Vertex reconstruction

in large liquid scintillator detectors

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Why a vertex reconstruction?

- *Novel track reconstruction* has been developed
- Holds great potential for any liquid scintillator detector
- Has a limited number of fundamental assumptions
- Gain topological energy deposition information

Novel track reconstruction needs a reference point

- Providing vertex to the *Novel track reconstruction*
  - Currently for LENA(low energy neutrino astronomy)
  - Operation in an energy range of a few MeV to GeV
  - Also works with a start point near the track

Time of flight

Time of flight for photon i

$$t_i = \frac{D(x_i(0), x_i(t))}{v_g}$$

- $t_i \hat{=}$ Time of flight for photon i
- $v_g \hat{=}$ Group velocity
- $D(x_i(0), x_i(t))$ distance $x_i(0)$ to $x_i(t)$

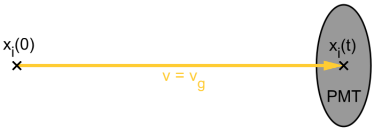


Figure : Time of flight for a photon.

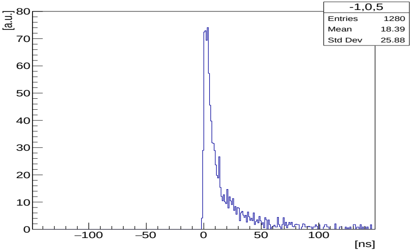
Not considered

- Scattering
- Absorption with reemission
- Scintillation decay time
- Electronic effects

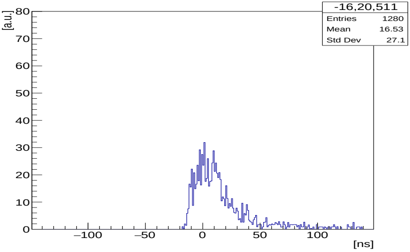
Time difference histogram

$$t_{i,dif} = t_{i,hit} - t_i$$

- $t_{i,dif} \triangleq$ Difference in time for photon i
- $t_{hit} \triangleq$ Measured time for photon i
- $t_i \triangleq$ Time of flight for photon i



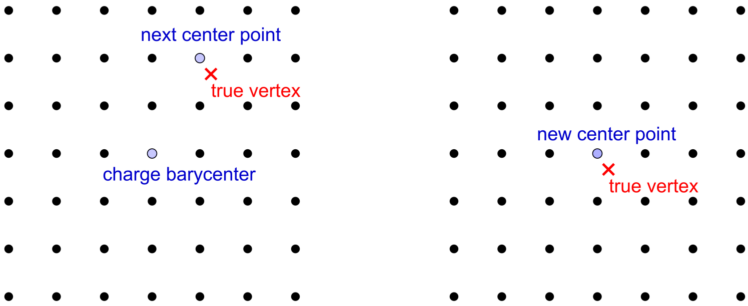
(a) Near the true vertex



(b) ~5 m away from true vertex

Figure : Examples for time difference histograms at the true vertex and 5 m aside from the true vertex.

Grid



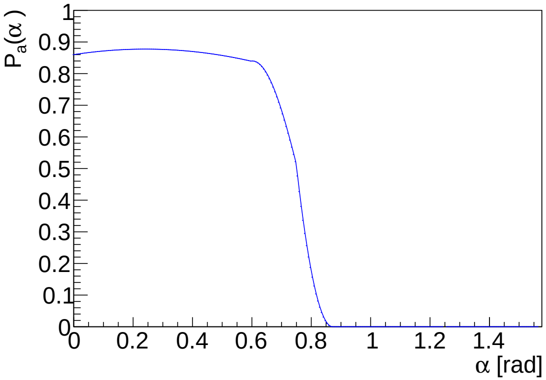
(a) First iteration (b) Following iteration

Figure : 2 dimensional example grid to illustrate the vertex finding.

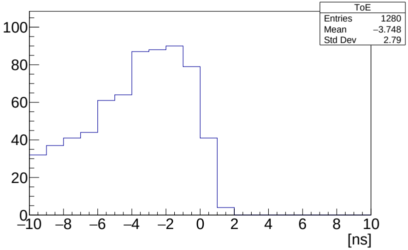
Angular acceptance of PMTs

$$\cos\alpha = \frac{\vec{p}\cdot\vec{n}}{|\vec{p}|\cdot|\vec{n}|}$$

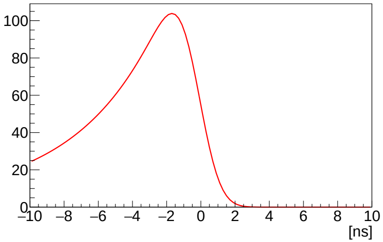
- α incident angle
- $\vec{n}$ PMT normal vector
- $\vec{p}$ incident vector



Time fitting and evaluation algorithm



(a) Histogram at determined vertex



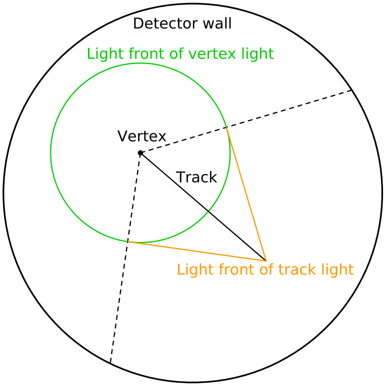
(b) Fit for (a)

The fit considers:

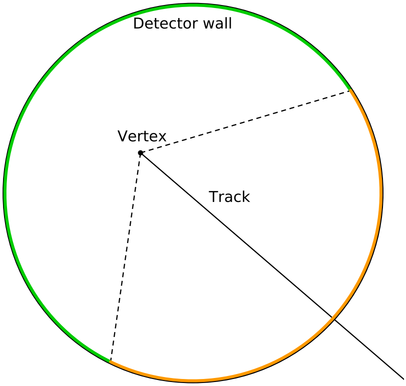
- Scintillation decay time
- PMT time resolution

$$t_{i,dif} = t_i - t_{i,hit}$$

High energy event development



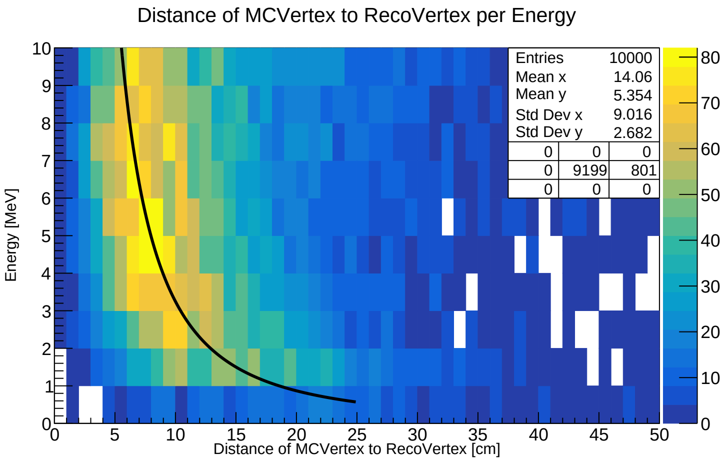
(a) A few nanoseconds after the events start



(b) First hit distribution after the event

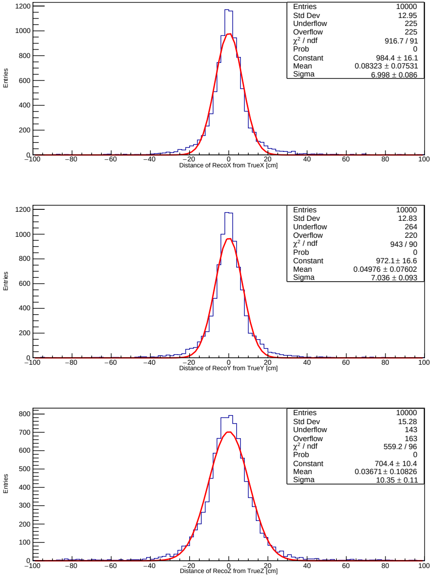
Figure : Distribution of first hit information

LEVertex



Figure

MeV positional reconstruction results



- Results for 10k electron events
- Fit for X,Y and Z direction
- 0.5 to 10.0 MeV Energy
- Random position in the detector
- $\sigma_{x,y,z} = \pm 14.34$ cm

Time reconstruction results

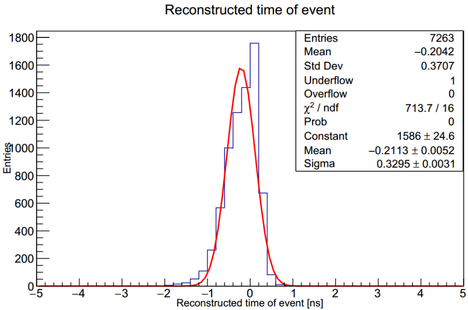


Figure : Event time reconstruction results in MeV range

- Only results within 20 cm of true vertex
- From fit σ_t ± 0.33 ns
- Gaussian distribution around 0 ns expected
- Shift and excess due to underestimated TOFs

Reconstruction of a GeV muon

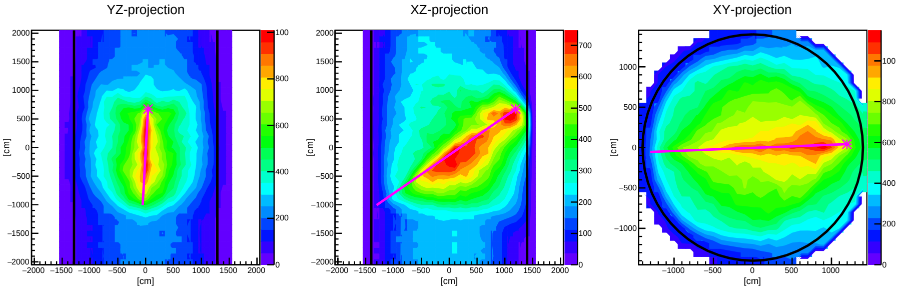
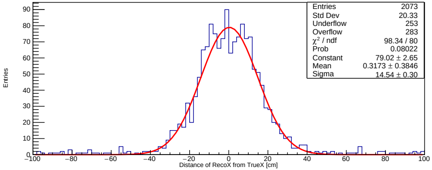
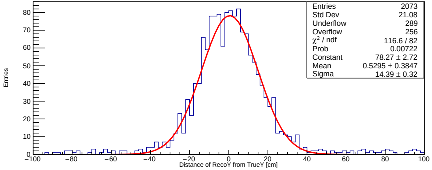


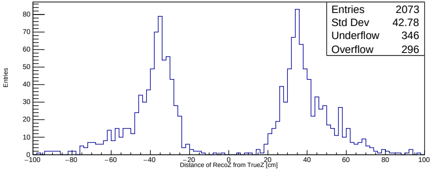
Figure : Example muon event

- 5.8 GeV Simulated event energy

GeV positional reconstruction results

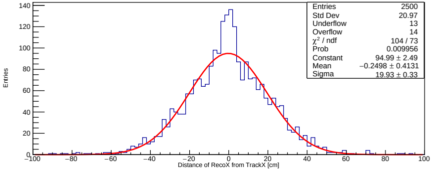


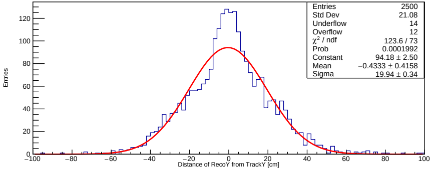


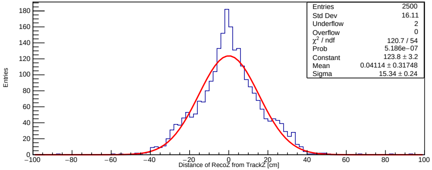


- Results for 2500 muon events
- Fit for X,Y and Z direction
- 5.0 to 10.0 GeV Energy
- Random position in the detector

GeV positional reconstruction near track







- Distance to true track
- Point near track is enough for *Novel track reconstruction*
- Fit for X,Y and Z direction
- $\sigma_{x,y,z} = \pm 34.56$ cm

GeV time reconstruction

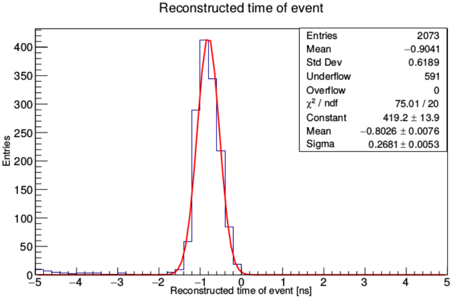


Figure : Event time reconstruction results in GeV range

- Only results within 20 cm of true vertex
- From fit σ_t ± 0.27 ns
- Gaussian distribution around 0 ns expected
- Shift due to underestimated TOFs and shift of reconstructed vertex along track

Summary & Outlook

Conclusion:

- Determination of time and position is achieved
- Applicable for a energy range of a few MeV to GeV
- MeV range: position: $\sigma_{x,y,z} = \pm 14.34$ cm, time σ_t ± 0.33 ns
- GeV range: position: $\sigma_{x,y,z} = \pm 34.56$ cm, time σ_t ± 0.27 ns
- Direction determination 99.2% with in 25°
- Build on *Novel track reconstruction* software foundation:
  - Results can be provided to the *Novel track reconstruction*
  - Simple integration is possible
- Parallelization & Fast algorithm (a few seconds for GeV events)

Outlook:

- Implementation of a energy reconstruction
- Consideration of time delay effects
- Full adaptation for JUNO detector

Thank you for your attention.

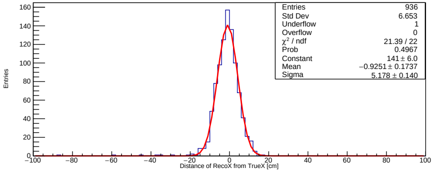
Literature

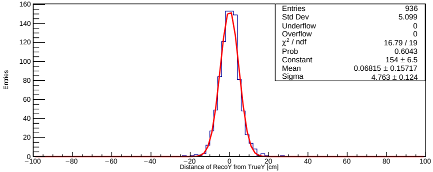
Juno collaboration.
Neutrino physics with juno.
http://arxiv.org/pdf/1507.05613v2.pdf.

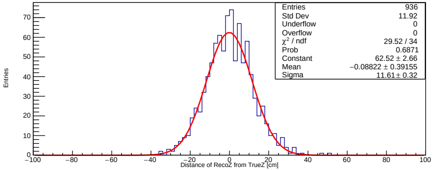
S. Lorenz.
Topological Track Reconstruction in Liquid Scintillator and LENA as a Far-Detector in an LBNO Experiment.
Dissertation, Physik-Department, der Universität Hamburg, Dezember 2016.

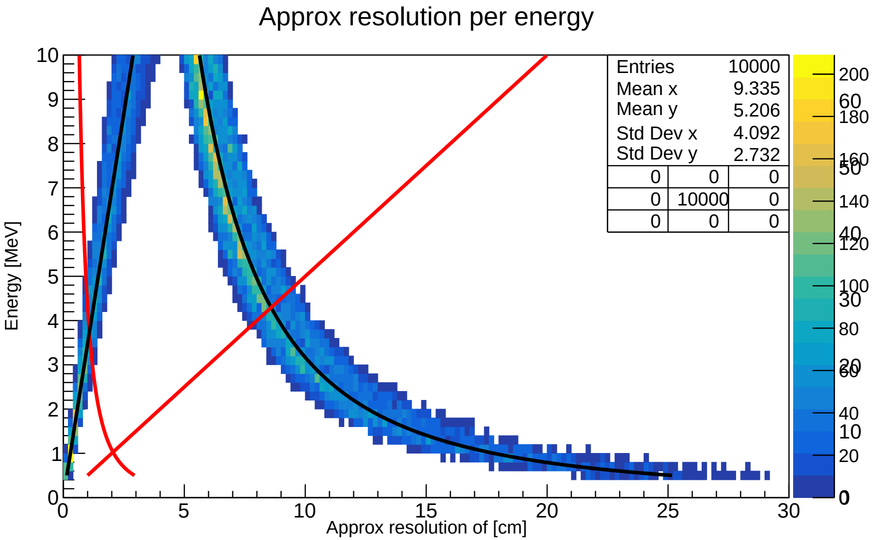
T. Stempfle.
Reconstruction of spatially extended events in borexino.

For single energy at 3 MeV



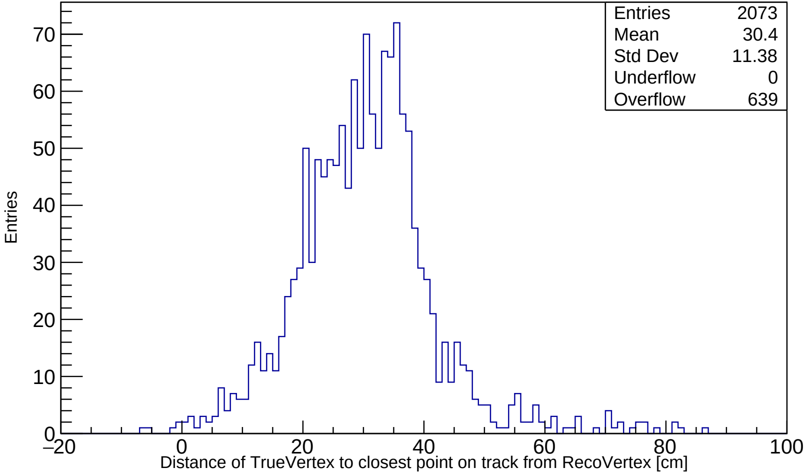





Approx resolution per energy
Entries 10000
Mean x 9.335
Mean y 5.206
Std Dev x 4.092
Std Dev y 2.732
0 0 0
0 10000 0
0 0 0
Energy [MeV]
Approx resolution of [cm]
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
200
180
160
140
120
100
80
60
40
20
0
60
50
40
30
20
10
0

Figure

Shift along track



Figure

Reconstruction close to the track

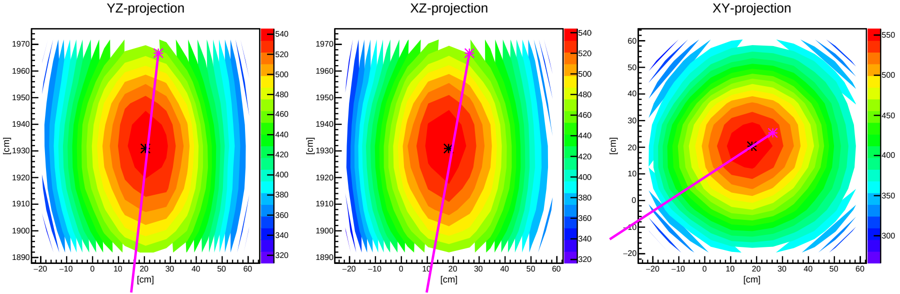
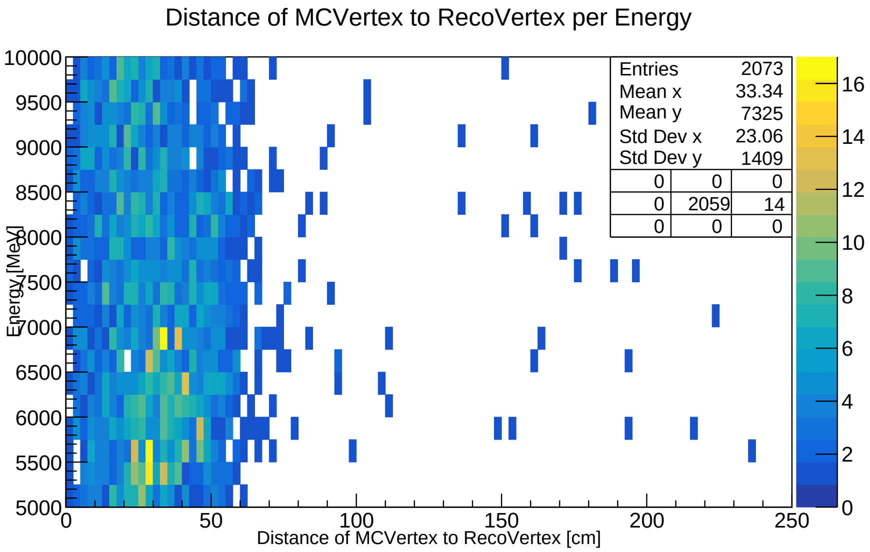


Figure : Example for a reconstructed vertex near the track.


Distance of MCVertex to RecoVertex per Energy
Entries 2073
Mean x 33.34
Mean y 7325
Std Dev x 23.06
Std Dev y 1409
0 0 0
0 2059 14
0 0 0
Energy [MeV]
Distance of MCVertex to RecoVertex [cm]
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
10000
0
50
100
150
200
250
0
2
4
6
8
10
12
14
16

Figure

Example reconstruction in the JUNO detector

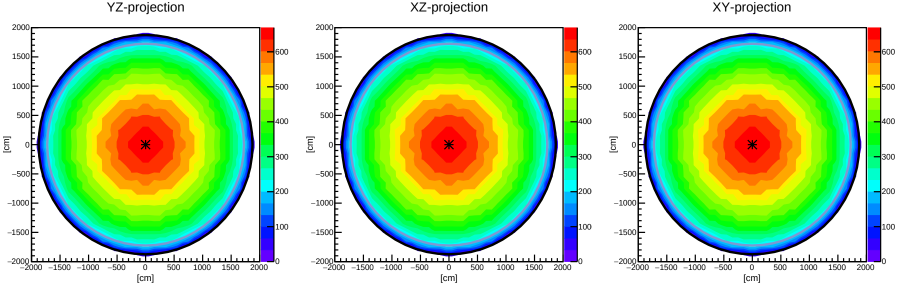


Figure : Example for a reconstructed vertex inside the JUNO detector.

- True vertex simulated at the center
- No adjustments for acrylic or water
- Symmetry effects enable correct reconstruction

Reconstruction of a MeV electron

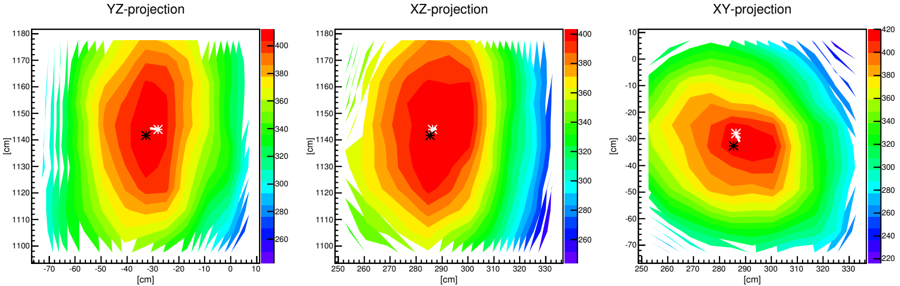
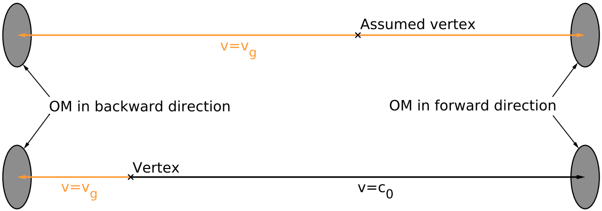
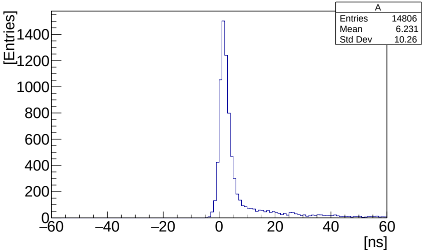


Figure : Example electron event. 6.70 MeV Simulated event energy

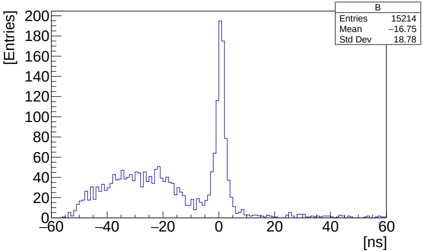
- 5.32 cm Distance true (white) to reconstructed vertex (black)
- 5.46 cm Approximated statistical resolution
- $\sim$9 cm for BOREXINO
- $\sim$3 cm for JUNO (simulated in center)

Direction determination





(a)



(b)

Direction reconstruction

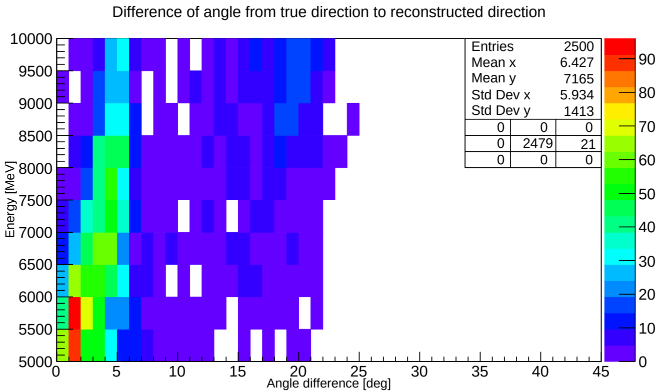
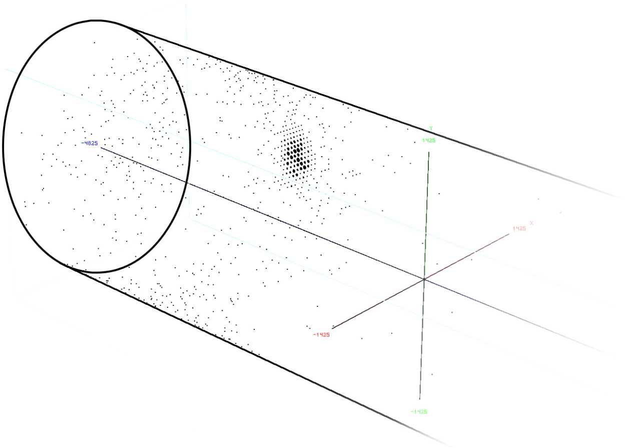


Figure : Direction determination for event GeV range

- For 99.2% the direction was determined within 25°
- For 75.7% the direction was determined within 7°

Charge barycenter

$$\vec{P}_{bc}(pmt) = \frac{\sum_{pmt=1}^{PMT} \vec{p}_{pmt} \cdot Hit_{pmt}}{\sum_{pmt=1}^{PMT} Hit_{pmt}}$$



Survival probability

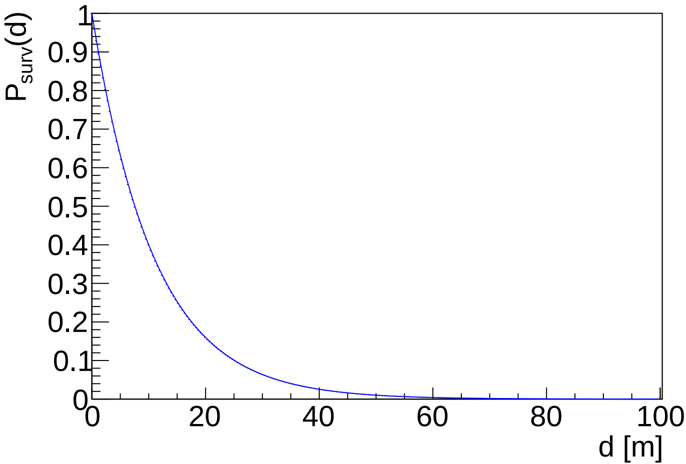


Figure : Photon survival probability. $P_{sp}(s) = exp(-\frac{s}{A_L})$

Hit probability

$$P_{hit} = \frac{r_{pmt}^2 \cdot (\vec{V}_{pmtNormal} \cdot (\vec{V}_{vertex} - \vec{V}_{pmt}))}{4 \cdot |\vec{V}_{vertex} - \vec{V}_{pmt}|^3}$$

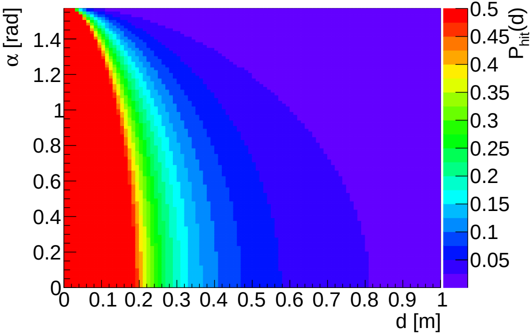


Figure : Hit probability.

Neutrino oscillation

- Homestake Experiment => Solar neutrino problem
- Solution: Neutrino oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\ e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\ e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} \mathrel{\hat{=}} \cos(\Theta_{ij})$ $s_{ij} \mathrel{\hat{=}} \sin(\Theta_{ij})$ $\Theta_{ij} \mathrel{\hat{=}}$ mixing angle $\delta \mathrel{\hat{=}}$ CP-violating phase

Transition probability

$$P(\alpha \to \beta; t) = \sum_i |U_{\alpha i} U^*_{\beta i}|^2 + 2\mathrm{Re} \sum_{j>i} U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} \exp\left(-i\, \frac{\Delta m^2_{ij}}{2}\, \frac{L}{E}\right)$$

$L \mathrel{\hat{=}}$ travel distance $E \mathrel{\hat{=}}$ energy $\Delta m^2_{ij} = m^2_i - m^2_j$

Neutrino Mass Ordering

Parameters that have been determined are:

$$\Theta_{12}, \Theta_{13}, \Theta_{23}, \Delta m^2_{21} \text{ and } |\Delta m^2_{31}|$$

Sign of Δm^2_{31} is unknown:

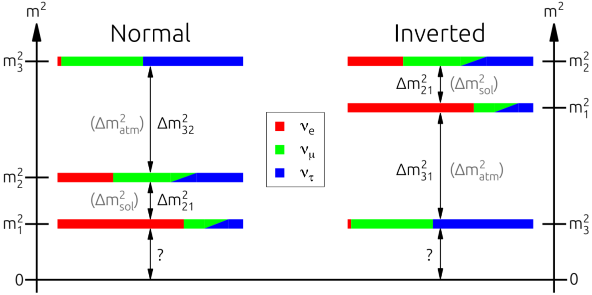


Figure : Neutrino Mass Ordering [2]

Determining the Neutrino Mass Ordering

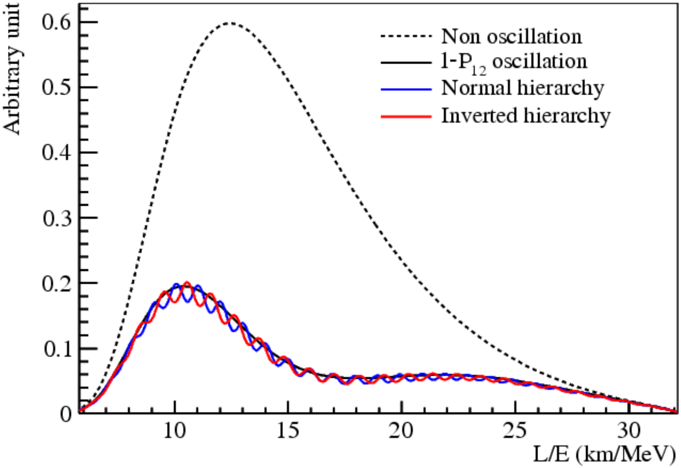


Figure : Reactor antineutrino flux [1]

Jiangmen Underground Neutrino Observatory

- Is being built in China
- Antineutrino experiment
- IBD: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Muon rate $\sim$3 Hz

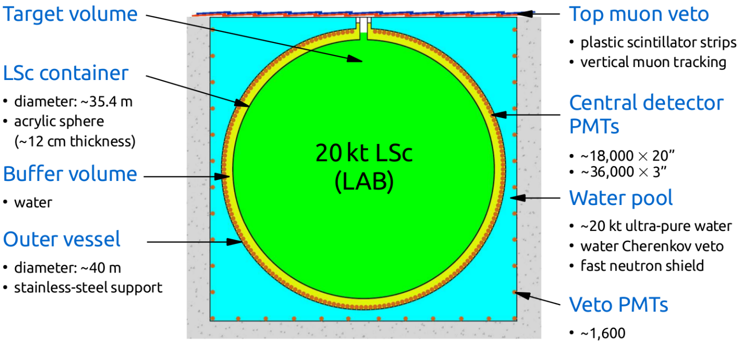


Figure : Outline of the JUNO detector [1]