# Reconstruction of hadronic cascades in large-scale neutrino telescopes

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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KM3NeT

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- Hadr. cascades accompany all reactions
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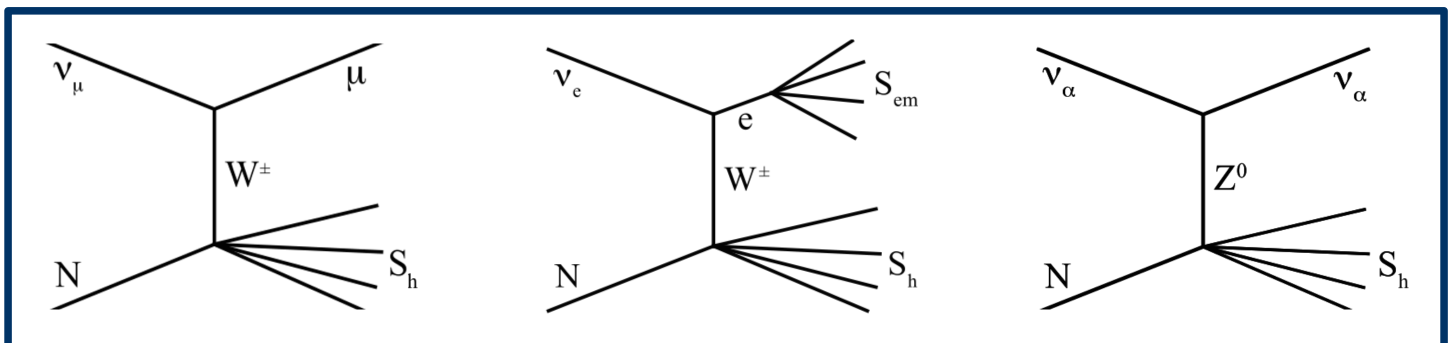

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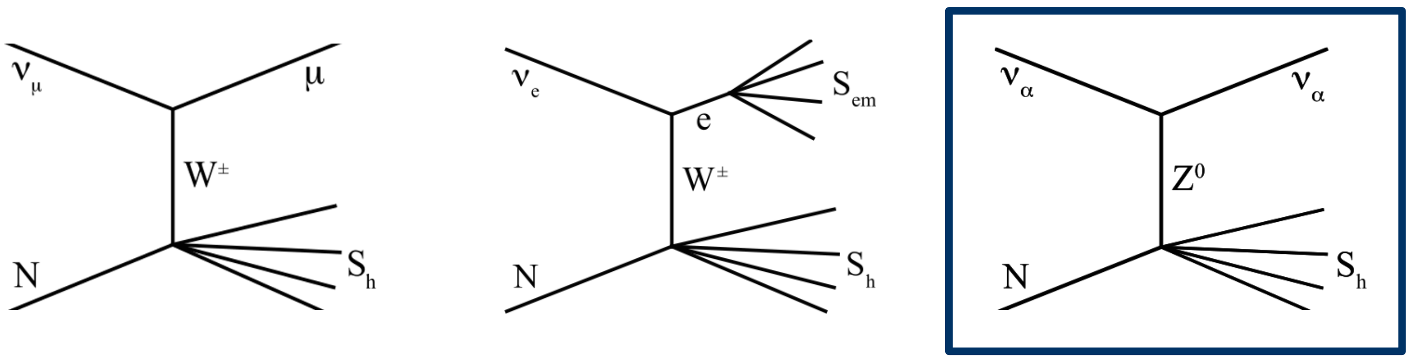




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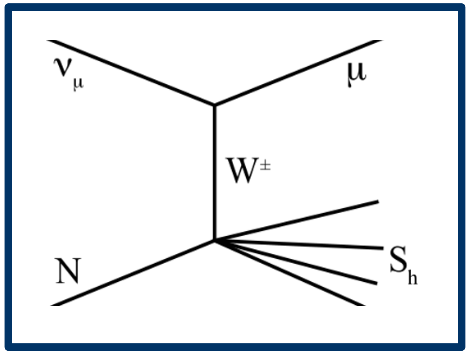


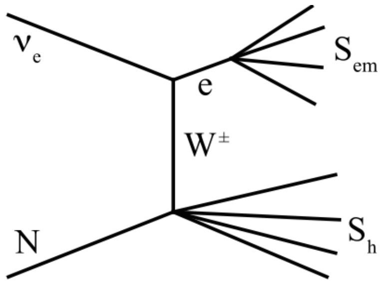


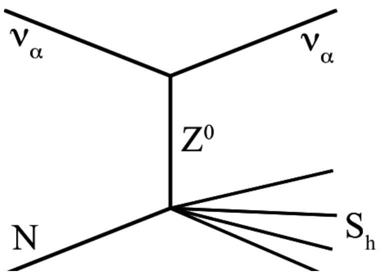

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- quite good enery resolution for showers
  $\longrightarrow$ diffuse flux detection

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- quite good enery resolution for showers
  → diffuse flux detection

Showers can contribute
very valuable information !

# Topology Of Showers (some Aspects)

## Muons
- track-like events
  big lever arm, good angular resolution
- „small“ amplitudes
- big effective volume
- sharp 42° Photon-Cerenkov-emission

## Showers
- „point-like“ events
  „almost contained“, good energy resolution
- „big“ amplitudes
- effective volume ~ Can
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→ mostly time based reconstruction

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- very big fluctuations in Cerenkov-emission

→ time and amplitude based reco possible



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## Shower Reconstruction – Basics

- Very generic strategy
  $\rightarrow$ applicable for all types & sizes of neutrino telescopes with only minor modifications
- Based on Maximum Likelihood Method *(MLH)*
- Amplitude information and timing information used simultaneously
  $\rightarrow$ maximum of event information at each reco step available

# MLH Modelling – Part I

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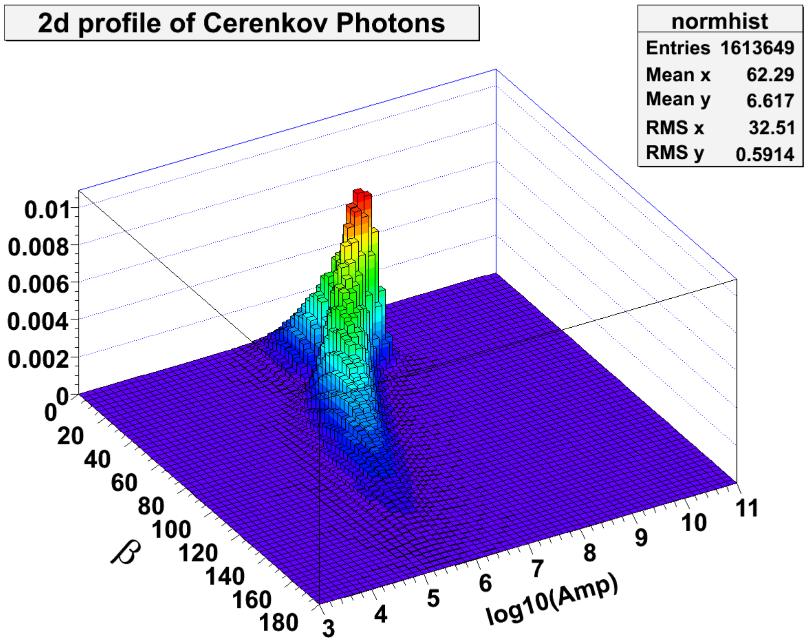
$$P^{A}_{Shower} = \sqrt[\#\mathrm{Hits}]{\prod_{i=1}^{\#\mathrm{Hits}} p^{A}_{i}(\theta(x,y,z),\phi(x,y,z),E)}$$

- find $p^{A}_{i}$

| | | |
|---|---|---|
| $x,y,z$ | : | Vertex in karthesian coordiantes |
| $\phi$ | : | Cascade Enery |
| $\theta$ | : | Zenith angle of cascade axis |
| $E$ | : | Azimuth angle of cascade axis |

# $p_i^A$ From MC Simulations

- GEANT based simulation
- Water@2.5km depth, $10^2$-$10^7$GeV, 50k Event, 0kHz BG




$$\beta = \beta(\theta, \phi) = \arccos(\vec{d}_{Axis} \circ \vec{d}_{PM})$$

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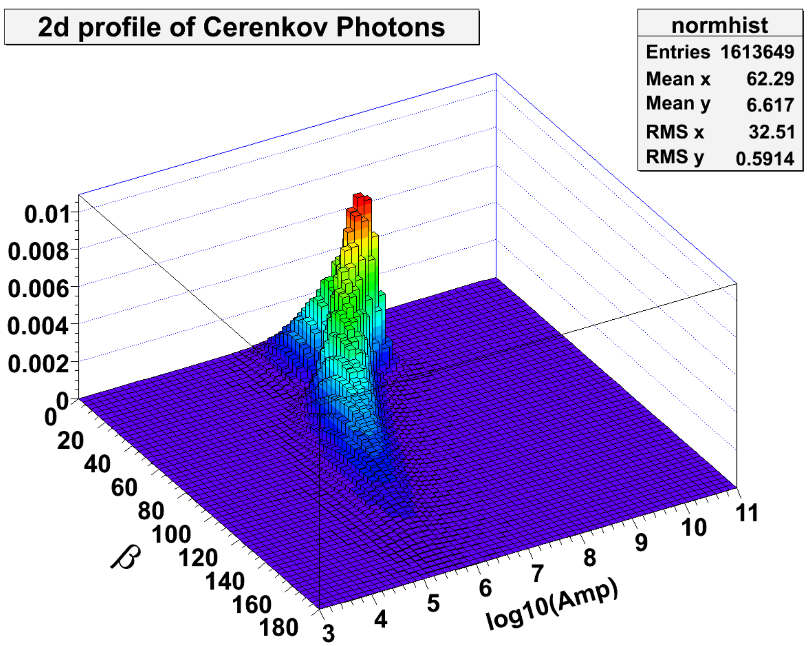


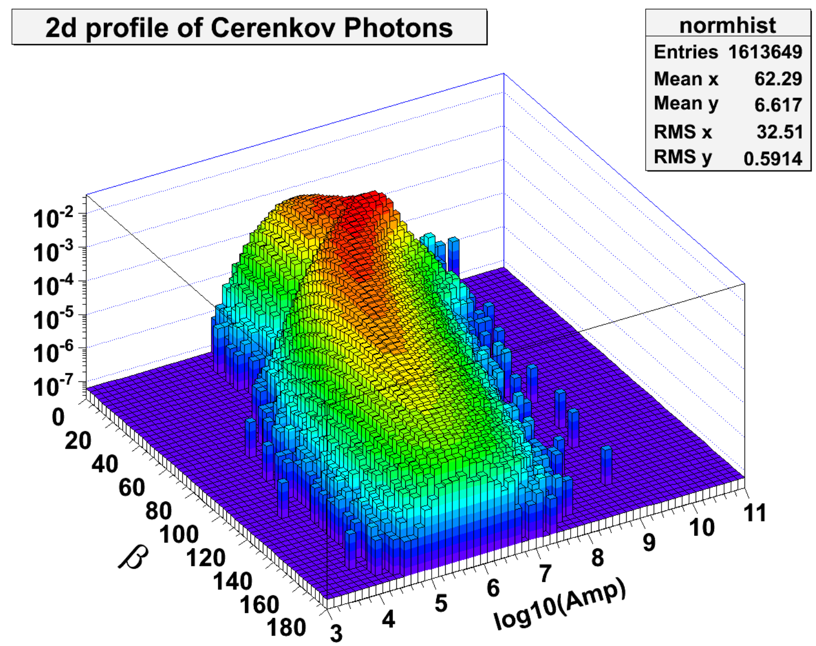


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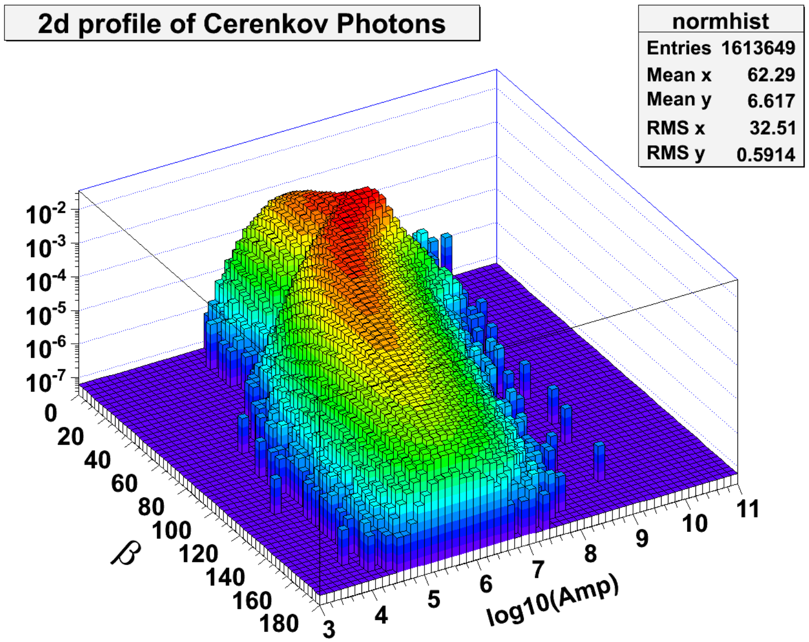
**Very big fluctuations in Cerenkov emission!**

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# MLH Modelling – Part II

$$P^{A}_{Shower} = \sqrt[\#\mathrm{Hits}]{\prod_{i=1}^{\#\mathrm{Hits}} p_i^{A}(\theta(x,y,z),\phi(x,y,z),E)}$$

- find $p_i^{A}$

# MLH Modelling – Part II

$$P_{Shower}^{A} = \sqrt[\#\mathrm{Hits}]{\prod_{i=1}^{\#\mathrm{Hits}} p_i^A(\theta(x,y,z),\phi(x,y,z),E)}$$

- find $p_i^A$

$$P_{Shower}^{T} = \sqrt[\#\mathrm{Hits}]{\prod_{i=1}^{\#\mathrm{Hits}} p_i^T(x,y,z,t_0,E)}$$

- find $p_i^T$

$x,y,z$ : Vertex in karthesian coordiantes

$E$ : Cascade Enery

$t_0$ : Starttime of the event

# $p_i^T$ From MC Simulations

- GEANT based simulation
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- Electronics taken into account!

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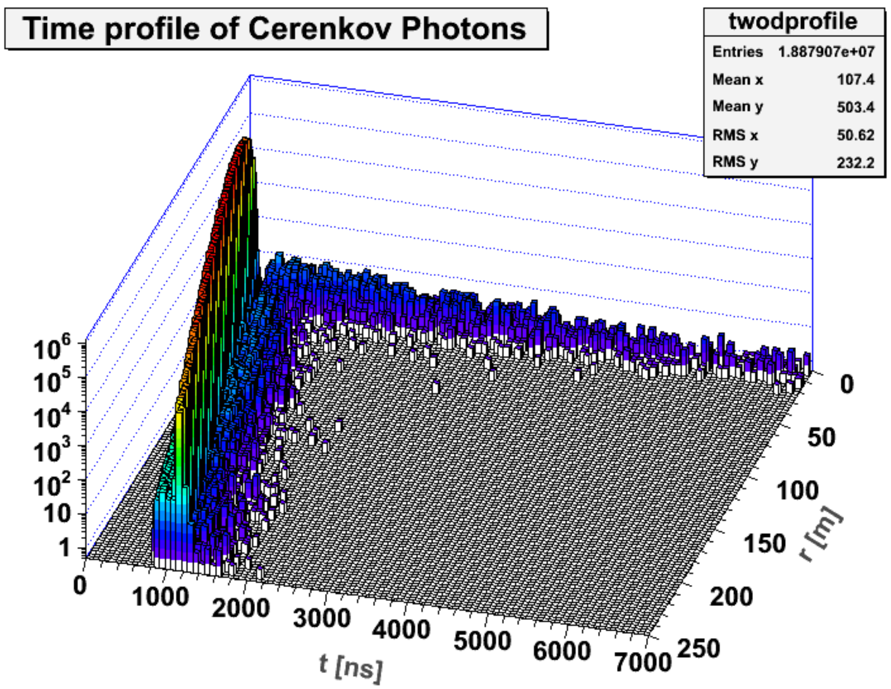

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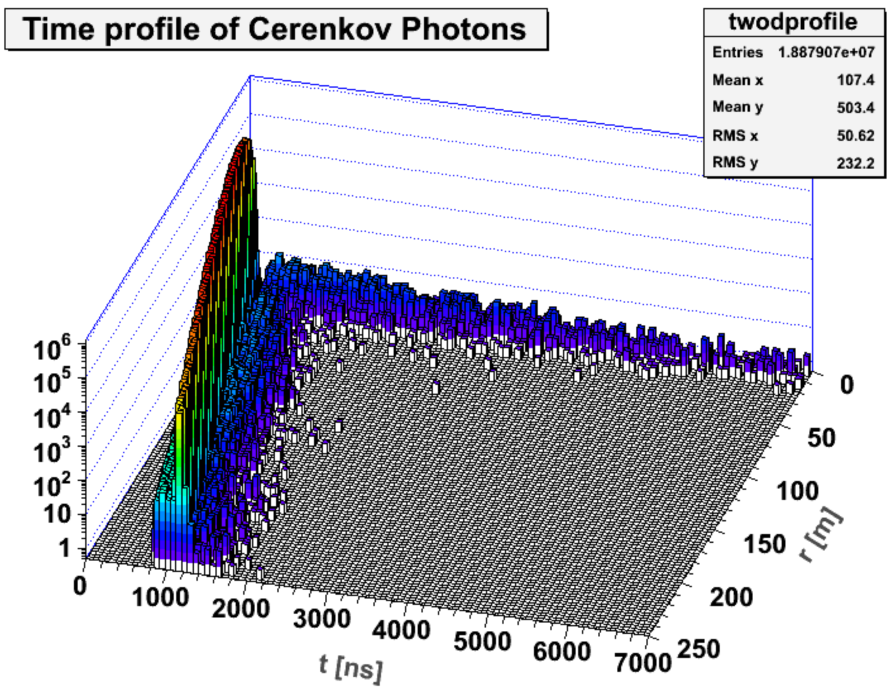


**Arrival time of photons not a linear function!**



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# $p_i^T$ Details: Effect Of RO-Electronics On E.T.A.

d = 70m (~ Att.lenght)

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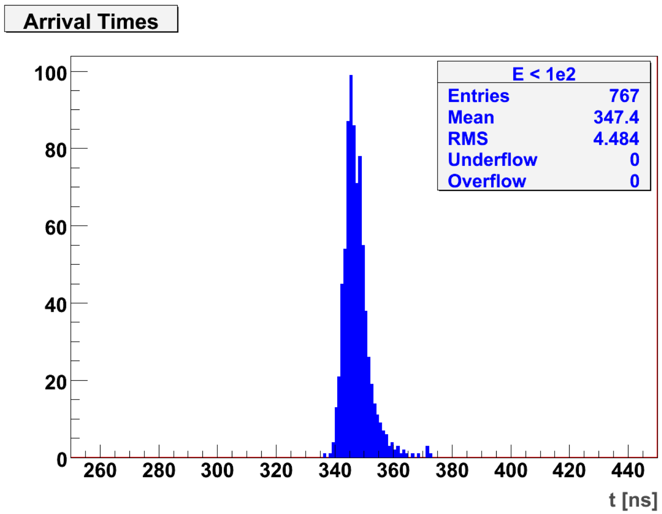


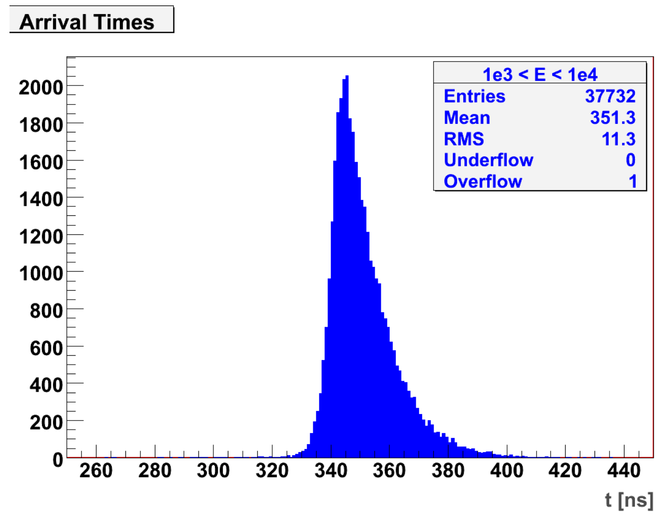


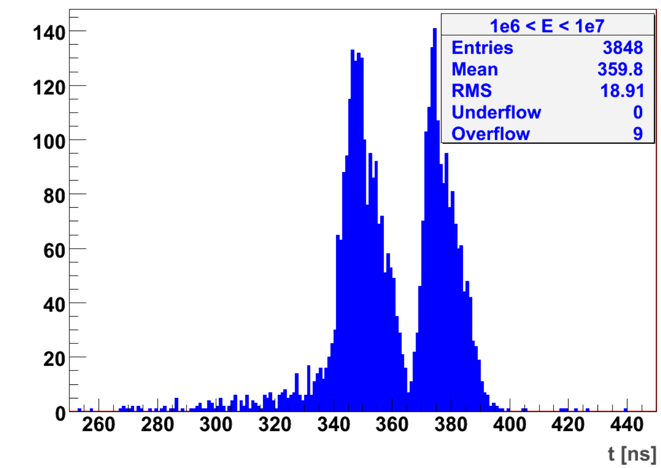


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# MLH Modelling – Part III

$$P^{A}_{Shower} = \sqrt[\#\mathrm{Hits}]{\prod_{i=1}^{\#\mathrm{Hits}} p_i^{A}(\theta(x,y,z),\phi(x,y,z),E)}$$

- find $p_i^A$

$$P^{T}_{Shower} = \sqrt[\#\mathrm{Hits}]{\prod_{i=1}^{\#\mathrm{Hits}} p_i^{T}(x,y,z,t_0,E)}$$

- find $p_i^T$

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- find $p_i^T$

$$P_{Shower} = \left[ P^A_{Shower} \cdot (P^T_{Shower})^W \right] =$$

$$= \sqrt[\#]{\prod_{i=1}^{\#\mathrm{Hits}} p_i^A(\theta(x,y,z),\phi(x,y,z),E)} \cdot \left( \sqrt[\#]{\prod_{i=1}^{\#\mathrm{Hits}} p_i^T(x,y,z,t_0,E)} \right)^W$$

- One free parameter: weight $W$ (== 1)

# MLH Modelling – Part IV

- Switching to Log-Likelihood representation:

$$P_{Shower} \rightarrow P'_{Shower} = -\ln\left(P_{Shower}\right) = -\ln\left[P_{Sh}^{A} \cdot \left(P_{Sh}^{T}\right)^{W}\right]$$

$$P'_{Shower} = -\frac{1}{\#\mathrm{Hits}} \cdot \left[\sum_{i=1}^{\#\mathrm{Hits}} \ln\left(p_i^A(\theta(x,y,z),\phi(x,y,z),E)\right) + \right.$$
$$\left. + W \cdot \sum_{i=1}^{\#\mathrm{Hits}} \ln\left(p_i^T(x,y,z,t_0,E)\right)\right]$$

$\rightarrow$ 7 dimensional minimization problem!

# Minimization Technique – Overview

- 7 dimensional phase space:
  - $x,y,z$ : depending on detector size & geo
  - $t_0$ : depending on DAQ parameters
  - $\theta,\varphi$ : usually fixed ( $0..\pi$, $0..2\pi$ )
  - $E$ : go for the max!

- Very complex structure of LLH function with lots of local minima !
- A good Minimization algorithm is needed ! (Also: lot of computing power...)

# Minimization Technique – Details

- Using sophisticated algorithm:
  „Simulated Annealing“ :
  - combines random-walk ideas with thermodynamic processes („cooling“)
    - Defining Boltzman-Factors, etc.
  - many clever enhancements
    - ensure convergence
    - make algorithm very robust w.r.t. starting values, etc.
    - capable of „strange“ boundary conditions
    - escaping local minima

# Reference Detector

Using ANTARES detector layout:

- Mediterranean sea @ 2400 m depth
- 12 Strings, ~60m horizontal spacing
- 75 Storeys per String, 14.5m vertical spacing
- 3 10“ Hamamatsu PMTs per Storey,
  looking downwards 45° w.r.t. to horizontal
- total of 900 PMTs
- ~200m x 200m x 300m = 0.01km$^3$ i. volume
- Simulation of ANTARES readout electronics
  2ARS/PMT, 25ns integration gate, 250ns
  deadtime

# Reference Event Sample & Constraints

- Using GEANT based event simulation:
  - isotropic ($4\pi$ ) flux
  - 10GeV < E < 10 PeV Energy range
    ($E^{-1}$ spectrum to get more (U)HE events)
  - 120kHz Background (white noise)
  - Events generated within the Can
    (instumented Volume + 1 atten. lenght)

- Reco conditions:
  - only hits ≥ 3*npe* taken into account
  - „Trigger“ constraints:
    5 Hits, 5 OMs, 3 Storeys, 3 Strings



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# Preliminary Results – Part I

„What-goes-in-
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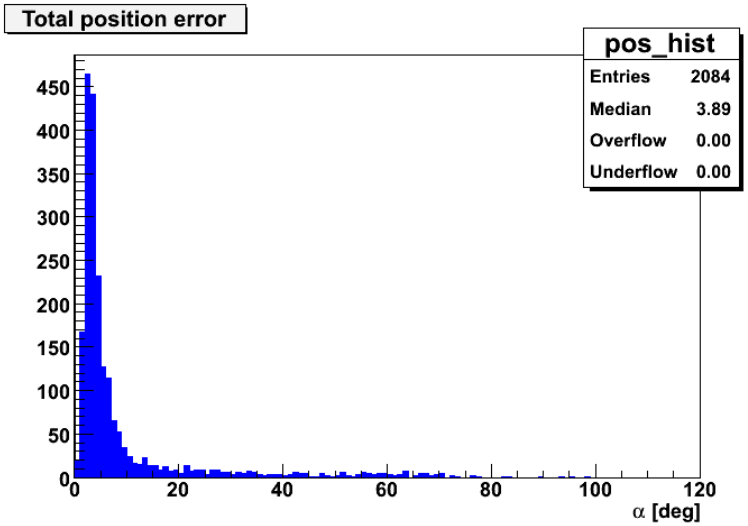


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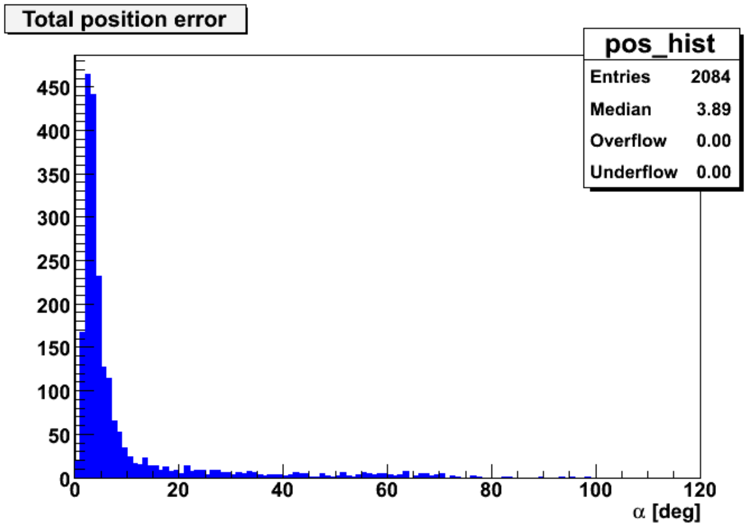


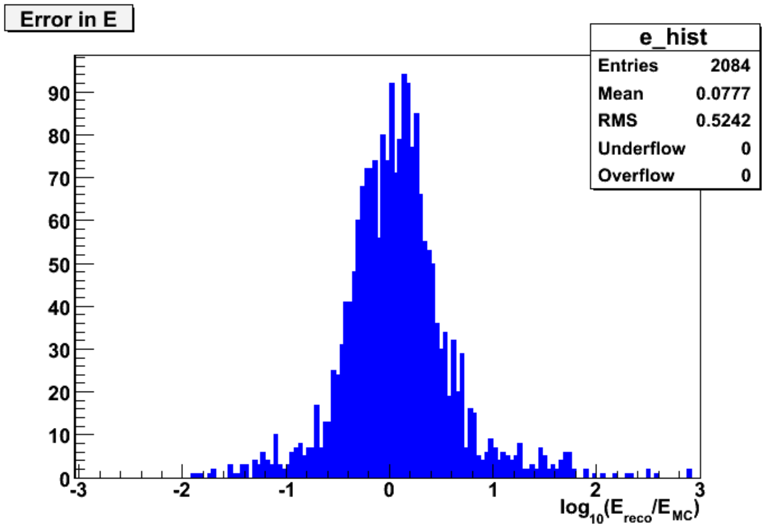


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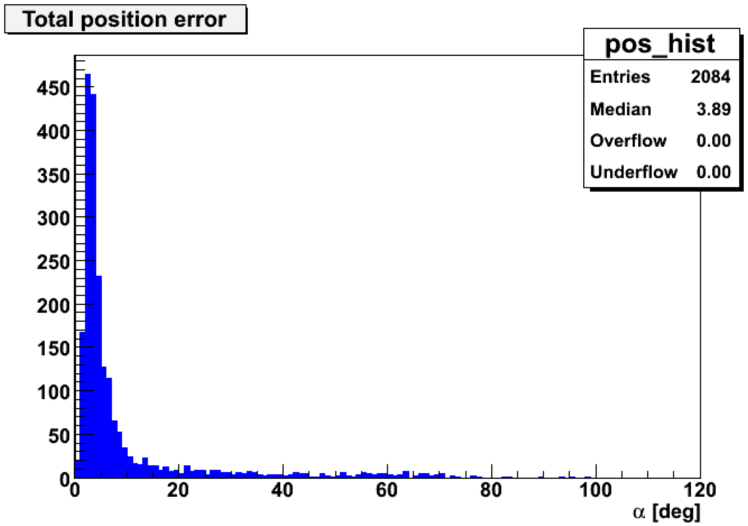


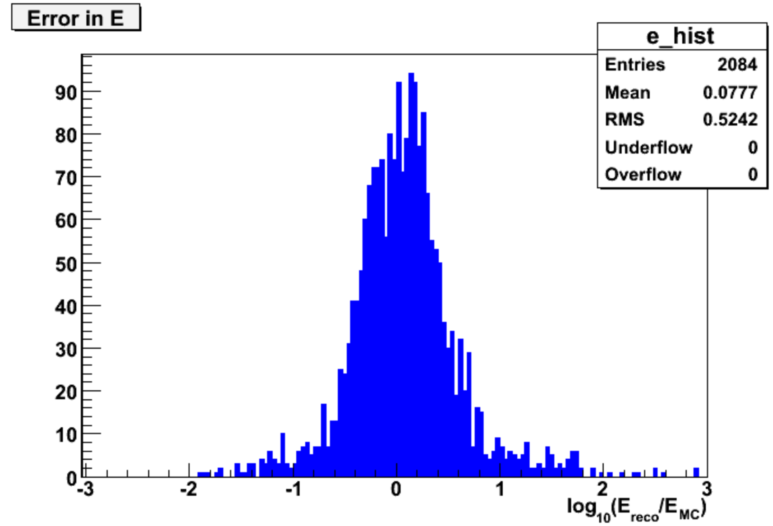


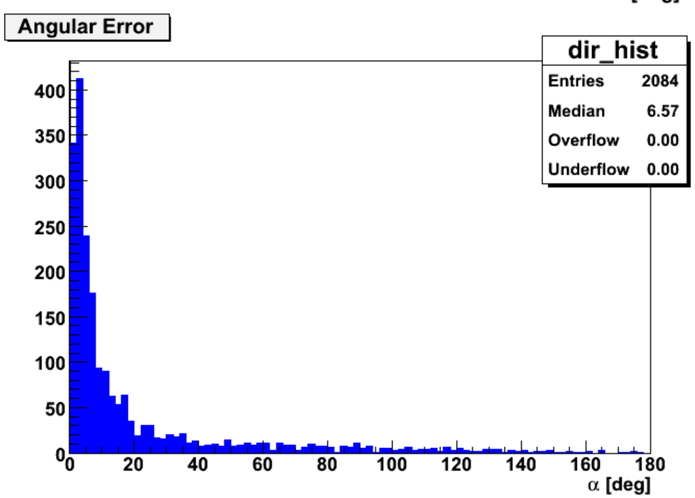


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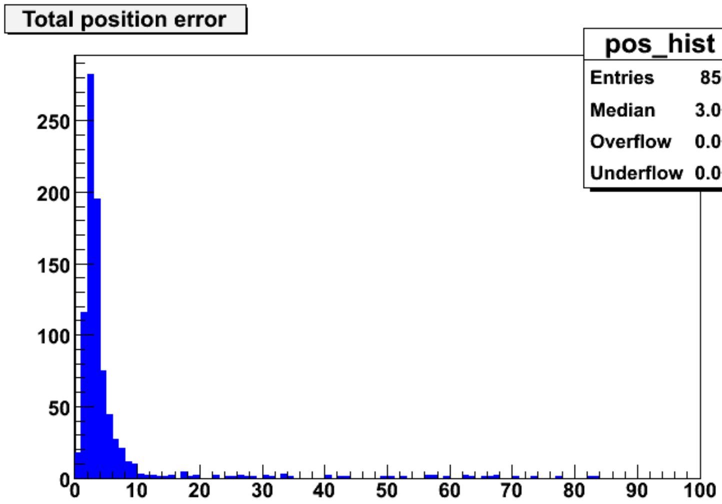


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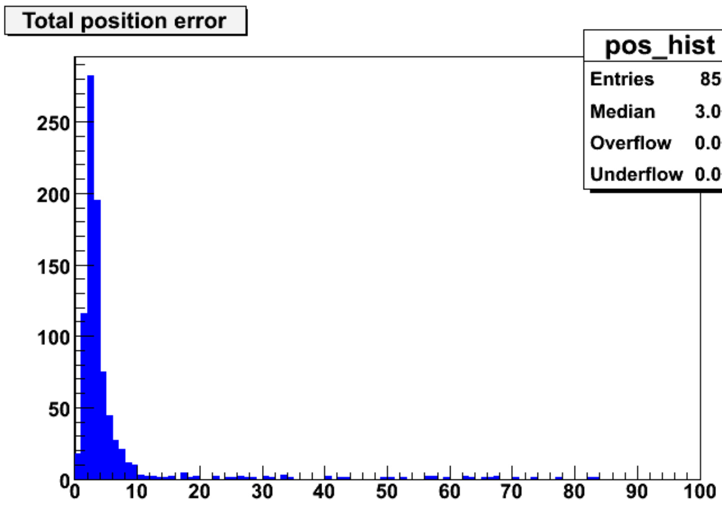


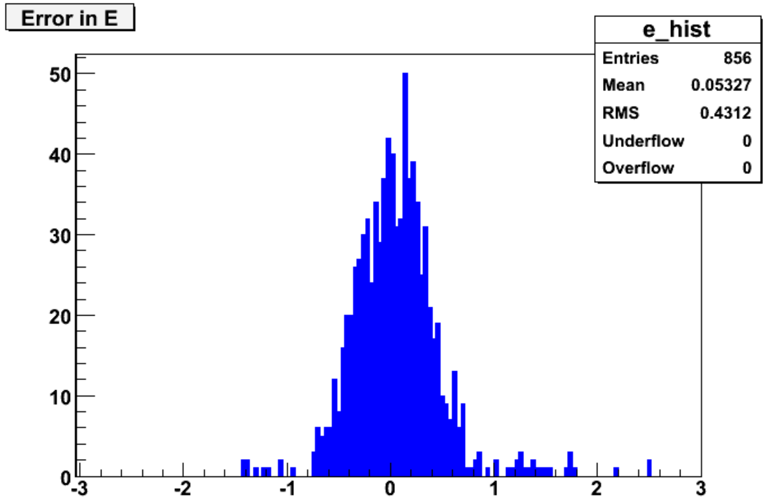


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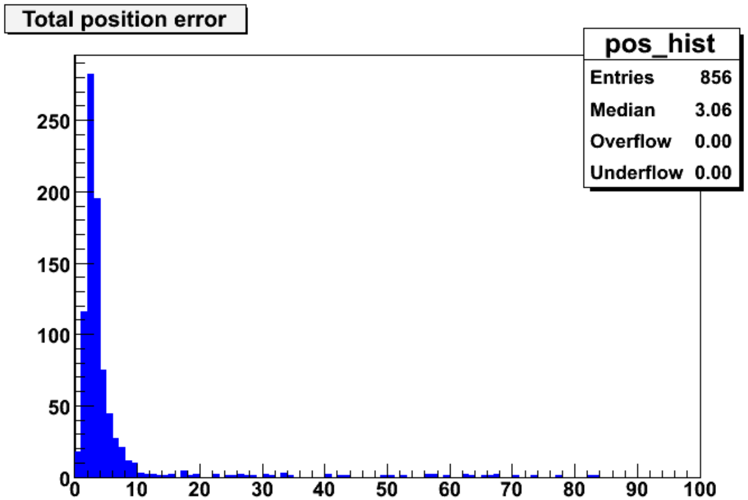


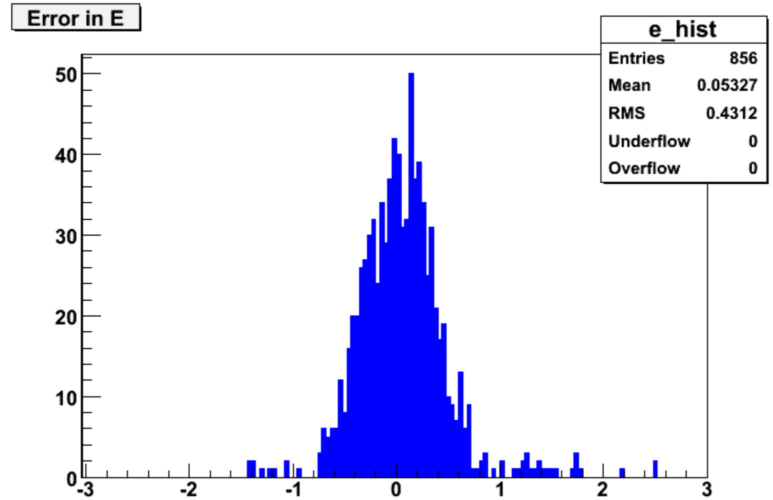


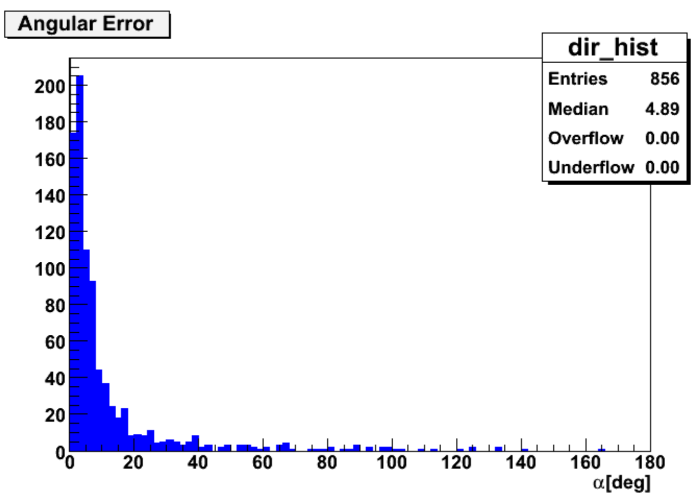


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# Conclusions & Outlook

- Showers are worth looking at, for they really do improve all physics studies!
- Very generic reconstruction algorithm has been developed
- Preliminary results look very promising on MonteCarlo studies

- Detailed MonteCarlo studies for $km^3$ sized detector are going on right now
- Analysis of „real“ ANTARES data is about to start! *

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