Lepton track reconstruction in LENA

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6th- 14th October 2010

Contents

Detector Layout

- Cylindrical detector (h = 100m, r = 15m)
- Outer two meters contain non/only weakly scintillating buffer
- Inner part filled with liquid scintillator $\sim$50 kt (LAB or PXE with dodecane as solvent, PPO as primary fluor)
- $\sim$30% photocoverage
  - $\Rightarrow$ 13 500 Super-K type PMTs
  - $\Rightarrow$ 45 000 8“-PMTs with Winston cones
- Surrounded by 2m water as shielding and muon veto, additional muon veto scintillator panels on top
- Overburden $>$ 4000mwe
- Preferred sites:
  - Pyhäsalmi, Finland
  - Frejus, France

Physics potential

Low-energy neutrino physics

- Solar neutrinos at high statistics ($\sim$ 4500 ^{7}Be $- \nu$ d^{-1})
- Supernova neutrinos ($\sim$10000 events)
- Diffuse supernova neutrino background
- Geoneutrinos ($\sim$ 1000 ν a^{-1})

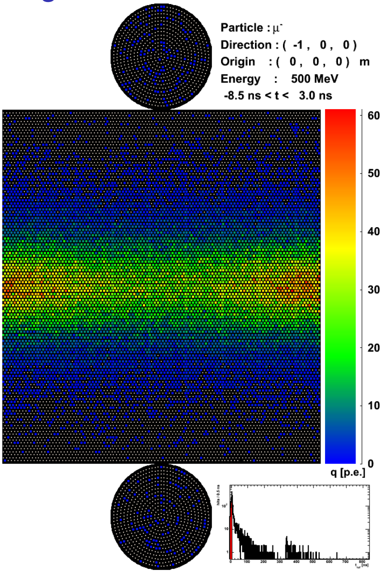
Neutrino physics at GeV scale

- Search for proton decay
- Atmospheric neutrinos
- Neutrino beams
  - Superbeam
  - β-beam

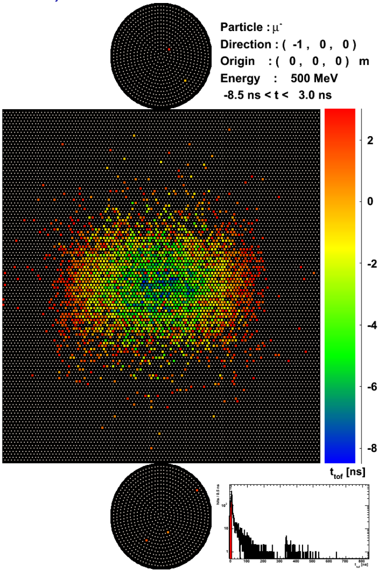
$\Rightarrow$ Reconstruction of events in GeV range required

Event signature

Charge



(First-)hit-time



General considerations for track reconstruction

- Assumptions:
  - Range straggling and multiple scattering neglectable
  - muons decay at rest

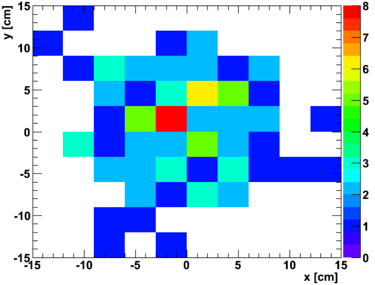
$\Rightarrow$ Lepton propagation can be described using the CSDA

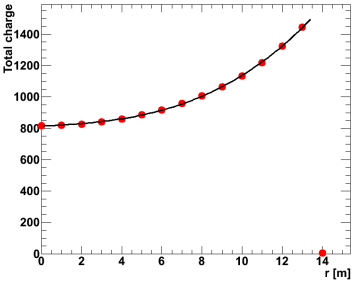
- 7 fit parameters :
  - Kinetic energy $\rightarrow$ 1 parameter
  - Coordinates of track start point $\rightarrow$ 3 parameters
  - Direction of the track $\rightarrow$ 2 parameters
  - Start time of event $\rightarrow$ 1 parameter
- Fit parameters energy and track start position highly correlated
  $\Rightarrow$ Determine energy and track-position in different fits

Estimation of start parameters

1. Charge based barycenter fit
2. Electron-muon-discrimination (decay electron)
3. Energy $E = q_{\text{tot}} \cdot a \cdot f(r_{\text{bary}})$
4. Distinguish between vertical-like and horizontal-like events
    - Vertical like events:
      Get start point via fit to first-hit-times in ring with first hit
    - Horizontal like events:
      Get start point via first tof-corrected hits

$\Rightarrow$ Start values for fit parameters

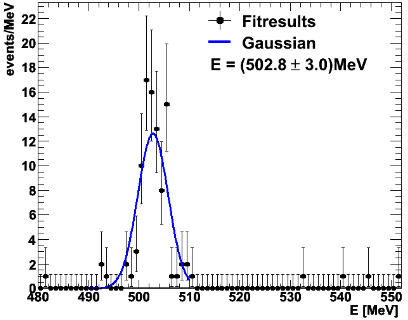


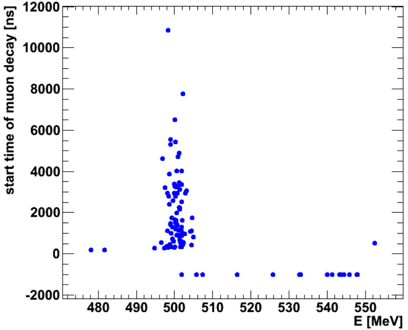


Charge based energy fit

- Comparison: Predicted charge $\leftrightarrow$ Obtained charge signal
- PDF given by Poisson distribution
- Calculation includes:
  - Track parameters $\longrightarrow \frac{dL}{dx}$-profile (quenching included)
  - Solid angle
  - Scattering and absorption

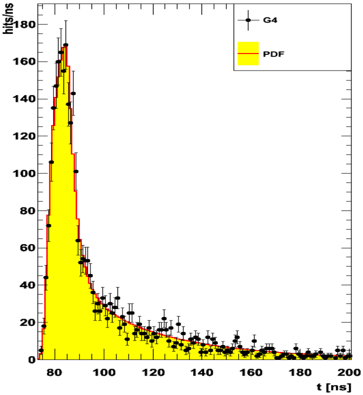
$\Rightarrow$ Energy via log-likelyhood fit to full event

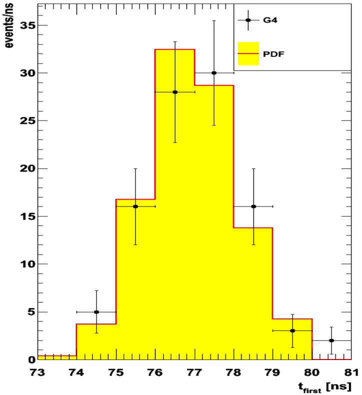




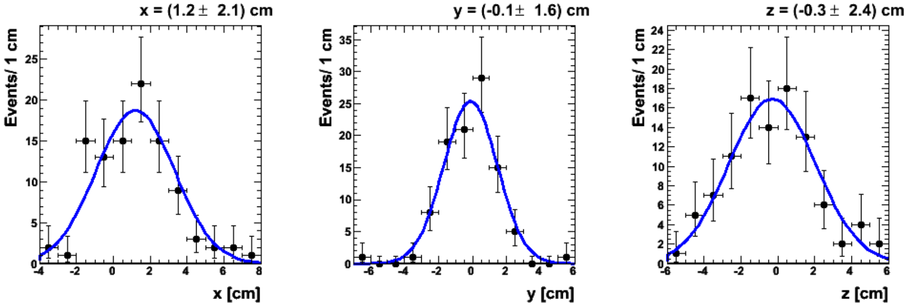
First-hit-time based track fit

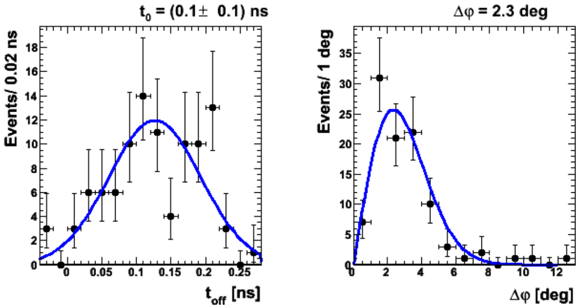
- Comparison: Predicted first hit $\leftrightarrow$ Obtained first hit
- PDF calculation includes:
  - Track parameters $\longrightarrow \frac{dL}{dx}$-profile (quenching included)
  - Solid angle and time jitter of PMT
  - Decay time spectum of scintillator
  - Delay induced by scattering (reemission time included)





Results





Particle: mu-

Energy: 500 MeV

Origin: (0.0 , 0.0 , 0.0)

Direction: (-1 , 0 , 0)

Conclusion

Track reconstruction at the 1 GeV scale

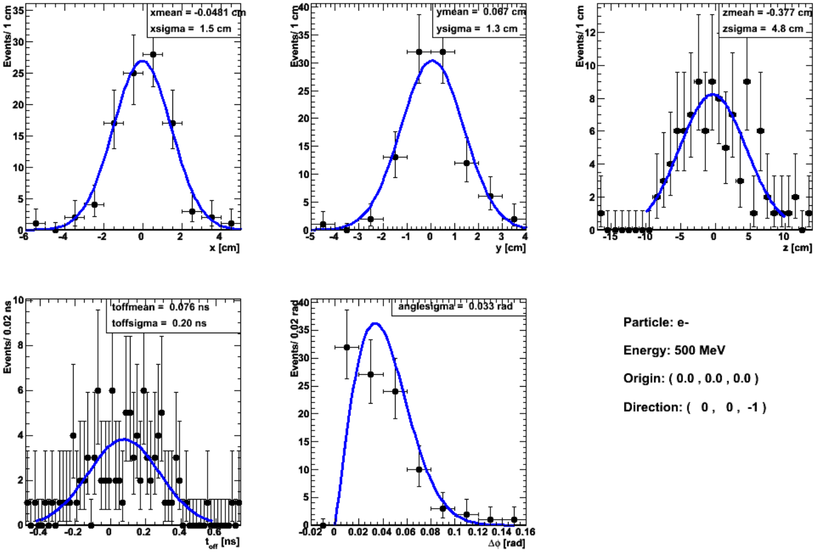
- Electron-muon discrimination possible via observation of the muon's decay electron
- Energy reconstruction by a global fit to the collected PMTs' charges
- Track reconstruction by a global fit to the arrival times of the first photons
- Similar methods can be applied for reconstruction of electron and muon tracks

Next steps

- Look at real ν-interactions
- Look at $\pi^{\pm}$ background for ν_{μ} appearance
- Determine physics potential using a "realistic" β-beam

Appendix

Track fit results for electrons



Particle: e-

Energy: 500 MeV

Origin: (0.0 , 0.0 , 0.0)

Direction: (0 , 0 , -1)

PDF for the charge based energy fit

Basic PDF

- Use Poisson distribution to describe probability of a PMT being hit by n photons

$\Rightarrow$ $P_{\lambda}^{PMT}(n) = \frac{\lambda^n}{n!}\exp(-\lambda)$

- λ: expected number of photons on the PMT ($\in \mathbb{R}$)

Calculate λ for each PMT

- $\lambda = \int_{\vec{x}_s}^{\vec{x}_e} ds\, \frac{\Omega(s)}{4\pi} \cdot \exp(-\frac{|\vec{r}_{PMT}-\vec{s}|}{\lambda_{tot}}) \cdot \left(\frac{dL}{dx}(\vec{s})\right) \cdot \frac{1}{R(\vec{s})}$

with

- $\Omega(s) = \frac{A_{PMT}}{|\vec{r}_{PMT}-\vec{s}|^3}(\vec{p} - \vec{r}_{PMT}) \cdot \hat{n}_{PMT}$
- $\frac{1}{\lambda_{tot}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{ray}} + \frac{1}{\lambda_{iso}}$
- Direct ratio R($\vec{s}$)
- Number of photons per unit path length $\frac{dL}{dx}(\vec{s})$

The hit time PDF for a point like PMT without scattering

- $$P^{PMT}_{\gamma,dir,point}(t) = \frac{1}{\lambda^{PMT}_{dir}} \int_{\vec{x}_s}^{\vec{x}_e} ds \frac{\Omega(s)}{4\pi} \cdot \exp\left(-\frac{|\vec{r}_{PMT}-\vec{s}|}{\lambda_{tot}}\right) \cdot \frac{dL}{dx}(\vec{s}) \cdot \left\{ \left[\Theta(t - t_{sh}(\vec{s})) \sum_i^N \frac{f_i}{\tau_i} \exp\left(-\frac{t-t_{sh}(s)}{\tau_i}\right) \right] * Res_{PMT}(t) \right\}(t)$$
- with:
  - $t_{sh} = \frac{1}{c_L}|\vec{r}_{PMT} - \vec{s}| + \Delta t_\mu(\vec{x}_s, \vec{s}) + t_o$
  - τ_i : Scintillator decay constants
  - f_i : Weights of each decay mode
  - $Res_{PMT}(t)$: PMT time resolution function (gaussian with $\sigma = 1$ns)

PDF for an extended PMT without scattering

- $$P^{PMT}_{\gamma,dir}(t) = \frac{1}{\gamma^{PMT}_{dir}} \int_{\vec{x}_s}^{\vec{x}_e} ds \int_{\partial PMT} dA \frac{\frac{d\Omega}{dA}(\vec{r}_A,\vec{s})}{4\pi} \cdot \exp(-\frac{|\vec{r}_A-\vec{s}|}{\lambda_{tot}}) \cdot \frac{dL}{dx}(\vec{s}) \cdot$$
  $$\cdot \left\{ \left[\Theta(t - t_{sh}(\vec{s},\vec{r}_A)) \sum_i^N \frac{f_i}{\tau_i} \exp(-\frac{t-t_{sh}(s,\vec{r}_A)}{\tau_i}) \right] * Res_{PMT}(t) \right\} (t)$$
- Approximation:
  - $\vec{r}_A = \vec{r}_{PMT,0} + \vec{r}'$

  $$\Rightarrow \quad |\vec{r}_A - \vec{s}| \approx |\vec{r}_{PMT,0} - \vec{s}| + \frac{(\vec{r}_{PMT,0}-\vec{s})}{|\vec{r}_{PMT,0}-\vec{s}|} \cdot \frac{\vec{r}'}{|\vec{r}'|} |\vec{r}'|$$

$$\Rightarrow \quad P^{PMT}_{\gamma,dir}(t) = \frac{1}{\lambda^{PMT}_{dir}} \int_{\vec{x}_s}^{\vec{x}_e} ds \frac{\Omega(s,\vec{r}_{PMT,0})}{4\pi} \cdot \exp(-\frac{|\vec{r}_{PMT,0}-\vec{s}|}{\lambda_{tot}}) \cdot \frac{dL}{dx}(\vec{s}) \cdot$$
$$\cdot \frac{1}{A} \int_{\partial PMT} dA \left\{ \left[\Theta(t - t_{sh}(\vec{s},\vec{r}_A,)) \sum_i^N \frac{f_i}{\tau_i} \exp(-\frac{t-t_{sh}(s,\vec{r}_A)}{\tau_i}) \right] * Res_{PMT}(t) \right\}$$
$$= \frac{1}{\lambda^{PMT}_{dir}} \int_{\vec{x}_s}^{\vec{x}_e} ds\, g(\vec{s}) \cdot F(t - t_{sh}(\vec{s},\vec{r}_{0,PMT}), \angle(\vec{s} - \vec{r}_{PMT,0}, \hat{n}_{PMT}))$$

PDF for an extended PMT with scattering

Basic approach

- $$P_\gamma^{PMT}(t) = \frac{1}{\lambda} \int_{\vec{x}_s}^{\vec{x}_e} ds \frac{g(\vec{s})}{R(\vec{s})} \left[R(\vec{s}) F(t - t_{sh}, \xi) + (1 - R(\vec{s})) G(t - t_{sh}, \vec{s}) \right]$$
$$= \frac{1}{\lambda} \int_{\vec{x}_s}^{\vec{x}_e} ds \frac{g(\vec{s})}{R(\vec{s})} B(t - t_{sh}(\vec{s}), \rho, |\Delta\phi|, |\Delta z|)$$

with $\xi = \angle(\vec{s} - \vec{r}_{PMT,0}, \hat{n}_{PMT})$

Calculation of time distribution of scattered photons G

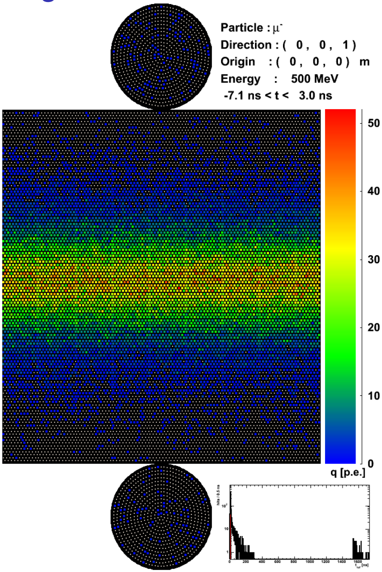
- Approximation:
$G(t - t_{sh}(\vec{s}), \xi, \rho, |\Delta\Phi|, |\Delta z|) \approx G(t - t_{sh}(\vec{s}), |\vec{r}_{PMT,0} - \vec{s}|)$
- $G(t - t_{sh}(\vec{s}), |\vec{r}_{PMT,0} - \vec{s}|) \approx [F(t', 1) * P_{scat}(t')](t)$

PDF for first hits

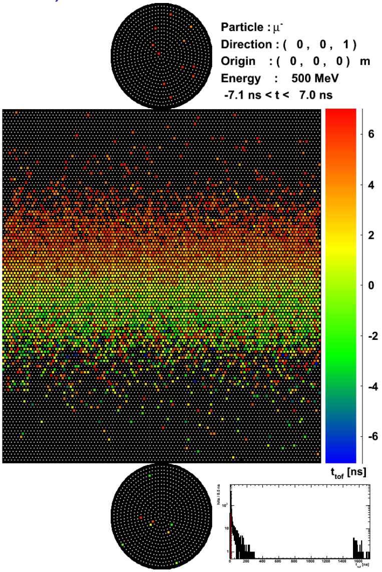
- $$P_{1^{st}\gamma}^{PMT}(t) = P_\gamma^{PMT}(t) \left[1 - \int_{-\infty}^{t} dt' P_\gamma^{PMT}(t') \right]^{(n_\gamma - 1)} \cdot n_\gamma$$

Eventdisplay with upward going neutrinos

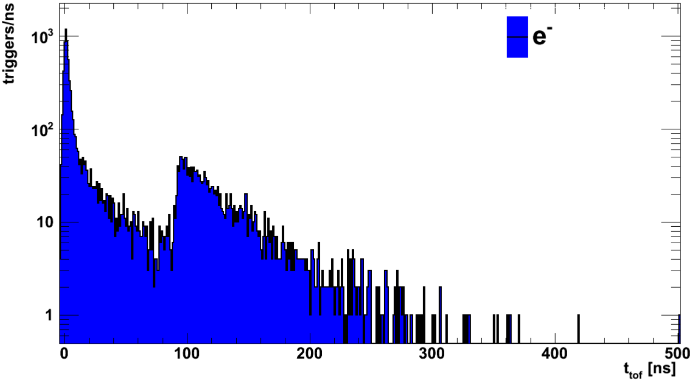
Charge



(First-) hit time



Borexino electronics



Borexino electronics