Tuning the JUNO Top Tracker Simulation using the Top Tracker Prototype

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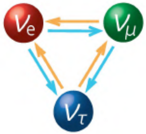
A brief introduction to Neutrino Physics

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) unitary matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino oscillation probability (3 flavor case):

$$\mathrm{P}_{\nu_\alpha \to \nu_\beta}\left(\theta_{jk}, \Delta m^2_{jk}\right) = \sum_{j,k} U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k} e^{-i\Delta m^2_{jk} \frac{L}{2p}}, \qquad \Delta m^2_{jk} = m^2_j - m^2_k$$

$\theta_{12}, \theta_{23}, \theta_{13}$: neutrino mixing angles

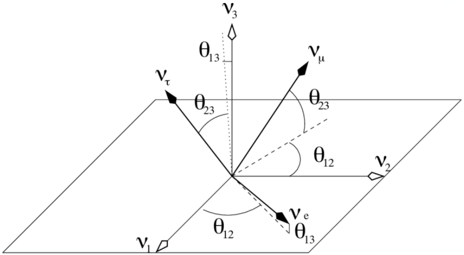
δ : leptonic CP-violating phase

m_1, m_2, m_3: mass eigenvalues

Δm^2_{jk} : neutrino mass splitting

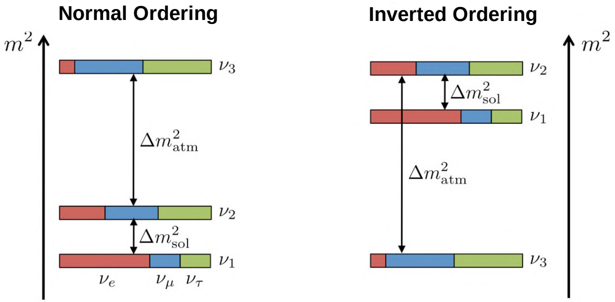
Unknowns:

- Which neutrino is the lightest?
- δ?



Expected measurements at JUNO

- Neutrino Mass Ordering:



JUNO goals:

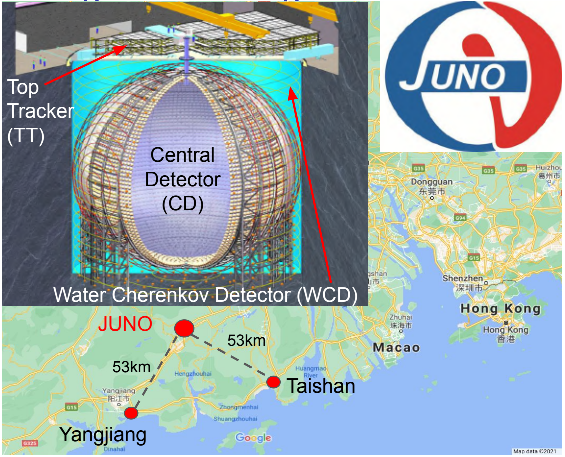
- Determine the neutrino mass ordering
- Precision oscillation measurements

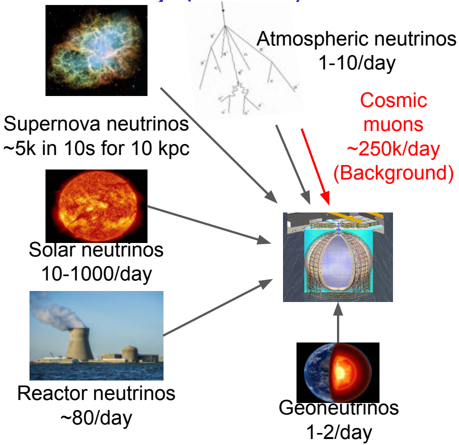
	Current precision	**JUNO precision**
$\sin^2\theta_{12}$	4.1%	0.67%
Δm^2_{21}	2.6%	0.59%
$\lvert\Delta m^2_{31}\rvert$	2.7%	0.44%

- ... and other topics in Particle Physics/Astrophysics...

Resources: F. An et al., Neutrino Physics with JUNO [arxiv: 1507.05613v2]

The Jiangmen Underground Neutrino Observatory (JUNO)

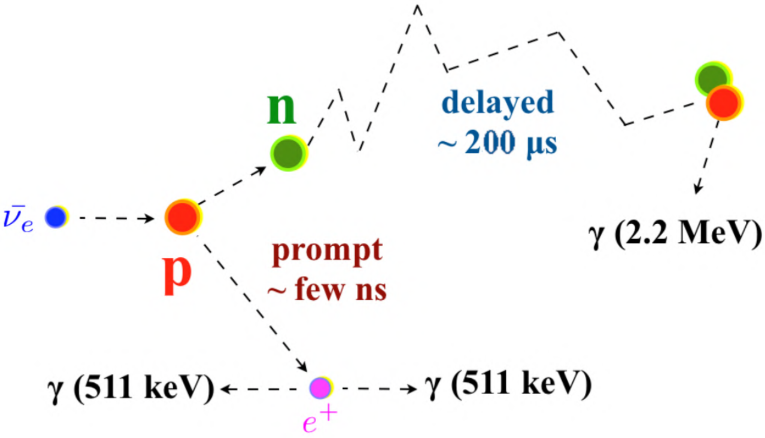




- Reactor electron anti-neutrino ($\bar{\nu}_e$) detector under construction in Jiangmen, China
- Design energy resolution (E_{res})= 3% (at 1MeV)
- Planned to begin data acquisition in 2023

Detecting anti-neutrinos: Inverse beta-decay (IBD)

- IBD: $\bar{\nu}_e + p \rightarrow n + e^+$
- Prompt-delayed signal coincidence $\longrightarrow$ significant background suppression



Backgrounds

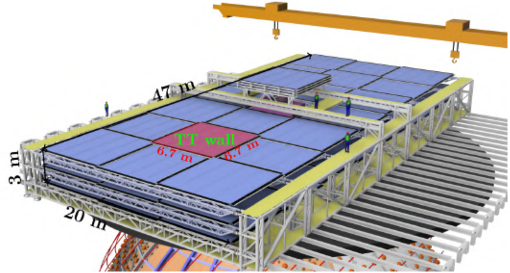
- Accidental Backgrounds
  - Accidental coincidences between unrelated background events
- Cosmogenic ^{9}Li/^{8}He isotopes
  - $\beta - \mathrm{n}$ decays mimicking the IBD signature
- $^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$
  - α particles from natural isotopes react with the ^{13}C in the Liquid scintillator
- Geo-neutrinos
  - $\bar{\nu}_e$ from radioactive decay of natural isotopes of U/Th

<table>
<tr><th>Selection</th><th>IBD efficiency</th><th>IBD</th><th>Geo-νs</th><th>Accidental</th><th>^{8}He/^{9}Li</th><th>fast n</th><th>(α, n)</th></tr>
<tr><td>–</td><td>–</td><td>83</td><td>1.5</td><td>$\sim 5.7 \times 10^{4}$</td><td>84</td><td>–</td><td>–</td></tr>
<tr><td>Fiducial volume</td><td>91.8%</td><td>76</td><td>1.4</td><td rowspan="3">410</td><td>77</td><td rowspan="5">0.1</td><td rowspan="5">0.05</td></tr>
<tr><td>Energy cut</td><td>97.8%</td><td rowspan="3">73</td><td rowspan="3">1.3</td><td rowspan="3">71</td></tr>
<tr><td>Time cut</td><td>99.1%</td></tr>
<tr><td>Vertex cut</td><td>98.7%</td><td>1.1</td></tr>
<tr><td>Muon veto</td><td>83%</td><td>60</td><td>1.1</td><td>0.9</td><td>1.6</td></tr>
<tr><td>Combined</td><td>73%</td><td>60</td><td colspan="5">3.8</td></tr>
</table>

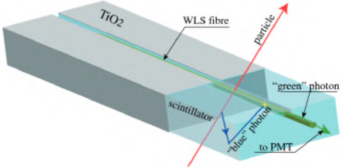
Table 1: The efficiencies of antineutrino selection cuts, signal and backgrounds rates (per day).

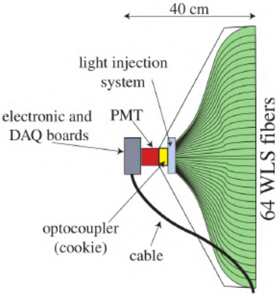
Resources: F. An et al., Neutrino Physics with JUNO [arxiv: 1507.05613v2]

The Top Tracker



- Array of plastic scintillator strips
- $2.6 \times 2.6 \mathrm{cm}^2$ granularity
- coverage: $20 \times 47 \mathrm{m}^2$, 3 layers
- 64-channel MA-PMTs, 992 MA-PMTs
- 64k channels

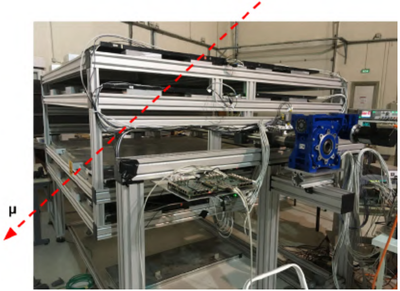




8×8 Channels

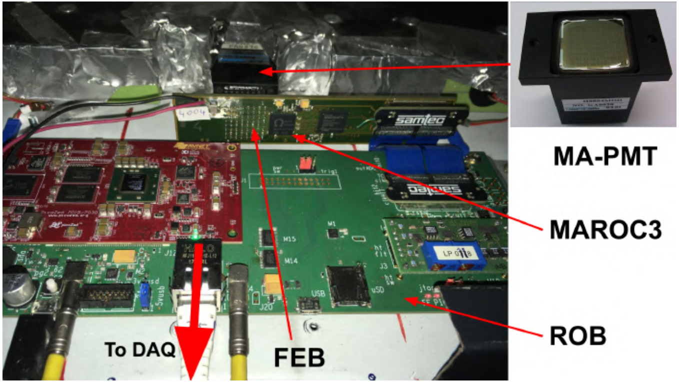
Resources: F. An et al., [arxiv: 1507.05613v2], T. Adam et al. [OPERA], Nucl.Instrum.Meth.A577:523-539 (2007), JUNO Collab., [arxiv: 2104.02565]

The Muon Telescope and the Top Tracker Electronics



The Muon telescope: The Top Tracker prototype

- Built with same materials as Top Tracker
- 64 strips along x and y-directions per sub-layer
- 8 end-caps (512 channels)



- Front-End Board (FEB): PMT digitization and gain correction, noise level control
- Read-Out Board (ROB): High voltage supply to MA-PMTs, control of the calibration LEDs

Characterization of PMT channels: Bellamy's function

$$S_{\mathrm{real}}(x) = \left[\underbrace{\frac{(1-\mathrm{w})}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(\mathrm{x}-\mathrm{Q}_0)^2}{2\sigma_0^2}\right)}_{\text{Type 1 background (Pedestal)}} + \underbrace{\mathrm{w}\theta(\mathrm{x}-\mathrm{Q}_0)\alpha \exp(-\alpha(\mathrm{x}-\mathrm{Q}_0))}_{\text{Type 2 background (events missing the photo−cathode)}} \right] e^{-\mu}$$

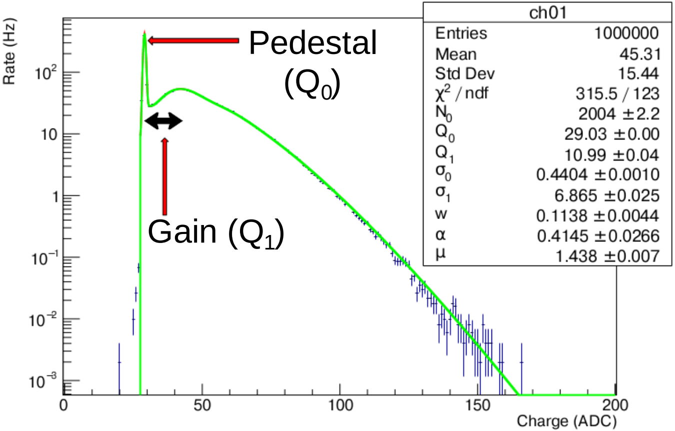
$$+ \underbrace{\sum_{\mathrm{n}=1}^{\infty} \left[\frac{\mu^{\mathrm{n}} \mathrm{e}^{-\mu}}{\mathrm{n}!} \frac{1}{\sigma_1\sqrt{2\pi\mathrm{n}}} \exp\left(-\frac{(\mathrm{x}-\mathrm{Q}_0-\mathrm{Q}_{\mathrm{sh}}-\mathrm{nQ}_1)^2}{2\mathrm{n}\sigma_1^2}\right)\right]}_{\text{Convolution of Gaussians of different number of PEs}}$$

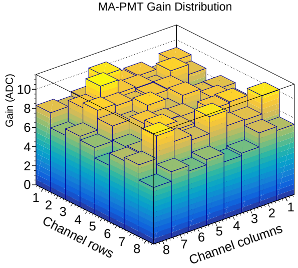
Q_0 = mean of the pedestal
σ_0 = standard deviation of the pedestal
Q_1 = PMT channel gain
σ_1 = Standard deviation of the gain
μ = mean no. of PEs collected
w = Probability that a given background event is of type 2 background
α = coefficient of decrease of the type 2 background
$\theta(x)$ = Heaviside function
$Q_{\mathrm{sh}} = \frac{\mathrm{w}}{\alpha}$

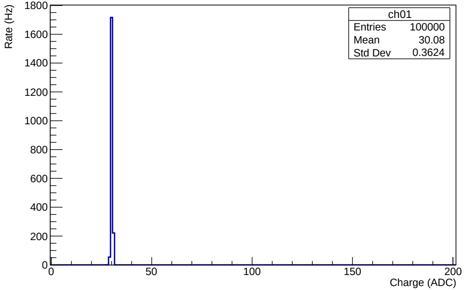
Resources: E.H. Bellamy et al., Nucl.Instrum.Meth.A339 (1994) 468-476

Characteristic analysis of PMT channels

- Non-uniform gain on MA-PMTs
- Expected gain by JUNO: 10^6 (10.5 ADC units)

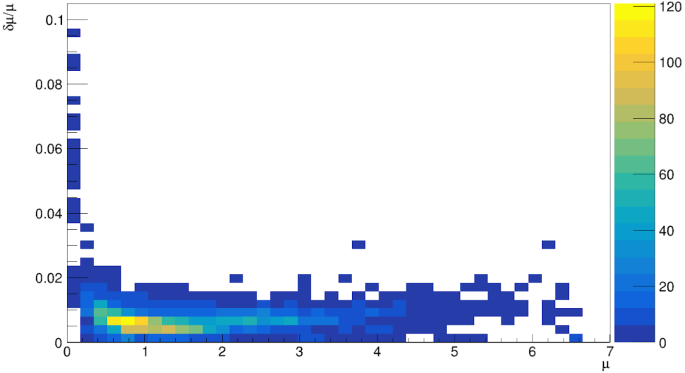






Complementary Analyses (1)

1.Analysis of relative accuracy of light collection



- $<$ 1% relative accuracy on μ at $\mu \in$(1,1.6)

- Tested a new PE number evaluation method
  - based on the no. of events in the pedestal

$$\frac{\sigma\mu_0}{\mu} = \frac{1}{\sqrt{N}}\sqrt{\frac{e^{\mu}-1}{\mu^2}}$$

μ_0 = No. of events in the pedestal
N = Total no. of events
$\sigma\mu_0$ = error of the no. of events in the pedestal

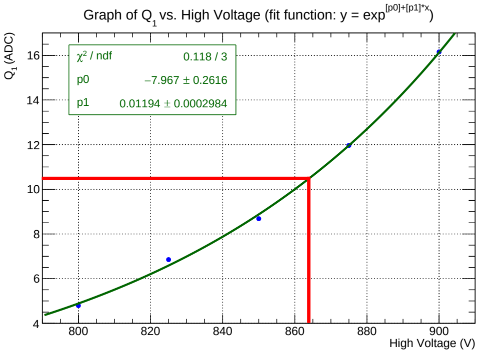
- LED data obtained at different LED biases

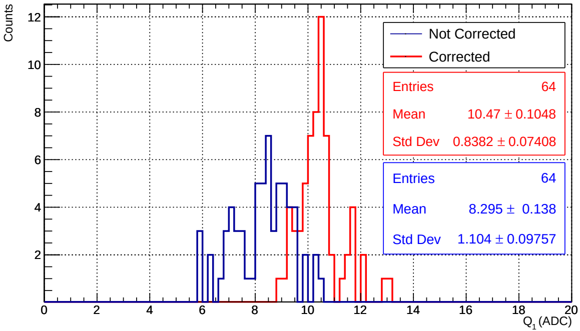
Resources: N. Anfimov et al., Nucl. Instrum.Meth.A 939 61-65 (2019)

Gain Calibration

- Find the high voltage corresponding to a gain of 10.5 ADC on the highest-gain channel
- Take LED data at the calculated high voltage
- Calculate correction factors: $K_i = \frac{Q_{1(max)}}{Q_{1(i)}}, \quad i \in \{1, 2, ..., 64\}$

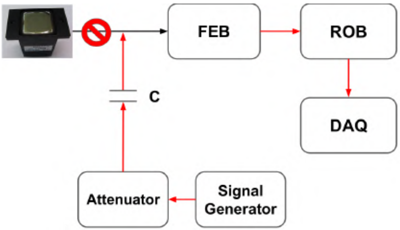
  $Q_{1(i)}$ = gain of the channel i
  $Q_{1(max)}$ = gain of the highest-gain channel.

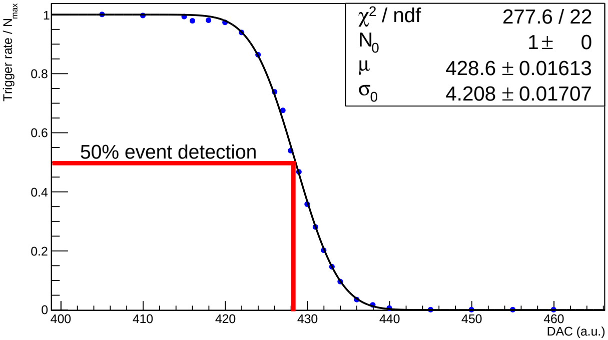




Electronics Calibration

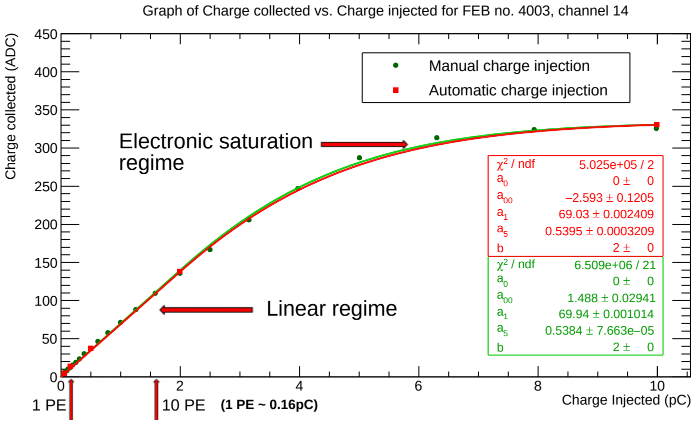
Determination of Digital-to-Analog Converter (DAC) threshold:





- Common detection threshold set to all channels
- Measure very small charges as low as 1/3PE (0.056pC) while keeping noise levels as low as possible
- Expected charge deposition for a muon: 3-6 PE

Charge Calibration



- Only 5 data points taken per FEB during mass testing of 1200 FEBs

- The fit function:

$$f(x) = \begin{cases} a_0 + a_1 x & , x \leq b \\ a_{00} + a_2\left(1 - e^{-a_3 x^{a_4}}\right) & , x > b \end{cases}$$

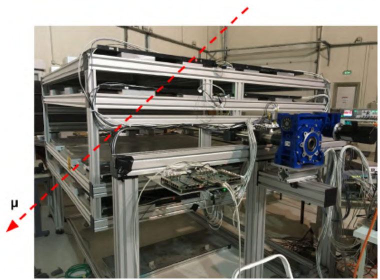
$a_5 = a_3 b^{a_4}$

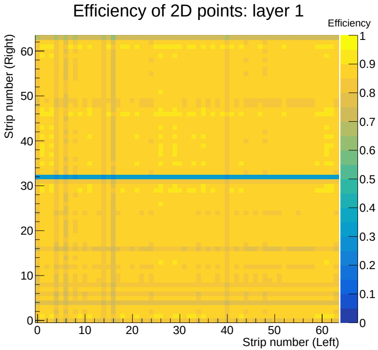
  - Continuity and differentiability of f(x) imposed

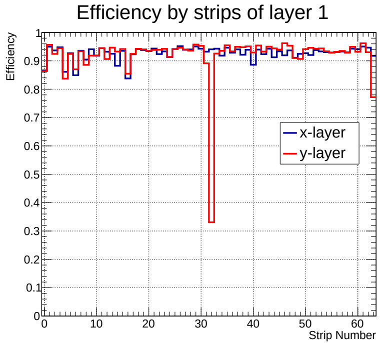
- no. of free parameters reduced
- a_0 fixed to 0 and b fixed to 2
- This result has been already presented to the JUNO Europe-2021 meeting.

Cosmic Muon detection

- Once calibrated, the Muon Telescope can be used to:
  - Test TT electronics in a realistic environment
  - Tune JUNO simulation
- Muon Telescope has 4 layers (instead of 3 in JUNO TT)
  - facilitates layer-wise efficiency calculation
- Majority of strips have ∼90% efficiency

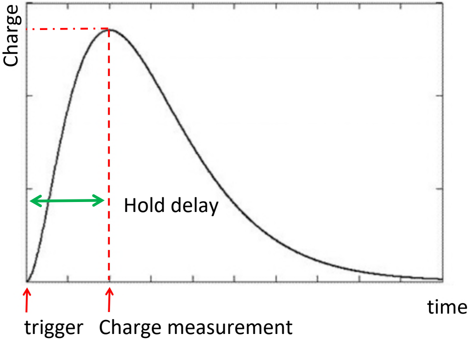


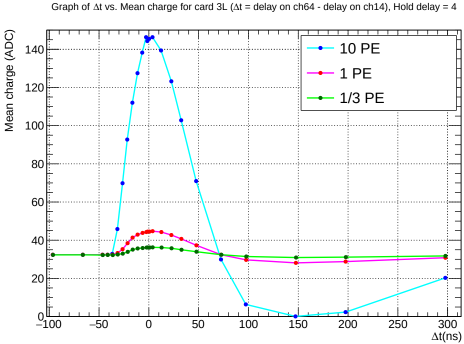




Complementary Analyses (2)

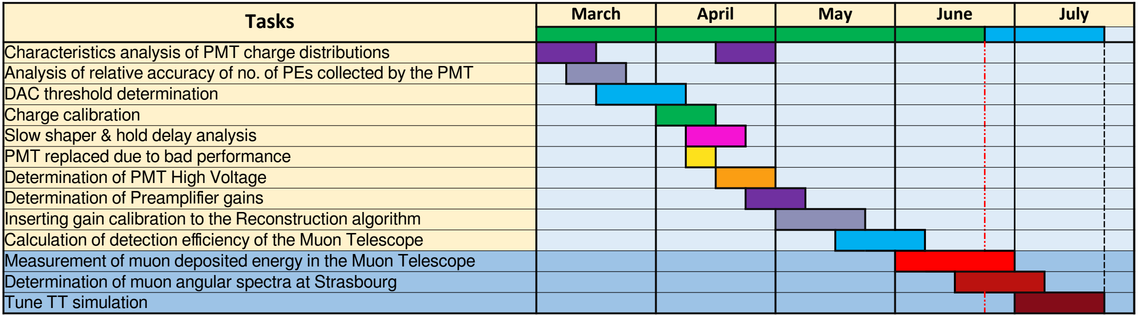
2. Slow shaper & hold delay analysis





- Charges are measured by measuring the peak of the temporal response curve
  - Peak amplitude $\propto$ total charge
- Hold delay = time difference between trigger and measurement
- Slow shaper curve is reconstructed by varying the delay between trigger and signal

Conclusion

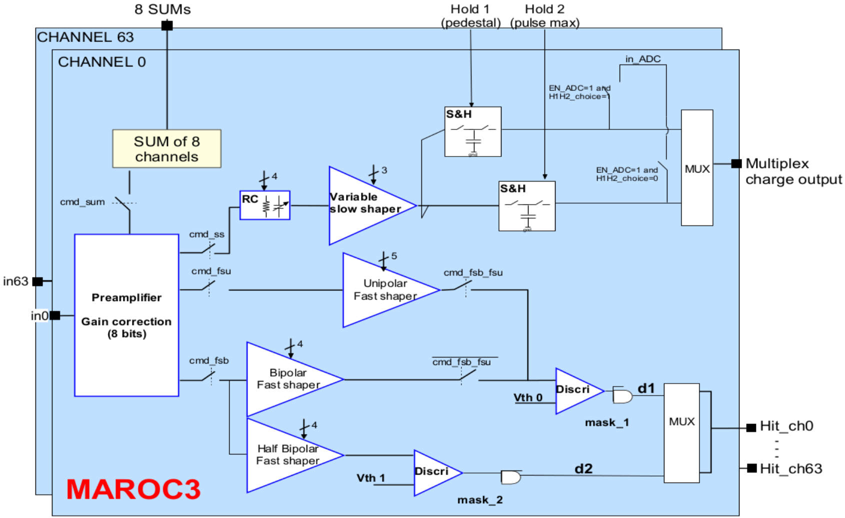


- The tasks fulfilled during this internship were instrumental in developing a thorough understanding of the JUNO Top Tracker, which will be crucial for the succession of the relevant Ph.D. activities.

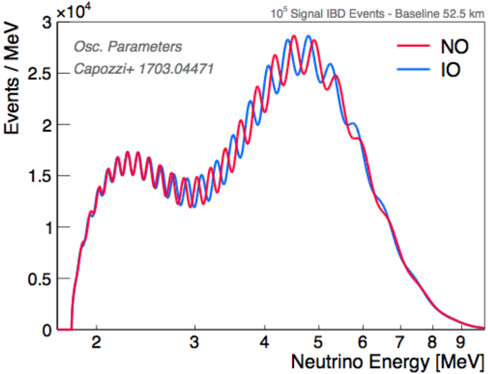
Thank You!

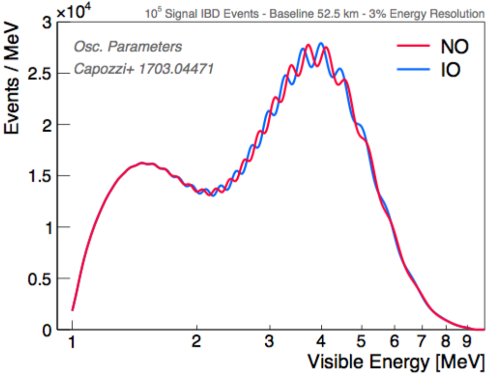
Backup

Multi-Anode Readout Chip v.3 (MAROC3)



JUNO Experiment





- First experiment to see both oscillations (solar and atmospheric) at the same time
- JUNO is a disappearance experiment
- JUNO baseline (53km) is chosen in order to place it at $\bar{\nu}_e$ oscillation minimum
- With the expected good energy resolution, it can discriminate between the 2 mass orderings (hierarchies).

Detection Channels

- IBD: $\bar{\nu}_e + p \rightarrow n + e^+$ (Dominant Channel)
- $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ $(E_{th,\nu} = 17.34\ MeV)$
- $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$ $(E_{th,\bar{\nu}} = 14.39\ MeV)$
- $\nu_\alpha + {}^{12}C \rightarrow \nu_\alpha + {}^{12}C^*$ (Clear signal of SNν's, sensitive to μ and τ flavors due to their high energy)
- $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$ (most sensitive to ν_e's, used to detect prompt SNν_e bursts)
- $\nu_\alpha + p \rightarrow \nu_\alpha + p$

Resources: F. An et al., Neutrino Physics with JUNO [arxiv: 1507.05613v2]