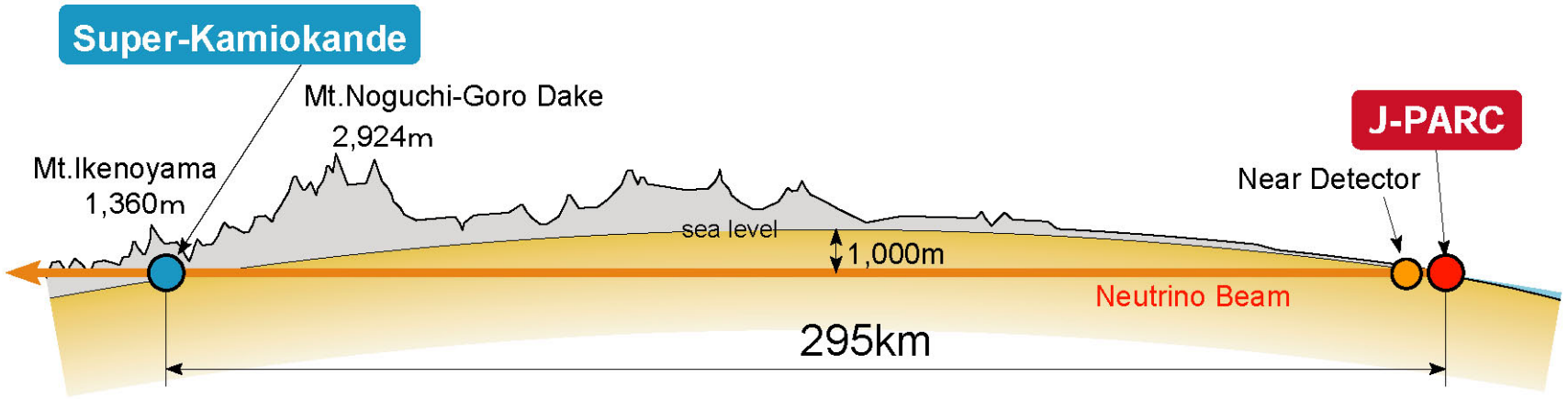
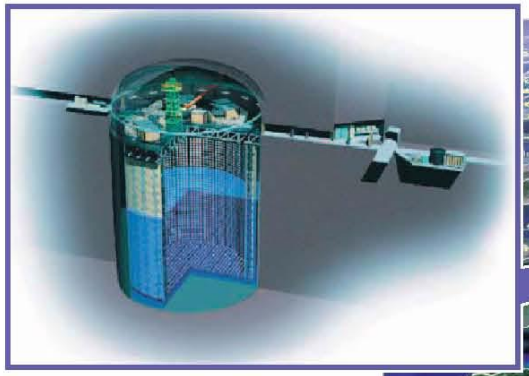
Recent Results from T2K and Future Prospects

Konosuke Iwamoto (University of Rochester)
On behalf of the T2K Collaboration

T2K Experiment





Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

Neutrino Oscillation at T2K

At desired energy spectrum (E=0.6 GeV) and baseline L=295 km …

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

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

$$-\alpha \sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\hat{\Delta} \frac{\sin[\hat{\Delta}x]}{x} \frac{\sin[(1-x)\hat{\Delta}]}{(1-x)}$$

$$+\alpha \cos\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\hat{\Delta} \frac{\sin[\hat{\Delta}x]}{x} \frac{\sin[(1-x)\hat{\Delta}]}{(1-x)}$$

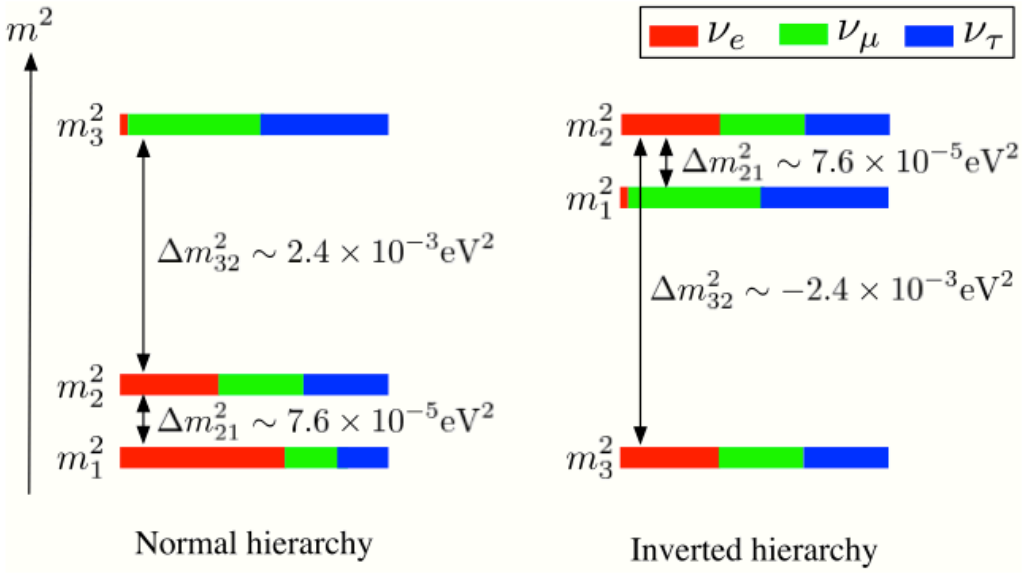
$$+ O(\alpha^2) \qquad \Delta m^2_{ij} = m^2_i - m^2_j \qquad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \hat{\Delta} = \frac{\Delta m^2_{31} L}{4E} \qquad x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

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

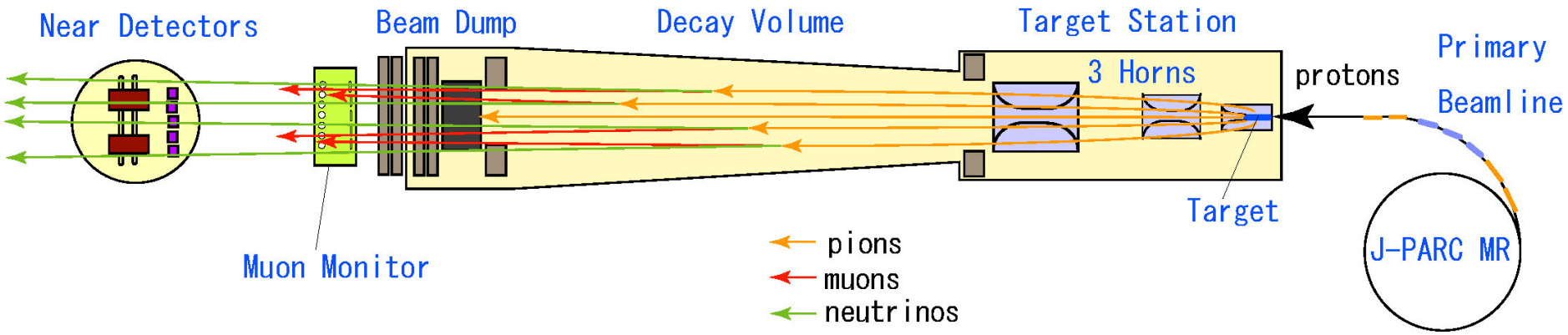
- CPT test with $P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$
- CP odd phase δ changes sign for $\overline{\nu}$-mode $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

Oscillation Parameter Dependence

- **$\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$**
  - Leading terms
  - "Octant" dependence; whether $\theta_{23} > 45^o$, $\theta_{23} < 45^o$, or $\theta_{23} = 45^o$
- **δ_{cp}: $\pm$27% effect at T2K for $\theta_{23} = 45^o$**
  - $\delta_{cp} \sim -\frac{\pi}{2}$: enhances $P(\nu_\mu \rightarrow \nu_e)$, suppresses $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - $\delta_{cp} \sim +\frac{\pi}{2}$: suppresses $P(\nu_\mu \rightarrow \nu_e)$, enhances $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- **Mass hierarchy**: **$\pm$10% effect at T2K**
  - Normal: enhances $P(\nu_\mu \rightarrow \nu_e)$, suppresses $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Inverted: suppresses $P(\nu_\mu \rightarrow \nu_e)$, enhances $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

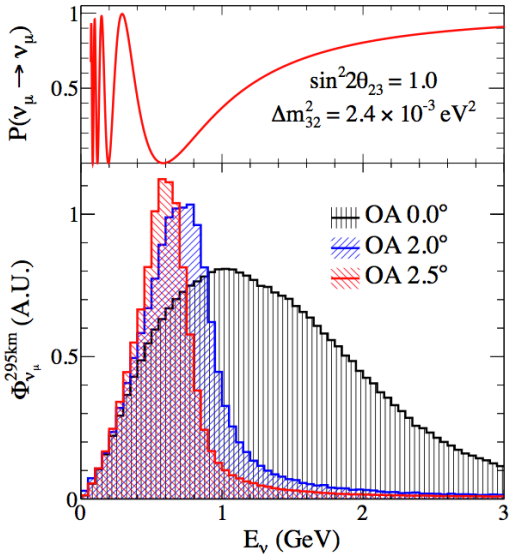


J-PARC and Neutrino Beamline



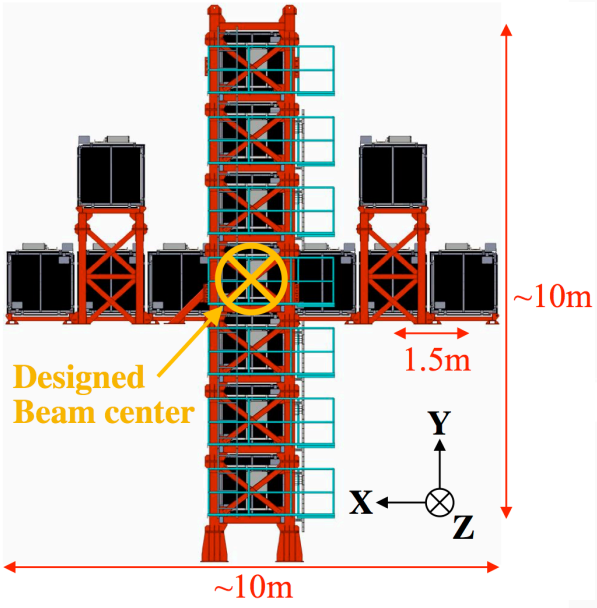
- 30 GeV proton beam generated by J-PARC Main Ring (MR) directed to the graphite target
- Secondary pions collected and focused by the magnetic horns
  - ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (Forward horn current)
  - $\overline{\nu}$ beam: $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$ (Reverse horn current)

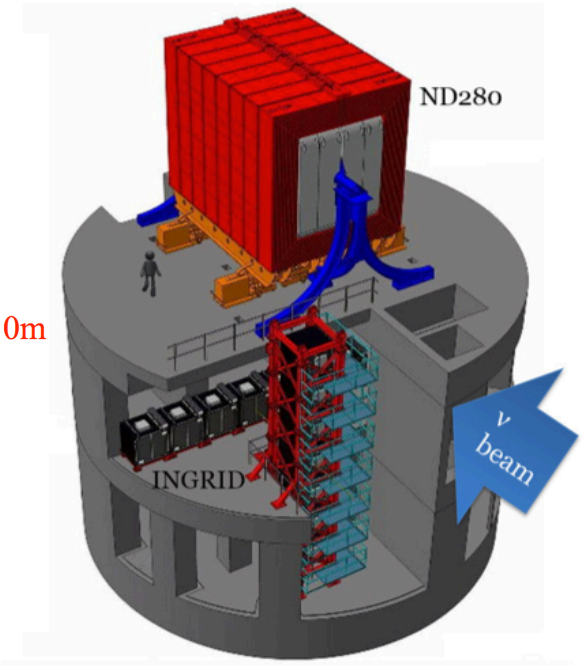
- Uses off-axis method to make the spectrum peak at 600 MeV
  - Expected oscillation maximum at L=295 km

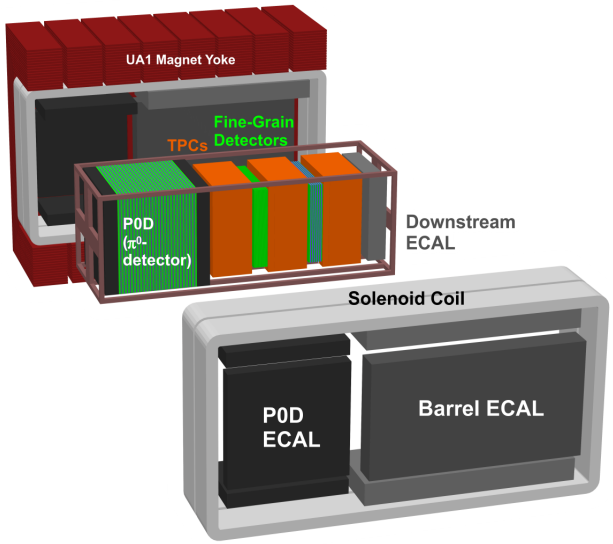


T2K Near Detectors

- On-axis **INGRID** and off-axis **ND280**





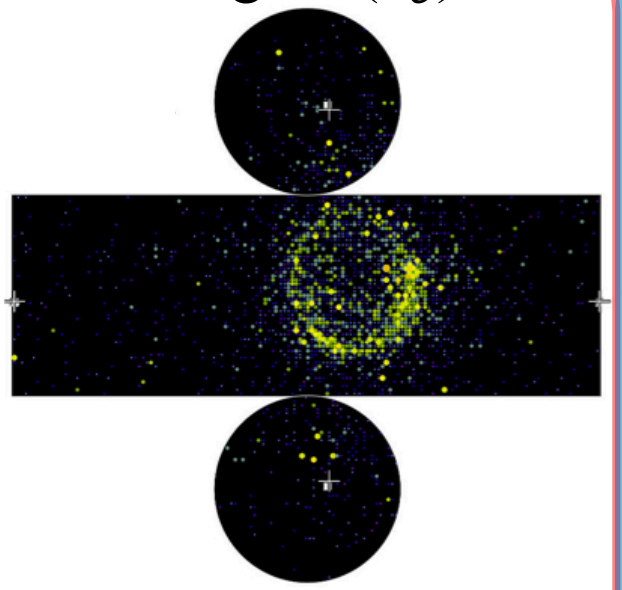


ND280
- Scintillators and water targets
- Consists of trackers, calorimeters, and muon detectors
- UA1 magnet (0.2T)
- Tracks the neutrino prior to oscillations

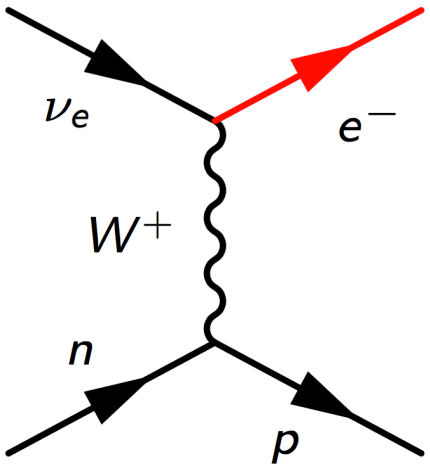
INGRID
- Scintillators and iron targets
- measure neutrino beam direction and stability

Neutrino Detection at SK Far Detector

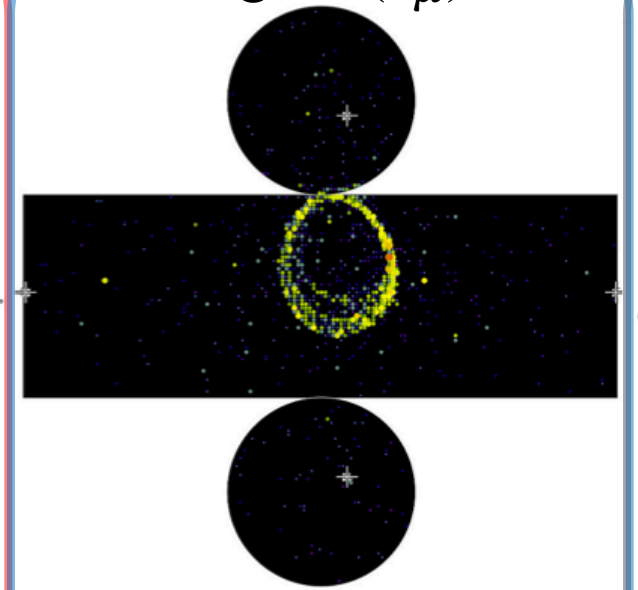
Signal (ν_e)



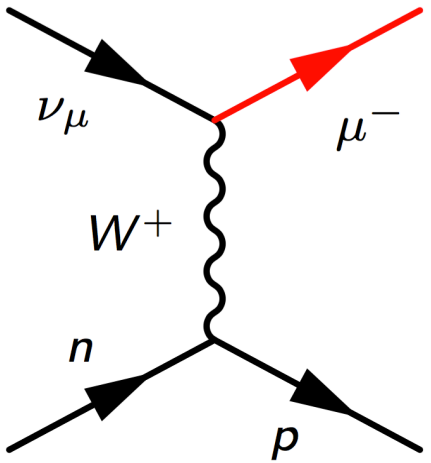
ν_e CCQE



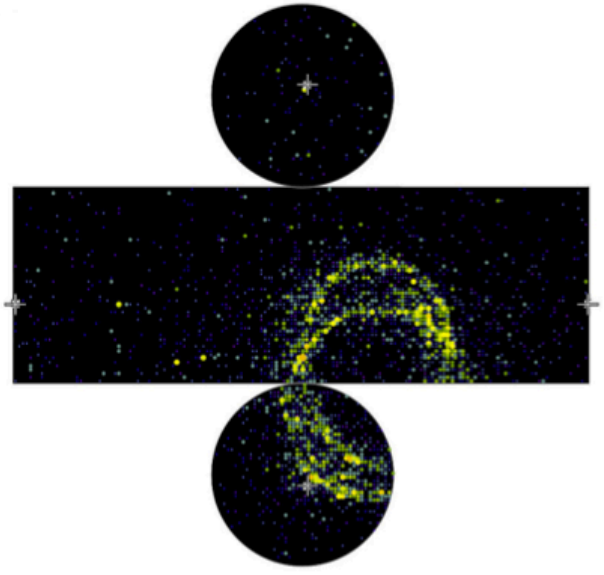
Signal (ν_μ)



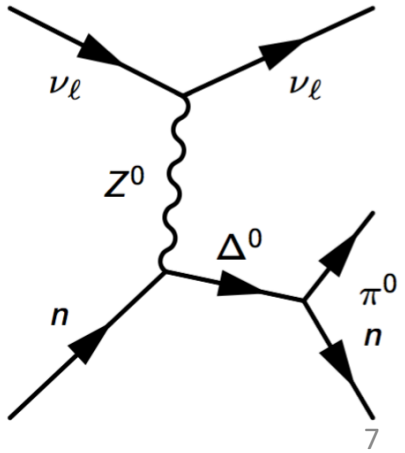
ν_μ CCQE



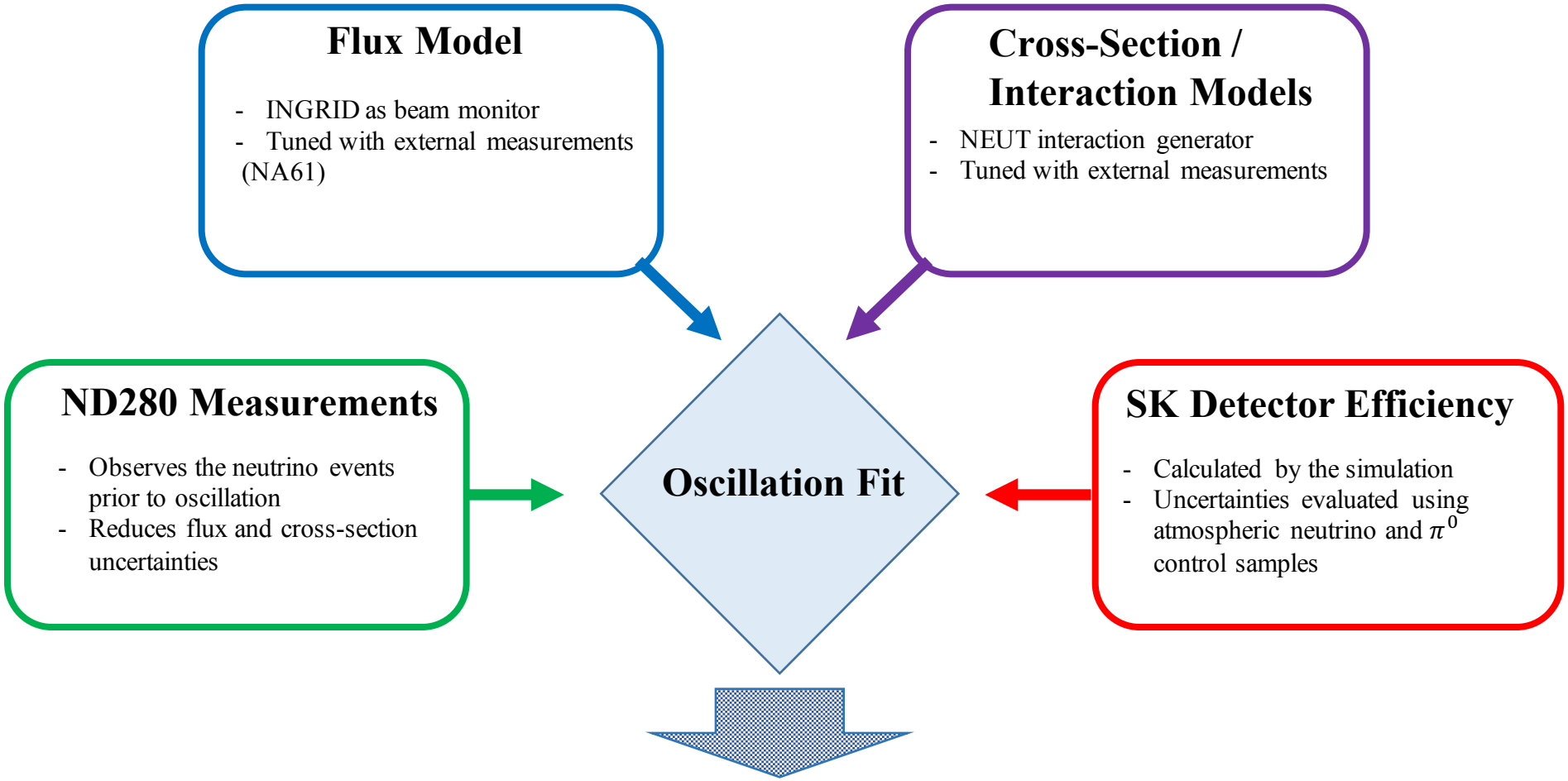
Background



ν_ℓ NC1π^0



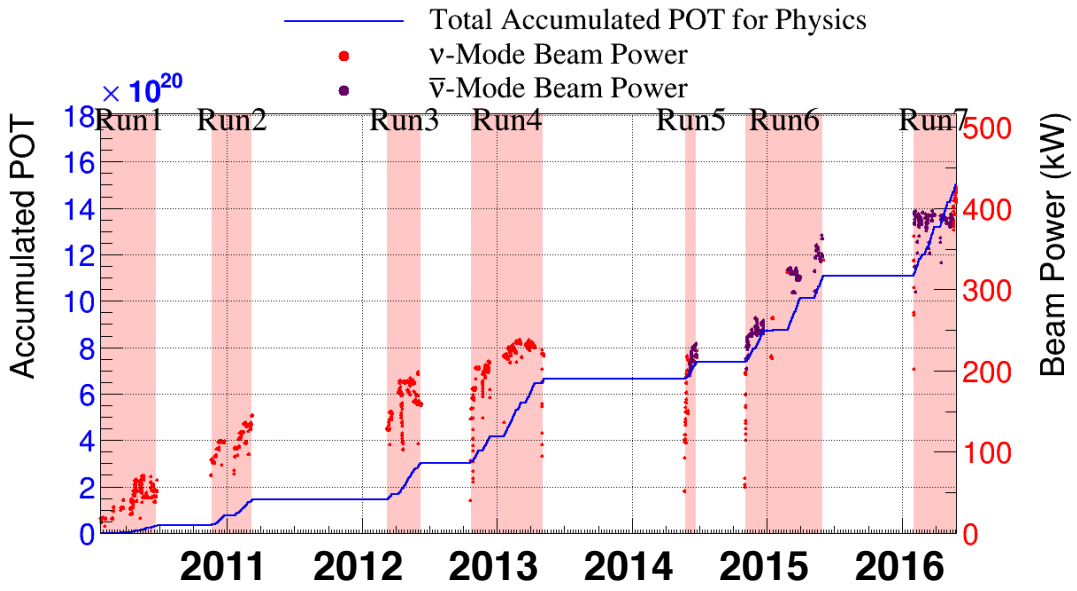
T2K Analysis Method



Oscillation Parameters ($\theta_{13}, \delta_{cp}, \Delta m^2_{32}, \theta_{23}$)

The Latest Results from the T2K Experiment

Update since Neutrino 2016 (7/4/2016)



27 May 2016
POT total: 1.510×10²¹
(POT = Proton on target)

ν-mode POT: 7.57×10²⁰ (50.14%)
ν̄-mode POT: 7.53×10²⁰ (49.86%)

Three major updates since Neutrino 2016:

1) Update with full data (May 27)
   - ν-mode: 7.48×10^{20} POT (additional 0.48×10^{20} POT)
   - $\bar{\nu}$-mode: 7.47×10^{20} POT
2) $\bar{\nu}_\mu$ disappearance analysis as a test of the CPT theorem
3) Selection of additional ν_e CC1π^+ sample

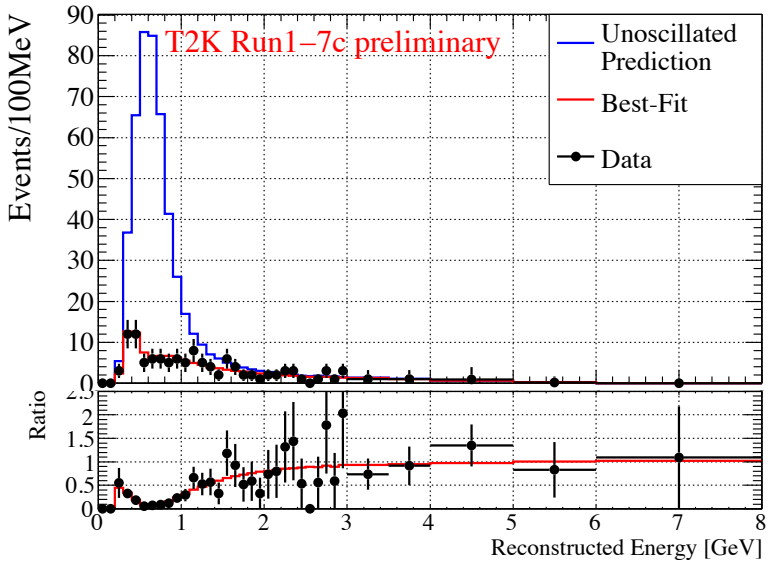
$\nu_\mu/\bar{\nu}_\mu$ Disappearance Analysis

(CPT Violation or Non-Standard ν Interaction Research)

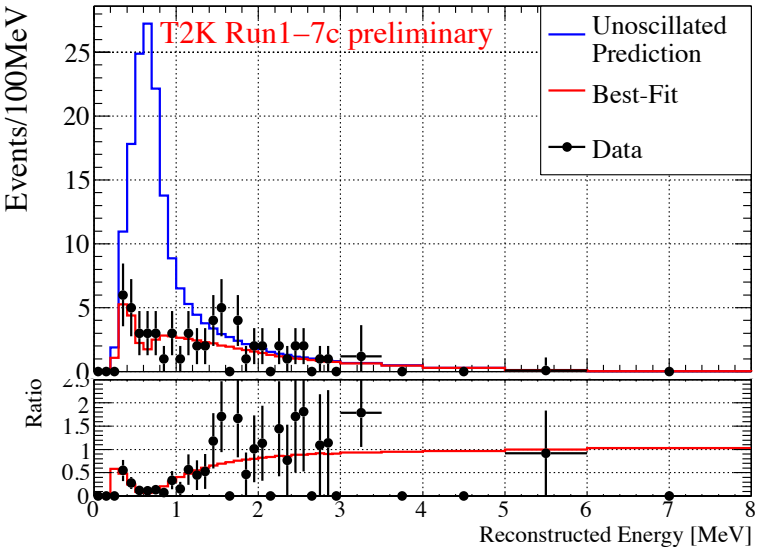
$\nu_\mu/\bar{\nu}_\mu$ Disappearance Analysis

- CPT test by comparing $(\nu_\mu \rightarrow \nu_\mu)$ and $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ modes

ν_μ



$\bar{\nu}_\mu$



135 events observed

(+10 events since Neutrino 2016)

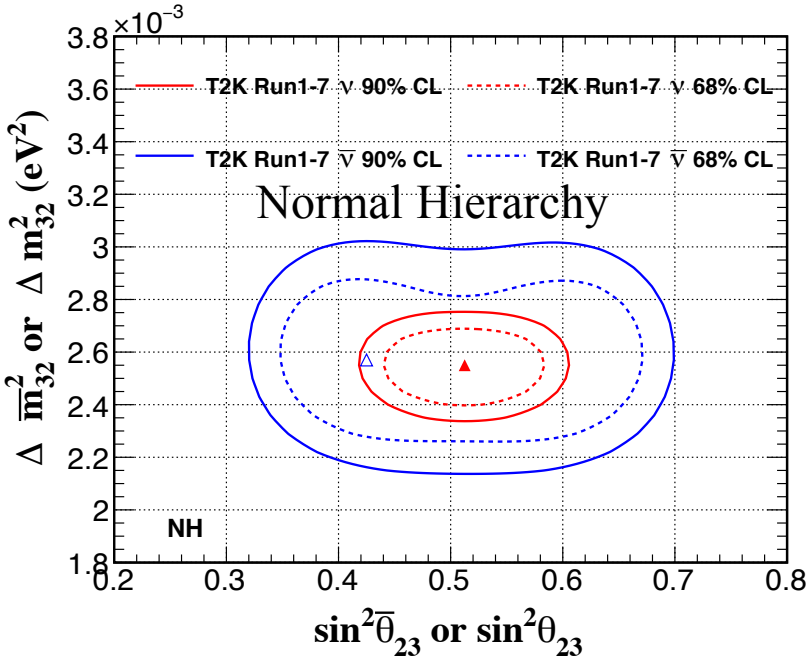
(135.8 events expected)

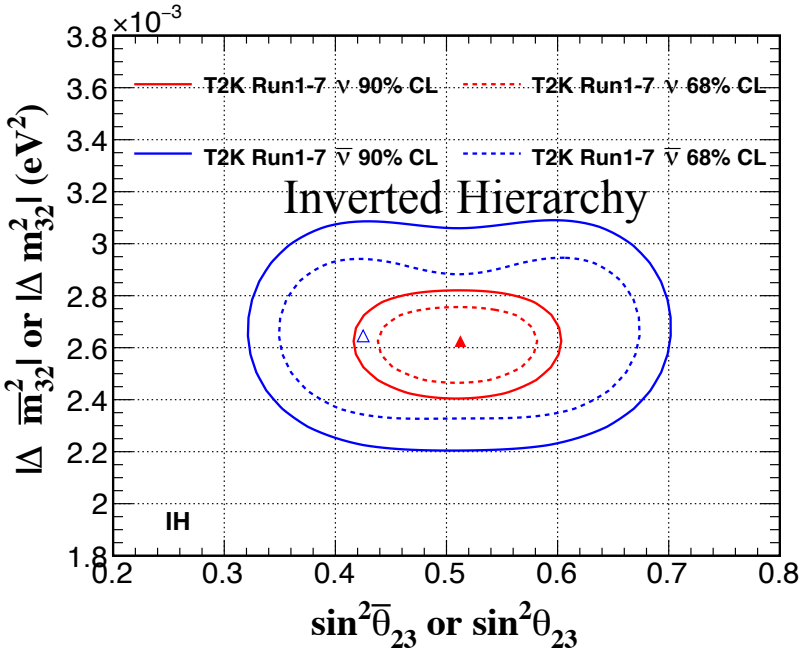
66 events observed

(64.2 events expected)

θ_{23} and Δm^2_{32} Comparison

- No hint of CPT violation





$\Delta\overline{m}^2_{32} = [2.16, 3.02]\times10^{-3}eV^2(NH)$ at 90% CL

$\sin^2\overline{\theta}_{23} = [0.32, 0.70](NH)$ at 90% CL

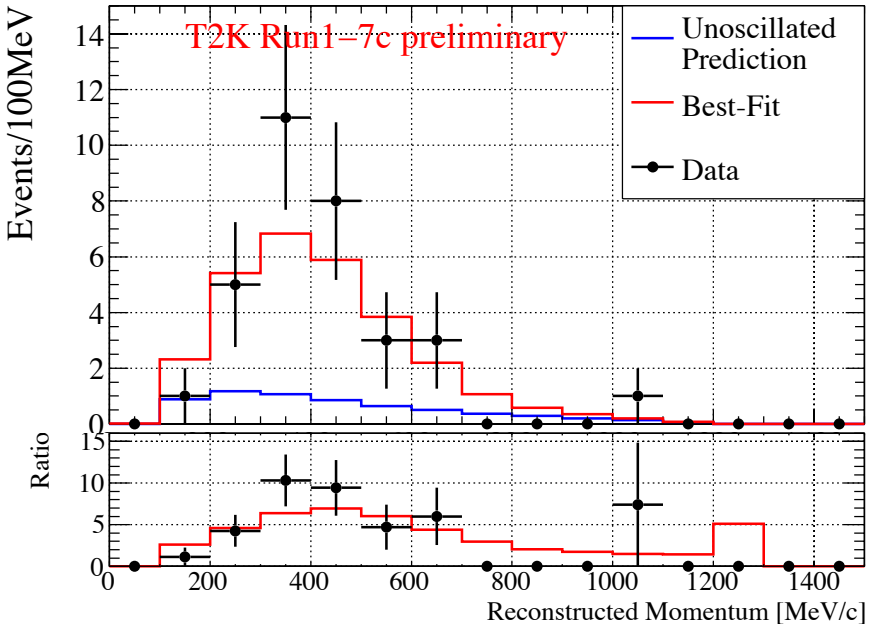
$\Delta m^2_{32} = [2.34, 2.75]\times10^{-3}eV^2(NH)$ at 90% CL

$\sin^2\theta_{23} = [0.42, 0.61](NH)$ at 90% CL

Update with Full Data (until May 27)

Full Joint Fit Analysis

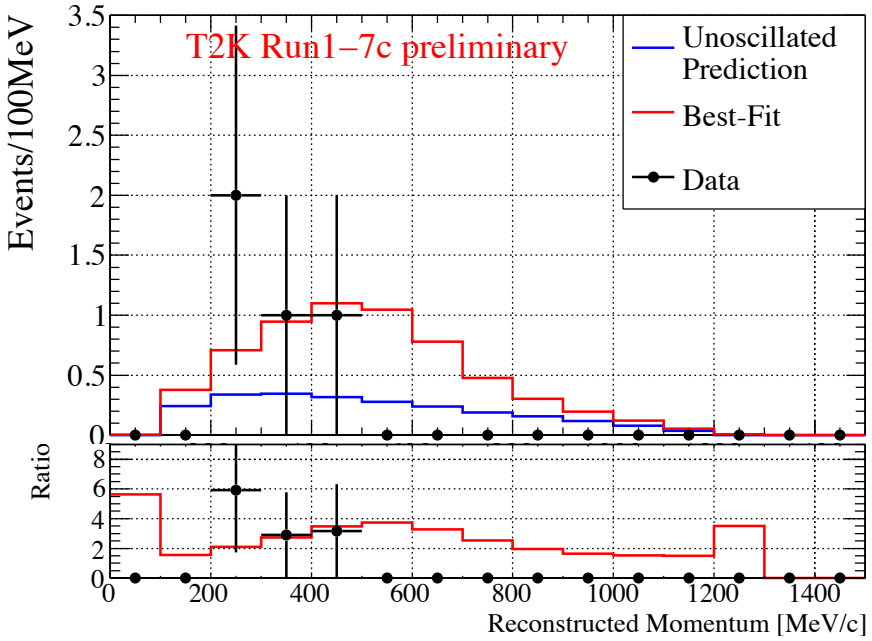
ν_e



32 events observed

(+0 events since Neutrino 2016)

$\bar{\nu}_e$

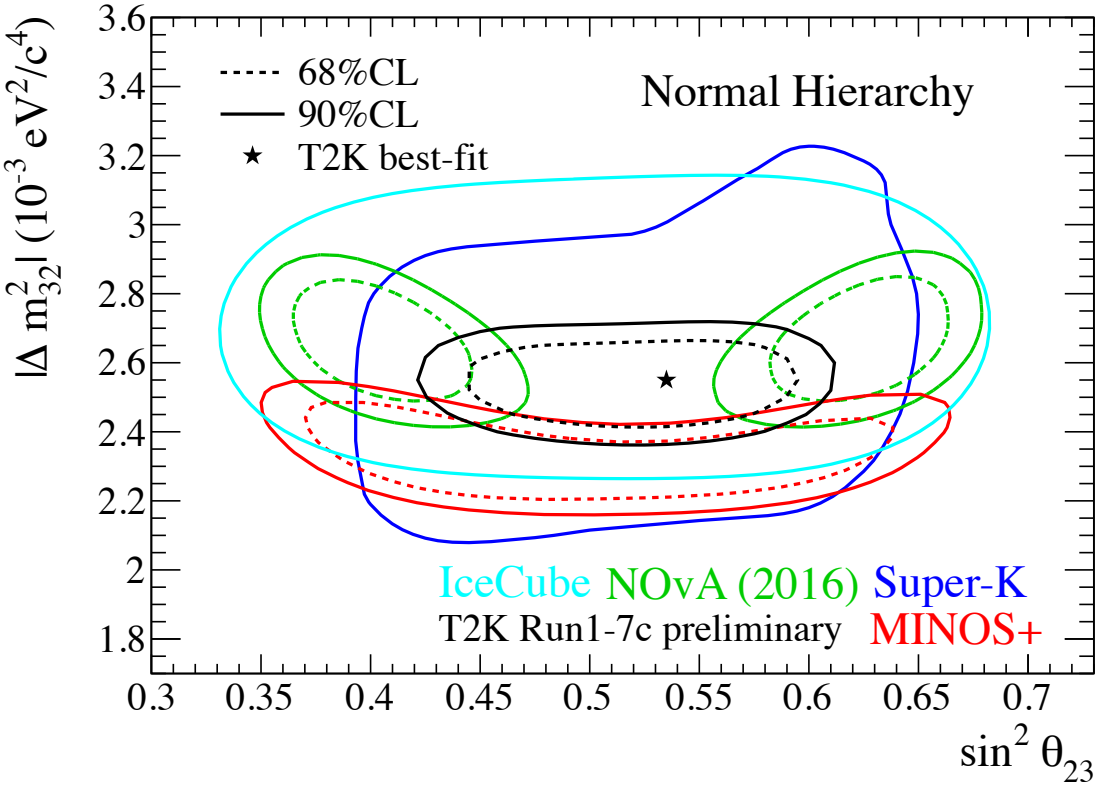


4 events observed

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

θ_{23} and Δm^2_{32}

- Consistent with maximal mixing

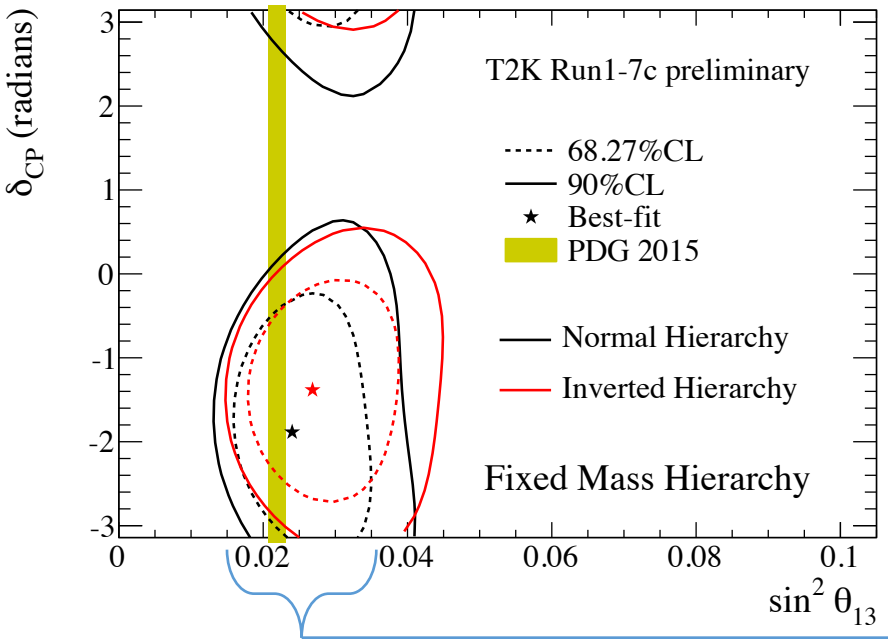


Daya Bay:
$|\Delta m^2_{ee}| = (2.45 \pm 0.08) \times 10^{-3} eV^2$
90% CL (NH)

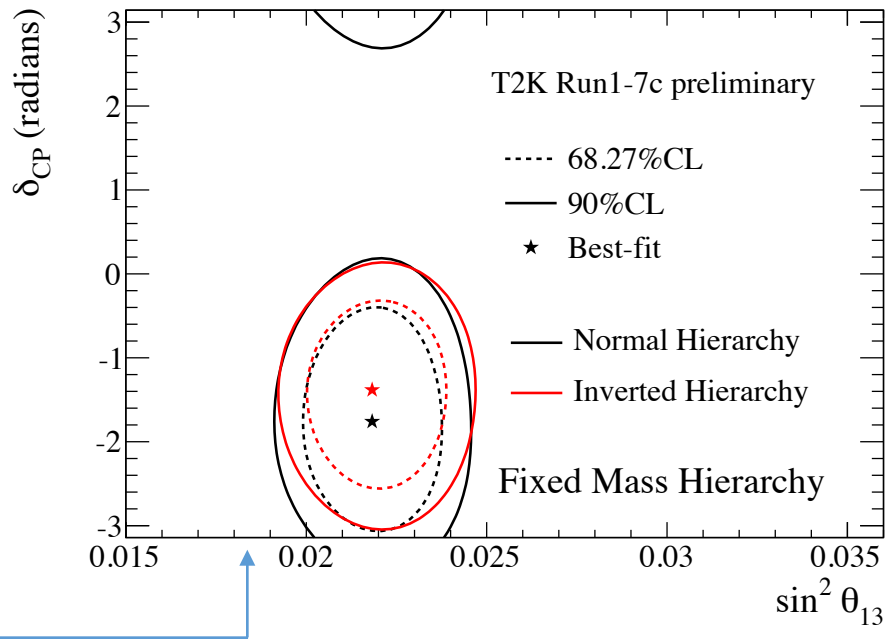
	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\text{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

θ_{13} and δ_{cp}

T2K-Only



T2K Result with Reactor Constraint
($sin^2 2\theta_{13} = 0.085 \pm 0.005$)

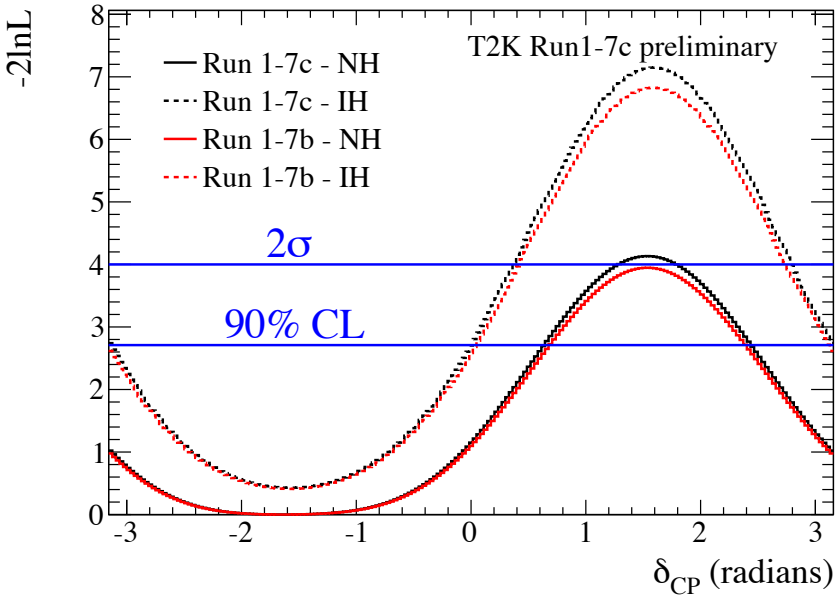


- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

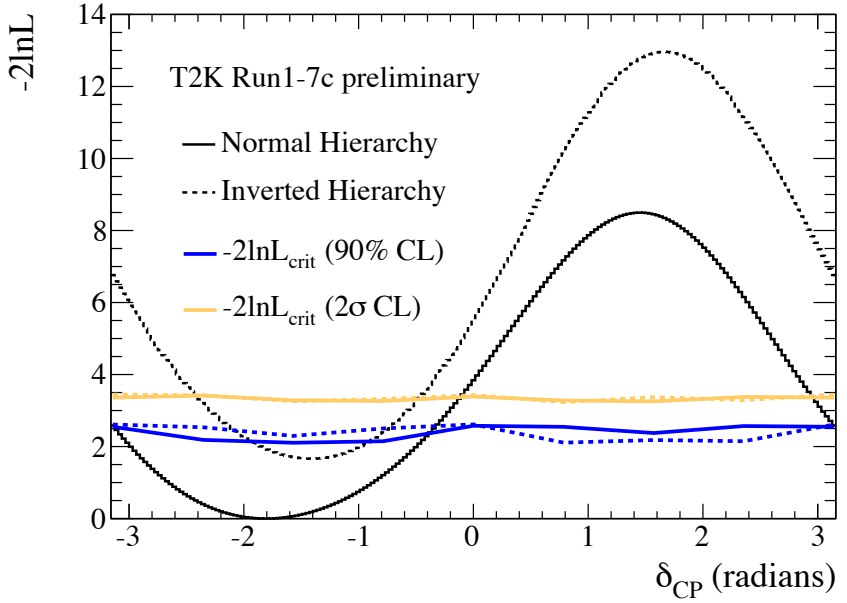
θ_{13} and δ_{cp}

- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

Sensitivity (Simulation)



Measurement (Data)



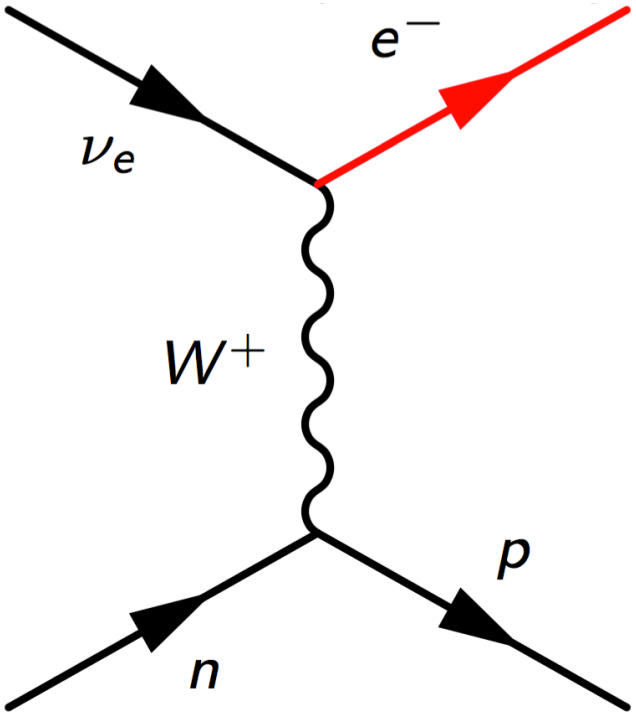
$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH)$ at 90% CL

Selection of Additional ν_e CC1π^+ Appearance Sample

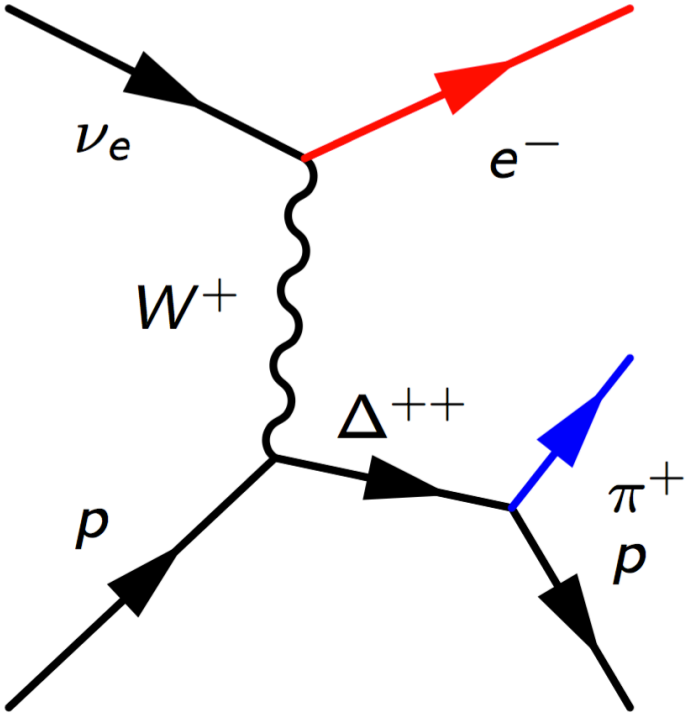
ν_e CC1π^+ Appearance Sample

- Introduce ν_e single-ring, electron-like events with one Michel electron

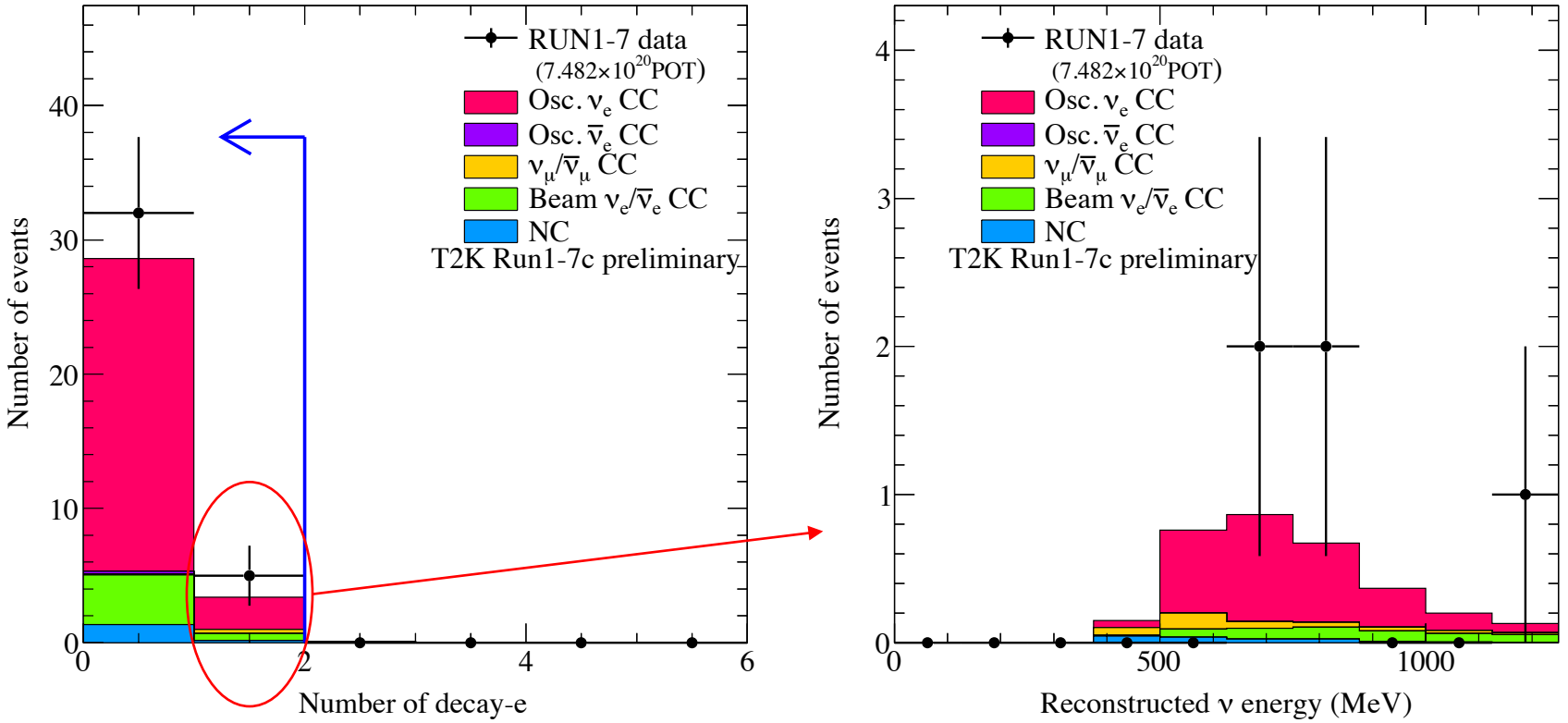
ν_e CCQE



ν_e CC1π^+



ν_e CC1π^+ Appearance Event Selection

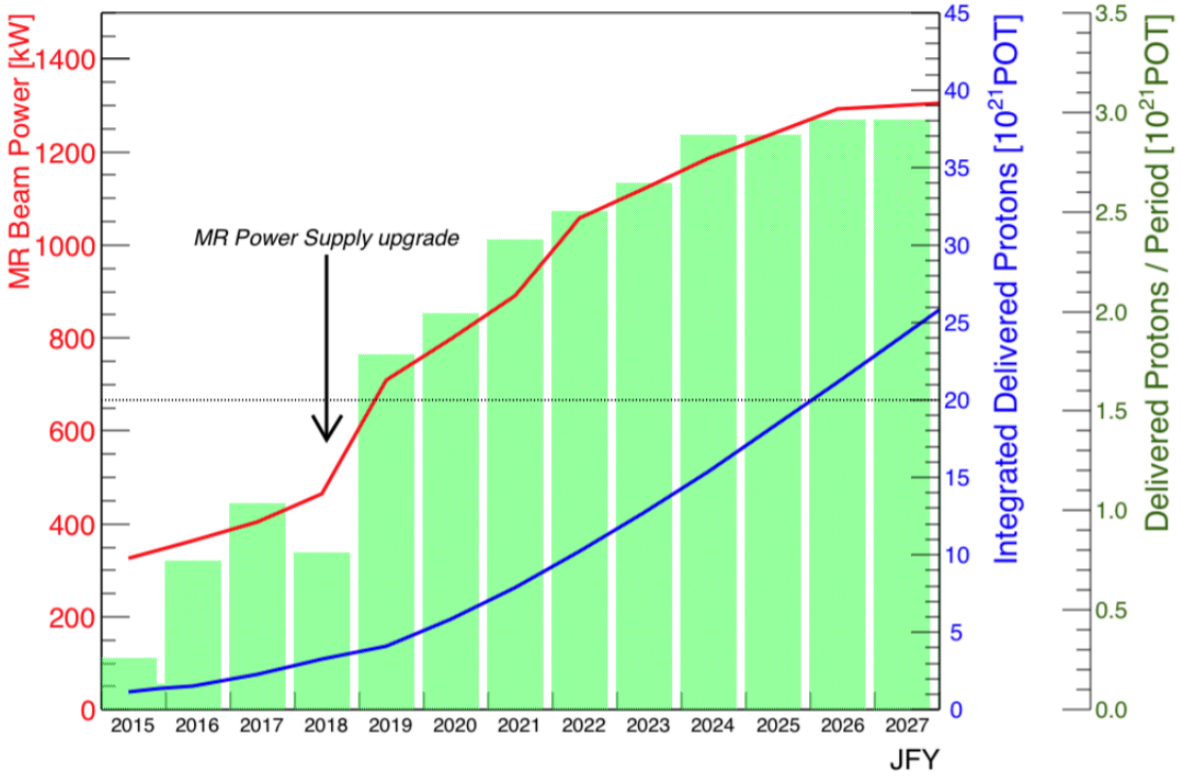


	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_eCC1π^+	3.1	2.8	2.3	2.7	5

- ~11% more events in the appearance analysis ($\delta_{cp} = -\pi/2$)
- Oscillation analysis with inclusion of the ν_e CC1π^+ sample in progress

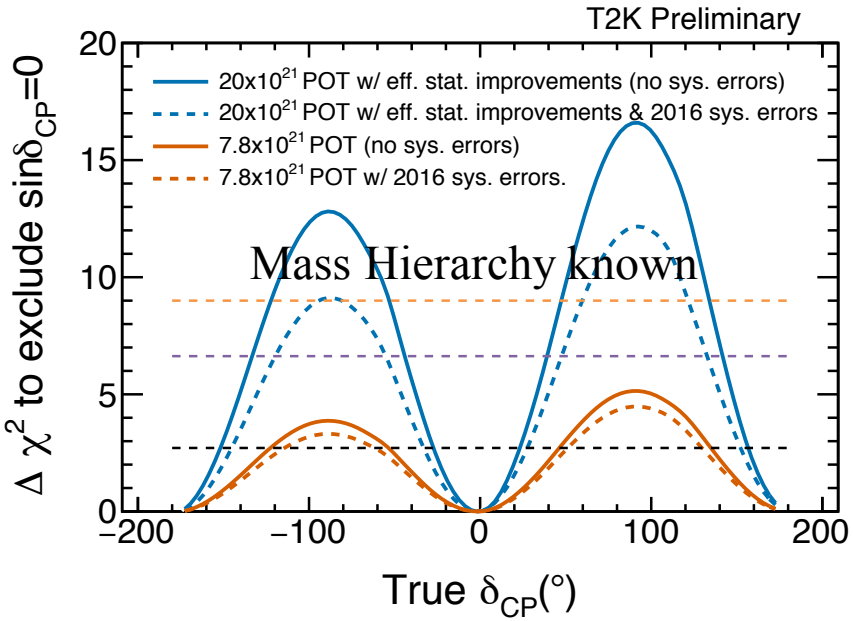
T2K-II: a Proposed Extension of the T2K Experiment

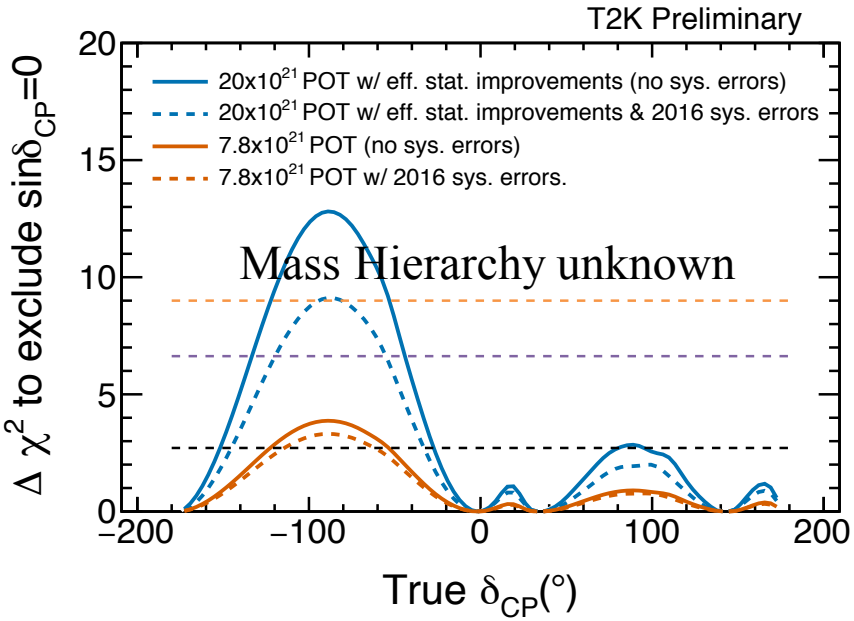
T2K to T2K-II

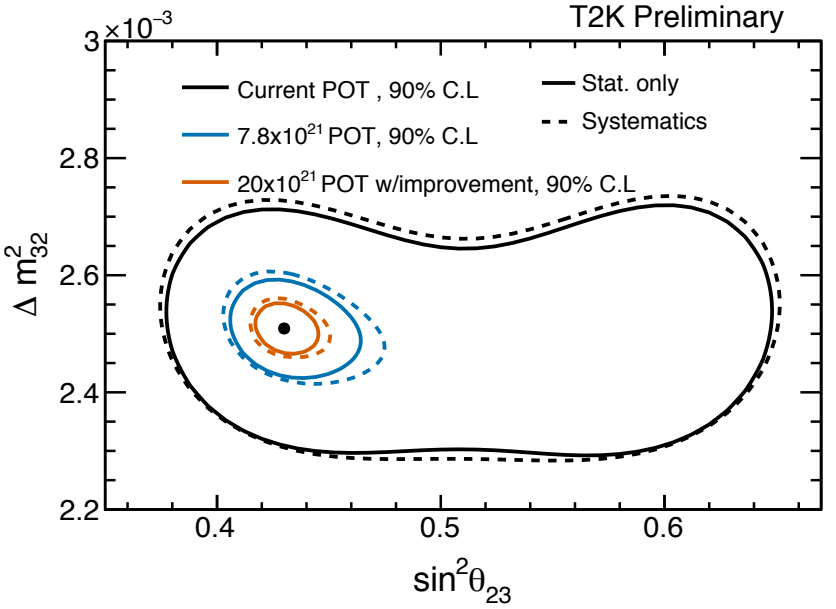


- Approved T2K statistics 7.8×10^{21} POT, expected around 2020
- 1st stage of J-PARC main ring power supply upgrade approved
  - Aiming for > 1 MW beam power (currently 420 kW)
- T2K-II extends T2K run to 20×10^{21} POT on the time scale of 2026
- Requires accelerator and beam-line upgrade to reach 1.3 MW

Physics Potential of T2K-II







- ~50% increase in effective POT
- ~3σ sensitivity to δ_{cp}
- Precise measurement of θ_{23}
  - resolution of 1.7%

Conclusion

Conclusion

- Statistical update since Neutrino 2016
  - Data continue to prefer maximal θ_{23} mixing, $\delta_{cp} \sim -\frac{\pi}{2}$, NH
    - $\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH)$ at 90% CL
  - No hint of CPT violation
  - Event selection of ν_e CC1π^+ sample
    - Inclusion of ν_e CC1π^+ sample in oscillation analysis in progress
- Propose to extend T2K to T2K-II
  - Primary goals to achieve $> 3\sigma$ sensitivity to δ_{cp} and θ_{23} resolution to 1.7%

Posters

- **Neutrino Oscillation Physics Potential of A Possible Extension of The T2K Experiment**:
  Son Cao

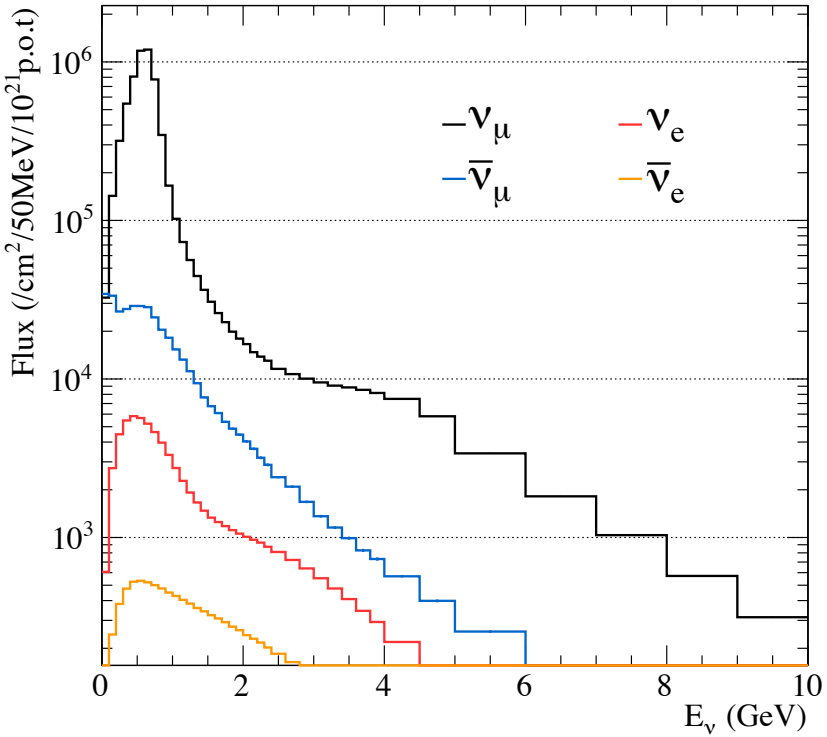
- **A Measurement of the ν_μ Charged-Current Cross Section on Water with Zero Pions in the Final State at T2K**:
  Tianlu Yuan

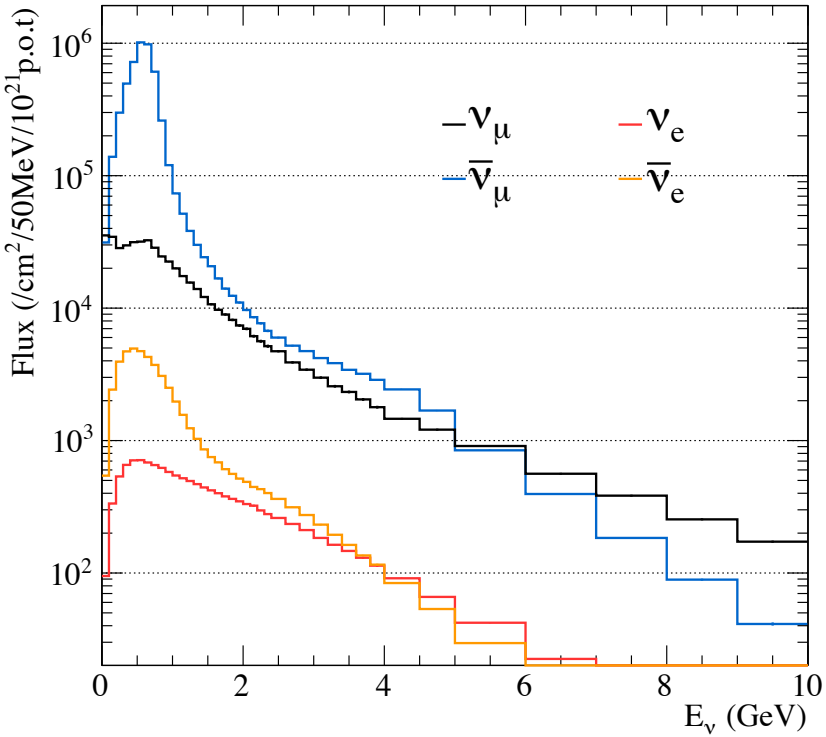
- **CCQE Model Differences in 1p1h and 2p2h Interactions**:
  Matt Dunkman

- **Single Pion Production in Neutrino-Nucleon Reactions**:
  Monireh Kabirnezhad

Back-Up Slides

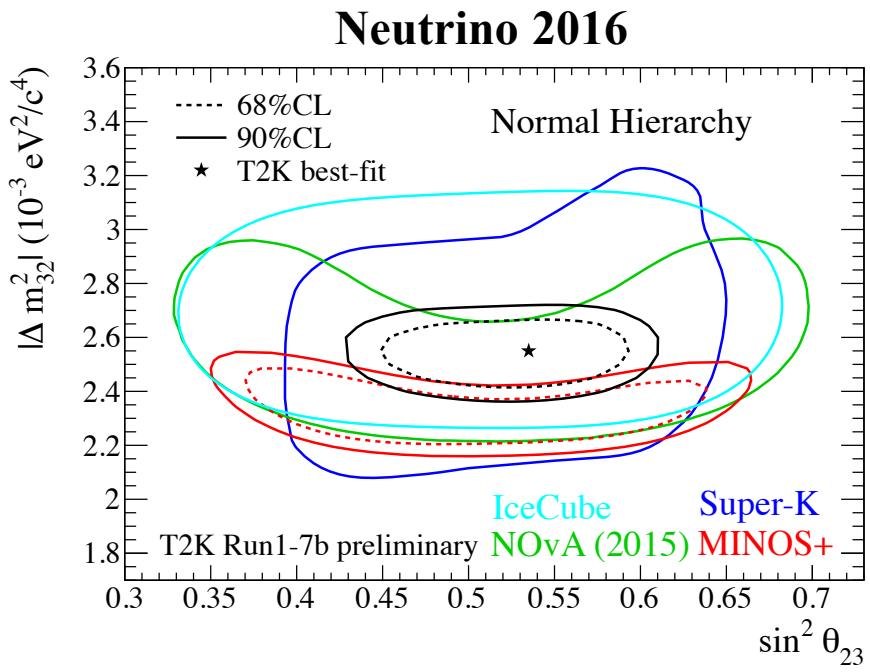
Neutrino and Antineutrino Flux at SK

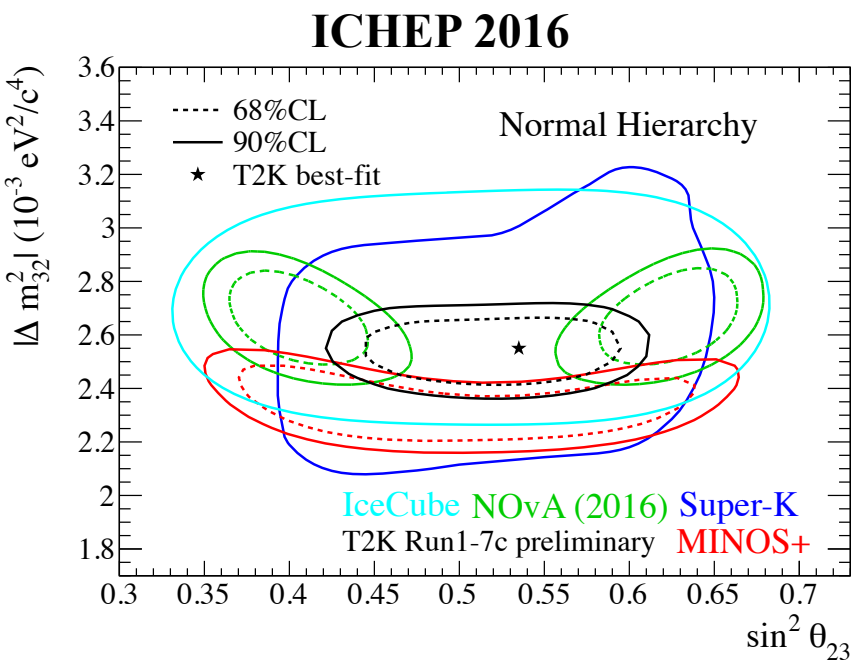




θ_{23} and Δm^2_{32}

- Consistent with maximal mixing



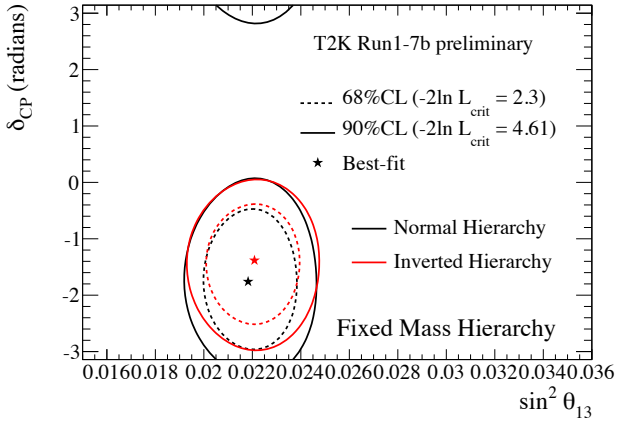


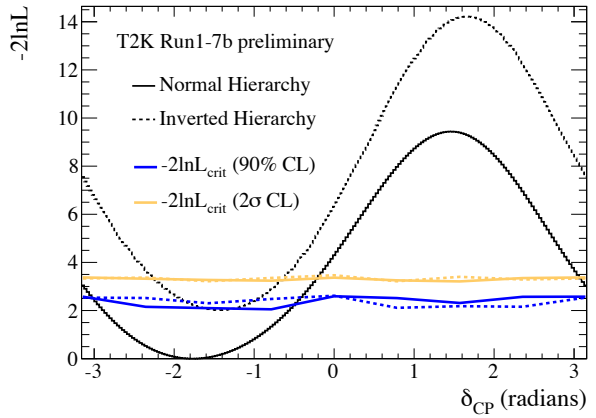
	NH (Neutrino 2016)	IH (Neutrino 2016)	NH (ICHEP 2016)	IH (ICHEP 2016)
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\text{eV}^2]$	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

θ_{13} and δ_{cp}

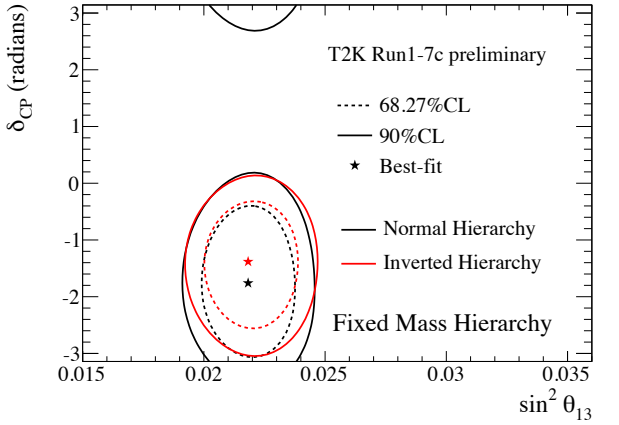
- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

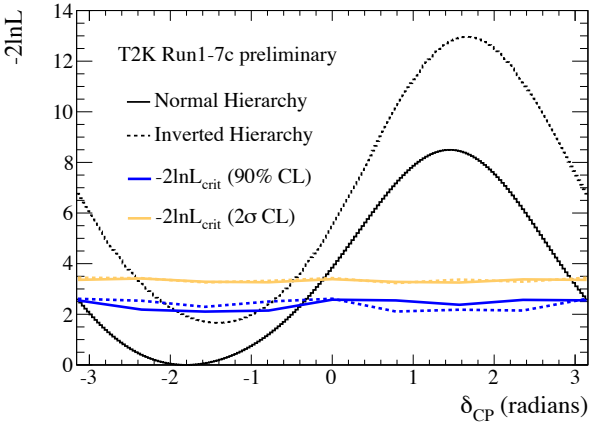
Neutrino 2016





ICHEP 2016





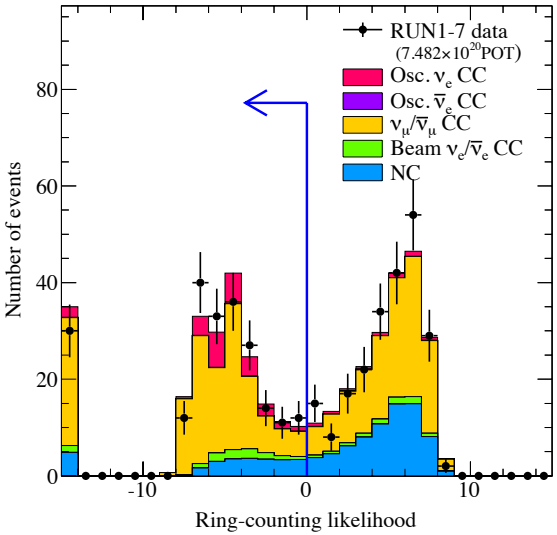
Neutrino 2016: $\delta_{cp} = [-3.02, -0.49](NH), [-1.87, -0.98]\ (IH)$ at 90% CL

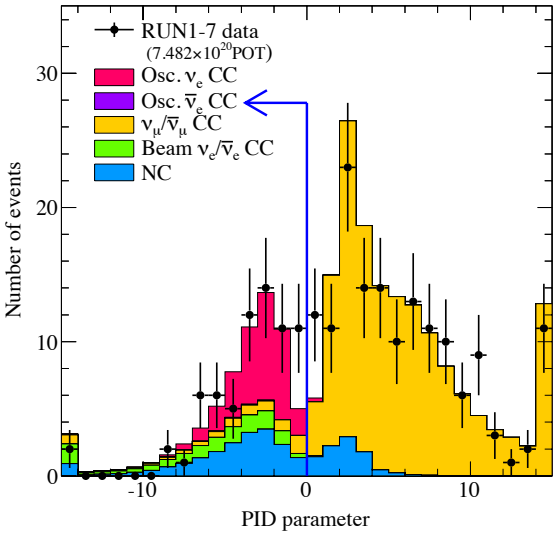
ICHEP 2016: $\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH)$ at 90% CL

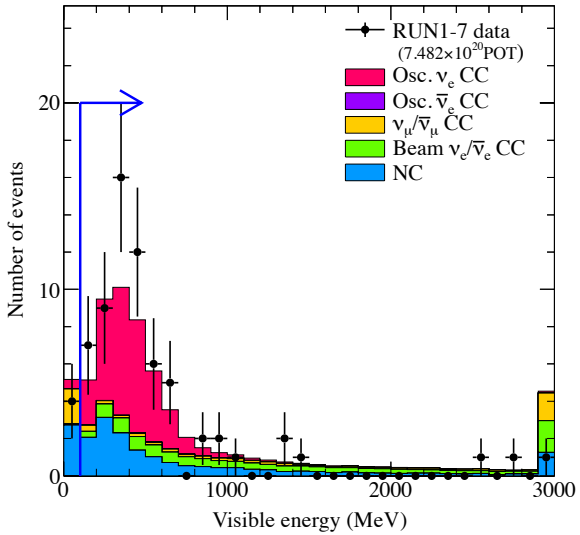
T2K-SK ν_e Selection: ν-mode

	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Bkg. total	$\nu_\mu \rightarrow \nu_e$	DATA
In FV	365.2	18.6	327.0	0.4	711.2	35.6	654
FCFV	280.6	18.1	99.0	0.4	398.1	34.9	438
1R	153.8	11.2	28.8	0.3	194.0	30.0	220
e-like	6.5	11.1	19.6	0.3	37.5	29.6	70
Evis>100	4.6	11.0	16.9	0.3	32.8	29.1	66
0 Decay-e	1.0	9.0	14.3	0.3	24.5	26.2	51
Erec	0.3	4.3	10.9	0.2	15.6	25.2	46
π^0 rej.	0.1	3.7	1.4	0.2	5.3	23.3	32
Eff. (%)	0.0	19.8	0.4	46.2	0.7	65.6	

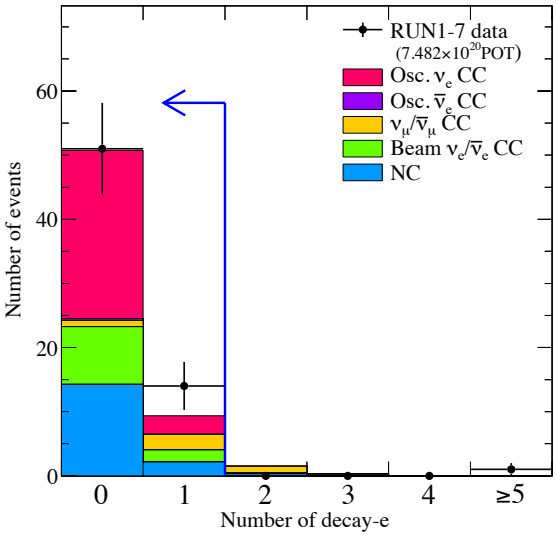
T2K-SK ν_e Selection: ν-mode

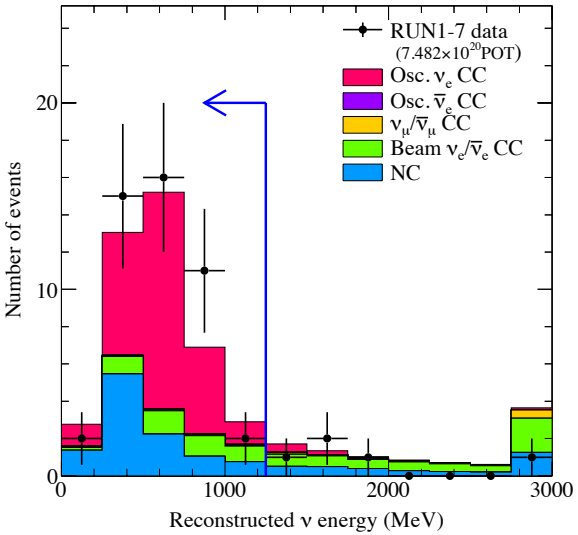


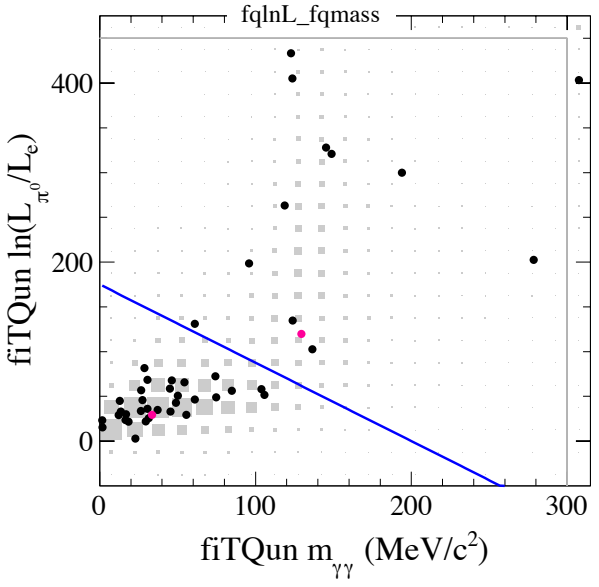




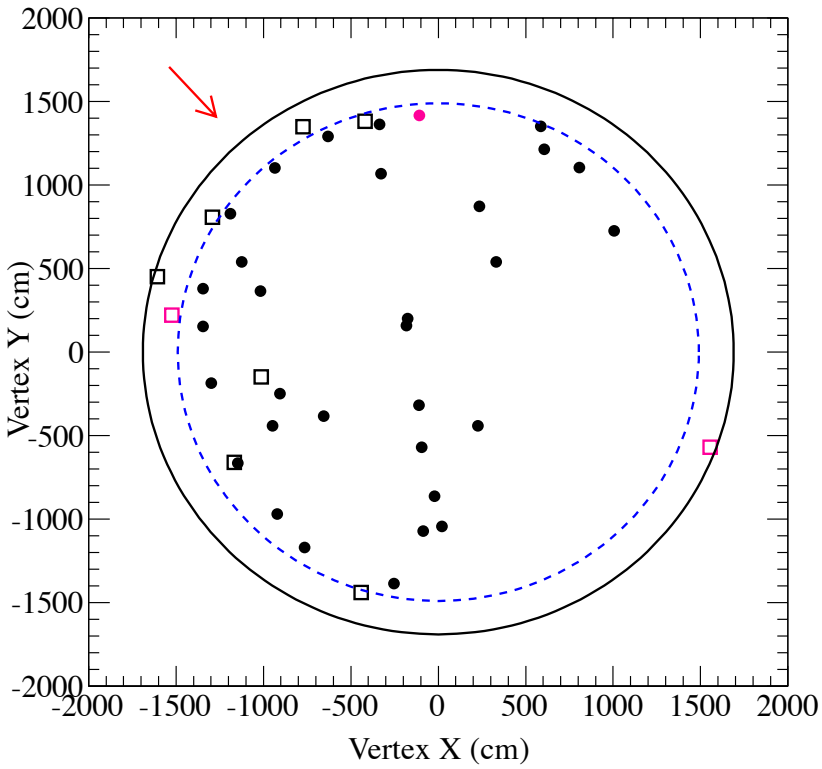
T2K-SK ν_e Selection: ν-mode

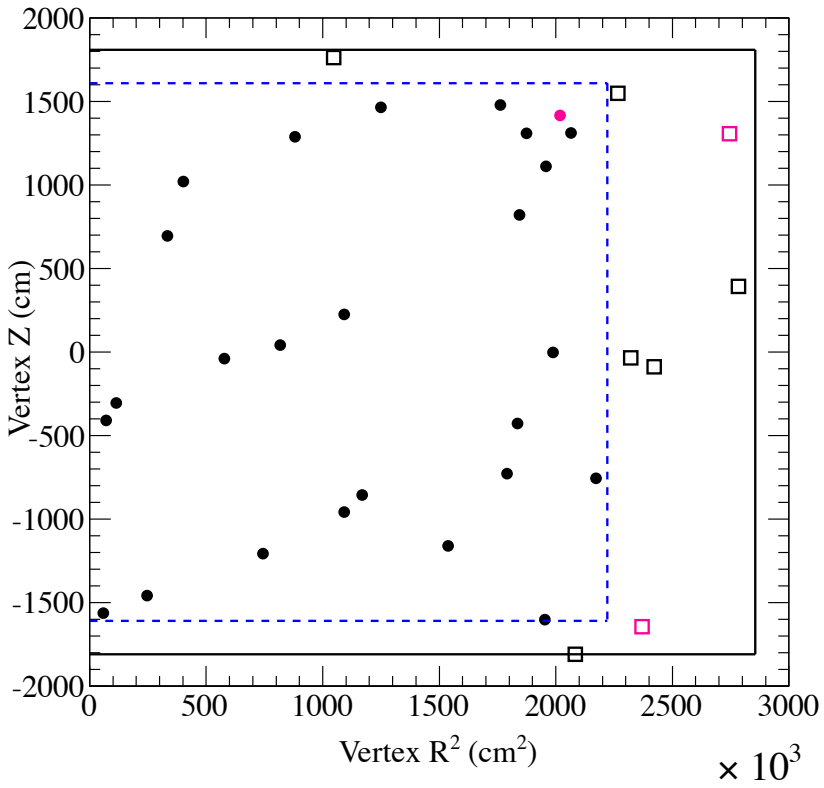






T2K-SK ν_e Selection: ν-mode

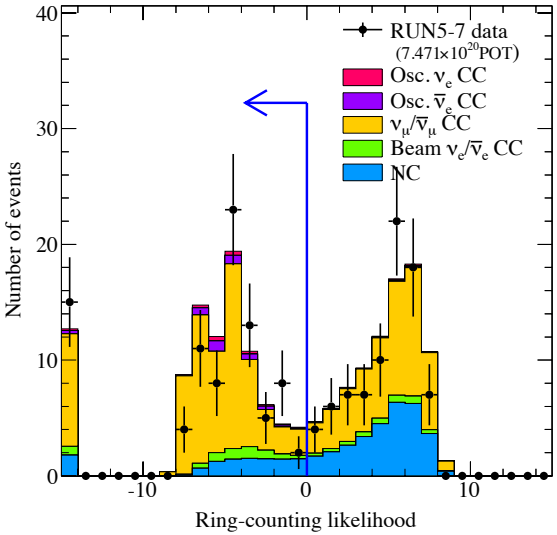


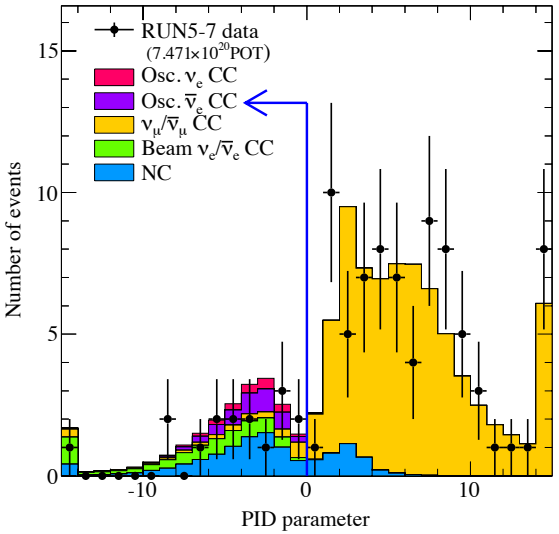


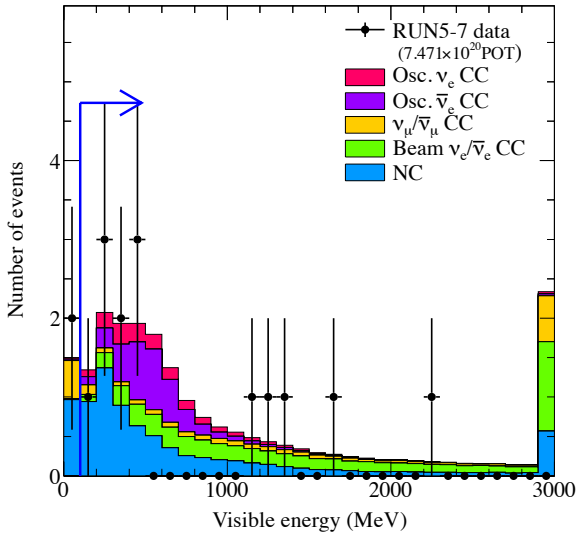
T2K-SK ν_e Selection: $\bar{\nu}$-mode

	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu \rightarrow \nu_e$	Bkg. total	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	DATA
In FV	164.0	9.0	132.8	4.3	308.1	2.3	263
FCFV	123.2	8.8	42.1	4.2	176.3	2.2	170
1R	73.2	5.5	11.9	3.7	92.3	1.7	94
e-like	2.3	5.5	8.4	3.7	17.8	1.7	16
Evis>100	1.8	5.5	7.4	3.7	16.4	1.7	14
0 Decay-e	0.3	4.7	6.2	3.7	12.7	1.5	12
Erec	0.1	1.9	4.8	3.4	8.0	1.2	9
π^0 rej.	0.0	1.6	0.6	3.0	3.2	1.0	4
Eff. (%)	0.0	17.5	0.4	70.8	1.1	45.7	

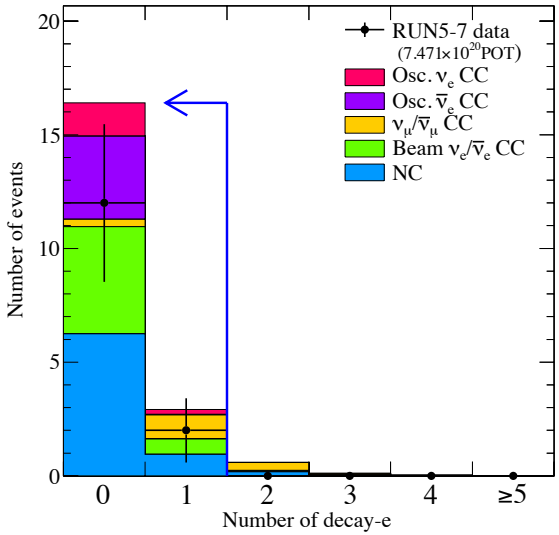
T2K-SK ν_e Selection: $\bar{\nu}$-mode

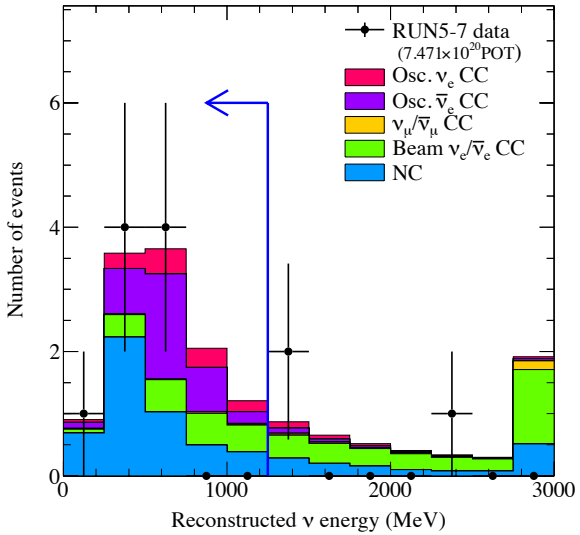


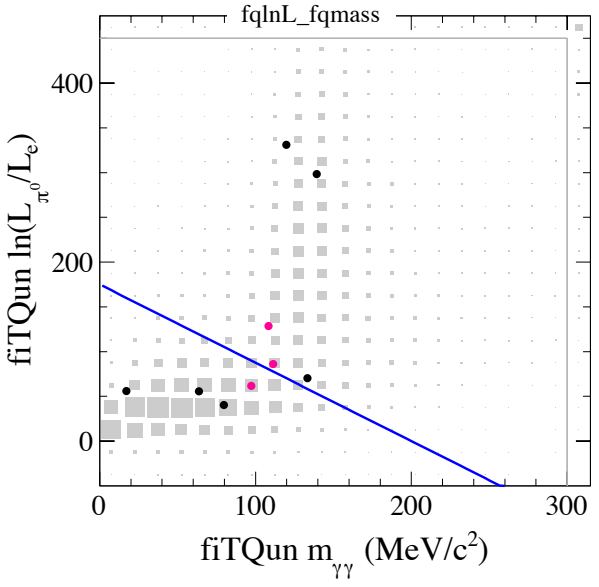




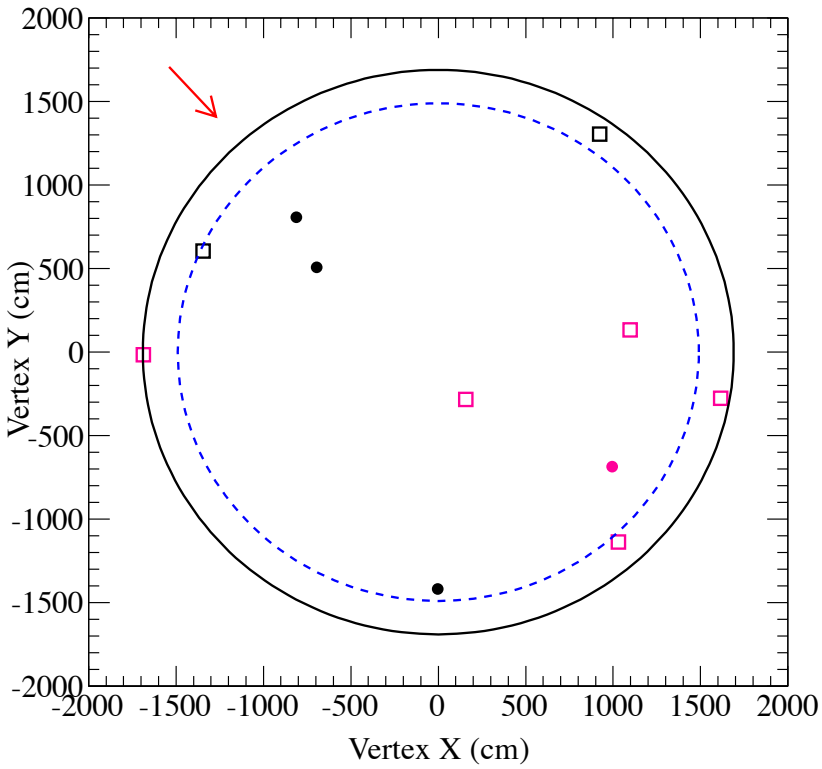
T2K-SK ν_e Selection: $\bar{\nu}$-mode

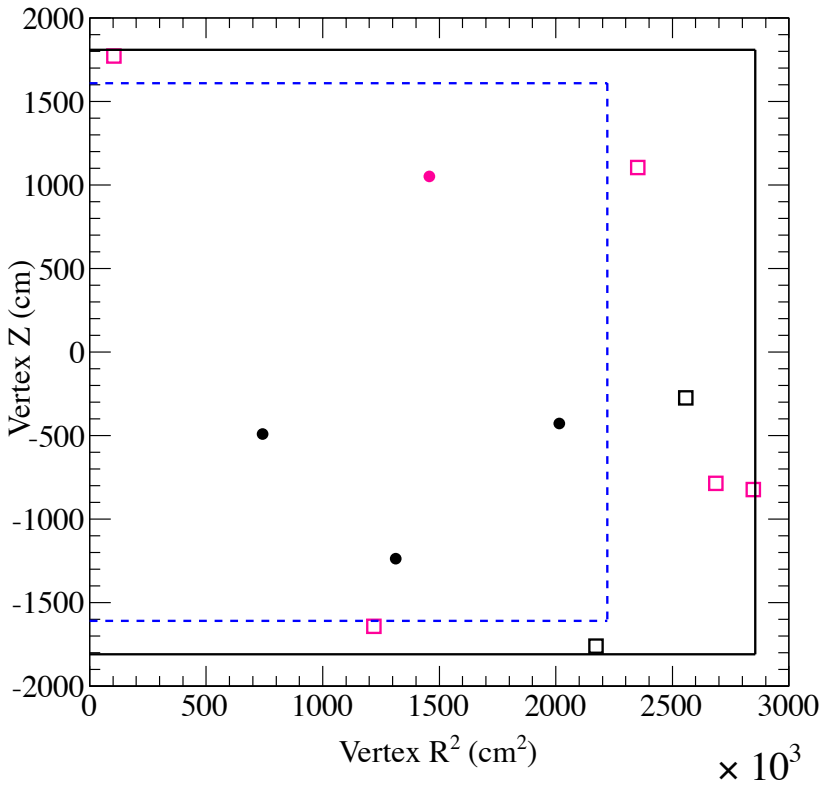






T2K-SK ν_e Selection: $\bar{\nu}$-mode

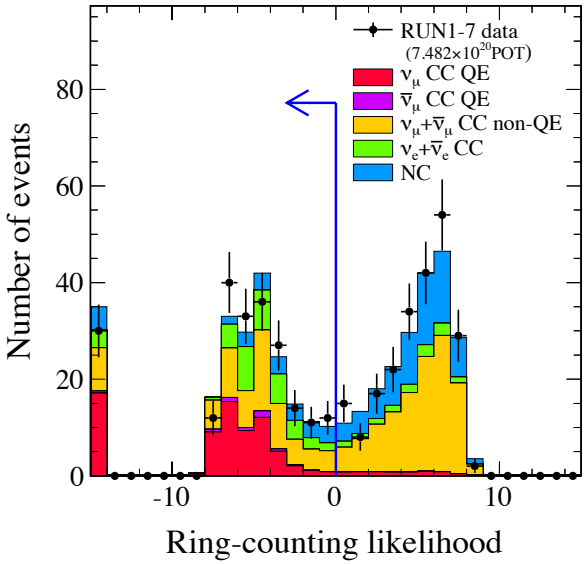


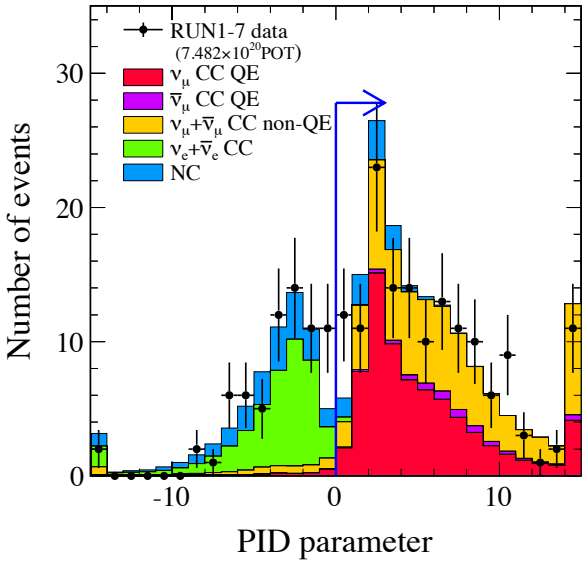


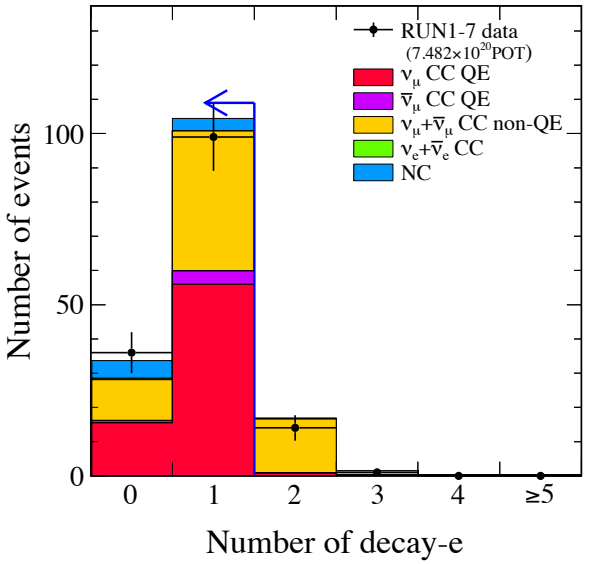
T2K-SK ν_μ Selection: ν-mode

	$\nu_\mu + \bar{\nu}_\mu$ nonCCQE	$\nu_e + \bar{\nu}_e$ CC	NC	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	MC Total	DATA
In FV	258.3	54.5	327.0	100.4	6.5	746.8	654
FCFV	196.7	53.4	99.0	79.0	4.9	432.9	438
1R	75.4	41.5	28.8	73.7	4.7	224.1	220
μ-like	70.2	0.5	9.2	72.4	4.7	157.0	150
p_μ>200	70.2	0.5	9.1	72.2	4.7	156.6	150
0/1 Decay-e	52.7	0.5	8.8	71.5	4.6	138.1	135
Eff. (%)	20.4	0.8	2.7	71.2	71.8	18.5	

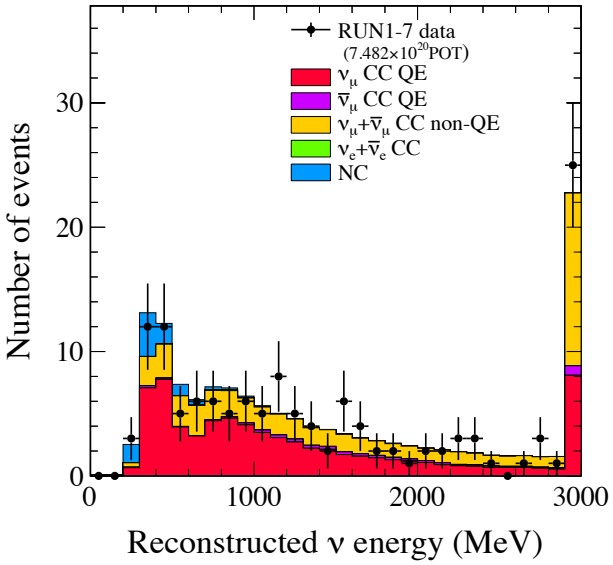
T2K-SK ν_μ Selection: ν-mode

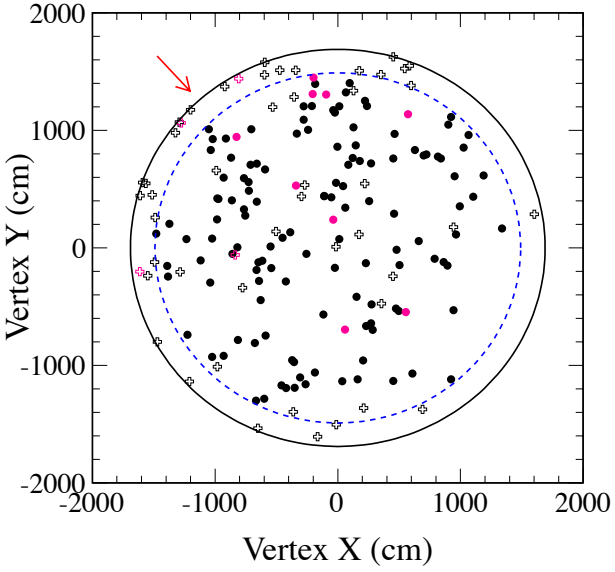


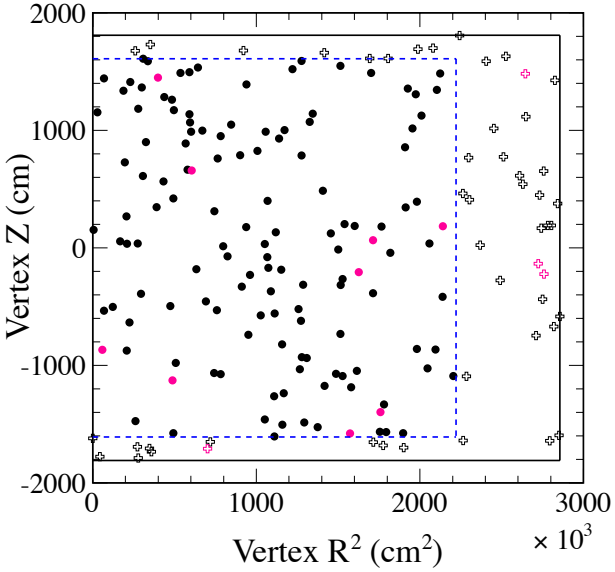




T2K-SK ν_μ Selection: ν-mode



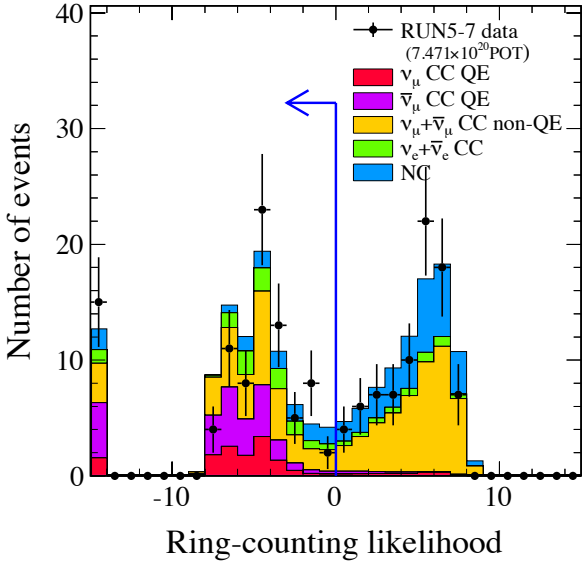


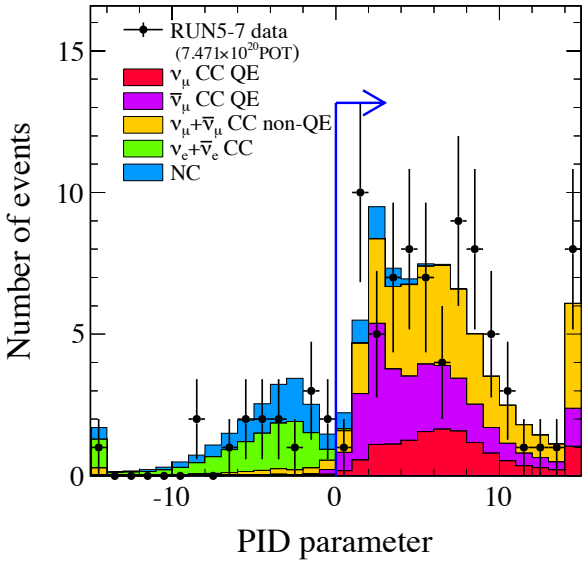


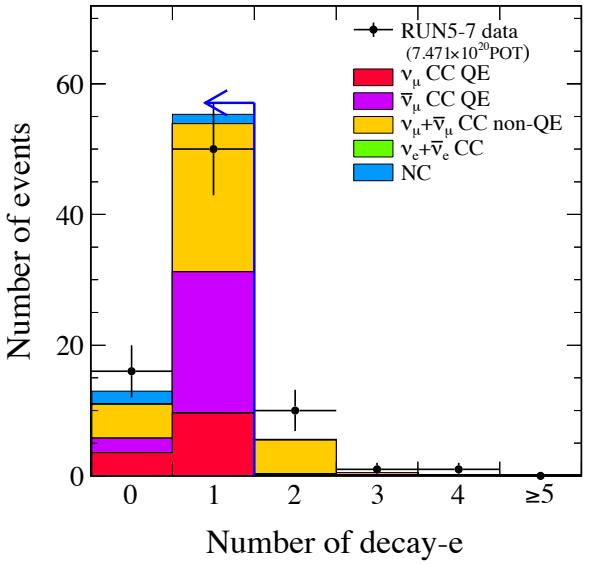
T2K-SK ν_μ Selection: $\bar{\nu}$-mode

	$\nu_\mu + \bar{\nu}_\mu$ nonCCQE	$\nu_e + \bar{\nu}_e$ CC	NC	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	MC Total	DATA
In FV	113.2	15.6	132.8	20.0	30.8	312.4	263
FCFV	83.3	15.2	42.1	15.0	24.9	180.5	170
1R	35.4	11.0	11.9	13.5	24.3	96.1	94
μ-like	33.6	0.1	3.5	13.4	24.0	74.5	78
p_μ>200	33.5	0.1	3.5	13.4	23.9	74.4	78
0/1 Decay-e	27.8	0.1	3.4	13.2	23.8	68.3	66
Eff. (%)	24.5	0.6	2.5	65.8	77.5	21.9	

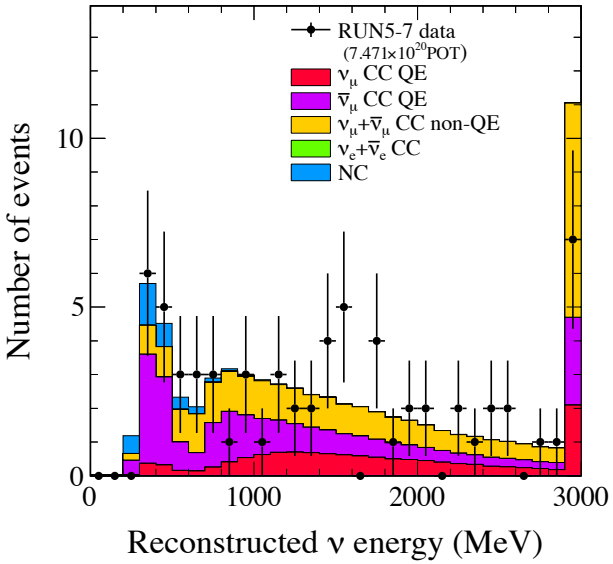
T2K-SK ν_μ Selection: $\bar{\nu}$-mode

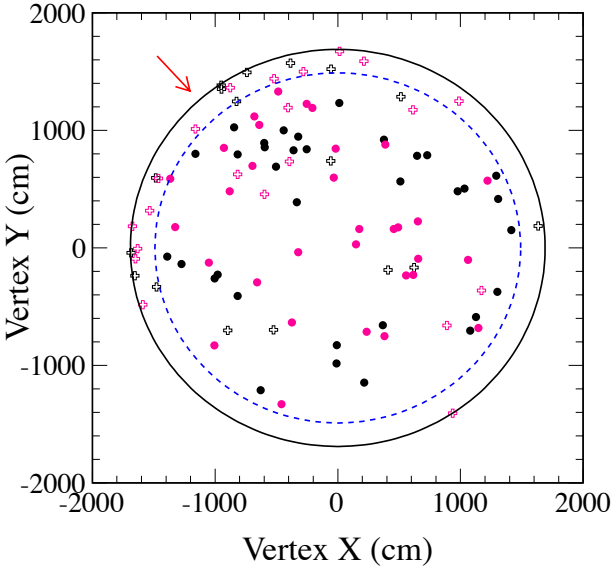


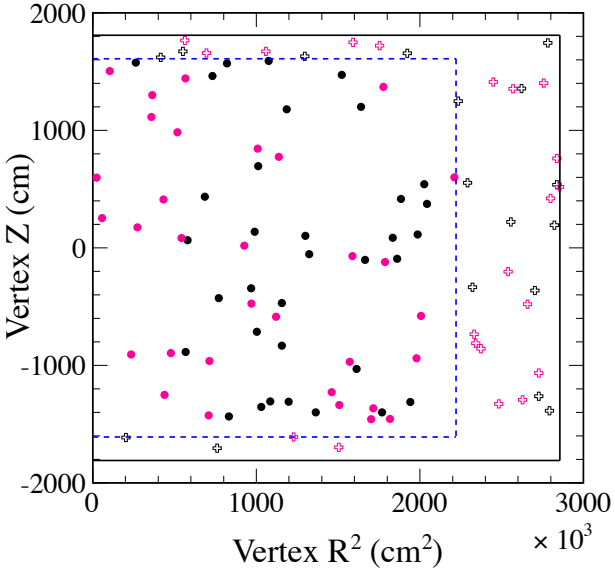




T2K-SK ν_μ Selection: $\bar{\nu}$-mode



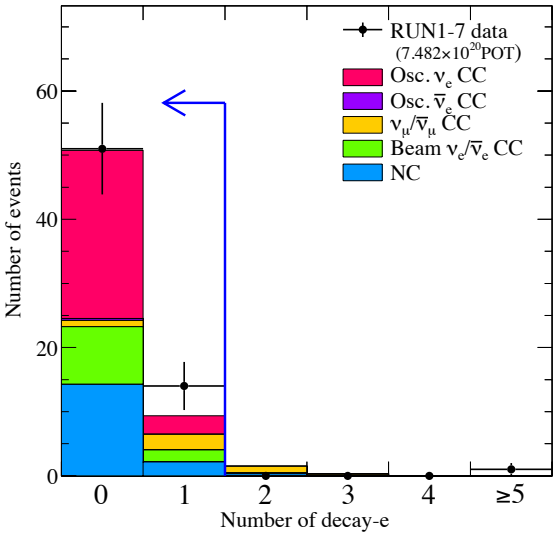


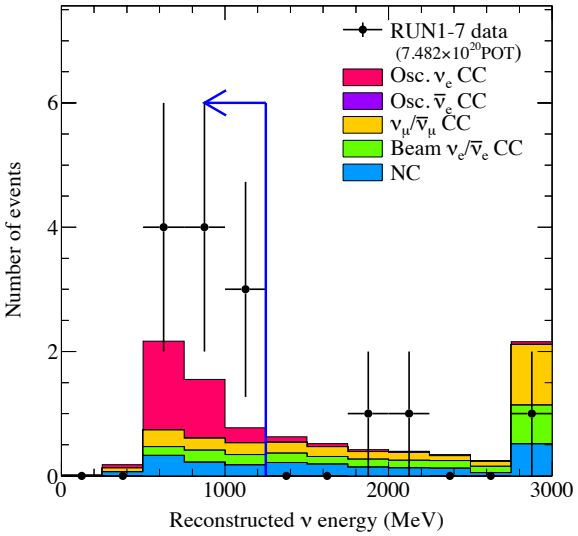


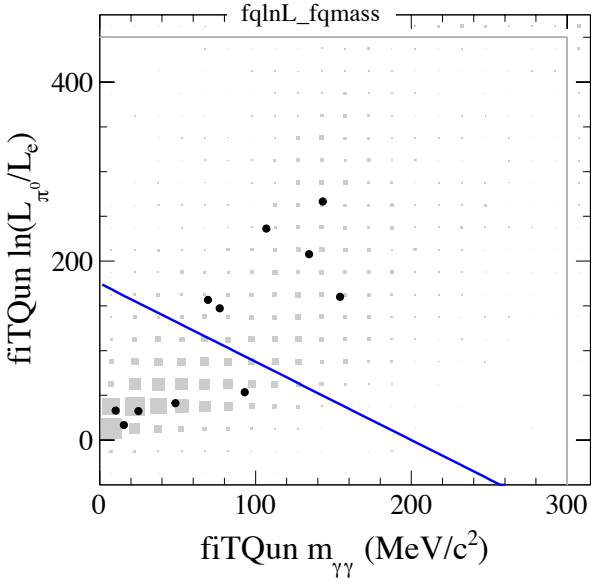
T2K-SK ν_e CC1π^+ Selection: ν-mode

	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Bkg. total	$\nu_\mu \rightarrow \nu_e$	DATA
In FV	365.2	18.6	327.0	0.4	711.2	35.6	654
FCFV	280.6	18.1	99.0	0.4	398.1	34.9	438
1R	153.7	11.2	28.8	0.3	194.0	30.0	220
e-like	6.5	11.1	19.6	0.3	37.5	29.6	70
Evis>100	4.6	11.0	16.9	0.0	32.8	29.2	66
1 Decay-e	2.4	1.9	2.1	0.0	6.5	2.9	14
Erec	0.7	0.5	0.8	0.0	2.0	2.7	11
π^0 rej.	0.3	0.4	0.1	0.0	0.8	2.3	5
Eff. (%)	0.0	2.2	0.0	0.0	0.1	6.5	

T2K-SK ν_e CC1π^+ Selection: ν-mode







ν_e CC1π^+ Data Quality Check