Waveform Reconstruction of IBD and Muon Events in JUNO

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Physics Motivation

- 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/\text{MeV}})
- Discrimination between NH and IH with \sim 3\sigma after 6 years with E_{\text{unit}} = 3\% and \sim 100,000 IBD events

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 \( E_{\text{vis}} \) is related to kinetic energy of antineutrino: \( E_{\nu_e} = E_{\text{vis}} - 782 \text{ keV} \)
- PMTs convert photons into photo-electrons (PE)
- IBD events have a low occupancy rate (=“hit density”), typically \leq 3 PE per PMT
- Waveform is FADC trace of the PMT read-out electronics
- Sample frequency is 1 GHz
- Waveforms feature PEs as peaks

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

Waveform Template Fit:

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

Results

- Charge resolution for threshold at 4% of signal height
- Deconvolution method: Residual charge non-linearity of 1%

Muon Waveform Reconstruction

- 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

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
- Charge: Charge resolution with RMS = 0.17 obtained

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

References

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