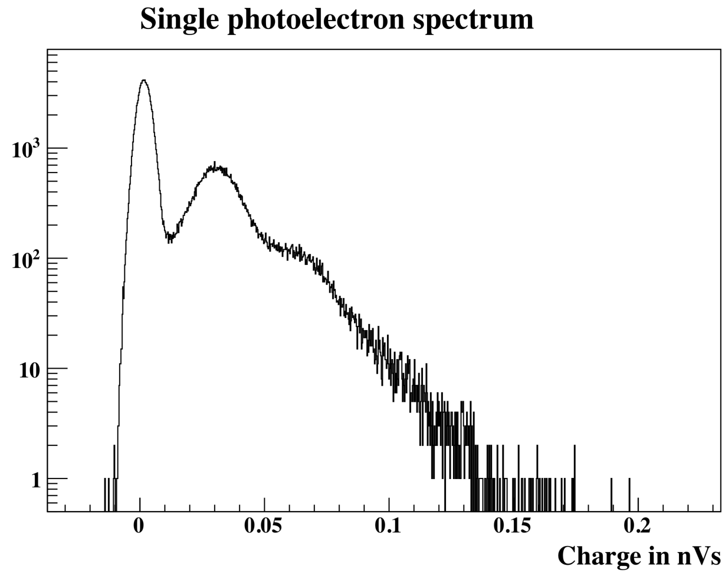
$$p_n = \frac{\mu^n}{n!}\, e^{-\mu}$$, p_1 is the probability for 1PE creation, p_2 for 2PE , etc…

- The Poissonian mean holds the information of the light source and, jointly, the conversion-collection processes.
- PE amplification, S(x). The PDF mean is the gain.
- Multi-PE amplification, $S_n(x)=(S*S\ldots)(x)$.

$$S_{ID}(x) = \sum_{n=0}^{+\infty} p_n S_n(x)$$

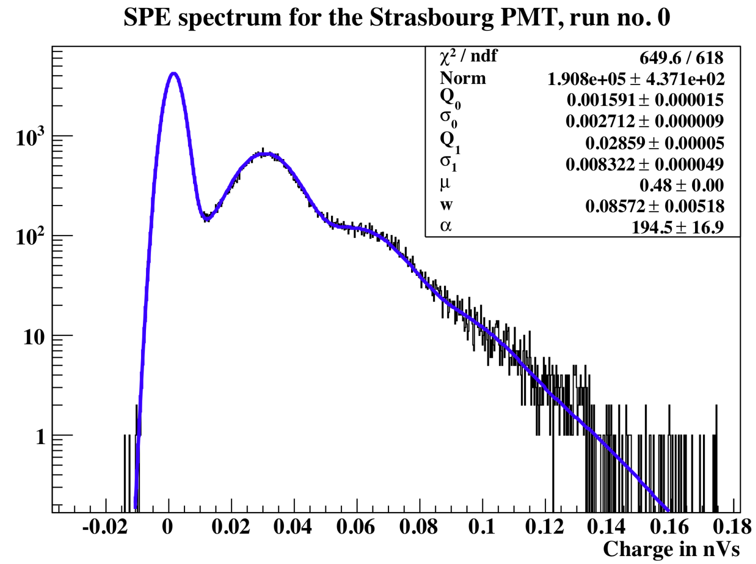
- Incorporating the background,

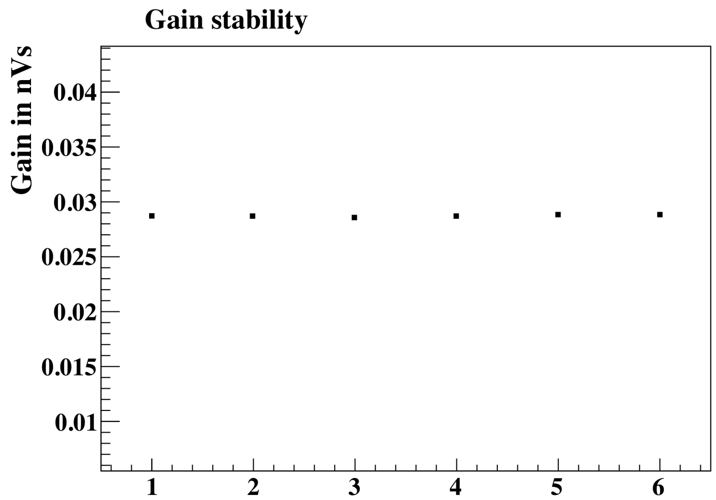
$S_R(x)=(S_{ID}*B)(x)$



The Gaussian model

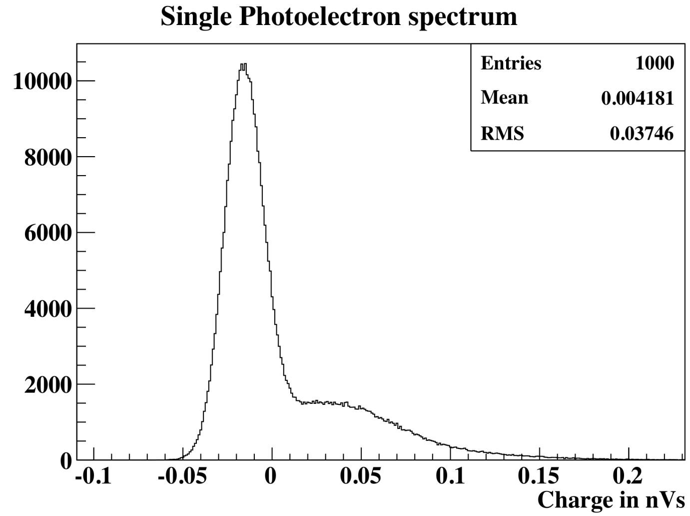
- This method, to attack gain calibration is mostly used to newly purchased PMT.
- The amplification profile can be adequately parameterised by a simple gaussian.
- Assuming that the BG can be described by a gaussian also, the mathematics of the model can be done analytically.
- This offers us a very flexible and powerful model.
- More details: NIMA339(1994) 468-476.
- An accuracy of 1% in the gain can be achieved.
- Fast and powerful method.
- Gain monitoring is, like this, possible in a routinely performed procedure.





Motivation for this work

- The technique thus described finds great application mostly on newly manufactured PMT.
- Good resolution, charge amplification and collection so that the SPE response can be parameterized with a single Gaussian.
- Older PMT do not have a clear SPE peak.
- Other techniques were used in the past.

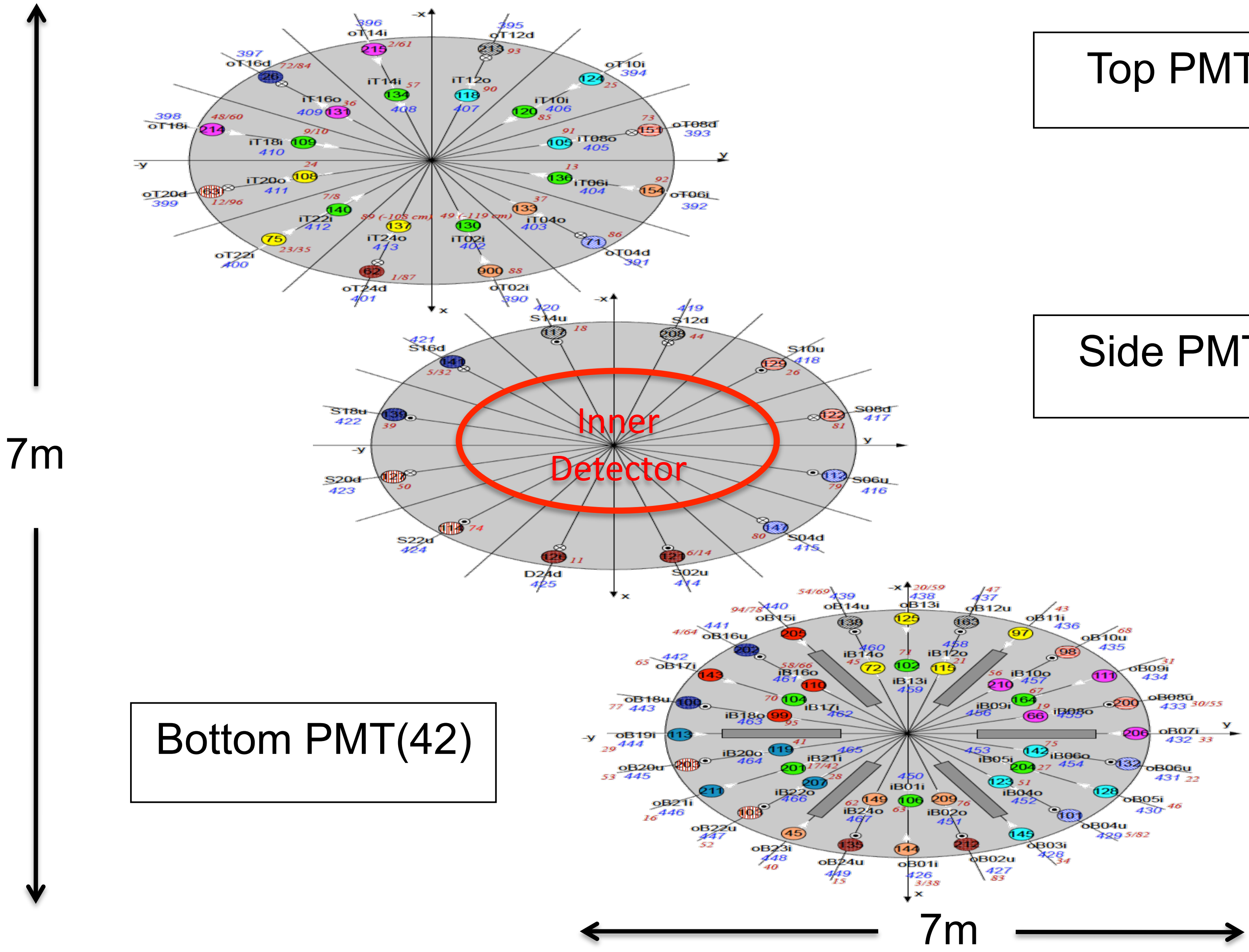


- This is exactly the case also for the Inner Veto PMT of the Double Chooz detector.
- A typical charge likelihood is highly asymmetric having an exponential like decay tail.
- The method we shall put forward was developed for the gain determination and monitoring of the Double Chooz Inner Veto (IV) PMT.

The Double Chooz detector

- The Double Chooz target consists of 10.3 m^3 of liquid scintillator.
- It is viewed by 390 PMTs; 10 inches R7081 Hamamatsu PMT.
- The Inner Veto is a cylindrical volume (110 m^3) filled with liquid scintillator that surrounds the neutrino target.
- Its sole purpose is to tag background events.
- It is viewed by 78 10 inches diameter PMT.
- R1408 Hamamatsu PMT first purchassed for the IMB detector.

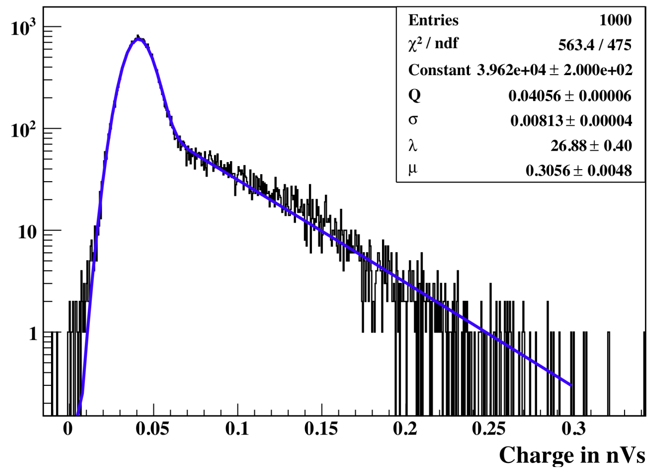
Inner Veto geometry



Exponential model

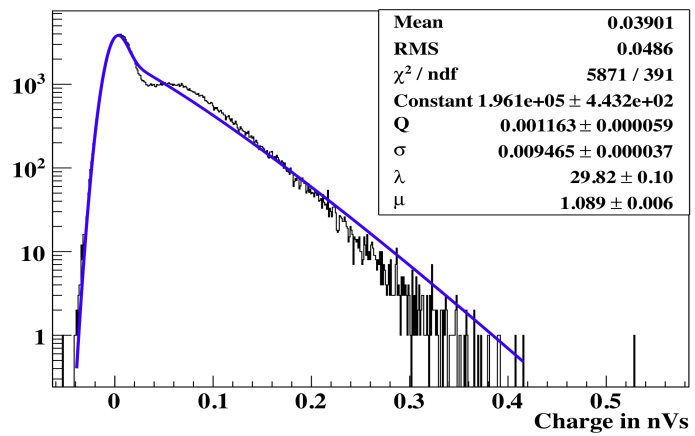
- In view of the exponential-like tail it is tempting to parameterize the SPE amplification law with an exponential distribution.
- One could try:

$$S(x) = \lambda\ e^{-\lambda x}\ \Theta(x)$$



- The multi-PE amplification can be readily worked out:

$$S_n(x) = \frac{\lambda}{(n-1)!}(x\lambda)^{n-1}\ e^{-\lambda x}\ \Theta(x)$$

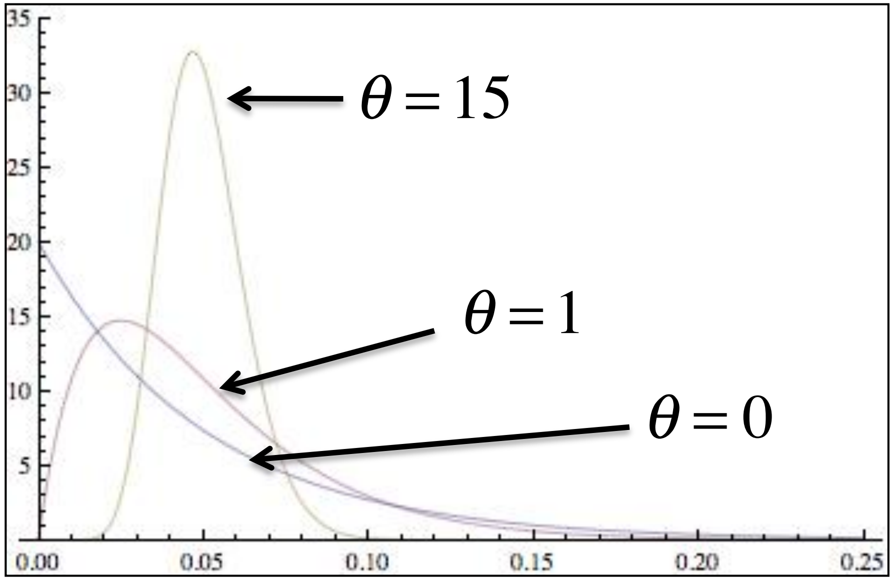


- The BG incorporation, final convolution, can be done analytically.
- This model is adequate to describe some of the Inner Veto PMT.
- Nonetheless, this model fails to describe the SPE bump that seems to be sometimes present.

Gamma distribution

- Modification of the simple-minded exponential distribution.

$$S(x) = \lambda(1+\theta)\frac{[\lambda(1+\theta)x]^{\theta}}{\Gamma(1+\theta)}\; e^{-\lambda(1+\theta)x}\;\Theta(x)$$



- In this incarnation sometimes referred as the "Polya" function (In the past used on MWPC).
- The old model still present when $\theta=0$.
- Improvements evident from natural logistics; one extra parameter/ degree of freedom.
- Mean value: $1/\lambda$. Variance: $1/[\lambda^2(1+\theta)]$.
- The incorporation of the BG (gaussian distribution) is not that straightforward.
- It can be done numerically; although a good optimisation is needed for quick results.

Analytical Solution

- The mathematics can be turned out, so that the analytical solution can be found.
- A brute-force calculation.

$$S_R(x) = \sum_{n=0}^{+\infty} p_n S_R^{(n)}(x) \qquad S_R^{(n)}(x) = (S_n * B)(x)$$

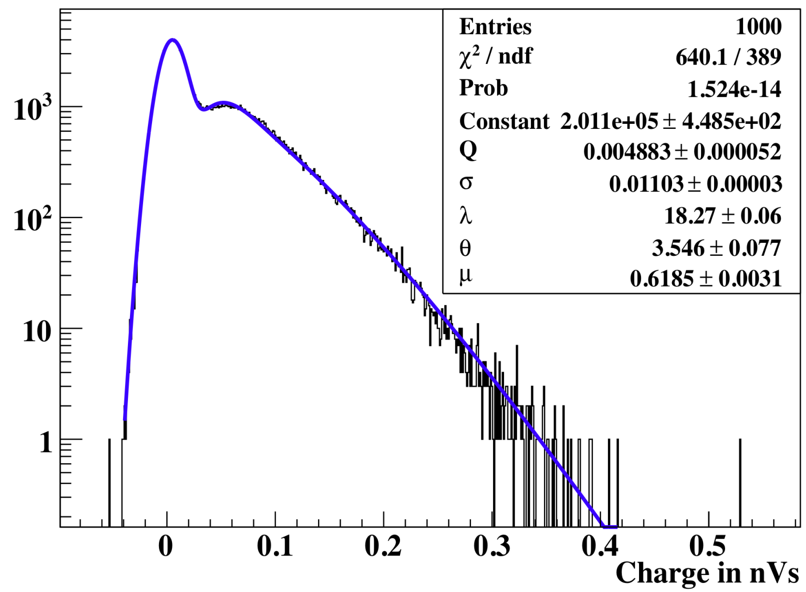
$$S_R^{(n)}(x) = \frac{1}{\sqrt{2\pi}\sigma} \times \frac{[\lambda(1+\theta)]^{n(1+\theta)}}{\Gamma(n(1+\theta))} \times I_n$$

$$I_n = \int_0^{\infty} t^{n(1+\theta)-1}\, e^{-\lambda(1+\theta)t}\, e^{-\frac{(x-Q-t)^2}{2\sigma^2}}\, dt$$

- The last integral I_n can be done in terms of the Kummer's hypergeometric functions on the first and second kind.
- The formulas can be then anchored in a controllable and compact code so that the solution can done by adding the first say, five or ten terms (depending on the required accuracy).

Performance of the model

- A toy Monte Carlo model can be developed so that the performance of the model can be checked.
- In all cases, we were able to recover the initial injected parameters.
- We are not ruled out by unwanted correlations.
- The resulting model (owing to this extra parameter θ) is very flexible.
- In particular, it can treat a vast number of similar PMT.
- Very good χ^2/NDOF.
- Quick and reliable results.

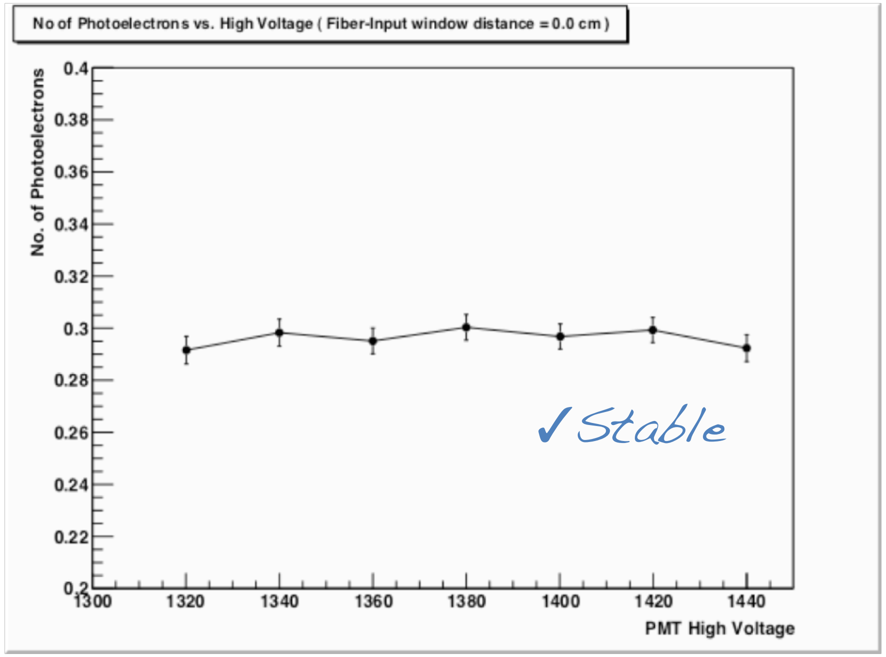


Consistency and cross-checks

- The gain and its resolution are constants of the PMT.
- Depend also on the temperature and external magnetic fields.
- They should not change as we increase the input light luminosity.
- This reflects the linear character of charge amplification.
- This is indeed the case for the model we developed.
- Also the model should be able to determine/deconvolute efficiently the Poissonian mean.

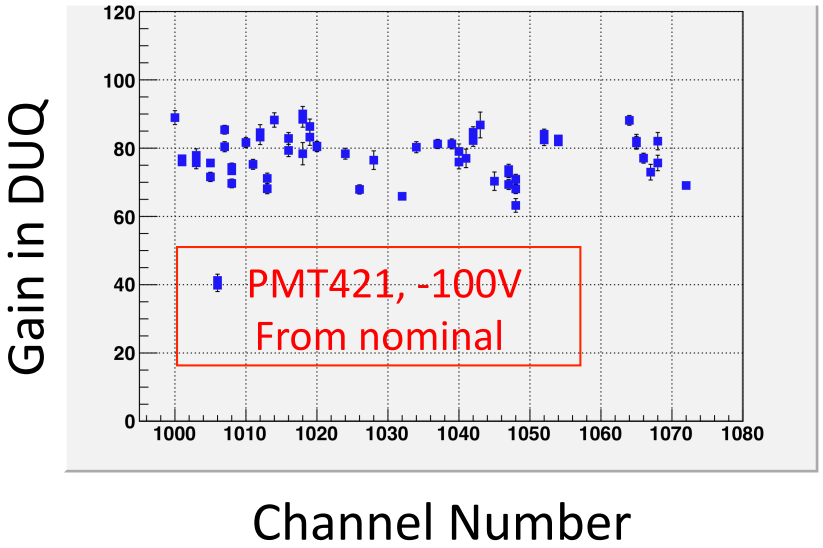
Polya Model

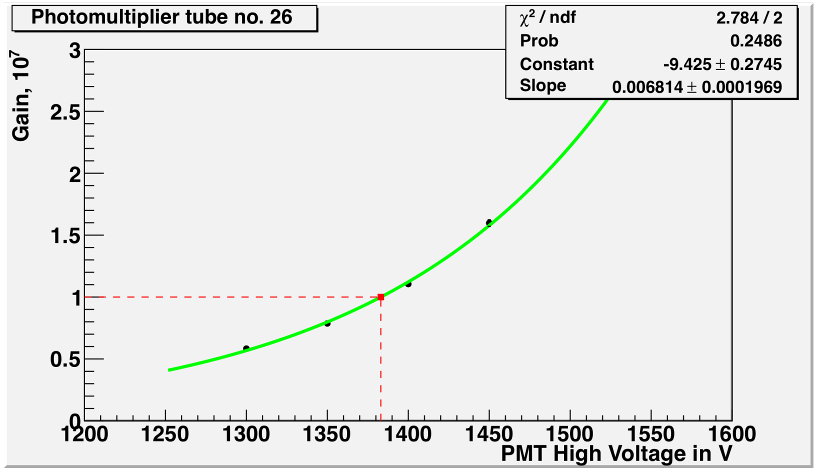
λ	$\pm\delta\lambda$	θ	$\pm\delta\theta$	μ	$\pm\delta\mu$
18.1473	0.0690661	3.77557	0.0828358	0.251455	0.00145313
18.0799	0.0423102	3.81046	0.0527141	0.313064	0.00109643
18.1389	0.0516575	3.70146	0.0622883	0.356322	0.00150365
18.1656	0.0422534	3.65092	0.0506732	0.40963	0.00140413
18.2683	0.0475186	3.56288	0.05566	0.445517	0.00168955
18.1353	0.0583767	3.60454	0.0730343	0.504144	0.00240364
18.2705	0.0649074	3.47268	0.0764942	0.620917	0.00322124

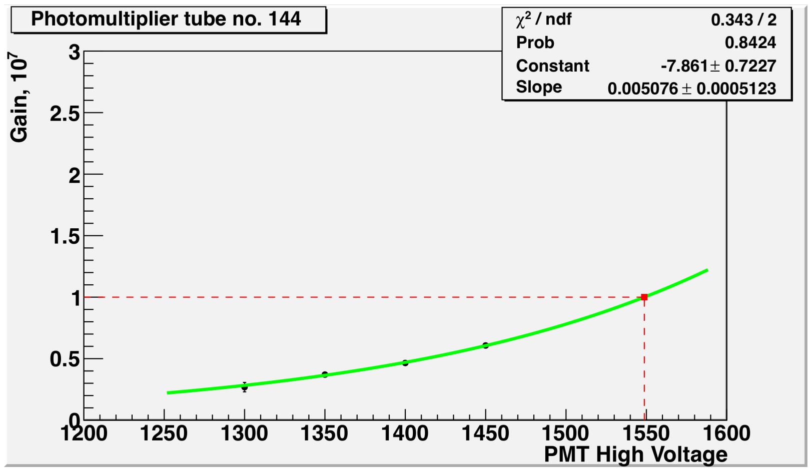


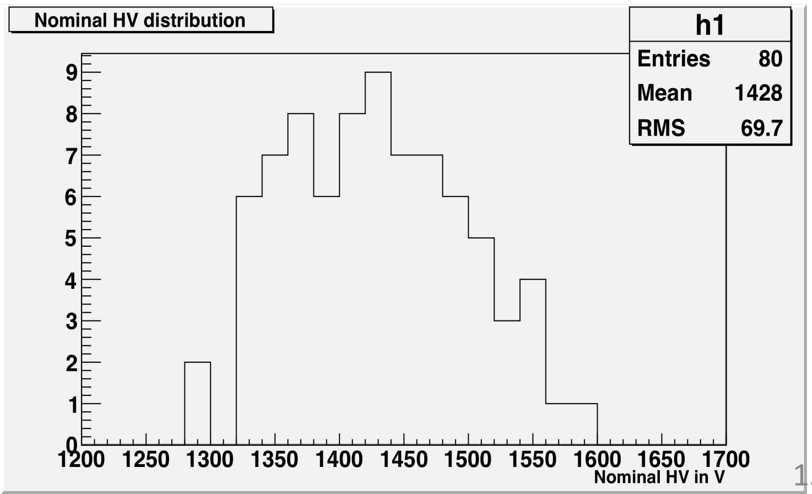
HV tuning

- SPE spectra for four distinct HV values.
- The gain increases with the applied HV following an exponential law.
- Different behaviour for different PM.
- Fit with an exponential to take the slope.
- Then interpolate the nominal high voltage value for each photomultiplier.
- Nominal HV: where gain equals 10^7.
- Reasonable results; narrow distributions.



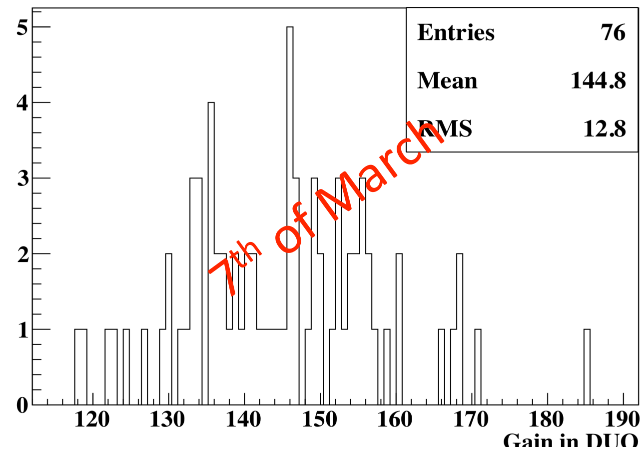


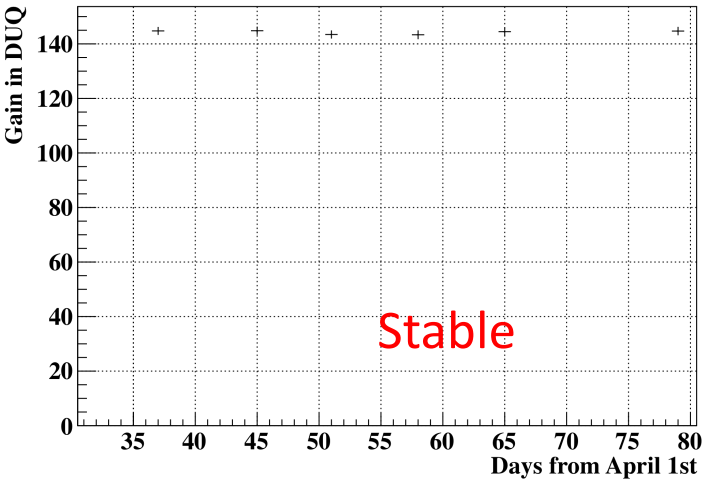


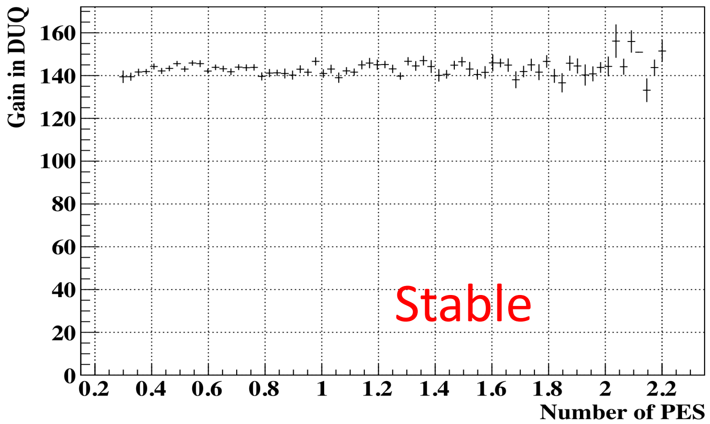


In situ gain calibration

- With the Inner Veto Light Injection system (IV-LI) we take calibration data once per week.
- Well developed software that reaps the data and obtains the charge likelihoods.
- Then the SPE fitting model is directly applied, providing us the answers.
- All this proceeds in a production mode chain.
- Independence in the number of pes.
- This stability is quite impressive.
- The mean, and the variation over the mean, are stable for one short period between May 5 and July 18 2011.
- Channel-wise info also stable.







Summary

- We presented a mathematical edifice that can realistically model the response of a PMT.
- The model is mature enough and flexible to treat a wide class of PMT.
- It passes all cross-checks, signalling consistency.
  - Independence with input light flux
  - No deformation of the Poissonian mean.
- It results reliable results, and it can be used to measure and monitor the gain parameter to very good accuracy.
- A valuable toll for measurements at the SPE mode.
- We found it useful:
  - Configure/commission the IV of the Double Chooz detector.
  - Measure and monitor the IV PMT gains in a regular basis.
- It can be used to calibrate other types of PMT also.

Thank you very much

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BACKUP

Solving the integral

$$I_n = \frac{1}{2}\,(\sqrt{2}\sigma)^{n(1+\theta)}\; e^{-\frac{(x-Q)^2}{2\sigma^2}} \left(\Gamma\left(\frac{n}{2}(1+\theta)\right) \mathcal{M}\left(\frac{n}{2}(1+\theta), \frac{1}{2}, \omega^2\right) + \frac{2\omega}{\sqrt{2}\sigma}\Gamma\left(\frac{1+n(1+\theta)}{2}\right) \mathcal{M}\left(\frac{1+n(1+\theta)}{2}, \frac{3}{2}, \omega^2\right) \right), \quad \omega = \frac{x-Q-\lambda(1+\theta)\sigma^2}{\sqrt{2}\sigma}$$

$$I_n = \begin{cases} \frac{1}{2}\,(\sqrt{2}\sigma)^{n(1+\theta)}\; e^{-\frac{(x-Q)^2}{2\sigma^2}+\omega^2} \left(\Gamma\left(\frac{n}{2}(1+\theta)\right) \mathcal{M}\left(\frac{1}{2}-\frac{n(1+\theta)}{2}, \frac{1}{2}, -\omega^2\right) + \frac{2\omega}{\sqrt{2}\sigma}\Gamma\left(\frac{1+n(1+\theta)}{2}\right) \mathcal{M}\left(1-\frac{n(1+\theta)}{2}, \frac{3}{2}, -\omega^2\right) \right) & , \quad \omega > 0 \\ \left(\frac{\sigma}{\sqrt{2}}\right)^{n(1+\theta)} \Gamma\left(n(1+\theta)\right)\; e^{-\frac{(x-Q)^2}{2\sigma^2}}\; \mathcal{U}\left(\frac{n}{2}(1+\theta), \frac{1}{2}, \omega^2\right) & , \quad \omega < 0 \end{cases}$$