Status of particle tracking at GeV energies

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Contents

Basics

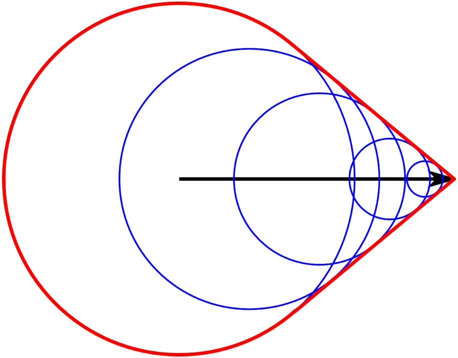
Problem: Scintillation photons are emitted isotropically

$\Rightarrow$ No directional information from the charge distribution

$\Rightarrow$ Use photons' arrival times for track reconstruction

General idea

- Isotropic emission over total track length
- Superposition of spherical ”waves“ leads to first photon cone
- The shape of the cone contains information about the track direction

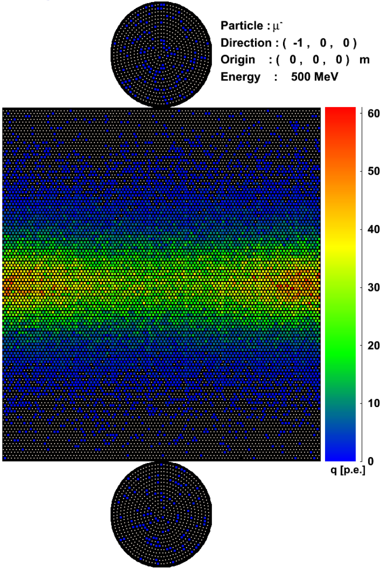


First exploration of tracking capabilities: Juha Peltoniemi's Scinderella

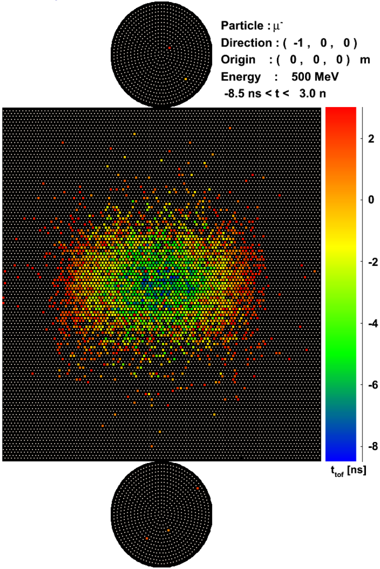
- Java based simulation + analysis application
- Showed great potential
  - Reconstructed lepton energy error 5%
  - Reconstructed vertex position error 11 cm
- Shortcomings:
  - Strongly simplified primary vertex physics
  - No hadron interactions
  - No neutrons
  - Simplified 1D em.-shower evolution
  - No multiple scattering
  - No scattering in the scintillator

Event signature

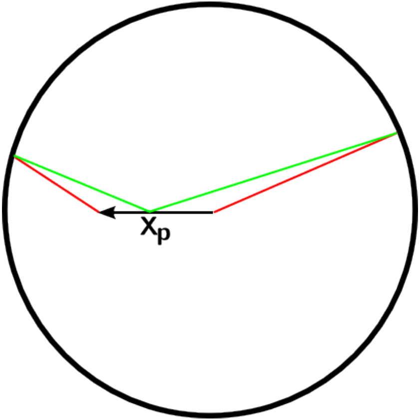
Charge



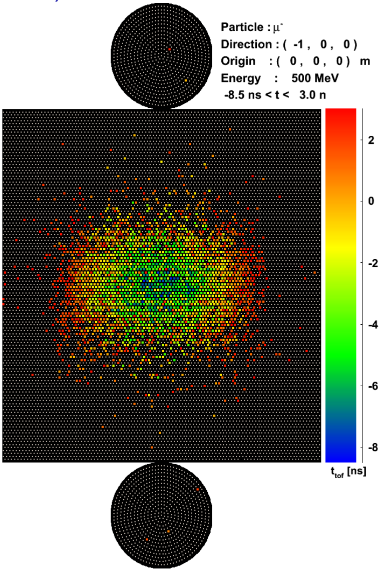
(First-)hit-time



Event signature



(First-)hit-time



Fit parameters

Assumptions

- Track length fluctuations and multiple scattering neglectable
- Muons decay at rest

7 fit parameters: $\boldsymbol{X}$

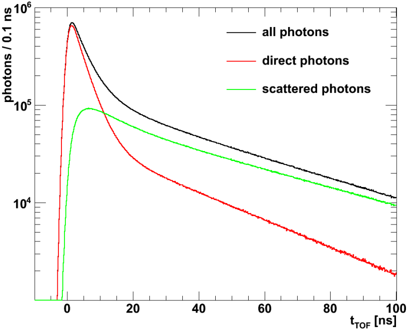
- Kinetic energy $\rightarrow$ 1 parameter: T
- Coordinates of track start point $\rightarrow$ 3 parameters: $\boldsymbol{x}_s$
- Direction of the track $\rightarrow$ 2 parameters: (ϑ, φ)
- Start time of event $\rightarrow$ 1 parameter: t_s

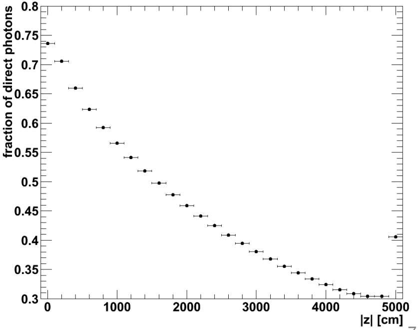
Costs of going beyond a pure track

- Point like energy deposition at the vertex: + 1 parameter
- Additional track from same vertex: + 3 parameters
- Additional track from different vertex: +5 to 7 parameters

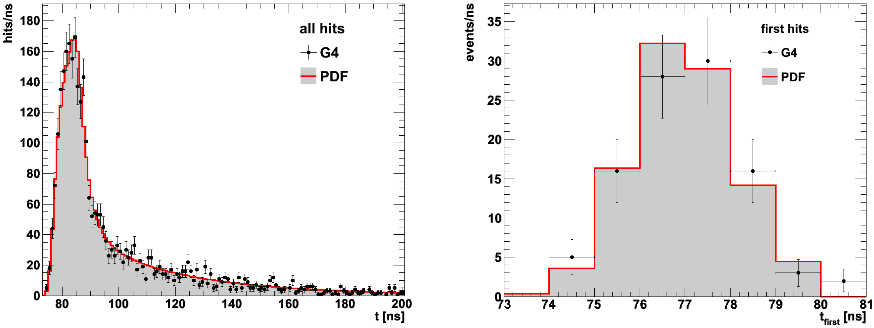
Considerations for calculating the PDF

- Mean number of photons emitted per unit track length
- Particle/shower propagation in time
- Time resolution of the PMTs
- Finite dimensions of the PMTs
- Decay time distribution of the scintillator
- Attenuation/scattering of light in the scintillator (changes both, the number of detected photons as well as their arrival times, have to use MC input)



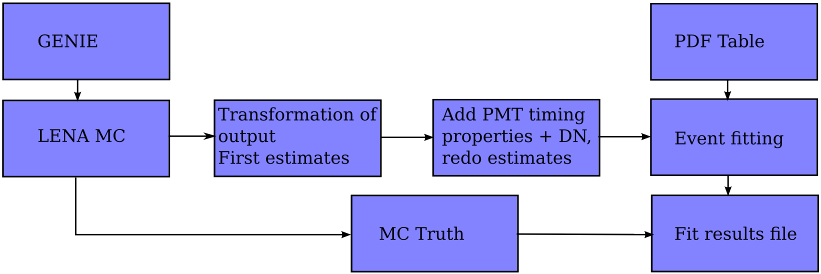


Comparison of time PDF with Geant4



- Good agreement for total spectrum as well as for first-hit spectrum
- Agreement gets worse for lower energies as assumptions are no longer valid

Data flow

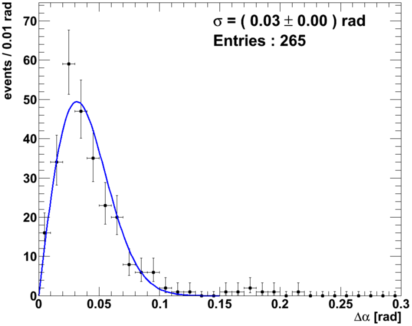


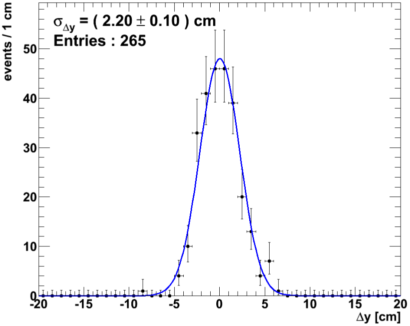
- Data transfer between the different stations is done using ROOT files
- A 500 MeV muon requires $\sim$ 3 MB of disk space.
- The PDF table requires 1.1 GB.

Current status of the tracking software

- Currently in the process of software-redesign
  - Point fit works well (for $|z| < 25\,\mathrm{m}$).
  - Basic internal PDF table works fine.

$\Rightarrow$ Just reimplemented the tracking possibilities
  - Single muon track
  - Single electron track (have to simulate $\frac{dL}{dx}$-tables for LAB)
  - Two-muon tracks (does not converge, no first estimates)
  - Point-like events





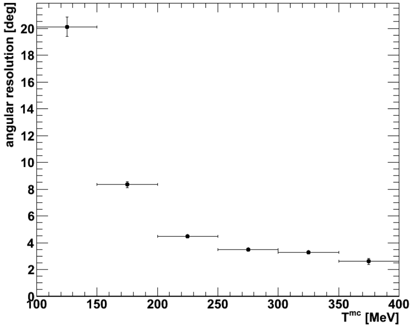
Approaching more complicated events: The β-beam

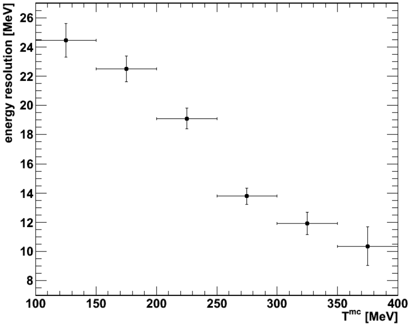
Modeling quasielastic events

- At β-beam energies: Nucleon path length $\lesssim 20\,\text{cm}$

$\Rightarrow$ Model track as pure track with additional point-like vertex

Performance

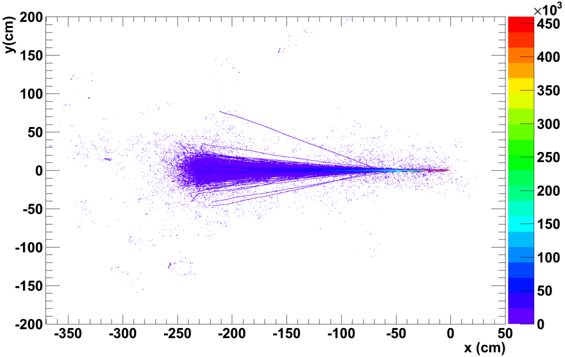




But: Better energy resolution obtained using LENA as a calorimeter.

Challenges arising with higher energies

- Much more complicated vertex geometry (DIS dominant)
  - $\Rightarrow$ Higher number of (possibly correlated) parameters required
- Increased event by event fluctuations
- Increased probability of inelastic hadronic interactions
  - $\Rightarrow$ Secondary vertices
- Only partly contained events ($\sim$ 50% for ν_μ)
- Increased computation time required in simulation and analysis (fitting!)



Future plans

Planned development

- Thoroughly test the reimplemented track fits
- Add option to use all detected photons in the fits
- Change PDF to also include areas near top/bottom of detector
- Increase the energy range
- Change PDF to deal with non contained events
- Multi track fits

Further things to do

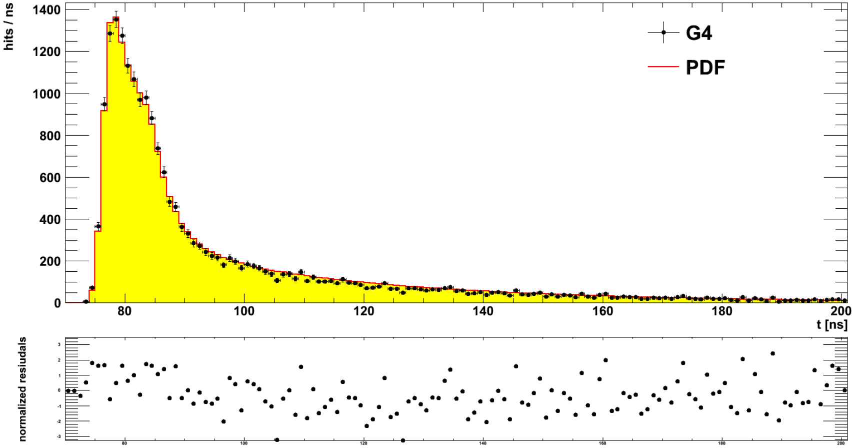
- Require seeds for the multi track fits
- Use results of tracking for particle identification
  $\rightarrow$ likelihood-ratio
- Feed all results into GLoBES

Conclusion

- For a convincing Study, a full MC is required
- The PDF is already able to describe the results from the MC very well.
- Simple events can be reconstructed by a negative logarithmic likelihood fit to the first hit times and the charge.
- High energy events challenging due to the more complicated event structure
- First experience with full events from fitting simulated β-beam events
- Software currently in transition phase, will hopefully reach next stable version soon

BACKUP SLIDES

MC-G4 comparison for a two track fit



Basic functionality

Parameter estimation

- Use charge $\boldsymbol{q}$ and first hit time $\boldsymbol{t}$ of each PMT as signal
- Calculate PDF $P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X})$
- Minimize NLL $\mathcal{L}(\boldsymbol{X}|\boldsymbol{q}, \boldsymbol{t}) = -\ln\left[L(\boldsymbol{X}|\boldsymbol{q}, \boldsymbol{t})\right] = -\ln\left[P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X})\right]$

Basic structure of PDF

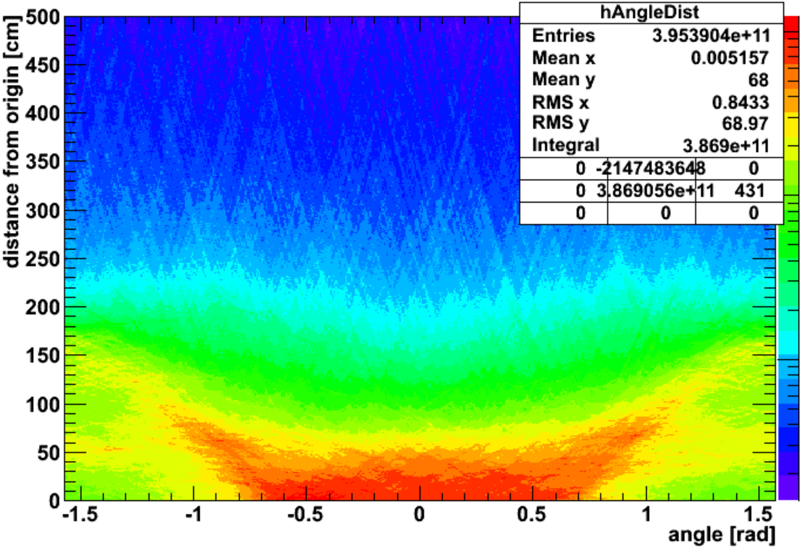
- PDF $P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X})$ of very high dimension
- Assume all PMTs to be equal and independent

$$\Rightarrow \quad P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X}) = \prod_{i=1}^{N_{\text{PMT}}} P_i(q_i, t_i|\boldsymbol{X}) = \prod_{i=1}^{N_{\text{PMT}}} P(q_i, t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i)$$

- For PMTs with $q_i = 0$ the PDF is independent of t_i
- For PMTs with $q_i \neq 0$ the PDF can be decomposed:
  $P(q_i, t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i) = P(q_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i)P(t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i, q_i)$

$\Rightarrow$ The overall PDF is of the form:

$$P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X}) = \prod_{i}^{q_i=0} P(q_i = 0|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i) \prod_{i}^{q_i \neq 0} P(q_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i)P(t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i, q_i)$$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Mean y 68
RMS x 0.8433
RMS y 68.97
Integral 3.869e+11
0 -2147483648 0
0 3.869056e+11 431
0 0 0
distance from origin [cm]
angle [rad]