Waveform Reconstruction of IBD and Muon Events in JUNO

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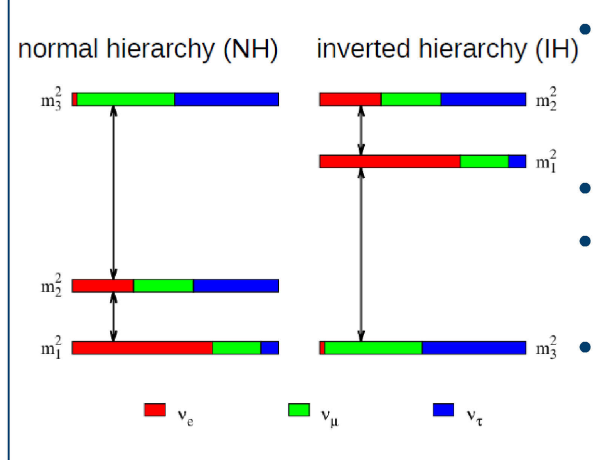
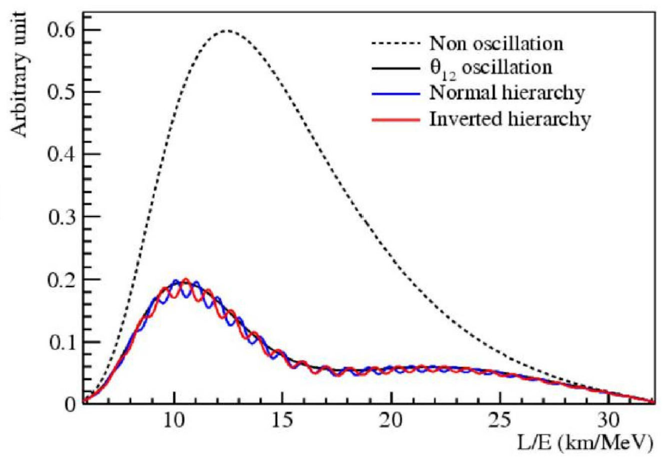
Physics Motivation [1]



Neutrino mass hierarchy

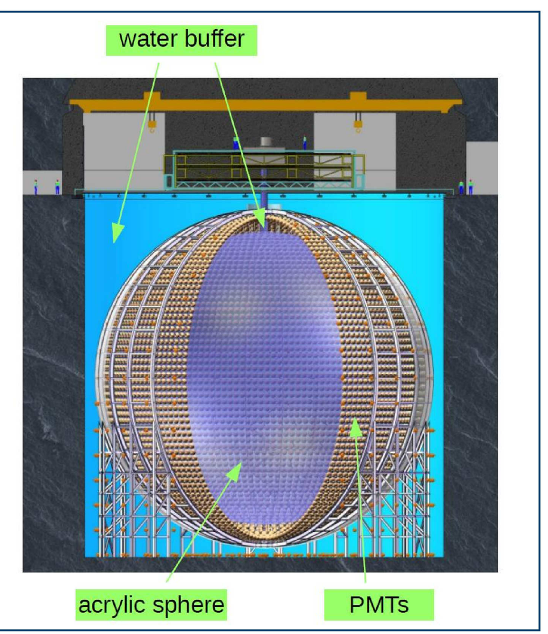
- Measurement of neutrino mass hierarchy: confirm either normal hierarchy (NH) or inverted hierarchy (IH)
- Phase of oscillation is different for NH and IH
- Requires good energy resolution (design: $3\%/\sqrt{E/MeV}$)
- Discrimination between NH and IH with ~3σ after 6 years with E_{res} = 3% and ~100,000 IBD events



Neutrino reactor spectrum

Experiment [2]

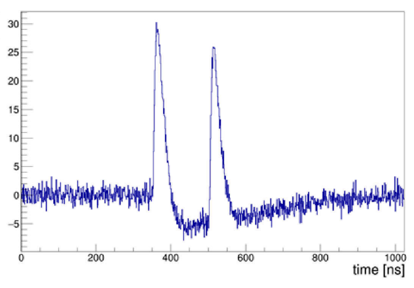
- 20 kton liquid scintillator detector
- Acrylic sphere: 35 m diameter
- 18,000 large PMTs (20" diameter)
  - 5,000 Hamamatsu PMTs
  - 13,000 NNVT PMTs
- 25,000 small PMTs (3" diameter)
- 650 m underground
- 52 km baseline
- Location: Jiangmen in China
- Data-taking will start in 2021



IBD Waveform Reconstruction

Introduction

- Antineutrinos are detected via the Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$
- Positron annihilates with electron into 2 photons
- Total visible energy E_{vis} is related to kinetic energy of antineutrino: $E_{vis} \approx E_\nu$ – 782 keV
- PMTs convert photons into photo-electrons (PE)
- IBD events have a low occupancy rate (="hit density"), typically ≤ 3 PE per PMT
- Waveform is FADC trace of the PMT read-out electronics
- Sample frequency is 1 GHz
- Waveforms feature PEs as peaks

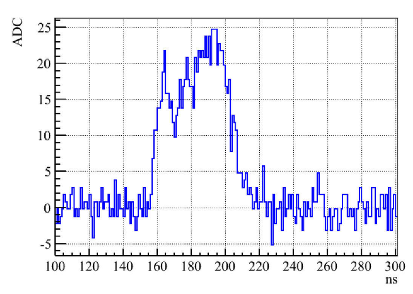

Example of IBD waveform

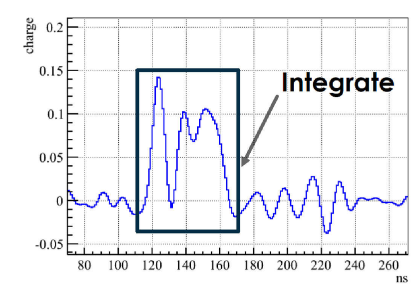
- IBD waveform reconstruction methods under study:
  - **Deconvolution method**
  - **Waveform template fit**
  - Waveform integration
  - Hit counting

Methods

Deconvolution Method:

- Waveform results from convolution of photon hit distribution with single PE (SPE) response plus noise
- Deconvolution method reconstructs charge and time of each hit based on Discrete Fourier Transforms (DFT) from the integral of the peak area and peak position
- SPE hit reconstruction possible from frequency domain

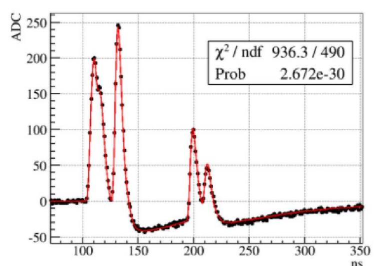

Example of simulated waveform [3]



Waveform after deconvolution [3]

Waveform Template Fit:

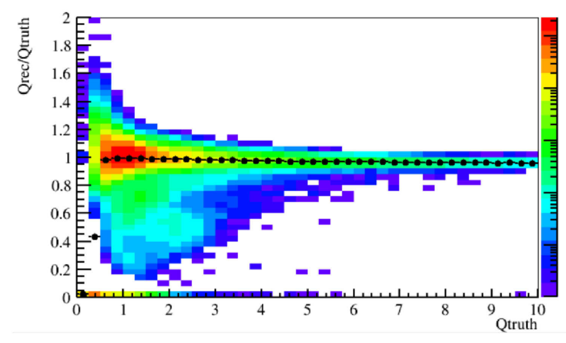
- Waveform is fitted with template fit
- Template describes SPE response
- Charge and time are reconstructed from fit parameters

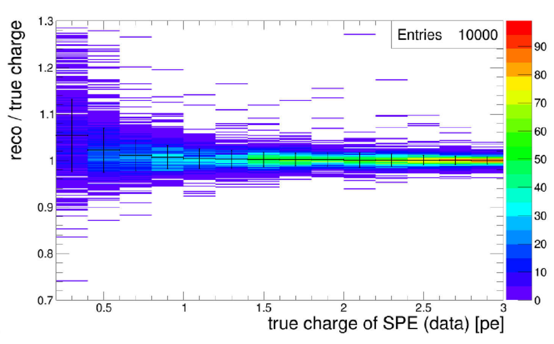

Example of waveform template fit [4]

Results

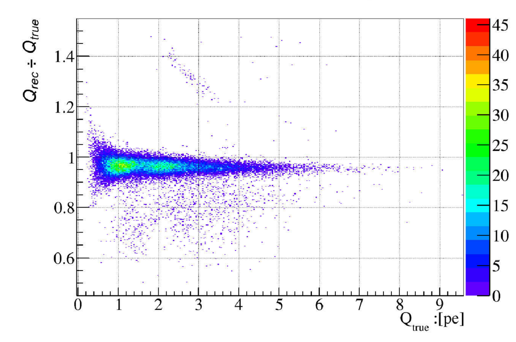
Deconvolution Method:

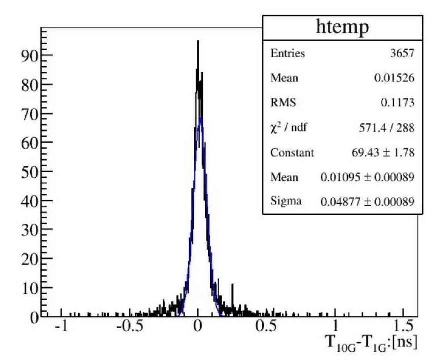
- Residual charge non-linearity of 1 %


Charge resolution for 0 – 10 PEs per waveform [3]


Charge resolution for SPE waveforms

Waveform Template Fit:

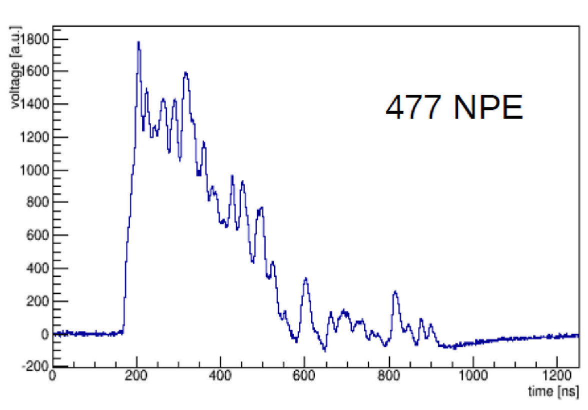

Charge resolution for 0 – 10 PEs per waveform [4]


Time resolution [4]

Muon Waveform Reconstruction

Introduction

- Waveforms of muon events feature a high number of PE (NPE), typically 500 – 5000 PE
- Reconstruction of each photon like for IBD events not possible
- First hit time (fht), charge, and rise time are needed to reconstruct muon tracks for muon vetoes [5]

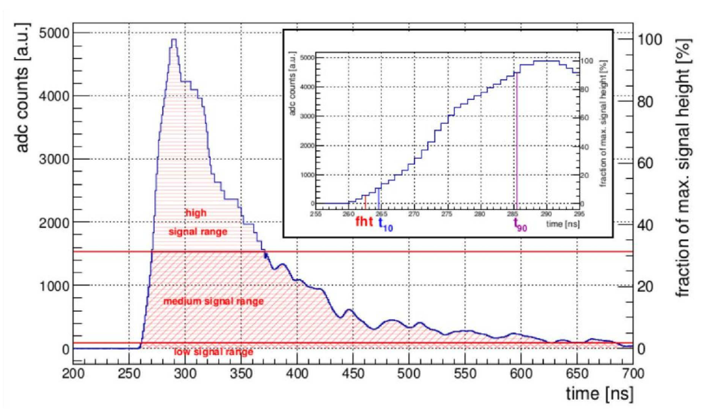


Example of muon waveform

Methods

Time:

- Find fht in typically steeply rising edge of waveform
- Use Constant Fraction Discriminator (CFD) approach:
  - Set fht when waveform passes threshold
  - Set threshold as relative fraction of waveform height



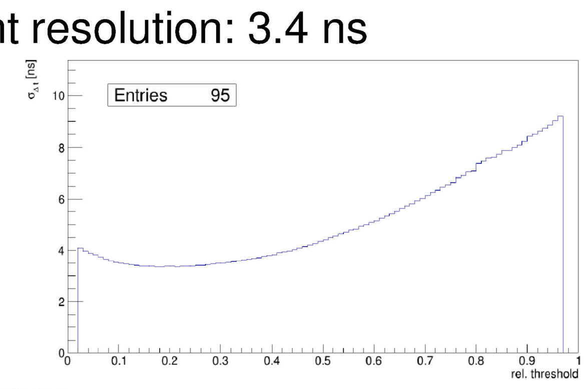
Charge:

- Charge reconstruction done by integrating the entire waveform after baseline correction

Results

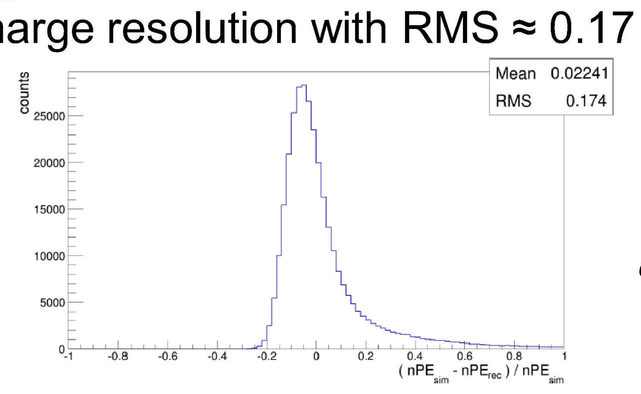
Time:

- Best fht resolution for threshold at 4% of signal height
- Fht resolution: 3.4 ns


Fht resolution in dependence on relative threshold height

Charge:

- Charge resolution with RMS ≈ 0.17 obtained


Distribution of true – reconstructed charge relative to true charge

Conclusion & Outlook

IBD Waveform Reconstruction:

- IBD results show a charge non-linearity of 1%
- Further studies are conducted on the time reconstruction for each single PE
- IBD waveform reconstruction by deep learning recently started

Muon Waveform Reconstruction:

- Muon waveform reconstruction allows good muon track reconstruction for muon veto [5]
- Muon waveform reconstruction study continued based on deep learning

References

[1] JUNO collaboration, F. An et al., *Neutrino Physics with JUNO*, 1507.05613.
[2] JUNO collaboration, Z. Djurcic et al., *JUNO Conceptual Design Report*, 1508.07166.
[3] Zeyuan Yu, Institute of High Energy Physics, Beijing
[4] Yaping Cheng, Forschungszentrum Jülich GmbH & Institute of High Energy Physics, Beijing
[5] Christoph Genster et al., *Muon reconstruction with a geometrical model in JUNO*, JINST, 13 (2018) T03003

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