Study on Neutrino Interaction Using T2K Beam at KamLAND

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1, Open questions in ν oscillation

- CP-violation (CPV) phase δ_{CP}
- Mass hierarchy (sign of Δm^2_{32})

[1] S. Pascoli et al., Nucl.Phys.B 774:1-52 (2007)

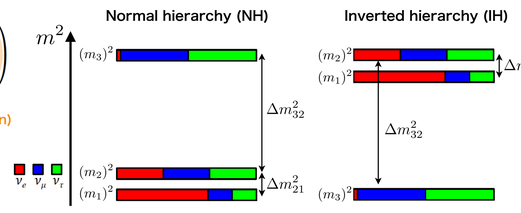
Lepton CPV can be larger than quark's
→ Matter dominant universe through "Leptogenesis"

$$\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{i\delta_{cp}}\\0&1&0\\-s_{13}e^{-i\delta_{cp}}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix}$$

PMNS matrix — CPV parameter

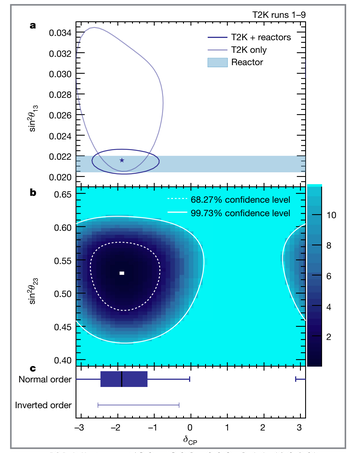
Flavor (interaction) — Mass (propagation)

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$\Delta m^2_{ij} = m^2_i - m^2_j$

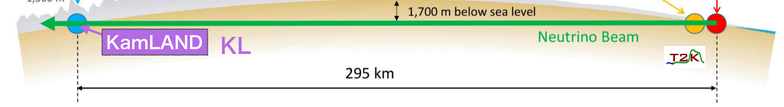


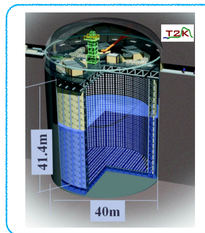
2, T2K & ν-N interaction

- 295-km-baseline ν oscillation experiment
- Constraint on δ_{CP}
  - CP conservation is excluded by **2σ [2]**
  - Systematic error : **~ 7%**
  - Dominant error source : **ν-nucleus (ν-N) interaction (~ 4%)**



[2] Nature 580 7803, 339-344 (2020)

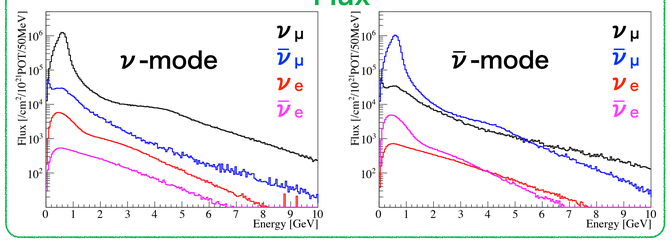




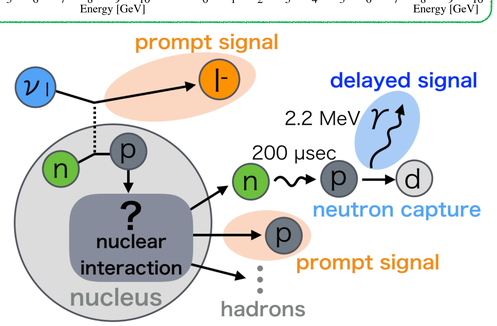
SK

- **50kt water Cerenkov**
  - Main target ; ^{16}O
- High energy ν (~GeV)
- Track recon. & PID (e/μ)
- Neutron tag. eff. : **~ 20%**

Flux



- **ν-N interaction uncertainty**
  - Depend on Final State Interaction (FSI) models
    - Nuclear effect (re-scatter)
  - Leads to miss-recon. of neutrino energy using CCQE
  - Have to measure **hadrons** to constrain the model



- **Neutrons** from ν-N interaction
  - SK : ~ 20% eff.
  - NDs : Difficult to measure
  - **High eff. is desired**

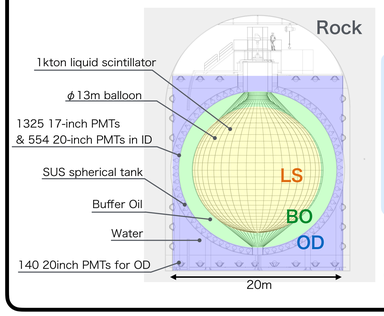
Our proposal,
"How about using KamLAND?"

3, KamLAND ⊗ T2K

- **1kt liquid scintillator**
  - Main target ; ^{12}C
- Lower energy ν (~MeV)
- n tag. eff. : **~ 100%**
- SK ⇄ KL : **~ 75m**
  - **T2K beam is available**

KL has unique features

	SK	KL
Energy	~ GeV	~ MeV
Main Target	^{16}O	^{12}C
Light emission	Cerenkov	Sintillation
n tag. eff.	~ 20%	~ 100%



KL unique T2K ν study
- Neutrons from ν-N
- Residual nucleus decay
- NC interaction

LS : Liquid Scintillator, BO : Buffer Oil
OD : Outer Detector, ID : Inner Detector

History & status

- KL received beam timing data since the beginning of T2K for the veto
  - Detail beam profiles are not included
- Synchronized KL data with beam timing
  - **KL surely detected T2K events so far !!**
  - **Measure neutrons by T2K ν events**
- Very preliminary results were shown in T2K Collaboration meeting (Jul, 2019)
- **T2K and KL Collaborations sign a MoU to promote this study (Sep, 2019)**
- **Now working on re-analysis using T2K internal data**
  - POT, flux, bad spill flag, etc.
- Improving analysis tools (energy, track, etc.)

4, Analysis

- **Data set** : Run3-Run9
- **KL POT** : Scale T2K POT [3] by KL livetime ratio **(~ 85%)**
- **ν interaction simulator** : NEUT(v5.4.0.1), GENIE(v3.00.06)
- **Detector simulator** : KamLAND Geant4 (KLG4)
- **Flux data :** Open to public [4]

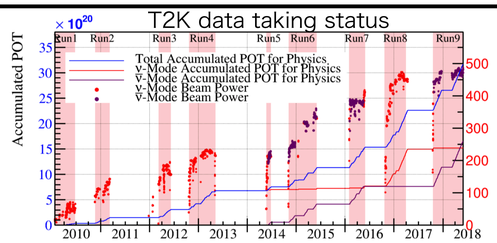
T2K POT & KL POT

	T2K POT [10^{21}]	KL POT [10^{21}]
ν-mode	1.37	1.24
$\bar{\nu}$-mode	1.65	1.30

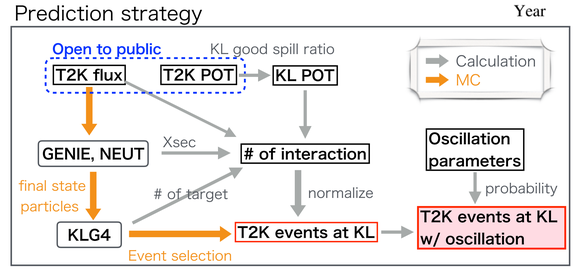
Osc. params. based on [5]

Normal hierarchy	
Δm^2_{21}	7.37e-5 [eV^2]
Δm^2_{31}	2.56e-3 [eV^2]
$\sin^2\theta_{23}$	0.425
$\sin^2\theta_{13}$	0.0215
$\sin^2\theta_{12}$	0.297
δ_{CP}	1.38π
ρ	2.7 [g/cm^3]
L	295 km

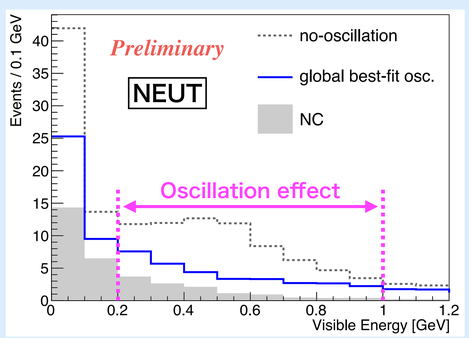
[3] Phys. Rev. D 96, 092006 (2017)
[4] http://t2k-experiment.org
[5] Phys. Rev. D 98, 030001 (2018)



Prediction strategy



Results *Data is confidential…*

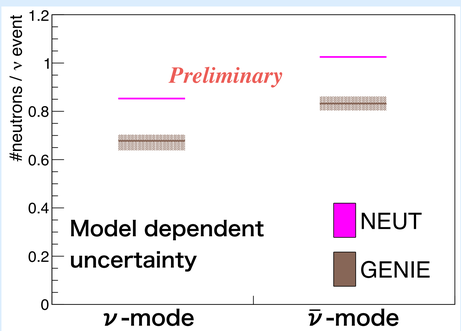


ν-mode & $\bar{\nu}$-mode combined energy spectrum

	# exp. evt. (NC)
ν-mode	60.7 (23.9)
$\bar{\nu}$-mode	27.8 (10.4)
Total	88.5 (34.3)

- Large osc. effect at flux peak
- NC events can be observed with high efficiency

w/ OD veto
No vertex cut



Average neutron production (*)

	ν-mode	$\bar{\nu}$-mode
NEUT	0.85	1.03
GENIE	$0.68^{+0.02}_{-0.04}$	0.83 ± 0.02

- Prompt Energy ≥ 200 MeV
- Assuming eff. = 100%
- GENIE : Syst. error using reweight package

(*)

Summary

- **ν-N interaction** has large uncertainty in δ_{CP} measurements
- KL can perform unique T2K ν study (**neutron**, etc.)
- History, status and results (MC only) are shown