Physics Laboratory
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KM3NeT
Opens a new window on our universe

Measuring the sea water optical parameters with a dedicated laser beam and a Multi-PMT Optical Module

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Outline

- Introduction
- Experimental setup
- Simulation of the experiment
- Analysis technique
- Results
- Summary

Introduction - Motivations

Event simulation/reconstruction techniques rely on the accurate description of the PMT signal

Accurate description of the Cerenkov light characteristics detected by the PMTs

- Good knowledge of particles producing the light (generation of secondaries)
- Good knowledge of optical photon processes in the sea water
- Good knowledge of the PMT functional characteristics

KM3NeT Multi-PMT optical module consists of 31 3-inch PMTs

- Each PMT covers a part of the full solid angle

→ The Multi-PMT optical module is sensitive to the direction of the incident photons

Optical photon processes in the sea water

- Absorption
- Scattering
    - Mie (particulate) scattering from macroscopic particles in sea water
    - Rayleigh scattering from sea water molecules

Introduction – Scattering model used in this study

A combination of Mie and Rayleigh scattering

Scattering angle distribution (phase function)

$$\frac{dP}{d\Omega_s} = F(cos\theta_s; p, a_{Rayl}, a_{Mie}) = p \times g(a_{Rayl}, cos\theta_s) + (1-p) \times f(a_{Mie}, cos\theta_s)$$

p: Rayleigh contribution
θ_s: scattering angle

Mie (particulate) scattering from macroscopic particles in sea water

Henyey-Greenstein function

$$f(a_{Mie}, cos\theta_s) = \frac{1}{4\pi} \frac{(1-a_{Mie}^2)}{(1+a_{Mie}^2 - 2a_{Mie} cos\theta_s)^{\frac{3}{2}}}$$

$$\langle cos\theta_s \rangle = a_{Mie}$$

Rayleigh scattering from sea water molecules

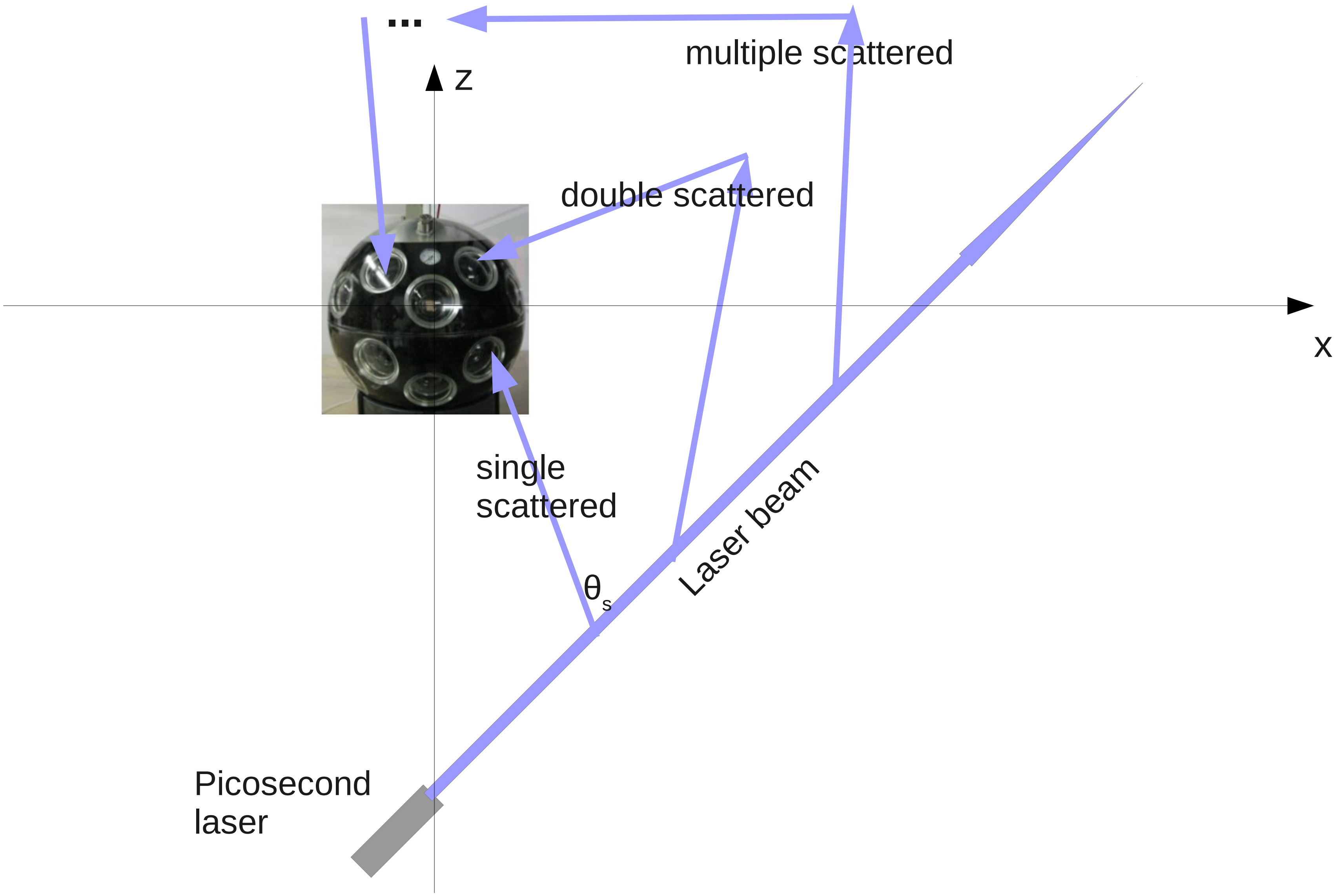
Phase function

$$g(a_{Rayl}, cos\theta_s) = \frac{(1+a_{Rayl} \cos^2\theta_s)}{4\pi(1+\frac{1}{3}a_{Rayl})} \qquad a_{Rayl} \neq 1$$

$$\langle cos\theta_s \rangle = 0$$

Experimental setup

Optical Module at (0,0,0)
Pico-second laser at (0,0,-10 m) producing bursts of synchronous photons
Beam on xz plane with 45 degrees angle with respect the z-axis



Simulation of the experiment

Simulation with full tracking mode of the HOURS (Hellenic Open University Reconstruction & Simulation) package.

Simulated 1.3 million bursts of 400,000 photons each

Optical photon absorption and scattering parameters for the simulation

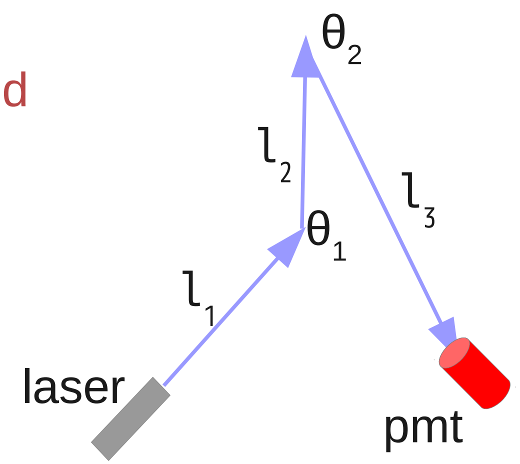
λ (nm)	Absorption length (m) - L_a	Scattering length (m) - L_s	Rayleigh contribution – p	a_{Rayl}	$a_{Mie} = \langle cos\theta_s \rangle_{Mie}$
400	40.9	20	0.17	0.853	0.924

Simulation of the experiment – reweighting

During the simulation, for each detected photon we keep:

- The length of each linear segment of the photon track (l_i i=1,N)
- The scattering angle each time the photon is scattered (θ_i i=1,N-1)

With this information every detected photon can be reweighted for a different set of absorption/scattering lengths and scattering parameters



Probability for a photon to follow the corresponding track from the laser to the PMT:

$$P(p, a_{Rayl}, a_{Mie}) = e^{-L/L_a} \times \left[\prod_{i=1}^{N-1} \frac{1}{L_s} \cdot e^{-l_i/L_s} \cdot F(\cos\theta_i; p, a_{Rayl}, a_{Mie})\right] \times e^{-l_N/L_s}$$

$$L = \sum_{i=1}^{N} l_i$$

probability not to be absorbed

probability to be scattered with angle θ_i after crossing distance l_i

Total photon track length

probability not to be scattered at the last segment

Reweighting validity has been checked by simulation with different parameters

Analysis technique

In the following the absorption length is fixed to 40.9 m (400 nm)

1) Choose the set of scattering parameters used for the simulation as reference parameters (supposedly representing the actual sea water parameters)

L_s (m)	p	a_{Rayl}	a_{Mie}
20	0.17	0.853	0.924

2) Select a new set of parameters randomly in the range -20% to +20% of the reference parameters. Reweight the simulation data to obtain the new arrival time distributions of the detected photons.

3) Compare the new arrival time distributions with the reference ones (supposedly representing the real data) for each PMT.
   The comparison is done by calculating the corresponding χ^2 value between the reference and the new distributions

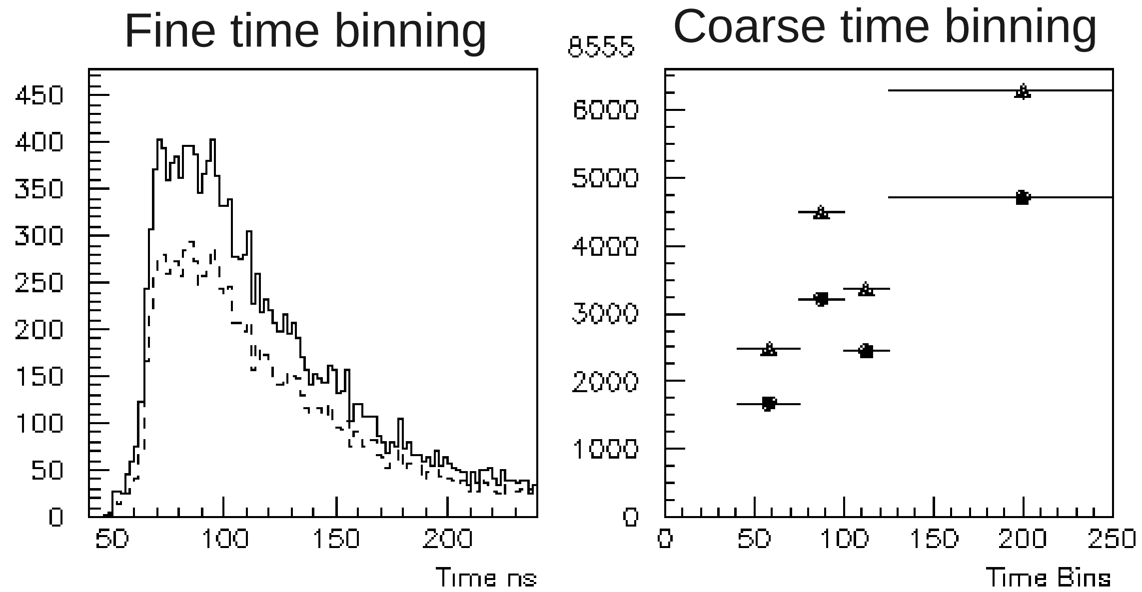
4) Repeat steps (2) and (3) until a χ^2 minimum is found

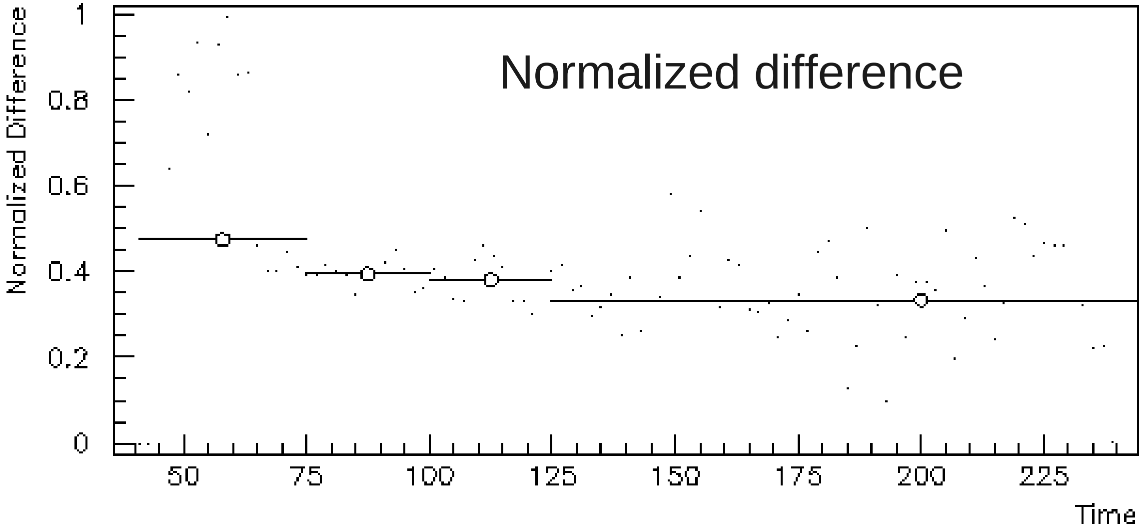
5) Find the error of the estimated parameters at the χ^2 minimum by a fitting a parabola in 4 dimensions

Results I – How much different are the arrival time distributions by varying the scattering length?

Example for PMT #26

Dashed histogram/circles
L_s=20m,
Solid histogram/triangles
L_s=18 m (10% lower)



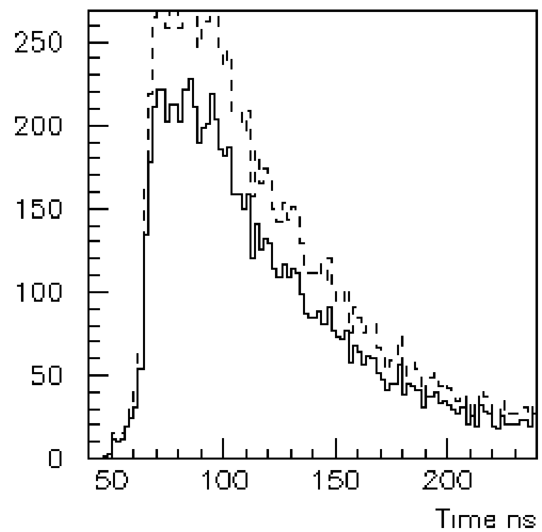


Results II – How much different are the arrival time distributions by varying the Rayleigh contribution?

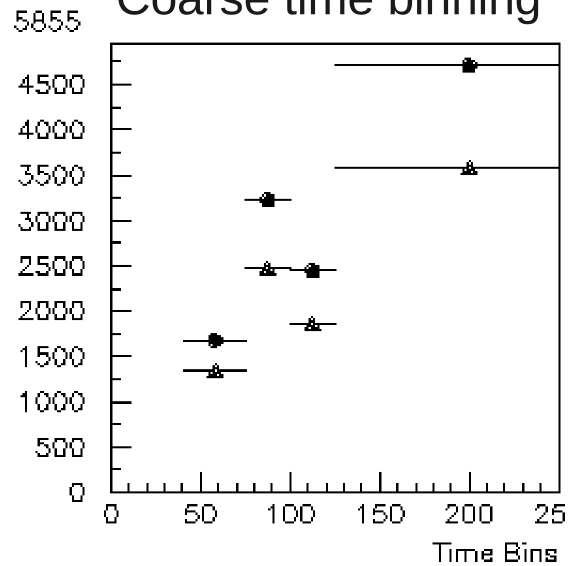
Example for PMT #26

Dashed histogram/circles
p=0.17,
Solid histogram/triangles
p=0.153 (10% lower)

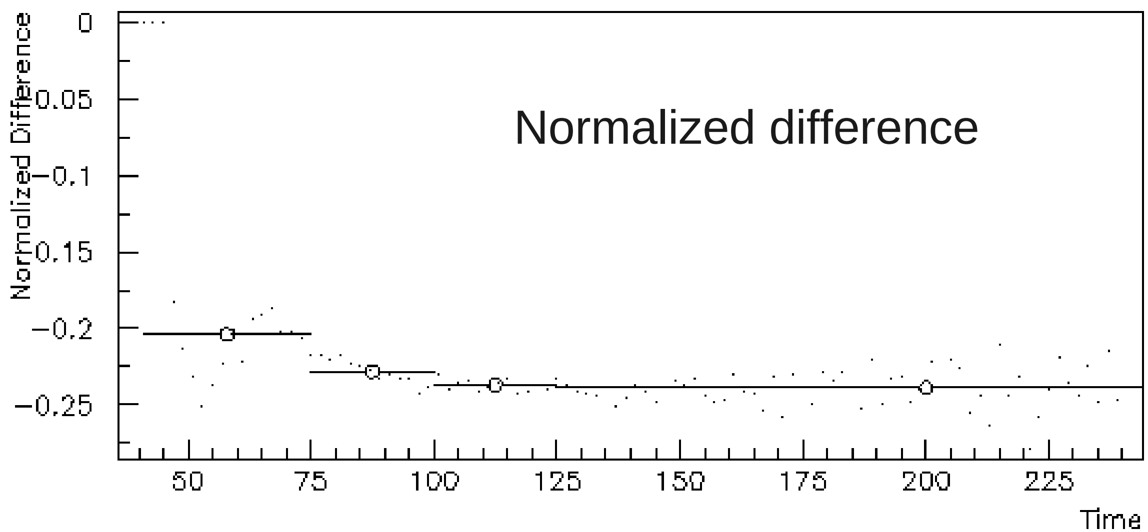
Fine time binning



Coarse time binning



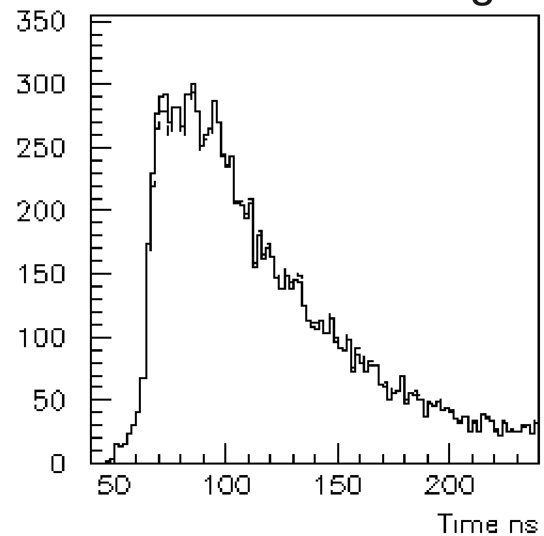
Decreasing the Rayleigh contribution the light is more forward scattered
➨ Less light to back looking PMTs



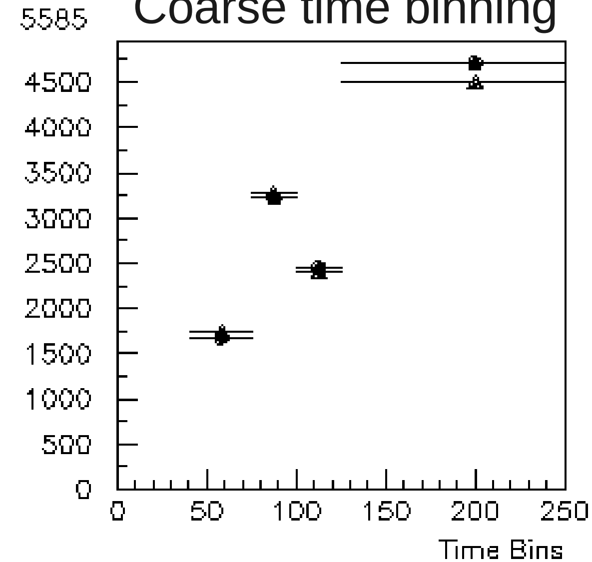
Results III – How much different are the arrival time distributions by varying the Rayleigh constant (anisotropy factor)?

Example for PMT #26

Fine time binning



Coarse time binning



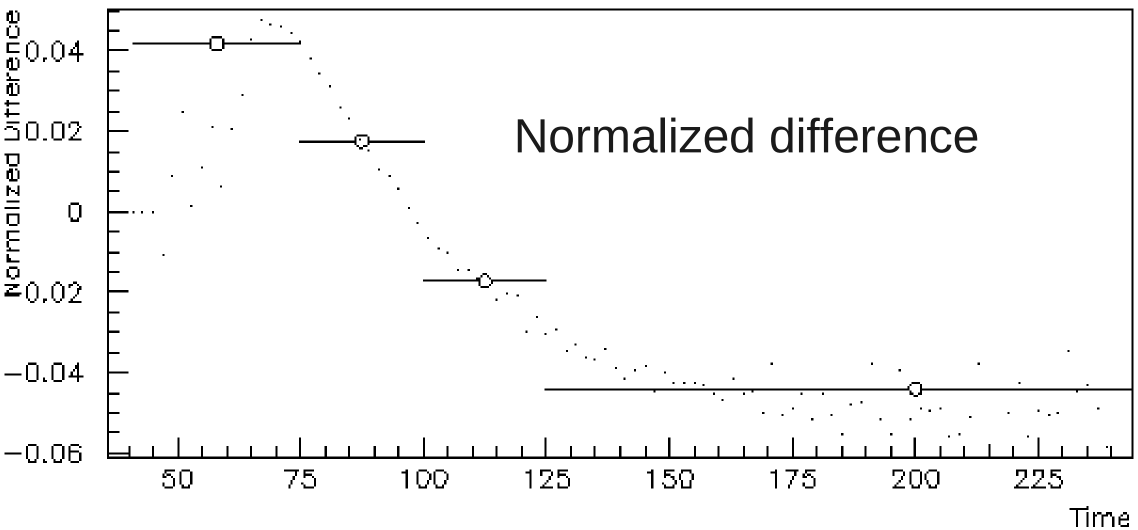
Dashed histogram/circles

a_{Rayl}=0.853,

Solid histogram/triangles

a_{Rayl}=0.77 (10% lower)

Small variations of Rayleigh constant don't change too much the distributions



Results IV – How much different are the arrival time distributions by varying the Mie constant (mean cosine of scattering angle)?

Example for PMT #26

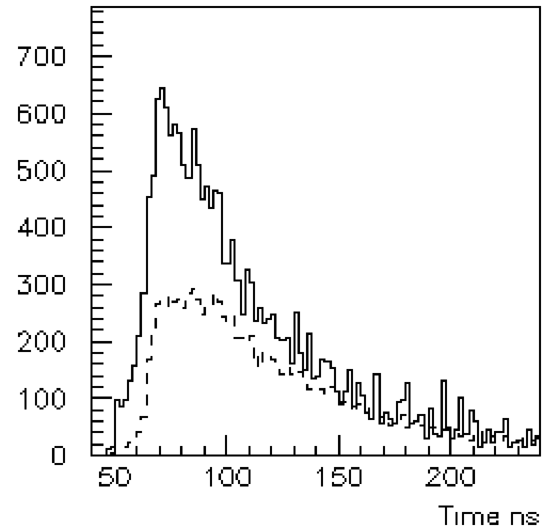
Dashed histogram/circles

a_{Mie}=0.924,

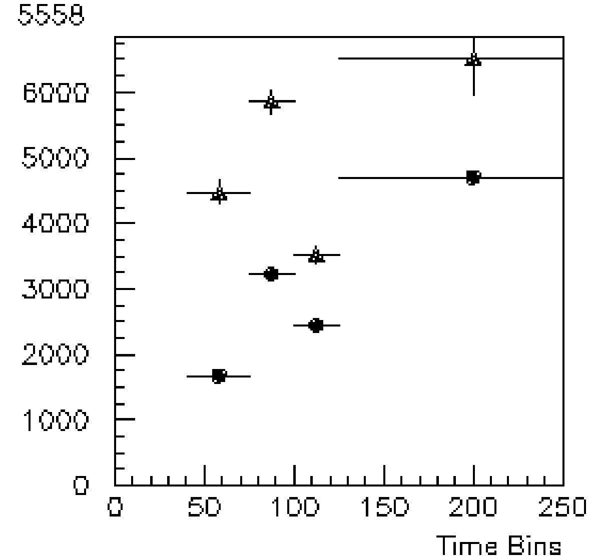
Solid histogram/triangles

a_{Mie}=0.83 (10% lower)

Fine time binning

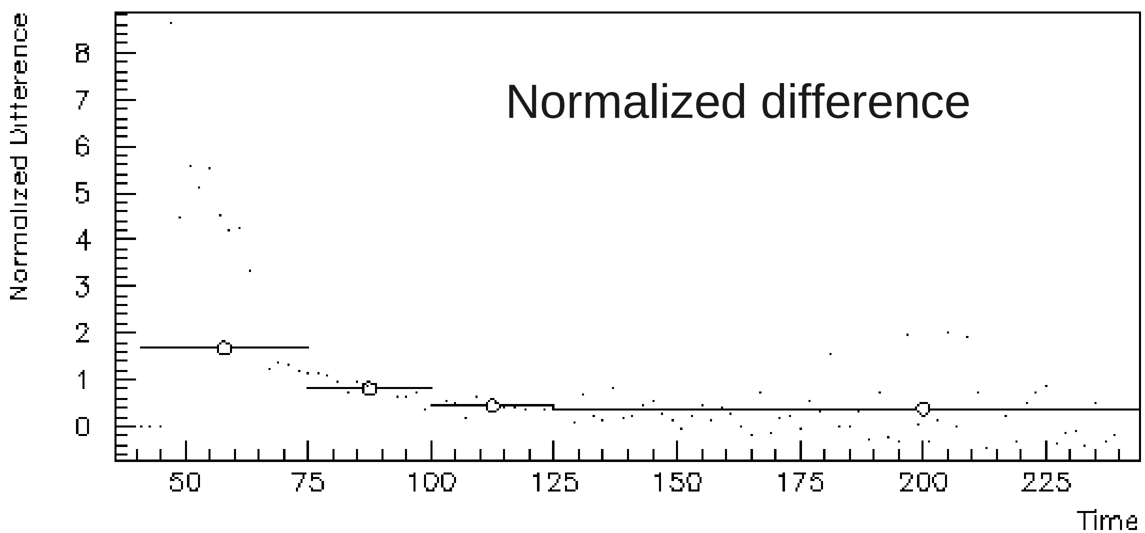


Coarse time binning



Increasing the mean Mie scattering angle (a_{Mie} ↓) the light is more backward scattered

➨ More light to back looking PMTs

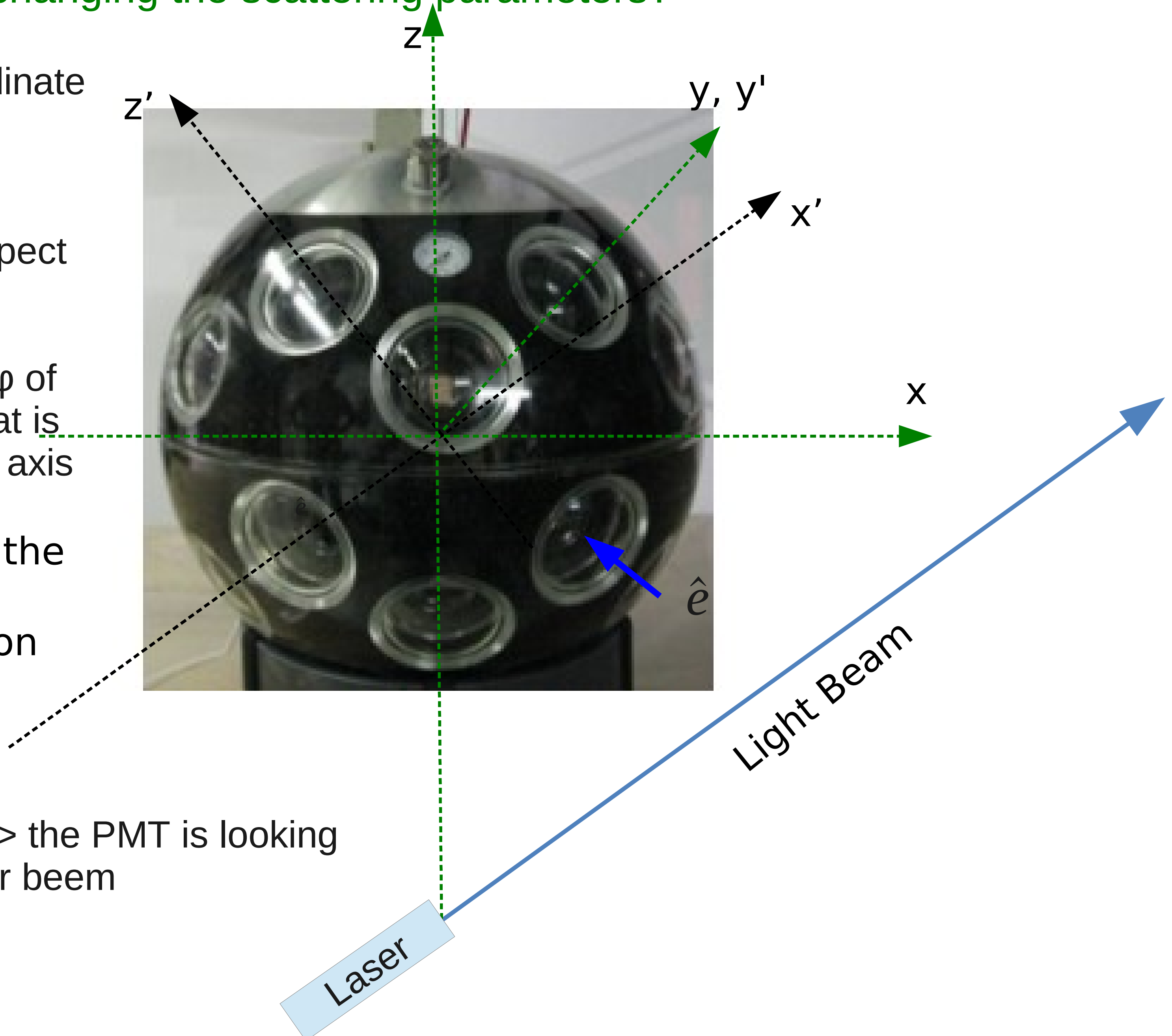


Results V – How much different are the total number of detected photons for each PMT when changing the scattering parameters?

Define a new coordinate system (x',y',z') to distinguish PMTs according to their orientation with respect to the laser beam

Find the angles θ, φ of the unit vector $\hat{e}$ that is parallel to the PMT axis

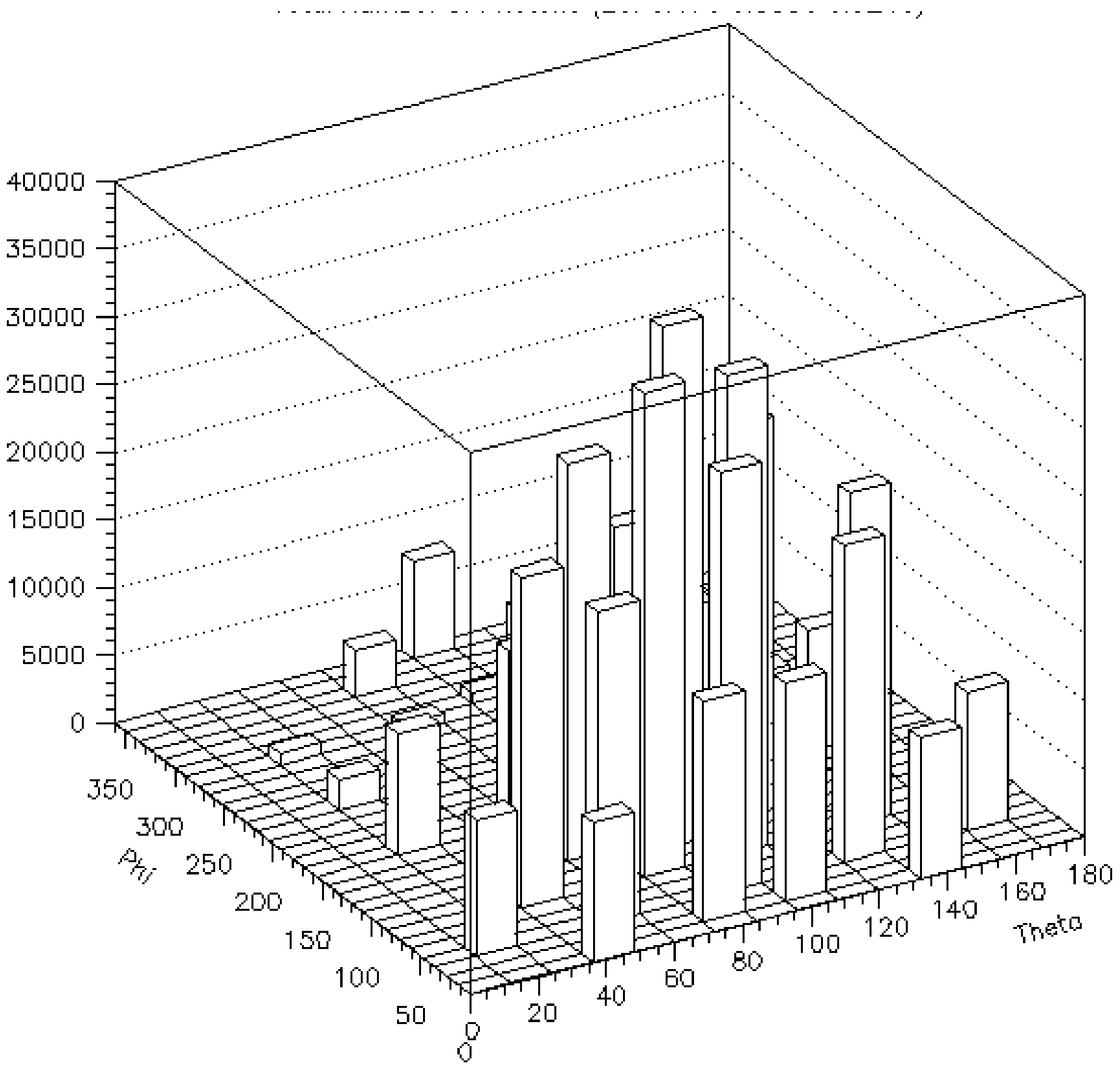
θ with respect to the y' axis
φ is the azimuth on the x'z' plane



θ, φ =90degrees -> the PMT is looking directly at the laser beem

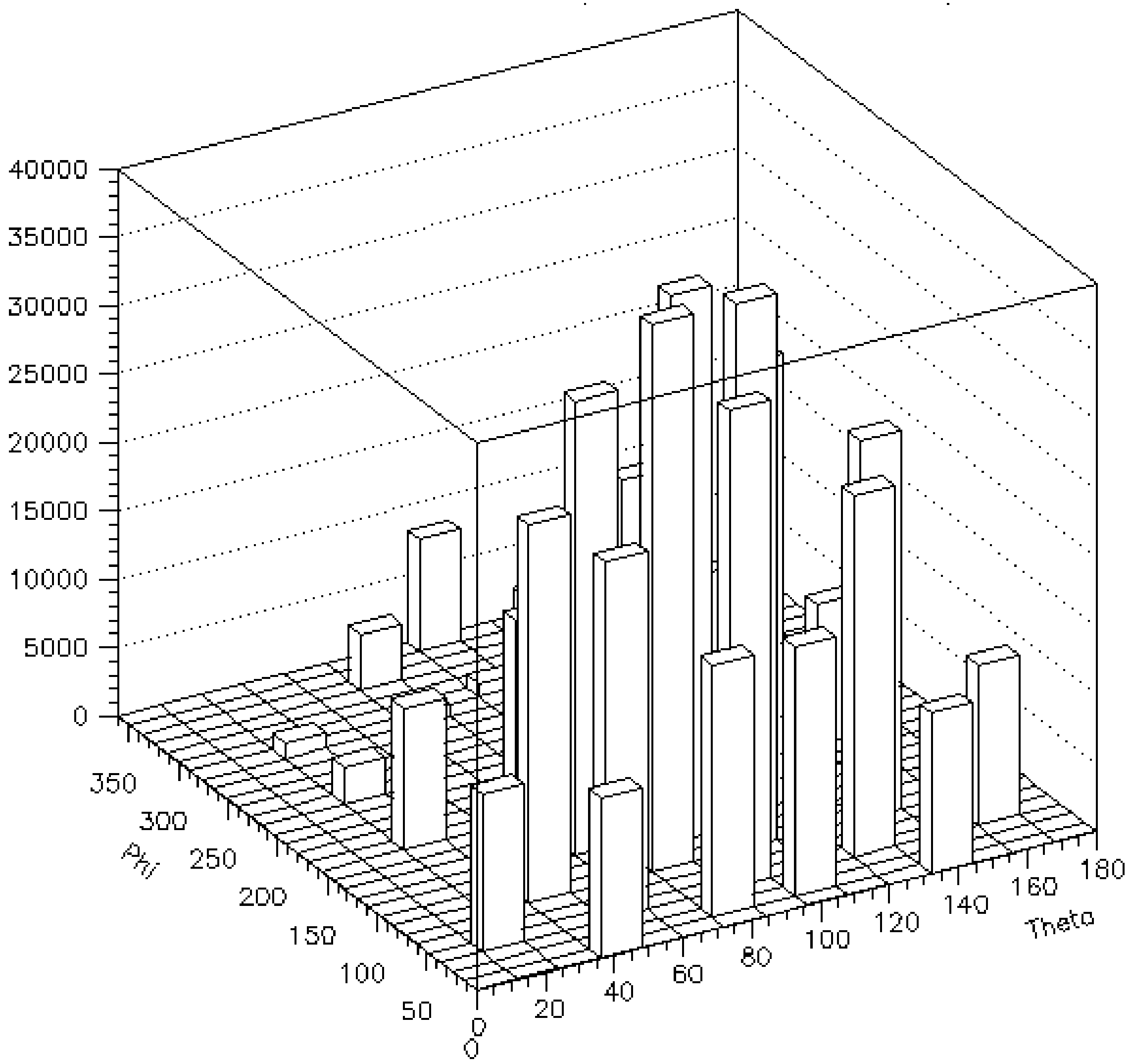
Results V – How much different are the total number of detected photons for each PMT when changing the scattering parameters?

L_s=20 m
p = 0.17
a_{Rayl}=0.853
a_{Mie}=0.924



Results V – How much different are the total number of detected photons for each PMT when changing the scattering parameters?

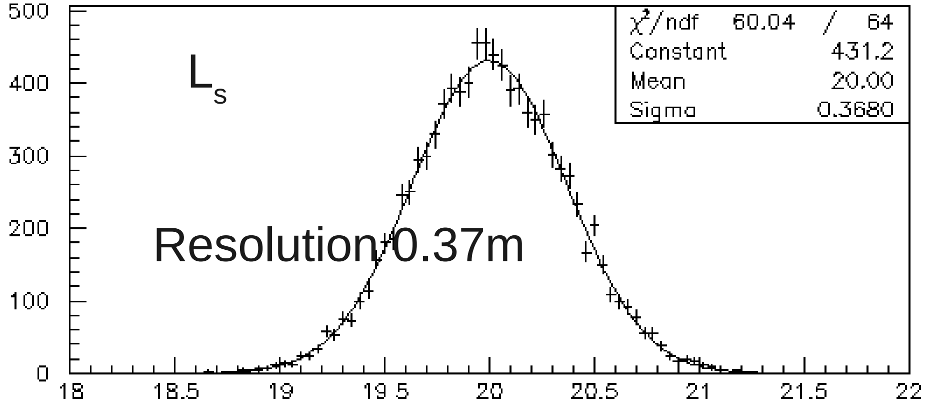
L_s=18.4 m
p = 0.184
a_{Rayl}=0.853
a_{Mie}=0.924



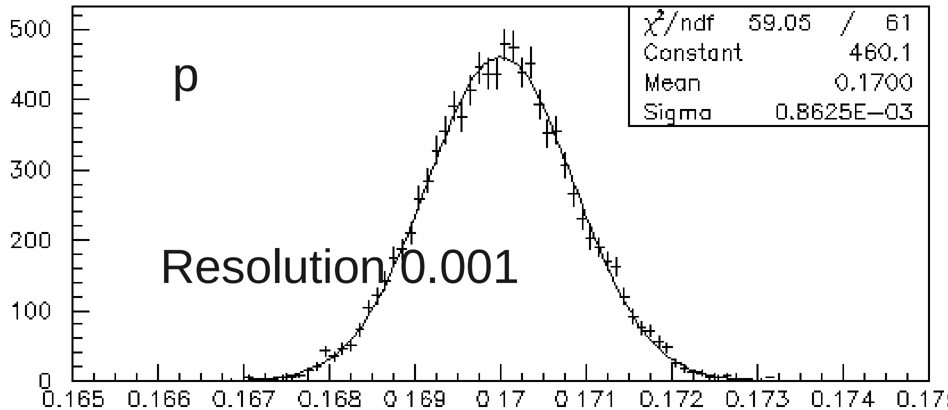
Results V – Estimation resolution of the scattering parameters using 1.3 Million Laser pulses, 400k photons each

Repeat the experiment many times by creating data sets according to the reference parameter values

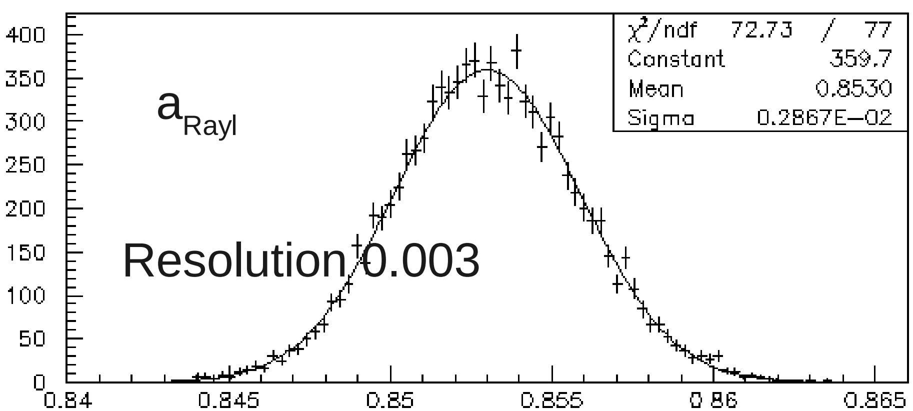
Scattering length



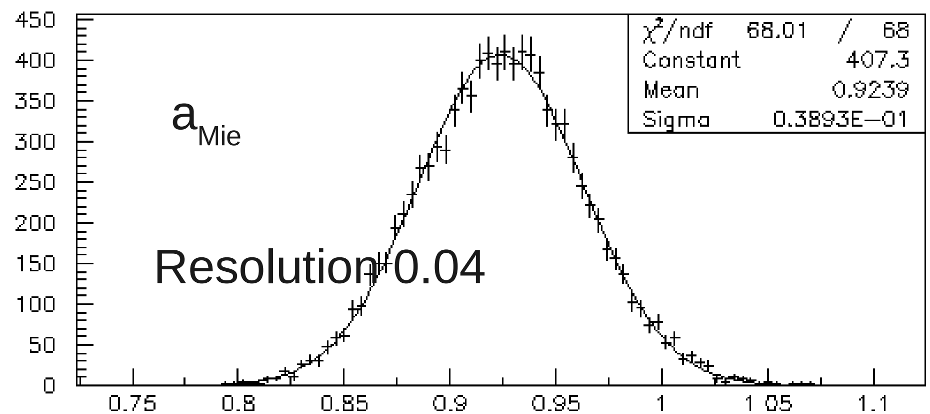
Rayleigh contribution



Rayleigh constant

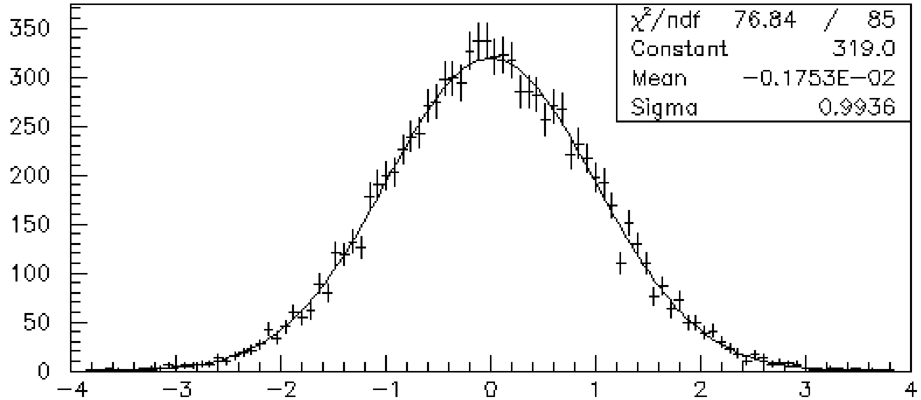


Mie constant ($\langle cos\theta_s \rangle_{Mie}$)

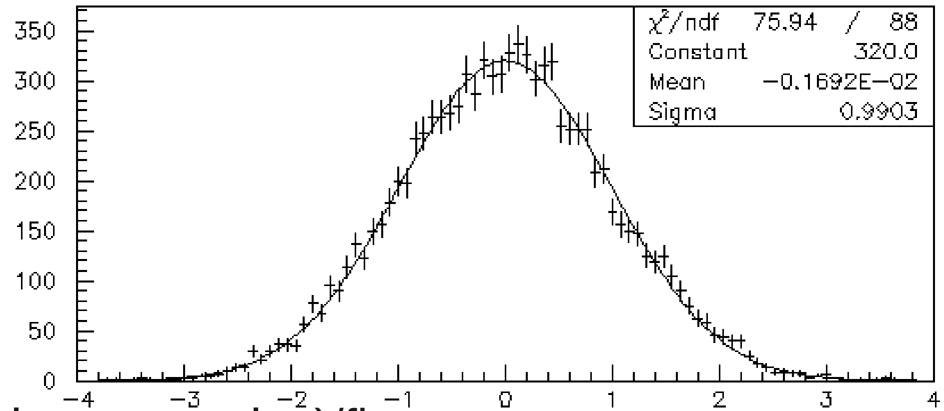


Results V – Estimation resolution II – goodness of fit (pools)

Scattering length

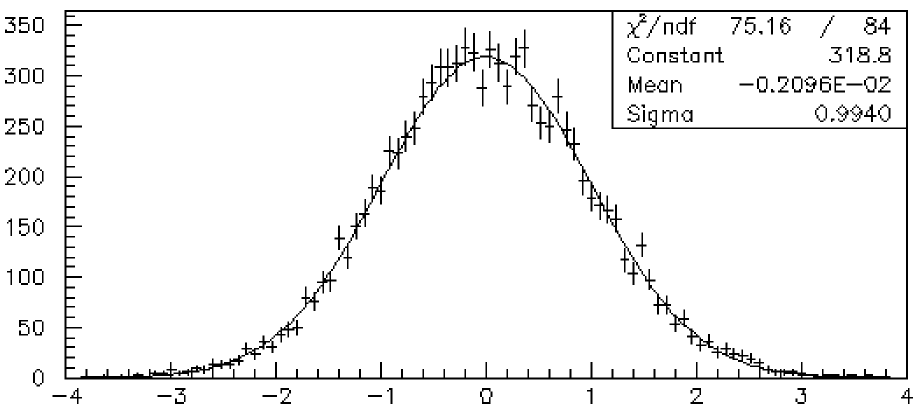


Rayleigh contribution

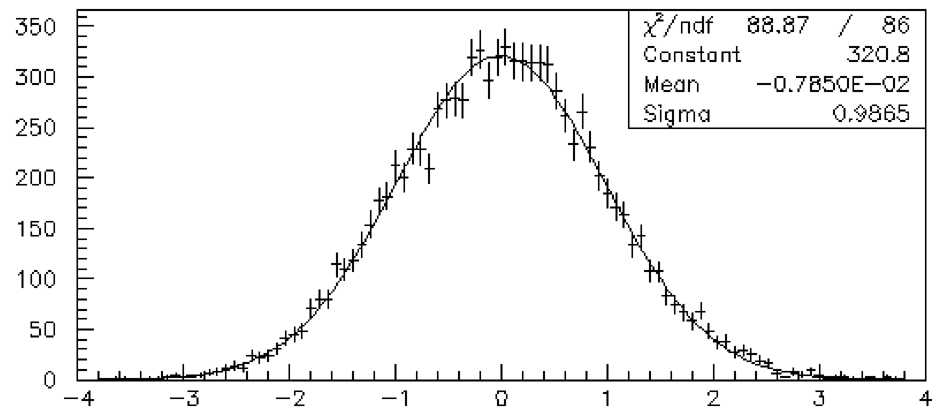


(estimated value -true value)/fit error

Rayleigh constant



Mie constant ($\langle cos\theta_s \rangle_{Mie}$)



(estimated value -true value)/fit error

CORRELATION MATRIX

1.000000	-0.7619029	-0.3107599	-0.9340226
-0.7619029	1.000000	0.8162224	0.9244111
-0.3107599	0.8162224	1.000000	0.6109608
-0.9340226	0.9244111	0.6109608	1.000000

Summary

- Event simulation/reconstruction techniques rely on the accurate knowledge of sea water optical properties
- The Multi-PMT optical module is sensitive to the direction of the incident photons
- The profile of the arrival time distributions and the number of the detected photons depend on the optical photon absorption and scattering characteristics
- Using a picosecond laser and examining the characteristics of the scattered light detected by a Multi-PMT optical module, we can accurately estimate the scattering parameters

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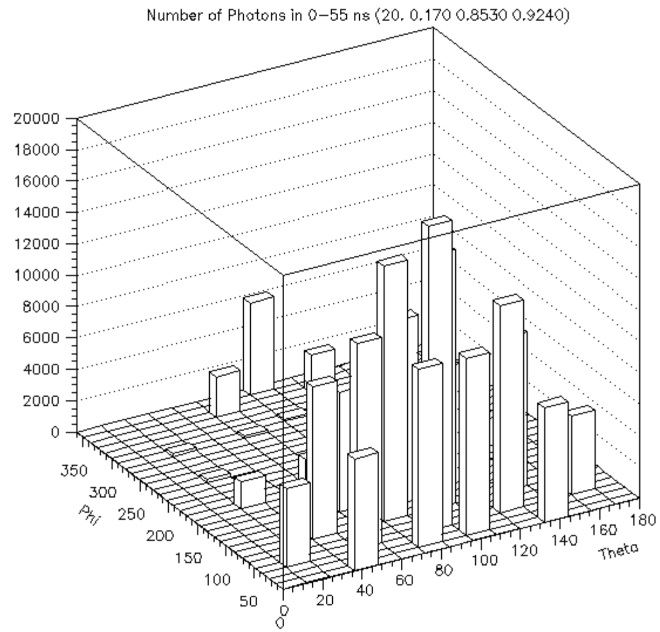
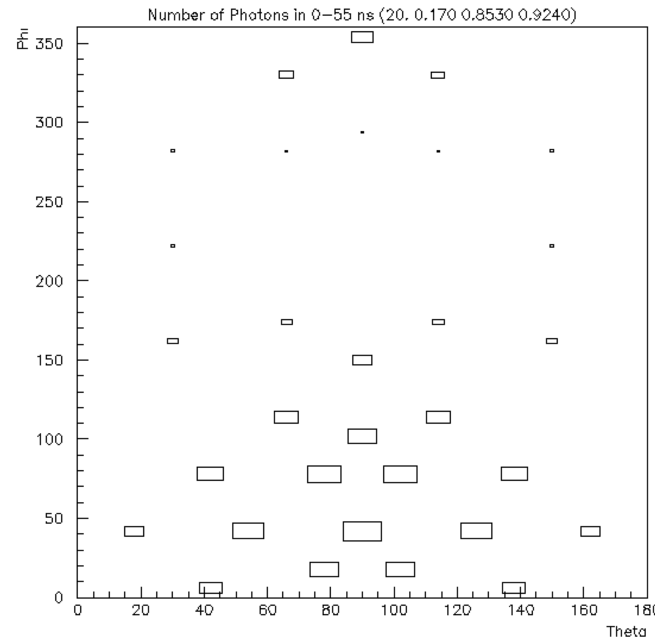
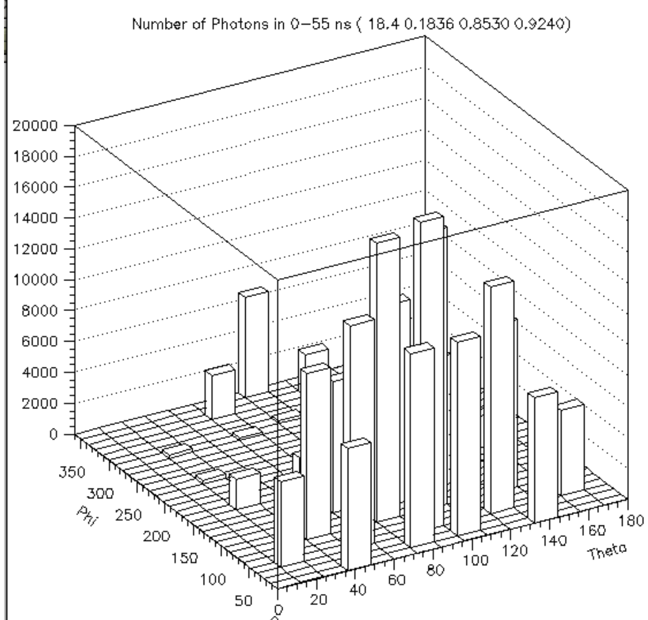
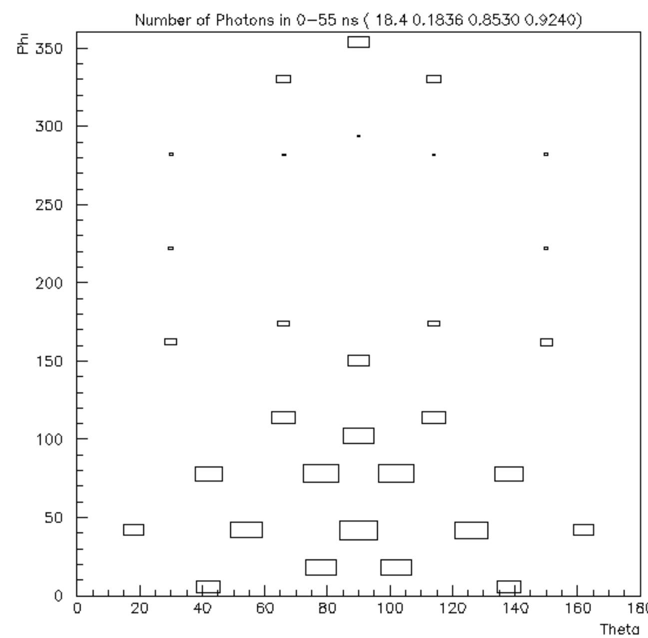
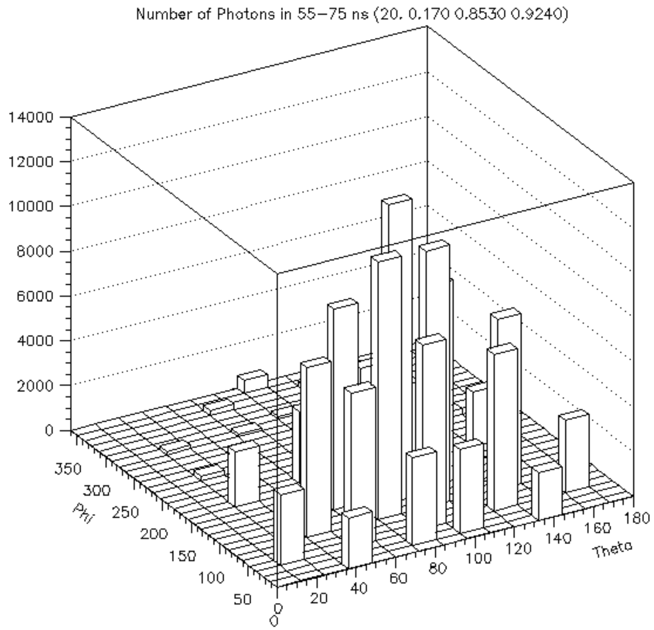
Backup

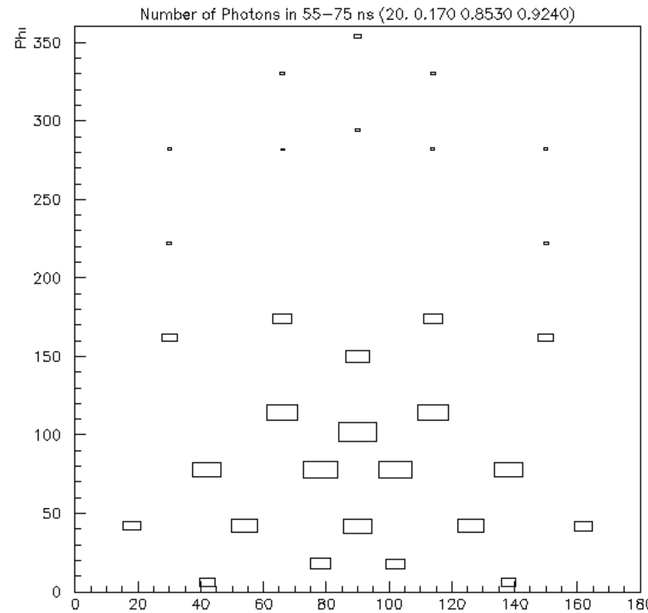

Number of Photons in 0–55 ns (20. 0.170 0.8530 0.9240)
Phi
Theta

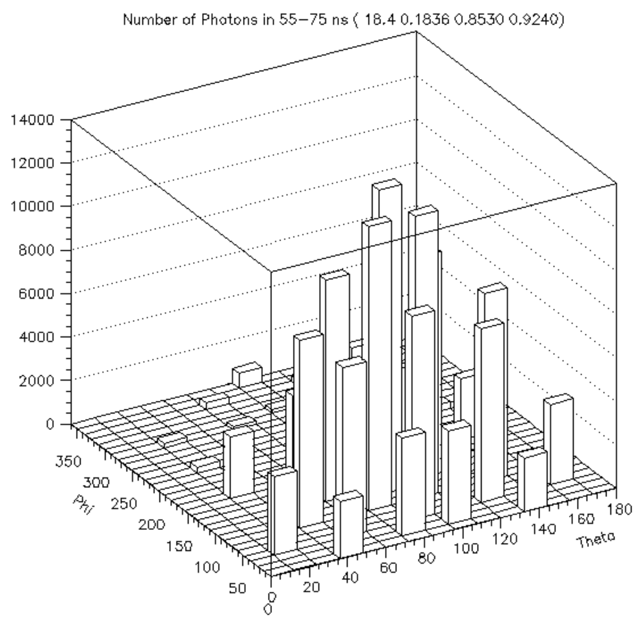

Number of Photons in 0–55 ns (20. 0.170 0.8530 0.9240)
Phi
Theta

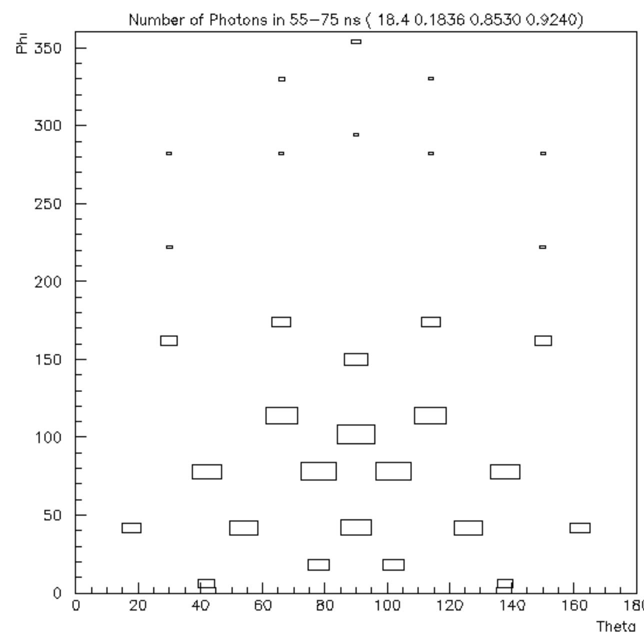

Number of Photons in 0–55 ns (18.4 0.1836 0.8530 0.9240)
Phi
Theta


Number of Photons in 0–55 ns (18.4 0.1836 0.8530 0.9240)
Phi
Theta

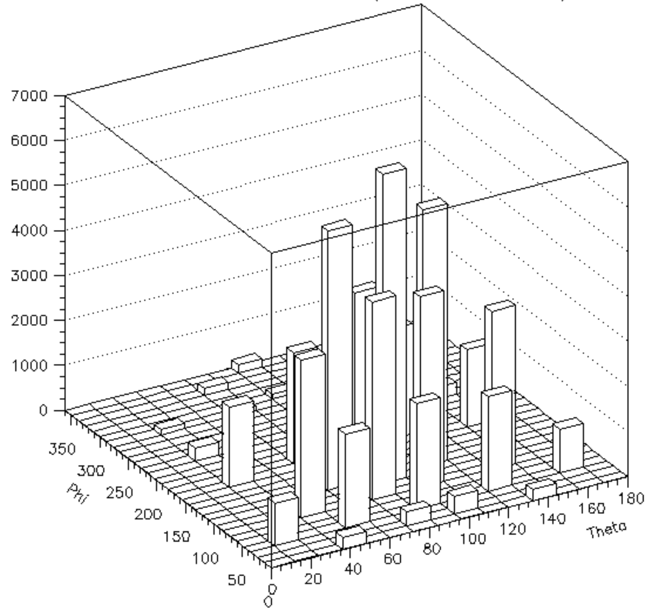

Number of Photons in 55−75 ns (20. 0.170 0.8530 0.9240)
Phi
Theta


Number of Photons in 55−75 ns (20. 0.170 0.8530 0.9240)
Phi

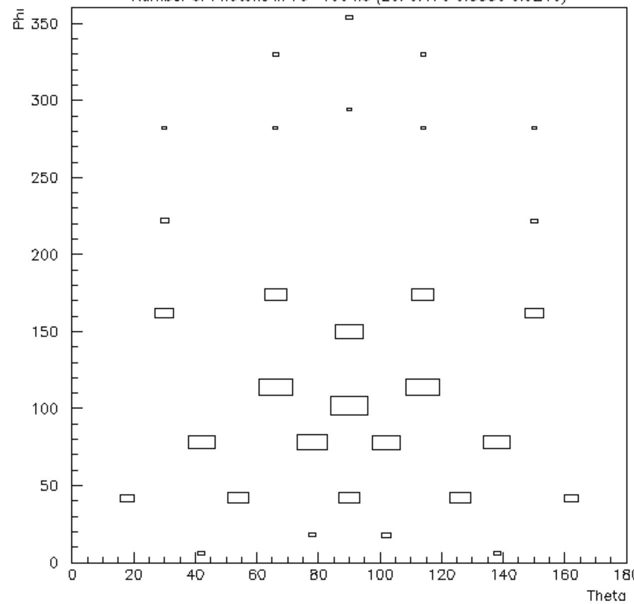

Number of Photons in 55−75 ns (18.4 0.1836 0.8530 0.9240)
Phi
Theta


Number of Photons in 55−75 ns (18.4 0.1836 0.8530 0.9240)
Phi
Theta

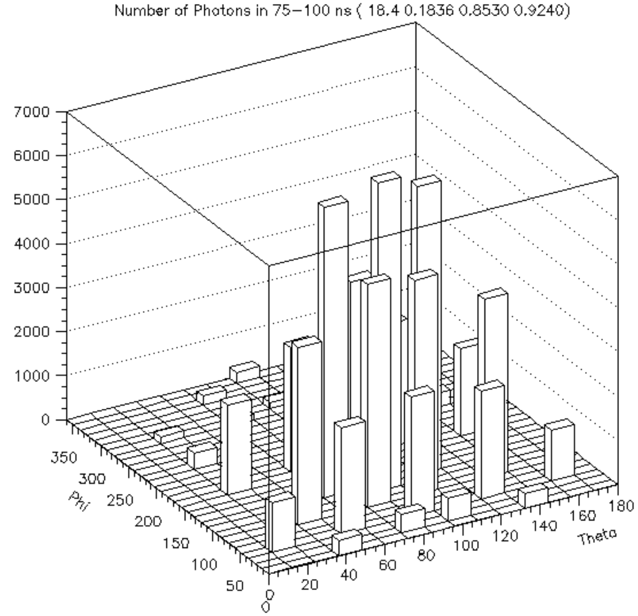
Number of Photons in 75–100 ns (20. 0.170 0.8530 0.9240)



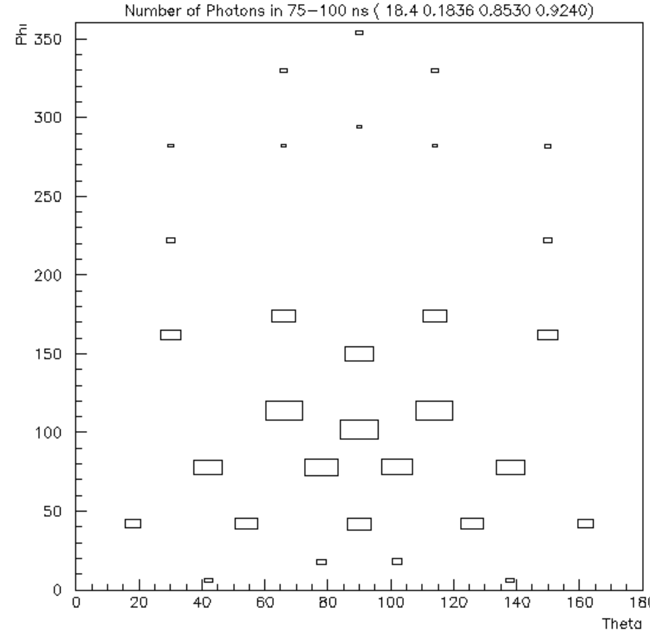
Number of Photons in 75–100 ns (20. 0.170 0.8530 0.9240)

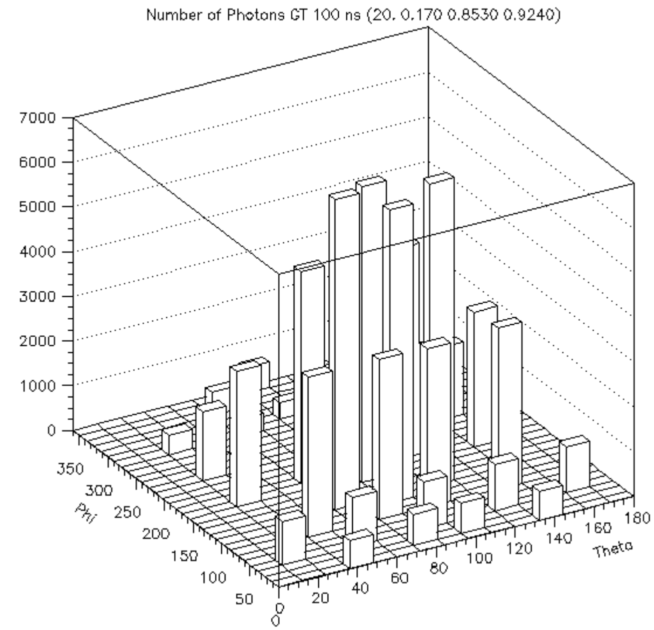


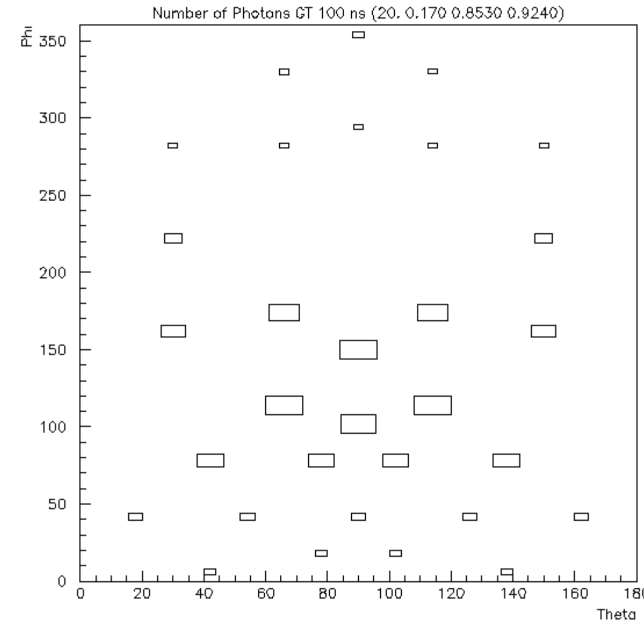
Number of Photons in 75–100 ns (18.4 0.1836 0.8530 0.9240)

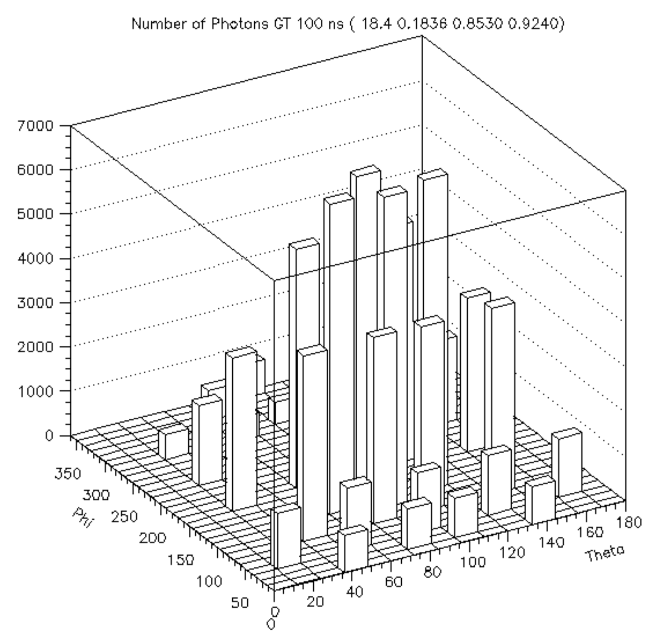


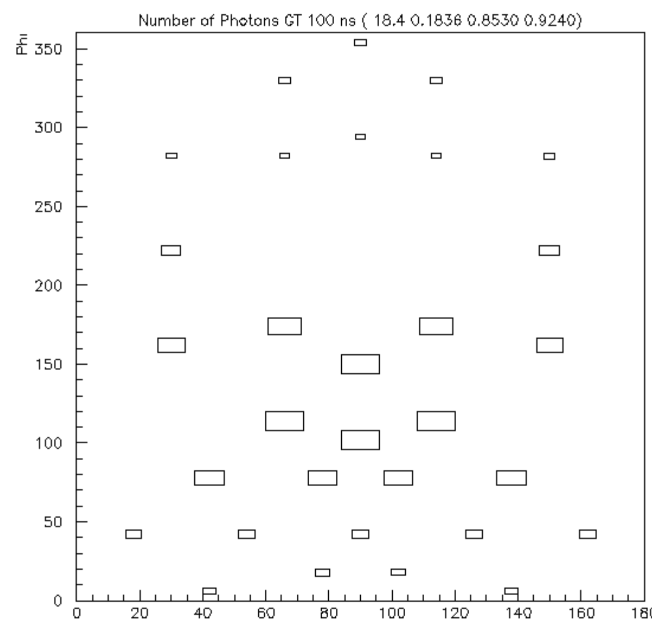
Number of Photons in 75–100 ns (18.4 0.1836 0.8530 0.9240)




Number of Photons GT 100 ns (20. 0.170 0.8530 0.9240)
Phi
Theta


Number of Photons GT 100 ns (20. 0.170 0.8530 0.9240)
Phi
Theta


Number of Photons GT 100 ns (18.4 0.1836 0.8530 0.9240)
Phi
Theta


Number of Photons GT 100 ns (18.4 0.1836 0.8530 0.9240)
Phi
Theta