Muon Energy Reconstruction in the ANTARES Detector

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Jutta Schnabel
VLVnT 2011,
Erlangen, Germany
12th October 2011

Friedrich-Alexander-Universität Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

ANTARES

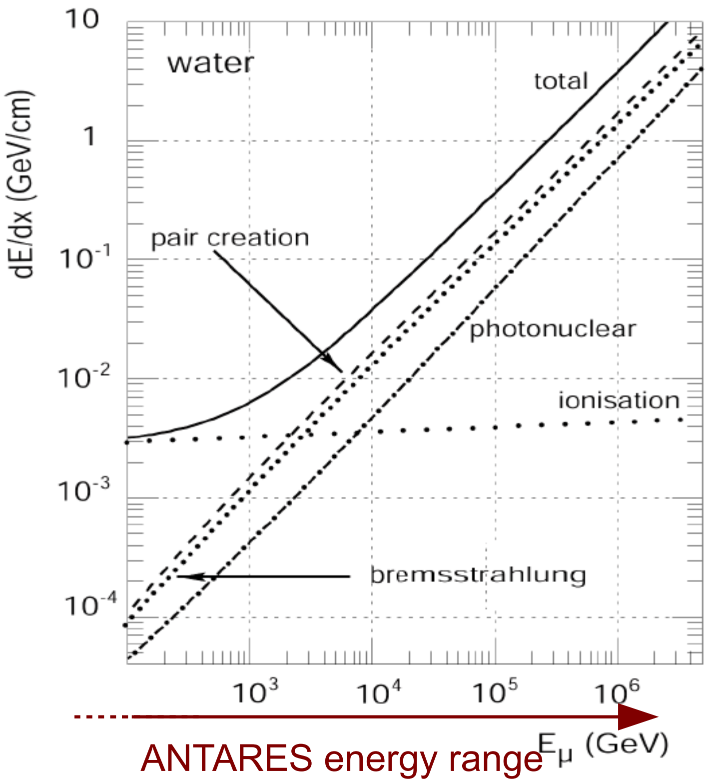
Task and Tools

What there is

$$-dE/dx = a(E) + b(E)E$$

Muon energy loss

- is highly stochastic,
- consists of almost constant ionization loss a(*E*)
- and energy dependent radiative losses b(*E*)*E,* dominant above 1 TeV.



What we have

Muon energy is correlated to

- number of photons emitted per unit length,
- total charge measured by the detector,
- distribution of photons in the detector
- time residuals of photons

$$E(A, N, x, t)$$

The four ways towards energy

Challenge in ANTARES:
Hit selection is needed to suppress K40 and bioluminescence background
(eg. using all hits within a certain distance and time residual relative to the track)

For ANTARES four different energy reconstruction methods exist,
using various features of the muon energy loss processes,
applying different statistical methods,
reaching different levels of complexity.

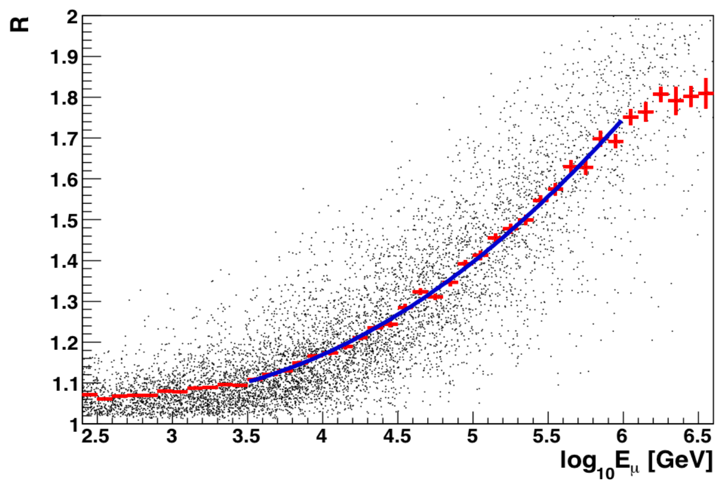
R-Estimator	dE/dx	ANN	Max. Likelihood
parameter fitting		PDF modelling	
hit counting	charge estimate	machine based	analytical
N, t	*A*	*A, N, x, t*	*A, N, x, t*

Using Timing Information: the R-Estimator

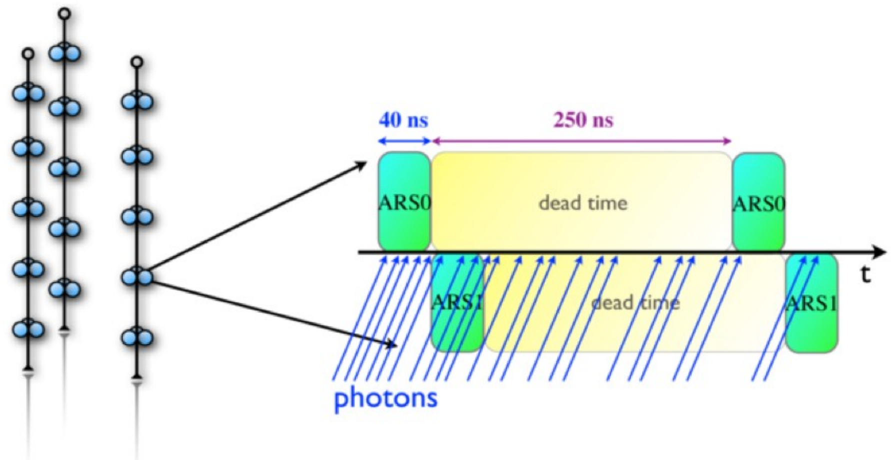
$$E(A, N, x, t)$$

R = number of hit repetitions per OM

- within 100m from the track
- with time residuals < 500ns



Parameter correlated to arrival time and Number of hits,
used for polynomial fit on MC to find *E(R)*



- specialized to E > 10 TeV
- used for Diffuse Flux analysis (Phys.Lett.B696:16-22,2011)

Using Charge Deposition: dE/dx estimator

$$E(A, N, x, t)$$

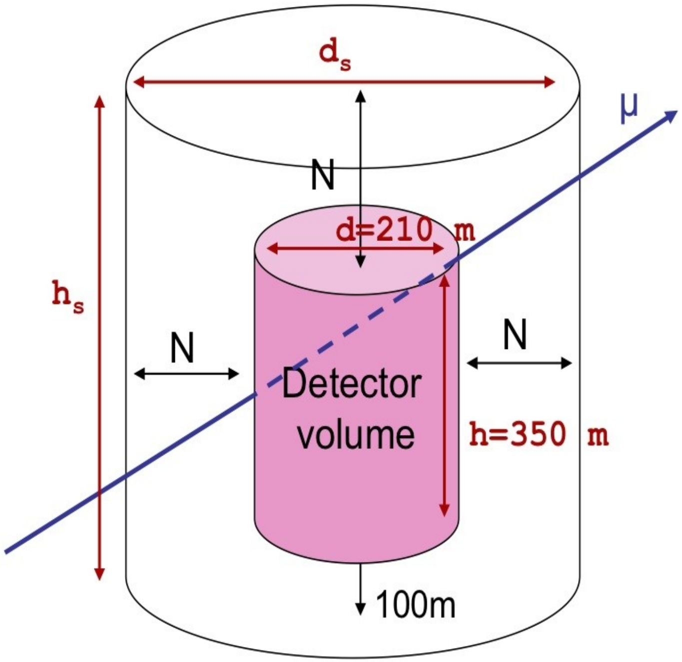
Estimate energy loss from total charge A

$$\left\langle \frac{dE}{dx} \right\rangle \approx \rho = \frac{1}{L_{Det}} \frac{\sum A}{p_{acc}}$$

Weighted by

L_{Det} track length in sensitive volume

p_{acc} total detector acceptance



E(ρ) derived from fit on MC

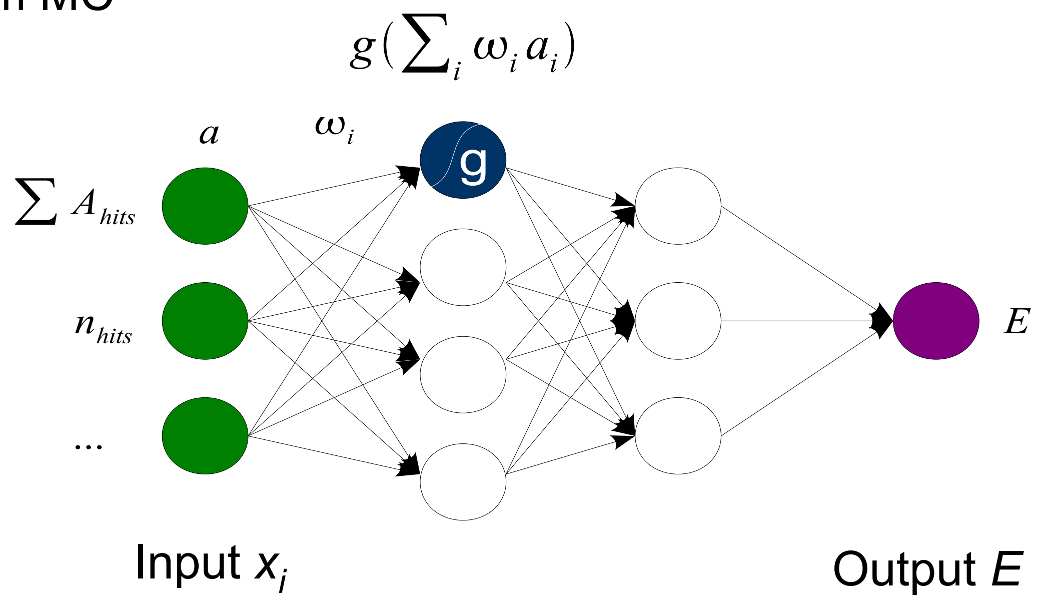
Use it all: Artificial Neural Nets (ANNs)

$$E(A, N, x, t)$$

PDF modelling by machine learning

- 56 parameters x_i describe location, charge and time of hits and track
- preprocessing performed to distinguish independent features
- training sets of (x_i , E) derived from MC

- Modelling of PDF by applying learning algorithm to ANN (adjusting connection weights for error minimization on training set)



Alternative: Maximum Likelihood method

$E(A, N, x, t)$

Likelihood of energy from analytical PDF

$$L_{Det}(E) = \prod_{i}^{N_{OM}} P_i(E)$$

For each hit OM, the probability of seeing a given amplitude is multiplied

$$P(A;\langle n\rangle) = \sum_{n=1}^{n_{max}} P_p(n;\langle n\rangle) P_g(A;n)$$

$P_p(n;\langle n\rangle)$ Poissonian probability to measure *n* photons if average is <*n*>

$P_g(A;n)$ Gaussian probability of *n* photons to produce amplitude *A*

For each OM without hit, the probability to see nothing is used

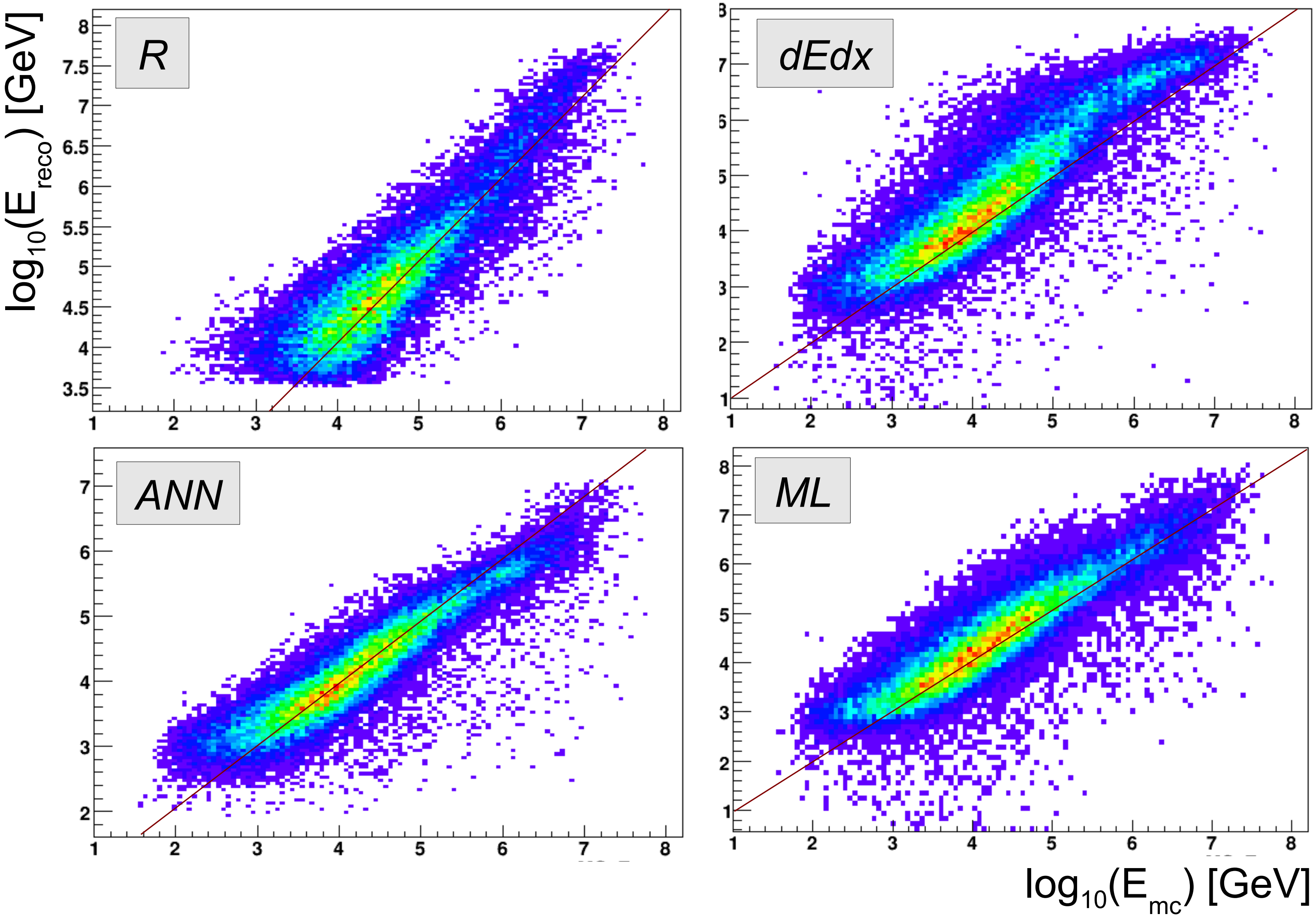
$$P(0,\langle npe\rangle) = e^{-\langle n\rangle} + P_{threshold}(\langle n\rangle)$$

$P_{threshold}(\langle n\rangle)$ Probability to have a photon below the PMT threshold

The energy is derived from minimizing $-\log(L_{Det}(E))$ using $\langle n\rangle(E)$ of the PDF.

Overall performance

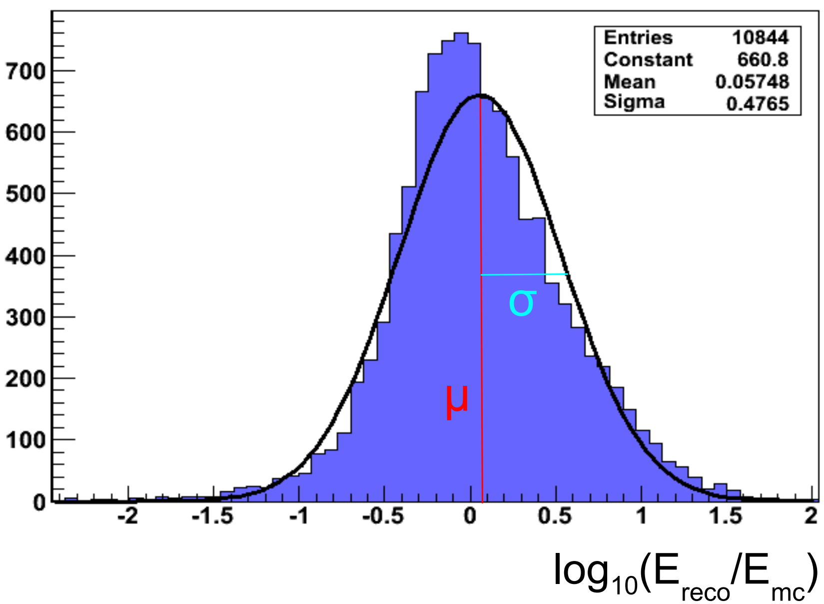
MC, upgoing neutrinos, Aafit track, $E^{-1.4}$

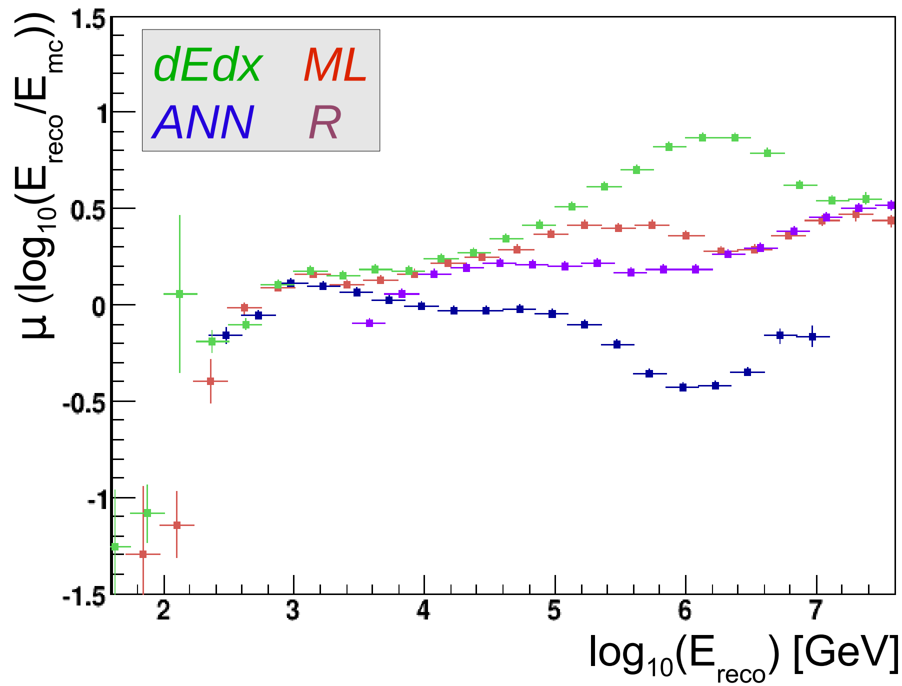


Quantifying reconstruction errors

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

If reconstruction yields E_{reco}, what do I know about the true energy?



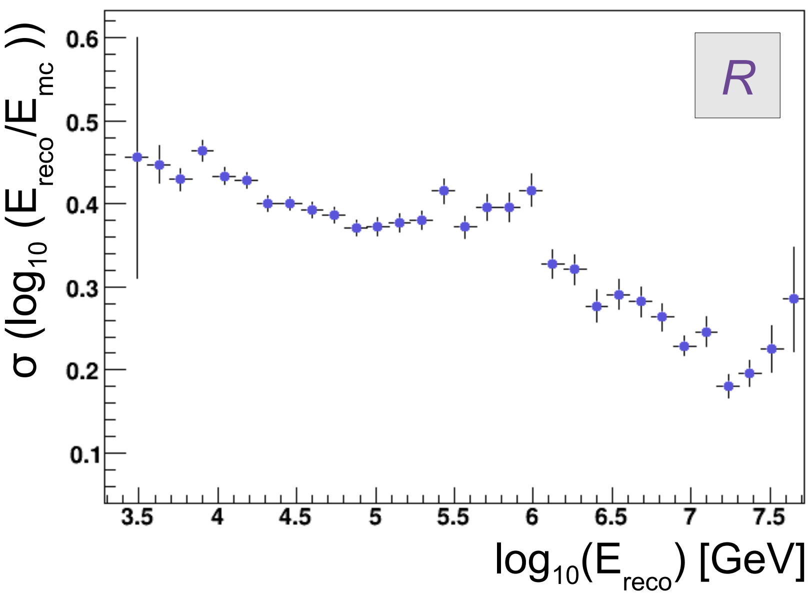


Resolution is measured by a Gaussian fit of $\log_{10}(E_{reco}) - \log_{10}(E_{mc})$ in bins over reconstructed or MC energy axis.

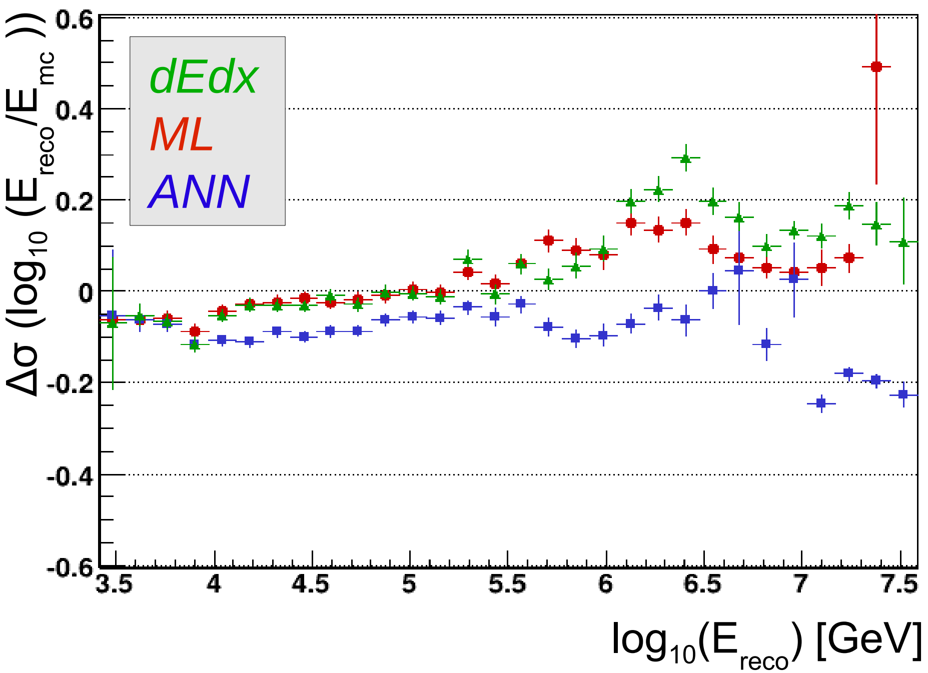
Performance on neutrino induced muons

R-Estimator has already been used for diffuse flux analysis

- taken as reference for newer methods



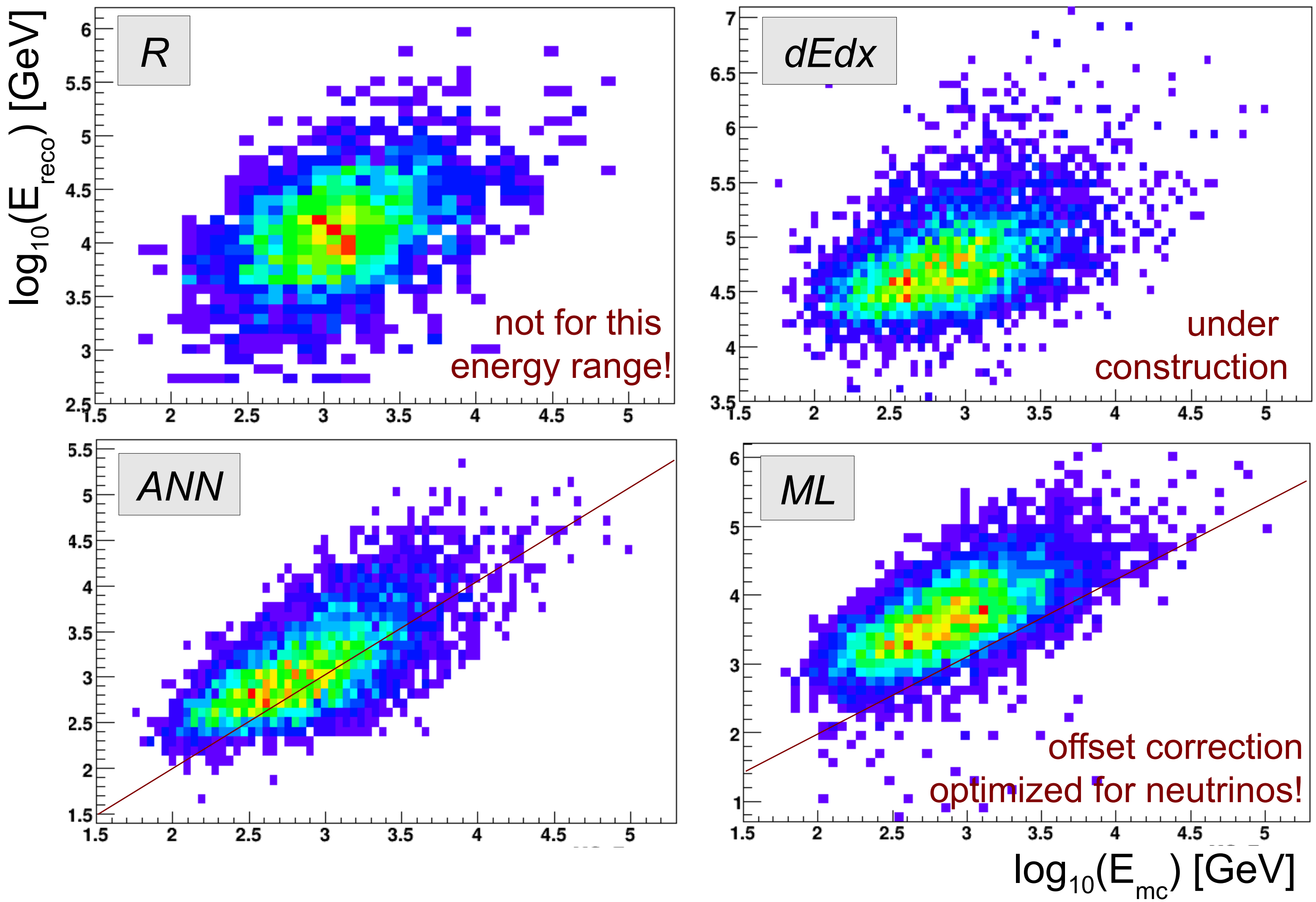
$$\Delta\sigma = \log_{10}(E_{reco}/E_{MC})_{method} - \log_{10}(E_{reco}/E_{MC})_R$$



Good resolution of factor 2 can be reached above 10 TeV

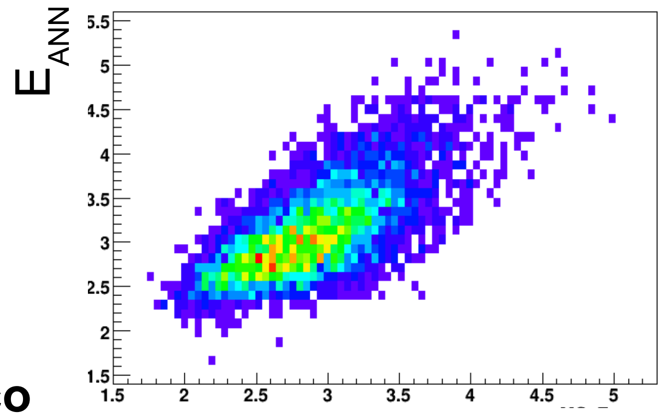
Applying estimators on atmospheric muon

MC, atmospheric muons, MC track



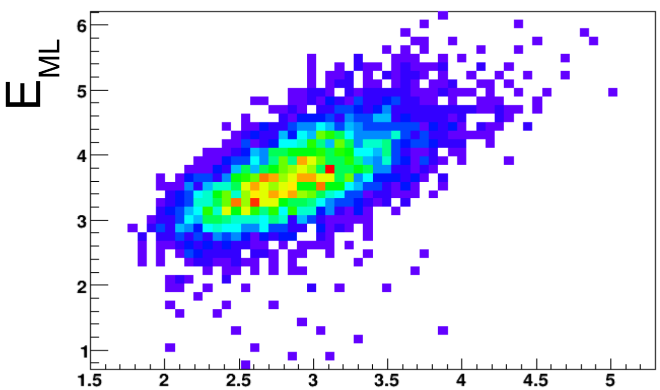
Correlation between reconstruction errors?

MC track



cov(Eann,Emc) = 0.10 E_{MC}

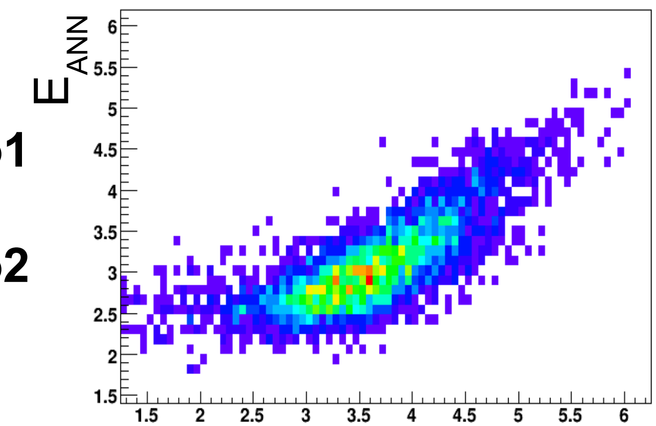
Ereco vs Etrue



cov(Eml,Emc) = 0.081 E_{MC}

Reconstructed track

Ereco1 vs Ereco2



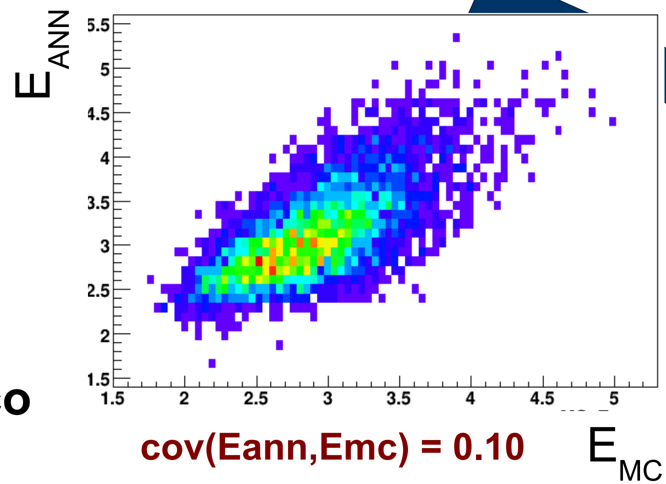
cov(Eann,Emc) = 0.117 E_{ML}

Correlation between reconstruction errors?

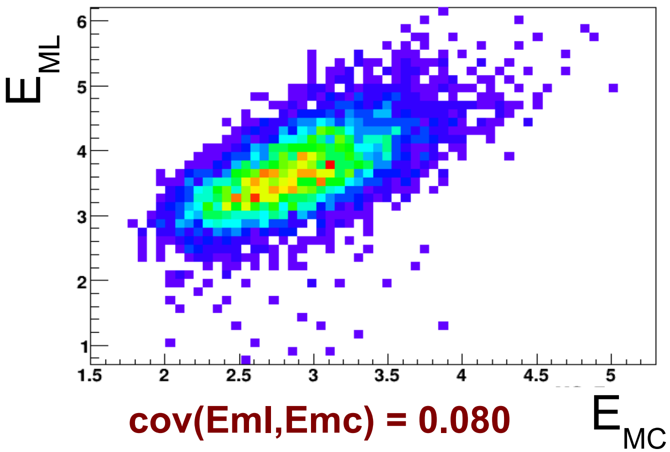
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

MC track

Ereco vs Etrue



cov(Eann,Emc) = 0.10

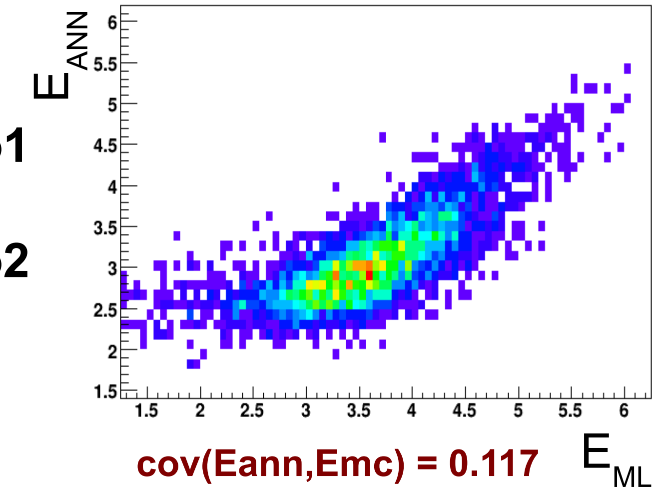


cov(Eml,Emc) = 0.080

Track reconstruction errors similarly effect both methods

Reconstructed track

Ereco1 vs Ereco2



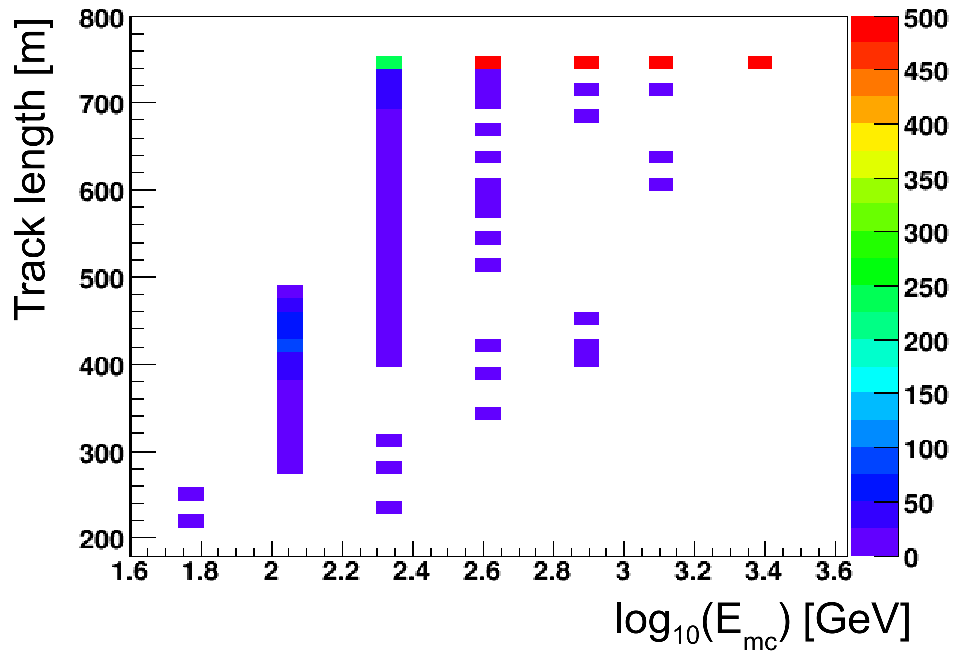
cov(Eann,Emc) = 0.117

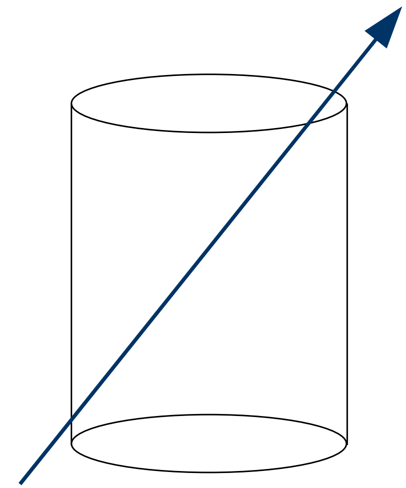
+ Some stochastic effect due to energy loss characteristics?

Estimating effect of energy loss fluctuations

Idea: - Simulate the same track with the same energy repeatedly
- Scan detector using various tracks and different energies
- (reconstruct events)

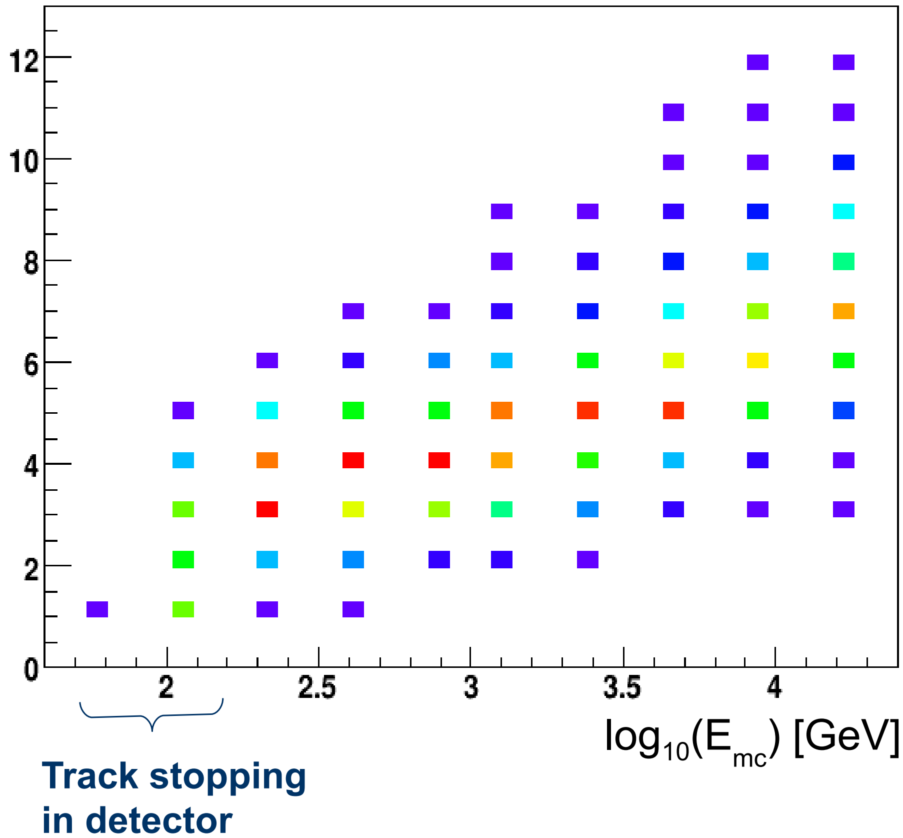
Example: Zenith = 130º, through detector center,
Energy = 63 GeV – 15 TeV (at simulation can),
500 repetitions



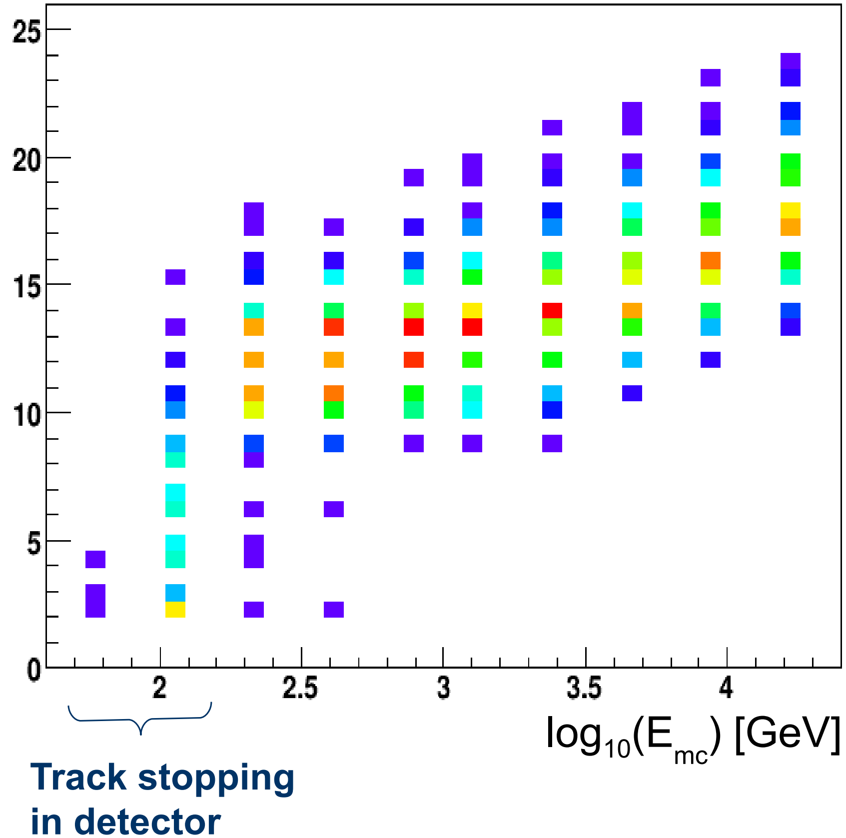


Detection units with photons from track

Number of lines with hits

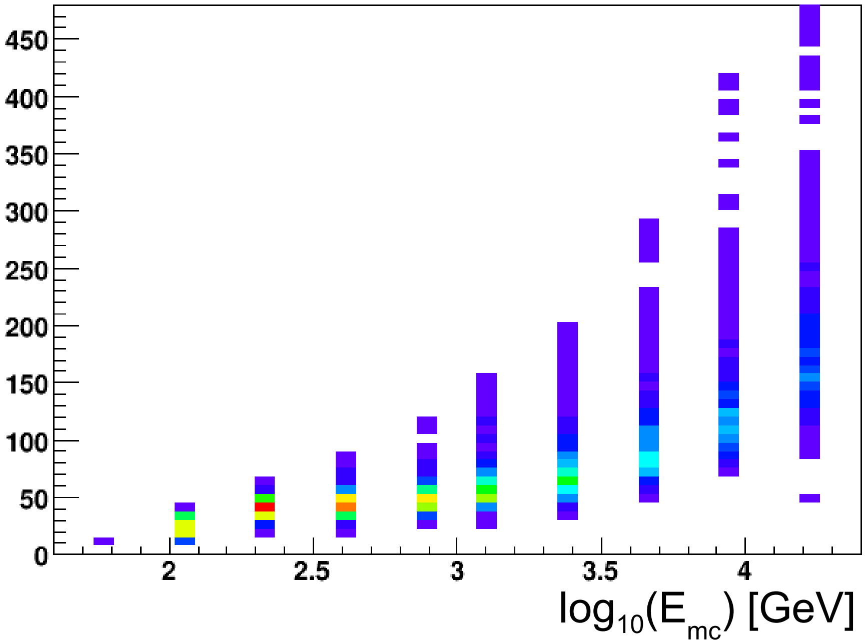


Number of storeys with hits



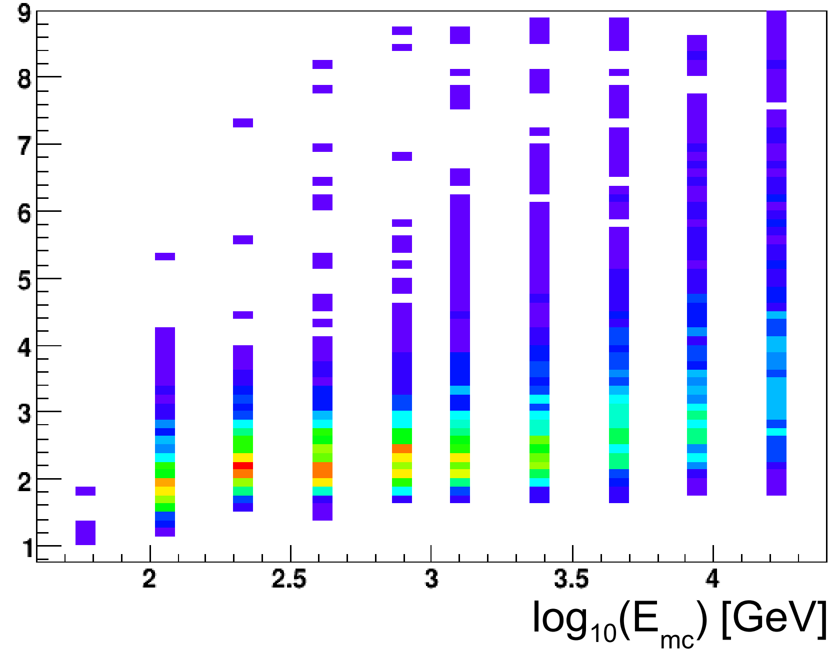
Charge deposition and hit numbers

Number of hits



Onset of photon production through radiative processes

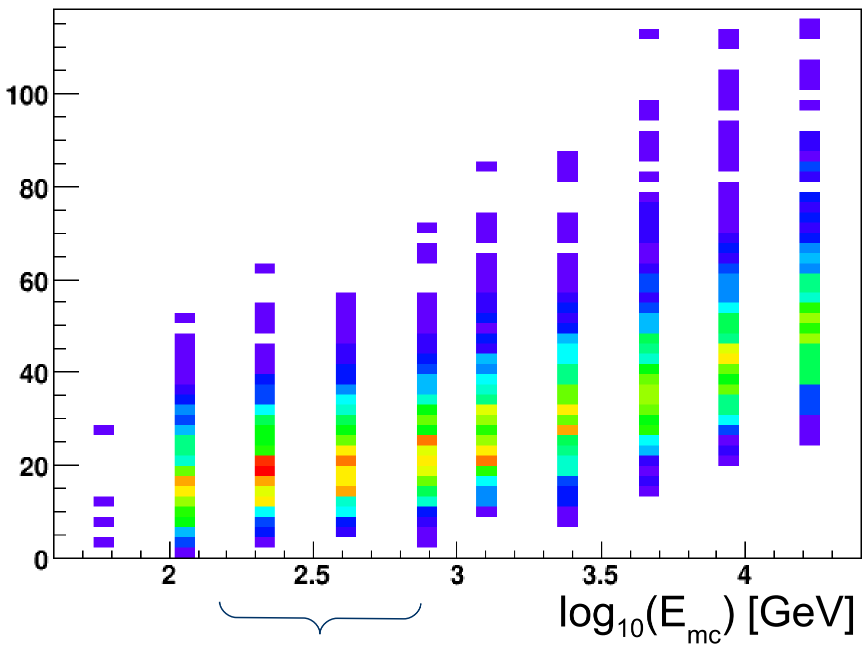
Average charge per hit (p.e.)



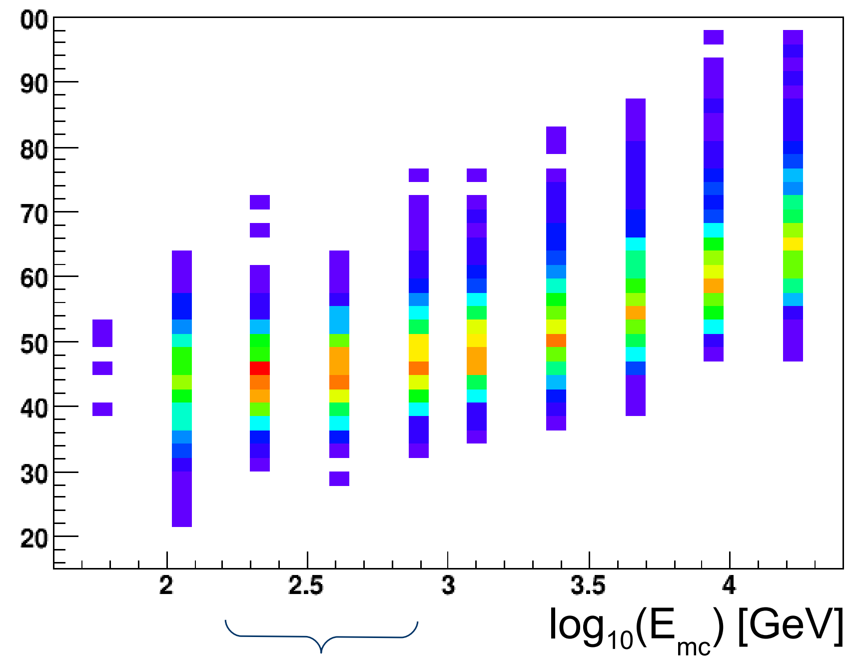
Onset of photon production through radiative processes

Hit times and location

Average time residual* of hits



Average Cherekov distance* of hits



Track traversing whole detector, constant energy loss from ionization

*Arrival time and distance of photon assuming emission from track under Cherenkov angel

➡ Work in progress! Systematic studies can be used to understand the influence of stochastic energy loss on reconstruction.

Summary and Outlook

Four energy reconstruction methods are used at ANTARES and have been presented,

- Using both parameter fits and pdf-related estimates,
- Reaching a resolution between 0.25 – 0.4 in log10(ΔE) for upgoing muons above 10 TeV,
- Showing correlated reconstruction behavior which are partly due to energy loss characteristics.
- Systematic studies of energy loss characteristics can be used to understand and increase the estimator performance for the analysis of muon energies below 1 TeV.