Development of a New Reconstruction Algorithm for JUNO Top Tracker

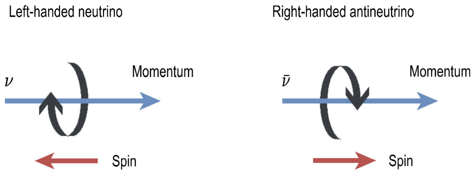
Mohd Talha (M2-PSA)

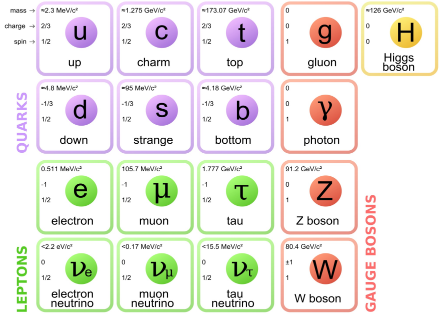
Internship supervisor: J. P. A. M. de André
Faculty of Physics and Engineering (Neutrino Group)
University of Strasbourg

June 23, 2022

Neutrino properties

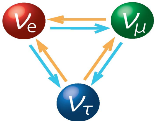
- Proposed by Pauli in 1930.
- Spin 1/2 neutral elementary particles.
- Interact via weak interactions.
- Massless in Standard Model.
- Sources:
  - Solar neutrinos
  - Atmospheric neutrinos
  - Cosmic (Relic, supernova,...) neutrinos
  - Reactor (anti)neutrinos
  - Accelerator neutrinos
  - Geoneutrinos





Neutrino Oscillations

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



Neutrino oscillation probability (3 flavor case):

$$P_{\nu_\alpha \to \nu_\beta}(L, p) = \sum_{j,k} U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k} e^{-i\Delta m^2_{jk} \frac{L}{2p}},$$

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

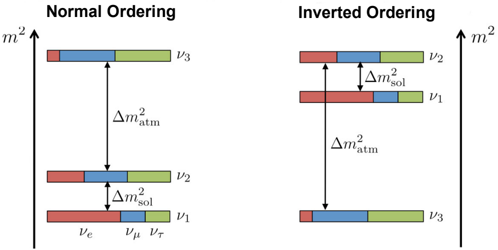
δ : leptonic CP-violating phase

m_1, m_2, m_3: mass eigenvalues

$\Delta m^2_{jk} = m^2_j - m^2_k$: neutrino mass squared difference

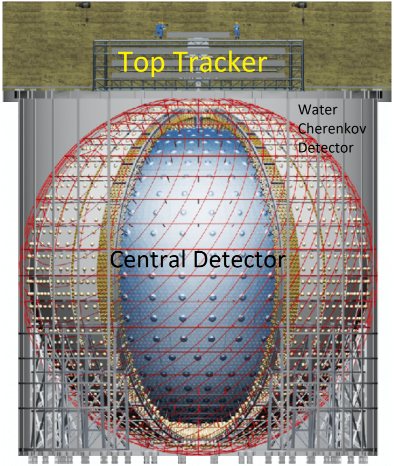
Unknowns:

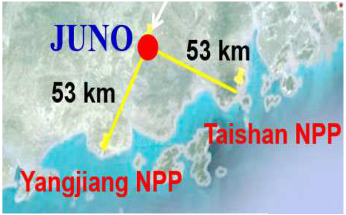
- Which neutrino is the lightest?
- δ?

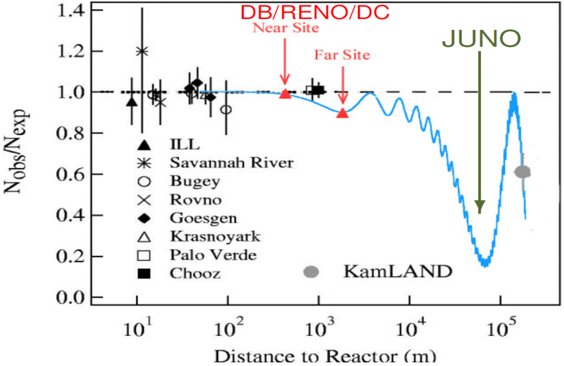


JUNO Experiment

- Neutrino experiment based in South China.
- Surrounded by various Nuclear Power Plants.
- Primary goal to determine Neutrino Mass Ordering.







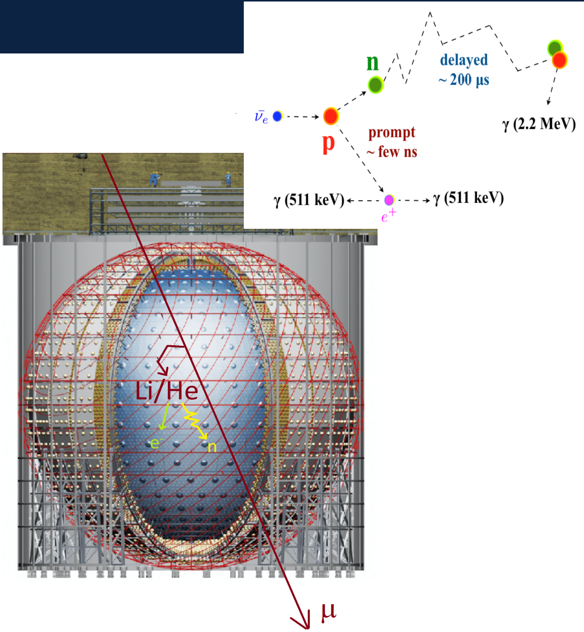
Neutrino detection & μ background

$\bar{\nu}_e$ detection

- Inverse beta decay reaction is used to detect $\bar{\nu}_e$ $(\bar{\nu}_e + p \longrightarrow e^+ + n)$.
- IBD events: $\sim 83/\text{day}$.

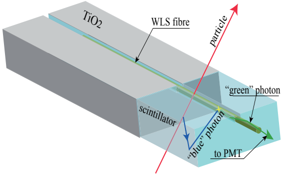
μ crossing CD

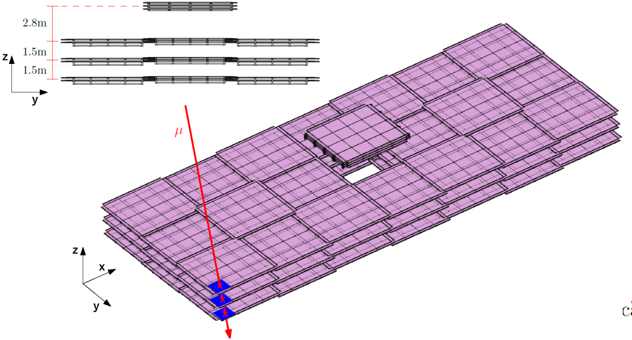
- Muons are one of major backgrounds.
- Tracking muon is the key.
- Cosmogenic isotopes (^{9}Li/^{8}He): $\sim 84/\text{day}$.

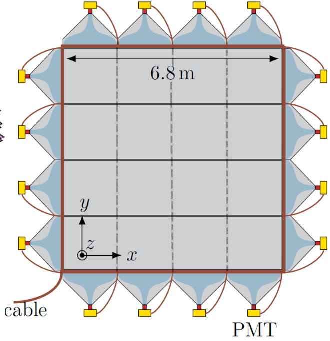


Top Tracker

- 63 6.8 x 6.8 m^2 square walls made of plastic scintillator strips.
- coverage: 20×47 m^2, 3 layers.
- 2.6×2.6 cm^2 spatial granularity.
- Conditions for good muon hits:
  - XY coincidence
  - Charge greater than 0.056pC $\sim$ 1/3rd p.e. (to remove electronic noise).

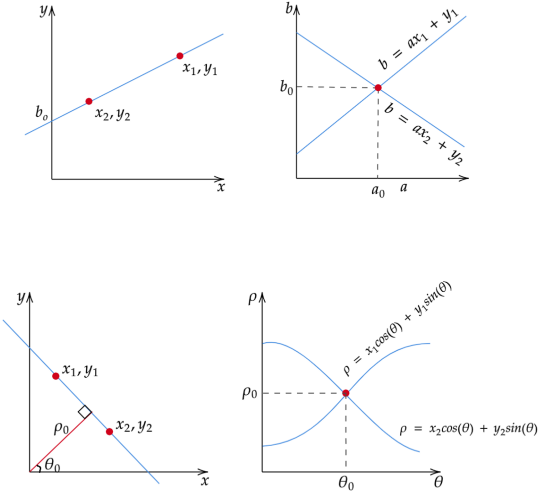




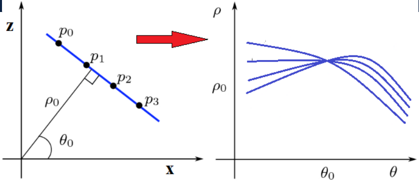


Hough Transform

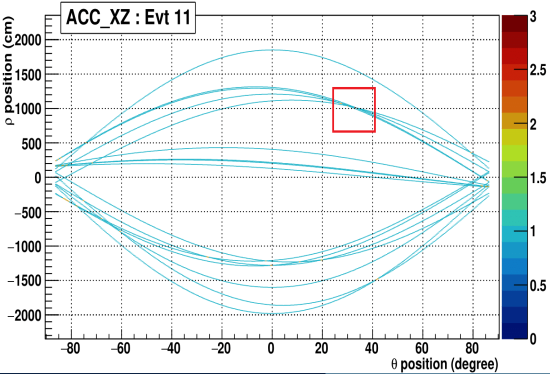
- Technique to isolate features of particular shape within an image.
- Image space (Cartesian space) $\rightarrow$ Parameter space (Hough space)
- Points in the image space $\rightarrow$ lines in the parameter space.
- collinear points $\rightarrow$ lines crossing at single point.
- Construct all such transformations.
- Define accumulator array.
- Vote memory locations.
- Extract peaks.

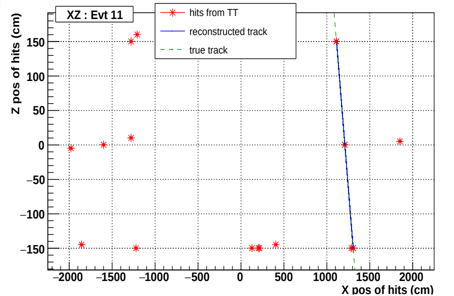


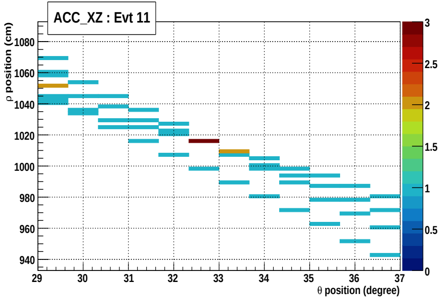
Event display



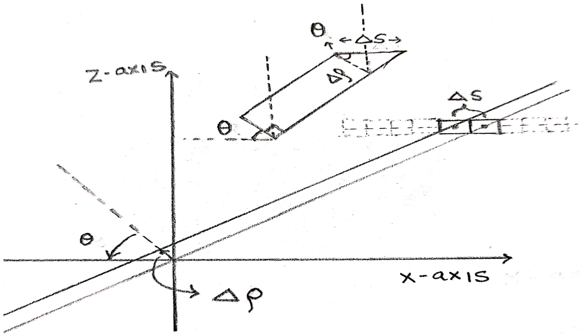
$$\rho = x.\cos\theta + z.\sin\theta$$

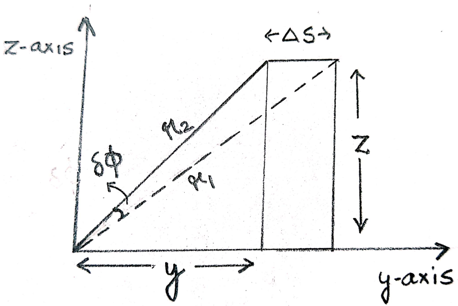


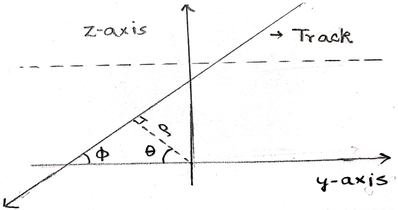




Detector Granularity



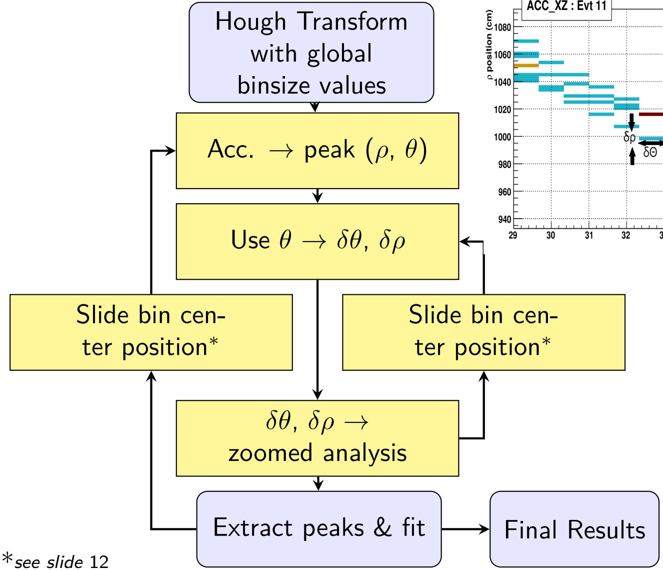


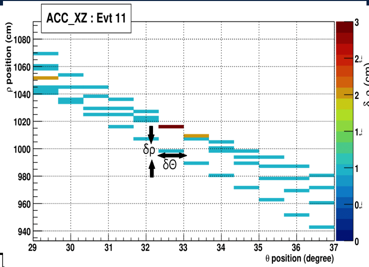


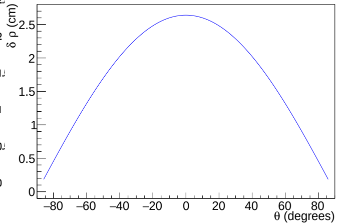
Formula Used

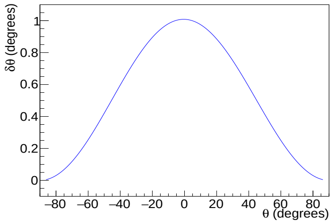
- $\Delta\rho = \Delta s \times \cos(\theta)$, $\Delta s = 2.64$ cm.
- $\Delta\theta = \arccos(\frac{r_1^2 + r_2^2 - \delta s^2}{2.r_1.r_2})$
- $\theta = \pi/2 - \phi$, $\delta\theta = \delta\phi$

Detector Granularity (cont.)









*see slide 12

Efficiency and Angular Resolution

$$\text{Efficiency} = \frac{N_{reconstructed}}{N_{true}}$$

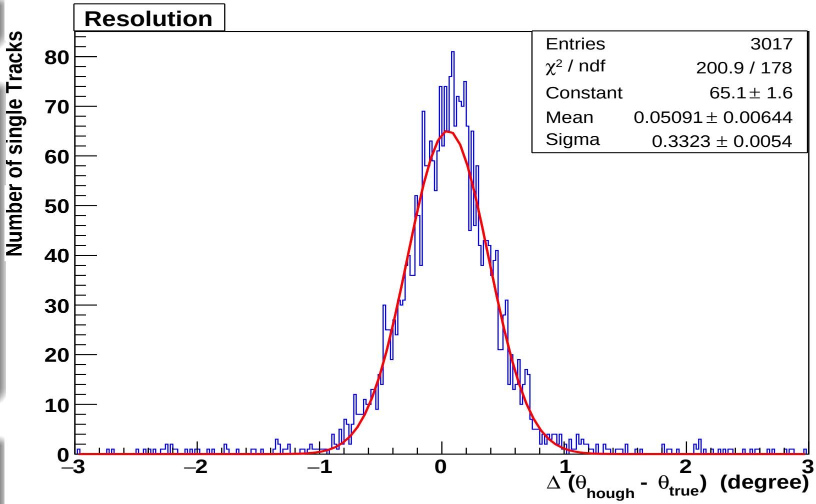
Efficiency

Simulated 12000 events
Single true track: 3187

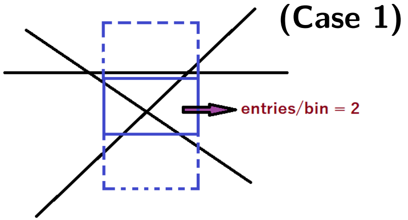
- Efficiency in XZ Proj: 0.946 $\pm$ 0.004
- Efficiency in YZ Proj: 0.952 $\pm$ 0.003
- $\epsilon \sim 93\%$ from the official reco.

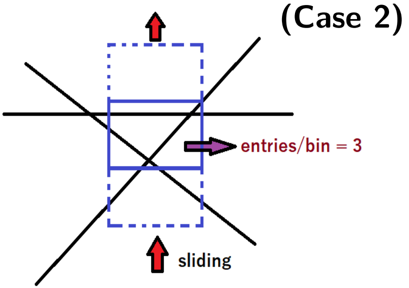
Angular Resolution

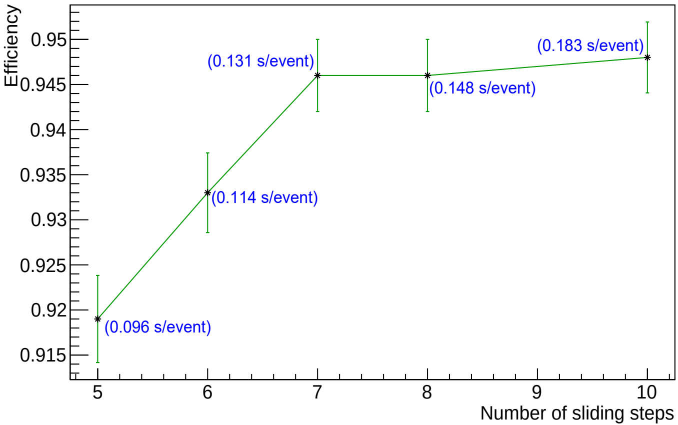
$\sigma \sim 0.3°$
(as expected)



Optimization and sliding the bin center

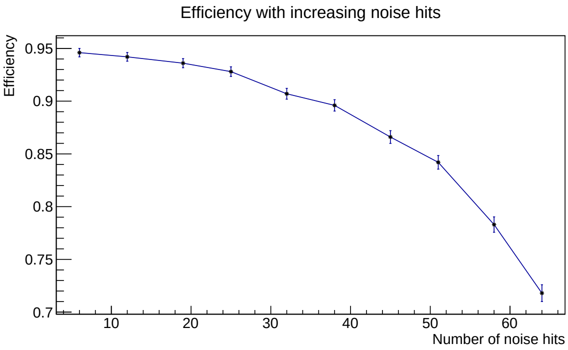


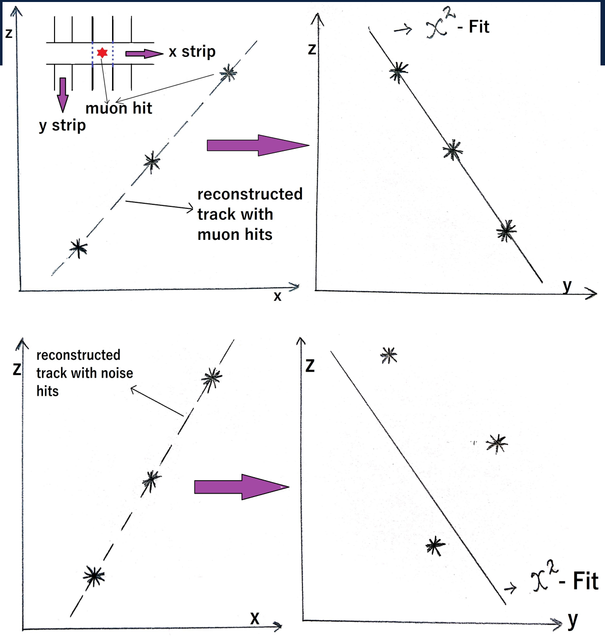




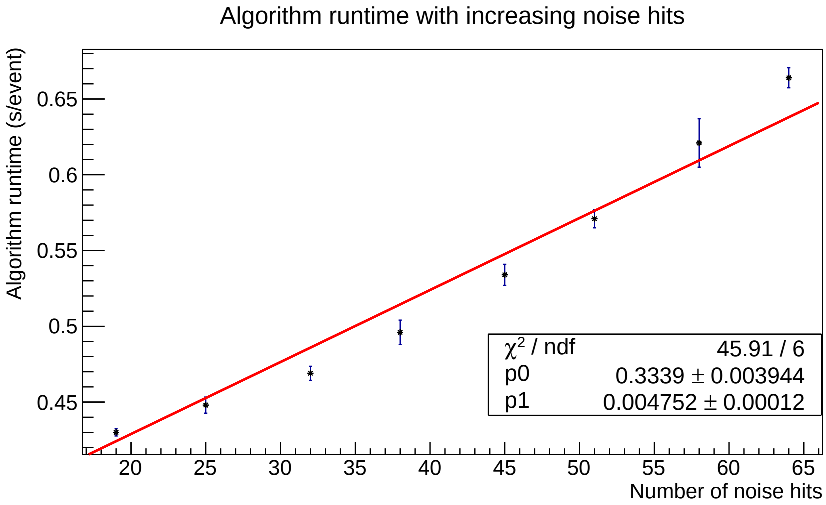
- Proposed number of steps = 8

Noise Implementation





Noise vs algorithm runtime



Conclusion

- New TT muon track reconstruction method was developed $\rightarrow$ Hough Transform method.
- Varying granularity implemented.
- Noise implementation started.

Results

Efficiency:

- in XZ projection: 0.946 ± 0.004
- in YZ projection: 0.952 ± 0.003

Algorithm runtime:

- 0.148 s/event

Angular resolution (σ): $0.332^{\circ} \pm 0.005^{\circ}$

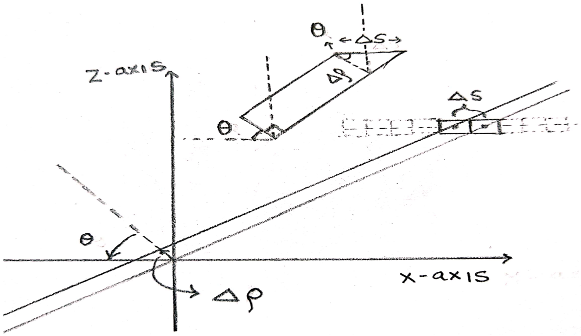
Next Steps

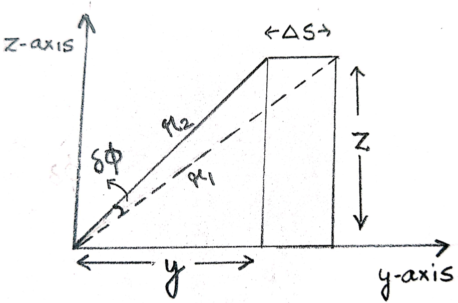
- Improve fake track rejection from noise.
- Implementation of the algorithm in the official JUNO software.

Thank You!

Back Up!

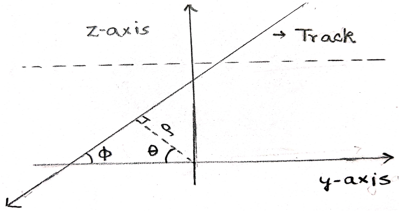
Bin Sizes Calculation



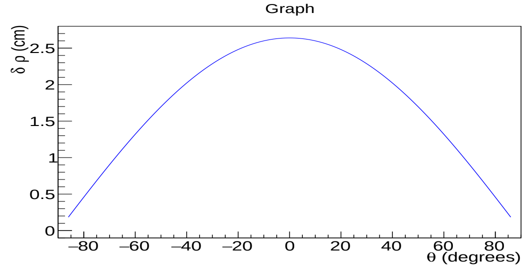


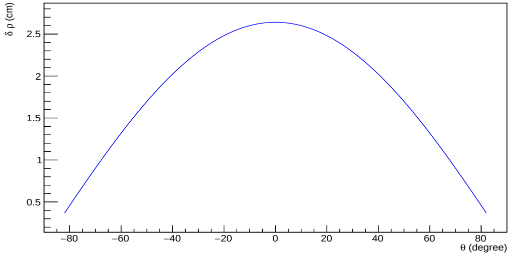
Formula Used

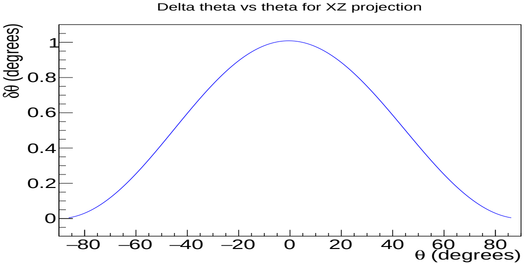
- $\Delta\rho = \Delta s \times \cos(\theta)$, $\Delta s = 2.64$ cm.
- $\Delta\theta = cos^{-1}(\frac{r_1^2 + r_2^2 - \delta s^2}{2.r_1.r_2})$
- $\theta = \pi/2 - \phi$, $\delta\theta = \delta\phi$

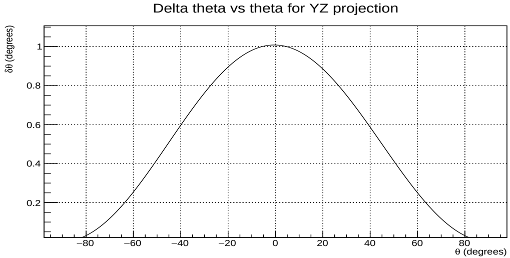


Binsize distribution

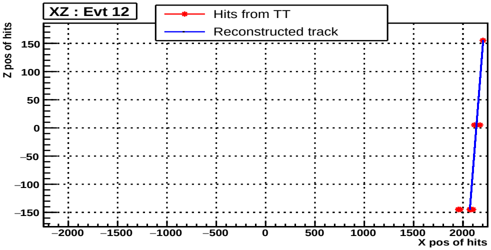


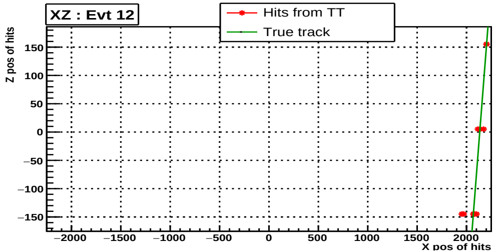


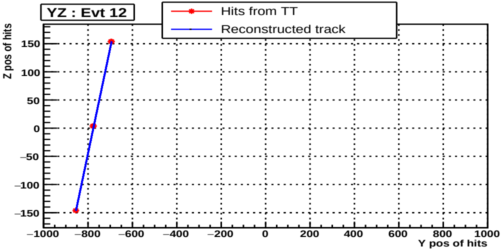


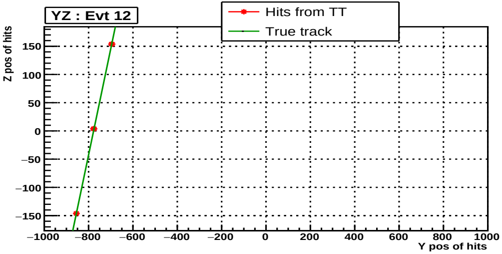


Reconstructed vs Simulated Tracks



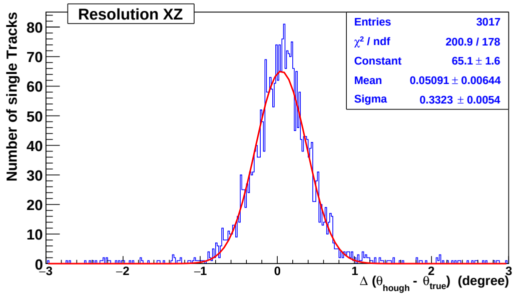


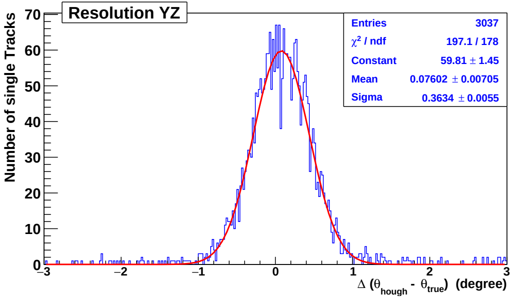




Angular Resolution

- Uncertainty in efficiency: $\delta e = \sqrt{\frac{e(1-e)}{N}}$





Backgrounds

- Accidental Backgrounds:
  - Radioactivity-Radioactivity: 1.1/day
  - Radioactivity-Cosmogenic isotope: <0.01/day
  - Radioactivity-Spallation neutrons: negligeable
- Cosmogenic $^{9}Li/^{8}He$ isotopes
  - most dangerous type
  - $\beta - n$ decays mimicking the IBD signature
  - Production cross-section $\propto E_{\mu}^{0.74}$

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

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

Overburden	Muon flux	$< E_{\mu} >$	R_{μ} in CD	R_{μ} in WP
748 m	0.003 Hz/m^2	215 GeV	3.0 Hz	1.0 Hz

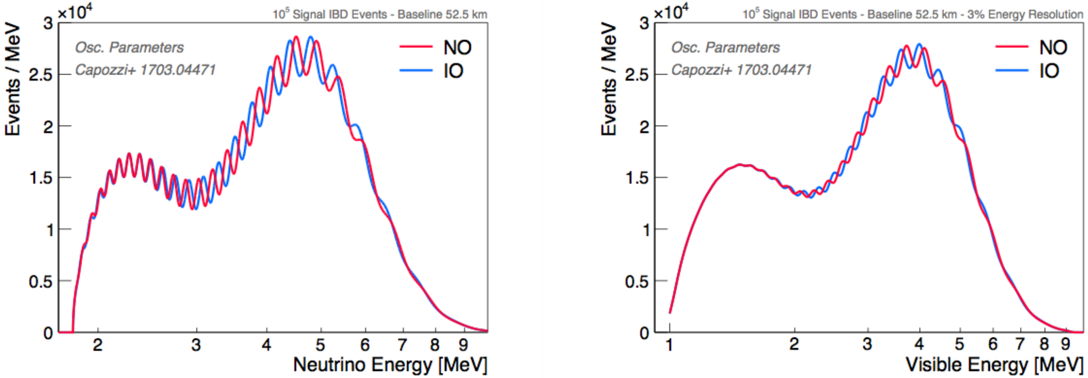
Resources: F. An et al., Neutrino Physics with JUNO [arxiv: 1507.05613v2]

Multiplicity	1	2	3	4	5	6
Fraction	89.6%	7.7%	1.8%	0.6%	0.3%	0.07%

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

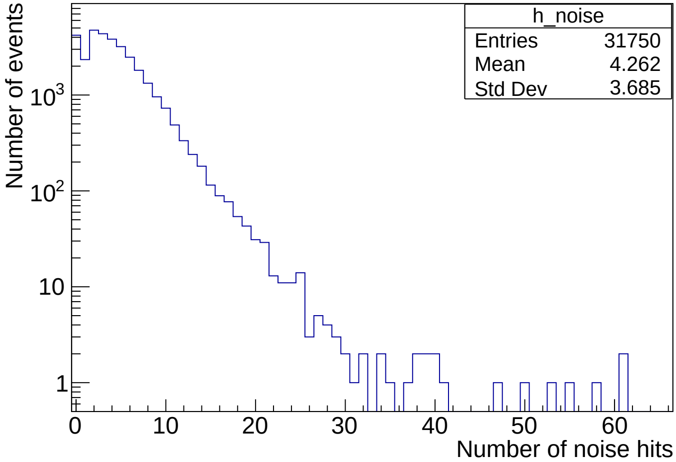
- $^{13}C(\alpha, n)^{16}O$
  - α particles from natural isotopes in surrounding rock react with the ^{13}C in the Liquid scintillator
- Geo-neutrinos
  - $\bar{\nu}_e$ from radioactive decay of natural isotopes of surrounding rock

JUNO Experiment

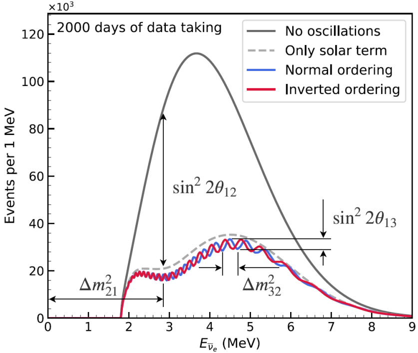


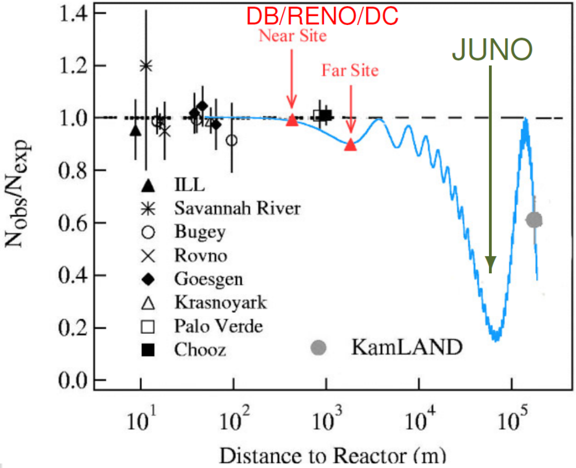
- First experiment to see both oscillations (solar and atmospheric) at the same time
- JUNO is a disappearance experiment
- JUNO baseline (53km) is chosen in order to place it at $\bar{\nu}_e$ oscillation minimum
- With the expected good energy resolution, it can discriminate between the 2 mass orderings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

Noise Simulation



Neutrino oscillation ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)





- Oscillation region is different for different baseline.
- JUNO is placed at the minimum induced by Δm^2_{21}.

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]