Development of a muon reconstruction algorithm for JUNO

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Standard Model

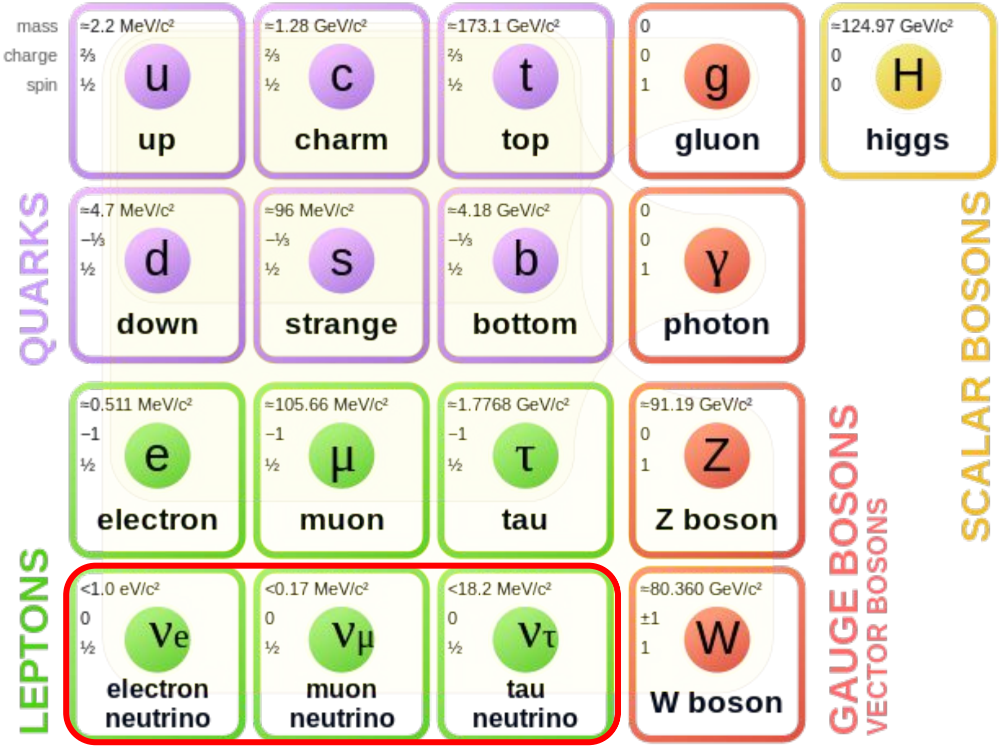
Successful theory, but there are limitations.

Neutrinos:

- massless leptons
- only interact with weak force
- 3 flavors

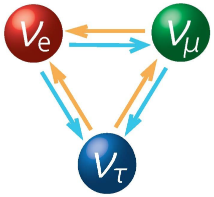
Limitations:

- does not explain neutrinos masses and oscillations



Neutrinos oscillations

Super-Kamiokande - 1998, Sudbury Neutrino Observatory - 2002.



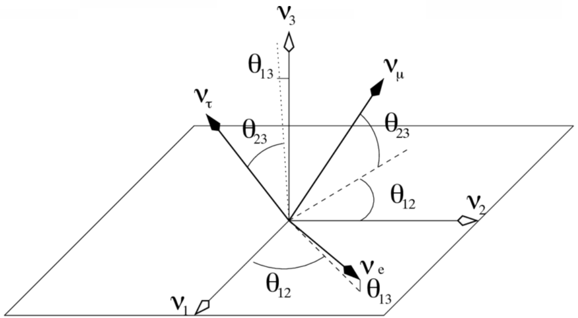
Change flavor during propagation.

Two basis: $(\nu_e, \nu_\mu, \nu_\tau)$ and (ν_1, ν_2, ν_3)

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

PMNS matrix depends on :

- θ_{12}, θ_{13}, and θ_{23}
- δ_{CP}



Neutrinos oscillations

Neutrino oscillation probability:

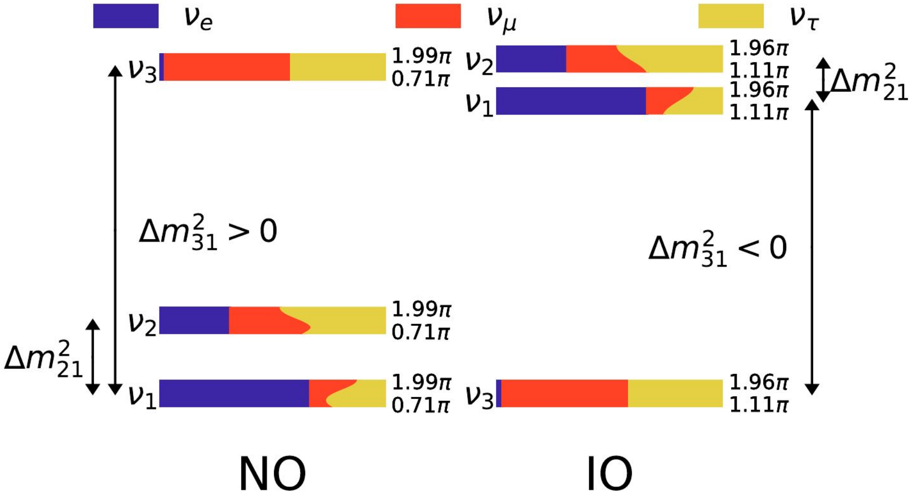
$$P_{\nu_\alpha \to \nu_\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} e^{-i\left(\frac{\Delta m^2_{jk} L}{2E}\right)}, \text{ with } \Delta m^2_{jk} = m^2_j - m^2_k$$

Neutrinos oscillations → 6 parameters:

- $\theta_{12}, \theta_{13}, \text{and } \theta_{23}$
- δ_{CP}
- $\Delta m^2_{12}, \text{ and } \Delta m^2_{13}$

Remaining issues:

- δ_{CP}
- $\Delta m^2_{13} > 0$?

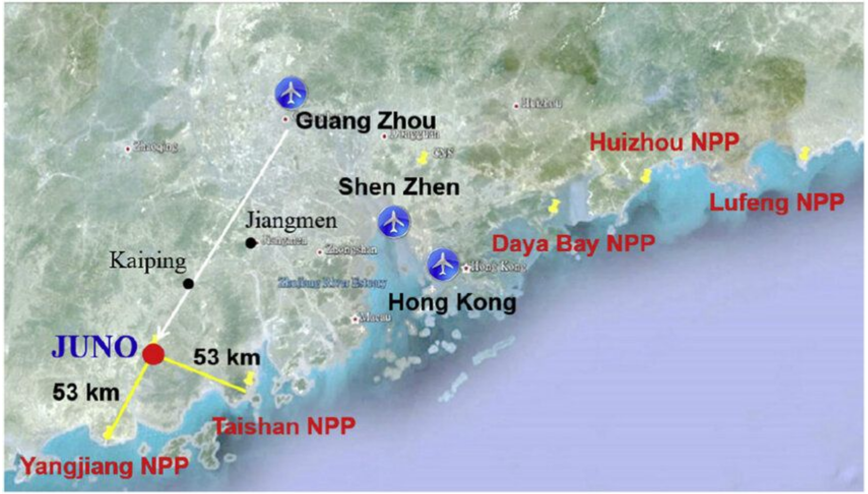


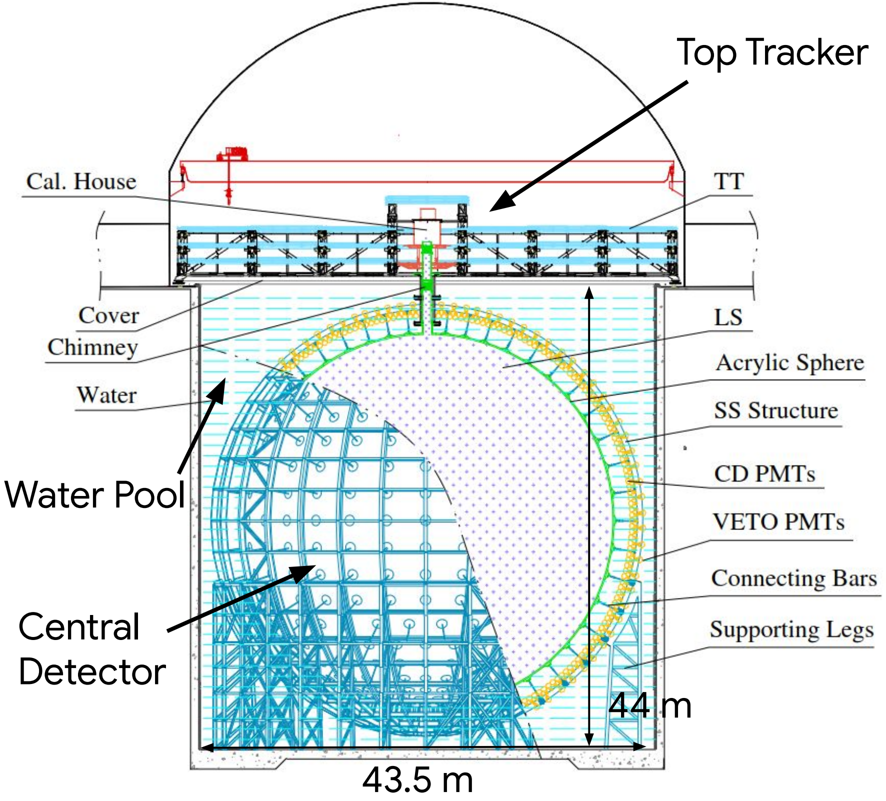
P. F. de Salas and al. ; 2020 Global reassessment of the neutrino oscillation picture [arXiv:2006.11237]

Jiangmen Underground Neutrino Observatory (JUNO)

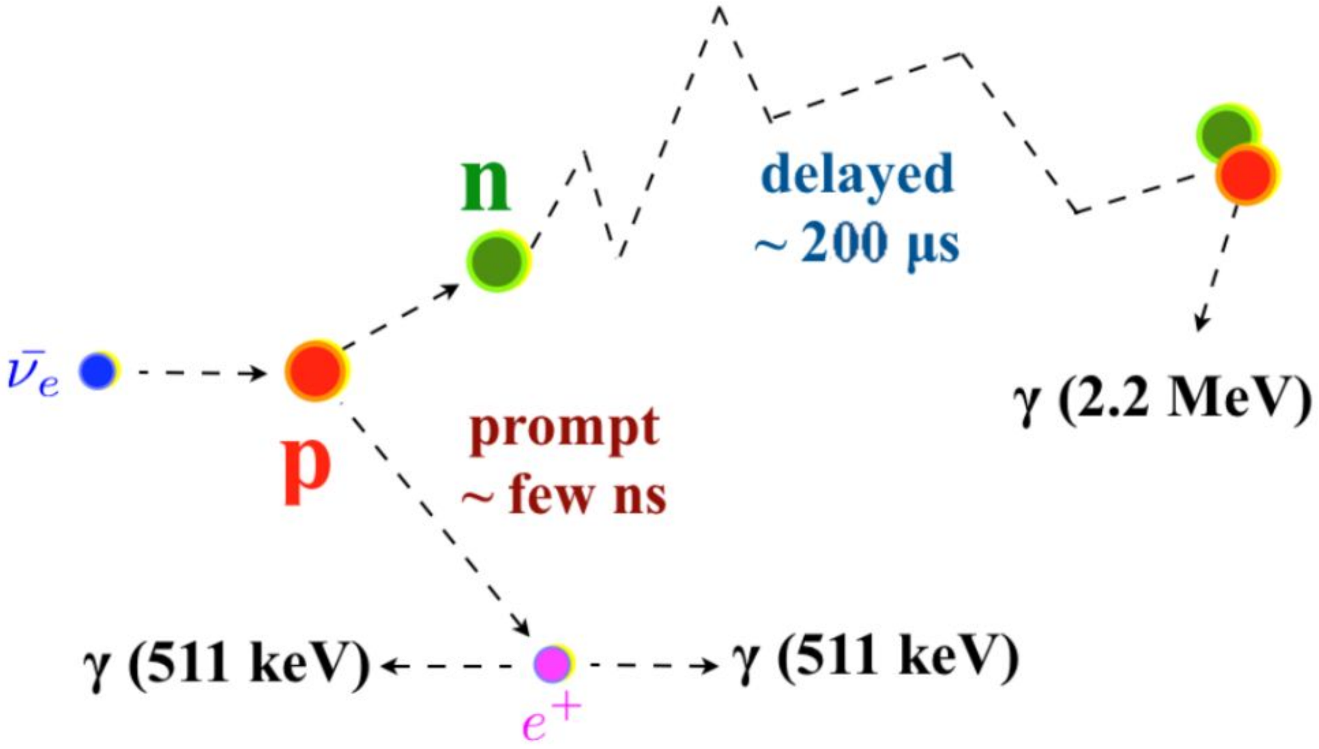
Main goal: determine the neutrino mass ordering.

JUNO is composed of: Central Detector, Water Pool, and Top Tracker.





Inverse Beta Decay (IBD)



Background sources

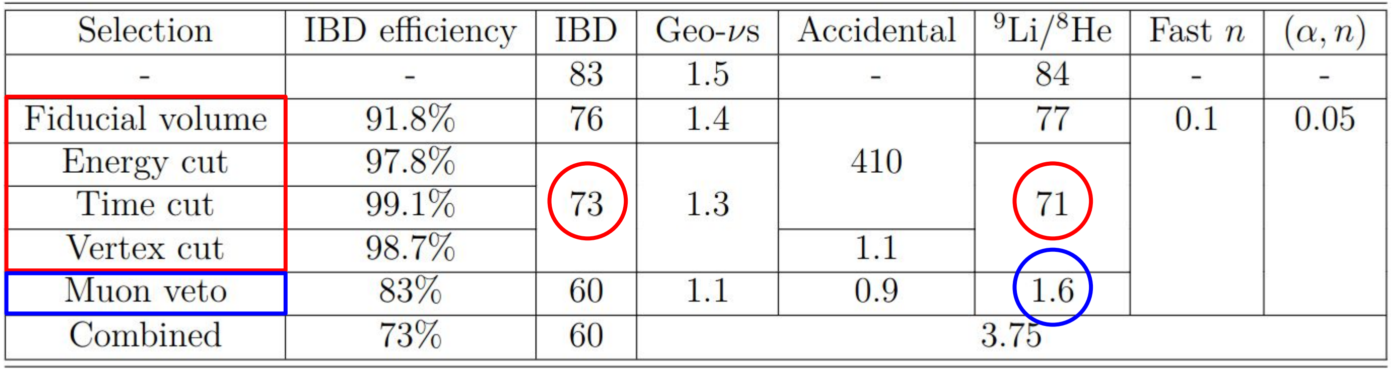
Accidental backgrounds: random coincidences between unrelated processes.

Cosmogenic isotopes: ^{8}He and ^{9}Li, created by the passage of a muon, beta-n decay.

Fast neutrons: created by the passage of a muon, unpredictable interactions.

^{13}C(alpha, n)^{16}O process: alpha particles react with the ^{13}C of the Liquid Scintillator.

Geo-neutrinos: decay of U and Th.



Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	-	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.75				

JUNO Collaboration ; JUNO physics and detector [arXiv:2104.02565]

Muon veto

Veto CD if detection of a muon ⟶ reject for 1.2 s.

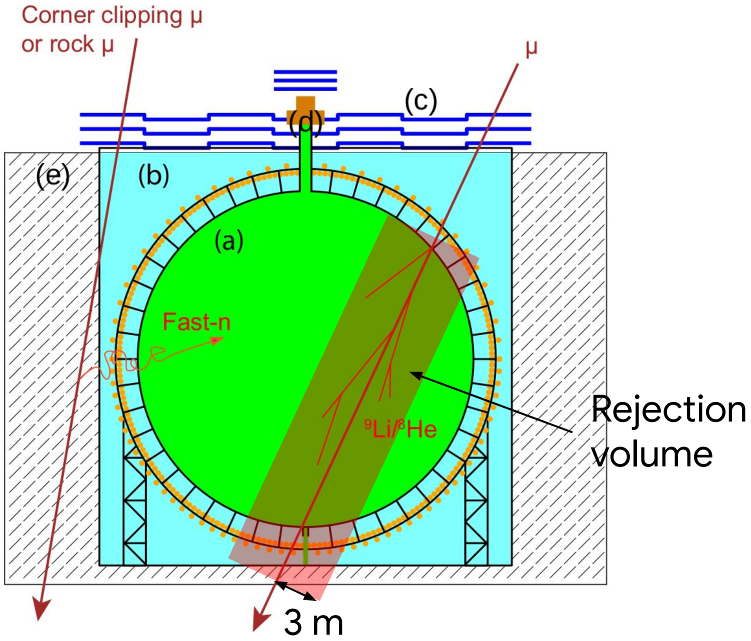
JUNO level ⟶ muon rate ~3 Hz, ~215 GeV.

If veto CD ⟶ no live time in the detector.

Isotopes space/time correlation with muon ⟶ rejection volume around trajectory.

High precision of knowledge of the trajectory ⟶ reconstruction algorithm.

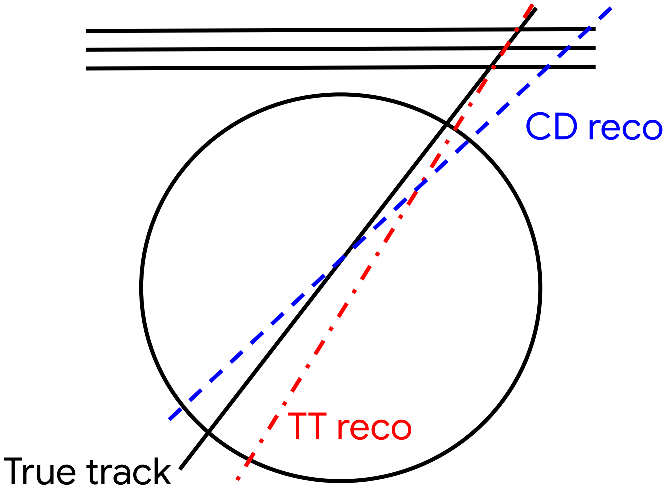
$$^{8}\mathrm{He} \xrightarrow[0.119s]{16.0\%} {}^{7}\mathrm{Li} + \mathrm{n} + \mathrm{e}^{-} + \overline{\nu_{\mathrm{e}}} \qquad {}^{9}\mathrm{Li} \xrightarrow[0.178s]{50.8\%} {}^{8}\mathrm{Be} + \mathrm{n} + \mathrm{e}^{-} + \overline{\nu_{\mathrm{e}}}$$



Current state of cosmic muon reconstruction in JUNO

Several reconstruction methods have already been implemented.

Good performances, but they do not use all sub detectors.



All sub detectors → increase the accuracy → reduce rejection volume → reduce dead zone of JUNO.

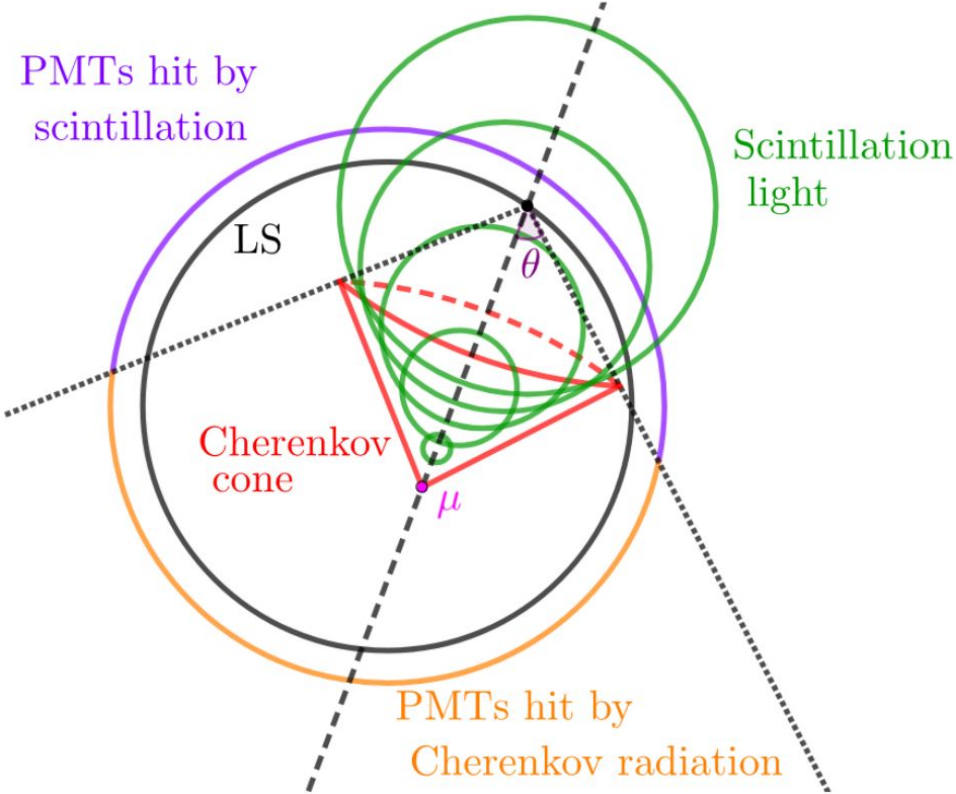
Goal : create reconstruction algorithm using all sub detectors.

Initially → only use CD, and reproduce results of an already existing algorithm.

Reconstruction in the Central Detector (CD)

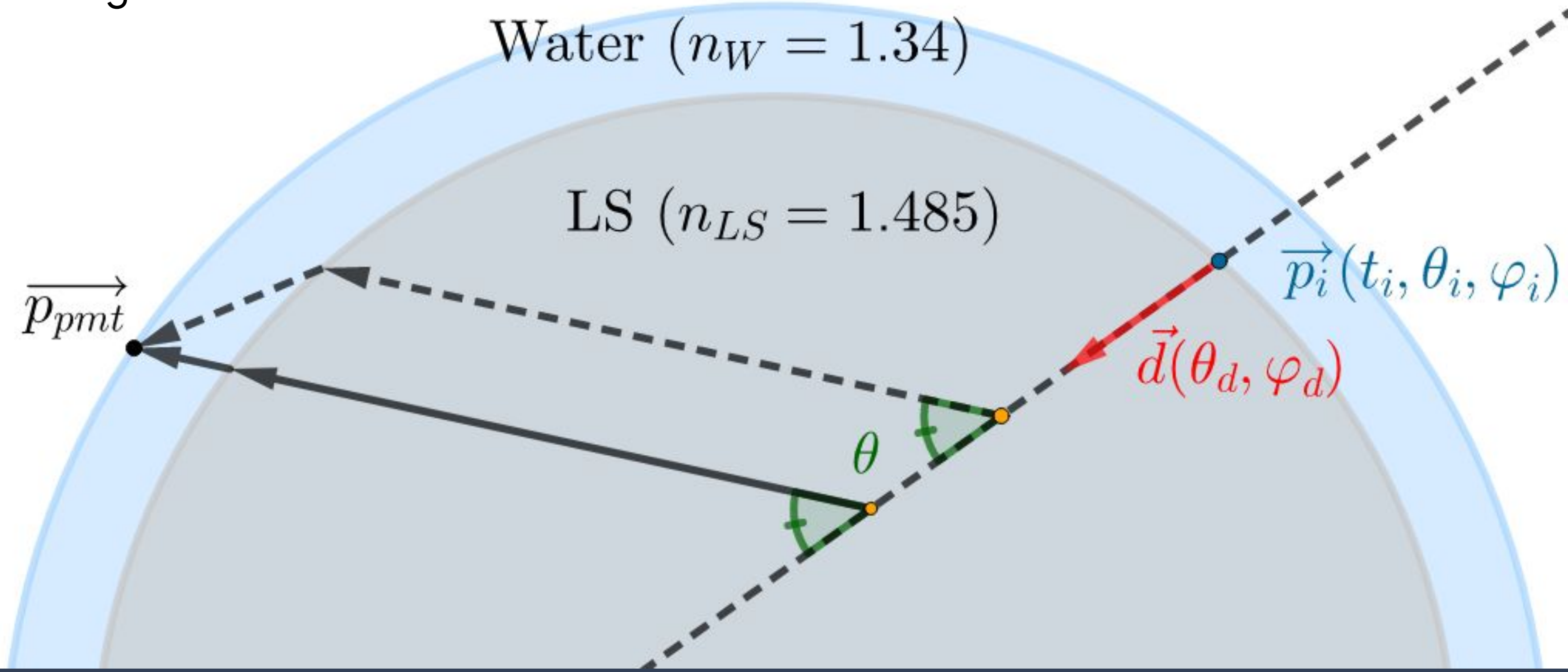
- Cherenkov radiation → directional, prompt.
- Scintillation light → isotropic, delayed.
- Calculate First Hit Time (FHT) geometrically → depends on track parameters.
- 5 parameters:

$$t_i, \theta_i, \phi_i, \theta_d, \phi_d$$



Reconstruction in the Central Detector (CD)

First approximation → don't take into account the change of medium.



Reconstruction in the Central Detector (CD)

- Calculation for each PMT.

$$\chi^2 = \sum_{i=1}^{17612+25600} \left(\frac{t_{i,theo} - t_{i,meas}}{\sigma_i} \right)^2$$

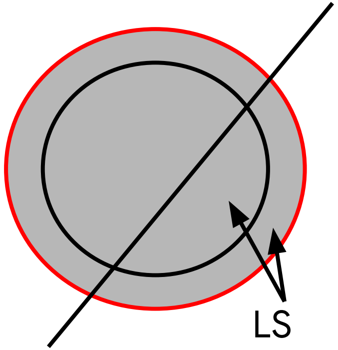
- Minimization (Minuit2, ROOT librarie).

- Initializer for first parameter estimation → important step.

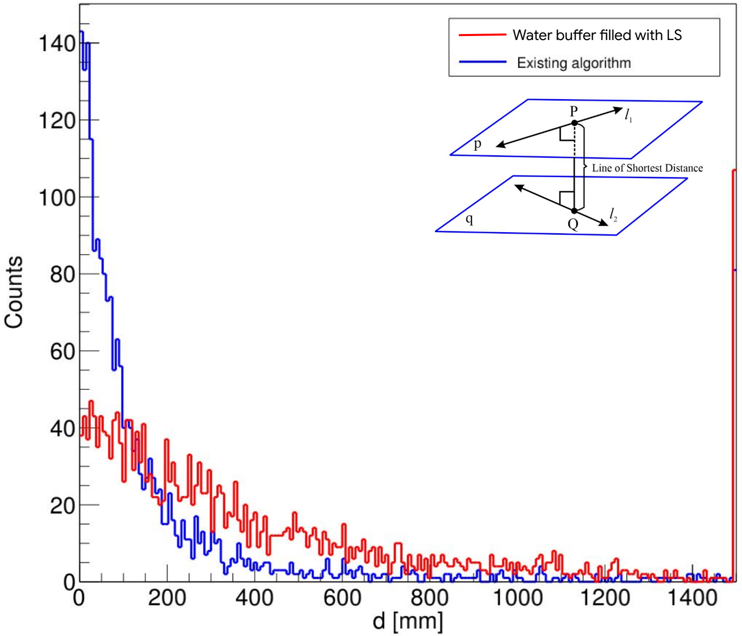
- Filters to further increase performance

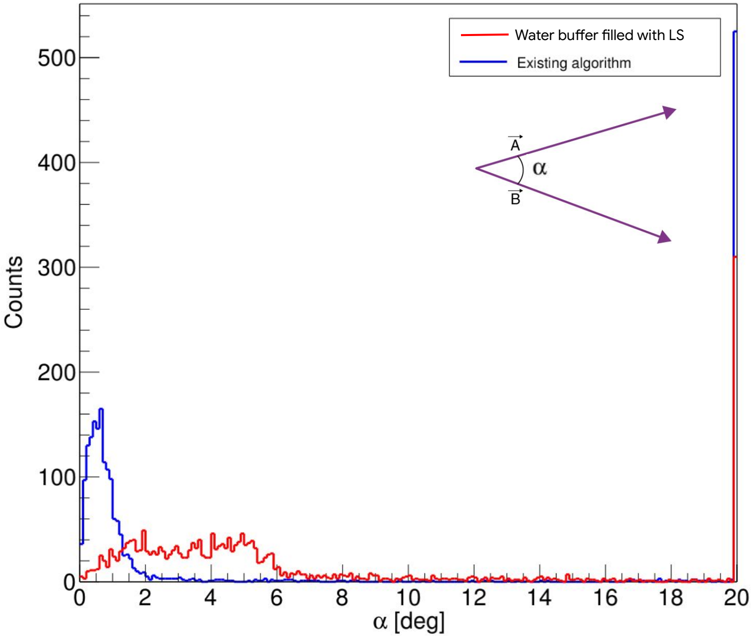
Muon reconstruction performance

Water buffer filled with LS:
40 cm, 2-5°.



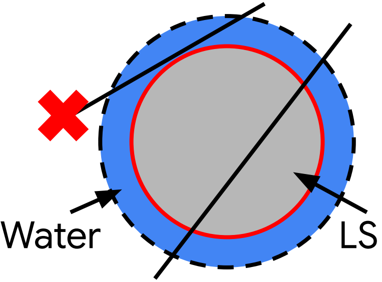
Existing algorithm:
<20 cm, <2°.



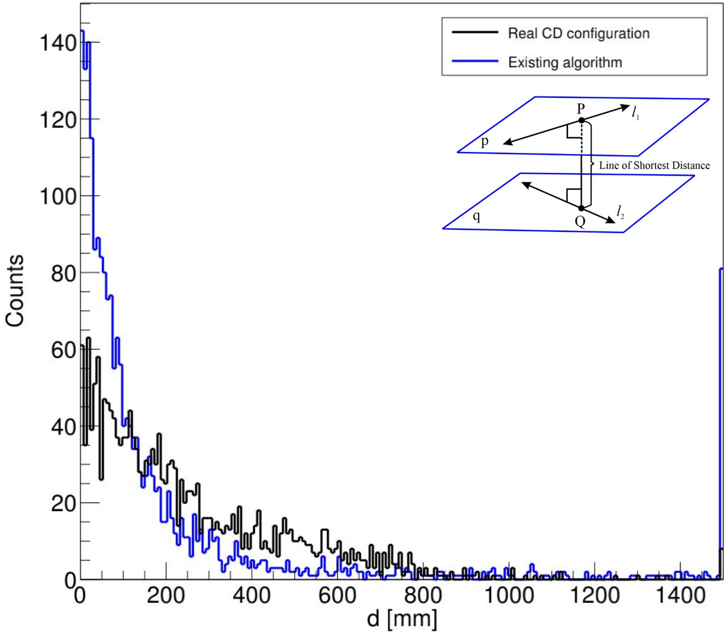


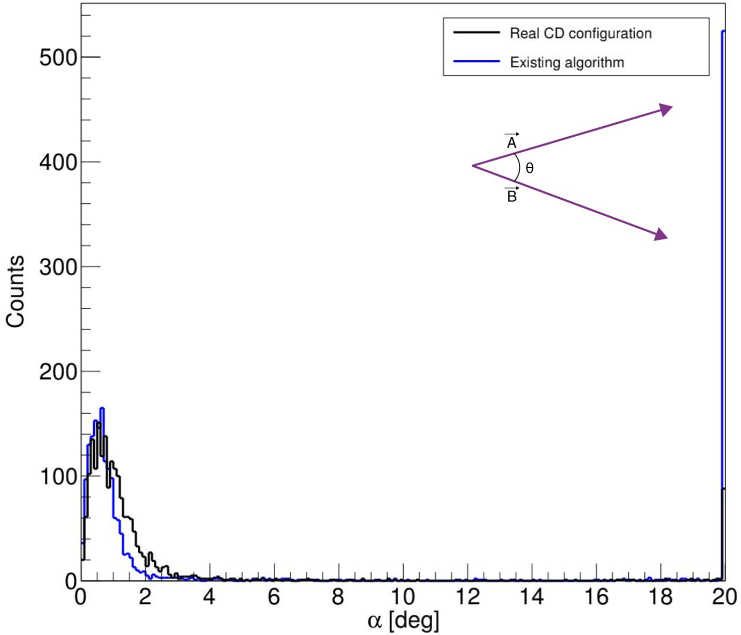
Muon reconstruction performance

Real CD config:
30 cm, 0.5-1°.

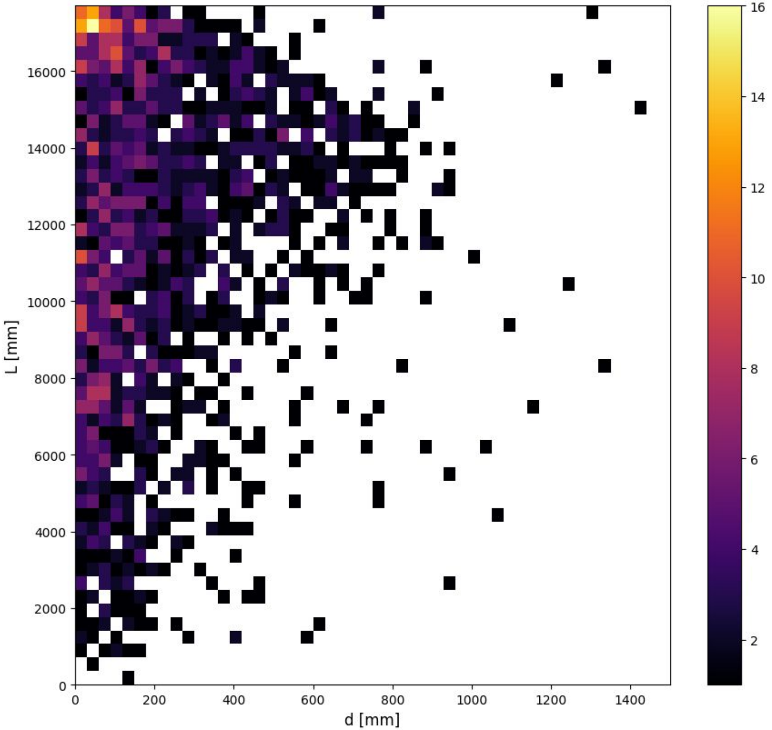


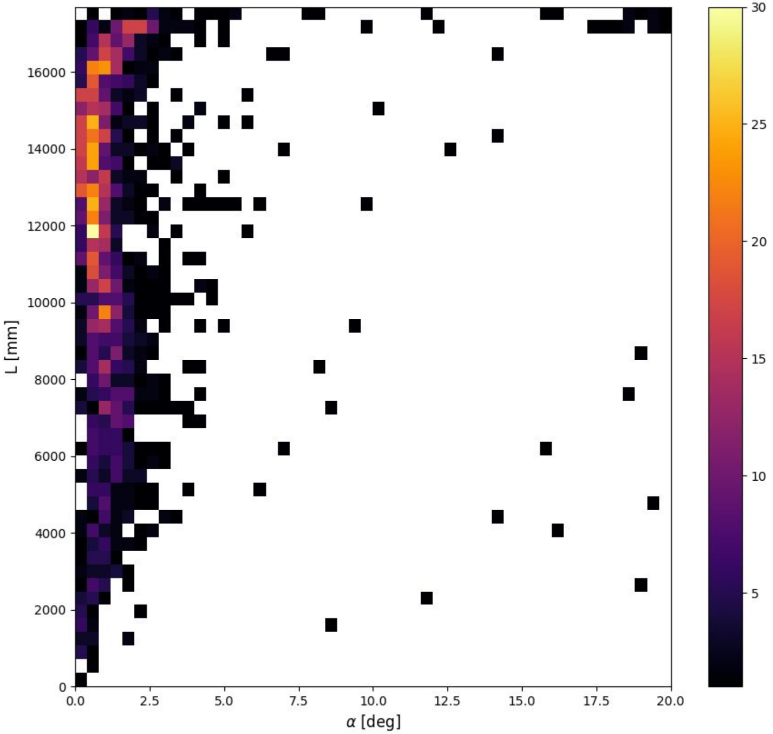
Existing algorithm:
<20 cm, <2°.

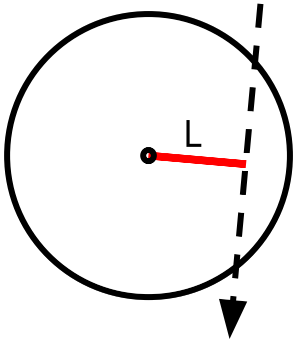




Clipping muons







Muon at the edges of the detector → less precise.

Conclusion (for now)

Implemented a reconstruction algorithm with good spatial and angular resolution for a first test.

⟶ Close to the already existing algorithm.

Only considering the Central Detector.

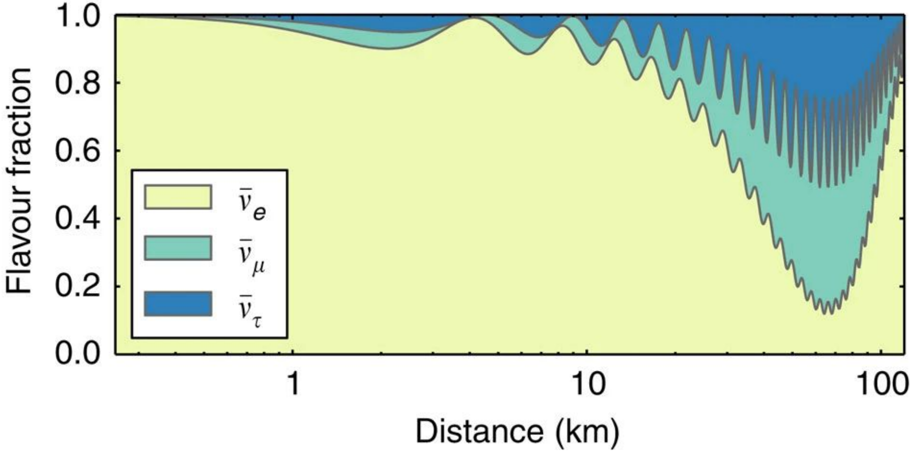
But the internship isn't over yet, and there's still a month to go.

Improvements

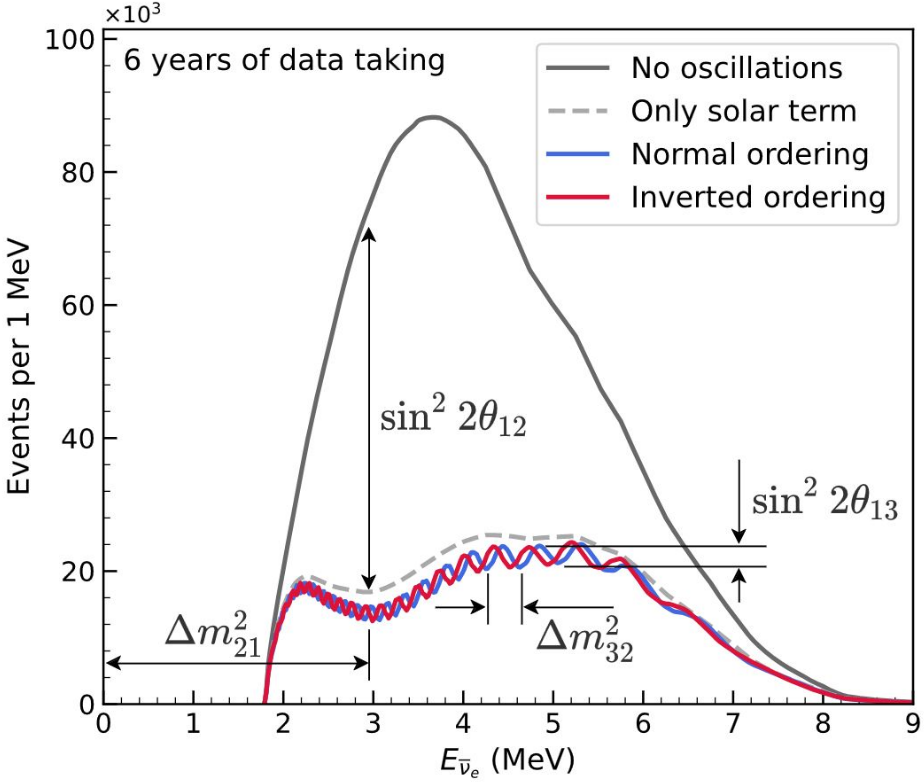
- Use of the Water Pool and Top Tracker.
- Create a new First Hit Time calculation.

Thanks for your attention!

Backup - Neutrinos oscillations



4 MeV

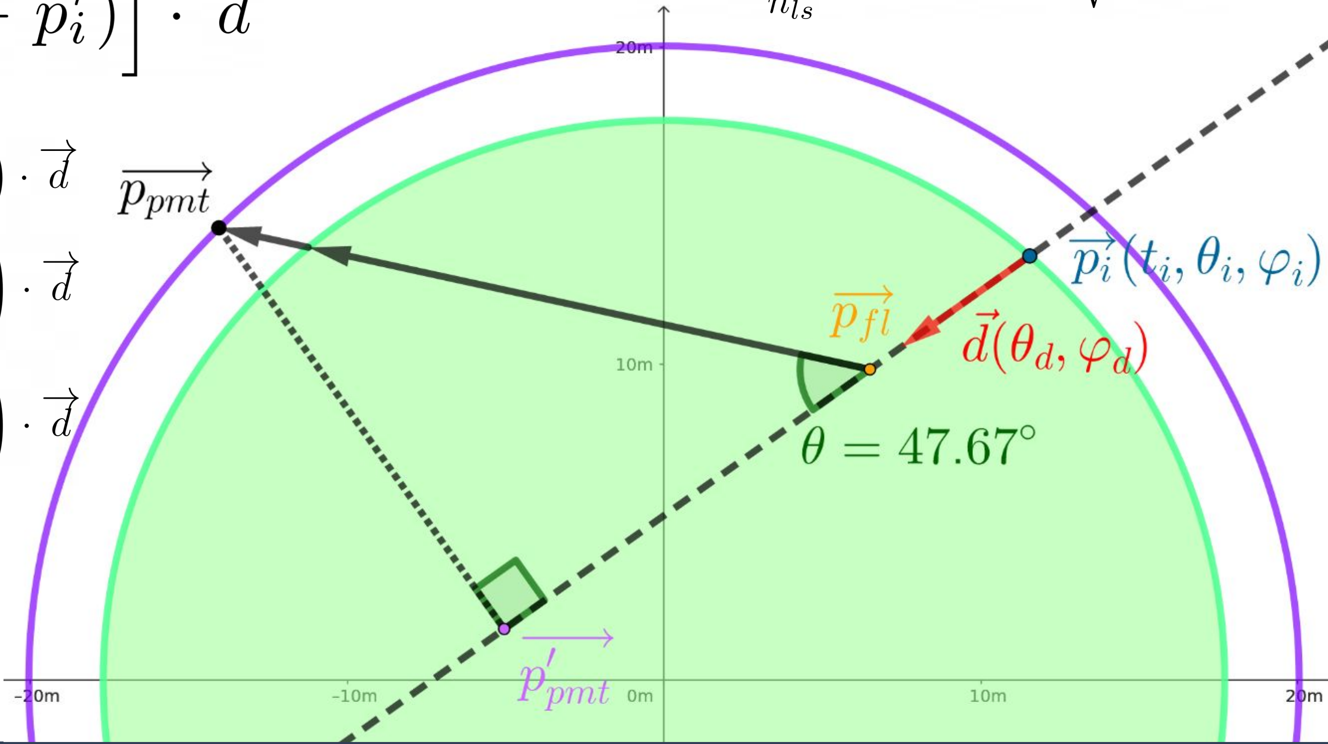


Backup - FHT

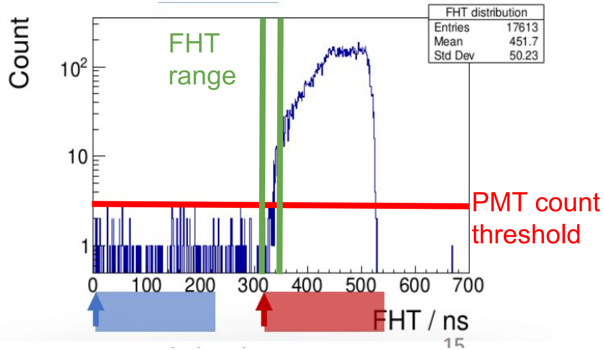
$$\overrightarrow{p'_{pmt}} = \left[\overrightarrow{d}\cdot\left(\overrightarrow{p_{pmt}} - \overrightarrow{p_i}\right)\right]\cdot\overrightarrow{d}$$

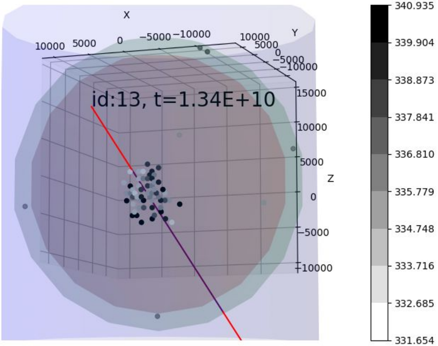
$$\begin{aligned}\overrightarrow{p_{fl}} &= \left(\overrightarrow{p'_{pmt}}\cdot\overrightarrow{d} - \left|\overrightarrow{p'_{pmt}} - \overrightarrow{p_{fl}}\right|\right)\cdot\overrightarrow{d}\\ &= \left(\overrightarrow{p'_{pmt}}\cdot\overrightarrow{d} - \frac{\left|\overrightarrow{p_{pmt}} - \overrightarrow{p'_{pmt}}\right|}{\tan(\theta)}\right)\cdot\overrightarrow{d}\\ &= \left(\overrightarrow{p'_{pmt}}\cdot\overrightarrow{d} - \frac{\left|\overrightarrow{p_{pmt}} - \overrightarrow{p'_{pmt}}\right|}{\sqrt{n_{ls}^2-1}}\right)\cdot\overrightarrow{d}\end{aligned}$$

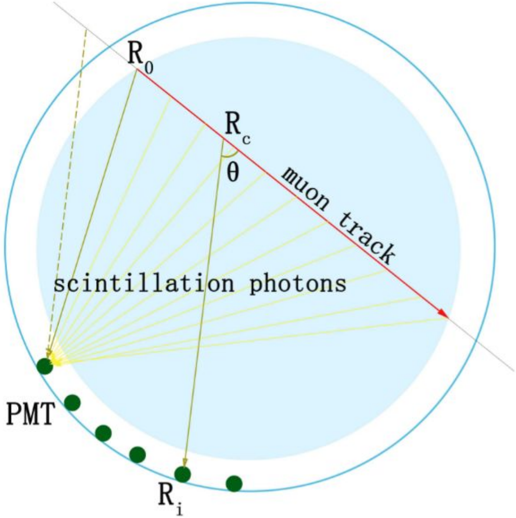
$$\cos(\theta) = \frac{1}{n_{ls}} \implies \tan(\theta) = \sqrt{n_{ls}^2 - 1}$$



Backup - Initialisation/filters

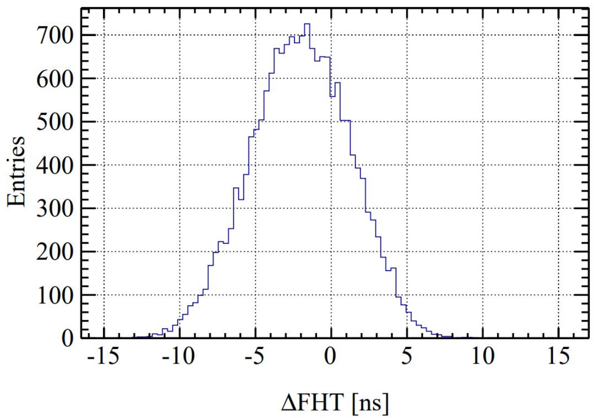


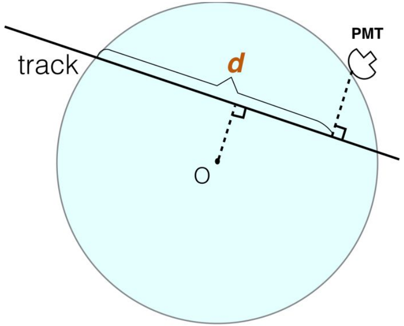


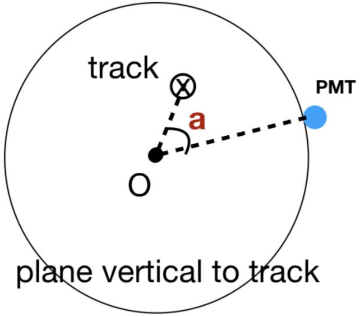


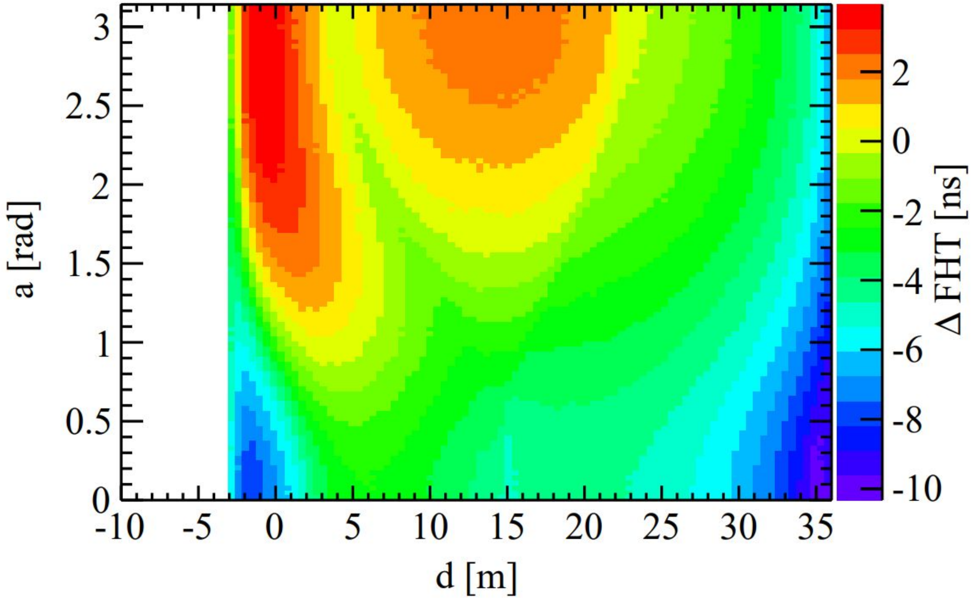
$$\mathbf{c} = \frac{1}{\sum_i c_i} \sum_i c_i \mathbf{x}_i$$

Backup - Corrector









Backup - Arc length