Recent results from the T2K experiment on CP violation in the lepton sector

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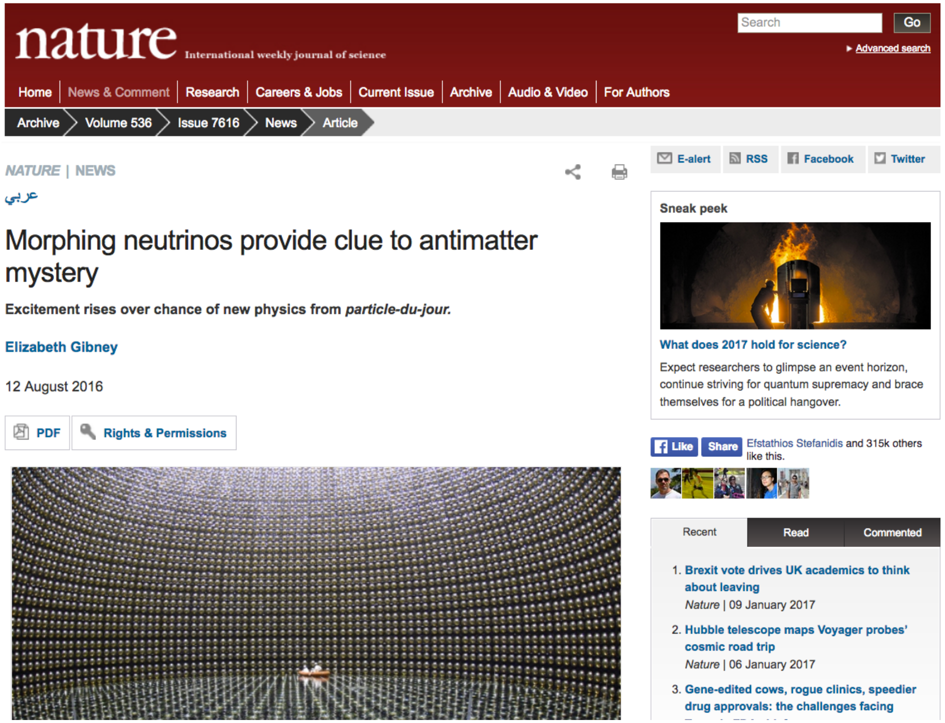
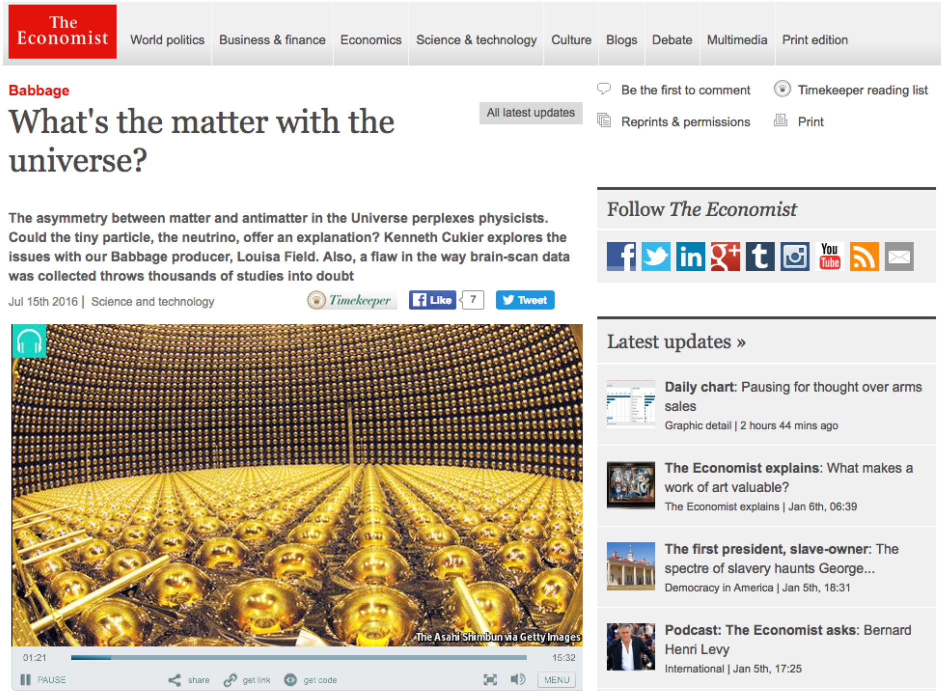
March 7, 2017

No surprises in this talk!

Our recent results (arXiv:1701.00432) are widely publicised already!





In a nutshell: A recent joint 3-flavour analysis of all T2K neutrino and antineutrino data disfavours CP conservation at 90% C.L.

First CP results from NOvA in agreement with T2K.

Outline

- Neutrino mixing
- Open questions
- Leptonic CP violation
- T2K
- Testing leptonic CP violation at T2K
- Recent results
- Future prospects

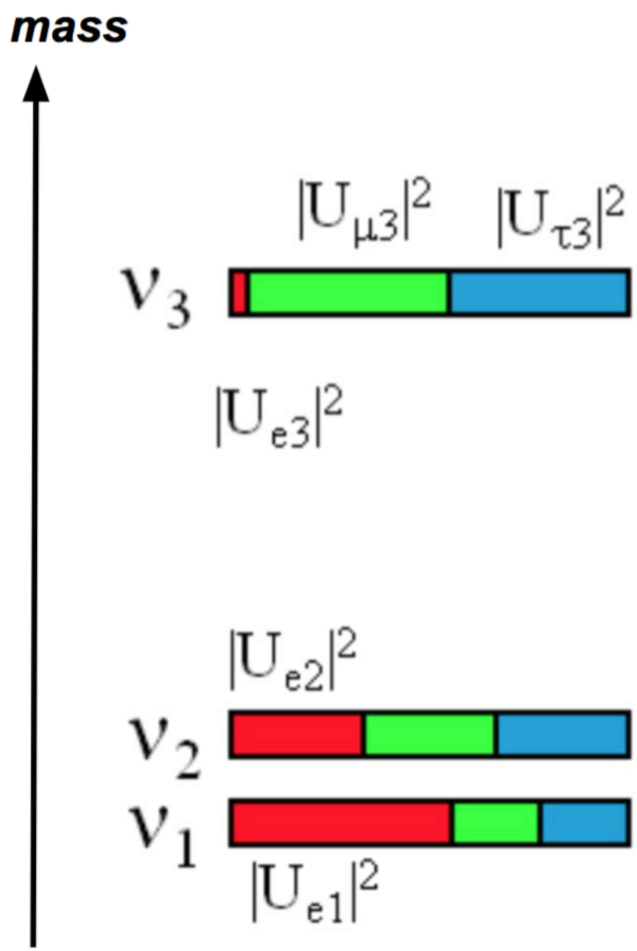
Each flavour eigenstate is a **superposition of mass eigenstates**.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

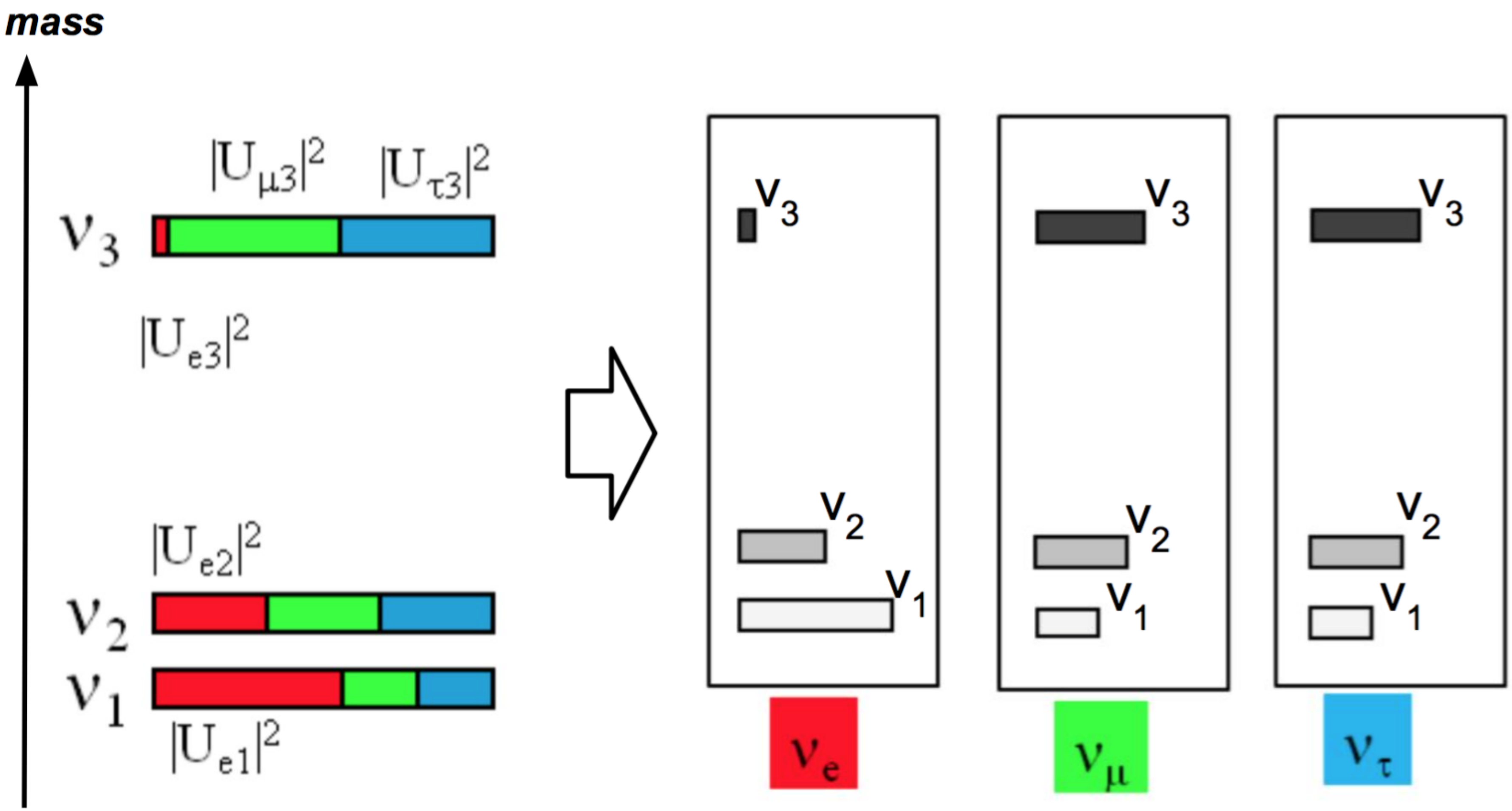
For antineutrinos:

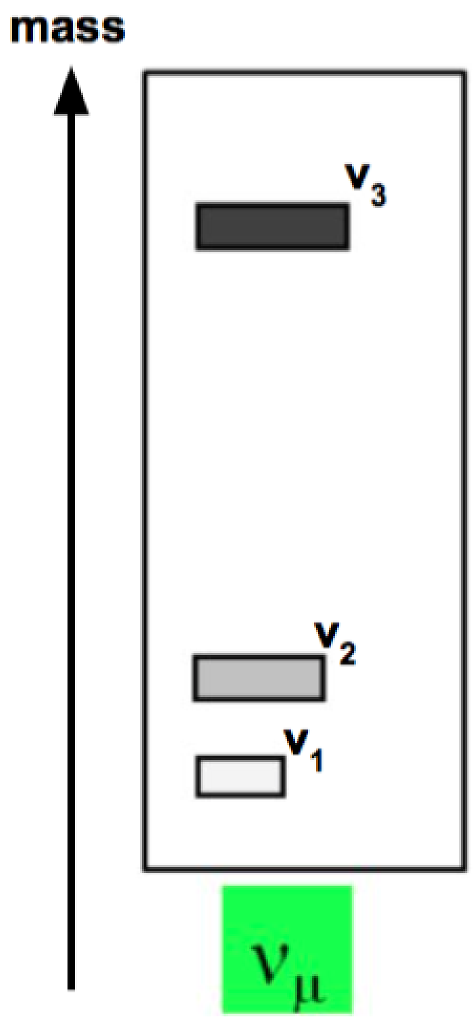
$$U_{PMNS} \rightarrow U^{\star}_{PMNS}$$

PMNS: **P**ontecorvo-**M**aki-**N**akagawa-**S**akata



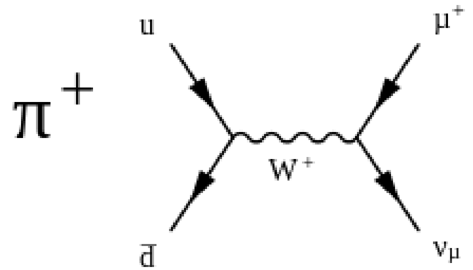
Neutrino oscillations





A muon-neutrino, **at the very moment it gets created**, is described by the following state:

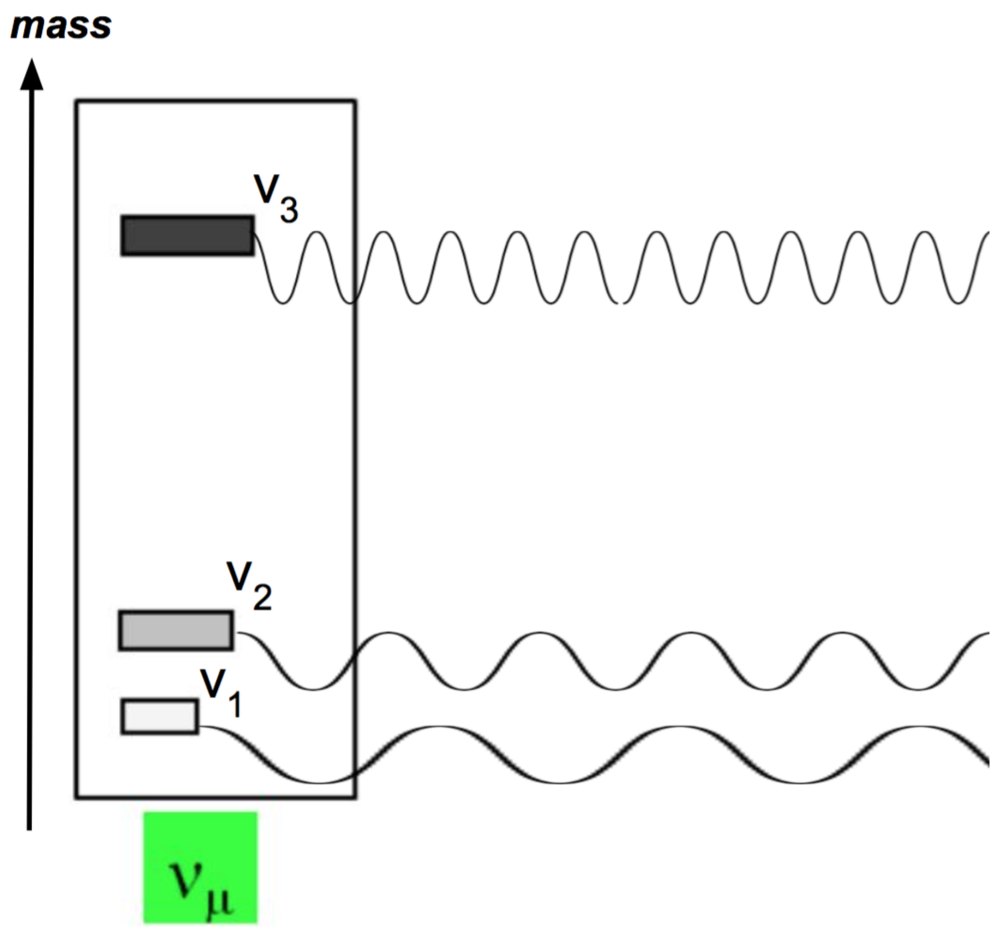
$$|\nu_\mu > \approx 0.4 \cdot |\nu_1 > + \, 0.6 \cdot |\nu_2 > +0.7 \cdot |\nu_3 >$$



So, at that time, a muon-neutrino is:

- $100 * (0.4)^2 \approx 15\% \ \nu_1$
- $100 * (0.6)^2 \approx 35\% \ \nu_2$
- $100 * (0.7)^2 \approx 50\% \ \nu_3$

Neutrino oscillations



The propagation of each mass eigenstate i (i=1,2,3) is described by a plane wave:

$$|\nu_i(L)> = e^{-i m_i^2 L/2E} \cdot |\nu_i(0)>$$

Immediately after its creation, **the superposition** that makes up a flavour eigenstate **gets altered**.

The neutrino now has a **finite probability to be observed as a different flavour state**.

What do we measure in neutrino oscillation experiments?

Probability for $\nu_\alpha \rightarrow \nu_\beta$ $(\alpha, \beta : e, \mu, \tau)$ flavour oscillation:

$$P_{\alpha\beta} = \delta_{\alpha\beta} \quad - \quad 4\sum_{i>j} Re[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin^2(\frac{1}{4}\frac{L}{E}\Delta m^2_{ij})$$
$$+ \quad 2\sum_{i>j} Im[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin(\frac{1}{2}\frac{L}{E}\Delta m^2_{ij})$$

Sensitivity to oscillations by tuning L/E (baseline to energy ratio)

For a purely phenomenological description of neutrino oscillations, assuming 3 active neutrinos, we need:

- Any 2 squared mass splittings (e.g. Δm^2_{21},Δm^2_{32})
- 3 mixing angles (θ_{12}, θ_{13}, θ_{23})
- 1 CP invariance violating phase (δ_{CP})

What do we measure in neutrino oscillation experiments?

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

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

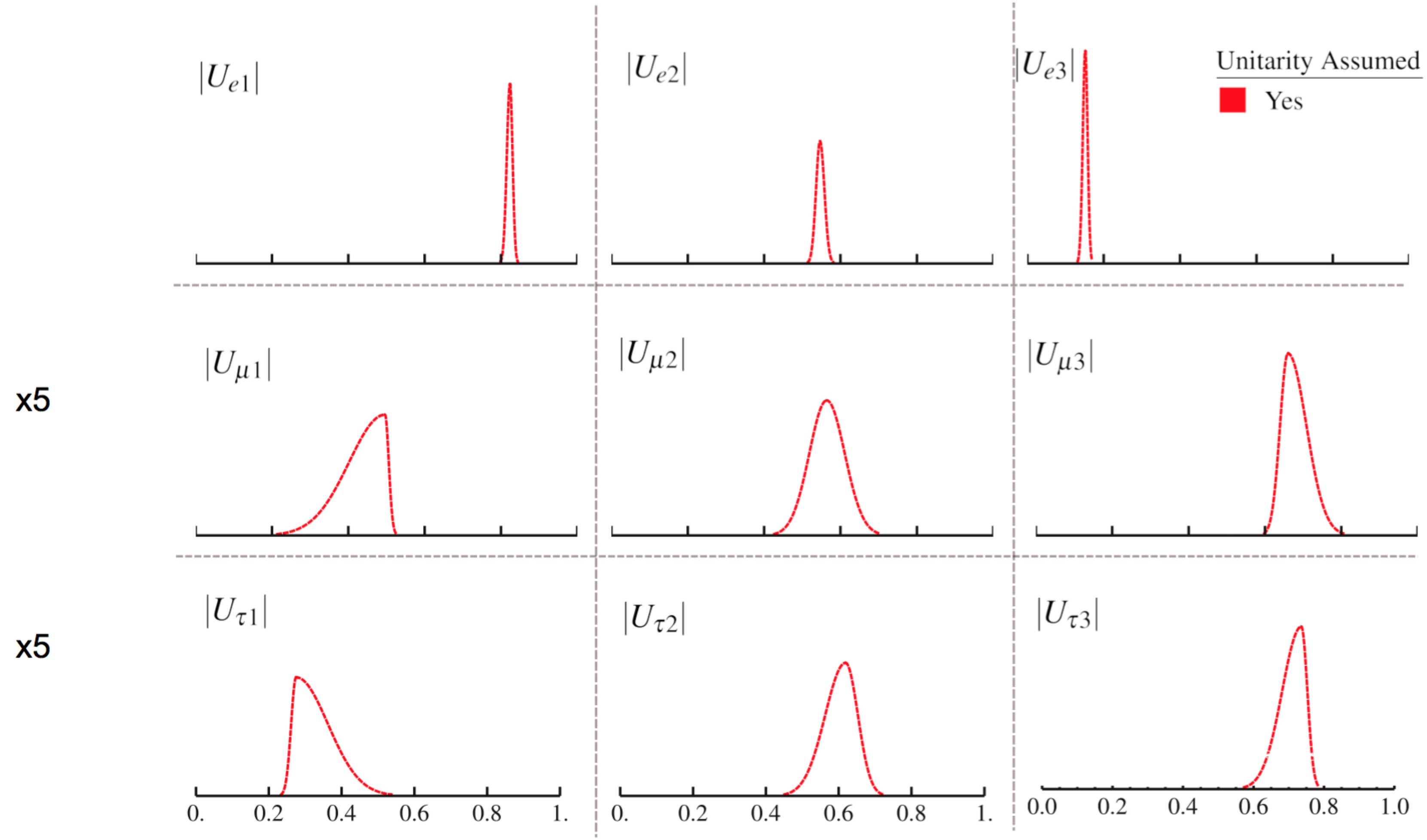
$s_{ij} = \sin\theta_{ij}$

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$

$$U_{PMNS} \approx \begin{pmatrix} 0.80 & 0.55 & 0.15 \\ 0.40 & 0.60 & 0.70 \\ 0.40 & 0.60 & 0.70 \end{pmatrix}$$

Several unknowns: Is U_{PMNS} unitary?

U_{PMNS} matrix elements:

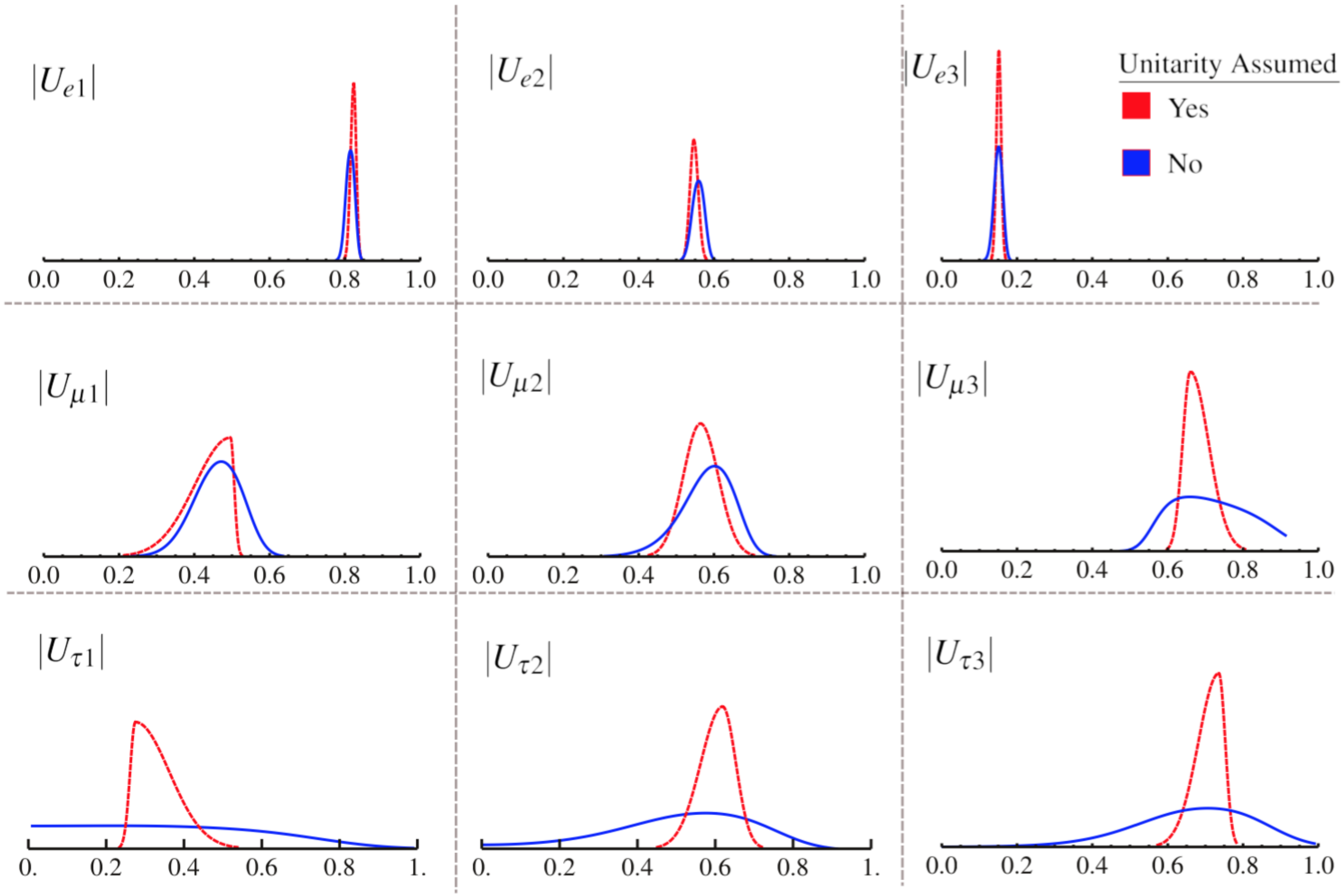


Several unknowns: Is U_{PMNS} unitary?

U_{PMNS} matrix elements:

x5

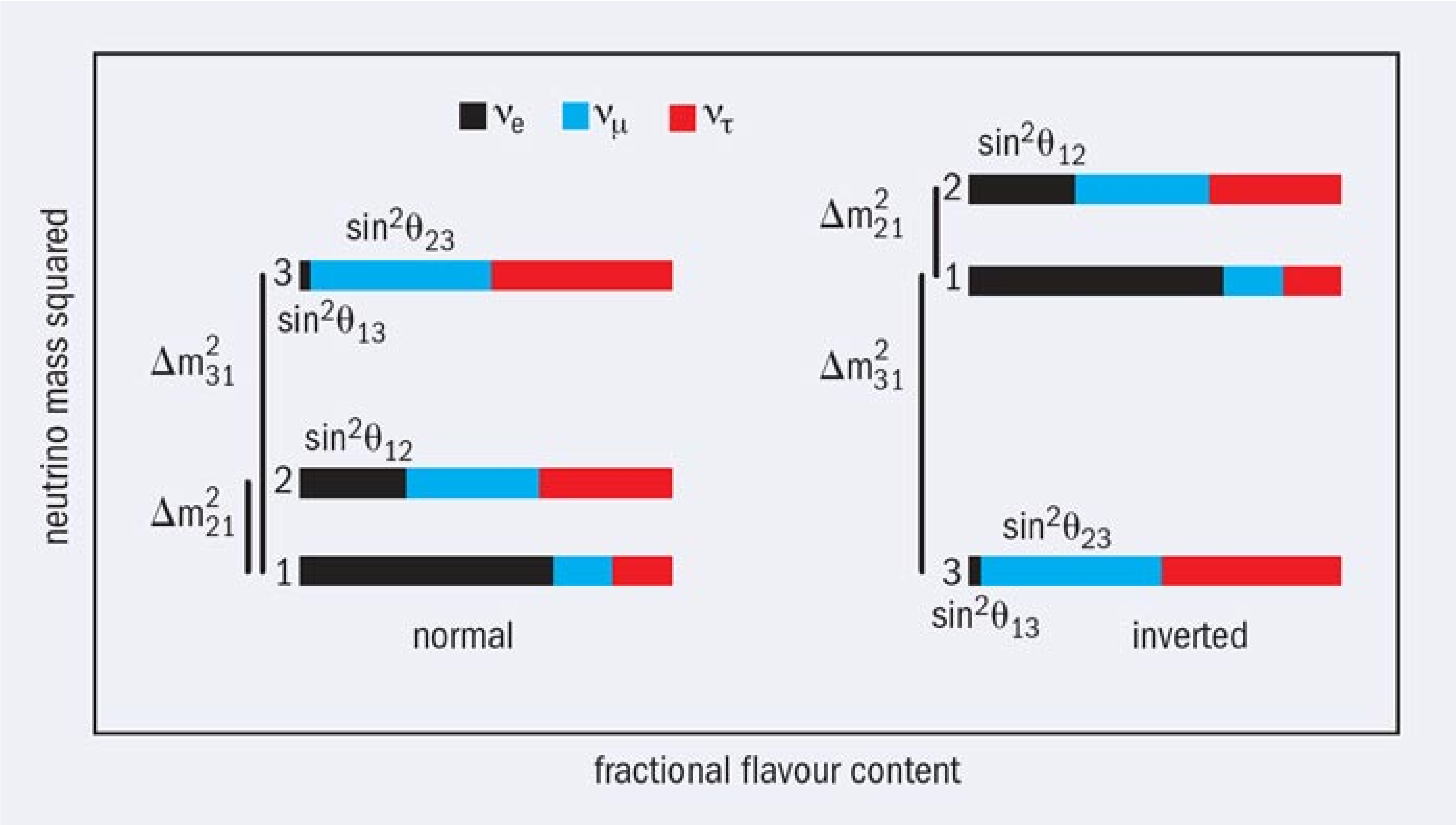
x5



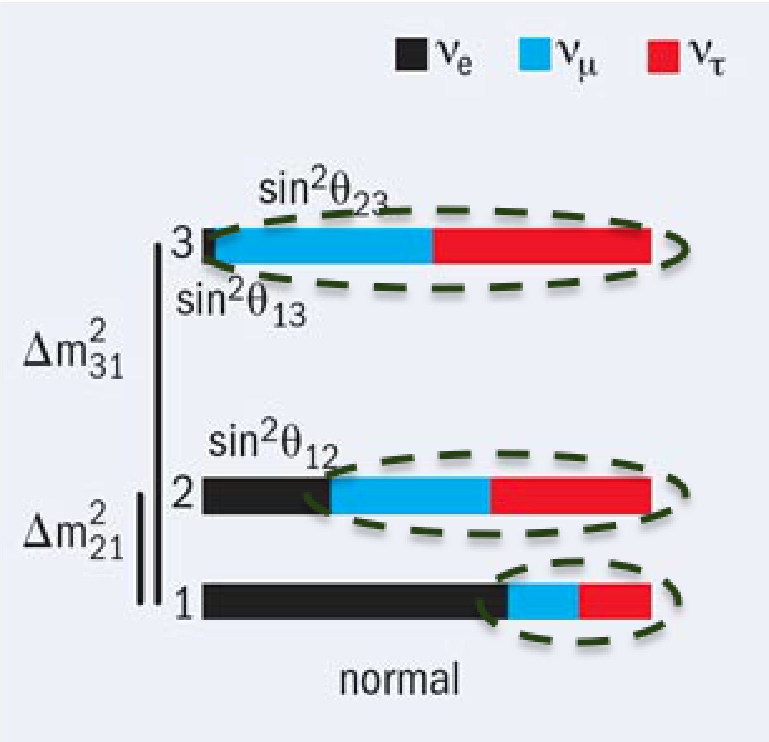
Several unknowns: What is the neutrino mass hierarchy?

The sign of Δm^2_{21} known ($m_2 > m_1$) but the **sign of Δm^2_{31} is unknown**.

- 1 heavy + 2 light neutrinos (normal hierarchy)?
- Or, 2 heavy + 1 light neutrinos (inverted hierarchy)?



Several unknowns: is θ_{23} maximal?



Are μ and τ flavours interchangeable?

Or, equivalently, **is θ_{23} maximal** (45^o)?

This is currently unknown!

A maximal mixing could imply some previously unknown discrete symmetry, and hint at connections between the PMNS and CKM mixing matrices.

Several unknowns: Is there leptonic CP violation?

The CP-violating phase in PMNS is largely unconstrained.

The magnitude of the CP effect is given by the **Jarlskog Invariant**:

$$J_{CP}^{PMNS} = \frac{1}{8} \, sin2\theta_{12} \; sin2\theta_{13} \; sin2\theta_{23} \; cos\theta_{13} \; sin\delta_{CP}$$

Given the current best fit values, and assuming the normal hierarchy:

$$J_{CP}^{PMNS} = 0.035 \; sin\delta_{CP}$$

In contrast, in the quark sector, despite the large value of the CP phase:

$$J_{CP}^{CKM} \approx (3 \pm 1) \times 10^{-5}$$

J_{CP}^{PMNS} is **potentially large!**

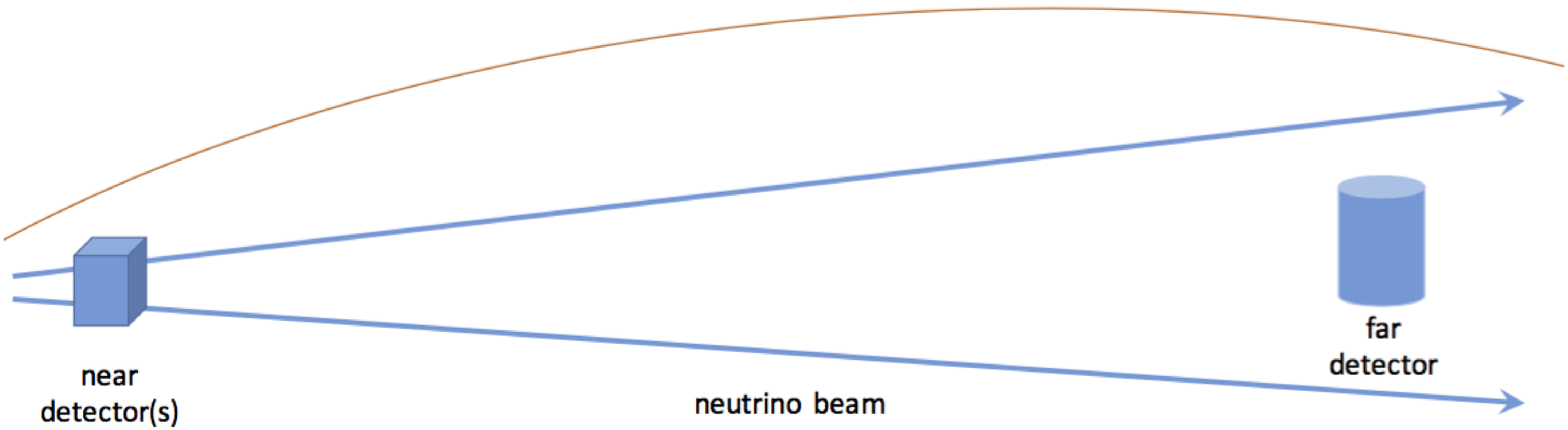
Measurement of leptonic CPV could have a tremendous impact on our understanding of the origin of the **Baryon Asymmetry of the Universe**.

T2K Experiment $\rightarrow$ CPV

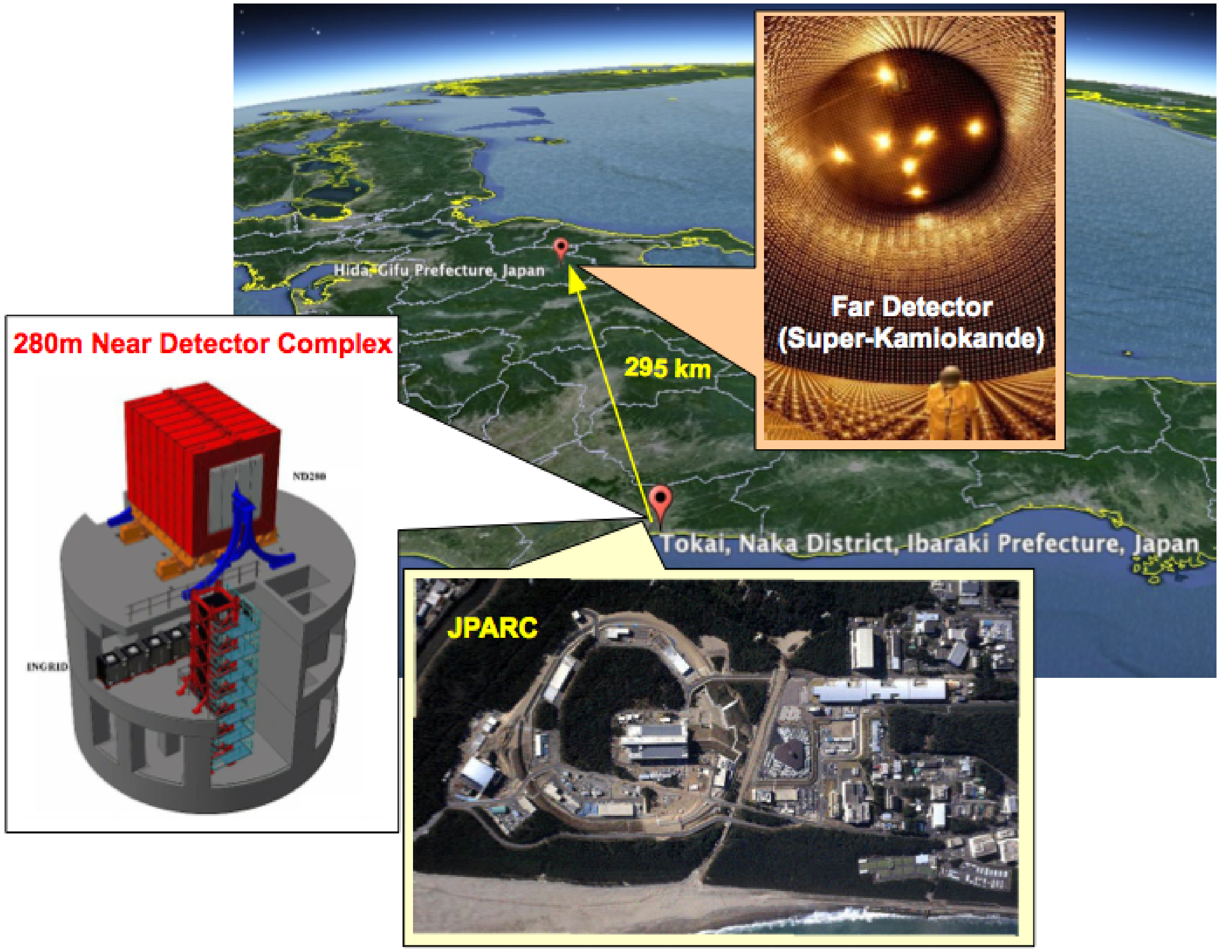
- T2K is an experiment designed to measure $\nu_\mu \rightarrow \nu_e$ oscillations.
- This goal was accomplished with the first 10% of data!!
- The observation of $\nu_\mu \rightarrow \nu_e$ opened the possibility of testing for CP violation in neutrino oscillations.
- T2K 're-invented' itself to address the fundamental question of CP.

T2K Experiment (minimalist version)

Have i) a neutrino beam, ii) a "near" detector, and iii) a "far" detector



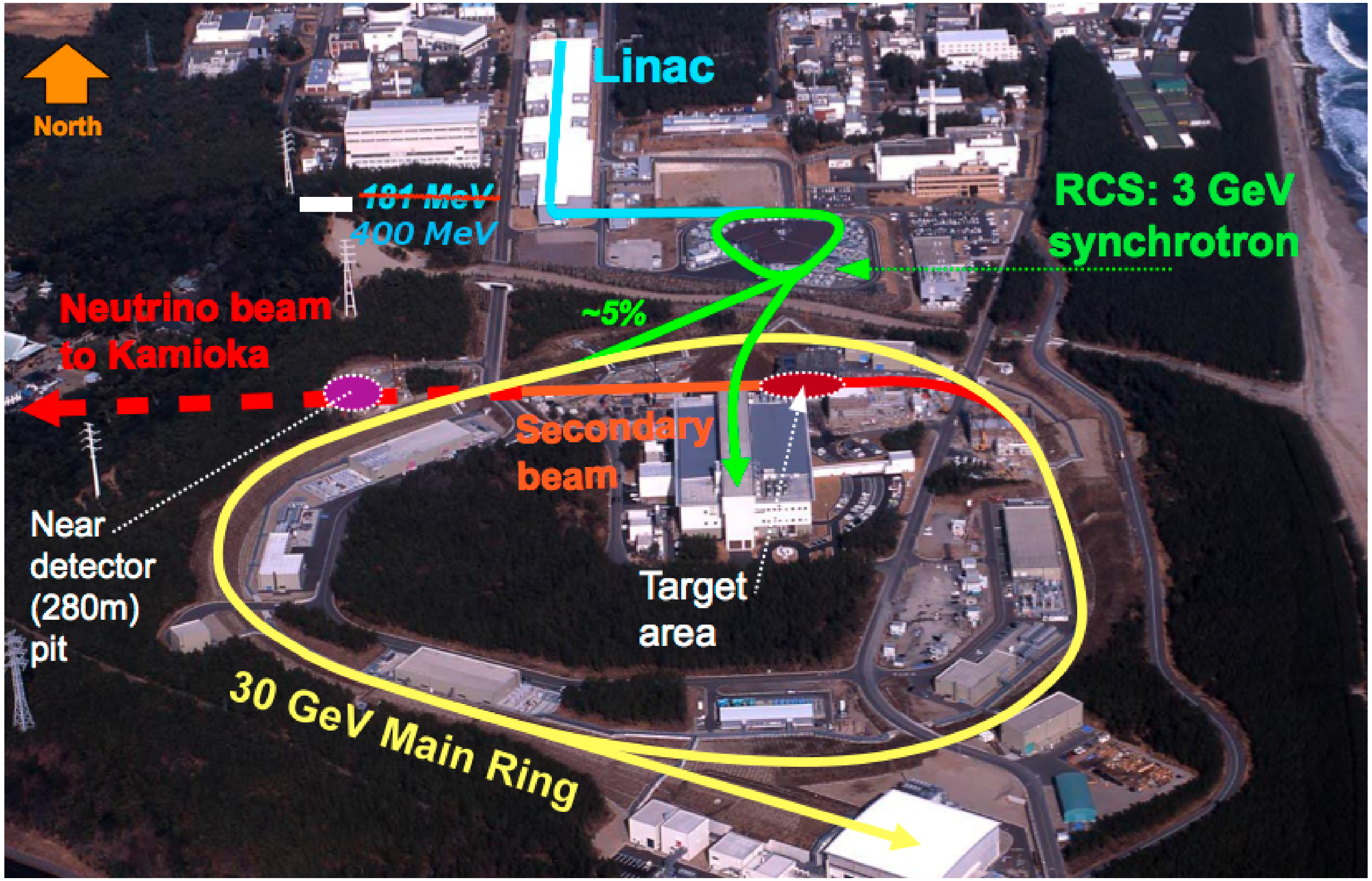
T2K Experiment



- Pure ν_μ beam.
- Produced using the 30-GeV proton beam at J-PARC
- Design Power of 750 kW (420 kW achieved to date)
- Far detector: SuperK 50-kton (22.5 kton fiducial) water Cherenkov detector, 2.5 degrees off-axis, 295 km away.
- Neutrino flux at SuperK peaked at $\sim$0.6 GeV.
- L/E tuned to the 'atmospheric' Δm^2 scale ($\sim 2.4 \times 10^{-3}$ eV^2/c^4).

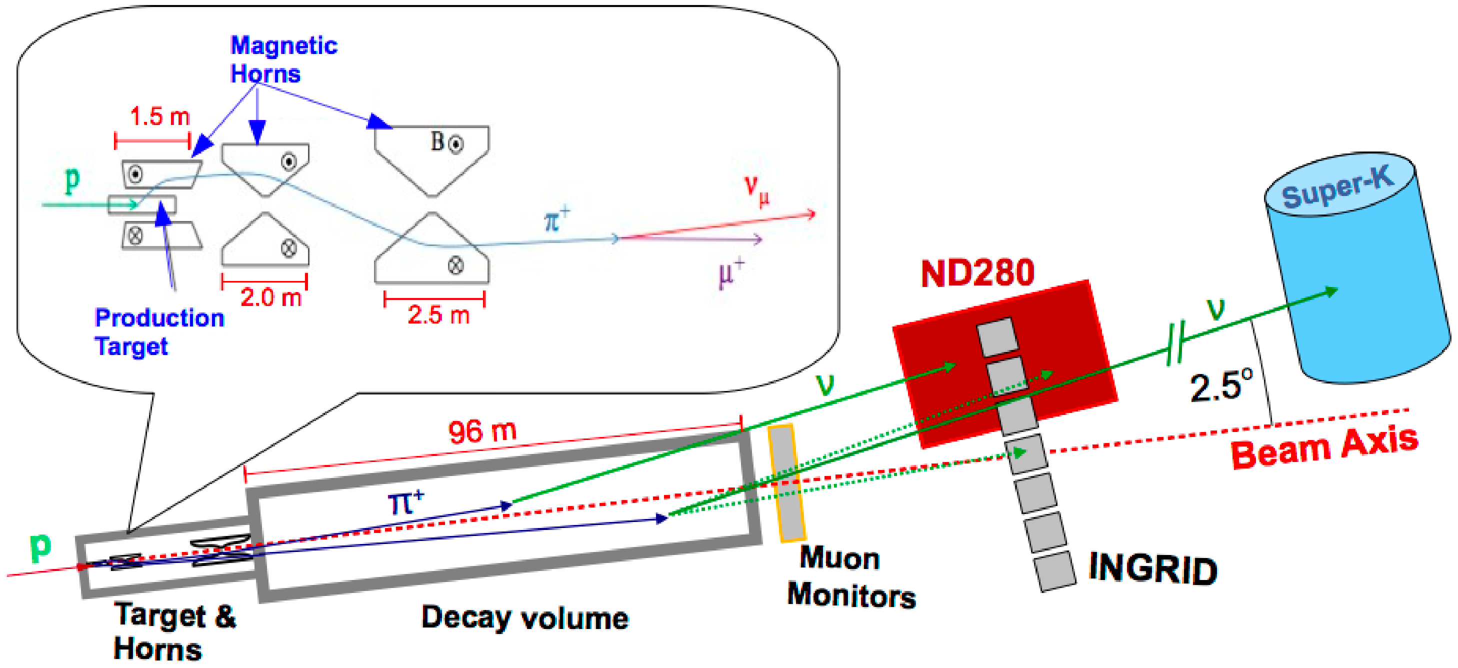
Making a neutrino beam

Primary proton beam from the 30-GeV J-PARC proton accelerator.



- Fast extraction
- 8 bunches/spill
- 581 nsec bunch interval
- 58 nsec bunch width
- Rep. rate (May '16): 2.48 sec
- p/spill (May '16): 2.2×10^{14}
- p/spill (design): 3.3×10^{14}
- Power (May '16): 420 kW
- Power (design): 750 kW

Making a neutrino beam



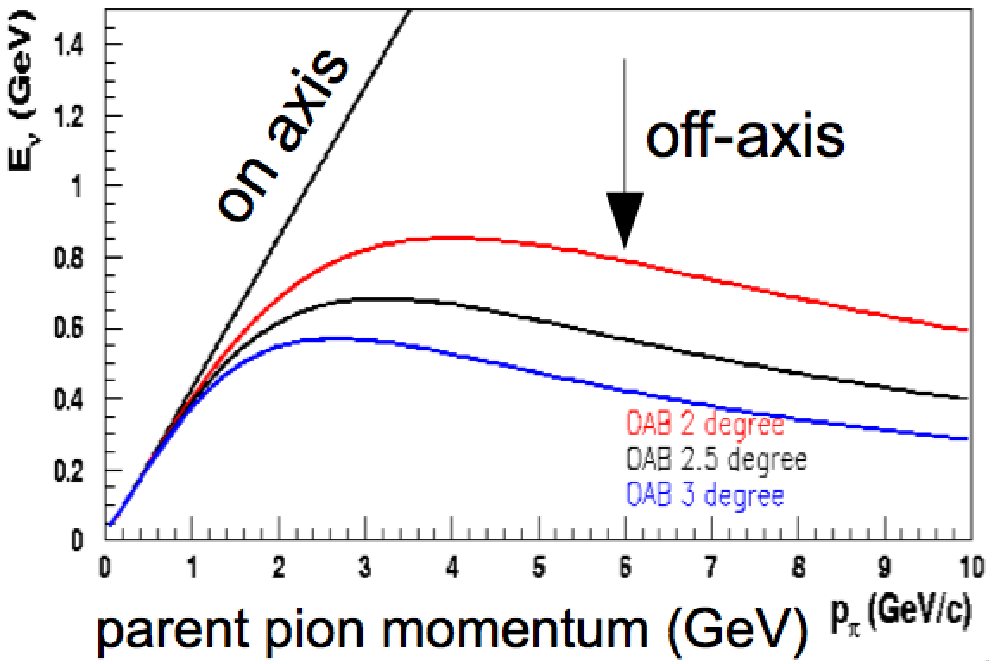
Where do our ν's come from?

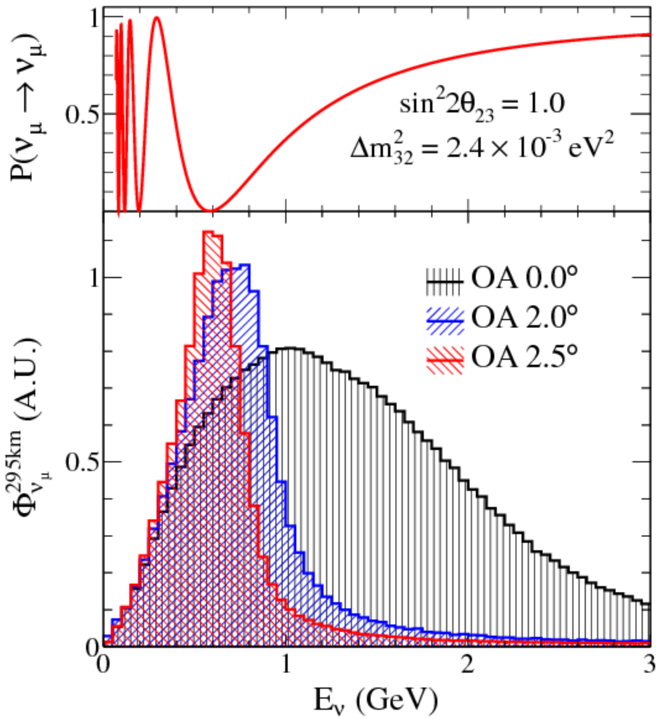
$\pi^+ \to \nu_\mu + \mu^+$
$\pi^- \to \bar{\nu}_\mu + \mu^-$
$\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+$
$\mu^- \to \bar{\nu}_e + \nu_\mu + e^-$
$K^+ \to \nu_\mu + \mu^+$
$K^+ \to \nu_e + \pi^0 + e^+$
$K^+ \to \nu_\mu + \pi^0 + \mu^+$
$K^- \to \bar{\nu}_\mu + \mu^-$
$K^- \to \bar{\nu}_e + \pi^0 + e^-$
$K^- \to \bar{\nu}_\mu + \pi^0 + \mu^-$
$K^0_L \to \bar{\nu}_\mu + \pi^+ + \mu^-$
$K^0_L \to \nu_\mu + \pi^- + \mu^+$
$K^0_L \to \bar{\nu}_e + \pi^+ + e^-$
$K^0_L \to \nu_e + \pi^- + e^+$

Target: A 2.6 cm wide, 91.4 cm (1.9 interaction lengths) long graphite rod
Focussing: 3 magnetic horns pulsed with 250 (max 320) kA currents generating $\sim$2 T field: $\sim$16$\times$ increase in ν flux w.r.t unfocussed beam.
Decay volume: A 96 m long steel decay tunnel

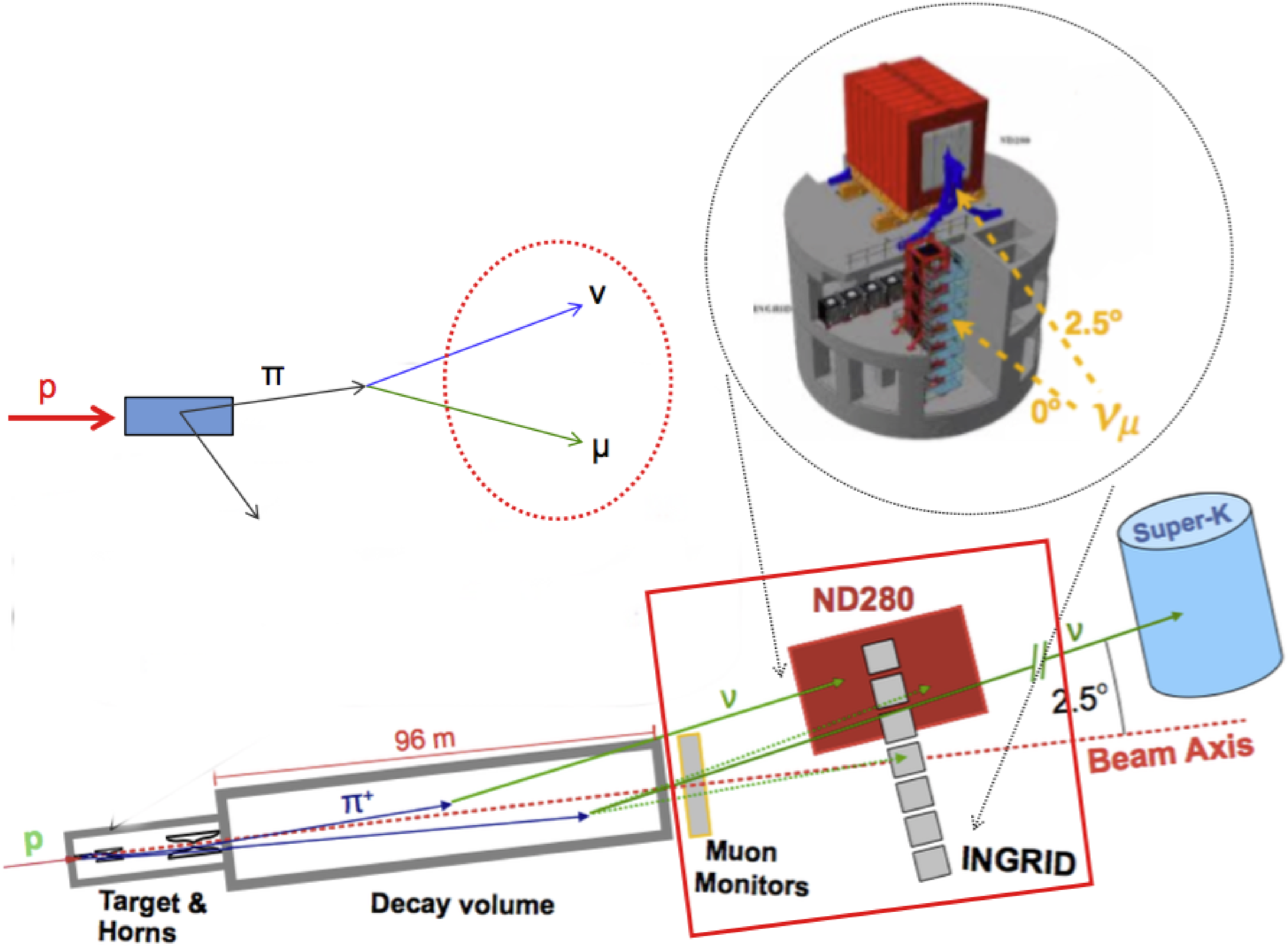
T2K was the first accelerator experiment going off-axis.

Exploits kinematical properties of pion decay to create a narrow-band neutrino beam peaked at an energy chosen so as to maximize the oscillation probability at the SuperK location.

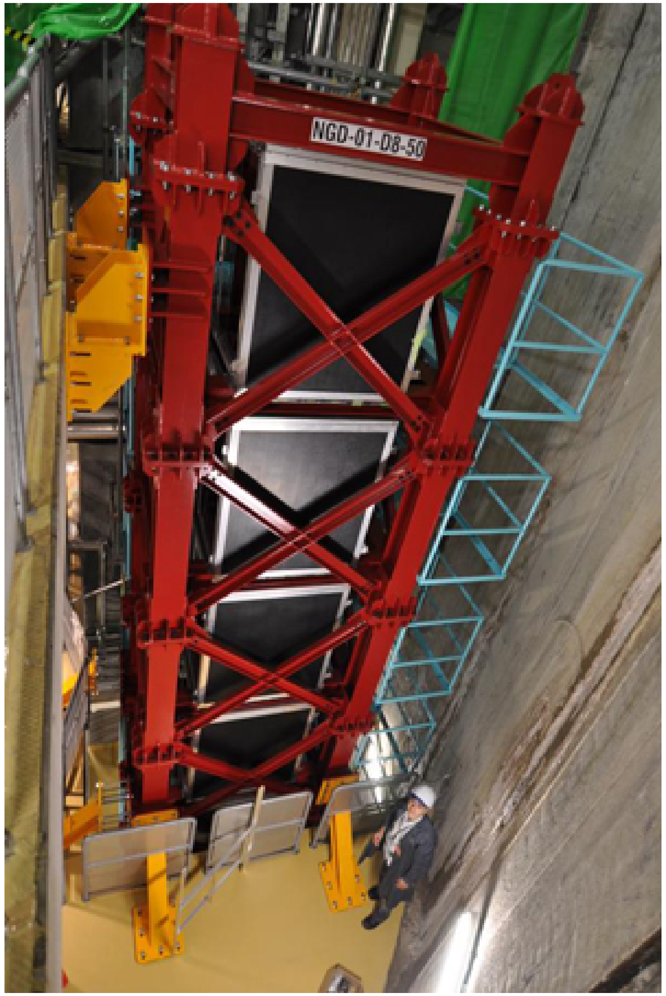


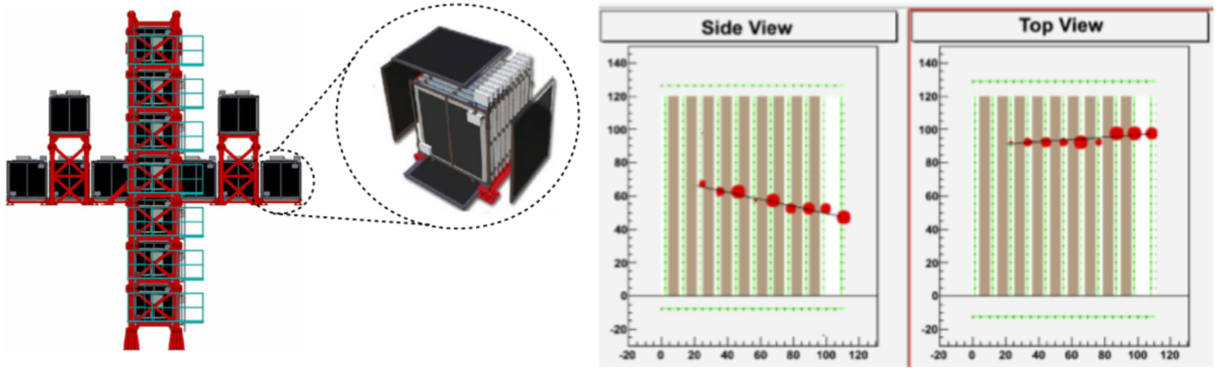


Near detector complex



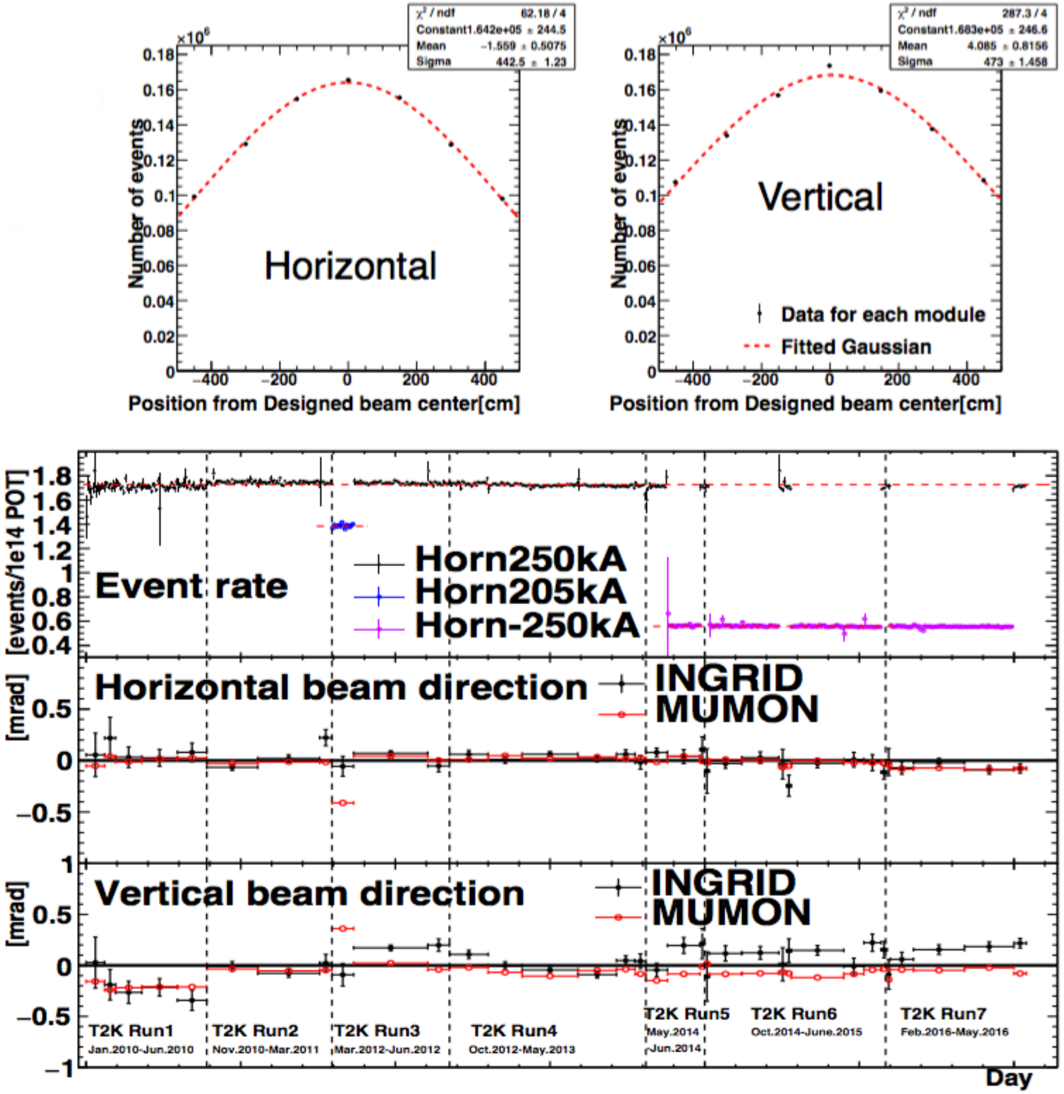
Neutrino beam monitoring





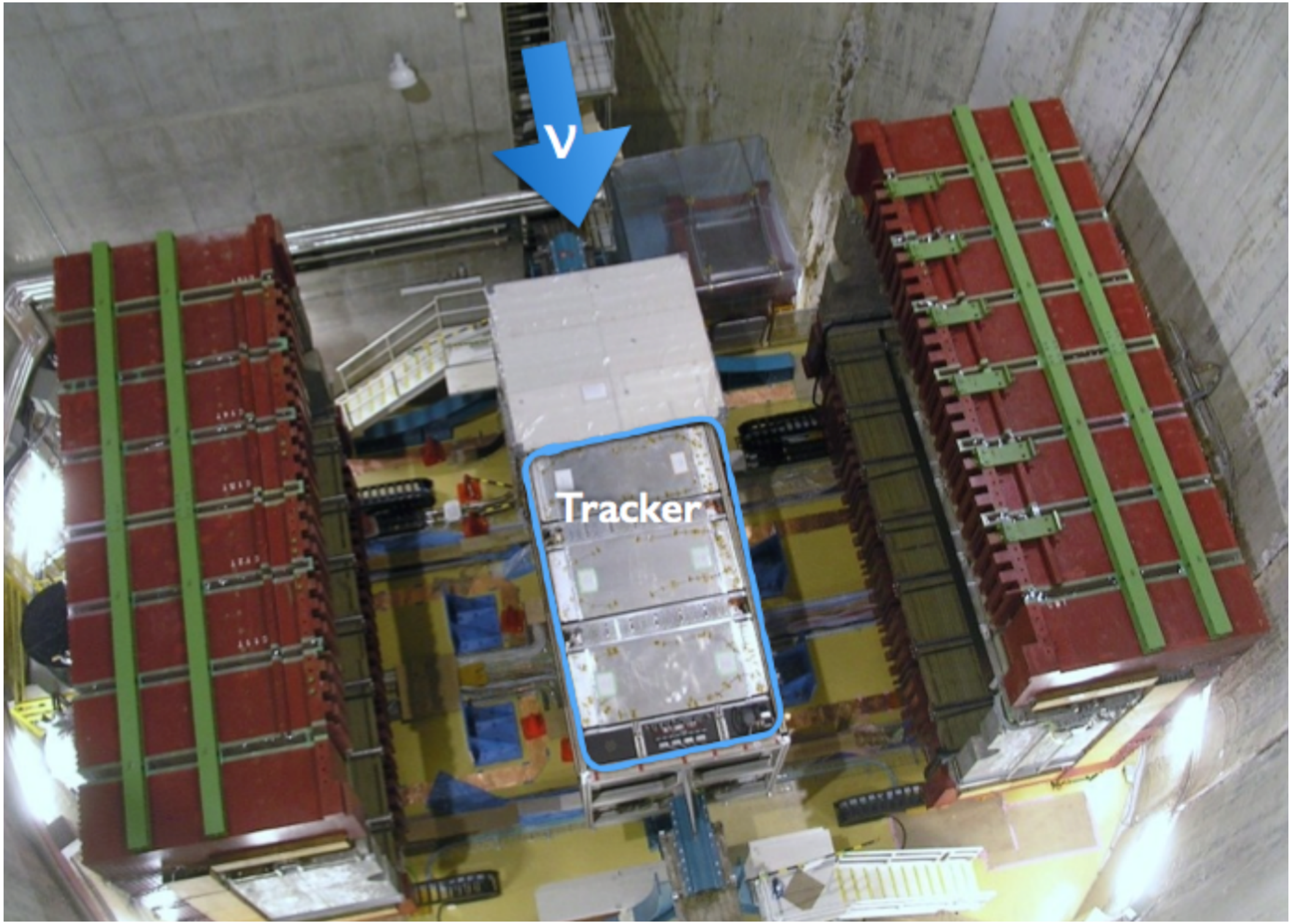
- 16 modules (14 in cross configuration).
- Each module: 7 tons, alternating scintillator / iron planes.
- 10 m $\times$ 10 m beam area coverage
- 1 event per $\sim 6 \times 10^{13}$ protons on target.
- Monitors neutrino beam rate and profile.

Neutrino beam monitoring



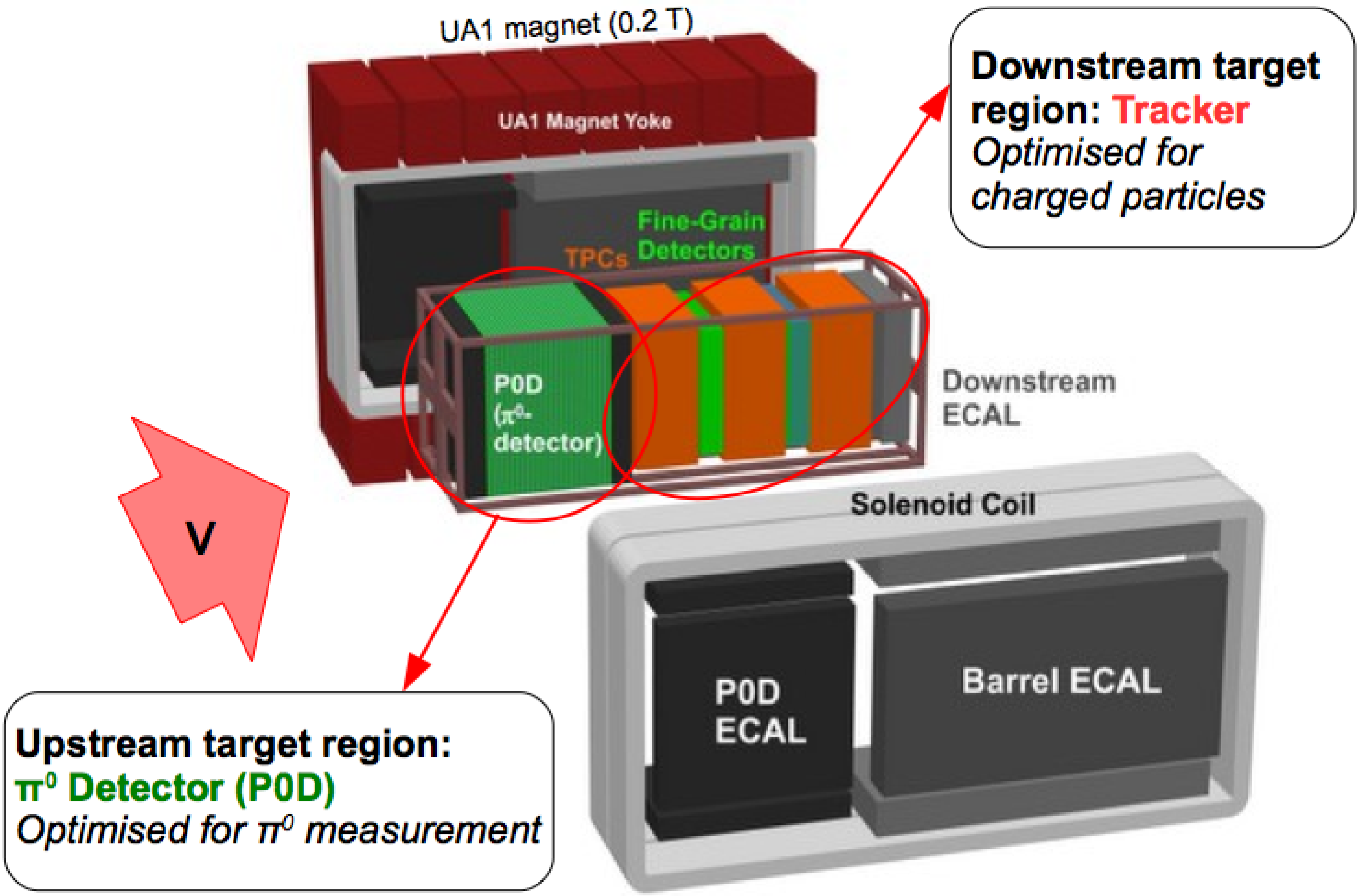
- Beam direction stable within 1 mrad (corresponding to less than $\sim$2% peak energy shift at SuperK)
- POT (Protons On Target) normalised event rate stable to better than 1%

Off-axis Near Detector at 280 m

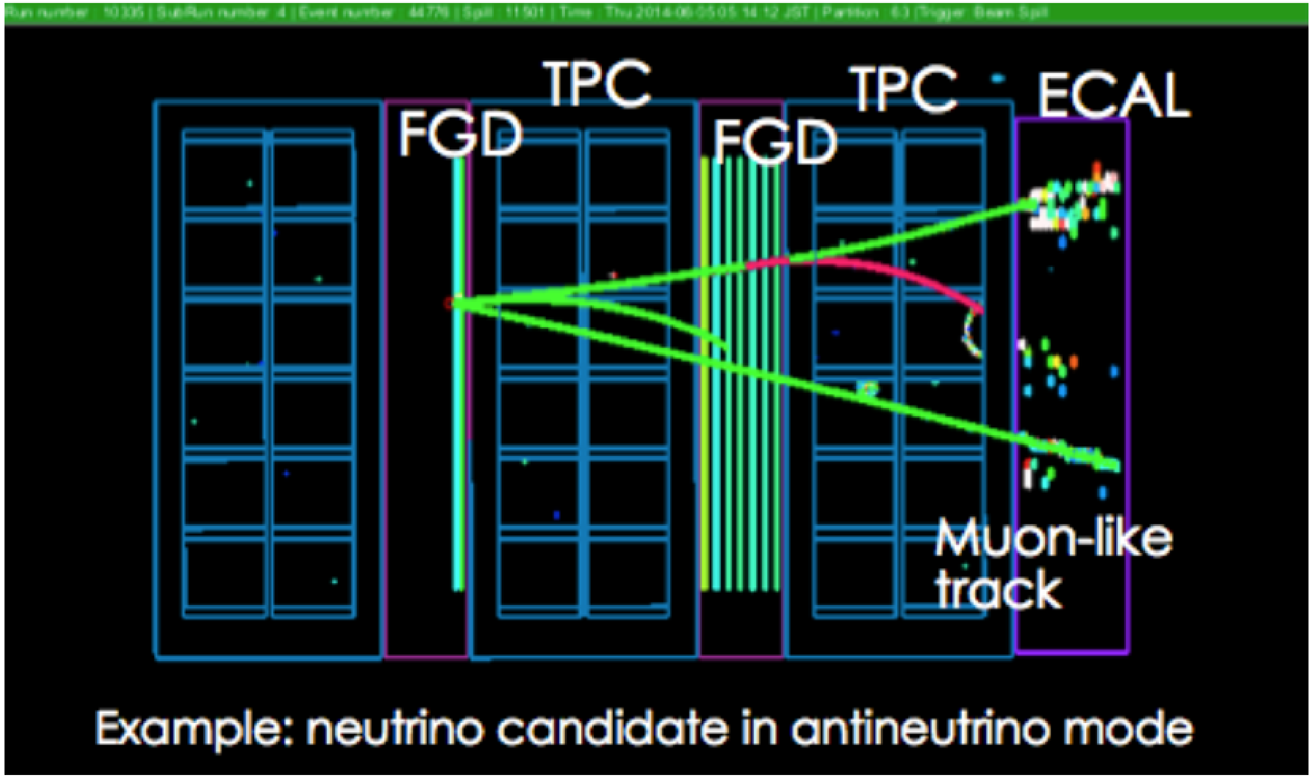


Off-axis Near Detector at 280 m

Tracking Calorimeters and Time Projection Chambers in a 0.2 T B field.
Polystyrene and water targets.

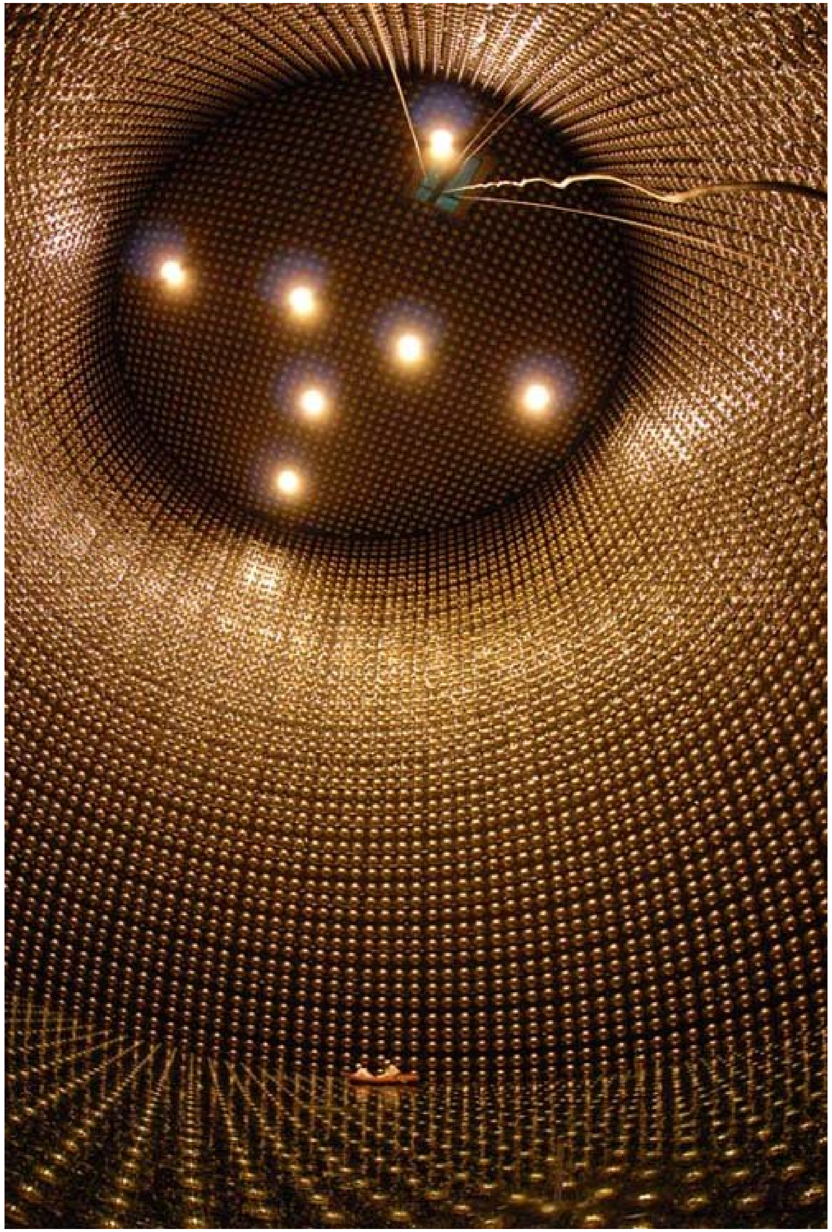


Tracker system @ Off-axis Near Detector at 280 m



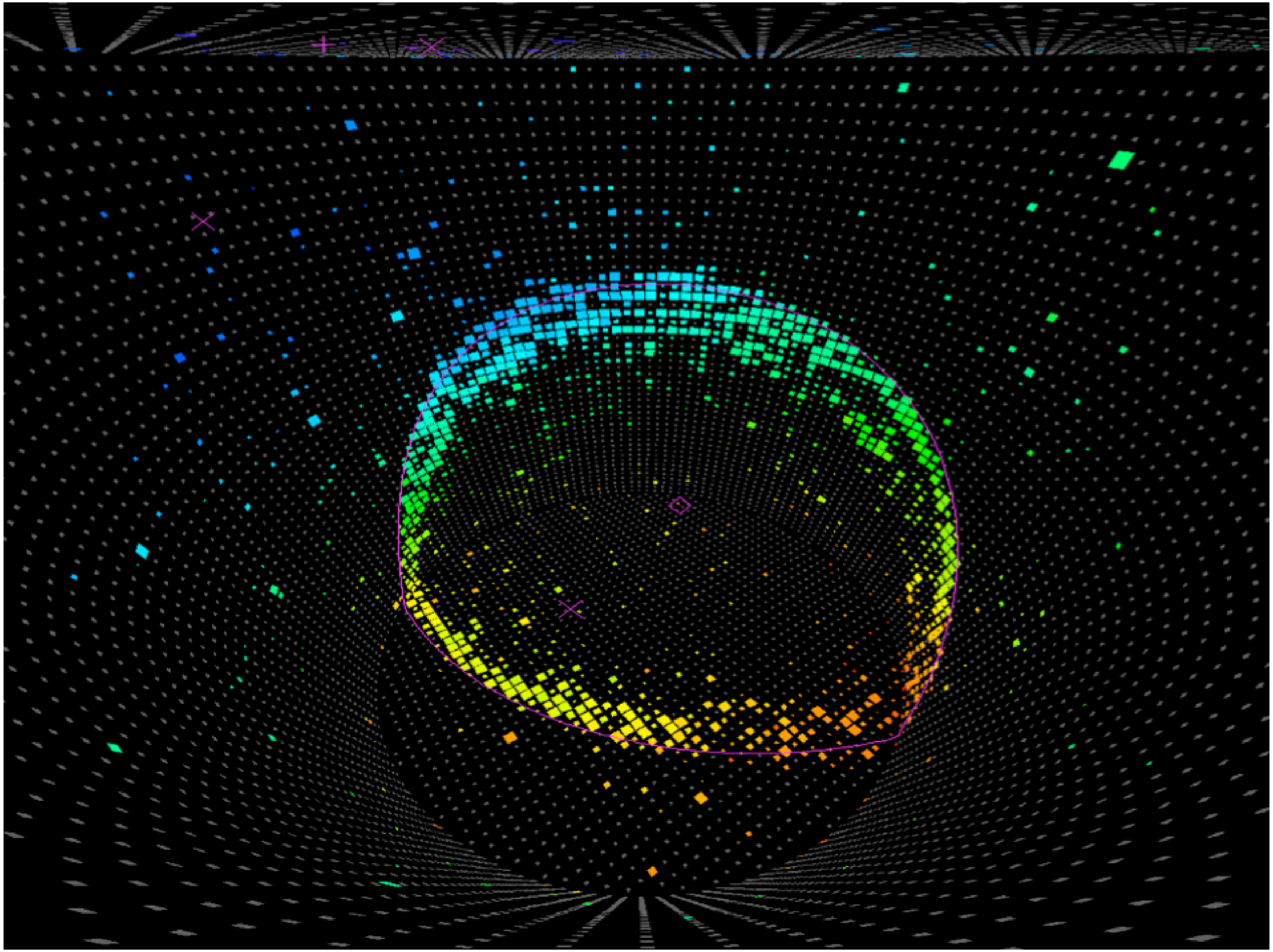
- 2 fine-grained scintillator detectors (FGDs) + 3 time projection chambers (TPCs).
- FGDs provide the target mass
  (FGD1: 1 ton scintillator, FGD2: 0.5 ton scintillator + 0.5 ton water).
- Momentum measurement of charged particles, PID via dE/dx.
- Better than 10% dE/dx resolution, and 10% momentum resolution at 1 GeV.

The Far Detector (Super-Kamiokande IV)



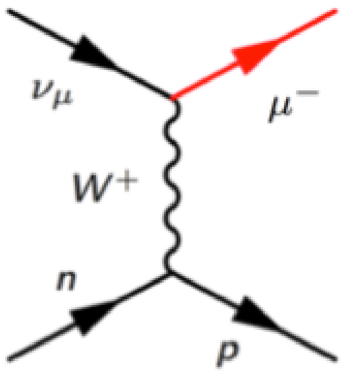
- 50 kt Water Cherenkov detector (22.5 kton fiducial)
- Overburden (shielding): 2700 mwe
- Inner Detector (ID): 11,129 20" PMTs (40% photo-cathode coverage)
- Outer Detector (OD): 1,885 8" PMTs
- DAQ: No dead-time
- Energy threshold: $\sim$ 4.5 MeV

Water Cherenkov Imaging

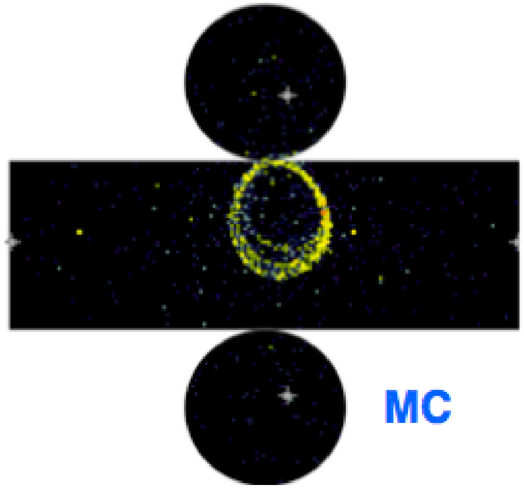


Water Cherenkov Imaging: Identifying $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$

ν_μ CCQE

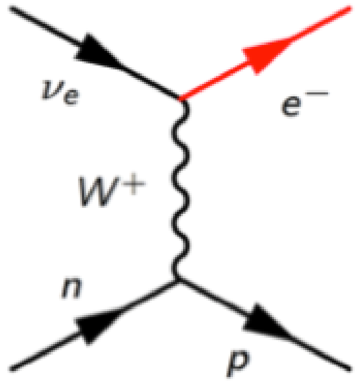


- Low scattering
- Ring with sharp edge
- Protons below Cherenkov threshold

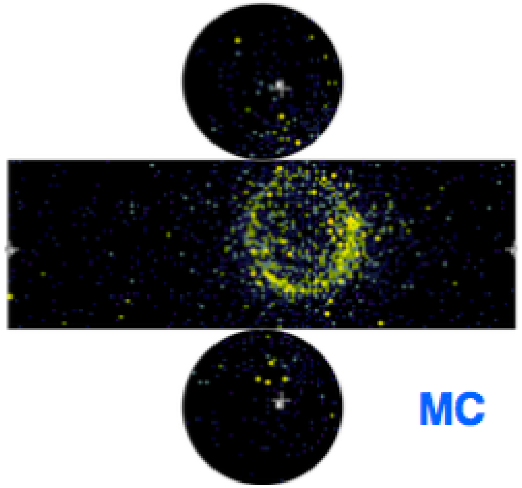


MC

ν_e CCQE

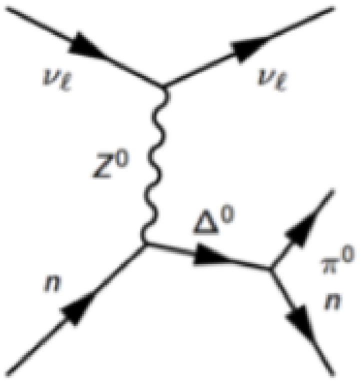


- Multiple scattering
- EM shower
- Ring with “fuzzy” edge

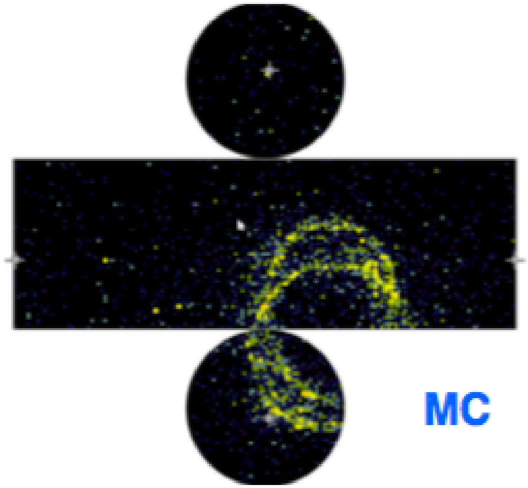


MC

Background



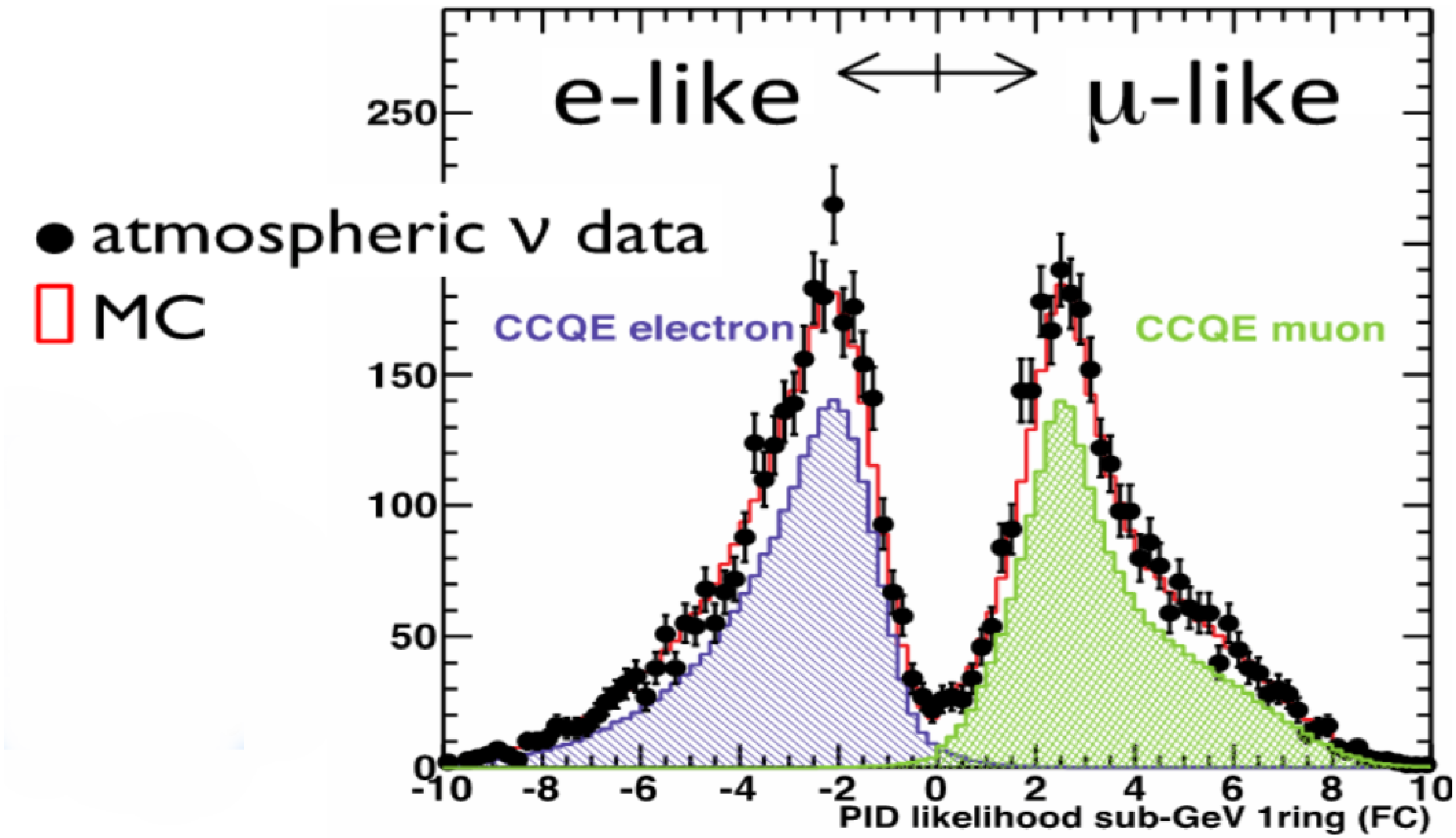
- EM shower from $\pi^0 \to \gamma\gamma$
- Can be misidentified as an electron



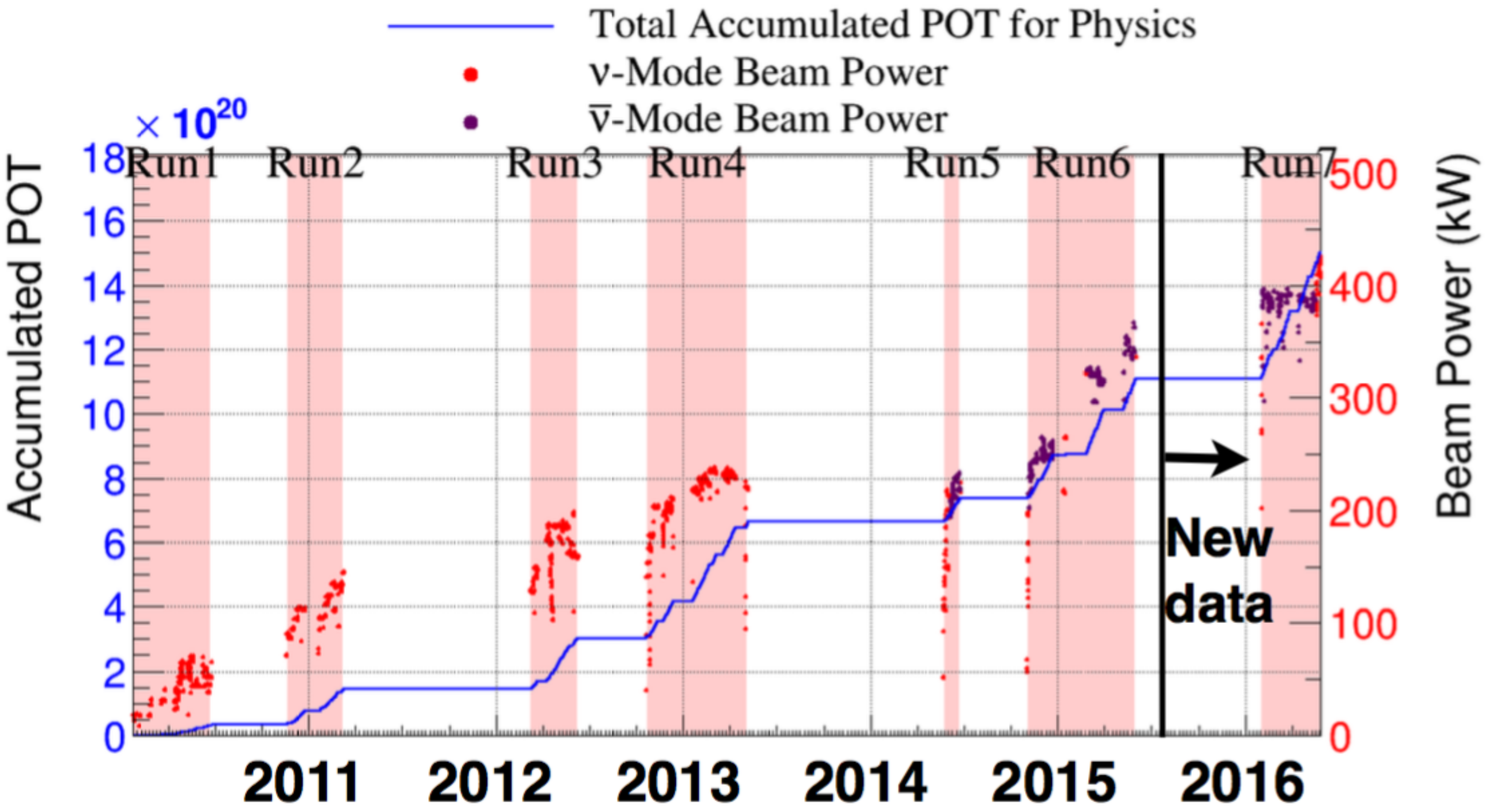
MC

Water Cherenkov Imaging: Identifying $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$

- Excellent e/μ separation.
- Probability to misidentify a muon as an electron is smaller than 1%.



T2K Datasets



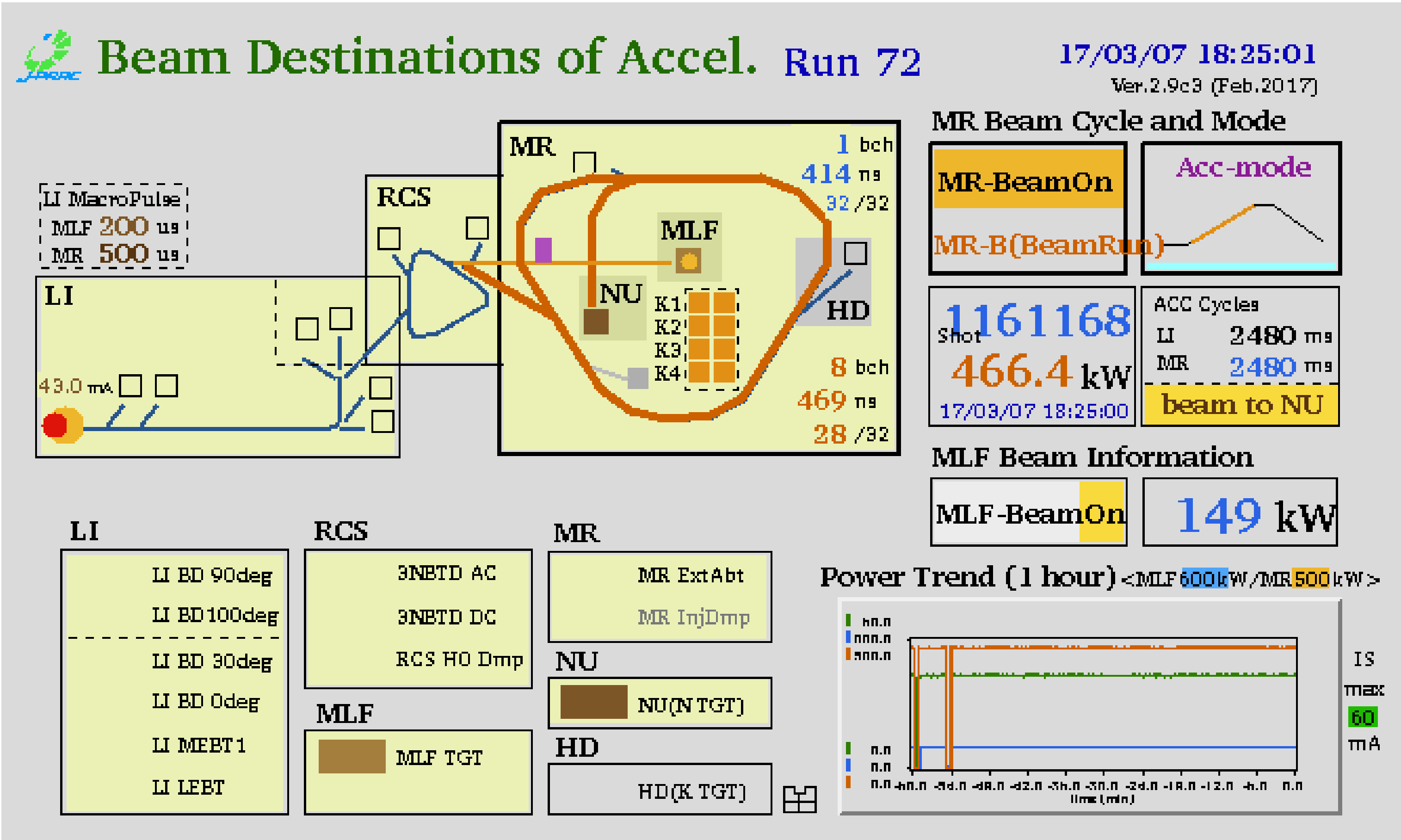
Mode	Exposure in protons on target (POT)
Neutrino	7.57×10^{20}
Antineutrino	7.53×10^{20}
Combined	1.510×10^{21}

- Steady improvement of beam power (increased up to 420 kW).
- Double antineutrino exposure in 2016.

We take more data as we speak

Live updates:
http://j-parc.jp/ctrl/jkwww/accsts/li/rss/BeamDestShot.png

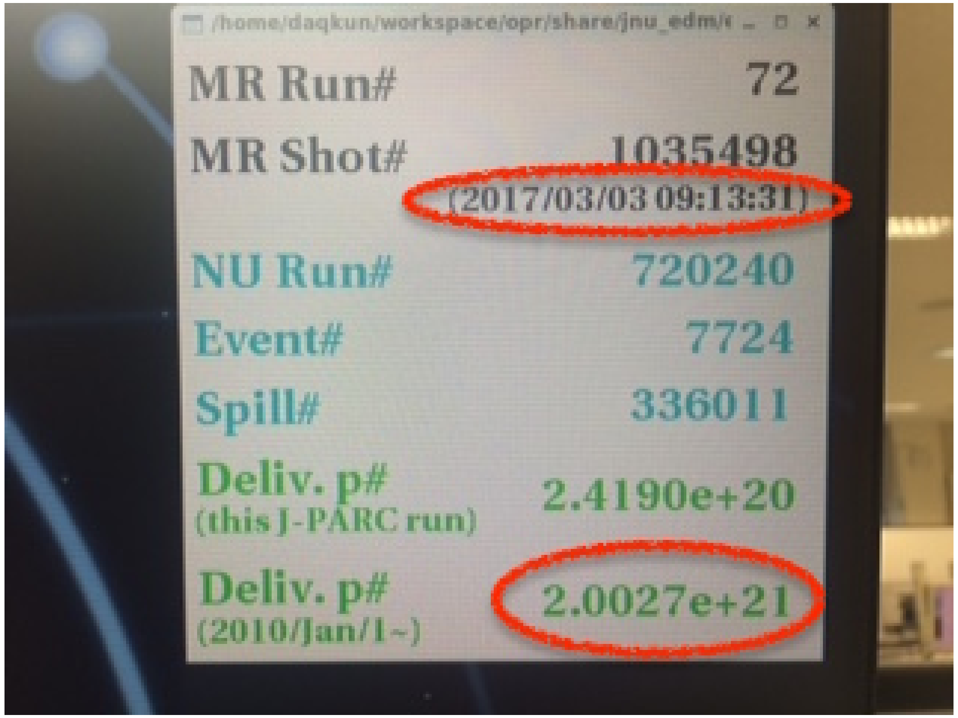
Screenshot from earlier today:



We take more data as we speak

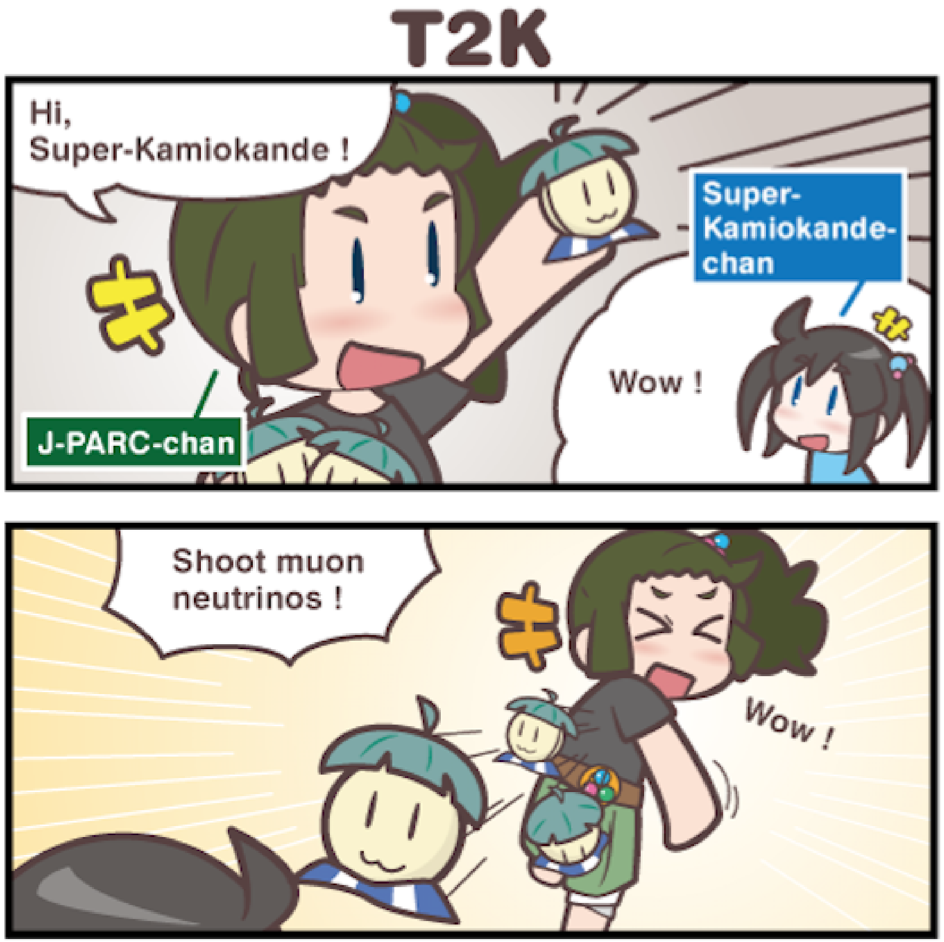
Reached 2×10^{21} **POT 4 days ago!**

Already have 30% more data than I am presenting here.



Measuring neutrino oscillations at T2K

Measuring neutrino oscillations at T2K



J-PARC-chan
lives in Tokai-mura, Naka-gun, Ibaraki, Japan.

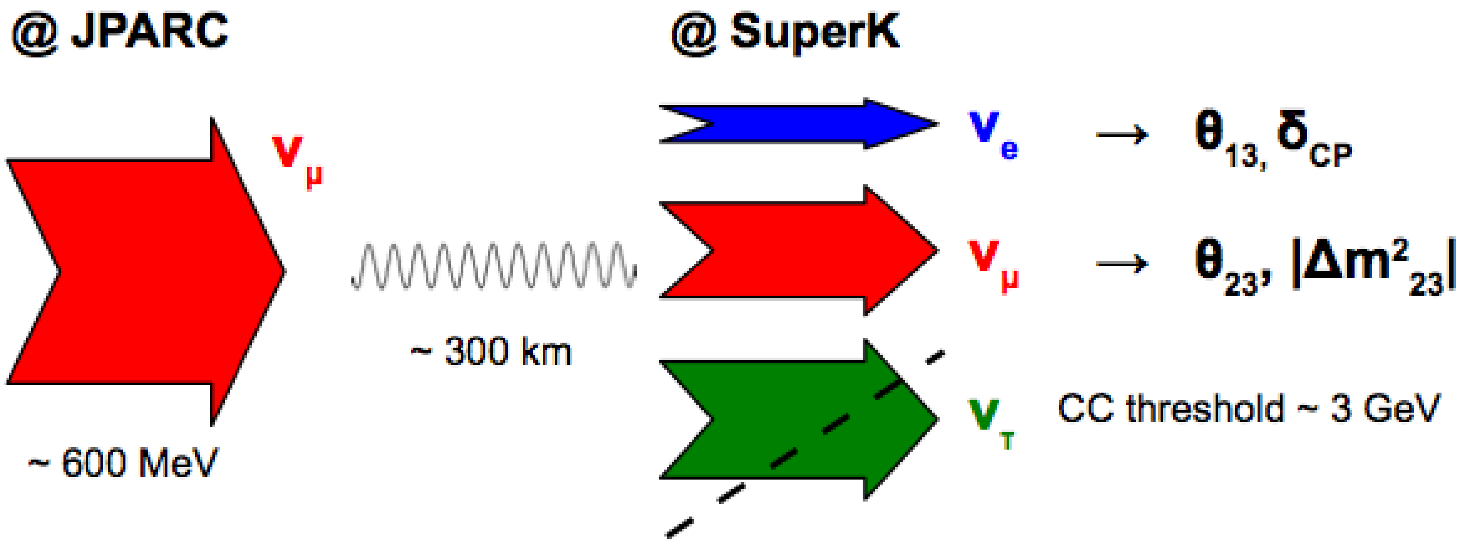
Super-Kamiokande-chan
lives in Kamioka-cho, Hida-city, Gifu, Japan.

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

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - cos^4\theta_{13} \cdot sin^2 2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$

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

$$P(\nu_\mu \rightarrow \nu_e) = 4 \cdot cos^2\theta_{13} \cdot sin^2\theta_{13} \cdot sin^2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$



Measuring neutrino oscillations at T2K

$$P(\nu_\mu \to \nu_e) \simeq \boxed{\sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}}$$

Phys. Rev. D64 (2001) 053003

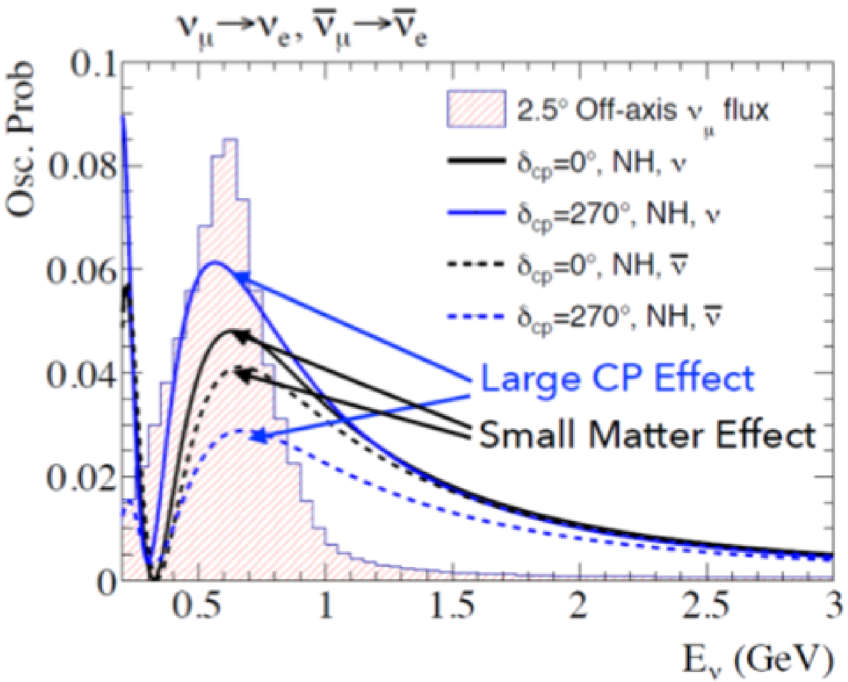
Leading term

CP violating $\quad - \alpha \sin\delta_{CP} \times \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

"+" for antineutrino

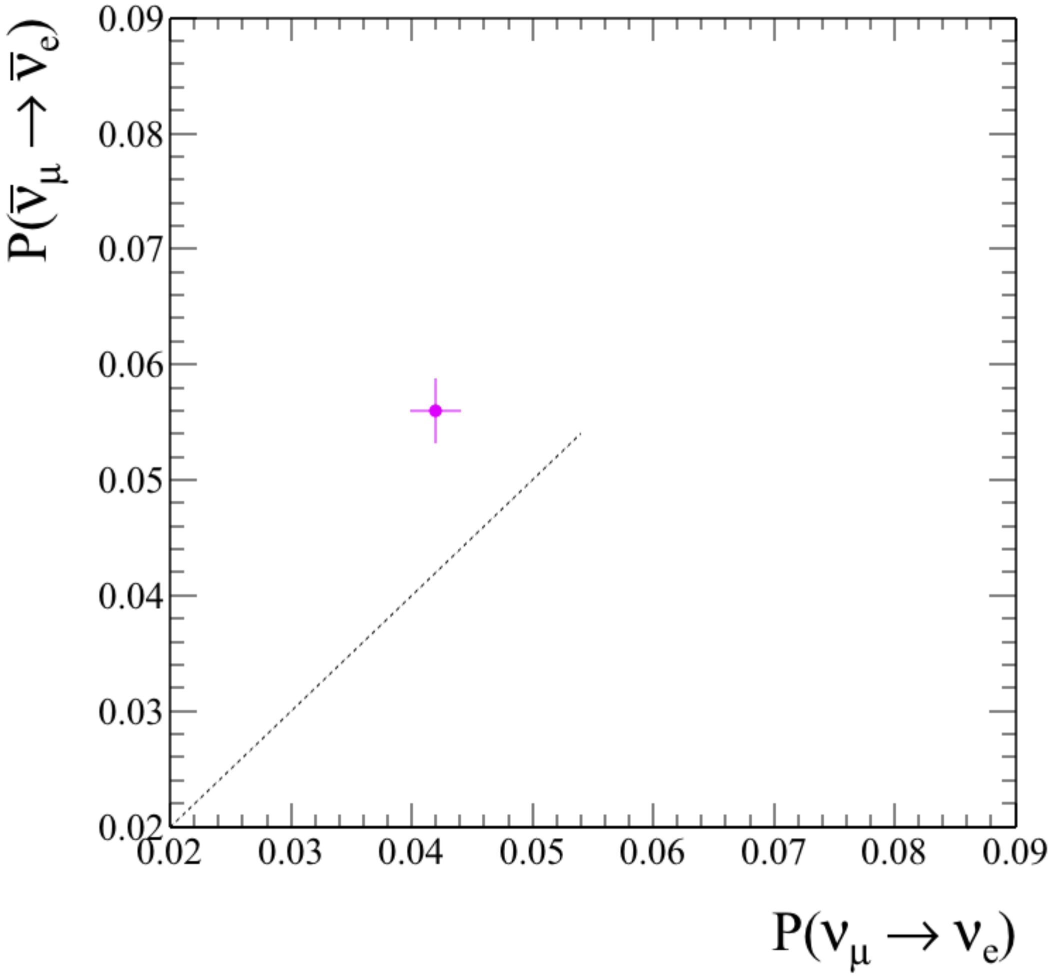
CP conserving $\quad \alpha \cos\delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

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



- δ_{CP} has asymmetric effect on $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - $\delta_{CP} = -\pi/2$: Maximizes $P(\nu_\mu \to \nu_e)$, minimizes $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - $\delta_{CP} = +\pi/2$: vice versa...
- δ_{CP} effect is $\pm$ 20-30%
- Matter effect is $\pm$ 10%

Measuring δ_{CP}



If CP is violated:

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

So a measurement in the

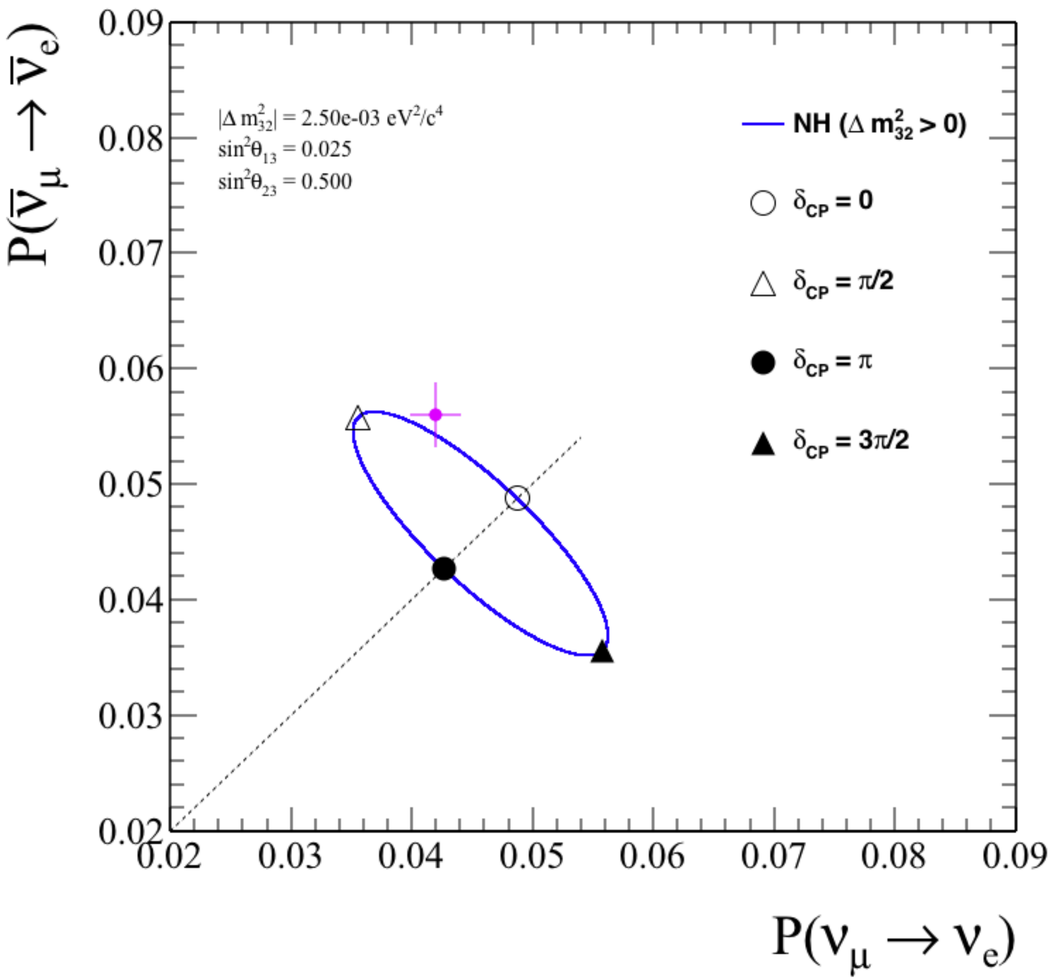
$$\left(P(\nu_\mu \rightarrow \nu_e), P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \right)$$

space will be off the diagonal.

Within the standard 3-flavour model, the only source of CP violation is the δ_{CP} phase:
This measurement can be used to determine the value of δ_{CP}.

Measuring δ_{CP}

Within the standard 3-flavour model, the only source of CP violation is the δ_{CP} phase: It enters as an $e^{\pm i\delta_{CP}}$ term, so it has a **cyclical effect**.

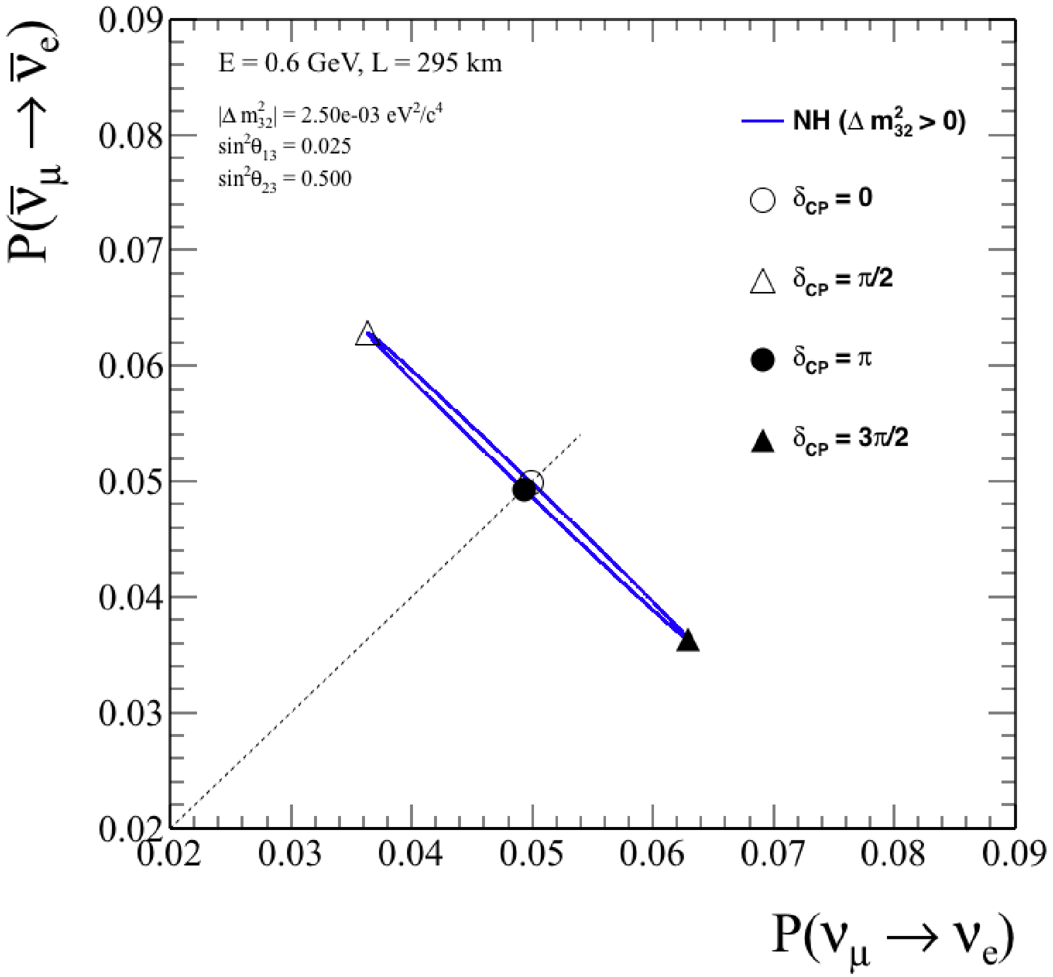


Note that:

- Points for $\delta_{CP} = 0$ or π are on the diagonal (no CP).
- $\pi/2$ corresponds to more $\bar{\nu}_e$ appearance
- $3\pi/2$ ($-\pi/2$) corresponds to more ν_e appearance

Measuring δ_{CP}

Unfortunatelly, T2K is less able to discriminate between the CP conserving values of δ_{CP} $(0, \pi)$, so the ellipse is flattened.



Large ranges of δ_{CP} values give nearly-identical asymmetry: Difficult to do much more than just discriminating between the $(0, \pi)$ and $(\pi, 2\pi)$ ranges...

So the T2K δ_{CP} measurement resolution is quite poor.

This is made even worst by matter effects, ignored in this plot (vacuum oscillation probabilities are shown).

Measuring δ_{CP}

Matter effect can play an important role in neutrino oscillations.

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

In the 3-flavour model, A_{CP} can be approximated as:

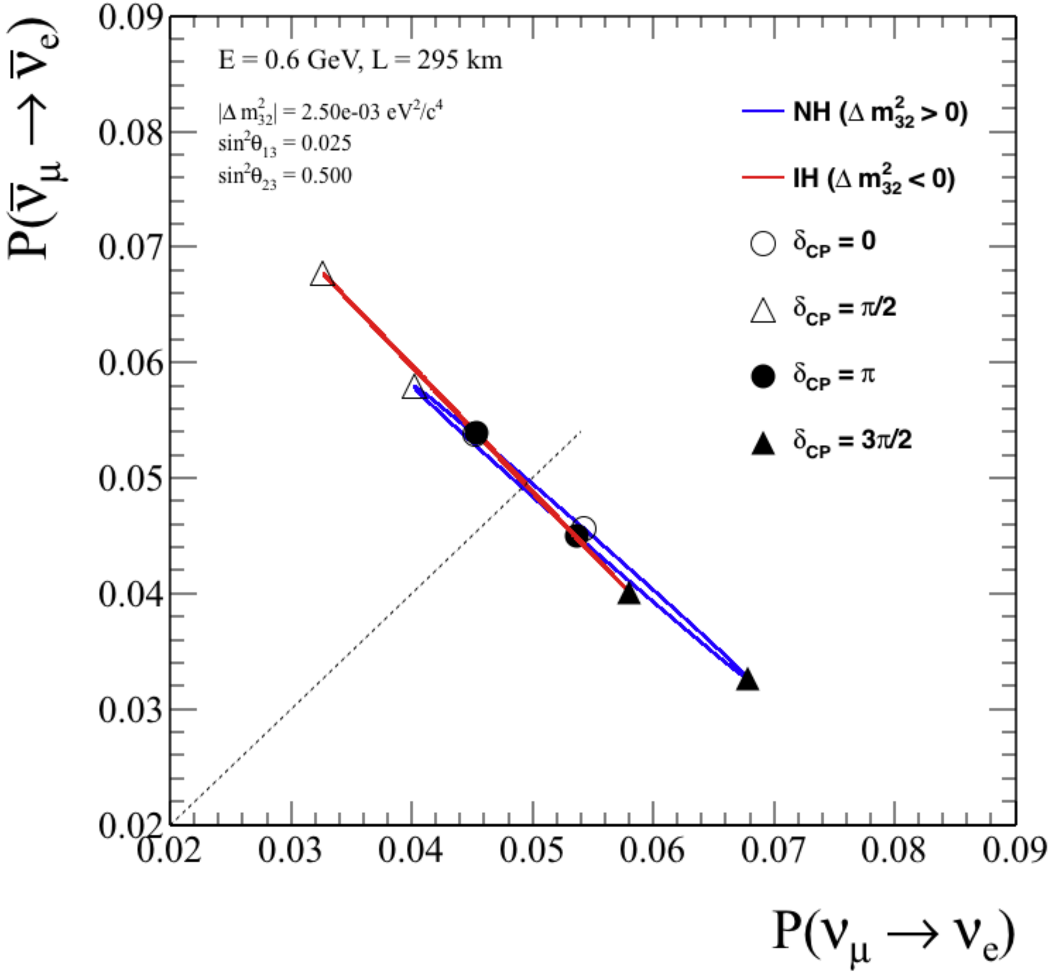
$$A_{CP} \approx \frac{cos\theta_{23} sin2\theta_{12} sin\delta_{CP}}{sin\theta_{23} sin\theta_{13}} \left(\frac{\Delta m^2_{21} L}{4E} \right) + \text{ matter effects}$$

Matter induced asymmetry in $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in addition to CP.

Experimental sensitivity to CP violation and the MH from measurements of the total asymmetry between $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ requires the **disambiguation of the asymmetries** induced by matter and CP violation.

Measuring δ_{CP}

Matter effect can play an important role in neutrino oscillations.



Important to know the MH.

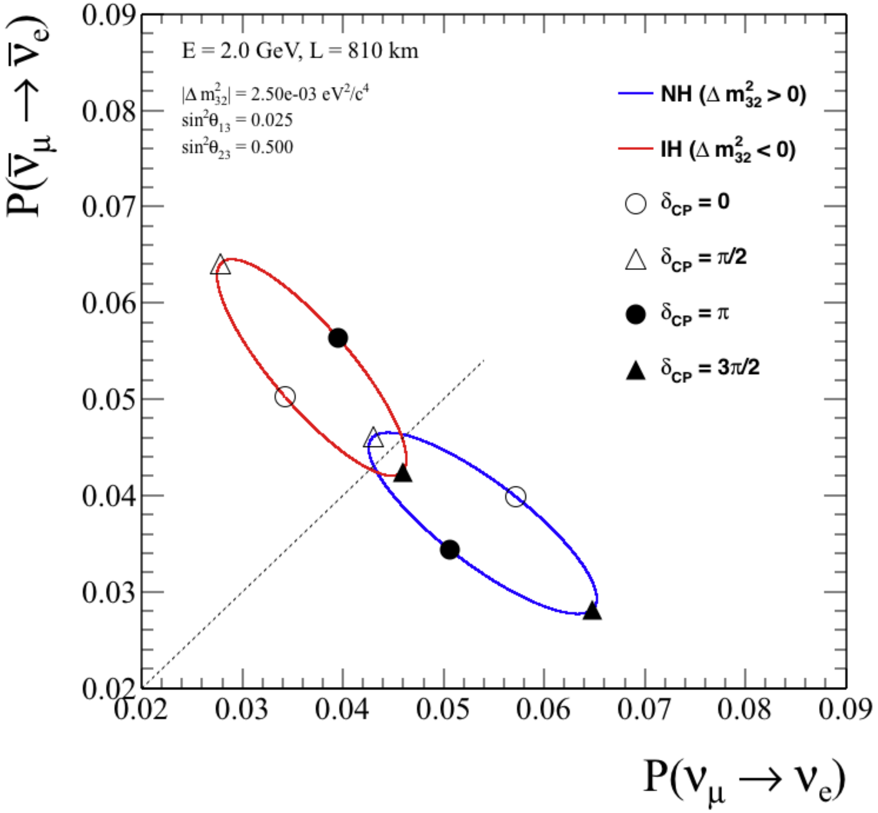
- For NH, ν_e appearance is enhanced and $\bar{\nu}_e$ appearance is suppressed.
- For IH, ν_e appearance is suppressed and $\bar{\nu}_e$ appearance is enhanced.

Matter effects useful for lifting degeneracies, identifying the hierarchy and measuring δ_{CP}.

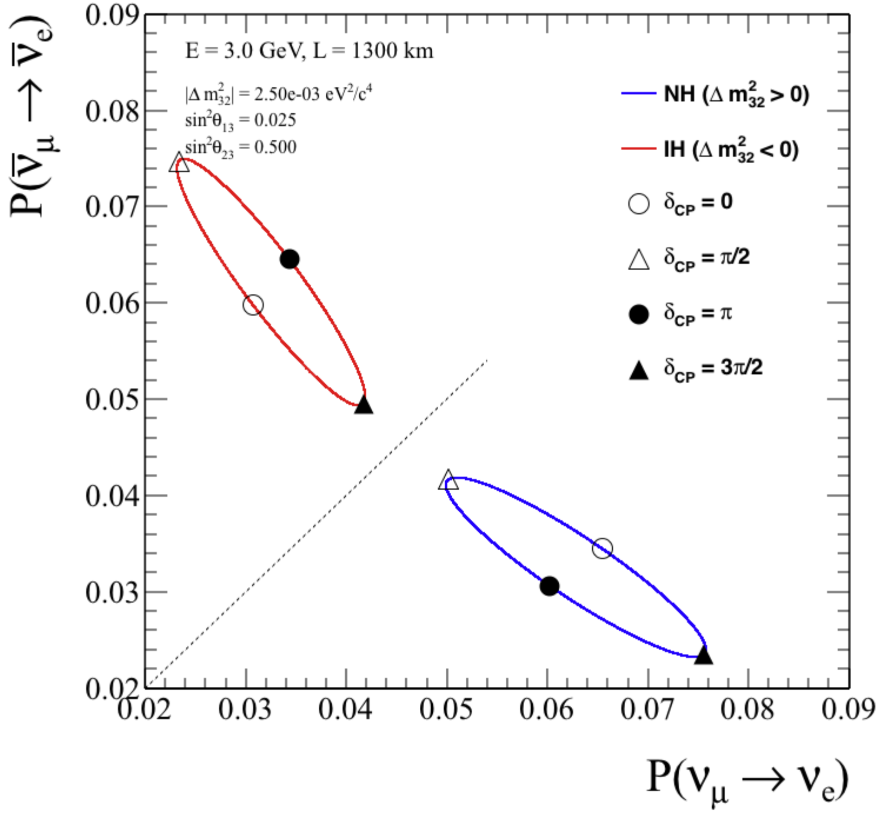
T2K: Not enough matter effect!

Measuring δ_{CP}

Example: NOvA

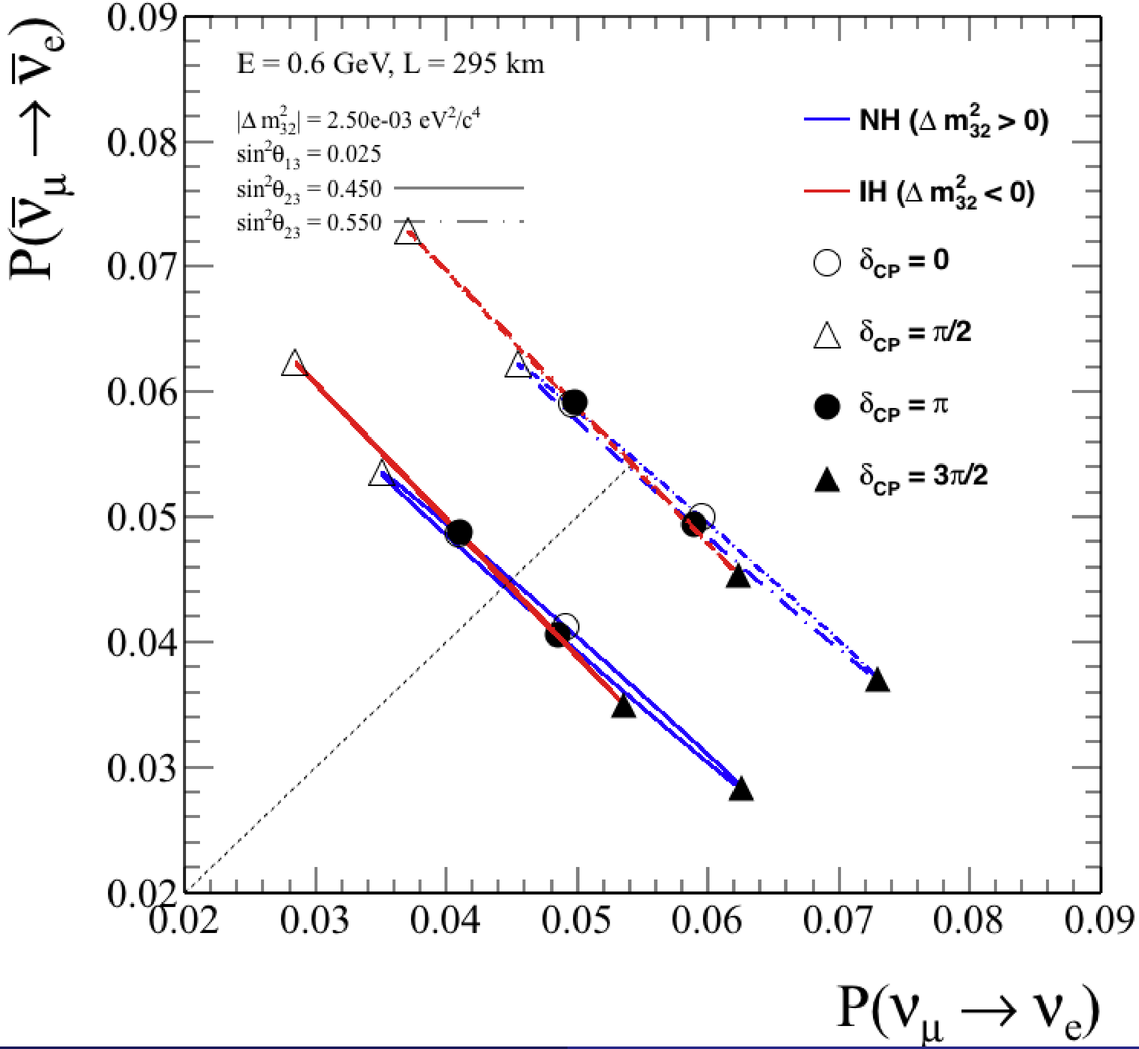


Example: DUNE



Measuring δ_{CP}

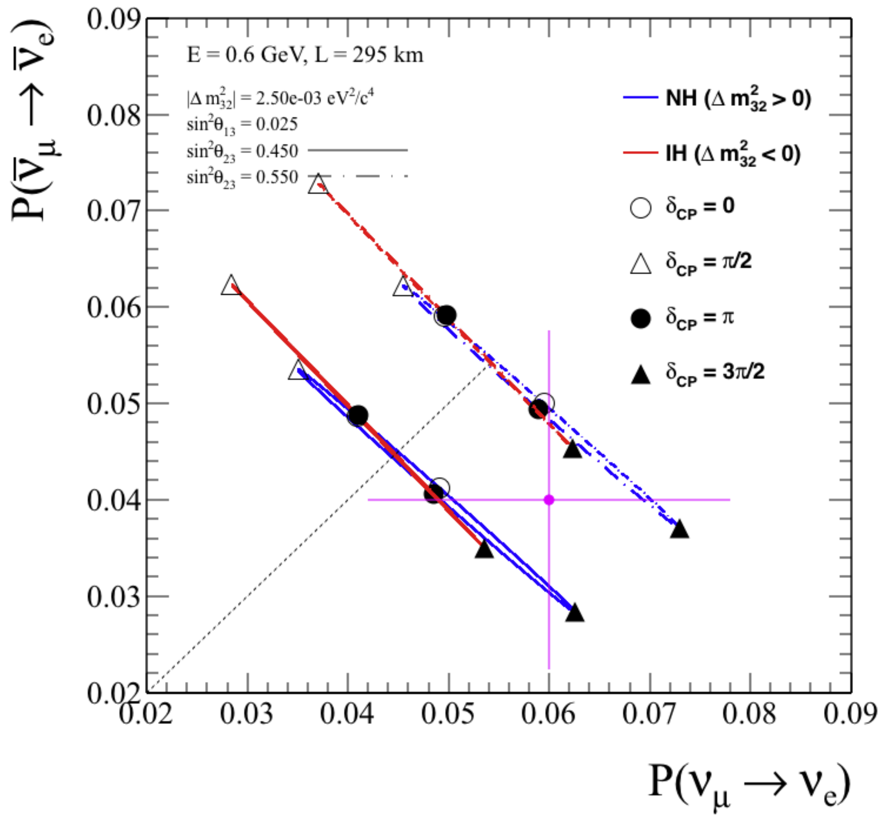
The θ_{23} **octant degeneracy** further limits our CP sensitivity and measurement resolution.



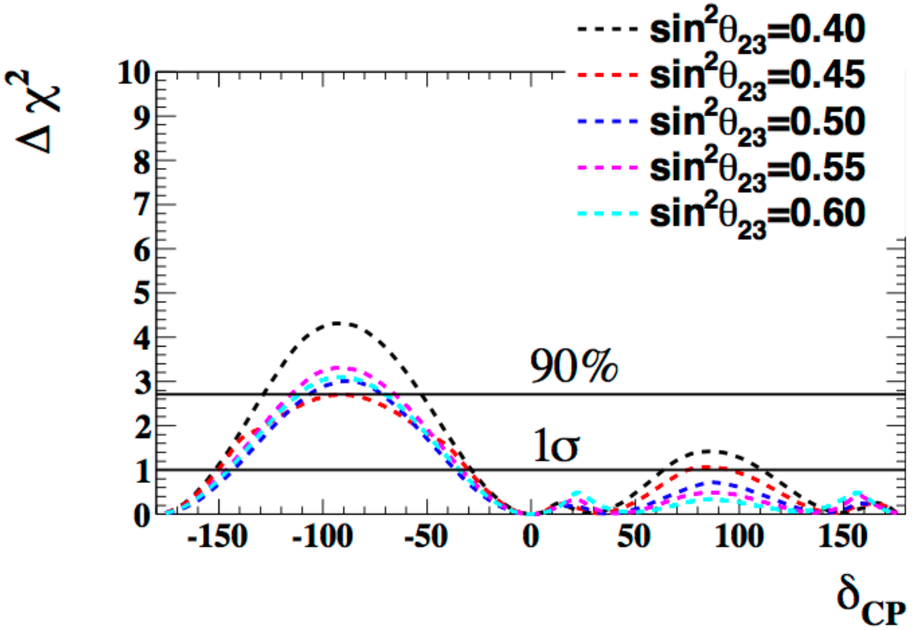
$$1 - P(\nu_\mu \to \nu_\mu) \propto sin^2 2\theta_{23}$$

$$P(\nu_\mu \to \nu_e) \propto sin^2\theta_{23}$$

T2K could exclude the '$sin\delta_{CP}=0, \pi$' (conserved CP) hypothesis, at some modest significance level, and only if the true δ_{CP} value lies in a very favourable region...

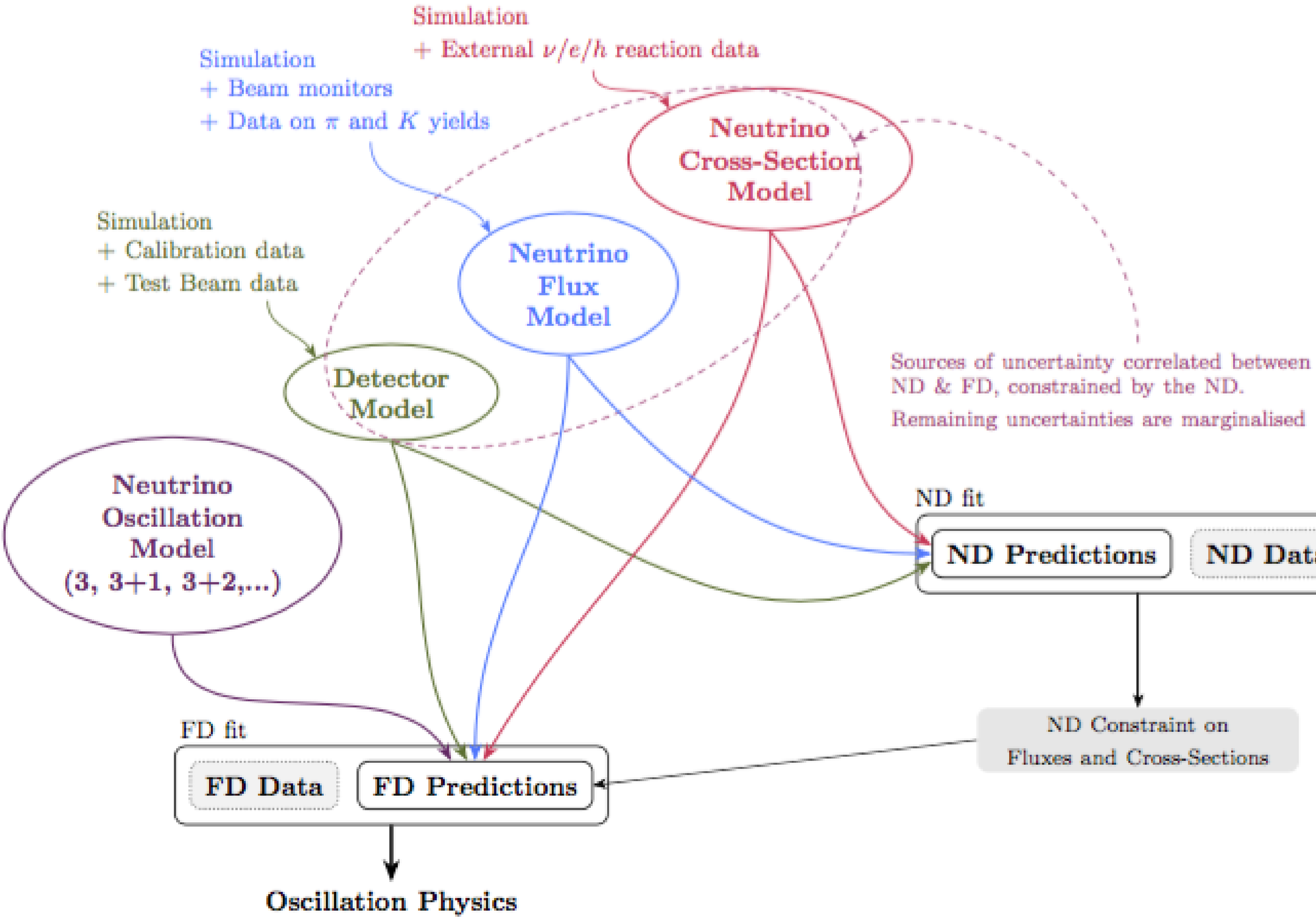


True MH: NH, Full T2K exposure,
50% ν - 50% $\bar{\nu}$



Data reduction and oscillation analysis

Oscillation analysis method

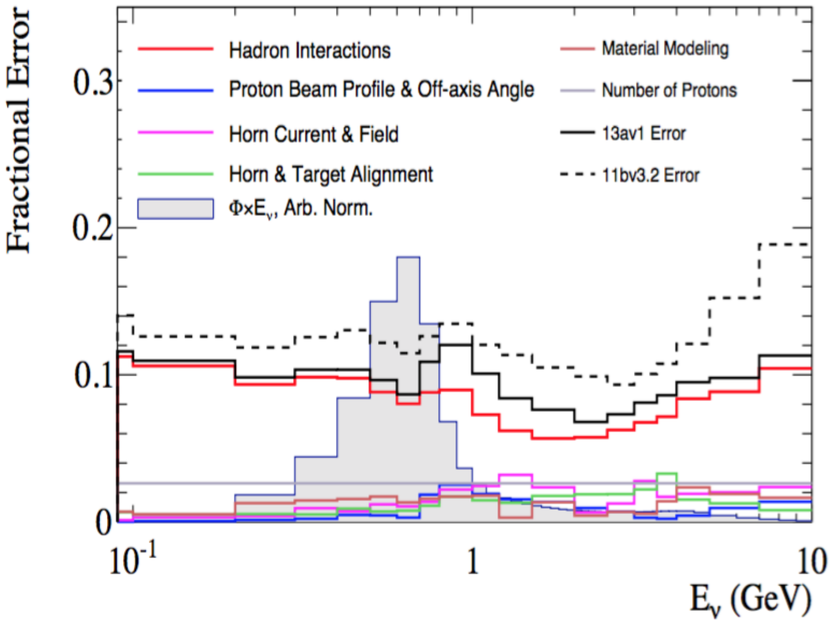


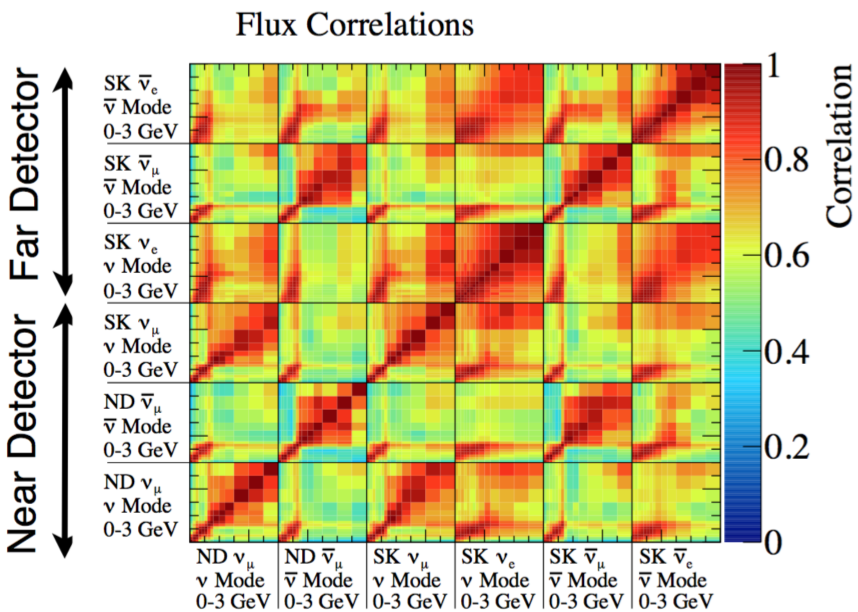
Prior systematic error constraints

Neutrino flux tuned using hadro-production data from **NA61/SHINE**: Pion, proton and kaon production with a 31 GeV/c proton beam on

- a thin carbon target (4% of an interaction length) [EPJ C76, 84 (2016)]
- a T2K replica target [EPJ C76, 617 (2016)]

Data cover almost the full T2K kinematic space.
Flux systematic uncertainty reduced from $\sim$30% to $\sim$10%.



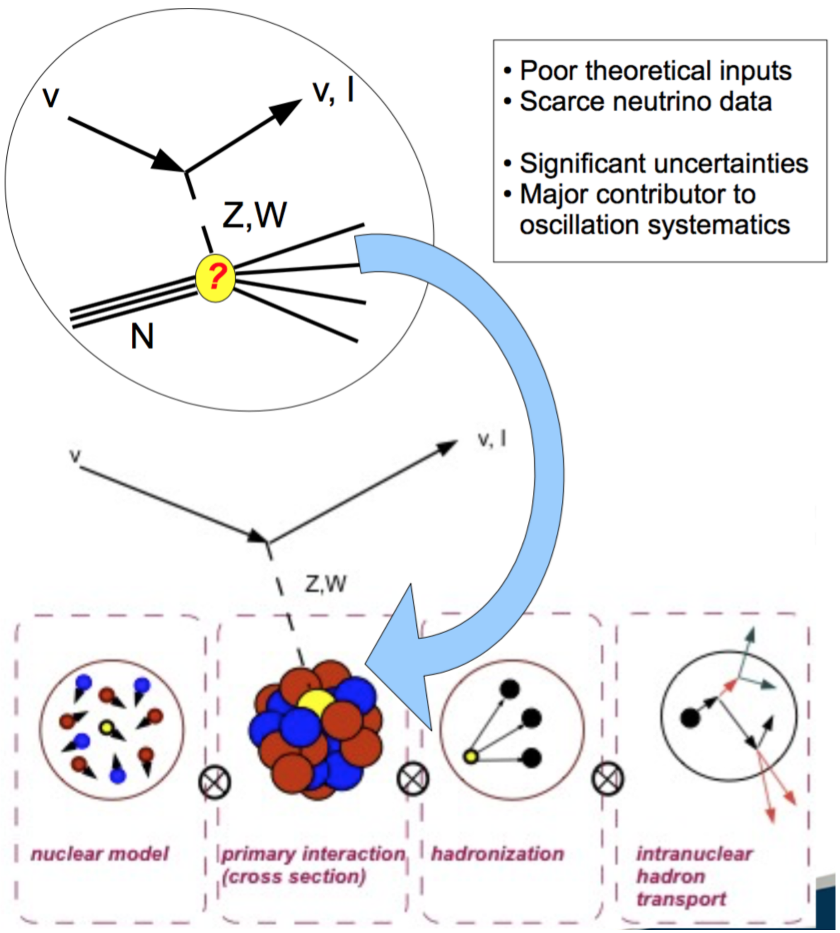


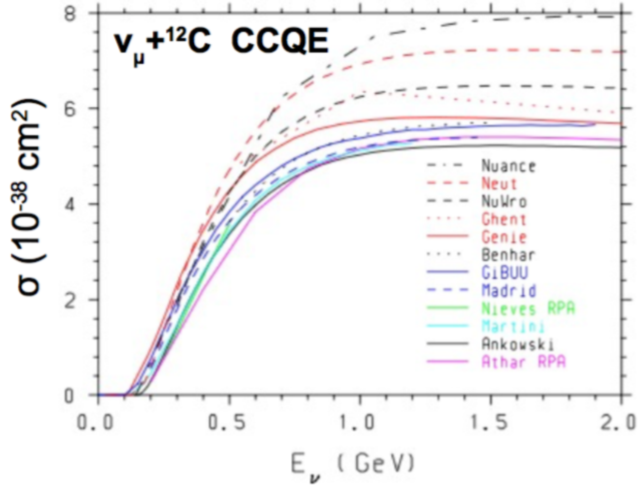
Prior systematic error constraints

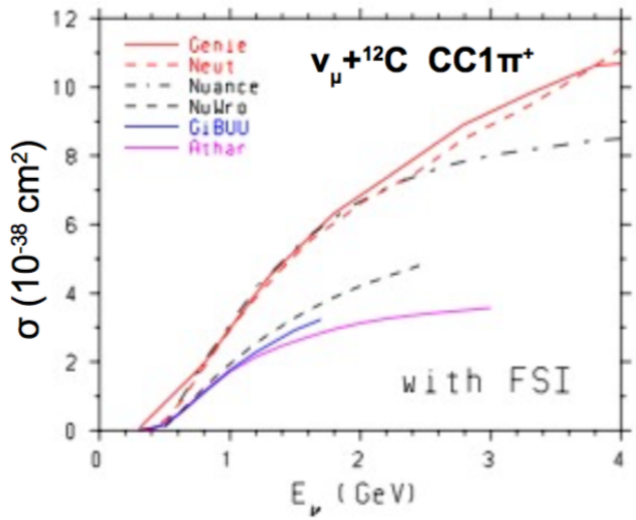
Neutrino cross-section model tuned to external data. Models not predictive enough and severe tensions between datasets: Substantial uncertainties remain.

- Poor theoretical inputs
- Scarce neutrino data

- Significant uncertainties
- Major contributor to oscillation systematics







Systematics constraint from the Near Detector

Substantial flux and cross-section uncertainties remain from the tuning of MC simulations using external data.

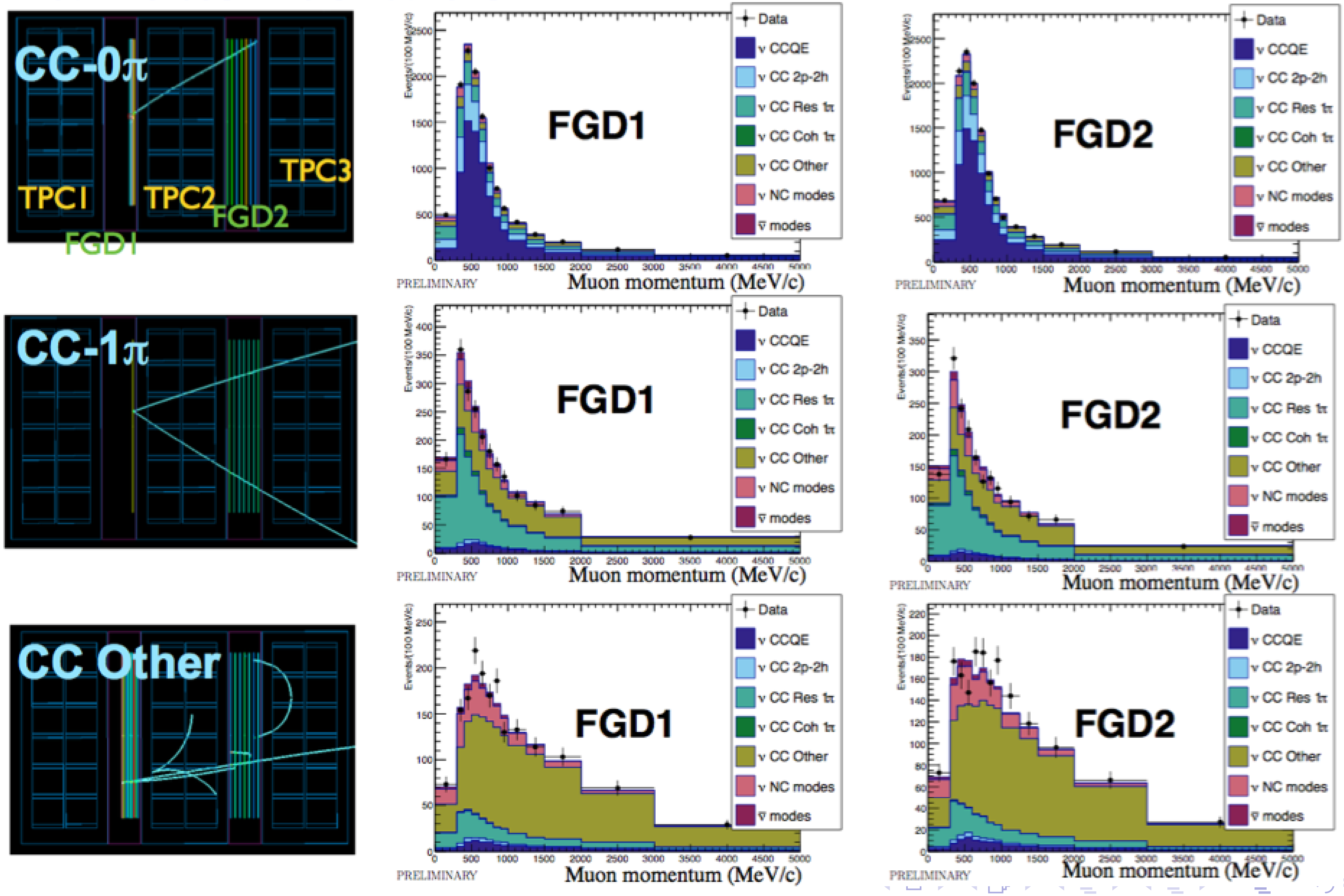
Further reduction of systematic errors possible using Near Detector data:

- Fit of flux and cross-section systematic parameters using several exclusive / semi-inclusive Near Detector samples.
- Each observed event sample populates a different area of the kinematic phase space (E_ν, W, Q^2)
- Each observed event sample has

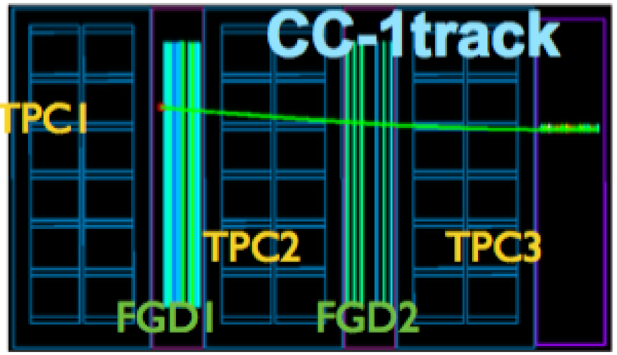
Possible to **cut the correlations between systematic parameters** and place **stringent constraints**.

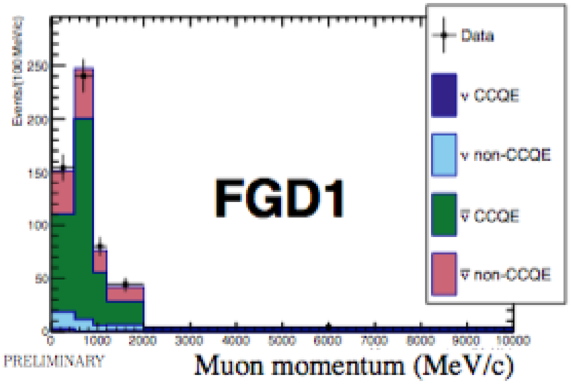
Best-fit values of systematic parameters also provide an 'indirect extrapolation' from the Near to the Far detector.

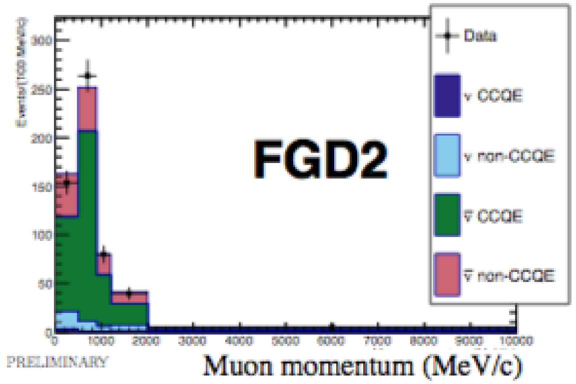
Systematics constraint from the Near Detector

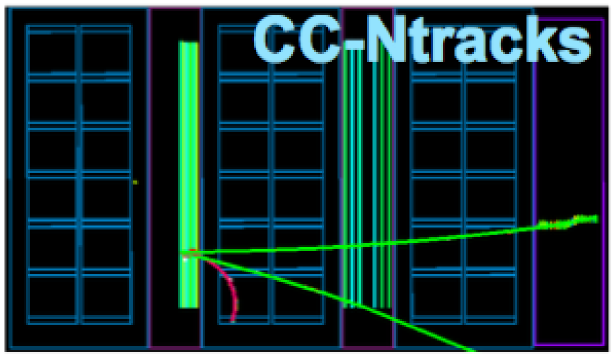


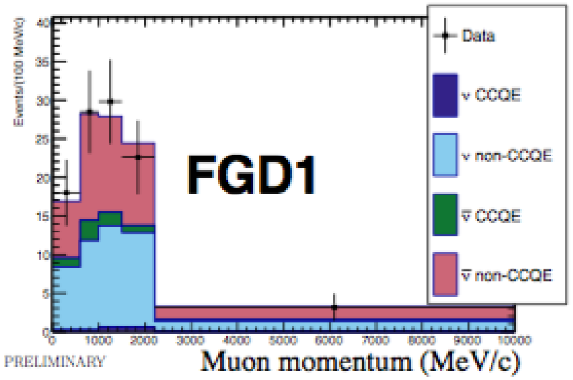
Systematics constraint from the Near Detector

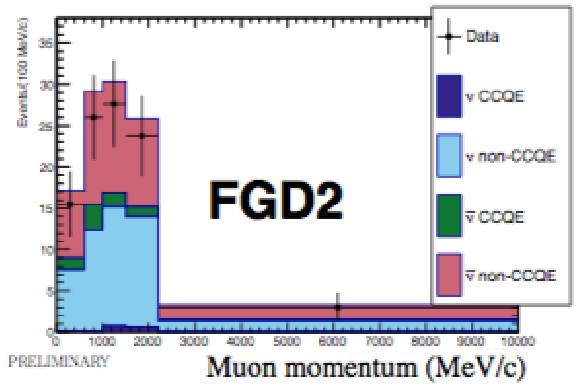




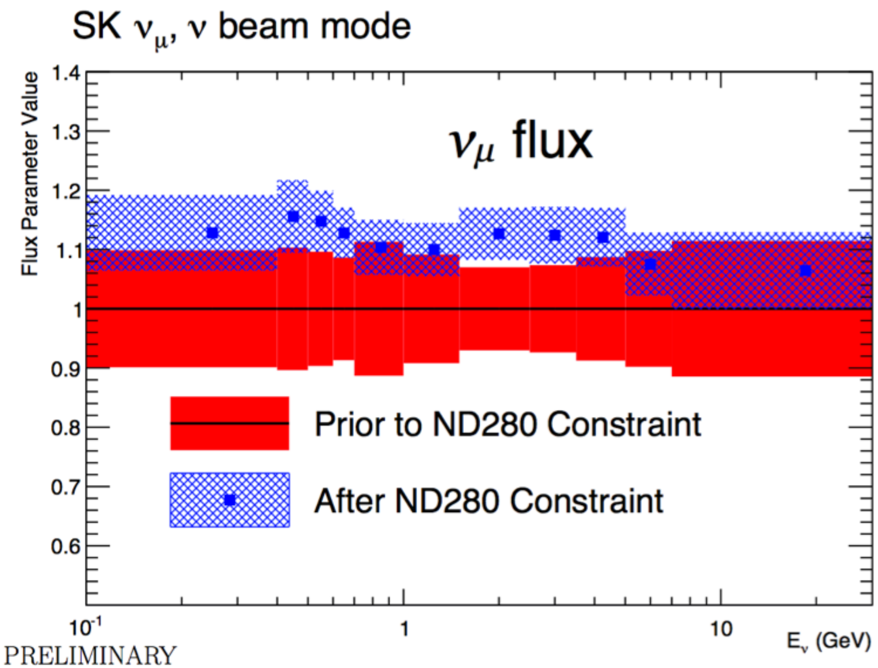




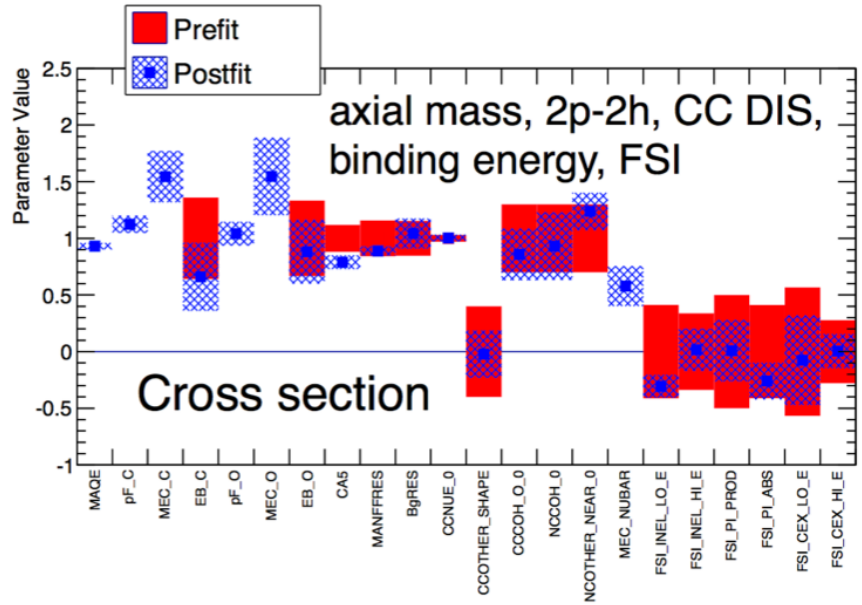




Simultaneous fit to Near Detector neutrino and anti-neutrino event samples **constraints flux and cross-section systematics**.



PRELIMINARY



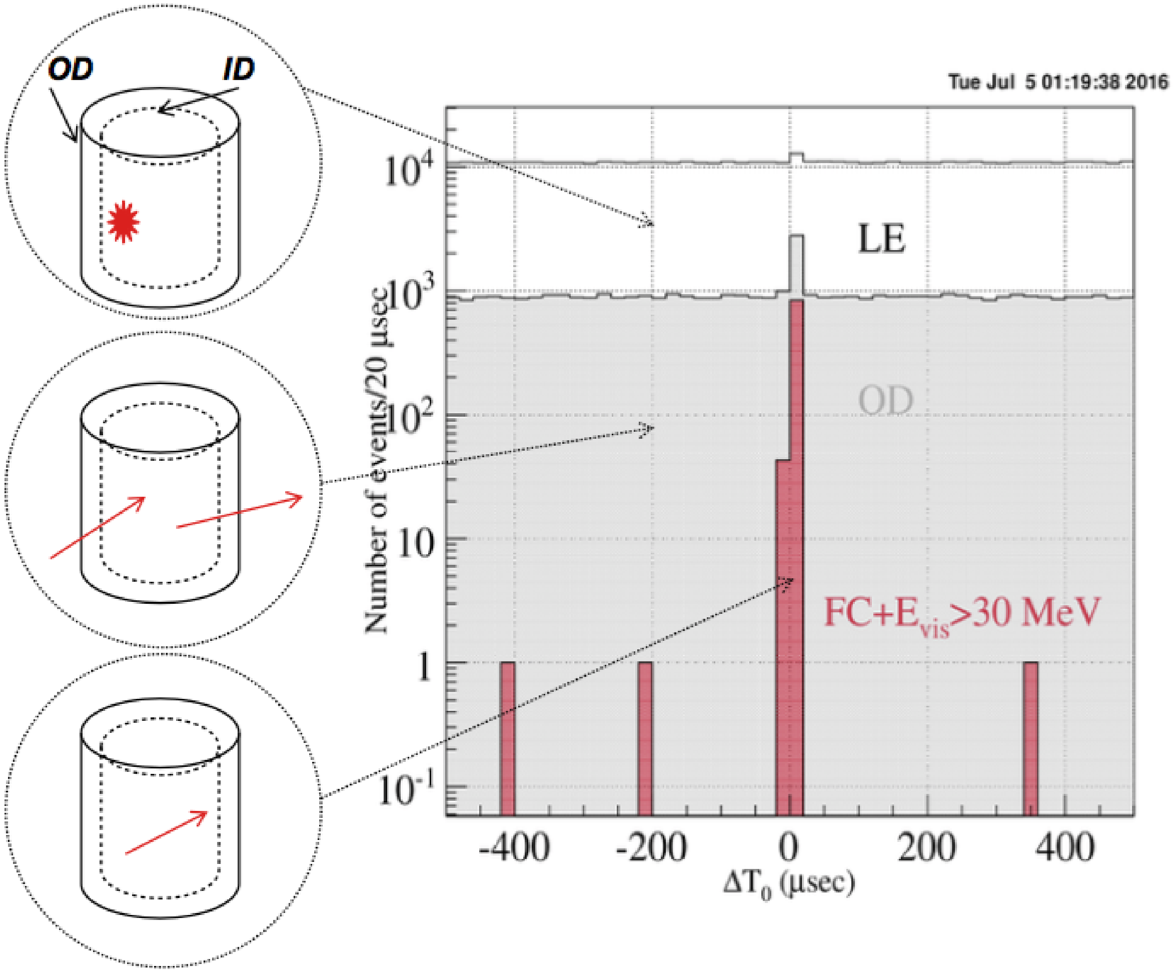
PRELIMINARY

- Flux parameters increase by $\sim$15%.
- Cross-section parameters consistent with nominal values.
- Flux and cross-section parameter highly anti-correlated after the Near Detector data fit.
- Systematic uncertainties in neutrino oscillation analyses from 12-14% to 5-6%.

SuperK event reduction

12.8M 'good spills' $\rightarrow$ 917 'on-time' FC (Fully Contained) events.

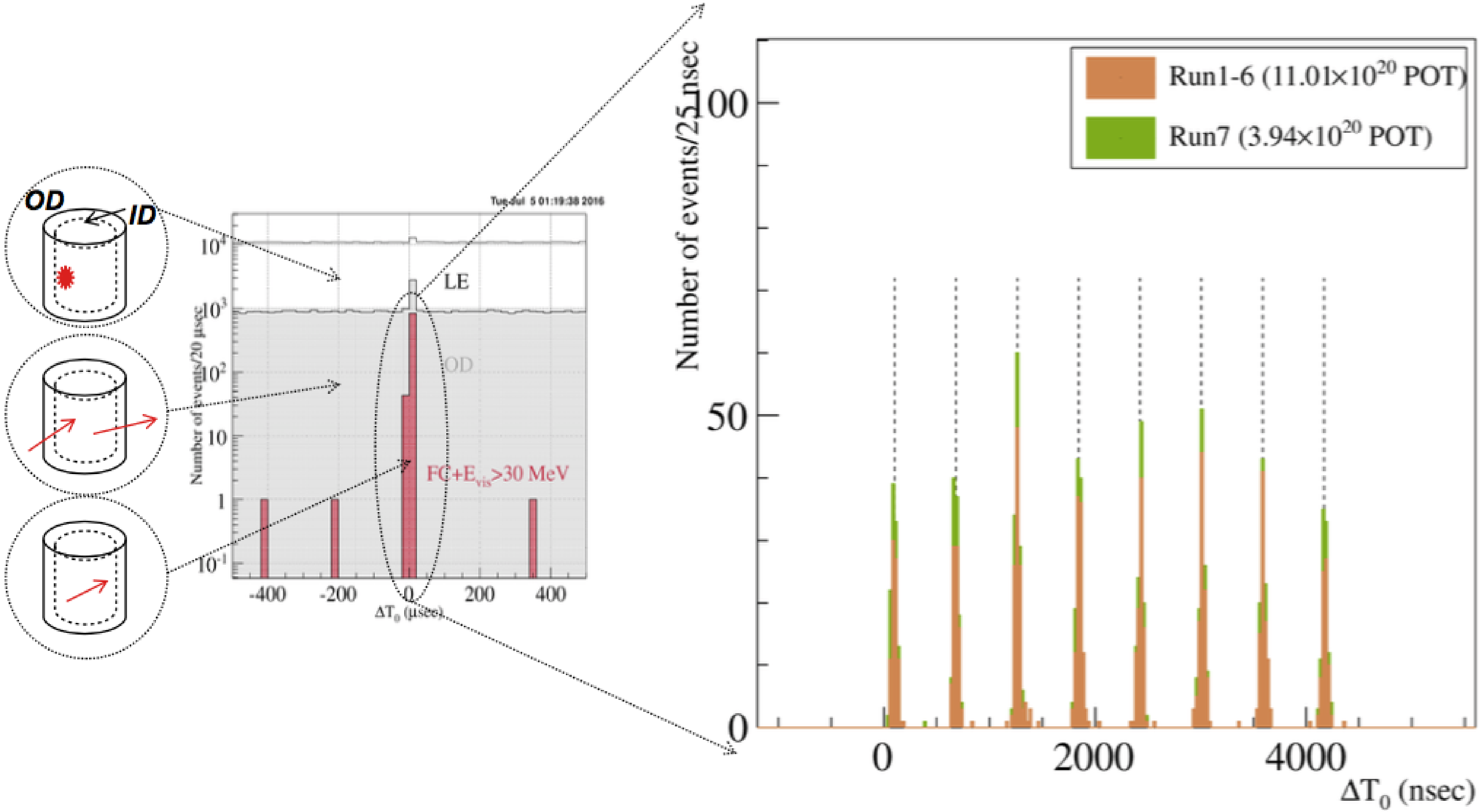
('on time': within -2 μsec to +10 μsec from the arrival time of the leading edge of the spill)



Left: ΔT_0 distribution of events at 1 msec window around the beam arrival time.

SuperK event reduction

Below: ΔT_0 distribution of all FC events zoomed into the spill on-timing window. The 8 bunch structure (581 nsec interval between bunches) of the J-PARC proton beam can be seen with neutrinos.



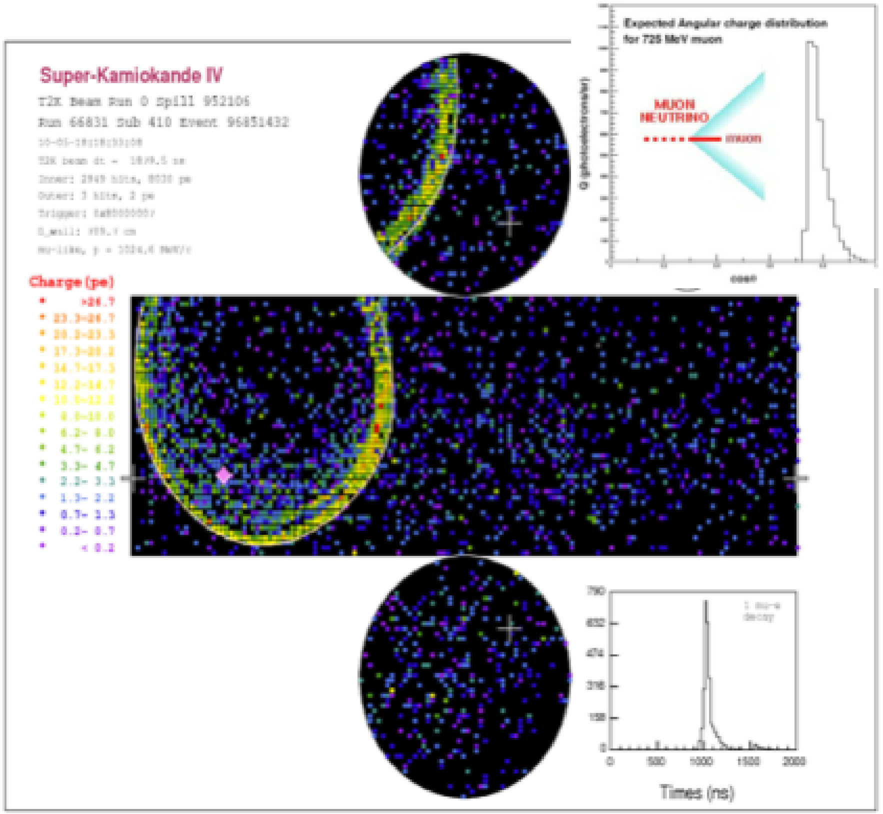
SuperK event reduction

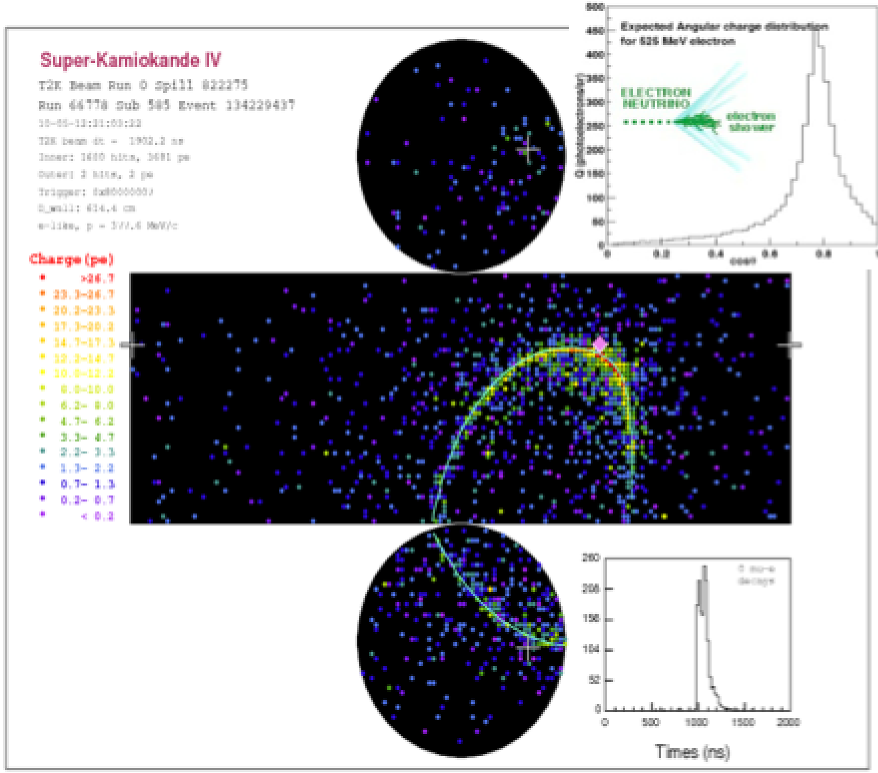
Out of the **917 FC events** (654 in ν mode + 263 in $\bar{\nu}$ mode):

- **603 events** (433 in ν mode + 170 in $\bar{\nu}$ mode) events belong to the **FCFV subset**:
  - They have visible energy above 30 MeV, and
  - a vertex in the fiducial volume (2m away from a tank wall).
- The FCFV events are subdivided further based on the ring topology.

Sample	Runs 1-7 (neutrino) Data	MC $\sin^2\theta_{13}=0.02$	MC $\sin^2\theta_{13}=0$	MC Unosc.	Runs 5-7 (antineutrino) Data	MC $\sin^2\theta_{13}=0.02$	MC $\sin^2\theta_{13}=0$	MC Unosc.
FC	654	614.8	569.1	1289.2	263	255.9	248.1	472.3
FCFV	433	427.8	396.0	877.8	170	180.6	175.2	329.7
Single Ring	217	221.4	193.7	616.6	94	96.2	91.5	228.1
1R μ-like	147	155.1	156.5	565.6	78	74.5	75.1	209.0
$p_\mu > 200$ MeV/c	147	154.8	156.2	564.5	78	74.4	75.0	208.8
1R e-like	70	66.3	37.2	51.0	16	21.7	16.3	19.1
$p_e > 100$ MeV/c	66	61.2	32.6	38.7	14	20.2	14.9	16.6
Multi-ring	216	206.4	202.3	261.2	76	84.4	83.7	101.6
MR μ-like	108	101.4	100.9	140.3	33	41.7	41.7	54.6
MR e-like	108	104.9	101.4	120.9	43	42.7	42.0	47.0
2R π^0	26	25.0	24.5	25.5	9	11.0	10.9	10.9
non-π^0 w/ decay-e	53	51.9	51.0	67.1	19	20.2	20.1	24.5
non-π^0 no decay-e	29	28.0	25.9	28.2	15	11.6	11.0	11.5
FC non-FV	186	156.2	142.6	340.9	81	65.2	62.9	126.1

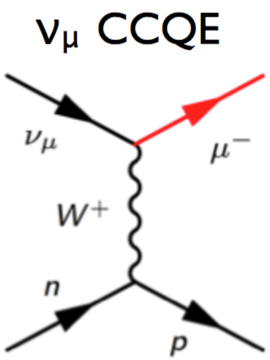
Current oscillation analysis is based only on events with
- a **single** μ-like ring (ν_μCC-like events), or
- a **single** e-like ring (ν_eCC-like events)

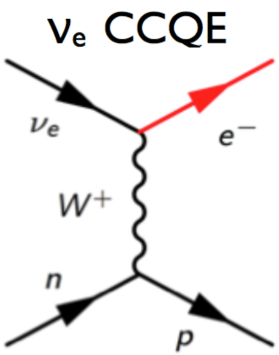




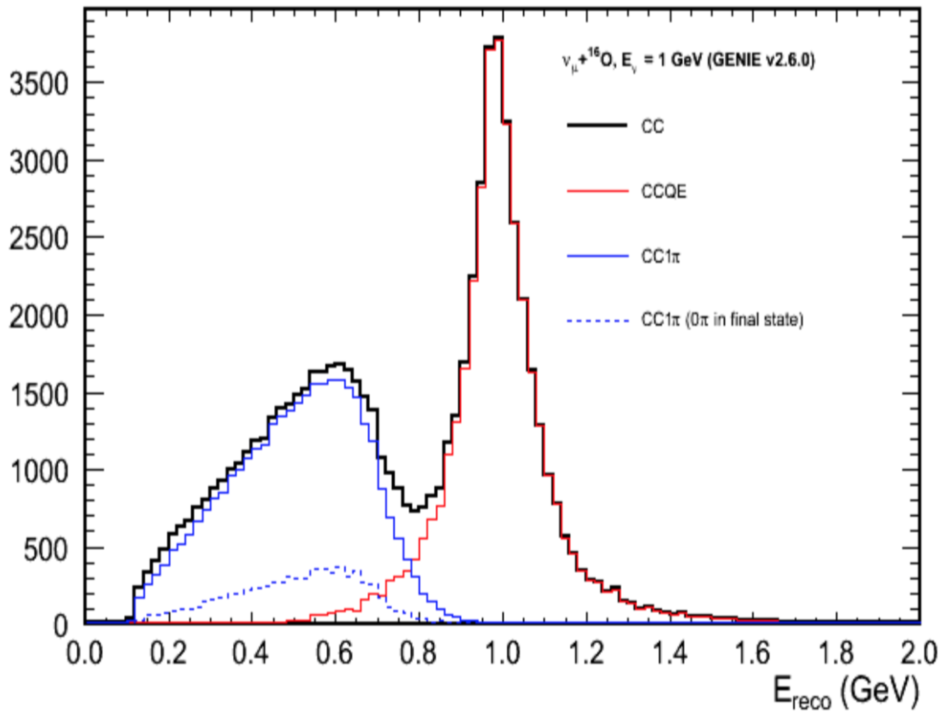
Further cuts are made to suppress NC and inelastic CC backgrounds.

Single-ring event samples are **CCQE-enhanced**: They are a 'golden' samples because the neutrino energy can be reconstructed from the observed final state lepton momentum and scattering angle.

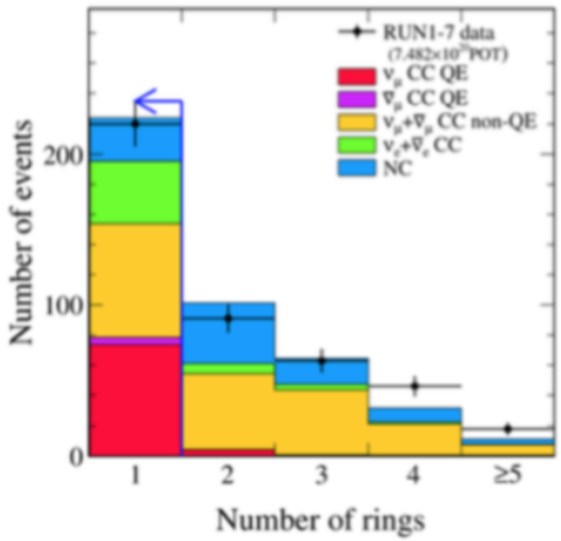




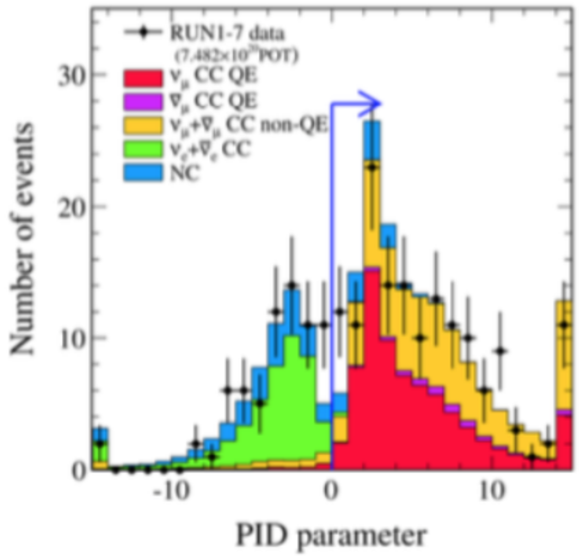
(and similarly for anti-neutrinos).



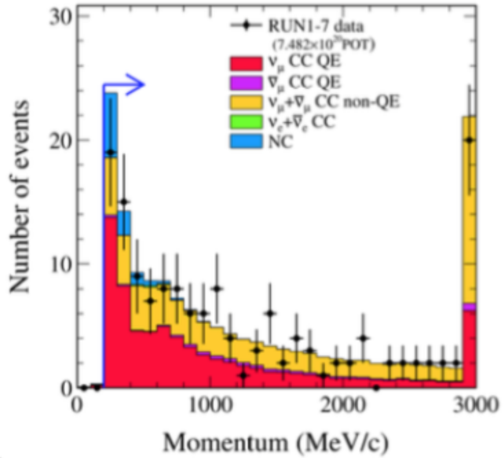
Single ring event



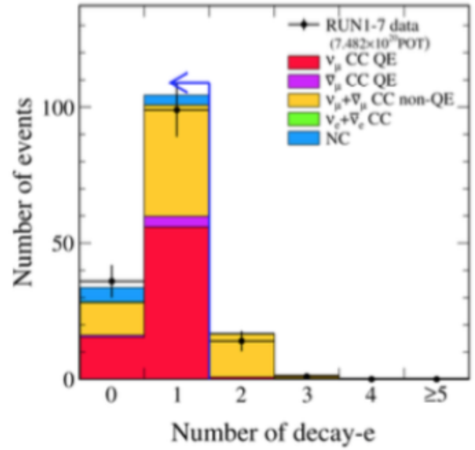
μ-like PID

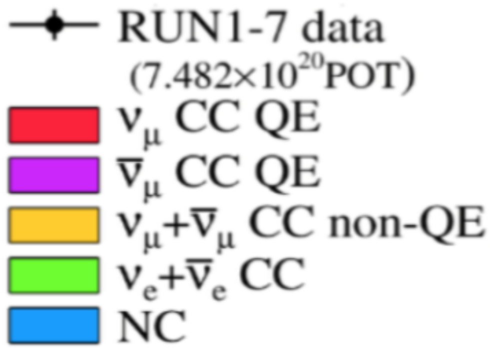


Momentum > 200 MeV



decay electron ≤ 1





$\nu_\mu/\bar{\nu}_\mu$ selections at SuperK

Neutrino mode:

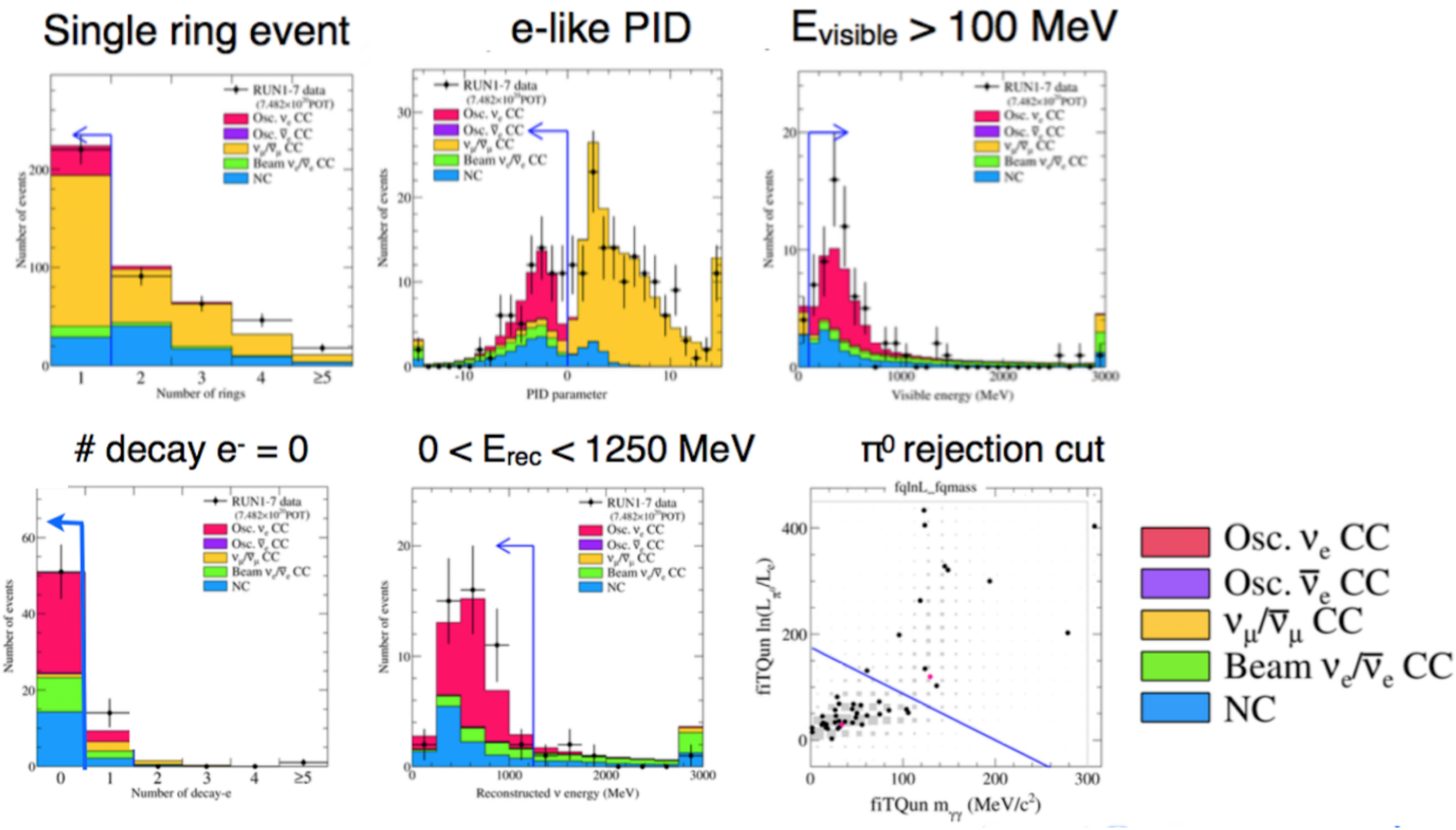
Runs 1-7	Data	Expected					
		MC Total	ν_μ CCQE	$\bar{\nu_\mu}$ CCQE	$\nu_\mu + \bar{\nu_\mu}$ CC non-QE	$\nu_e + \bar{\nu_e}$ CC	NC
Interactions in FV	654	744.8921	100.1736	6.4485	257.7017	54.4102	326.1581
FCFV	438	431.8500	78.7501	4.8507	196.2819	53.2462	98.7212
Single ring	220	223.4921	73.4936	4.6957	75.2087	41.4106	28.6836
Muon-like PID	150	156.5553	72.2189	4.6532	70.0611	0.4657	9.1563
p_μ >200 MeV/c	150	156.2370	72.0336	4.6504	70.0029	0.4657	9.0844
$N_{decay-e} \leq 1$	135	137.7559	71.2831	4.6272	52.6050	0.4645	8.7760
Efficiency from Interactions [%]	-	18.5	71.2	71.8	20.4	0.8	2.7
Efficiency from FCFV [%]	-	31.9	90.5	95.4	26.8	0.9	8.9

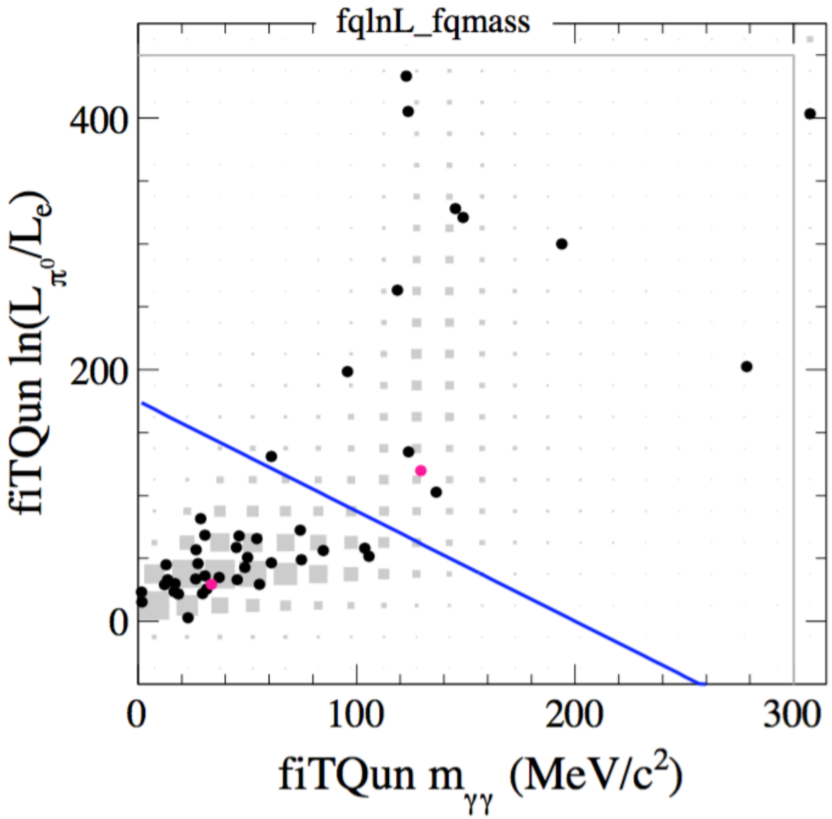
Antineutrino mode:

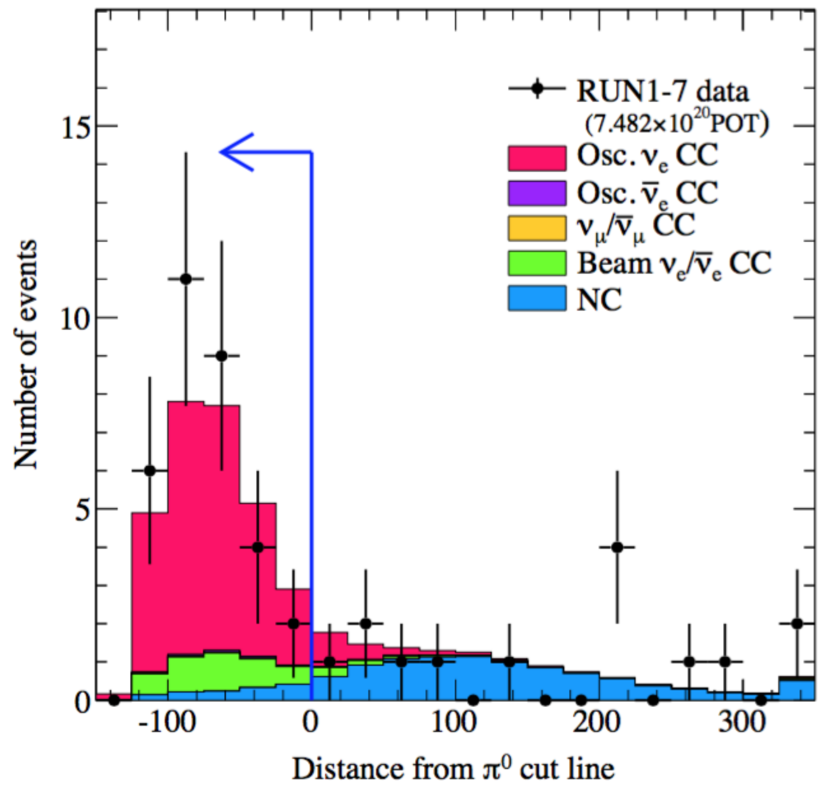
Runs 5-7	Data	Expected					
		MC Total	ν_μ CCQE	$\bar{\nu_\mu}$ CCQE	$\nu_\mu + \bar{\nu_\mu}$ CC non-QE	$\nu_e + \bar{\nu_e}$ CC	NC
Interactions in FV	263	312.3842	20.0413	30.7730	113.2287	15.5890	132.7521
FCFV	170	180.4835	15.0375	24.9456	83.2607	15.1875	42.0523
Single ring	94	96.0647	13.5195	24.2846	35.4103	10.9755	11.8747
Muon-like PID	78	74.5169	13.3959	23.9567	33.5551	0.0922	3.5170
p_μ >200 MeV/c	78	74.4175	13.3862	23.9221	33.5368	0.0922	3.4802
$N_{decay-e} \leq 1$	66	68.2621	13.1816	23.8472	27.7887	0.0917	3.3528
Efficiency from Interactions [%]	-	21.9	65.8	77.5	24.5	0.6	2.5
Efficiency from FCFV [%]	-	37.8	87.7	95.6	33.4	0.6	8.0

Parameters used: $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 0.0217$, $\sin^2\theta_{23} = 0.528$, $\delta_{CP} =$ -1.601,
$\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, MH: normal, L = 295 km, Earth density = 2.6 gr/cm^3

$\nu_e/\bar{\nu}_e$ selections at SuperK




fqlnL_fqmass
400
200
0
0
100
200
300
fiTQun $\ln(L_{\pi^0}/L_e)$
fiTQun $m_{\gamma\gamma}$ (MeV/c^2)


RUN1-7 data
(7.482×10^{20} POT)
Osc. ν_e CC
Osc. $\bar{\nu}_e$ CC
$\nu_\mu/\bar{\nu}_\mu$ CC
Beam $\nu_e/\bar{\nu}_e$ CC
NC
15
10
5
0
-100
0
100
200
300
Number of events
Distance from π^0 cut line

$\nu_e/\bar{\nu}_e$ selections at SuperK

Neutrino mode:

Runs 1-7	Expected						Data
	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	$\bar{\nu}_\mu \to \bar{\nu}_e$	BG Total	$\nu_\mu \to \nu_e$	
Interactions in FV	364.3239	18.5526	326.1581	0.3909	709.4254	35.4668	654
FCFV	279.8826	18.0883	98.7212	0.3815	397.0736	34.7765	438
Single ring	153.3979	11.1480	28.6836	0.3153	193.5449	29.9473	220
Electron-like PID	6.4647	11.0647	19.5273	0.3130	37.3697	29.5672	70
Evis >100 MeV	4.5915	11.0085	16.8090	0.3114	32.7205	29.0584	66
No Decay-e	0.9690	8.9694	14.2433	0.3062	24.4879	26.1140	51
E_ν^{rec}	0.2526	4.2586	10.8493	0.2163	15.5767	25.1362	46
fiTQun π^0 cut	0.0890	3.6754	1.3494	0.1807	5.2945	23.2523	32
Efficiency from Interactions [%]	0.0	19.8	0.4	46.2	0.7	65.6	-
Efficiency from FCFV [%]	0.0	20.3	1.4	47.4	1.3	66.9	-

Antineutrino mode:

Runs 5-7	Expected						Data
	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	$\bar{\nu}_\mu \to \bar{\nu}_e$	BG Total	$\nu_\mu \to \nu_e$	
Interactions in FV	164.0430	9.0049	132.7521	2.2885	308.0886	4.2956	263
FCFV	123.2438	8.7503	42.0523	2.2411	176.2875	4.1961	170
Single ring	73.2145	5.5119	11.8747	1.7265	92.3276	3.7371	94
Electron-like PID	2.3068	5.4784	8.3577	1.7060	17.8489	3.6989	16
Evis >100 MeV	1.8266	5.4625	7.3923	1.6866	16.3680	3.6791	14
No Decay e	0.3284	4.7127	6.2416	1.4595	12.7421	3.6571	12
E_ν^{rec}	0.0828	1.8870	4.8261	1.1858	7.9816	3.4192	9
fiTQun π^0 cut	0.0190	1.5754	0.5968	1.0456	3.2368	3.0432	4
Efficiency from Interactions [%]	0.0	17.5	0.4	45.7	1.1	70.8	-
Efficiency from FCFV [%]	0.0	18.0	1.4	46.7	1.8	72.5	-

Parameters used: $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 0.0217$, $\sin^2\theta_{23} = 0.528$, δ_{CP} = -1.601,
$\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, MH: normal, L = 295 km, Earth density = 2.6 gr/cm^3

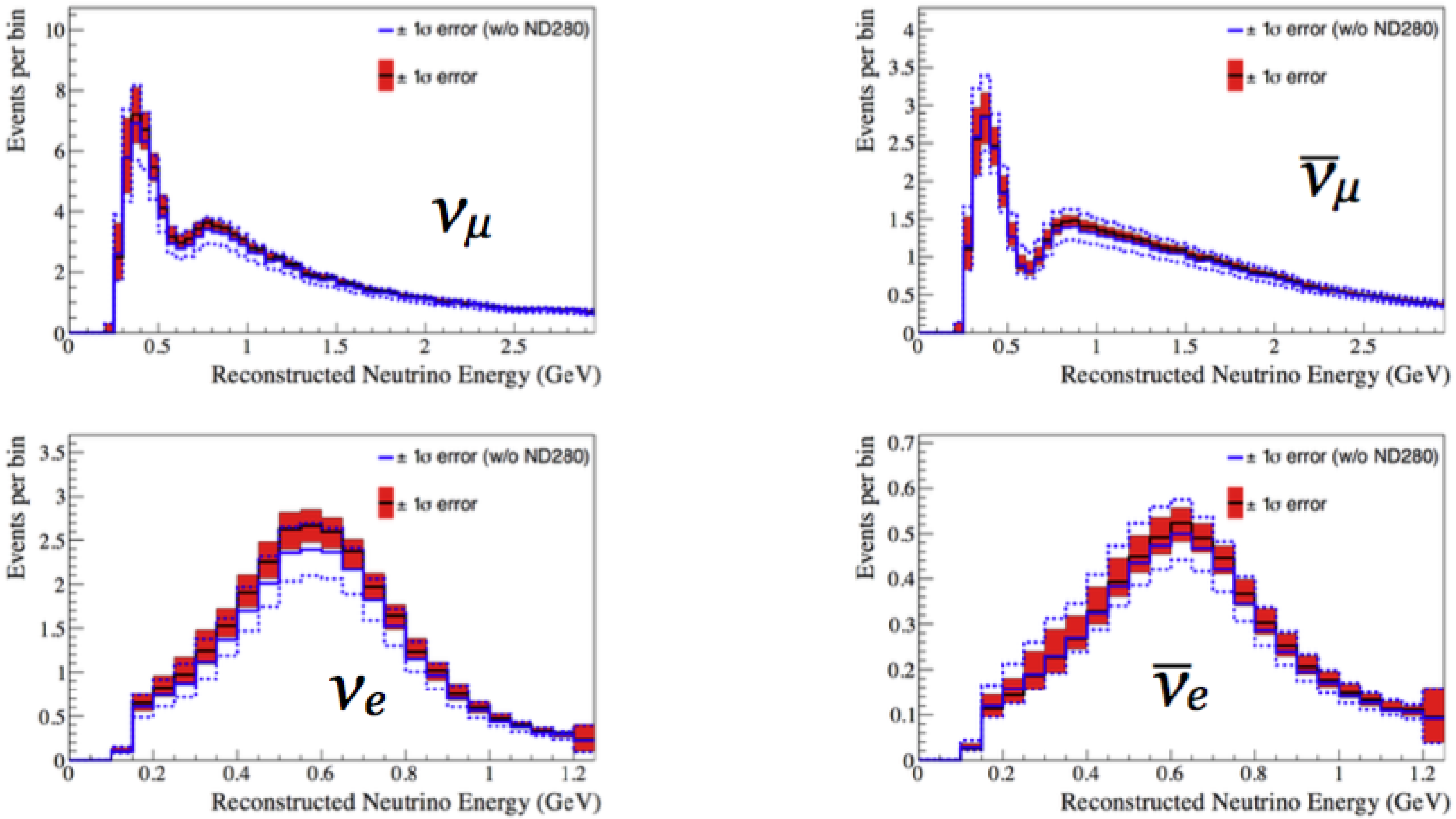
Impact of systematic uncertainties

Substantial systematic error reduction with ND280 data:

	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux with ND280	3,6%	3,6%	3,8%	3,8%
ν cross-section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross-section with ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross-section	2,9%	4,2%	3,4%	4,6%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%
Super-K detector	3,9%	2,4%	3,3%	3,1%
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	**5,0%**	**5,4%**	**5,2%**	**6,2%**

Total $\delta N_{SK}/N_{SK}$			
Beam mode	**sample**	**w/o ND280**	**ND280**
neutrino	**μ-like**	**12.0%**	**5.0%**
neutrino	**e-like**	**11.9%**	**5.4%**
antineutrino	**μ-like**	**12.5%**	**5.2%**
antineutrino	**e-like**	**13.7%**	**6.2%**

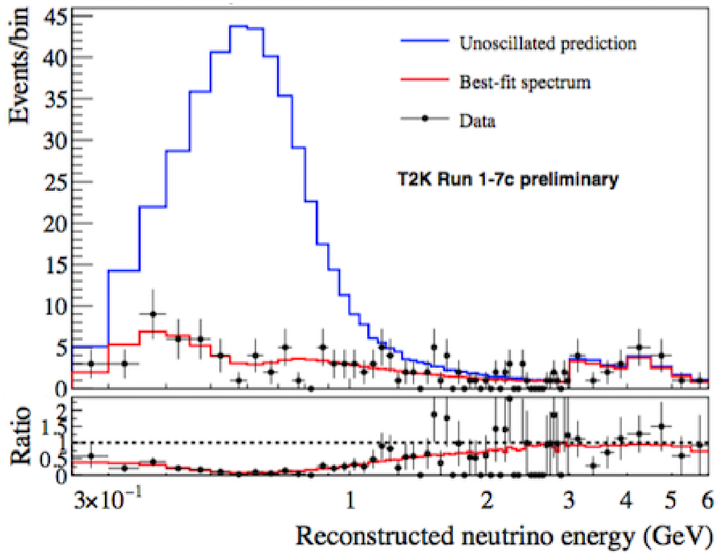
Impact of systematic uncertainties



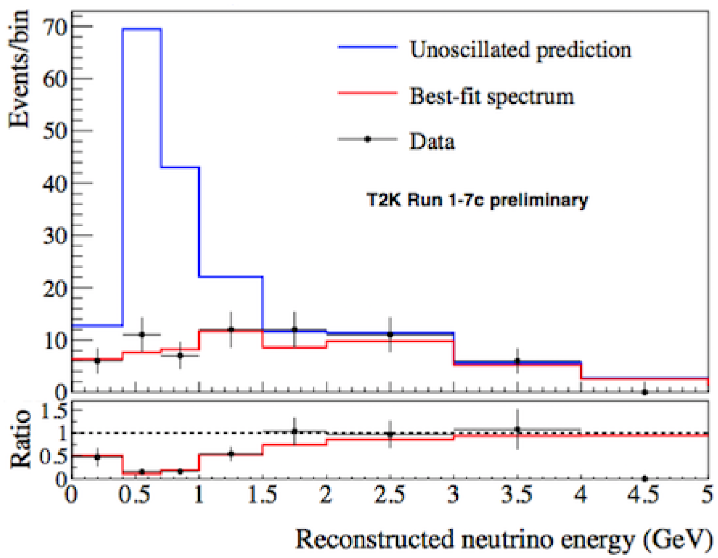
Low energy uncertainties mainly due to NC.

T2K ν_μ and $\bar{\nu}_\mu$ disappearance

ν-mode, 1-ring μ-like candidates:



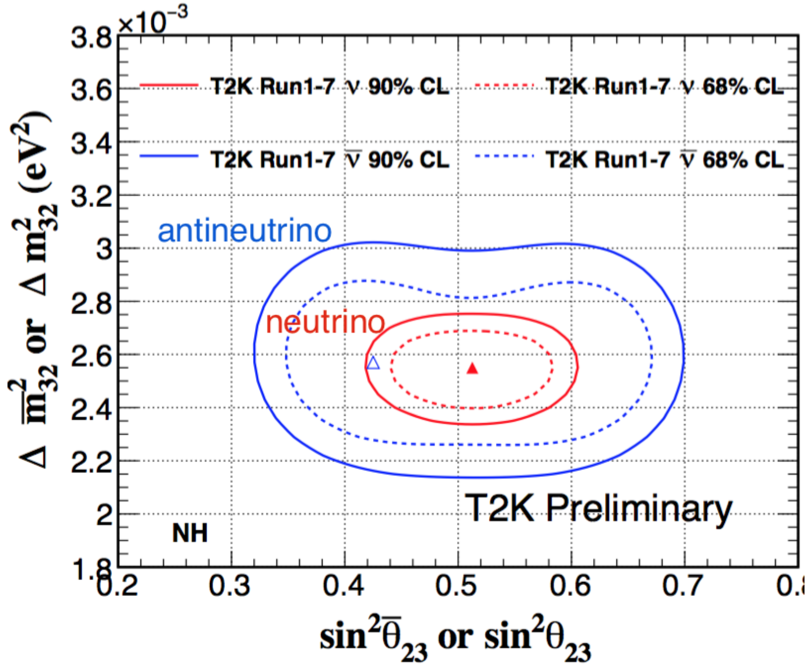
$\bar{\nu}$-mode, 1-ring μ-like candidates:



Mode	Expected (no osc.)	Observed
Neutrino	521.8	135
Antineutrino	184.8	66

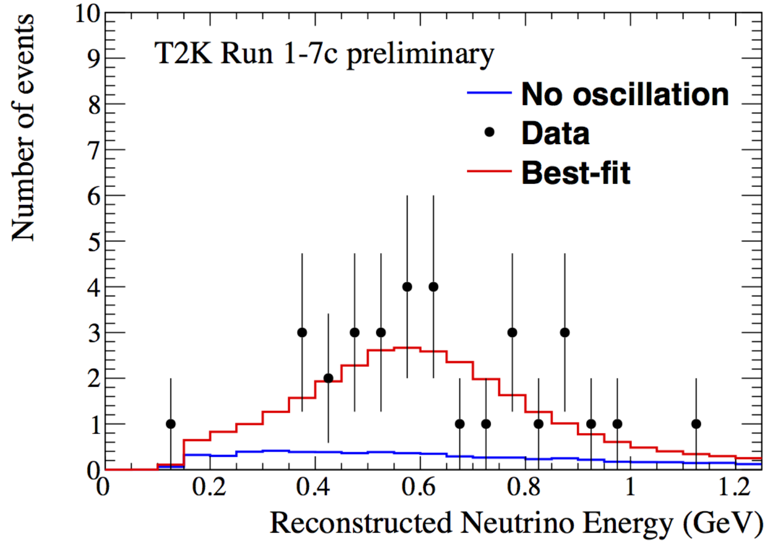
Dramatic energy-dependent deficit allows stringent constraints on ν_μ and $\bar{\nu}_\mu$ disappearance parameters.

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - cos^4\theta_{13} \cdot sin^2 2\theta_{23} \cdot sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

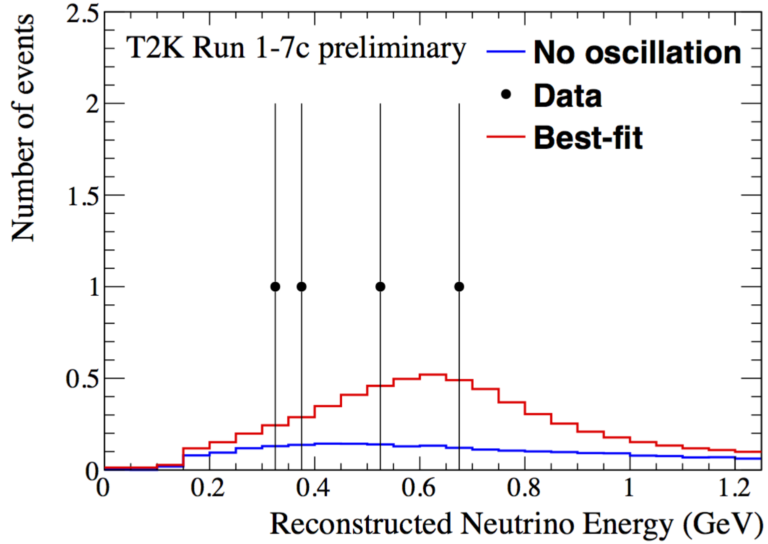


T2K ν_e and $\bar{\nu}_e$ appearance

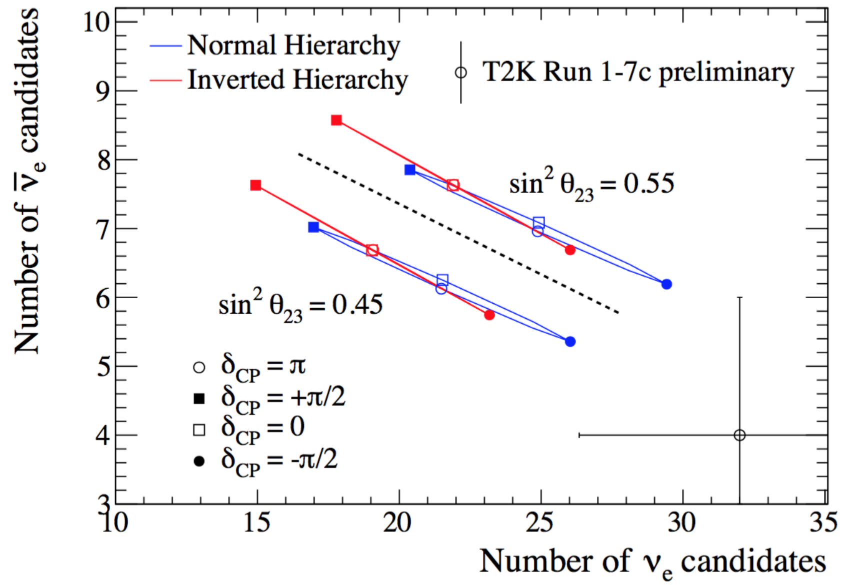
ν-mode, 1-ring e-like candidates:



$\bar{\nu}$-mode, 1-ring e-like candidates:



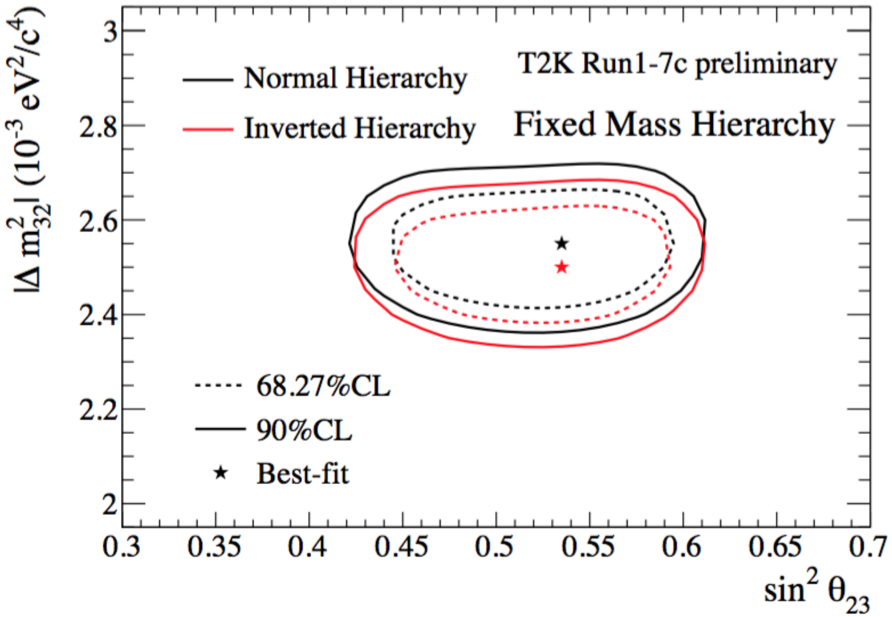
- more ν_e-like event appearance than expected in neutrino mode, and
- less ν_e-like event appearance than expected in anti-neutrino mode

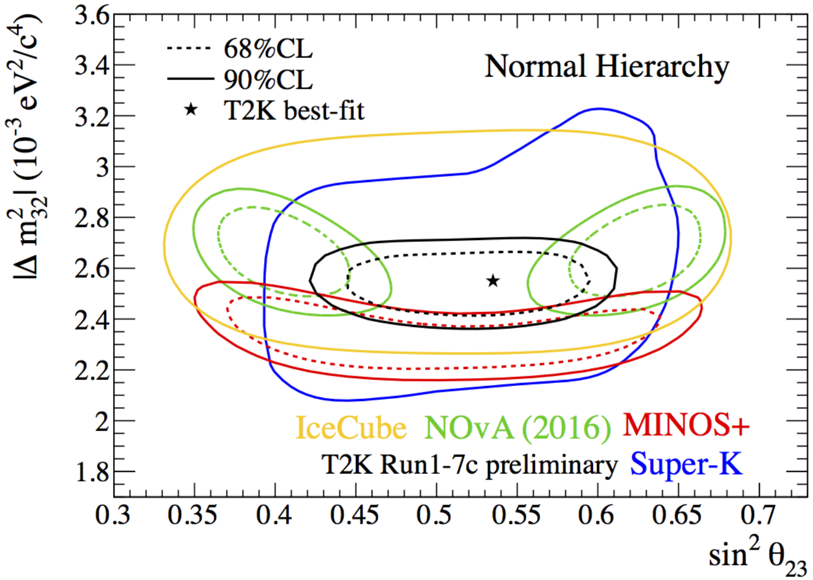


Mode	δ_{CP}, Normal hierarchy				Obs.
	$-\pi/2$	0	π	$\pi/2$	
ν	28.7	24.1	24.2	19.6	32
$\bar{\nu}$	6.0	6.9	6.8	7.7	4

Joint measurement of $sin^2\theta_{23}$ and $|\Delta m^2_{32}|$

- The ν_μ, $\bar{\nu}_\mu$ disappearance constrain $sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$.
- The ν_e, $\bar{\nu}_e$ appearance samples help lift the θ_{23} octant degeneracy.





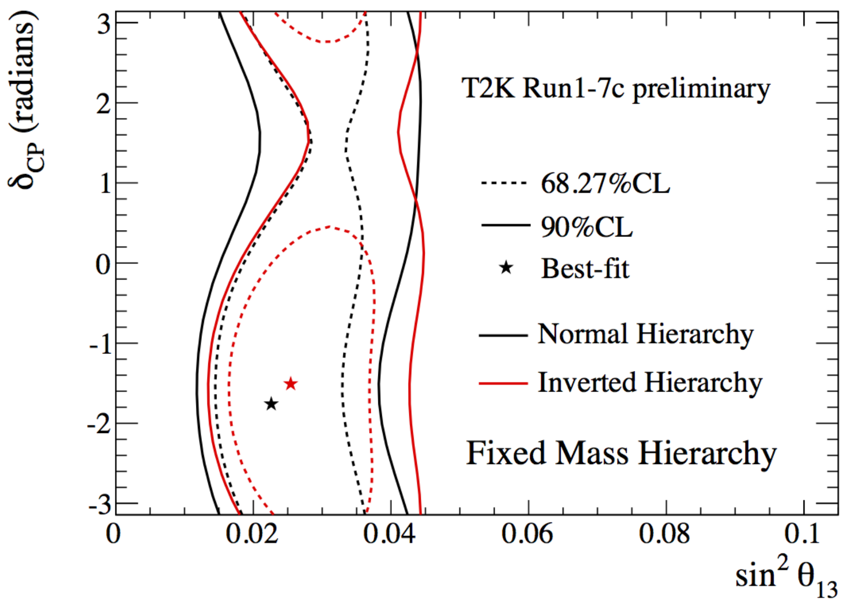
- Consistent with **maximal mixing**.
- Some tension with NOvA results.

Best-fit parameter	NH	IH
$sin^2\theta_{23}$	0.532	0.534
$\|\Delta m^2_{32}\|$ ($\times 10^{-3}$ eV^2)	2.545	2.510

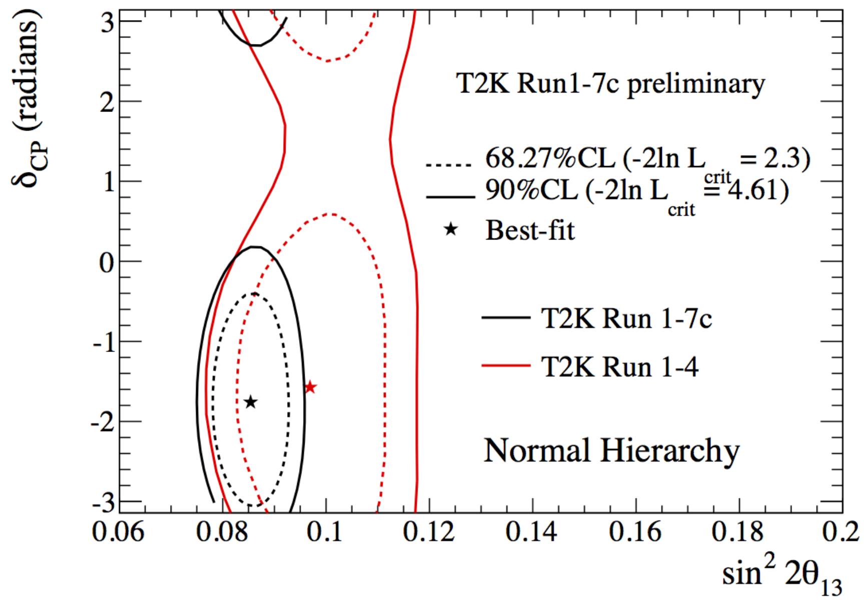
T2K joint 3-flavour analysis: θ_{13} and δ_{CP}

- Confidence intervals are slightly tighter than expected ones.

T2K sensitivity, $\delta_{CP} = \pi/2$



T2K-only data fit

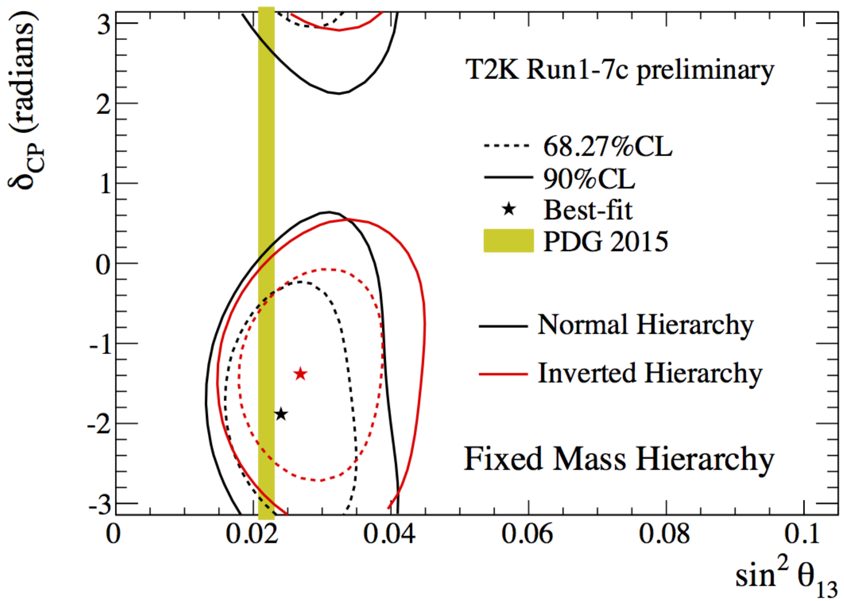


Mass hierarchy is fixed to either normal or inverted. Contours with constant $\Delta\chi^2$ method (gaussian approximation)

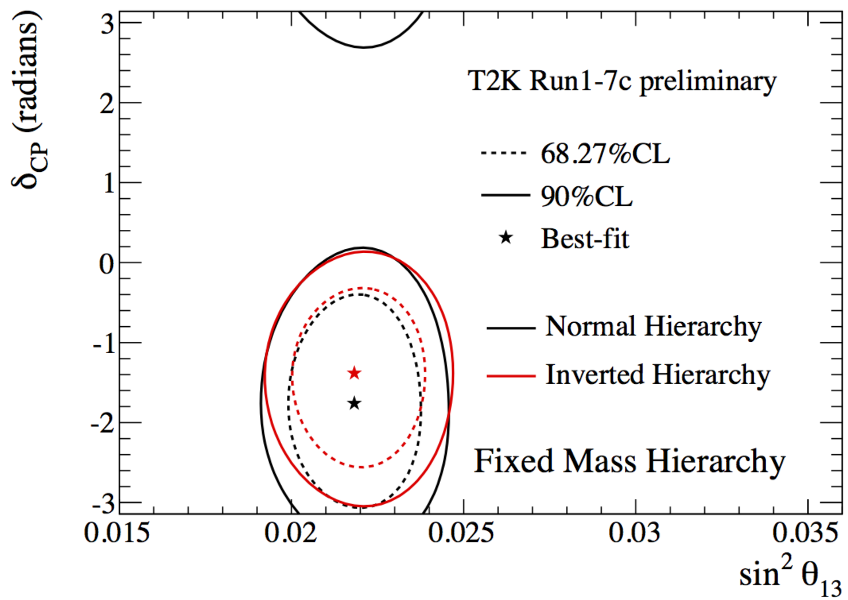
T2K joint 3-flavour analysis: θ_{13} and δ_{CP}

- Good agreement with the reactor measurement of θ_{13}
  - $sin^2 2\theta_{13} = 0.085 \pm 0.005$ [PDG2015]
- T2K-only data **disfavor the region of δ_{CP} around $\pi/2$**.
- T2K **prefers -$\pi/2$** for both NH and IH.

T2K-only data fit



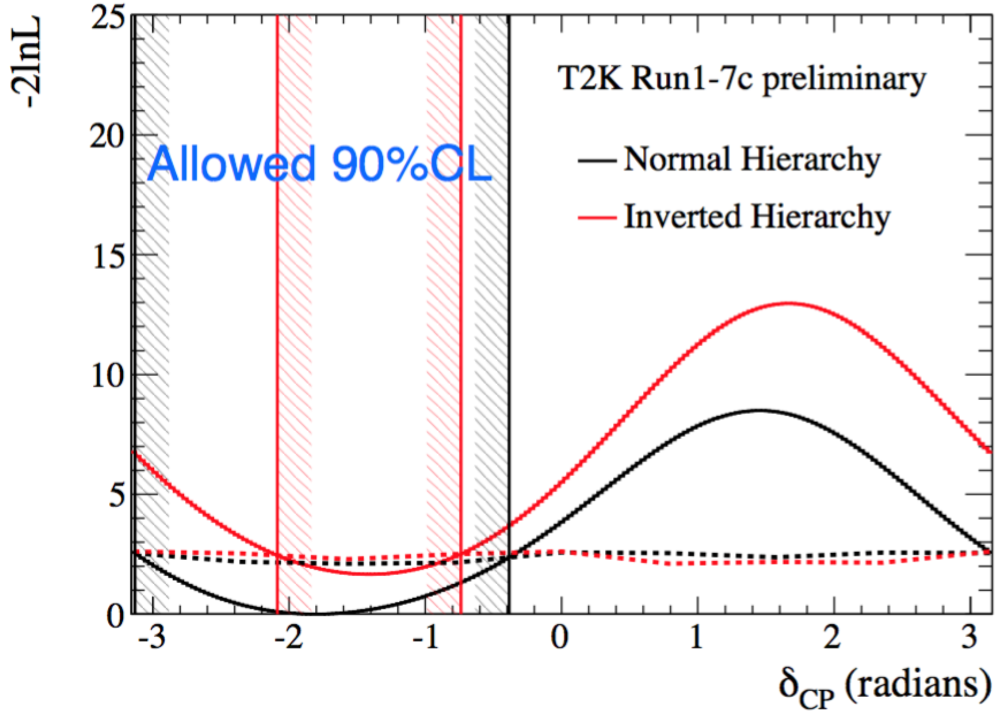
T2K data fit with reactor constraint



Mass hierarchy is fixed to either normal or inverted. Contours with constant $\Delta\chi^2$ method (gaussian approximation)

T2K joint 3-flavour analysis: δ_{CP}

- Best-fit: δ_{CP} = -1.885, NH
- $\delta_{CP} = 0$ is excluded at 2σ C.L., while $\delta_{CP} = \pi$ is excluded at 90% C.L.
- Allowed 90% C.L. regions: [-3.13,0.39] (NH), [-2.09,-0.74] (IH)

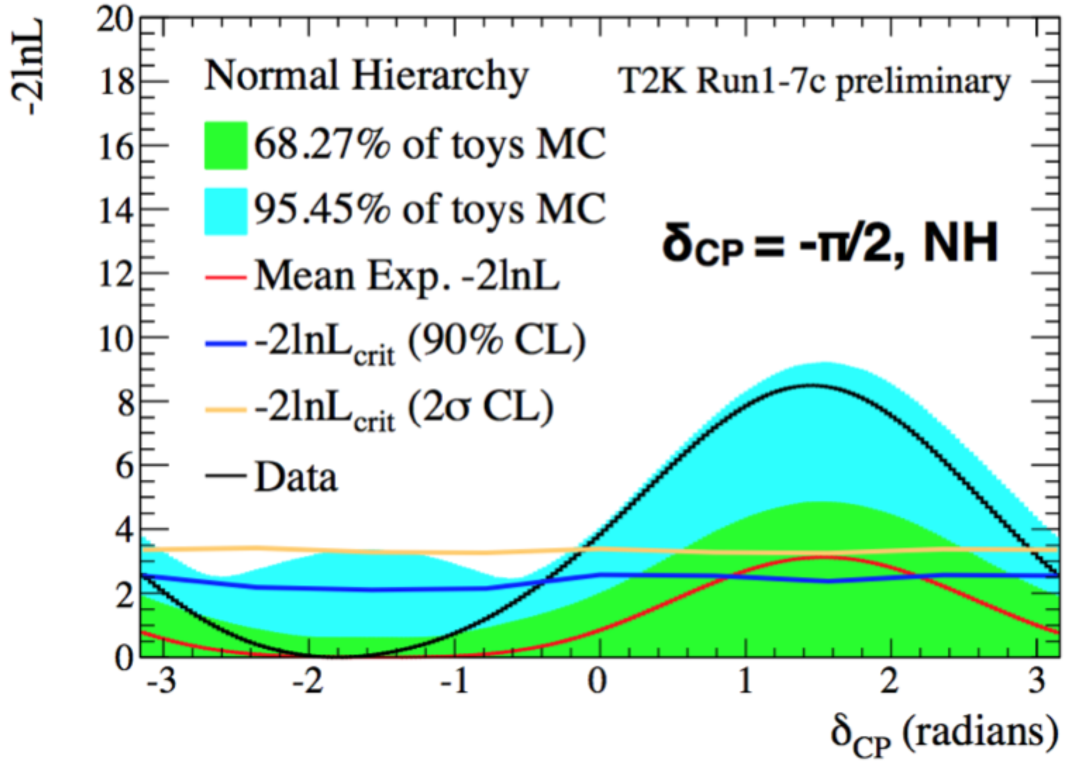


"Conserved CP' hypothesis excluded at 90% C.L.

$$sin^2 2\theta_{13} = 0.085 \pm 0.005 \text{ [PDG2015]}$$

Confidence intervals computed with Feldman-Cousins method to guarantee frequentist coverage.

With the current exposure, there is about 5% chance to exclude the conserved CP hypothesis at 90% C.L., even if CP is actually conserved.



For NH and $\delta_{CP} = \pi/2$:

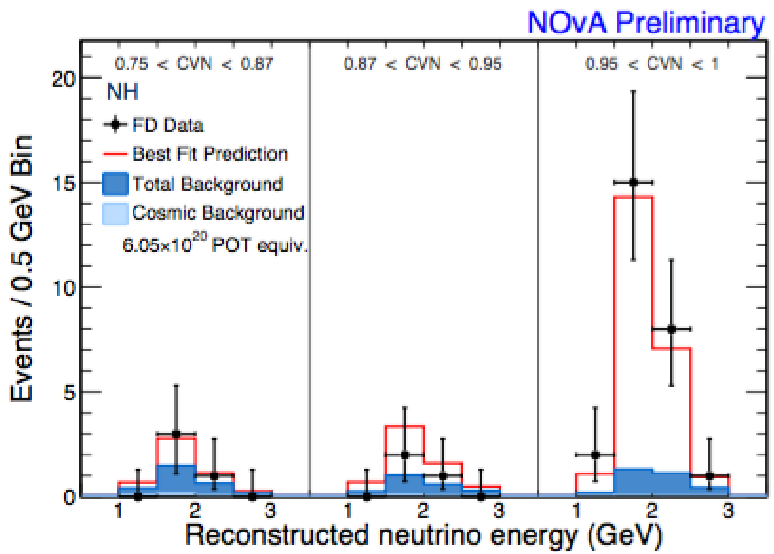
- Probability to exclude $\delta_{CP} = 0$ at 2σ: 9.2%
- Probability to exclude $\delta_{CP} = \pi$ at 90% C.L.: 17.3%

Similar results from NOvA

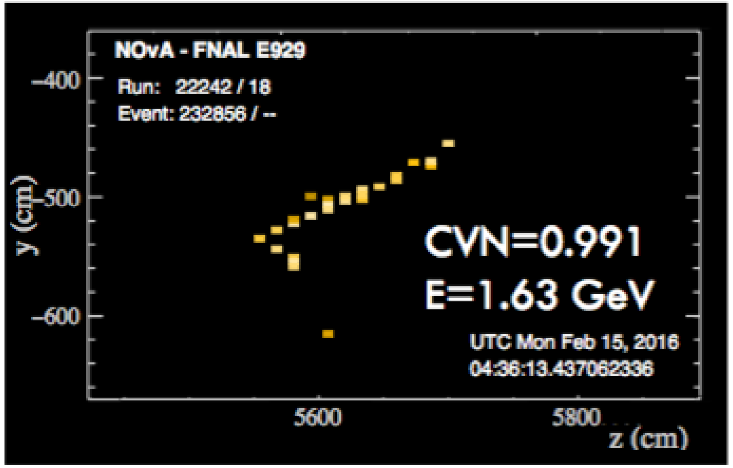
NOvA also observes a strong ν_e appearance signal in the neutrino mode (They have just started data-taking in anti-neutrino mode).

P.Vahle, Neutrino 2016, New results from NOvA

>8σ electron neutrino appearance signal



- Observe 33 events in FD
  - background 8.2±0.8

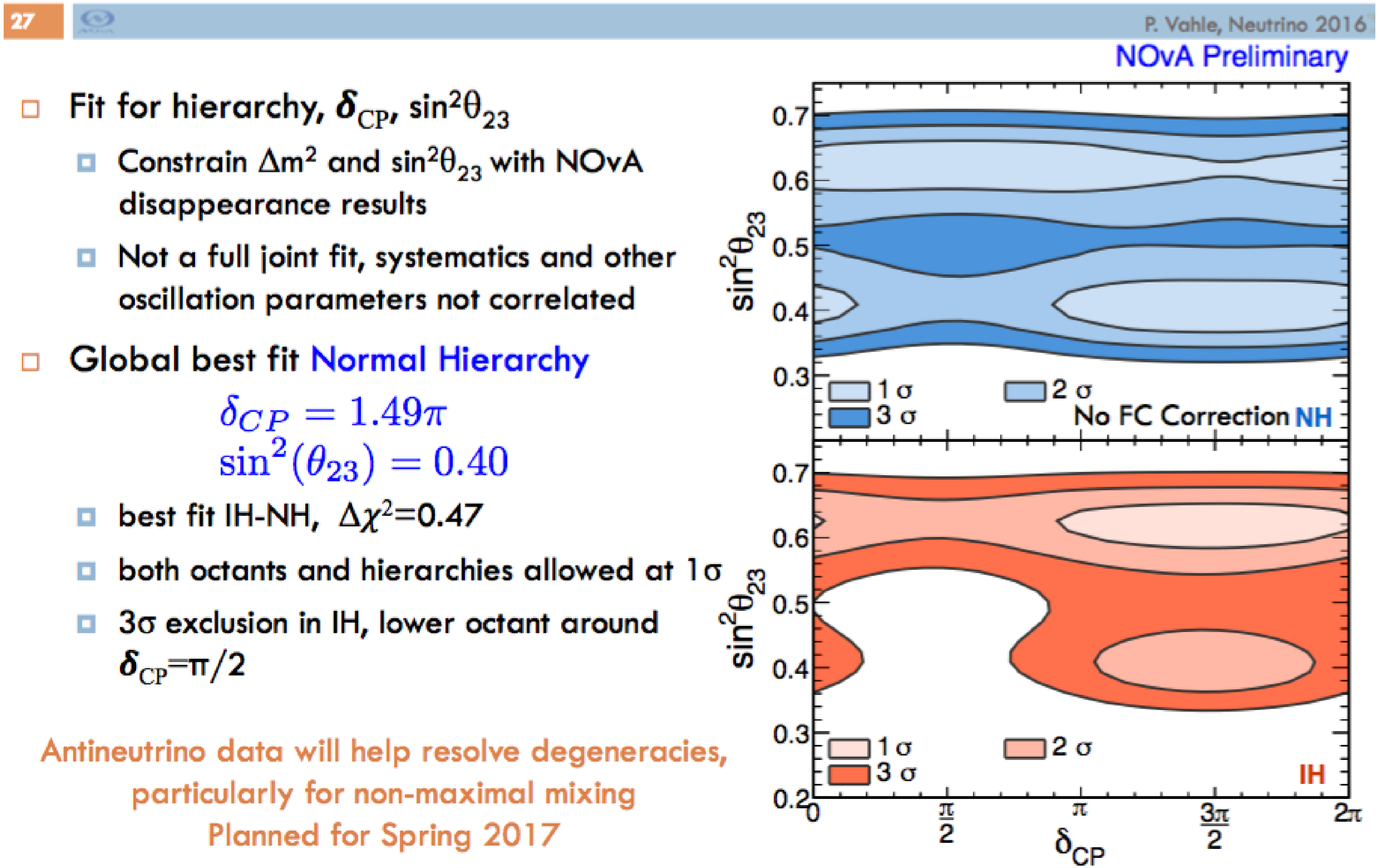


Alternate selectors from 2015 analysis show consistent results
LID: 34 events, 12.2±1.2 BG expected
LEM: 33 events, 10.3±1.0 BG expected

Similar results from NOvA

First NOvA results on δ_{CP} consistent with T2K.

P.Vahle, Neutrino 2016, New results from NOvA



T2K: Future prospects

Expect to reach the approved T2K exposure (7.8×10^{21} POT) around 2021.

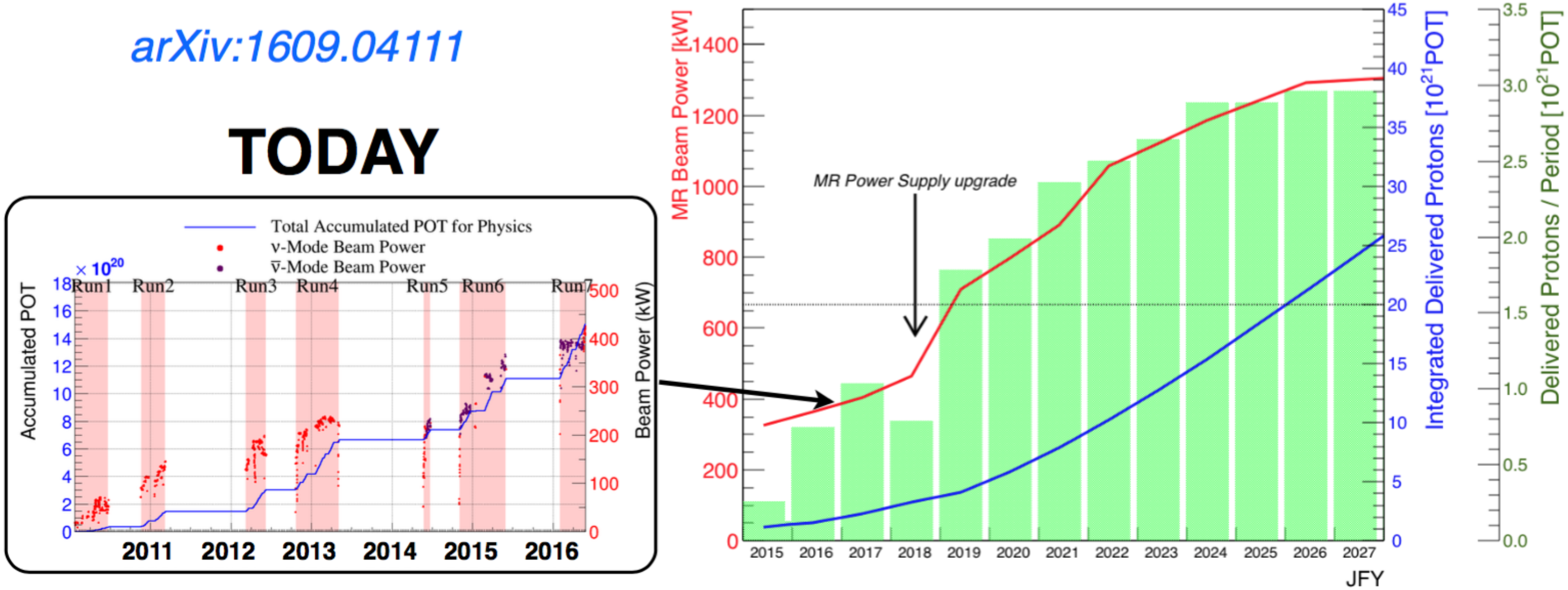
There is a proposal to extend the T2K run (T2K-II) to 20×10^{21} POT by 2025.

- Stage-I approval by JPARC PAC.

Aiming for >1 MW intensity for 2021 and 1.3 MW in 2026.

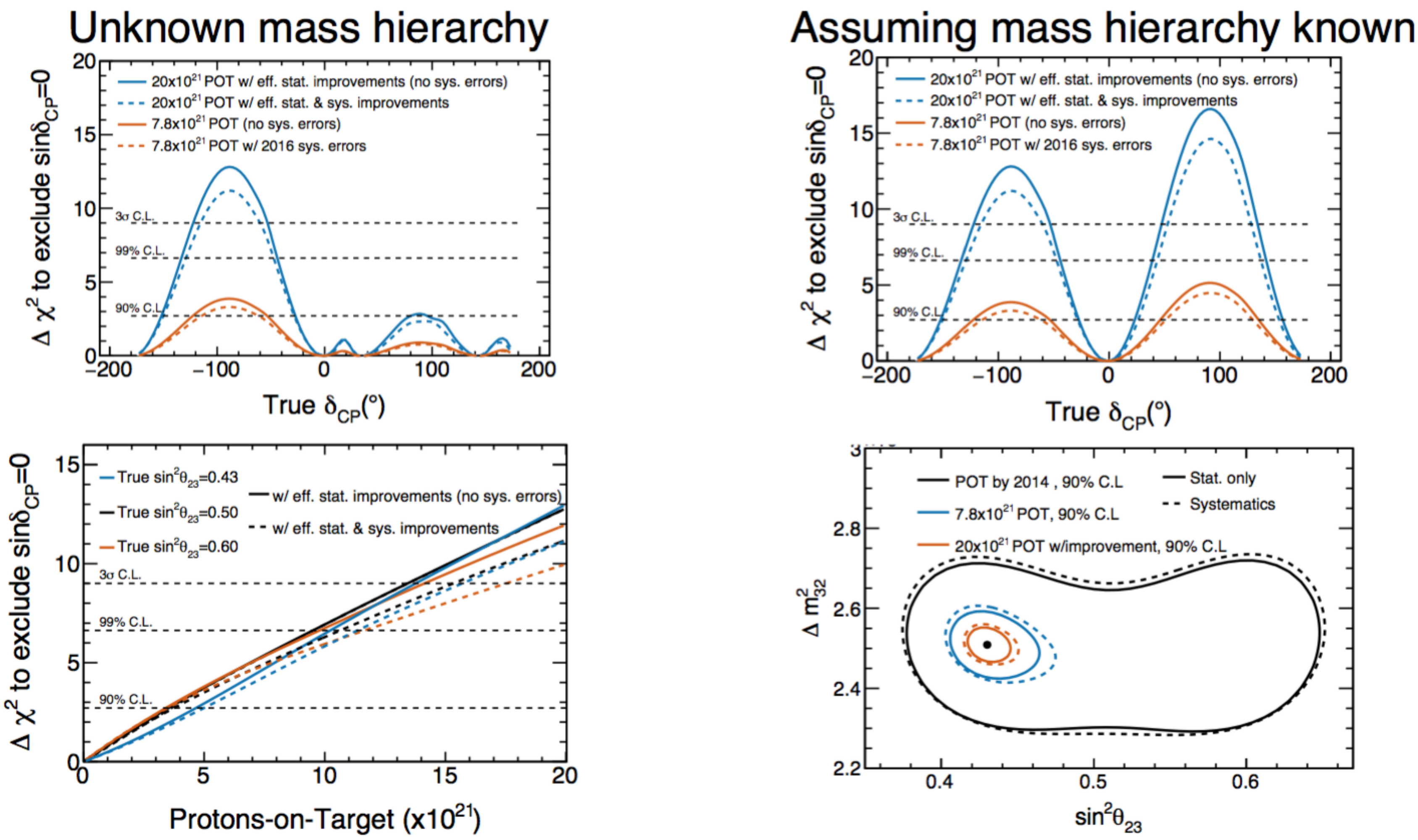
- Accelerator and beam-line upgrade is needed

Demonstrated 3.41×10^{13} protons per pulse operation $\rightarrow$ 1 MW equivalent.



T2K: Future prospects

- Exclude CP conservation hypothesis at more than 3σ if $\delta_{CP} \approx \pi/2$ and NH.
- Measure θ_{23} with resolution of $\leq 1.7^o$.

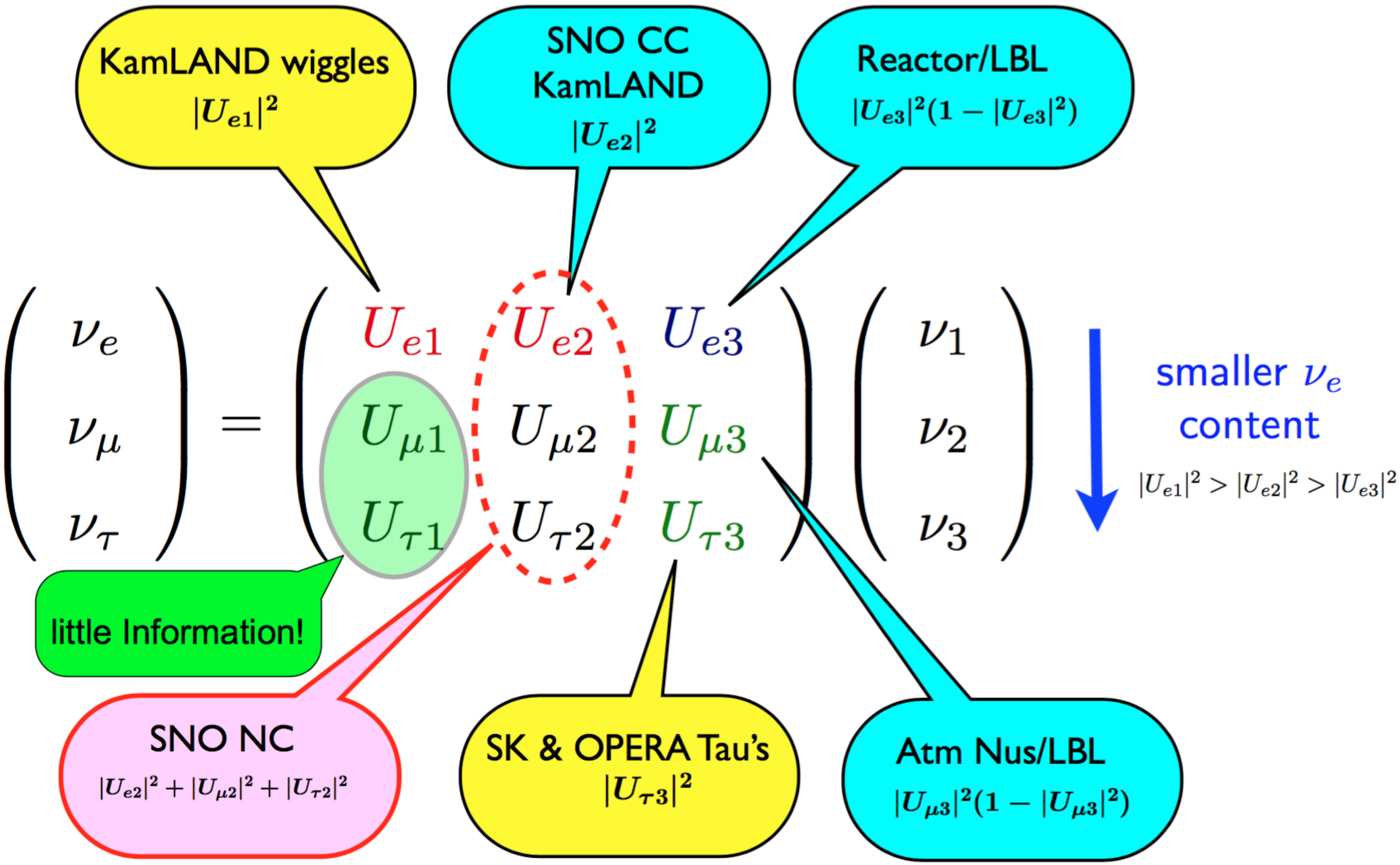


Summary

- **Neutrino oscillation results from T2K Runs 1-7**
  (7.5×10^{20} POT in neutrino + 7.5×10^{20} POT in antineutrino mode)
  - **CP conservation excluded at 90% C.L.**
  - δ_{CP} = [-3.13,0.39] (NH) or [-2.09,-0.74] (IH) at 90% C.L.
- Expecting to **double our data by summer 2017**
  - Reached 20×10^{20} POT 4 days ago.
- **Adding new analysis samples**
  - $\nu_e CC1\pi^+$: $\sim$10% additional ν_e data
- Tremendous interest in updated result: Ironing out a fluctuation, or consolidating an anomaly?
- Expecting to reach an exposure of 7.8×10^{21} POT by 2010.
- Proposal for extending running till 2025 to reach 20×10^{21} POT.
- Possibility of Near Detector upgrade to further reduce systematics.

Supplementary slides

Measuring the PMNS mixing matrix



Neutrino flux estimates

Fraction for each flavors

Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
	Flux Percentage of Each Flavors			
Secondary				
$\pi^\pm$	60.0%	41.8%	31.9%	2.8%
$K^\pm$	4.0%	4.3%	26.9%	11.3%
K^0_L	0.1%	0.9%	7.6%	49.0%
Tertiary				
$\pi^\pm$	34.4%	50.0%	20.4%	6.6%
$K^\pm$	1.4%	2.6%	10.0%	8.8%
K^0_L	0.0%	0.4%	3.2%	21.3%