Recent LBL Neutrino Oscillation Results

NuTheories:

Physics of neutrinos beyond the standard 3 x 3 oscillation framework

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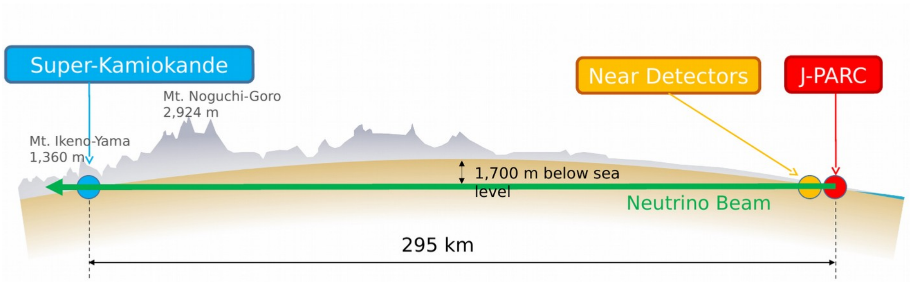
Outline

- Motivation
- T2K and NOνA Experiments
- Oscillation Results:
  - Muon (+Anti-)Neutrino Disappearance
  - Electron (+Anti-)Neutrino Appearance
  - Joint Fits
- Prospects, Outlook and Summary



3-Flavor Mixing

- 3-flavor mixing describes (almost) all neutrino oscillation phenomena (3 mixing angles, 2 independent mass splittings, 1 CPV phase)

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

Atmospheric & accelerator:
$\theta_{23} \sim 45^o$
$(\Delta m_{23})^2 \sim 2.4\mathrm{x}10^{-3}\ \mathrm{eV}^2$

Interference:
$\theta_{13} \sim 9^o$ and δ_{CP}=??

Solar & reactor:
$\theta_{12} \sim 34^o$
$(\Delta m_{12})^2 \sim 8\mathrm{x}10^{-5}\ \mathrm{eV}^2$

Muon neutrino disappearance ($\nu_\mu \rightarrow \nu_\mu$) :

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^2\theta_{13}\sin^2 2\theta_{23})\sin^2(\Delta m^2_{32}\frac{L}{4E})$$

→ **Sensitive to:**
θ_{23}, $|\Delta m^2_{31}|$ (~$|\Delta m^2_{32}|$)
($\Delta m^2_{32} = m^2_3 - m^2_2$)

Electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$):

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$

Leading term

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

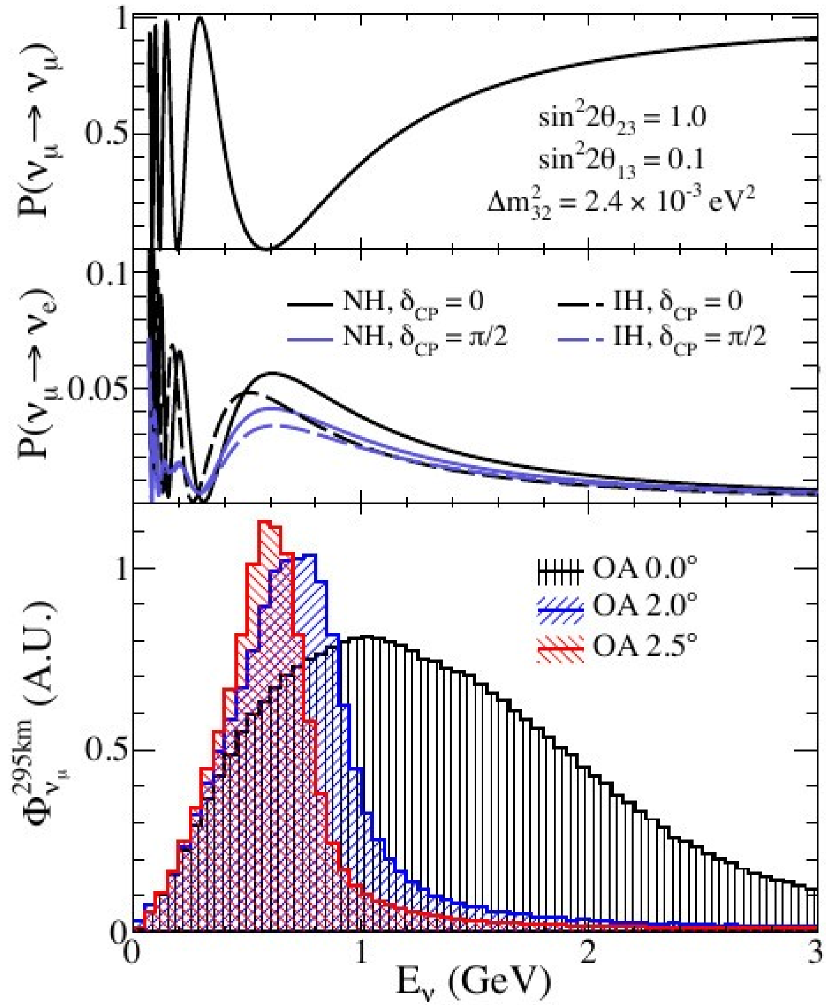
CP violating

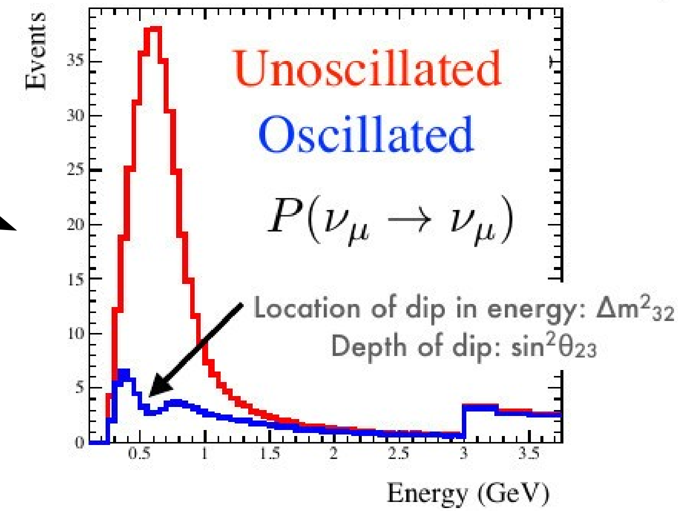
[($P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ δ turns into – δ and a to -a (“a” matter effect term)]

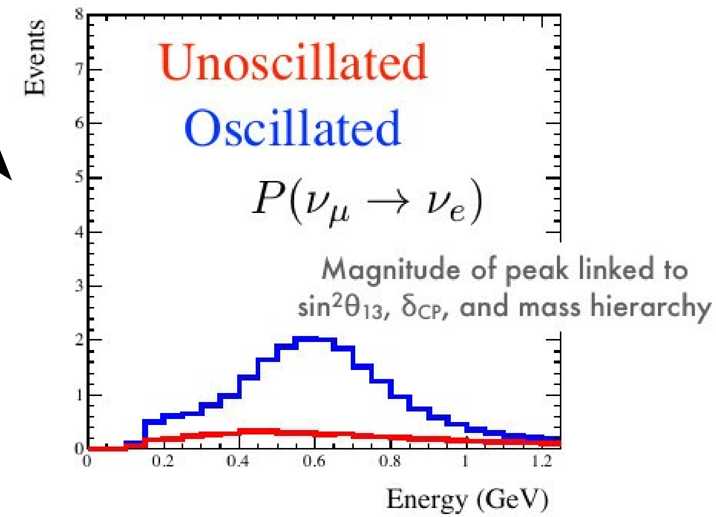
→ **Sensitive to:**
θ_{13}, δ_{CP}, θ_{23}, Δm^2_{31}

Depends on sign of mass difference: *i.e.* Mass Ordering

Oscillation Primer







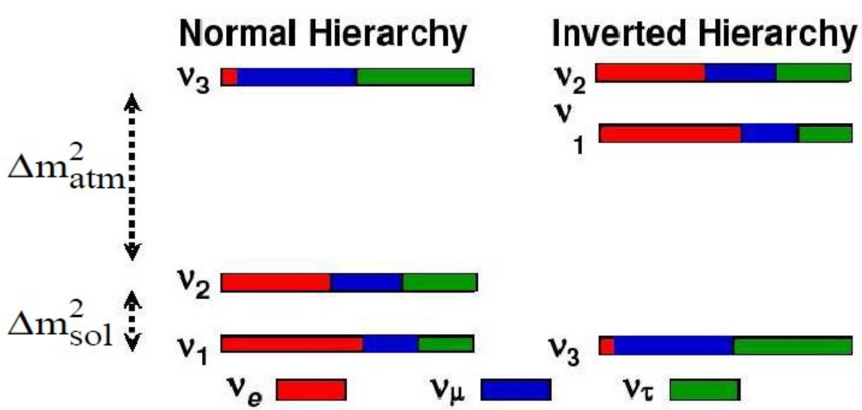
What Do We Know?

Solar+KamLAND → $\theta_{12} \sim 34^0$

SK, MINOS, T2K, NOνA → $\theta_{23} \sim 45^0$

Daya Bay, Reno, Double Chooz → $\theta_{13} \sim 9^0$

(T2K: $\theta_{13} \neq 0$ → In Appearance Channel)



$\Delta m^2_{21} = (7.65 + \pm 0.23) \times 10^{-5}$ eV^2

sign of the mass difference, $\Delta m^2_{21} > 0$.

$\Delta m^2_{32} (\approx \Delta m^2_{31}) = (2.40 \pm 0.12) \times 10^{-3}$ eV^2

What We Don't Know?

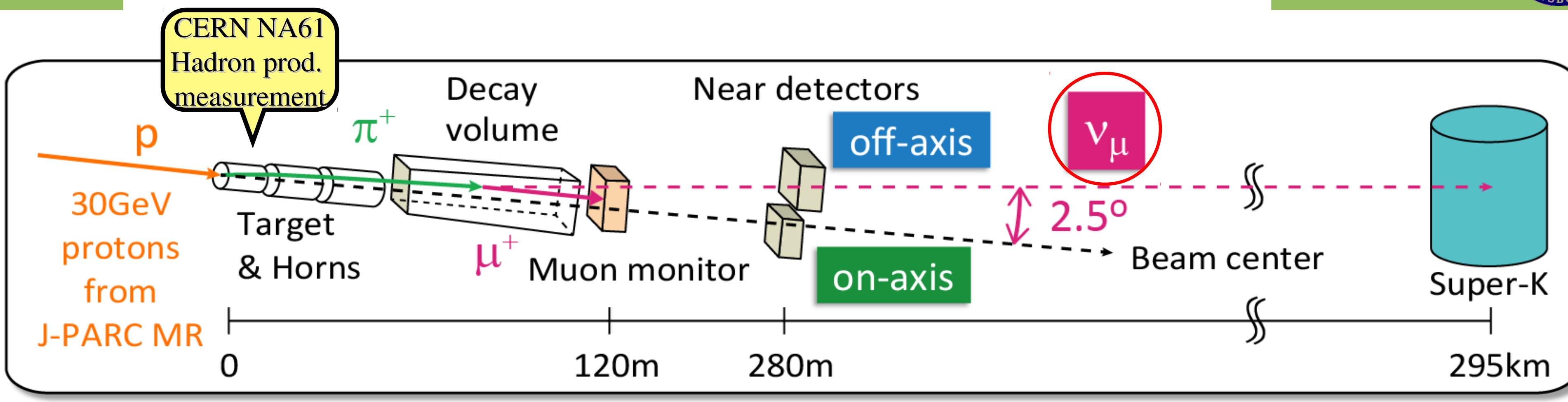
- **Value CP-Violating Phase:** δ
- θ_{23} **Maximal? Octant? (< or > 45^0)**
- **Sign of the mass difference:** $\Delta m_{32}^2 = m_3^2 - m_2^2$
  - **Normal Ordering (NO) > 0**
  - **Inverted Ordering (IO) < 0**
- **Are there any more ν's? (sterile)**
- **Are Neutrinos Dirac or Majorana?**
- **Absolute Mass Scale**

The T2K Experiment
(Tokai to Kamioka)

Goals:

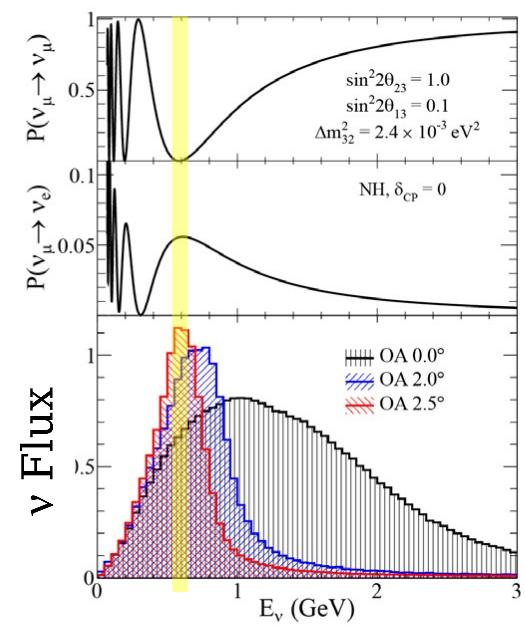
- Study ν_e and $\bar{\nu}_e$ appearance ($\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$): Explore δ_{CP} and $\theta_{13,\,23}$
- Precision measurement of ν_μ and $\bar{\nu}_\mu$ disappearance: Explore θ_{23} and Δm^2_{23}

Overview of T2K: Beam

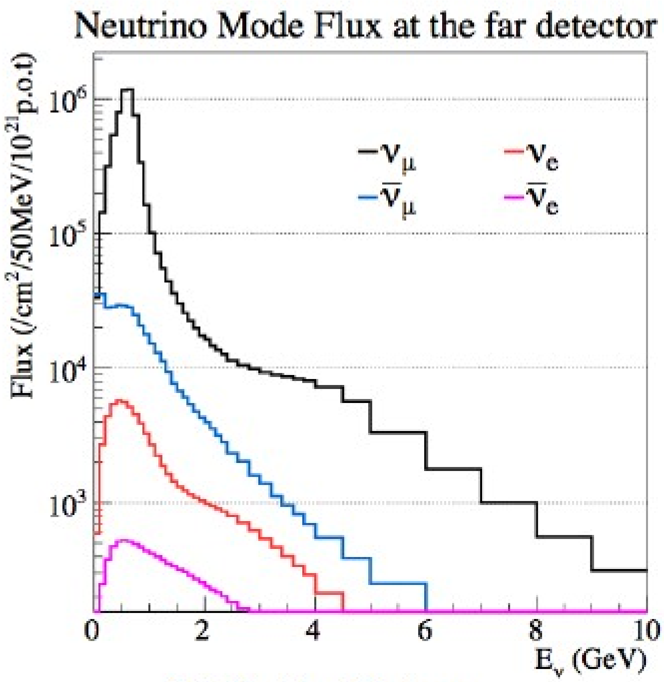


First Use of Off-axis ν_μ Beam:

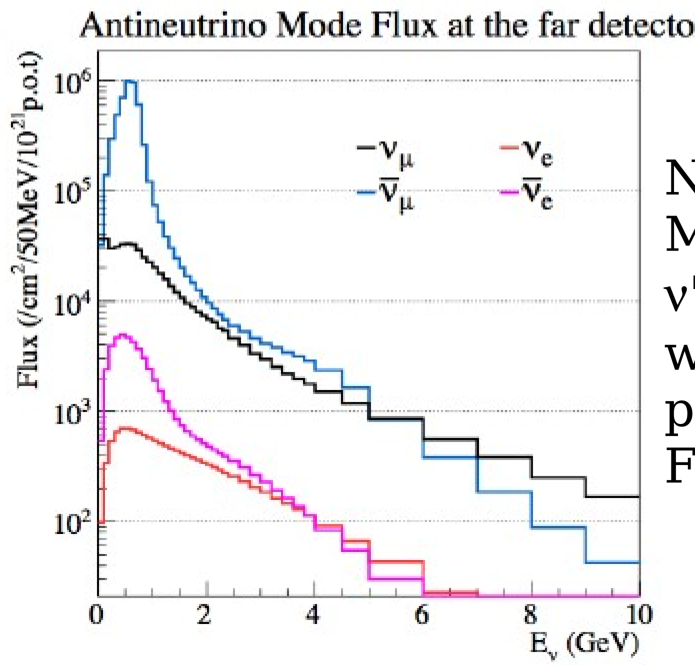
- Intense & high-quality beam (Beam direction stability < 1mrad)
  - ~1 mrad shift corresponds to ~2% energy shift at peak
- Low-energy narrow-band beam
- Can choose between ν and $\bar{\nu}$ by changing current direction in horns
- E_ν peak around oscillation maximum (~0.6 GeV)
- Small high-energy tail → reduces feed-down background events
- π,K production at target was measured using CERN NA61 exp.



Beam Configurations



SK: Neutrino Mode, ν_μ



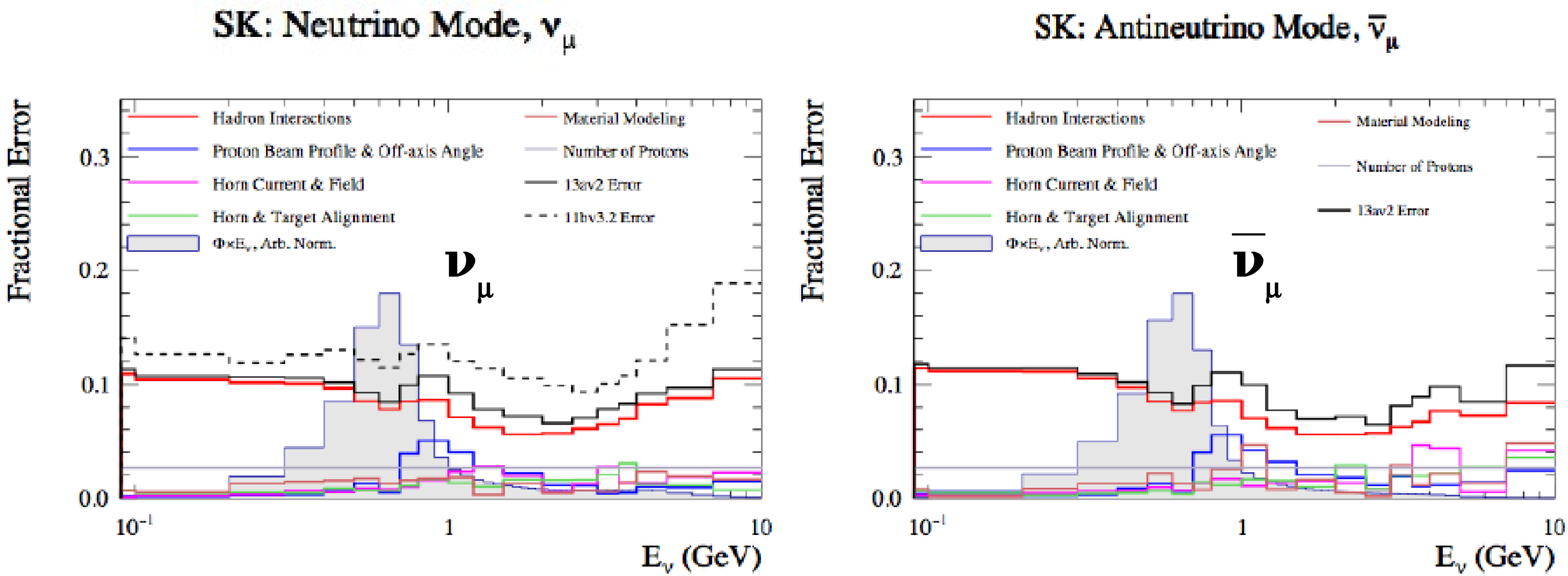
SK: Antineutrino Mode, $\bar{\nu}_\mu$

Note: More “WS” ν's in RHC when compared to FHC

ν – mode known as “forward horn current” (FHC) or “positive focusing” (PF)

$\bar{\nu}$ – mode known as “reverse horn current” (RHC) or “negative focusing” (NF)

Neutrino fluxes



- Present flux uncertainties smaller than 8% (at peak)
- Main systematics due to the hadron interactions modeling →
  - With NA61/SHINE measurements using T2K replica target → goal <5%

At These Energies Neutrino Cross-sections are Poorly Known

- **ν oscillations:**

→ We are now in a period of precision neutrino oscillation measurements

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23})\sin^2((1.27\Delta m^2_{23}L)/E_\nu)$$

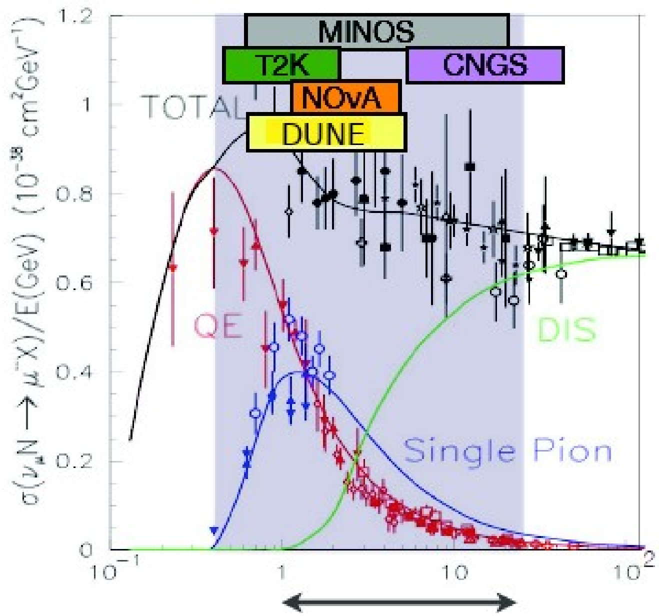
(ν_τ appearance example)

→ **Note oscillation probability depends on E_ν**

- However Experiments Calculate E_{rec}
- E_{rec} depends on Flux, σ, detector response, interaction multiplicities, target type, particle type produced and final state interactions: E_{rec} not equal to E_ν

→ Appearance Oscillation Measurements:

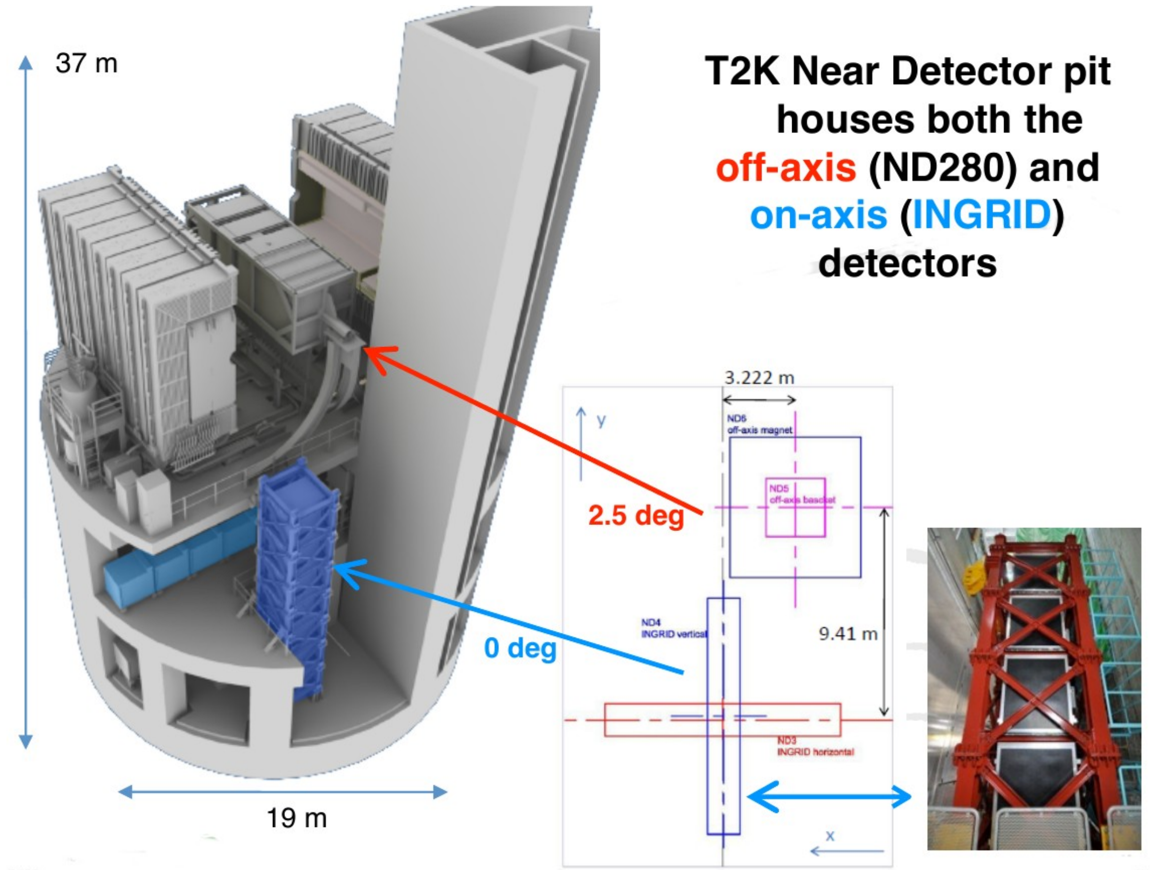
- Large Θ_{13} and CP violation - systematics important
- Need to understand backgrounds to ν_e searches:



MINERνA Energy Range

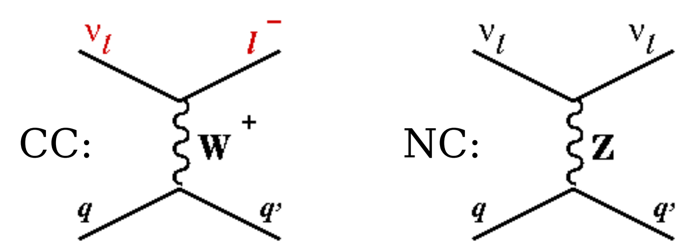
- **Need Precision understanding of Low energy (Few GeV) ν_μ & $\bar{\nu}_\mu$ cross sections to improve models.**

Overview of T2K: Near Detectors(ND280)



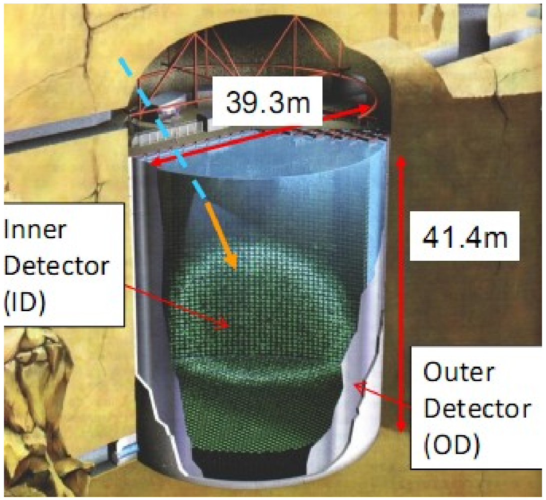
On-Axis Detector (INGRID) Monitor ν:
- **Beam direction**
- **Beam Intensity**

Off-Axis Detector:
- **In SK Direction**
- **Measure:**
  - **ν flux**
  - **Cross-section measurements using water targets to reduce systematic errors on oscillation parameters**



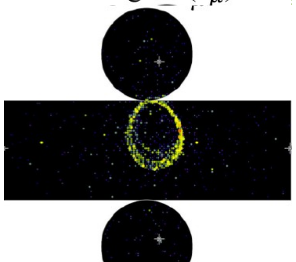
→ Used for monitoring of beam, flux constraints and systematic error reduction

The T2K Far Detector: Super-Kamiokande

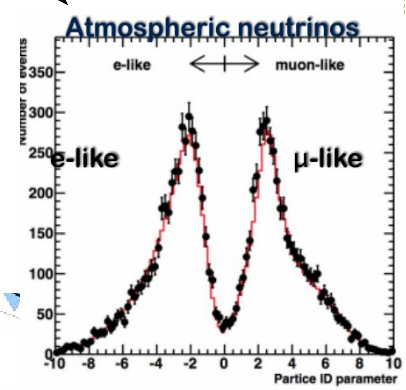


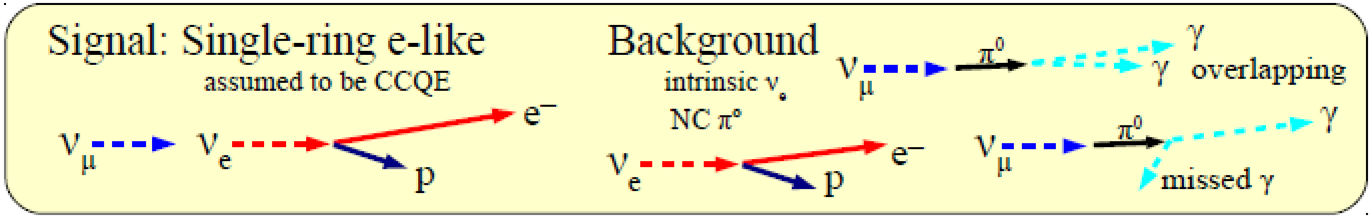
- 50 kiloton Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
- High ν_e signal efficiency plus high π^0 rejection
  - 32 kiloton inner volume:
    - Fiducial cut (*i.e.* cut on vertex distance to wall) optimized for each interaction type.
- Probability to misidentify muon as electron is small
- GPS time recorded in real-time for every spill
  - Associate events with J-PARC (beam)

Signal (ν_μ)

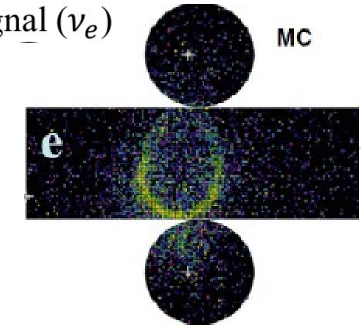


ν_μ CCQE



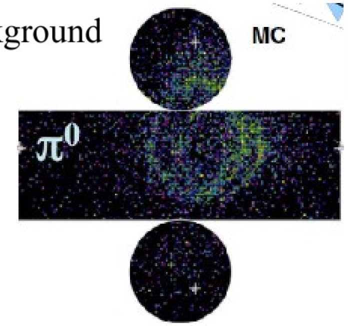


Signal (ν_e)



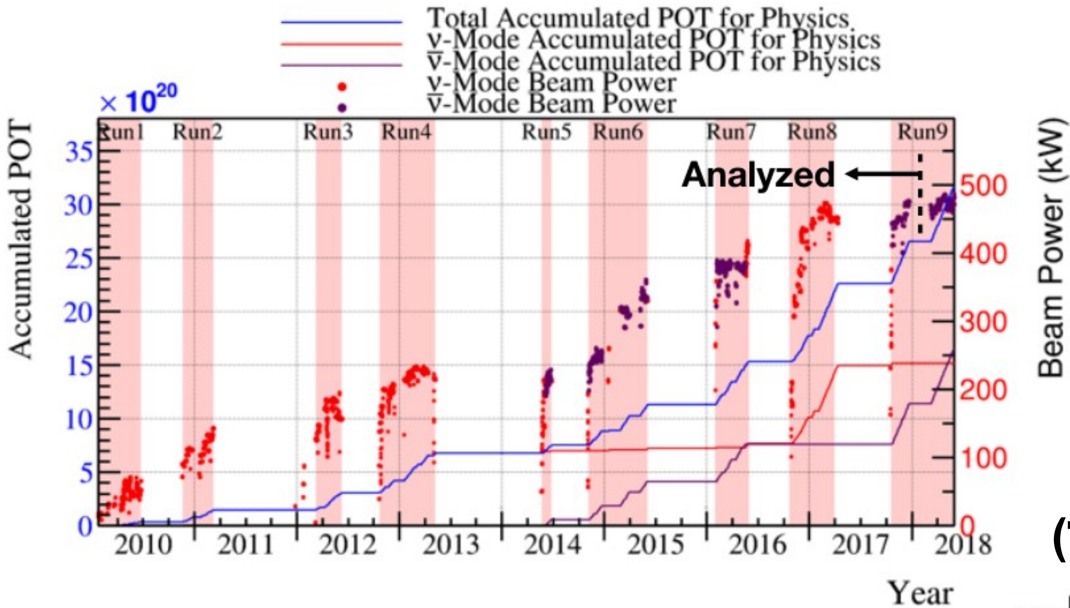
1 EM Shower:
1 Fuzzy Ring

Background



2 EM Showers:
2 or 1 Fuzzy Ring

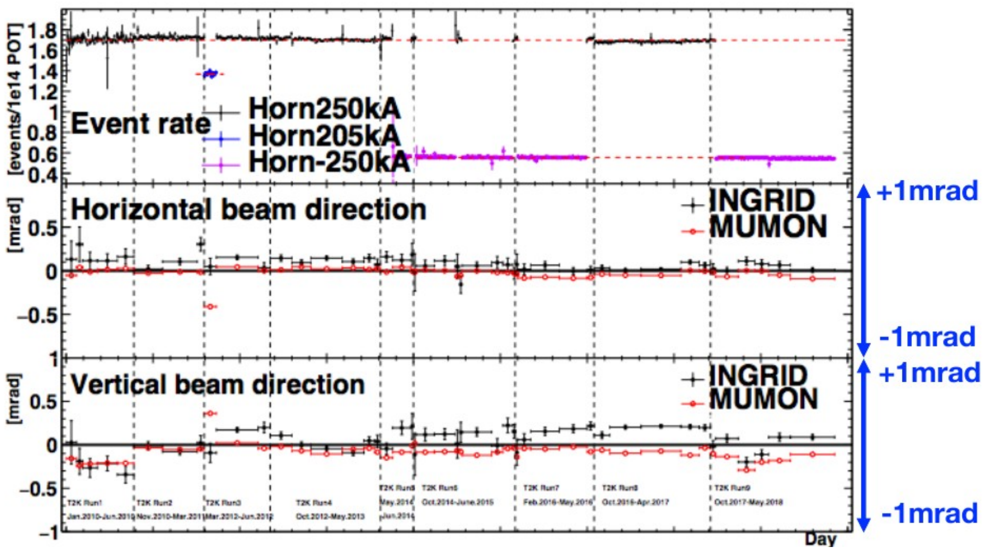
Analyzed Data



Analyzed data (December, 2017)
→ ν-mode: 14.9×10^{20} POT
→ $\bar{\nu}$-mode: 11.2×10^{20} POT (~50/50)
→ Total: 26.2×10^{20} POT
(POT – Protons on Target)

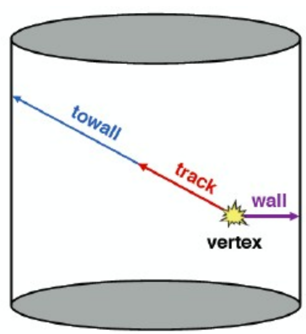
(Total delivered POT to T2K : 3.16×10^{21})

Required beam direction stability achieved (< 1mrad)

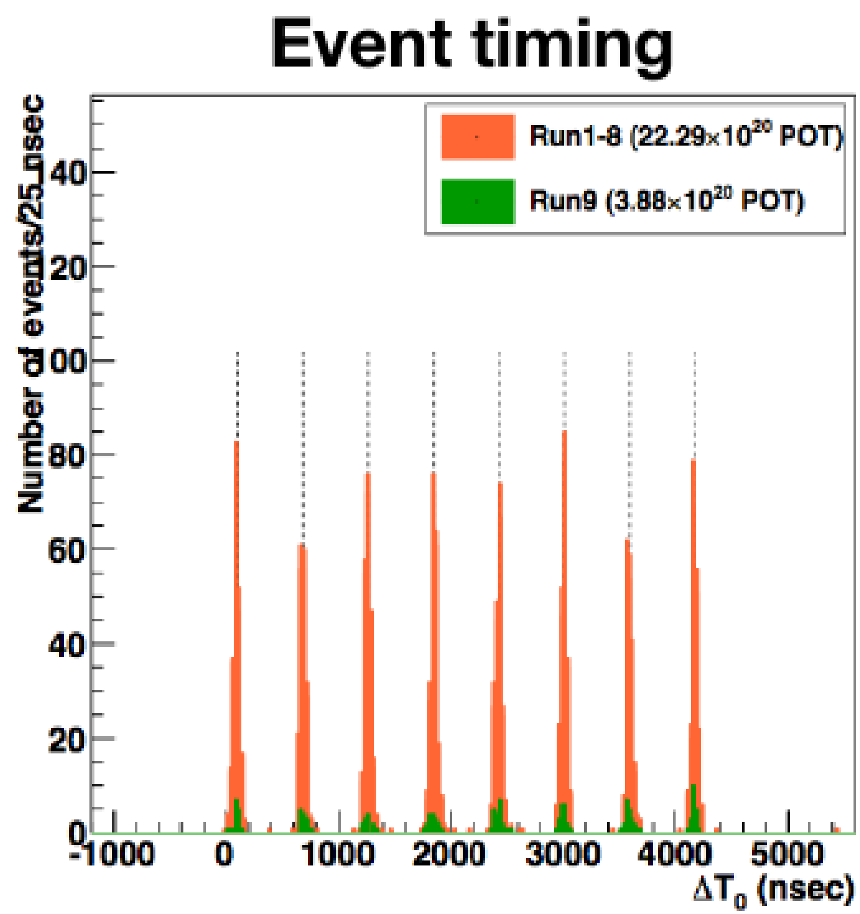


Far Detector (SK): Event Timing

- T2K beam timing
  - Time window of (−2μs, +10μs)
- Fully Contained (FC) definition
  - No signal in Outer Detector (OD)
- Fiducial volume definition:



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

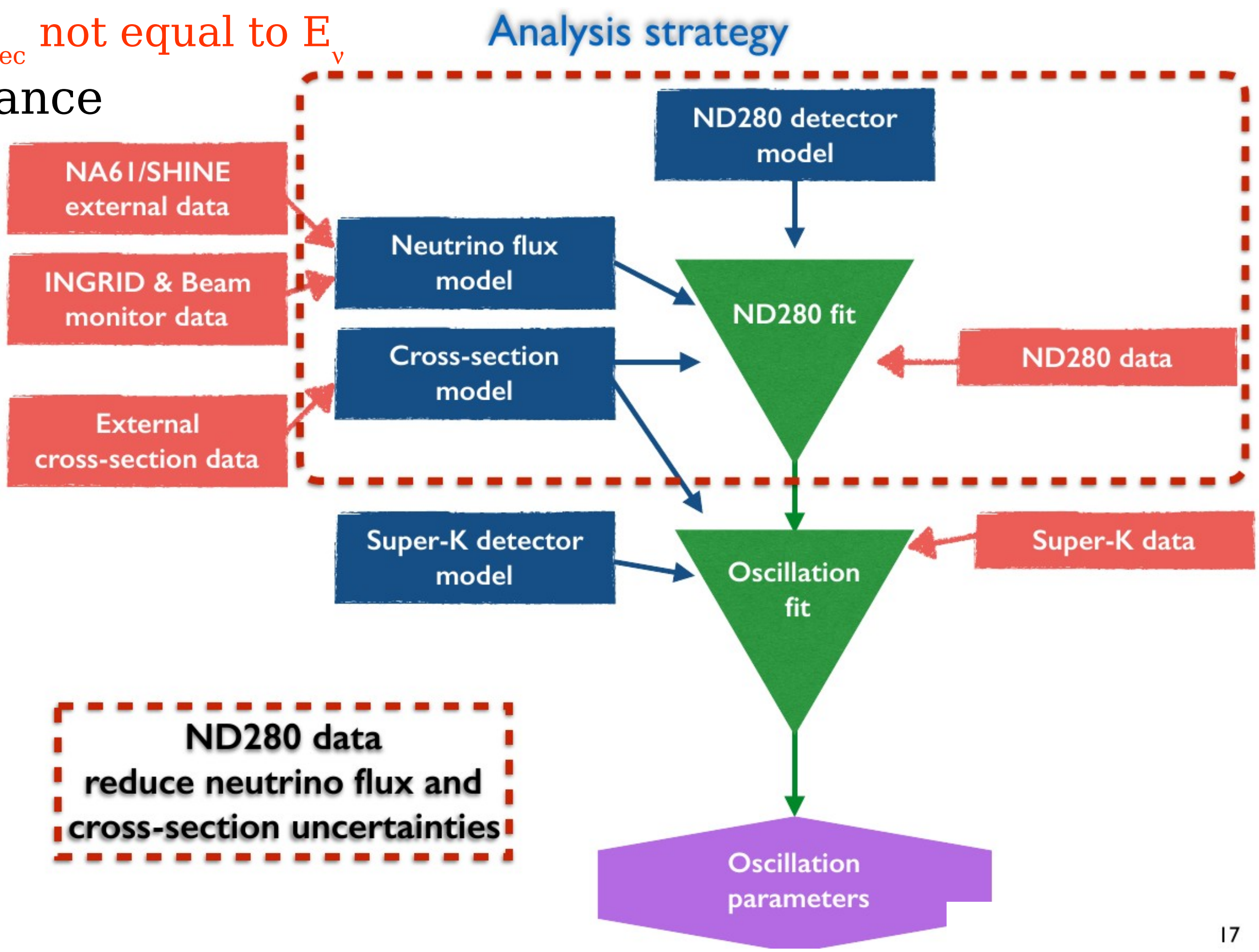


(JPARC: 8 bunches/spill)

Oscillation Parameter Fitting Procedure

To extract ν oscillation parameters we need to model:

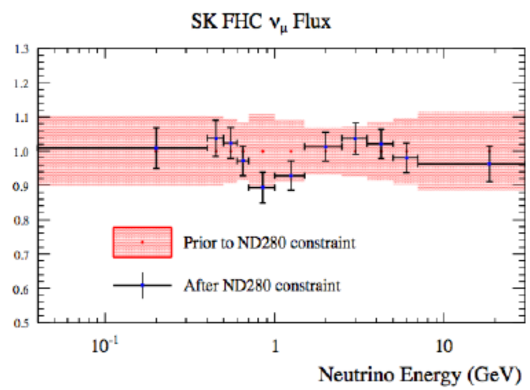
- The neutrino flux
- Neutrino interactions: E_{rec} not equal to E_{ν}
- Understand the performance of the near and far detectors



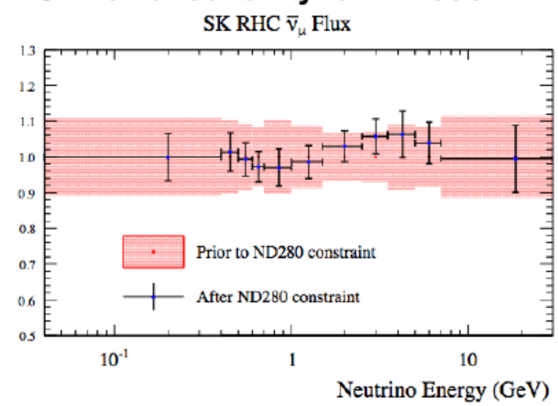
Flux & ν Background Constraints using ND280

- Select charged-current (CC) events in ND280
- Separate into 3 categories (CCQE, CC Resonance, CC DIS)
  - Parameters from simultaneous fit of 3 samples
  - Used for prediction of Super-K neutrino spectrum w/o oscillation

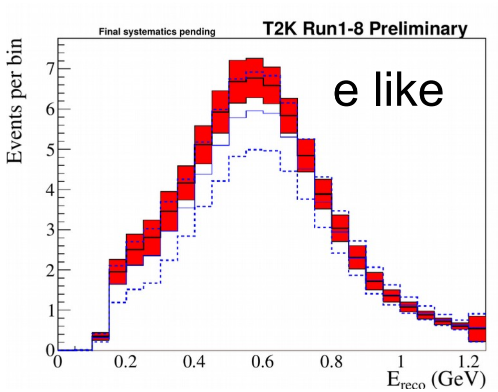
SK flux uncertainty for ν-mode



SK flux uncertainty for $\bar{\nu}$-mode

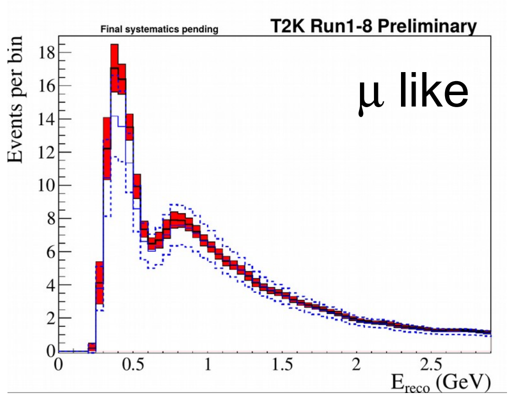


ND280 constraint provides significant reduction of uncertainty at Super-K:
Increases the effectiveness of each proton on target



(Appearance)

	μ-like ν-mode	e-like ν-mode	μ-like $\bar{\nu}$-mode	e-like $\bar{\nu}$-mode
Total Systematics (without ND280)	13.9 %	15.9 %	11.7 %	13.7 %
Total systematics (with ND280)	4.3 %	7.3 %	3.8 %	7.7 %



(Disappearance)

Oscillation Results

Disappearance (anti-)neutrino results…
(Test for CPT Violation or a search for non-standard ν interactions)

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^2 \underline{\theta_{13}} \sin^2 \underline{2\theta_{23}}) \sin^2(\Delta m^2_{32} \frac{L}{4E})$$

Sensitive to:
θ_{23}, $|\Delta m^2_{31}|$ ($\sim|\Delta m^2_{32}|$)

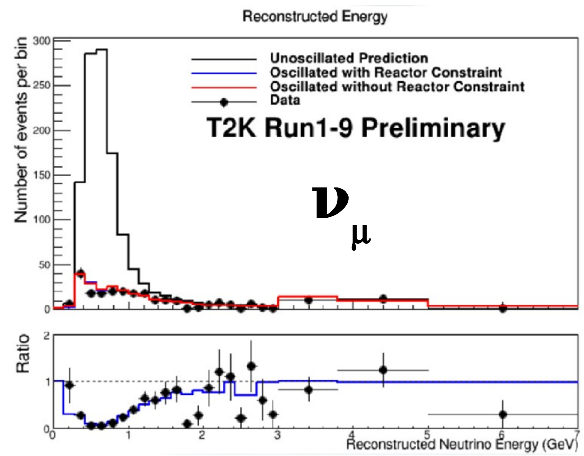
- **θ_{23} Maximal? Octant? (< or > 45^0)**

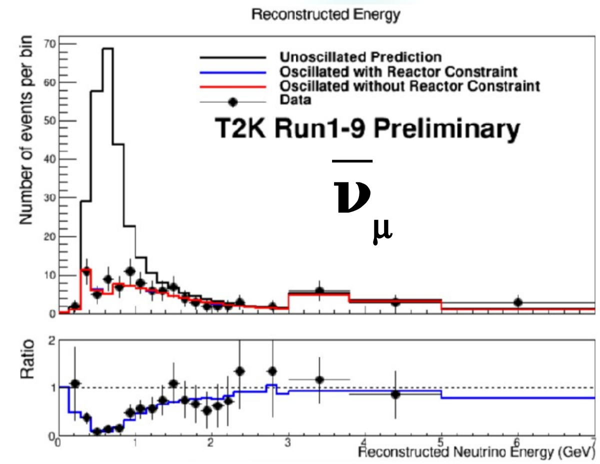
T2K: Disappearance Event Selection

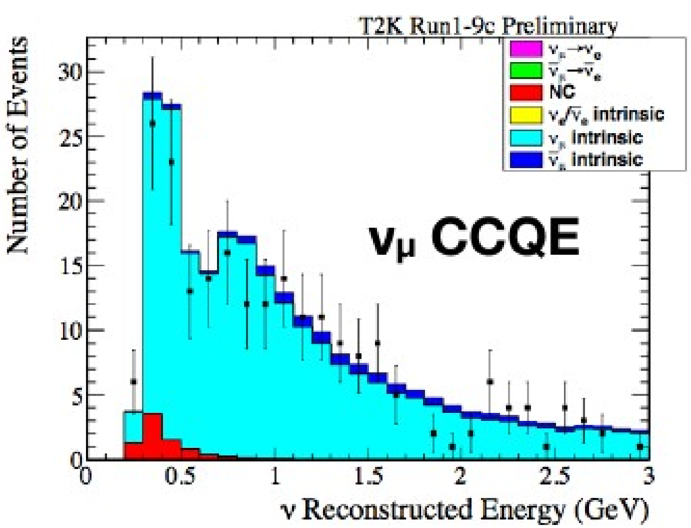
ν_μ ($\bar{\nu}_\mu$) event selection

(Disappearance):

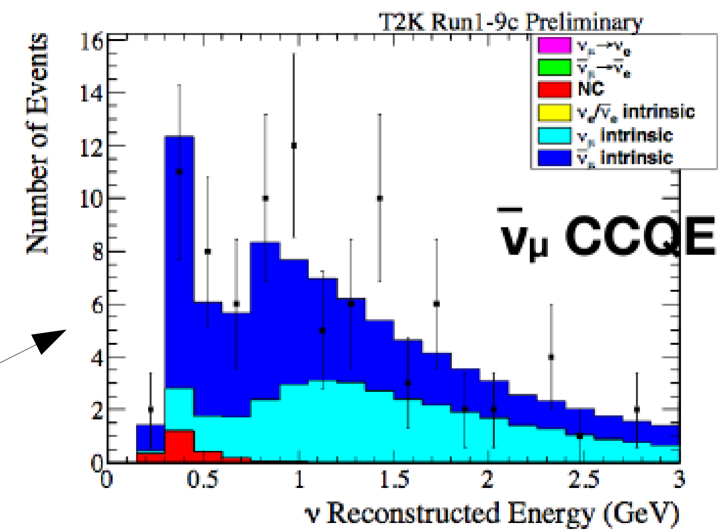
- Fully contained fiducial volume
- Single-ring μ-like event
- $p_\mu > 200$ MeV/c
- # of decay electron ≤ 1







243 events

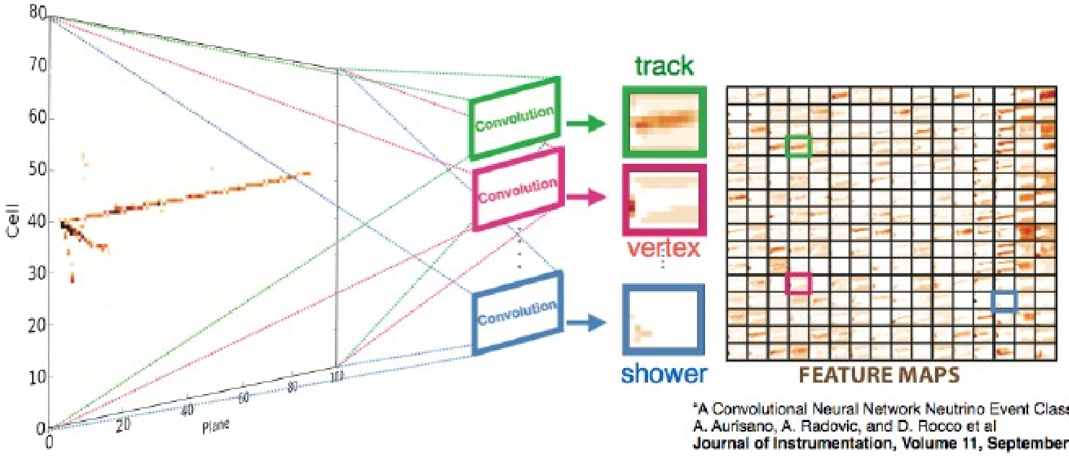


102 events

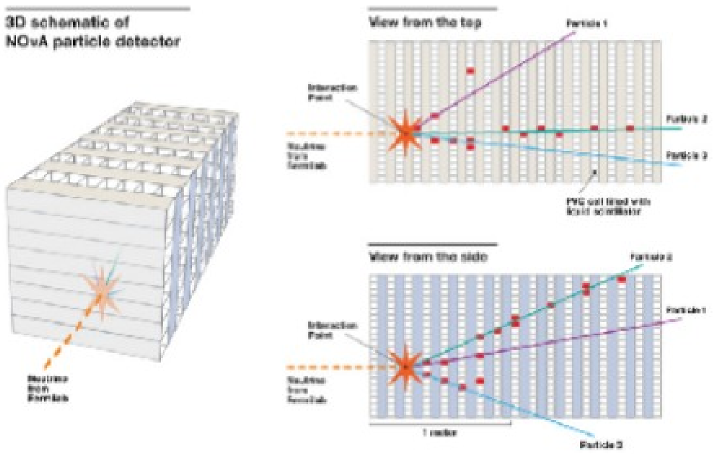
The NOvA Experiment:

8.9 x 10^{20} POT ν mode
6.9 x 10^{20} POT $\bar{\nu}$ mode

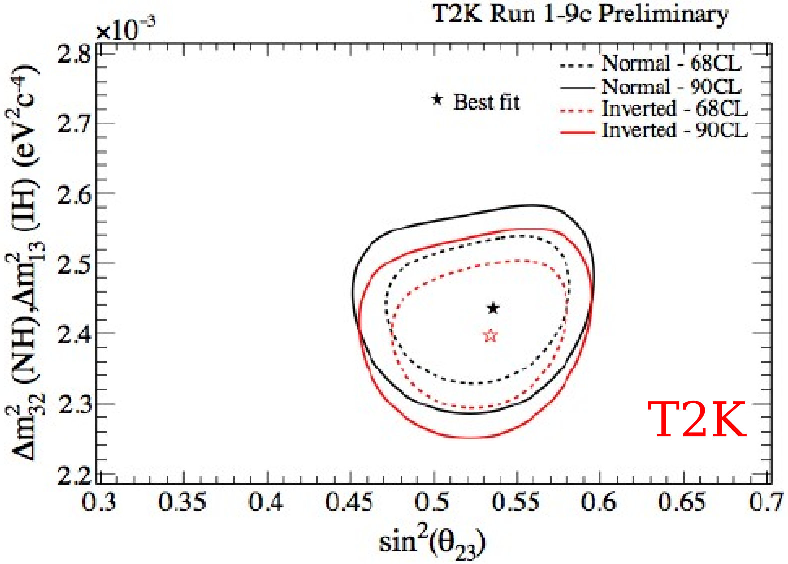
- **US based Long-baseline neutrino oscillation experiment:**
- FNAL neutrino beam to Ash River, MN (on surface)
  - Off-axis neutrino beam: $<E_\nu>$~2 GeV
    - > 700 kW beam achieved
- Functionally identical near/far detectors (~~T2K~~)
  - Segmented liquid scintillator bars
    - → Different technology than T2K
  - Far: 14 kton total mass (65% active mass)
- Data analysis based on:
  - Event classification with Convolutional Neural Network



"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016



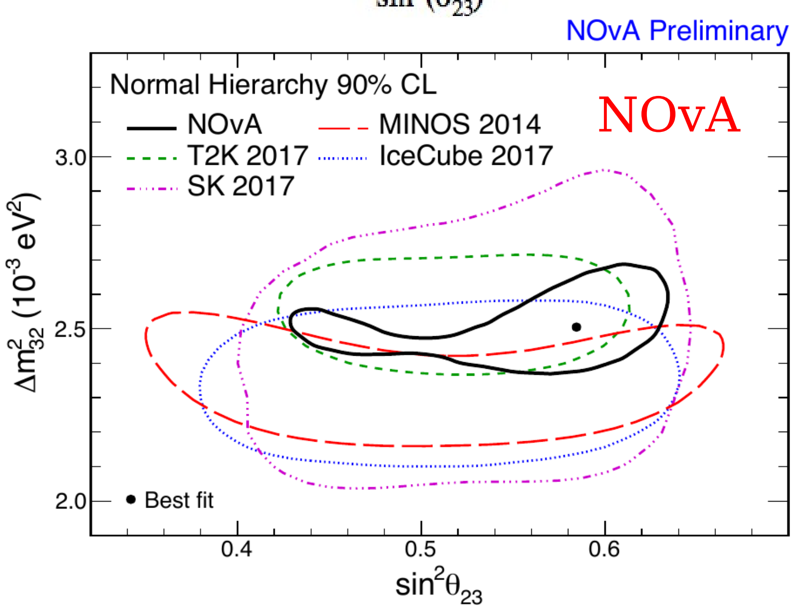
Disappearance



T2K →

	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2_{32}\rvert$ (eV^2/c^4)	2.434 ± 0.064 $\times 10^{-3}$	$2.410^{+0.062}_{-0.063}$ $\times 10^{-3}$

→ No obvious diff. between ν and $\bar{\nu}$ observed… And consistent with maximal mixing (Θ_{23}=45°)



NOvA →

→ They observed 113 events in ν (expect 730 +38/-49(syst.) w/o oscillations),

→ 65 events in $\bar{\nu}$ (expect 266 +12/-14(syst.) w/o oscillations).

Best fit:

Normal Ordering

$\sin^2\theta_{23} = 0.58 \pm 0.03$

$\Delta m^2_{32} = (2.51^{+0.12}_{-.08}) \cdot 10^{-3}\ eV^2$

→ Prefer non-maximal θ_{23} at 1.8σ

Oscillation Results

Appearance (anti-)neutrino results...

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2\sin^2\theta_{13}\right)\right)$$

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

[(P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) δ turns into – δ and a to -a ("a" matter effect term)]

Sensitive to:
θ_{13}, δ_{CP}, θ_{23}, Δm^2_{31}

We measure "P" → Degeneracies...

- **CP-Violating Phase: δ**

T2K: Appearance Event Selection

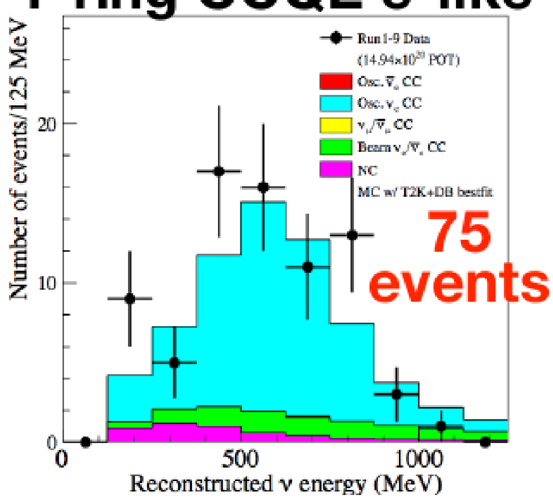
ν_e ($\bar{\nu}_e$) event selection (Appearance):

- Fully contained fiducial volume
- Single-ring e-like event
- Evisible > 100 MeV, Erec < 1250 MeV
- # of decay electron = 0
- π^0 rejection cut

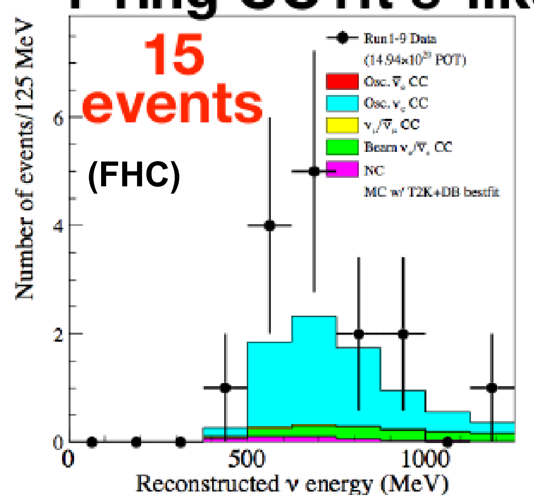
ν_e CCQE	75
$\bar{\nu}_e$ CCQE	9
ν_e CC1π	15

FHC

1-ring CCQE e-like

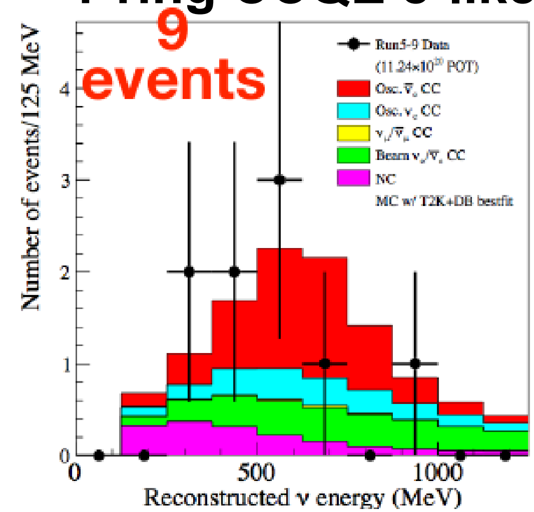


1-ring CC1π e-like



RHC

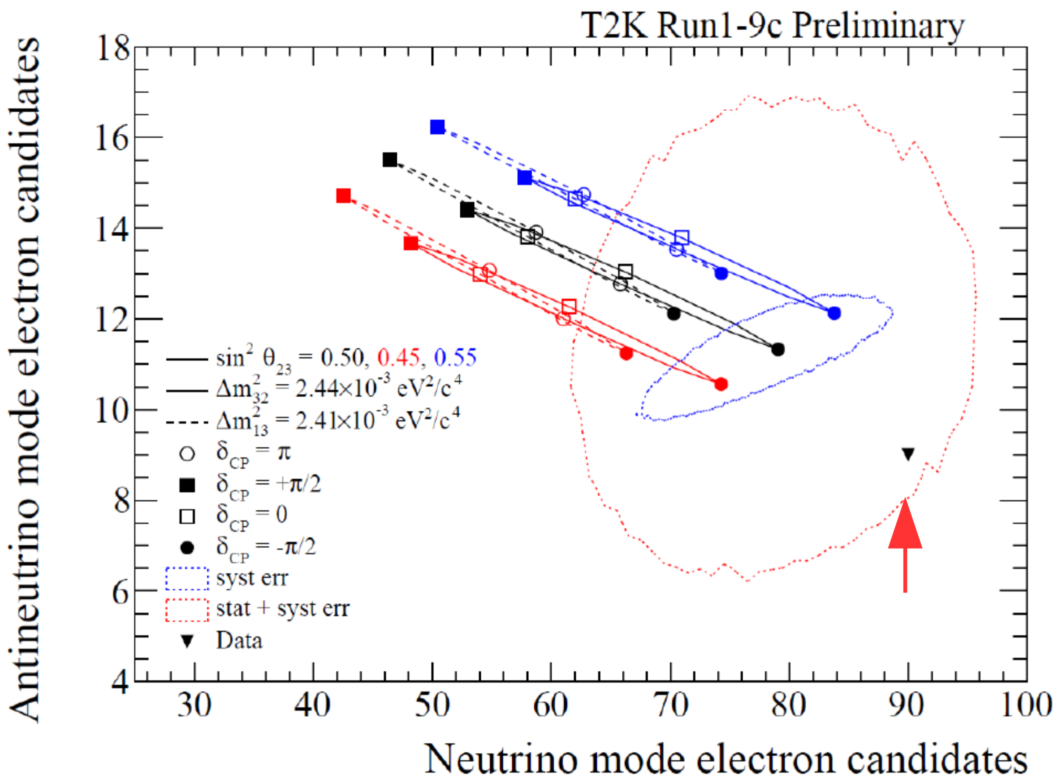
1-ring CCQE e-like



Oscillation probabilities as a function of parameters

For T2K:

- $\theta_{23} \rightarrow \nu_e$ and $\bar{\nu}_e$ appearance probabilities are affected in the same way
- $\delta_{CP} = -\pi/2 \rightarrow$ maximize ν_e appearance, minimize $\bar{\nu}_e$ (~30%)
- $\delta_{CP} = \pi/2 \rightarrow$ maximize $\bar{\nu}_e$ appearance, minimize ν_e (~30%)
- Normal hierarchy $\rightarrow$ same as δ_{CP}=-π/2 but smaller effect in T2K (~10%)
- Inverted hierarchy $\rightarrow$ same as δ_{CP}=π/2 but smaller effect in T2K (~10%)



(Errors shown for the case of $\delta_{CP} = -\pi/2$ and $\sin^2\theta_{23} = 0.5$, NO, w/reactor constraint)

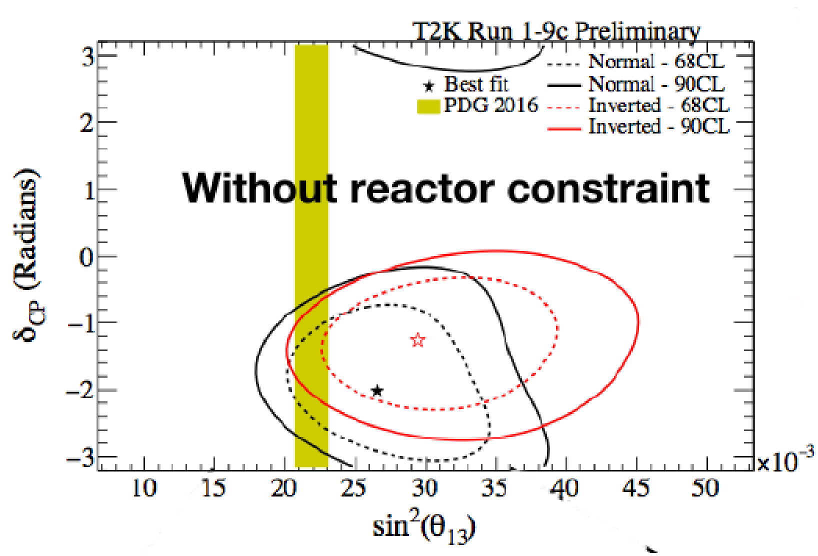
Expected # of events($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$):

Sample	Predicted rates				Observed rates
	δ=0	δ=π/2	δ=π	δ=-π/2	
ν-mode CCQE 1-ring μ-like	268.2	268.5	268.9	268.5	243
ν-mode CCQE 1-ring e-like	61.6	50.1	62.2	73.8	75
ν-mode CC1π 1-ring e-like	6.0	4.9	5.8	6.9	15
$\bar{\nu}$-mode CCQE 1-ring μ-like	95.3	95.5	95.8	95.5	102
$\bar{\nu}$-mode CCQE 1-ring e-like	13.4	14.9	13.3	11.8	9

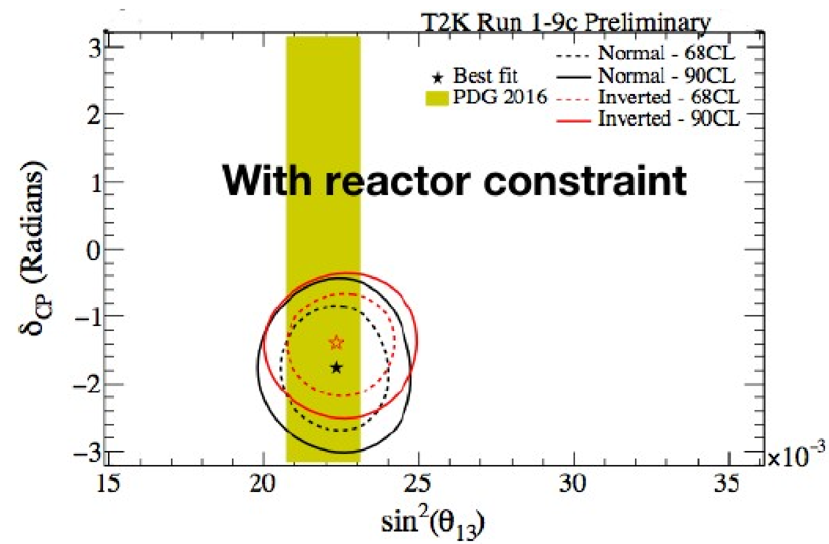
- Preference for δ_{CP}=-π/2 → maximize ν_e appearance probability, minimize $\bar{\nu}_e$ appearance
  - Larger effect in e-like+1π (2.5% probability of observing 15 events when 6.9 are expected)
  - For $\bar{\nu}_e$ appearance background level is ~6.3 events → No strong statistical conclusion
- In ν-mode deficit of μ-like events → compatible with our systematic uncertainties model

Joint Fits ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$): δ_{CP} *vs* Θ_{13}

T2K-Only



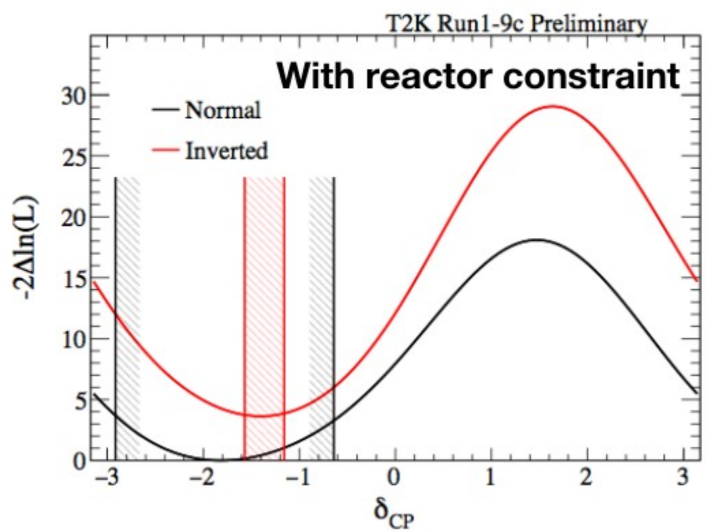
T2K Result with Reactor Constraint



- T2K results consistent with reactor results
- Data prefer maximal CPV: **δ_{CP}=-π/2**
  - With reactor constraints: stronger preference for values of δ_{CP} ~ -π/2
  - Even though statistics are small $\bar{\nu}_e$ results reinforce maximal CPV observed for ν_e data

Joint Fits ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$): δ_{CP} Measurement

T2K:



- **NO : [-2.914, -0.642]**
- **IO : [-1.569, -1.158]**

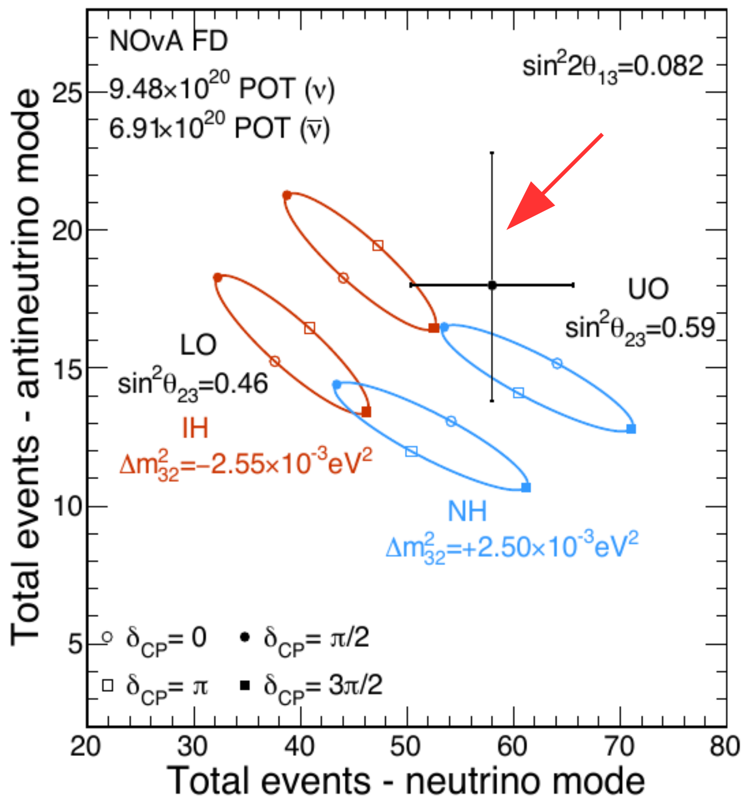
- 2σ interval calculated with Feldman&Cousins method
- CP conserving values (0, ±π) outside of 2σ region for both mass orderings

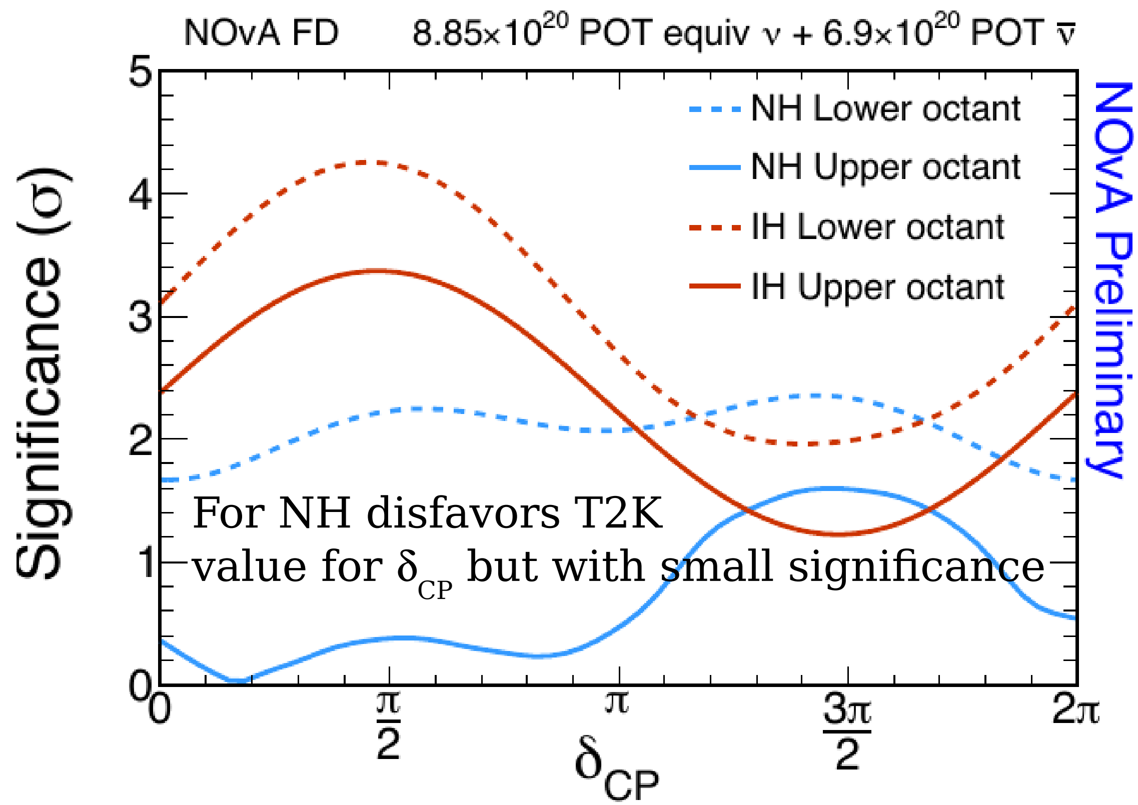
δ_{CP}: NOvA Recent Results

M. Sanchez @Neutrino2018

NOvA Observes:
58 (expected bkg 15) events in ν
18 (expected bkg 5.3) events in $\bar{\nu}$:
> 4 σ evidence of $\bar{\nu}_e$ appearance

Best fit: Normal Ordering
$\delta_{CP} = 0.17\pi$
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ eV^2$





T2K and NOνA Comparisons

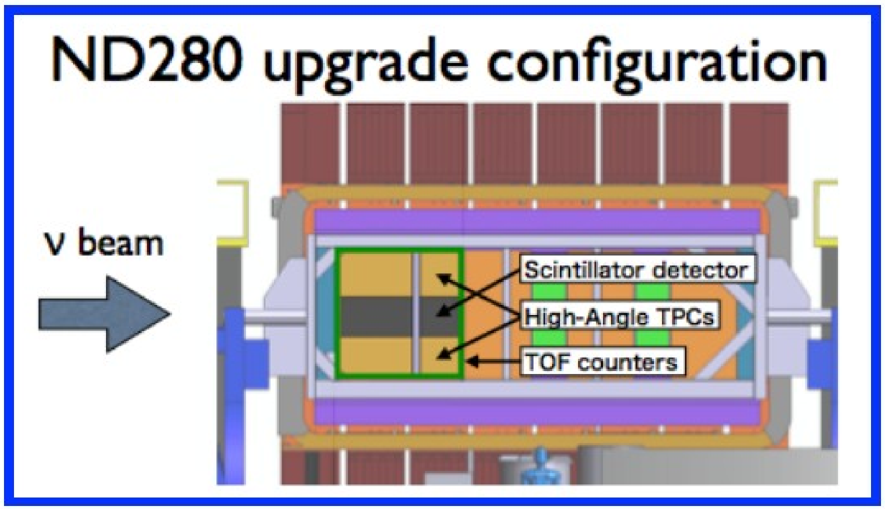
- Both T2K and NOνA are studying the same physics
  - However they are using different detection technologies
    - This is a good thing

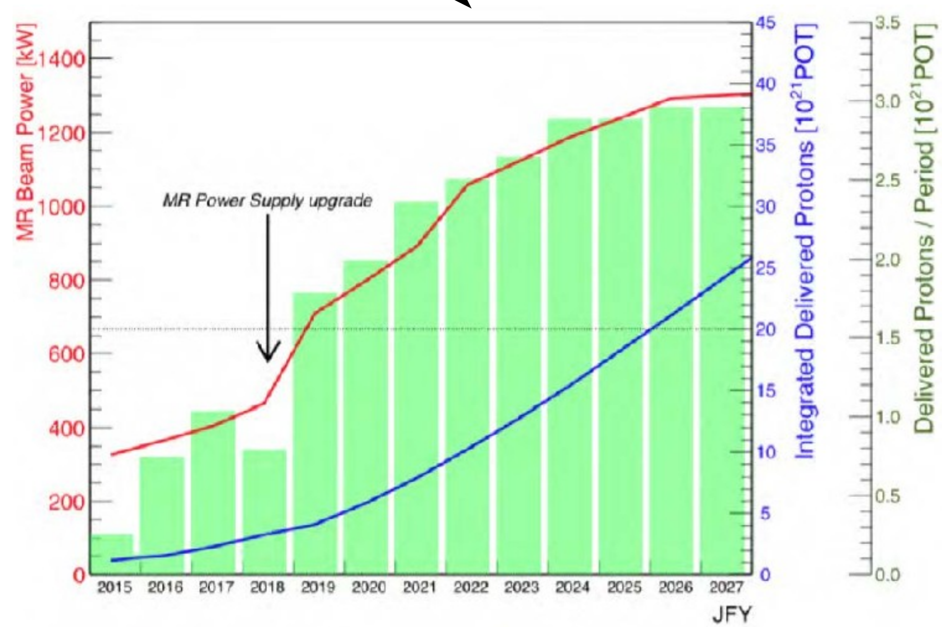
- As mentioned both measure $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ but...
  - In the PMNS framework these are functions of several parameters
    - *i.e.* Baseline for NOνA is 810km and 295km for T2K
      - Longer baselines have greater sensitivity to the Mass Ordering

- The joint measurements of T2K and NOνA important in untangling the physics parameters embedded in $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, specifically δ_{CP}
  - Preparing for a joint working group: Three workshops already held.

T2K Future

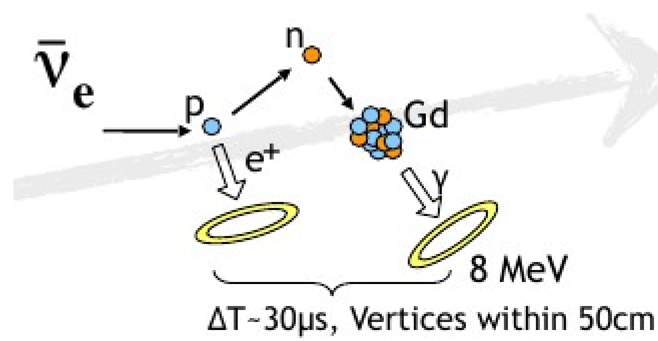
- JPARC expected to deliver higher power beam in the future
- T2K-II (run extension)
- Upgrade plans:
  - Near detector





→ T2K phase 2 goal: reduce systematics to ~4%

- Far detector (add Gd to SK)
  - Enhance neutron detection capability
  - Improved low energy $\bar{\nu}$ detection

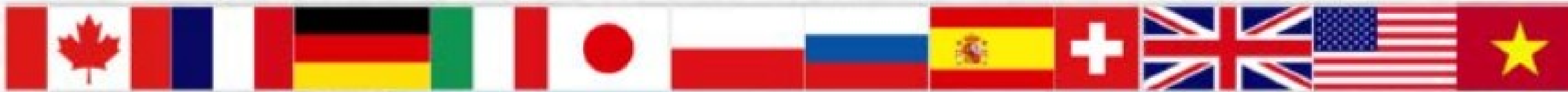


Summary and Outlook

- T2K has accumulated a total of 3.16×10^{21} POT (~50/50 ν and $\bar{\nu}$ modes) (~40% of T2K's approved POT – Full amount expected by 2020-21)
- Joint analysis across all modes of oscillation $\nu_{\mu,e}/\bar{\nu}_{\mu,e}$ disappearance, appearance
  - Constraints from near detector (ND280) measurements incorporated
  - These data show a preference for maximal θ_{23} mixing, δ_{CP} ~$-\pi/2$ and NH
    - Manifested by "maximal" $\nu_\mu/\bar{\nu}_\mu$ disappearance, "large" ν_e appearance, "small" $\bar{\nu}_e$ appearance
- Stable beam power @485 kW achieved this year
  - Approved upgrades for >750 kW operation
  - A proposed extension of T2K(T2K II). In 2016 Stage I approval:
    - Accelerator and beam line upgrades to improve beam power to 1.3 MW
      - Allowing 20×10^{21} POT to be accumulated by ~2026
    - Primary goals are >3σ sensitivity to CPV and < 2° resolution on Θ_{23}
- Healthy competition and complementarity between T2K and NOνA
  - Joint analysis plans in the works

→ Stay Tuned: More oscillation results to come...

The T2K Collaboration



~500 members, 64 Institutes, 12 countries

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U. Winnipeg
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LLR E. Poly.
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INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
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Kavli IPMU
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U. Washington

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IFIRSE
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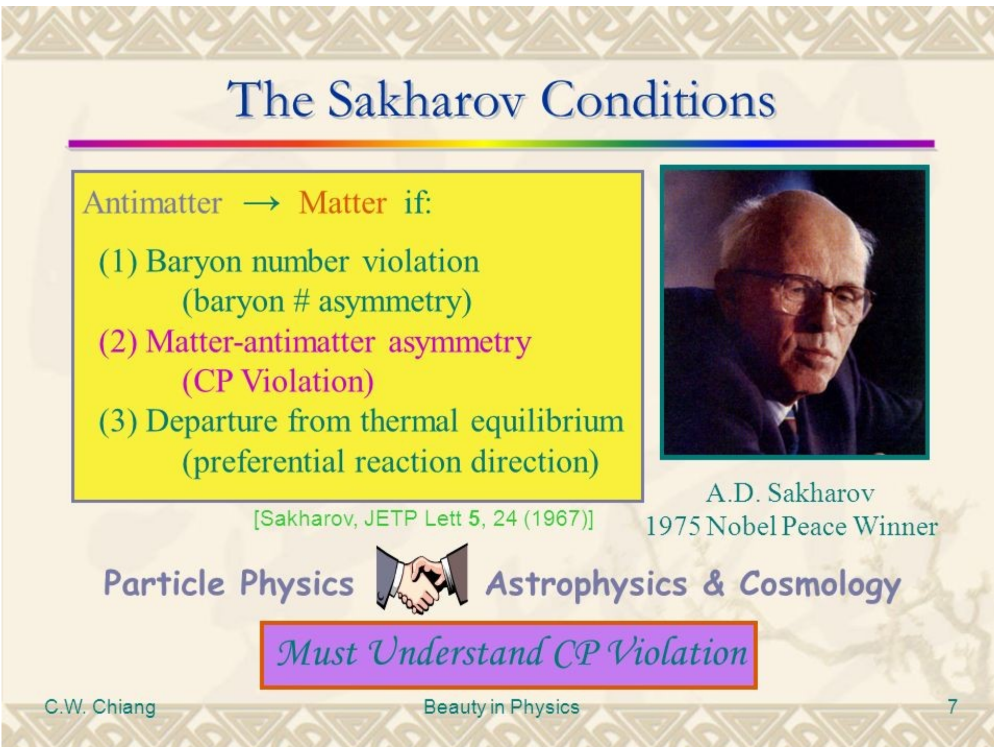
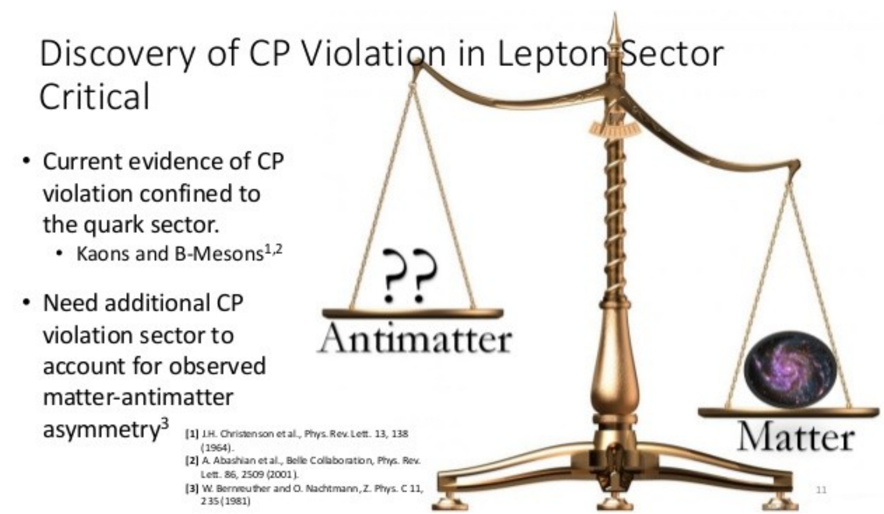
Backup Slides

Motivation



The Sakharov Conditions
Antimatter → Matter if:
(1) Baryon number violation
(baryon # asymmetry)
(2) Matter-antimatter asymmetry
(CP Violation)
(3) Departure from thermal equilibrium
(preferential reaction direction)
[Sakharov, JETP Lett 5, 24 (1967)]
A.D. Sakharov
1975 Nobel Peace Winner
Particle Physics
Astrophysics & Cosmology
Must Understand CP Violation
C.W. Chiang
Beauty in Physics
7



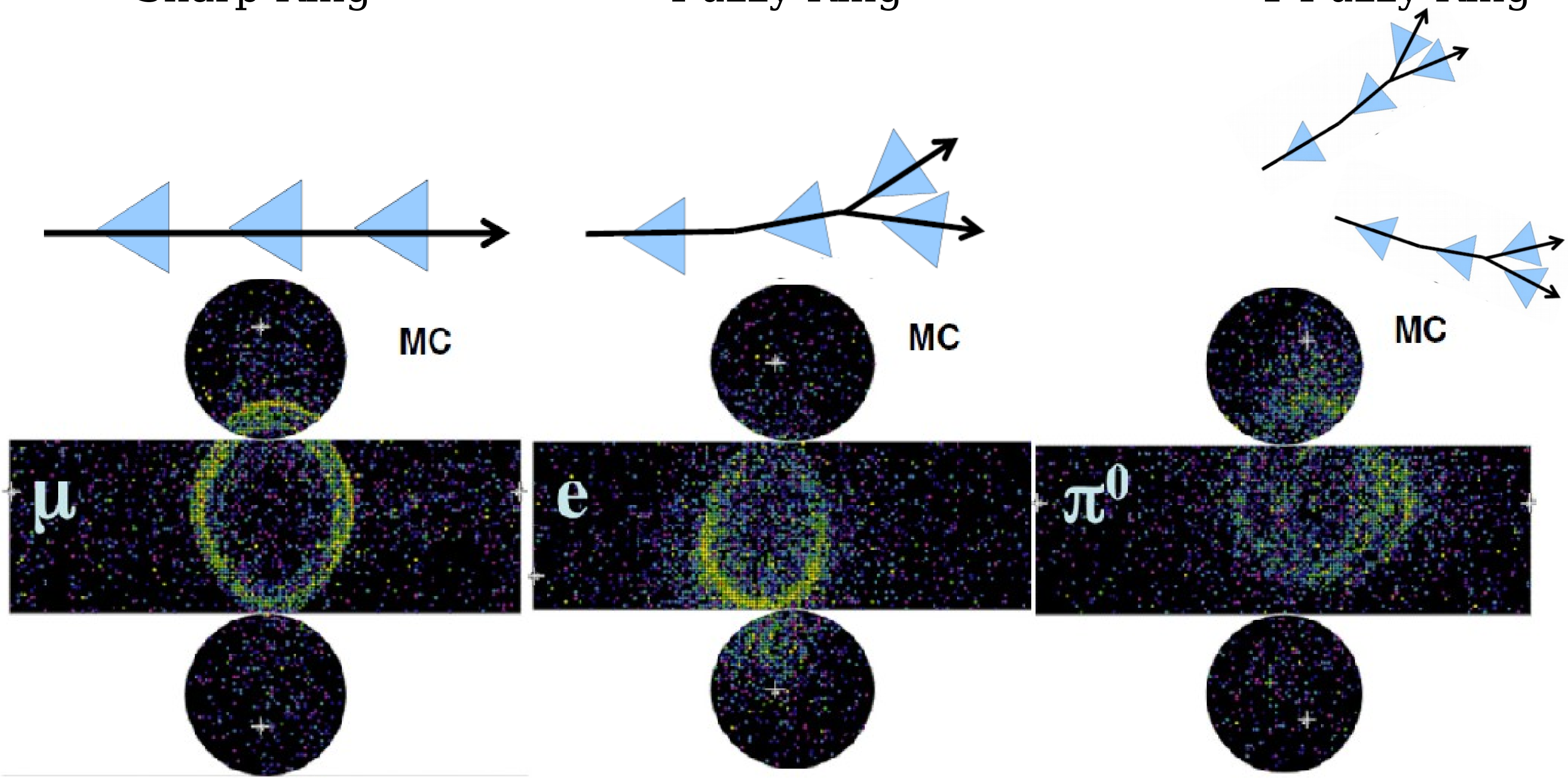
Discovery of CP Violation in Lepton Sector Critical
• Current evidence of CP violation confined to the quark sector.
• Kaons and B-Mesons[1,2]
• Need additional CP violation sector to account for observed matter-antimatter asymmetry[3]
[1] J.H. Christenson et al., Phys. Rev. Lett. 13, 138 (1964).
[2] A. Abashian et al., Belle Collaboration, Phys. Rev. Lett. 86, 2509 (2001).
[3] W. Bernreuther and O. Nachtmann, Z. Phys. C 11, 235 (1981)
??
Antimatter
Matter
11

Far Detector: Particle ID

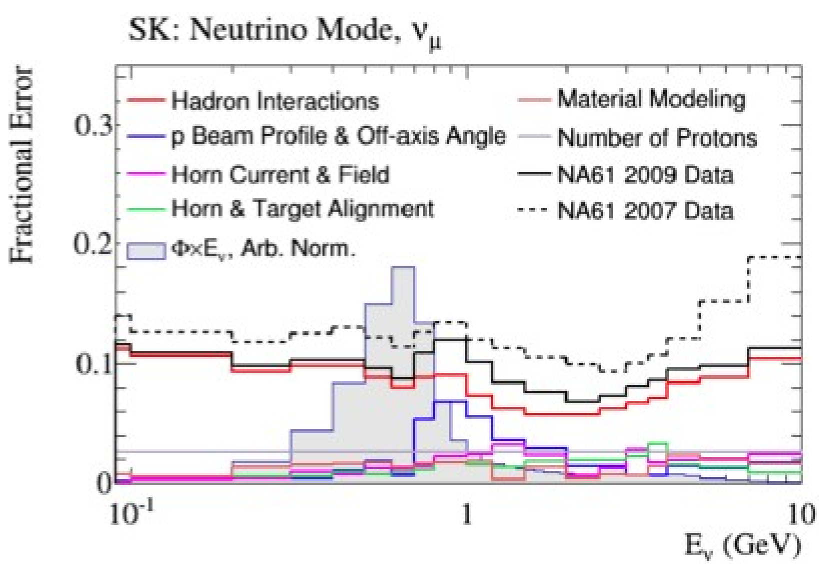
MS Small:
Sharp Ring

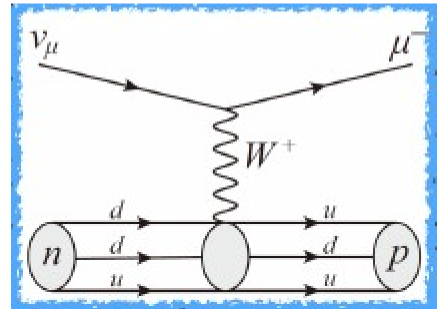
EM Shower:
Fuzzy Ring

2 EM Showers:
> 1 Fuzzy Ring

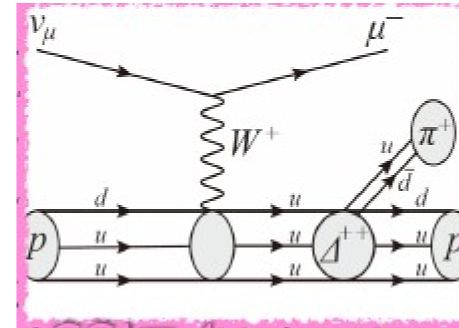


Near Detector Fit

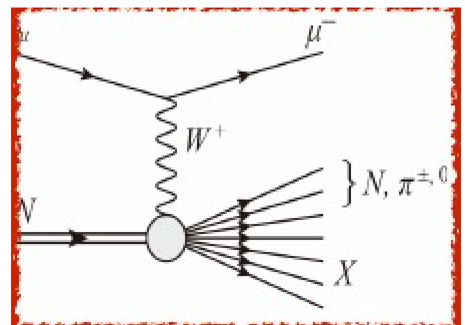




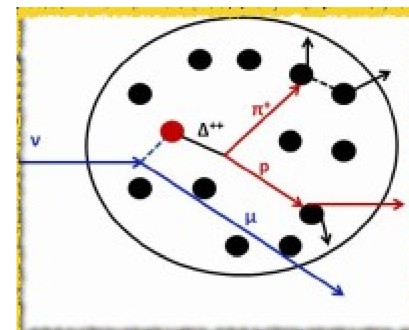
CC0π: 13 parameters (1p1h, 2p2h)



CC1π: 4 parameters (resonant and coherent)



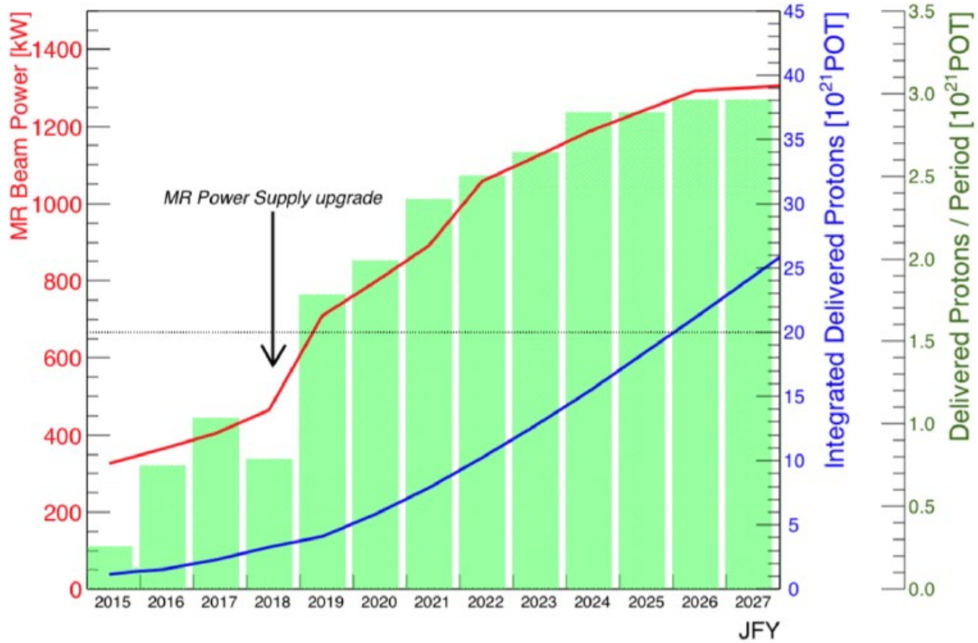
CC DIS: 1 parameter



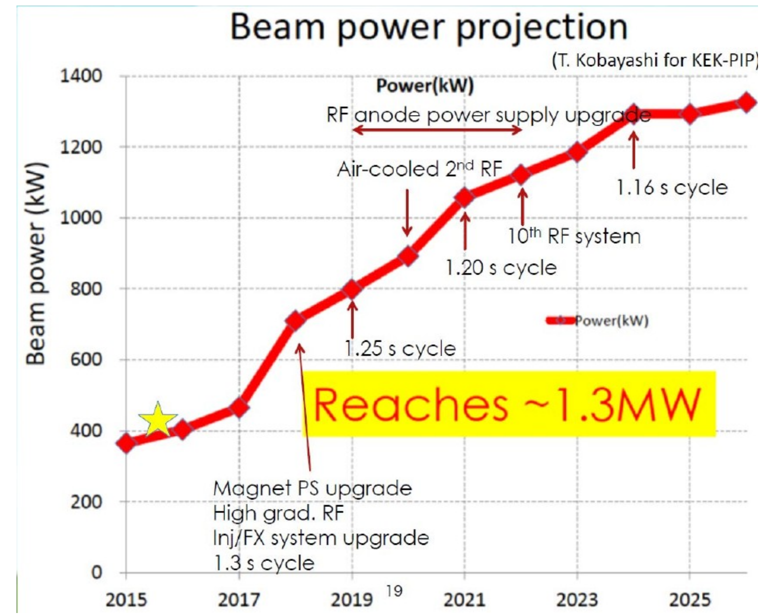
Final state Interactions (6 parameters)

- Combined flux and cross section systematic uncertainties produce ~15% systematic errors in T2K's oscillation analyses.

Future Prospects: T2K II



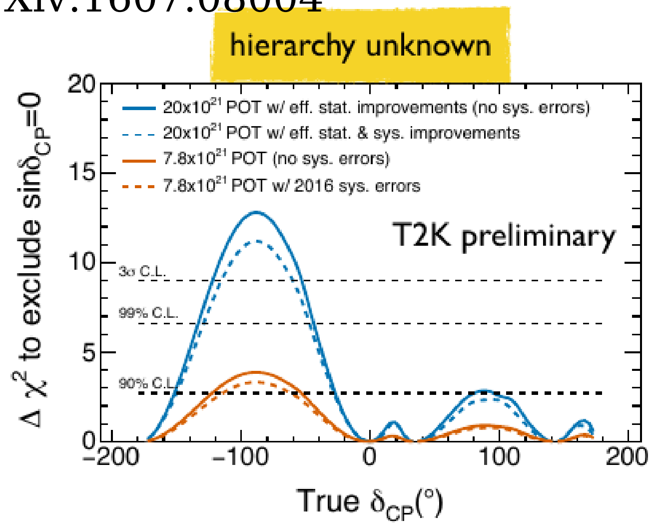
J-PARC Intensity Upgrade Plan:

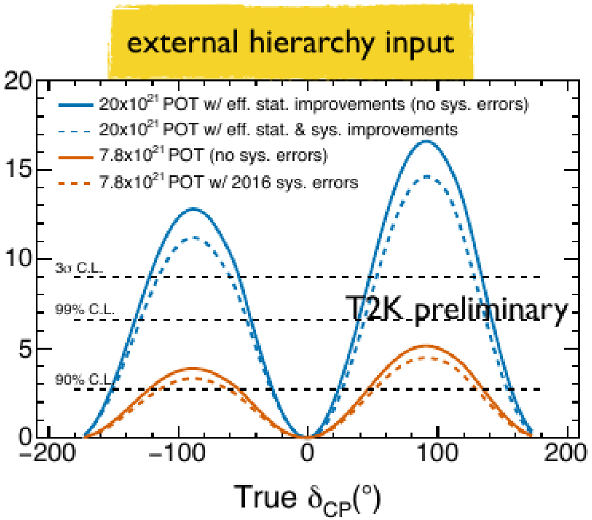


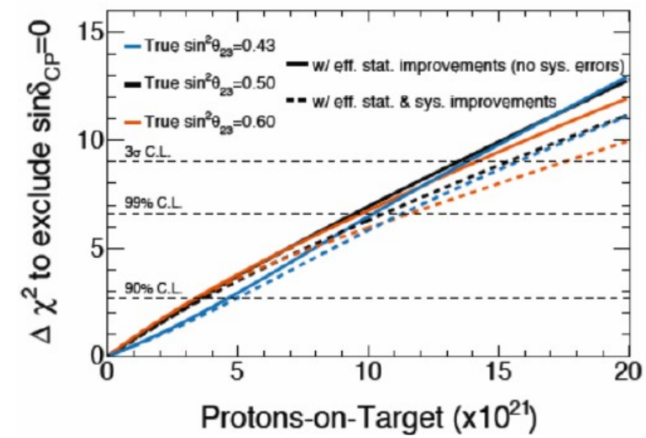
- Presently T2K approved for 7.8×10^{21} POT
  - Projected to reach around 2020
- 1st stage of J-PARC main ring power supply upgrade approved
  - Major step in achieving > 1 MW beam power (currently 420 kW)
- T2K-II extends T2K accumulated POT to 20×10^{21} POT
  - With further accelerator and beam-line upgrades expect 1.3 MW
  - Goal could be reached in 2026

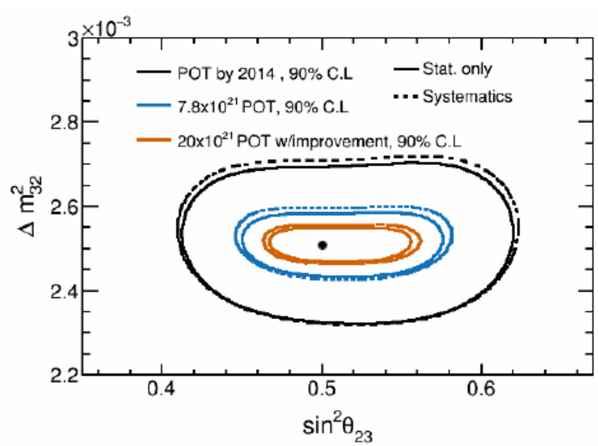
T2K II Sensitivity

arXiv:1607.08004









Goals:

- ~3σ sensitivity to CP violation for favorable (and currently favored) parameters
- Precise measurement of θ_{23}:
  - Octant resolution if θ_{23} at the edge of currently allowed region
  - Otherwise measure θ_{23} with a resolution of 1.7° or better

Put Title here