Development of a muon reconstruction algorithm for JUNO using all the sub-detectors

Thomas Raymond

Supervisors : Marcos Dracos, João Pedro Athayde Marcondes De André

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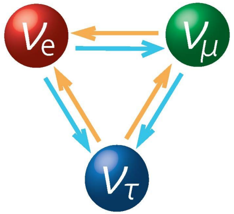
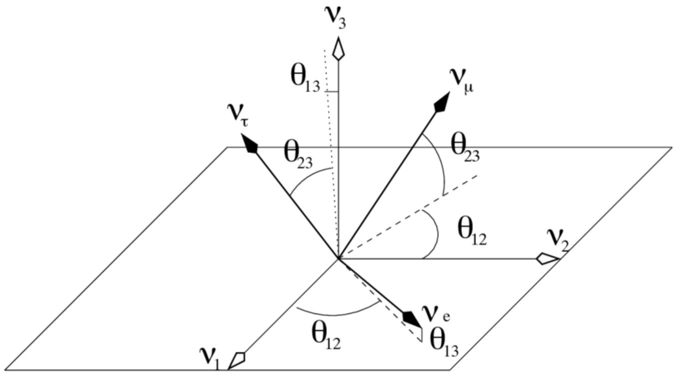
Neutrinos oscillations

Standard model: massless particles.

From experiments: massives because of oscillations.





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

Neutrino oscillation probability:

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

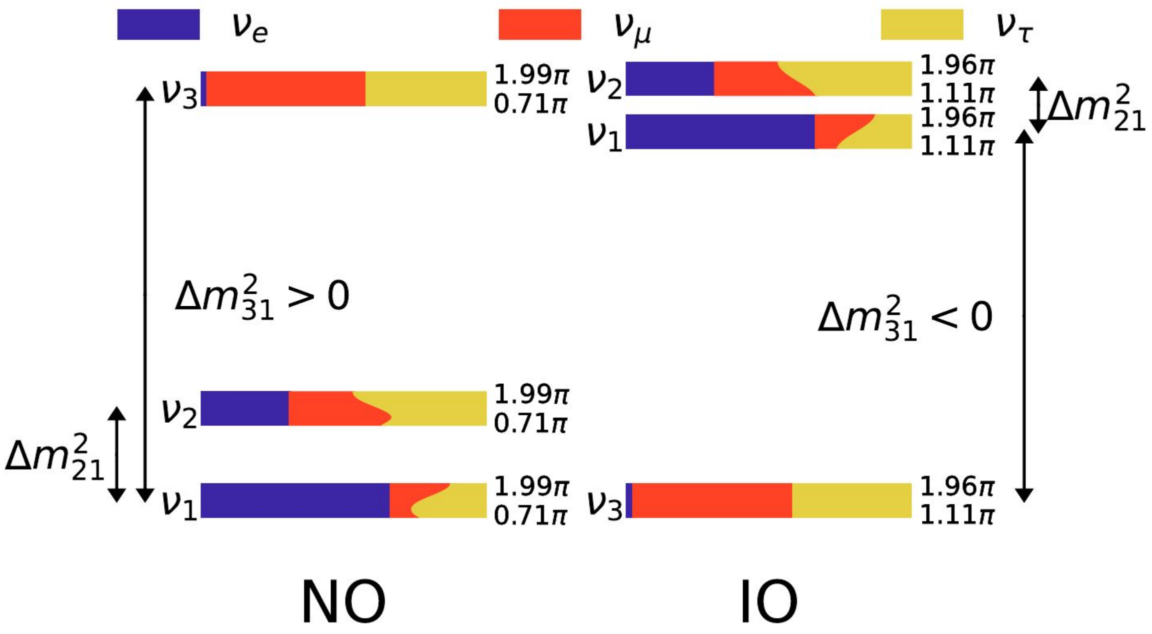
Neutrinos oscillations

Neutrinos oscillations → 6 parameters:

- θ_{12}, θ_{13}, and θ_{23}
- δ_{CP}
- Δm^2_{12}, and Δm^2_{13}

Some remaining unknowns:

- δ_{CP}
- $\Delta m^2_{13} > 0$?

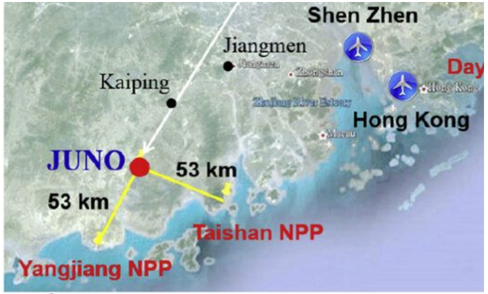


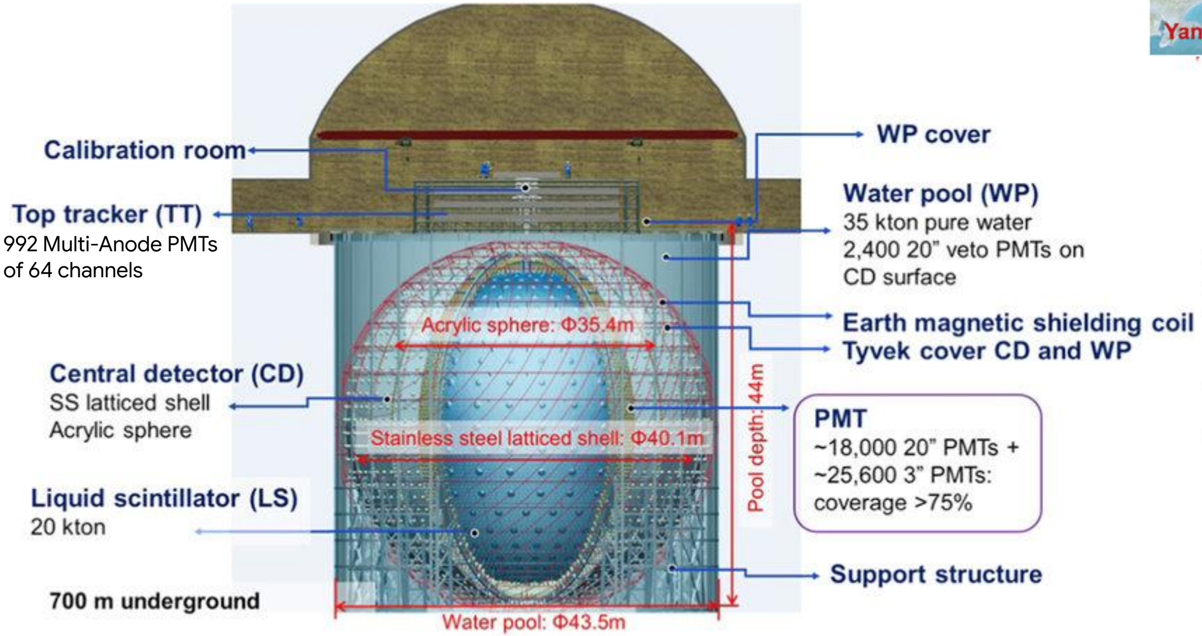
P. F. de Salas and al. ; 2020 Global reassessment of the neutrino oscillation picture [arXiv:2006.11237]

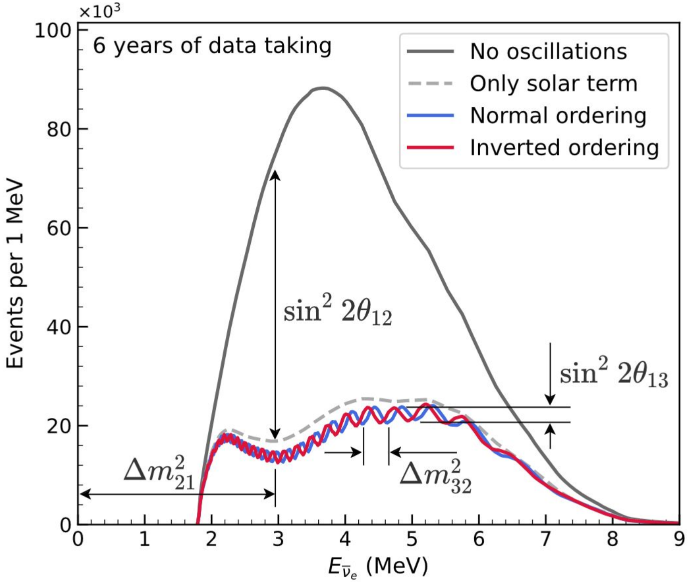
Jiangmen Underground Neutrino Observatory

Main goal: determine the neutrino mass ordering.

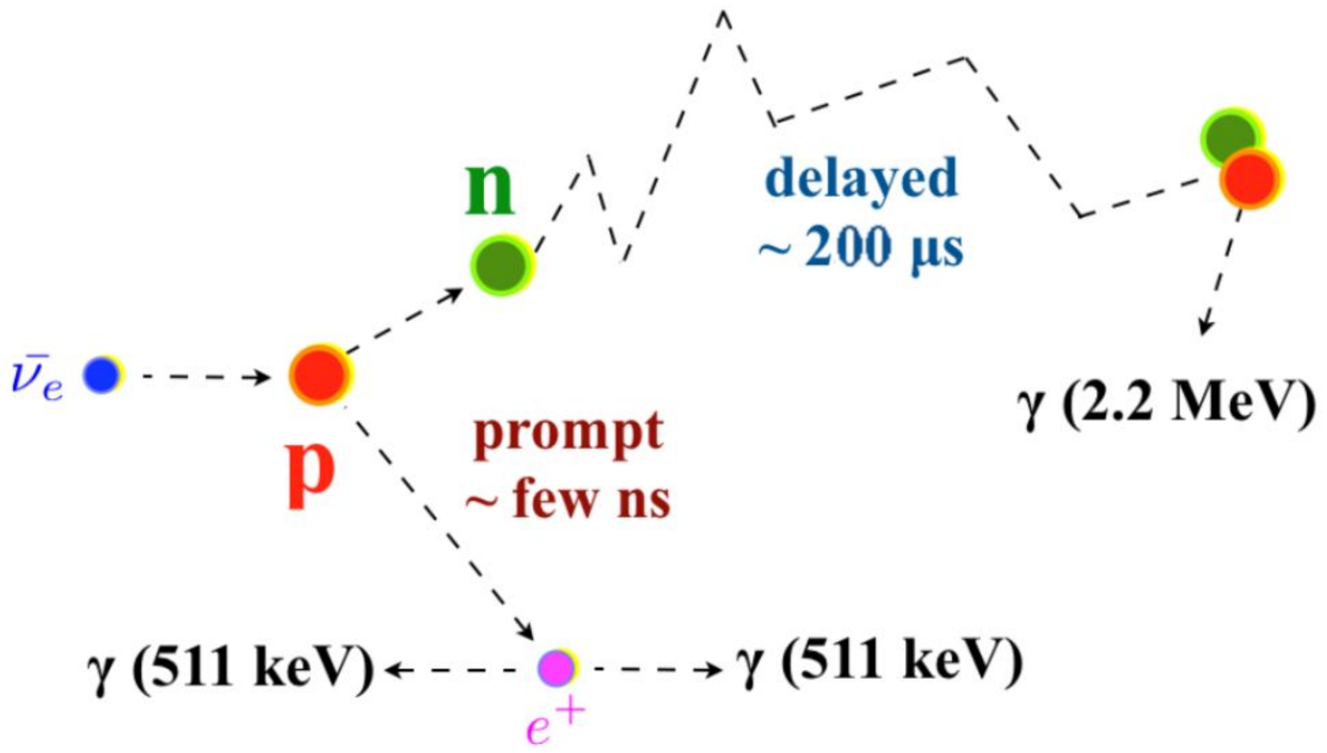
JUNO is composed of: Central Detector, Water Pool, and Top Tracker.







Inverse Beta Decay



Background sources

Selection	IBD efficiency [%]	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	^{13}C(α,n)^{16}O	World reactors
No cuts	100	57.4	1.5	5.7×10^4	84	-	-	-
Main cuts	89.7	51.5	1.3	1.1	71	0.1	0.05	-
+ Muon veto	82.2	47.1	1.2	0.8	0.8	0.1	0.05	1

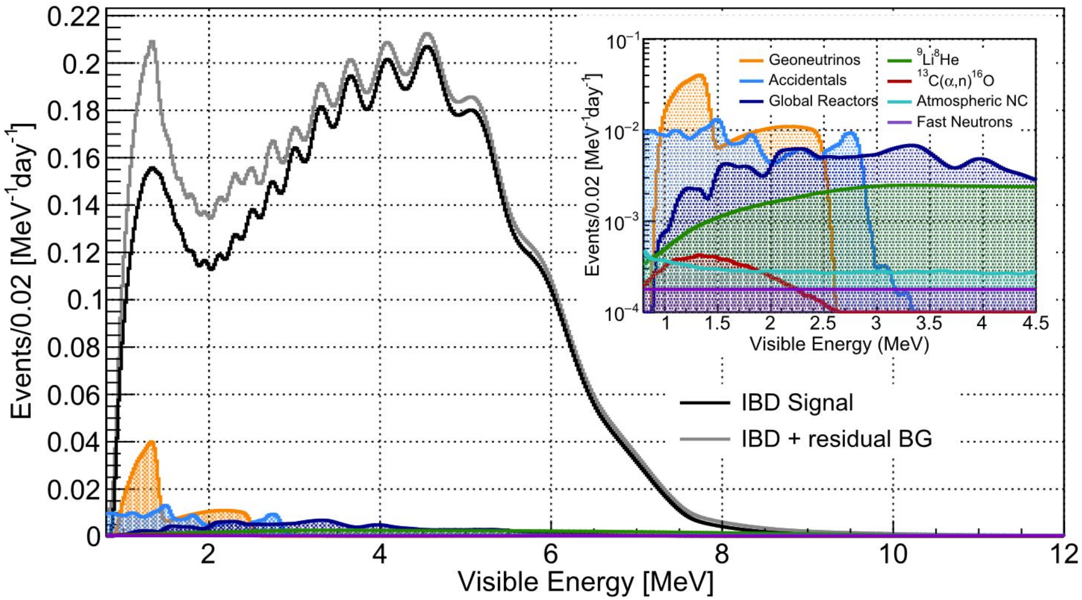
JUNO Collaboration ; JUNO physics and detector [arXiv:2104.02565]
JUNO Collaboration ; Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO [arXiv:2204.13249]

Cosmogenic isotopes (^{8}He and ^{9}Li):

- created by the passage of a muon
- beta-n decay → mimic IBD

$$^8\mathrm{He} \xrightarrow[0.119s]{16.0\%} {}^7\mathrm{Li} + \mathrm{n} + \mathrm{e}^- + \overline{\nu_e}$$

$$^9\mathrm{Li} \xrightarrow[0.178s]{50.8\%} {}^8\mathrm{Be} + \mathrm{n} + \mathrm{e}^- + \overline{\nu_e}$$



Muon veto

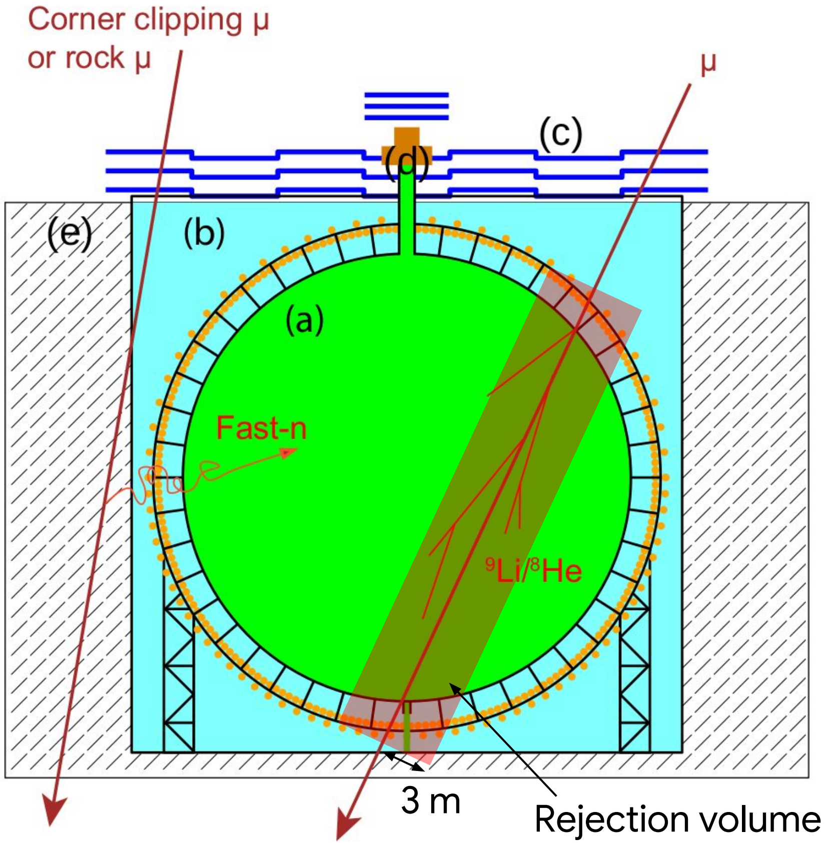
Veto if detection of a muon ⟶ reject for 1.2 s.

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

If veto the whole CD ⟶ impossible to detect neutrino events.

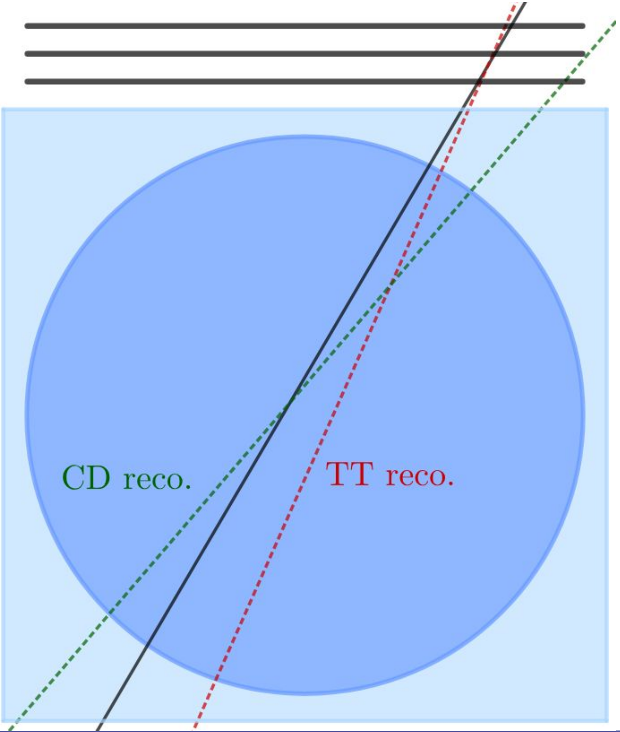
Isotopes ⟶ space/time correlation with muon ⟶ rejection volume along the trajectory.

High precision of knowledge of the trajectory ⟶ reconstruction algorithm.



Current state of cosmic muon reco. in JUNO

Several reconstruction methods have already been implemented (neural network, spherical harmonics, ...).



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 a reconstruction algorithm using all sub detectors.

Principle - Central Detector

Muon in LS ⇒ scintillation + cherenkov radiation.

First Hit Time (FHT) of a PMT = earliest moment where the PMT is triggered.

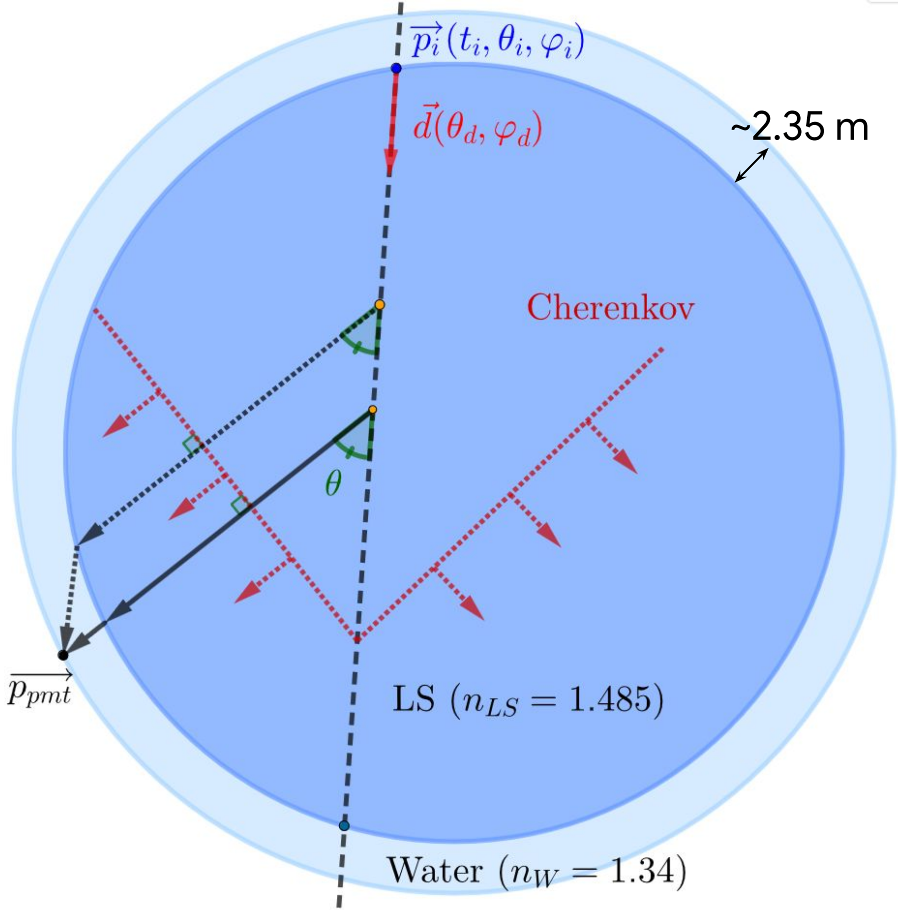
Calculate FHT geometrically ⇒ depends on the track parameters: $t_i, \theta_i, \phi_i, \theta_d, \phi_d$

Approximation: don't take into account the change of medium between LS and Water.

Calculate FHT for every PMT:

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

Minimize with Minuit2.



Principle - Water Pool

Muon entering water ⇒ cherenkov radiation.

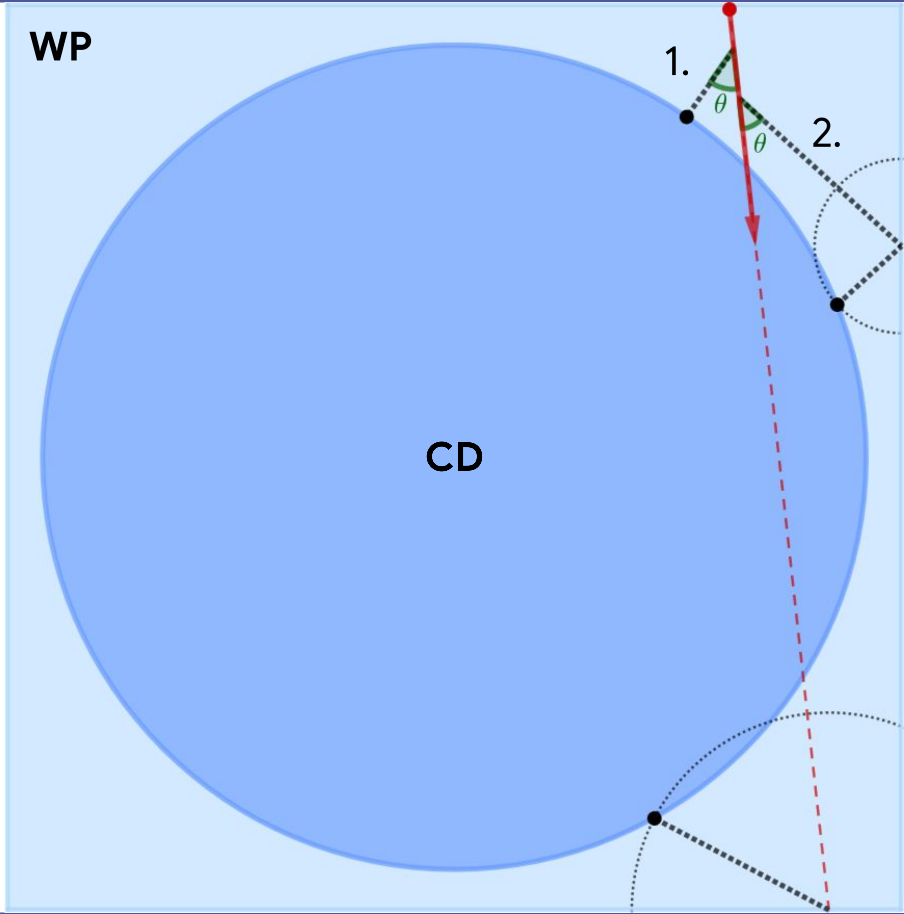
Same method as in the CD ⇒ FHT method.

1. Direct cherenkov.
2. Cherenkov + diffuse reflection (approximation: not taken into account).
3. End point diffuse reflection.

Calculate FHT for every PMT:

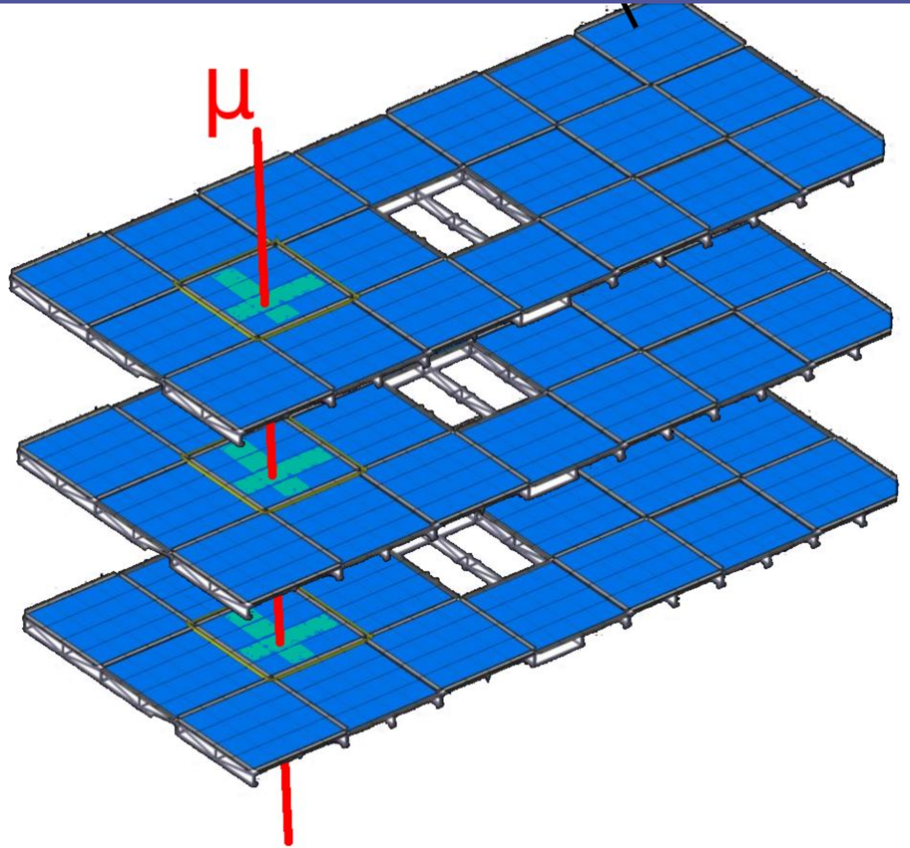
$$\chi^2 = \sum_{k=1}^{2400} \left(\frac{t_{k,theo} - t_{k,meas}}{\sigma_k} \right)^2$$

Minimize with Minuit2.



Principle - Top Tracker

TT ⇒ 3 layers of 7 x 3 walls.



Principle - Top Tracker

TT ⇒ 3 layers of 7 x 3 walls.

Each wall is composed of X and Y plastic scintillator ~~strips~~ Krampouz.

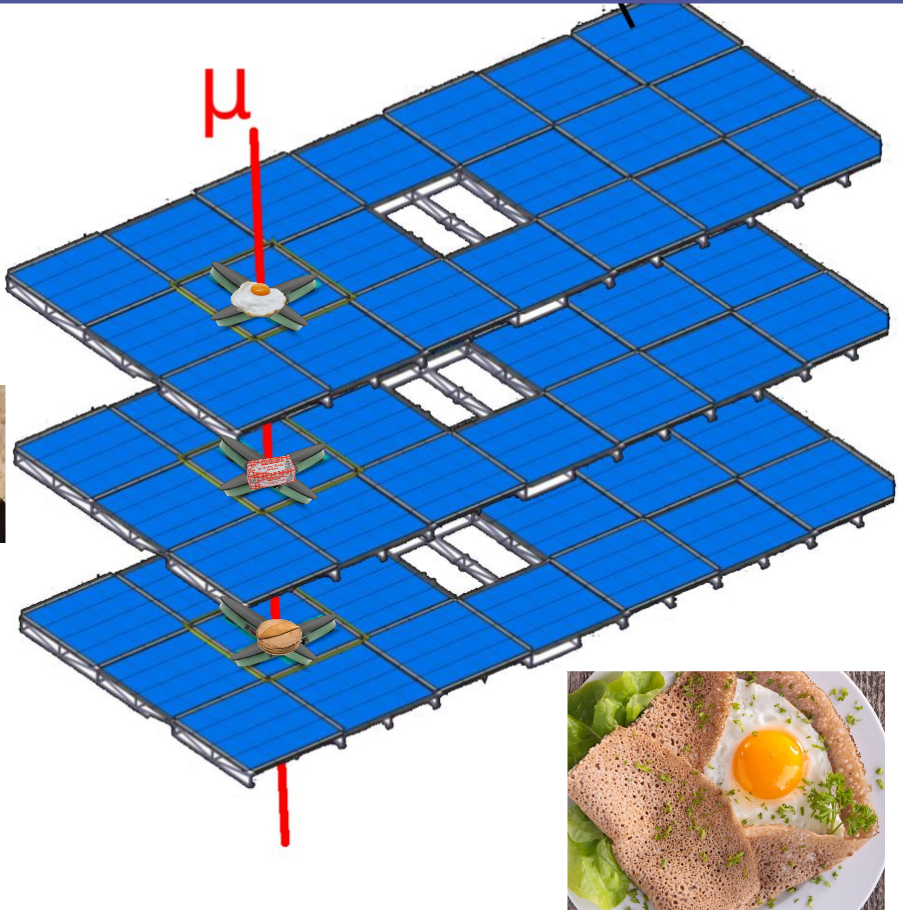
When a muon passes through a wall ⇒ hits both X and Y Krampouz ⇒ X-Y coincidence ⇒ 3 points: egg, ~~soft~~ **salted** butter, crepe.

These 3 grandma really do not fuck around, and if you are using soft butter you will end up in the nearby graveyard

Fit a line through the recipe.

$$\chi^2 = \sum_{k=1}^{3} \left(\frac{\left\| (\vec{p_k} - \vec{p_0}) \times \vec{d} \right\|}{\left\| \vec{d} \right\| \sigma_k} \right)^2$$

Minimize with Minuit2.



Joint reconstruction

All sub-detectors are using chi² minimization.

For joint reconstruction ⇒ sum each chi² (divided by their own ndf for now):

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

$$+ \frac{1}{ndf_{WP}} \sum_{j=1}^{2400} \left(\frac{t_{j,meas} - t_{j,theo}}{\sigma_j} \right)^2 \quad \cdots\cdots\rightarrow \textbf{WP}$$

$$+ \frac{1}{ndf_{TT}} \sum_{k=1}^{3} \left(\frac{\| (\vec{p_k} - \vec{p_0}) \times \vec{d} \, \|}{\| \vec{d} \, \| \sigma_k} \right)^2 \quad \cdots\cdots\rightarrow \textbf{TT}$$

Methodology

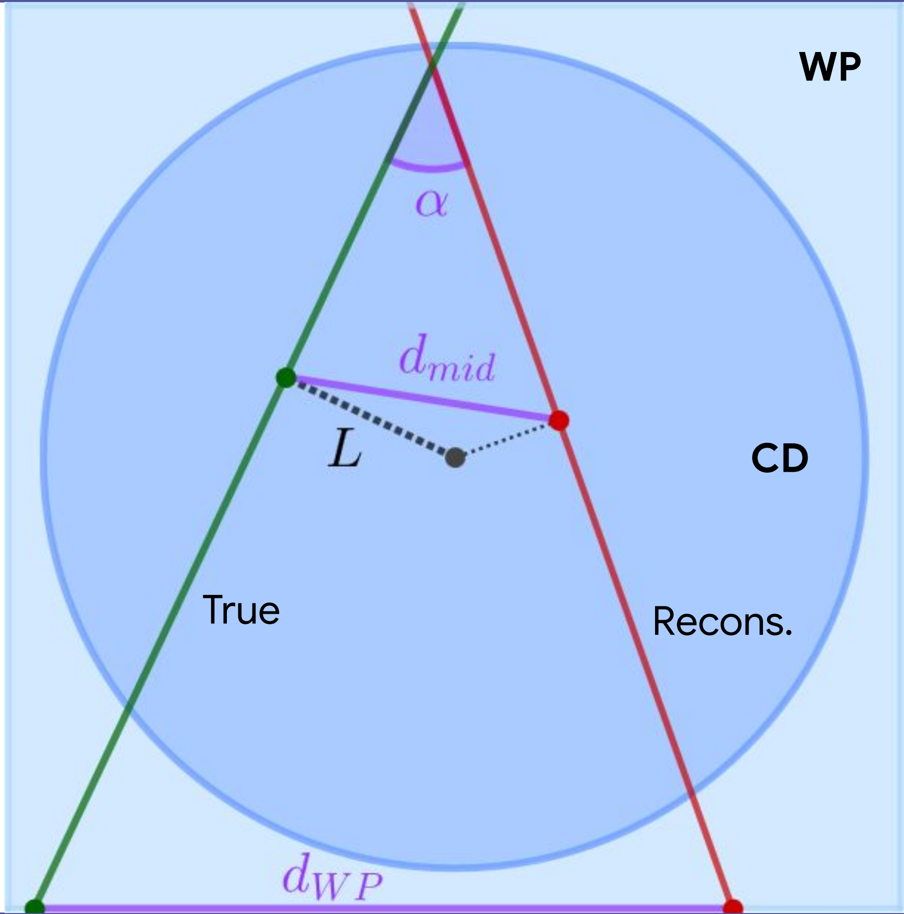
Sample:

Fully simulated data ⟶ ~7k CD events.

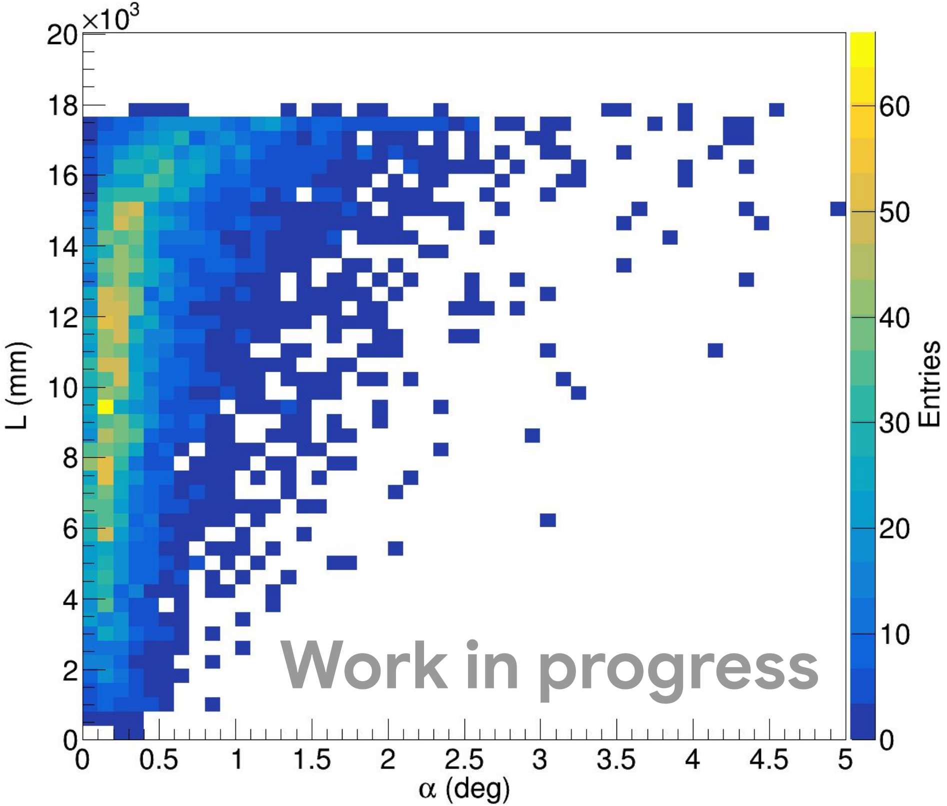
Selected only single muons passing through LS.

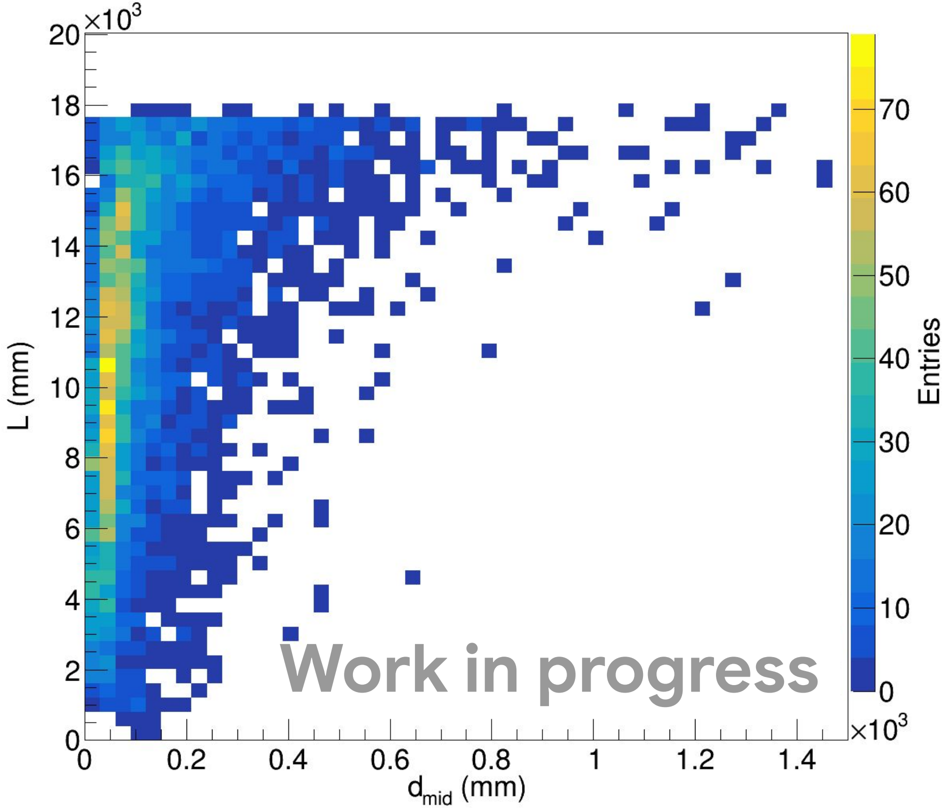
Metrics:

- α: angle between tracks.
- d_{mid}: distance between middle points.
- d_{WP}: distance between track at bottom WP
- L: clippingness of the true track



CD - Results

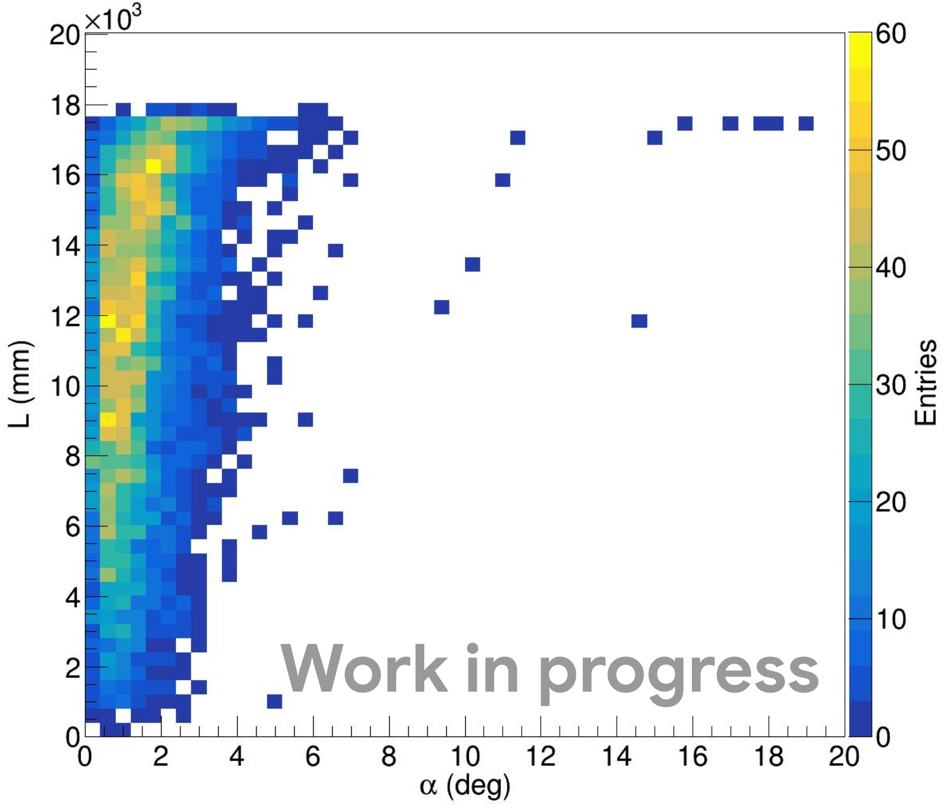


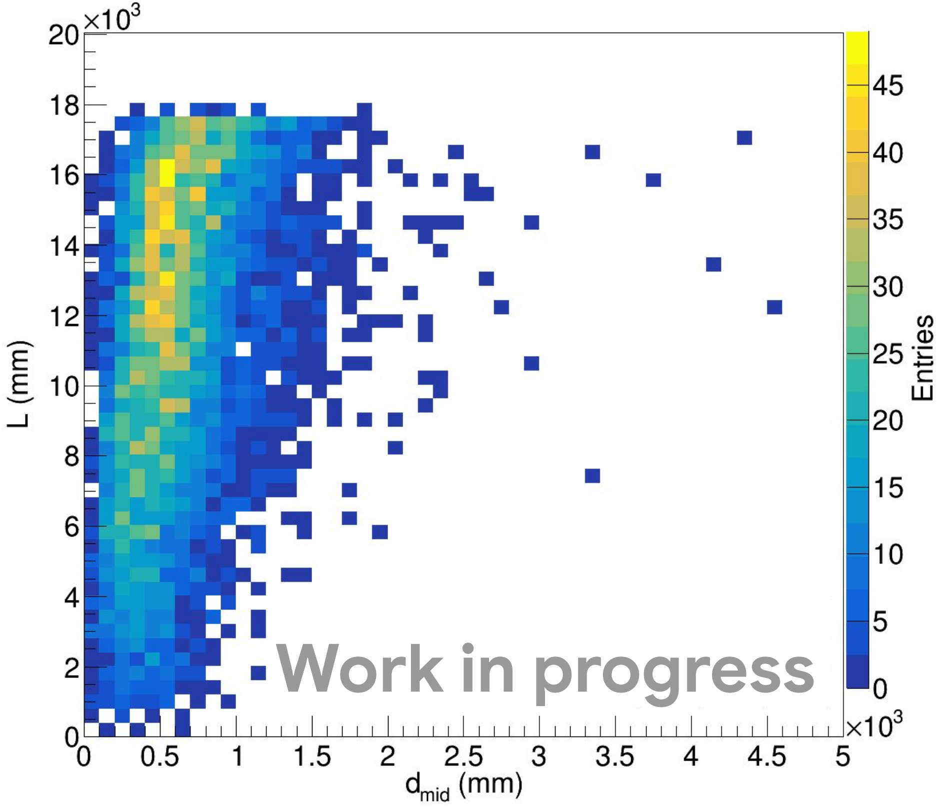


Mean = 0.5 degrees | 95.5% = 1.5 degrees

Mean = 12 cm | 95.5% = 41 cm

WP - Results



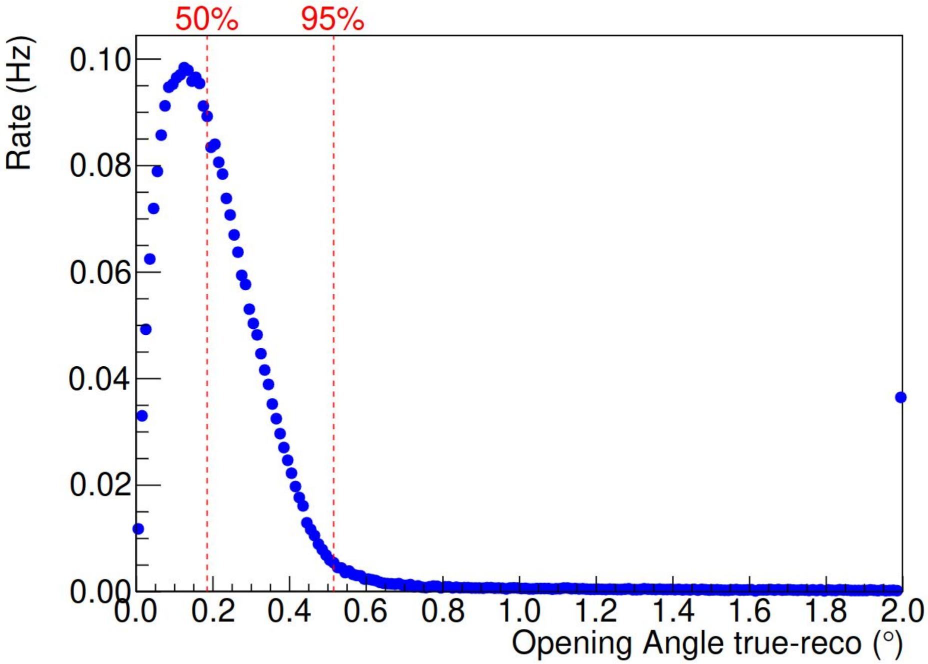


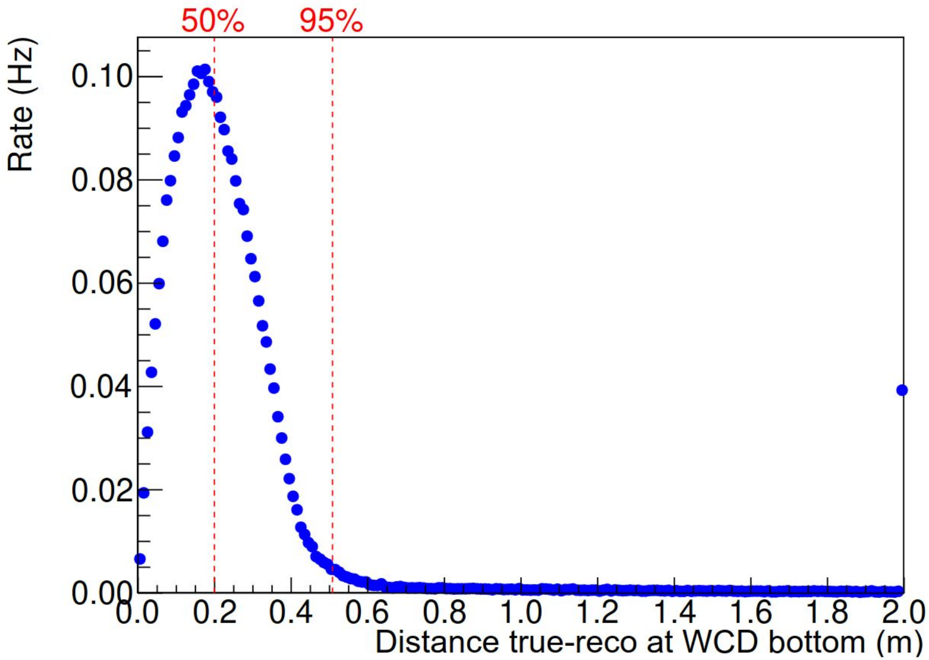
Mean = 1.5 degrees | 95.5% = 3.4 degrees

Mean = 62 cm | 95.5% = 1.3 m

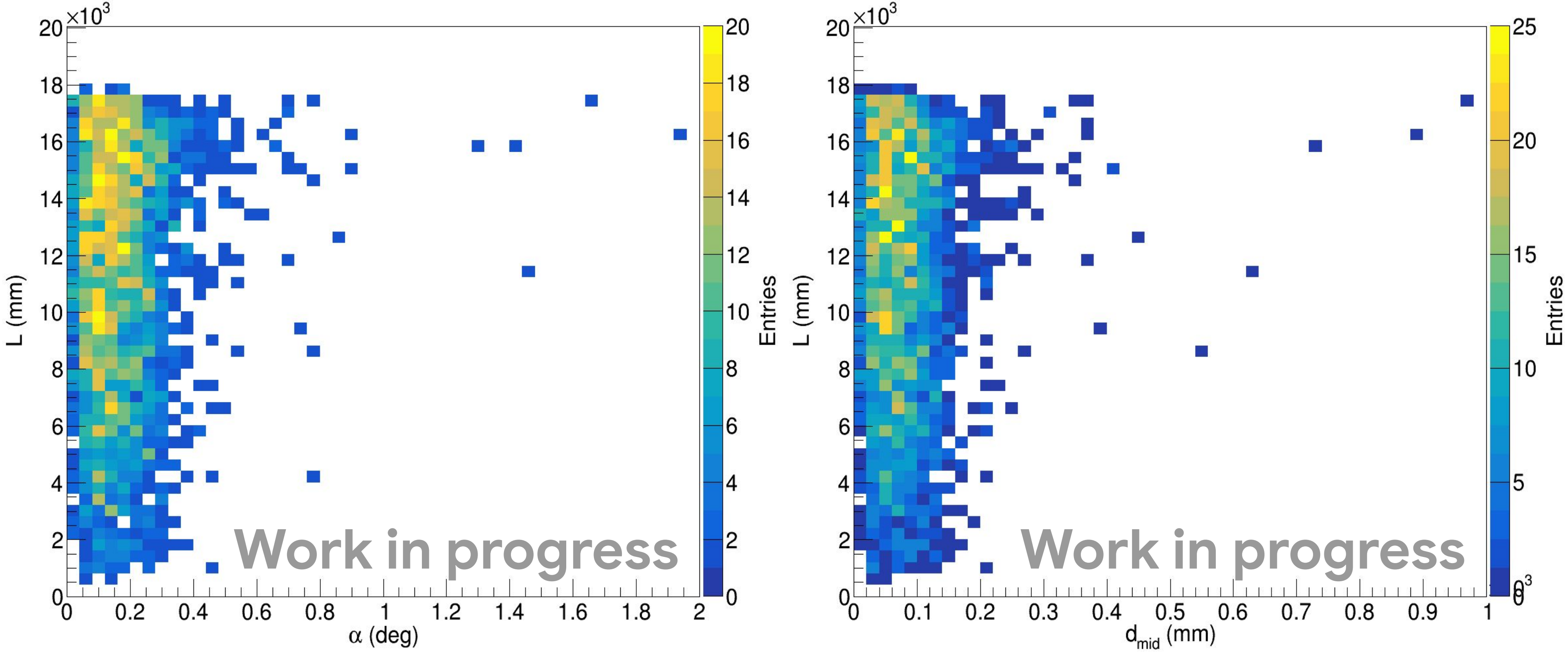
TT - Results

Results from arXiv:2303.05172.





Joint reconstruction - Results



95.5% = ~0.36 degrees (TT only = 0.5) 95.5% for distance bottom WP = ~36 cm (TT only = 50 cm)

Conclusion

Summary:

Created a muon reconstruction algorithm allowing to use jointly all the sub-detectors of the JUNO experiment.

Metric		CD	WP	TT	Joint
Angle (deg)	Mean	0.5	1.5	~0.2	< ~0.2
	95.5%	1.5	3.4	0.5	0.36

For now the main goal was the through-going muons. But we are currently working on improving the stopping muons, and also adapting our algorithm for bundle muons.

Next step:

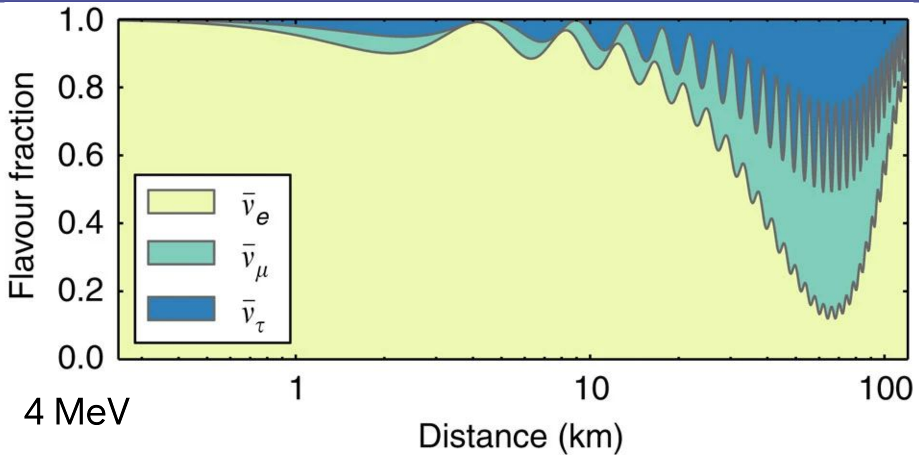
Continue the work of a previous PhD student, working on a background (cosmogenics) study → He used TT information for muon reconstruction ⇒ Try to improve his study with our joint method.

Waiting for JUNO to take its first data (maybe next year (they always say we will be ready next year but it never happen (6th year they are saying that))).

The JUNO project was approved by Chinese Academy of Sciences in February 2013. Data taking is expected in 2020.

Thanks for your attention!

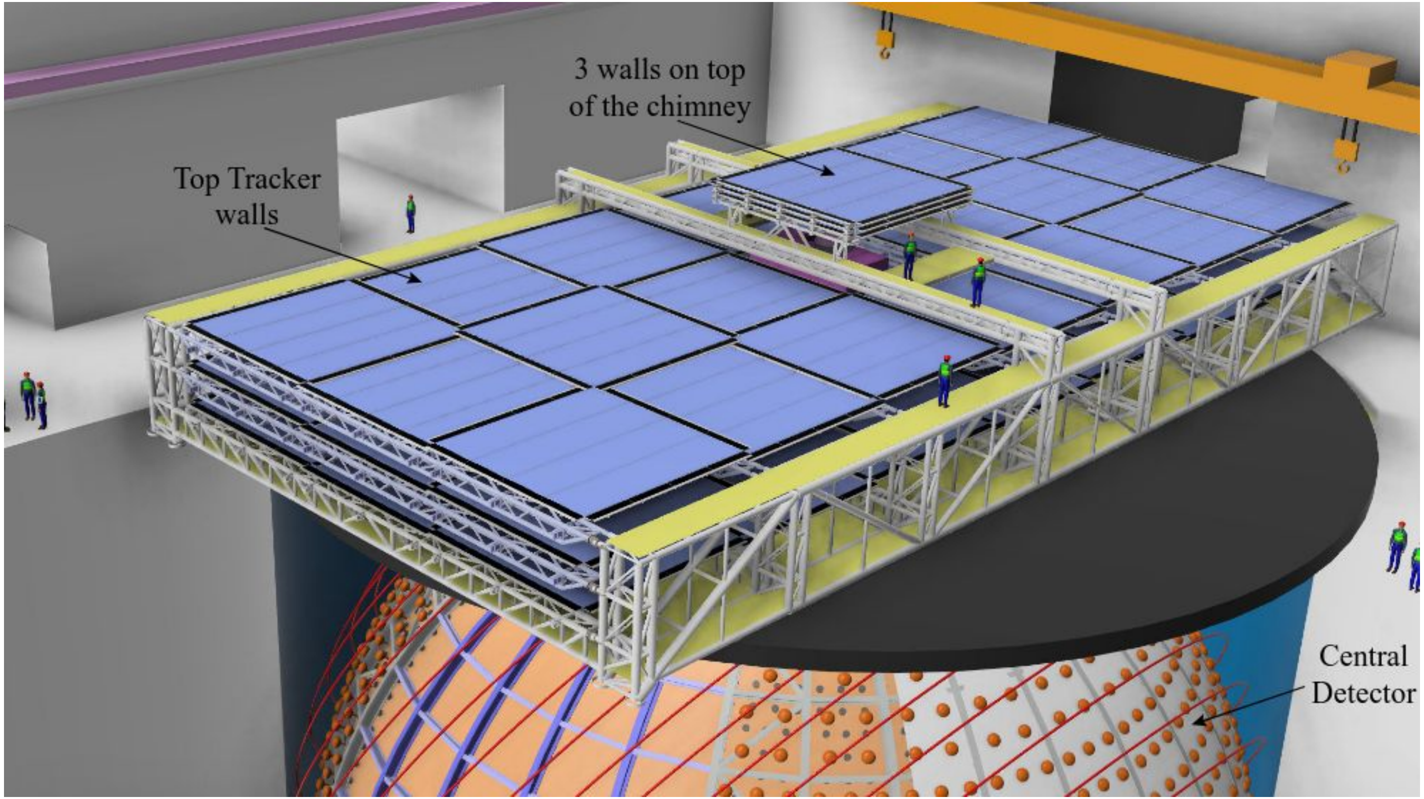
Backup - Neutrino oscillation



$$\begin{aligned}\mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) &= 1 - \sin^2 2\widetilde{\theta}_{12}\, \tilde{c}_{13}^4\, \sin^2 \widetilde{\Delta}_{21} - \sin^2 2\widetilde{\theta}_{13} \left(\tilde{c}_{12}^2 \sin^2 \widetilde{\Delta}_{31} + \tilde{s}_{12}^2 \sin^2 \widetilde{\Delta}_{32}\right) \\ &= 1 - \sin^2 2\widetilde{\theta}_{12}\tilde{c}_{13}^4 \sin^2 \widetilde{\Delta}_{21} - \frac{1}{2} \sin^2 2\widetilde{\theta}_{13} \left(\sin^2 \widetilde{\Delta}_{31} + \sin^2 \widetilde{\Delta}_{32}\right) \\ &\quad - \frac{1}{2} \cos 2\widetilde{\theta}_{12} \sin^2 2\widetilde{\theta}_{13} \sin \widetilde{\Delta}_{21} \sin(\widetilde{\Delta}_{31} + \widetilde{\Delta}_{32}),\end{aligned}$$

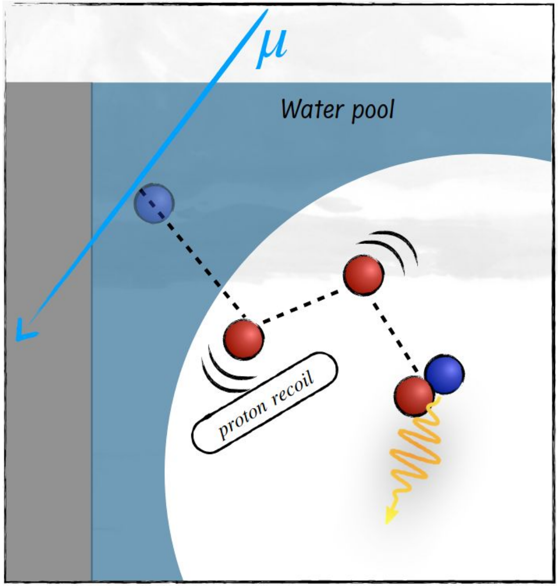
where $\tilde{c}_{ij} \equiv \cos\widetilde{\theta}_{ij}$, $\tilde{s}_{ij} \equiv \sin\widetilde{\theta}_{ij}$, $\widetilde{\Delta}_{ij} = \Delta\tilde{m}_{ij}^2 L/4E$, with $\widetilde{\theta}_{ij}\, (i, j = 1, 2, 3,\ i < j)$

Backup - JUNO TT



Backup - Background sources

Fast neutrons:



- scatter proton (prompt signal), while thermalising
- captured after thermalisation (delay signal)

$^{13}C(\alpha, n)^{16}O$:

- $^{13}C + \alpha \longrightarrow {}^{16}O + n$
- Prompt-like signal given by:
  - Proton recoils if the neutron is fast enough
  - de-excitation from excited ^{16}O state
- Delay-like signal given by the neutron capture

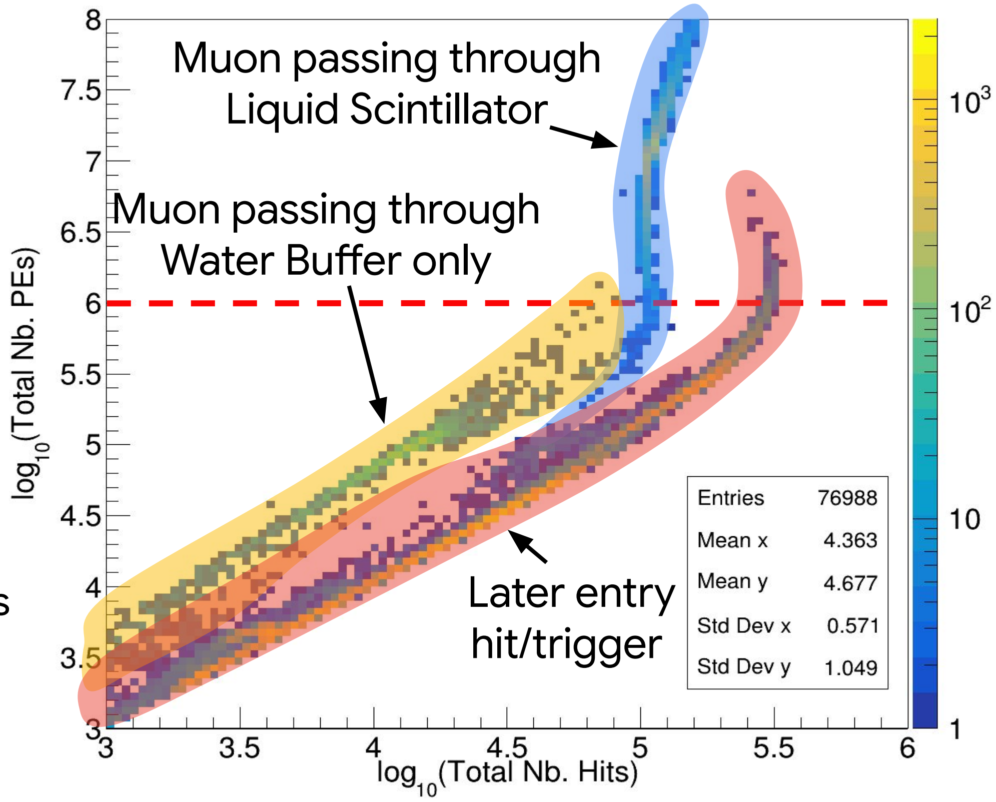
Backup - Checker

Currently, only reconstruction single not stopping muons passing through the LS.

Water Buffer muons ⇒ cannot be reconstructed because of parameters.

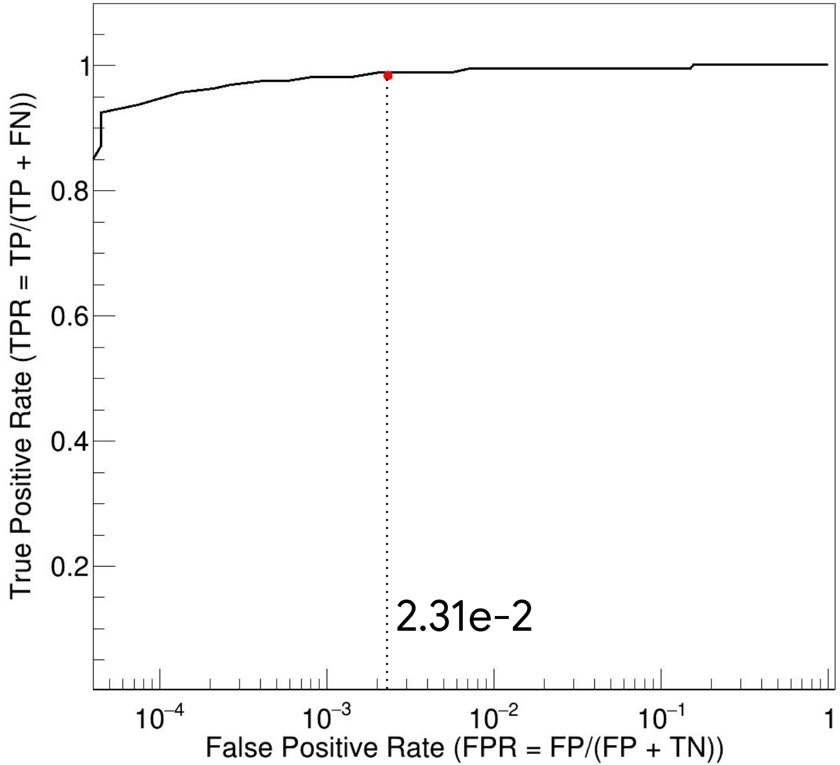
Same applies to stoppings and bundles, but not possible to reject them.

10^6 total P.E. threshold (only CD) to select muons (single / bundle / stopping) passing through LS ⇒ efficiency / purity ~ 98%



Backup - Checker

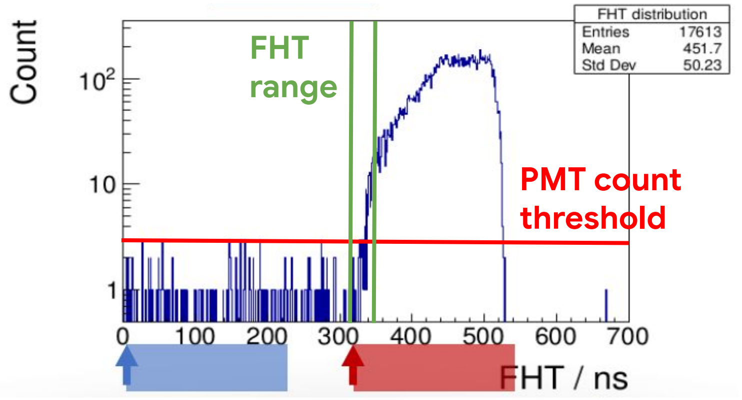
		Prediction	
	Total = P + N	Predicted Positive (PP)	Predicted Negative (PN)
Truth	Positive (P)	9425 True Positive (TP)	153 False Negative (FN)
	Negative (N)	156 False Positive (FP)	67254 True Negative (TN)



Receiver Operating Characteristic (ROC) curve

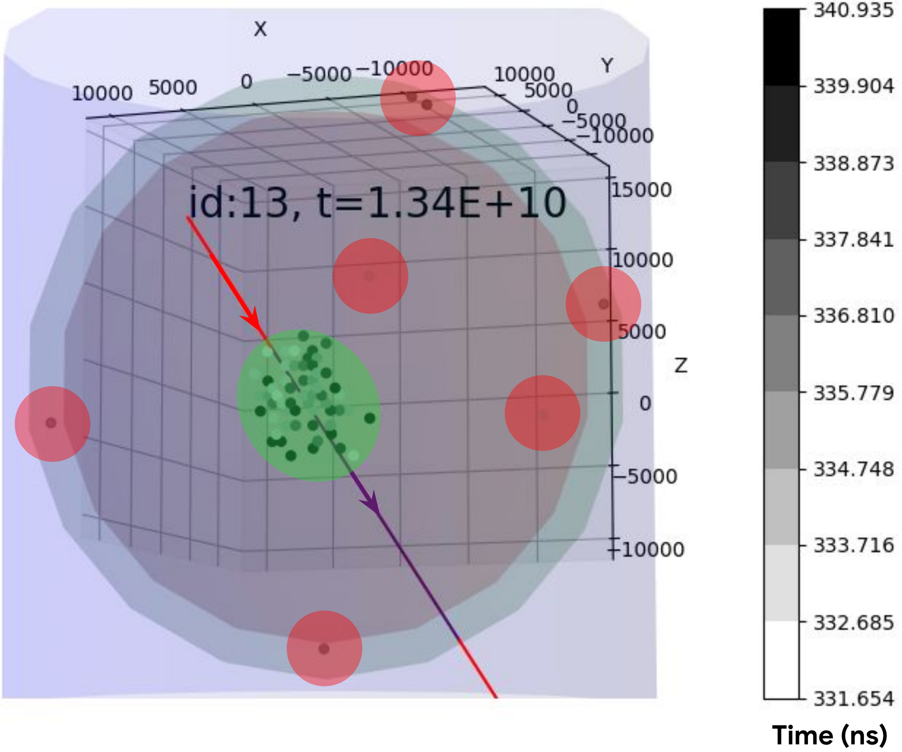
Backup - Initializer

Pos.: Get PMTs at the beginning of the FHT profile distribution → mean position.

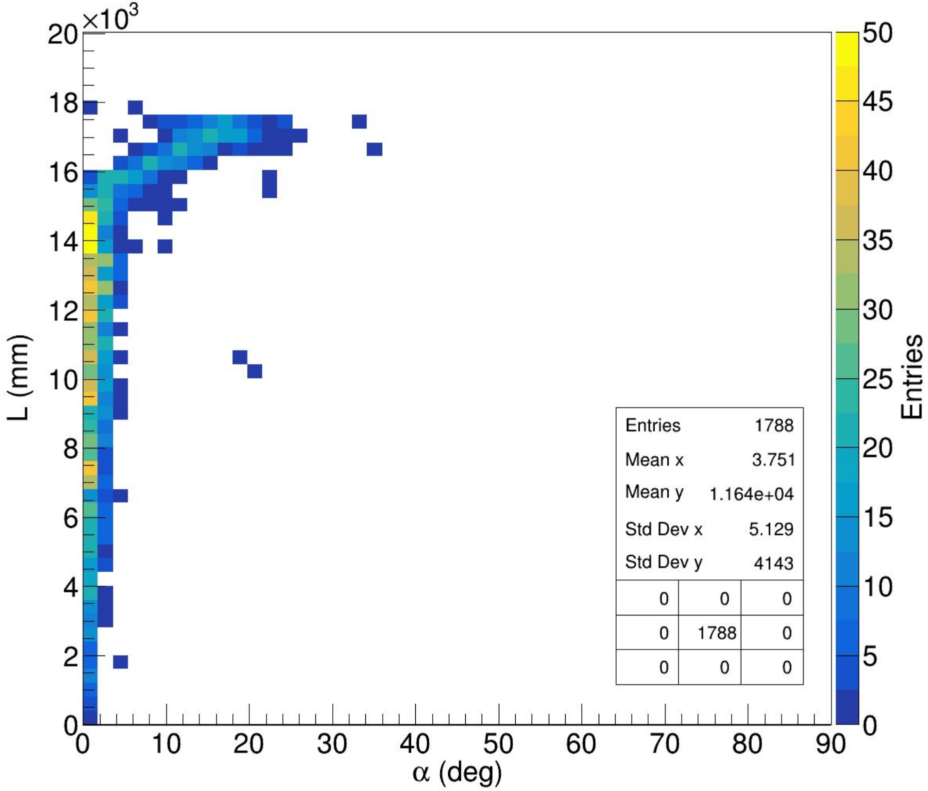


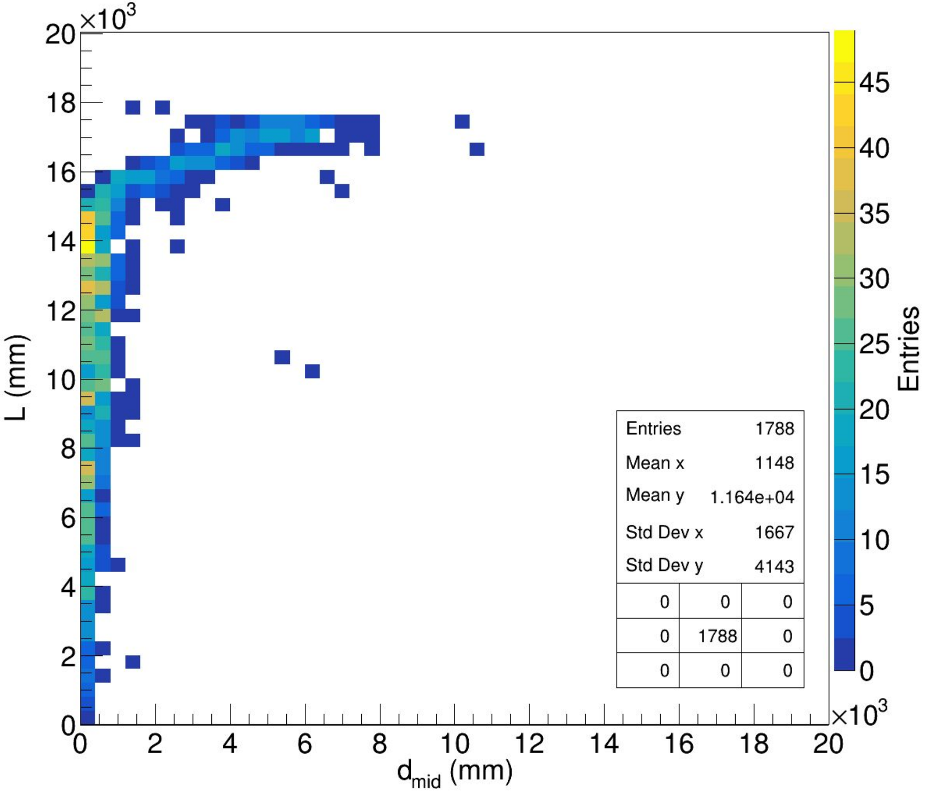
Dir.: Charge centroid x 1.5.

Initialization **only with 20-inch PMTs**.

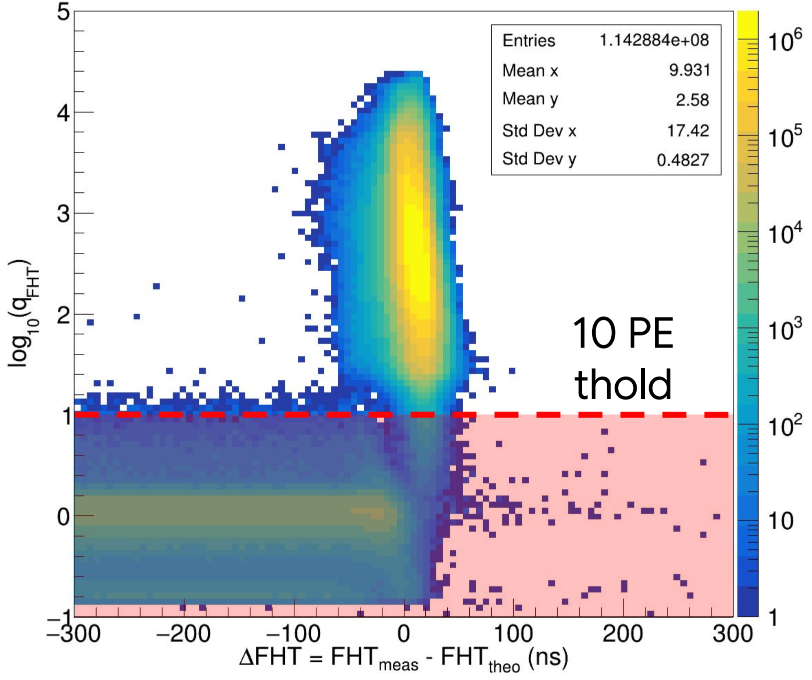


Backup - Initializer

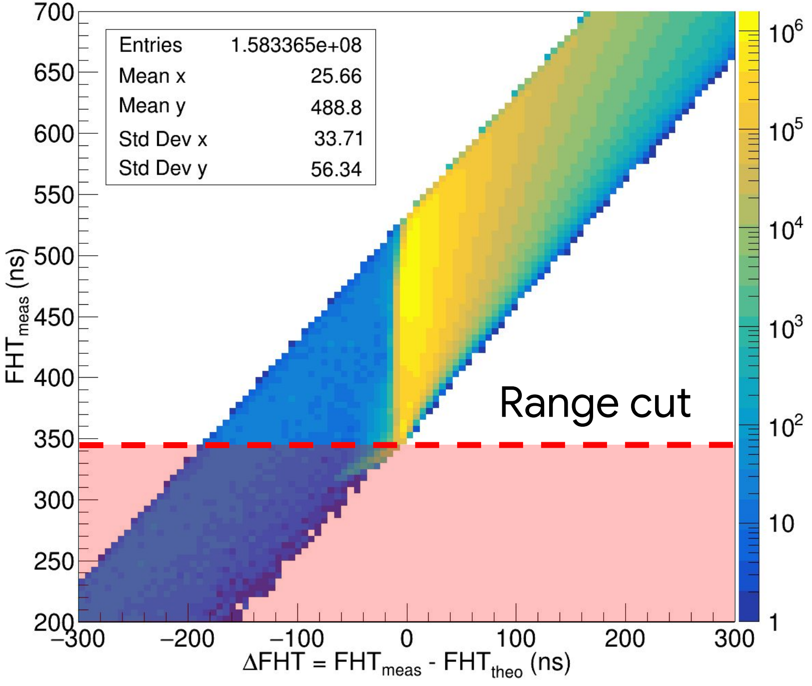




Actually better than this because we improved it.



20-inch PMTs



3-inch PMTs

We only want to keep PMTs with a ΔFHT ~ 0 ns.

Backup - FHT calculation

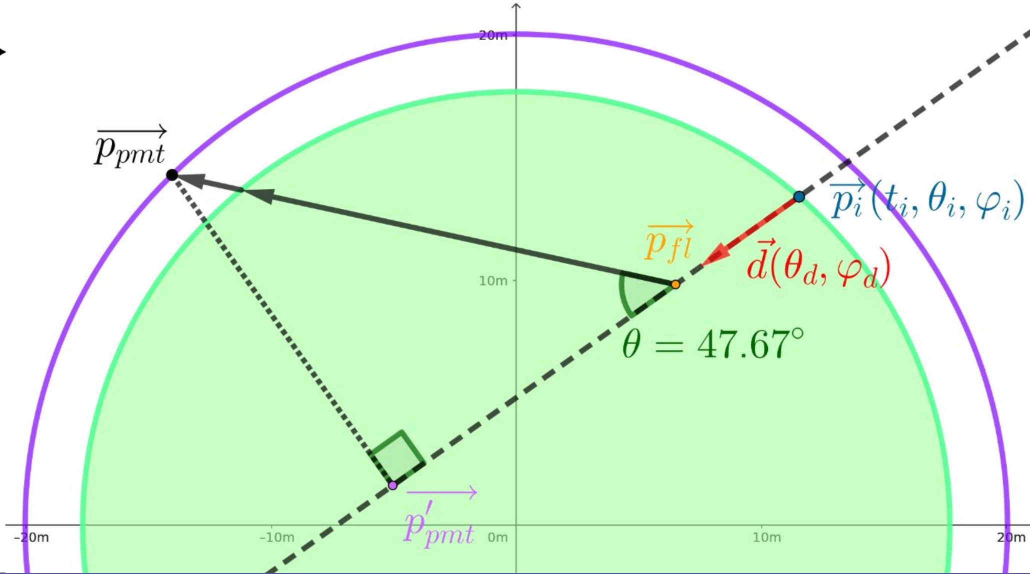
$$\overrightarrow{p_{\perp pmt}} = \left[\left(\overrightarrow{p_{pmt}} - \overrightarrow{p_i}\right) \cdot \overrightarrow{d}\right] \overrightarrow{d}$$

$$\overrightarrow{p_{fl}} = \overrightarrow{p_i} + \left(|\overrightarrow{p_{\perp pmt}} - \overrightarrow{p_i}| - \frac{|\overrightarrow{p_{pmt}} - \overrightarrow{p_{\perp pmt}}|}{\sqrt{n_{LS}^2 - 1}} \right) \overrightarrow{d}$$

$$\overrightarrow{p_{fl}} = \overrightarrow{p_i} + \left(|\overrightarrow{p_{\perp pmt}} - \overrightarrow{p_i}| - |\overrightarrow{p_{\perp pmt}} - \overrightarrow{p_{fl}}| \right) \overrightarrow{d}$$

$$\tan(\theta) = \frac{|\overrightarrow{p_{pmt}} - \overrightarrow{p_{\perp pmt}}|}{|\overrightarrow{p_{\perp pmt}} - \overrightarrow{p_{fl}}|}$$

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



Backup - Correction maps

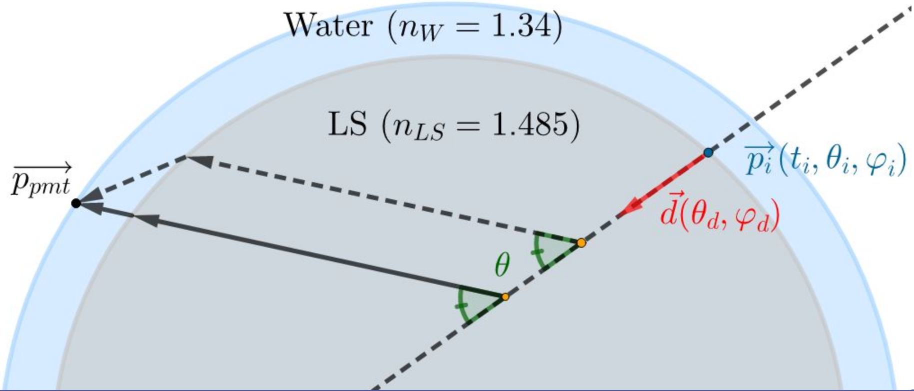
Theoretical calculation not quite accurate because of approximations → bias.

Create an empirical map that takes into account the full detector geometry.

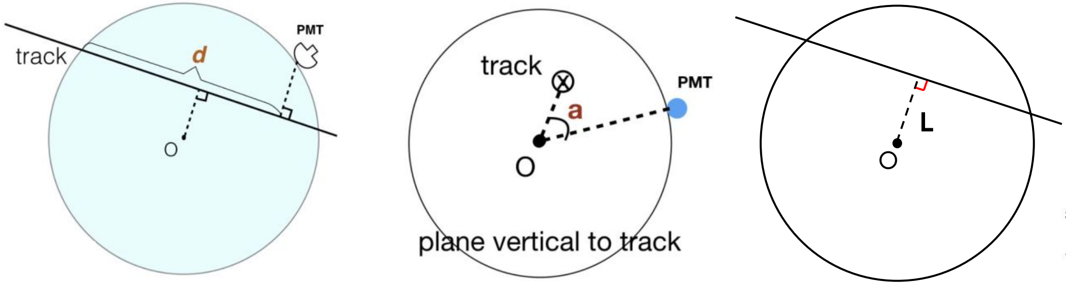
How to create: calculate the ΔFHT in function of three parameters that characterize PMTs position with respect to the track → 3D map. Use the true muon info.

How to use: introduce the FHT correction in the Chi^2 calculation.

$$\chi^2 = \sum_{k=1}^{17612+25600} \left(\frac{t_{k,theo} + \boxed{\Delta t_k} - t_{k,meas}}{\sigma_k} \right)^2$$

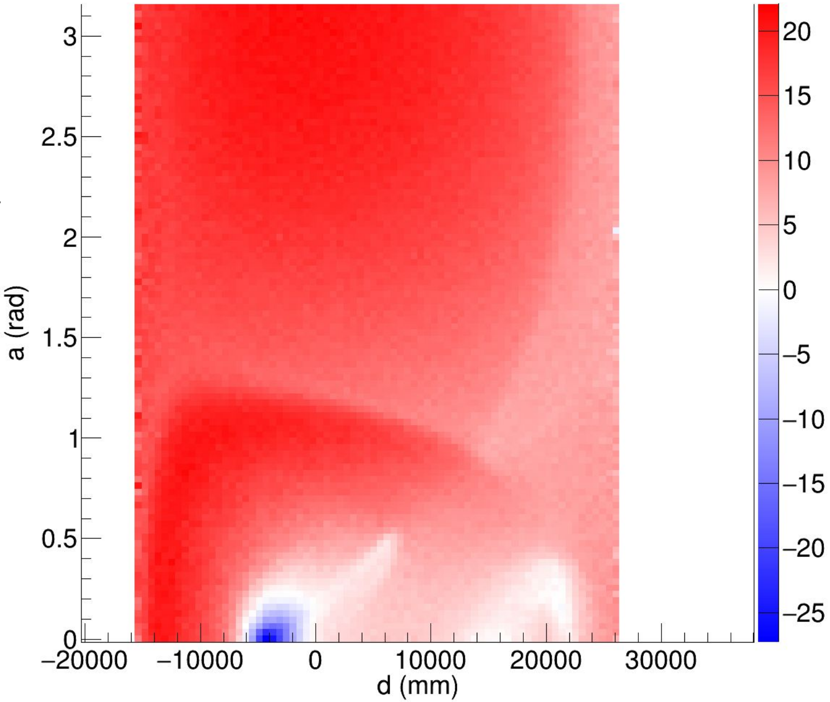


Backup - Correction maps



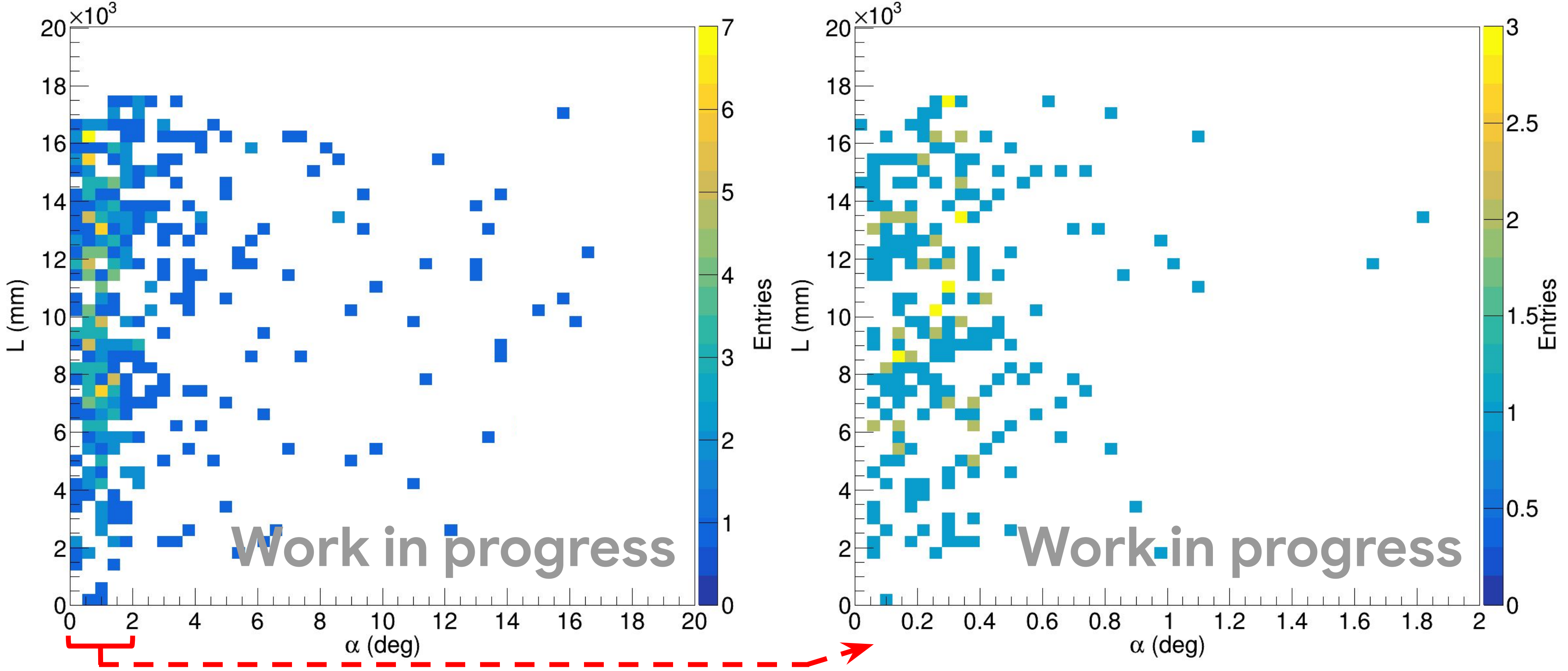
Map in function of d, a, and L.

Use half of our dataset to create the correction map, then use the other half to test the reconstruction.



Corr. map for CD LPMTs for clipping muons

Backup - Stopping muon



CD only

Joint reco.