Physics Laboratory
School of Science and Technology
Hellenic Open University

KM3NeT
Opens a new window on our universe

# Progress report on simulation and reconstruction developments

## & Progress report on observation strategies and estimation techniques (PART A)

**Apostolos G. Tsirigotis**, Antonis Leisos, Spyros Tzamarias
Physics Laboratory
H.O.U

- Progress report on simulation algorithms
- Progress report on reconstruction algorithms
- Progress report on DOM signal analysis
- Discovery potential for various KM3NeT layouts

# GEANT4 Simulation in HOURS

- **Any detector geometry can be described in a very effective way**
- **All the relevant physics processes are included in the simulation**

**Full GEANT4 simulation** SLOW

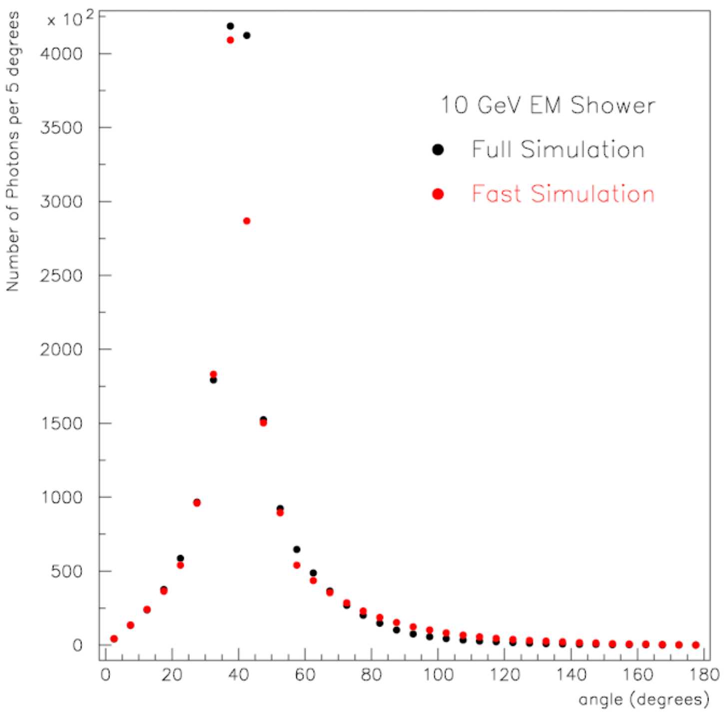
**Fast Simulation** 100 to several thousand times faster than full Simulation (depended on muon energy)

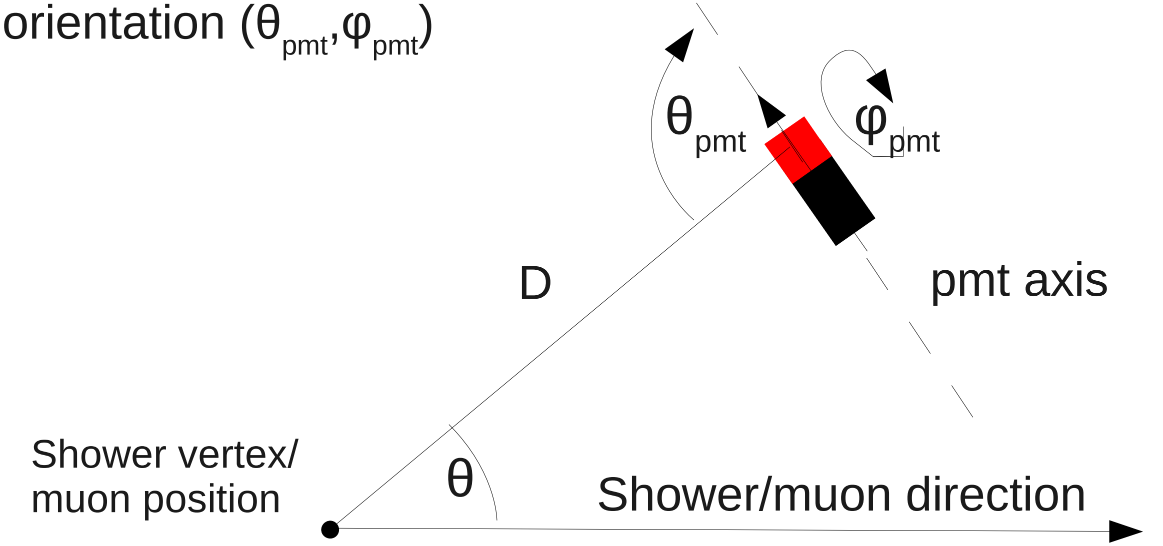
**Parametrizations for:**

- EM showers (from e-, e+, γ)
- HA showers (from long lived hadrons)
- Low energy electrons (from ionization)
- Direct Cherenkov photons (from muon)

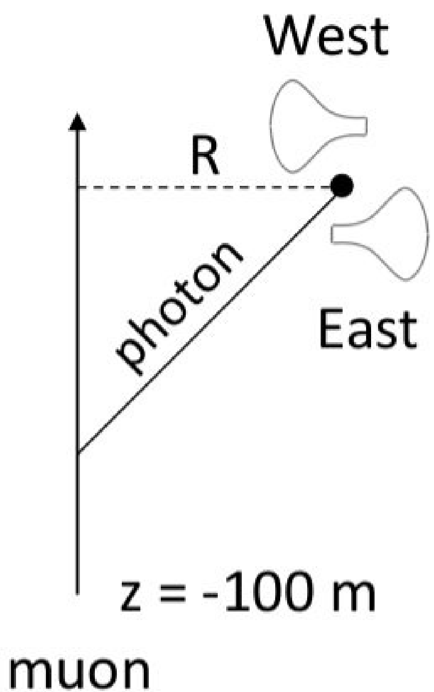
Each parametrization describes the number and time profile of photons arriving on a PMT in bins of:
Shower energy (E) (EM and HA showers)
PMT position (D,θ) relative to shower vertex/muon position,
PMT orientation ($\theta_{pmt}$,$\varphi_{pmt}$)

Angular Distribution of Cherenkov Photons



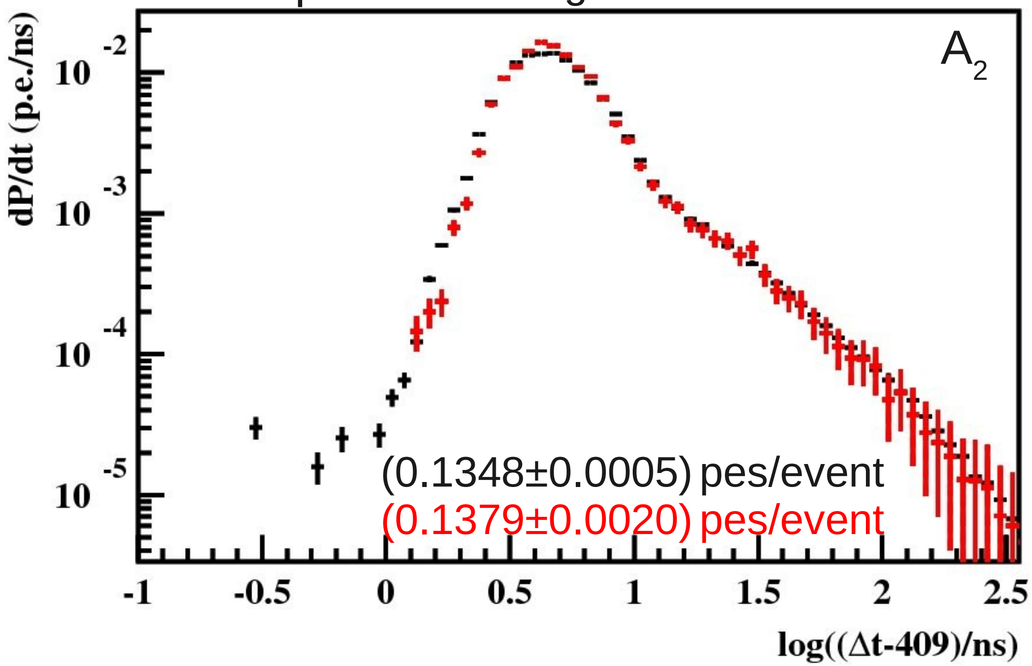
HOURS : comparison **with** and **without** parametrization **(full simulation)**
(for comparisons between different KM3NeT simulation softwares see talk by M. de Jong)



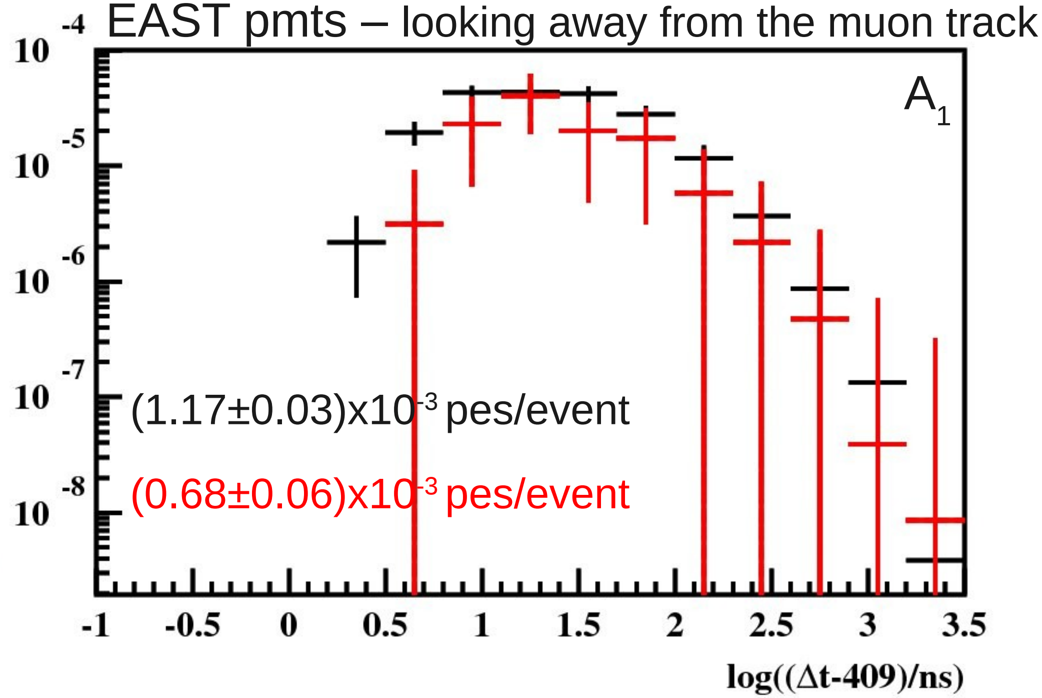

| | R [m] | $E_m$ [TeV] | PMT |
|---|---|---|---|
| $A_1$ | 25 | 0.1 | East |
| $A_2$ | 25 | 0.1 | West |
| $A_3$ | 50 | 0.1 | East |
| $A_4$ | 50 | 0.1 | West |

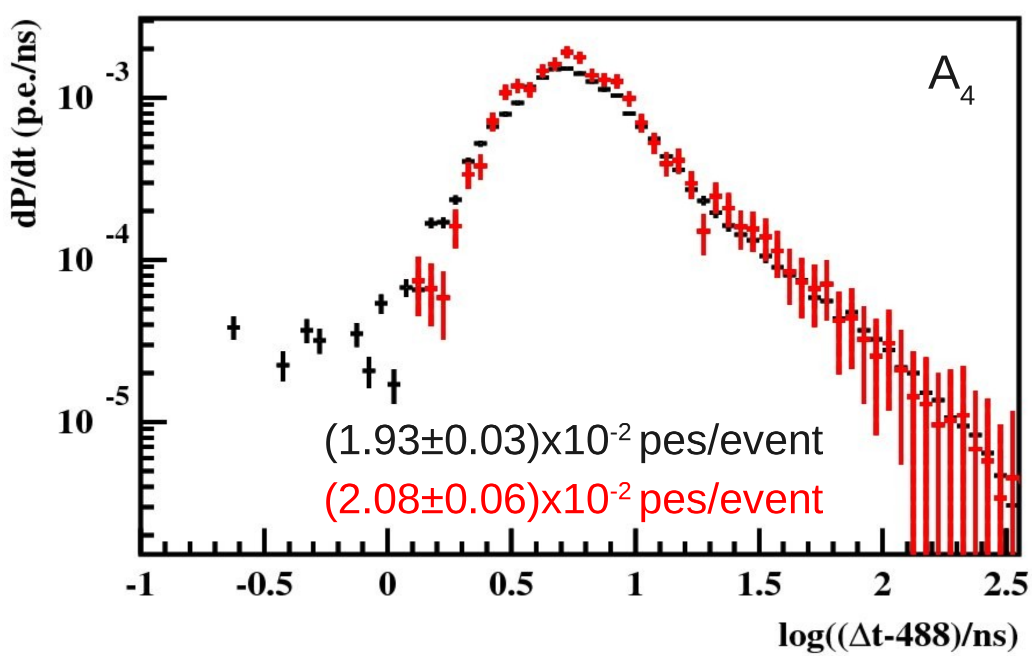
HOURS : comparison **with** and **without** parametrization **(full simulation)** $E_{muon}$=0.1 TeV

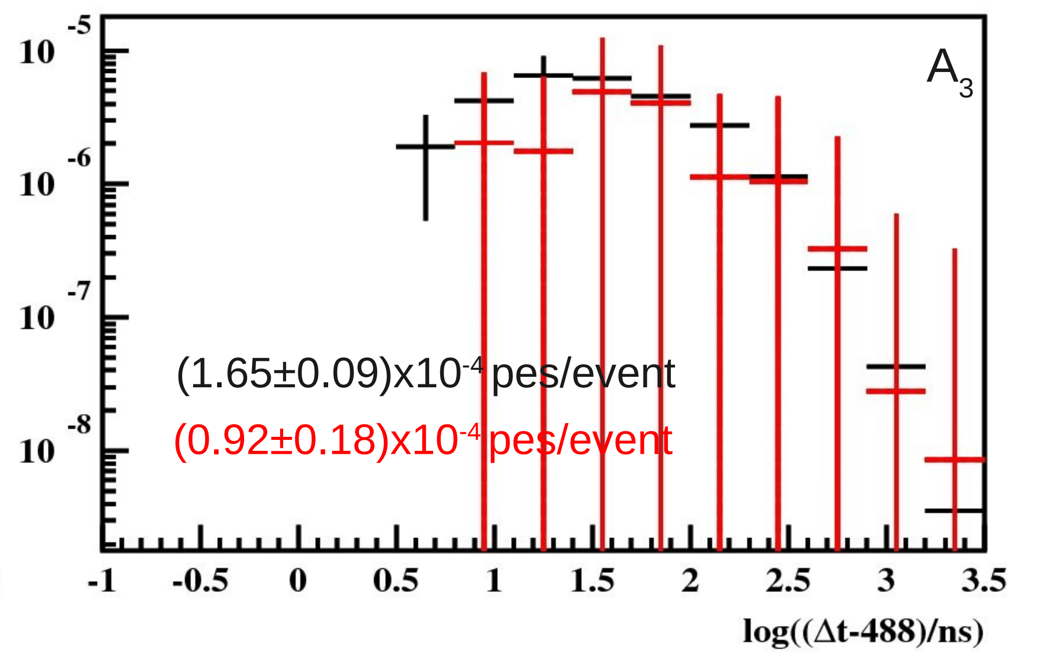
WEST pmts – looking to the muon track




EAST pmts – looking away from the muon track

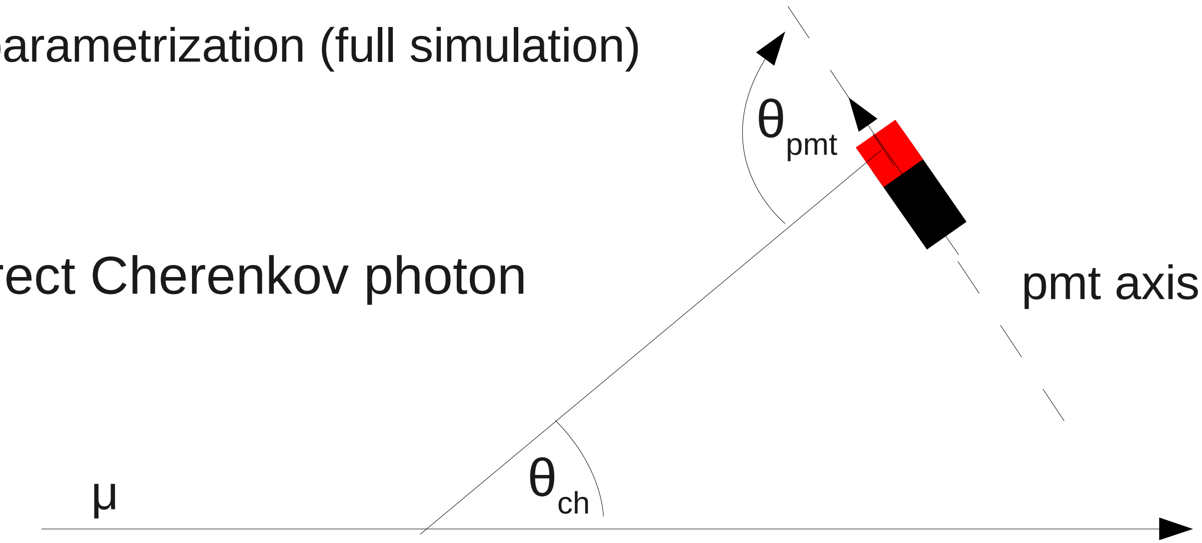


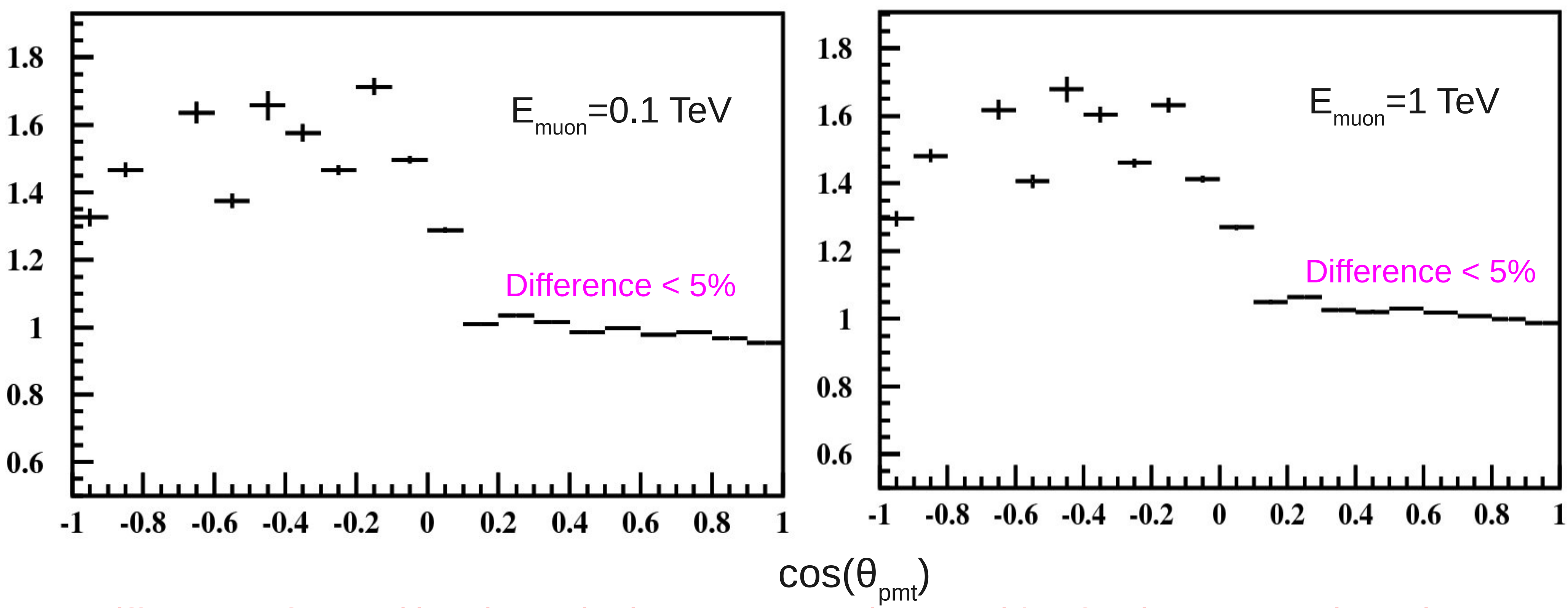



HOURS : comparison with and without parametrization (full simulation) for various pmt orientations

$\theta_{pmt}$=angle between pmt axis and direct Cherenkov photon track



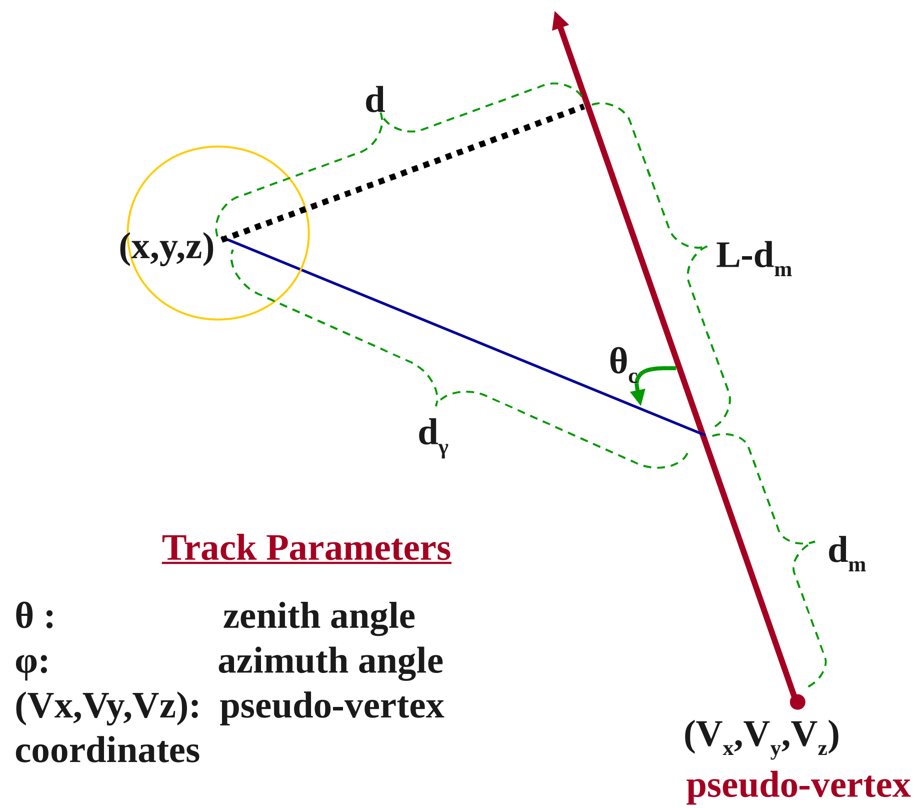

Number of pes/event with parametrized simulation divided by corresponding number with full simulation




Differences for cos(theta)<0.1 is due to coarse photon tables for these pmt orientations
Adjustment is under way

- Prefit and Filtering based on:
  - Optical Module Hit clustering (causality) filter & prefit using the clustering of candidate track segments (no apriori knowledge of the neutrino source)
  - Causality filters and prefit using the apriori known direction of the neutrino source

- Muon reconstruction algorithms
  - Combination of $\chi^2$ fit and Kalman Filter is used to produce many candidate tracks
  - The best candidate is chosen using the Multi-PMT Direction and arrival time Likelihood (track quality criterion)
  - Muon energy reconstruction using the Charge Likelihood



# A reconstruction method for neutrino induced muon tracks taking into account the apriori knowledge of the neutrino source

A.G. Tsirigotis*, A. Leisos, S. E. Tzamarias

*Physics Laboratory, School of Science & Technology, Hellenic Open University*

On behalf of the KM3NeT Consortium

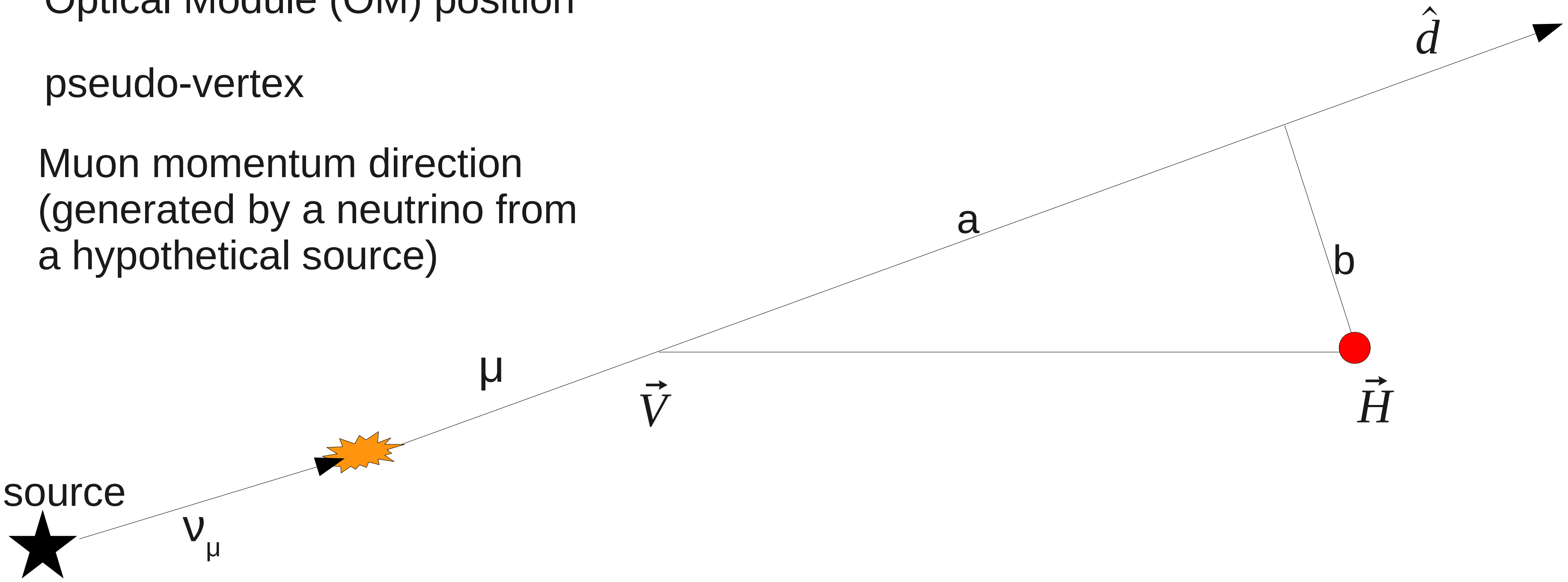
To appear in the Proceedings of VLVnT2011

## Background filtering technique using the apriori known neutrino point source
## Causality criterion

$\vec{H}$ Optical Module (OM) position

$\vec{V}$ pseudo-vertex

$\hat{d}$ Muon momentum direction (generated by a neutrino from a hypothetical source)




Expected arrival time to OM of a photon emitted by the muon with the Cherenkov angle, $\theta_c$ (direct photon):

$$ct_{expected} = a + b\tan\theta_c$$

$$a = \hat{d}\cdot(\vec{H} - \vec{V})$$

$$b = \left|\vec{H} - \vec{V} - a\hat{d}\right|$$ The vertical distance of OM to the muon track

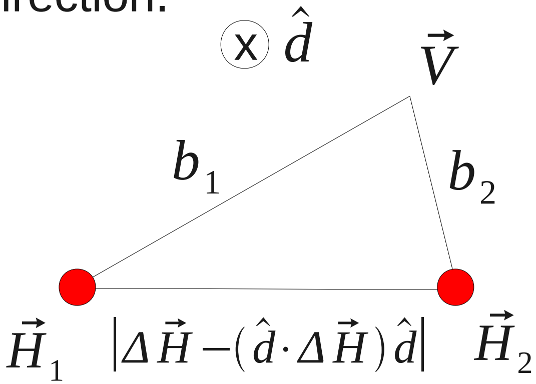
## Background filtering technique using the apriori known neutrino point source
## Causality criterion

Two direct photons with arrival times $t_1$, $t_2$ on the OMs with positions $\vec{H}_1$ , $\vec{H}_2$ should satisfy:

$$\frac{c\Delta t - \hat{d}\cdot\Delta\vec{H}}{\tan\theta_c} = \Delta b$$

$$\Delta t = t_1 - t_2$$
$$\Delta\vec{H} = \vec{H}_1 - \vec{H}_2$$
$$\Delta b = b_1 - b_2$$

Project the hits position and vertex on a plane perpendicular to the known direction.




Then from simple geometry:

$$|\Delta b| = \left|\frac{c\Delta t - \hat{d}\cdot\Delta\vec{H}}{\tan\theta_c}\right| < |\Delta\vec{H} - (\hat{d}\cdot\Delta\vec{H})\hat{d}|$$

# Background filtering technique using the apriori known neutrino point source
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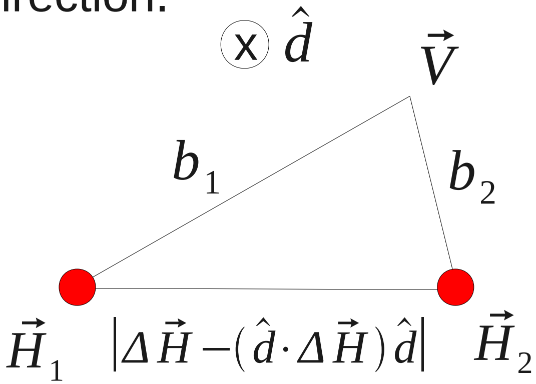



Then from simple geometry:

$$|\Delta b| = \left|\frac{c\Delta t - \hat{d}\cdot\Delta\vec{H}}{\tan\theta_c}\right| < |\Delta\vec{H} - (\hat{d}\cdot\Delta\vec{H})\hat{d}|$$

Causality criterion between two hits using the known direction of the source

$$|c\Delta t - \hat{d}\cdot\Delta\vec{H}| < \tan\theta_c |\Delta\vec{H} - (\hat{d}\cdot\Delta\vec{H})\hat{d}| + ct_s \qquad t_s = 10\mathrm{ns}$$

Relax the criterion (light dispersion, time jitter)

$$|\Delta\vec{H}\cdot\hat{d}| < 800\mathrm{m}$$

Longitudinal distance between the two OMs to the direction of the muon track

$$|\Delta\vec{H} - (\hat{d}\cdot\Delta\vec{H})\hat{d}| < 67.5\mathrm{m}\,(one\ absorption\ length)$$

Lateral distance

# Prefit and reconstruction technique using the known neutrino direction

- Causality criterion is used as background filtering
  - <0.3% of noise hits survive
  - >90% of signal hits survive

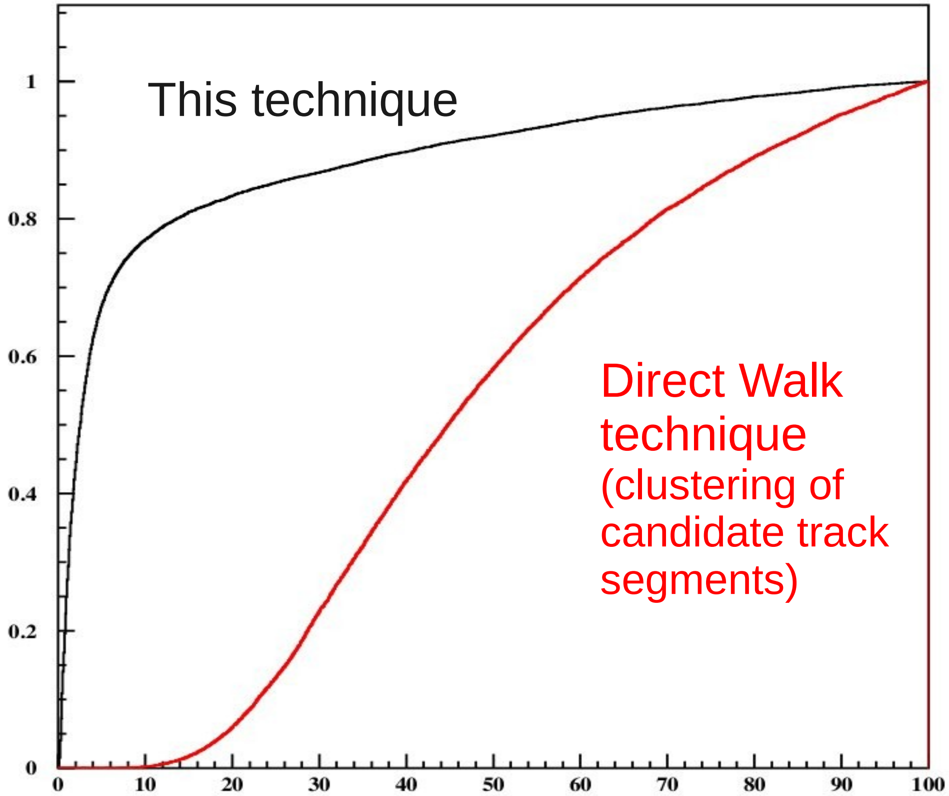
- For every three OMhits (on different OMs) that satisfy the causality criterion a pseudo-vertex can be found analytically.

- Many candidate pseudo-vertexes are found using different triplets of hits

- For signal events ($E_\nu$>100GeV) the clustering in space of all the candidate pseudo-vertexes can estimate the MC-true pseudo-vertex with accuracy ~ 2m

- The estimated pseudo-vertex and the known direction is used to further reduce the number of noise hits
  - ~0.03% of noise hits survive
  - ~90% of signal hits survive

Cumulative distribution of the distance between the estimated pseudo-vertex and the MC-true pseudo-vertex



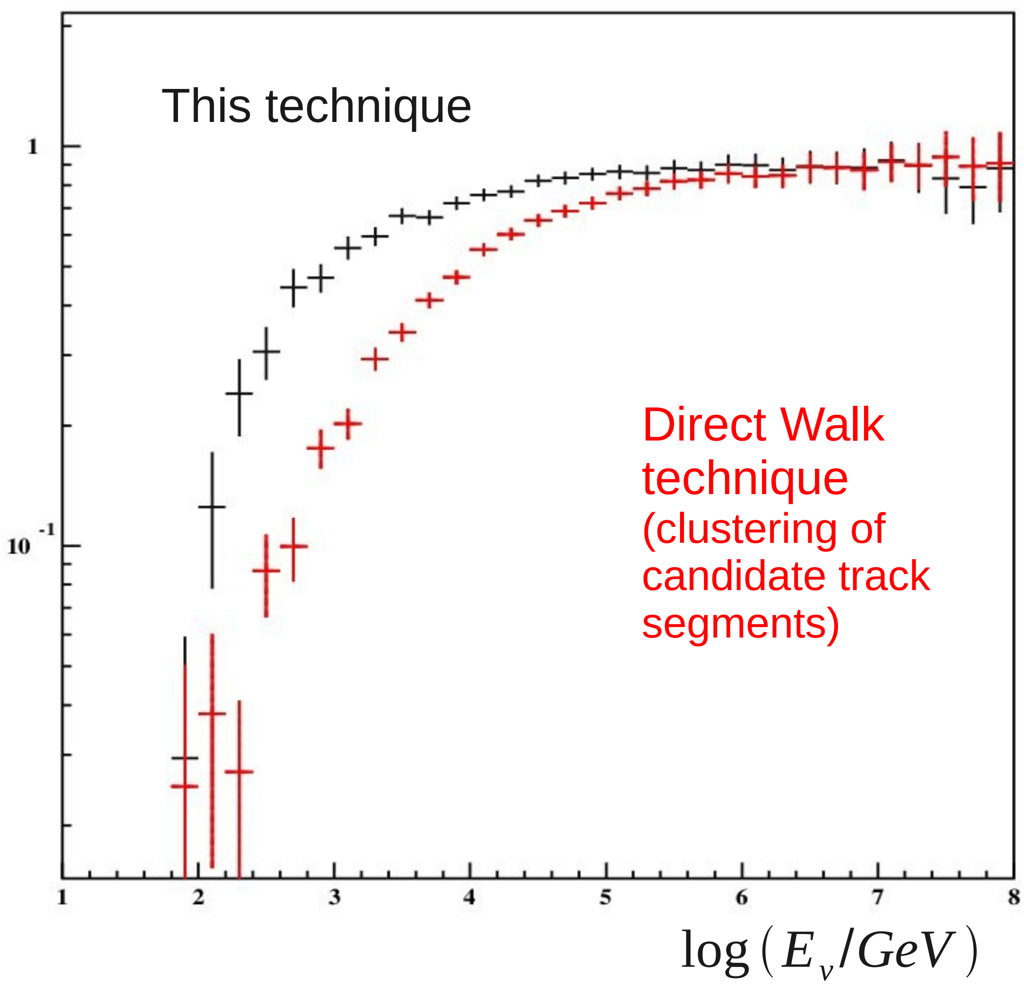

- Combination of $\chi^2$ minimization and Kalman Filter is used to produce many candidate tracks

- The best candidate is chosen using the timing and Multi-PMT direction Likelihood

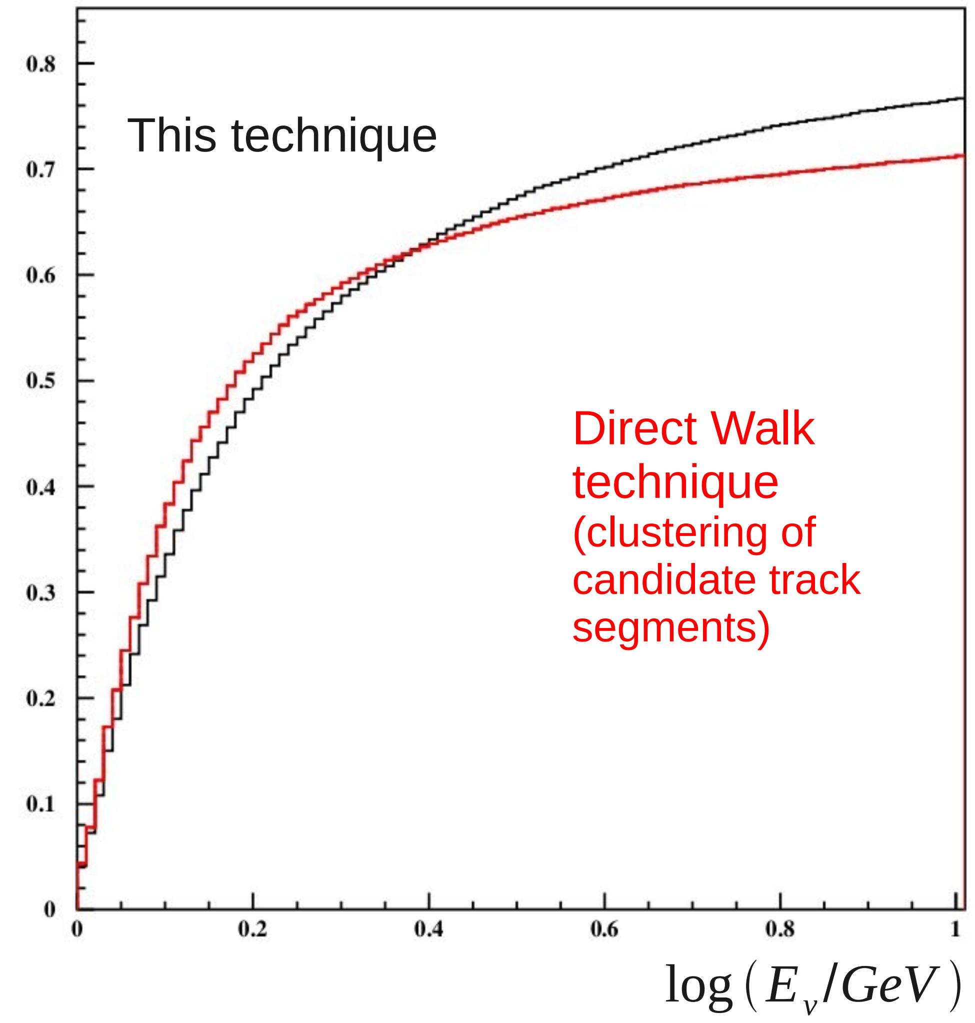
## Prefit and reconstruction technique using the known neutrino direction
## Reconstruction efficiency and angular resolution

- $E^{-2}$ neutrino generated spectrum (15GeV – 100PeV)
- $2.9km^3$ neutrino detector with 6160 DOMs (arranged in 154 Detection Units (Towers))
- Reconstructed tracks with at least 8 hits on different DOMs

Reconstruction efficiency vs neutrino energy for events with at least 3 L1 signal Hits



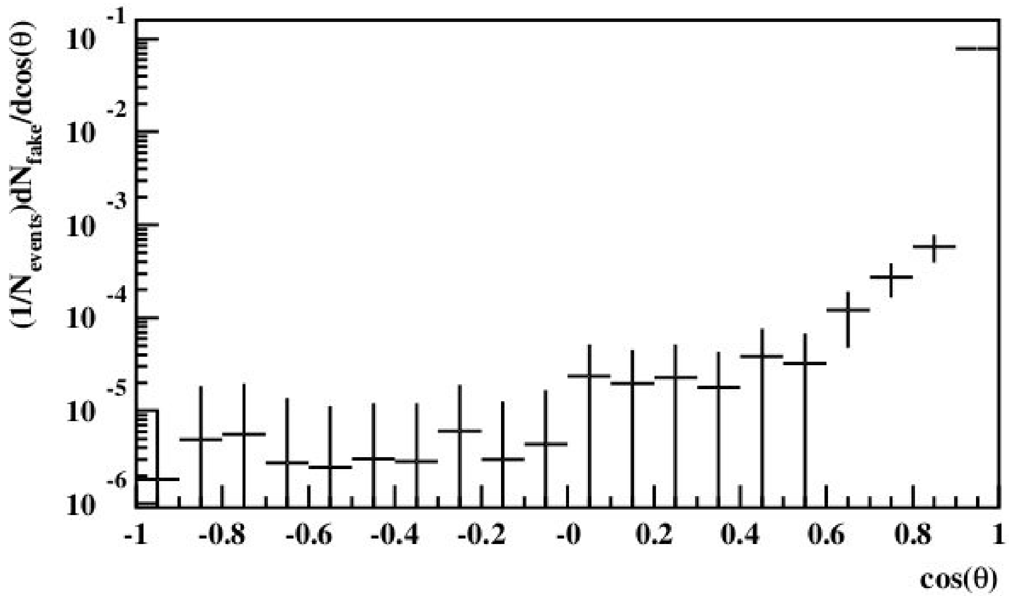

Point spread function for reconstructed events



# Reconstruction technique using the known neutrino direction
# Estimation of fake signal

For each atmospheric neutrino/shower event:

- Assume a candidate neutrino direction pointing to a hypothetical astrophysical source
- Apply filtering and prefit using the assumed direction
- Track reconstruction
- Accept the event if the angular difference between the assumed direction and the reconstructed muon direction < 1$^o$ (For point source searches this angular difference has to be further optimized)




- Fake signal can be further reduced by applying tracking quality criteria using the estimated tracking error.
- Fake tracks carry a very small weight in the unbinned method (talk "Progress report on detector optimization", by A. Leisos)

Figure 4: Probability of an atmospheric neutrino induced event to produce fake signal versus the cosine of the angular difference, $\theta$, between the true neutrino direction and the assumed direction of the source.

# Muon energy estimation

$$L(E)=\ln\left(\prod_{i=1}^{N_{hit}} P(Q_{i,data};E,D,\theta)\prod_{i=1}^{N_{nohit}} P(0;E,D,\theta)\right)$$

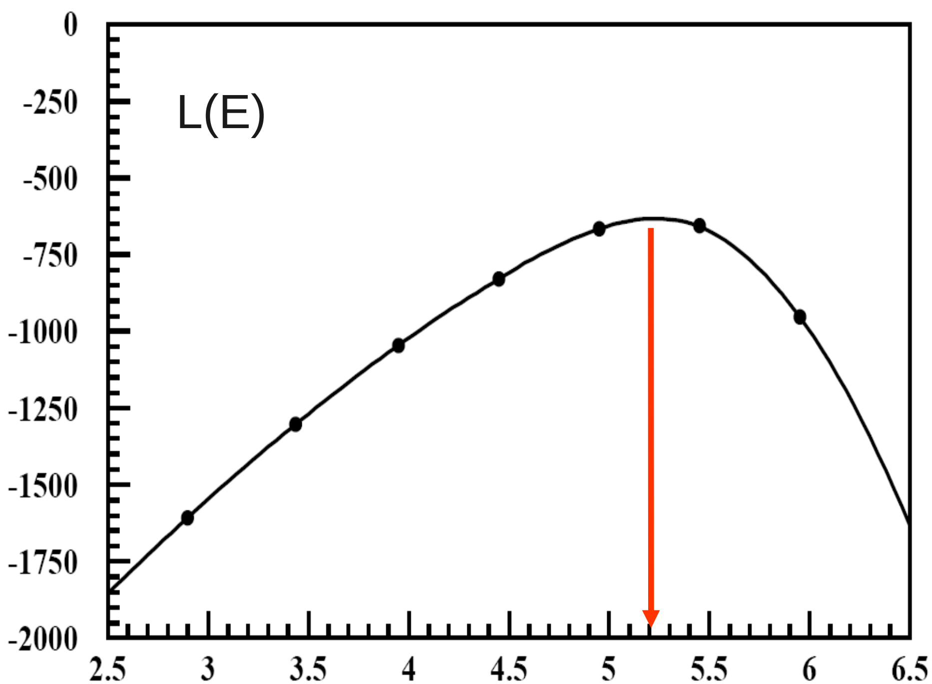
$Q_{i,data} \equiv$ Hit charge (**assumedly known exactly**) normalized to the charge of a single p.e. pulse

Probability depends on muon energy, E, distance from track, D, and PMT orientation with respect to the Cherenkov wavefront, θ:

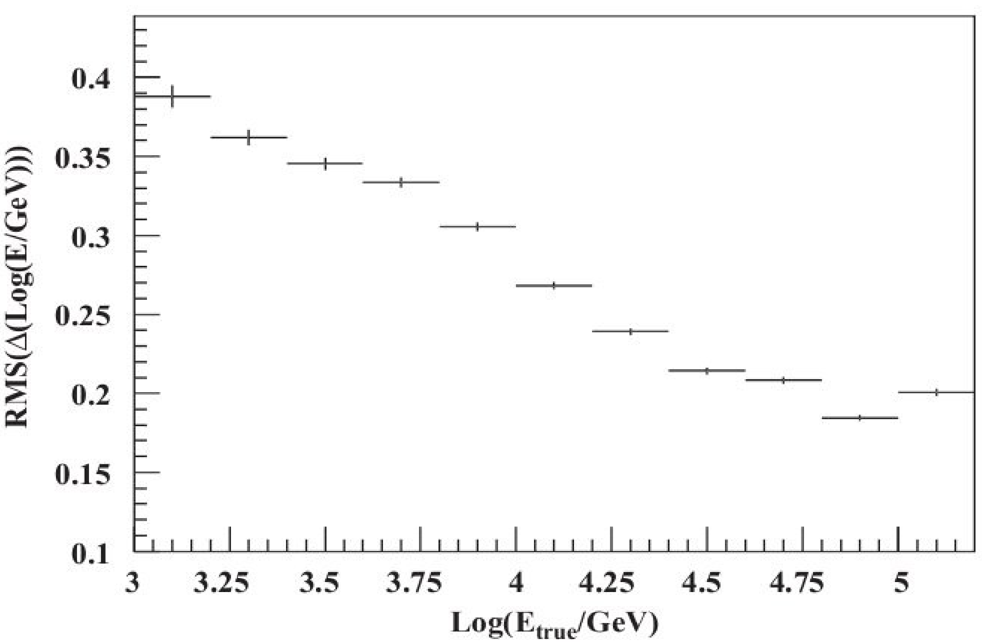
$$P(Q_{i,data};E,D,\theta)=\sum_{n=1}^{\infty} F(n;E,D,\theta)\,G(Q_{i,data};n,\sqrt{n}\,\sigma_{PMTresolution})$$

Convolution with the PMT charge response function (simplified model with Gaussian)

$F(n;E,D,\theta)$ Not a poisson distribution, due to discrete radiation processes



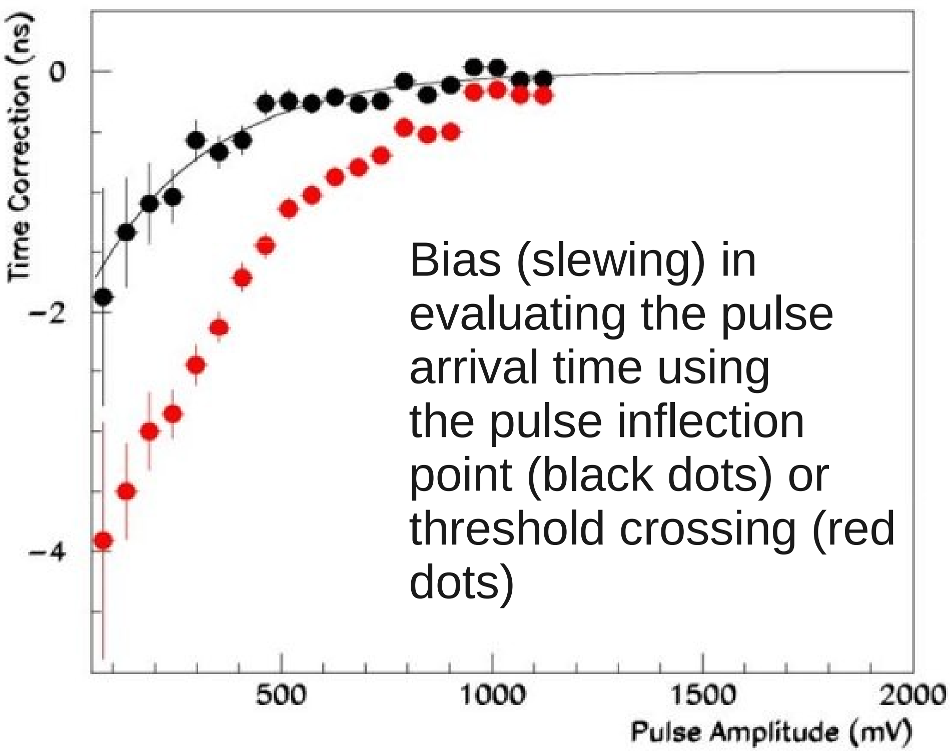

Muon energy estimation resolution



# Muon energy reconstruction and pulse arrival time corrections depend on pulse amplitude

## Examples

Data from 2003 NESTOR run (15 inch pmts) with calibration LED in deep sea




Bias (slewing) in evaluating the pulse arrival time using the pulse inflection point (black dots) or threshold crossing (red dots)

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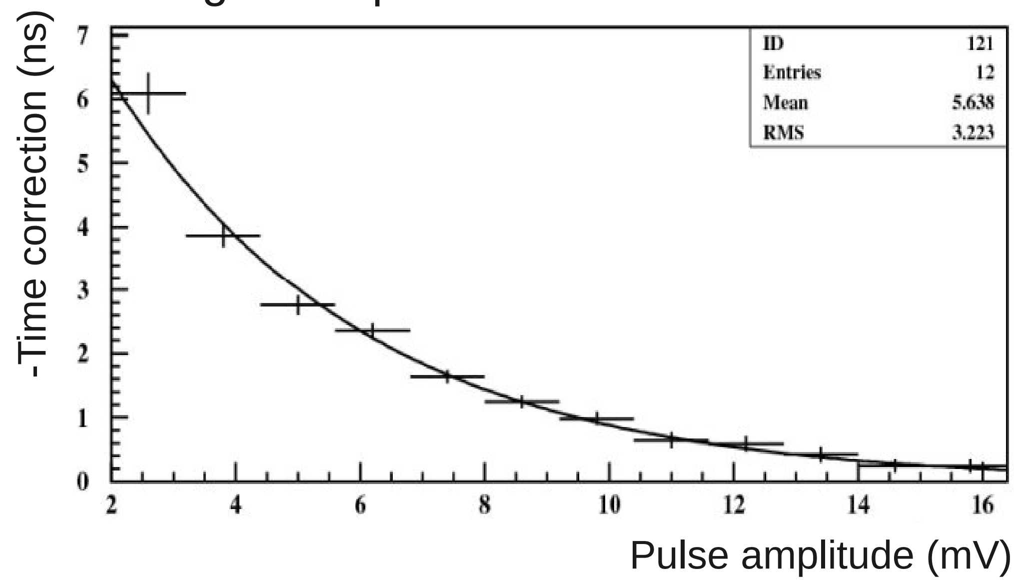
Operation and performance of the NESTOR test detector

G. Aggouras[a], E.G. Anassontzis[b,*], A.E. Ball[c], G. Bourlis[d], W. Chinowsky[e], E. Fahrun[f], G. Grammatikakis[g], C. Green[f], P. Grieder[h], P. Katrivanos[i], P. Koske[f], A. Leisos[a,d], J. Ludvig[e], E. Markopoulos[a], P. Minkowsky[j], D. Nygren[e], K. Papageorgiou[a], G. Przybylski[e], L.K. Resvanis[a,b], I. Siotis[i], J. Sopher[e], T. Staveris[a], V. Tsagli[a], A. Tsirigotis[a,d], V.A. Zhukov[k], The NESTOR Collaboration

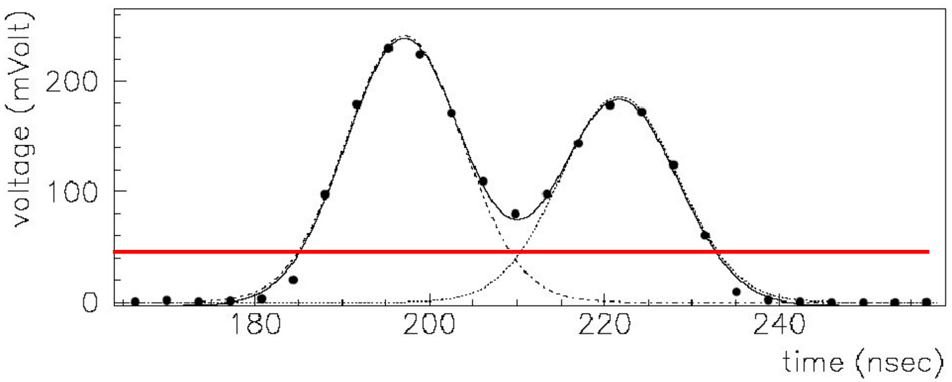
Data from HELYCON scintillator counters (¾ inch fast pmts, used also in H.E.S.S.) using atmospheric muons




How well can we estimate the pmt charge using 1,2,3 thresholds per 3-inch pmt in KM3NeT?

How the charge estimation resolution affects the muon direction and energy reconstruction resolution?

# Charge estimation resolution (G. Bourlis WORK IN PROGRESS)

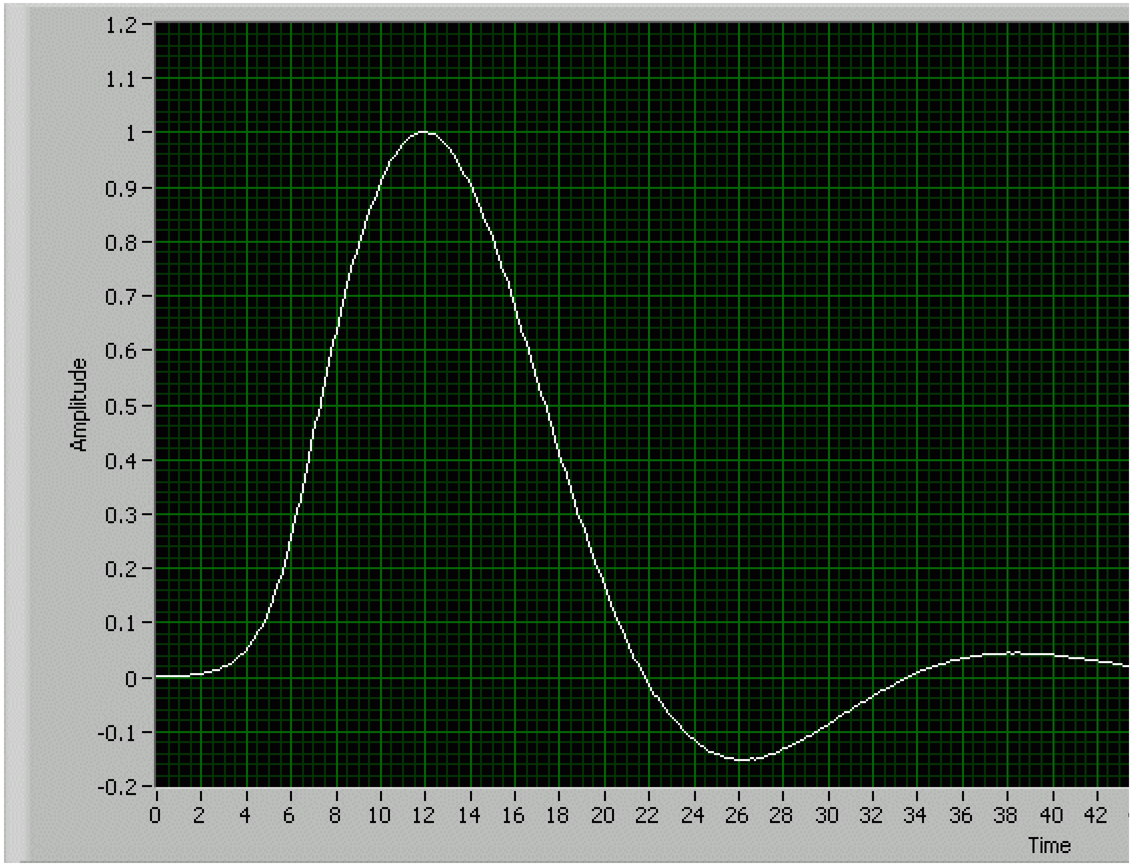



ET Enterprise Ltd. D783FL
3-inch diameter (tested in NIKHEF)

- TTS=2 ns
- Rise Time=5 ns
- FWHM=10 ns

After preampl.

31 3” PMTs inside
a 17” glass sphere

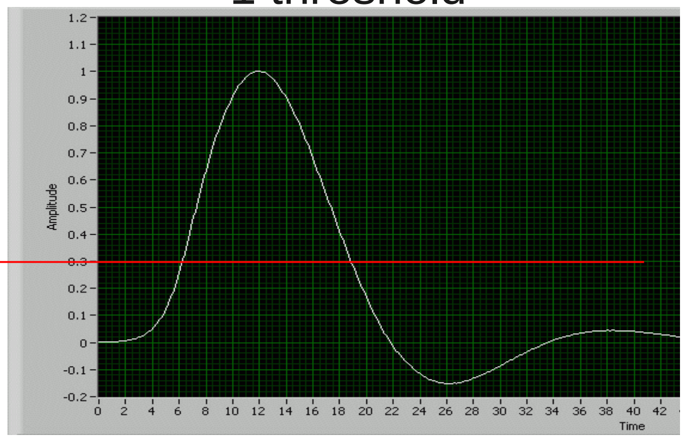



Mean pulse used in simulation

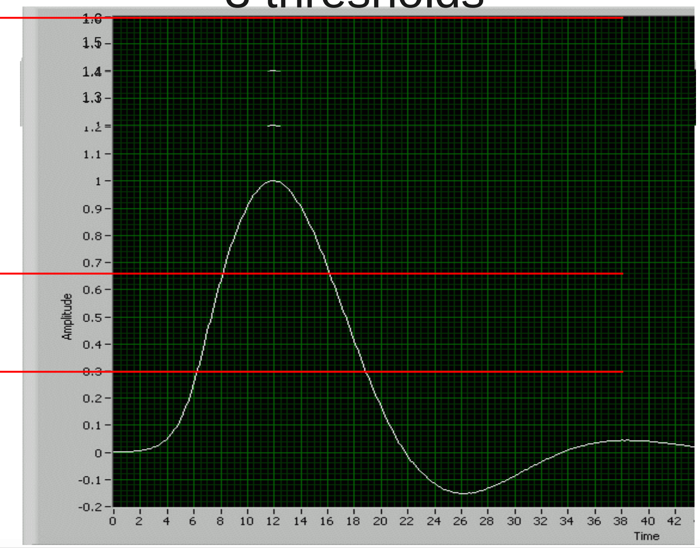
Charge estimation resolution of a single 3 inch pmt (WORK IN PROGRESS)

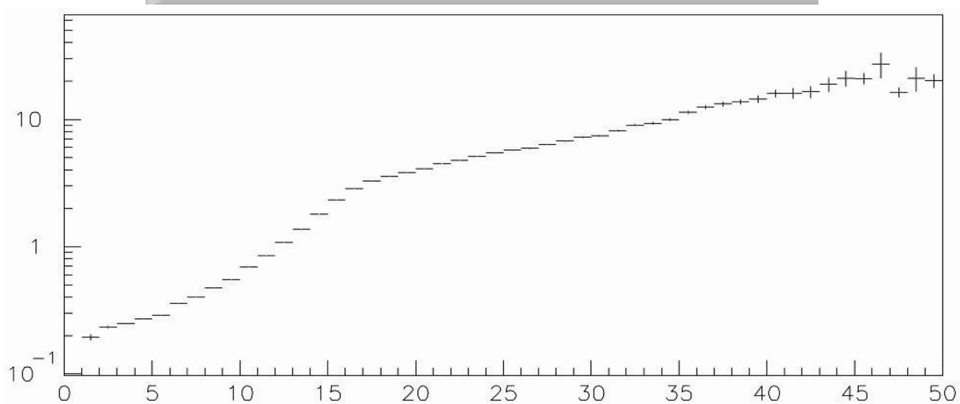
Simulated signal from muons (0.1Tev-100Tev)

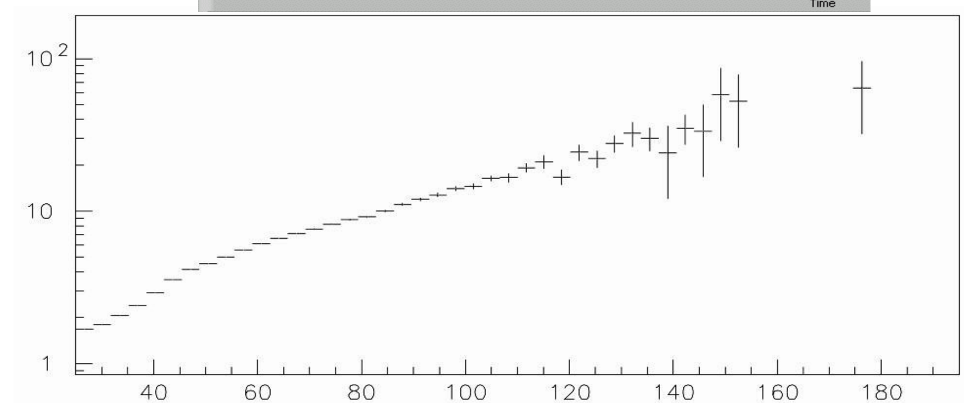
1 threshold

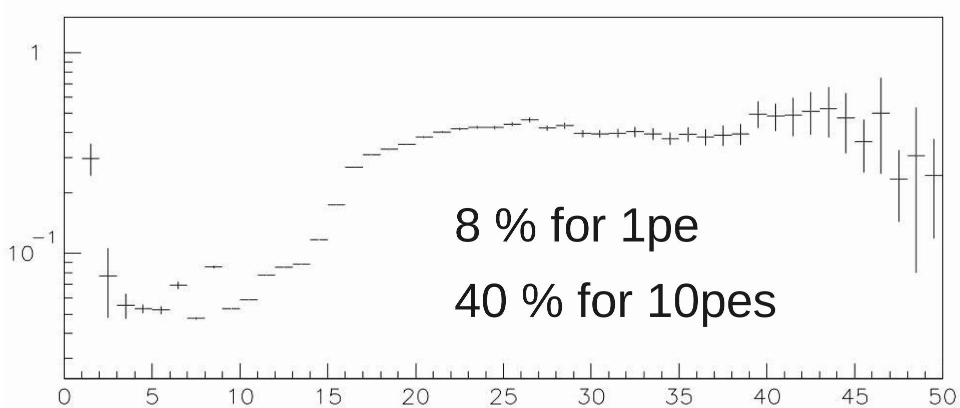



3 thresholds

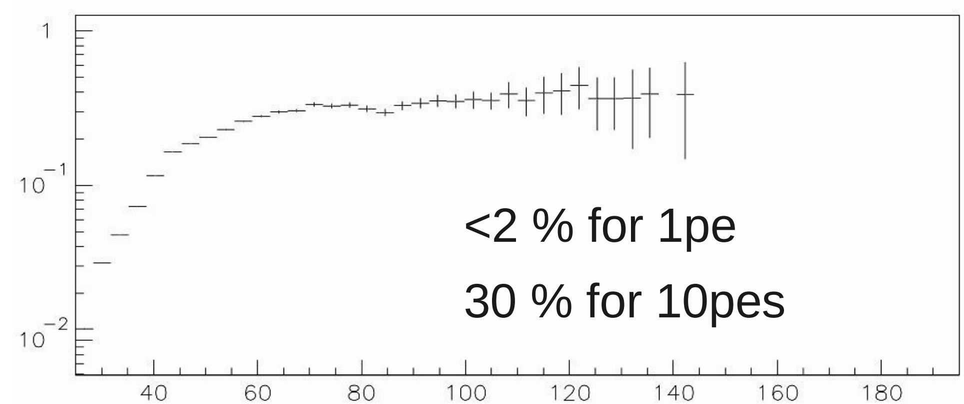





SToT=ToT1

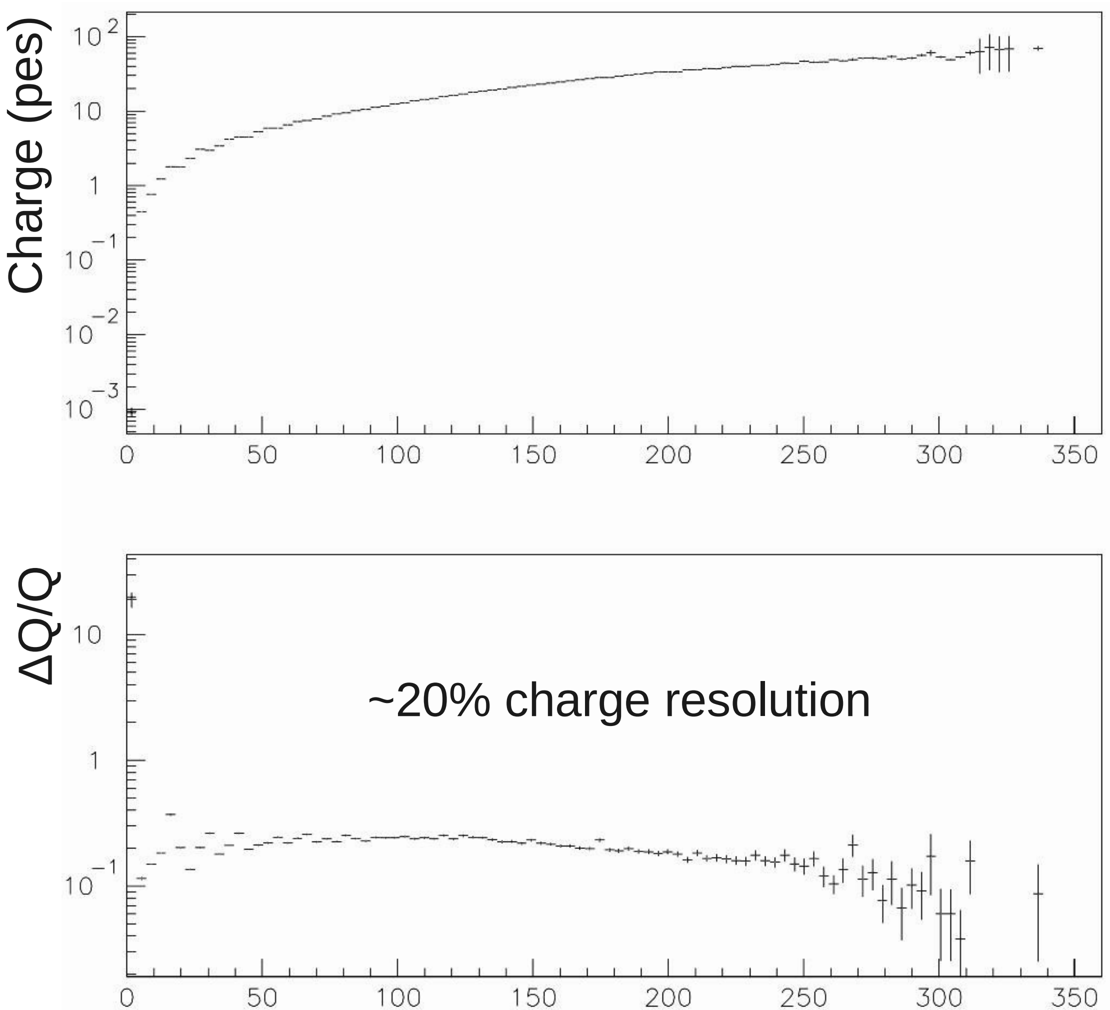



SToT=ToT1+ToT2+ToT3

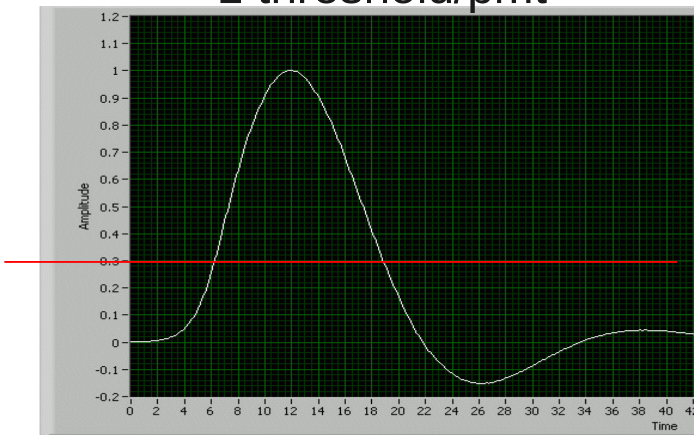
# Charge estimation resolution of the whole DOM (31x3 inch pmts) (WORK IN PROGRESS)

Simulated signal from muons (0.1Tev-100Tev)

1 threshold/pmt




0.3 pe




$$STоT = \sum_{i=1}^{i=31} ToT1_i$$

Single pmt charge resolution can be further improved by taking into account the correlations between neighboring pmts in the DOM (work in progress)

# Discovery potential for various KM3NeT layouts

# Studied Detector Geometrical Layouts-Towers

2 x 154 Towers with a mean distance between them:

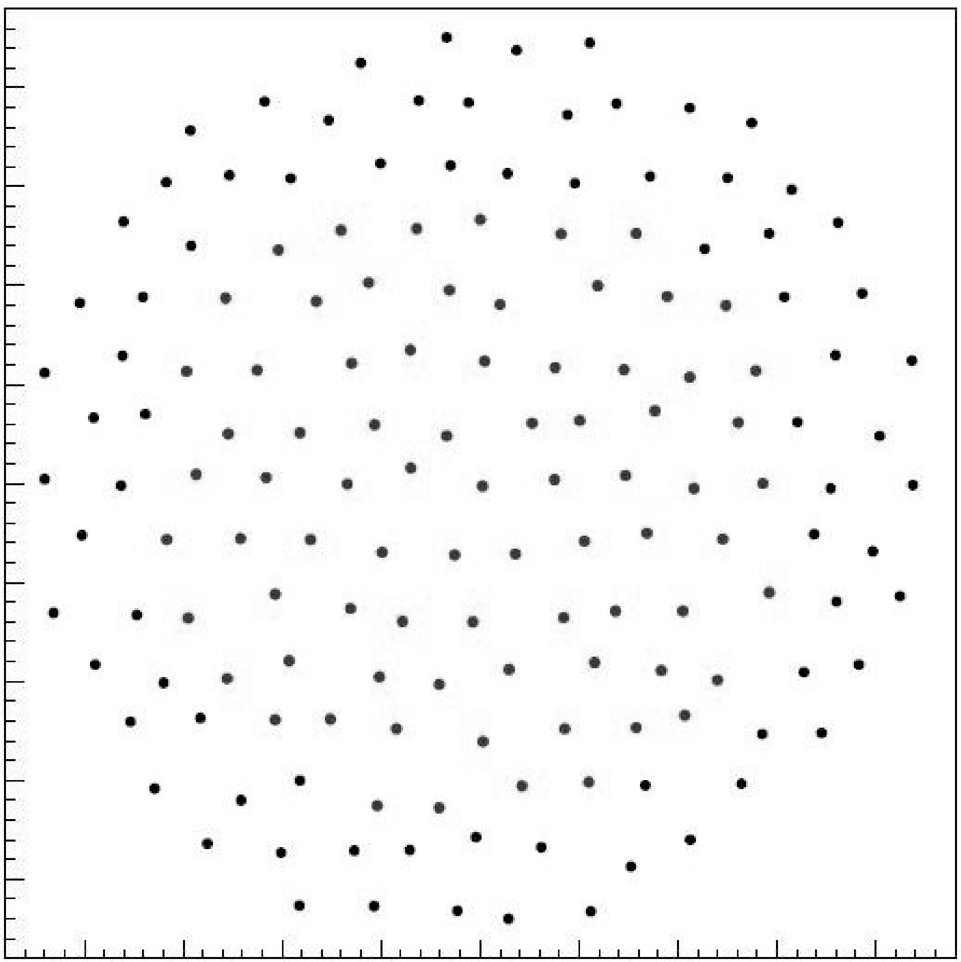
180m -> Instrumented volume 5.8 km$^3$ (308towers_180m)

150m -> Instrumented volume 4.0 km$^3$ (308towers_150m)

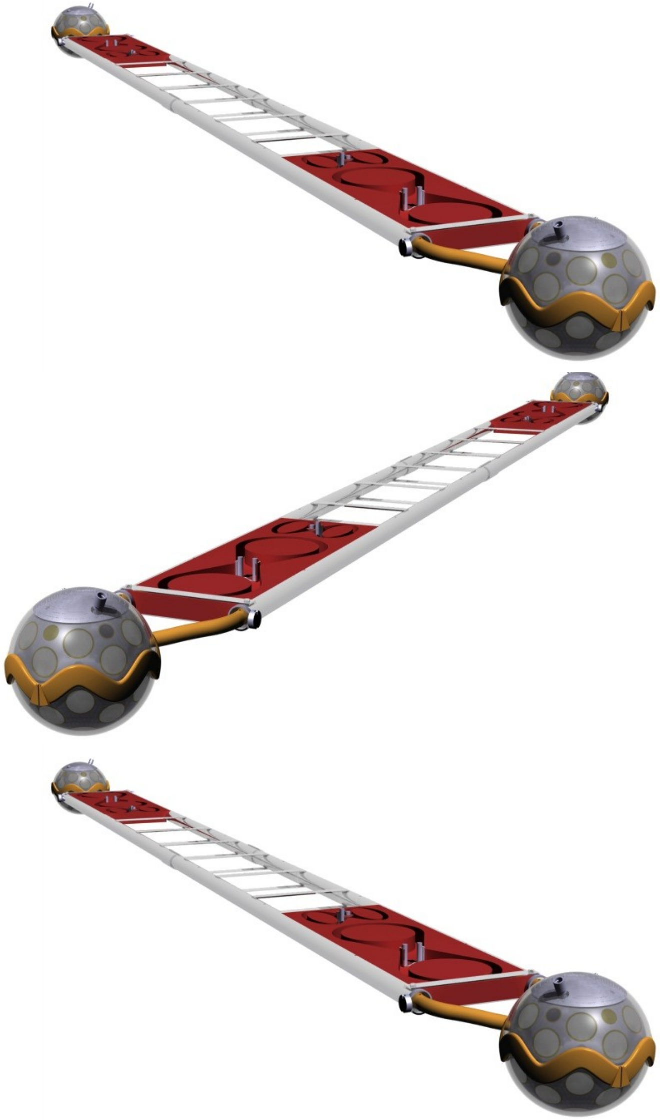
130m -> Instrumented volume 3.0 km$^3$ (308towers_130m)

Each Tower consists of 20 bars, 6m in length and 40m apart.
One DOM at each end of the bar.

2 x



154 Towers detector footprint



# Studied Detector Geometrical Layouts-Strings

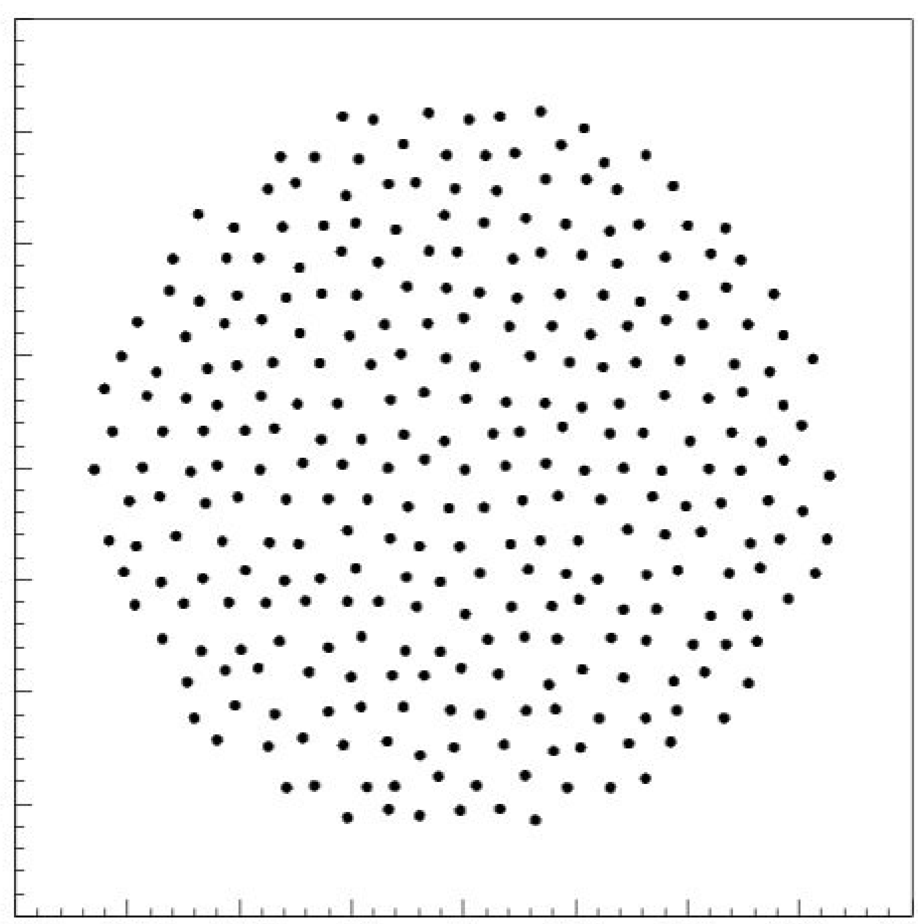
2 x 308 Strings with a mean distance between them:

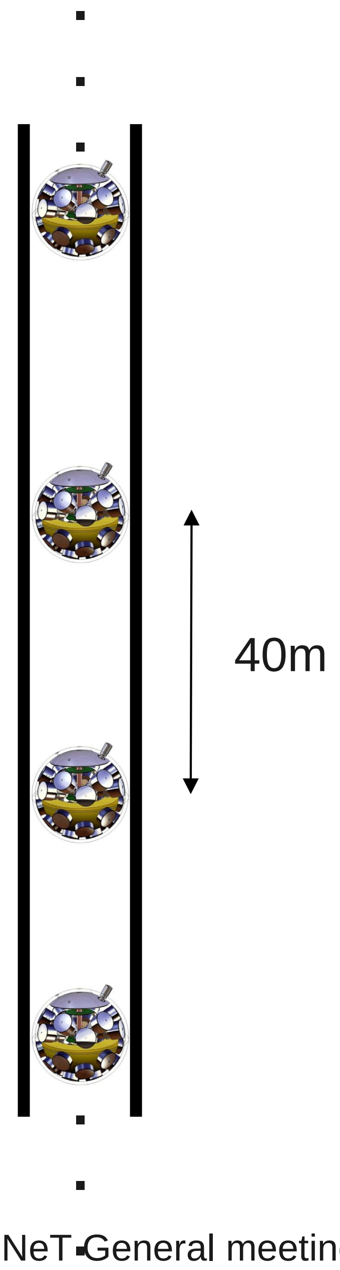
130m -> Instrumented volume 6.1 km$^3$ (616strings_130m)

100m -> Instrumented volume 3.6 km$^3$ (616strings_100m)

Each strings consists of 20 DOMs 40m apart.

2 x



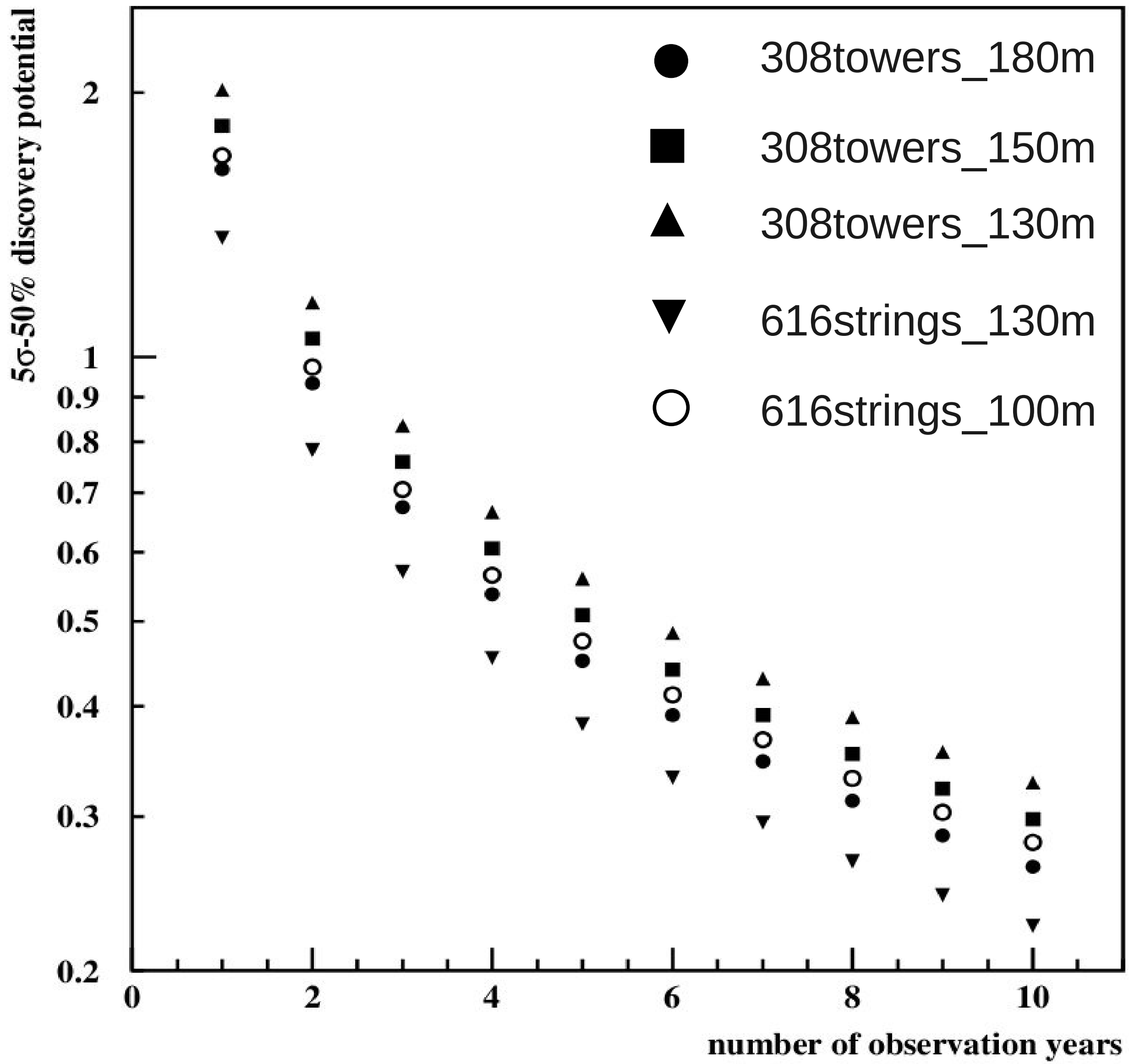


# 5σ-50% discovery potential

point source at -60 declination

$E^{-2}$ neutrino energy spectrum, binned technique

$x10^{-9} E^{-2} GeV^{-1} cm^{-2} s^{-1}$

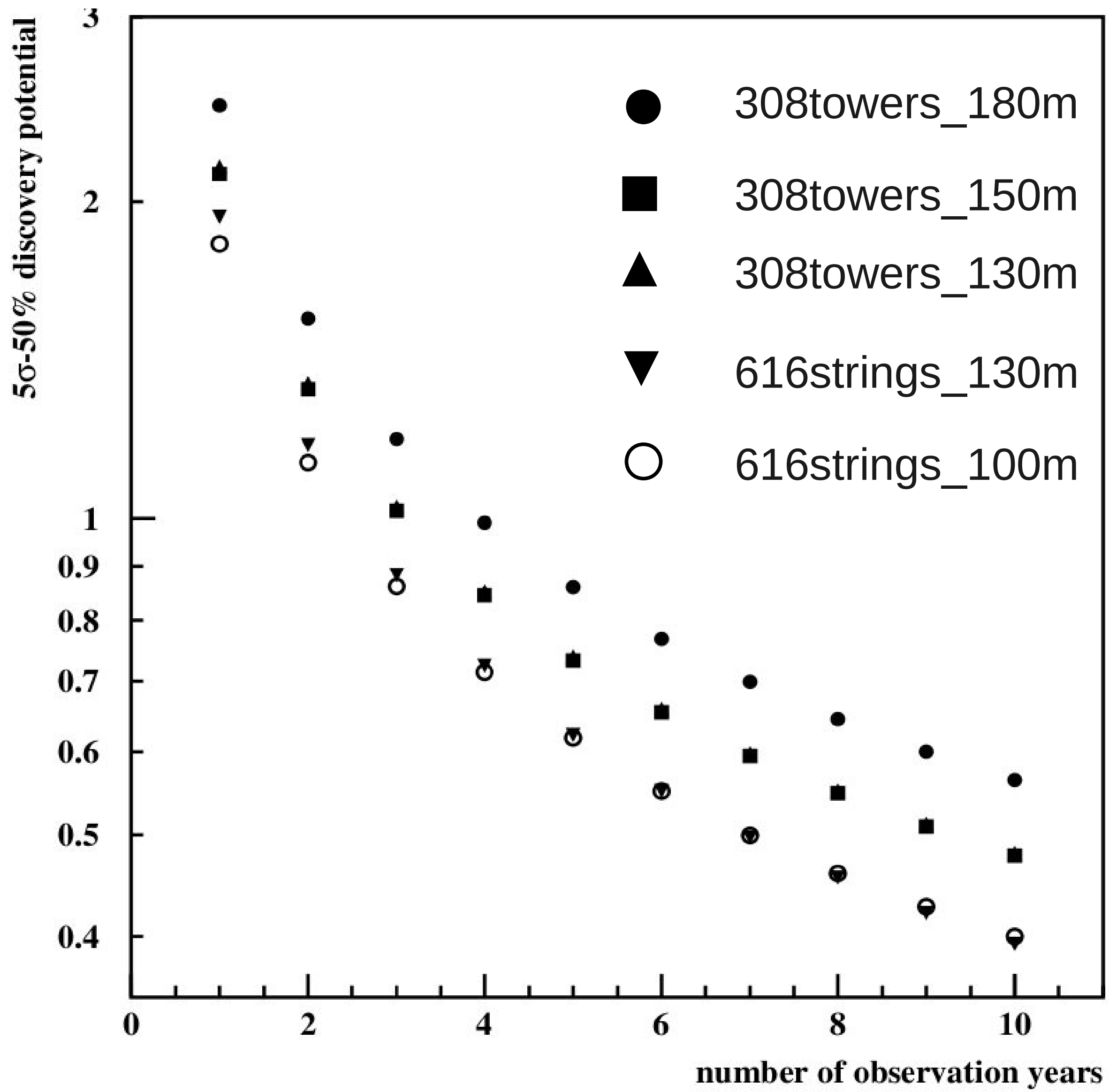


# 5σ-50% discovery potential

point source at -60 declination
RXJ1713 spectrum, binned technique)

$$\Phi(E) = 16.8 \times 10^{-15} \left[\frac{E}{\mathrm{TeV}}\right]^{-1.72} e^{-\sqrt{\frac{E}{2.1\ \mathrm{TeV}}}} \ \mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$$

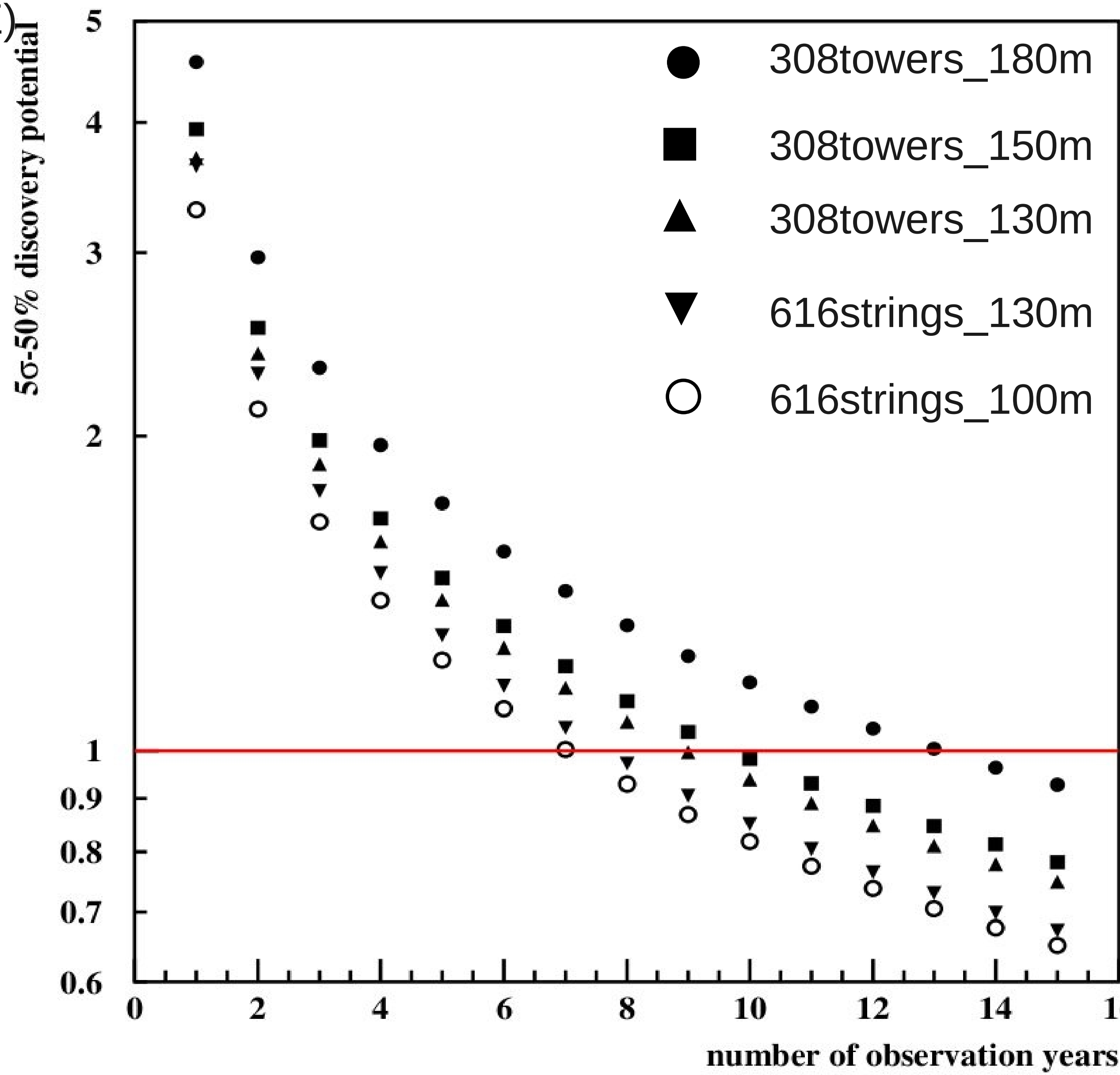
x Φ(E)



RXJ1713 5σ-50% discovery potential (0.6° radius, uniformly emitting disk, binned technique)

$$\Phi(E) = 16.8 \times 10^{-15} \left[\frac{E}{\mathrm{TeV}}\right]^{-1.72} e^{-\sqrt{\frac{E}{2.1\ \mathrm{TeV}}}} \quad \mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$$

x Φ(E)




13 years for discovery

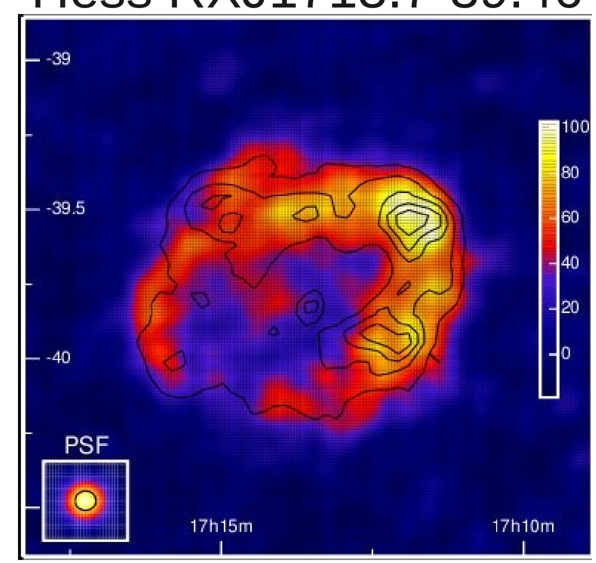
9.5 years for discovery

9 years for discovery

7.5 years for discovery

7 years for discovery

Hess RXJ1713.7-39.46




Unbinned technique results->
Talk by A. Leisos

# Conclusions and future plans

- We fine tune the HOURS simulation software to deal with minor inconsistencies between full and fast simulation

- We developed a filtering and prefit algorithm taking into account the apriori known direction of the neutrino source. The first results are very encouraging.
  - We should study further the elimination of fake signal created by imposing an apriori direction
  - Fake tracks have a low tracking quality which is reflected to the estimated tracking error, i.e. fake tracks carry a very small weight in the unbinned method. We are workings towards combining the known source direction technique with the unbinned method

- We are studying techniques for an accurate pmt charge estimation using 1,2,3 thresholds
  - We are studying the effect of pmt charge resolution on the track reconstruction accuracy

- The detector optimization is ongoing (for different depths, water properties, ...)

- Shower Reconstruction ?

# Backup slides

# Parameters and Definitions

Neutrino Flux: k=1.0x10$^{-9}$ E$^{-2}$ (GeV$^{-1}$cm$^{-2}$s$^{-1}$)

$n_{bg}$=mean number of expected background events
$n_s$= mean number of expected signal events

Sensitivity (90% CL): $k\dfrac{\bar{\mu}_{90}(n_{bg})}{n_s}$

$$\bar{\mu}_{90}(n_{bg}) = \sum_{N_o=0}^{\infty} \mu_{90}(N_o, n_{bg}) P(N_o | n_{bg})$$

$$\mu_{90}(N_o, n_{bg}) \equiv 90\%\, CL\ Feldman-Cousins\ Upper\ Limit$$

$N_o$=number of observed events

Discovery Potential (m sigma, 50%): $k\dfrac{d_m(n_{bg})}{n_s}$

$d_m$ = the mean number of signal events in order to have $n_0$ or more observed events with probability 50%

$$0.5 = \sum_{N_o=n_0}^{\infty} P(N_o | \boxed{d_m} + n_{bg})$$

$n_0$ = the minimum number of observed events to have a discovery of m sigma

$$\sum_{N_o=\boxed{n_0}}^{\infty} P(N_o | n_{bg}) \leqslant p_m$$

$p_3$=2.7x10$^{-3}$

$p_5$=5.73x10$^{-7}$