Progress report on low energy neutrino studies with the ORCA detector

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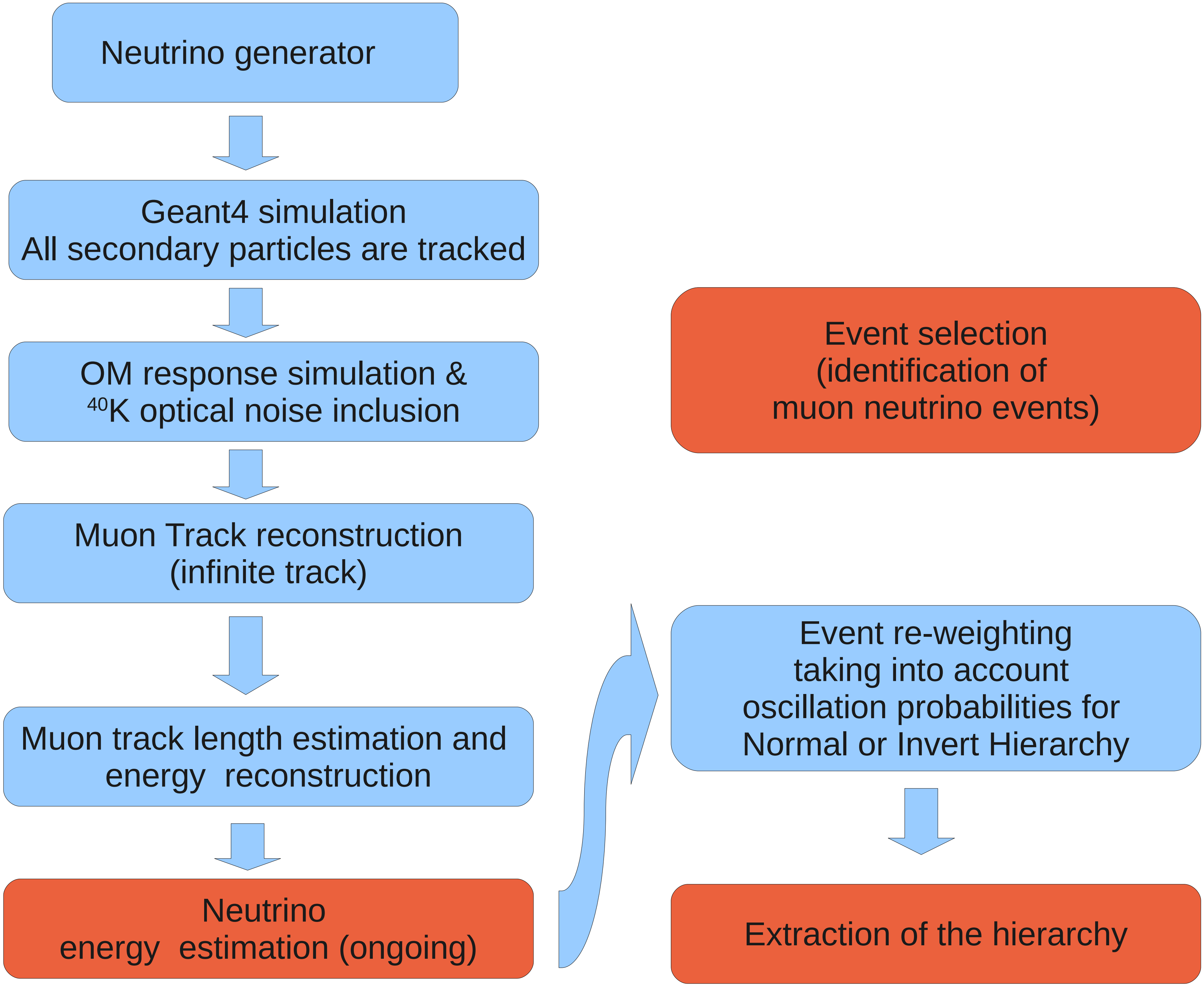
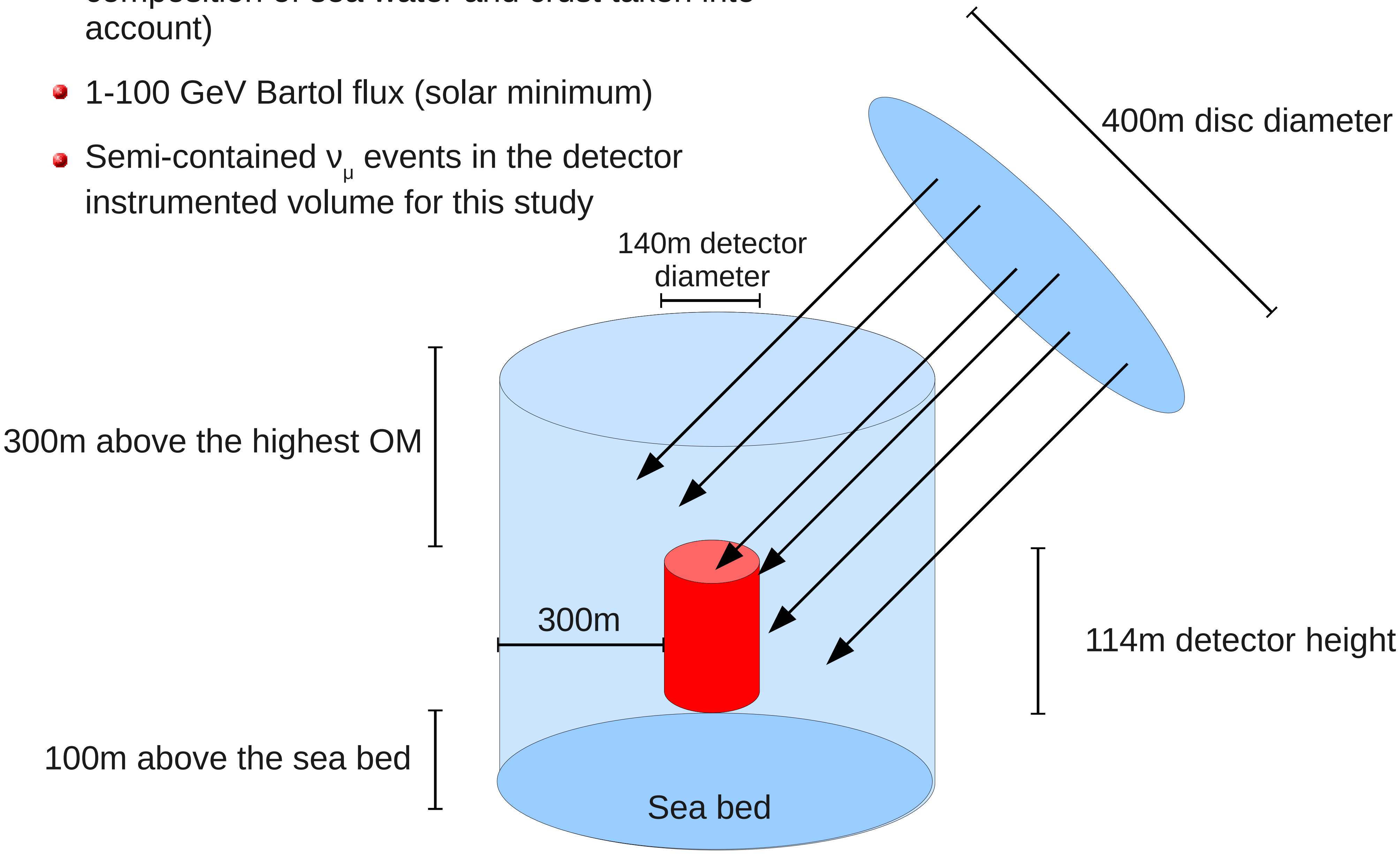
Simulation software chain



Neutrino generation

- Genie neutrino generator (complete composition of sea water and crust taken into account)
- 1-100 GeV Bartol flux (solar minimum)
- Semi-contained ν_μ events in the detector instrumented volume for this study



Geant4 simulation
All secondary particles are tracked

- **Any detector geometry can be described in a very effective way (GDML input)**
- **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 neutrino 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 (θ_{pmt},φ_{pmt})

Turned off for this study

Muon Track reconstruction
(infinite track)

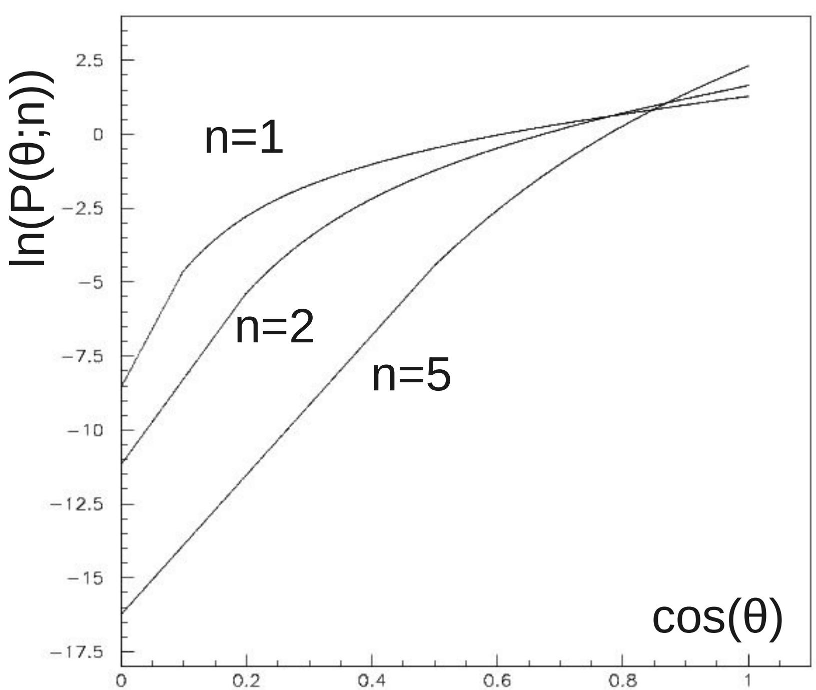
Multi-PMT direction Likelihood

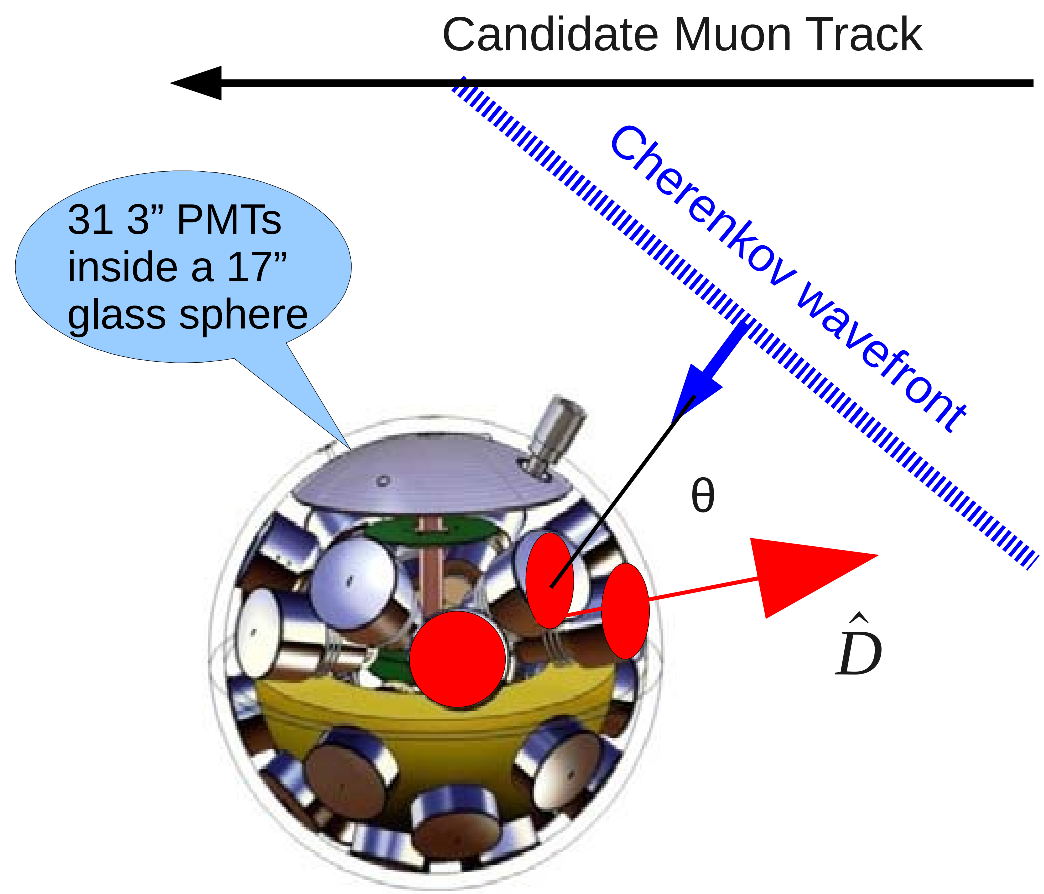
- **PDFs of the angle, θ, between the Ch wavefront direction and the active direction of the Multi-PMT**

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

- **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.**





Averaged direction of active PMTs

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

Muon Track reconstruction (infinite track)

The directionality PDFs are used in the formation of the Likelihood value for each candidate muon track.

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

Noise $PDF_{d,n} = constant$

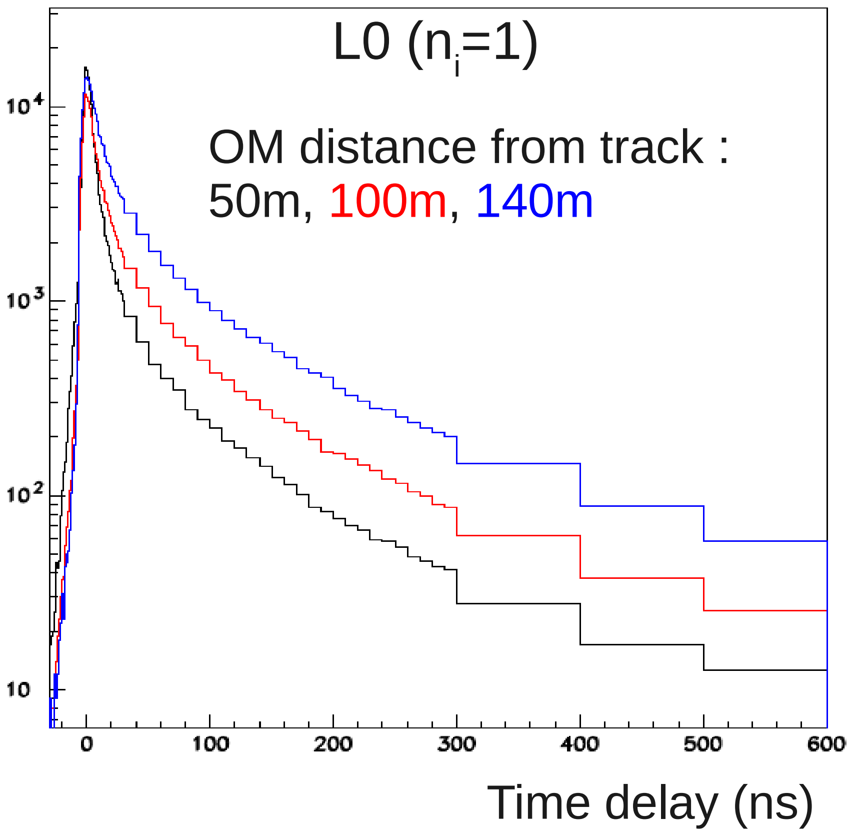
- $i=1,2,\ldots N$ the active Multi-PMTs
- n_i=the number of active elements in the i^{th} Multi-PMT
- θ_i=the angle between the average direction of the i^{th} active Multi-PMT with the reconstructed muon's Cherenkov wavefront

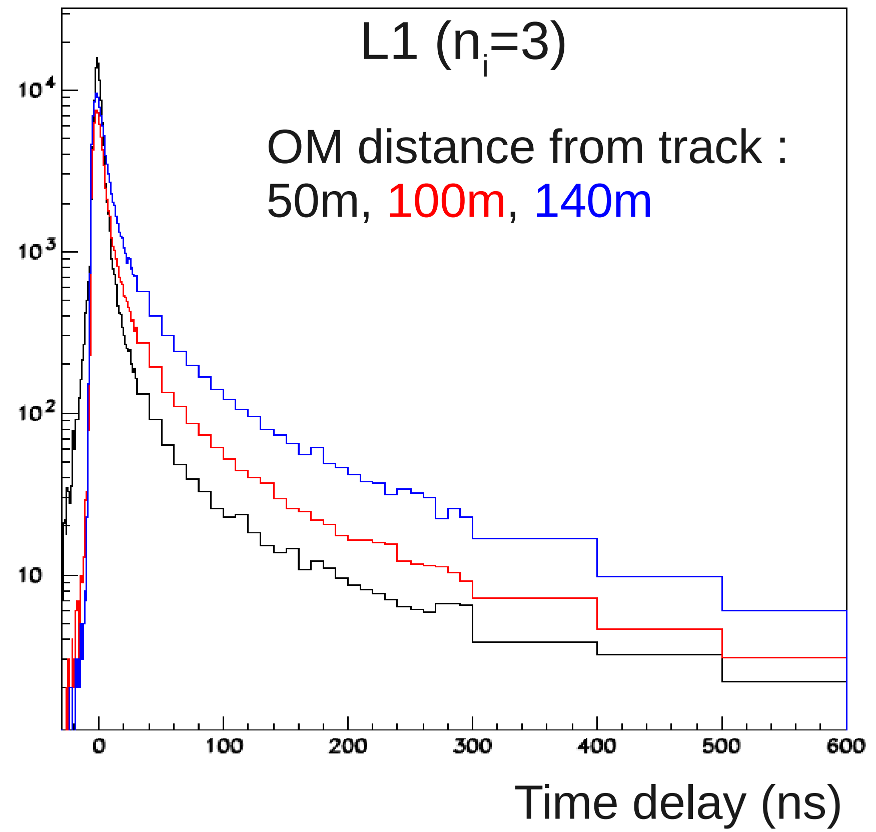
Also the timing likelihood is used

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

Noise $PDF_{t,n,i} = constant$

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





Muon Track reconstruction (infinite track)

- For each candidate track form the direction*timing likelihood value.

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

$p_{n,i}(N_{hit},n_i)\equiv$ Probability of the i^{th} hit to be noise

Timing PDFs

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

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 value is chosen

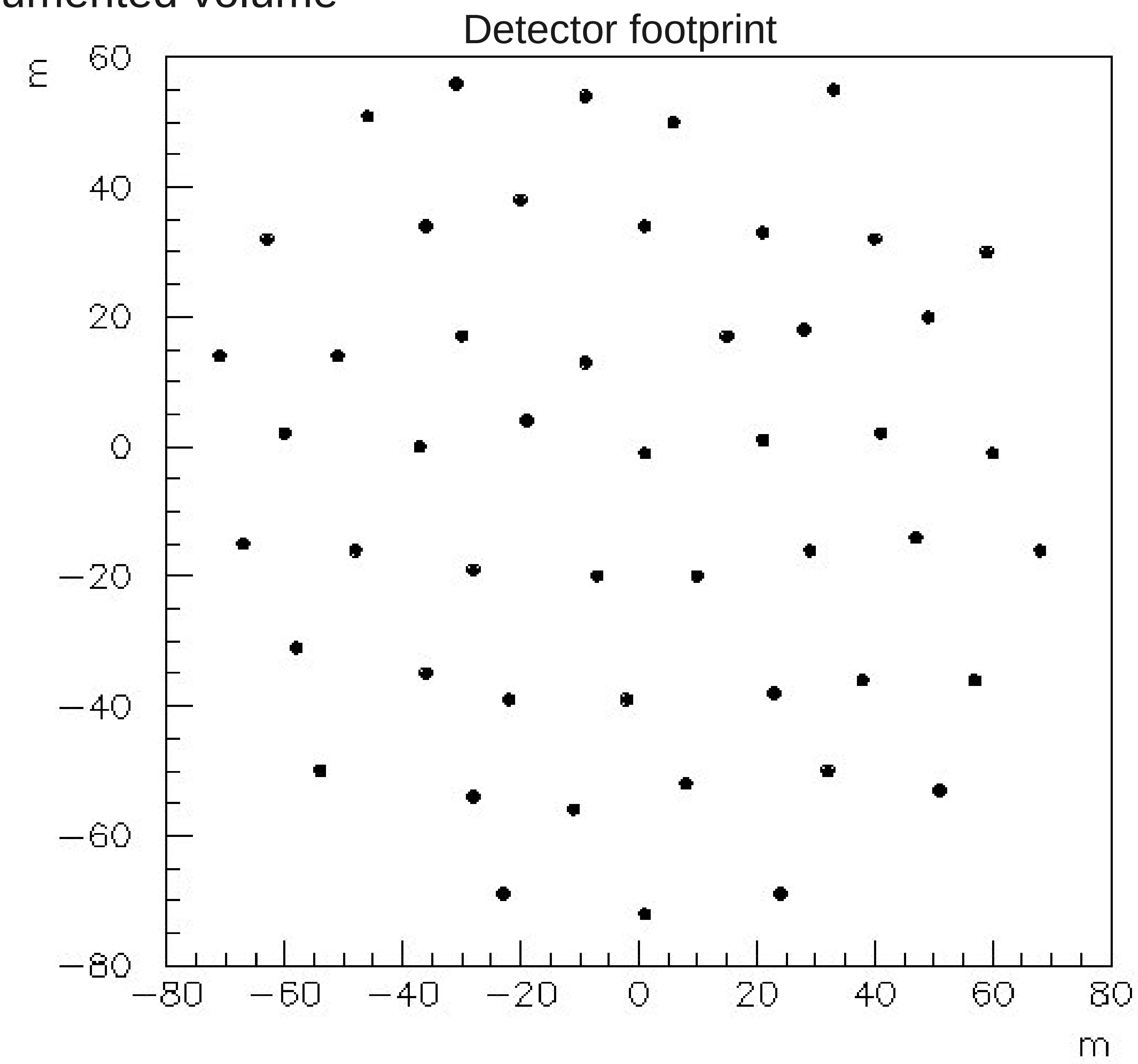
Optical noise filtering, prefit and muon reconstruction

- Prefit using only L1 hits (~1 per event expected from ^{40}K noise):
  - Linear prefit estimates the pseudo-vertex position with ~10m accuracy
  - Likelihood prefit
    - Scan the parameter space (pseudo-vertex, θ, φ) with steps (5m, 6°, 6°) up to a maximum (20m, 180°, 360°) around the linear prefit estimation
  - Reject L0 hits with residuals>20ns with respect to the prefit track

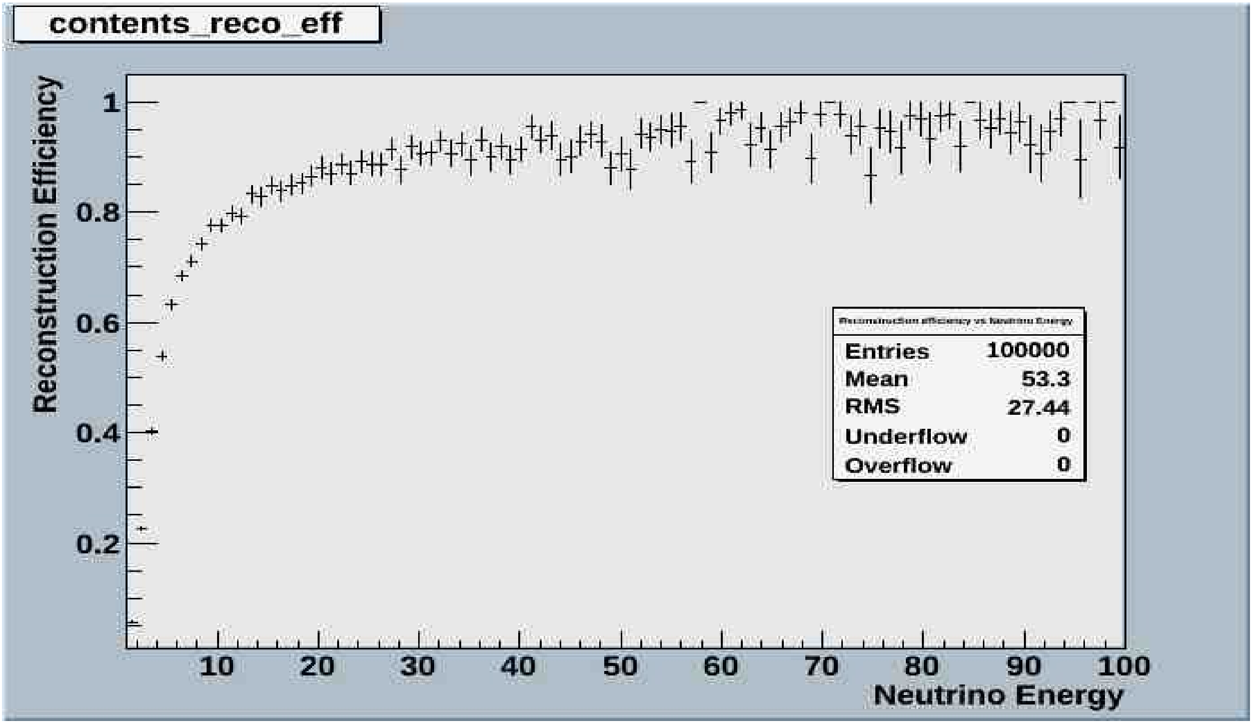
- Muon track reconstruction algorithms
  - Combination of χ^2 fit and Kalman Filter is used to produce many candidate tracks
  - The best candidate is chosen using the Multi-PMT Direction and arrival time Likelihood (track quality criterion)
  - Muon energy reconstruction using the estimated muon track length (see below)

Studied ORCA detector configuration

50 Strings, ~20m spaced
20 DOMs per string, 6m spaced
1,75 Mt instrumented volume



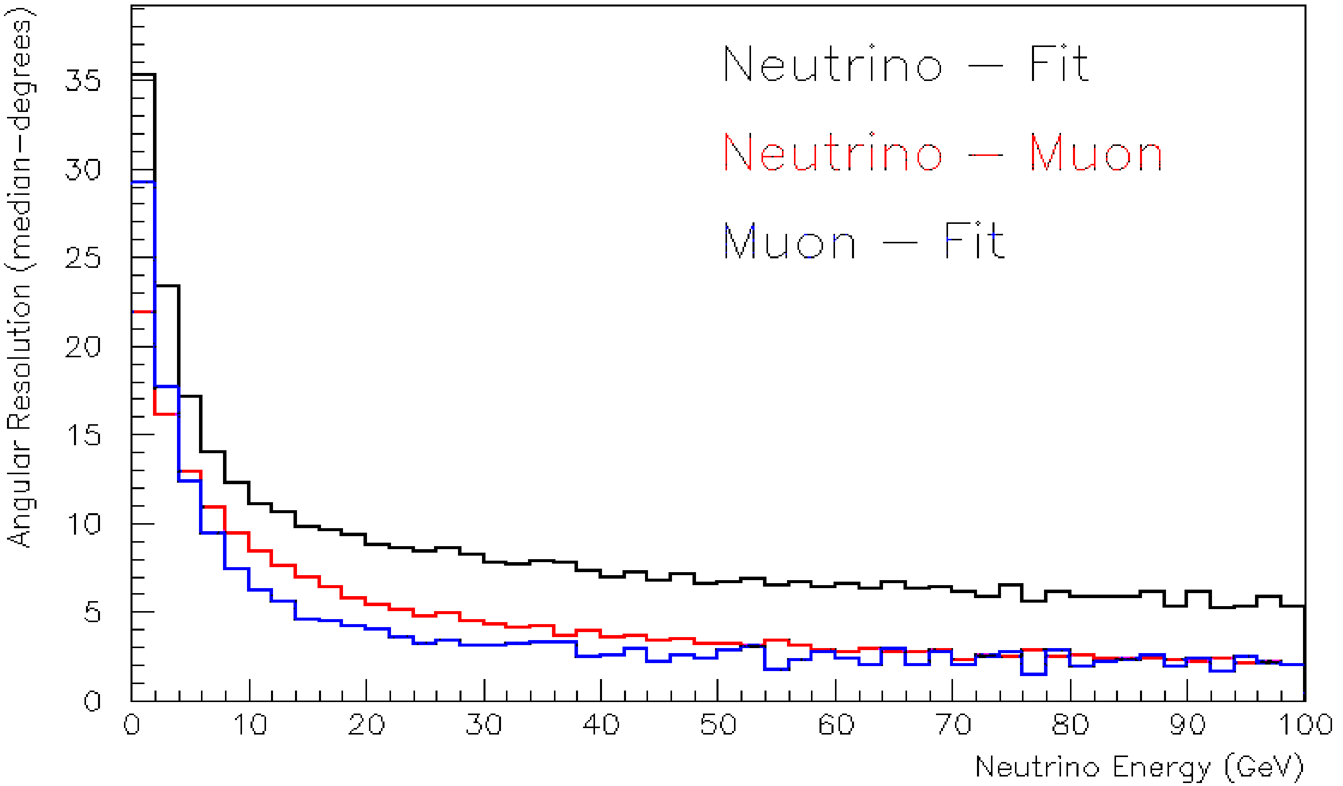
Muon Track reconstruction (infinite track)



First results

Reconstruction efficiency as a function of neutrino energy

- Events originating from inside the instrumented volume (semi – contained events)
- Events with at least 4 signal L1s
- No quality cuts after reconstruction.
- At 6 GeV a reconstruction efficiency of 70% is achieved



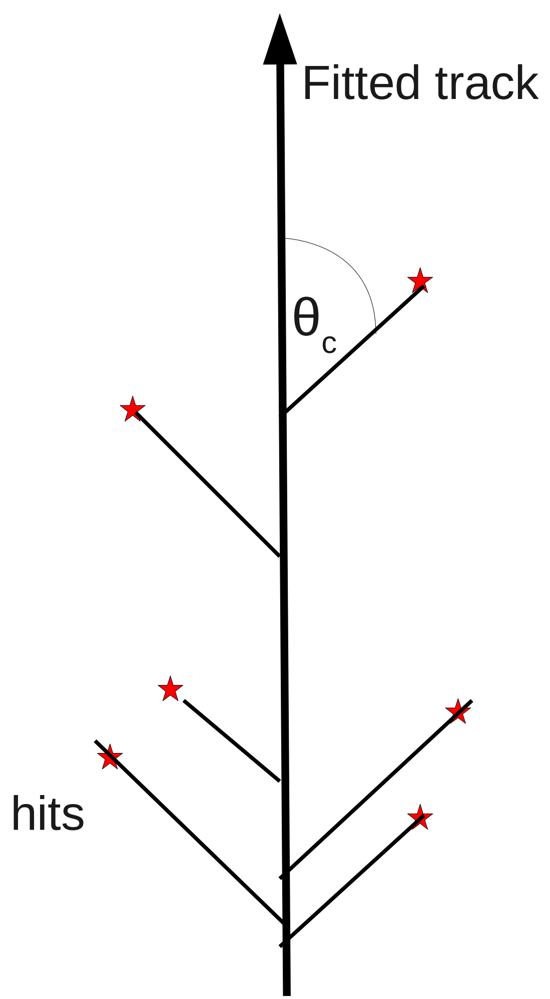
Angular resolution as a function of neutrino energy for semi-contained events.

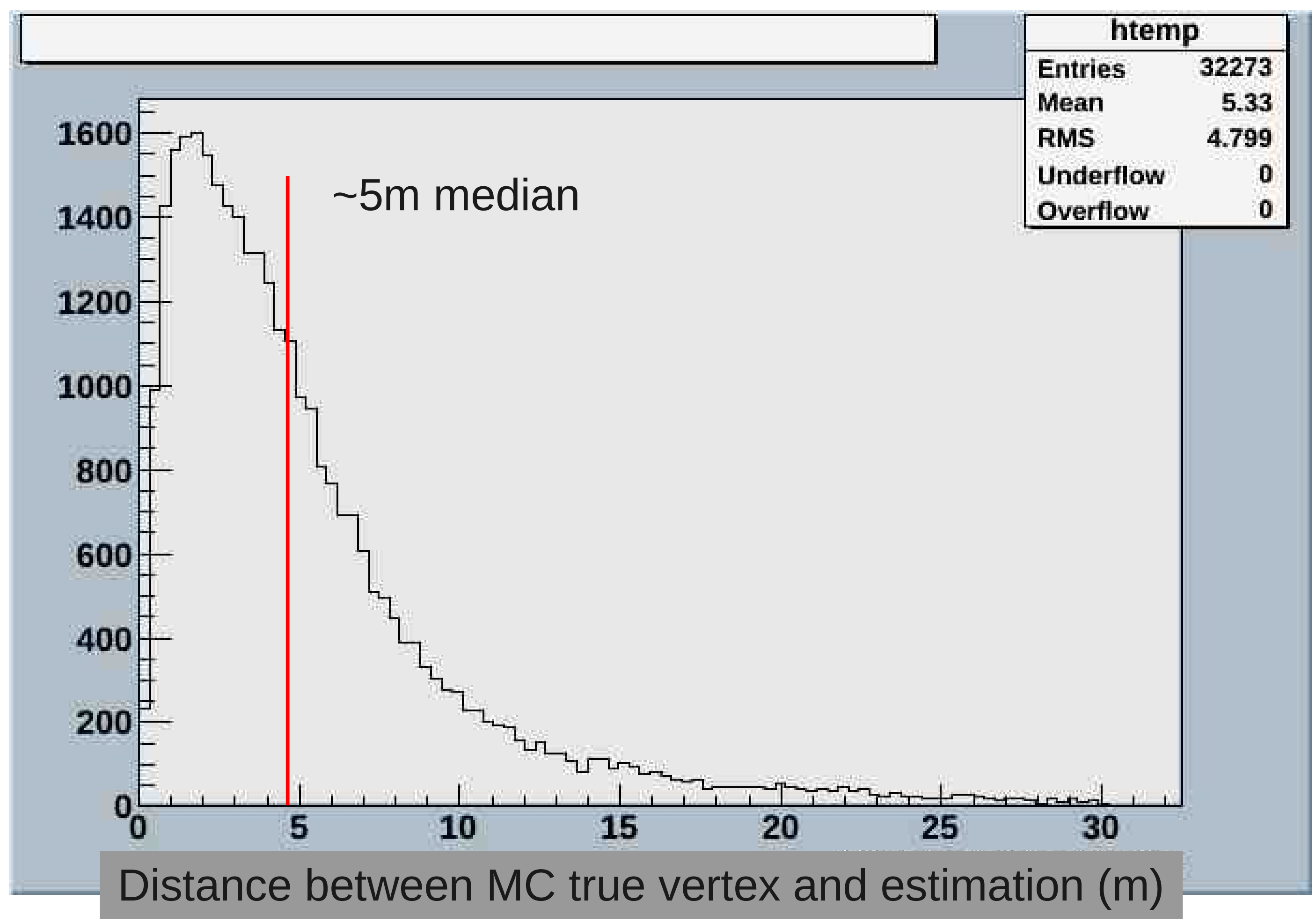
- Median angular resolution (black line) is below 15° for energies above 6 GeV.

Muon track length estimation and energy reconstruction

Estimation of the neutrino interaction vertex

- 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, reducing the ^{40}K noise contribution to a few per event (from an initial of ~130)
- From the first hits projection estimate the neutrino vertex
- The last hit define the track end

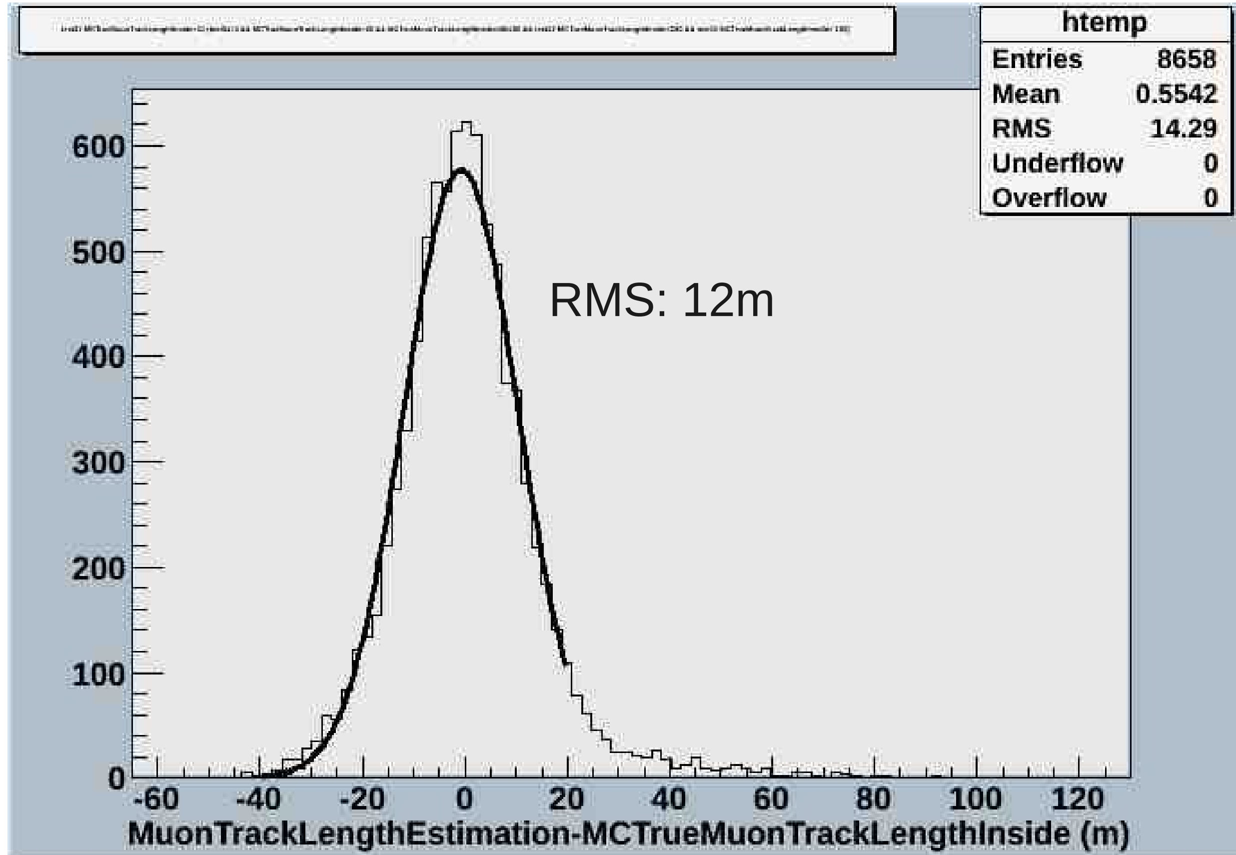




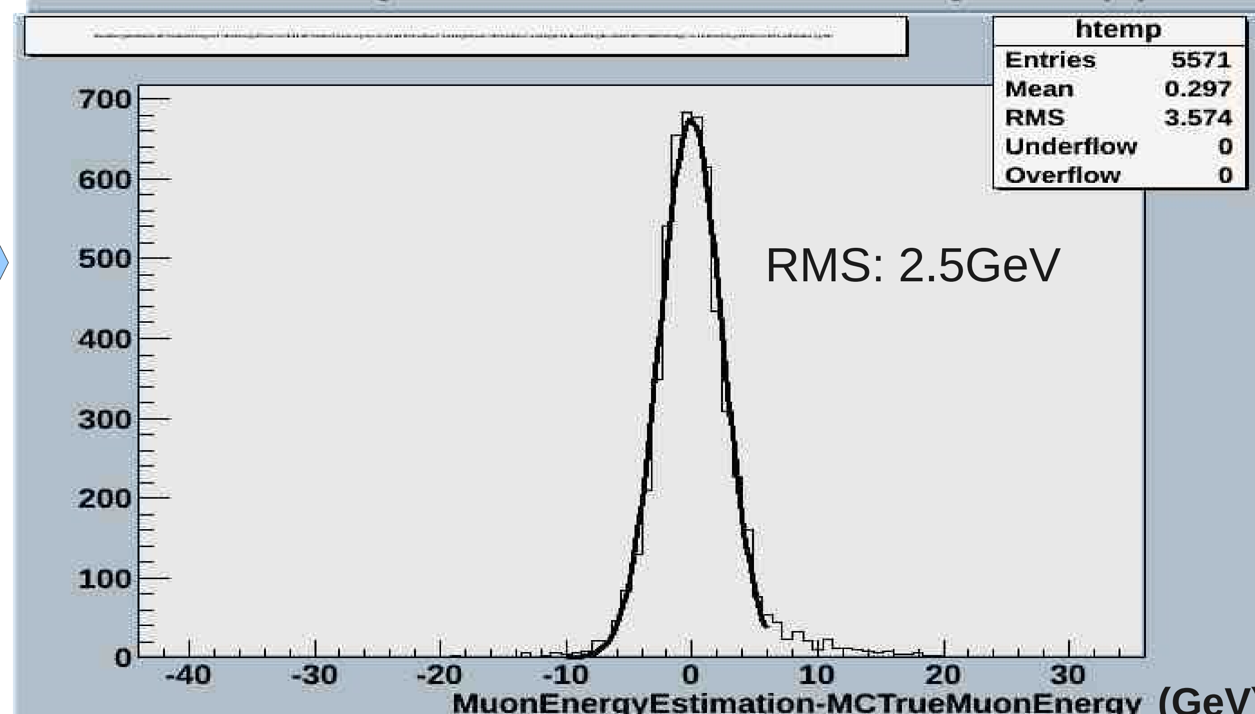
Muon track length estimation and energy reconstruction

Contained events with MC true muon track length>20m (~5GeV muon energy)

Muon track length resolution
For fully contained events



Muon energy estimation resolution for fully contained events



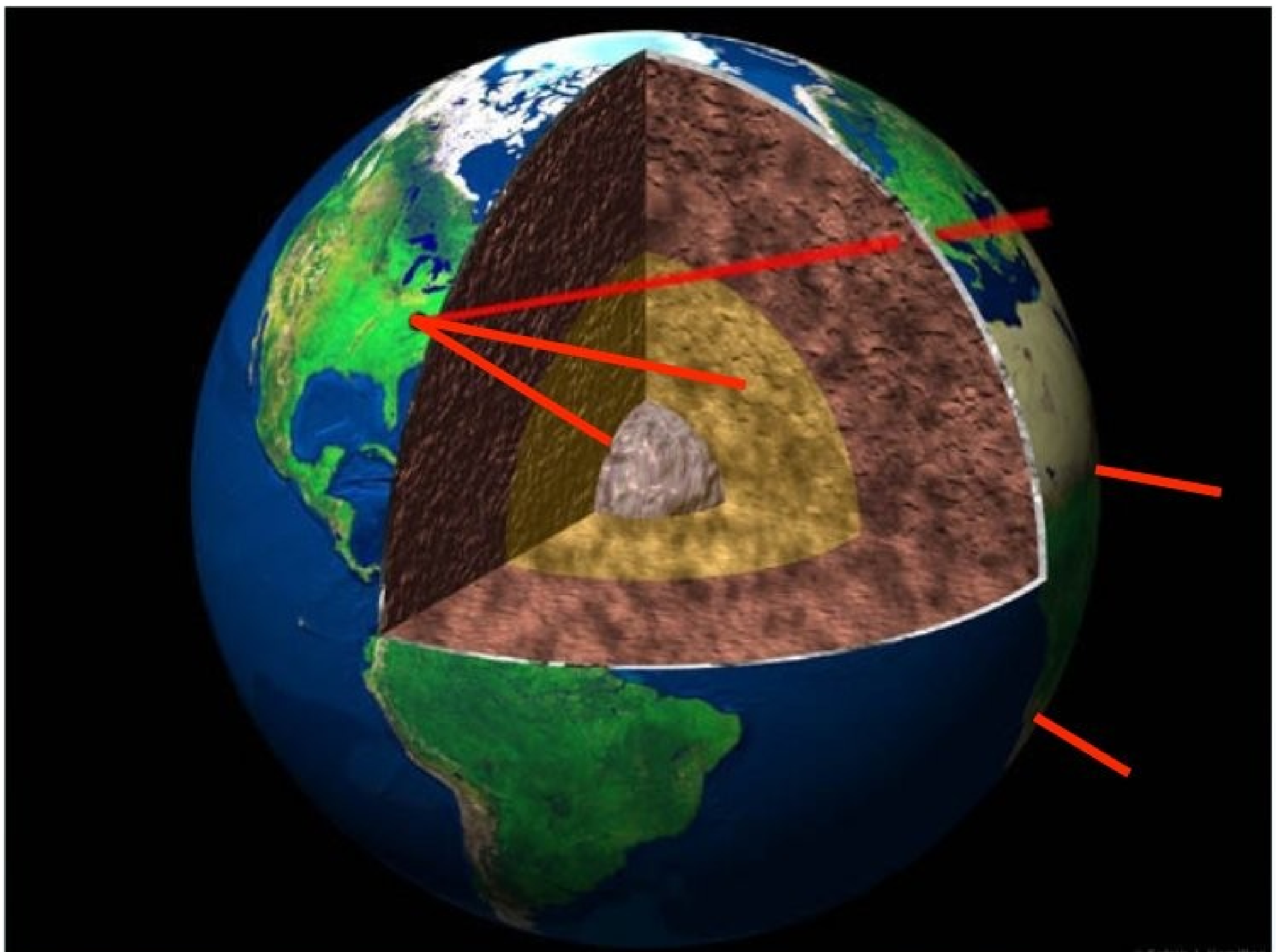
work under progress

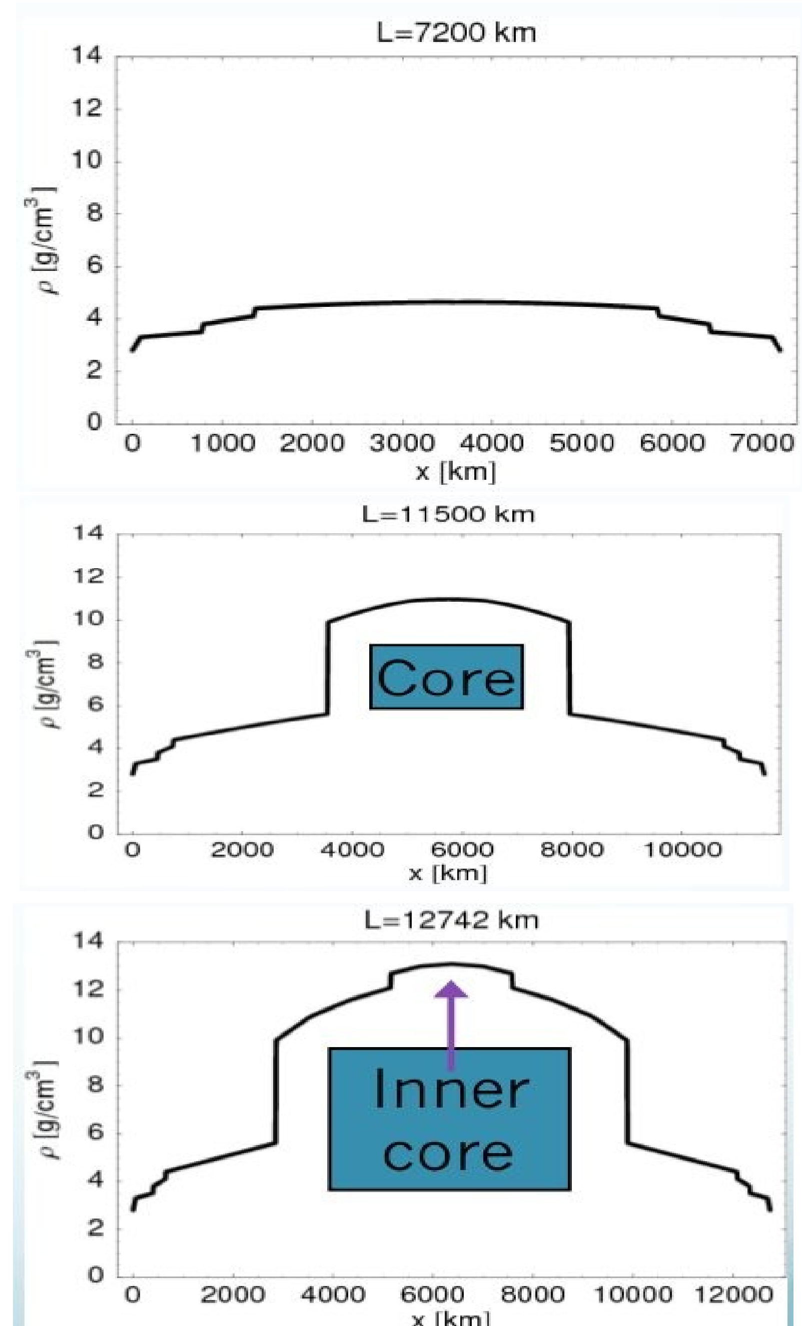
Neutrino energy reconstruction (global fit)

Event re-weighting taking into account oscillation probabilities for Normal or Invert Hierarchy

Earth density profile

Preliminary Reference Earth Model



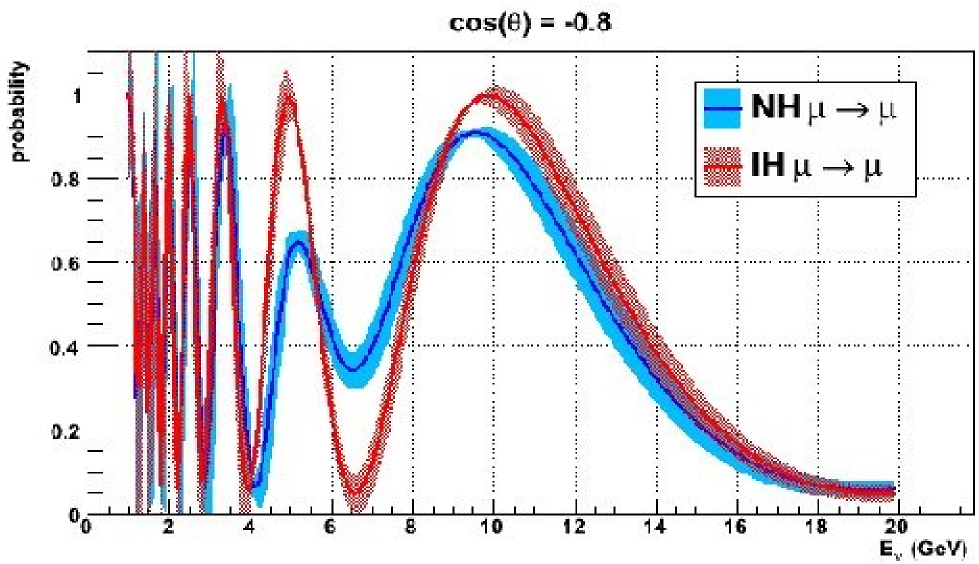


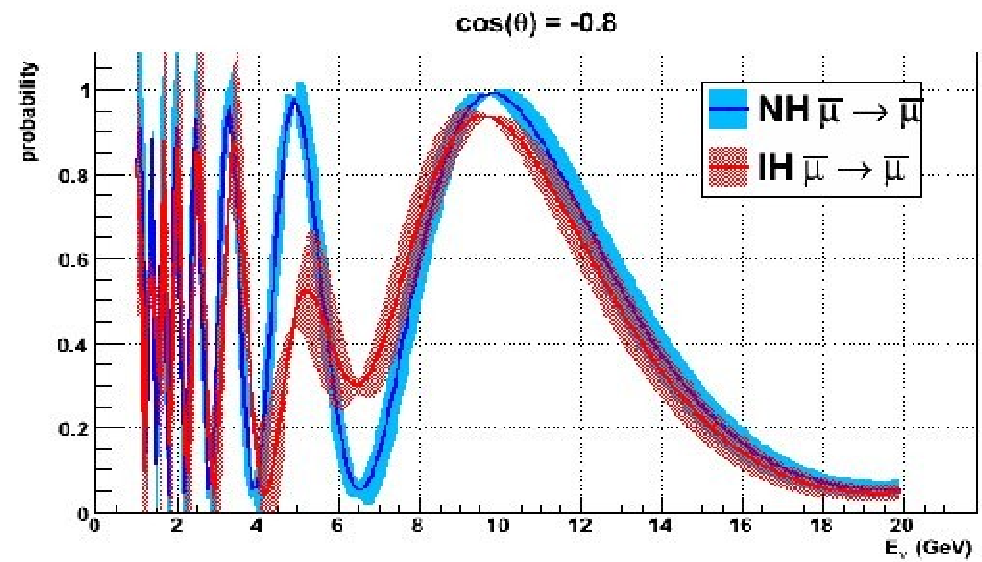
Event re-weighting taking into account oscillation probabilities for Normal or Invert Hierarchy

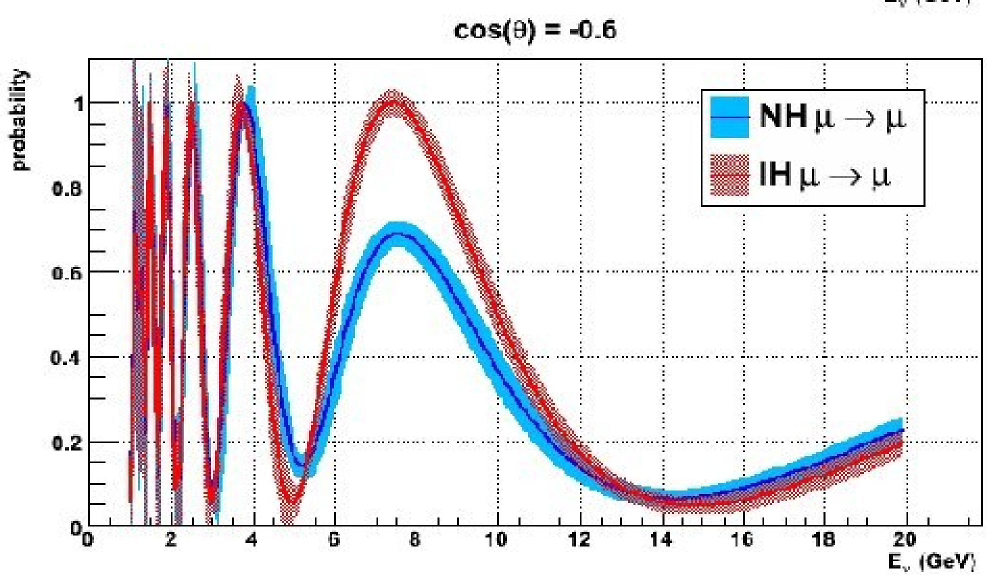
Atmospheric neutrino flux (with oscillations)

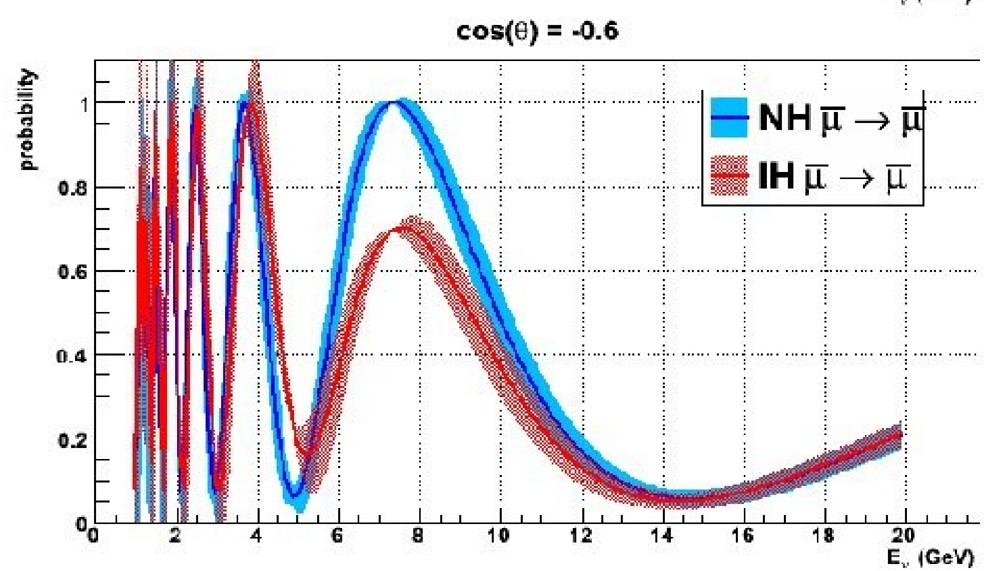
Atmospheric neutrino flux (no oscillations)

$$\Phi_\mu(E,\theta)=P(E,\theta;\nu_\mu\rightarrow\nu_\mu)*F_\mu(E,\theta)+P(E,\theta;\nu_e\rightarrow\nu_\mu)*F_e(E,\theta)$$



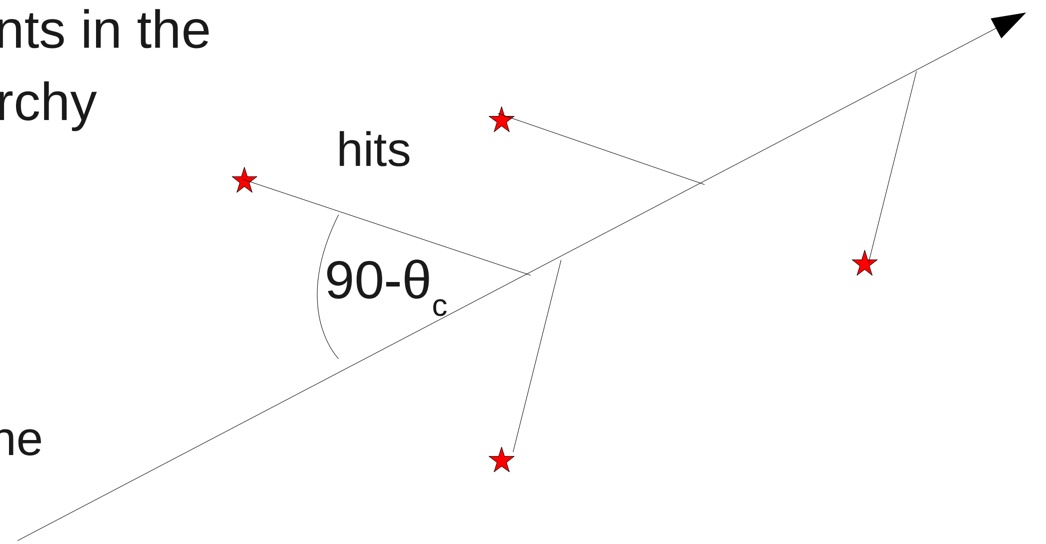






Event selection (identification of muon neutrino events)

How much different are ν_e from ν_μ events in the relevant energy region for Mass Hierarchy measurement? (under study)



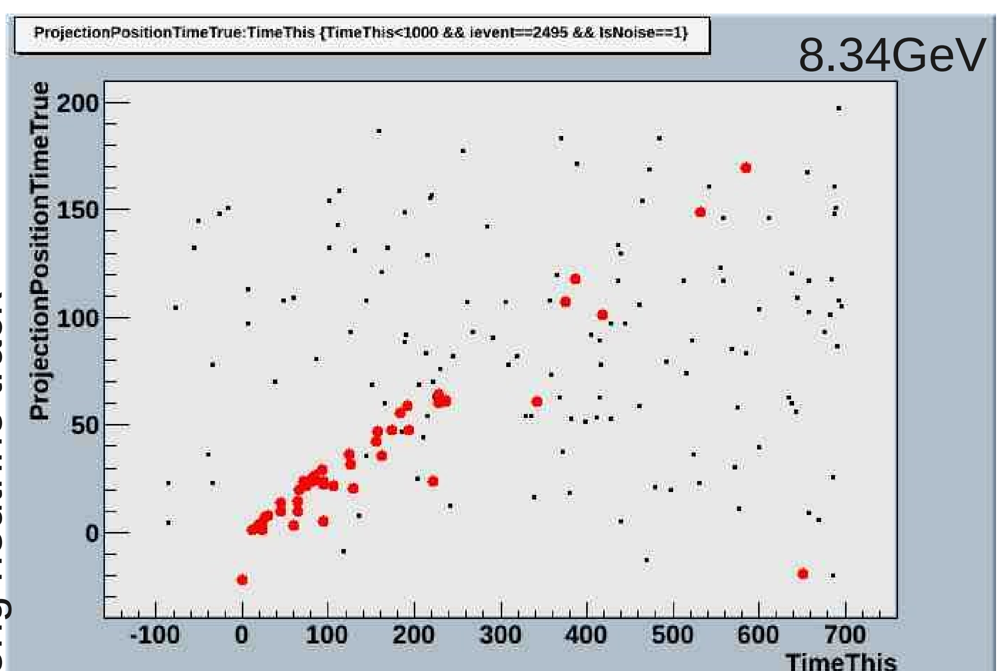
Time profile

- Projection forward with angle 90-θ_c
- Hits emitted with θ_c are along a straight line

Time profile – Example 1

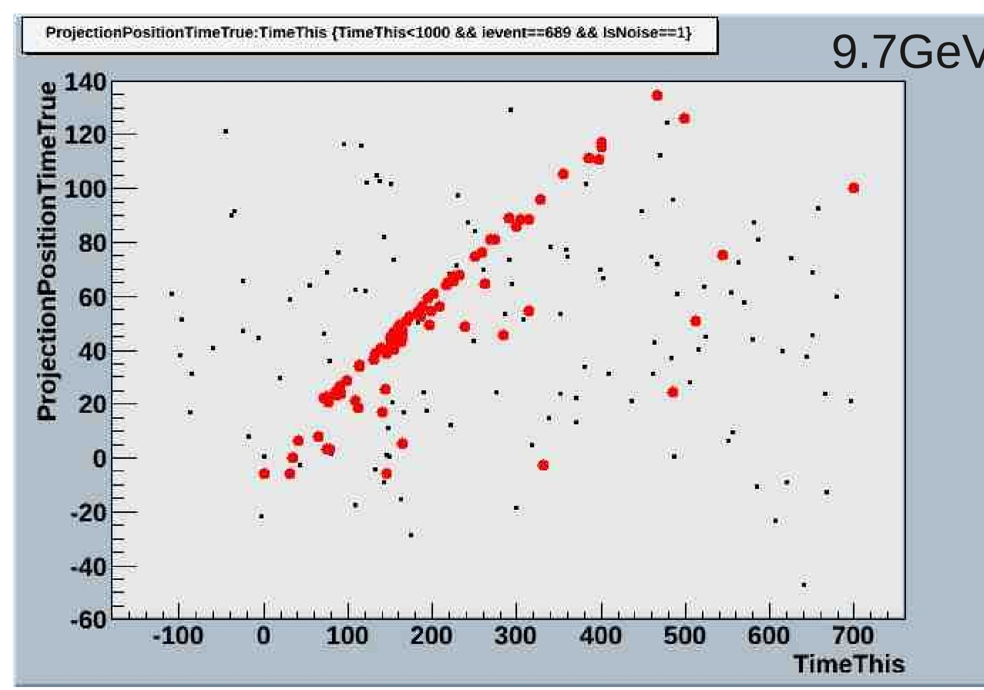
ν_μ event

Projection distance from ν vertex along neutrino track



Hit time

ν_e event



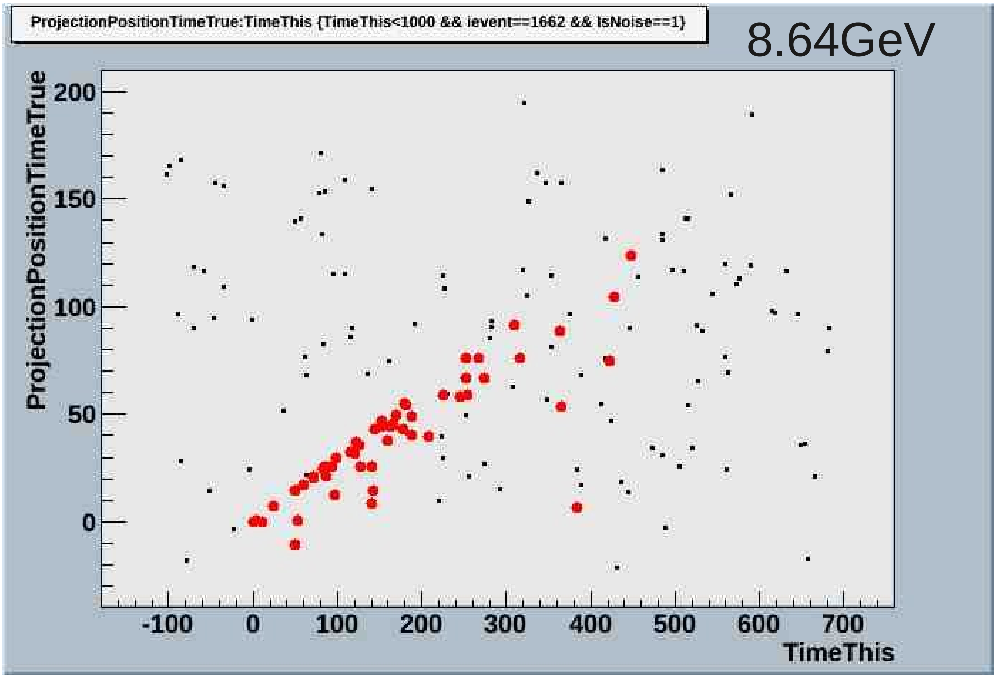
Hit time

Event selection (identification of muon neutrino events)

Time profile – Example 2

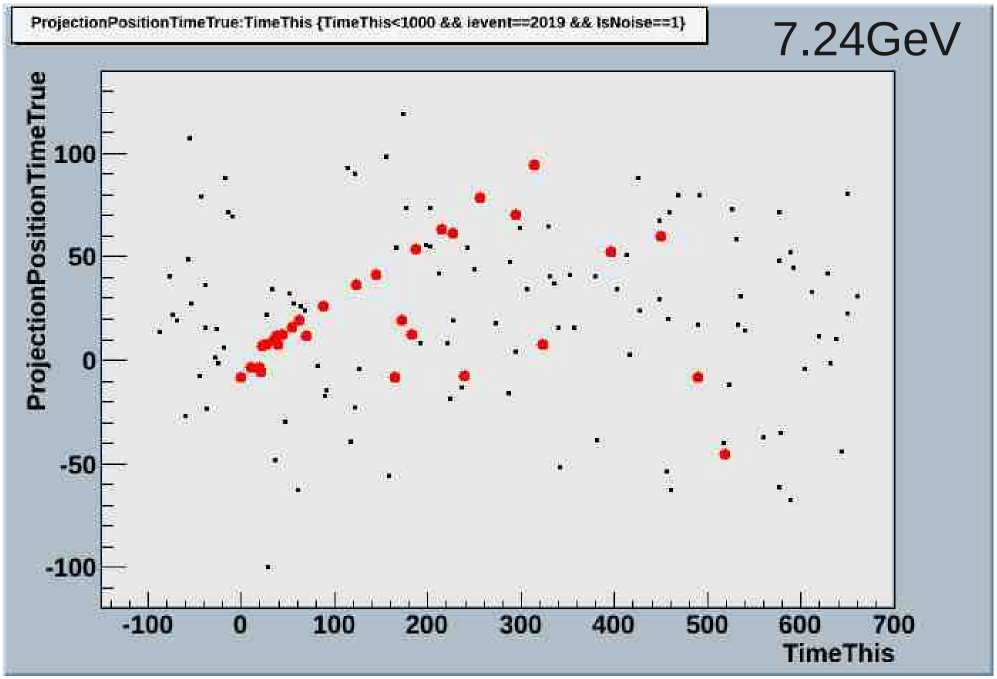
Projection distance from ν vertex along neutrino track

ν_μ event



Hit time

ν_e event



Hit time

Conclusions & Outlook

- Generation (Genie – genhen) & simulation is well established
- Track reconstruction gives promising results
  - Can be further improved
- Muon energy reconstruction resolution of ~2.5GeV can be achieved
- Neutrino energy reconstuction is under way
- Background contamination: need veto for atmospheric muons
- Distinguish between muon and electron/tau neutrino events
  - Can we separate low energy muon from electron/tau events in the presence of the ^{40}K noise?
  - How much the number of years needed to measure hierarchy will change if there is x% uncertainty of an event to be ν_μ ?

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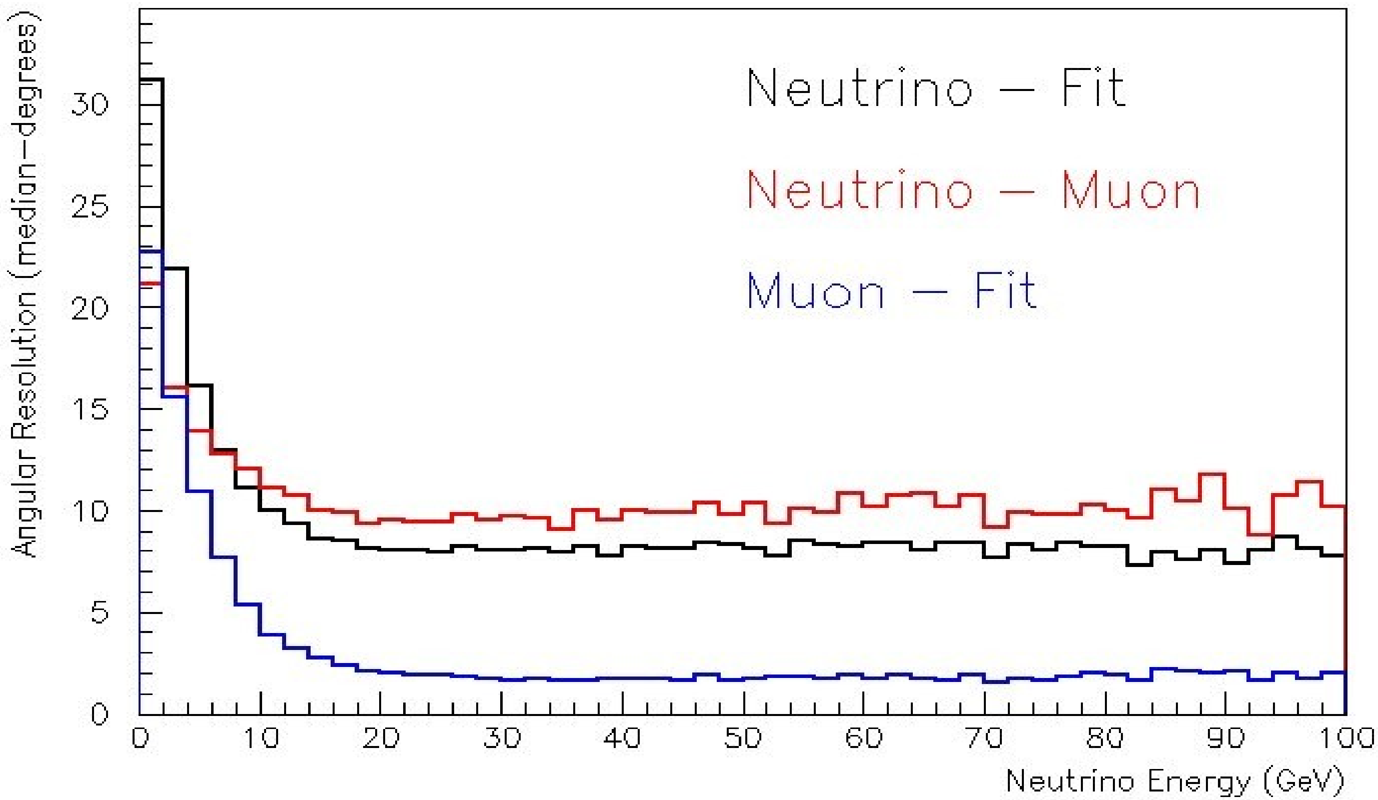
Backup slides

Muon Track reconstruction (infinite track)

Angular resolution as a function of neutrino energy for contained events.



Angular difference neutrino-fit is better than neutrino-muon

- for high energy neutrinos the contained events (low energy muons) have large kinematics angle
- Fit algorithm uses the light from all particles from neutrino interaction