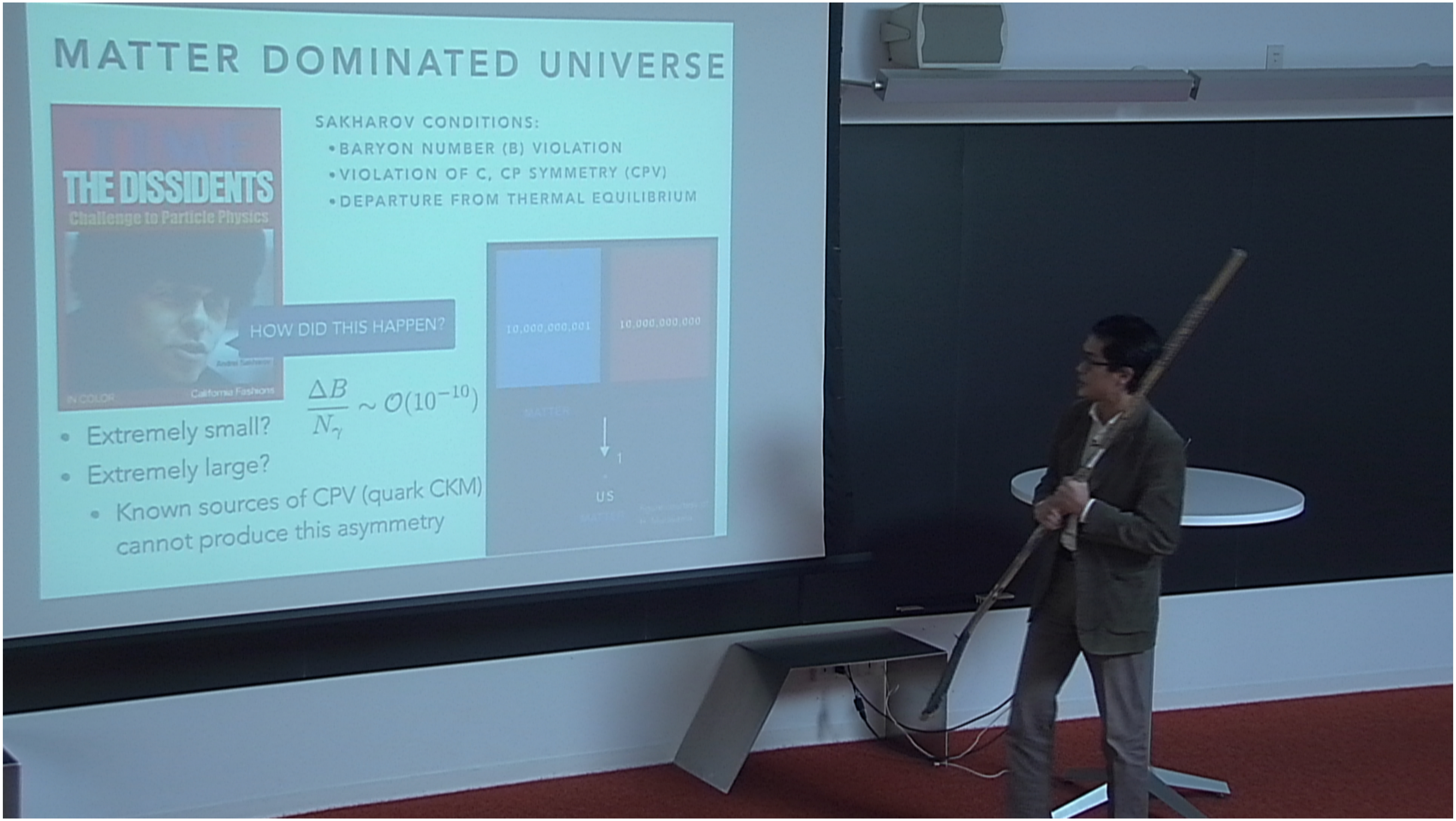
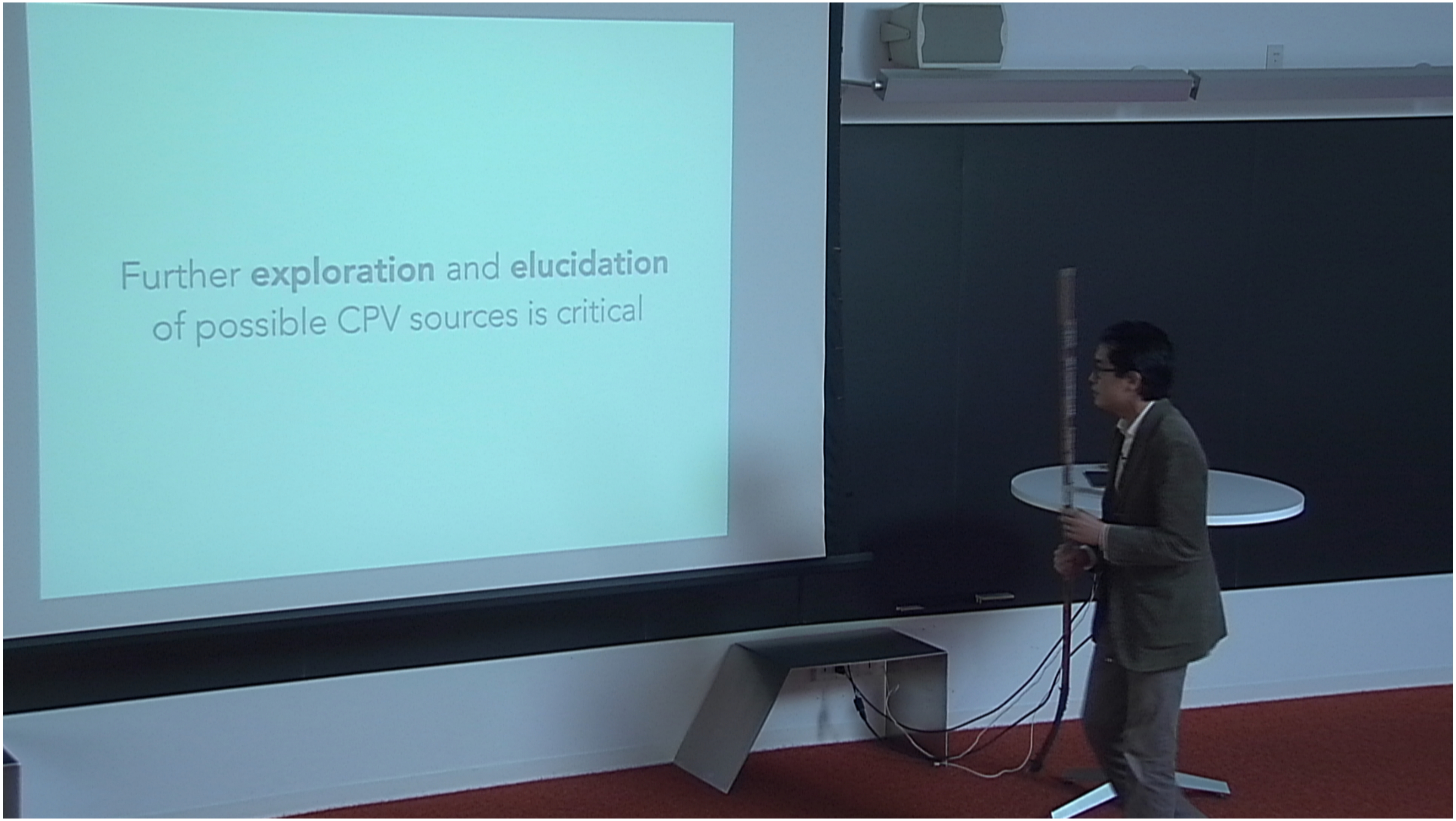
Title: Ghosts and Anti-Ghosts: The latest results from the T2K neutrino oscillation experiments

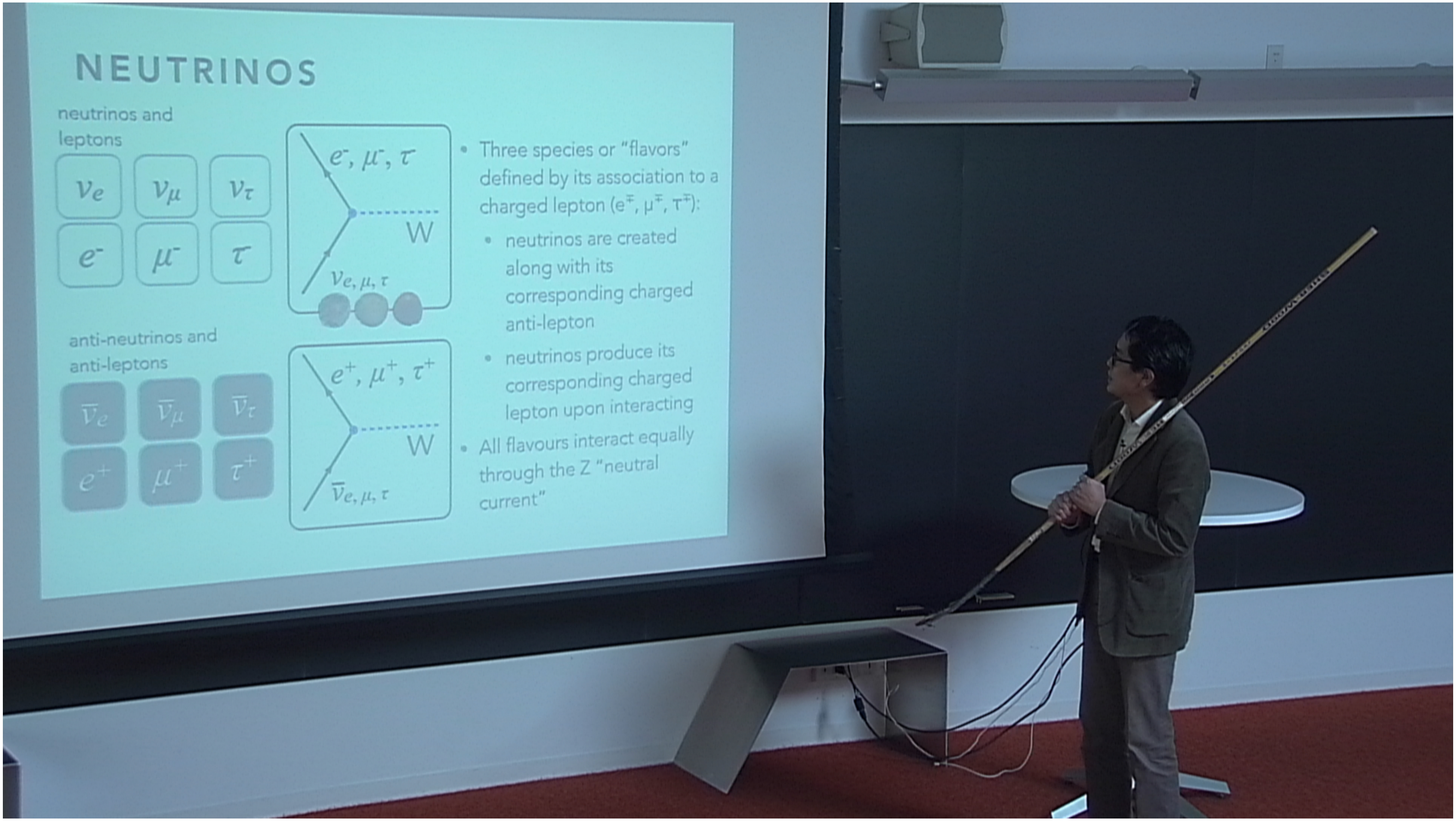
Date: Oct 14, 2016 02:00 PM

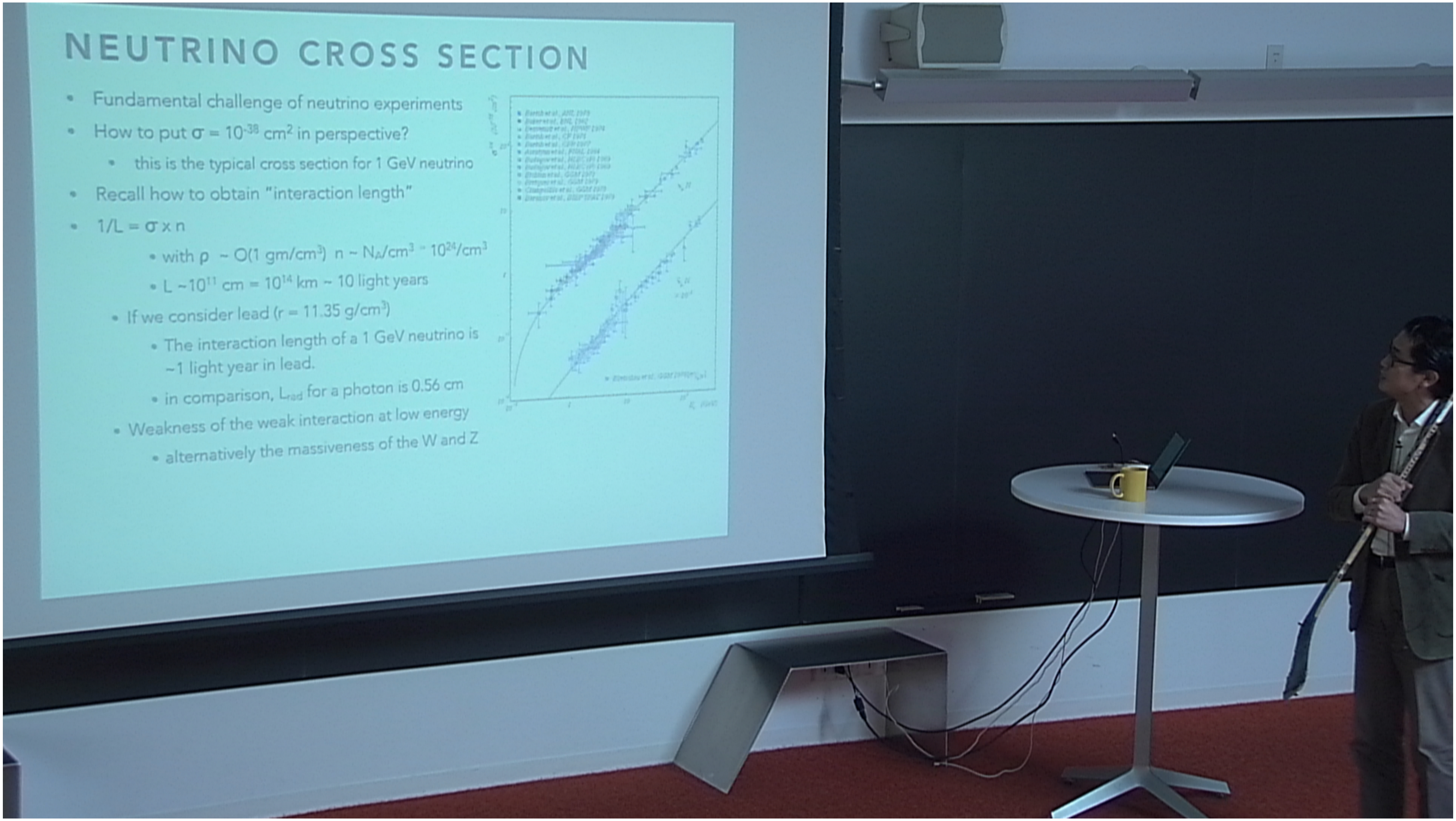
URL: http://pirsa.org/16100056

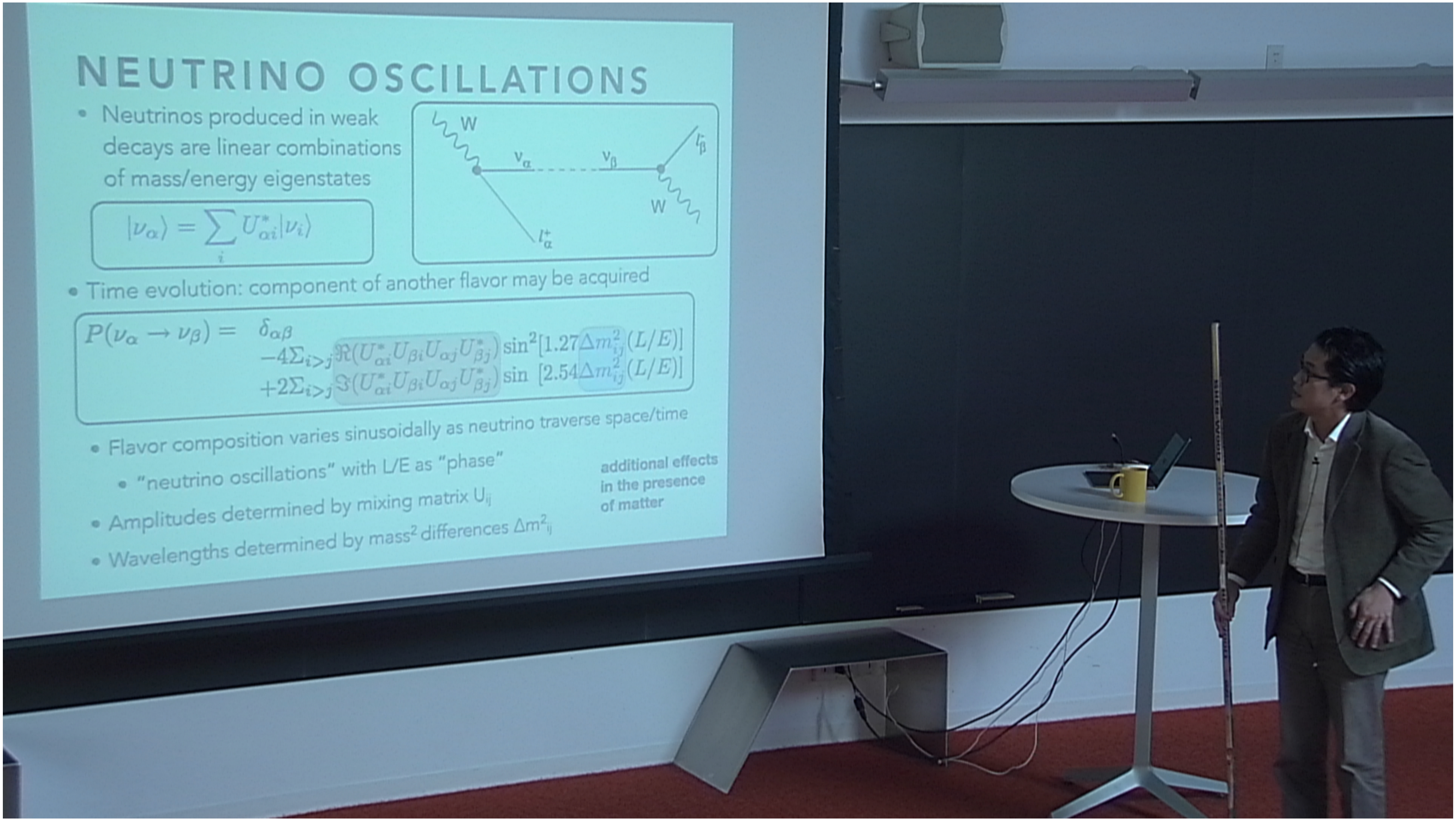
Abstract: <p>The T2K experiment studies neutrino properties by producing a beam of muon neutrinos and sending them 295 km across Japan to the Super-Kamiokande detector. En route, neutrinos undergo a transmutation known as â€œneutrino oscillationsâ€• wherein they can transition to two other species or flavours, electron and tau neutrinos. Starting in 2014, T2K has run with an antineutrino beam to study the corresponding antineutrino oscillations and the possibility that a complex phase in the neutrino mass and flavour mixing may lead to differences in neutrino and antineutrino oscillations. Such a difference may provide a critical clue into how our universe came to be dominated by matter. I will present the latest results from an analysis of T2K neutrino and antineutrino data taken through 2016 along with other recent results from other experiments, and discuss their implications for our understanding of neutrinos.</p>


MATTER DOMINATED UNIVERSE
SAKHAROV CONDITIONS:
•BARYON NUMBER (B) VIOLATION
•VIOLATION OF C, CP SYMMETRY (CPV)
•DEPARTURE FROM THERMAL EQUILIBRIUM
THE DISSIDENTS
Challenge to Particle Physics
HOW DID THIS HAPPEN?
IN COLOR
California Fashions
$\frac{\Delta B}{N_\gamma} \sim \mathcal{O}(10^{-10})$
10,000,000,001
10,000,000,000
1
US
• Extremely small?
• Extremely large?
• Known sources of CPV (quark CKM) cannot produce this asymmetry

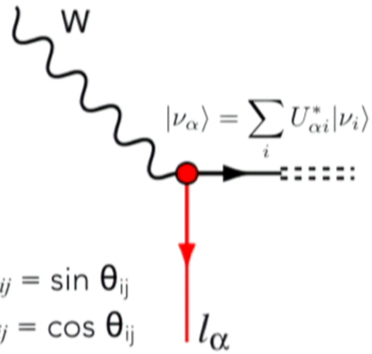

Further exploration and elucidation
of possible CPV sources is critical


NEUTRINOS
neutrinos and leptons
ν_e ν_μ ν_τ
e^- μ^- τ
e^-, μ^-, τ
W
$\nu_{e,\mu,\tau}$
anti-neutrinos and anti-leptons
$\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$
e^+ μ^+ τ^+
e^+, μ^+, τ^+
W
$\bar{\nu}_{e,\mu,\tau}$
Three species or "flavors" defined by its association to a charged lepton ($e^\mp$, $\mu^\mp$, $\tau^\mp$):
neutrinos are created along with its corresponding charged anti-lepton
neutrinos produce its corresponding charged lepton upon interacting
All flavours interact equally through the Z "neutral current"


NEUTRINO CROSS SECTION
• Fundamental challenge of neutrino experiments
• How to put σ = 10^-38 cm^2 in perspective?
• this is the typical cross section for 1 GeV neutrino
• Recall how to obtain "interaction length"
• 1/L = σ x n
• with ρ ~ O(1 gm/cm^3) n ~ N_A/cm^3 ~ 10^24/cm^3
• L ~10^11 cm = 10^14 km ~ 10 light years
• If we consider lead (r = 11.35 g/cm^3)
• The interaction length of a 1 GeV neutrino is ~1 light year in lead.
• in comparison, L_rad for a photon is 0.56 cm
• Weakness of the weak interaction at low energy
• alternatively the massiveness of the W and Z


NEUTRINO OSCILLATIONS
Neutrinos produced in weak decays are linear combinations of mass/energy eigenstates
$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$
W
ν_α
ν_β
l^-_β
W
l^+_α
Time evolution: component of another flavor may be acquired
$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\Sigma_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\Sigma_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin[2.54\Delta m^2_{ij}(L/E)]$
Flavor composition varies sinusoidally as neutrino traverse space/time
"neutrino oscillations" with L/E as "phase"
Amplitudes determined by mixing matrix U_{ij}
Wavelengths determined by mass^2 differences Δm^2_{ij}
additional effects in the presence of matter

MIXING OF THREE NEUTRINOS



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

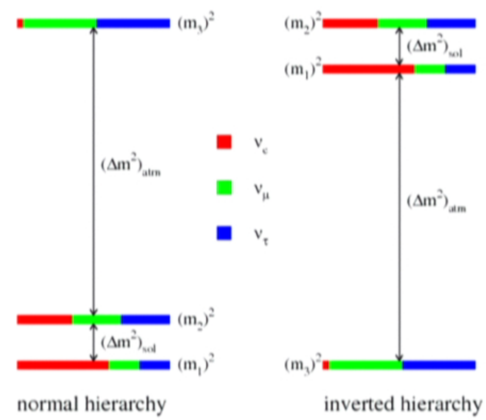
$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

"standard" parametrization

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
- One complex phase δ_{CP}
  - additional phases possible if neutrinos are "Majorana" (more on this later)
  - **changes sign for antineutrino oscillations**



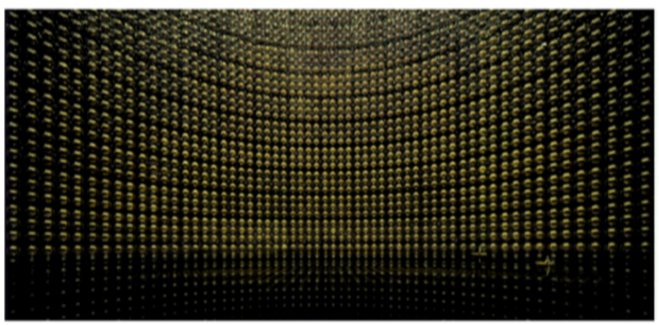
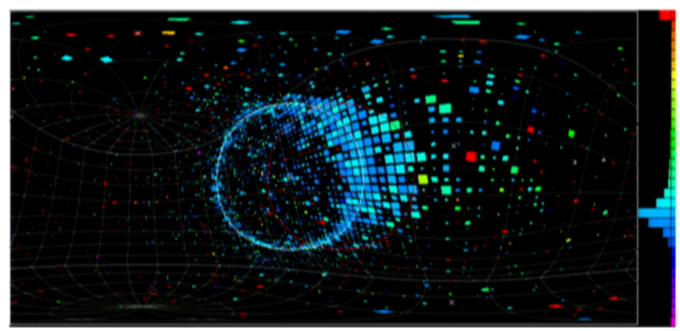
The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

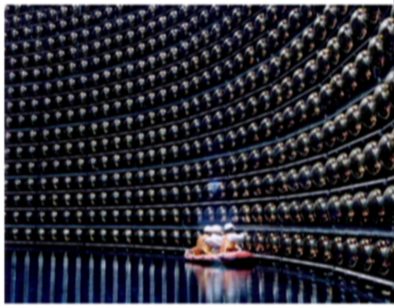
 

T2K

Super Kamiokande

ND280
"near" detector

J-PARC

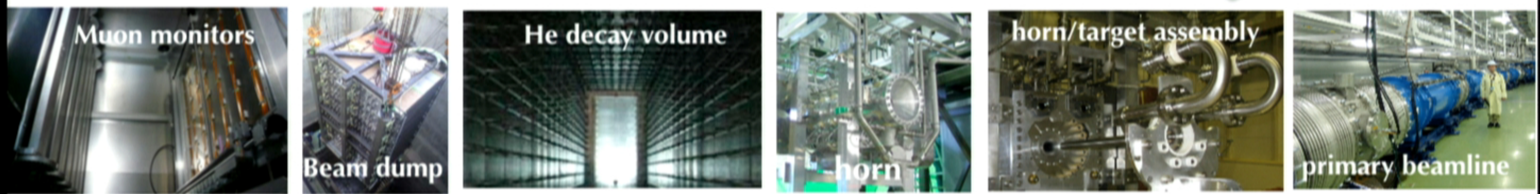


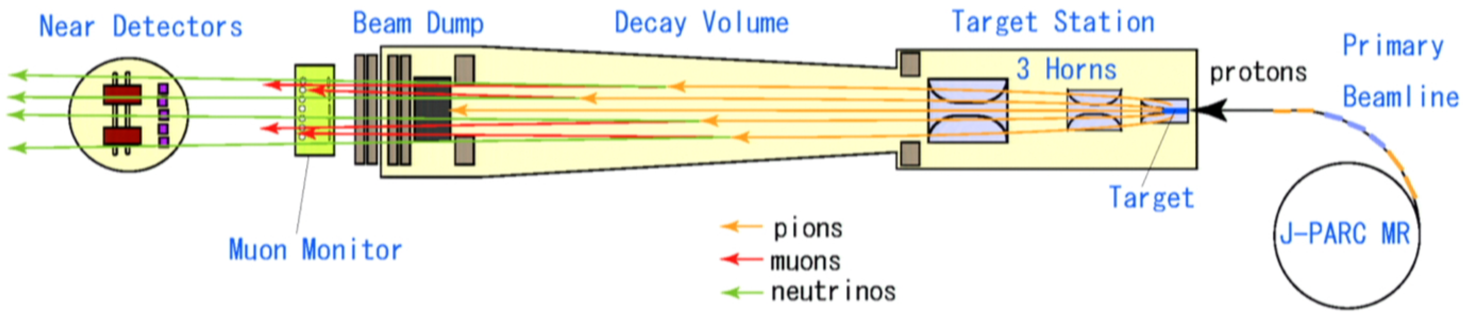
~500 collaborators from
58 institutions, 12 nations

Intense $\nu_\mu / \bar{\nu}_\mu$ beam sent 295 km across Japan and detected with the Super-Kamiokande detector to study neutrino oscillations

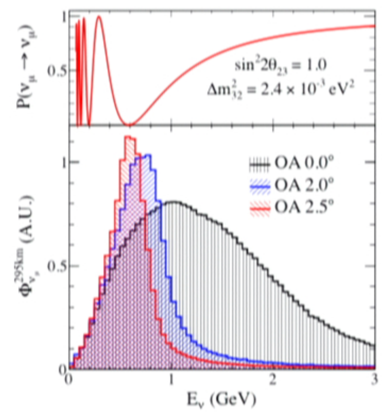
PRODUCING THE BEAM

T2K

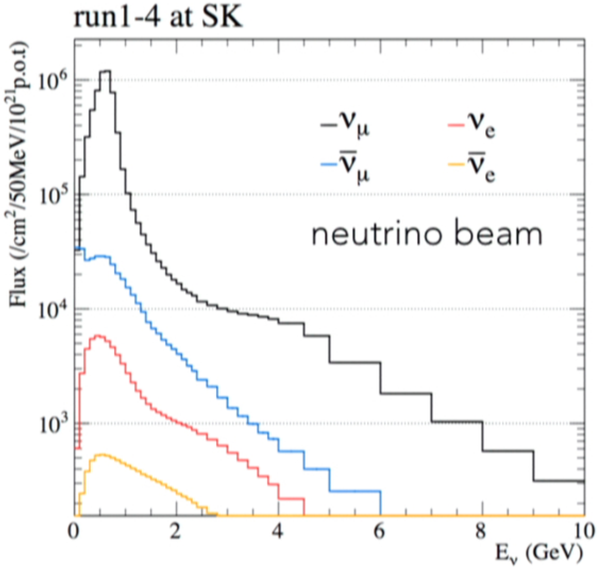


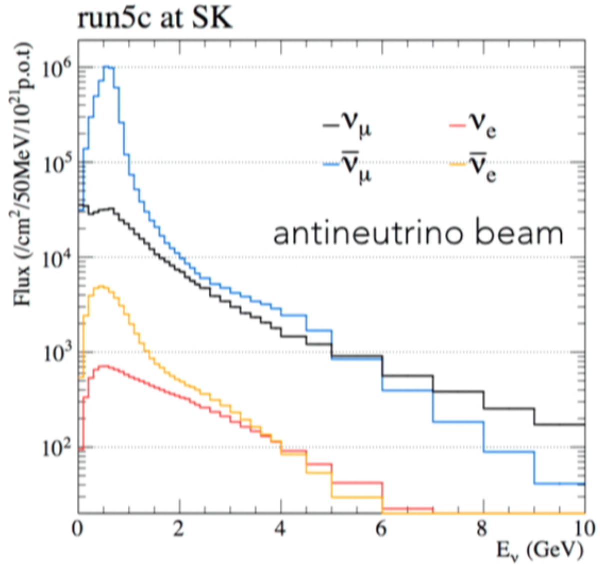


- 30 GeV protons extracted from J-PARC MR a target
  - secondary π^+ focussed by three EM "horns"
  - primarily ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - reverse polarity for antineutrino beam: $\pi^- \rightarrow \mu^+ + \nu_\mu$
  - spectrum peaked at 600 MeV "off axis"
    - expected oscillation "maximum" for L=295 km



NEUTRINO AND ANTINEUTRINO





$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

- <1% impurity from $\nu_e/\bar{\nu}_e$ at energy peak; important for backgrounds
- Magnetic focussing allows T2K to switch between a neutrino/anti-neutrino beam
- We can study neutrino and antineutrino oscillations.
- "POT" = protons-on-target is the currency for more neutrinos

ν OSCILLATIONS AT TOKAI→KAMIOKA

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

- Precision measurement of $\sin^2 2\theta_{23}$.
- CPT tests with antineutrino mode ($\nu_\mu \to \nu_\mu$)

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$
$$- \alpha \sin\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+ \alpha \cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+ \mathcal{O}(\alpha^2)$$

~30% max. effect

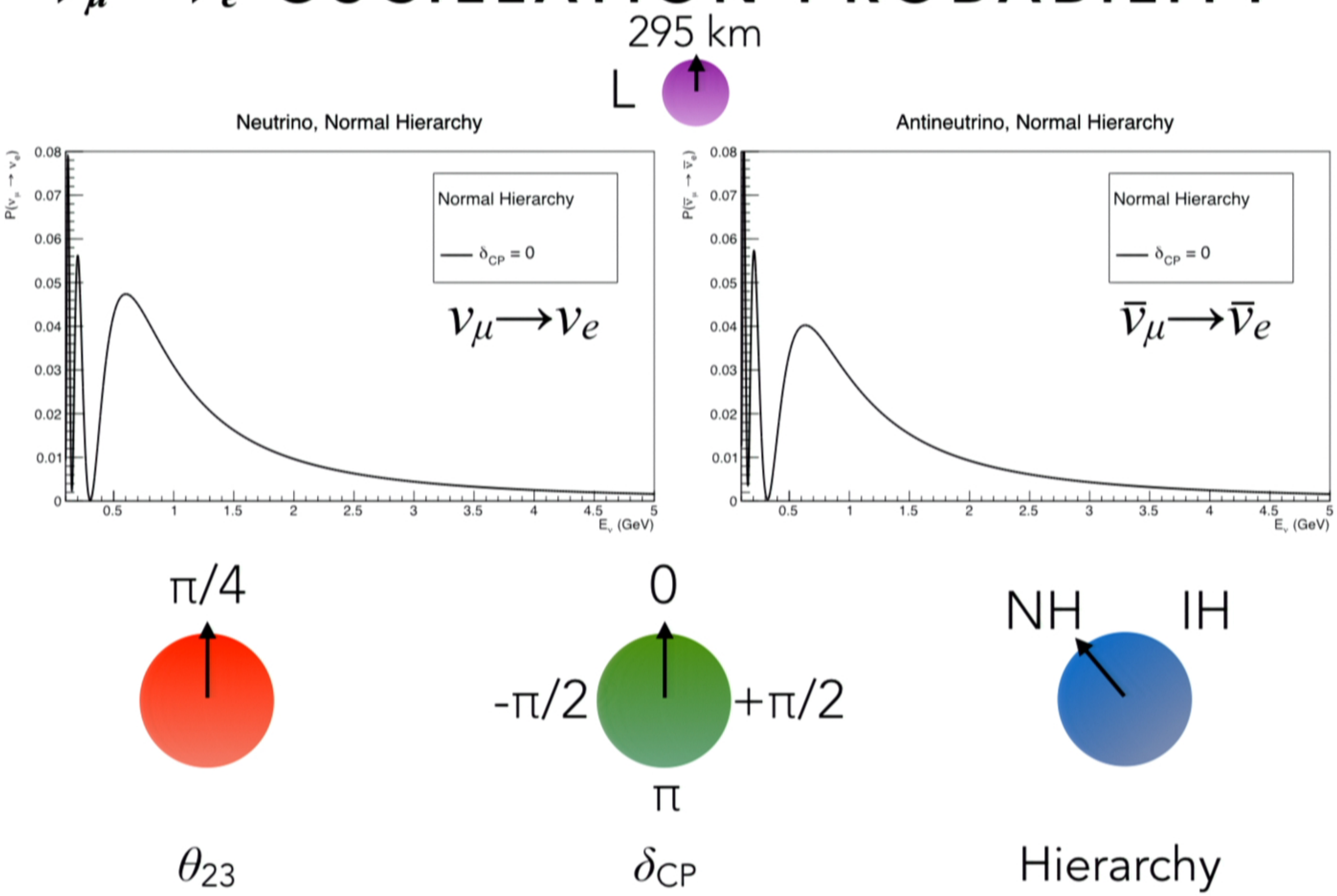
~±10%

$$\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

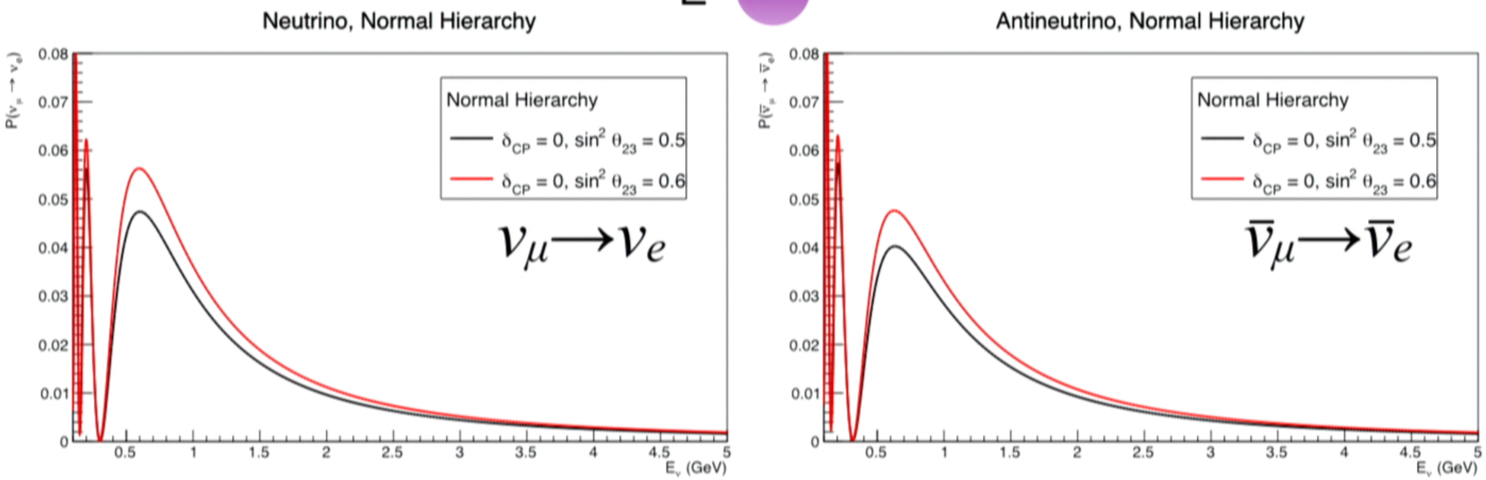
M. Freund, Phys.Rev. D64 (2001) 053003

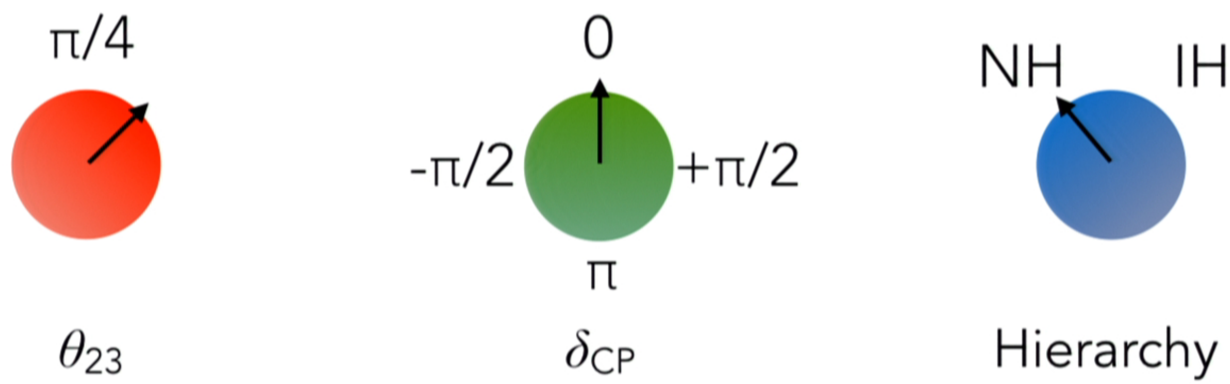
- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45°?)
- CP odd phase δ: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if sin δ ≠ 0
- Matter effect through x: ν_e ($\bar{\nu}_e$) enhanced in normal (inverted)

$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY

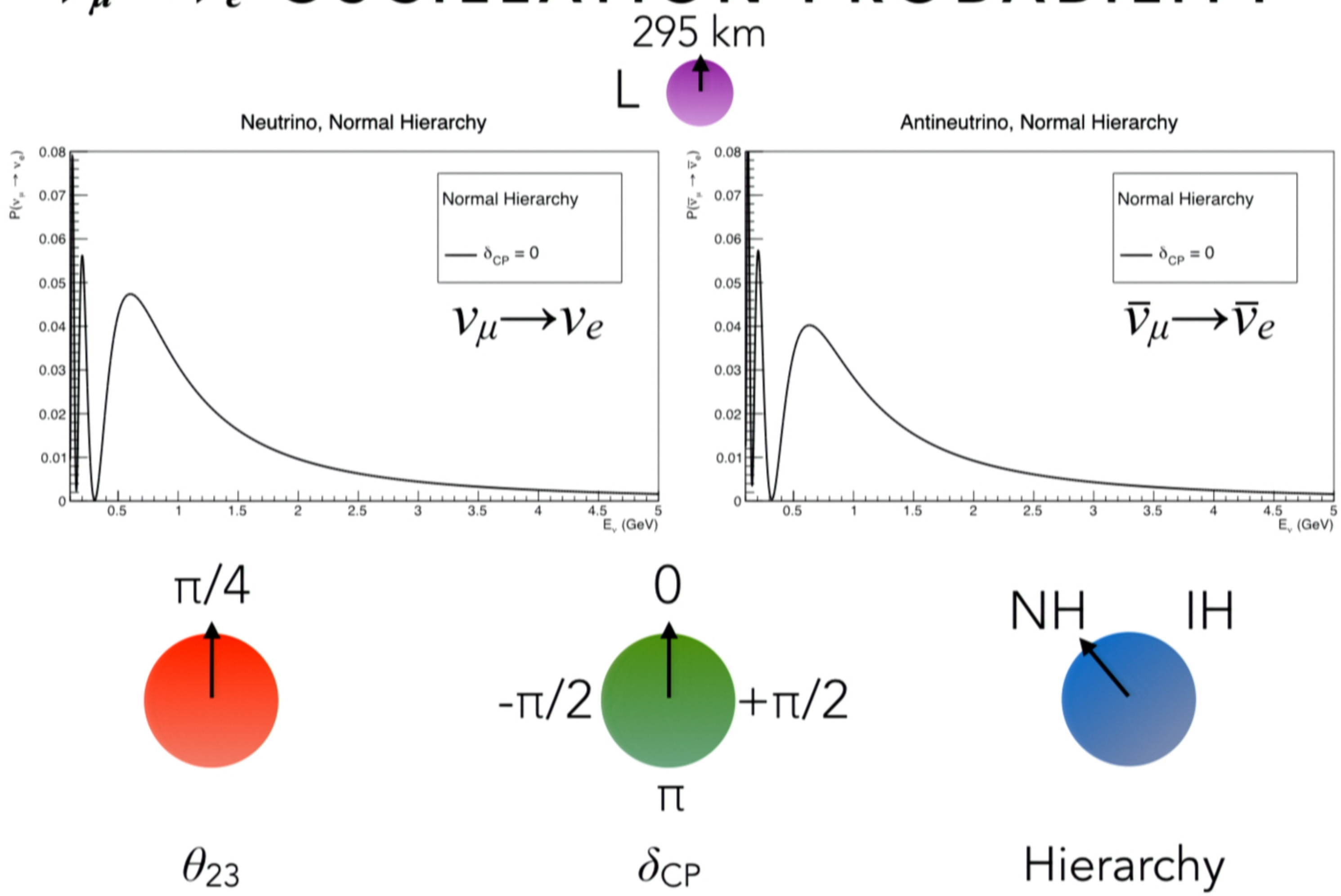


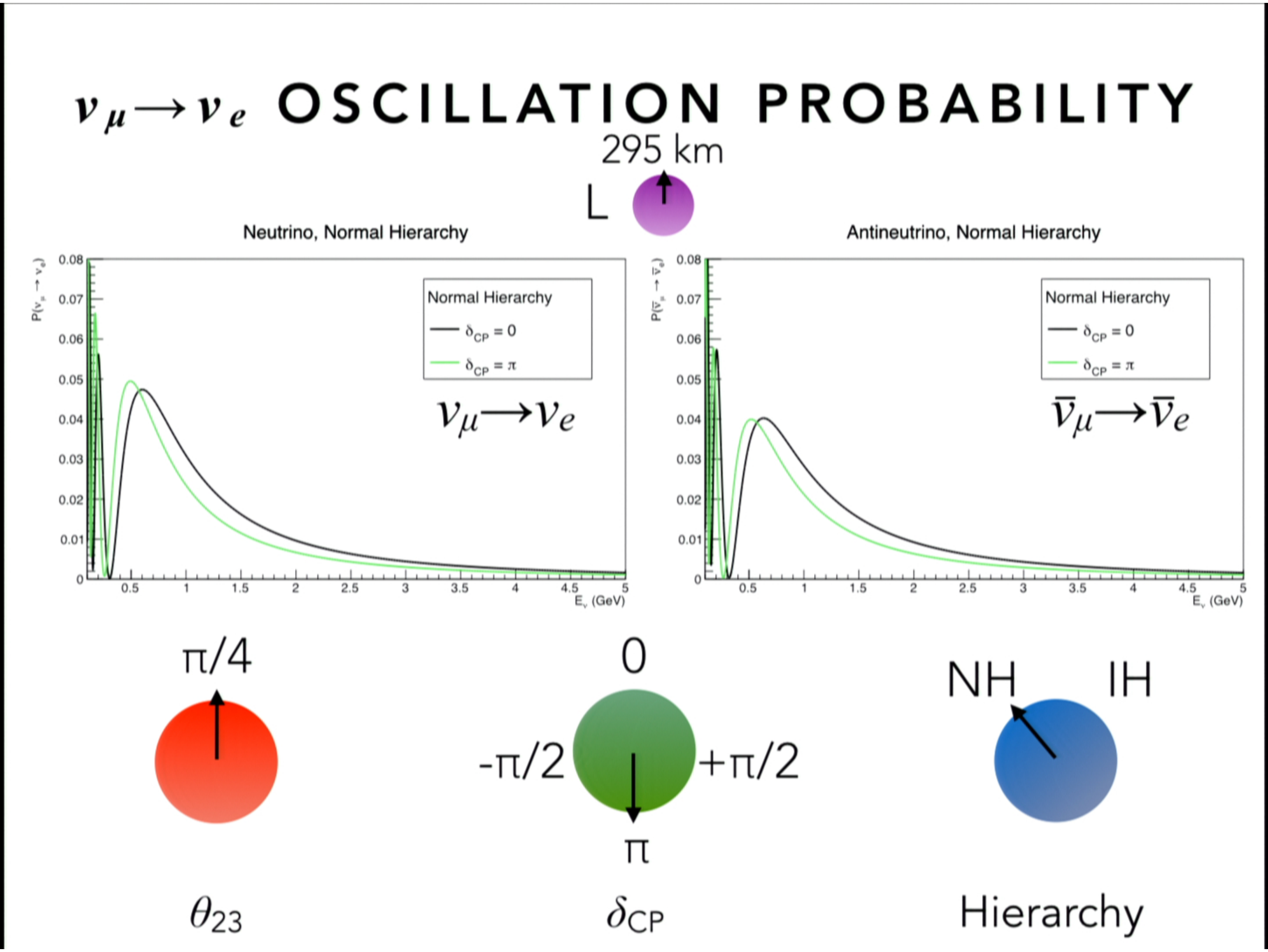
$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY





$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY

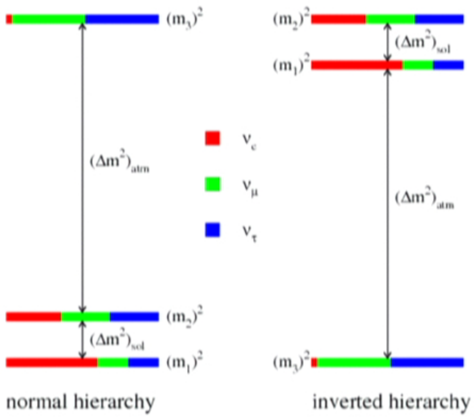




$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY
295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
Normal Hierarchy
$\delta_{CP} = 0$
$\delta_{CP} = \pi$
$\nu_\mu \rightarrow \nu_e$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
E_ν (GeV)
π/4
0
-π/2
+π/2
π
NH
IH
θ_{23}
δ_{CP}
Hierarchy

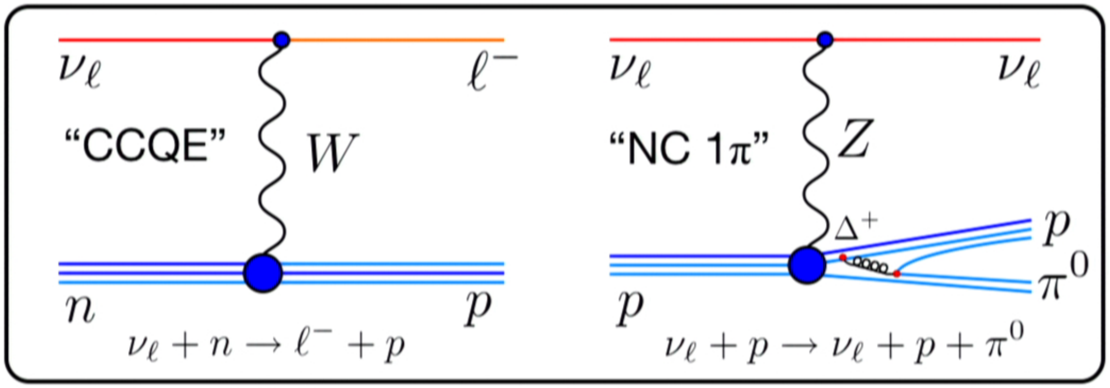
QUICK SUMMARY

- CP violating parameter δ_{CP}
  - δ_{CP} =0,π: no CP violation: vacuum oscillation probabilities equal
  - δ_{CP} ~-π/2: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - δ_{CP} ~+π/2: suppress $\nu_\mu \rightarrow \nu_e$, enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$
  - enhance both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- "normal" hierarchy:
  - enhance $\nu_\mu \rightarrow \nu_e$
  - suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



- "inverted" hierarchy:
  - suppress $\nu_\mu \rightarrow \nu_e$
  - enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

NEUTRINO INTERACTIONS



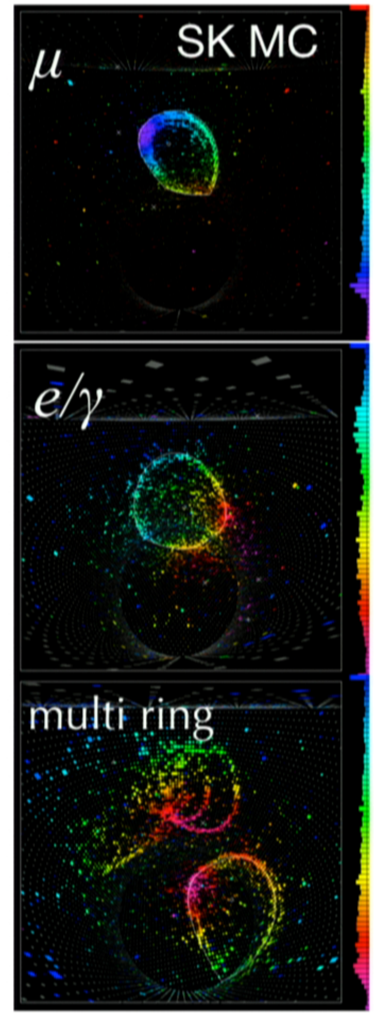
$\nu_\ell + n \rightarrow \ell^- + p$ **Signal**

- Single μ/e-like ring
- E_ν by energy/direction of ring relative to beam
    - assumes CCQE kinematics

$\nu_\ell + (n/p) \rightarrow \nu_\ell + (n/p) + \pi^0$ **Backgrounds**

$\nu_\ell + (n/p) \rightarrow \ell^- + (n/p) + \pi$

- $\pi^0 \rightarrow \gamma + \gamma$: ring counting, 2-ring reconstruction
    - γ misidentified as e from ν_e CCQE
- μ/π^+: ring counting, decay electron cut



ANALYSIS STRATEGY

Far (L=295 km)
$\nu_\mu \rightarrow \nu_e$ (θ_{23} , θ_{13}, δ_{CP})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($2\theta_{23}$, Δm^2_{32})
ν_μ, ν_e backgrounds

ANALYSIS STRATEGY

Far (L=295 km)
$\nu_\mu \rightarrow \nu_e$ (θ_{23} , θ_{13}, δ_{CP})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($2\theta_{23}$, Δm^2_{32})
ν_μ, ν_e backgrounds

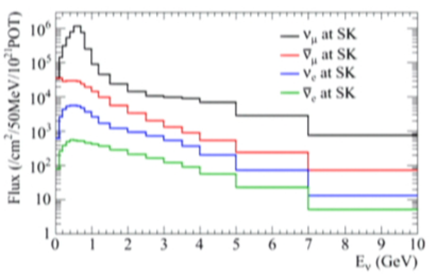
$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

ANALYSIS STRATEGY

Far (L=295 km)
$\nu_\mu \rightarrow \nu_e$ (θ_{23}, θ_{13}, δ_{CP})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($2\theta_{23}$, Δm^2_{32})
ν_μ, ν_e backgrounds

$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

φ_ν



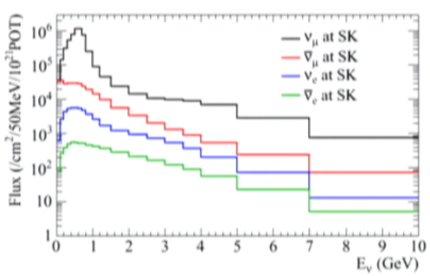
MC simulation of neutrino beamline tuned with external data + operational parameters

ANALYSIS STRATEGY

Far (L=295 km)
$\nu_\mu \rightarrow \nu_e$ (θ_{23} , θ_{13}, δ_{CP})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($2\theta_{23}$, Δm^2_{32})
ν_μ, ν_e backgrounds

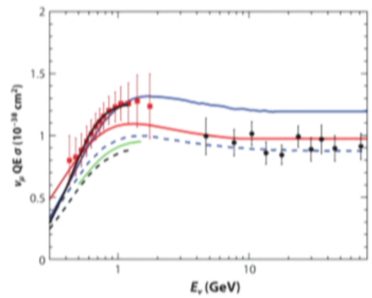
$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

φ_ν



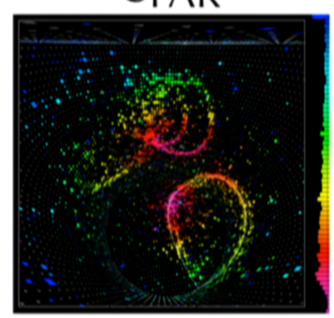
MC simulation of neutrino beamline tuned with external data + operational parameters

σ_ν



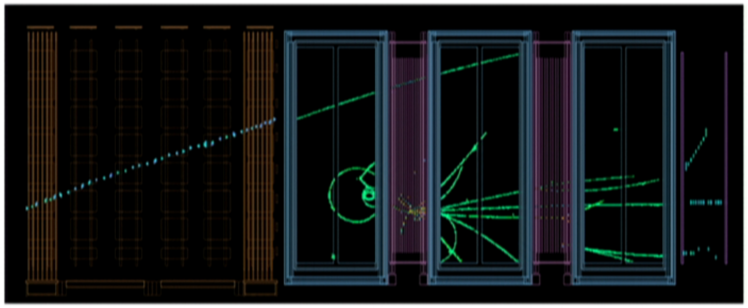
Neutrino cross section and interaction model tuned to external measurements

ε_{FAR}



Detector simulation to determine efficiencies/ backgrounds

ANALYSIS STRATEGY



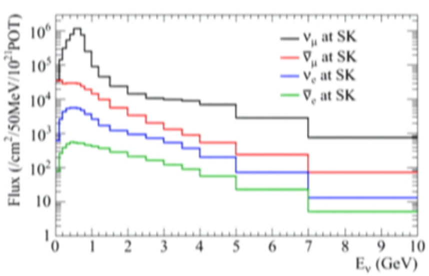
Near detectors observe the
neutrinos prior to oscillations

$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{NEAR}$

Far (L=295 km)
$\nu_\mu \rightarrow \nu_e$ $(\theta_{23}, \theta_{13}, \delta_{CP})$
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ $(2\theta_{23}, \Delta m^2_{32})$
ν_μ, ν_e backgrounds

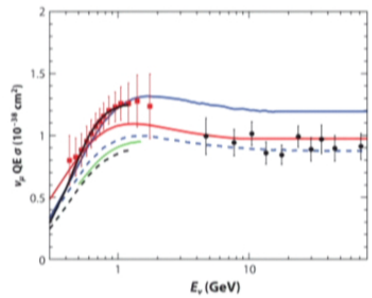
$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

φ_ν



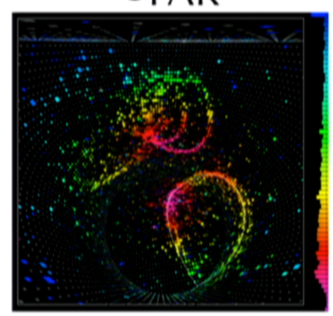
MC simulation of neutrino beamline tuned with external data + operational parameters

σ_ν



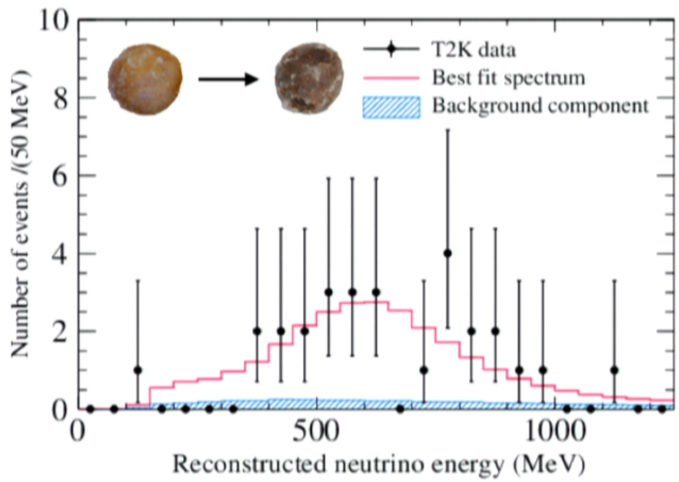
Neutrino cross section and interaction model tuned to external measurements

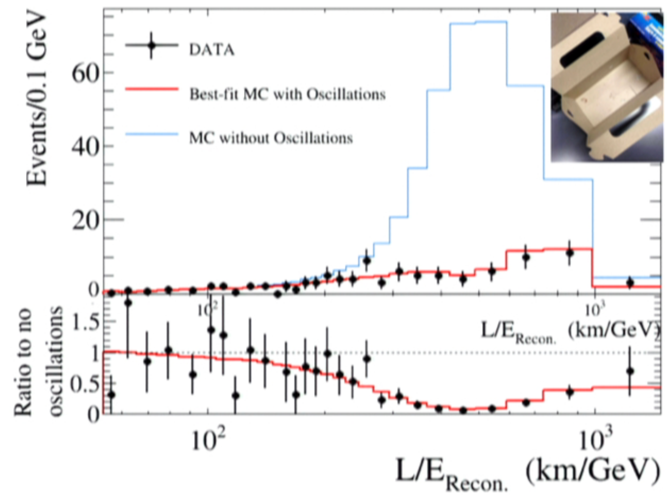
ε_{FAR}



Detector simulation to determine efficiencies/ backgrounds

NEUTRINO MODE DATA





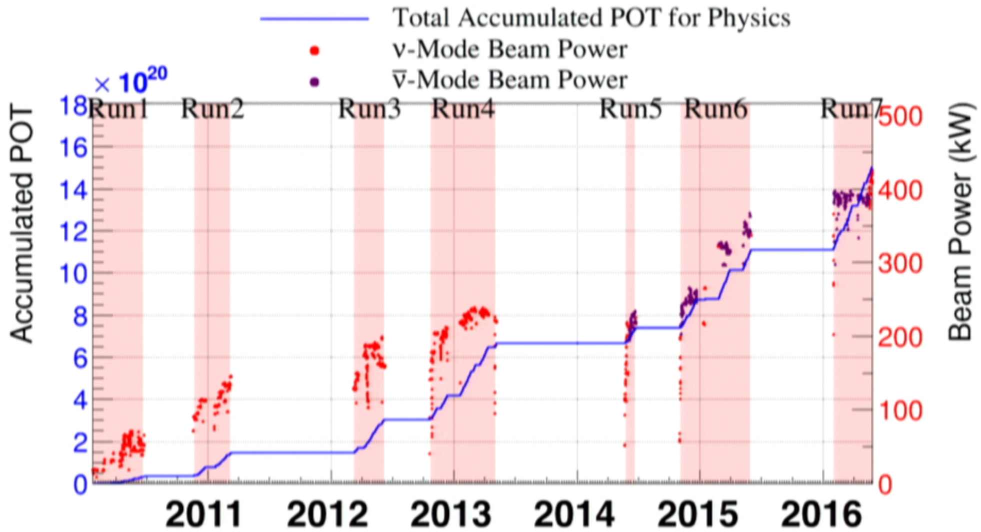
- 28 ν_e candidates observed
  - 5.0 expected in absence of osc. effects
  - definitive observation of $\nu_\mu \rightarrow \nu_e$ oscillations
- 120 ν_μ candidates observed
  - 446 expected in absence of osc. effects
  - Most precise determination of ν_μ disappearance

$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$
$$\Delta m^2_{32} = (2.51 \pm 0.51) \times 10^{-3}\ \mathrm{eV}^2/c^4$$

	Osc.	No osc.
ν_μ	0.9	1.4
$\overline{\nu}_\mu$	0.1	0.1
$\nu_e/\overline{\nu}_e$	3.3	3.5
$\nu_\mu \rightarrow \nu_e$	16.6	0.0
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	0.2	0.0
Total	21.1	5.0

expected number of ν_e candidates for $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, NH

SINCE LAST TIME

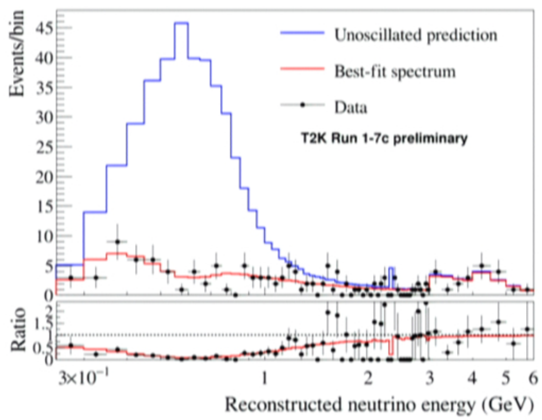


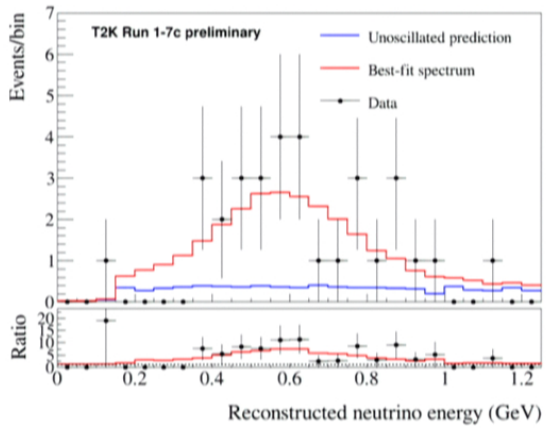
27 May 2016
POT total: 1.510×10^{21}

ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)

- Steady increase in beam power
  - ~240 kW in 2014 → 420 kW in 2016
  - more data, more quickly!
- Antineutrino beam
  - reverse polarity of focussing to collect and decay $\pi^- (\rightarrow \mu^- + \bar{\nu}_\mu)$

NEUTRINO MODE

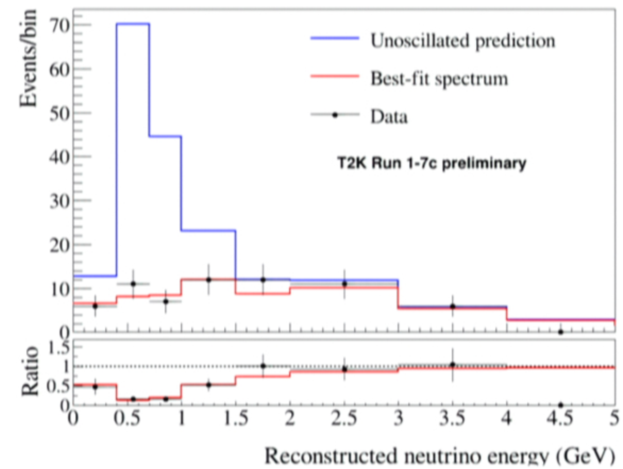


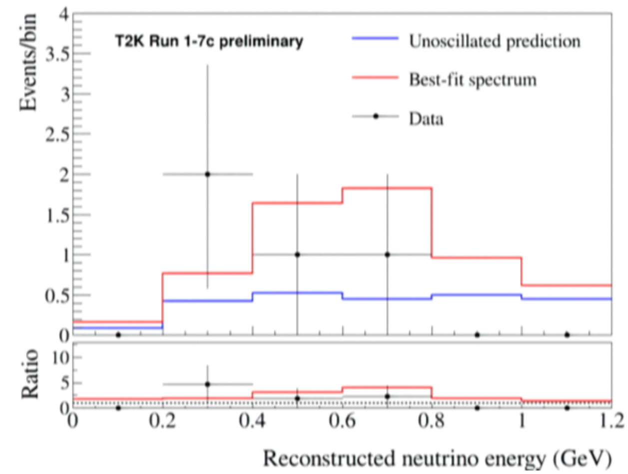


- ν_μ candidates:
  - 481 events expected in the absence of oscillations
  - 135 events observed
  - oscillation pattern precisely observed
- ν_e candidates
  - 6 events expected in the absence of $\nu_\mu \rightarrow \nu_e$ oscillations
  - 32 events observed

ANTINEUTRINO DATA

- ν_μ events
  - 177 events expected in the absence of oscillations
  - 66 observed
- ν_e events
  - 2.4 events expected in the absence of oscillations
  - 4 observed





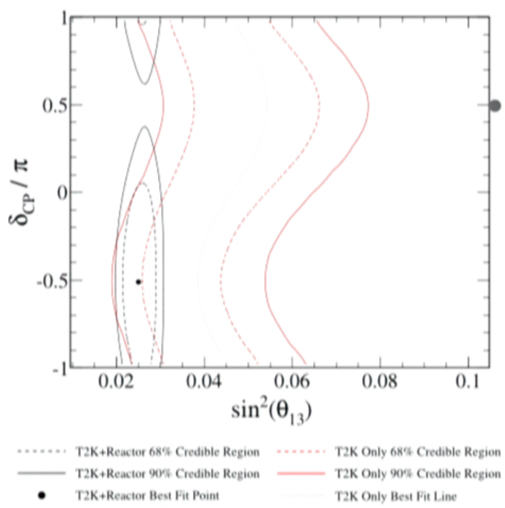
GUESS AT WHERE WE ARE

	MASS ORDER	$-\pi/2$	0	$+\pi/2$	π	OBS
ν_e	NH	28.7	24.2	19.6	24.1	32
	IH	25.4	21.3	17.1	21.3	
$\bar{\nu}_e$	NH	6.0	6.9	7.7	6.8	4
	IH	6.5	7.4	8.4	7.4	

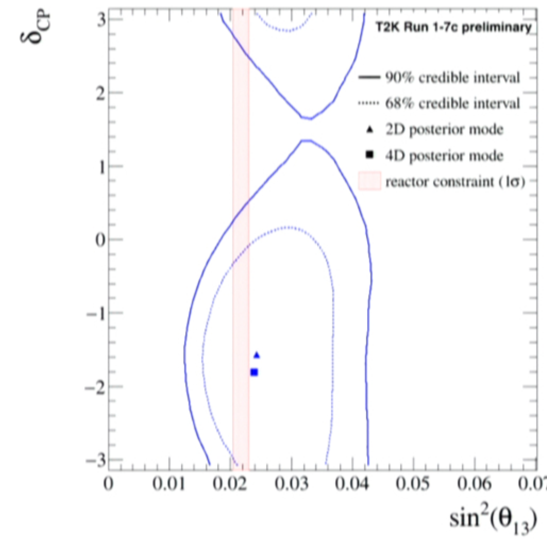
- At $\delta_{CP} = -\pi/2$
  - $\nu_\mu \rightarrow \nu_e$ is maximally enhanced
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is maximally surpassed
- Normal mass hierarchy
  - enhances $\nu_\mu \rightarrow \nu_e$
  - suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

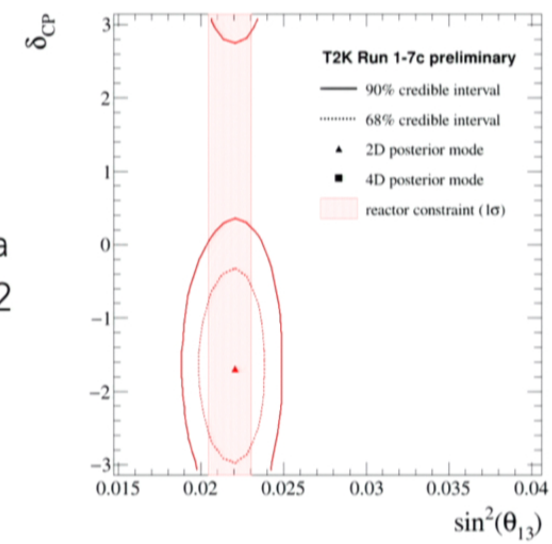
δ_{CP} AND θ_{13}

- Contours show
  - preference for δ_{CP}~-π/2
  - disfavour δ_{CP} ~ +π/2
  - Allowed θ_{13} values consistent with reactor measurement
- Contours shrink with reactor θ_{13} constraint



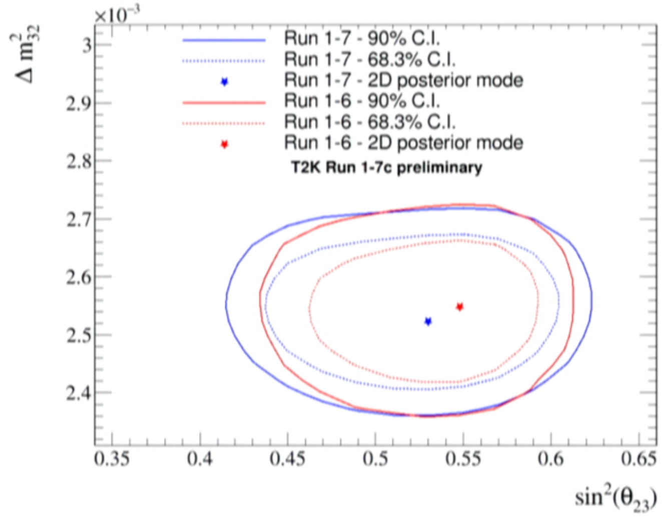
- Left:
  - with $\nu_\mu \rightarrow \nu_e$ only, reactor + T2K data favoured $\boldsymbol{\delta_{CP}}$ =-π/2

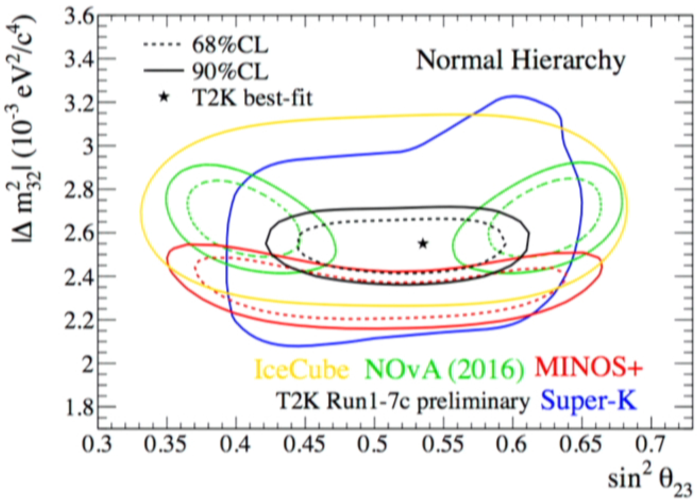


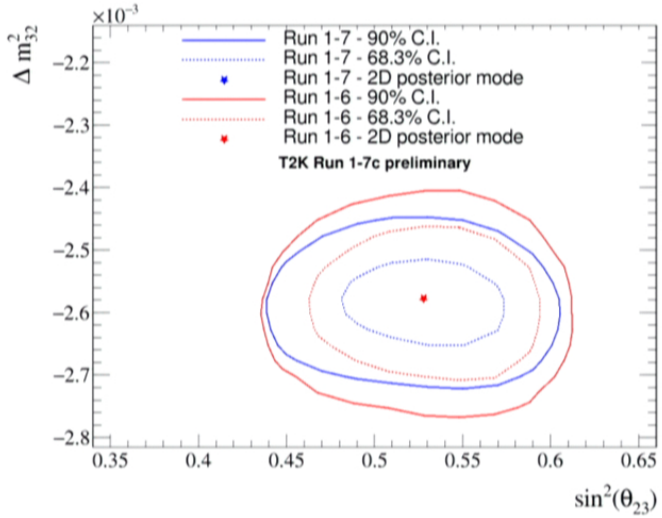


Θ_{23}

- Maximal values still favoured
  - $\sin^2\theta_{23}$ ~0.5 (θ_{23} ~$\pi/4$)
  - mild tension with recent NOvA measurements

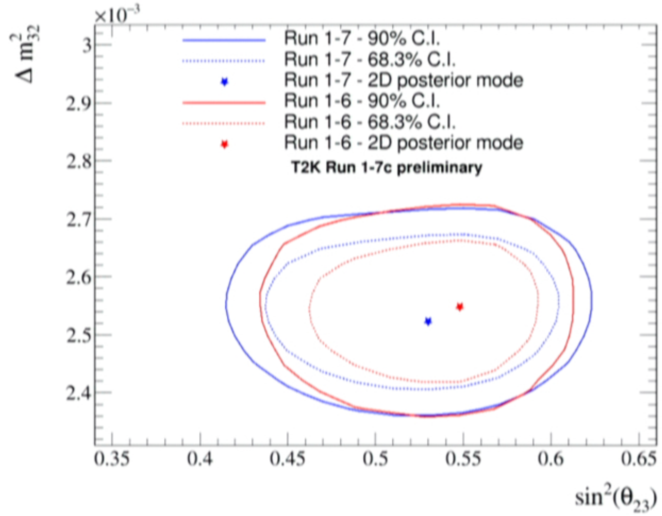


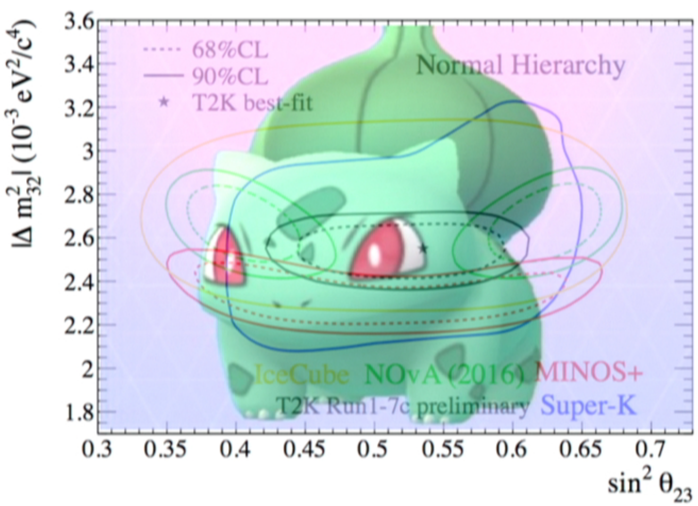


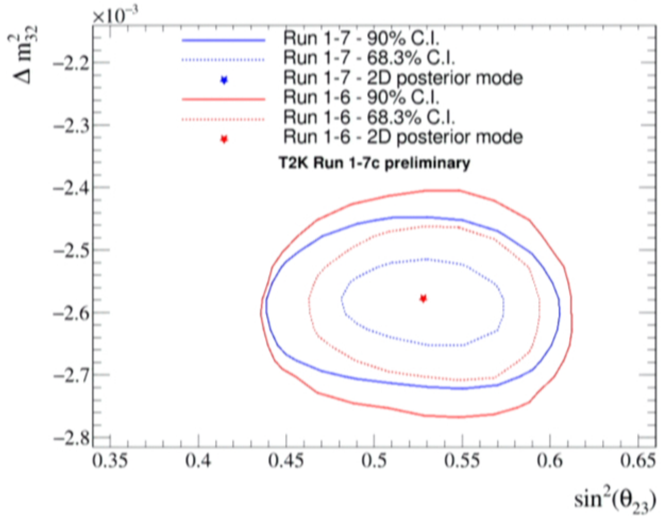


Θ_{23}

- Maximal values still favoured
  - $\sin^2\theta_{23} \sim 0.5$ ($\theta_{23} \sim \pi/4$)
  - mild tension with recent NOvA measurements

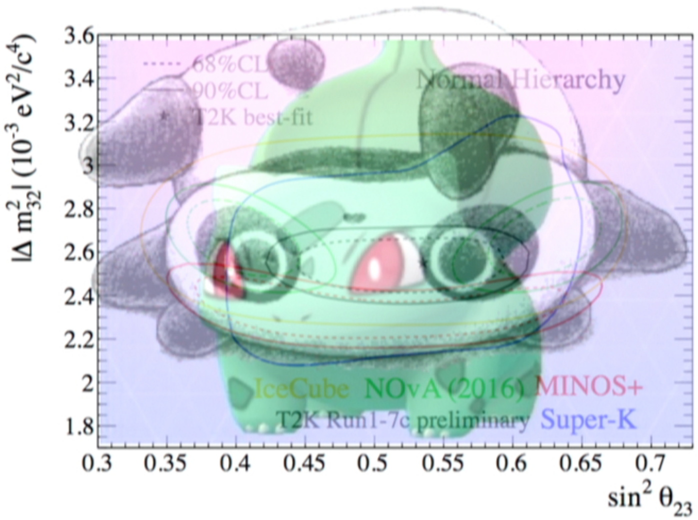


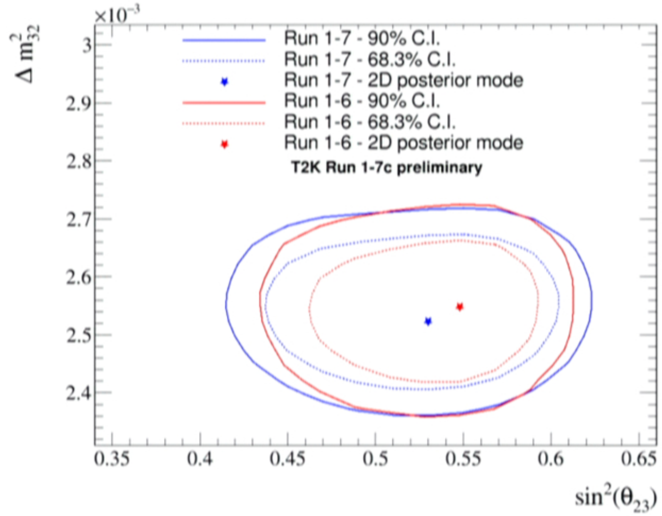


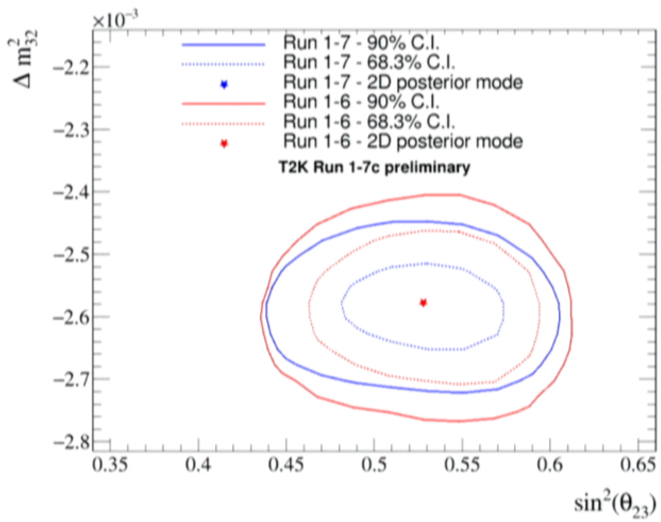


Θ_{23}

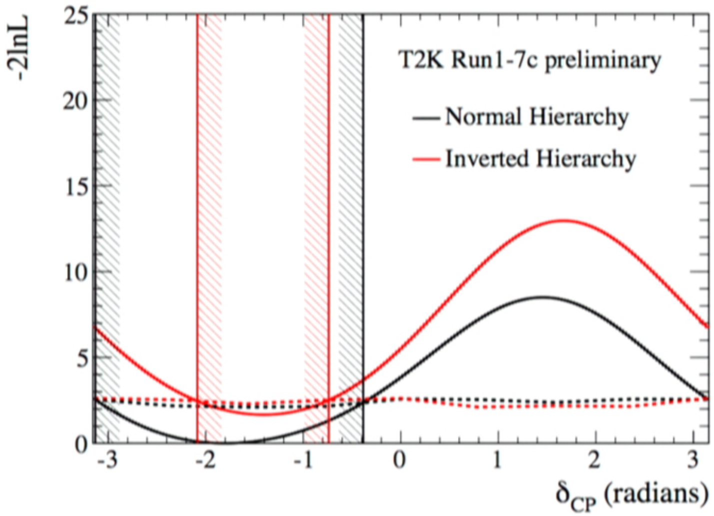
- Maximal values still favoured
  - $\sin^2\theta_{23}$ ~0.5 (θ_{23} ~π/4)
  - mild tension with recent NOvA measurements



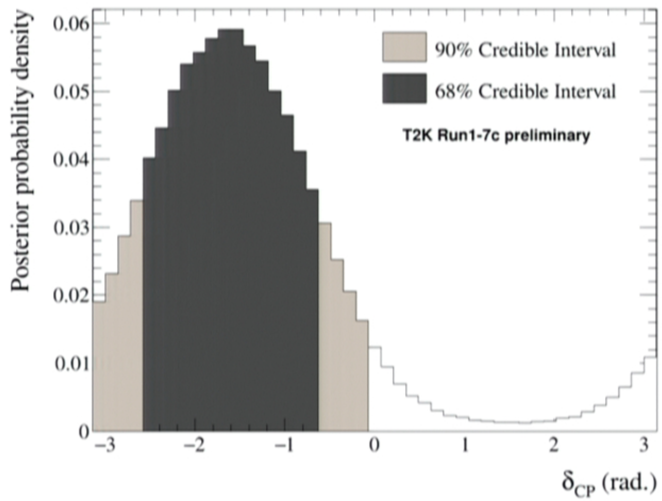


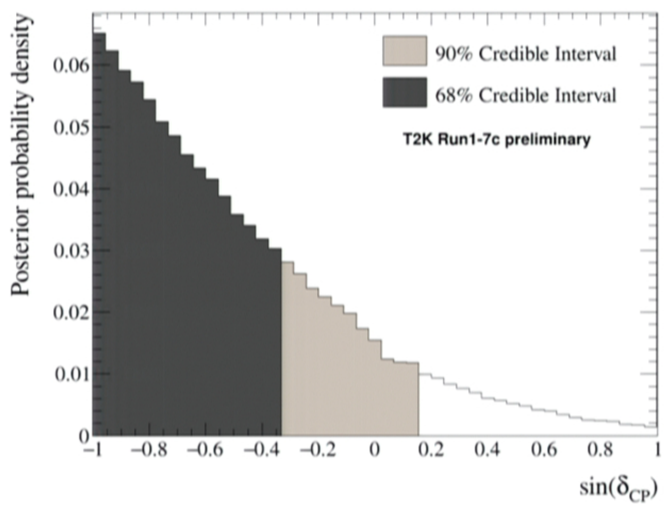


δ_{CP}



- Above: frequentist analysis:
  - sin δ_{CP}=0 excluded at 90% confidence level
- Right: Bayesian posterior density
  - Exclusion of sin $\delta_{CP} \neq 0$ depends on prior
  - data is still quite weak,
  - more statistics are needed



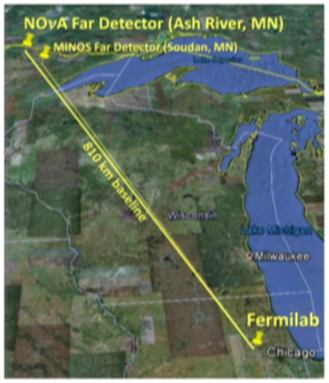


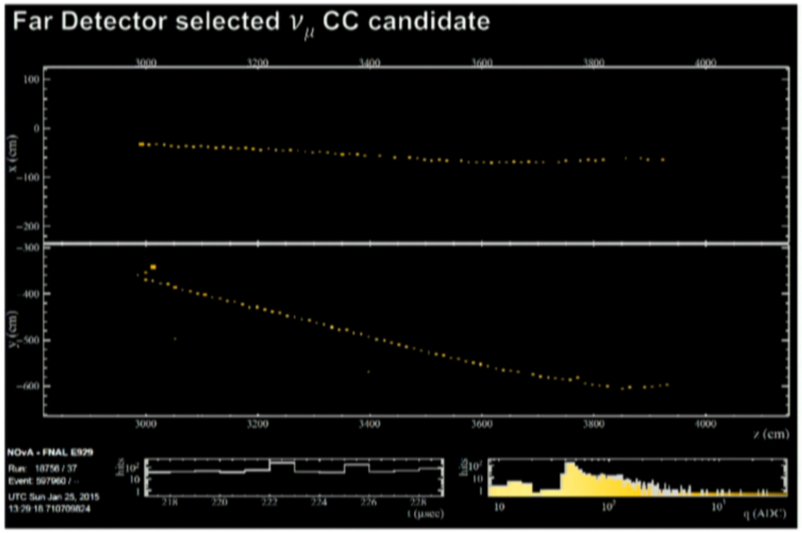
Θ_{23} OCTANT/MASS HIERARCHY

- We can also evaluate the posterior probabilities for the θ_{23} octant and mass hierarchy
  - marginalize over all other parameters to determine posterior probability for octant/hierarchy combinations
  - (as expected) slight preference for NH and $\sin^2\theta_{23} > 0.5$

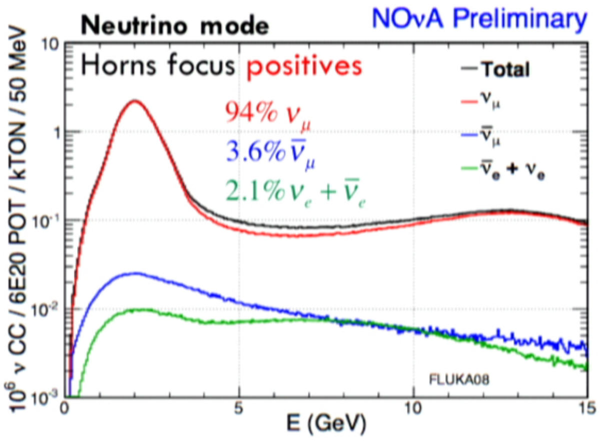
	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.232	0.087	0.319
$\sin^2\theta_{23} > 0.5$	0.487	0.193	0.681
SUM	0.719	0.281	1.000

NOVA



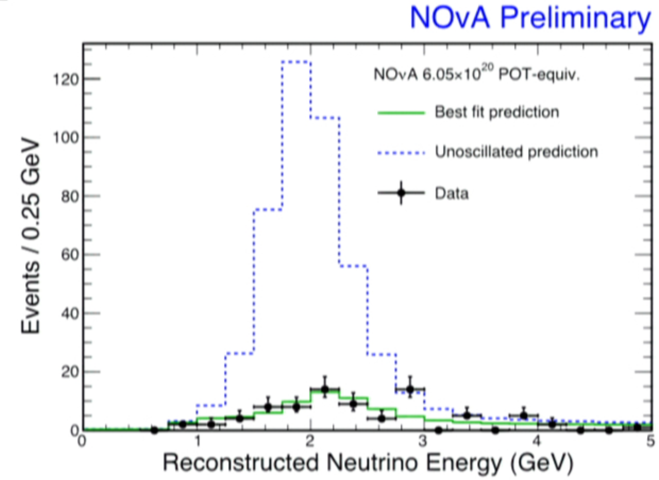


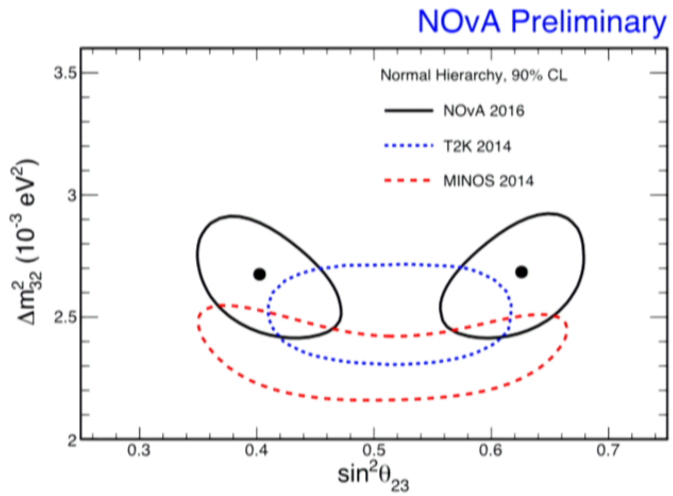
- Long baseline neutrino experiment from FNAL to Ash Hill with 810 km baseline
  - higher neutrino energy
  - larger matter effect and sensitivity to mass hierarchy
- Large 14kt fully active scintillating tracking detector

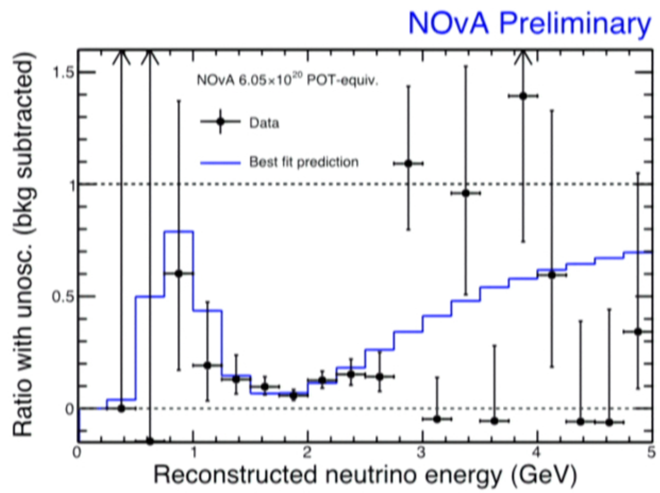


NOvA ν_μ DISAPPEARANCE

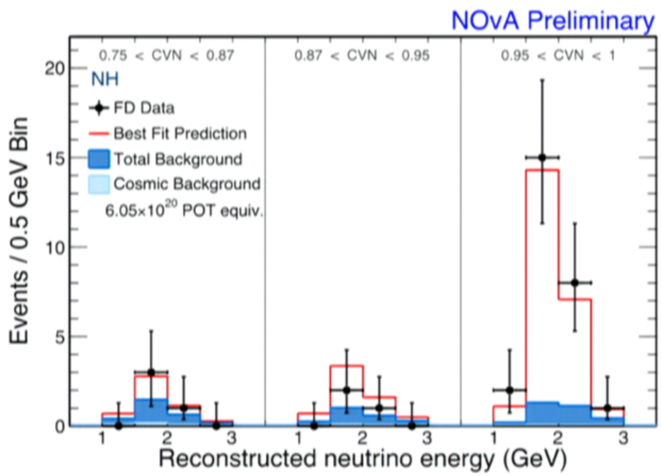
- ν_μ CC events seen at NOvA
- Like T2K, a dramatic deficit from neutrino oscillations observed
- Unlike T2K, the data suggests that the oscillation is not maximal
  - $\sin^2\theta_{23} = 0.5$ excluded at 2.5 σ



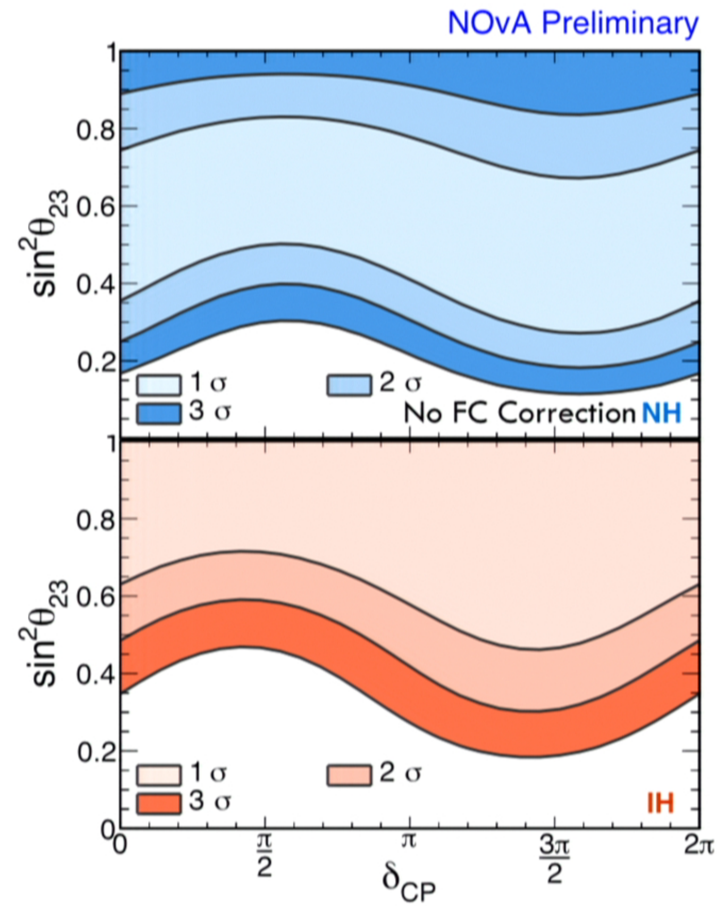




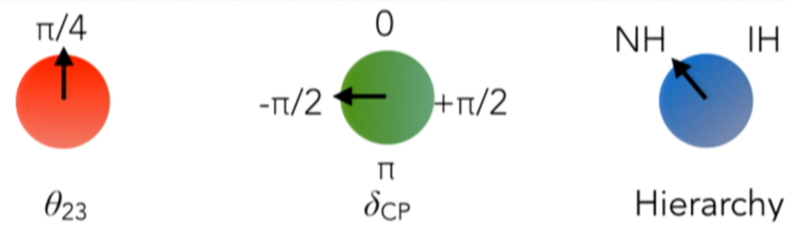
NOvA ν_e

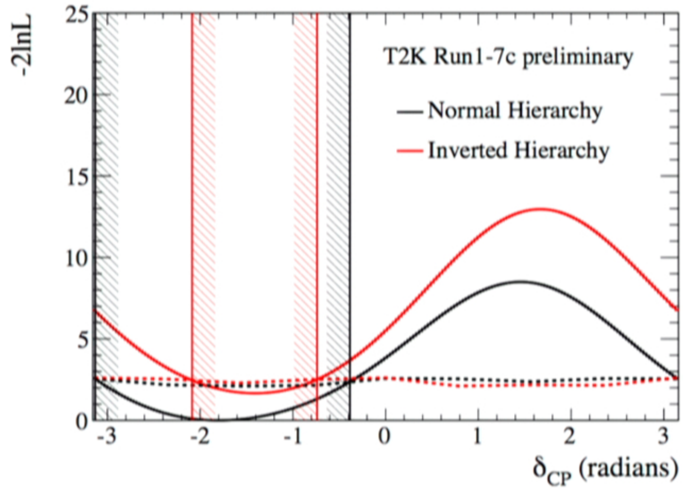


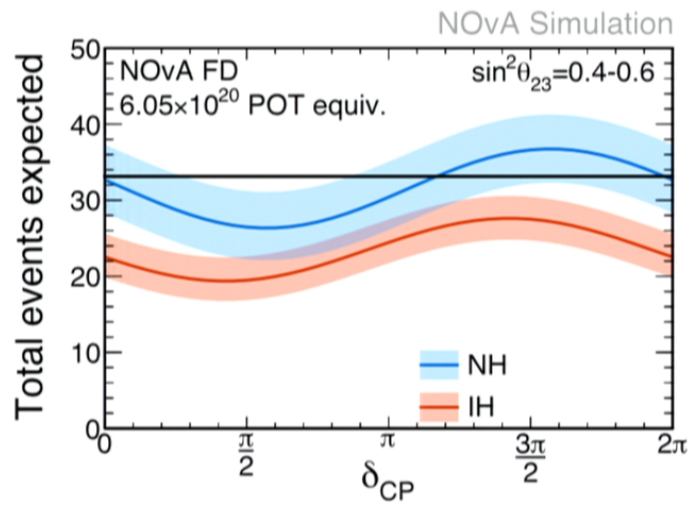
- 33 ν_e candidates observed
  - with θ_{23} and θ_{13} constrained by NOvA disappearance and reactor measurements, large fraction of inverted hierarchy disfavored.



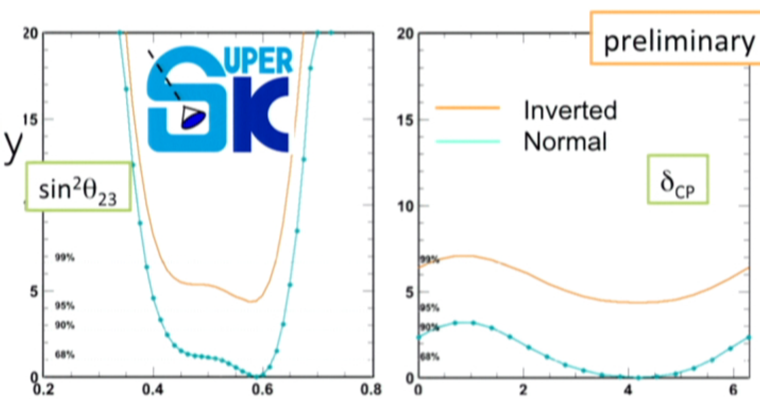
δ_{CP} GLOBALLY







- T2K, SK, and NOvA see large $\nu_\mu \rightarrow \nu_e$ appearance rate that weakly favours NH and δ_{CP} = -π/2



NEUTRINO ECONOMICS

	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \to \nu_e$	SIGNAL $\bar{\nu}_\mu \to \bar{\nu}_e$	BEAM ν_e	BEAM ν_μ	NC
ν MODE	0	145.8	**106.0**	1.2	20.6	0.7	17.2
	$-\pi/2$	170.9	**131.4**	0.8			
$\bar{\nu}$ MODE	0	47.5	5.6	**24.4**	8.6	0.2	8.6
	$-\pi/2$	41.5	6.5	**17.5**			

- Expected event rate for 50% ν/ 50% $\bar{\nu}$ running at T2K ~2021 with 7.8×10^{21} POT

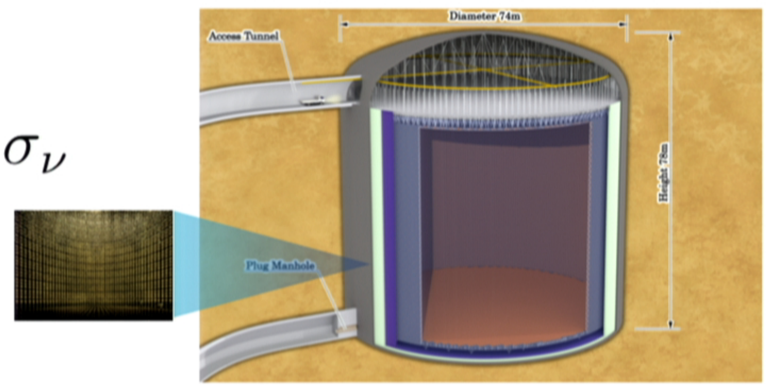
Neutrino source upgrades

- 400 kW → 750 kW →1.3 MW

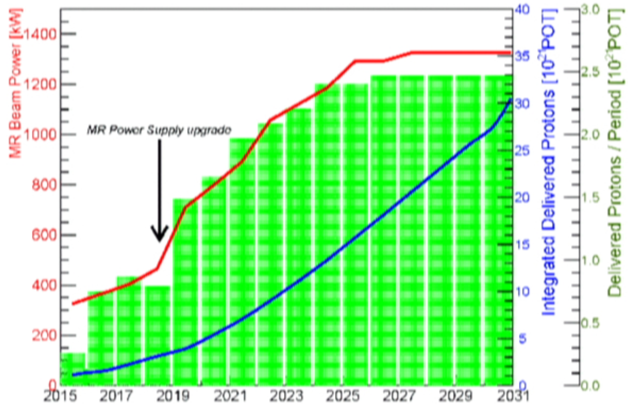
$$N \propto \boxed{\Phi_\nu} \times \boxed{V \times \rho \times \epsilon} \times \sigma_\nu$$

Detector upgrades

- Super-Kamiokande →Hyper-Kamiokande



J-PARC MAIN RING UPGRADE



JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX power [kW] (study/trial)	320	> 360	400	450	700	800	900
SX power [kW] (study/trial)	-	33 - 40	50	50-70	50-70	~100	~100
Cycle time of main magnet PS New magnet PS	2.48 s R&D	Large scale 1st PS	Mass production installation/test		1.3 s	1.3 s	1.2 s
High gradient rf system 2nd harmonic rf system VHF cavity	Manufacture, installation/test R&D, manufacture, installation/test R&D						
Ring collimators		Add.collimators (2 kW)	Add.collimators (3.5kW)				
Injection system FX system	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF septum, HF septa manufacture /test						
SX collimator / Local shields		Local shields					
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS					

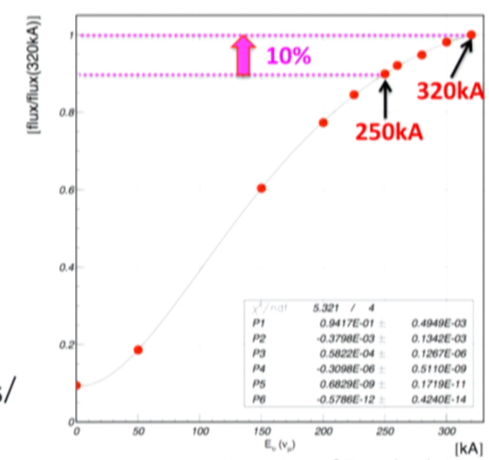
- Recent studies have shown the potential for high power neutrino running at J-PARC
  - Summer 2015: equivalent of 372 kW beam extracted with 2 out of 8 bunches with 2.48 acceleration cycle
    - with power supply upgrade (1.3 sec cycle) equivalent to >700 kW beam
    - design power of 750 kW is within reach!
- **MR power supply upgrade approved!**
  - now looking to 1 MW power and beyond to **1.3 MW**
  - **investigate extended T2K run to ~2026**

T2K-PHASE II STATISTICS

	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \to \nu_e$	SIGNAL $\bar{\nu}_\mu \to \bar{\nu}_e$	BEAM ν_e	BEAM ν_μ	NC
ν MODE	0	454.6	**346.3**	3.8	72.2	1.8	30.5
	$-\pi/2$	545.6	**438.5**	2.7			
$\bar{\nu}$ MODE	0	129.2	16.1	**71.0**	28.4	0.4	13.3
	$-\pi/2$	111.8	19.2	**50.5**			

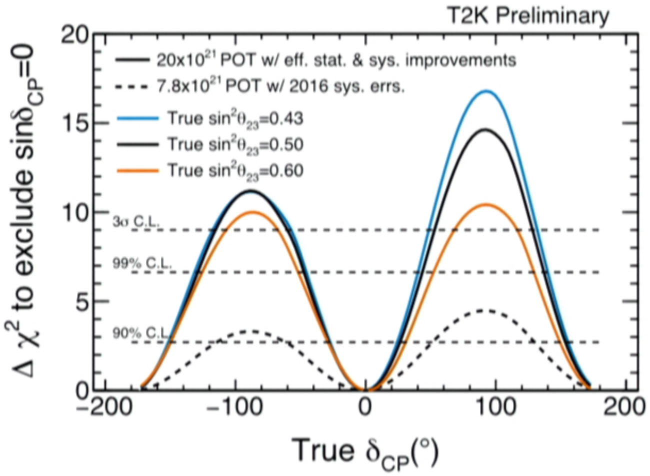
- Assumes 2.0×10^{22} POT
  - ~3x currently approved 7.8×10^{21} POT
- Increased horn current
  - ~10% higher Φ_ν/POT
  - less "wrong sign" contamination (e.g. ν in $\bar{\nu}$ beam)
- Enlarged SK samples for higher statistics
  - Following sensitivity plots assume 50% higher statistics/POT relative to current T2K

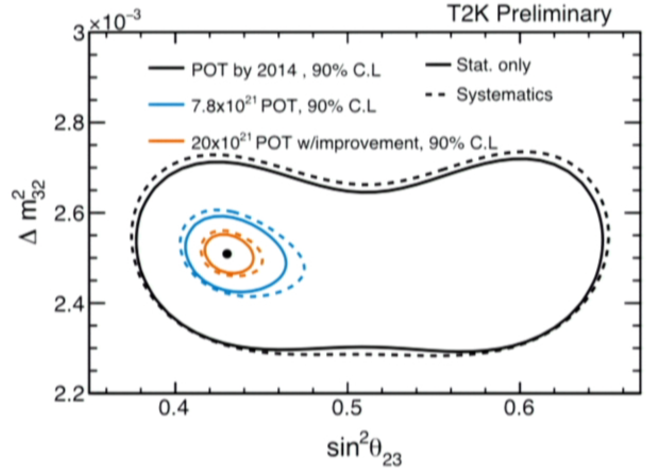
ν flux SK (0.4-1.0GeV, normlized)



Courtesy of T.Nakadaira

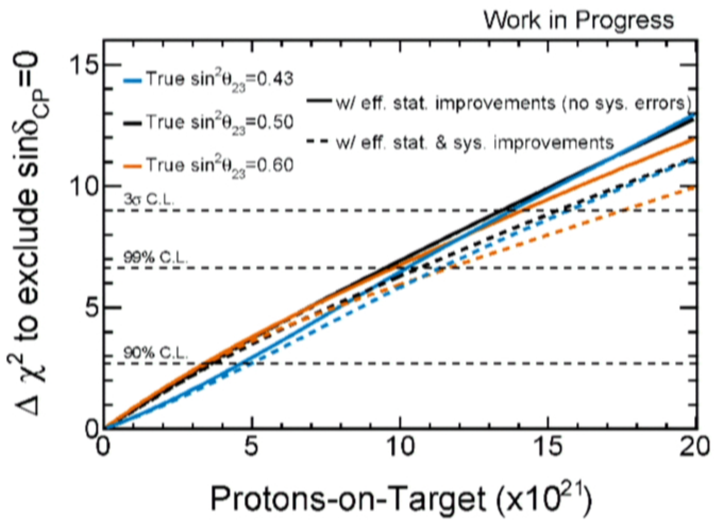
T2K-II SENSITIVITY





- If mass hierarchy is not resolved (left):
  - CP violation with δ_{CP} ~-π/2 can be observed with >3 x significance
- If mass hierarchy is resolved (e.g. T2K+NOvA)(right)
  - Expect 36% of δ_{CP} values give >3 σ significance for CP violation

IMPACT OF SYSTEMATICS

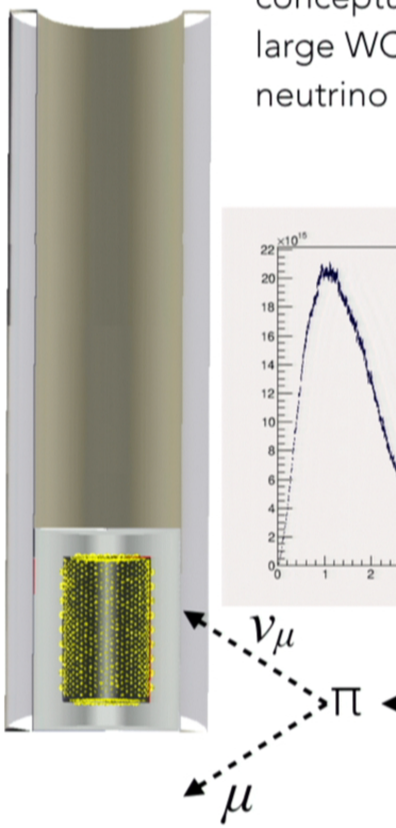


current T2K systematics

	1 RING μ		1 RING e		
	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	ν/$\bar{\nu}$
SK DETECTOR	4.6	3.9	2.8	4.0	**1.9**
SK FSI, HAD.	1.8	2.4	2.6	2.7	**3.7**
ND CONSTR. Φ, σ	2.6	3.0	3.0	3.5	**2.4**
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.0	0.0	2.6	1.5	**3.1**
NC 1γ	0.0	0.0	1.4	2.7	**1.2**
NC OTHER	0.7	0.7	0.2	0.3	**0.1**
TOTAL	5.6	5.5	5.7	6.8	**5.9**
	0.0	0.0	4.2	4.0	**0.1**

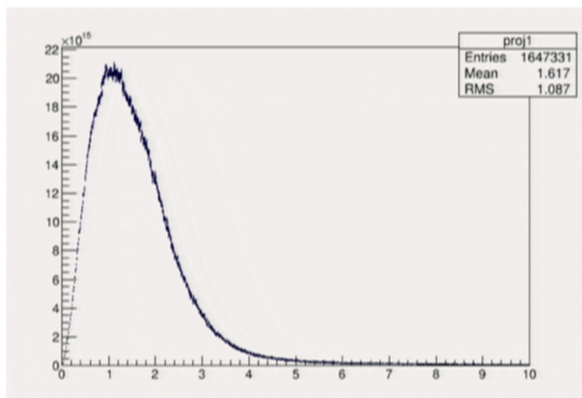
- systematics will have significant impact on ultimate sensitivity
  - sensitivity assumes that current T2K systematics are reduced to 2/3 of current size
- Largest systematics
  - final state interactions/hadronic interactions at SK
  - theoretical errors on the relative cross section of ν_e/ν_μ, $\bar{\nu}_e/\bar{\nu}_\mu$
  - nuclear modelling errors (multinucleon correlations, etc.)

NuPRISM

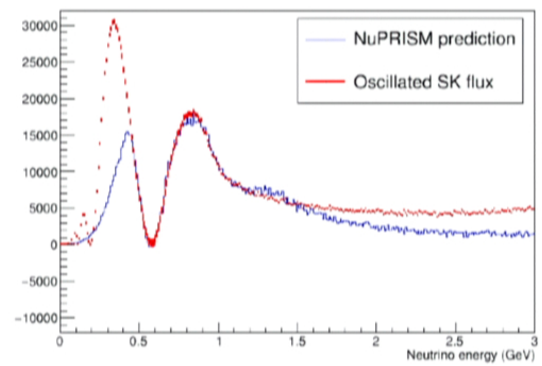


conceptual design:
large WC detector ~1 km from neutrino beam

$\Phi_\nu(E)$

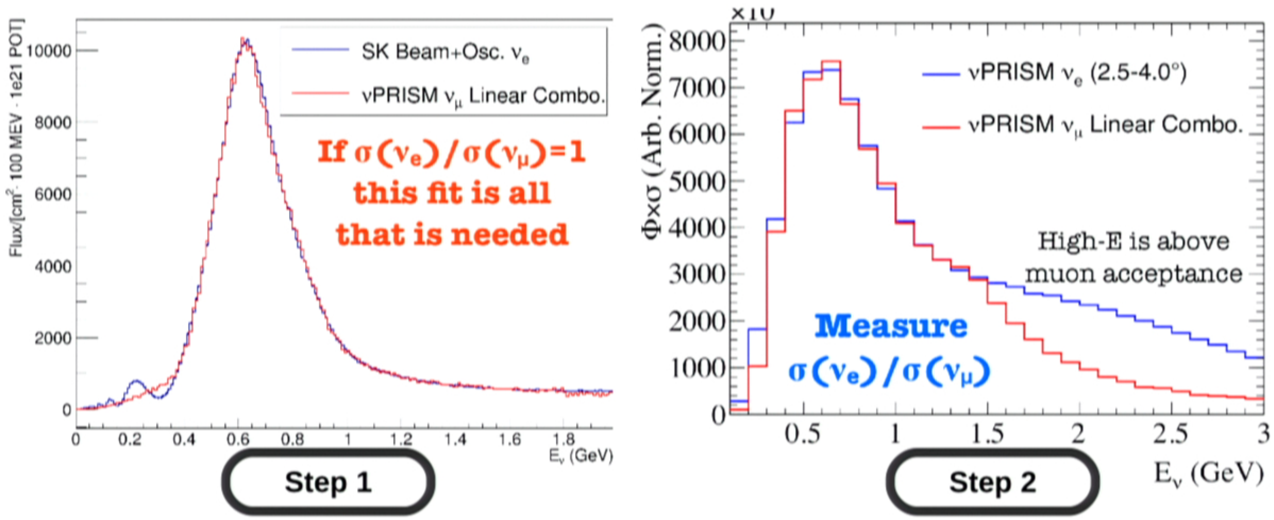


- A new concept to exploit the variation of the neutrino energy spectrum with off-axis angle
- Data taken with different spectra can directly predict neutrino interactions with arbitrary neutrino fluxes including effects from oscillation



$$N(\nu_\mu \rightarrow \nu_e) = \Phi_\nu(E_\nu) \times \sigma_\nu(E_\nu) \times \varepsilon(E_\nu) \times P(\nu_\mu \rightarrow \nu_e; E_\nu)$$

MEASURING ν_e/ν_μ CROSS SECTION

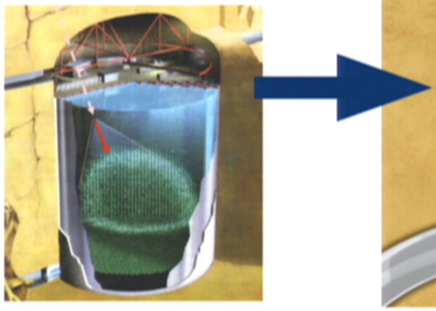


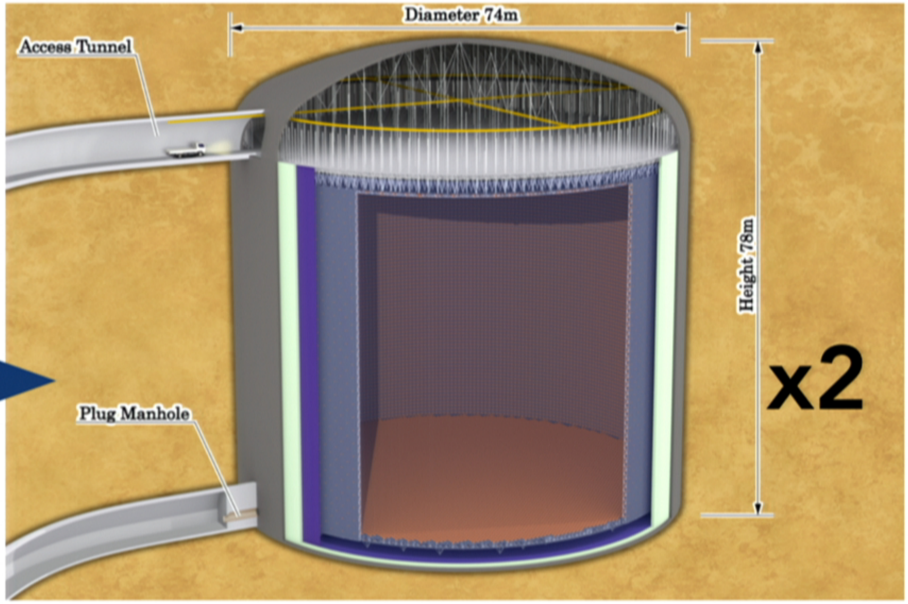
- Extension of concept allows measurement of energy dependence of ν_e/ν_μ ($\overline{\nu}_e/\overline{\nu}_\mu$) cross section
  - replicate ν_μ interactions expected from intrinsic ν_e spectrum
  - compare observed intrinsic ν_e events to directly obtain cross section ratio
- NuPRISM can directly address leading systematics in T2K
  - reduce model/theory dependent errors
  - reduce final state interaction and hadronic interaction uncertainties.
- Many other physics topics (short baseline neutrino oscillations from sterile neutrinos, NC cross sections,etc.)

Detector upgrades

- Super-Kamiokande →Hyper-Kamiokande

$$N \propto \Phi_\nu \times \boxed{V \times \rho \times \epsilon} \times \sigma$$





ELUCIDATING CPV

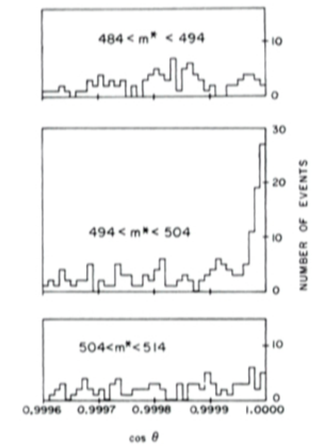


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

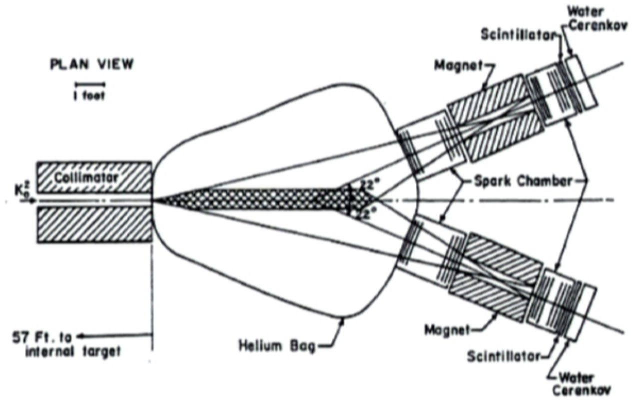
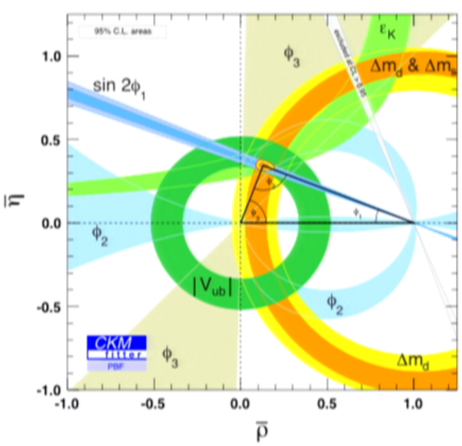
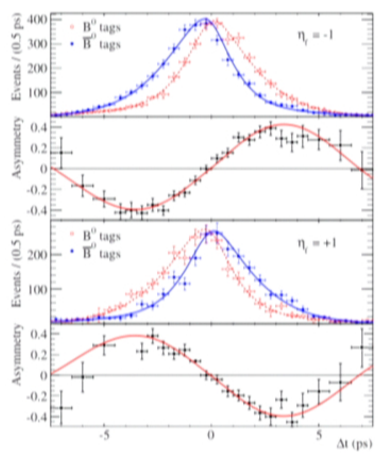


Fig. 9a. Set-up used to detect $K_2 \to \pi^+\pi^-$.



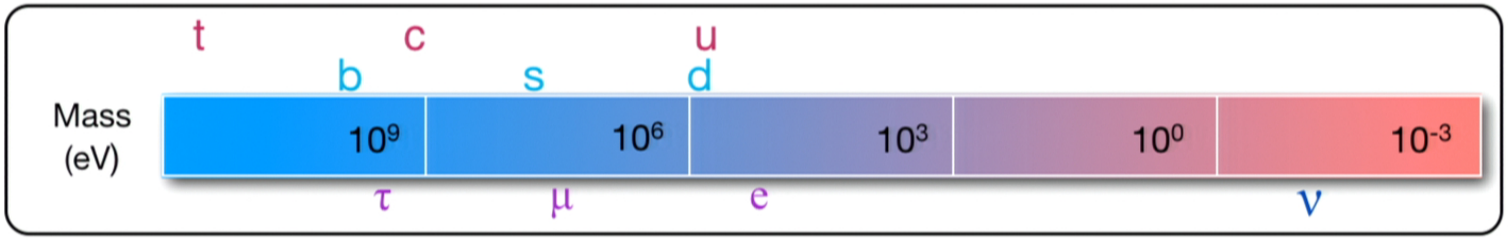


- 1964: Initial discovery of CP violation in $K_L \to \pi^+ + \pi^-$
- Nearly 50 years later, we know that this arises from a complex phase in quark mixing
- Observing CPV in neutrinos is the **beginning** of a program . . .

ANSWERS?

$$|U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix} \qquad |U_{MNSP}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quark **Lepton**

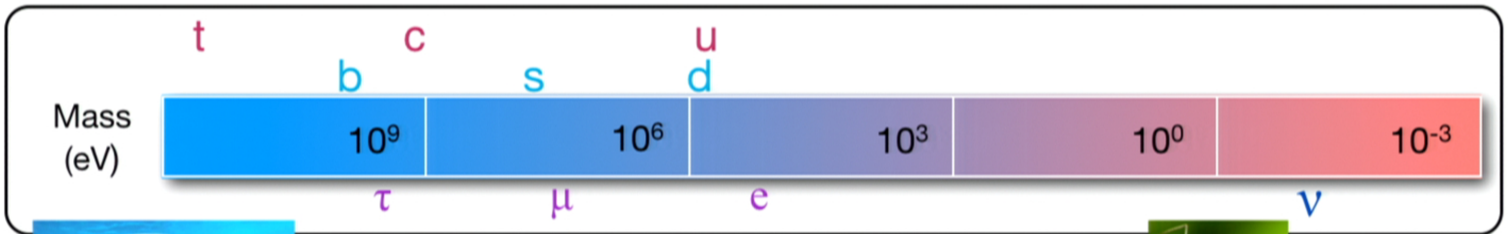


- Why is quark and lepton mixing so different?
  - is neutrino mixing "maximal"?
- Why are neutrino masses so tiny?
  - quarks/charged leptons masses from Higgs mechanism
  - do neutrinos get mass some other way?

ANSWERS?

$$|U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix} \qquad |U_{MNSP}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quark **Lepton**



u	c	t
d	s	b
ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

- Why is quark and lepton mixing so different?
  - is neutrino mixing “maximal”?
- Why are neutrino masses so tiny?
  - quarks/charged leptons masses from Higgs mechanism
  - do neutrinos get mass some other way?

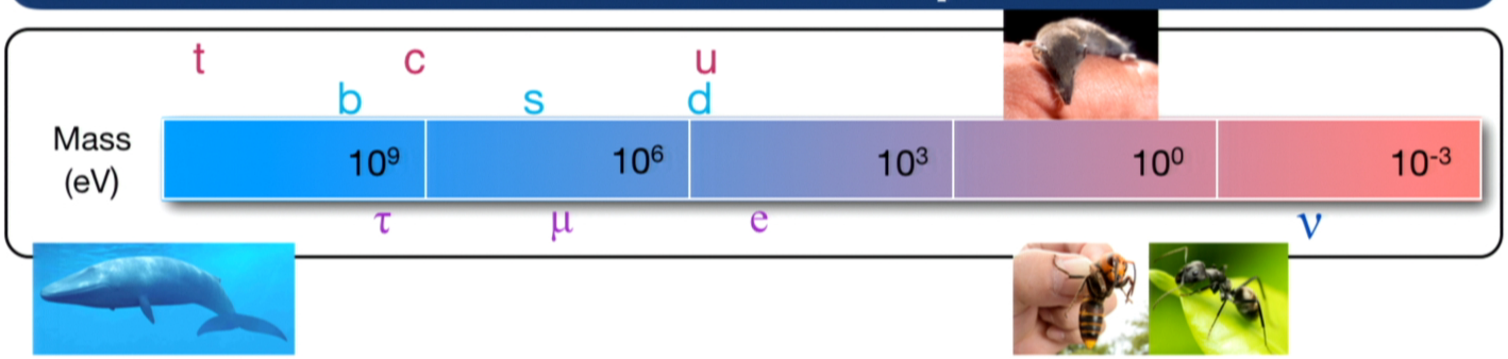
ANSWERS?

$$|U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$

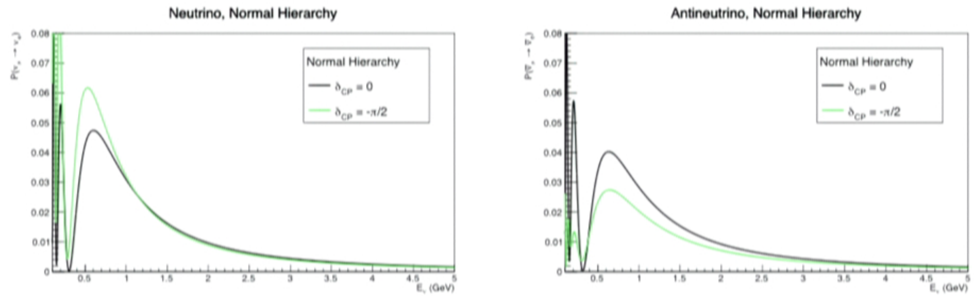
Quark

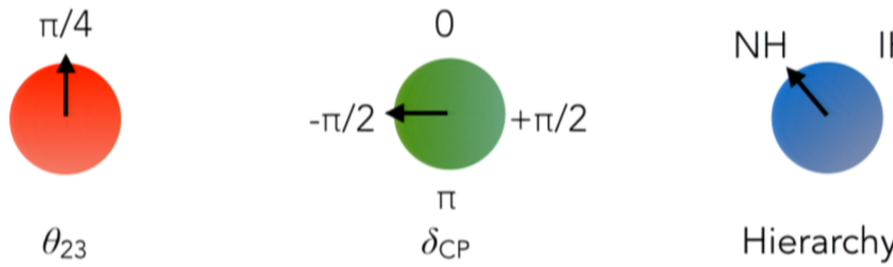
$$|U_{MNSP}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Lepton



- Why is quark and lepton mixing so different?
  - is neutrino mixing "maximal"?
- Why are neutrino masses so tiny?
  - quarks/charged leptons masses from Higgs mechanism
  - do neutrinos get mass some other way?





There is a most profound and beautiful question associated with the observed coupling constant. It is a simple number that has been experimentally determined to be close to 137.03597. It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it. Immediately you would like to know where this number for a coupling comes from: is it related to pi or perhaps to the base of natural logarithms? Nobody knows.
It's one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by man.

CONCLUSIONS

- A full understanding of CPV is needed!
  - we now know that neutrinos can have CPV in their mixing. Do they? How/Why?
- J-PARC is positioned to make decisive developments in neutrino CPV with
    - MW-class T2K beam line and near detectors
    - Super-Kamiokande detector
  - upcoming improvements
    - Ongoing analysis and hardware improvements at T2K
    - **J-PARC MR: 0.4 MW → >0.7 MW (2019)→ >1.3 MW (~2023)**
    - Hyper-Kamiokande: 22.5 kT → 192 kT (2026) → 384 kT (2032)
- A world-leading, continuous, staged program
  - T2K: leading LBL experiment (~2021) with NOvA towards possible first indications of CPV and MH resolution.
  - "T2K Phase II": first evidence for CP violation? (2021-2026)
  - Hyper-K: observation/precision measurement of CPV and other oscillation parameters towards elucidating its source (2026 and beyond)
    - + incredible program of proton decay, neutrino astrophysics, and more.