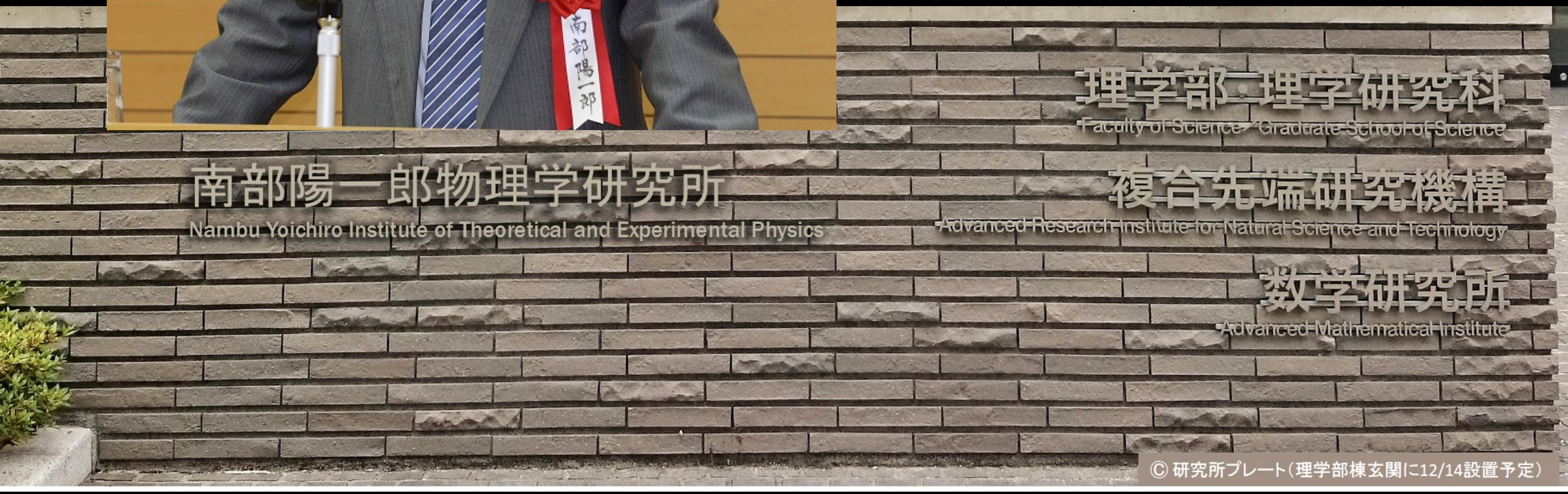
December 13, 2018
@Media Center, Osaka City University, Japan
International Symposium in Honor of Professor Nambu
for the 10th Anniversary of his Nobel Prize in Physics

Neutrino CP violation in the J-PARC neutrino experiments

T. Nakaya (Kyoto University)

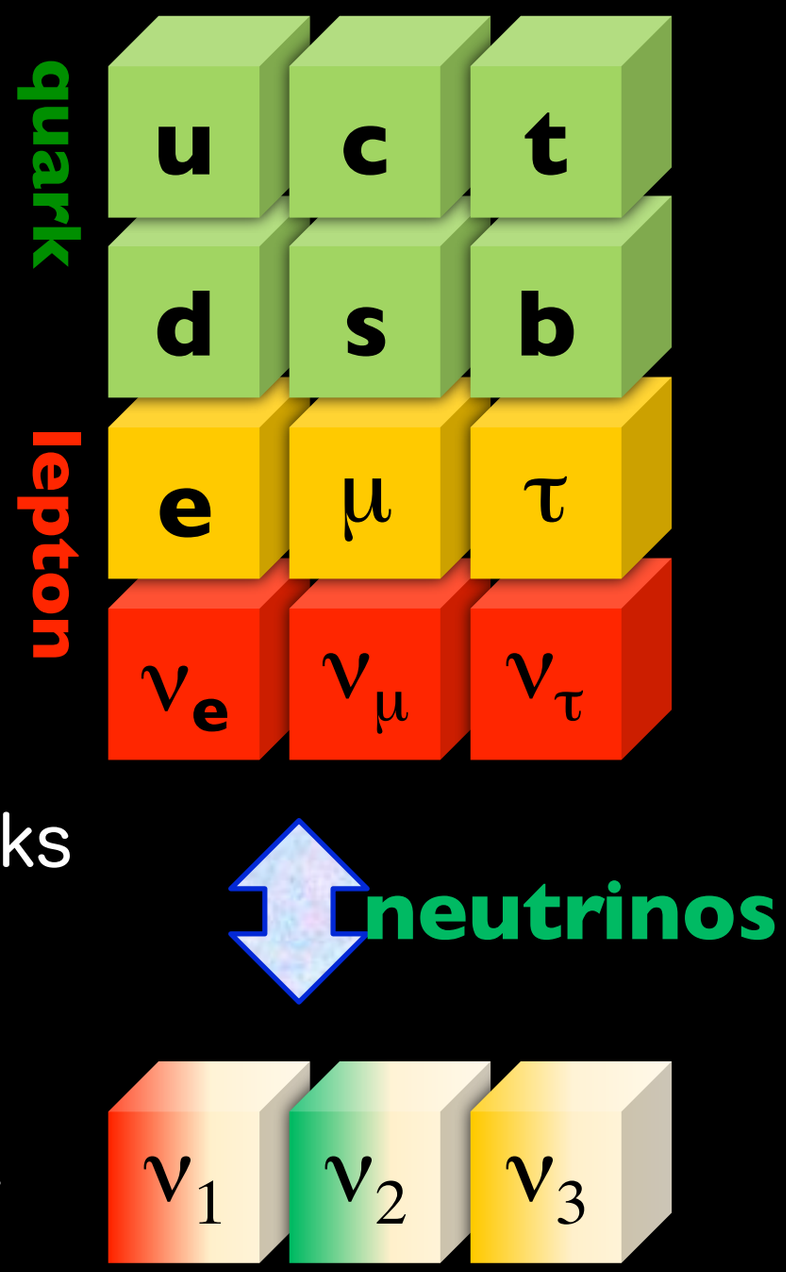
南部陽一郎物理学研究所HPより



© 研究所プレート（理学部棟玄関に12/14設置予定）

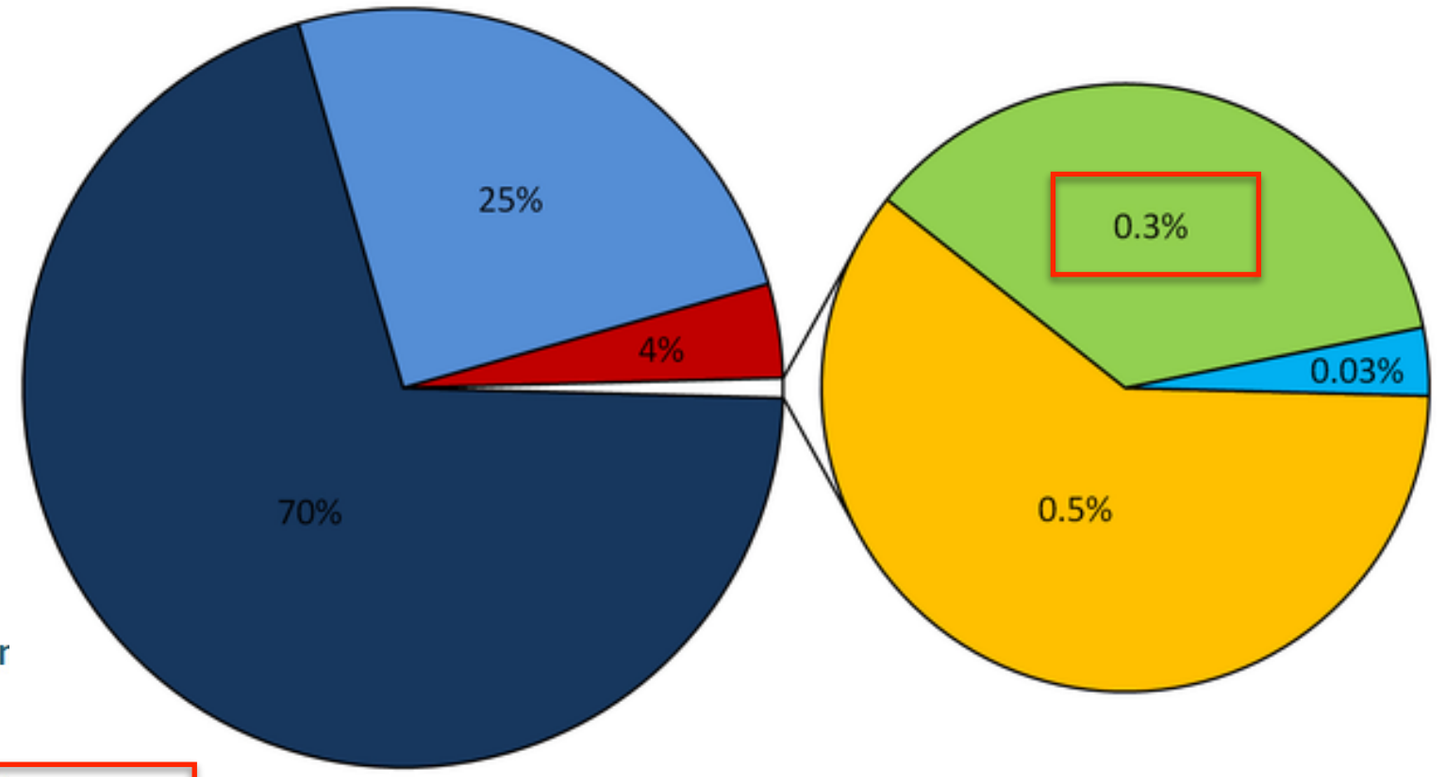
Neutrinos

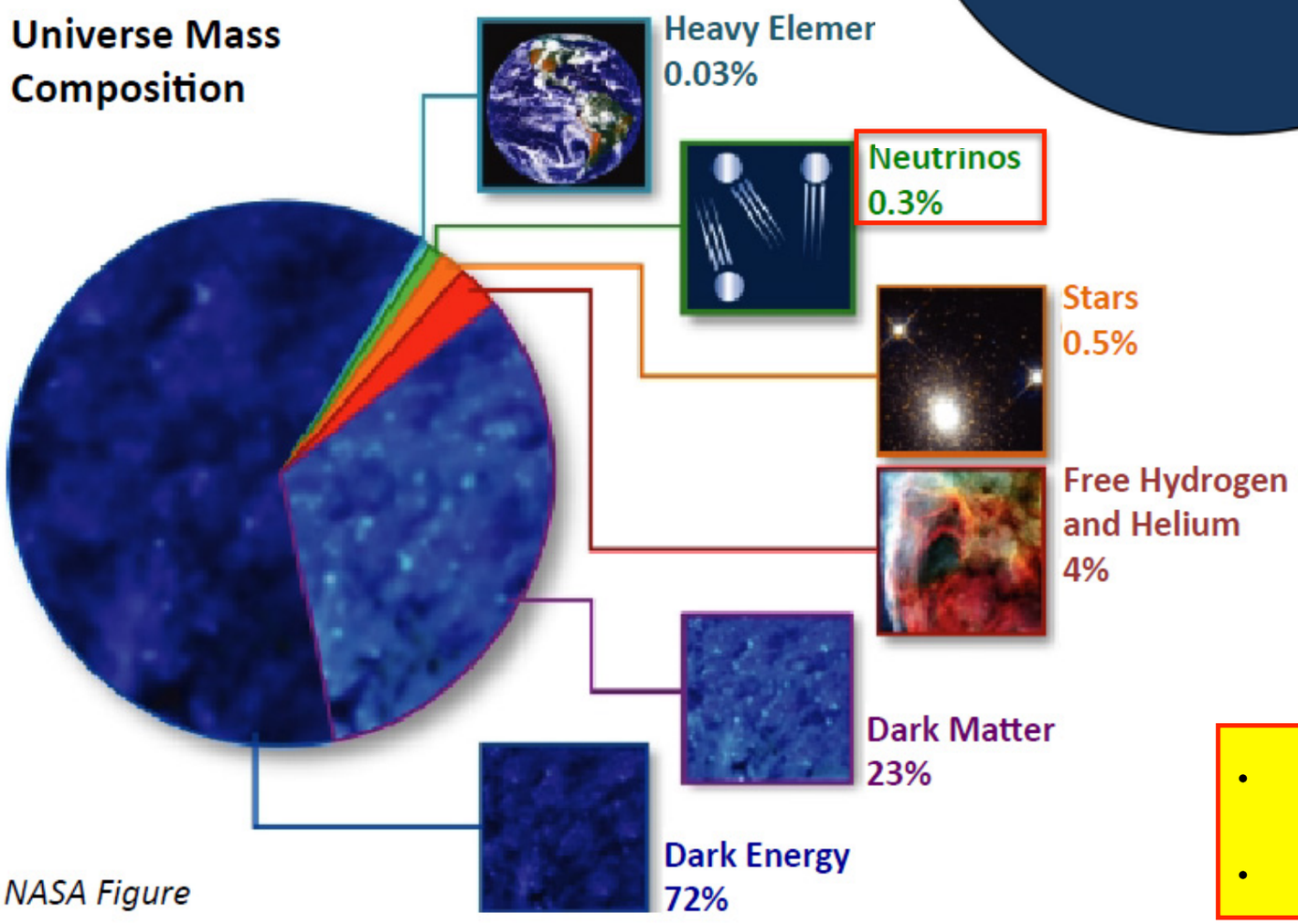
- Week interactions only
  - Small mass
    - Origin in physics beyond the standard model?
  - Mixing
    - 3 neutrinos are mixed
    - Different mixing patterns from that of quarks
      - What symmetry exists?
    - No experimental information on the CP symmetry (between a particle and the anti-particle)



Much exciting to study neutrinos after the discovery of neutrino oscillation in 1998

Abundant particles in our universe

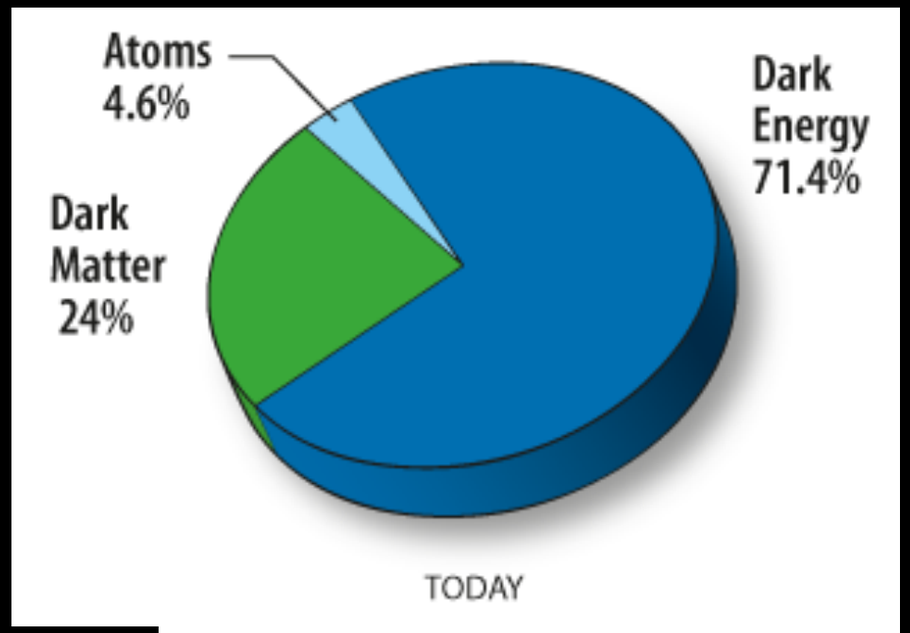




- $T_\nu = 1.95K$
- $\#N_\nu = 112 \times 3 cm^{-3}$

Our world is invisible

- Dark Energy
- Dark Matter
- Neutrinos
  - Cosmic Neutrino Background (0.03%)
  - (Relic) Supernova Neutrinos
  - Solar Neutrinos
  - Atmospheric Neutrinos
  - Geo-neutrinos
  - + We can make neutrinos by reactors and accelerators.



Credit: NASA/WMAP Science Team

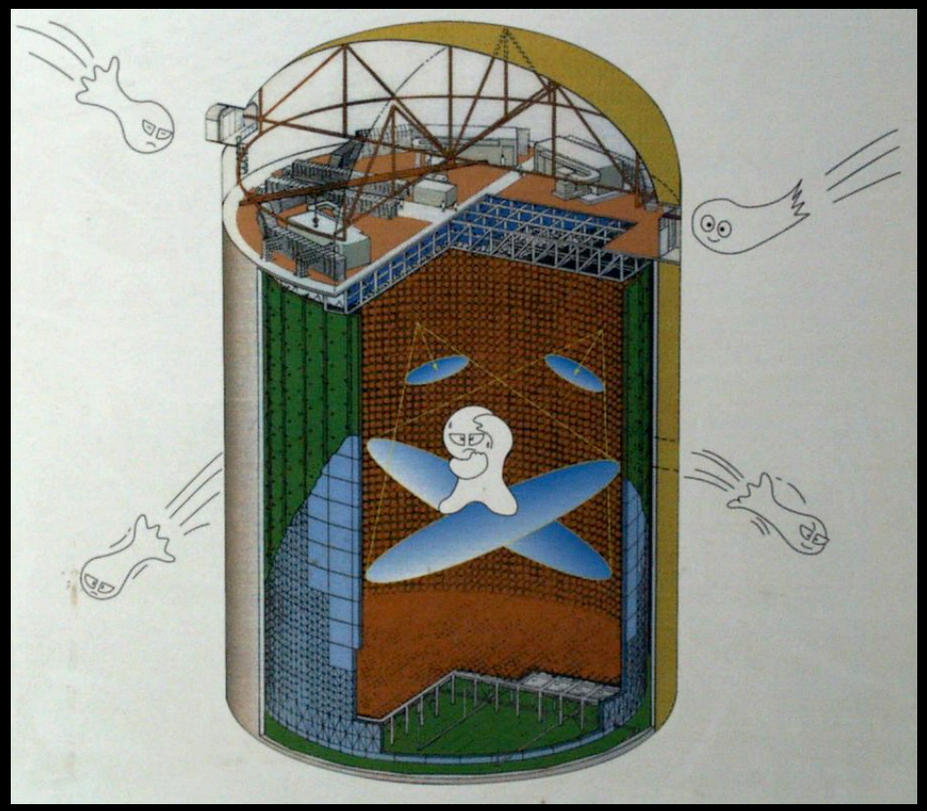
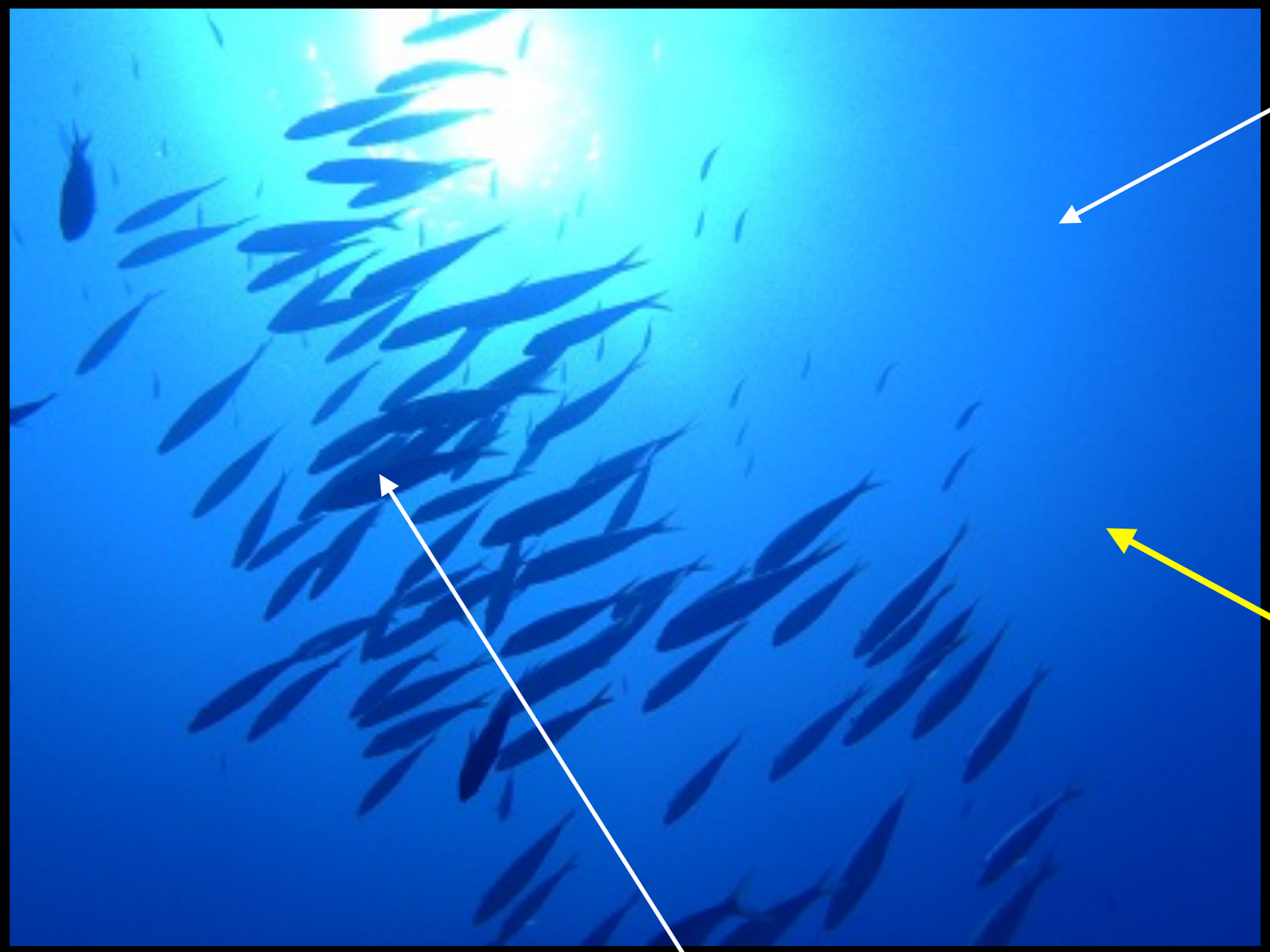


Image of our universe



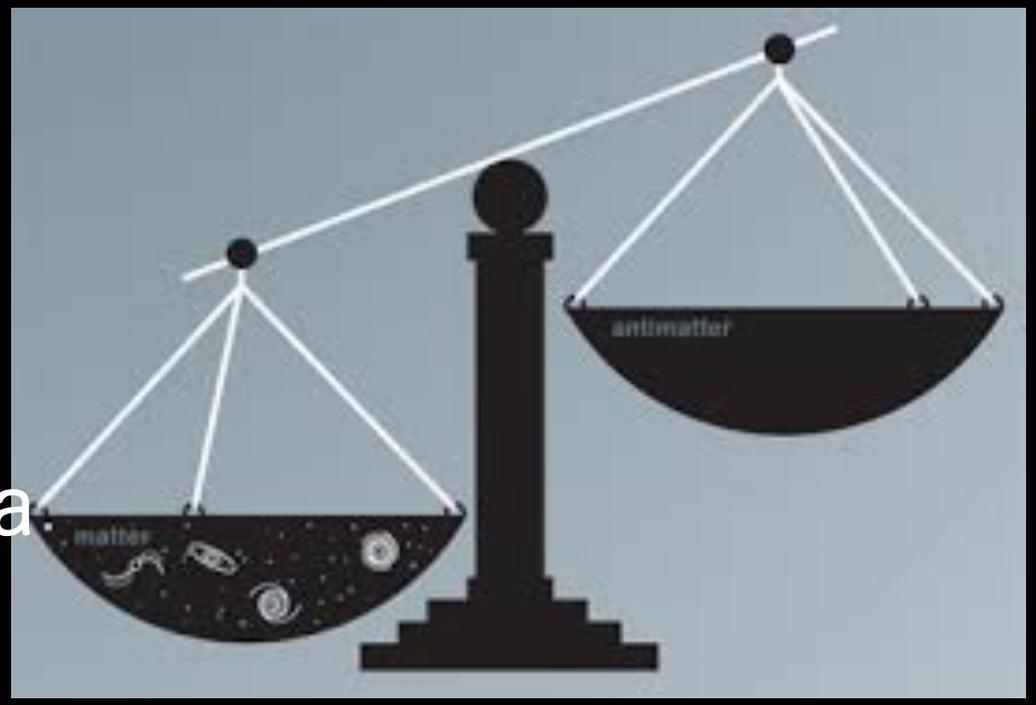
Dark Matter

Neutrinos

Matter

CP Violation

- In the Big-Bang, particles and anti-particles were produced in same amounts.
- Later, they would annihilate.
  - $e^+ + e^- \rightarrow$ photons
  - $p + p_{bar} \rightarrow$ photons



- Violation of the symmetry between a particle and the anti-particle.
  - CP violation

CP violation is necessary for particles only to survive and to form our universe.

Probing Neutrino CPV

- Neutrino Oscillations with CP violation [Mainly Experimental study]
  - Weak (flavor) state ≠ Mass state
  - 3 generations ➡ Imaginary Phase in a mixing matrix
    - [Neutrino] PMNS matrix ~ [Quark] CKM matrix
  - Example: $P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$
- Heavy Majorana Neutrino (N) if exists [Theoretical study]
  - NOT easy to access (very very difficult)
  - The decay of N
    - $P(N \to l_L + \overline{\phi}) \neq P(N \to l_L + \overline{\phi})$
  - Or, the oscillations of N

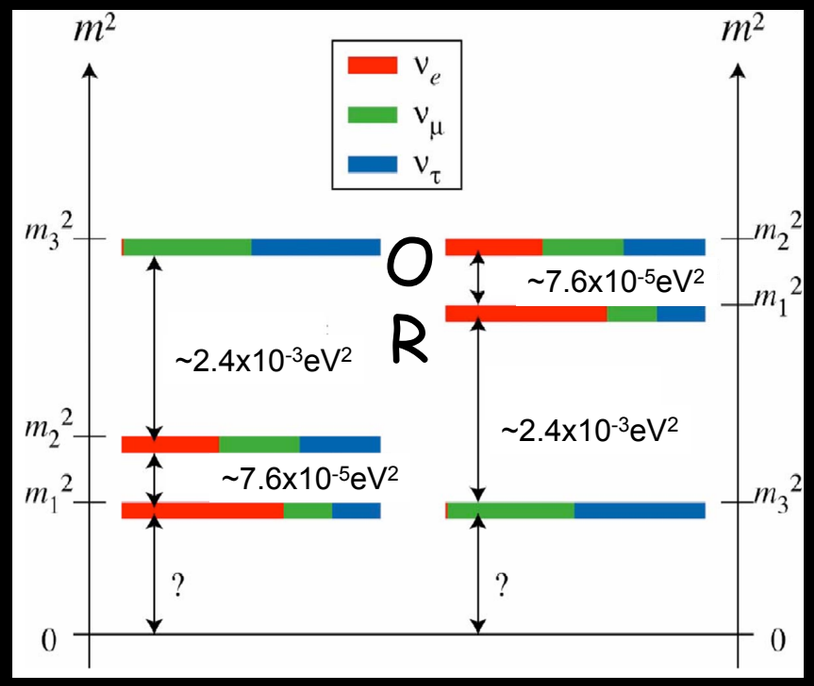
Leptogenesis and Neutrino CPV

- Saharov conditions for Baryon Asymmetry
  - [B] Baryon Number Violation
  - [CP] C and CP violation
  - [T] Interactions out of thermal equilibrium

- Leptogenesis and Low Energy CP violation in Neutrinos
  - [B] Sphaleron process for $\Delta(B+L)\neq 0$
  - [CP] Heavy Majorana Neutrino decay and/or Neutrino oscillations
    - [Phys. Rev. D75, 083511 (2007)] **$|\sin\theta_{13}\sin\delta|>0.09$** is a necessary condition for a successful "flavoured" leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix.
      - $\sin\theta_{13}\sim 0.15$ ➡ **$|\sin\delta|>0.6$**

How to measure neutrino CPV?

- Measure $P(\nu_\mu \to \nu_e)/P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq 1$
  - or $P(\nu_\mu \to \nu_\tau)/P(\bar{\nu}_\mu \to \bar{\nu}_\tau) \neq 1$ because of $P(\nu_\mu \to \nu_\mu)/P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1$
- Or, precisely measure $P(\nu_\mu \to \nu_e)$ with the assumption of 3 light neutrinos. Within the framework of 3 neutrinos, CP violation will be governed by the imaginary phase δ_{CP} in the neutrino mixing matrix.
- Matter effect can mimic the genuine CP violation. The measurement of the matter effect is equally important to study neutrino CP violation. The matter effect determine the neutrino mass ordering.



Formula of Oscillation Probability with CP violation

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{132}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

Leading

$$\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

CPV

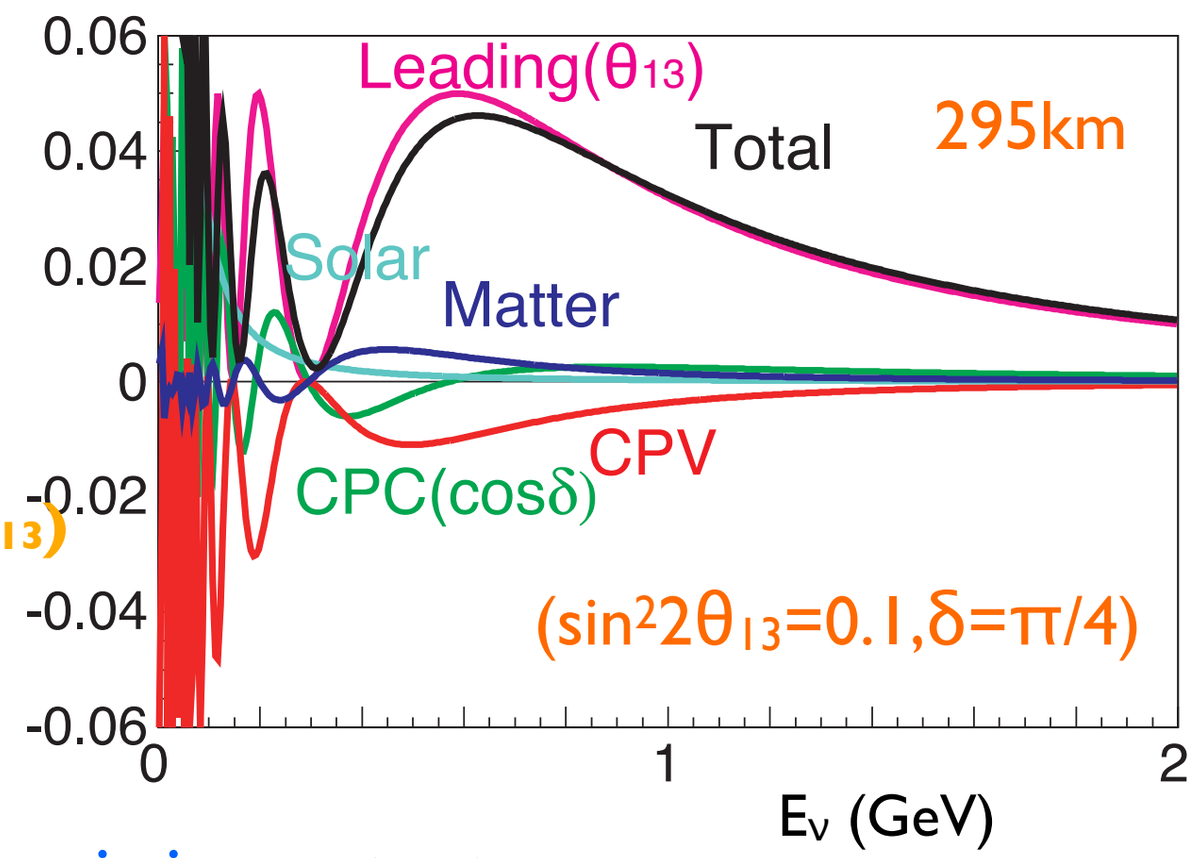
$$\frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \sin\delta$$

~0.03 ~11.8 (6.4 from $1/\sin\theta_{13}$)

$$\sim \frac{\pi}{4} \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{\sin^2\theta_{23} \sin\theta_{13}} \frac{E_{1st\max}}{E} [leading] \sin\delta$$

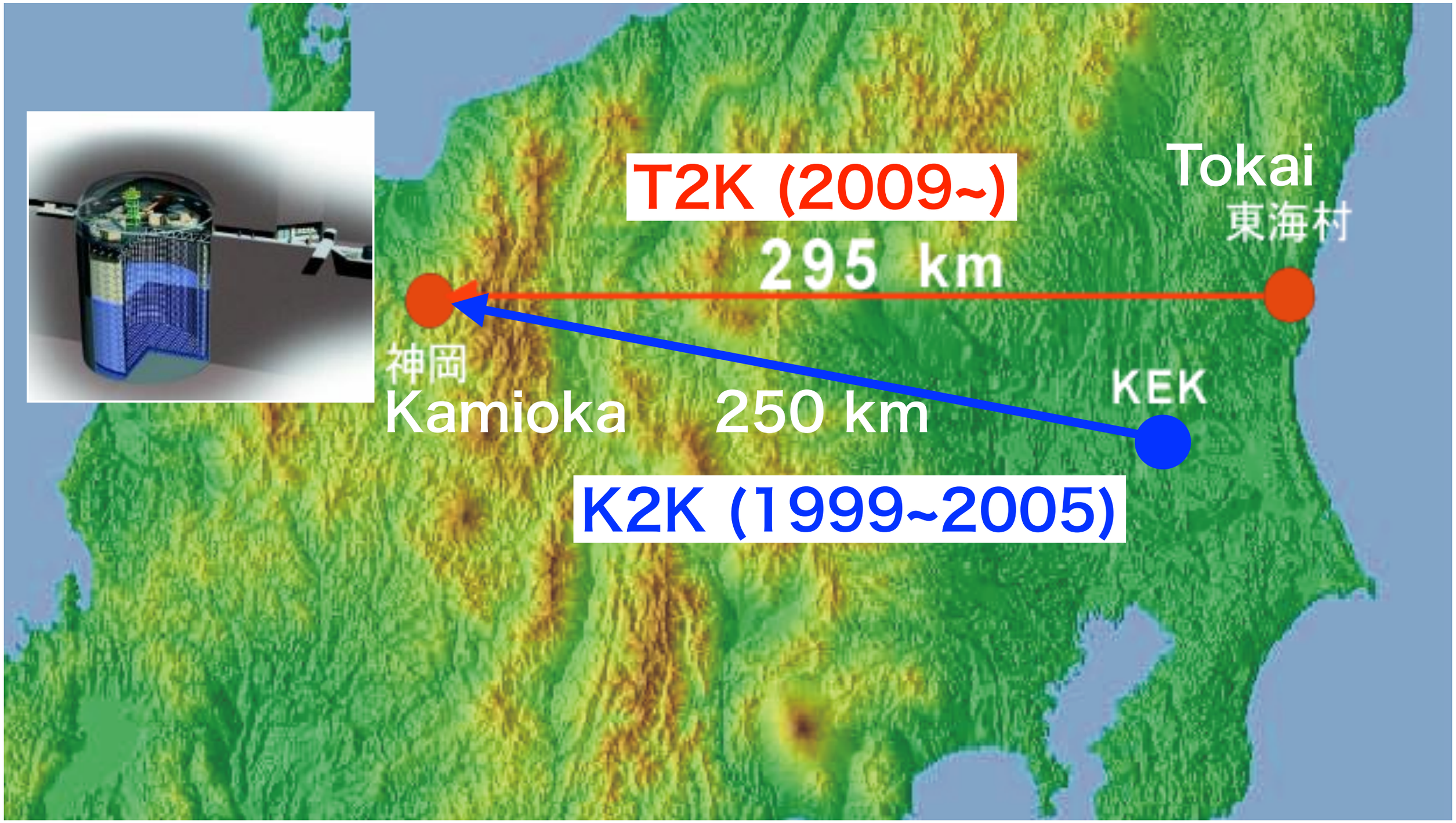
$$\sim 0.27 \times [leading] \times \frac{E_{1st\max}}{E} \times \sin\delta$$

27%

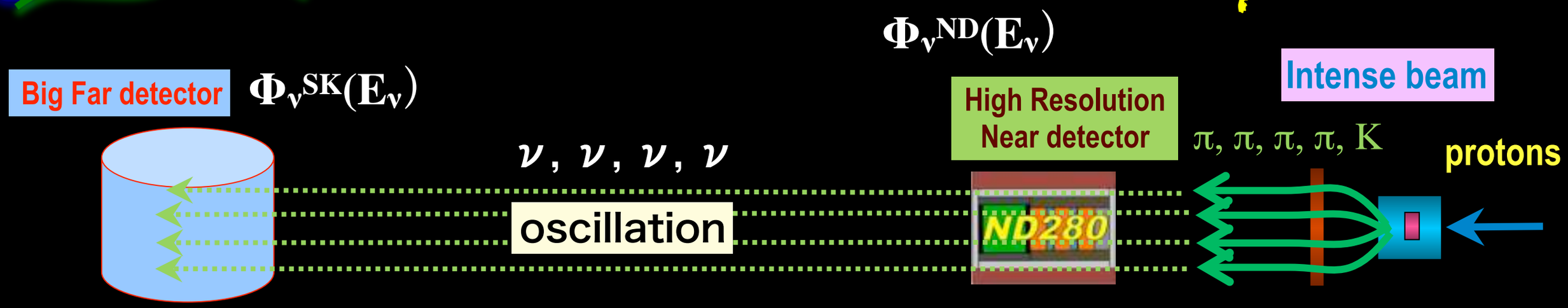


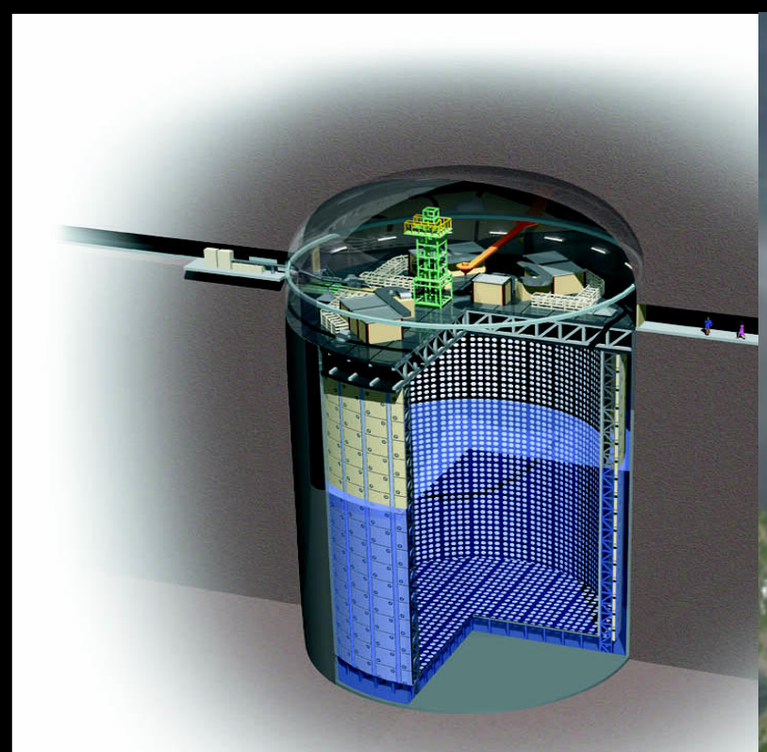
- Energy dependence is important.

K2K & T2K Experiments



T2K Accelerator Neutrino Experiment





The T2K Collaboration

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

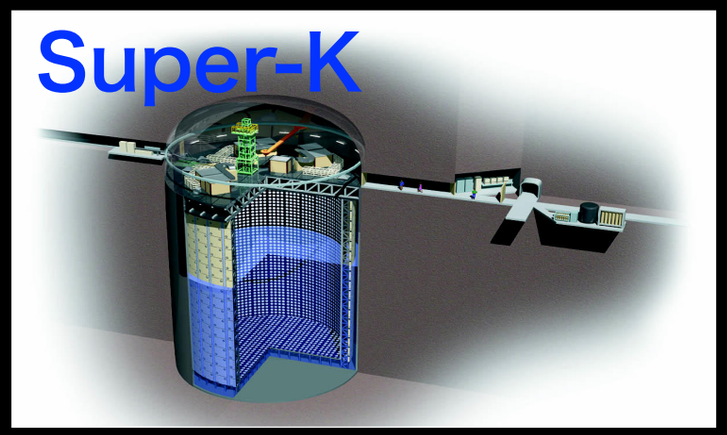
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

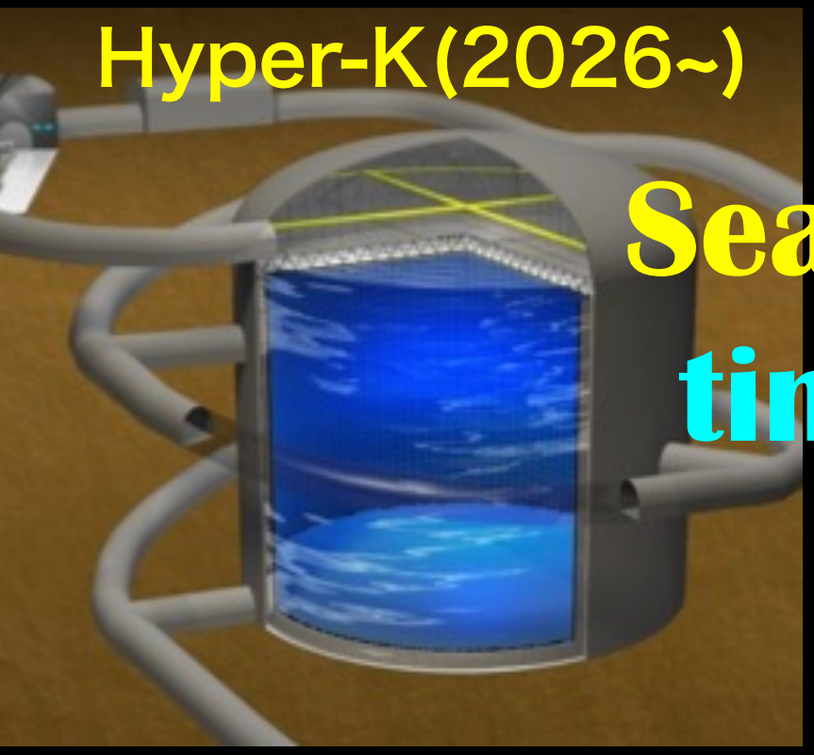
~500 members,
59 Institutes,
11 countries

Neutrino oscillation experiments in Japan

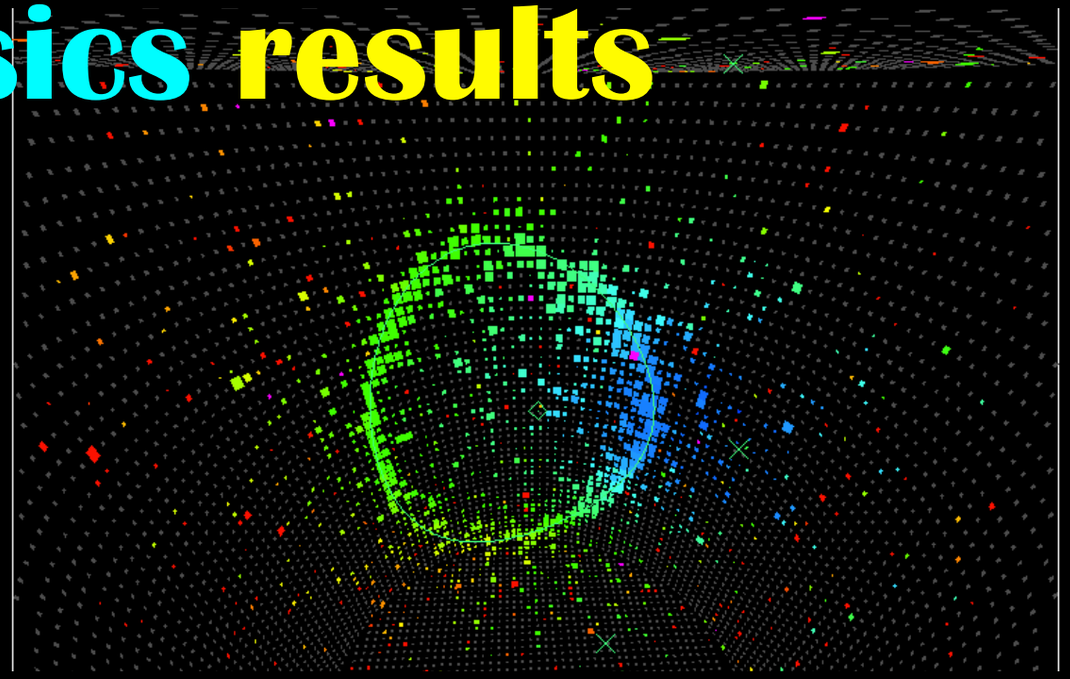
Intense Neutrino Beam for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ study



- 500 kW (today)
- ~1MW (2022)
- 1.3 MW (2026)

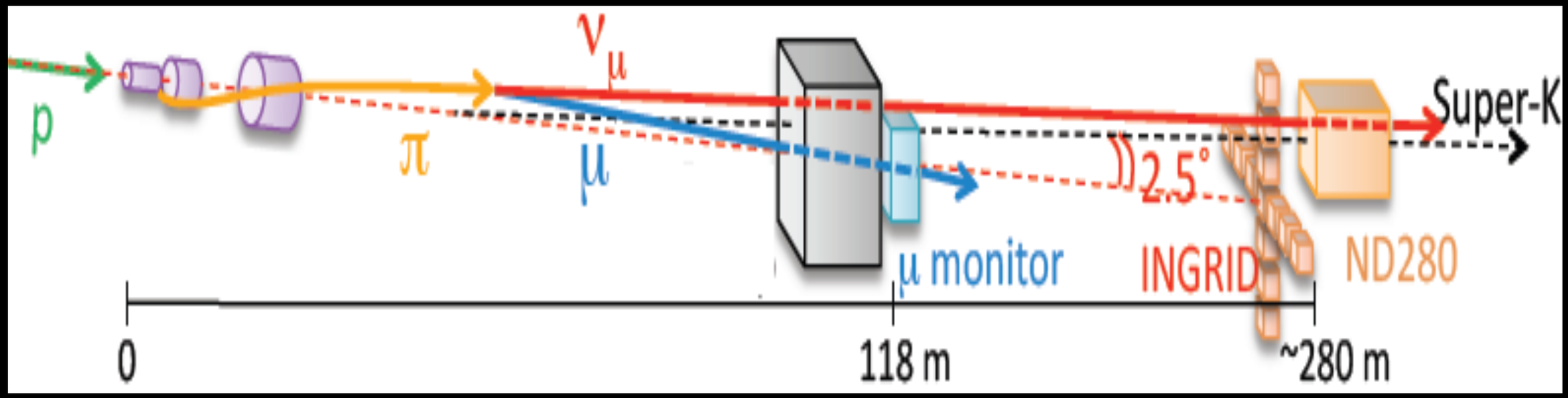


Seamless program with timely physics results



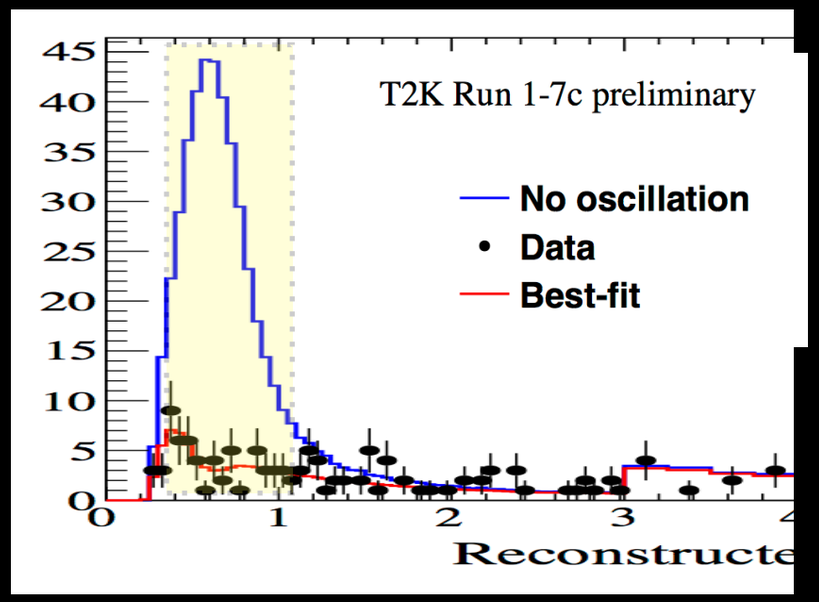
- 22.5 kton (Super-K, ~2026)
- 190 kton (Hyper-K, 2027~)

T2K ν beam



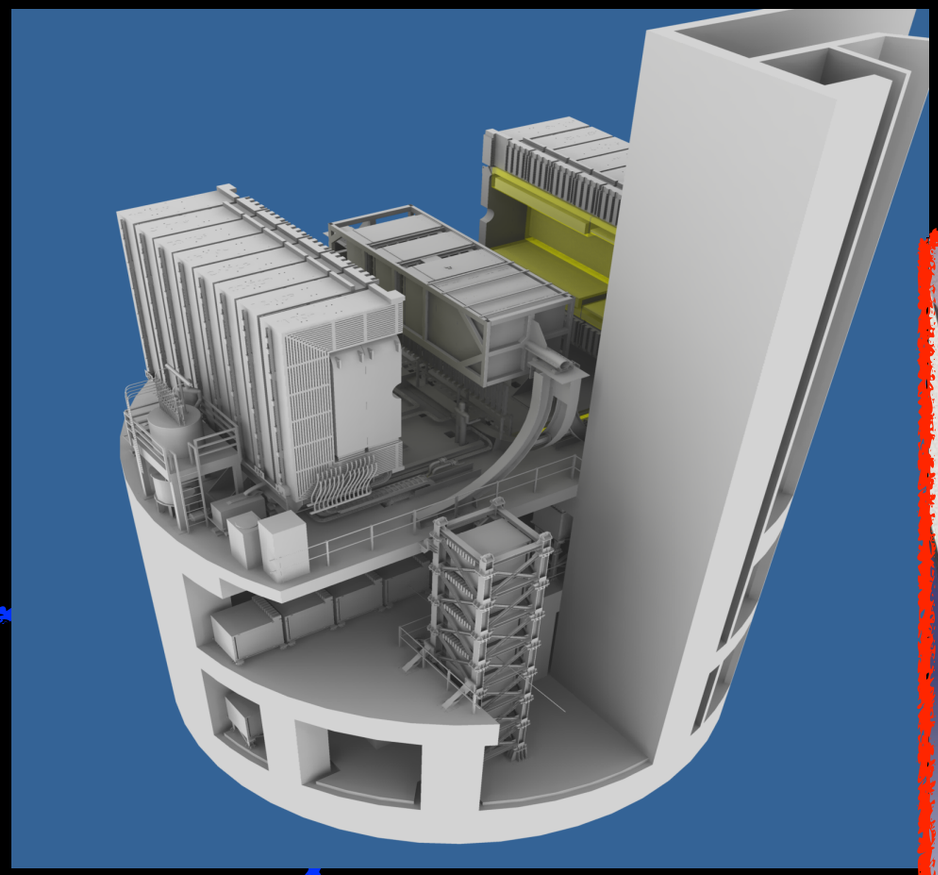
- 30 GeV ~2×10^{14} protons extracted every 2.5/1.3 sec. directed to the carbon target.
- Secondary $\pi^{\pm}$(and $K^{\pm}$) focused by three electromagnetic horns (±250kA/320kA)
- ν_μ beam from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e (1~2%) in the beam come from K and μ decays
  - Reversing the current of horns, Anti-neutrino beam (ν_μ) can be produced

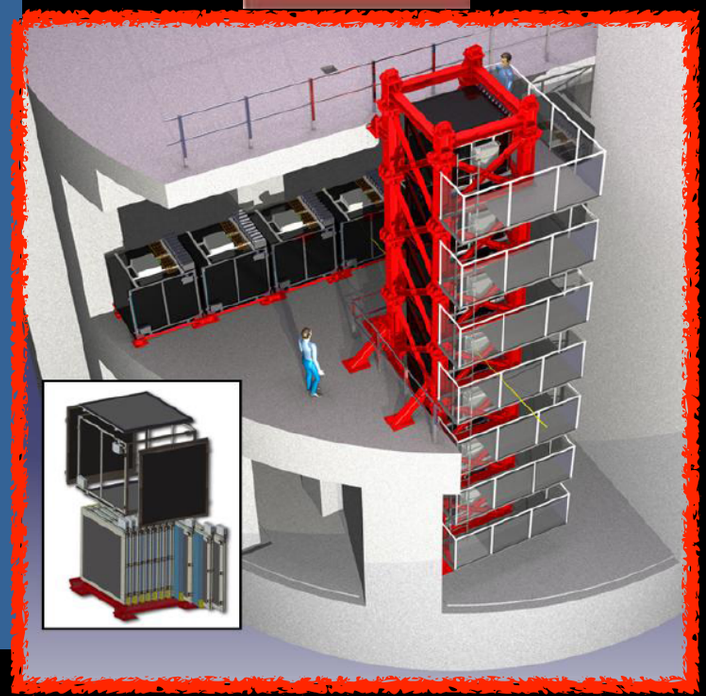
ν_μ oscillated at 295 km

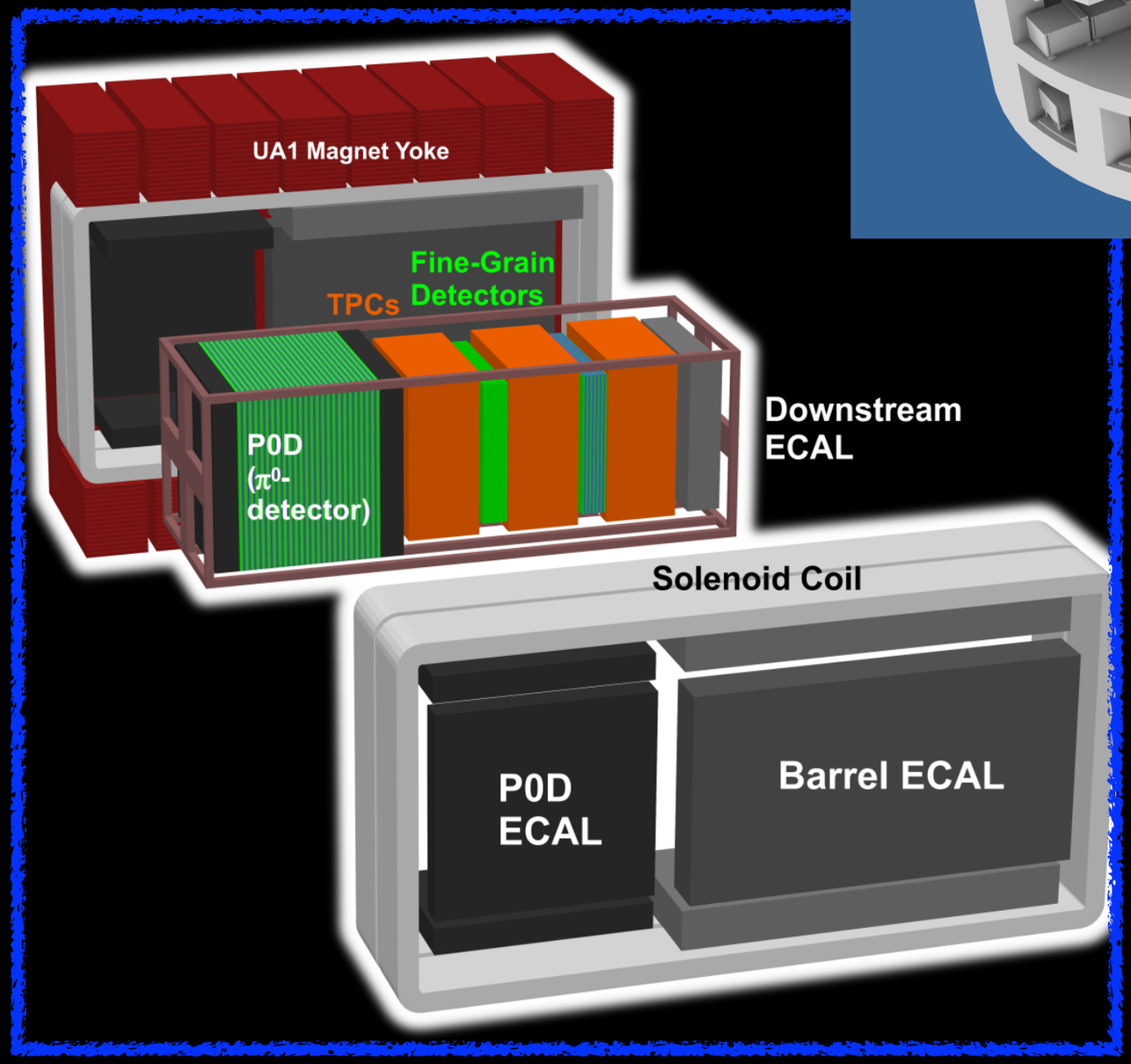


ND280

Near Detector @ 280m from the target



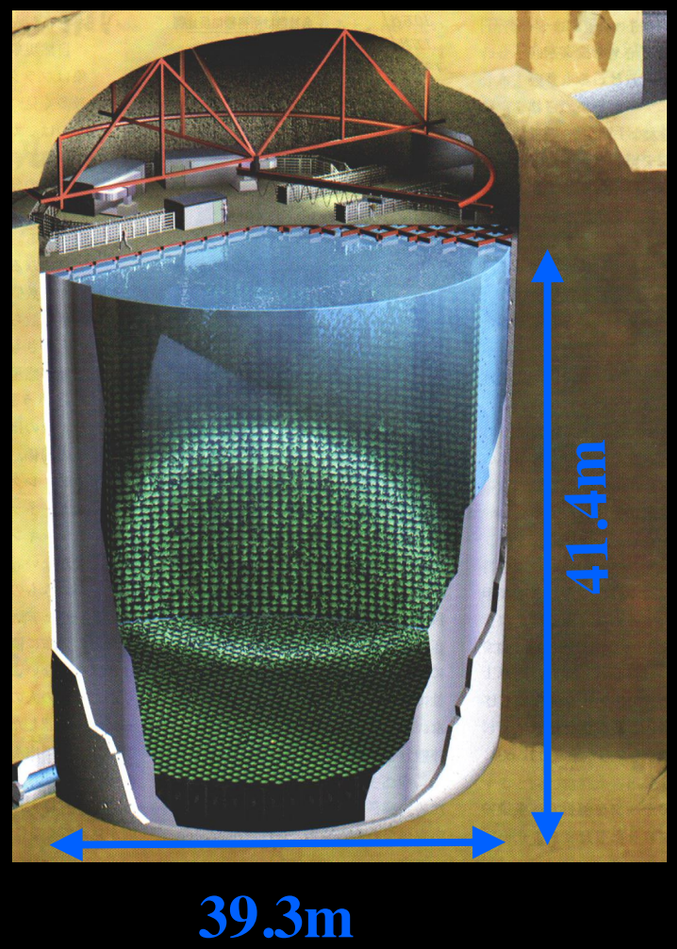


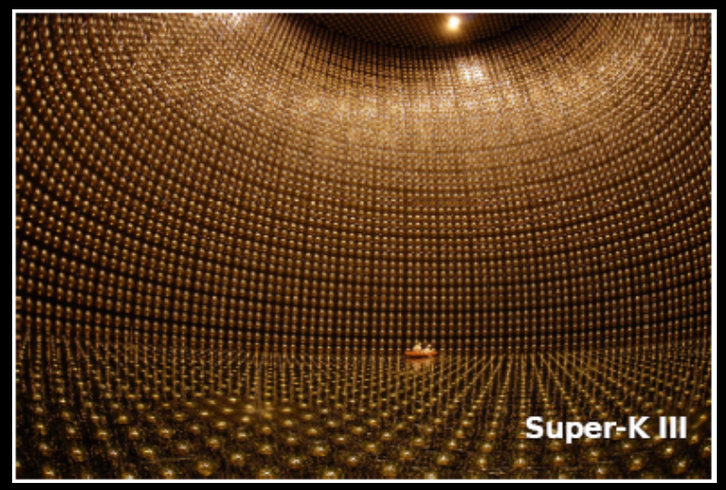


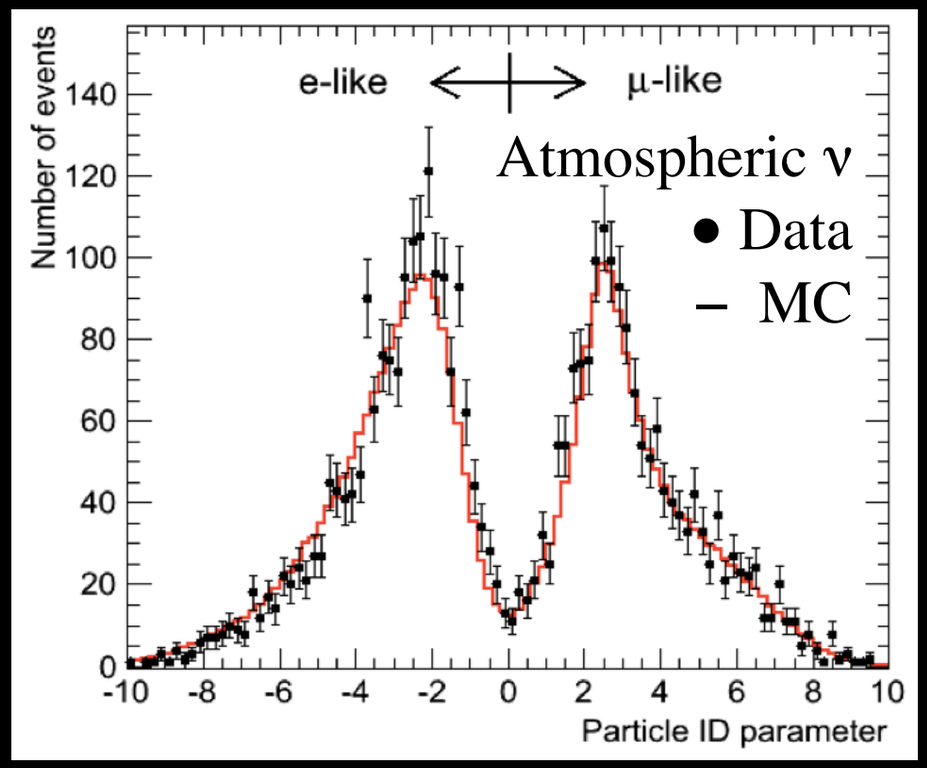
- INGRID @ on-axis (0 degree)
  - ν beam monitor [rate, direction, and stability]
- ND280 @ 2.5 degree off-axis
  - Normalization of Neutrino Flux
  - Measurement of neutrino cross sections.
    - Dipole magnet w/ 0.2T
    - P0D: π^0 Detector
    - FGD+TPC: Target + Particle tracking
    - EM calorimeter
    - Side-Muon-Range Detector

T2K-Far Detector: Super-Kamiokande

- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with 95% NC-1π^0 rejection
    - Inner tank (32 kton) :11,129 20inch PMT
    - Outer tank:1,885 8inch PMT

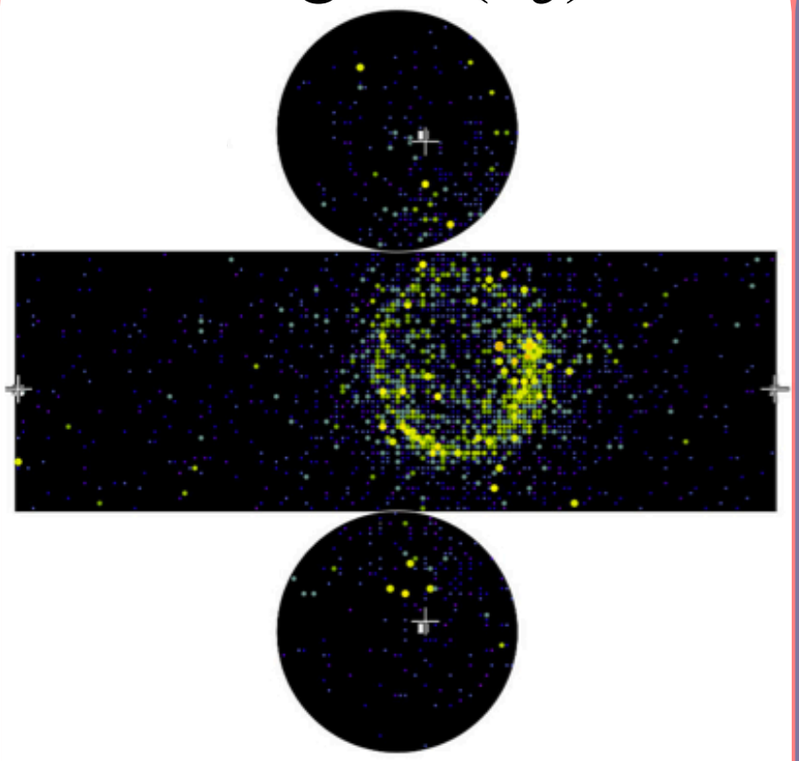




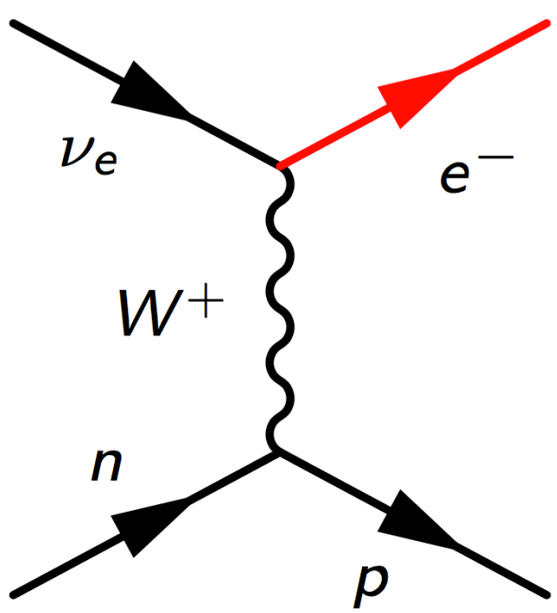


Neutrino Detection at SK Far Detector

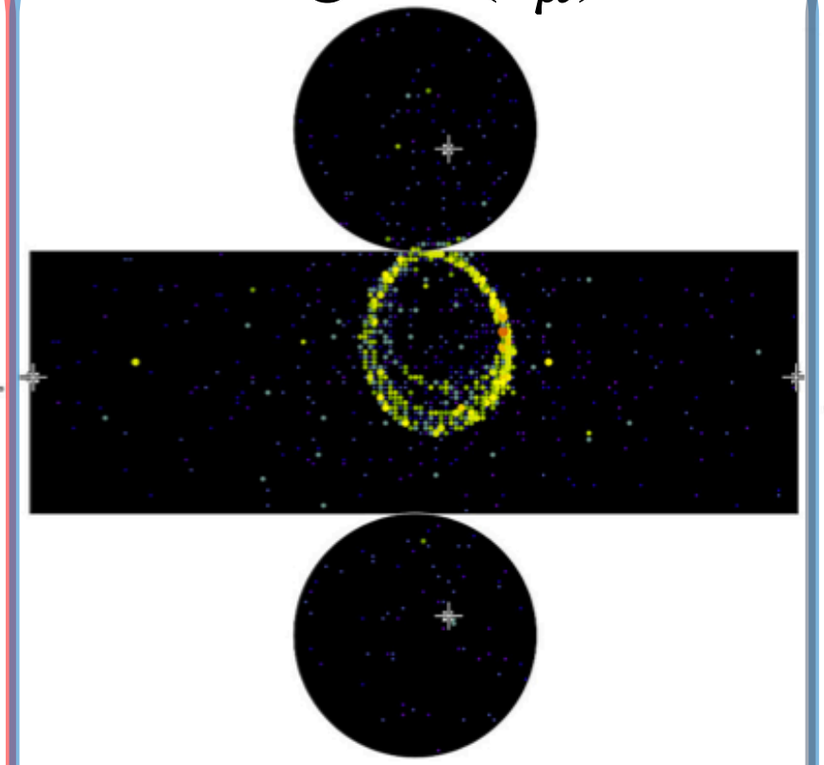
Signal (ν_e)



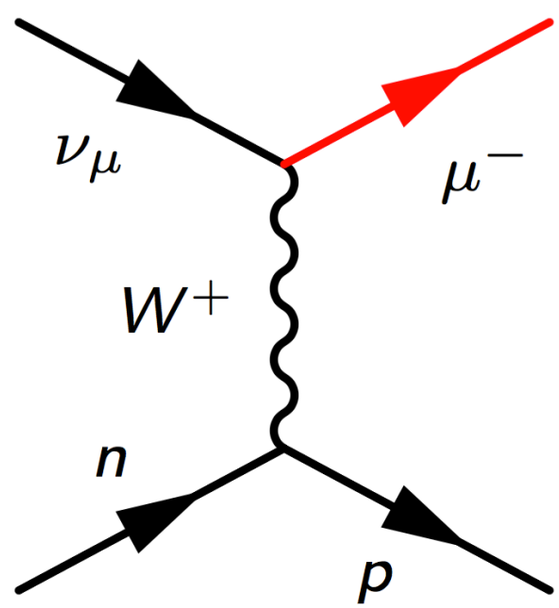
ν_e CCQE



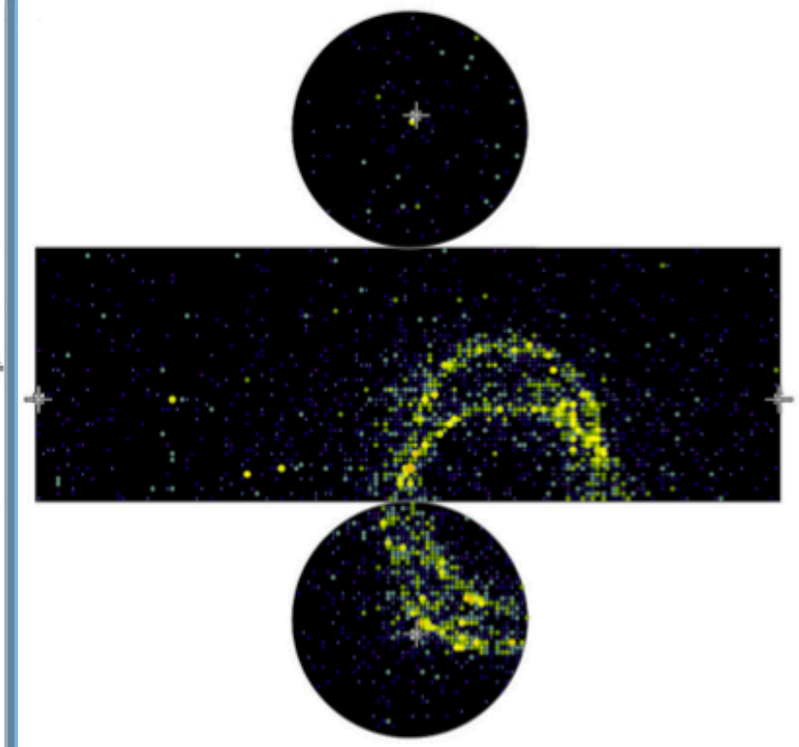
Signal (ν_μ)



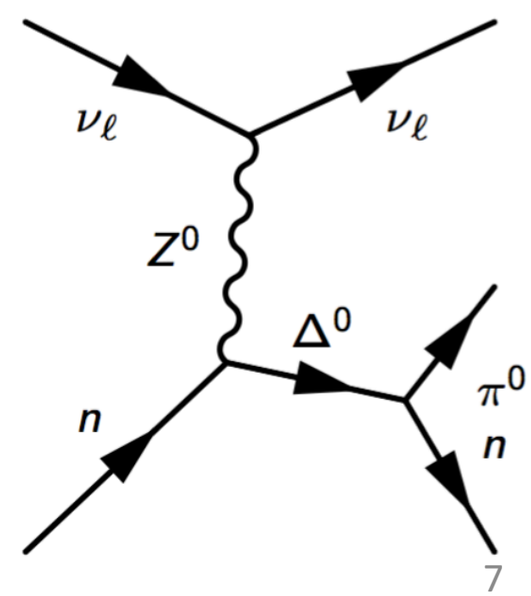
ν_μ CCQE



Background



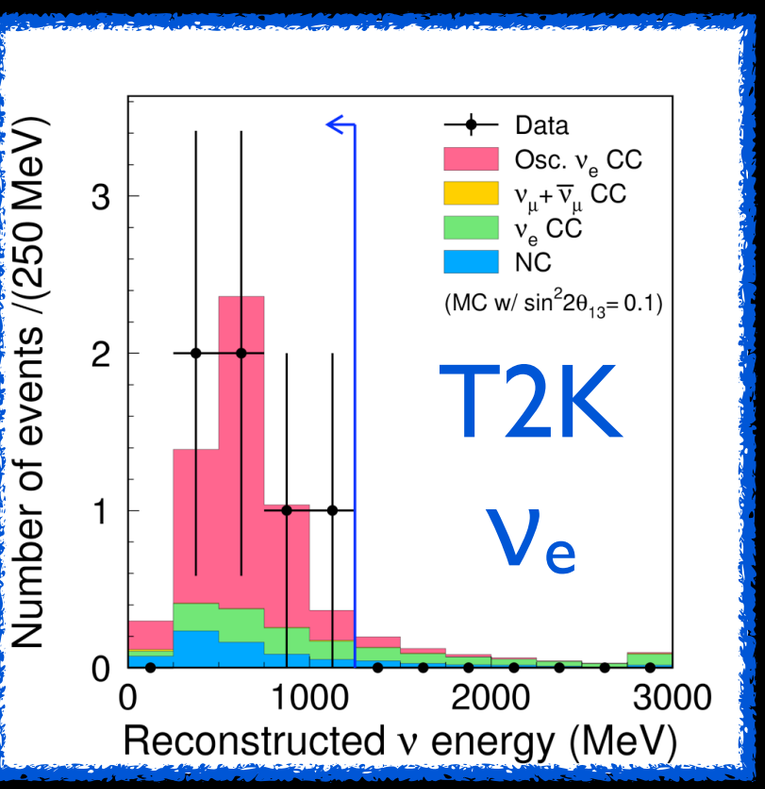
ν_ℓ NC1π^0



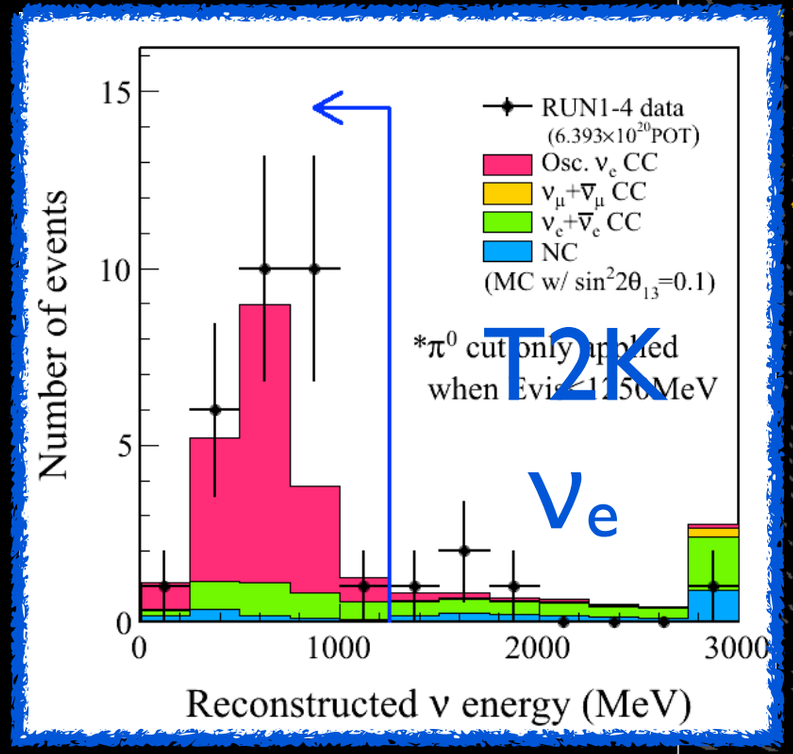
A door to Neutrino CP violation is opened

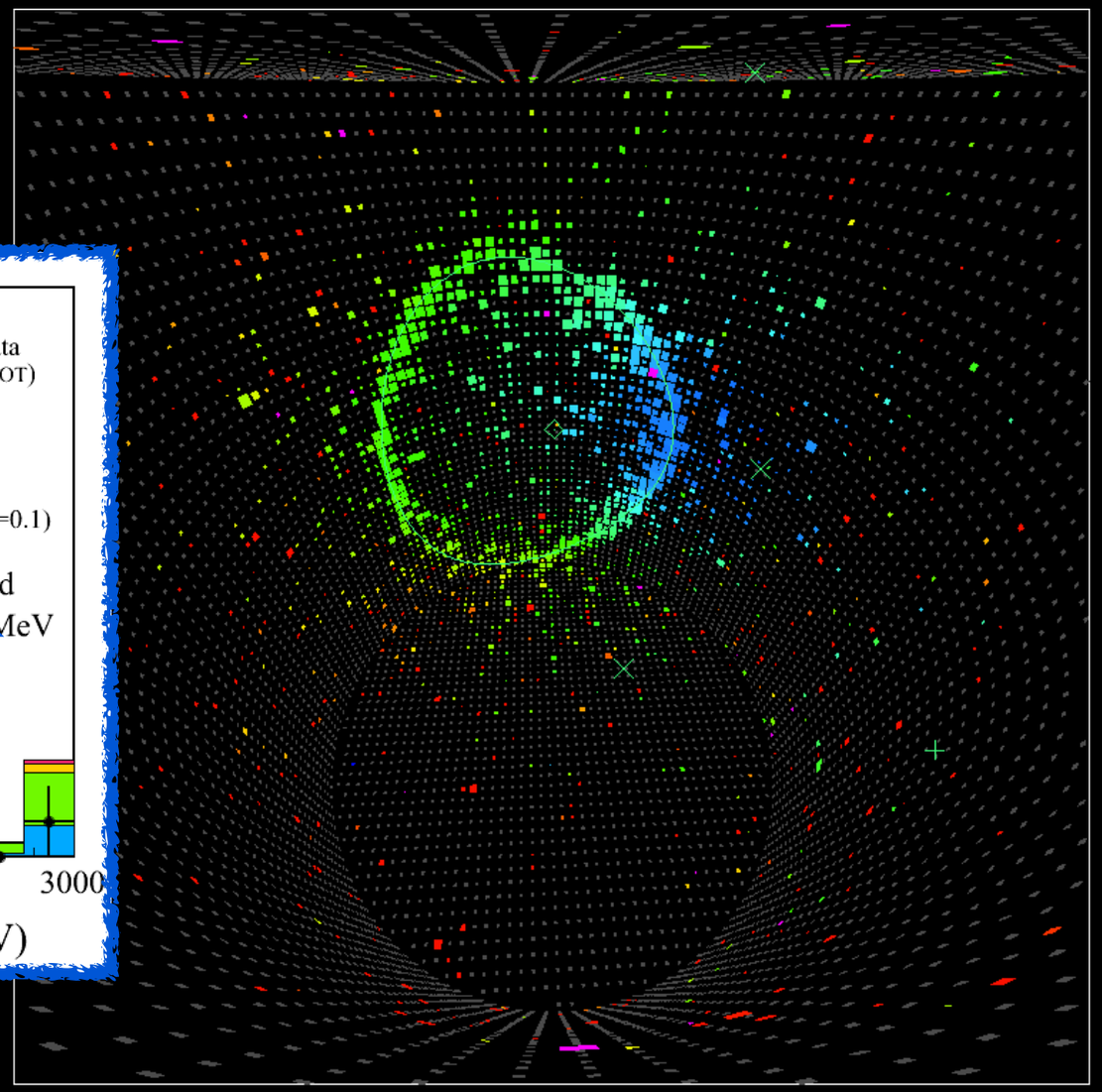
- $\nu_\mu \rightarrow \nu_e$ oscillation w/ Δm_{atm}^2 discovered by the T2K experiment
  - Indication in 2011 [PRL 107, 041801 (2011)]
  - Observation in 2013 [PRL 112, 061802 (2014)]

2011



2013





FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

BOARD TROPHY EVENTS NOMINATIONS NEWS CONTACTS
COMMITTEE PRIZES LAUREATES RULES

Search

LAUREATES

Breakthrough Prize Special Breakthrough Prize New Horizons Prize Physics Frontiers Prize

2016 2015 2014 2013 2012


Kam-Biu Luk and the Daya Bay Collaboration


Yifang Wang and the Daya Bay Collaboration


Koichiro Nishikawa and the K2K and T2K Collaboration


Atsuto Suzuki and the KamLAND Collaboration


Arthur B. McDonald and the SNO Collaboration

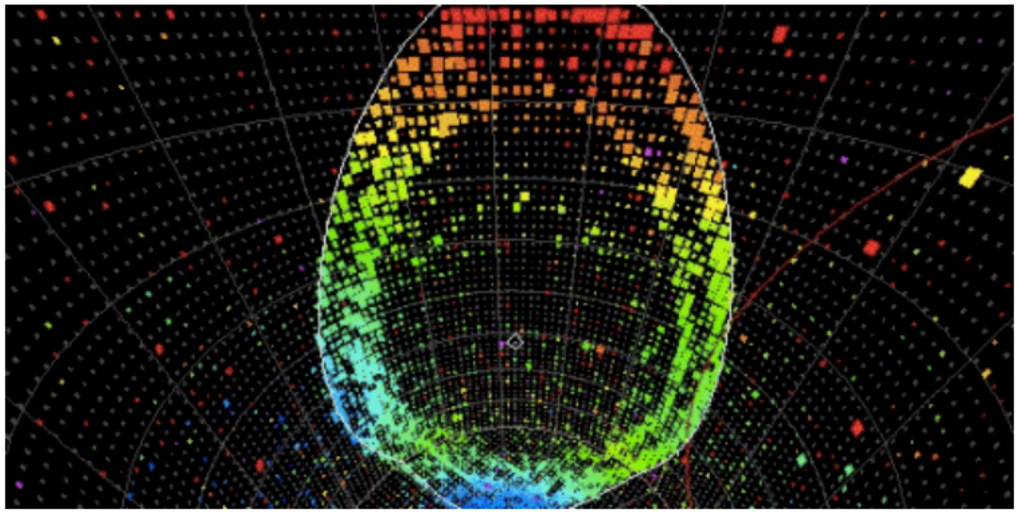

Takaaki Kajita and the Super K Collaboration


Yoichiro Suzuki and the Super K Collaboration

Synopsis: Inching Closer to *CP* Violation in Neutrinos

October 24, 2018

More data and improved analysis methods lead to better confidence that neutrinos and antineutrinos behave slightly differently.



Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), University of Tokyo

Nature must treat matter and antimatter differently, otherwise the early Universe would have created both in equal amounts. However, most particles obey "*CP* symmetry," which states that the laws of physics are the same if a particle is swapped with a mirror reflection of its antiparticle. Quarks violate this symmetry but not by enough to explain matter's dominance over antimatter. Now, researchers with the T2K Collaboration report with improved statistical confidence that *CP* symmetry is violated in neutrinos.

New T2K CPV Results in 2018

Ref. T2K 2017 CPV result is just published in PRL

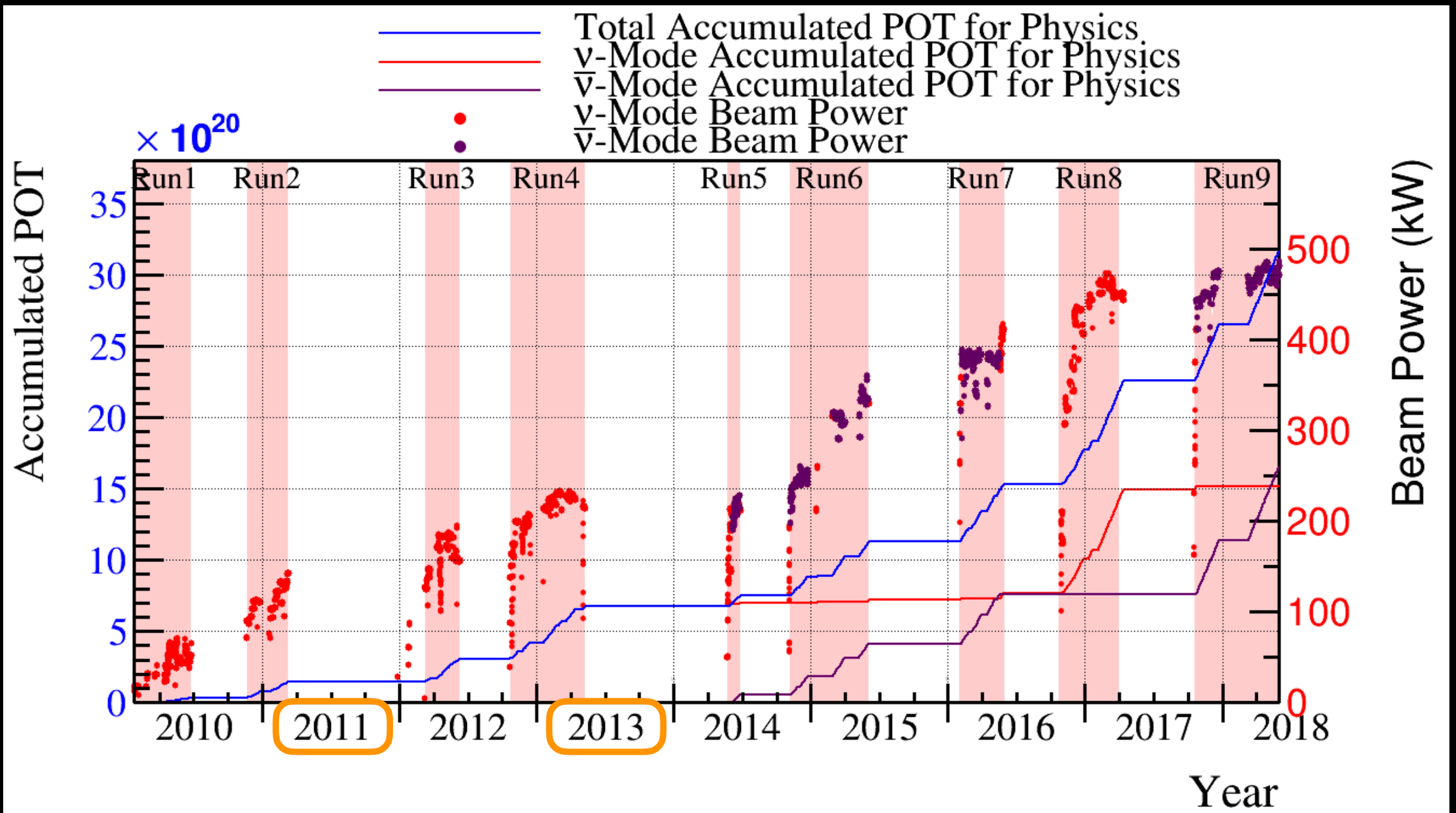
PHYSICAL REVIEW LETTERS **121,** 171802 (2018)

Editors' Suggestion Featured in Physics

Search for *CP* Violation in Neutrino and Antineutrino Oscillations by the T2K Experiment with 2.2×10^{21} Protons on Target

K. Abe,[48] R. Akutsu,[49] A. Ali,[20] J. Amey,[17] C. Andreopoulos,[46,27] L. Anthony,[27] M. Antonova,[16] S. Aoki,[24] A. Ariga,[2] Y. Ashida,[25] Y. Azuma,[34] S. Ban,[25] M. Barbi,[39] G. J. Barker,[58] G. Barr,[35] C. Barry,[27] M. Batkiewicz,[13] F. Bench,[27] V. Berardi,[18] S. Berkman,[4,54] R. M. Berner,[2] L. Berns,[50] S. Bhadra,[62] S. Bienstock,[36] A. Blondel,[12,*] S. Bolognesi,[6]

New T2K Data (3.16 E21 POT ← 2.2E21 POT)



23 Jan. 2010 – 31 May 2018

POT total: 3.16 x 10^{21}

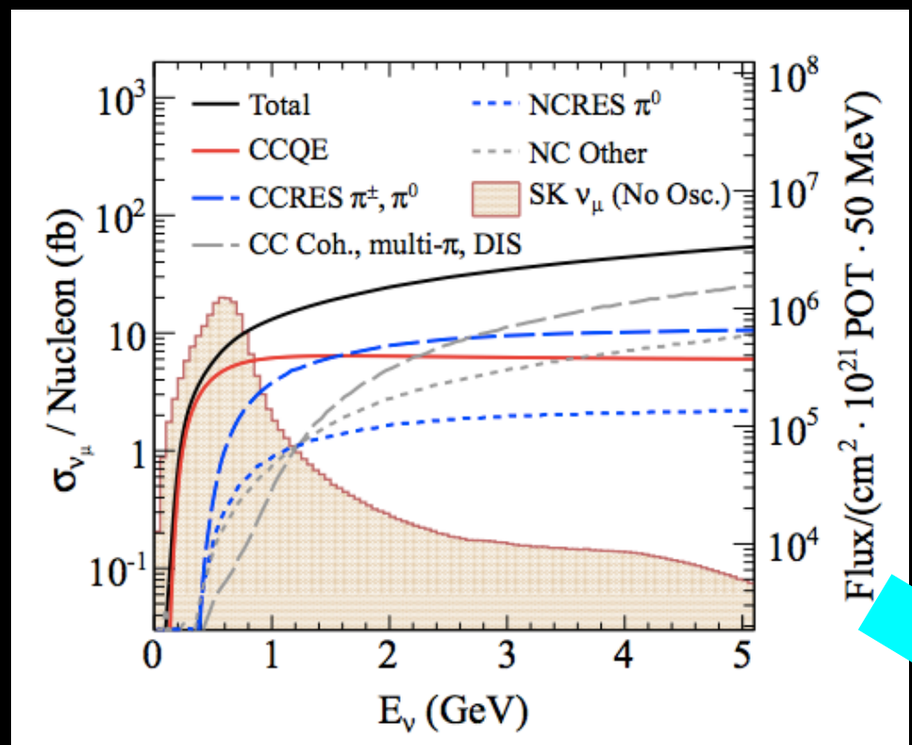
ν-mode 1.51 x 10^{21} (47.83%)

$\bar{\nu}$-mode 1.65 x 10^{21} (52.17%)

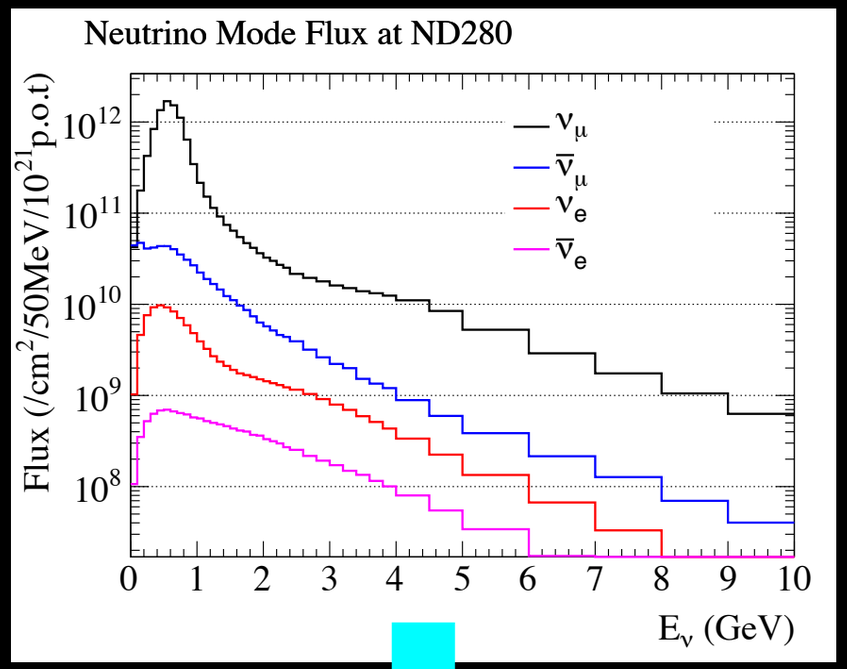
- J-PARC Accelerator has achieved stable operation with ~500 kW beam power

Oscillation Analysis: Step 1

Neutrino-nucleus Interaction Model

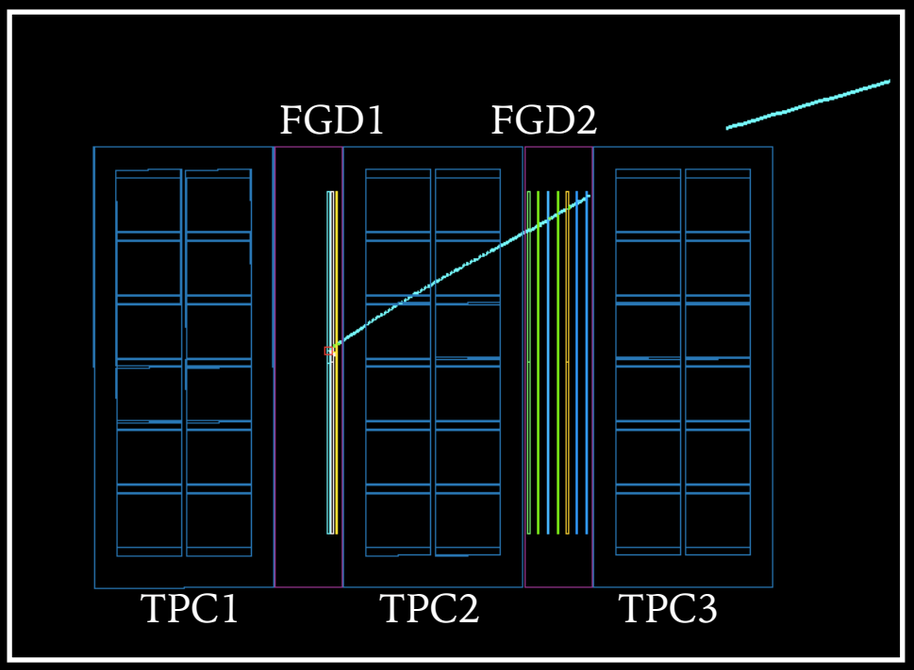


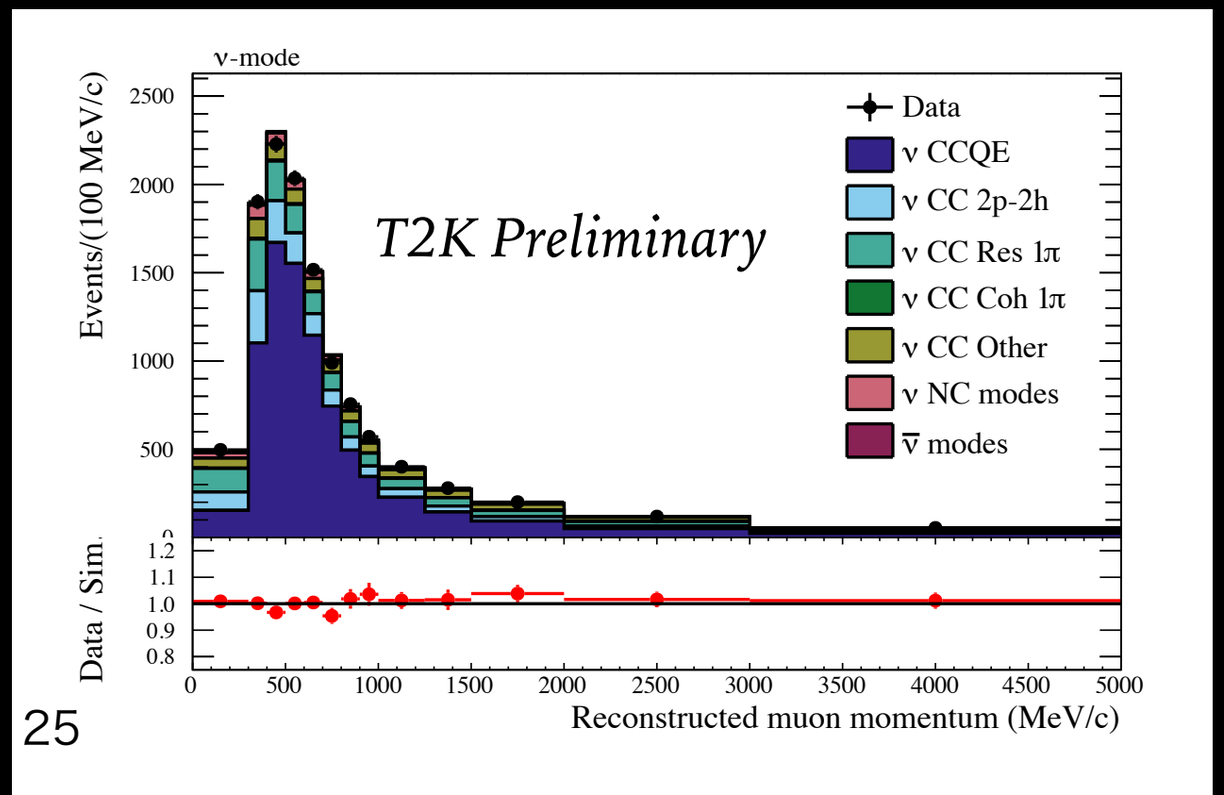
Neutrino Flux Model



Fit to ND280 data constrains neutrino flux parameters and interaction model parameters

ND280 Data





Challenges

- Systematic uncertainties from neutrino-nucleus cross sections -

A01

WAGASCI Project

Osaka City Univ.
Ken'ichi Kin
on behalf of the WAGASCI Collaboration

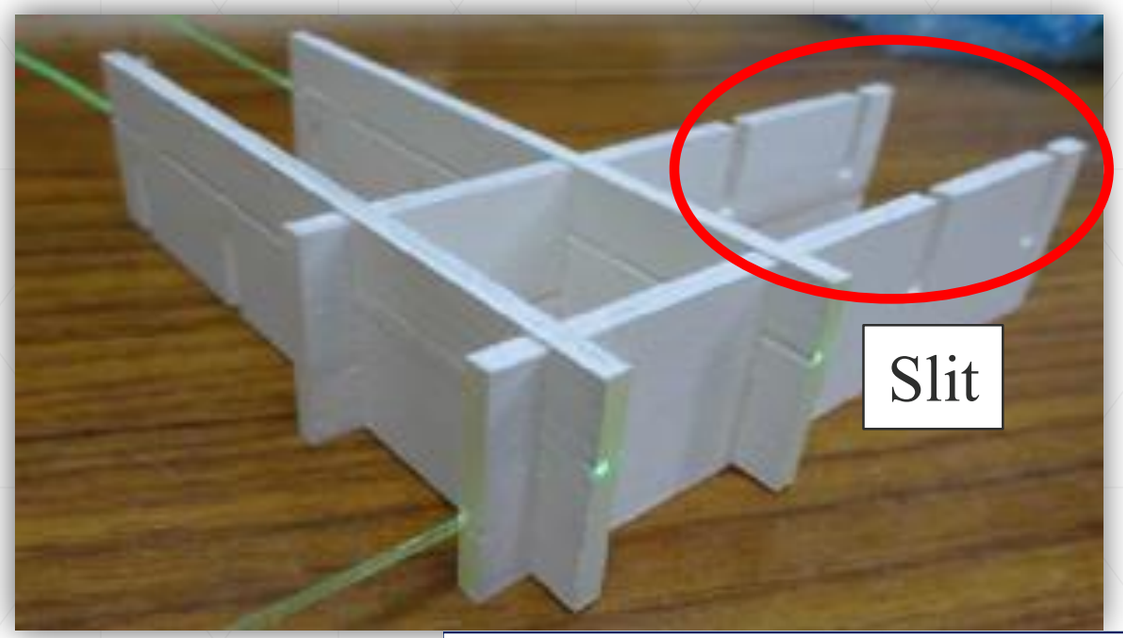
Neutrino Frontier Workshop 2016

WAGASCI Collaboration

Institute for Nuclear Research of the Russian Academy of Science.
M. Antonova, A. lzmaylov, M. Khabibullin, A. Khotjantsev, A. Kostin, Y. Kudenko, A. Mefodiev, O. Mineev, T. Ovsjannikova, S. Suvorov, N. Yershov
KEK
T. Ishida, T. Kobayashi
Kyoto University
S. V. Cao, T. Hayashino, A. Hiramoto, A. K. Ichikawa, A. Minamino, K. Nakamura, T. Nakaya, K. Yoshida
Laboratorie Leprince-Ringuet, Ecole Polytechnique
A. Bonnemaison, R. Cornat, O. Draper, O. Ferreira, F. Gastaldi, M. Gonin, J. Imber, M. Licciardi, T. Mueller, B. Quilain, O. Volcy
Osaka City University
Y. Azuma, T. Inoue, J. Harada, K. Kin, Y. Seiya, K. Wakamatsu, K. Yamamoto
University of Geneva
A. Blondel, F. Cadoux, K. Karadzhov, Y. Favre, E. N. Messomo, L. Nicola, S. Parsa, M. Rayner
University of Tokyo
N. Chikuma, F. Hosomi, T. Koga, R. Tamura, M. Yokoyama
Institute of Cosmic-Ray Research, University of Tokyo
Y. Hayato

8 Institute
53 Collaborators

Central detector

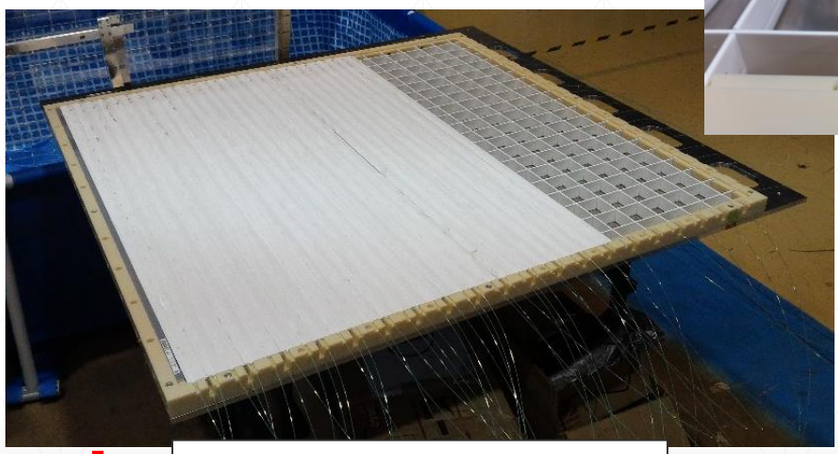


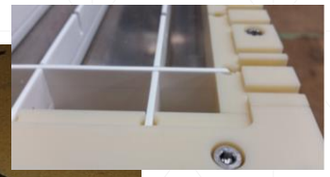
Goal of WAGASCI experiment

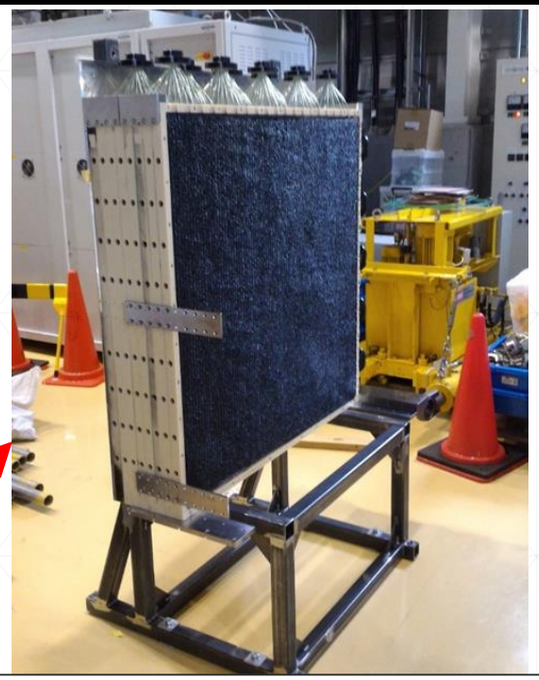
Measure neutrino cross sections of H_2O and CH with 10% accuracy.
Measure the neutrino cross section ratio btw. H_2O and CH within 3% accuracy

WAGASCI Construction

Layer & module assembly work

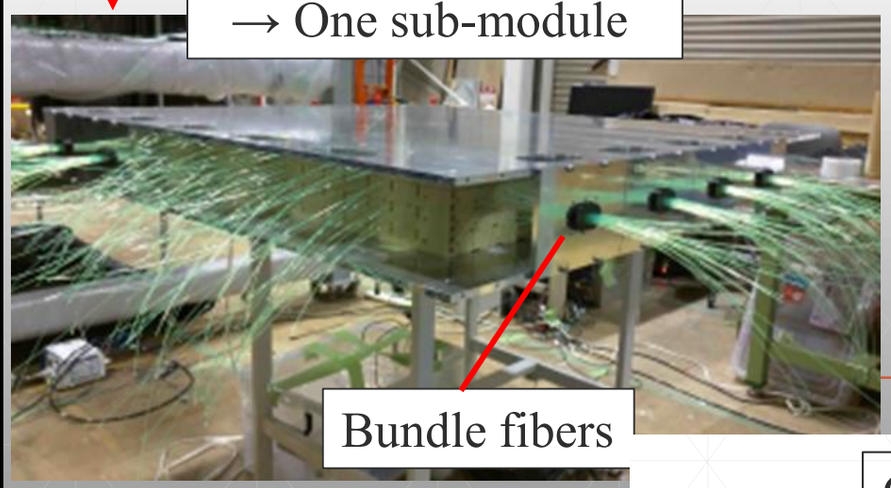






4 sub-modules → One target module

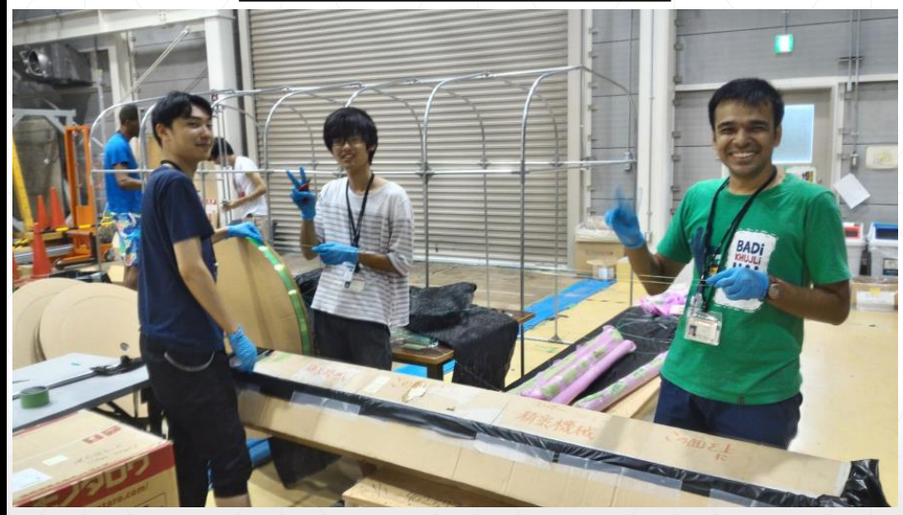
Four scintillator layers
→ One sub-module



Bundle fibers

Install into the water tank

Cutting WLS fibers



Light yield measurement by cosmic-rays

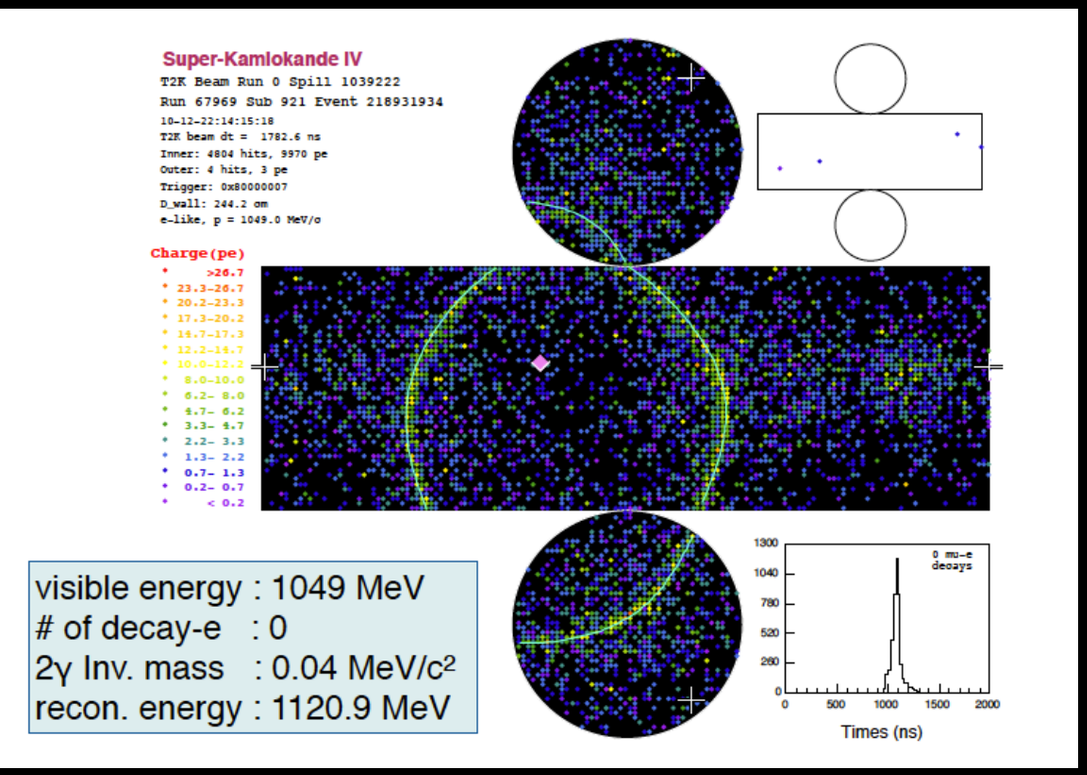
Oscillation Analysis: Step 2

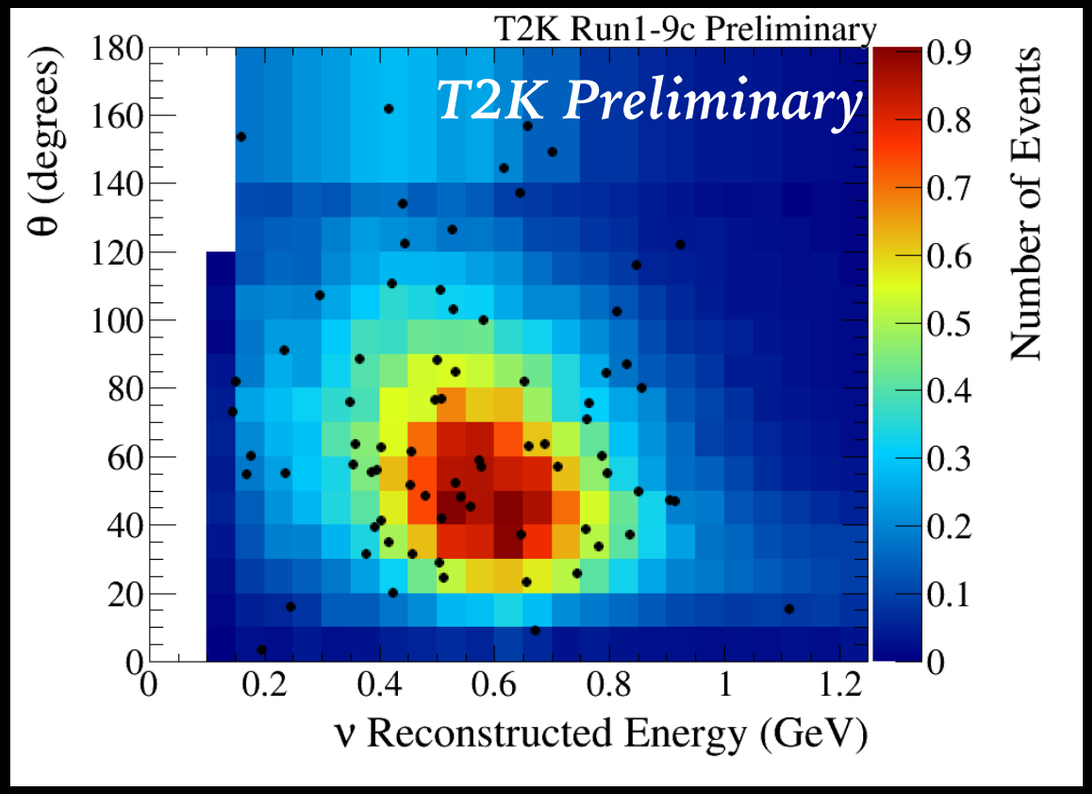
Prediction at Super-K Oscillation Probability Constrained by near detector

$$N(p_k,\theta_k;\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)=\sum_i^{E_\nu\ \mathrm{bins}}\sum_j^{flavors} P_{\nu_j\to\nu_k}(E_{\nu,i};\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)\,\Phi_j^{far}(E_{\nu,i})\,\sigma_k(E_{\nu,i},p_k,\theta_k)\,\epsilon(p_k,\theta_k)\,M_{det}$$

Fit to SK data to extract oscillation parameter intervals

T2K Super-K Data



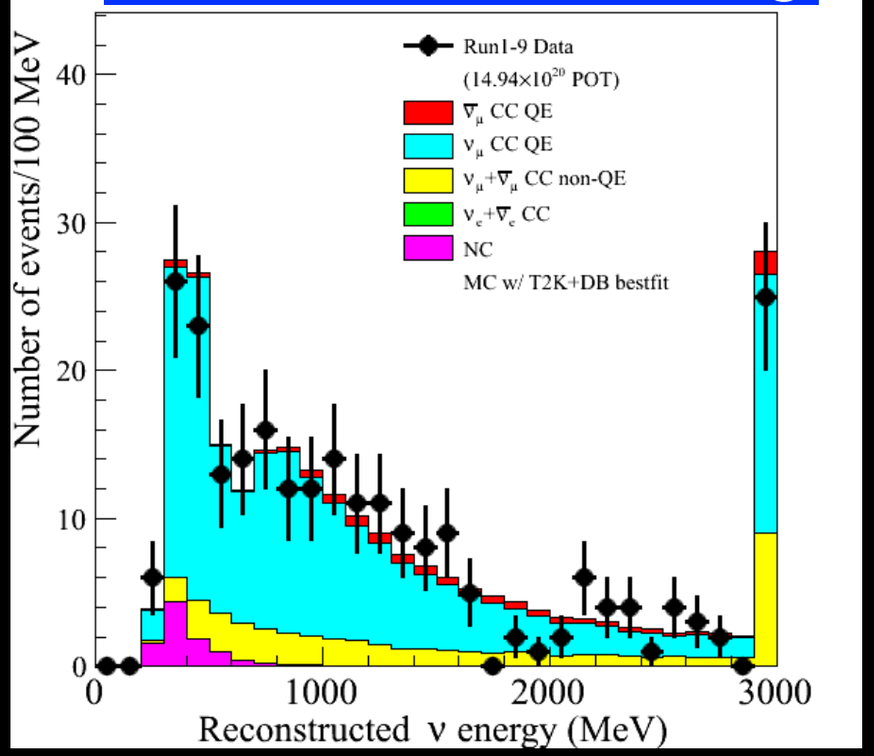


ν Mode ν_e Candidates

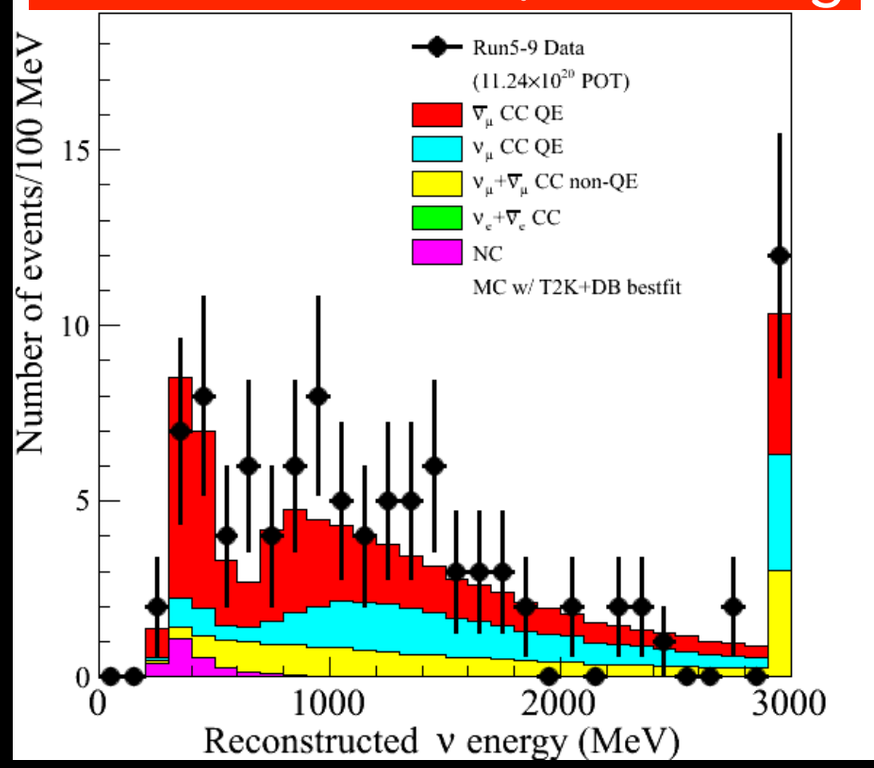
Observation at Super-K

T2K Preliminary

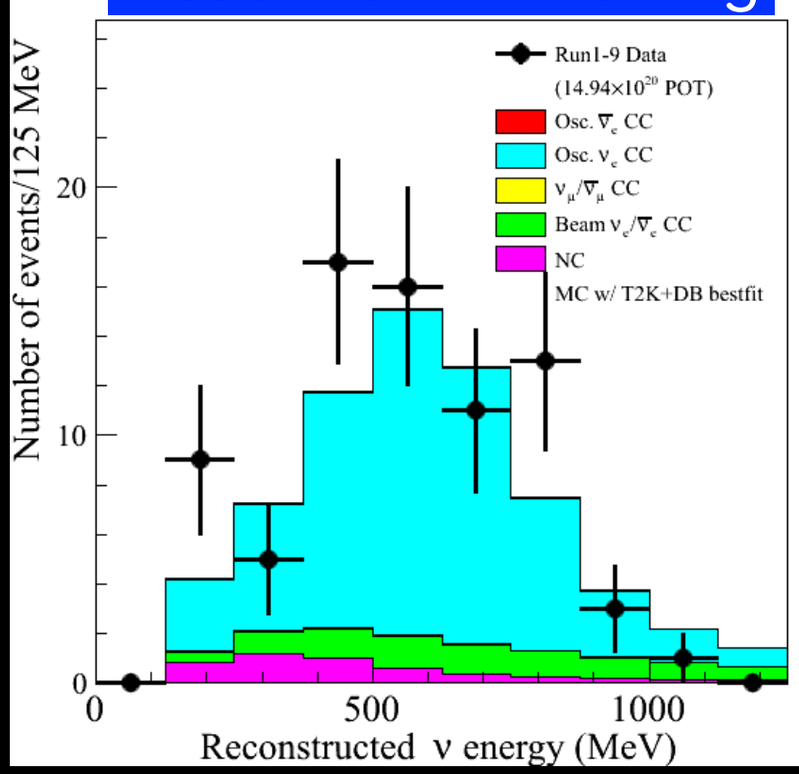
Neutrino 1 μ-like ring



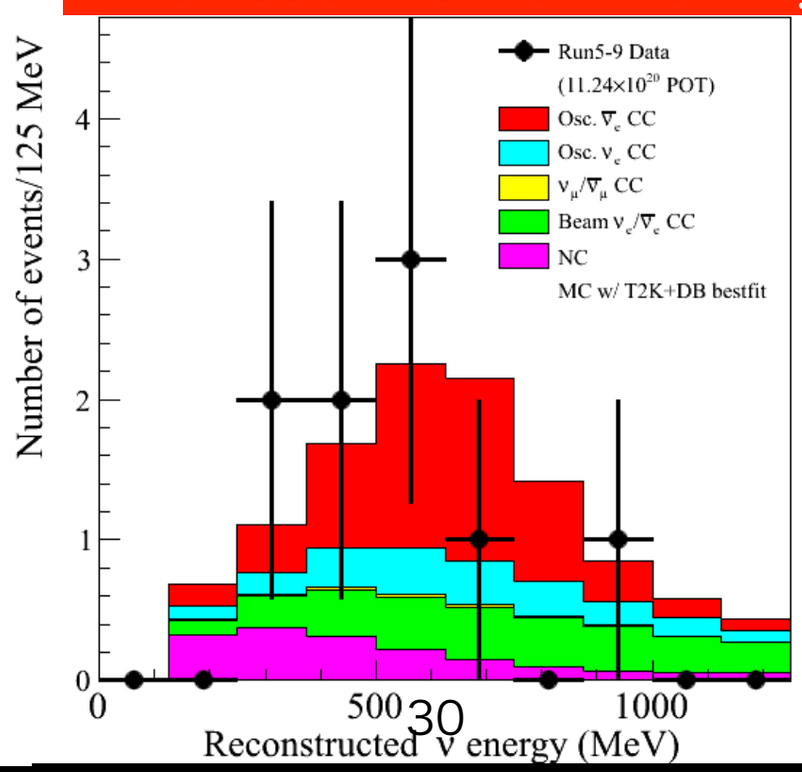
Antineutrino 1 μ-like ring



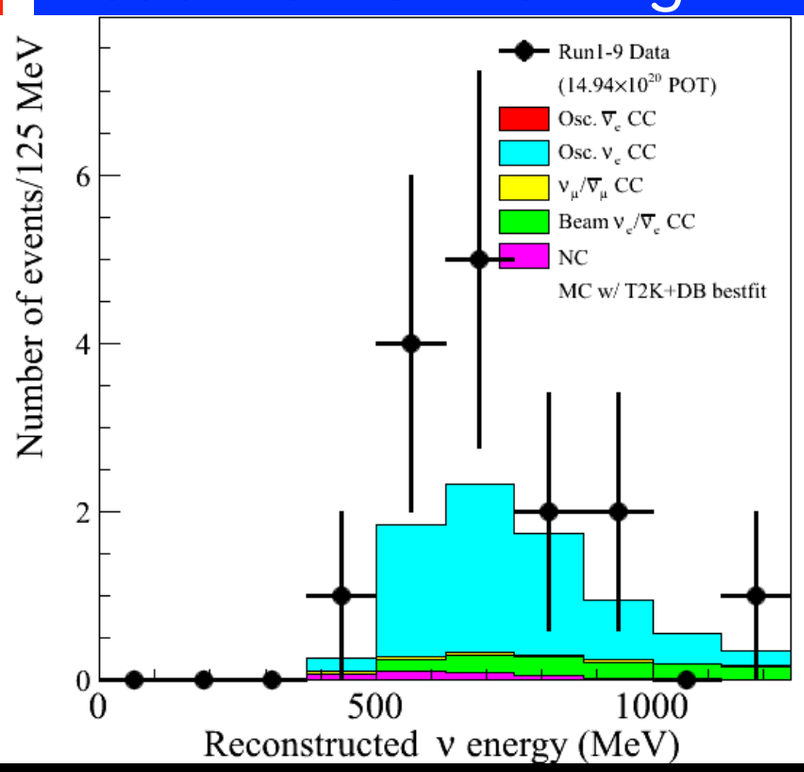
Neutrino 1e-like ring



Antineutrino 1e-like ring



Neutrino 1e-like ring + π



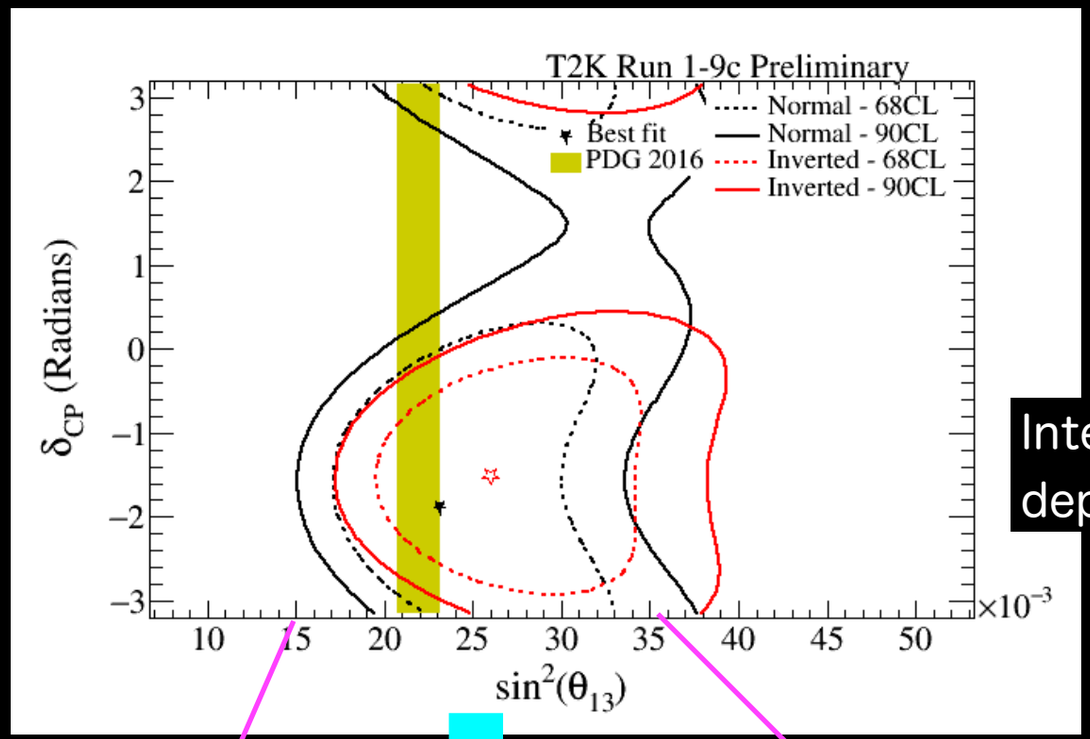
Predictions and Observation

Sample	Predicted Rates				Observed Rates
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	
e-like FHC	73.8	61.6	50.0	62.2	75
e-like+π FHC	6.9	6.0	4.9	5.8	15
e-like RHC	11.8	13.4	14.9	13.2	9
μ-like FHC	268.5	268.2	268.5	268.9	243
μ-like RHC	95.5	95.3	95.5	95.8	102

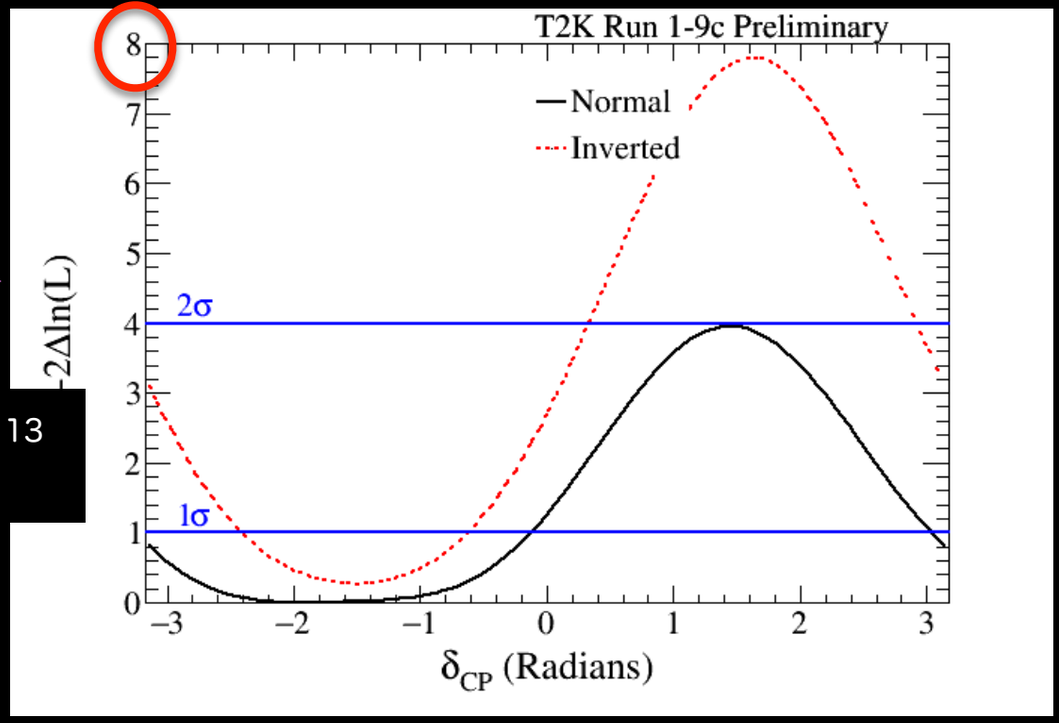
- The number of observed events are largely in line with the predictions after oscillations
  - The e-like samples have rates most consistent with the $\delta_{cp}=-\pi/2$ hypothesis
- The observed μ-like rate in neutrino mode is lower than prediction
  - consistent within statistical and systematic errors

(Simulation) Oscillation Parameter Sensitivities

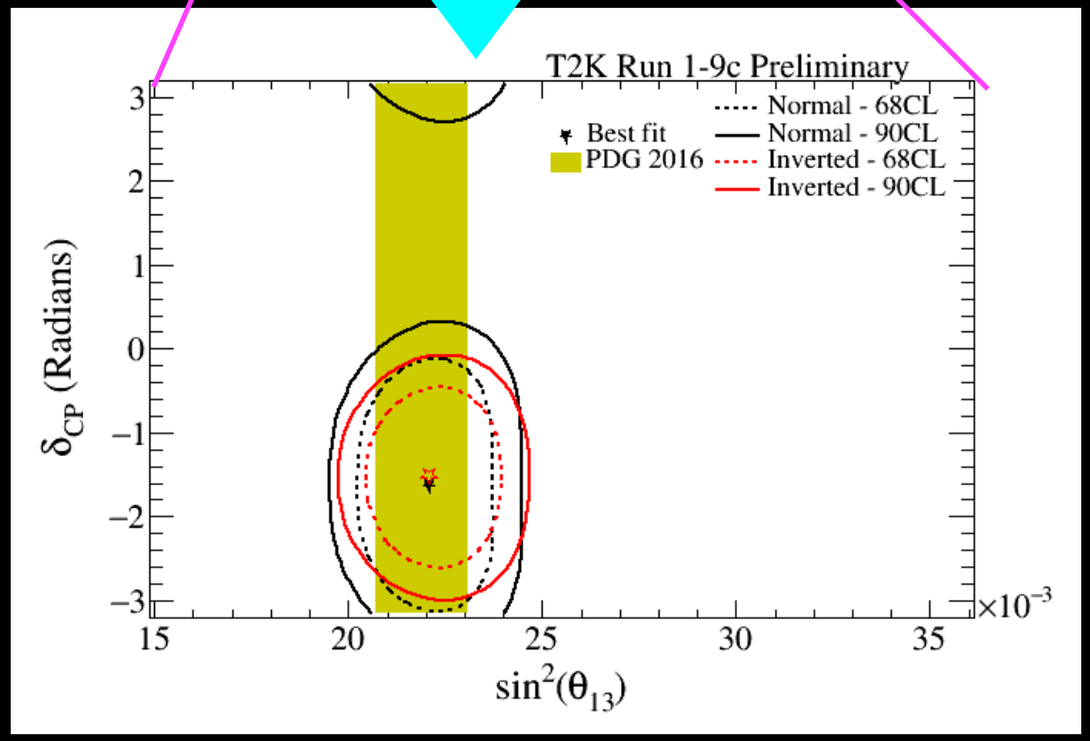
Without the reactor experiment constraint on $\sin^2 2\theta_{13}$



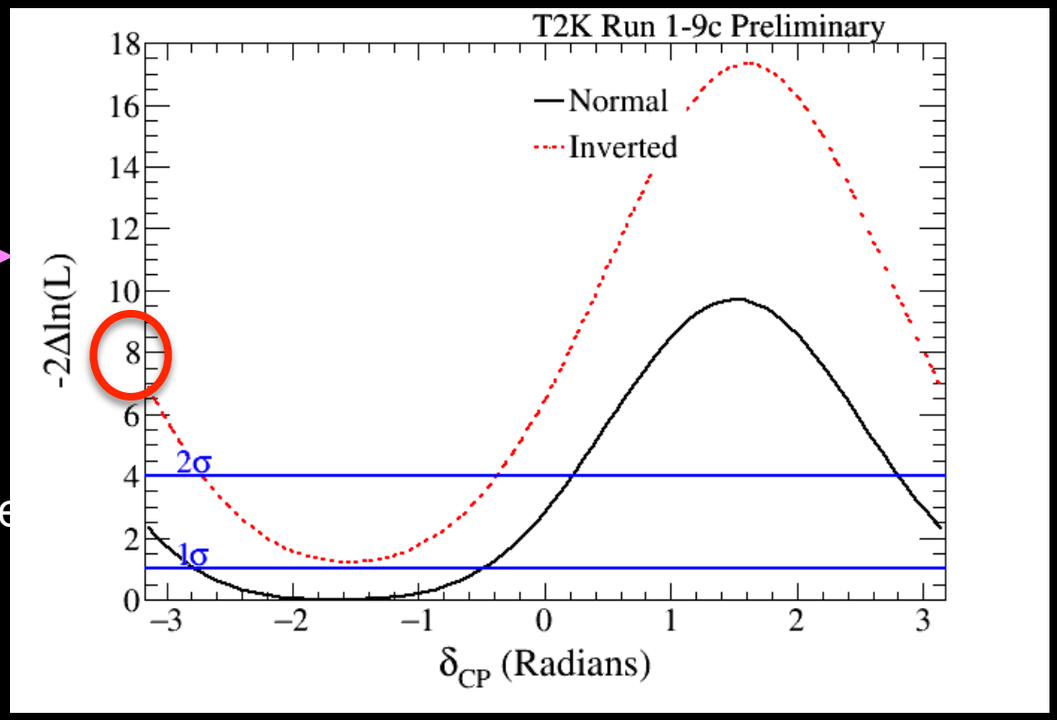
Integrate out $\sin^2\theta_{13}$ dependence



Reactor constraint on $\sin^2(2\theta)_{13}$ (PDG2016)

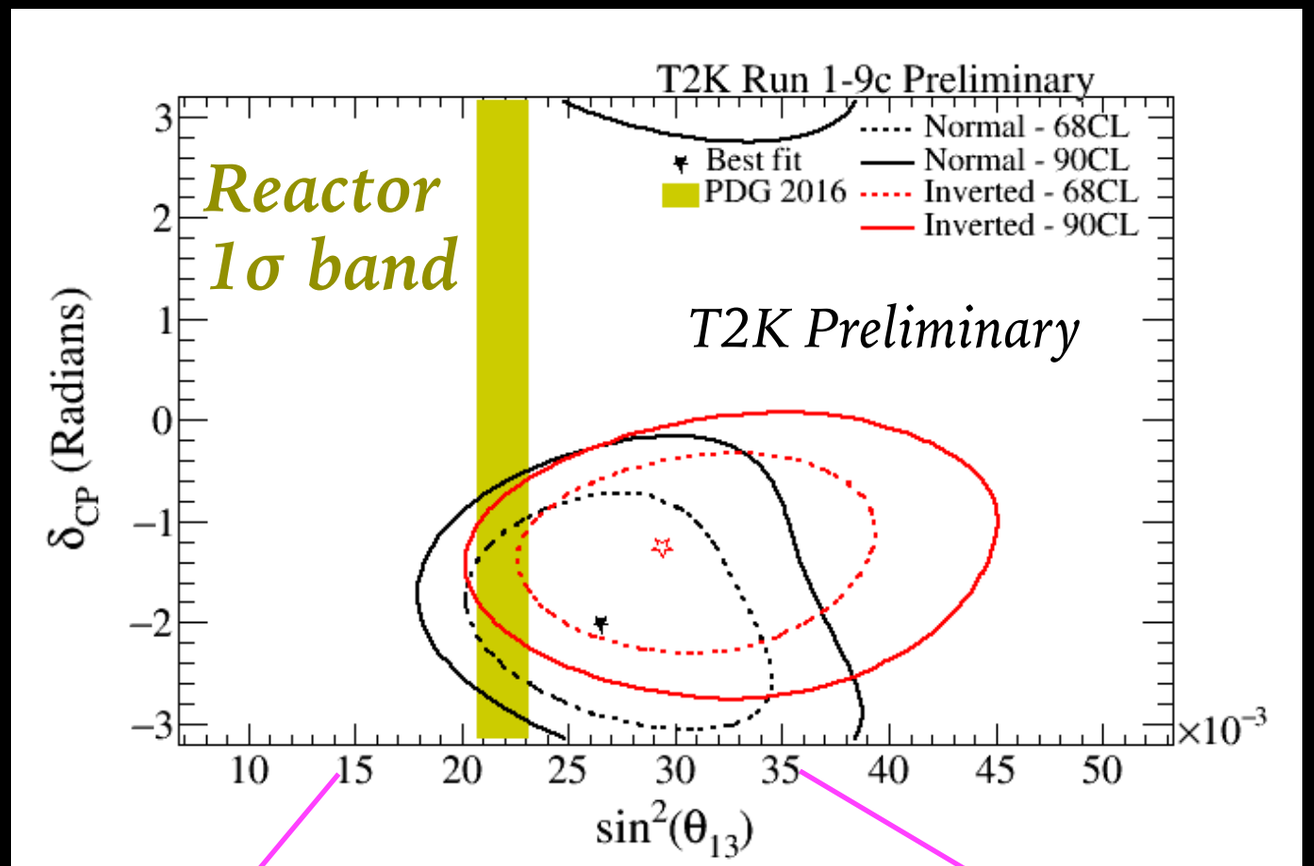


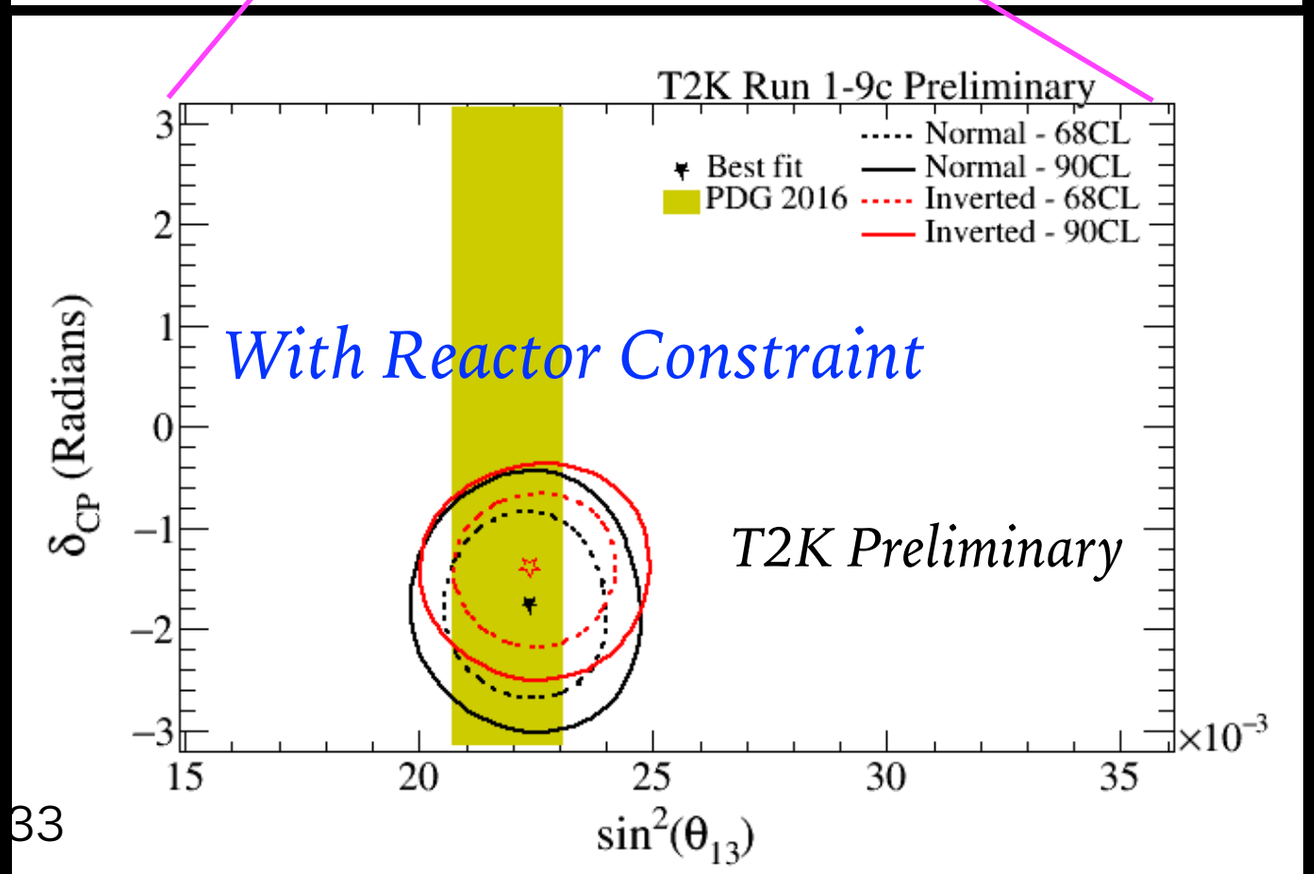
Integrate out $\sin^2\theta_{13}$ depende



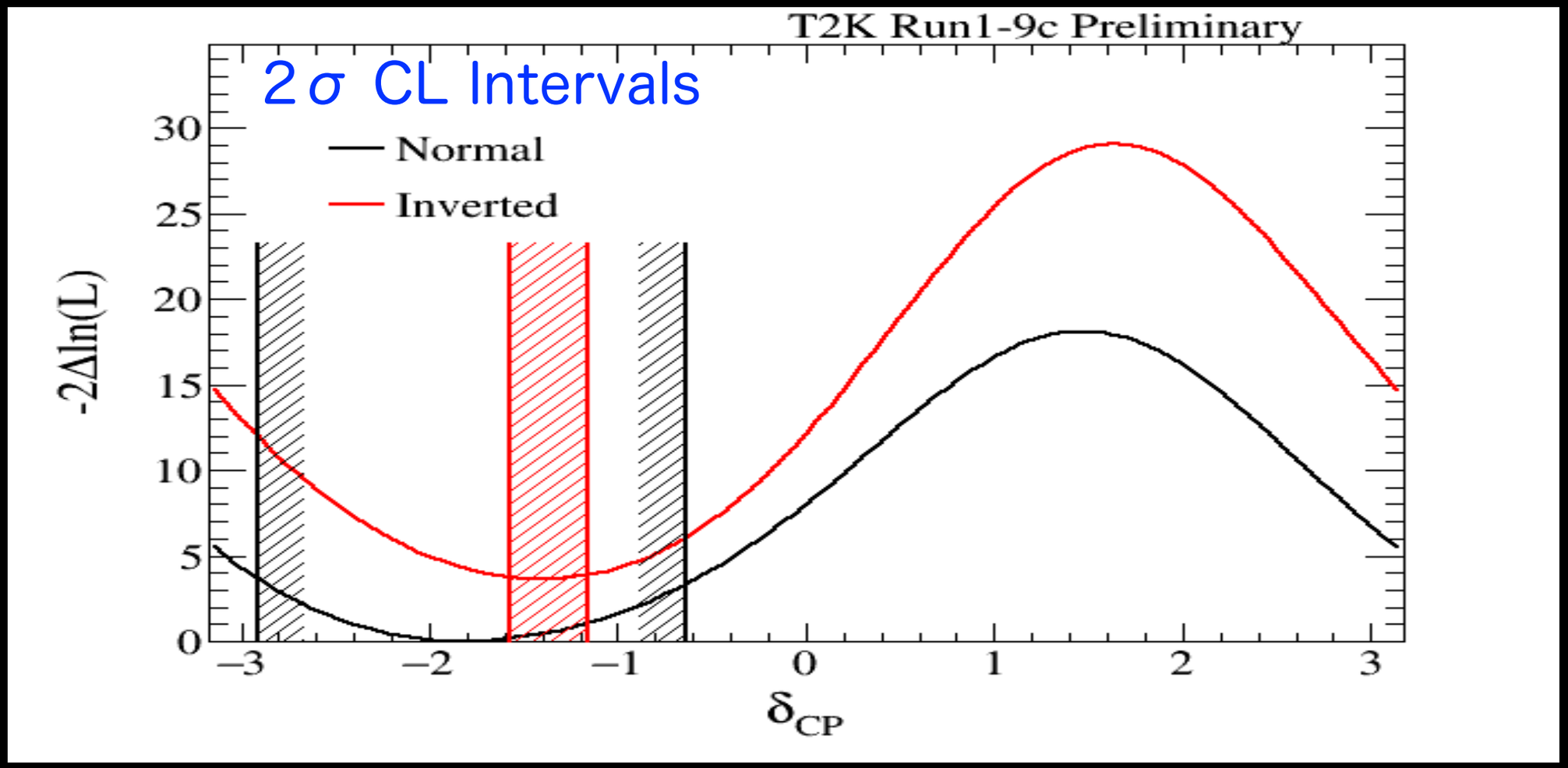
(Data) θ_{13} and δ_{CP}

- Fit without the reactor constraint: closed contours in δ_{cp} at 90% CL
- The T2K value for $\sin^2\theta_{13}$ is consistent with the PDG 2016
- Adding the reactor constraint improves the constraint on δ_{cp} average:





Measurement of δ_{cp} with reactor θ_{13}



Best fit point: -1.82 radians in Normal Hierarchy

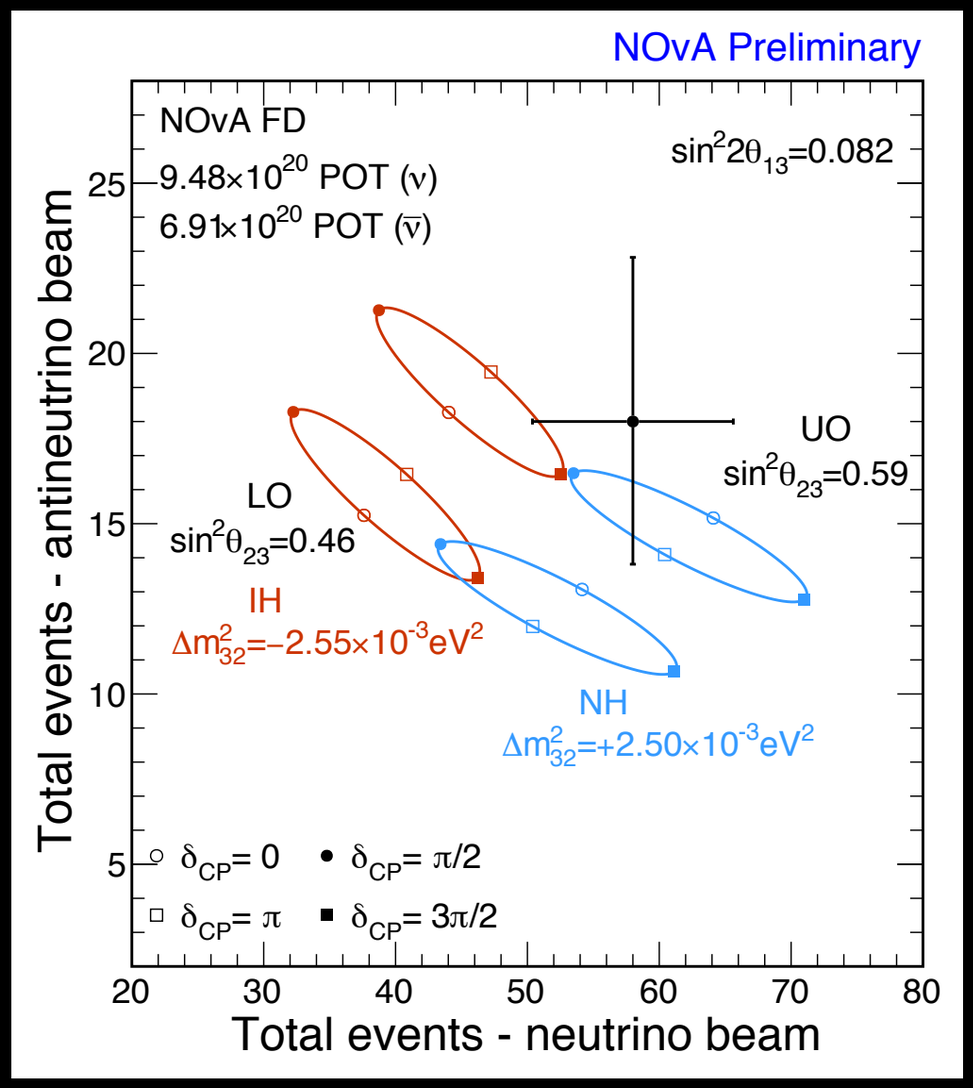
The 1σ CL confidence interval: Normal hierarchy: [-2.44, -1.23] radians

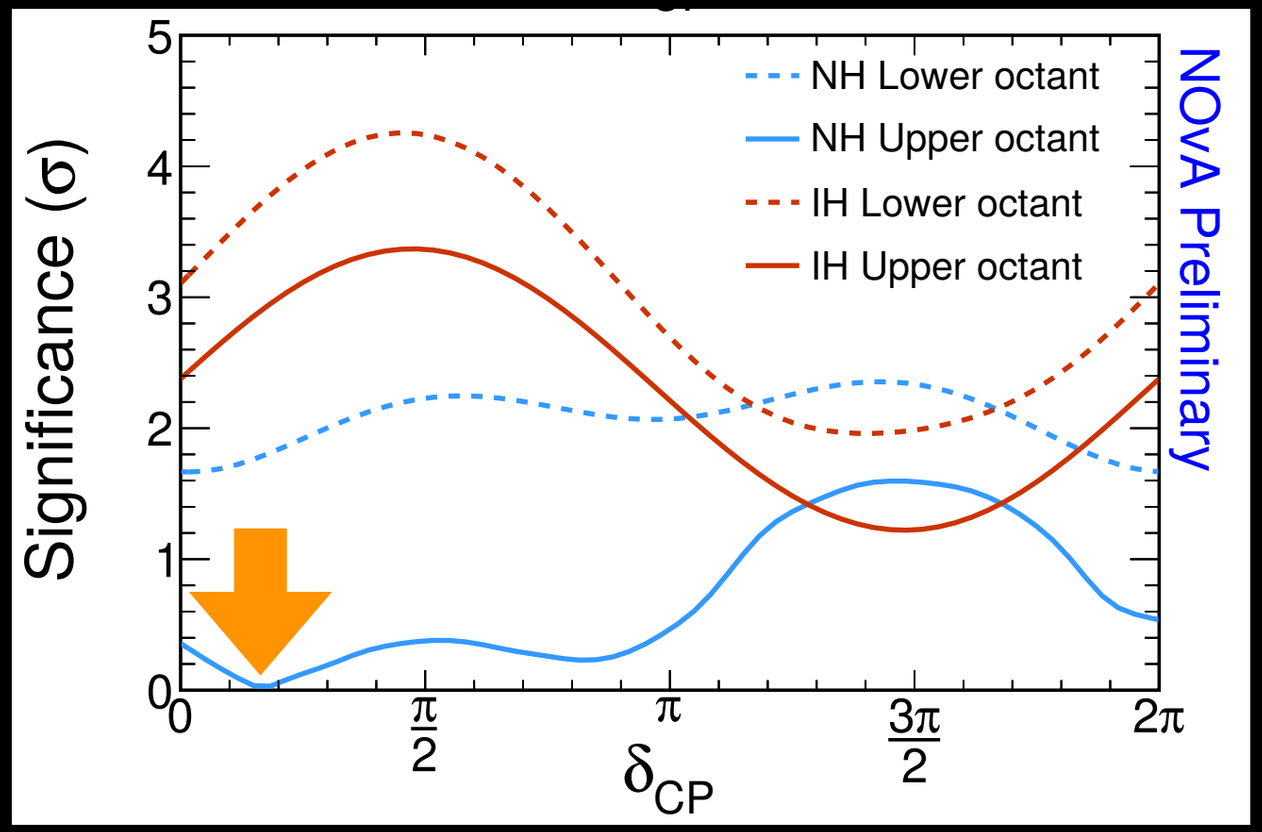
The 2σ CL confidence interval: Normal hierarchy: [-2.91, -0.85] radians
Inverted hierarchy: [-1.57, -1.16] radians

- CP conserving values $(0, \pi)$ fall outside of the 2σ CL intervals

NOvA at Fermilab

- Precise measurement of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$





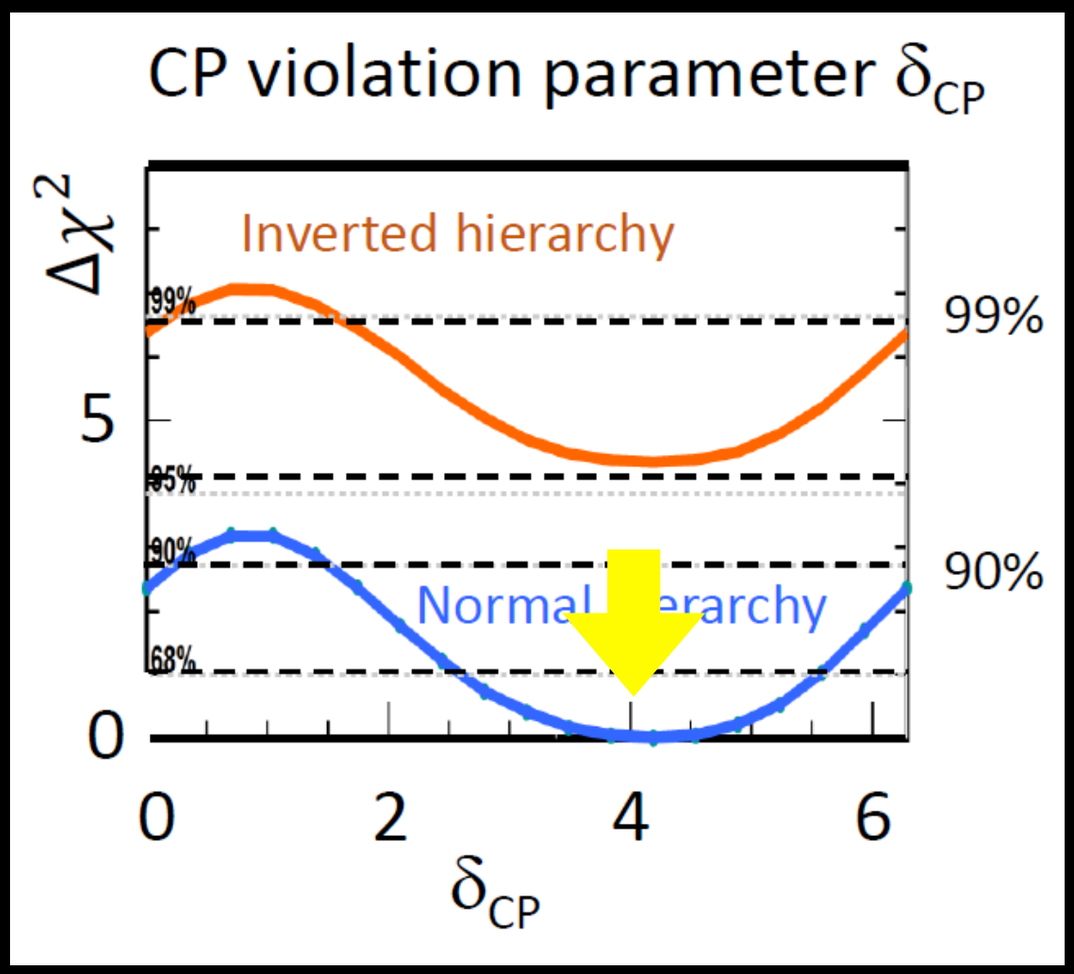
talk at NEUTRINO 2018

- Neutrino: 58 events observed with 15 background expected
- Anti-neutrino: 18 events observed with 5.3 background expected (>4 σ observation)

Super-K with atmospheric ν.

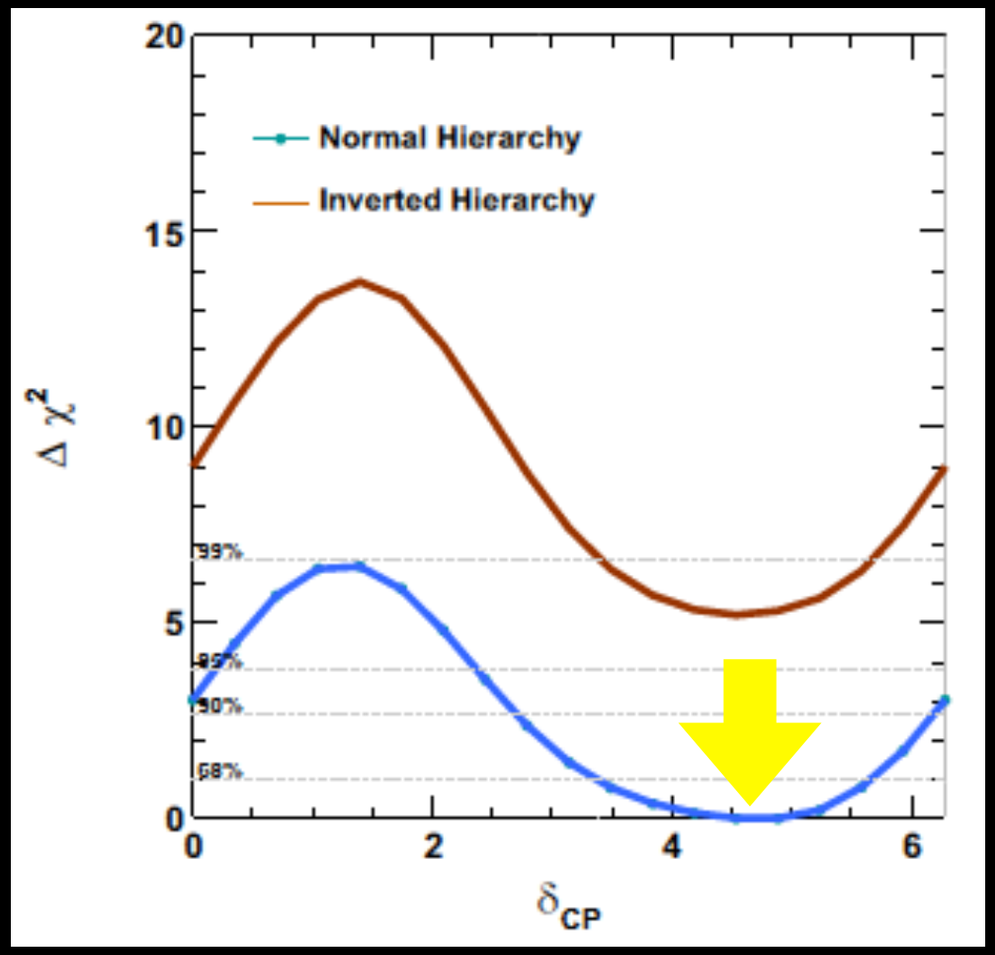
- In addition to CP violation, it is also sensitive to mass hierarchy.

SK only



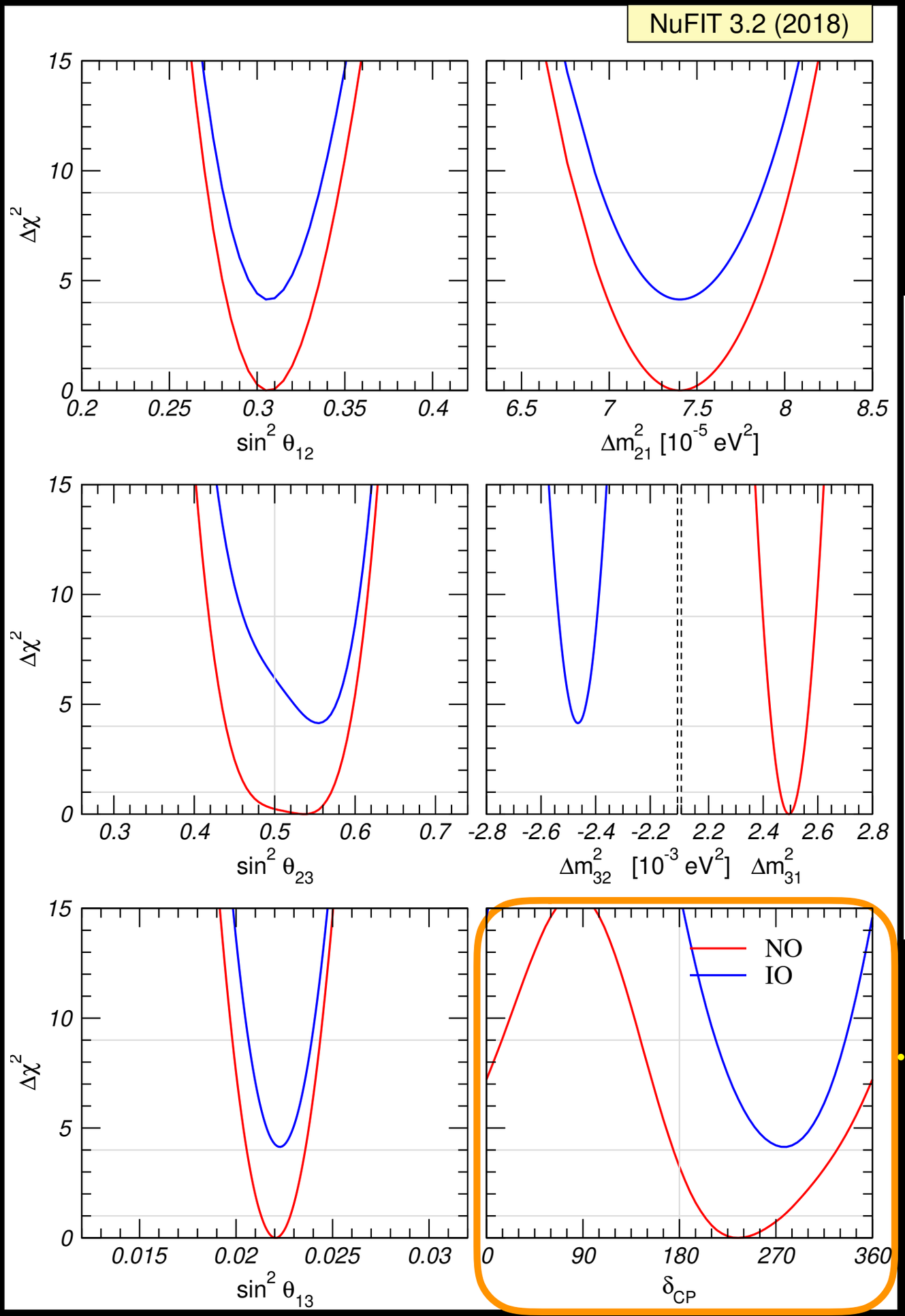
$\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$

SK+T2K



$\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$

talk at NEUTRINO 2018



Global FIT

I. M. Soler, Talk at NOW 2018

Comparison between different global fits

	Nufit[1]	Capozzi et al.,[2]	Salas et al.,[3]
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.304^{+0.014}_{-0.013}$	$0.320^{+0.20}_{-0.16}$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.551^{+0.019}_{-0.070}$	$0.547^{+0.20}_{-0.30}$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.0214^{+0.0009}_{-0.0007}$	$0.0216^{+0.00083}_{-0.00069}$
δ_{CP}	234^{+43}_{-31}	234^{+41}_{-32}	218^{+38}_{-27}
$\frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2}$	$7.4^{+0.21}_{-0.20}$	$7.34^{+0.17}_{-0.14}$	$7.55^{+0.20}_{-0.16}$
$\frac{\Delta m^2_{31}}{10^{-3}\mathrm{eV}^2}$	$2.494^{+0.033}_{-0.031}$	$2.455^{+0.035}_{-0.032}$	$2.50^{+0.03}_{-0.03}$

[1] NuFIT 3.2 (2018), www.nu-fit.org

[2] F. Capozzi, E. Lisi, A. Marrone, and A. Palazzo, Prog.Part.Nucl.Phys. 102 (2018) 48-72

[3] P.F. de Salas, D.V. Forero, C.A. Ternes, M. Tortola, J.W.F. Valle, Phys.Lett. B782 (2018) 633-640

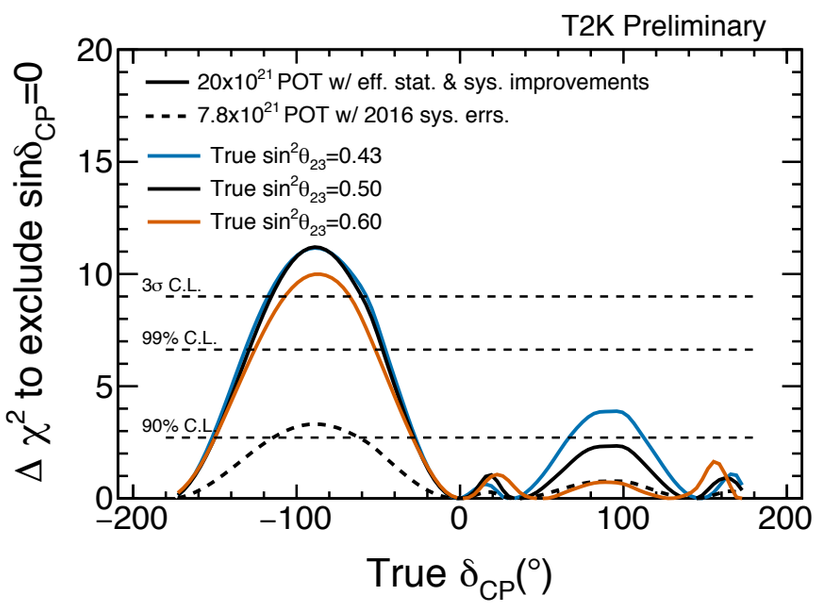
- CP violation (w/ δCP~-π/2) is preferable.

Prospect

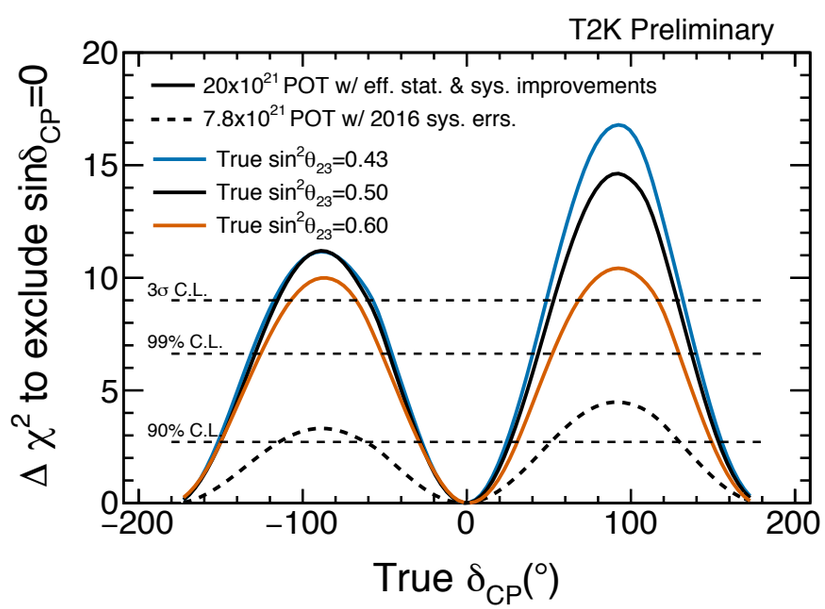
T2K-II

- 3σ sensitivity to CP violation for favorable parameters based on
  - 20×10^{21} Protons on Target with the upgrade of J-PARC to 1.3MW (~10 year long run) before year 2026.
  - 50 % more events with improvements of the beam line and event reconstructions.
  - ~2/3 smaller systematic uncertainties.

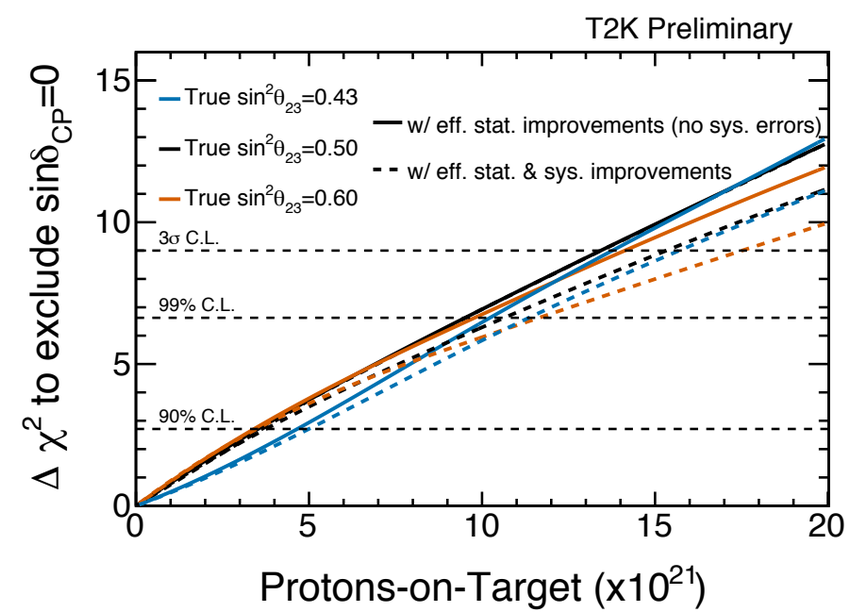
T2K-II: PHYSICS POTENTIAL



hierarchy unknown



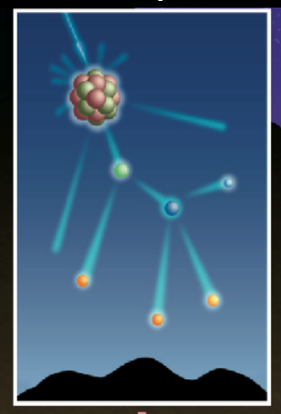
external hierarchy input



Hyper-Kamiokande

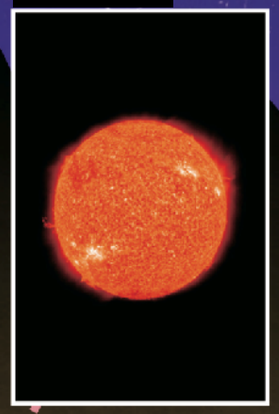
Accelerator Neutrino beam from J-PARC

Atmosphere

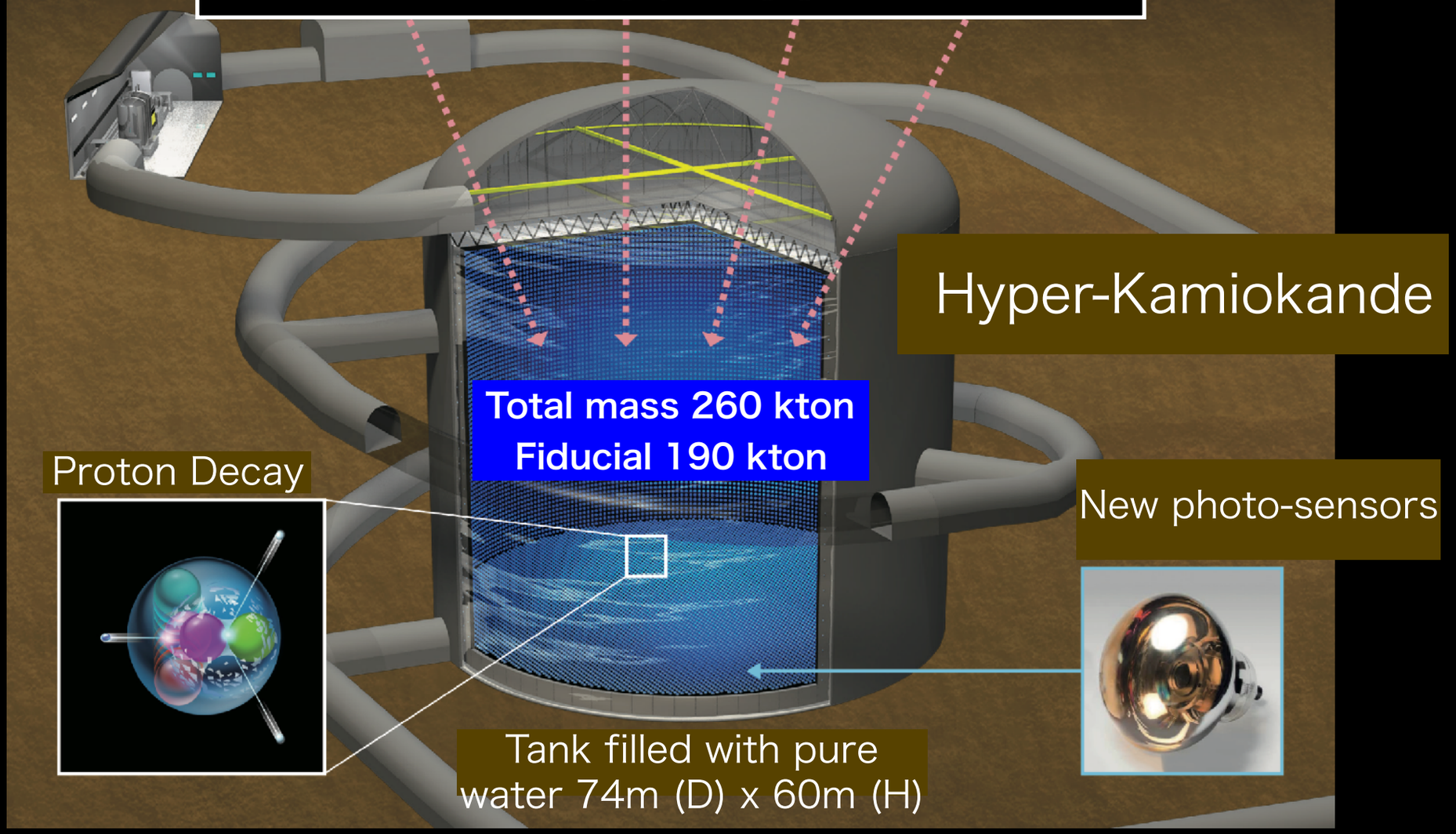


Supernova

Sun

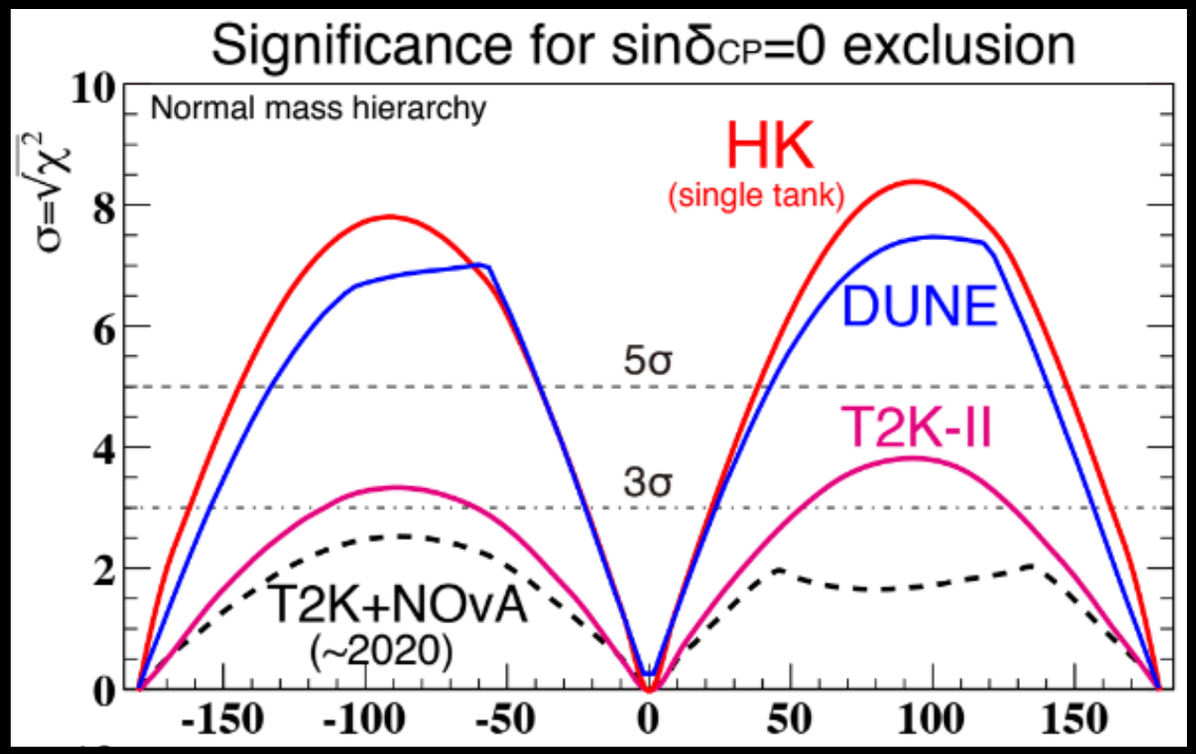


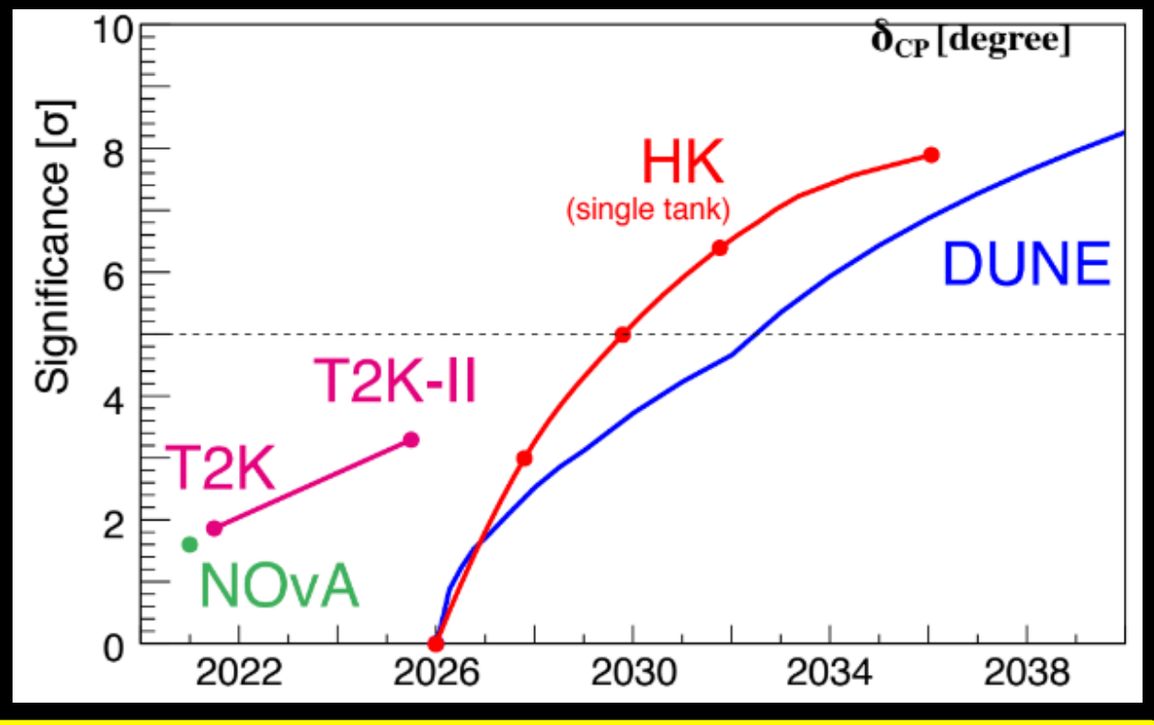
Neutrinos



CP violation in Hyper-K

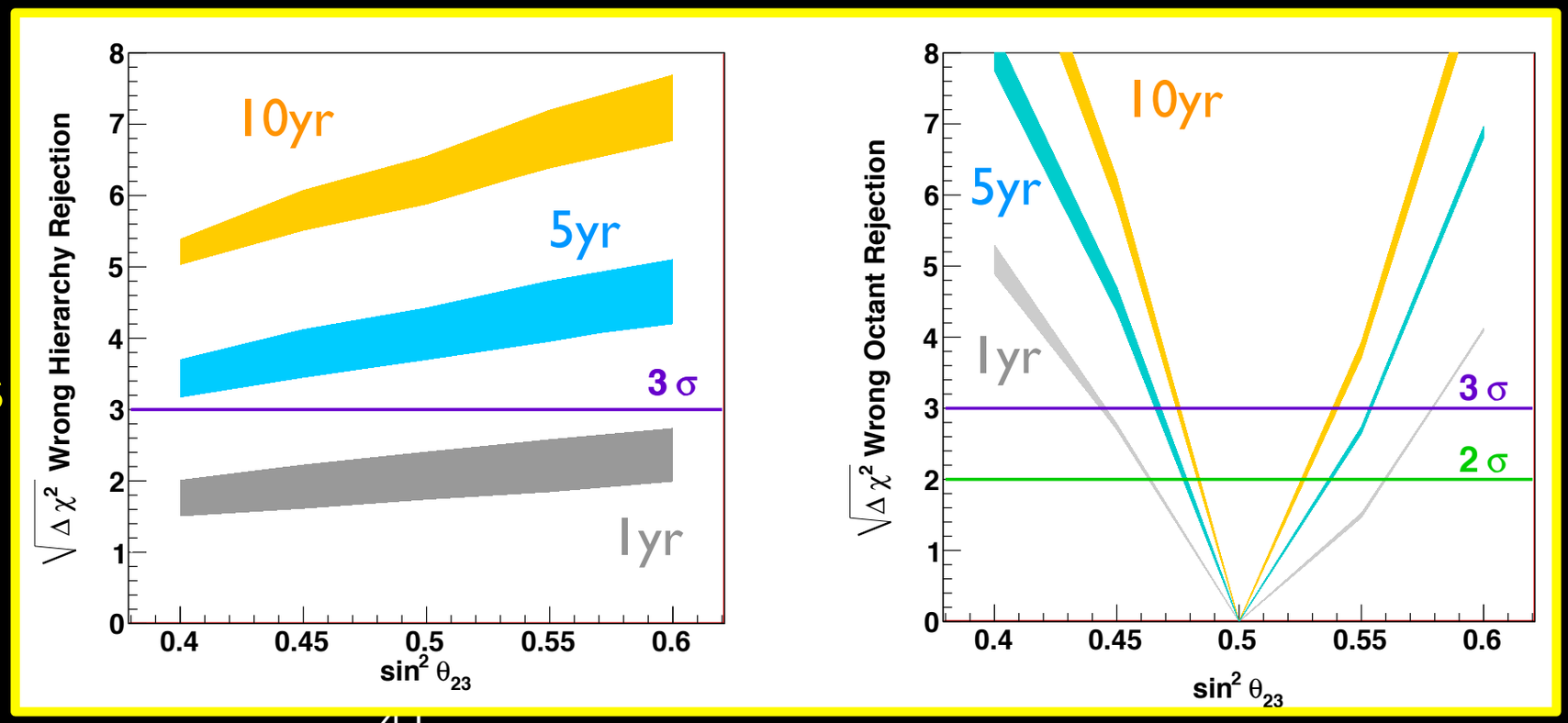
- beam ν





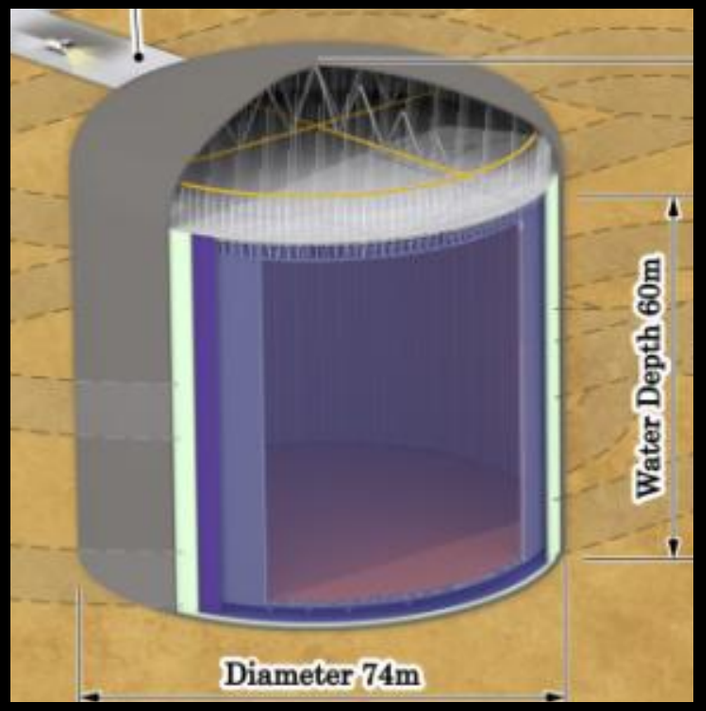
- beam ν + Atm. ν

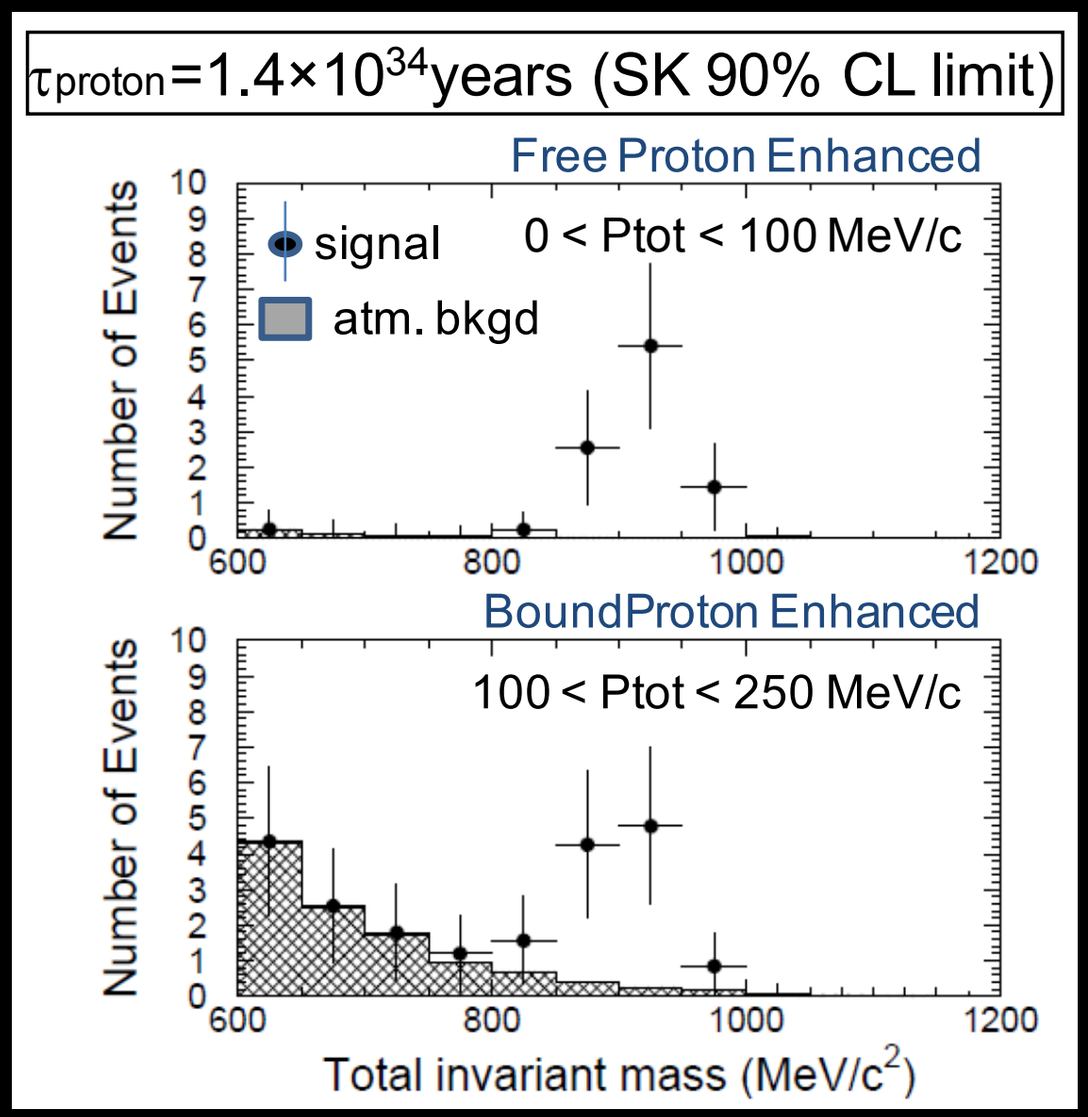
Better sensitivity on mass ordering and θ_{23} octant separation by combining atm. ν + beam ν

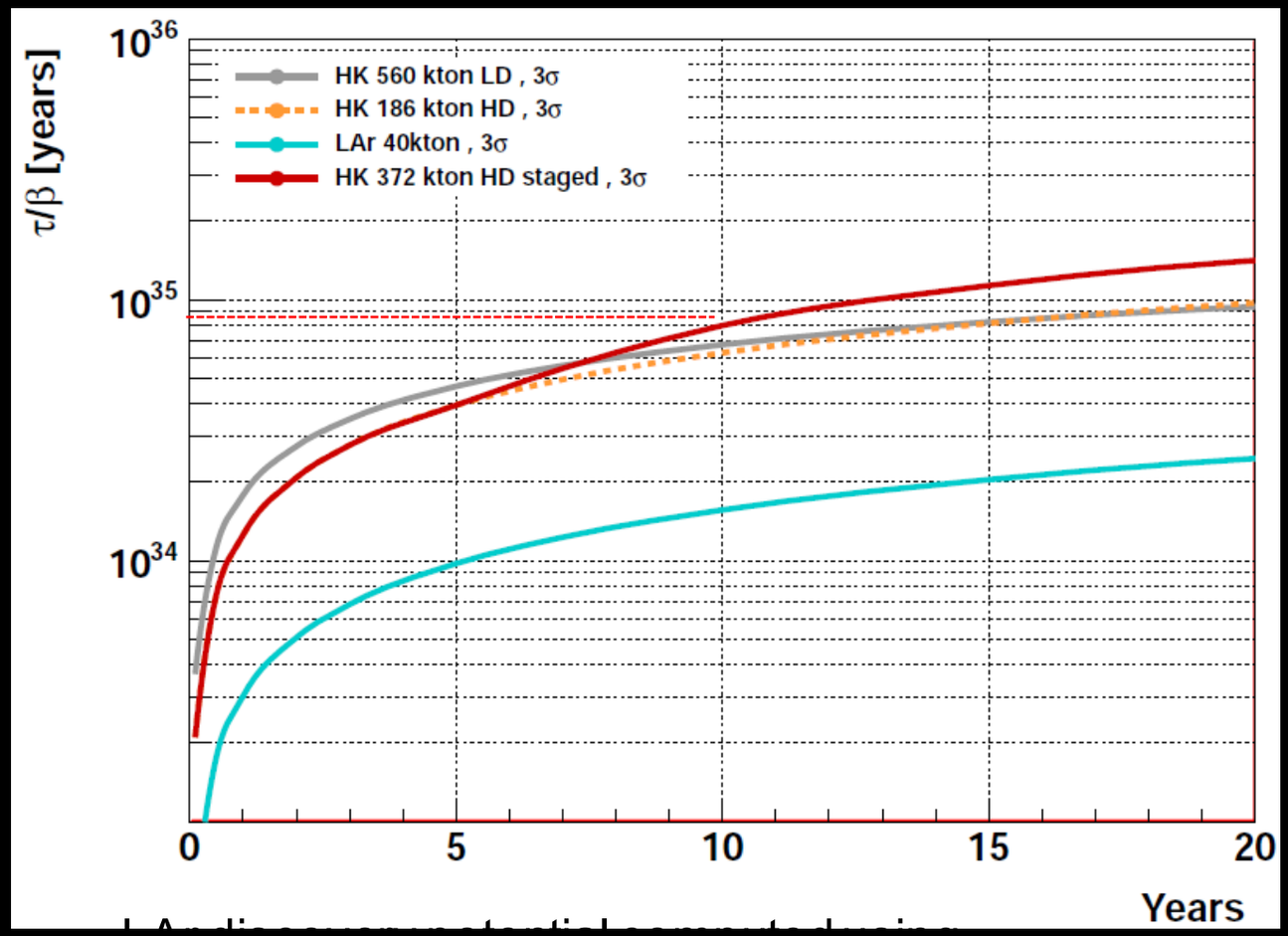


Proton Decay

- **Keep looking for GUT with neutrinos.**
- Example: $p \rightarrow e^{+}\pi^{0}$ in Hyper-K

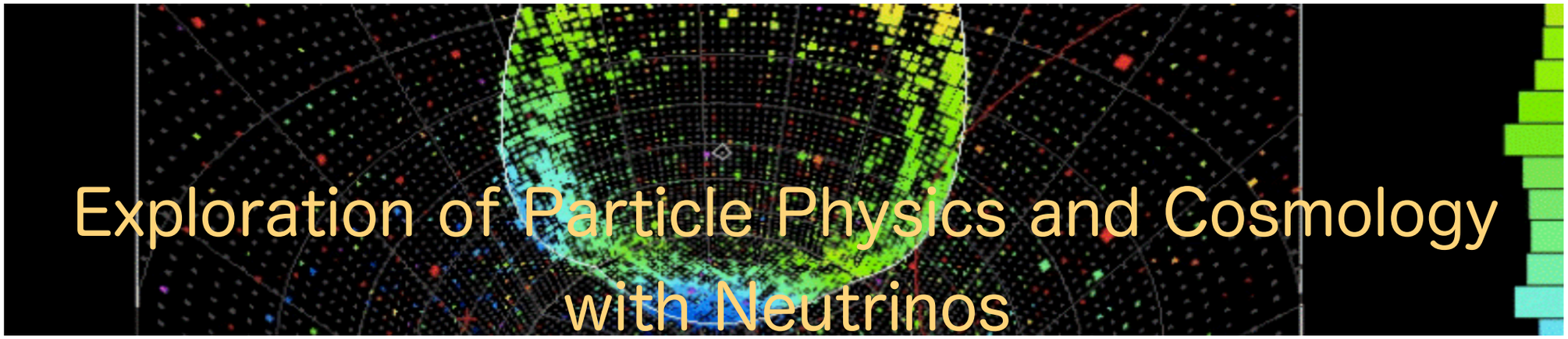




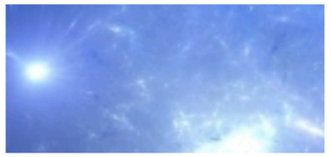


文部科学省 科学研究費補助金 新学術研究（研究領域提案型）

ニュートリノで拓く素粒子と宇宙



ごあいさつ



▸ Click

今月の４コマ

▸ Click

ニュートリノってなに？

▸ Click

はじめに

- 領域代表挨拶
- 研究概要

研究項目

- 総括班
- 実験・観測
- 技術開発
- 理論研究

研究組織

- 総括班
- 計画研究

研究状況報告

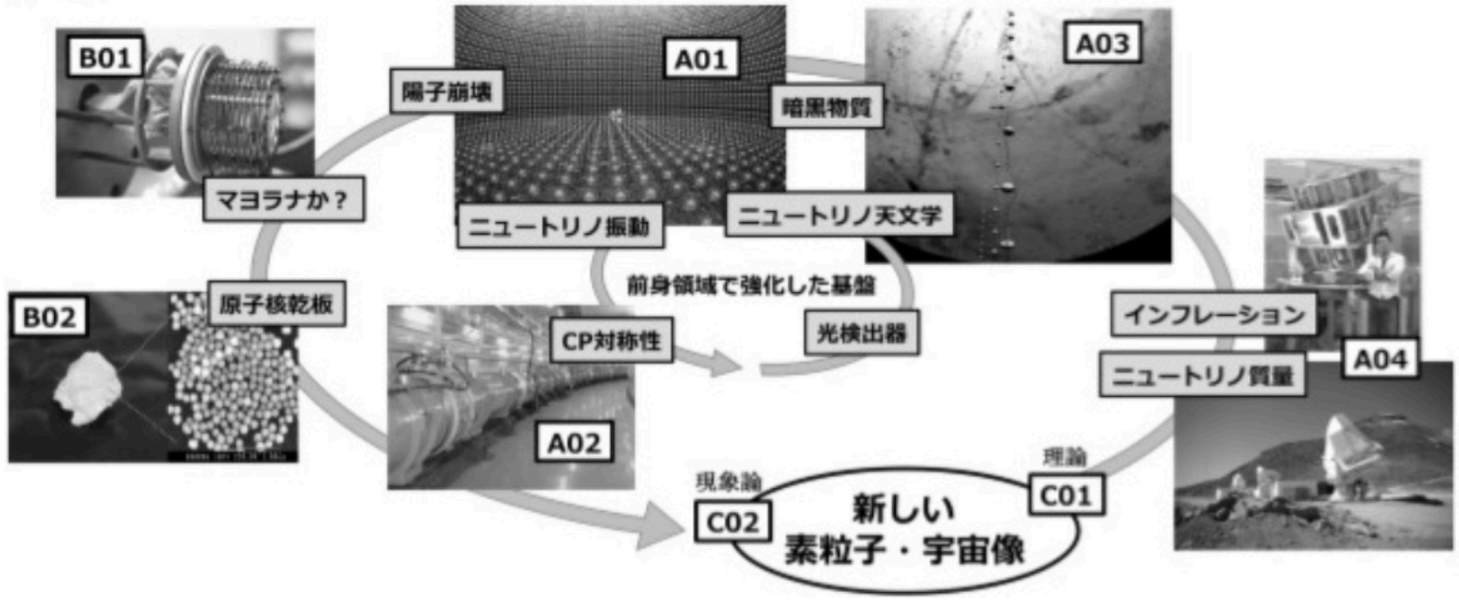
- メディア掲載情報
- 報告書

What's new

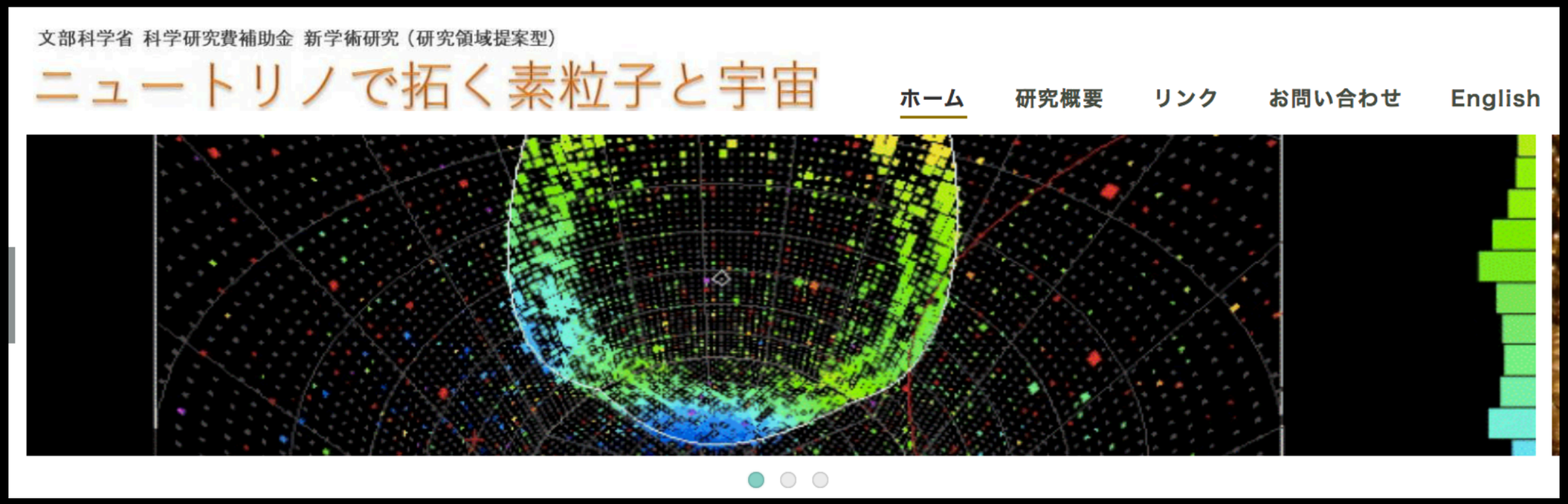
2018-09-18　ニュース　公募研究の募集を開始しました。[研究概要][英語版]

2018-09-14　研究会　新学術領域「ニュートリノで拓く素粒子と宇宙」研究会を開催します。(2018年10月6日(土)、東京大学柏キャンパス)[詳細]

本領域の目的



Exploration of Particle Physics and Cosmology with Neutrinos



Experimental group of T2K

A02: 加速器ニュートリノビームで探る素粒子の対称性

	氏名	所属	専門	担当
研究代表者	中家 剛	京都大学 教授	素粒子実験	総括、ニュートリノ振動測定
研究分担者	小関 忠	高エネルギー加速器研究機構 教授	加速器	ビームの大強度化
	中平 武	高エネルギー加速器研究機構 准教授	素粒子実験	ビームモニタリング
	清矢 良浩	大阪市立大学 教授	素粒子実験	水標的測定器の開発
	福田 努	名古屋大学 特任助教	素粒子実験	原子核乾板現象、画像解析
連携研究者	Bronner Christophe	東京大学 助教	素粒子実験	ニュートリノ反応シミュレーション
	Hartz Mark	東京大学 助教	素粒子実験	ニュートリノビームフラックス計算
	Friend Megan	高エネルギー加速器研究機構 助教	素粒子実験	ニュートリノビーム照射

他、研究者、大学院生、あわせて総計約15名

Review Committee

総括班評価者

	氏名	所属	専門
評価者	荻尾 彰一	大阪市立大学 教授	宇宙線
	高田 昌広	東京大学 国際高等研究所カブリ数物連携宇宙研究機構 教授	理論物理学(宇宙論)
	大野木 哲也	大阪大学 教授	素粒子論
	飯嶋 徹	名古屋大学 教授	素粒子実験・原子核実験
	幅 淳二	高エネルギー加速器研究機構 理事	素粒子実験

Summary

- A hint of CP violation in neutrinos.
  - 95% CL (2 σ) indication from T2K today
  - $\delta_{CP} \sim -\pi/2$ (CP violation) is preferable in the global fit
  - T2K-II is proposed to reach 3σ discovery sensitivity with 1.3 MW beam.
  - Hyper-K will be realized and will study neutrino CP violation with >5σ discovery.

Stay Tuned!

Backup

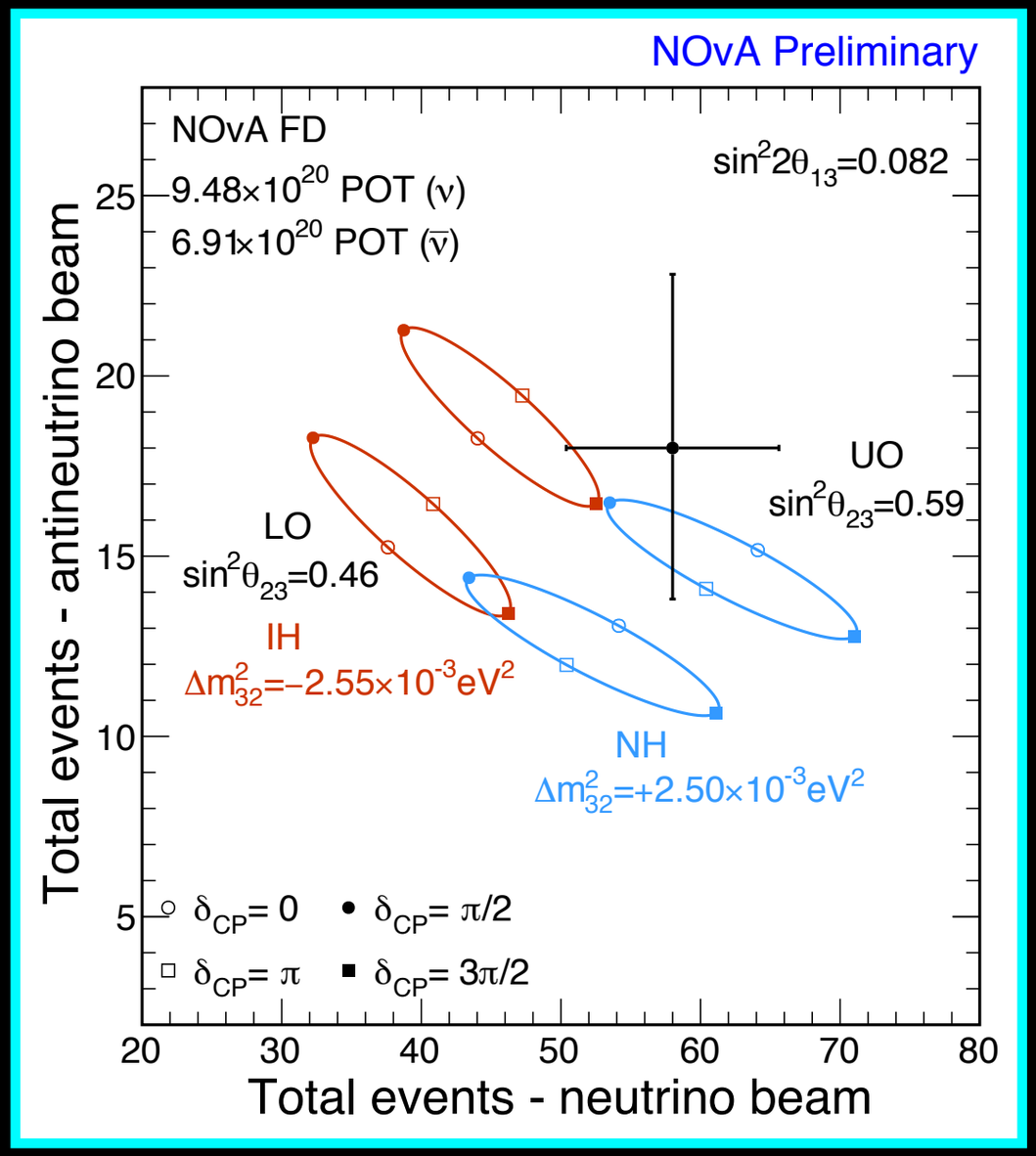
Systematic Errors

	% Errors on Predicted Event Rates (Osc. Para. A)					
	1R μ-like		1R e-like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
ND280 const. flux & xsec	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\nu_e)/\sigma(\nu_\mu)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Total Systematic Error	4.91	4.28	9.60	7.87	18.65	5.93

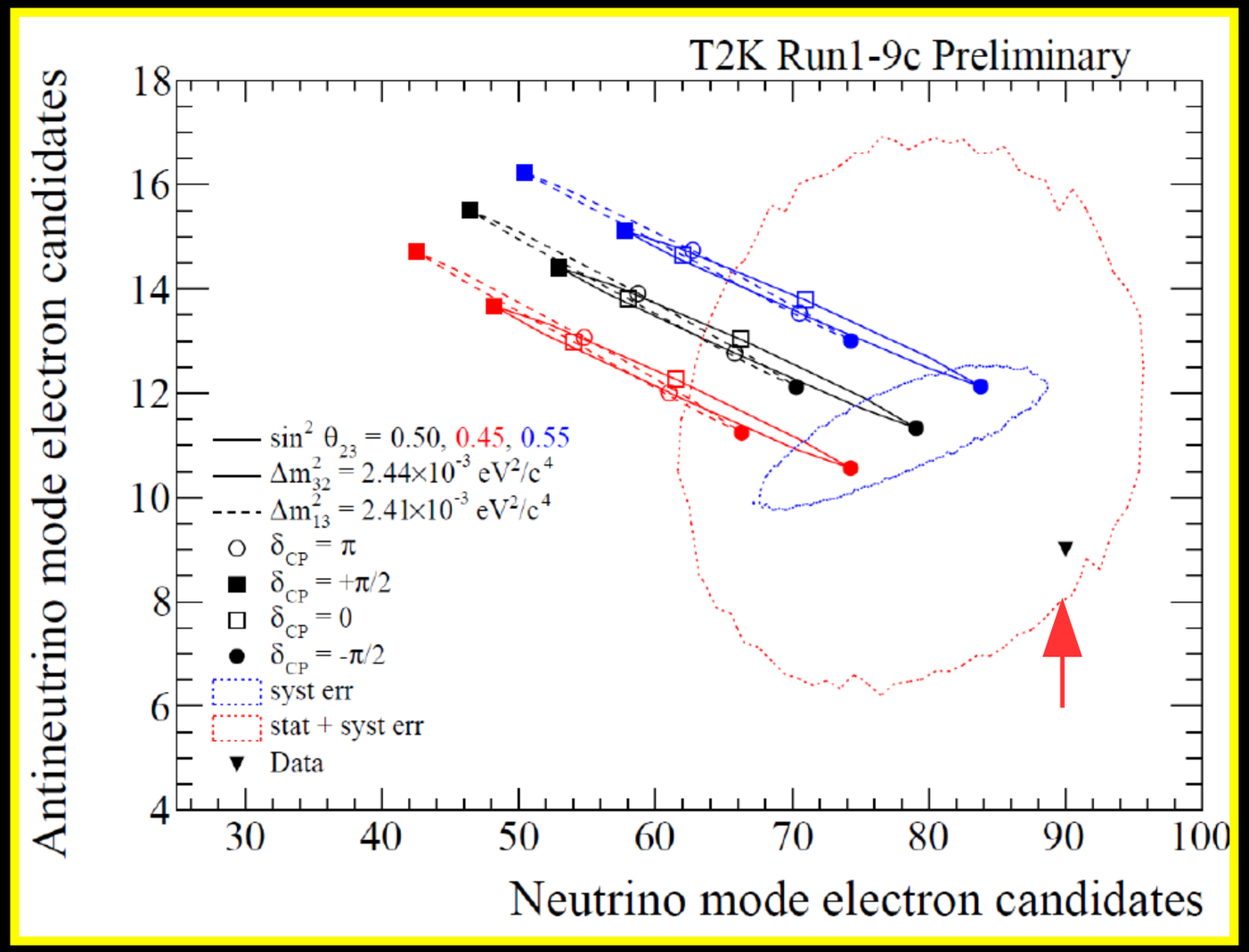
- Total error is in the 4-10% range. ~6% error on the relative rate for neutrino mode and antineutrino mode samples

NOvA and T2K

NOvA

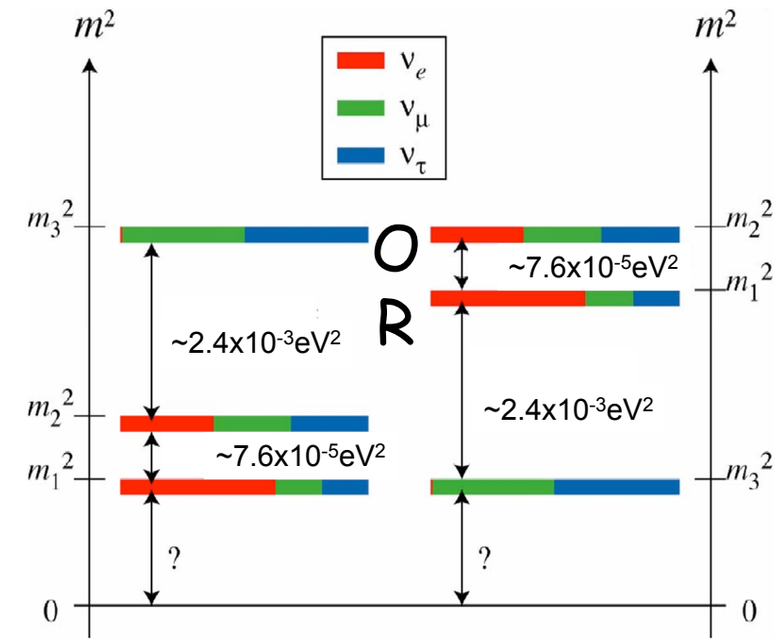


T2K



- It is a very interesting situation, and we need more data.

Neutrino Oscillation



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

Atm. ν、Acc. ν **Acc.ν、Rea. ν、** **(Atm.ν)** **Rea. ν、Solar ν**

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

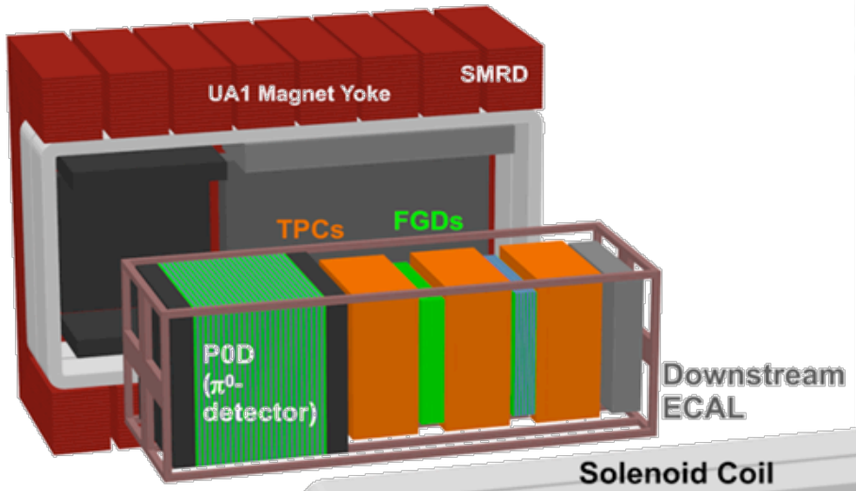
δ～unknown

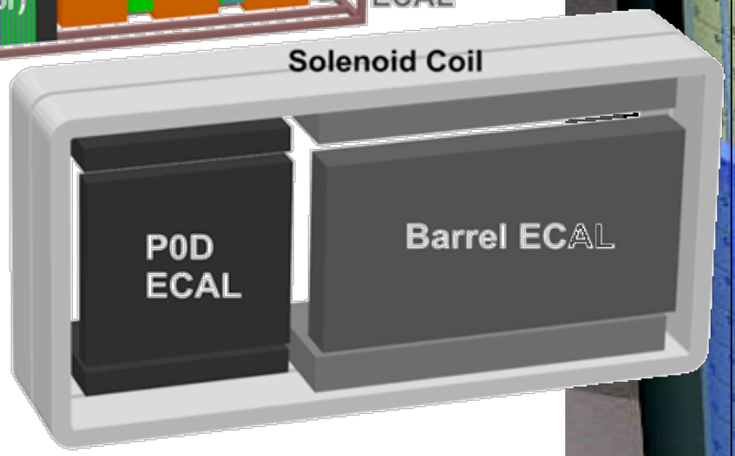
$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix}$$

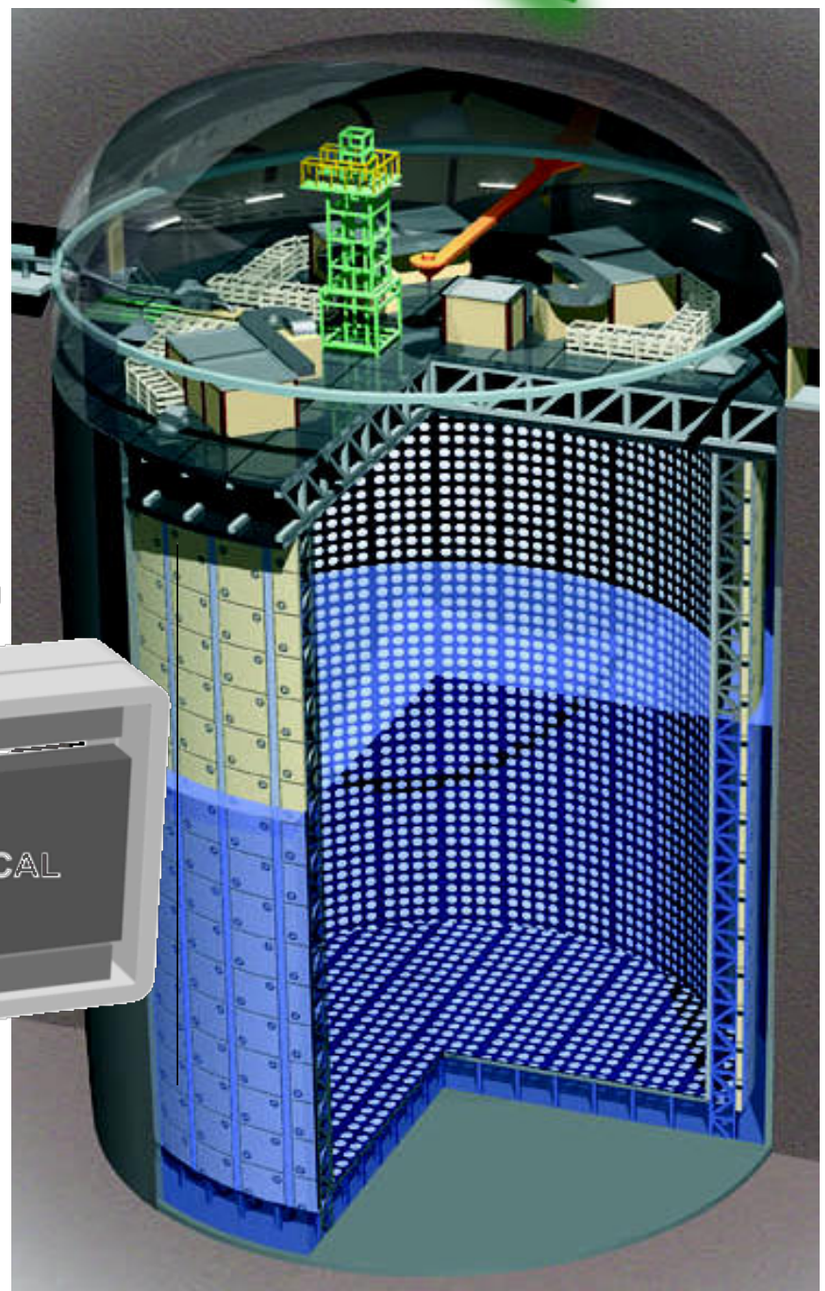
δ=60°

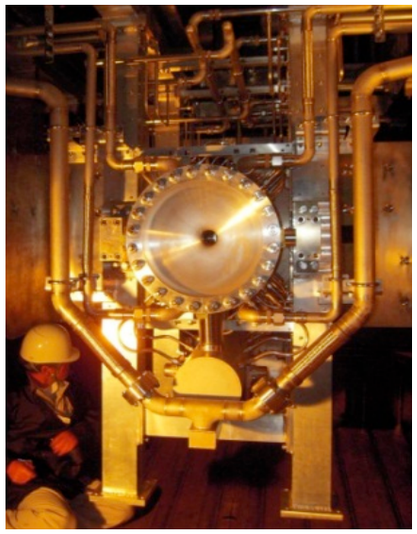
T2K

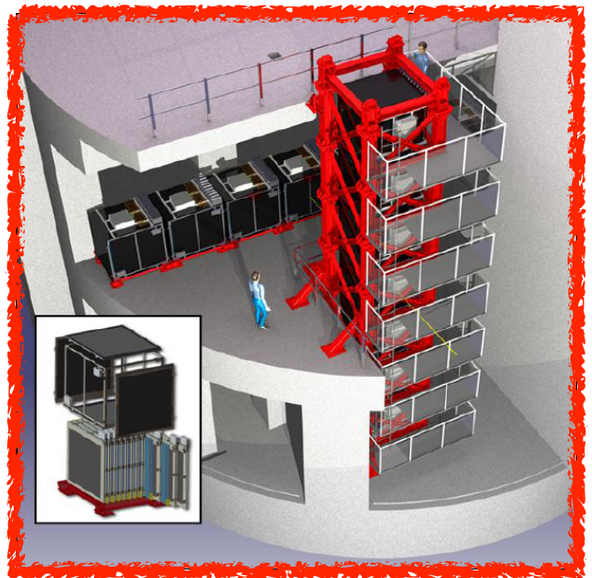

J-PARC


UA1 Magnet Yoke
SMRD
TPCs
FGDs
P0D
(π^0-
detector)
Downstream
ECAL


Solenoid Coil
P0D
ECAL
Barrel ECAL







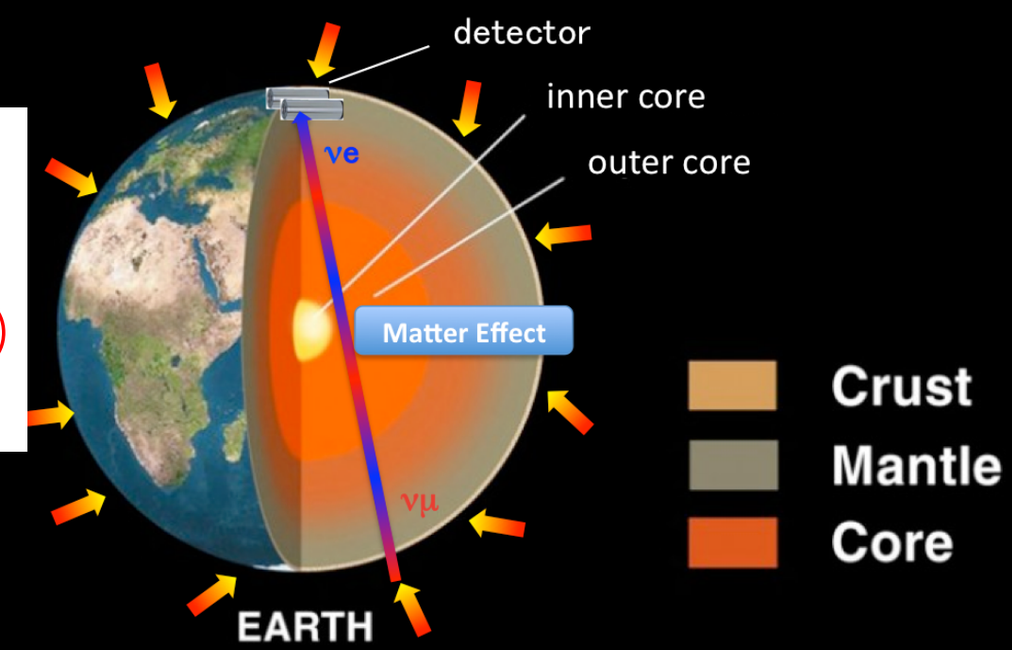
atmospheric neutrino oscillation

Nucl.Phys. B669, 255(2003) | Nucl. Phys. B680, 479(2004)

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$ Solar term

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$ Interference term (δCP)

$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1) \quad (3)$$ θ_{13} resonance term



r : μ/e flux ratio (~2 at low energy)

$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$

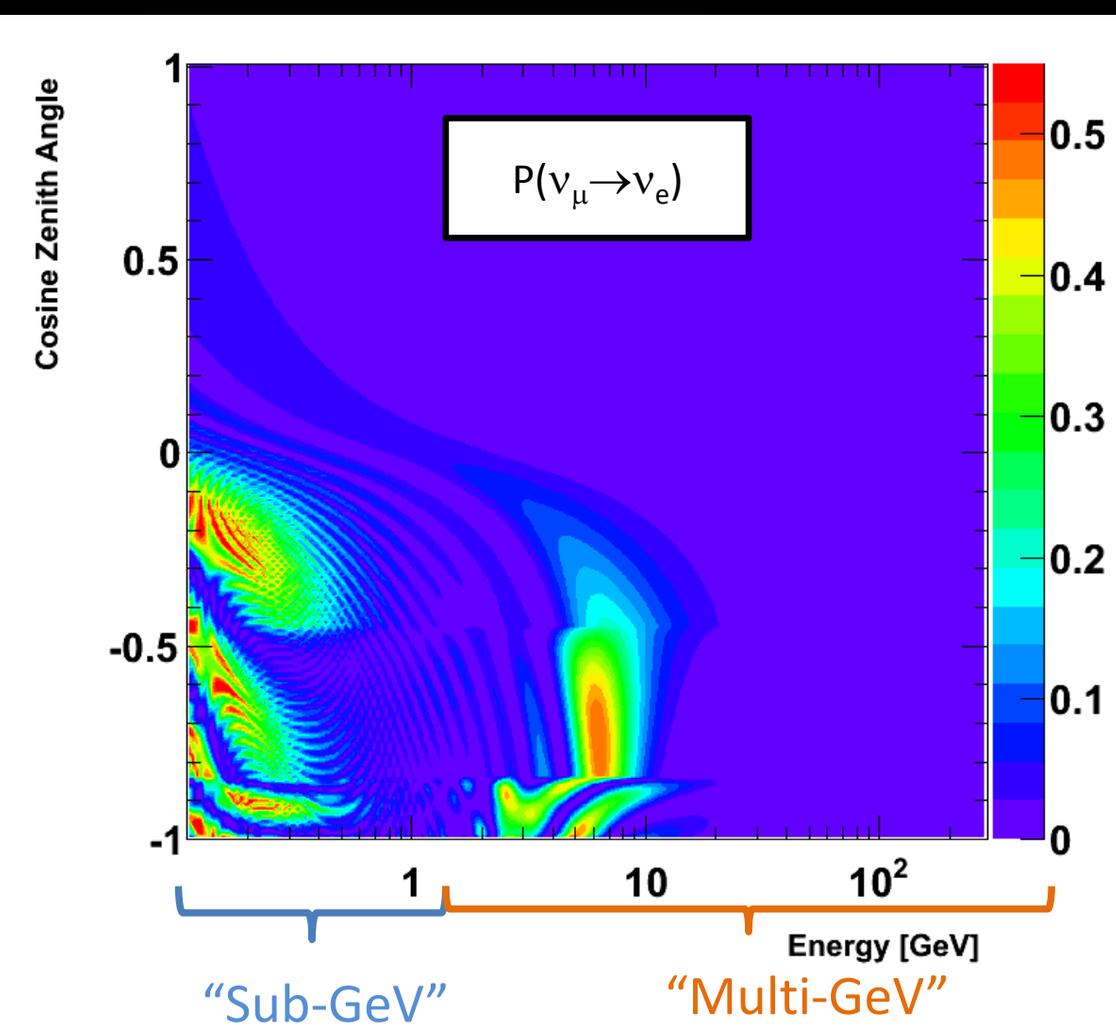
$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

A_{ee} : survival amplitude of the 2ν system

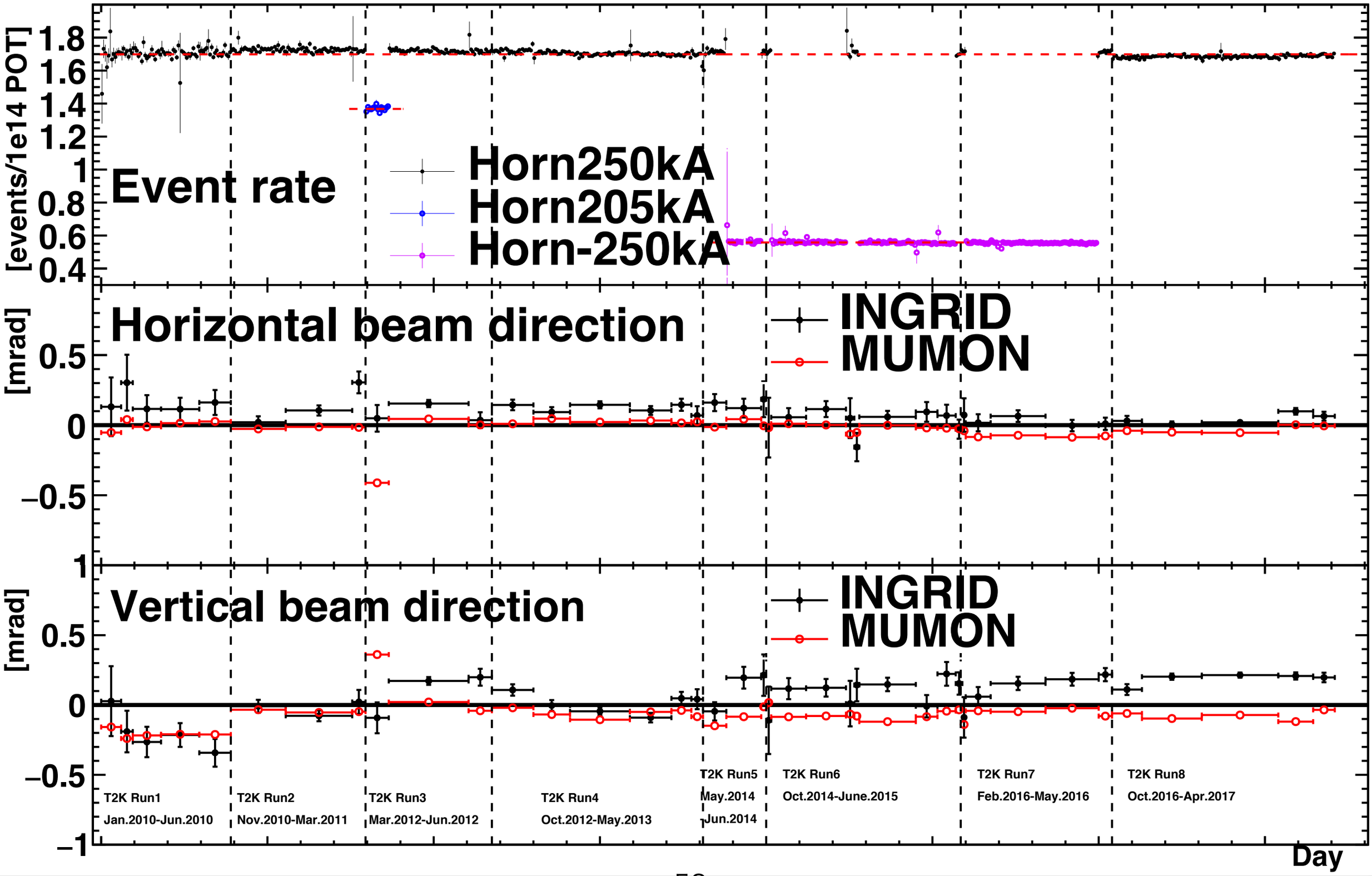
$A_{e\mu}$: transition amplitude of the 2ν system

ν_e appearance (and ν_μ disappearance) is expected with the matter effect in the Earth.

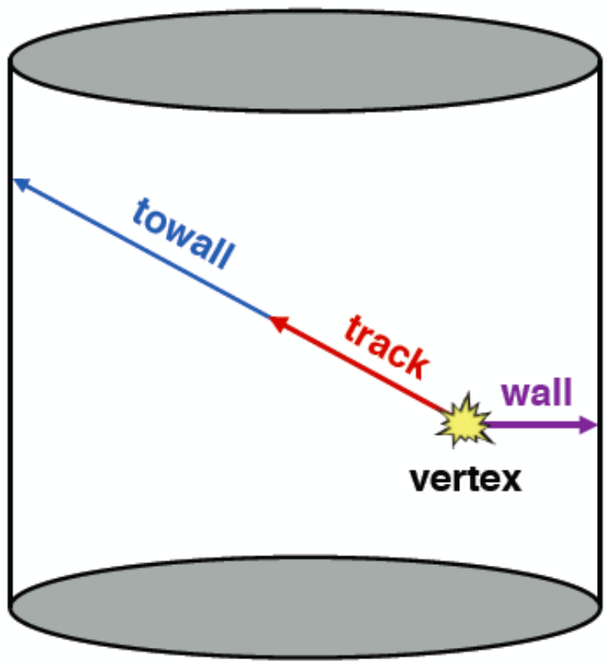
- effect for neutrinos in the case of normal mass ordering
- effect for anti-neutrinos in the inverted mass ordering

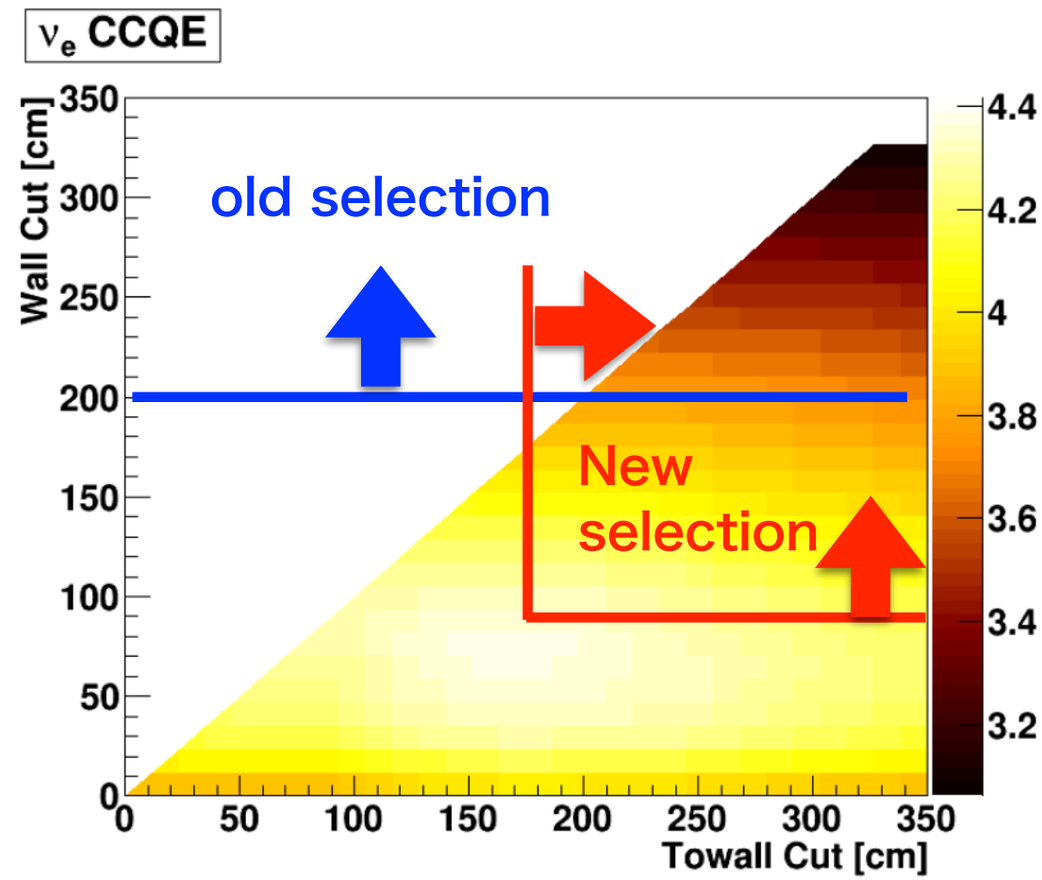


T2K Beam monitoring



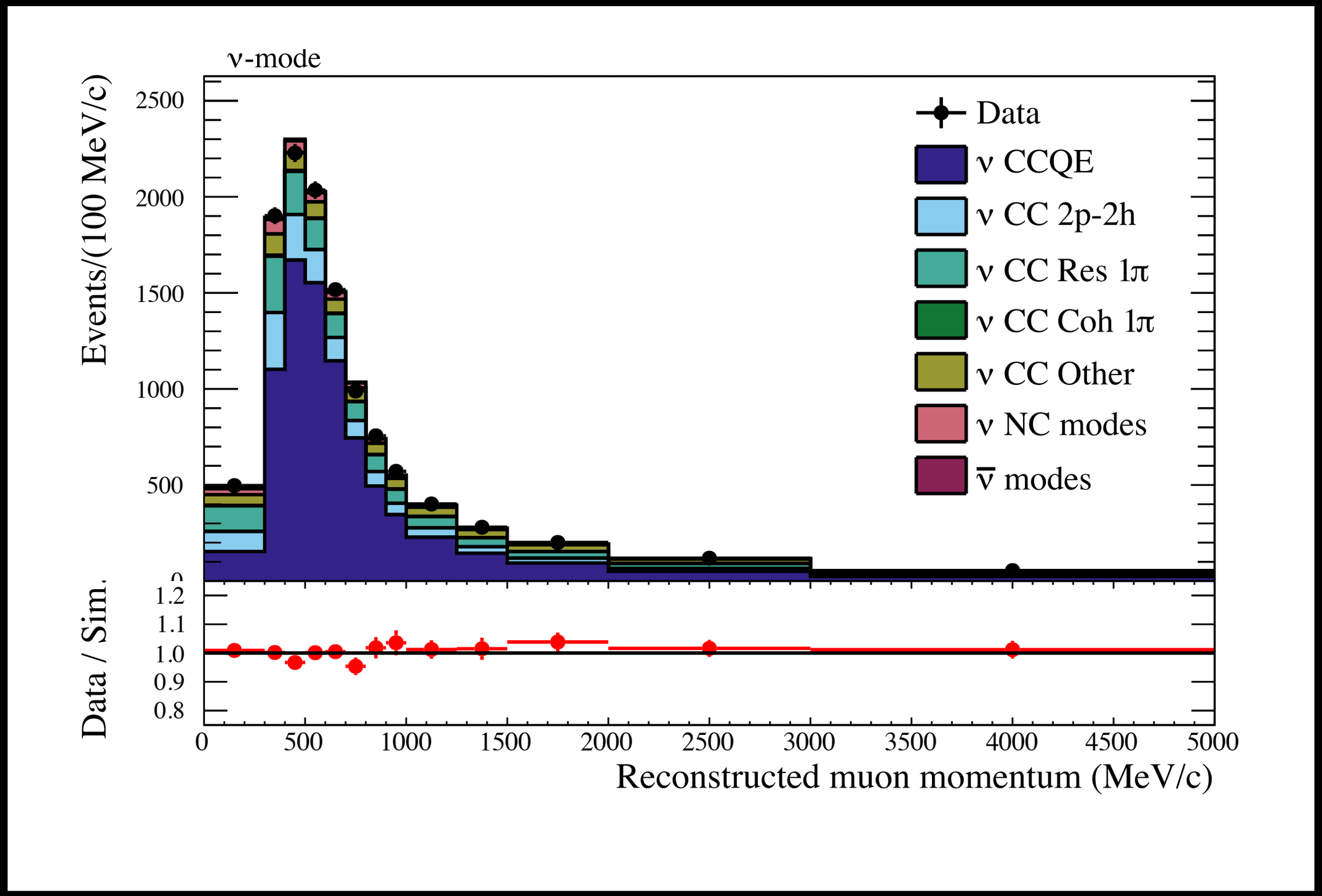
Expansion of the Fiducial Volume



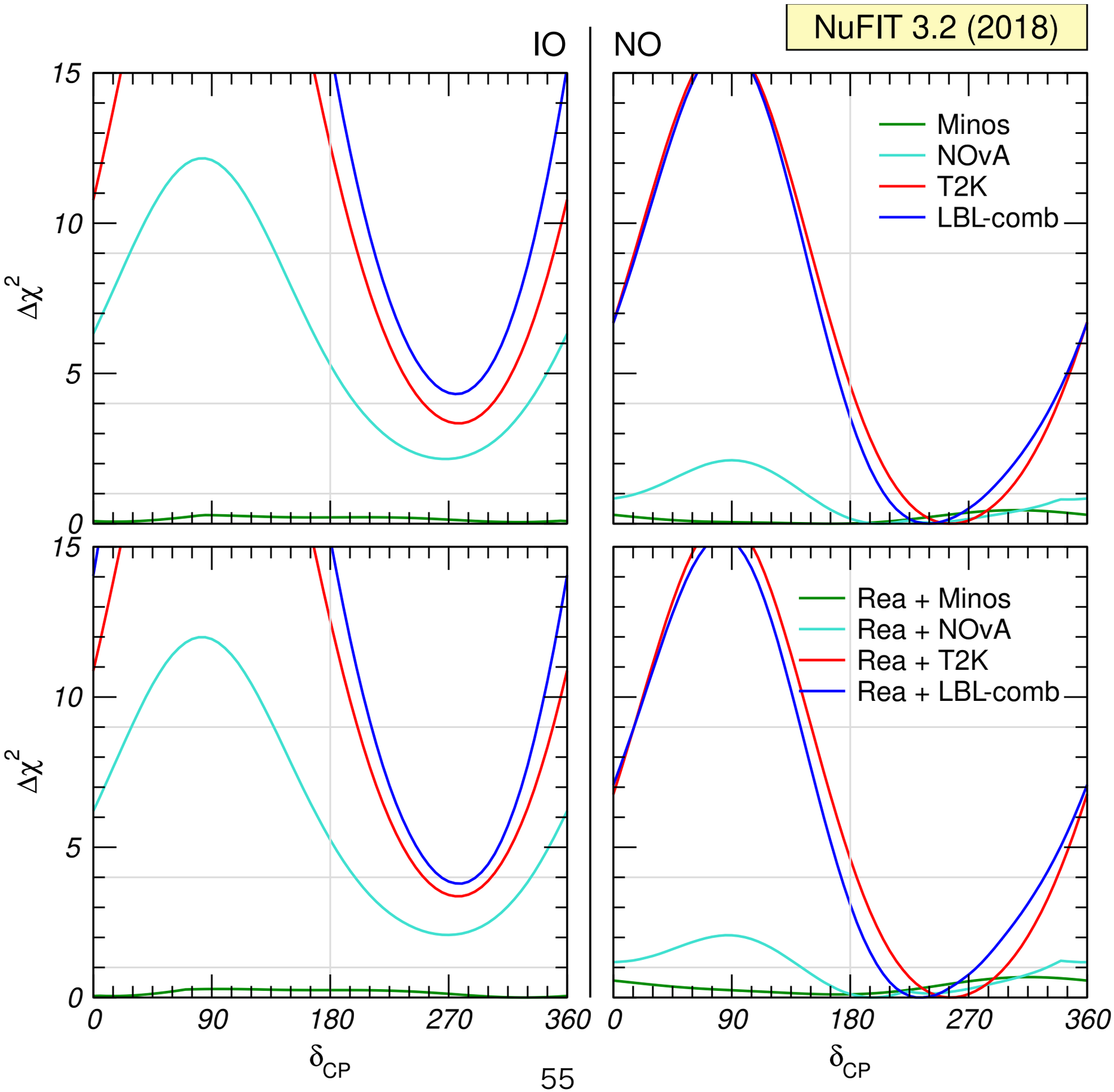


Sample	Towall Cut	Wall Cut
CCQE 1-Ring e-like FHC	170 cm	80 cm
CCQE 1-Ring μ-like FHC	250 cm	50 cm
CC1π 1-Ring e-like FHC	270 cm	50 cm
CCQE 1-Ring e-like RHC	170 cm	80 cm
CCQE 1-Ring μ-like RHC	250 cm	50 cm

Fitting ND280 Data

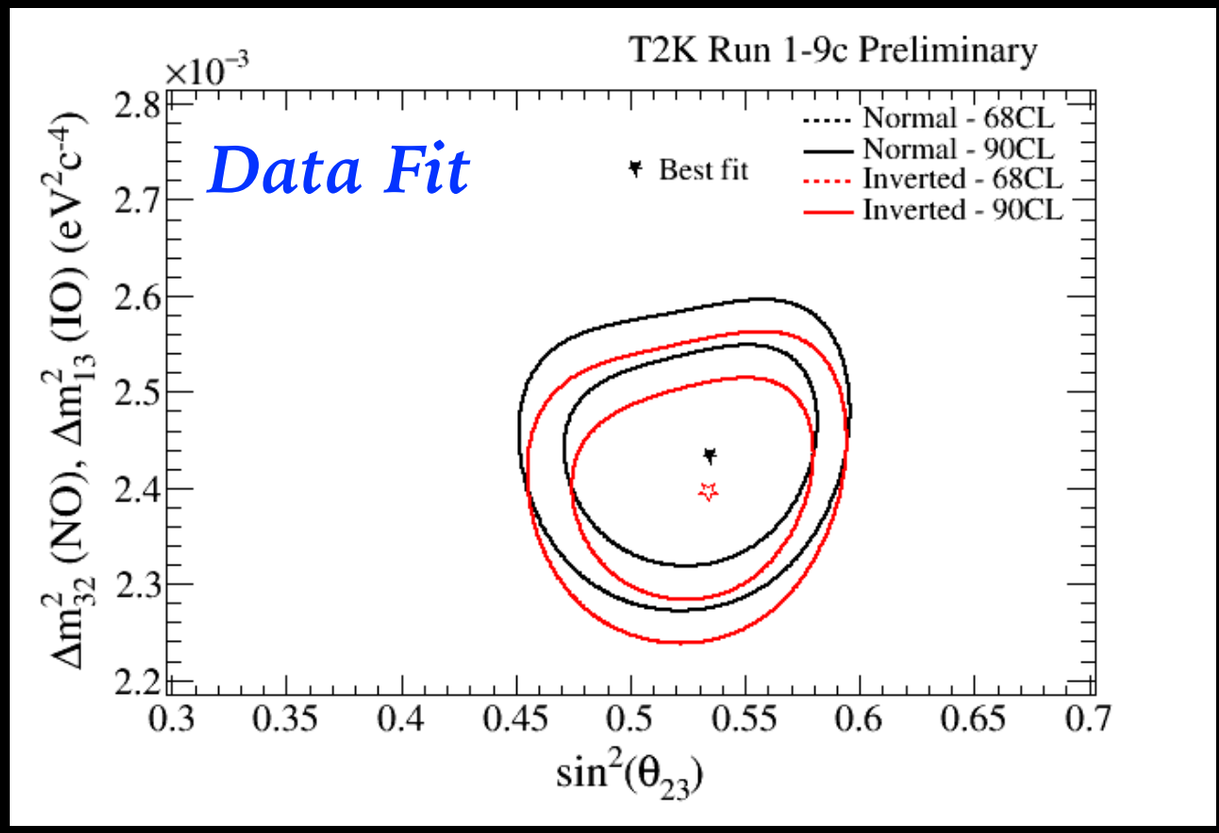


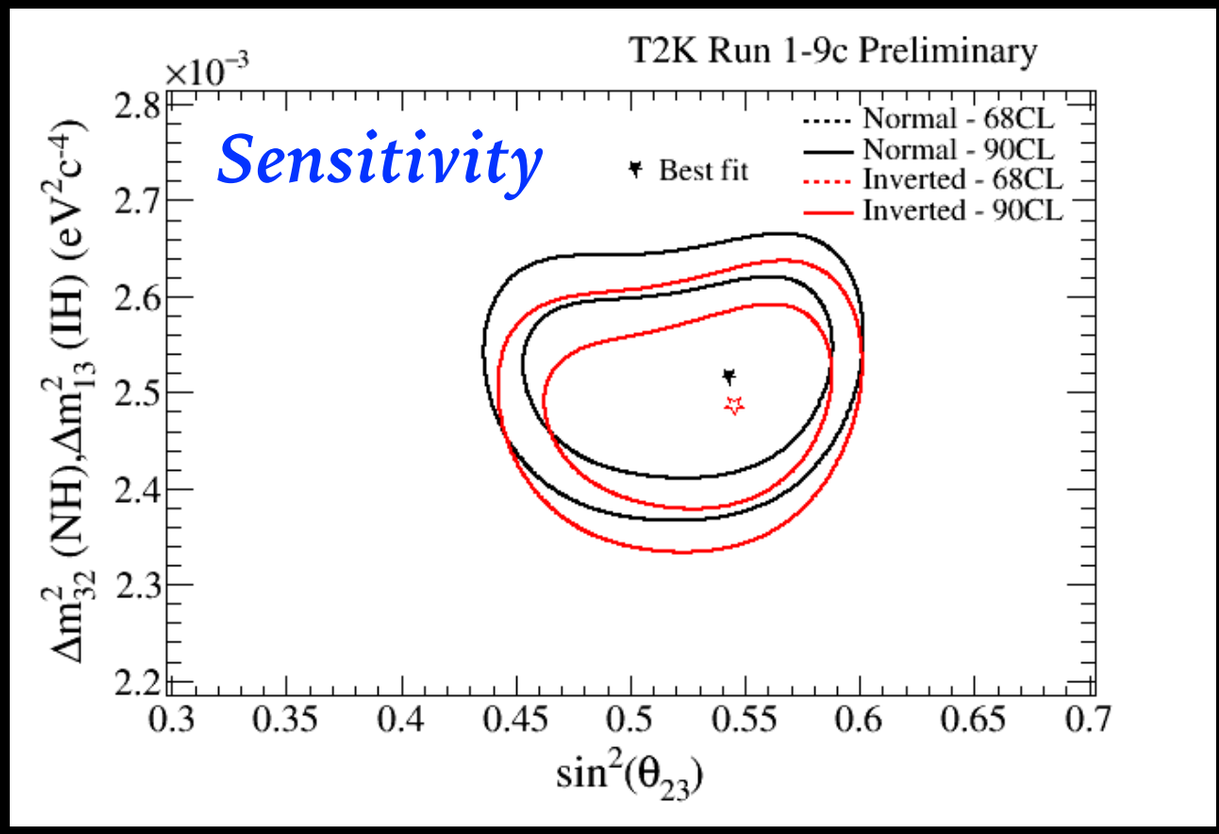
- Example fitted FGD2 (water) CC-0π muon momentum
- The fit reproduces the data well with a p-value of 0.47


NuFIT 3.2 (2018)
IO
NO
Minos
NOvA
T2K
LBL-comb
Rea + Minos
Rea + NOvA
Rea + T2K
Rea + LBL-comb
$\Delta\chi^2$
δ_{CP}
0
5
10
15
0
90
180
270
360

$\sin^2\theta_{23}$

- Fit the normal and inverted hierarchies separately
- Results with the reactor constraint on $\sin^2 2\theta_{13}$
- Constraint on $\sin^2\theta_{23}$ is slightly stronger than the sensitivity





θ_{23} octant and mass hierarchy

- Bayesian analysis: natural way to infer data preference for **θ_{23} octant** or **mass hierarchy**
- Assume equal prior probability for both octant and hierarchy hypotheses
- Fraction of steps from Markov Chain in each octant/hierarchy is posterior probability for the octant/hierarchy hypothesis
- T2K data prefers the normal hierarchy and upper octant

Posterior probabilities (with reactor constraint)

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{32} < 0$)	0.023	0.089	0.112
Sum	0.227	0.773	