Physics Laboratory
School of Science and Technology
Hellenic Open University

KM3NeT
Opens a new window on our universe

# HOU Reconstruction & Simulation (HOURS): A simulation and reconstruction package for neutrino telescopy

**Apostolos G. Tsirigotis**, George Boulis, Antonis Leisos, Dimitris Lenis,
Spyros Tzamarias
Physics Laboratory, Hellenic Open University

- Overview
- Event generation
- Detector description and Simulation
- Optical noise, PMT response and electronics simulation
- DOM charge reconstruction/Pulse arrival time corrections
- Prefit and filtering algorithms
- Event reconstruction
  - Event direction estimation
  - Energy reconstruction
- Analysis Tools

Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο

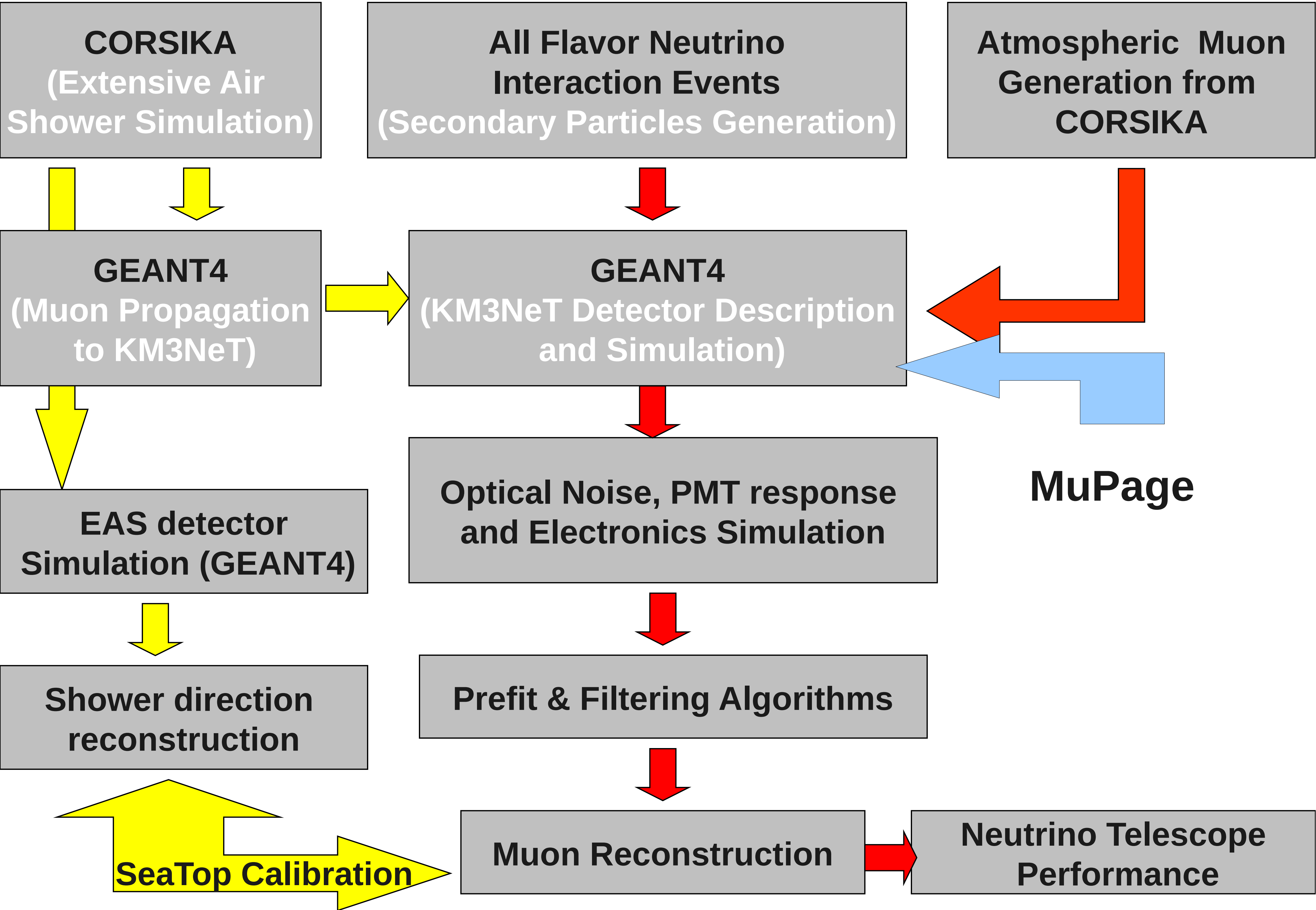
ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ & ΘΡΗΣΚΕΥΜΑΤΩΝ, ΠΟΛΙΤΙΣΜΟΥ & ΑΘΛΗΤΙΣΜΟΥ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ

ΕΣΠΑ
2007-2013
πρόγραμμα για την ανάπτυξη
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ

Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

KM3NeT Collaboration meeting, January 2013 CPPM

# HOURS - Simulation software chain



CORSIKA
(Extensive Air
Shower Simulation)

All Flavor Neutrino
Interaction Events
(Secondary Particles Generation)

Atmospheric Muon
Generation from
CORSIKA

GEANT4
(Muon Propagation
to KM3NeT)

GEANT4
(KM3NeT Detector Description
and Simulation)

MuPage

EAS detector
Simulation (GEANT4)

Optical Noise, PMT response
and Electronics Simulation

Shower direction
reconstruction

Prefit & Filtering Algorithms

SeaTop Calibration

Muon Reconstruction

Neutrino Telescope
Performance

# HOURS – Software developers/users/documentation/data format

Developed by HOU physics laboratory team

- Event generation (A. Tsirigotis, D. Lenis)
- Detector description and Simulation (A. Tsirigotis)
- Optical noise, PMT response and electronics simulation (A. Tsirigotis, G. Bourlis)
- DOM charge  reconstruction/Pulse arrival time corrections (G. Bourlis)
- Prefit and filtering algorithms (A. Tsirigotis)
- Event reconstruction (A. Tsirigotis, D. Lenis)
  - Event direction estimation
  - Energy reconstruction
- Analysis Tools (A. Tsirigotis, S. Tzamarias, A. Leisos)

Users

- HOU physics laboratory team

Documentation/availability

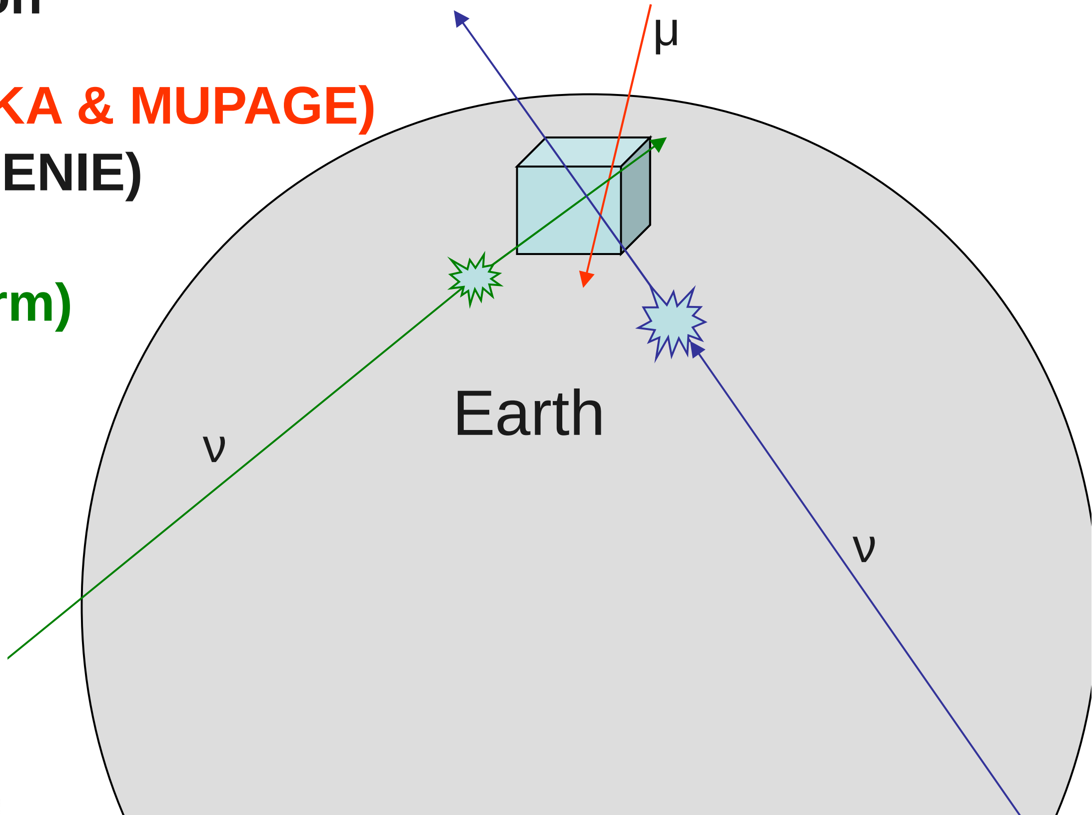
- Documentation and will be soon available (preparing user guide)
- Older package version already available at HOU website http://physicslab.eap.gr/EN/Simulation_software.html, will be updated soon

Simulation data format

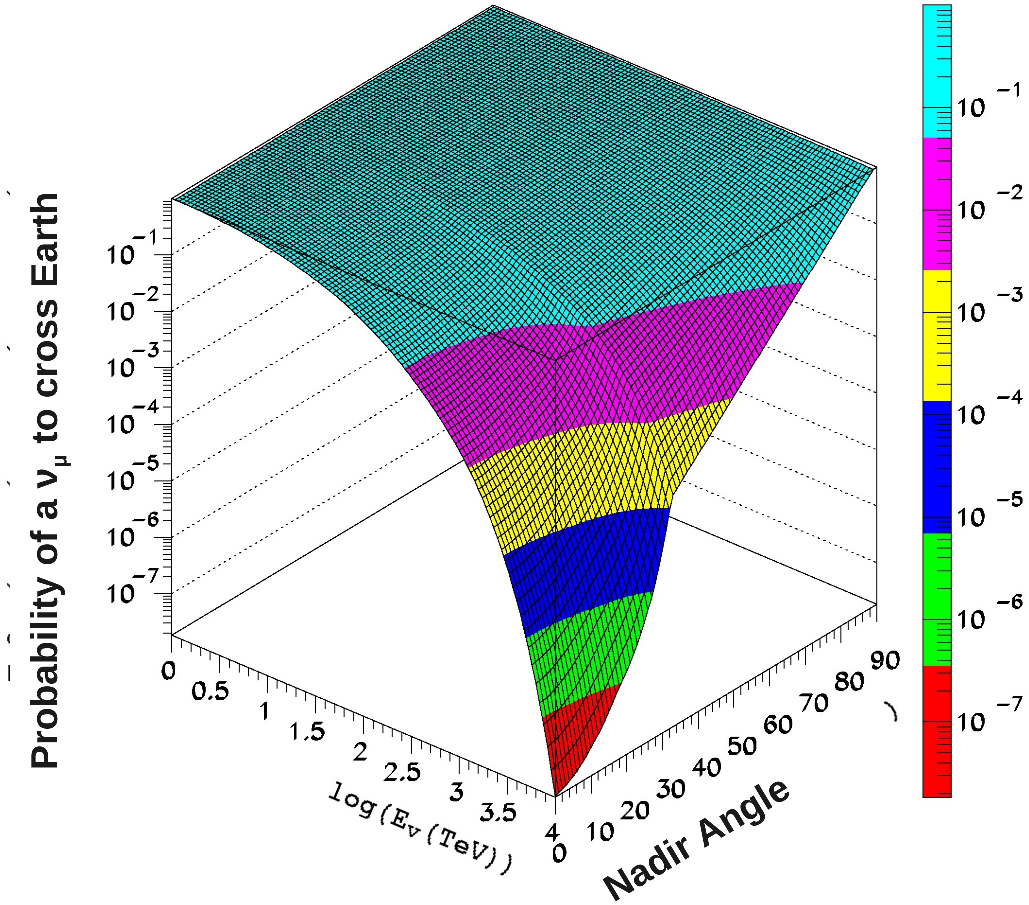
- ANTARES evt format

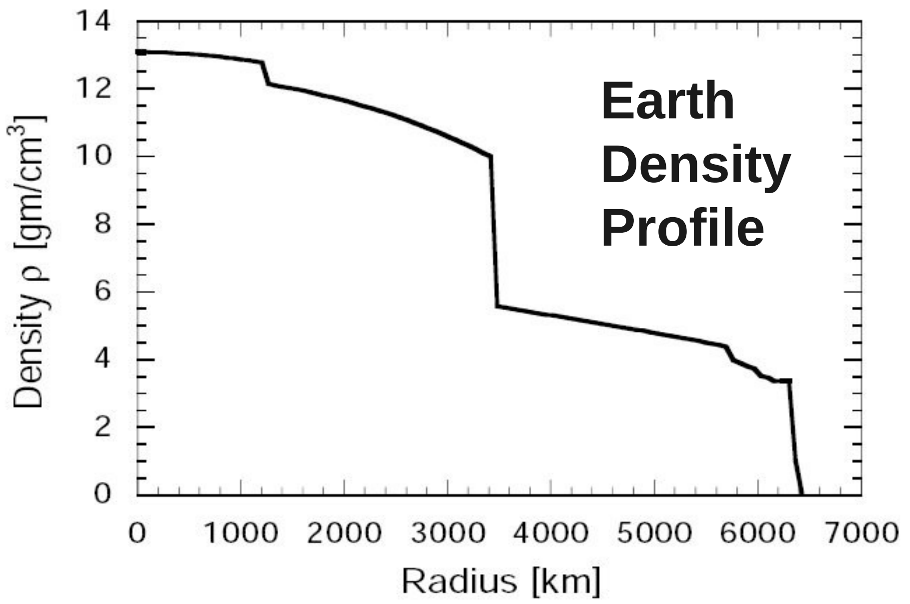
# Event Generation – Flux Parameterization

- Atmospheric Muon Generation (CORSIKA & MUPAGE)
- Neutrino Interaction Events (PYTHIA, GENIE)
- Atmospheric Neutrinos (Conventional Flux+Neutrinos from charm)
- Cosmic Neutrinos (AGN – GRB – GZK and more)



## Survival probability





# Detector description &Simulation

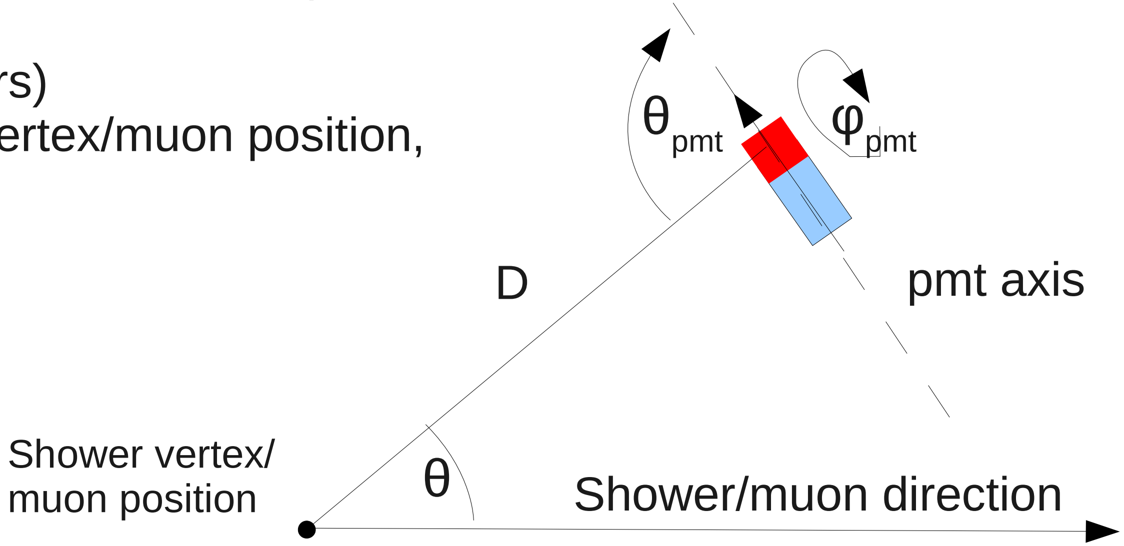
- **Any detector geometry can be described in a very effective way**
- **All the relevant physics processes are included in the simulation**

| | |
|---|---|
| **Full GEANT4 simulation** | SLOW |
| **Fast Simulation** | 2 to several thousand times faster than full Simulation (depended on muon energy) |

## Parametrizations for:

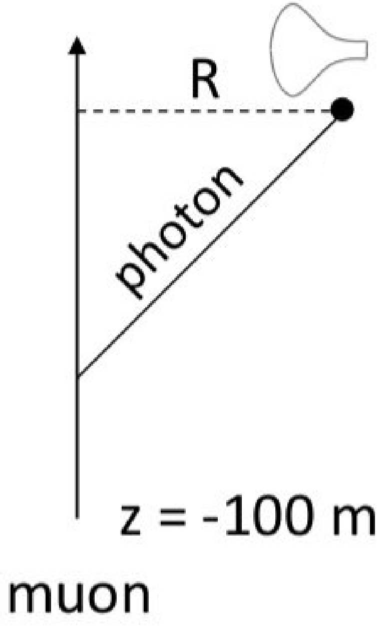
- EM showers (from e-, e+, γ)
- HA showers (from long lived hadrons)
- Low energy electrons (from ionization)
- Direct Cherenkov photons (from muon)

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 ($\theta_{pmt}$,$\varphi_{pmt}$)

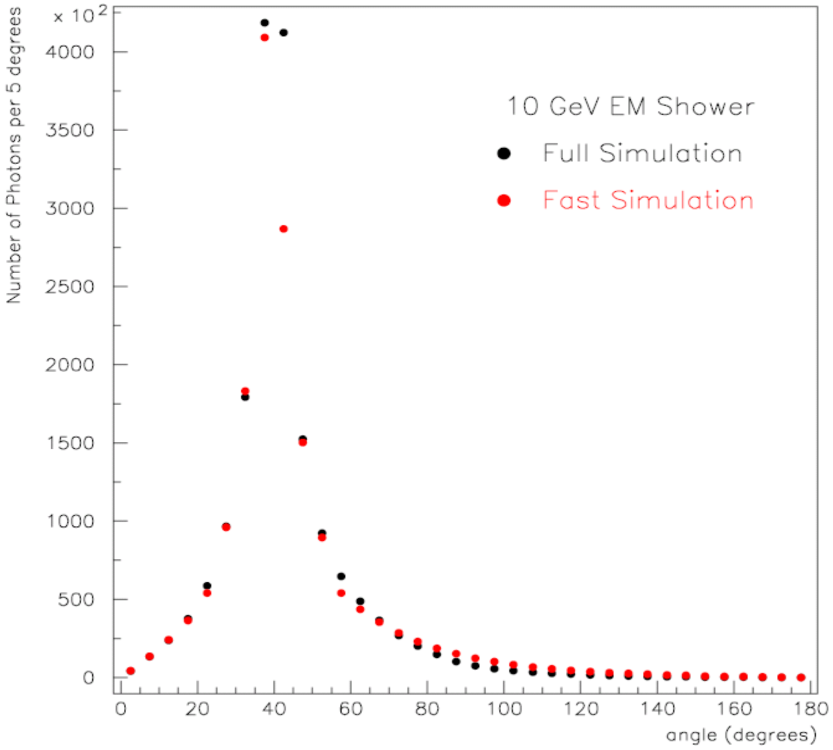


# Detector description &Simulation - Parametrized simulations/results

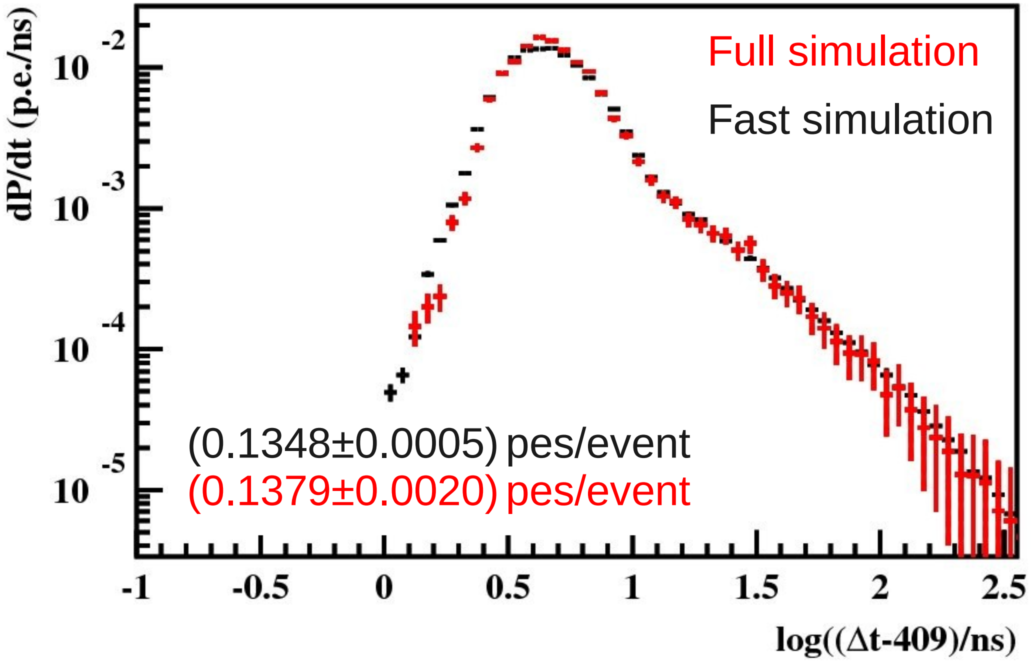
Comparison between Full & Fast Simulation



Angular Distribution of Cherenkov Photons for 10 GeV EM shower



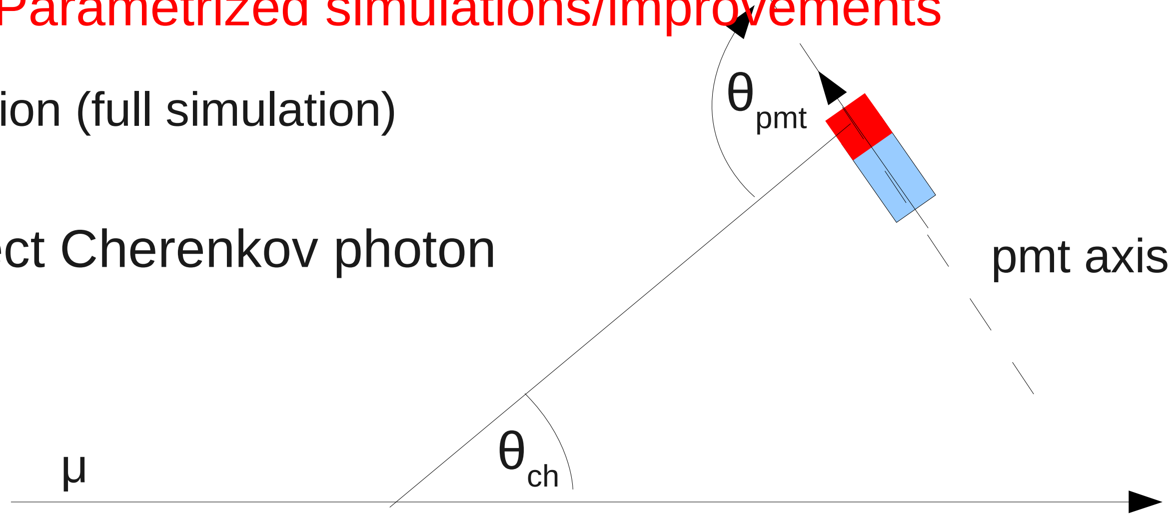
Arrival time distribution of Cherenkov Photons for 100 GeV muon (R=25m)



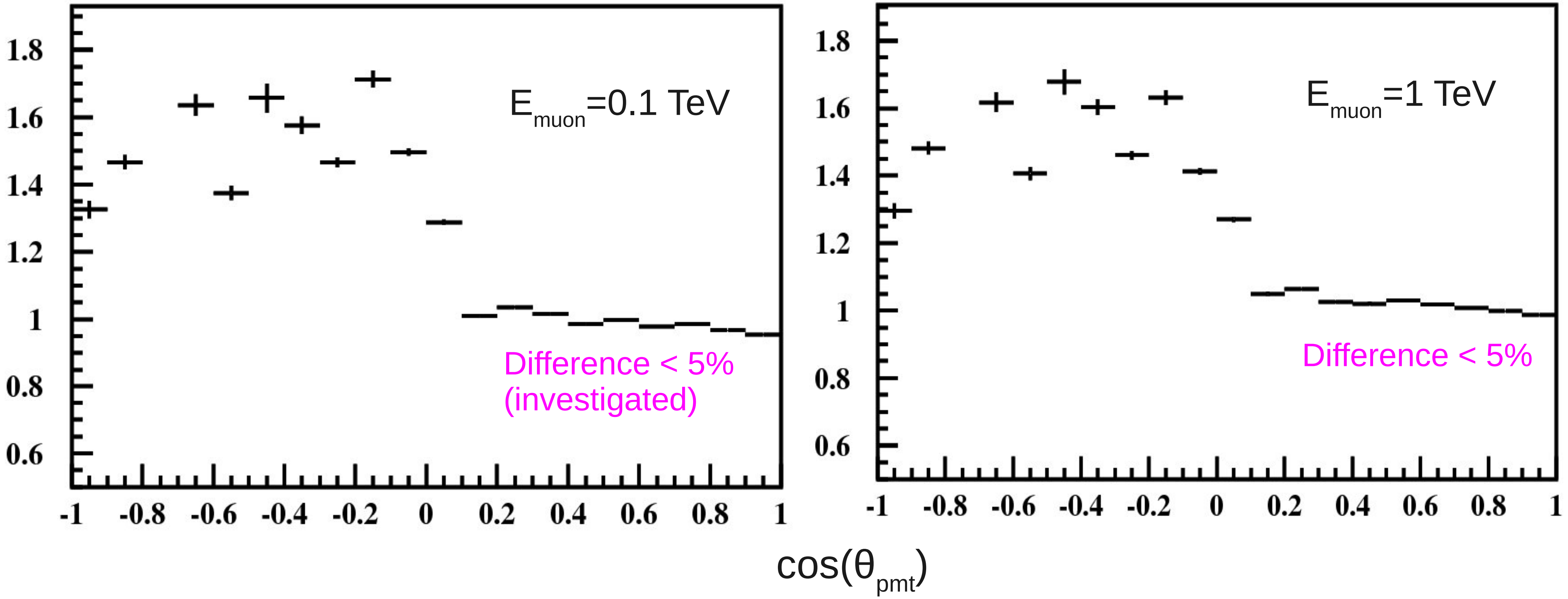
# **Detector description &Simulation -** Parametrized simulations/improvements

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

# Optical noise, PMT response and electronics simulation

$^{40}$K Optical noise includes single and multiple genuine coincidence rate (up to 6-fold coincidence)

- Rates per DOM estimated with full geant4 simulation of $^{40}$K decays, taking into account DOM functional characteristics

PMT response simulation

- Quantum/collection efficiency
- Time Jitter
- Single Photoelectron charge spectrum
- Waveform production

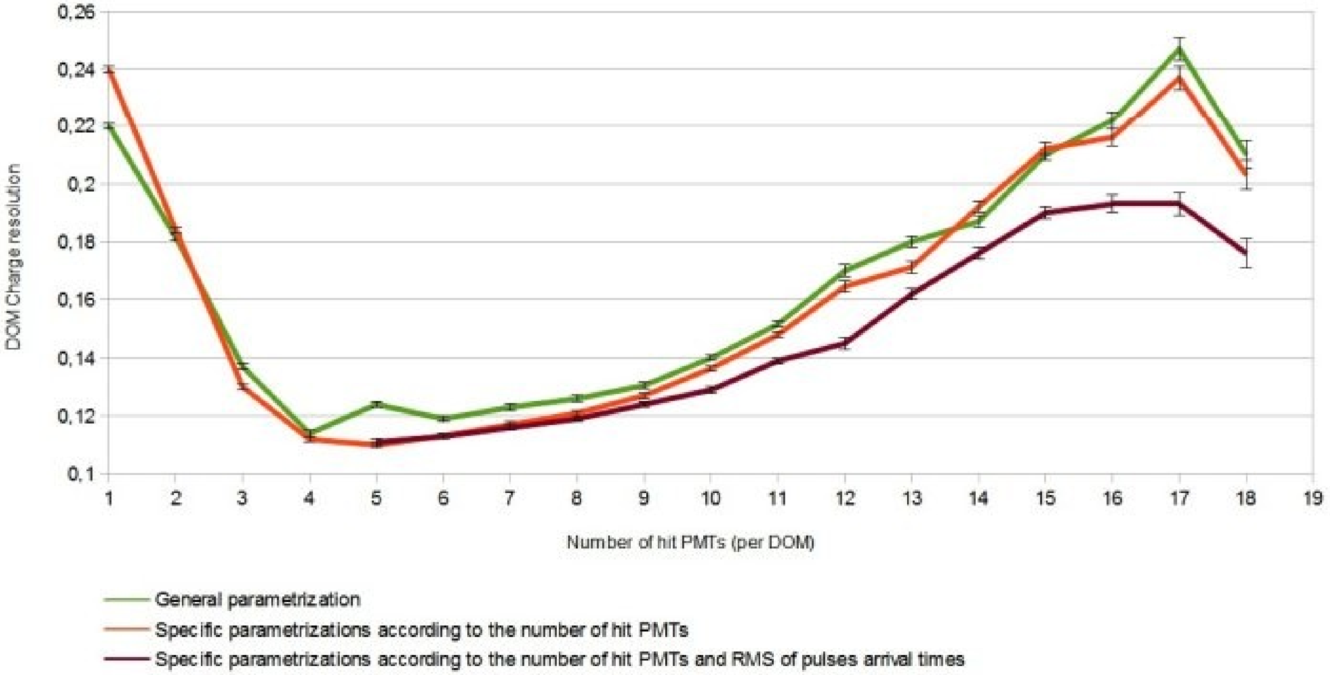
Electronics simulation

- Single – Multiple Threshold ToT electronics

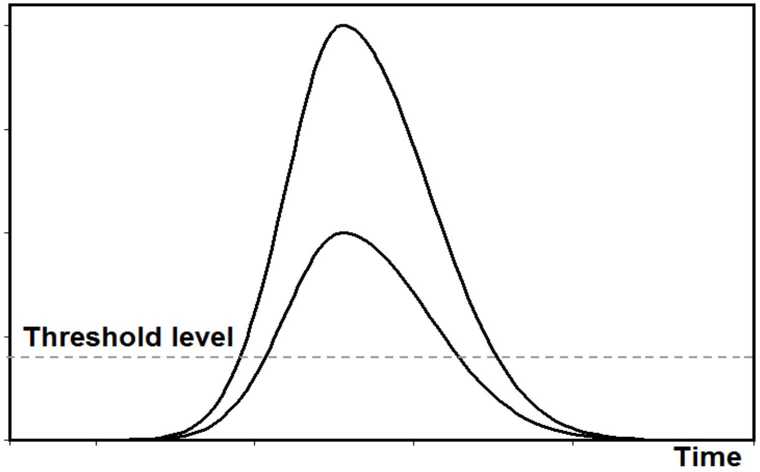
# DOM charge reconstruction/Pulse arrival time corrections

Take into account correlations between neighboring pmts in a DOM

- The DOM charge can be estimated with 10-20% accuracy depending on the number of the active pmts
- Adequate for the muon energy reconstruction



The slewing effect

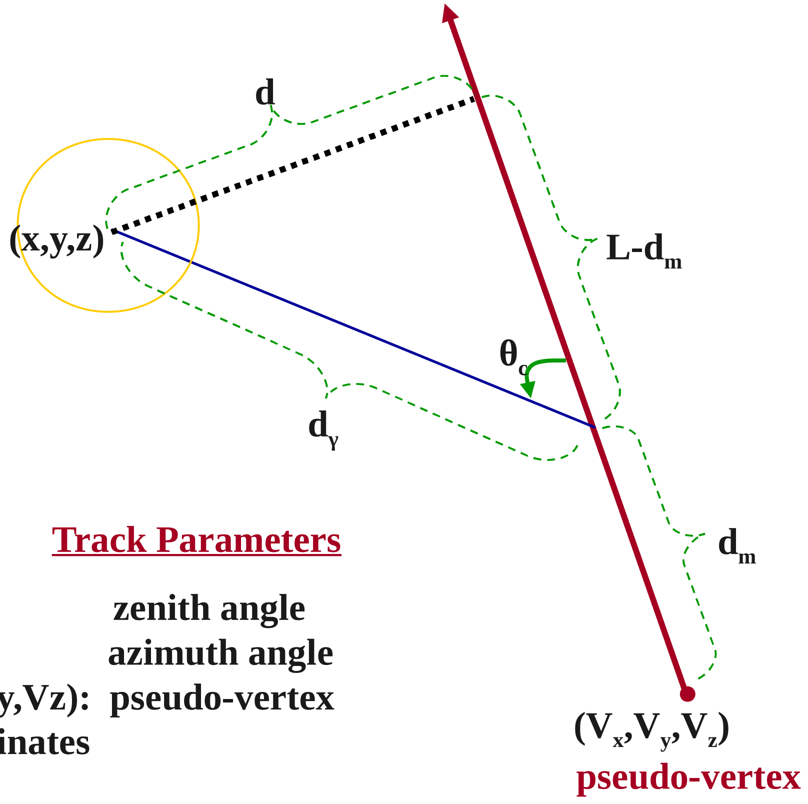


Slewing corrections can be estimated with accuracy ~5%

# Optical noise filtering, prefit and muon reconstruction

- Prefit and Filtering based on:
  - Linear+Scanning likelihood prefit (using only L1 hits)
  - 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 point source neutrino astronomy

- 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 (>1TeV muons), or estimated muon track length (<1TeV)



**Track Parameters**

**$\theta$ : zenith angle**
**$\varphi$: azimuth angle**
**(Vx,Vy,Vz): pseudo-vertex coordinates**

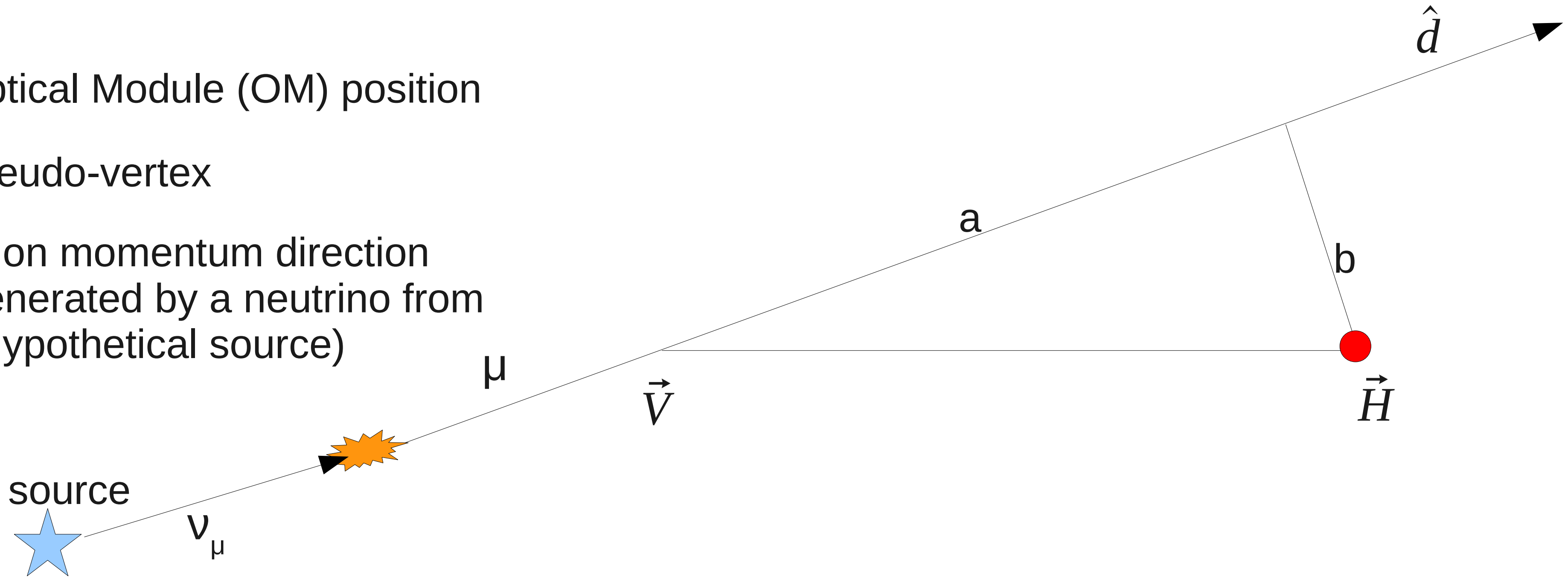
# Optical noise filtering, prefit and muon reconstruction

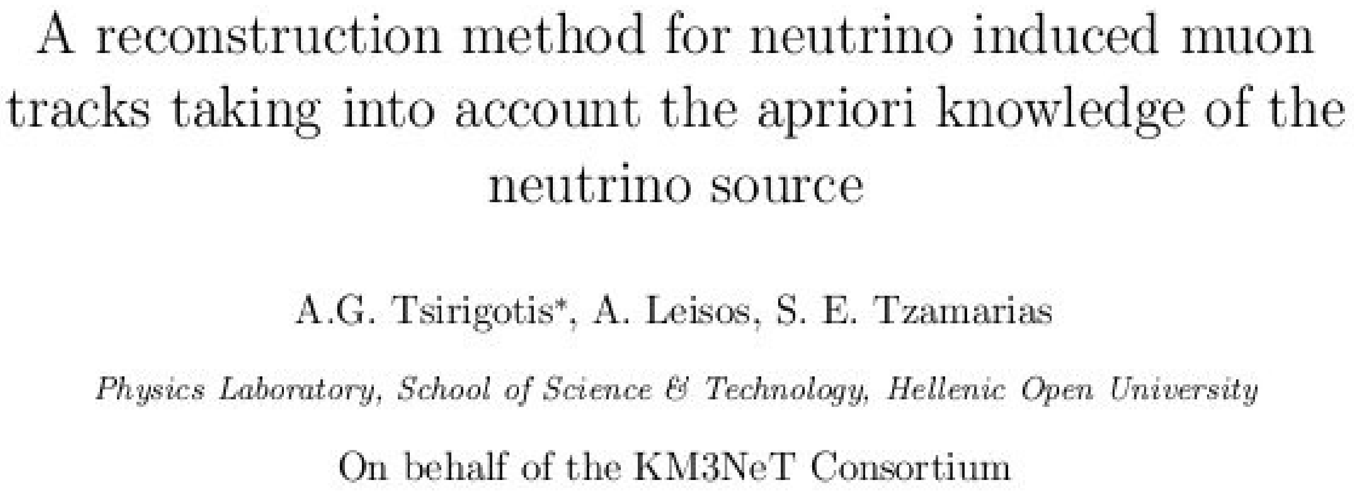
## Background filtering technique using the apriori known neutrino point source

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

$\vec{V}$ pseudo-vertex

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





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

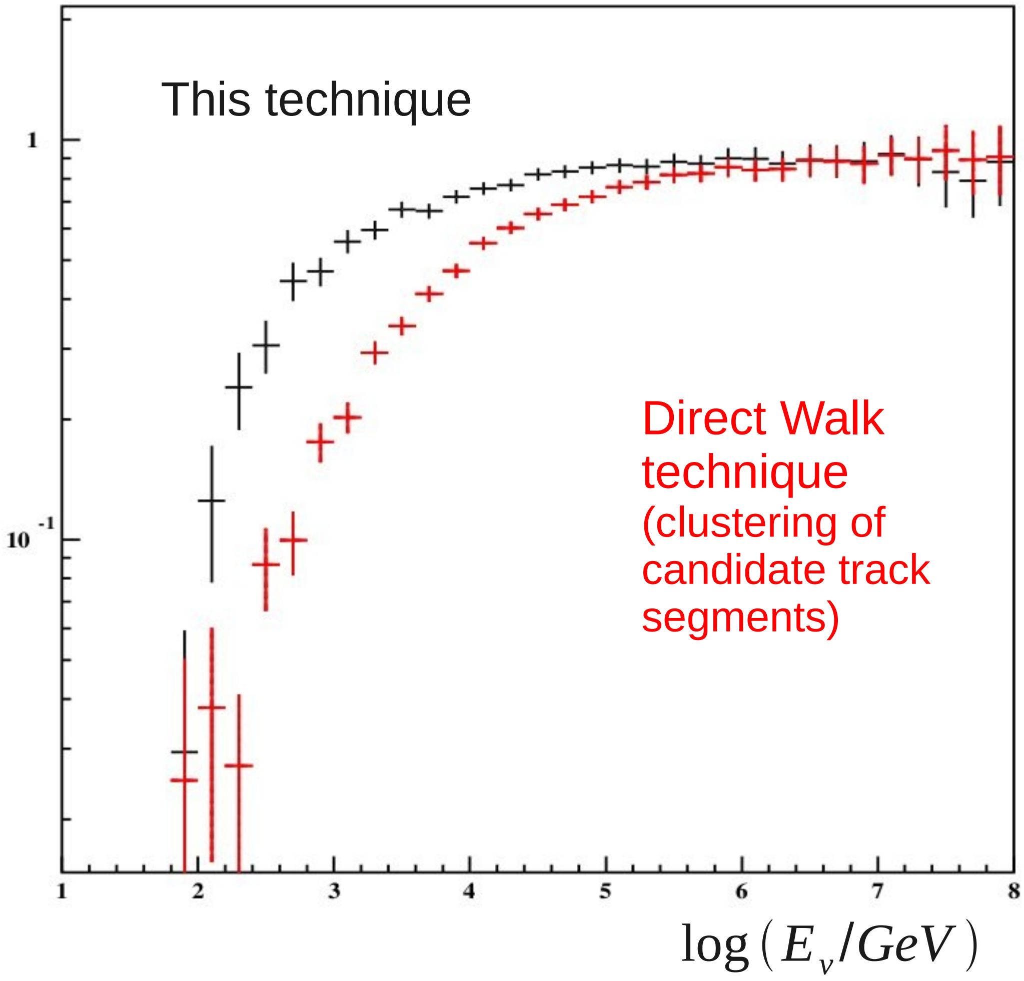
Proceedings of VLVnT2011

# Background filtering technique using the apriori known neutrino point source

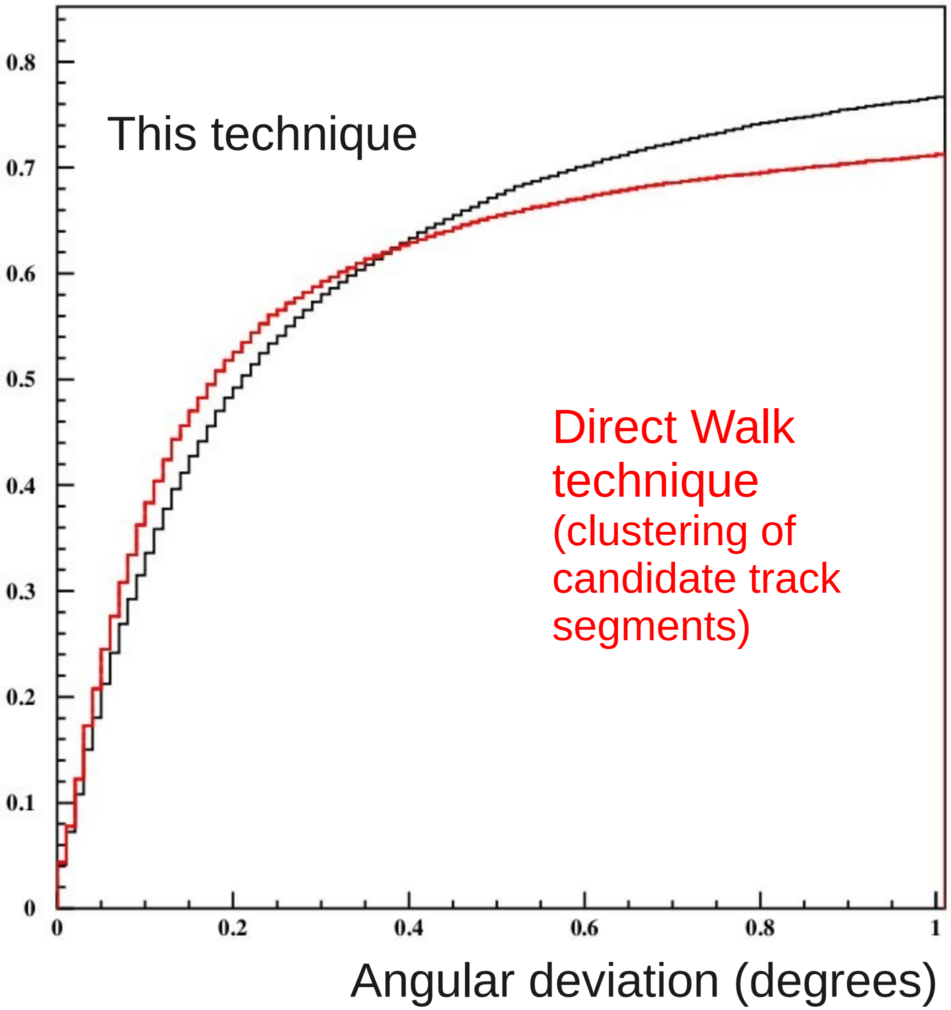
## Performance example

- $E^{-2}$ 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



# Muon Reconstruction - Kalman Filter

State vector $x = (V, \theta, \phi)$

Initial estimation $x_0, C_0$

Update Equations

$$x_k = x_{k-1} + K_k(t_k - t_k^{exp}(x_{k-1}))$$

$$C_k = (1 - K_k H_k) C_{k-1}$$

$$H_k = \left(\frac{\partial t^{\exp}}{\partial x}\right)_{x = x_{k-1}}$$

Kalman Gain Matrix

$$K_k = C_{k-1} H_k^T (V_k + H_k C_{k-1} H_k^T)^{-1}$$

timing uncertainty

$$V_k = \sigma_k^2$$

Updated residual and chi-square contribution (rejection criterion for hit)

$$r_k = t_k - t_k^{exp}(x_k)$$

$$R_k = (1 - K_k H_k) V_k$$

$$\chi_k^2 = r_k^2 / R_k$$

Many (40-200) candidate tracks are estimated starting from different initial conditions $(x_0, C_0)$. The best candidate is chosen using the Multi-PMT Direction and arrival time Likelihood (track quality criterion)

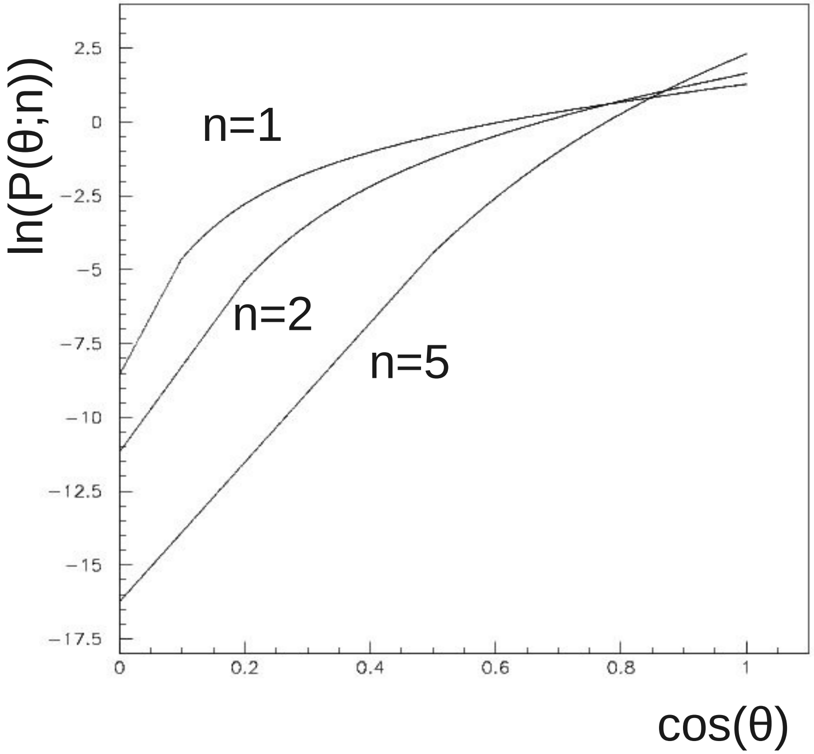
A.G.Tsirigotis et al,
Nucl.Instrum.Meth.A 602 (2009) 91

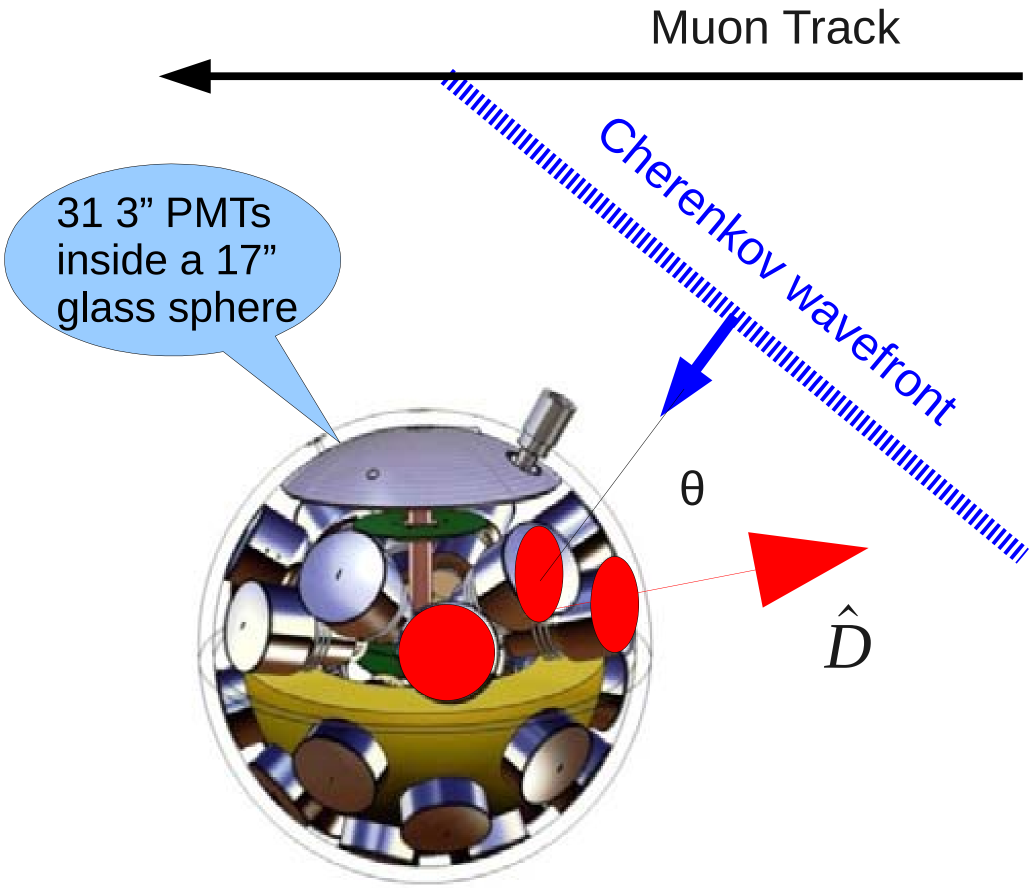
# Multi-PMT direction Likelihood

- **PDFs of the angle, θ, between the Ch wavefront direction and the active direction of the Multi-PMT**

$$PDF_{d,s}(\theta;n)$$

- **Separate parametrization for n=1,2,...18 active small pmts.**
- **For the parametrization only the angular acceptance and the directions of the small PMTs in the OM are used.**





Muon Track

Cherenkov wavefront

31 3” PMTs inside a 17” glass sphere

θ

$\hat{D}$

Averaged direction of active PMTs

$$\hat{D} = \sum_{i=1}^{N} d_i$$

# The directionality criterion is used for the selection of the best track candidate.

Signal $PDF_{d,s,i}(\theta_i; n_i)$

Noise $PDF_{d,n} = constant$

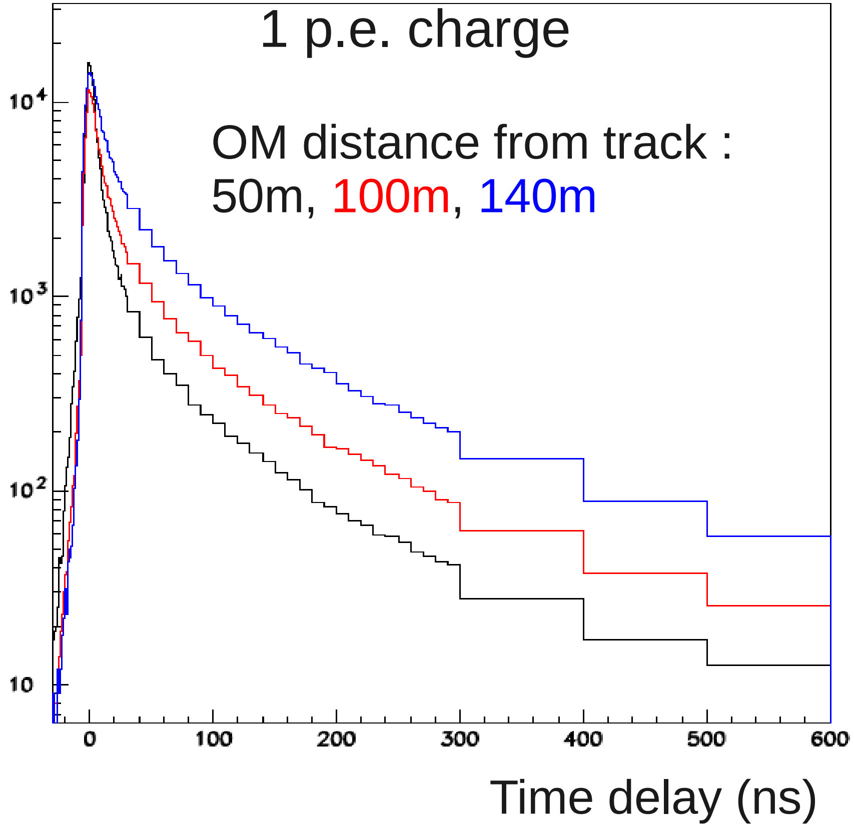
- i=1,2,...N the active Multi-PMTs
- $n_i$=the number of active elements in the $i^{th}$ Multi-PMT
- $\theta_i$=the angle between the weighted average direction of the $i^{th}$ active Multi-PMT with the reconstructed Cherenkov wavefront

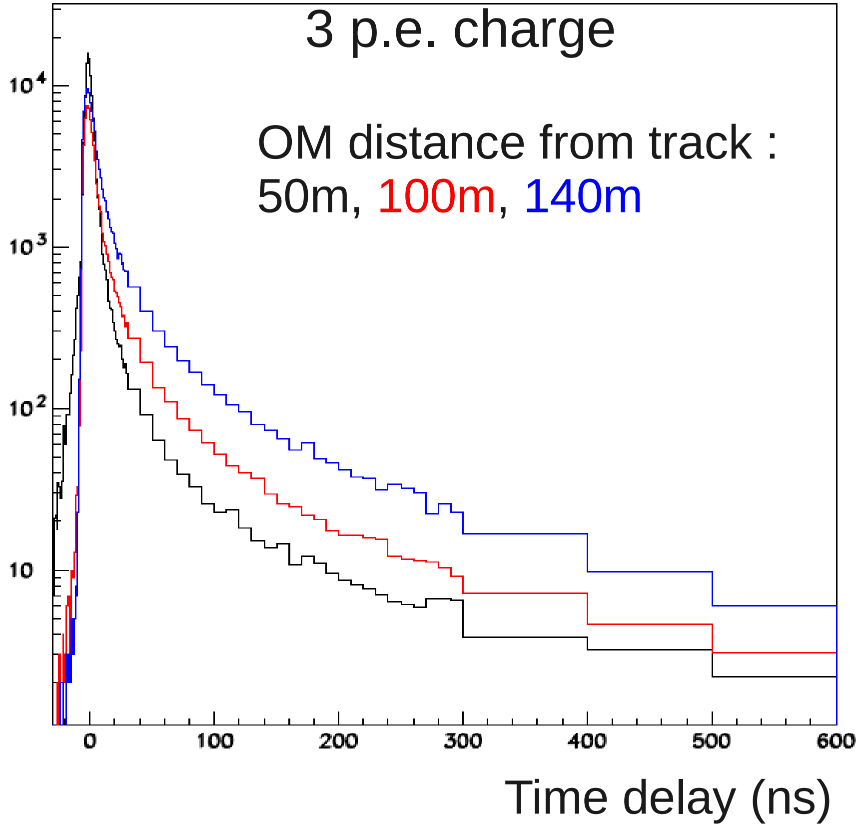
## For the selection of the best candidate track also the timing likelihood is used

Signal $PDF_{t,s,i}(t_i - t_{\exp}; q_i, d_i)$

Noise $PDF_{t,n,i}(t_i - t_{\exp}; d_i)$

$t_i$: hit arrival time,
$t_{exp}$:expected arrival time of direct photon
$q_i$: hit charge , $d_i$ : Hit distance from track





- The timing PDFs depend on the filtering and prefit stage
- They are created for the hits that pass these stages

For all the candidate tracks form the direction*timing likelihood for all hits that pass the final filtering stage (common for all candidate tracks)

$$L_{total}=\prod\left[p_{n,i}(N_{hit},q_i)\,PDF_{t,n,i}\,PDF_{d,n}+(1-p_n(N_{hit},q_i))\,PDF_{t,s,i}\,PDF_{d,s,i}\right]$$

$p_{n,i}(N_{hit},q_i)\equiv$ Probability of a hit to be noise

Timing PDFs

Signal $PDF_{t,s,i}(t_i-t_{\exp};q_i,d_i)$

Noise $PDF_{t,n,i}(t_i-t_{\exp};d_i)$

Direction PDFs

Signal $PDF_{d,s,i}(\theta_i;n_i)$

Noise $PDF_{d,n}=constant$

- The candidate track with the largest Likelihood is chosen
- Maximize further the Likelihood for the chosen candidate track

# Muon energy estimation (Charge Likelihood)

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

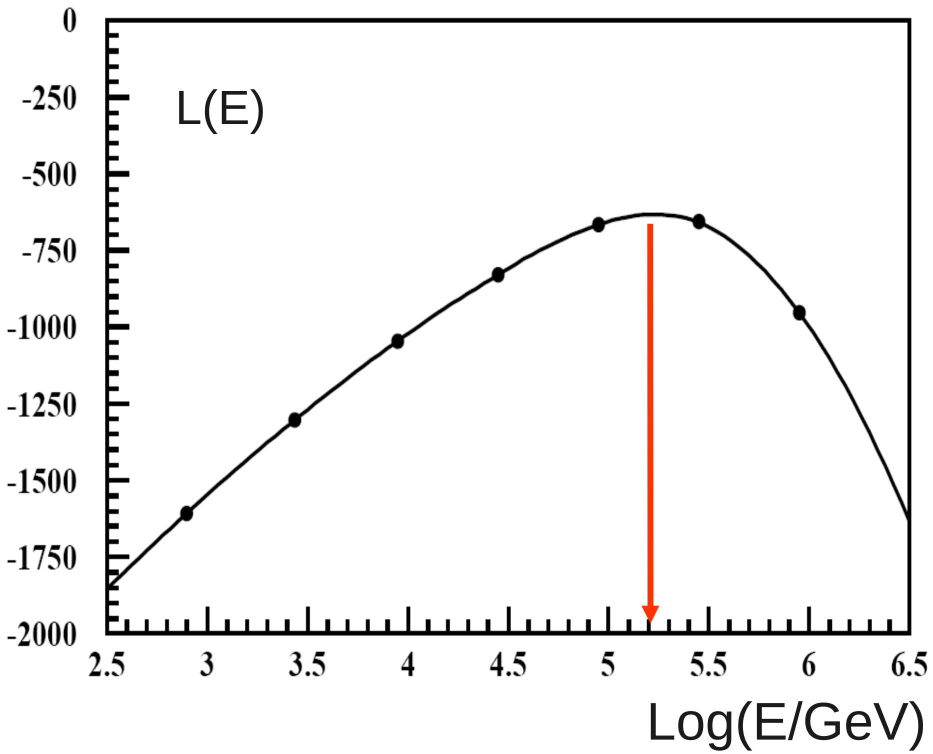
$Q_{i,data} \equiv$ Hit charge (**assumedly known exactly**) normalized to the charge of a single p.e. pulse

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

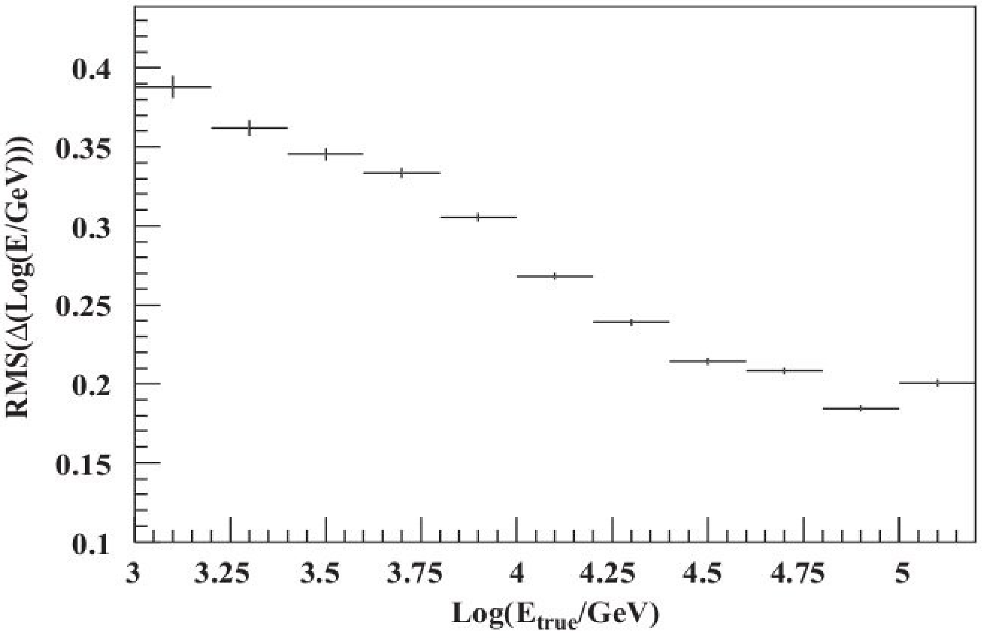
$$P(Q_{i,data};E,D,\theta)=\sum_{n=1}^{\infty} F(n;E,D,\theta)\,G(Q_{i,data};n,\sqrt{n}\,\sigma_{PMTresolution})$$

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

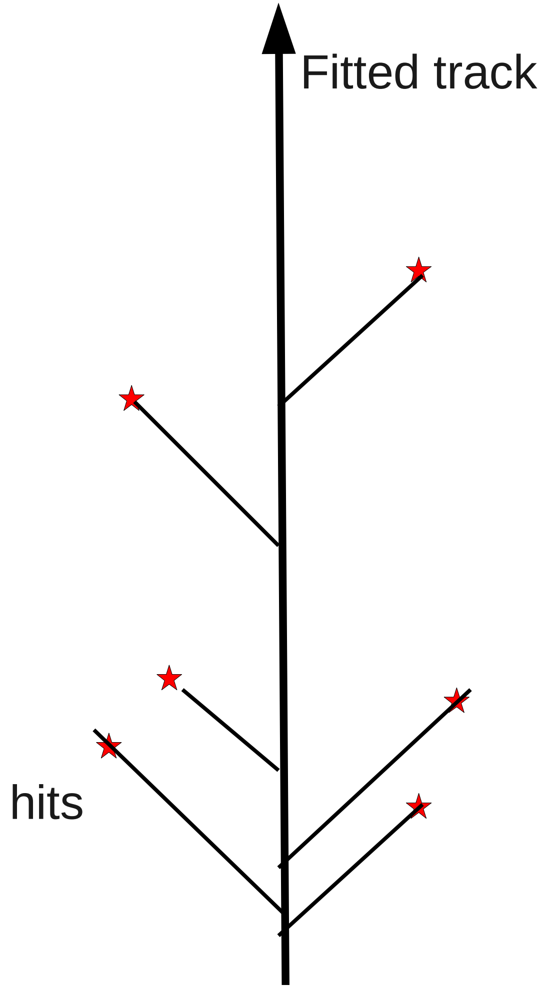


Muon energy estimation resolution

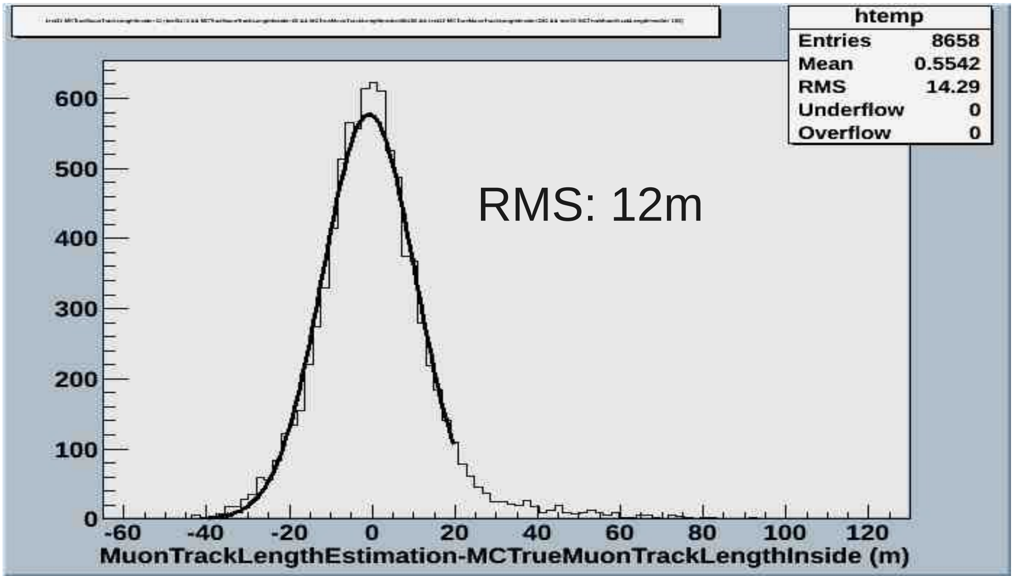


# Muon energy estimation (Track length)

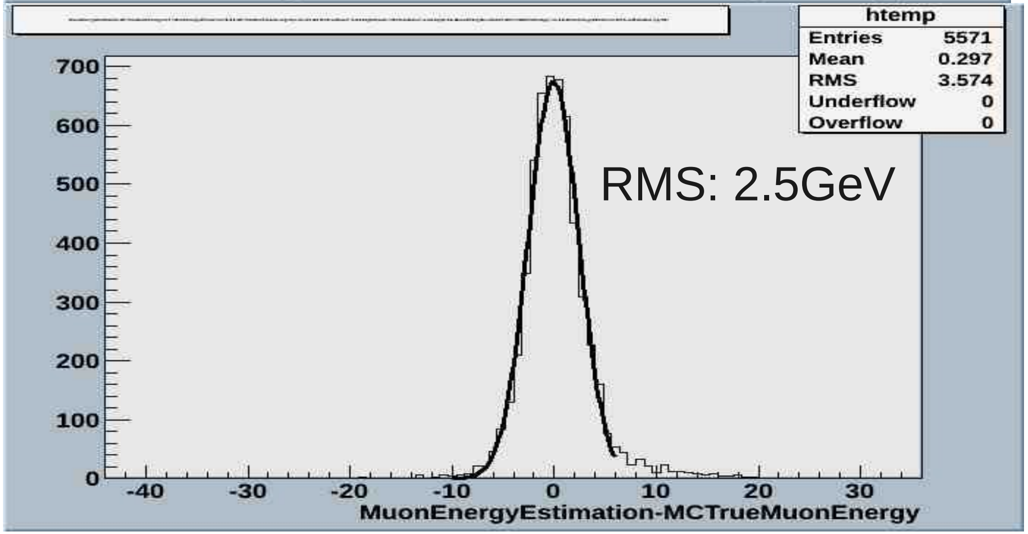
- Projections (with the Cherenkov angle) of the hit positions on the fitted track
- Accept only hits with residual<10ns and distance<40m from fitted track, to reduce the $^{40}$K noise contribution
- From the first hits projection estimate the neutrino vertex
- The last hit define the track end



Results (ORCA)



RMS: 12m



RMS: 2.5GeV

# Analysis Tools

Point/extended sources

- Binned technique
- Unbinned technique

SeaTop Calibration

- Estimation of angular systematic effects of the underwater telescope with the synchronous detection of Extensive Air Showers by an EAS sea surface detector

Supernova detection

- Multiple coincidences between the PMTs of the same DOM are utilized to suppress the noise produced by $^{40}$K and to establish a statistical significant signature of the SN explosion.

Neutrino Oscillations

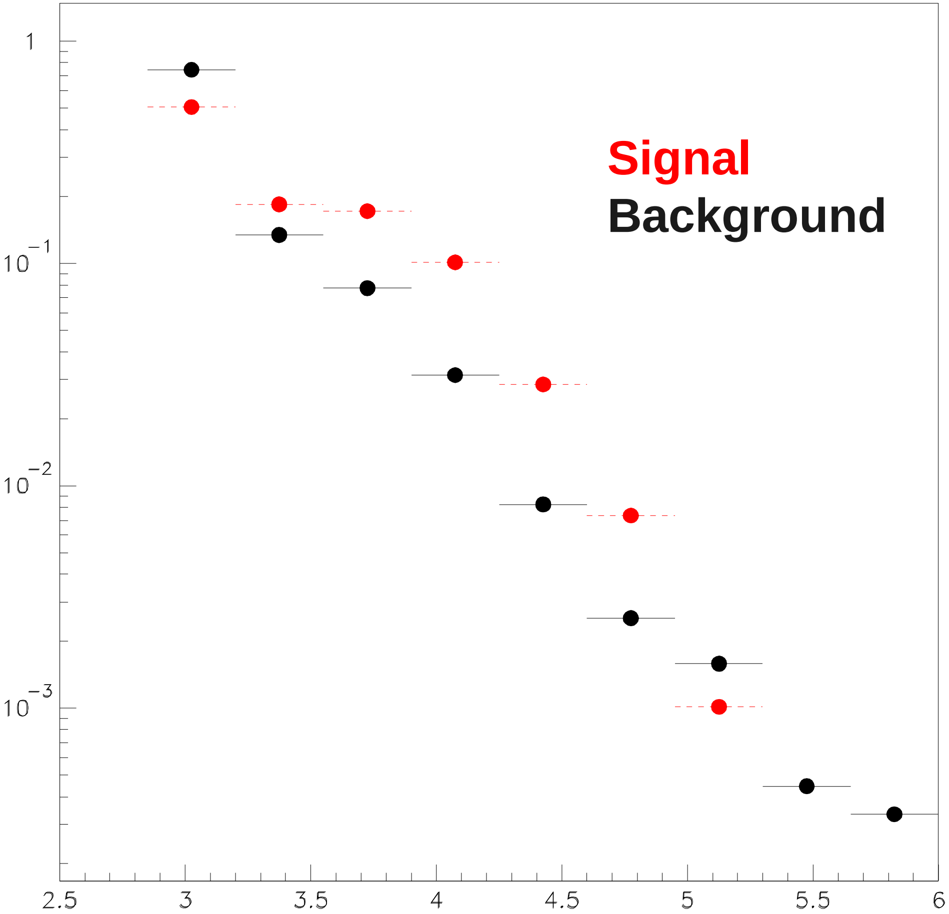
- Event re-weighting taking into account oscillation probabilities for various oscillation parameters and Normal or Invert Hierarchy
- Extraction of the hierarchy (under construction)

# Analysis Tools (point sources)- Unbinned technique

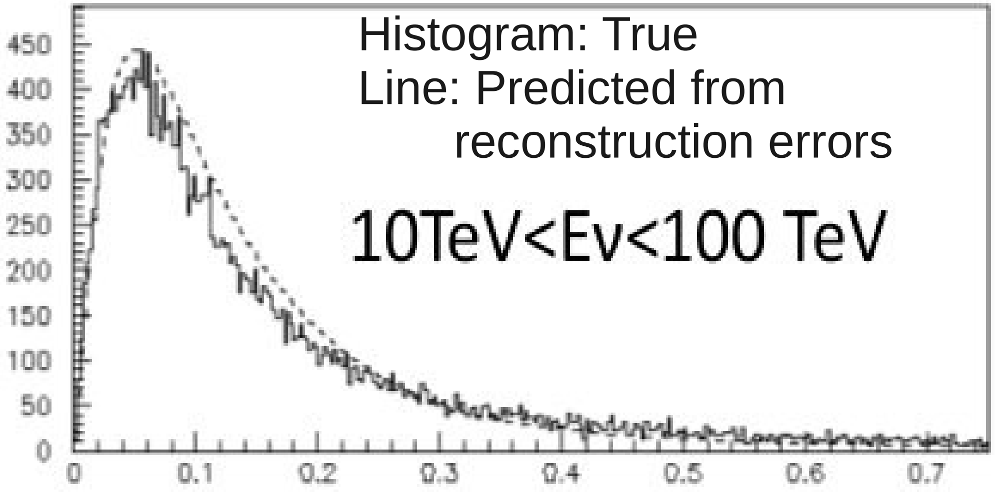
Use of the full experimental information on a track by track basis:

- reconstructed muon energy, and
- track resolution (muon reconstruction parameter errors)

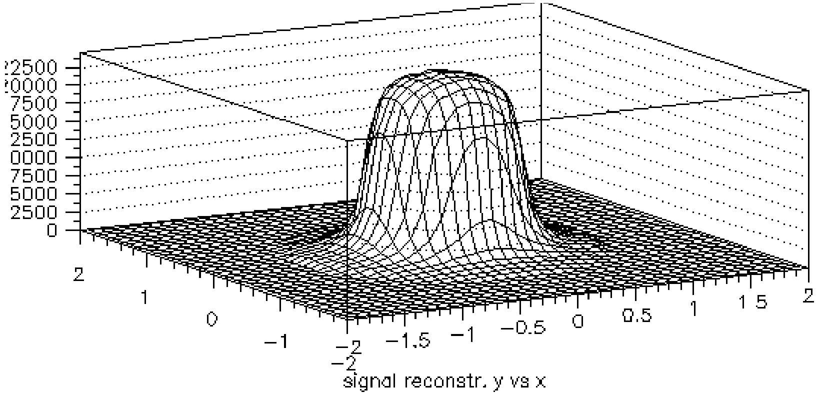
Energy distribution of signal (RXJ1713) and background (atmospheric neutrinos)



Reconstructed Energy (log(E/GeV))



Angle between reconstructed muon track and parent neutrino (Degrees)



# Summary & Outlook

- The HOU Reconstruction & Simulation (HOURS) software package is a complete simulation package of the detector response from the expected neutrino fluxes to the event reconstruction and sensitivity estimation for different neutrino sources.

- HOURS comprises a realistic simulation package of the detector response, including an accurate description of
  - all the relevant physical processes,
  - the production of signal and background
  - several analysis strategies for triggering and pattern recognition
  - event reconstruction, tracking and energy estimation.

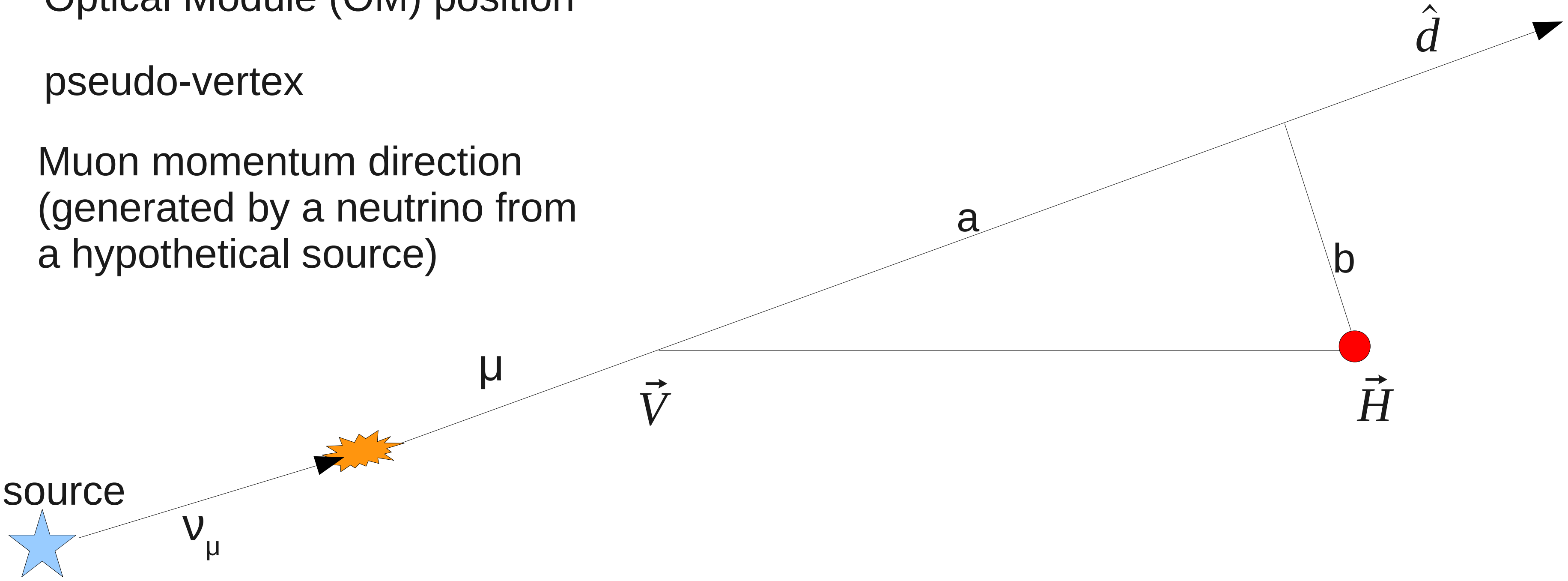
- Further improvements/additions are scheduled

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: “THALIS - HOU - Development and Applications of Novel Instrumentation and Experimental Methods in Astroparticle Physics”

# Backup slides

# 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

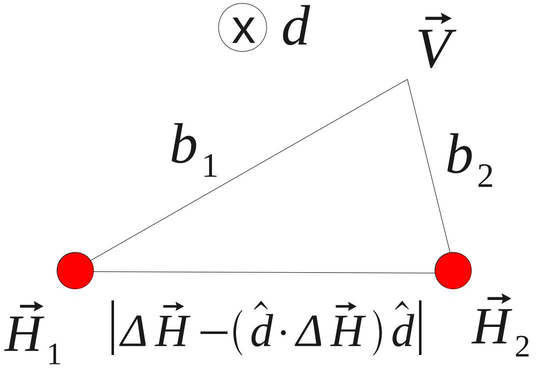
# Background filtering technique using the apriori known neutrino point source
## Causality criterion

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:

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

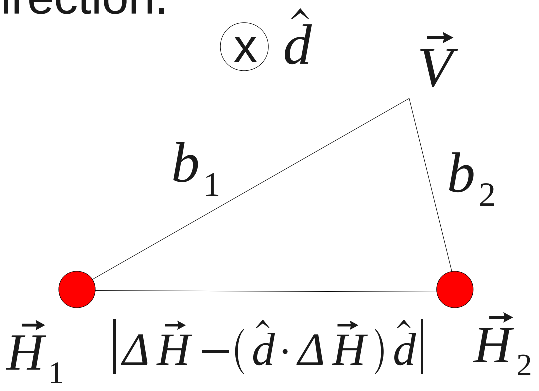
# Background filtering technique using the apriori known neutrino point source
## Causality criterion

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:

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

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

$$|c\Delta t - \hat{d}\cdot\Delta\vec{H}| < tan\theta_c|\Delta\vec{H} - (\hat{d}\cdot\Delta\vec{H})\hat{d}| + ct_s$$

$$t_s = 10\mathrm{ns}$$

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

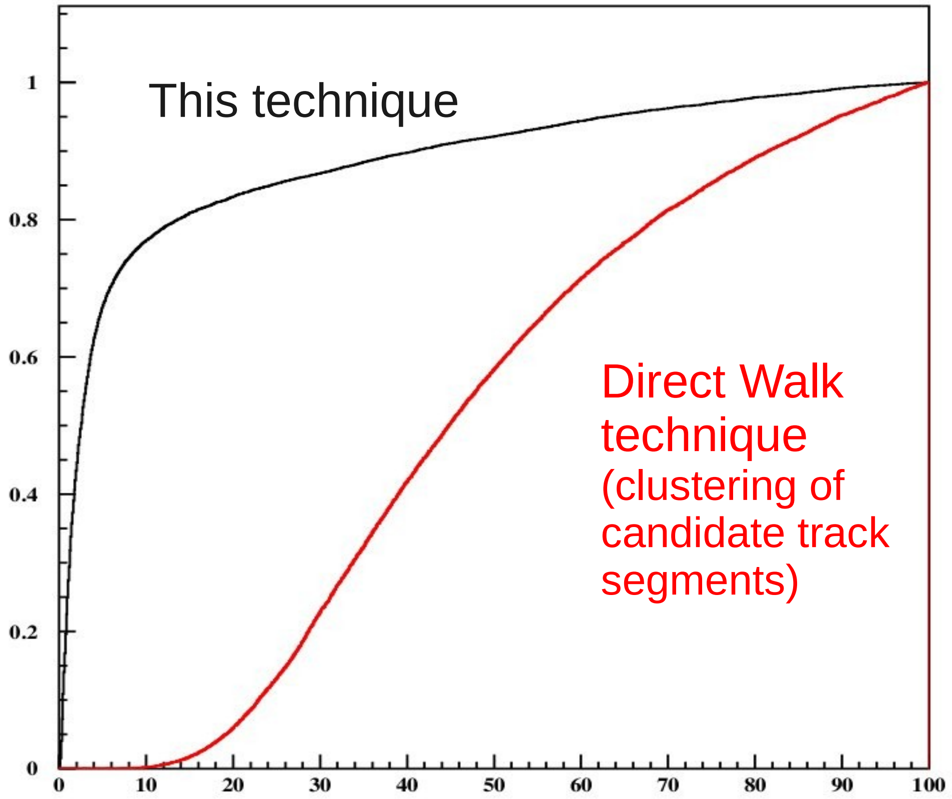
- For every three OMhits (on different OMs) that satisfy the causality criterion a pseudo-vertex can be found analytically.

- 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



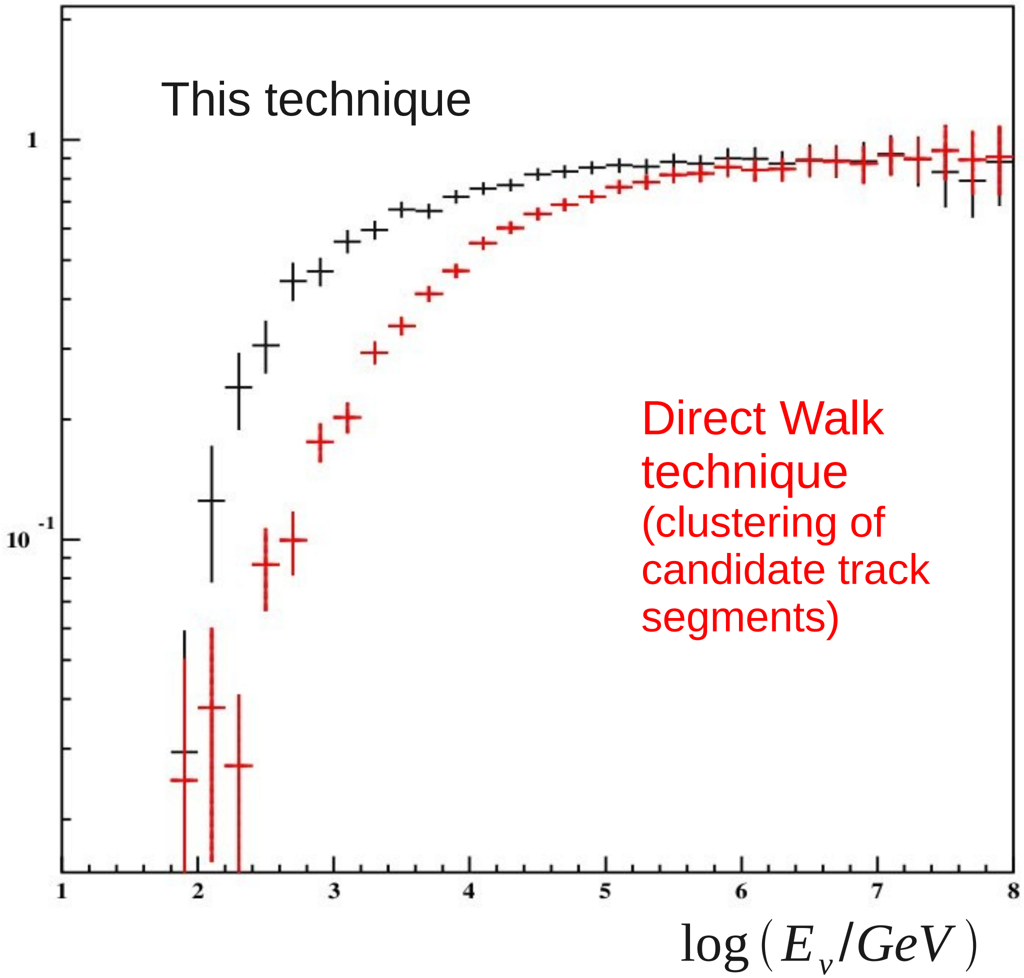
- Combination of $\chi^2$ minimization and Kalman Filter is used to produce many candidate tracks

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

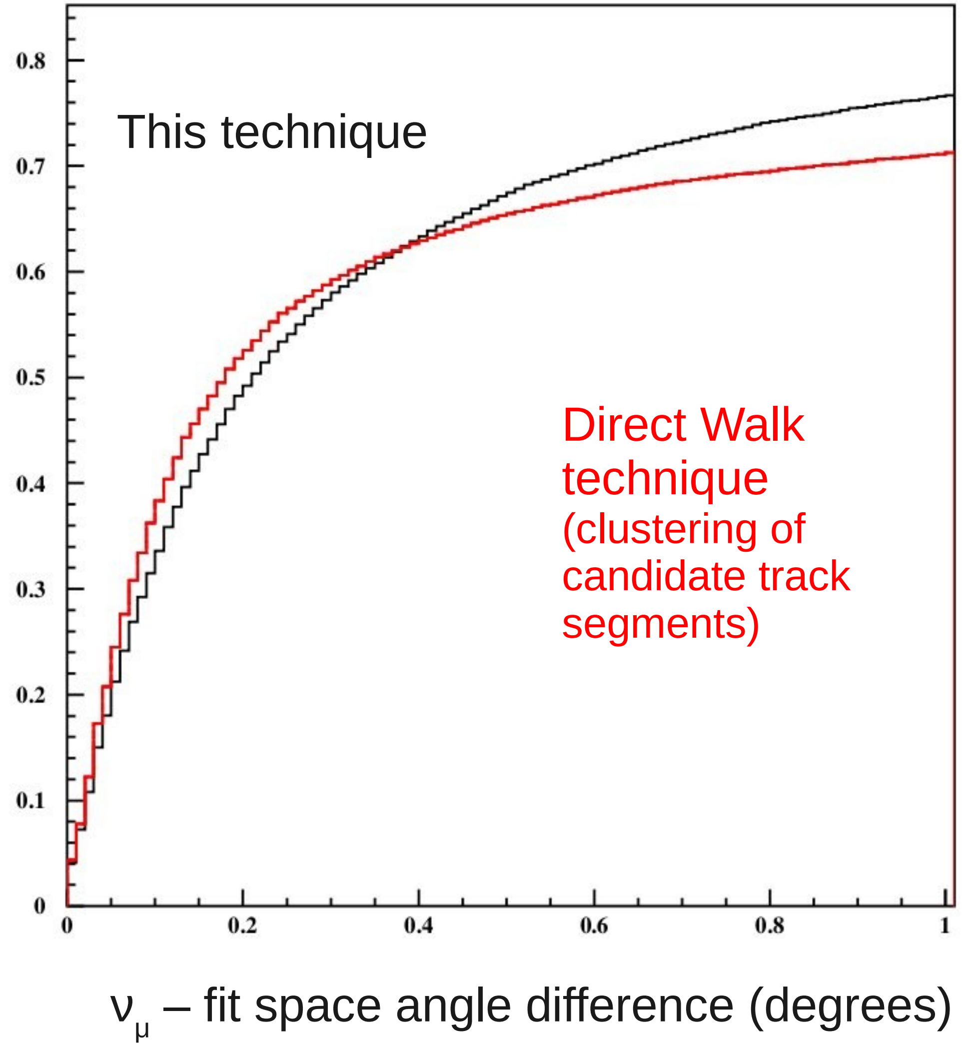
# Prefit and reconstruction technique using the known neutrino direction
# Reconstruction efficiency and angular resolution

- $E^{-2}$ 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

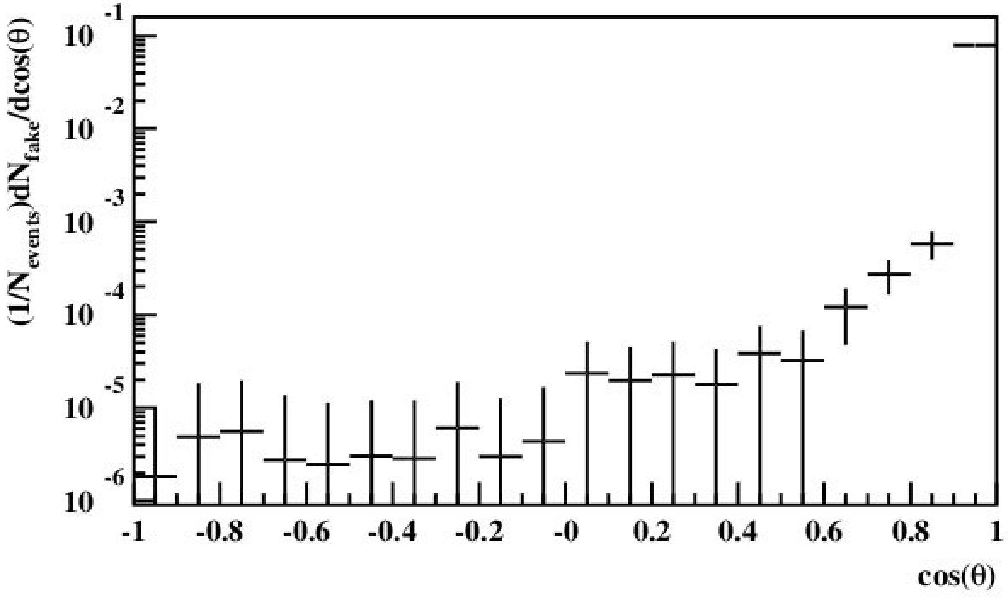


# Reconstruction technique using the known neutrino direction
## Estimation of fake signal

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 is further optimized)

With the application of this technique the required observation time for 5σ discovery of the RXJ1713 galactic source is reduced from 13 years to 9 years (Towers 180m and binned technique)



- 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

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.