CA NuLa 2023
(CAU Neutrino Lab)

Supervisor: Kim Siyeon

CAU HEP Center Workshop,
Dec.27 – Dec.28, Gonjiam Resort

Members:

Winter	Spring	Summer	Fall	Winter	
김시연 Siyeon (super)					
정유선 Yuseon (res)					
권순우 Sunwoo (grad)					"Hey, Dr. Gwon!"
정기영 Kiyoung (res)			Other institution		
김선홍 Sunhong (grad)			Off for Military Service		
박주성 Juseong (under-g)					(grad)
박유진 Yujin (under-g)		Off for Military Service			
유성식, 장준서		Undergraduate alumni			
			에마르 Emar (grad)		
			김수현 Suhyeon (grad)		
			고경의 Gyeongui (under-g)		
			박종인 Jongin	undergraduate	
				마수드 Masud (res)	

Research Activities: Publications

*J*inst

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Accepted: *January 30, 2023*
Published: *March 1, 2023*

Pulse shape discrimination using a convolutional neural network for organic liquid scintillator signals

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Neutron detection and application with a novel 3D-projection scintillator tracker in the future long-baseline neutrino oscillation experiments

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- 4 DUNE papers and another published

Research Activities: Events and Workshops

02.23~04.01 Sunwoo, Kiyoung, Yujin	Brookhaven National Lab, Cold Electronics for DUNE FD HD and VD
06.19~06.30 Sunwoo	Stony Brook University, Neutron beam test data analysis workshop DUNE FD3 Workshop
06.15~06.16	Advisory Board Invitation, C. K. Jung at Stony Brook University
07.20~07.21 Siyeon	K-Nu Symposium (Co-Organizer)
07.22~07.28	Advisory Board Invitation, K. Hagiwara at KEK
08.21~08.26 Siyeon	NuFACT 2023, Scientific Program Manager Public Lecture Organizer and chair
01.17~02.28, 2024 Sunwoo, Emar, Suhyeon, Juseong, Gyeongui	Brookhaven National Lab, Cold Electronics for DUNE FD HD and VD Water-based Liquid Scintillator Prototype, Data Taking and Analysis

CAU **DUNE** members as of January 2024 : Kim Siyeon, Mehedi Masud, Sunwoo Gwon, Emar Masaku, Suhyeon Kim, Juseong Park

NEOS and **AMoRE** : Kim Siyeon

Internal News

	Emar and Suhyeon joined NuLa at CAU. They are working on Neutrino Oscillation.
	Sunwoo passed Ph. D. defense. (Open Seminar on Dec.13) He became an expert of neutron study in neutrino experiments.
	Dr. Masud joined NuLa at CAU. He gave an introduction of his research interests.

Phenomenology of neutrino oscillation at long-baseline experiments

- Basics of oscillation physics and pending issues
- Effect of sterile neutrino on oscillation
- Nonstandard neutrino interaction
- Exploring Lorentz Invariance
- Other new physics

Talk given at:
Chung Ang University
Seoul, Korea, Dec 6, 2023

Mehedi Masud
Chung Ang University
Seoul, Korea

Neutron kinematic detection and its applications in long-baseline neutrino experiments

Sunwoo Gwon
Chung-Ang University, Seoul, Korea

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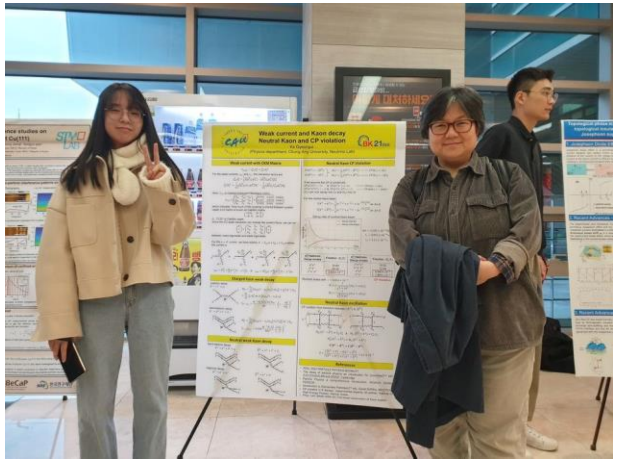
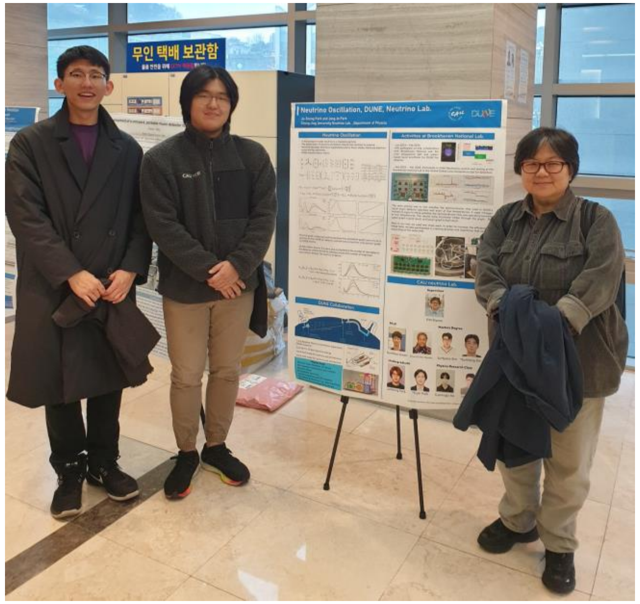
- 3-Dimensional Scintillator Tracker (3DST) detector
  - introduction
  - neutron detection
- Neutron detection applications from neutrino interaction
  - low-δp_T channel
  - flux constraint with $CC0\pi0p1n$ sample
- Neutron beam test and ongoing study
  - n-CH total neutron cross section
  - neutron elastic / inelastic study
  - scattered neutron energy reconstruction

Outline

Emar Masaku	Neutrino Oscillation and Matter Effect
Kim, Suhyeon	Neutrino Oscillation of DUNE Experiment and CP phases
Park, Juseong / Kim, Sunhong	Application of 3DST for reactor antineutrinos
Park, Juseong	Charged pion event selection at 3DST with DUNE muon neutrinos





To be followed by Dr. Yu Seon Jeong's Talk.

Tittle: Neutrino Oscillation in Matter

Emar Masaku

Date:2023/12/27

Content

- Introduction
- Oscillation probability of 3 neutrino in vacuum
- Neutrino oscillation in Matter
- Hamiltonian in vacuum/matter
- Discussion
- Ratio Probability of neutrino oscillation in vacuum/matter
- Conclusion

Oscillation probability of neutrino in vacuum

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

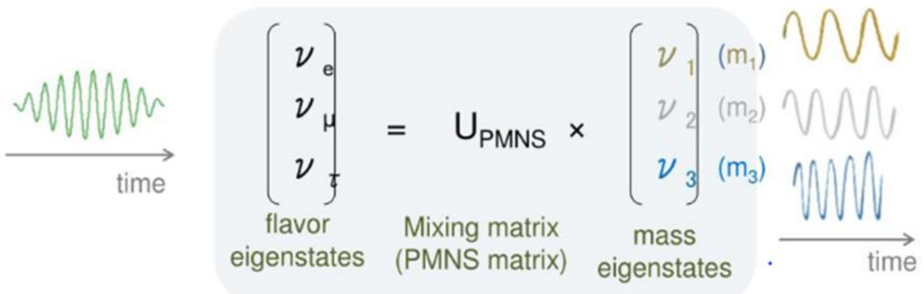
$$+ 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right),$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$ and we can rewrite:

$$\frac{\Delta m^2_{ij} L}{4E} \approx 1.267 \frac{\Delta m^2_{ij}[eV^2] \times L[km]}{E[GeV]}.$$

Neutrino oscillation

The flavor of neutrino changes periodically as it propagates



Mixing matrix depends on the mixing angles θ_{12}, θ_{23}, θ_{13} and the CP violating phase δ_{CP}.

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$(c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij})$

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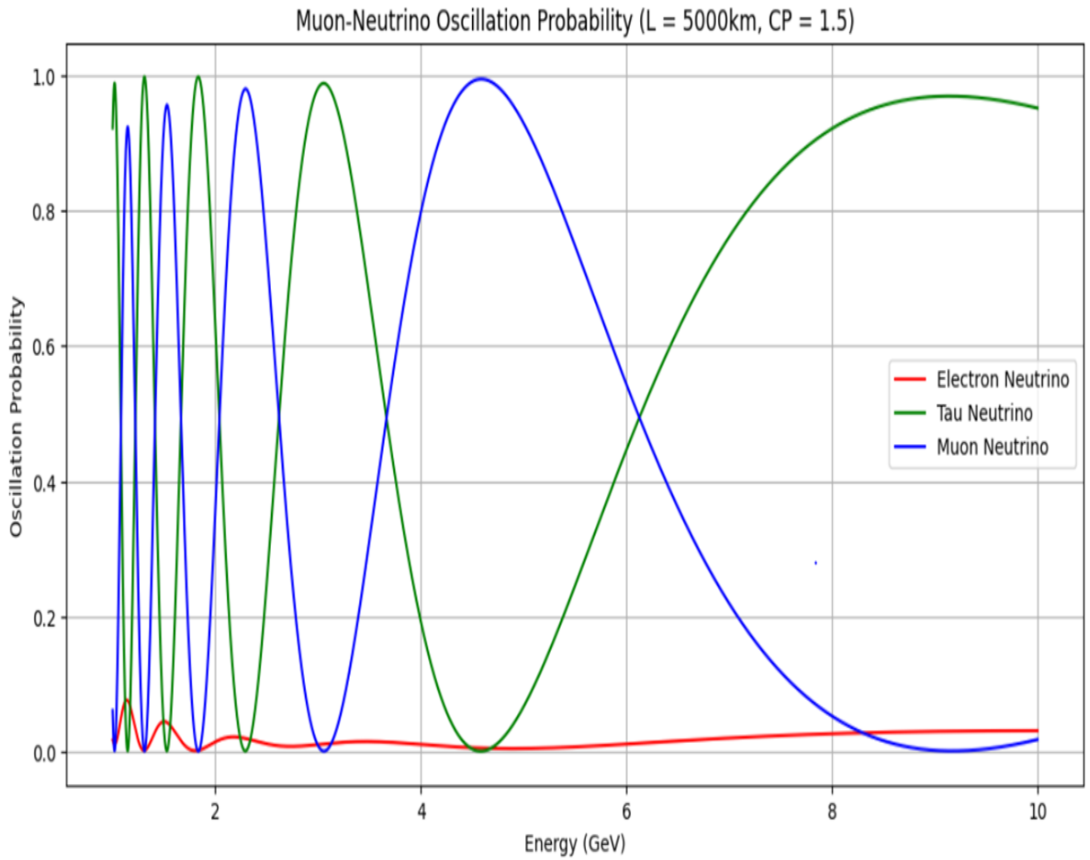
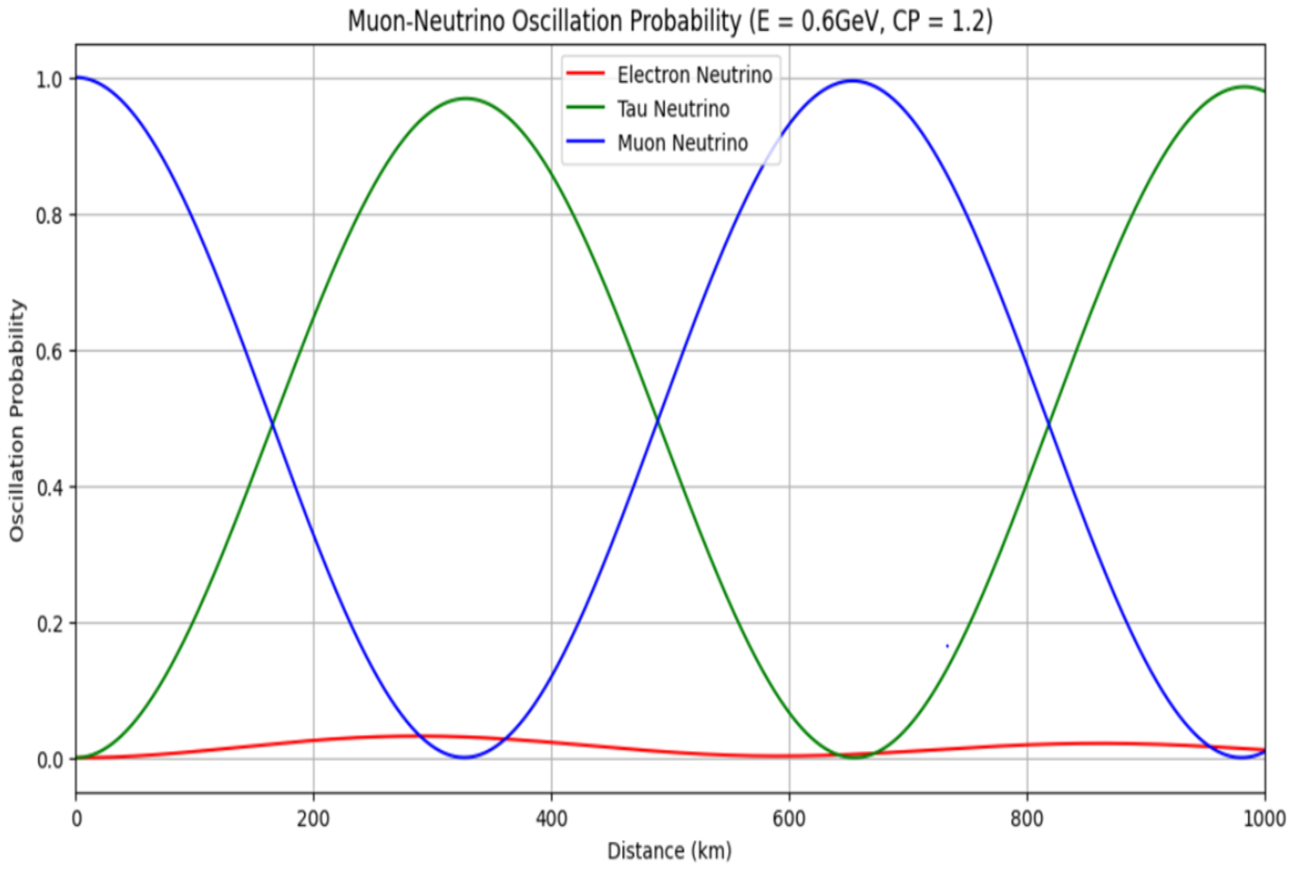
Plots for 3 Neutrino Oscillation Probability vs Distance/ Energy





How does neutrino propagate through matter

- ❖ Neutrinos can change their flavor as they travel through matter due to the interaction potential energy they acquire from forward scattering with ambient particles.
- ❖ The interaction potential depends on the type and density of matter, the flavor and energy of the neutrino, and the distance it travels.
- Two-way for forward scattering of neutrino
- VW is proportional to the number density of electrons in matter and affects only electron neutrinos and antineutrinos. (W_boson).

$$V_W = \begin{cases} +\sqrt{2}G_F N_e & \text{for } \nu_e \\ -\sqrt{2}G_F N_e & \text{for } \overline{\nu_e} \end{cases}$$

- VZ is proportional to the number density of neutrons in matter and affects all neutrino flavors and antiparticles. (Z-Boson).

$$V_Z = \begin{cases} -\frac{\sqrt{2}}{2} G_F N_n & \text{for } \nu \\ +\frac{\sqrt{2}}{2} G_F N_n & \text{for } \bar{\nu} \end{cases}$$

- The interaction potential modifies the Hamiltonian of the neutrino system and alters the oscillation probability in matter compared to vacuum

Hamiltonian in Vacuum/Matter

- Hamiltonian for neutrino in Vacuum

$$\mathcal{H}_{\mathrm{Vac}} = \frac{\Delta m^2}{4p}\begin{bmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{bmatrix} + \left(p + \frac{m_1^2 + m_2^2}{4p}\right)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

But With high relatively neutrino f

$$\mathcal{H}_{Vac} = \frac{\Delta m^2}{4E}\begin{bmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{bmatrix}$$

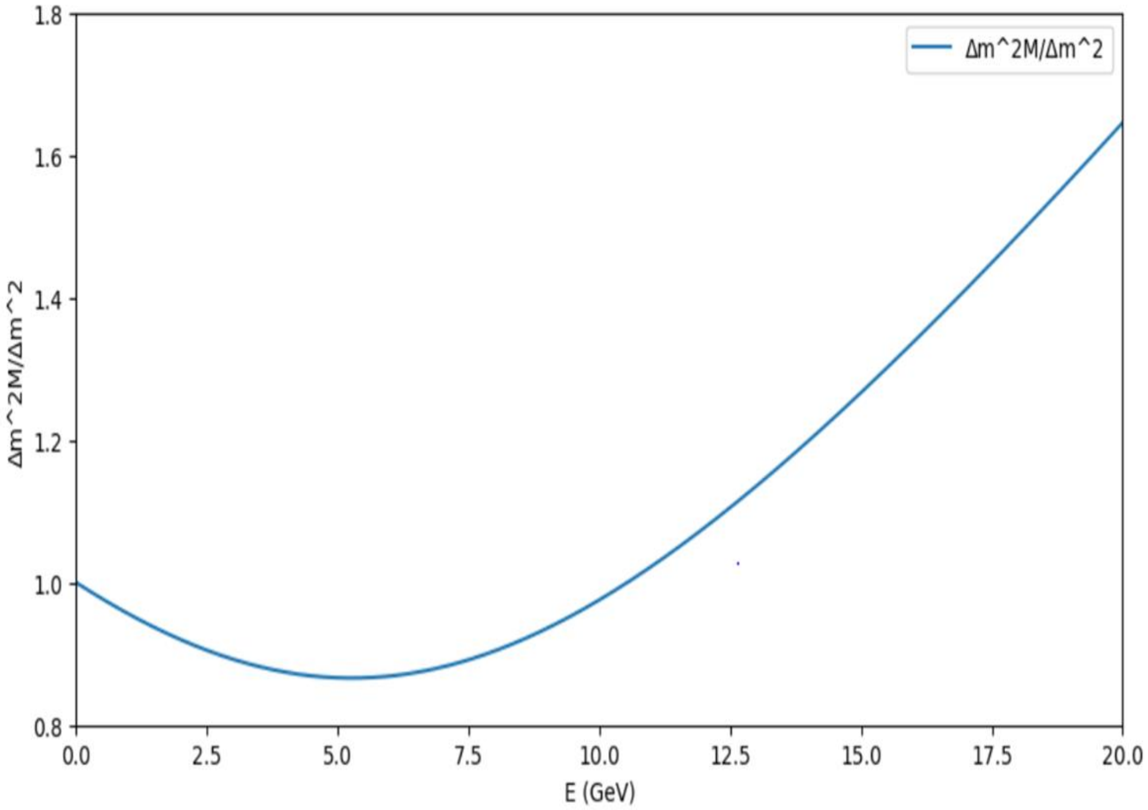
- Hamiltonian in matter; for interaction potential of Vz

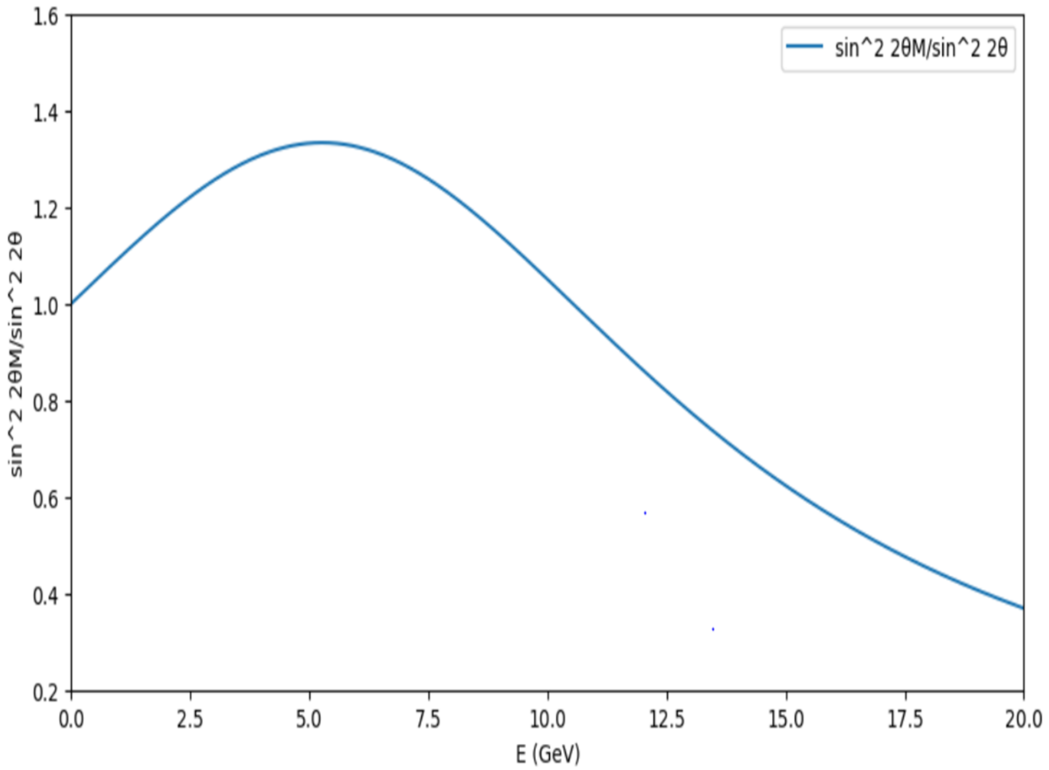
$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

$$\Delta m_M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

$$\mathcal{H}_M = \frac{\Delta m_M^2}{4E}\begin{bmatrix} -\cos 2\theta_M & \sin 2\theta_M \\ \sin 2\theta_M & \cos 2\theta_M \end{bmatrix}.$$

Ratio of Δm^2M /Δm^2 vs. E & sin^2 2θM/ sin^2 2θ vs. E

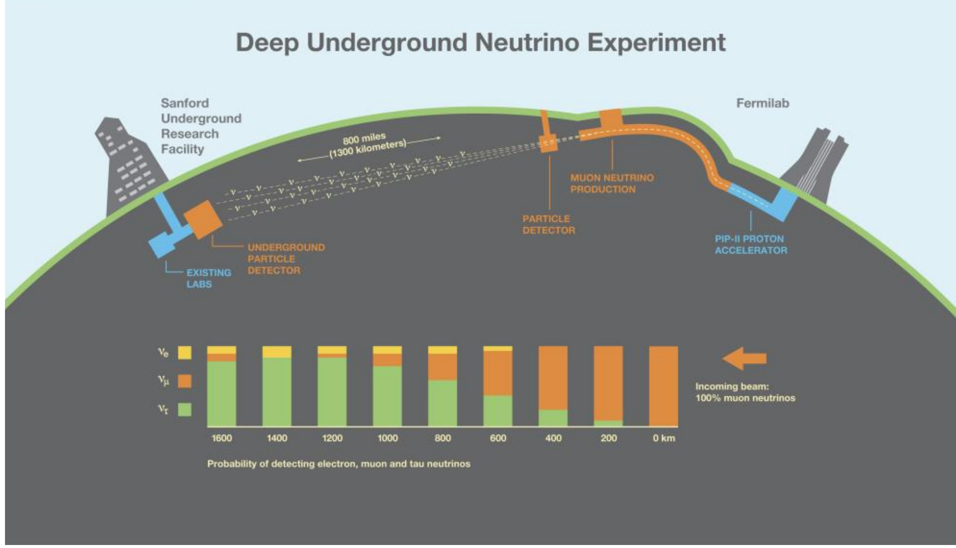




Neutrino Oscillation in DUNE experiment

Suhyeon Kim

DUNE's Setup



-Long Baseline : 1285 km

-Neutrino Energy : 0.5 – 8GeV

-Beam composition : Primarily composed of muon neutrinos at the time of production

-Far detector : LArTPC(Liquid Argon Time-Projection Chambers)

-Cross section : between Argon and neutrino

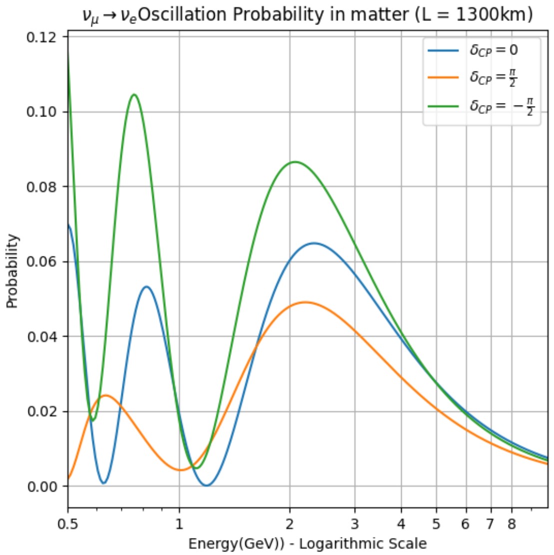
$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) &= \left| \sum_j U_{\alpha j}^* \, U_{\beta j} e^{-i \frac{m_j^2}{2E} L} \right|^2 \\
&= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*) \sin^2 \left(\frac{\Delta m_{ij}^2}{4E} L \right) \\
&\quad + 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*) \sin \left(\frac{\Delta m_{ij}^2}{2E} L \right)
\end{aligned}
$$

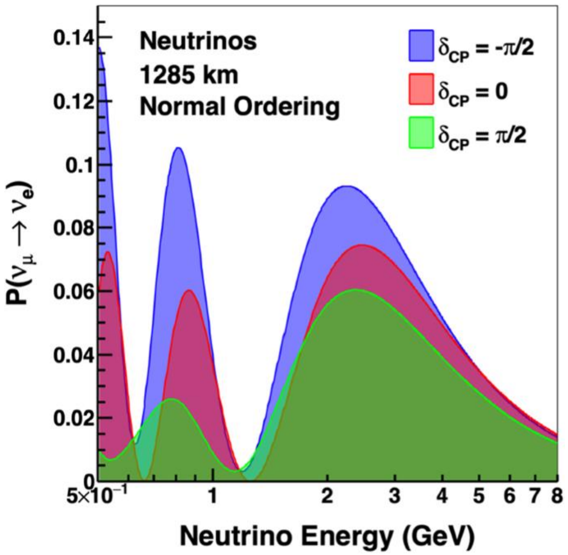
Oscillation Probability about energy

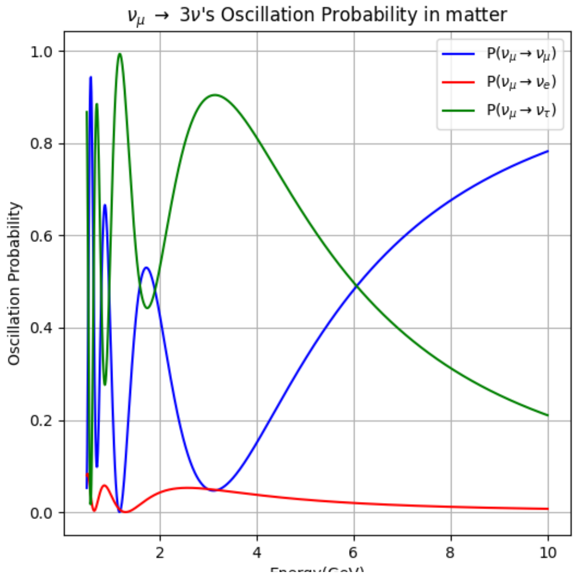
With different CP phase

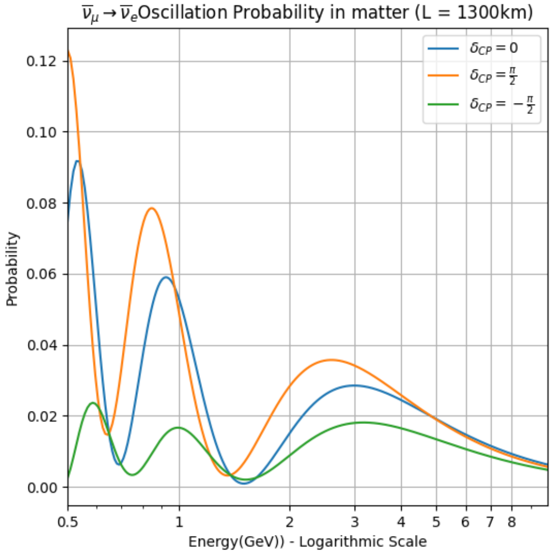
DUNE

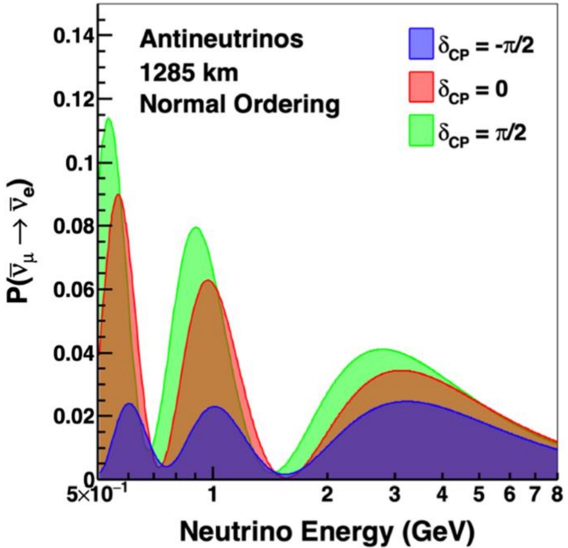
Comparison of Neutrino vs Anti-neutrino

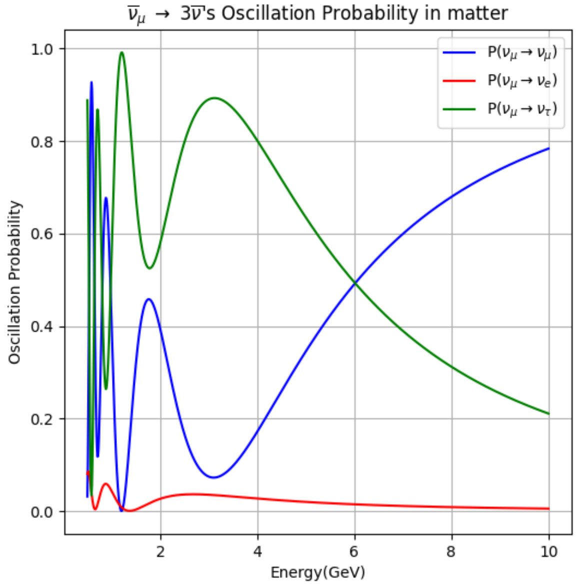








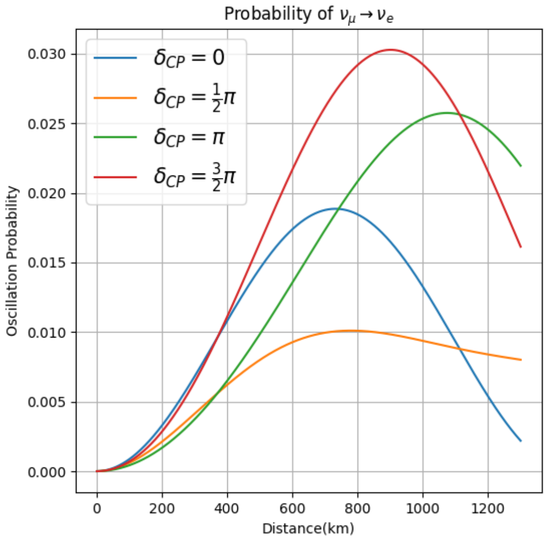


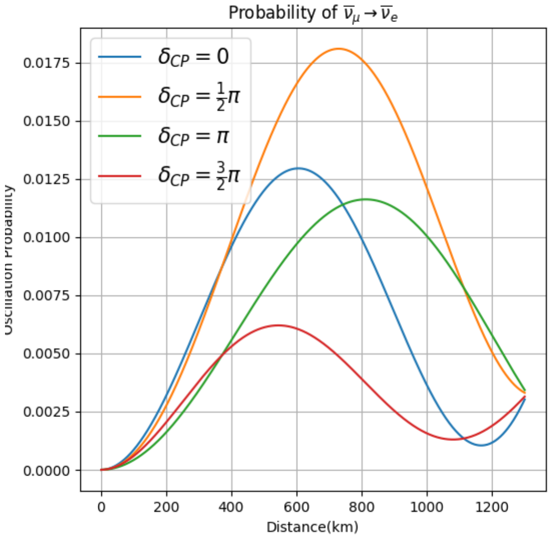


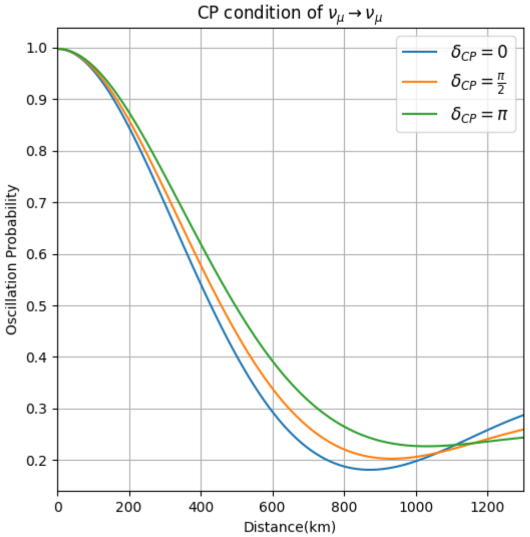
Oscillation Probability with neutrino flux

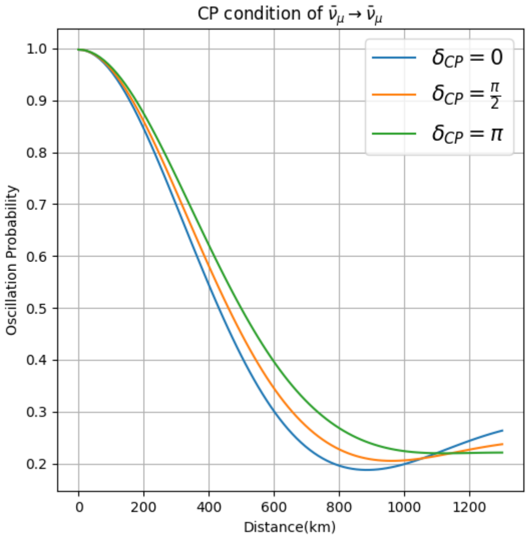
$$\frac{\int_{E_0}^{E_1} P(\nu_\alpha \to \nu_\beta) \cdot \frac{d\Phi(E)}{dE}\, dE}{\int_{E_0}^{E_1} \frac{d\Phi(E)}{dE}\, dE}$$

With different CP phase

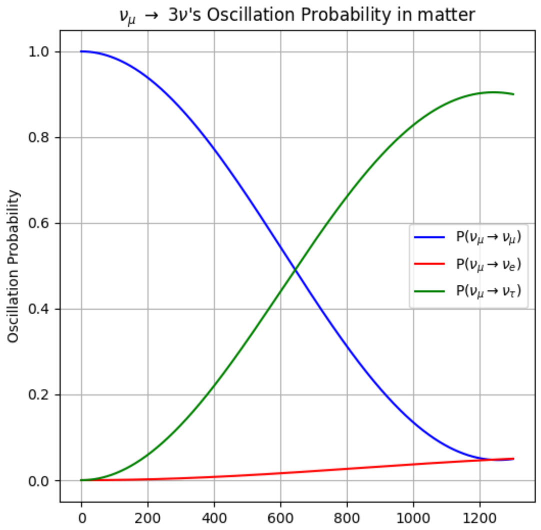


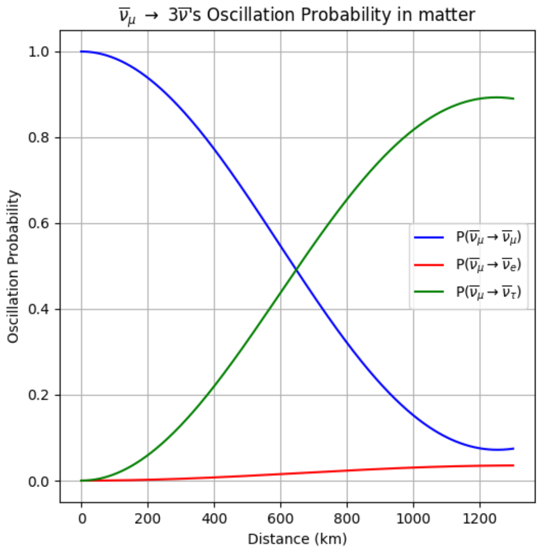






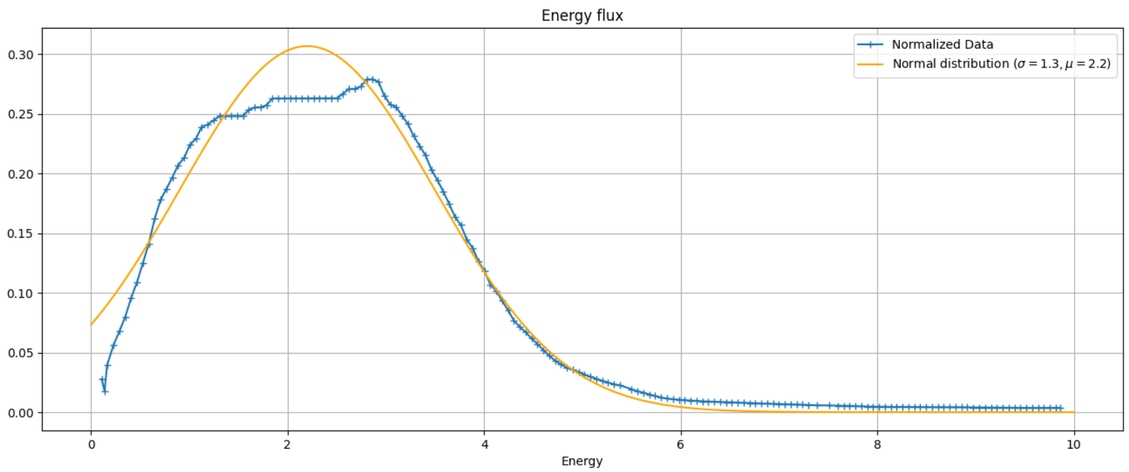
Comparison of Neutrino vs Anti-neutrino

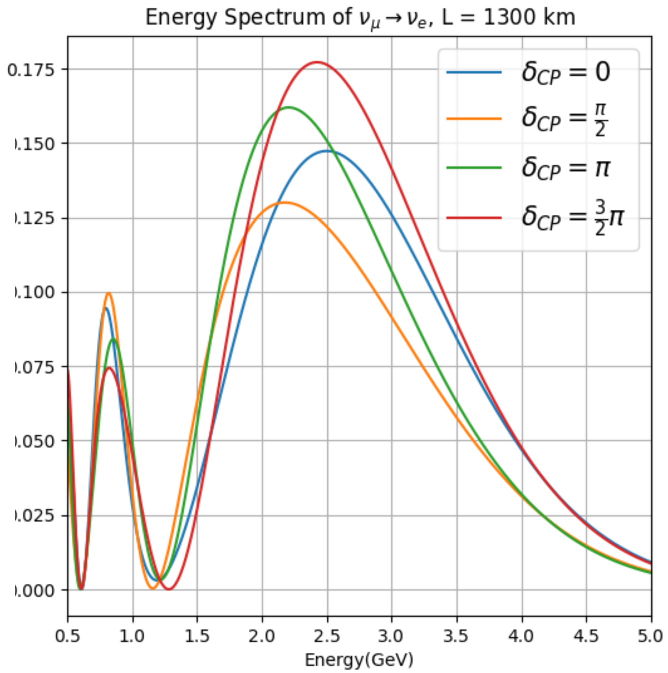


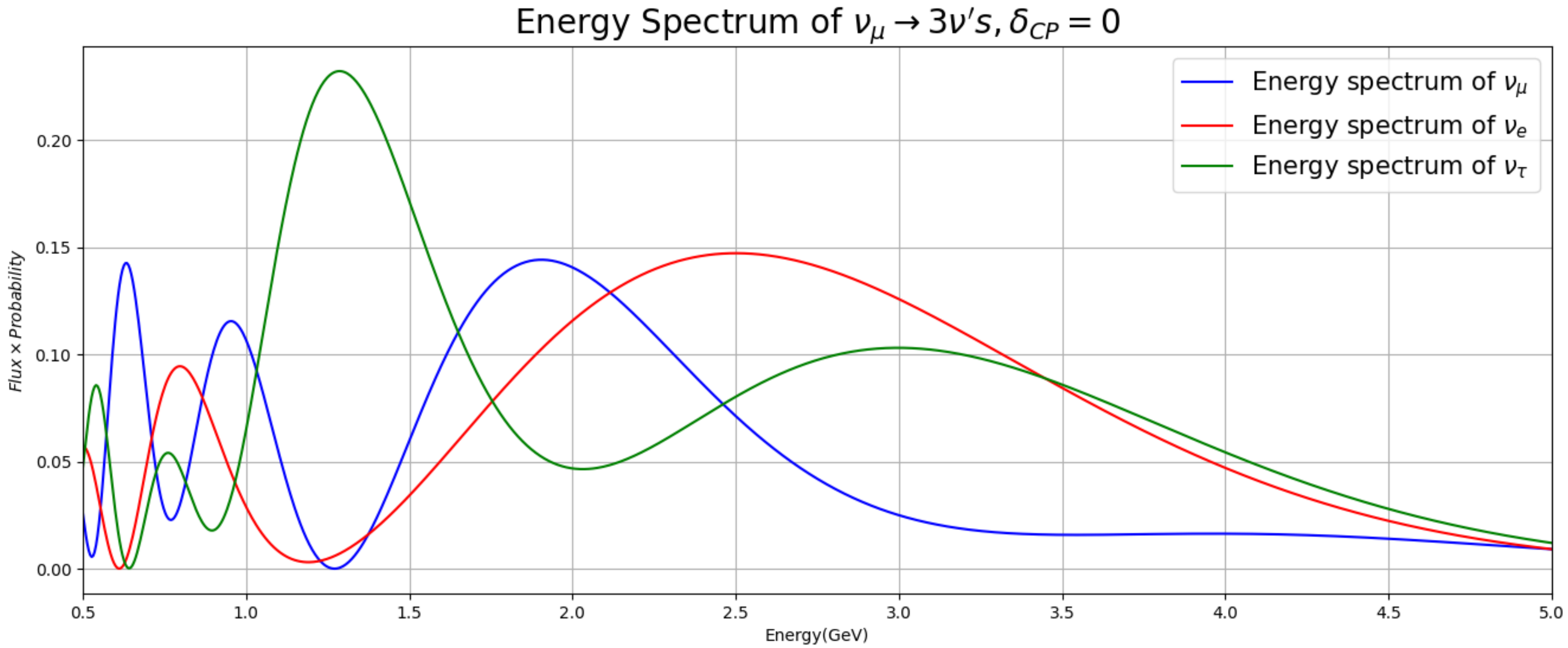


Energy(GeV)

Energy spectrum







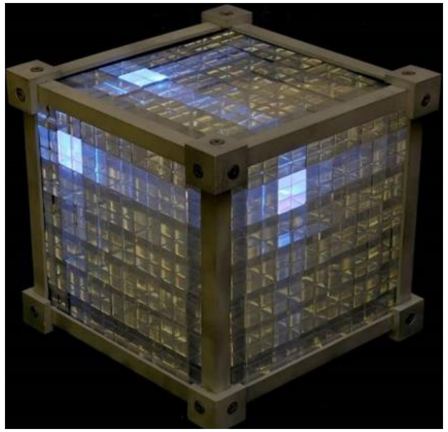
HEP workshop _ neutrino Lab.

Juseong Park

1. New Detector for Reactor Neutrino

Studied by SunHong Kim

1. New Detector for Reactor Neutrino



NULAT

At Plastic Scintillator, we detect antineutrino interaction

$$\bar{\nu_e} + p \rightarrow e^{+} + n$$

With Li doping, we can detect neutron interaction

$$n + {}^{6}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H} + 4.6MeV$$

Li/Gd doped Plastic Scintillator Cube with 3-D optical fiber detector

NULAT(Li doped) + SOLID + 3DST(optical fibers)

Most detectors are 1 m3 size – so 1 m x 1m x 1m detector active volume chosen. (40 x 40 x 40 cubes)

There are 5cm cube detector : SOLID, NULAT

1cm cube size is too small, -> made cube size as 2.5cm cube.

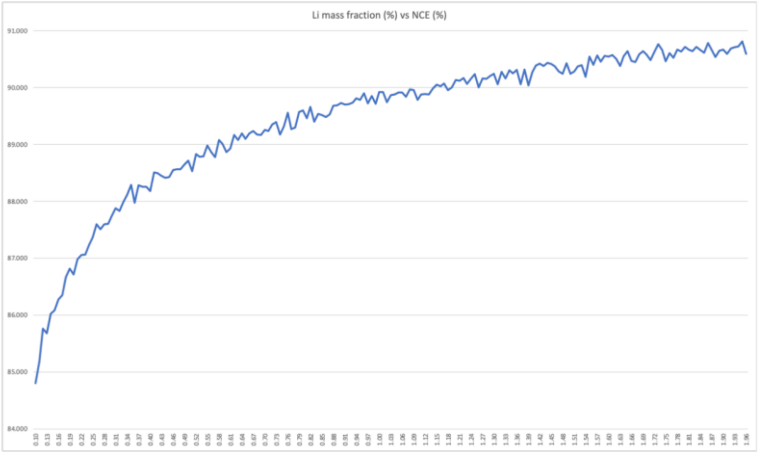
1. New Detector for Reactor Neutrino

Defined two physical quantities that represent the performance of the detector

· NCE : Neutron Capture Efficiency

- this parameter sets an upper limit on the anti-neutrino detection efficiency

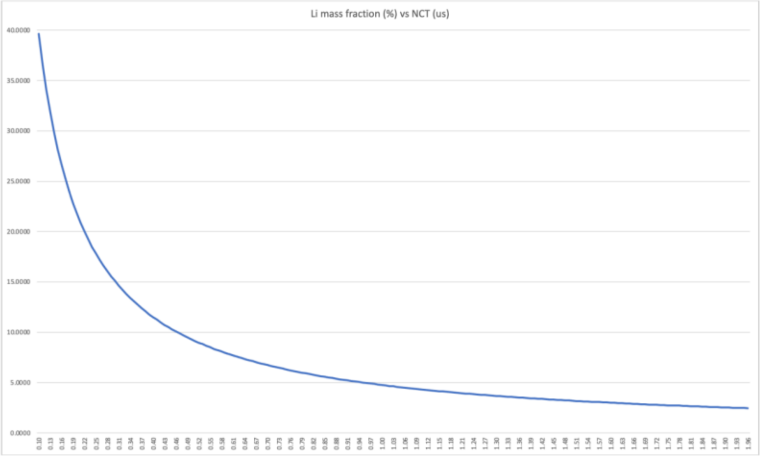
- as high as possible is desirable



· NCT : Mean neutron capture time

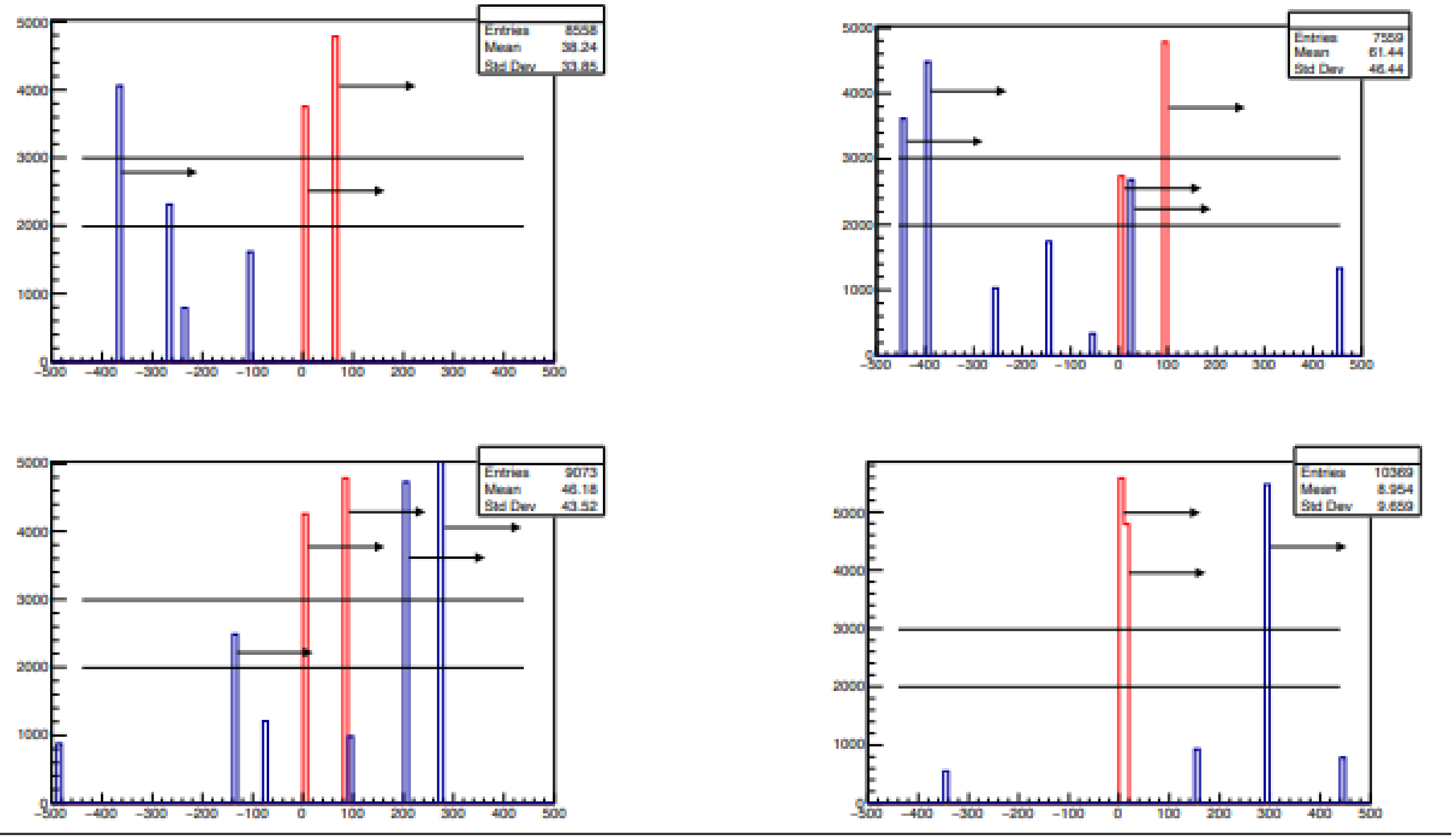
- Capturing neutron as fast as possible is desirable

- Reducing the neutron time is crucial for improving uncorrelated background rejection efficiency.



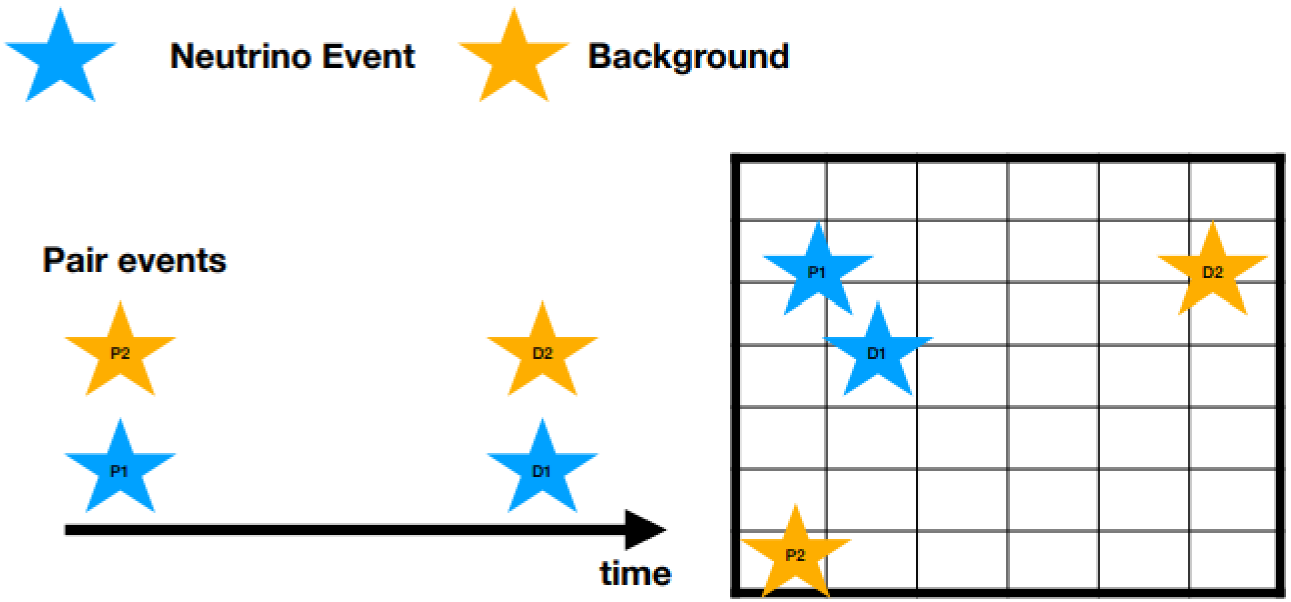
1. New Detector for Reactor Neutrino

Selection – events with 2MeV, Delayed Signals with 3MeV and 150 us



1. New Detector for Reactor Neutrino

Our detector can help the pair event selection



If the method is effective enough, there will be no needed to lower NCT for background rejection

Then we can set Lower limit. -> Li/Gd fraction can be optimized

1. New Detector for Reactor Neutrino

Our detector can help the pair event selection / comapirng with spatial information and not

Signal 15,000 events and Background 150,000 events generated.
NCPE : Number of Correct Pair Events

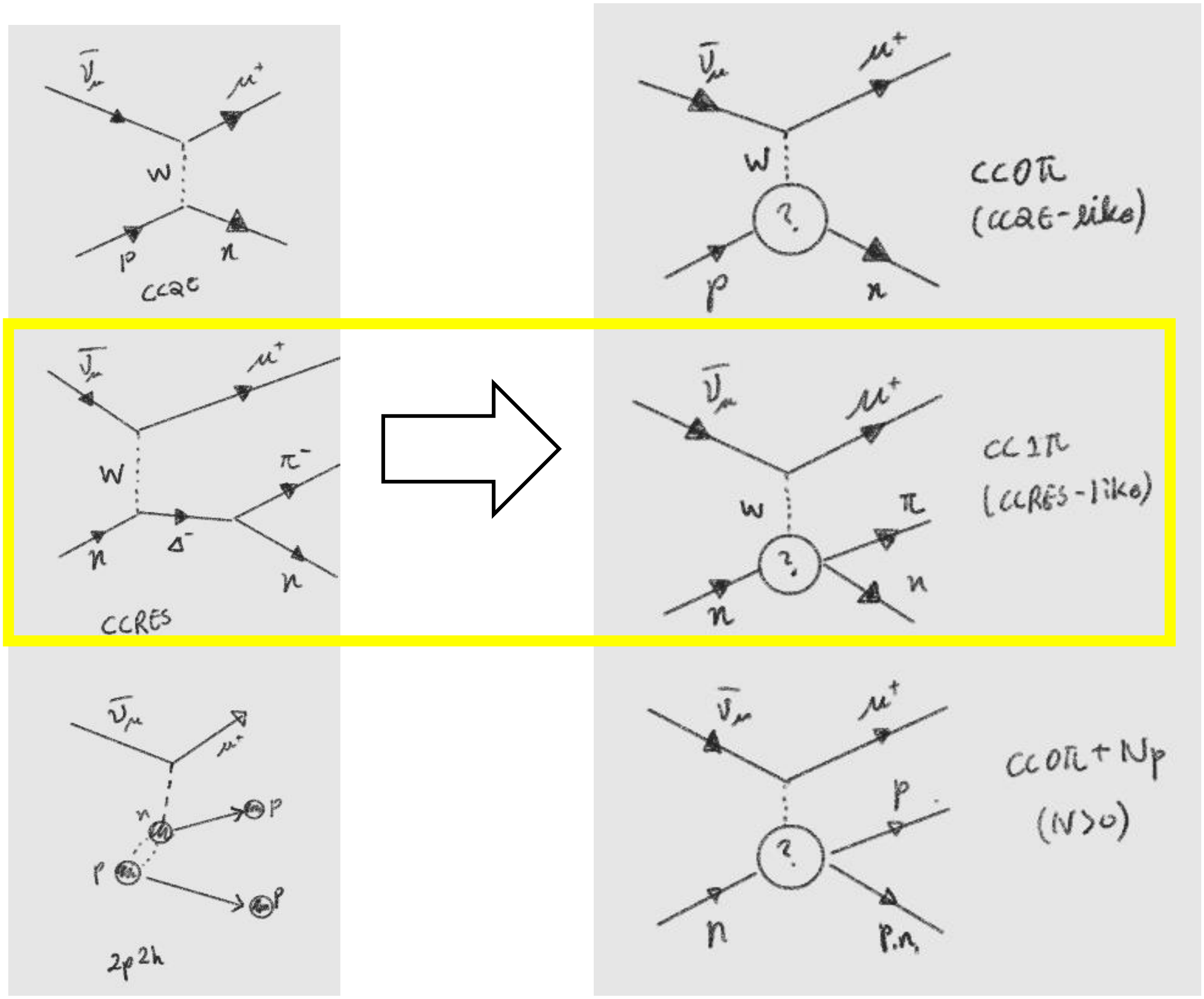
Li	0.10%			0.50%			1.00%		
NCPE wo SI	1589	1589	1583	1644	1665	1671	1391	1423	1423
NCPE w SI	1538	1527	1507	1662	1616	1643	1375	1413	1405
Accuracy wo SI	58.9610%	56.9943%	56.9015%	85.6696%	84.8192%	87.5786%	91.0937%	90.7526%	92.3426%
Accuracy w SI	93.8377%	93.7961%	92.2464%	97.5352%	96.3051%	96.5335%	97.3107%	97.4483%	97.0974%

2. CC1π^± Event Selection

Studied by Juseong Park

2. CC1π^± Event Selection

What do we actually measure?



There is many theoretical modes

But we can only measure things below:

1. Time and position that ‘event’ occurs
2. Energy

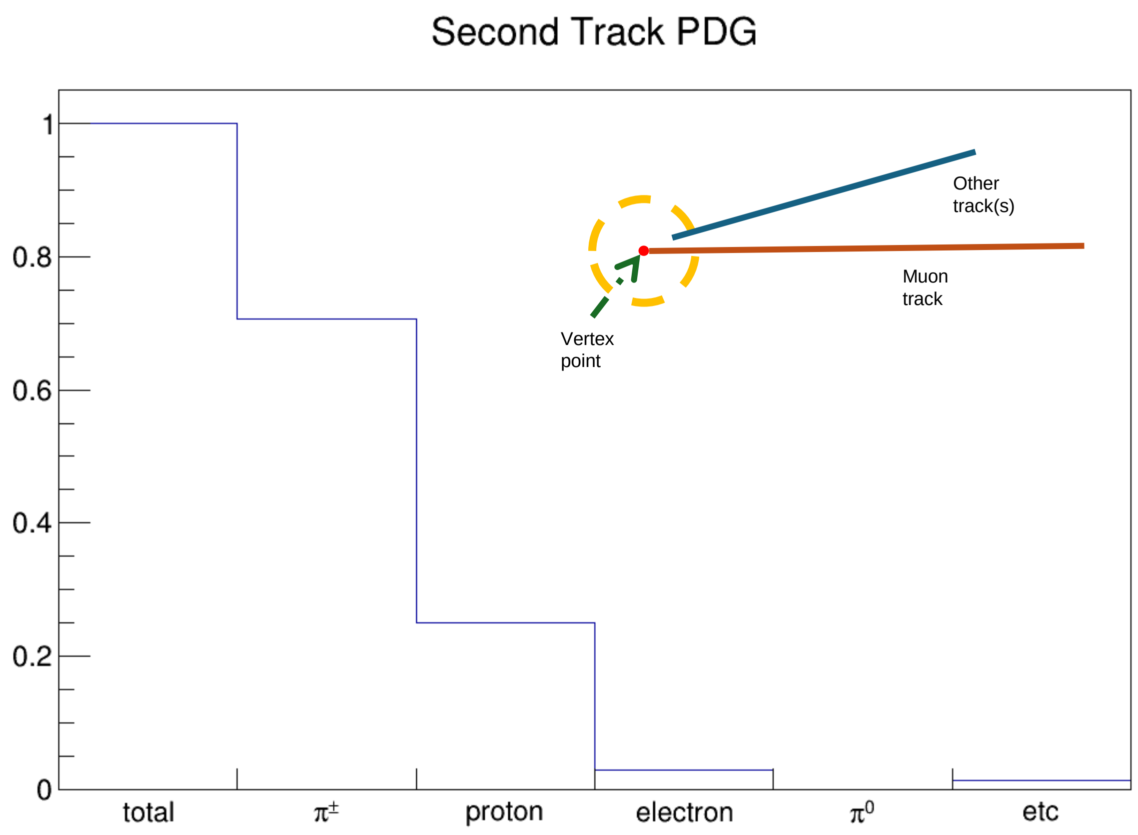
We cannot detect neutron directly,
So CCQE-like interaction will be identified by one muon track.

Similarly, CCRES-like interaction will make two track : muon and pion

2. CC1π^± Event Selection

The way to distinguish π and p

With the “two- track events”,
when muon is defined as the first track and others as "second track",
the distribution of the second track is as follows.



The biggest different point of them is mass

π mass 139.57 MeV : p mass 938.27 MeV

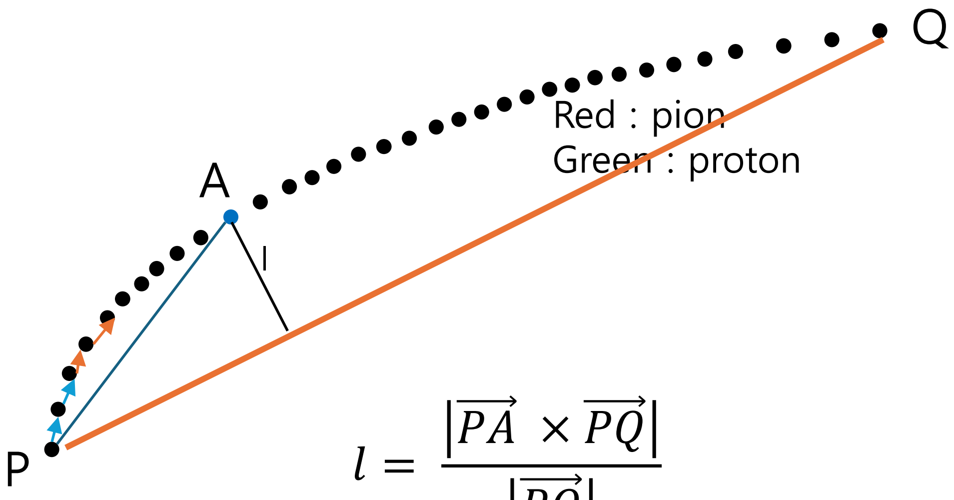
Ways to sort them

1. de/dx differential : the energy loss amount when particle moves
2. Track curvature difference (by Lorentz force)

2. CC1π^± Event Selection

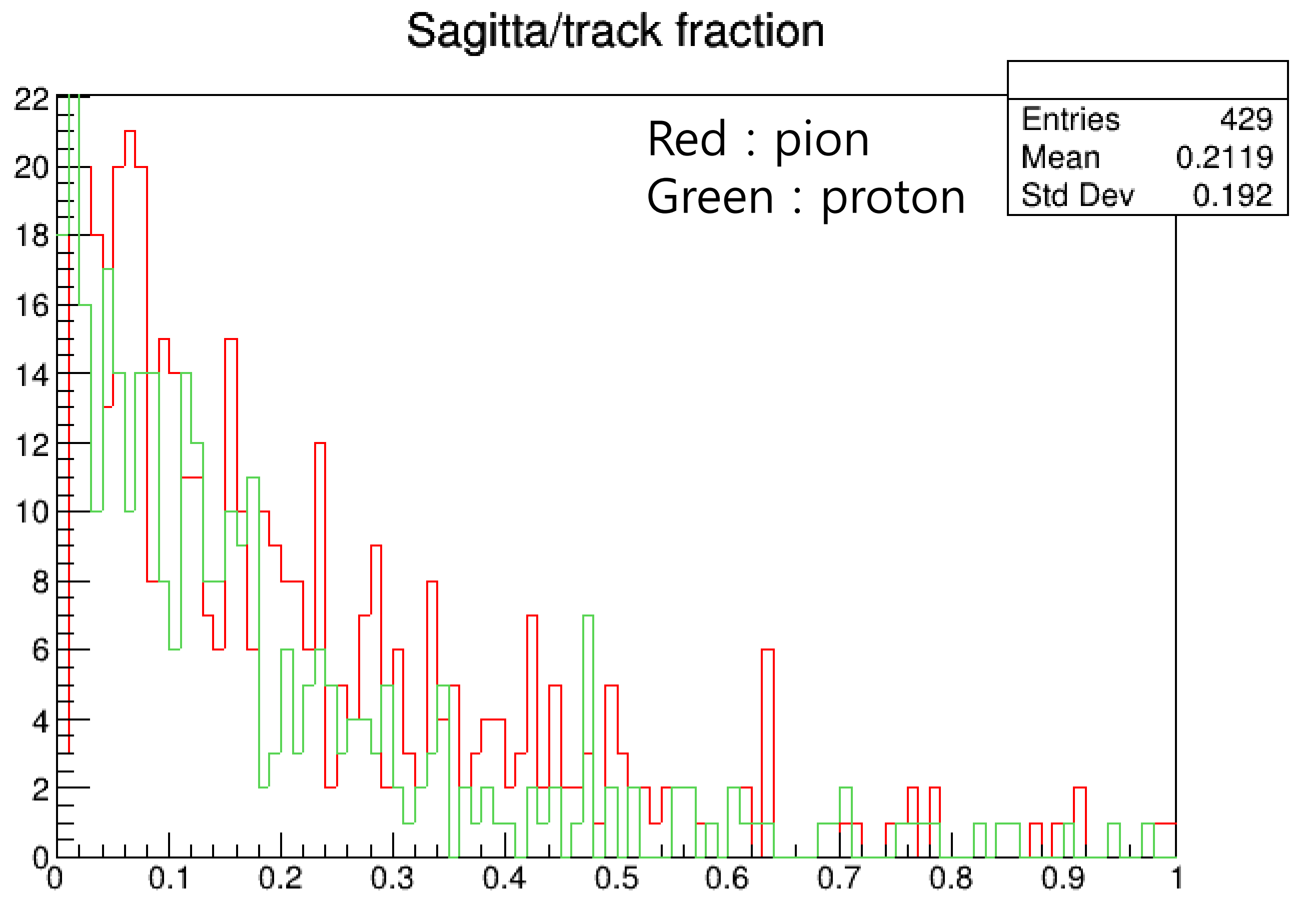
Sagitta : Curvature of Proton and Pion track

The longest length used



$$l = \frac{|\overrightarrow{PA} \times \overrightarrow{PQ}|}{|\overrightarrow{PQ}|}$$

$$fraction = \frac{|\overrightarrow{PA} \times \overrightarrow{PQ}|}{|\overrightarrow{PQ}||\overrightarrow{PQ}|}$$



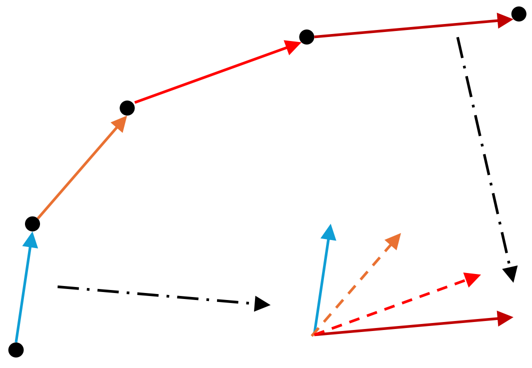
2. CC1π^± Event Selection

Average angle : Curvature of Proton and Pion track

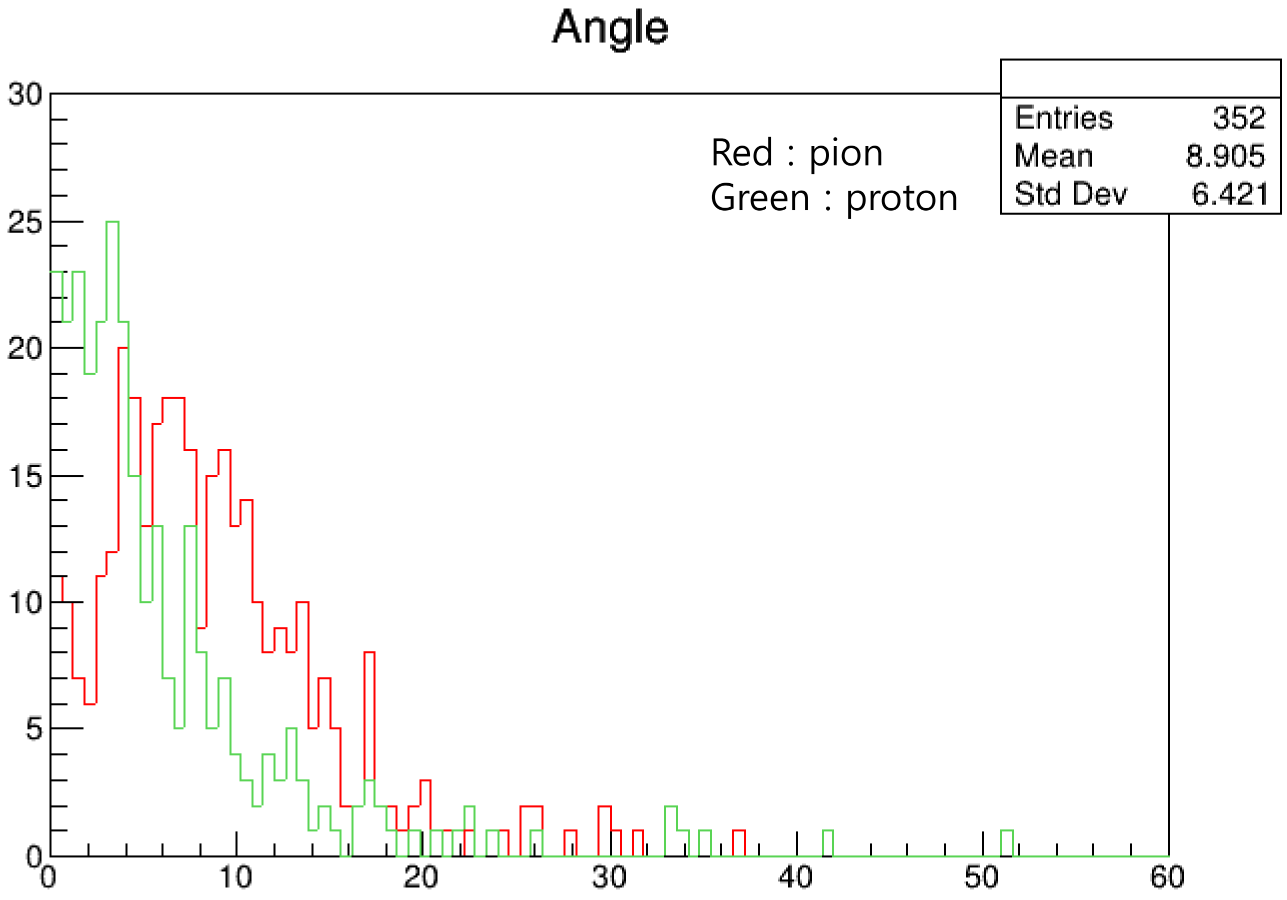
Only 'angle' with rad

Measured "until longest point"

Angle calculated with '3' points far

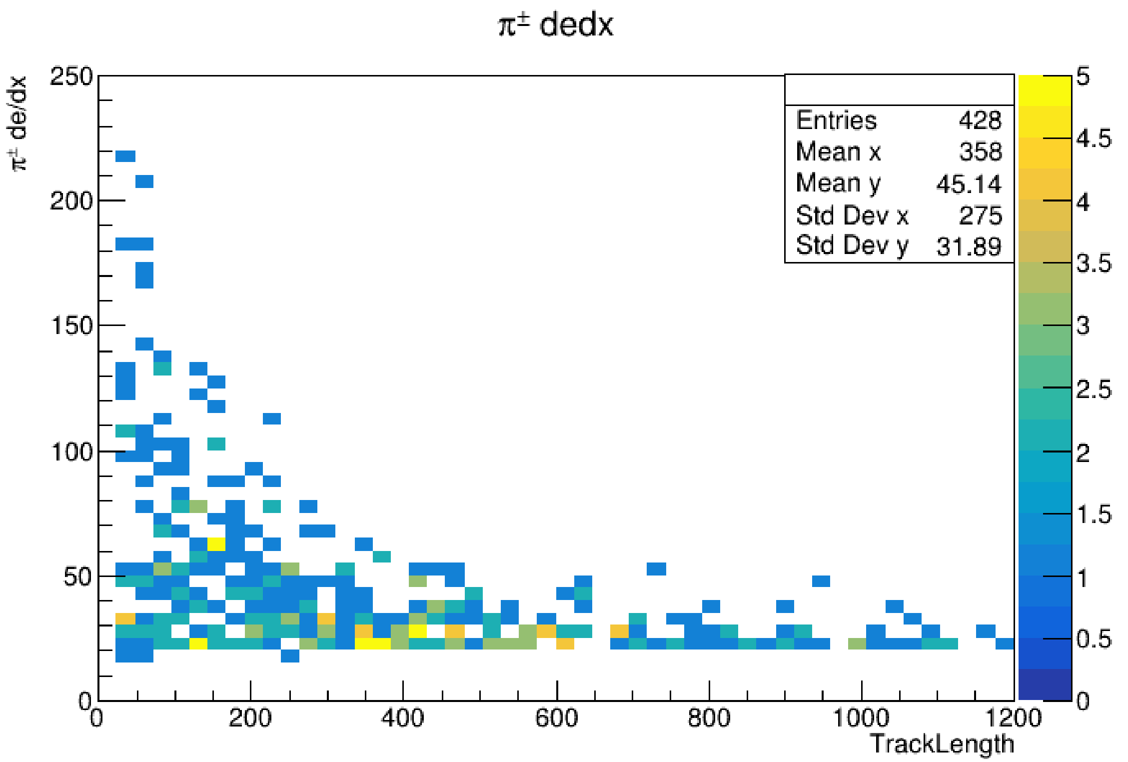


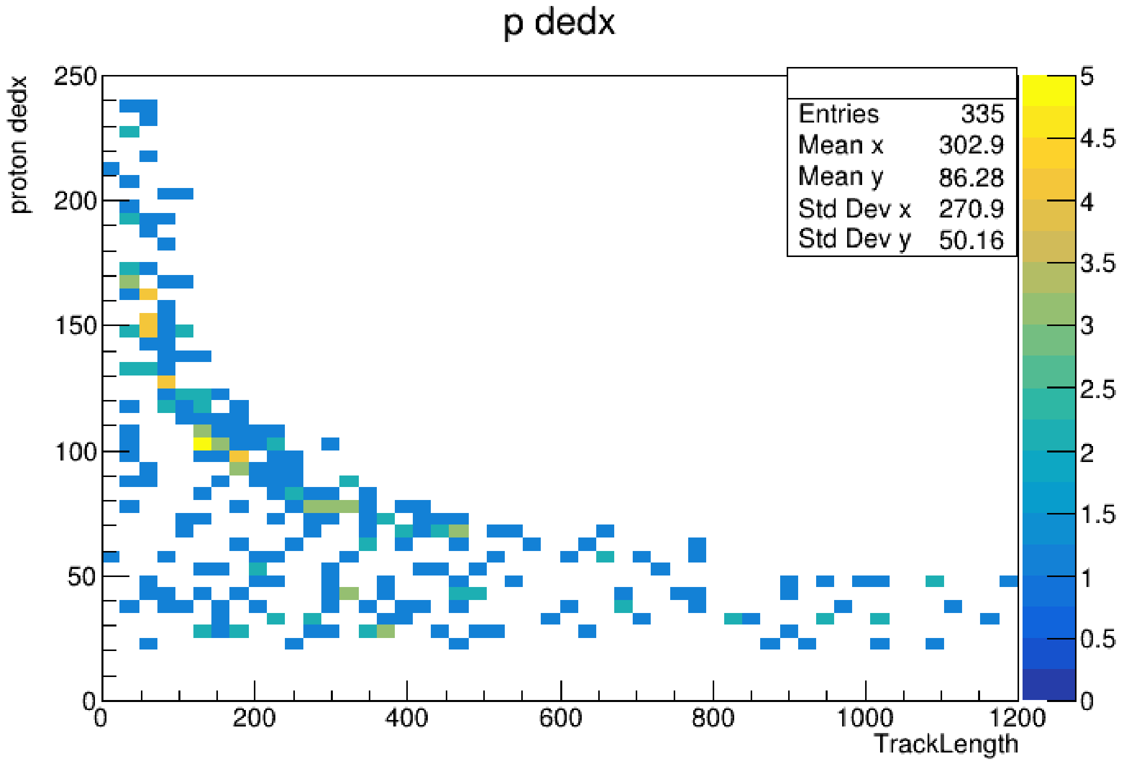
$$\theta_i = \cos^{-1}\frac{\vec{\alpha}\cdot\vec{\beta}}{|\vec{\alpha}||\vec{\beta}|}$$



2. CC1π^± Event Selection

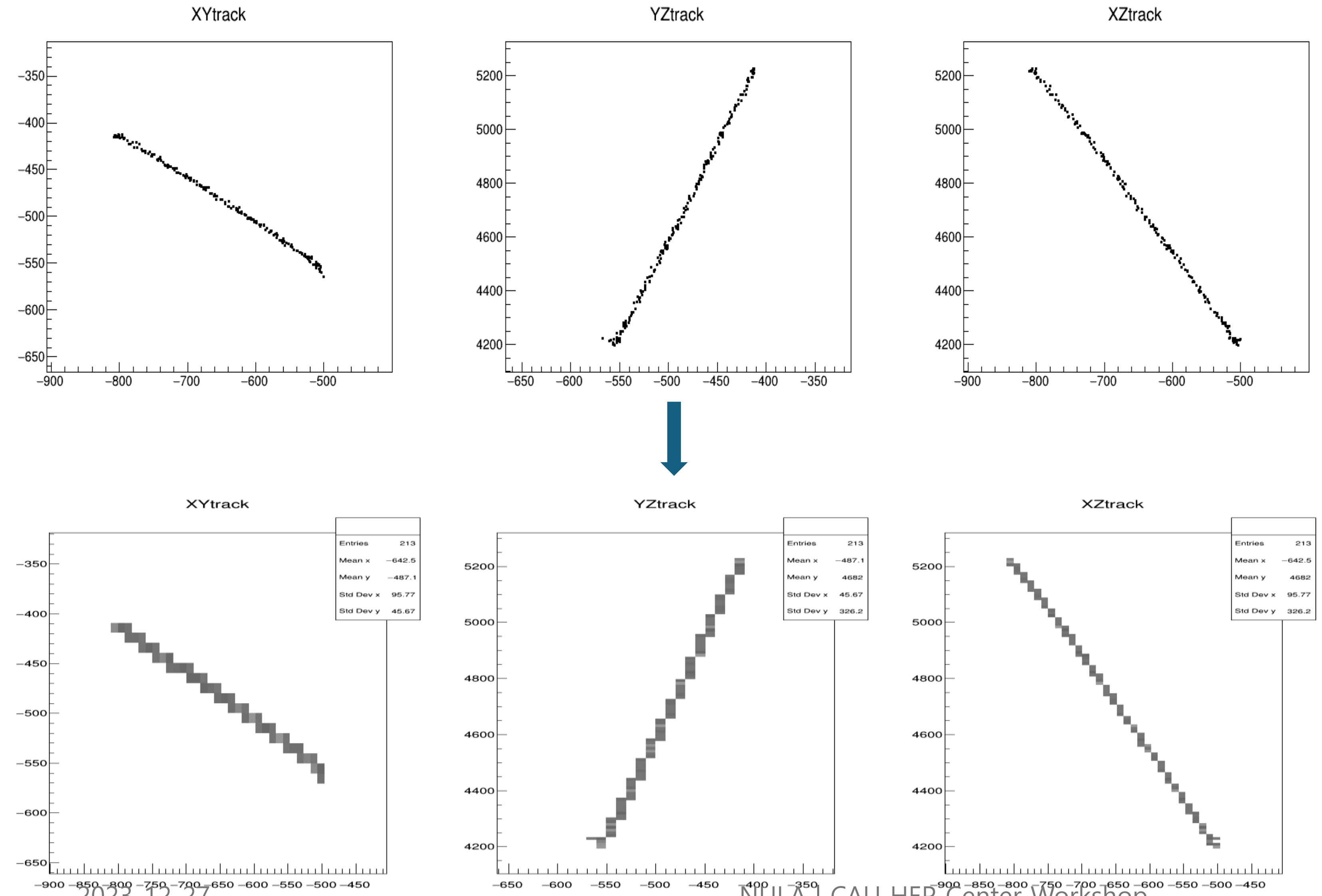
dE/dx vs Track Length





2. CC1π^± Event Selection

Future work : Let’s see one event of Pion



The representation of 1 cube
→ center point