H. A. TANAKA (TORONTO/IPP/TRIUMF)

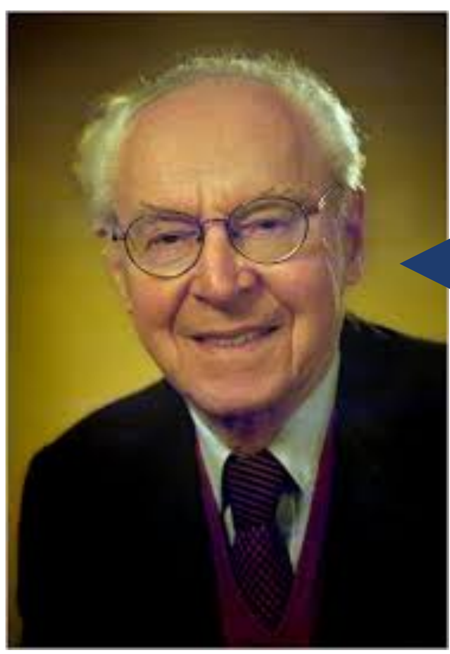
T2K: TOKAI-TO-KAMIOKA AND BEYOND

Gerry Garvey Symposium

10 December 2016, Seattle Washington

HOW I GOT STARTED:

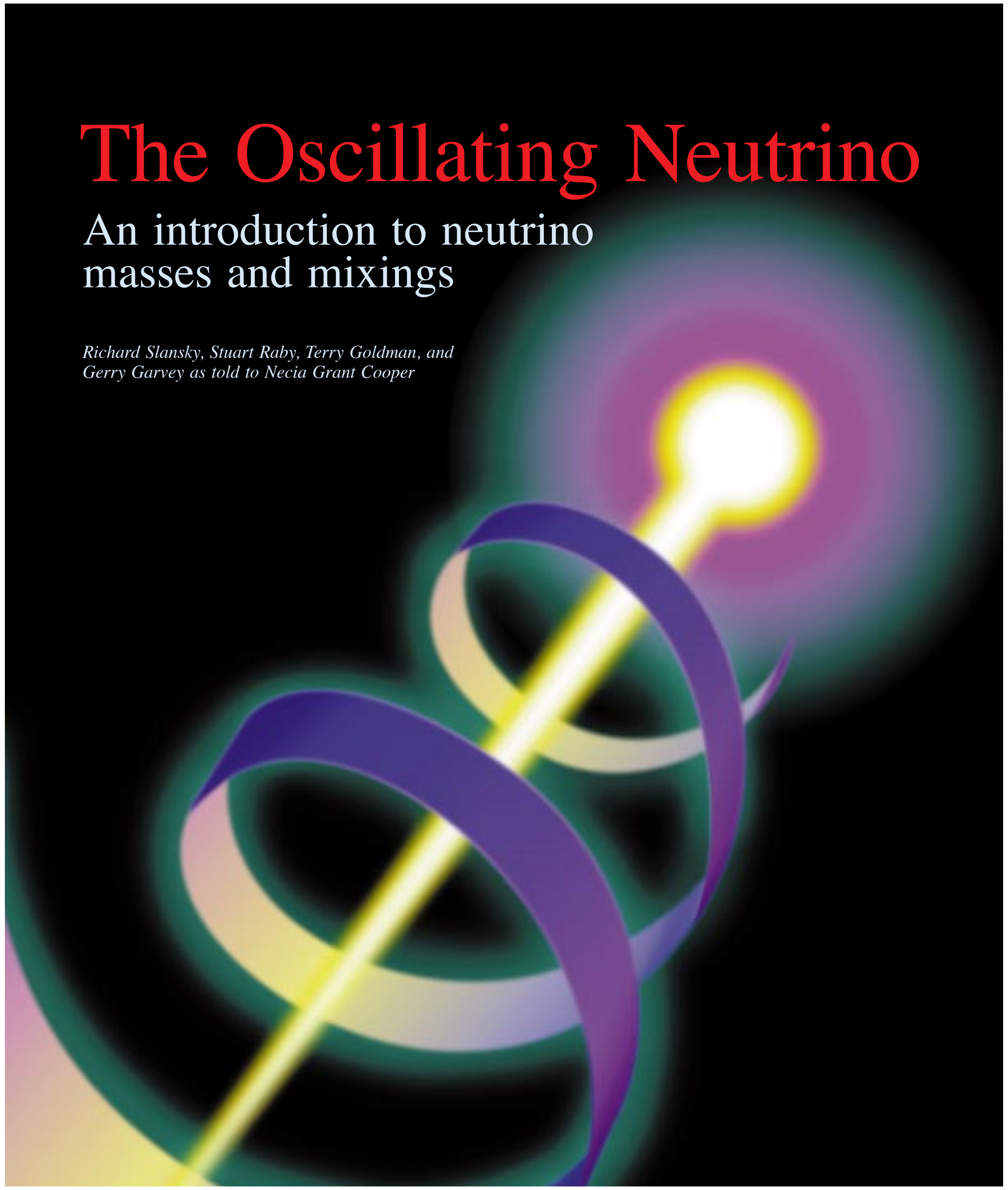
- As an undergraduate, the field of neutrino oscillations was in a rather uncertain state.
- Sounds interesting . . .



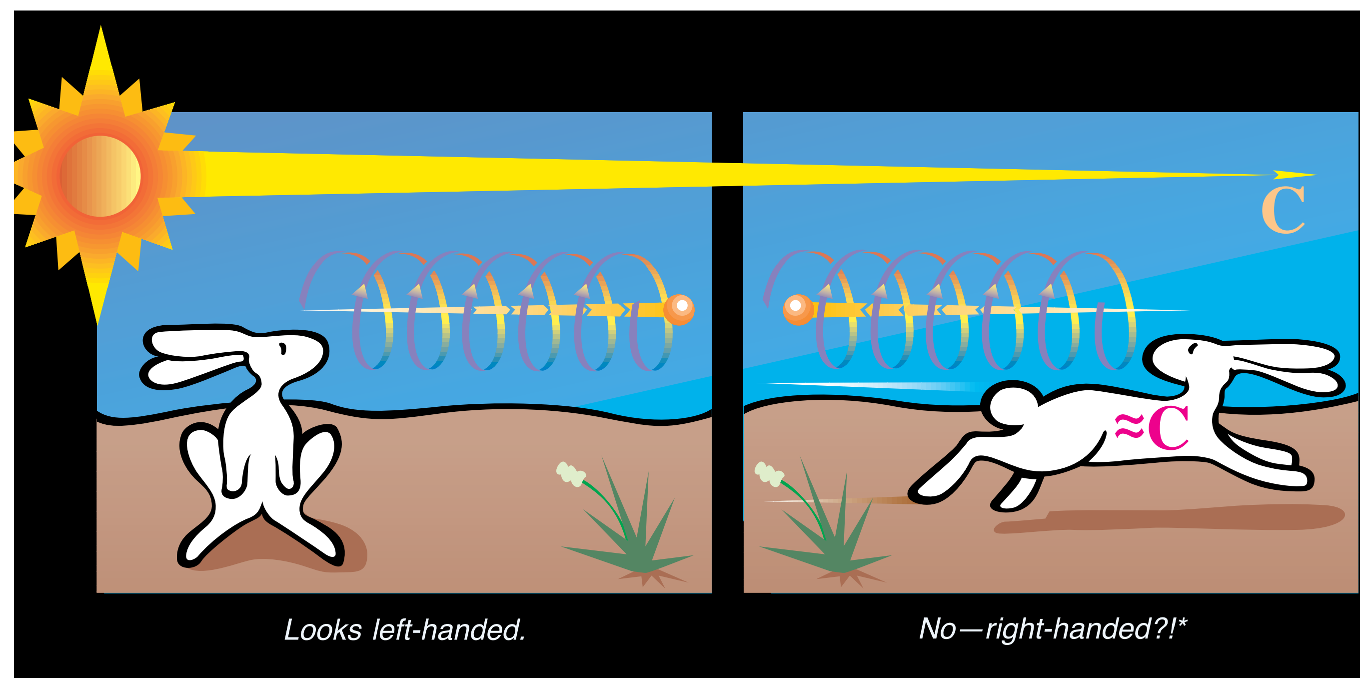
"Young man, listen carefully: neutrino oscillations are a communist plot."

- Didn't know what to make of that at the time . . ..
- As I was finishing my studies, this book appeared in the laboratory

CELEBRATING THE NEUTRINO



Gerry Garvey was born in New York City. He earned a B.S. in physics from Fairfield University and, in 1962, a Ph.D. in physics from Yale University. He then served as a faculty member at Yale and Princeton Universities, becoming a full professor in 1969. After being an Alfred Sloan Foundation Fellow from 1967 to 1969, he spent a year at the Clarendon Laboratory in Great Britain. In 1976, he became Director of the Physics Division at Argonne National Laboratory and in 1979 was named Associate Laboratory Director for Physical Science. From 1979 through 1984, Garvey was a professor at the University of Chicago, returning in 1980 to full-time research as a senior scientist at Argonne. In 1984, he joined Los Alamos as director of LAMPF. In 1990, Garvey stepped down from that position to become a Laboratory Senior Fellow, a position he currently holds. From 1994 through 1996, he served as the Assistant Director for Physical Science and Engineering in the White House Office of Science and Technology. Garvey is an active member of the American Physical Society, having been chairman and councilor for the Division of Nuclear Physics.



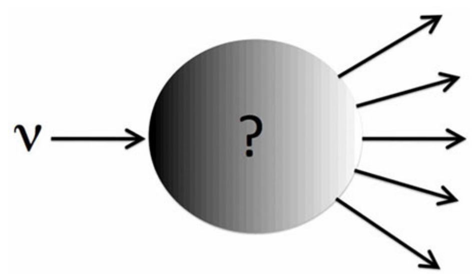
- Still one of the most beautiful books on neutrinos around
- A lot has happened since . . . a second edition would be welcome!

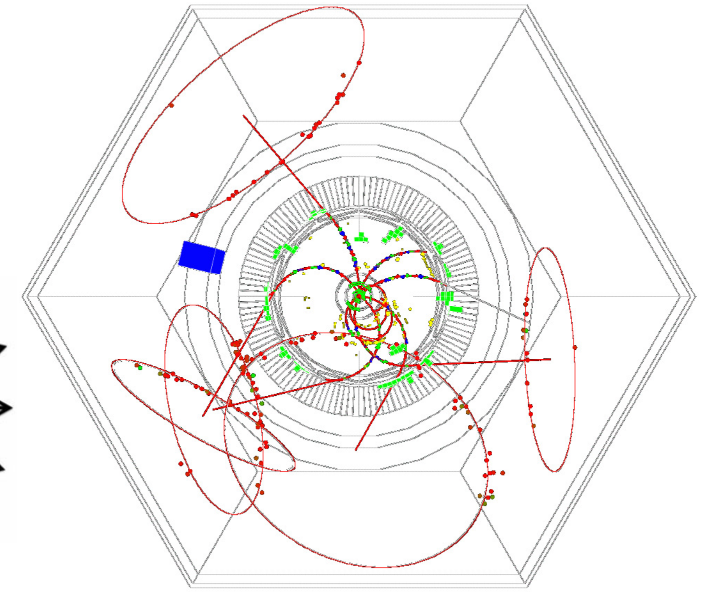
MINIBOONE

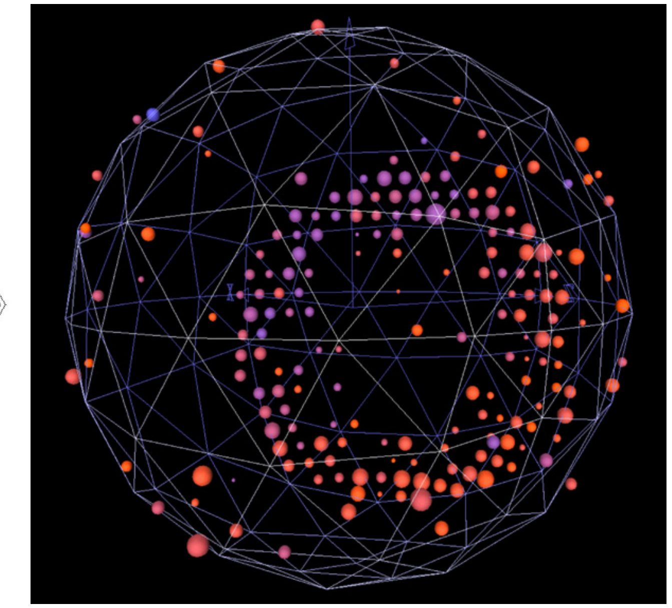
- I also became fascinated with CP violation so I went to work on BaBar for my PhD
- During this time, many exciting things happened in neutrinos
  - As I finished up my PhD, I recalled the LSND results . . . .

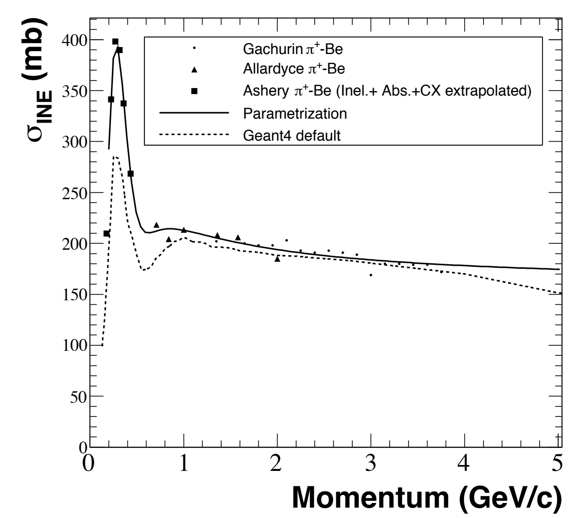
MINIBOONE

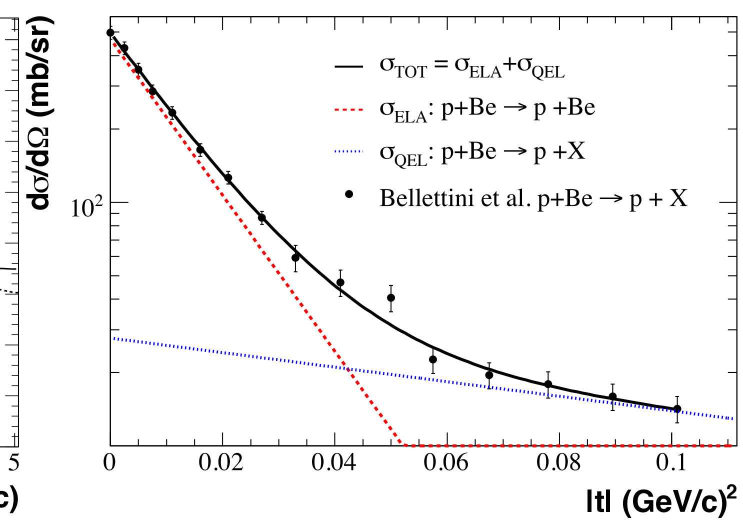
- Radiative Δ decays
- Coherent scattering
- Neutrino flux
  - secondary interactions for neutrino flux prediction
- Optical model for Marcol7
- Reconstruction algorithm
- Photonuclear effect

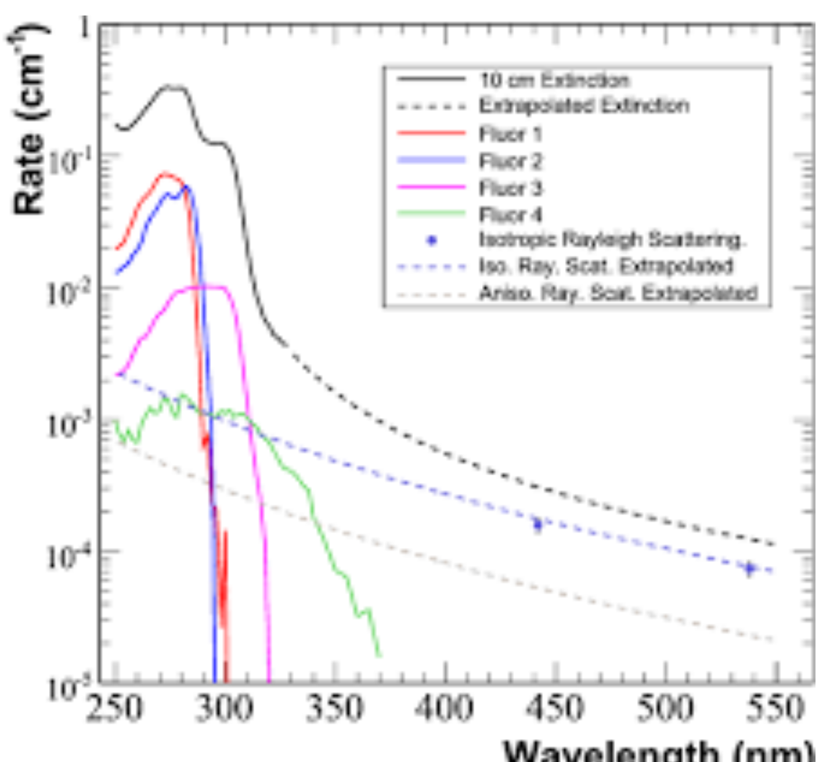










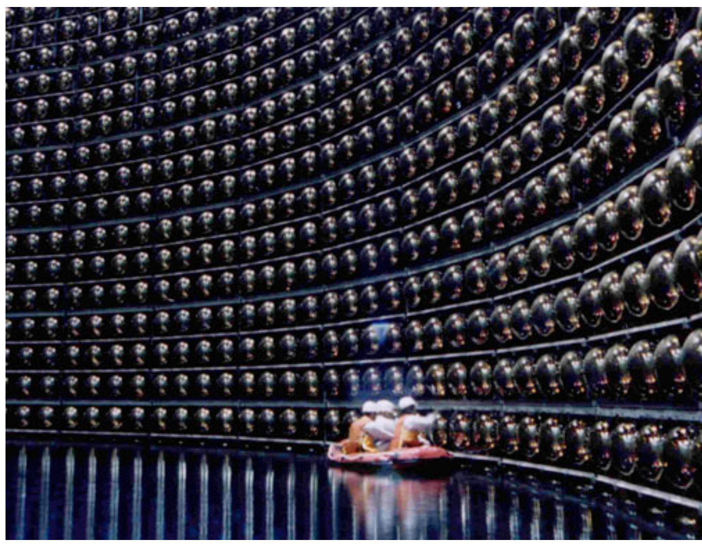


"Young man, keep your wits about you in this business. Many an unscrupulous rogue will gleefully sell you their snake oil."

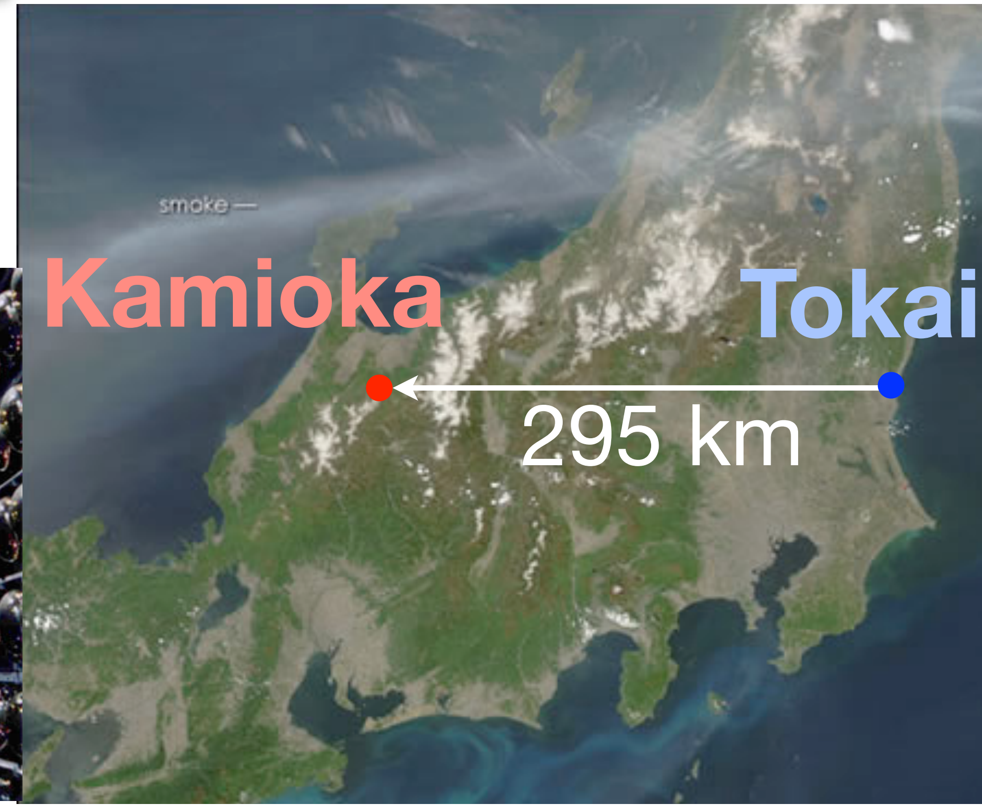
- "the Chinese have forgotten more than the rest of civilization ever knew"

T2K

Super Kamiokande



ND280
"near" detector



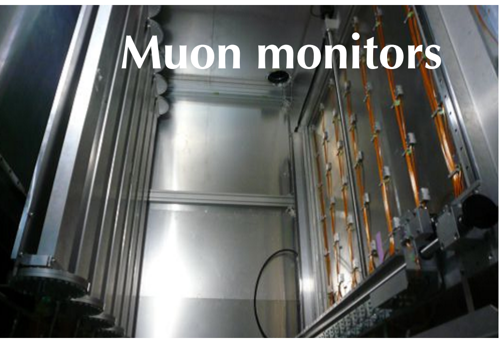
J-PARC

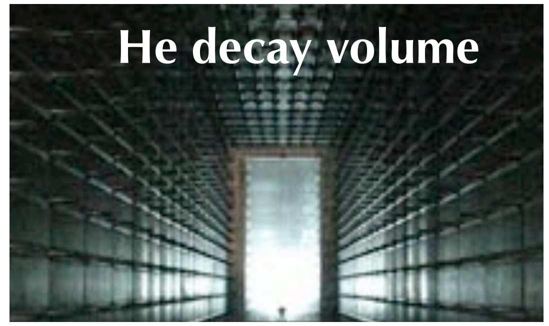
~500 collaborators from
58 institutions, 12 nations

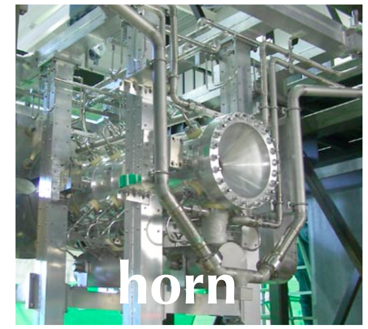
Intense $\nu_\mu / \bar{\nu}_\mu$ beam sent 295 km across Japan and detected with the Super-Kamiokande detector to study neutrino oscillations

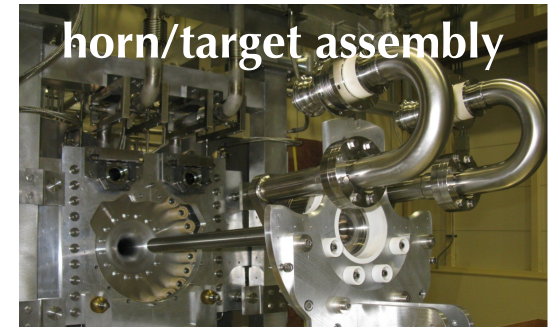
I can work on neutrino oscillations and CP violation!

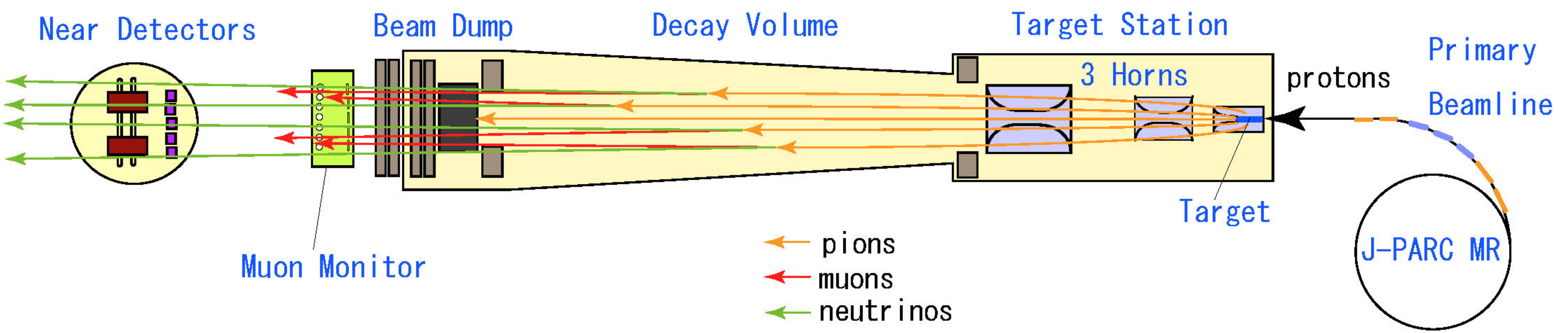
PRODUCING THE BEAM



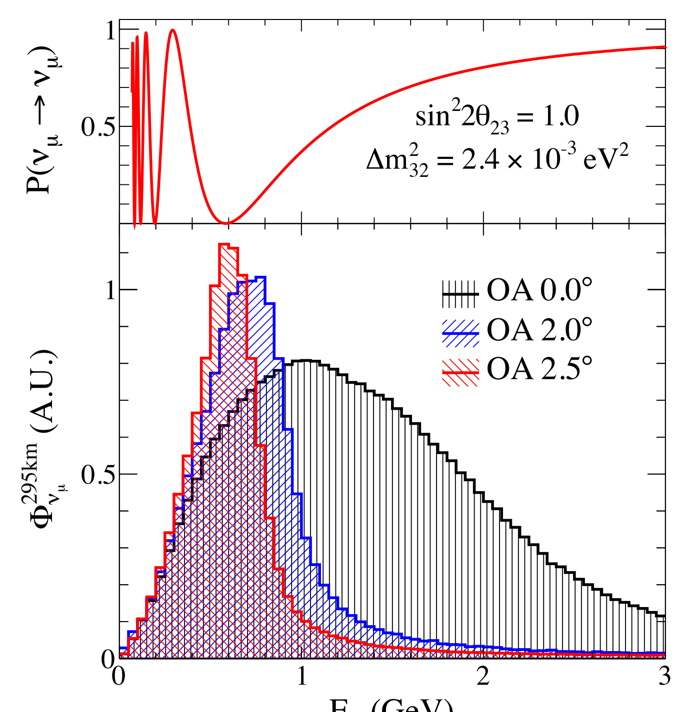








- 30 GeV protons extracted from J-PARC MR a target
  - secondary π^+ focussed by three EM "horns"
  - primarily ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - reverse polarity for antineutrino beam: $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$
  - spectrum peaked at 600 MeV "off axis"
   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



ν OSCILLATIONS IN LBL EXPERIMENTS

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

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

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

~30% max. effect

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

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

$$+\mathcal{O}(\alpha^2)$$

~±10%

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

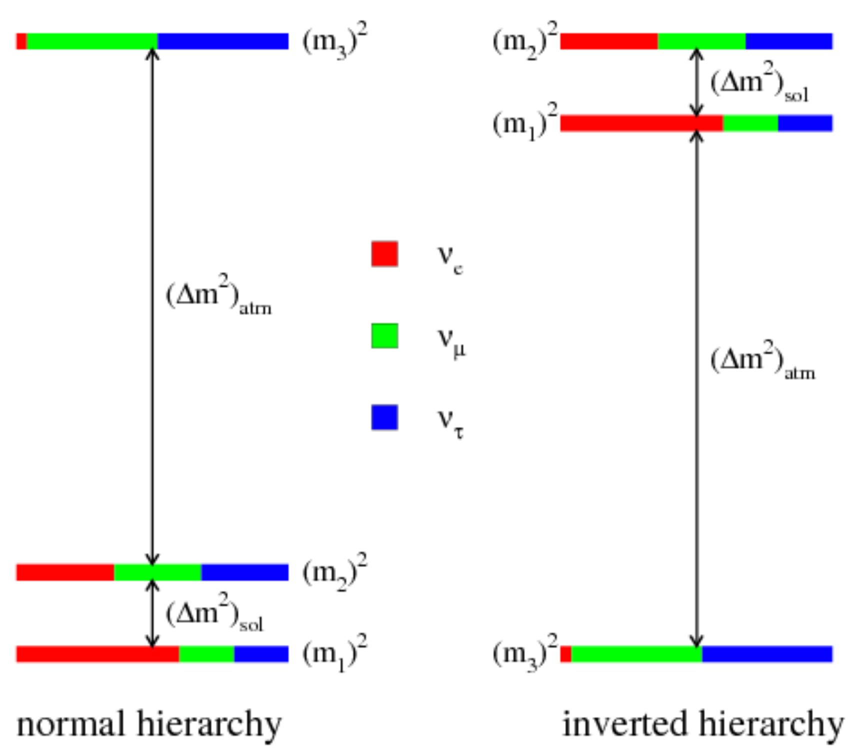
M. Freund, Phys.Rev. D64 (2001) 053003

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

QUICK SUMMARY

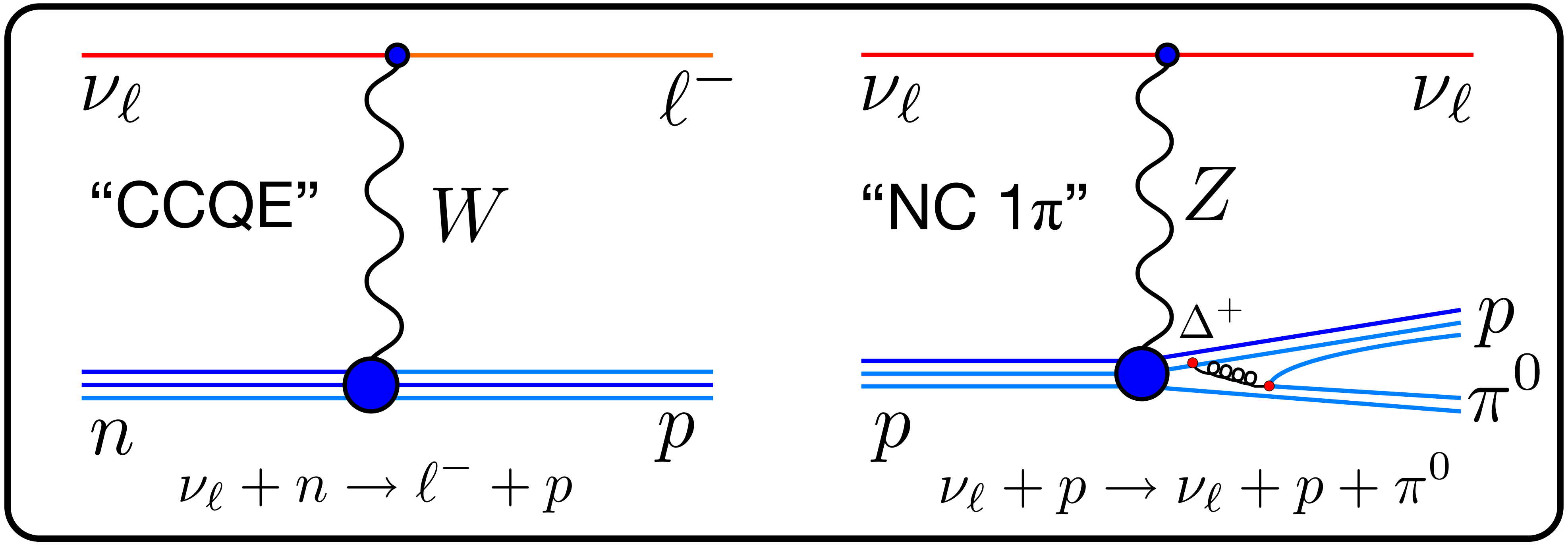
- CP violating parameter δ_{CP}
  - δ_{CP} =0,π: no CP violation: vacuum oscillation probabilities equal
  - δ_{CP} ~-π/2: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
  - δ_{CP} ~+π/2: suppress $\nu_\mu \rightarrow \nu_e$, enhance $\overline{\nu}_\mu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

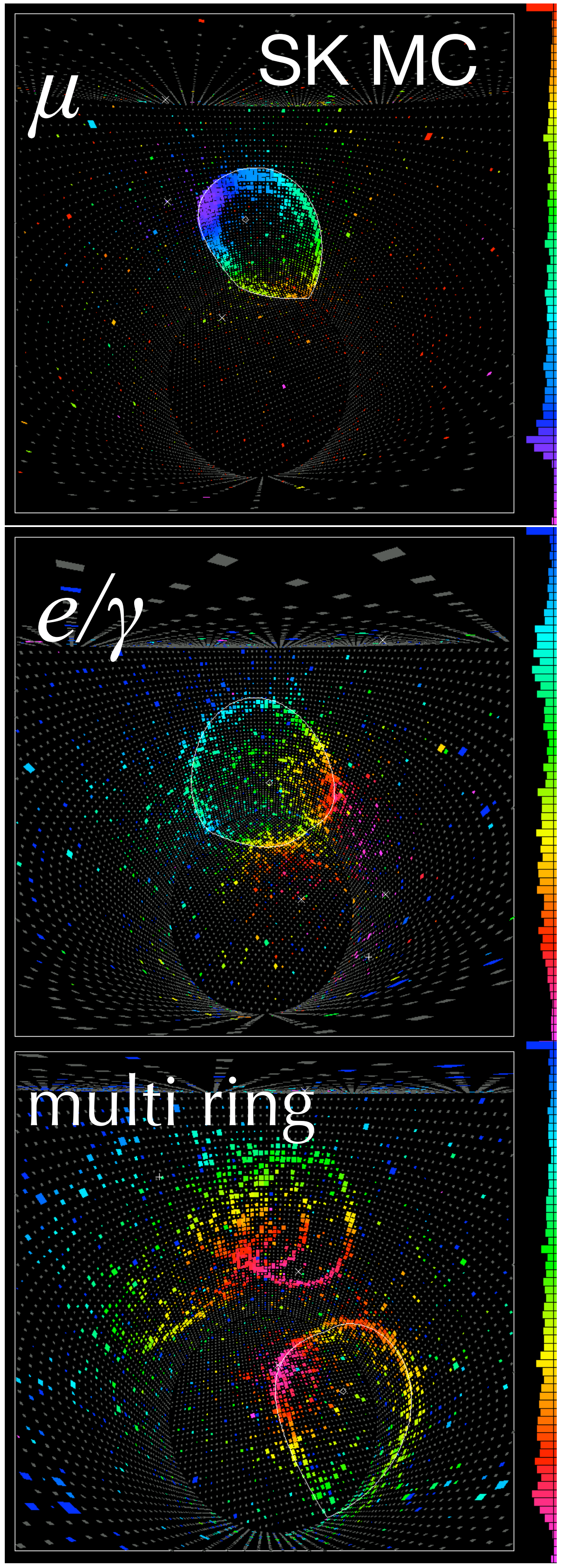
- “normal” hierarchy:
  - enhance $\nu_\mu \rightarrow \nu_e$
  - suppresses $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



- “inverted” hierarchy:
  - suppress $\nu_\mu \rightarrow \nu_e$
  - enhance $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

NEUTRINO INTERACTIONS





$\nu_\ell + n \to \ell^- + p$

Signal

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

$\nu_\ell + (n/p) \to \nu_\ell + (n/p) + \pi^0$

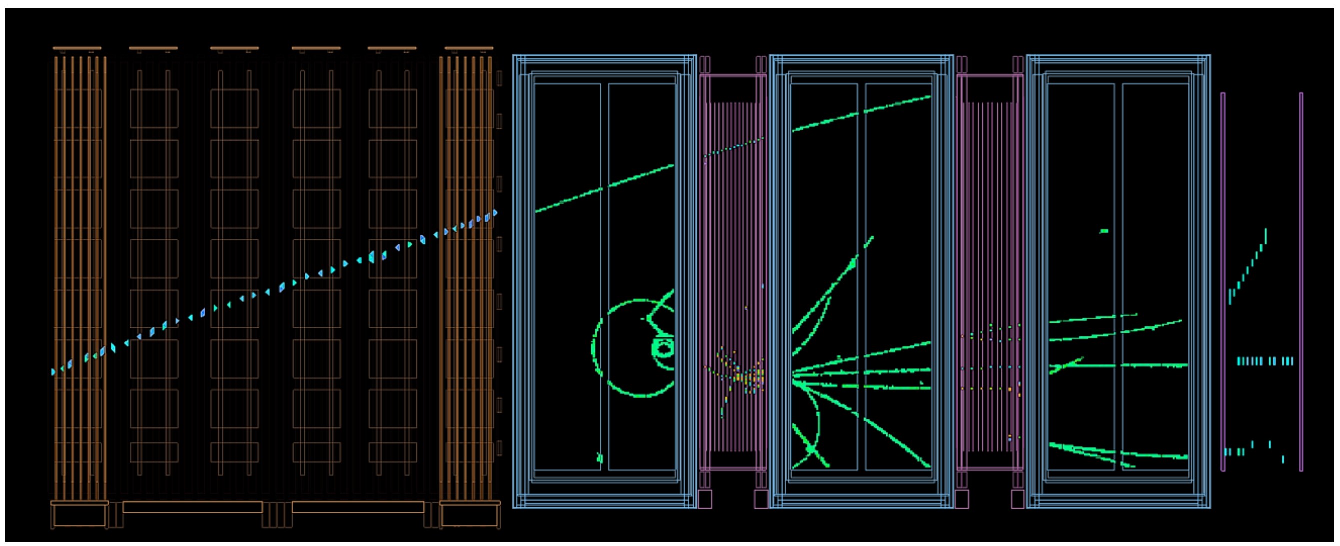
$\nu_\ell + (n/p) \to \ell^- + (n/p) + \pi$

Backgrounds

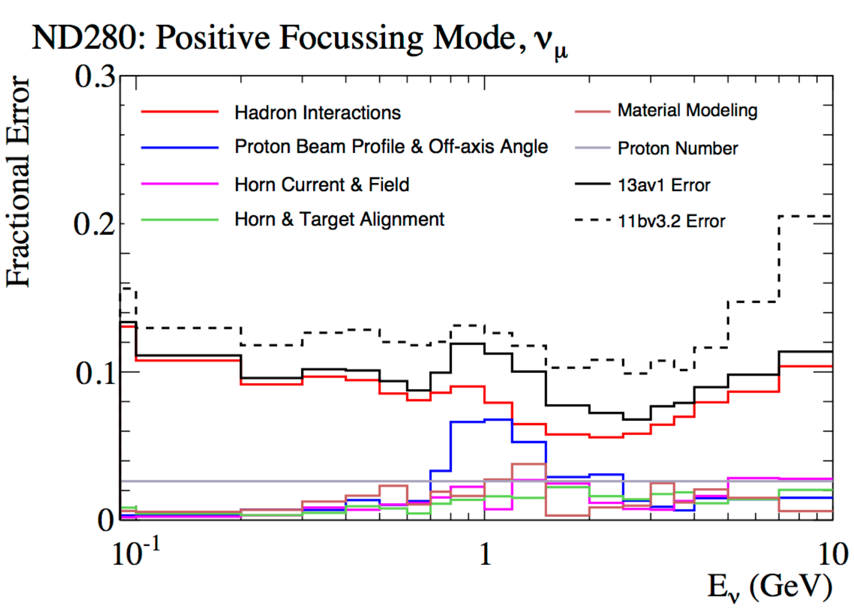
- $\pi^0 \to \gamma + \gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
- μ/π^+: ring counting, decay electron cut

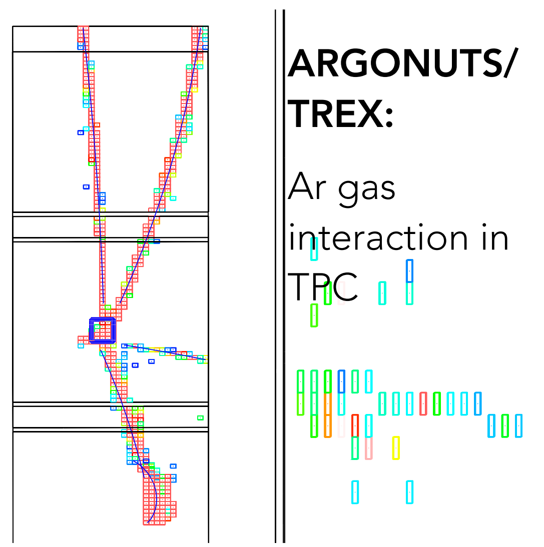
NEAR DETECTOR

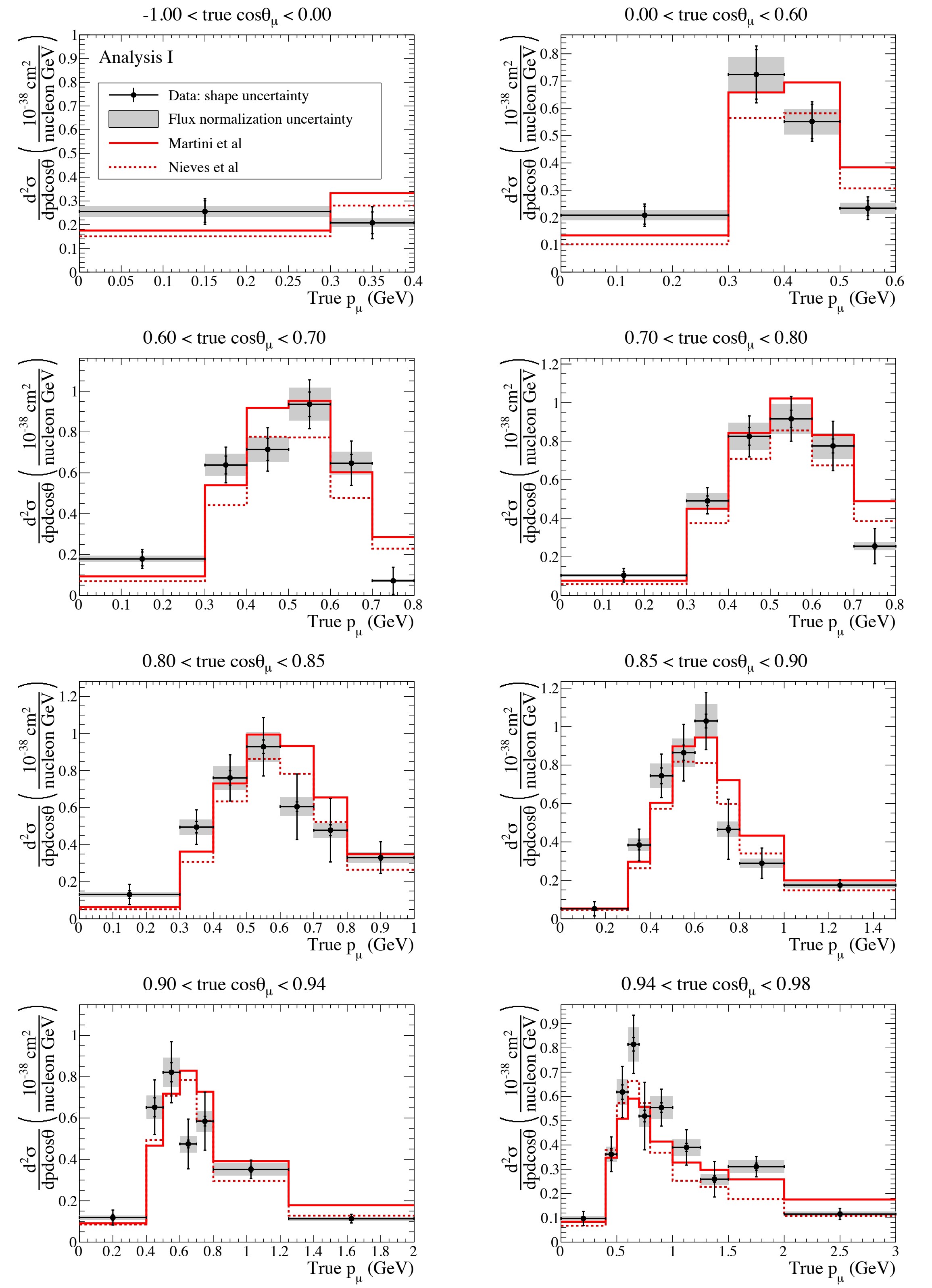
- Very active program of neutrino interaction measurements at T2K with near detector
- New generation of leaders emerging to confront persistent challenges and new opportunities
  - Direct legacy of MiniBooNE program



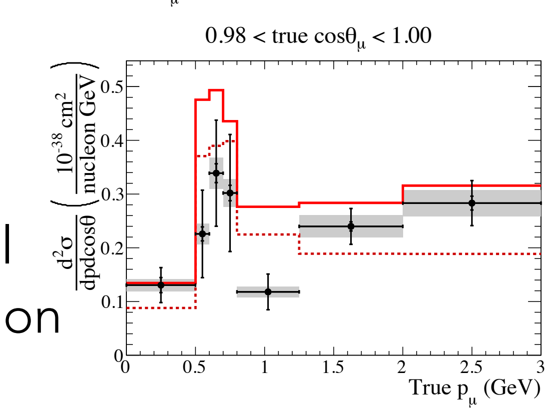
- Very strong effort on neutrino flux (NA61, etc.)



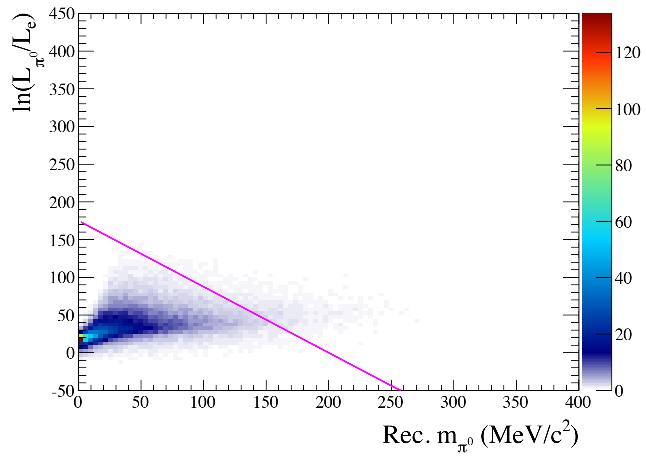


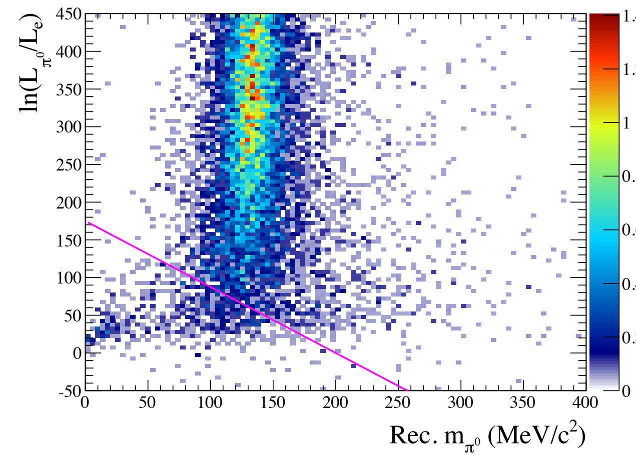


"CC0π" double differential cross section

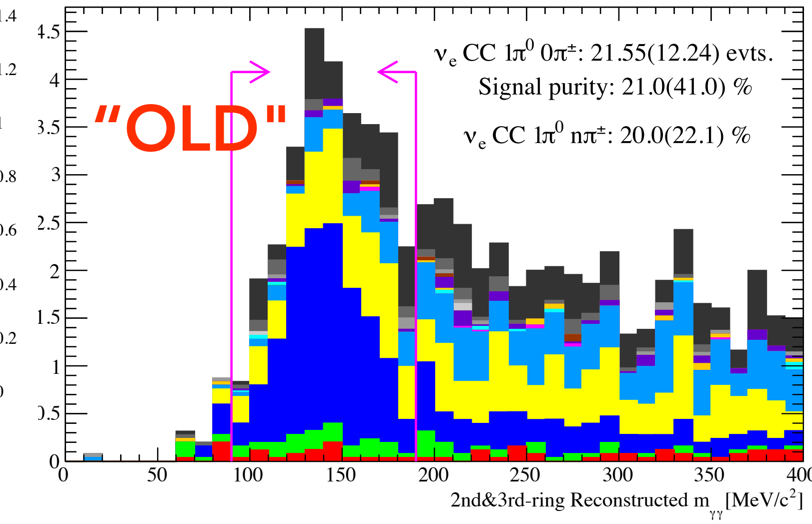


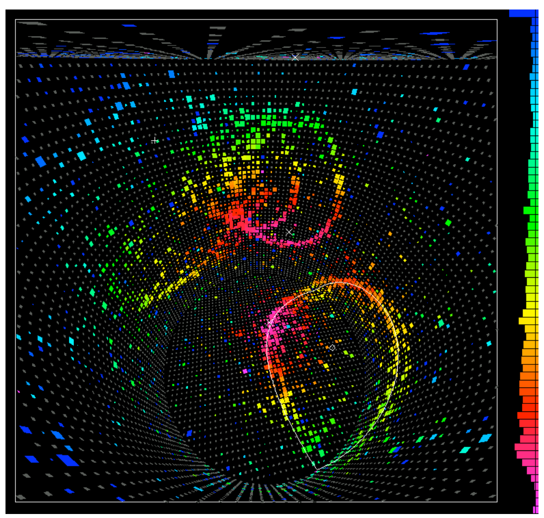
RECONSTRUCTION





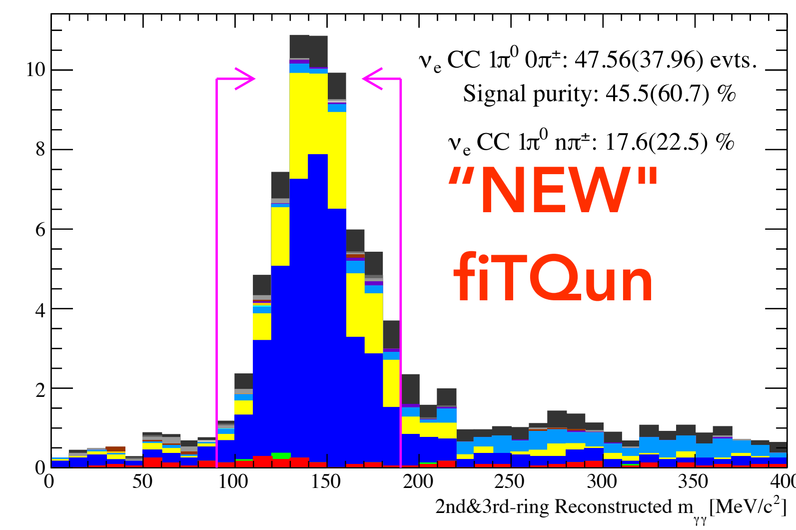
1GeV<E_{vis}<3.16GeV



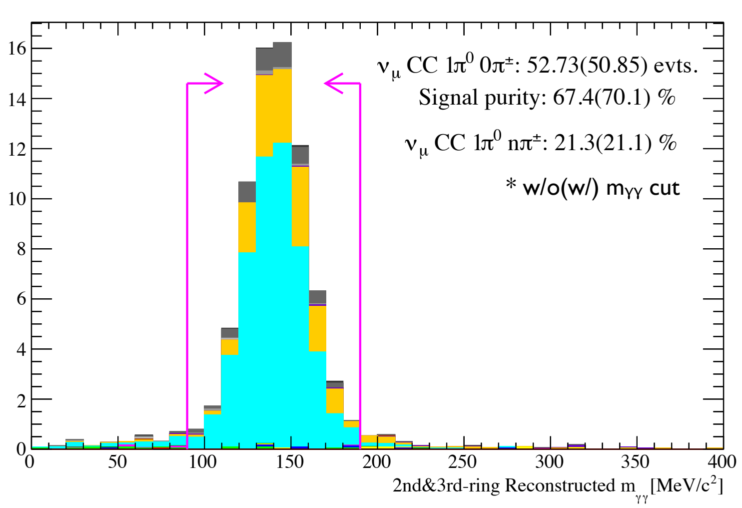


- Incredible reconstruction framework from MiniBooNE (R. B. Patterson et al.)
  - ~percent level π^0 contamination, ~90% efficiency
    - improvement of x3 over existing SK algorithm
  - ν_μ CC1π^+ (M. Wilking), ν_μ CC1π^0 (R. Nelson)
    - ⇒ multi-ring reconstruction
- Impact of MiniBooNE is everywhere in T2K

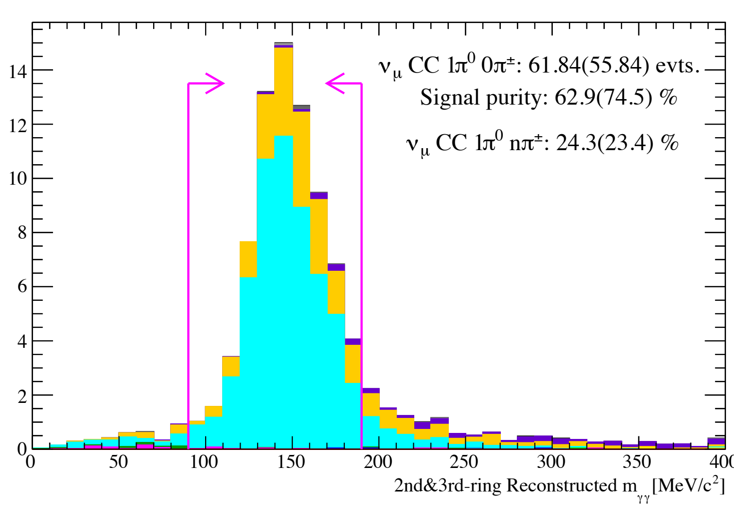
1GeV<E_{vis}<3.16GeV



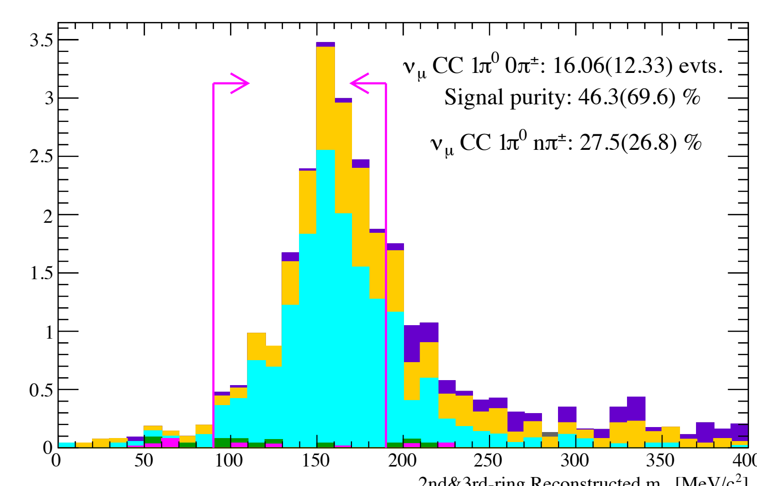
0.316GeV<E_{vis}<1GeV

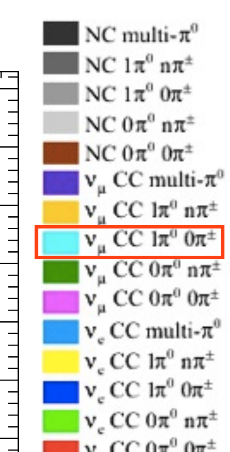


1GeV<E_{vis}<3.16GeV

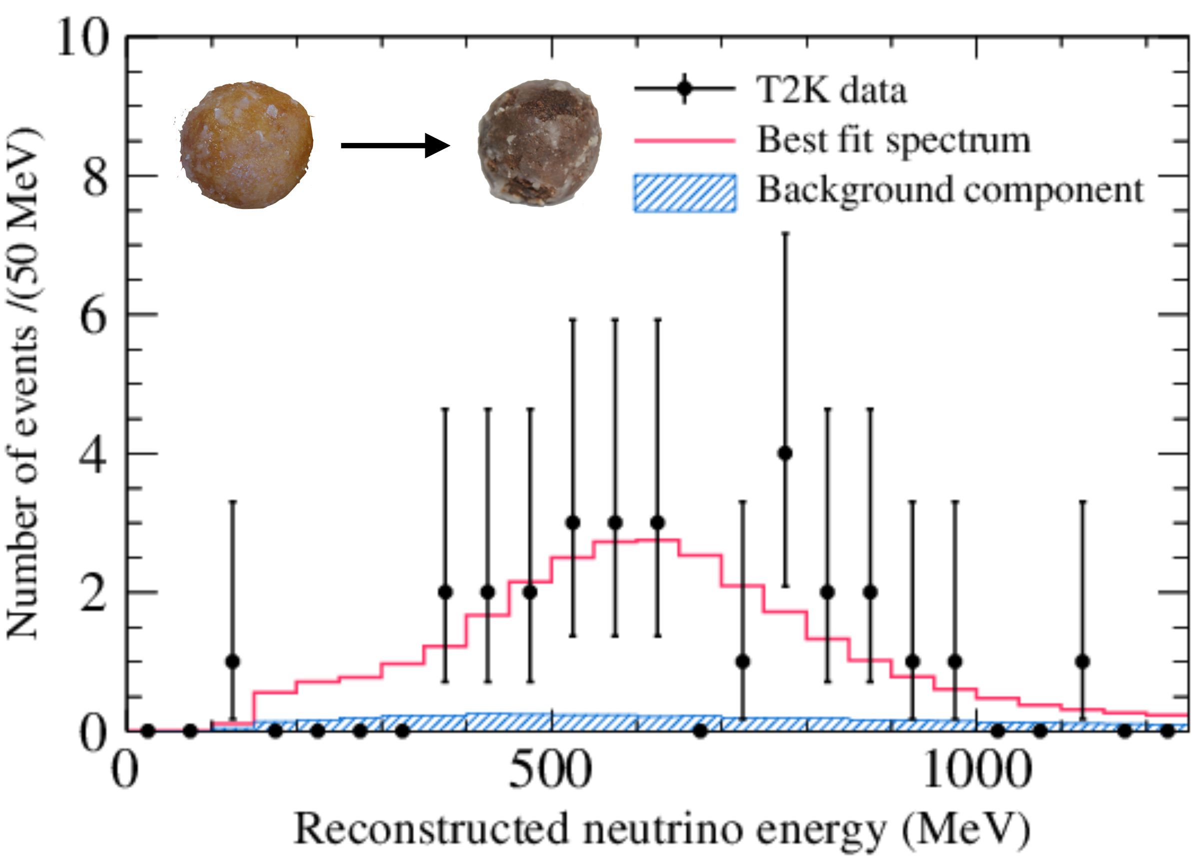


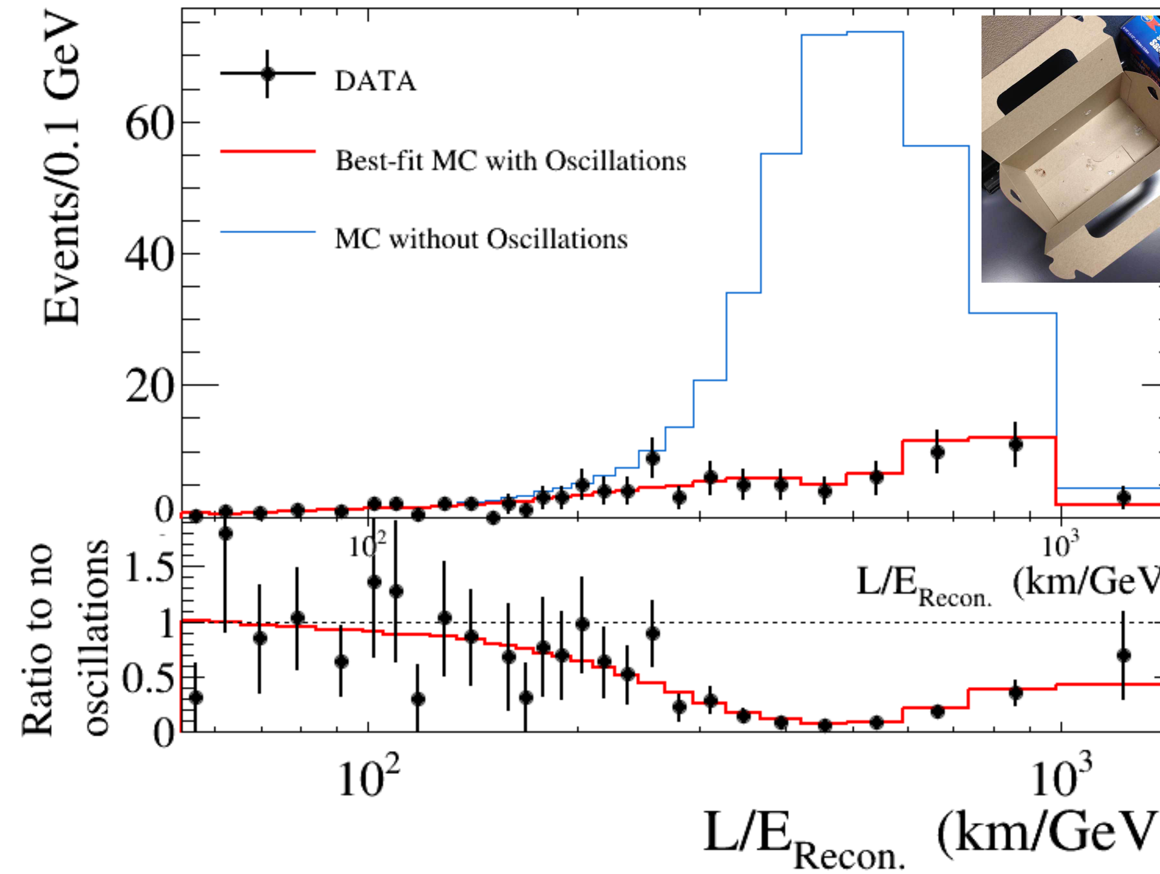
3.16GeV<E_{vis}<10GeV





2013: NEUTRINO MODE DATA





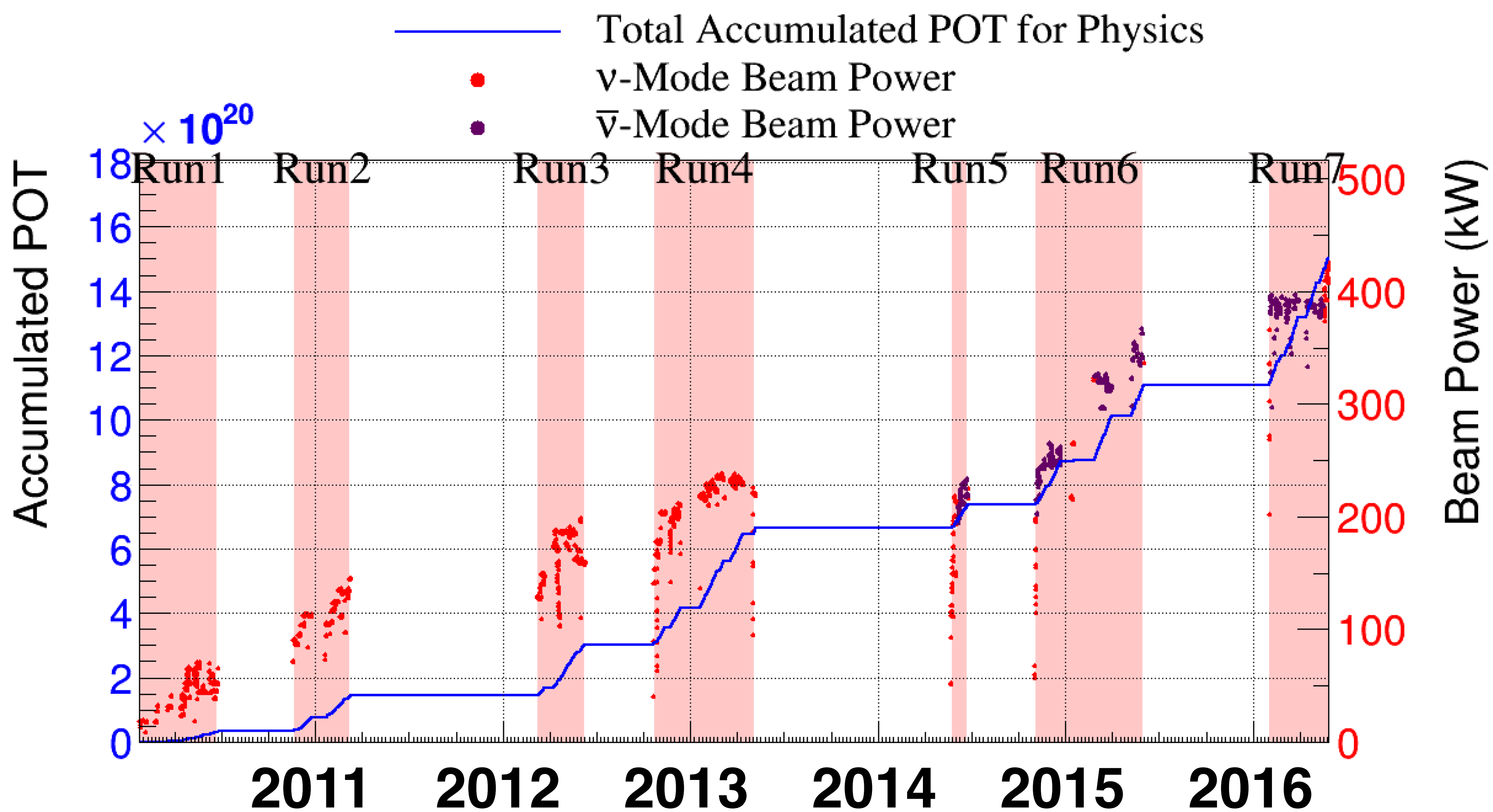
- 28 ν_e candidates observed
  - 5.0 expected in absence of osc. effects
  - definitive observation of $\nu_\mu \rightarrow \nu_e$ oscillations
- 120 ν_μ candidates observed
  - 446 expected in absence of osc. effects
  - Most precise determination of ν_μ disappearance

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

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

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

SINCE THEN . . . .

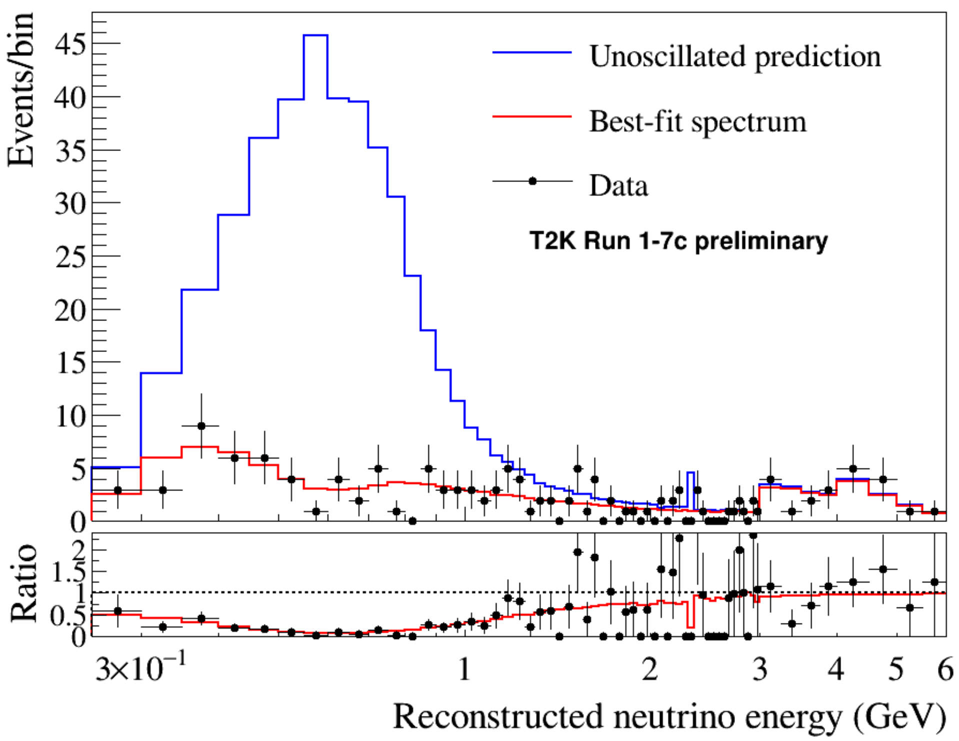


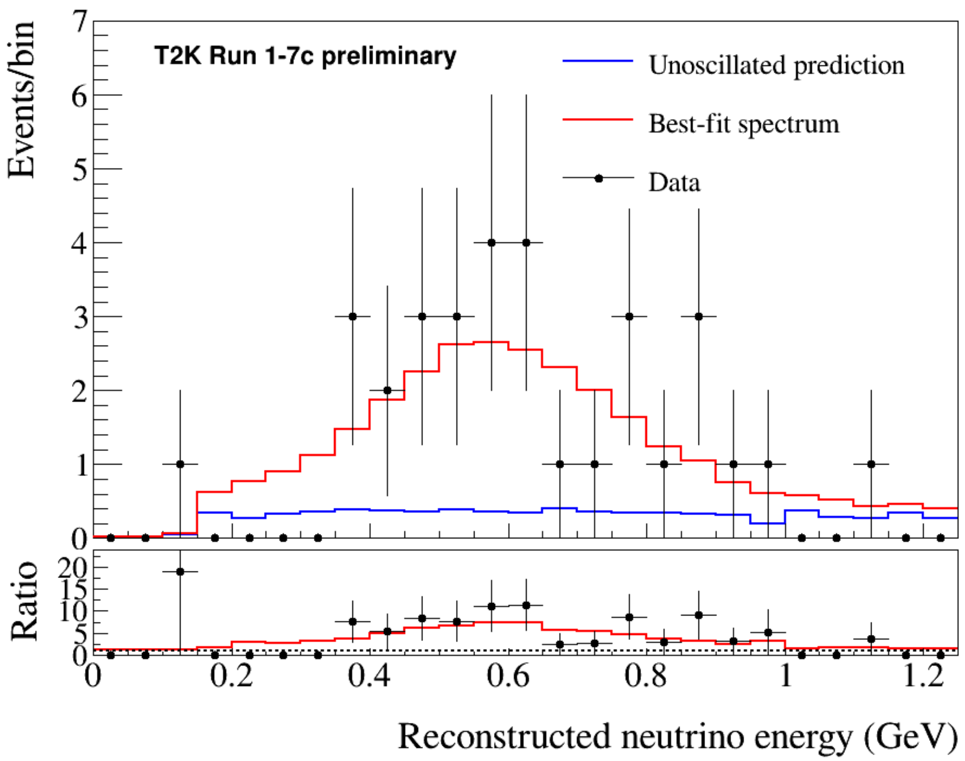
27 May 2016
POT total: 1.510×10^{21}

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

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

NEUTRINO MODE

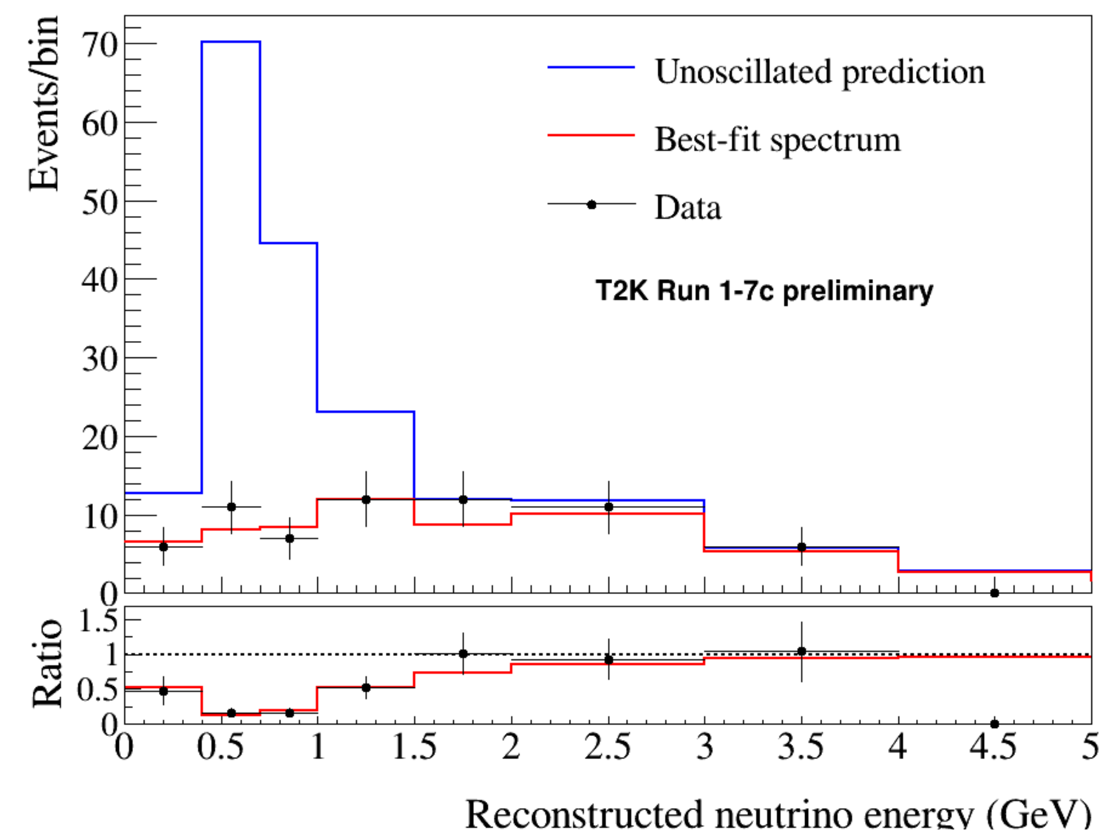


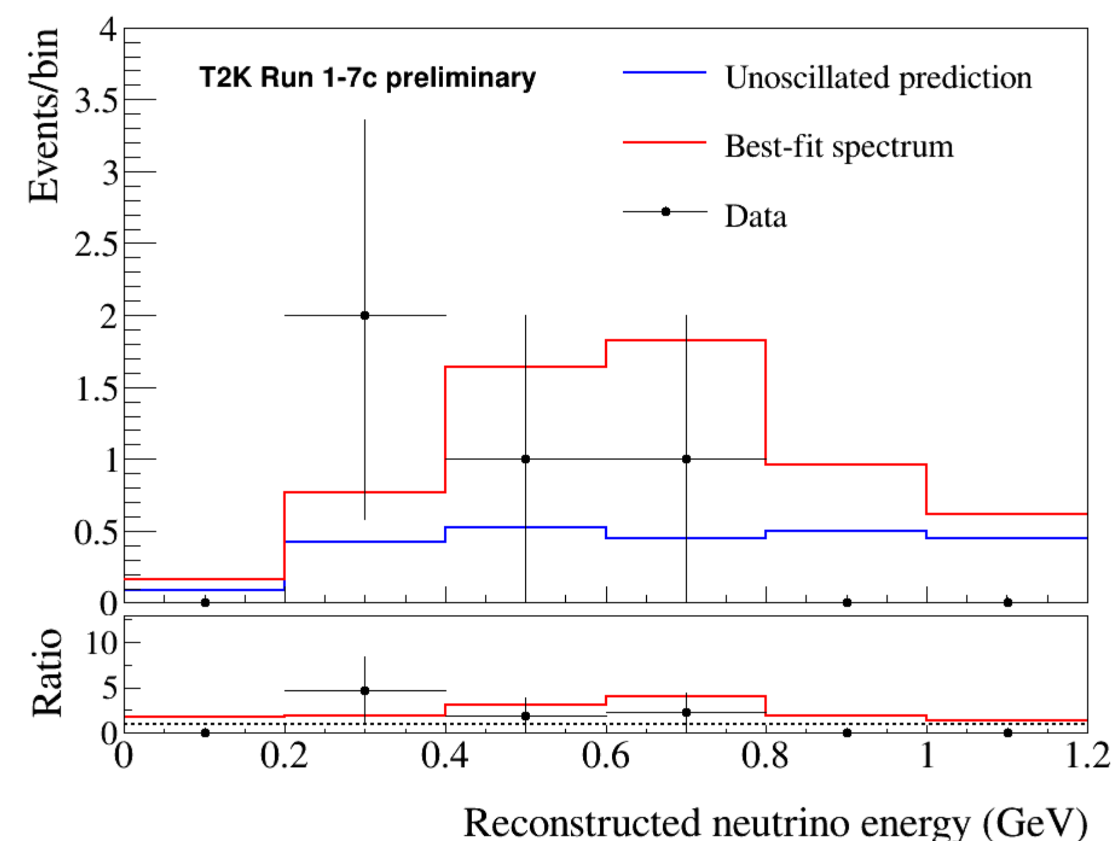


- ν_μ candidates:
  - 481 events expected in the absence of oscillations
  - 135 events observed
  - oscillation pattern precisely observed
- ν_e candidates
  - 6 events expected in the absence of $\nu_\mu \rightarrow \nu_e$ oscillations
  - 32 events observed

ANTINEUTRINO DATA

- $\bar{\nu}_\mu$ events
  - 177 events expected in the absence of oscillations
  - 66 observed
- $\bar{\nu}_e$ events
  - 2.4 events expected in the absence of oscillations
  - 4 observed





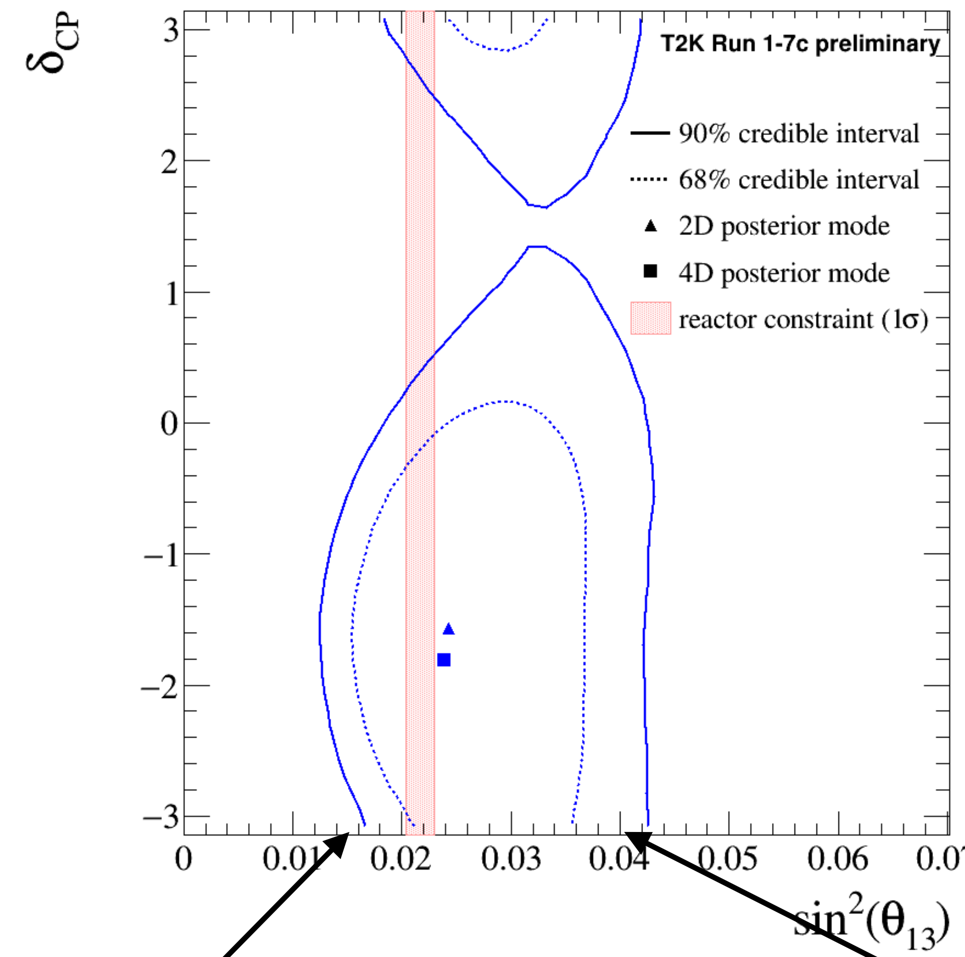
GUESS AT WHERE WE ARE

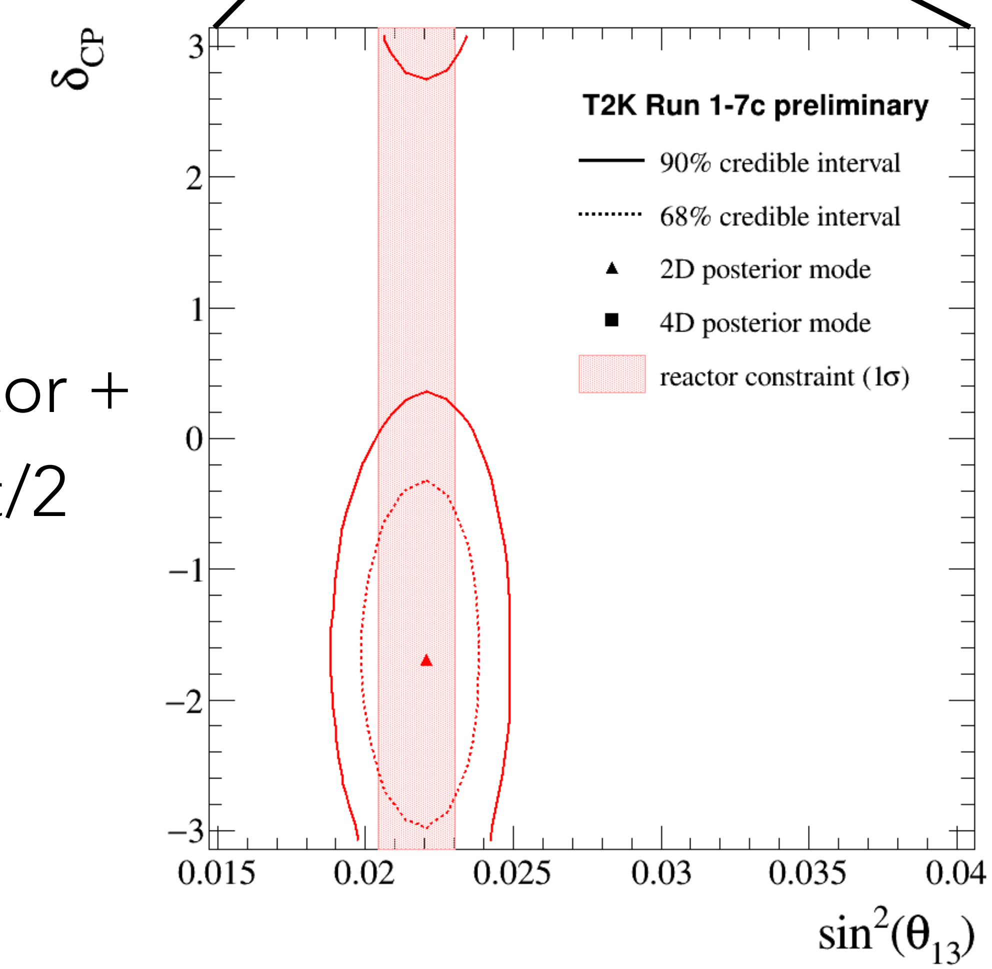
	MASS ORDER	-π/2	0	+π/2	π	OBS
ν_e	NH	28.7	24.2	19.6	24.1	32
	IH	25.4	21.3	17.1	21.3	
$\bar{\nu}_e$	NH	6.0	6.9	7.7	6.8	4
	IH	6.5	7.4	8.4	7.4	

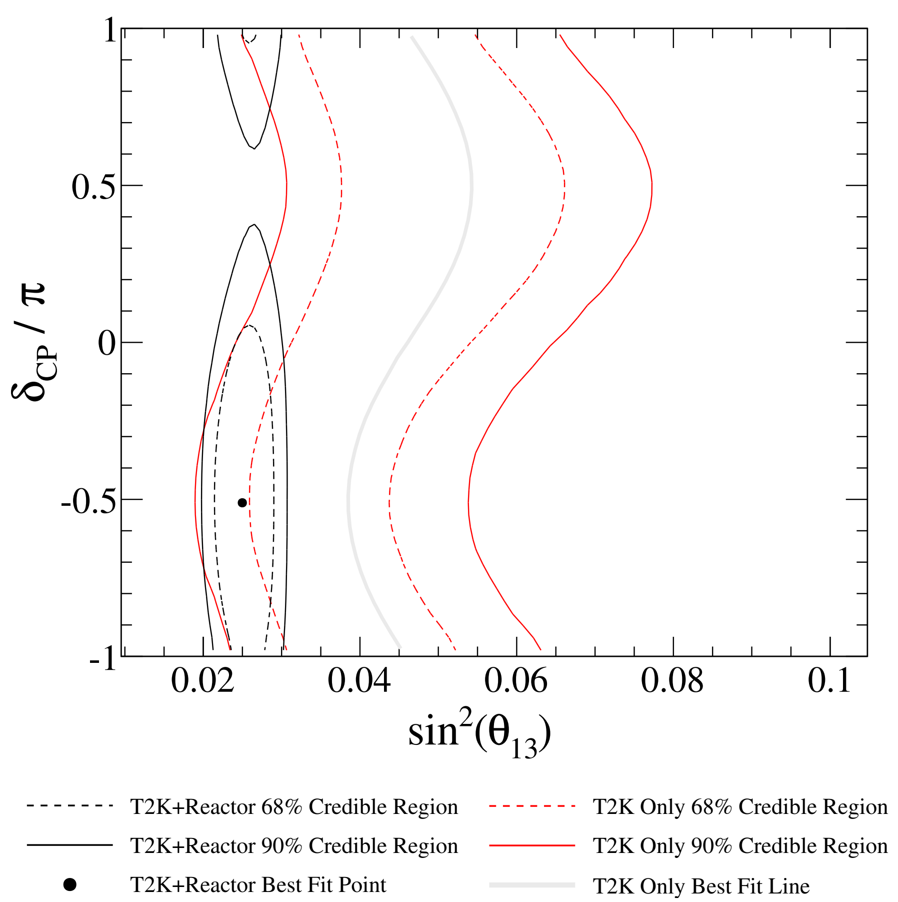
- At δ_{CP} = -π/2
  - $\nu_\mu \rightarrow \nu_e$ is maximally enhanced
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is maximally surpassed
- Normal mass hierarchy
  - enhances $\nu_\mu \rightarrow \nu_e$
  - suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

δ_{CP} AND θ_{13}

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





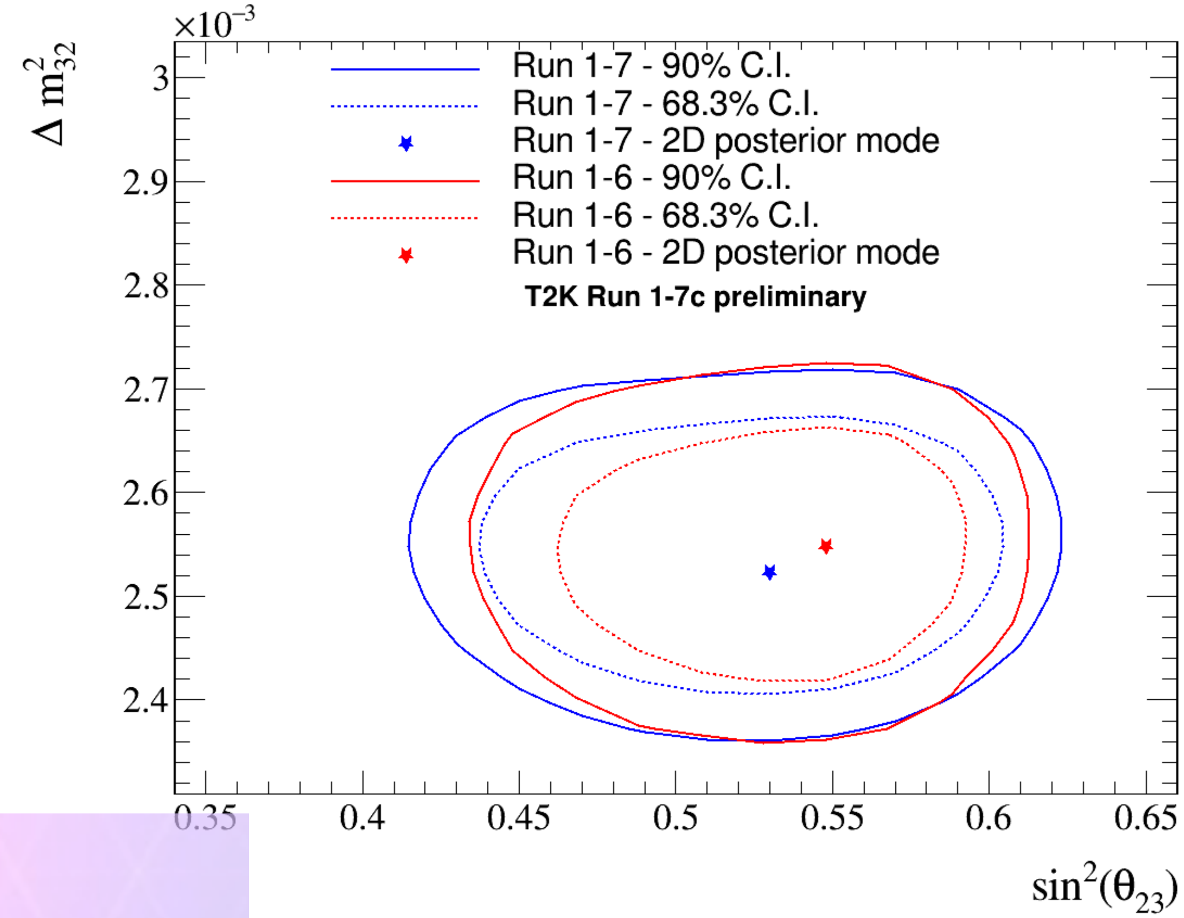


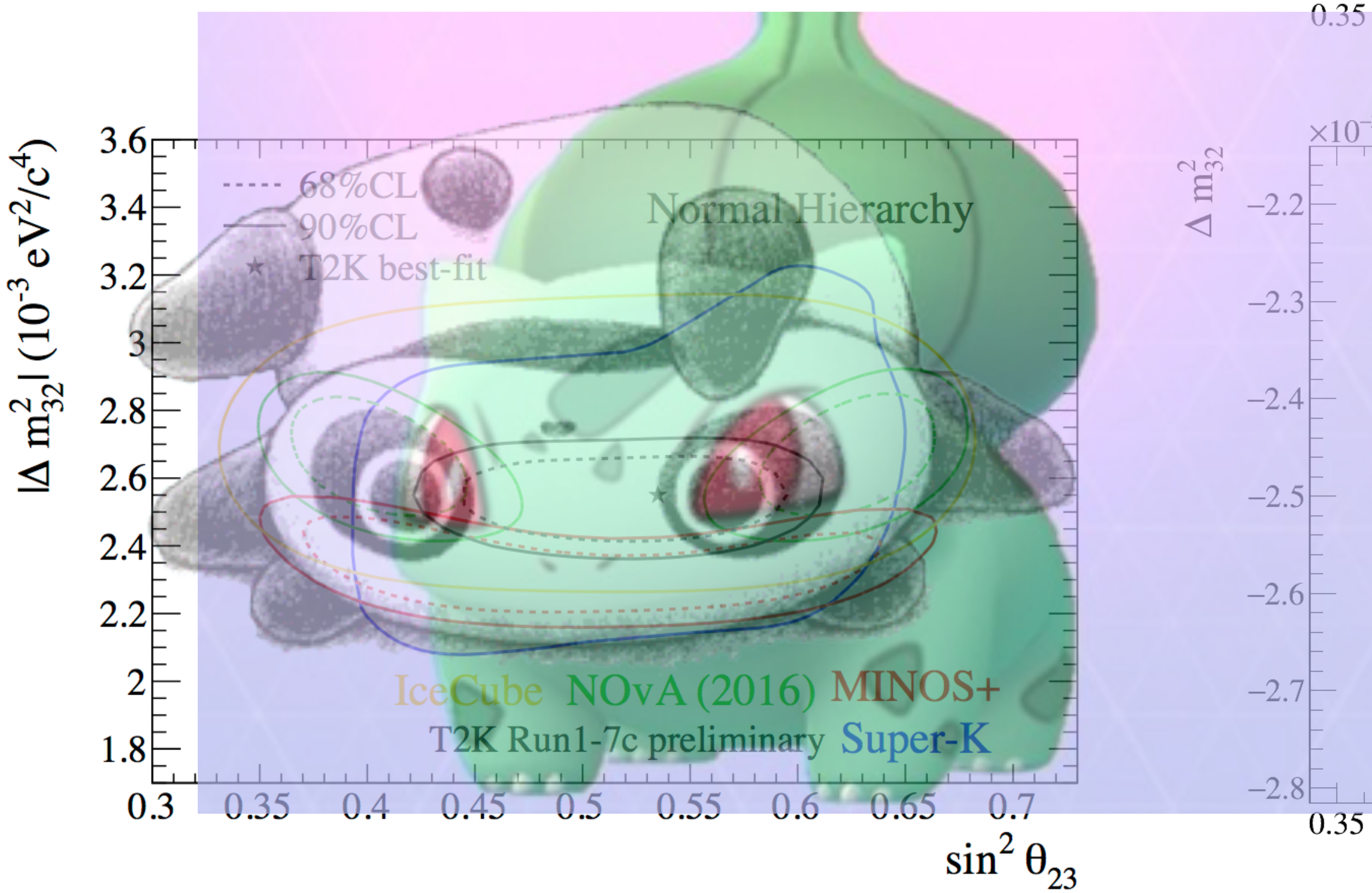
Left:

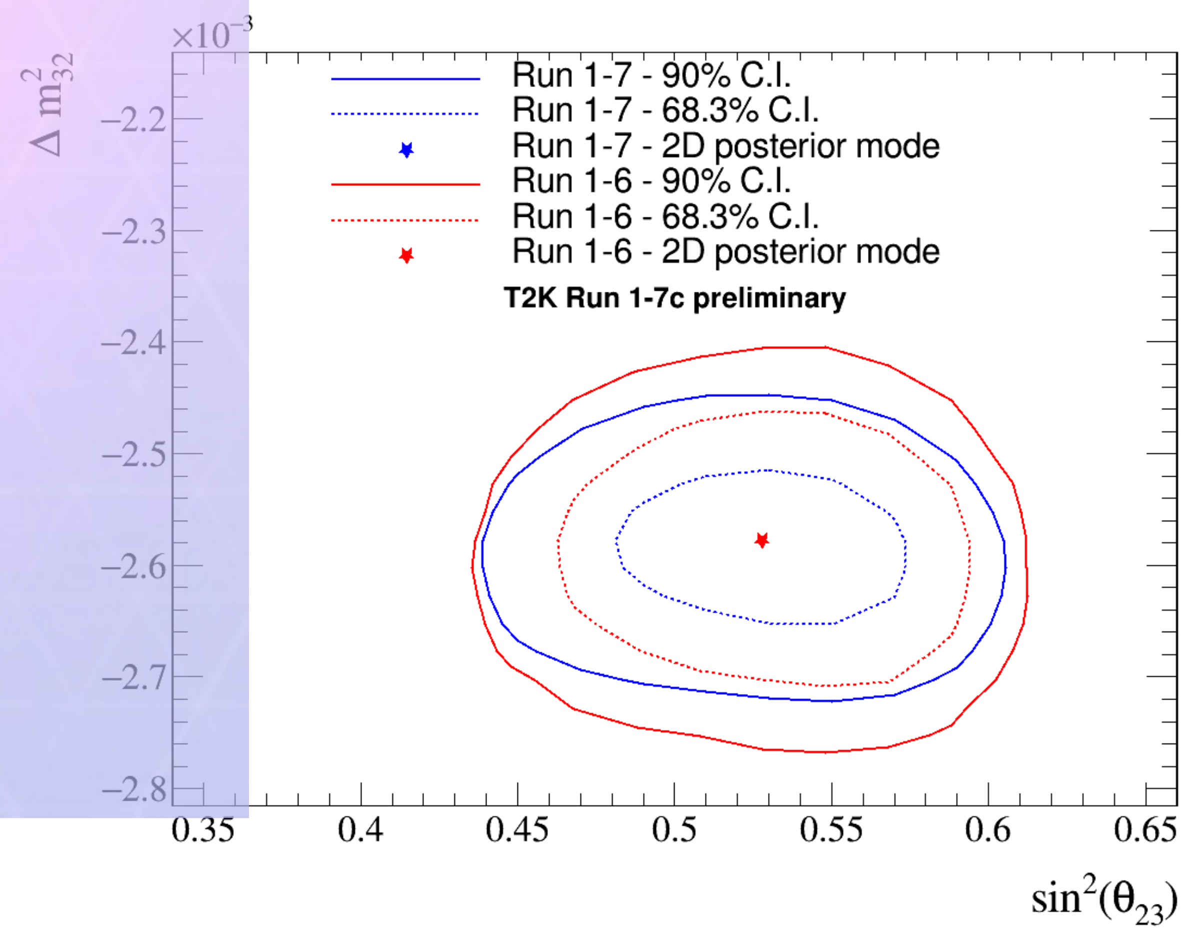
- with $\nu_\mu \rightarrow \nu_e$ only, reactor + T2K favoured $\boldsymbol{\delta}_{CP}$ =-π/2

Θ_{23}

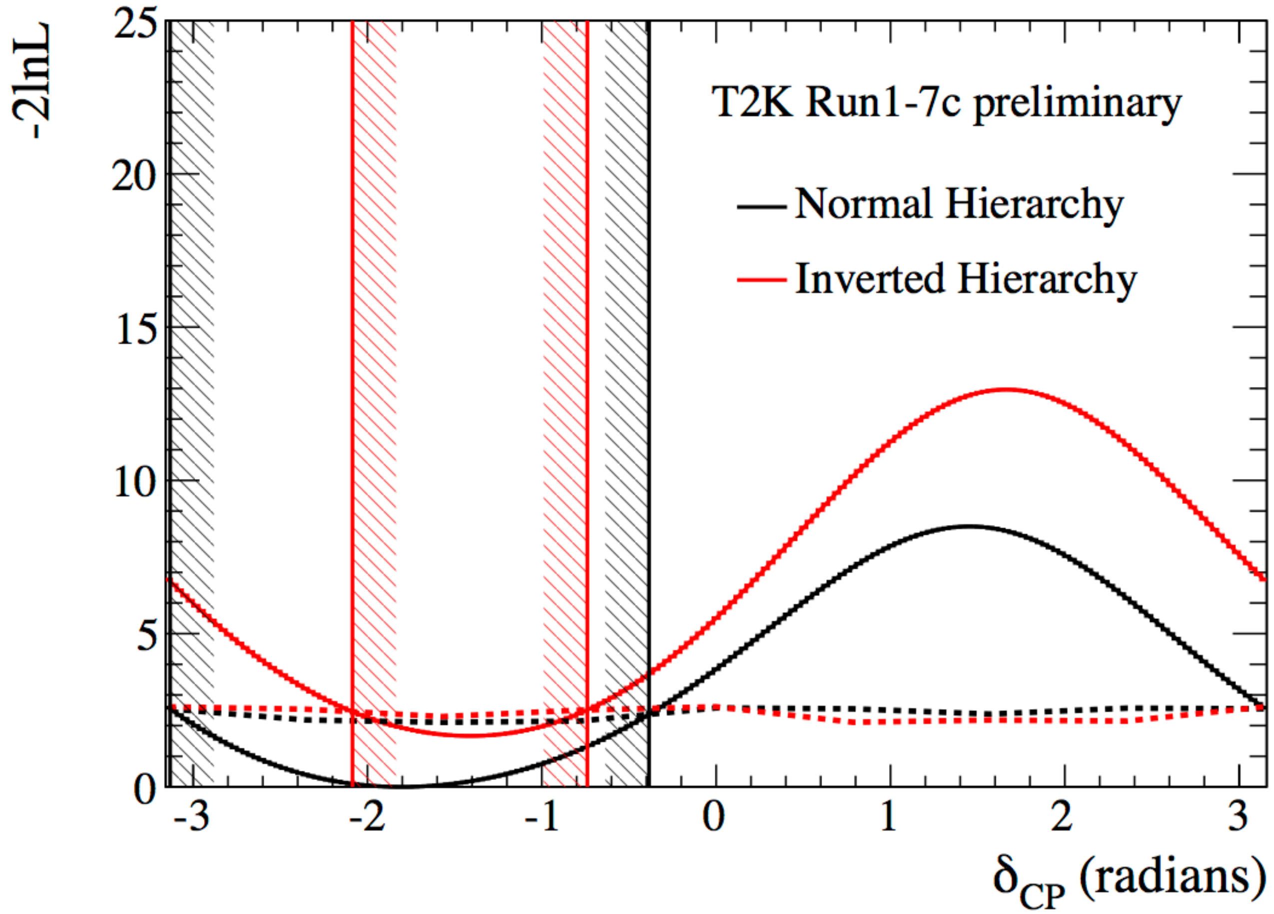
- Maximal values still favoured
  - $\sin^2\theta_{23}$ ~0.5 (θ_{23} ~$\pi/4$)
  - mild tension with recent NOvA measurements

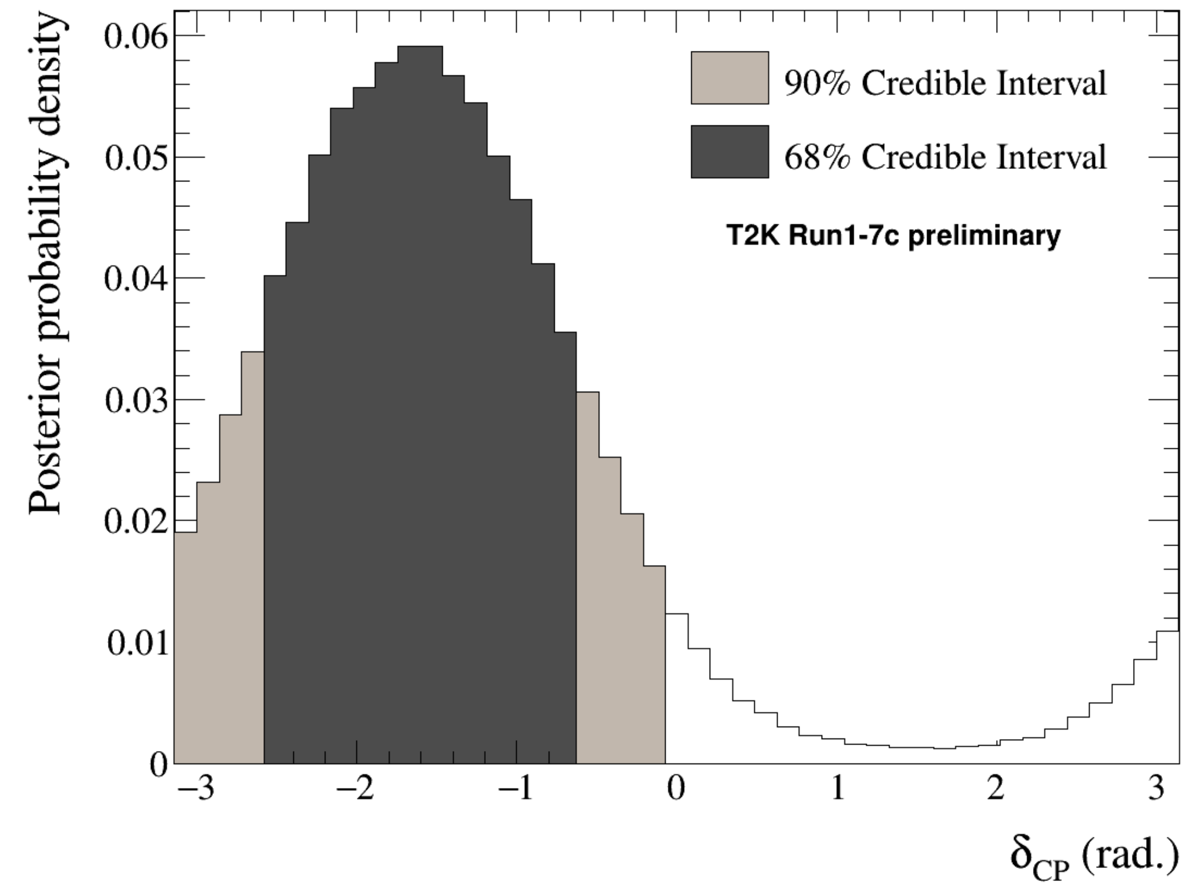




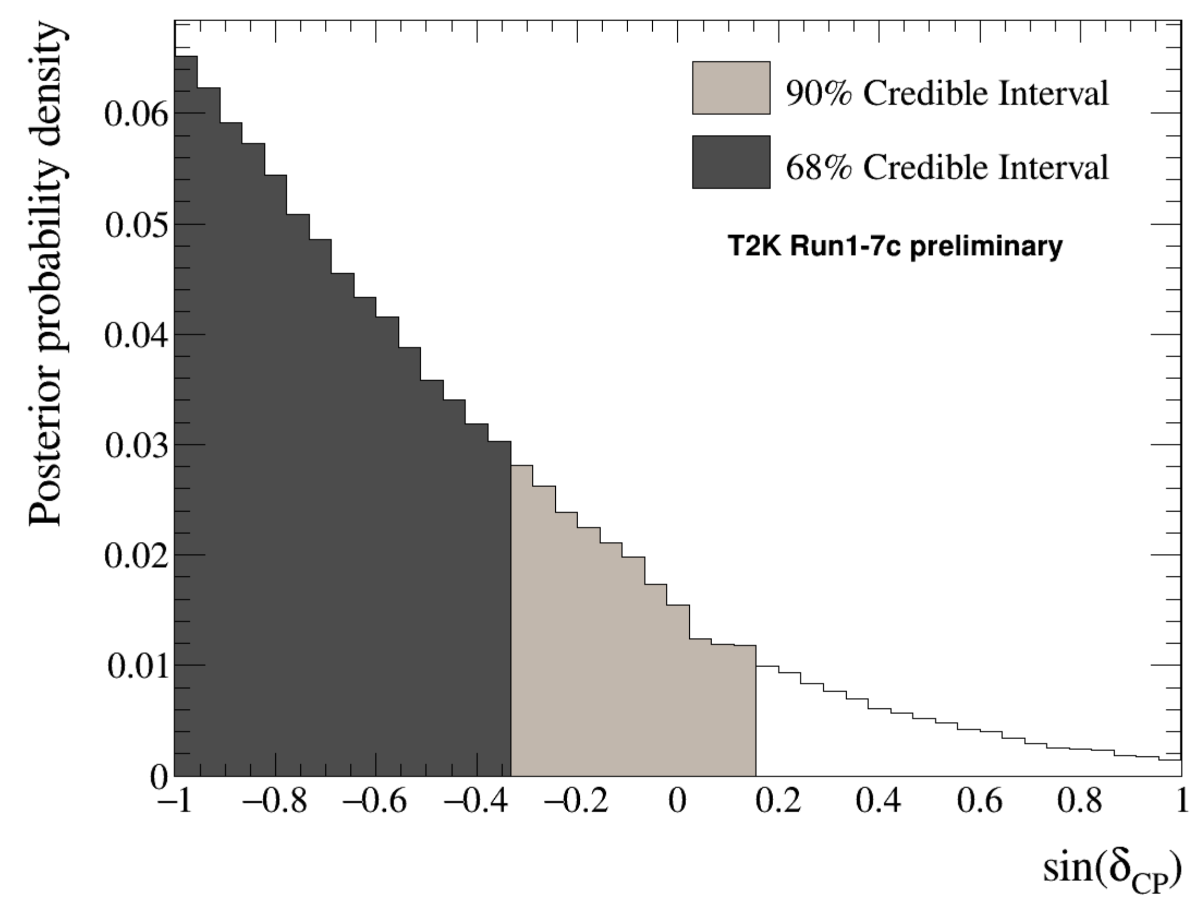


δ_{CP}





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



Θ_{23} OCTANT/MASS HIERARCHY

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

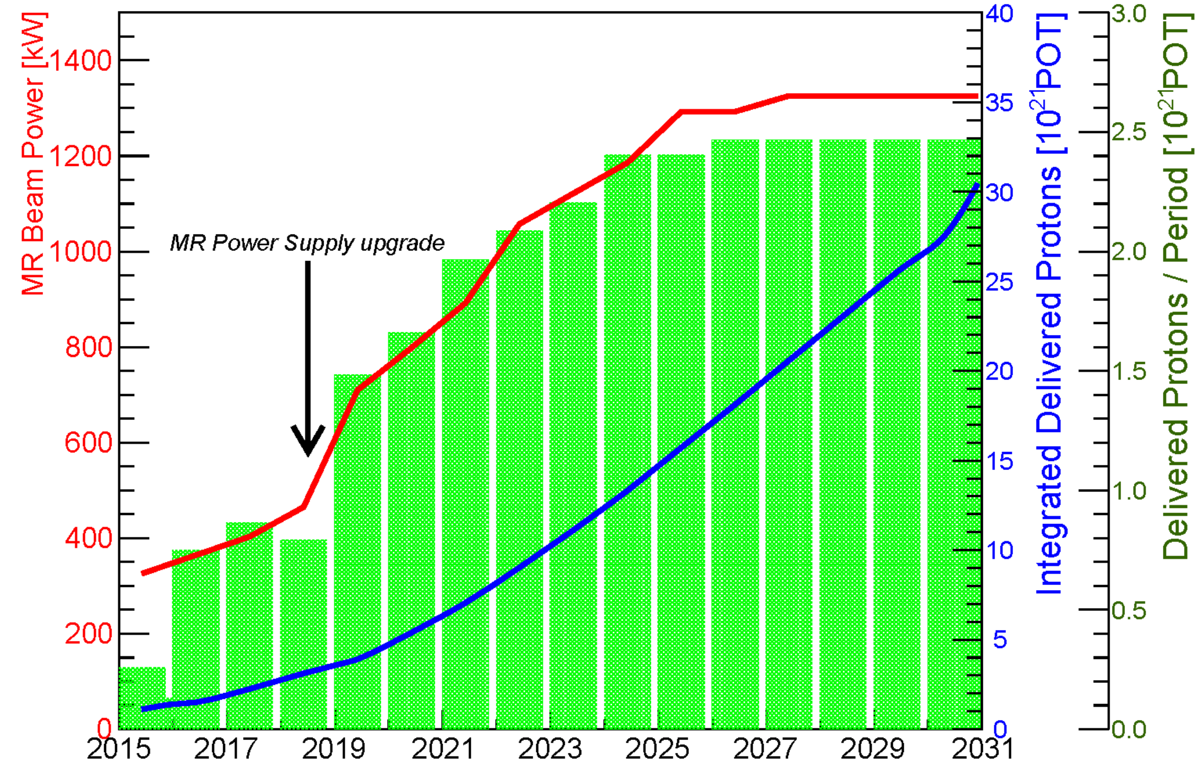
	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.23	0.09	0.32
$\sin^2\theta_{23} > 0.5$	0.49	0.19	0.68
SUM	0.72	0.28	1.000

NEUTRINO ECONOMICS

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

J-PARC MAIN RING UPGRADE

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

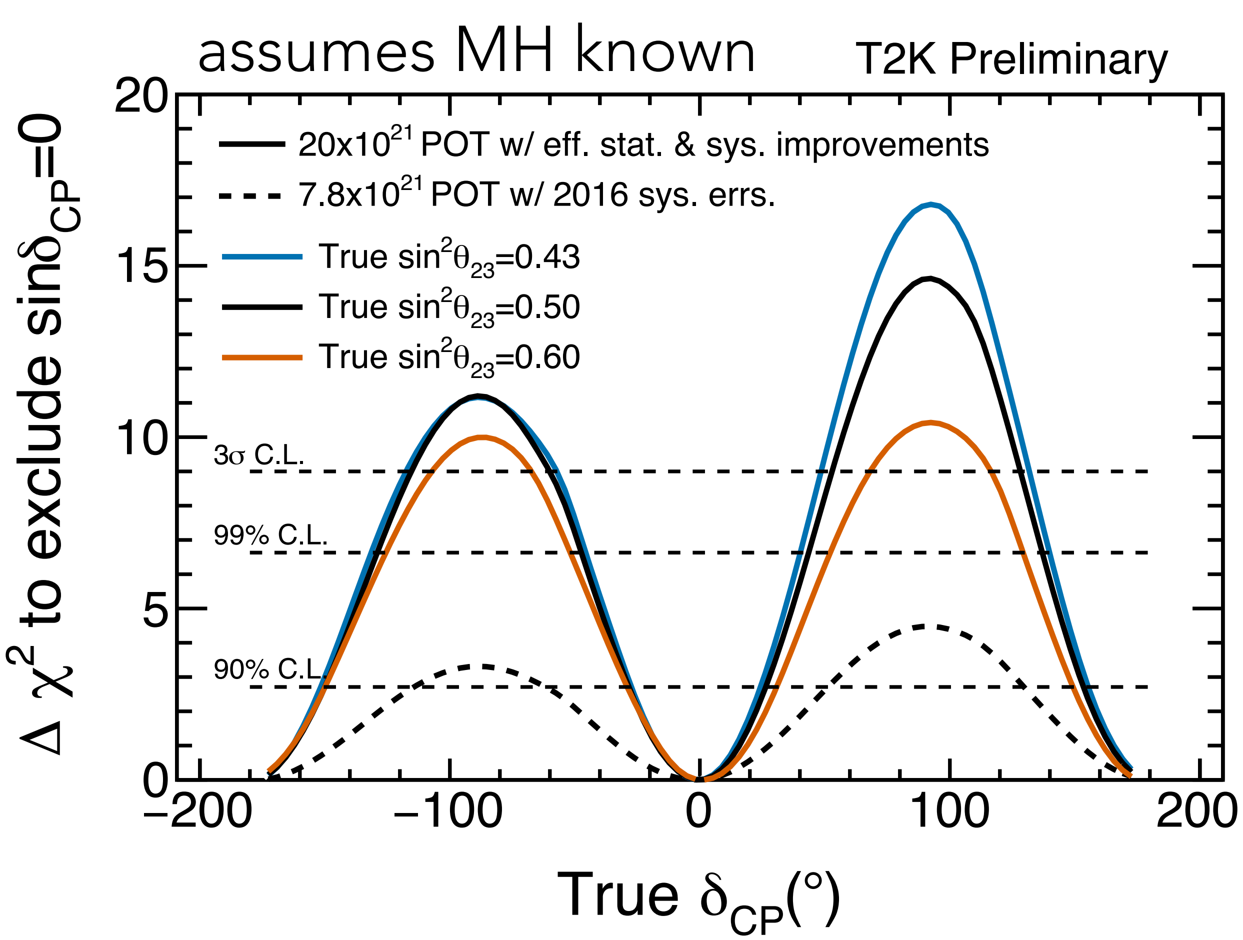


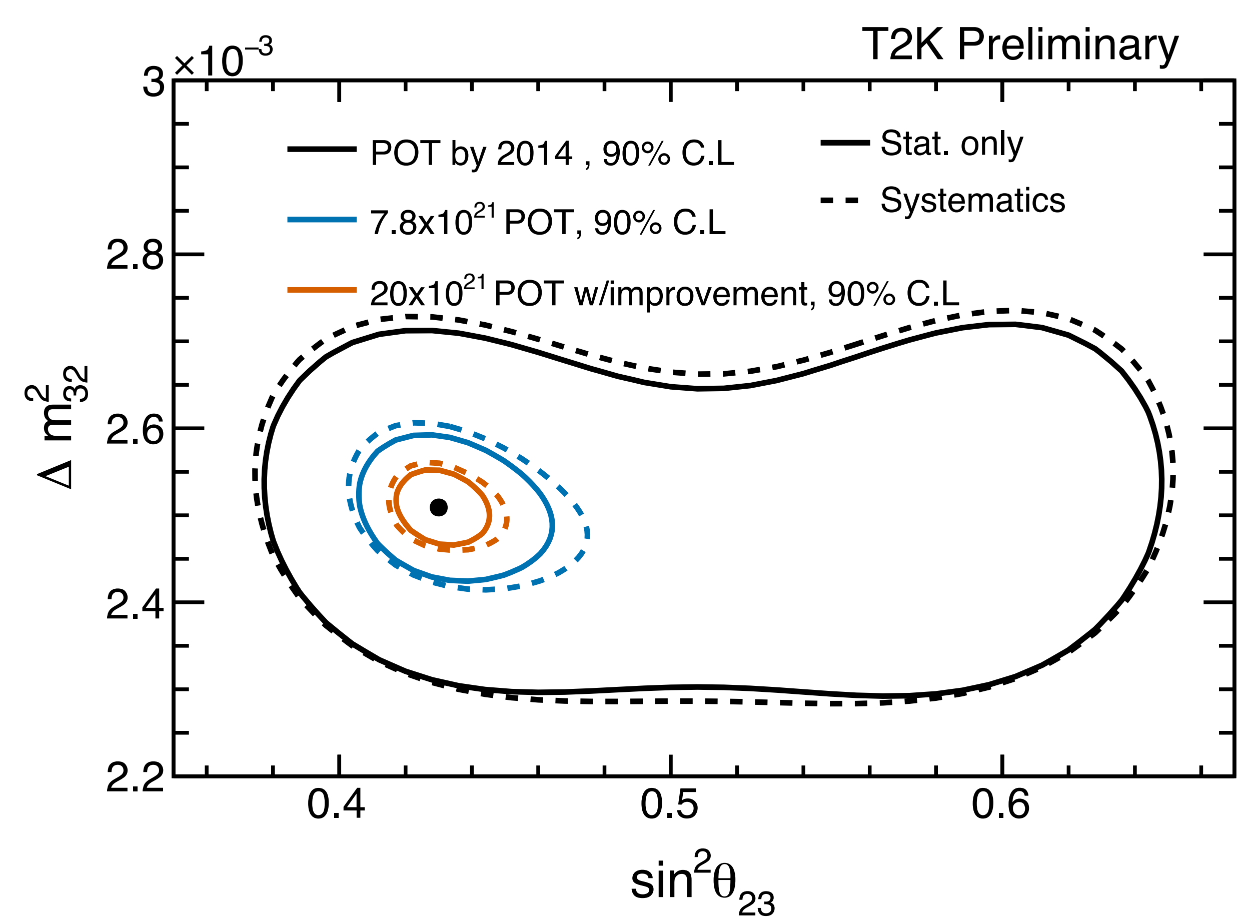
- First stage of MR power supply upgrade approved
    - Reduce MR acceleration cycle from 2.48 → 1.3 sec
    - with currently achieved power of 430 kW → 800 kW
- now looking beyond 1 MW to **1.3 MW beam**
    - **Highest priority** in Recent KEK Project Implementation Plan review
    - prepare for Hyper-Kamiokande and explore T2K run to ~2026

"T2K-II" GOALS

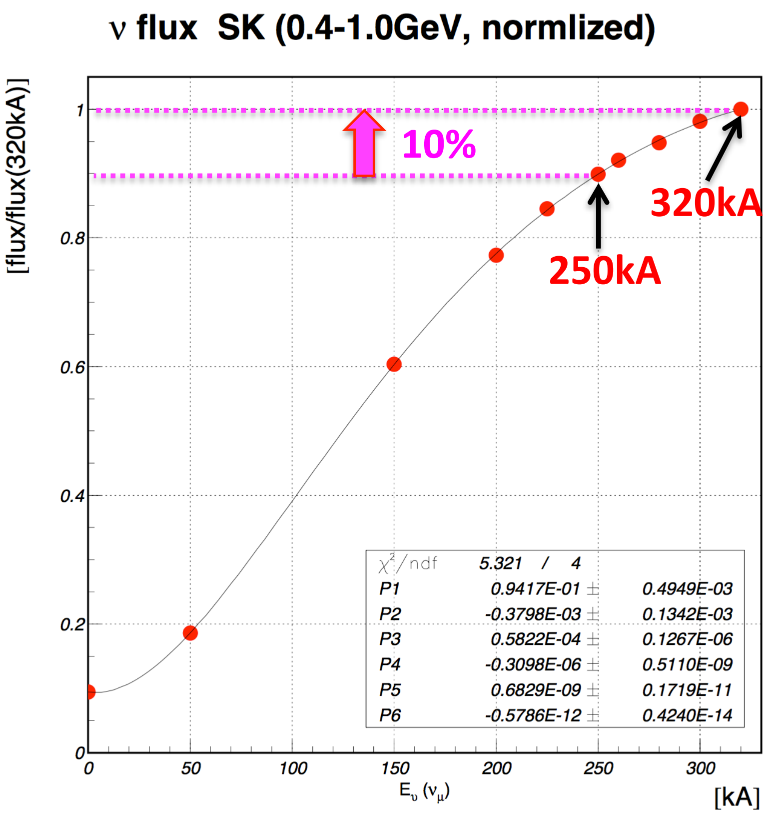
	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \to \nu_e$	SIGNAL $\bar{\nu}_\mu \to \bar{\nu}_e$	BEAM ν_e	ν_μ	NC
ν MODE	0	454.6	**346.3**	3.8	72.2	1.8	30.5
	$-\pi/2$	545.6	**438.5**	2.7			
$\bar{\nu}$ MODE	0	129.2	16.1	**71.0**	28.4	0.4	13.3
	$-\pi/2$	111.8	19.2	**50.5**			

- Accumulate 20×10^{20} POT by 2026
  - ~3x currently approved POT
  - in advance of next generation
- ~3 **σ** significance for CPV in (currently) favorable cases
- θ_{23} precision of better than 1.7°



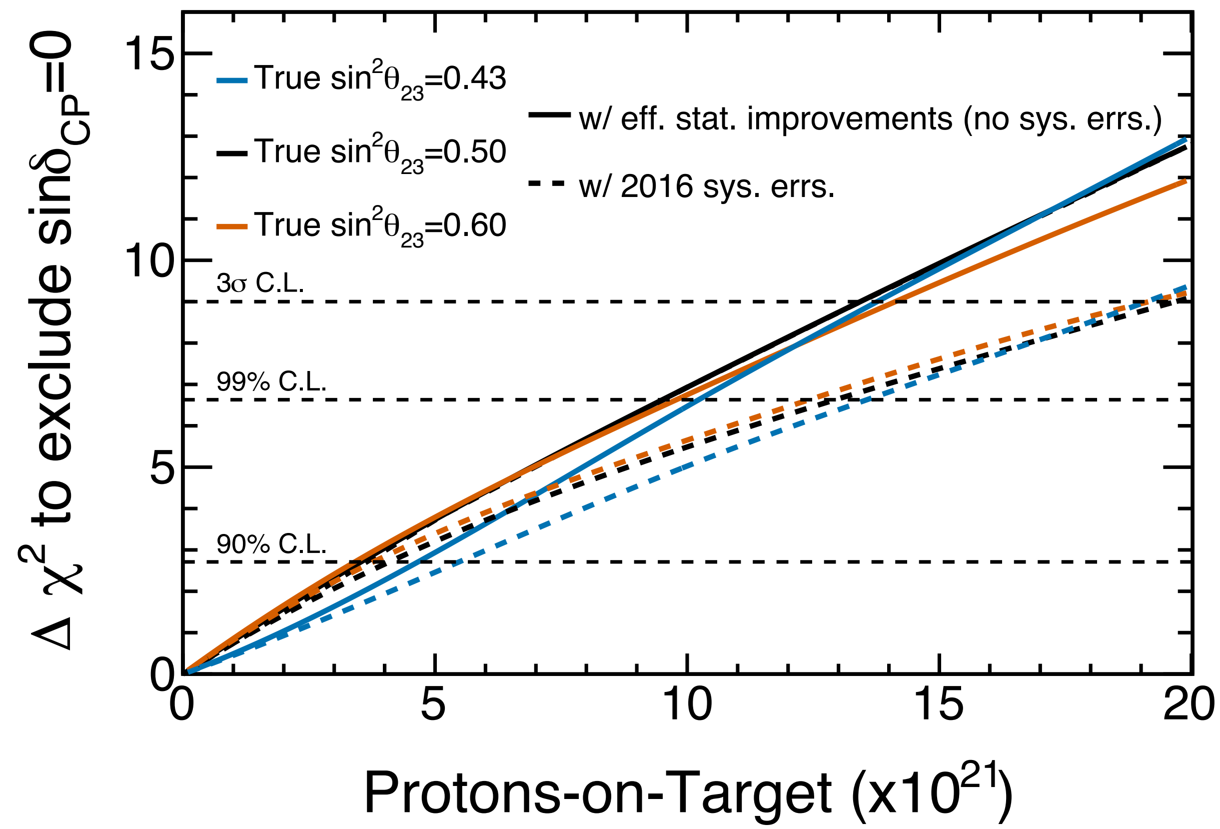


T2K-II NEEDS:



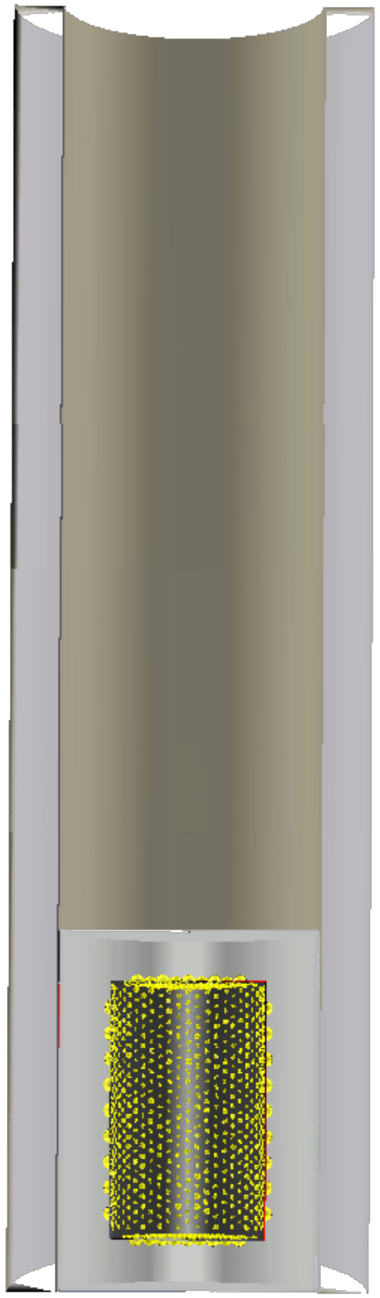
Courtesy of T.Nakadaira

- Goals require several significant developments
    - Increase horn current from 250 →325 kA, ~10% increase
        - power supply upgrade underway
- Increase effective efficiency of SK ν_e selection by 40%
    - increase fiducial volume
    - include additional inelastic channels into ν_e signal

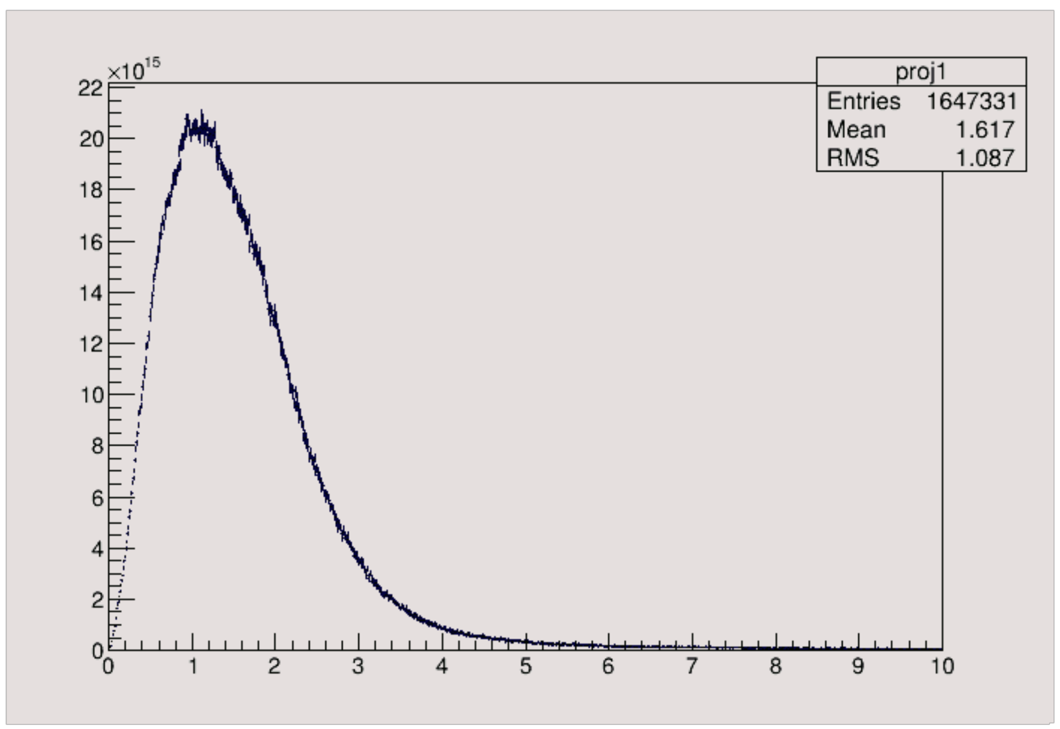


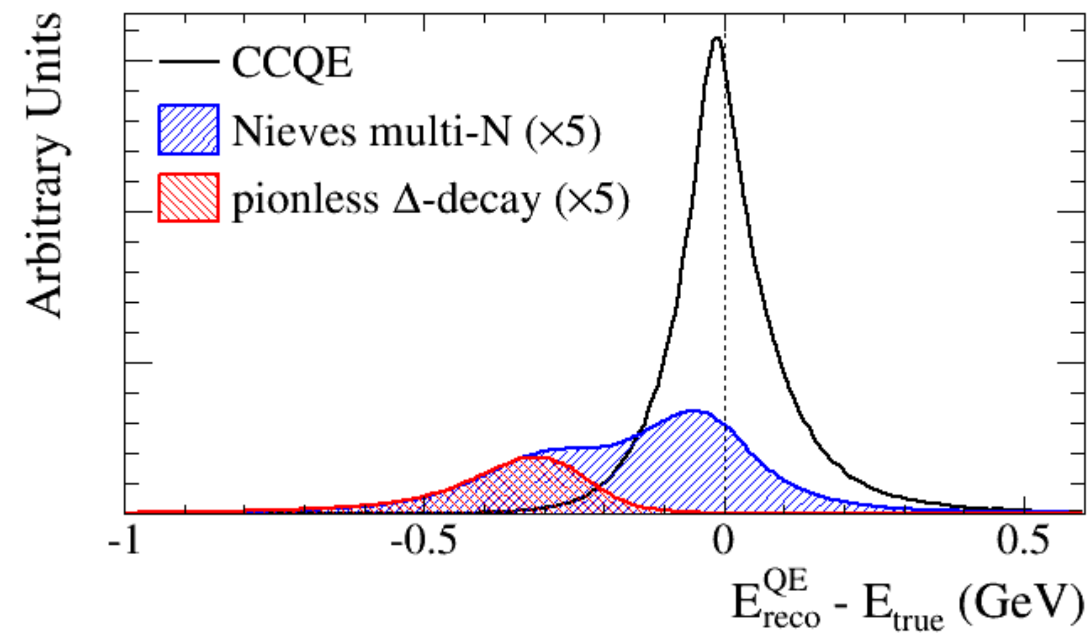
- Sensitivity significantly impacted by systematic errors
    - new near detector (NuPRISM) and other improvements to reduce impact of systematic errors
- **New opportunities ↔ New challenges**
    - **exciting several years ahead for T2K and NOvA**

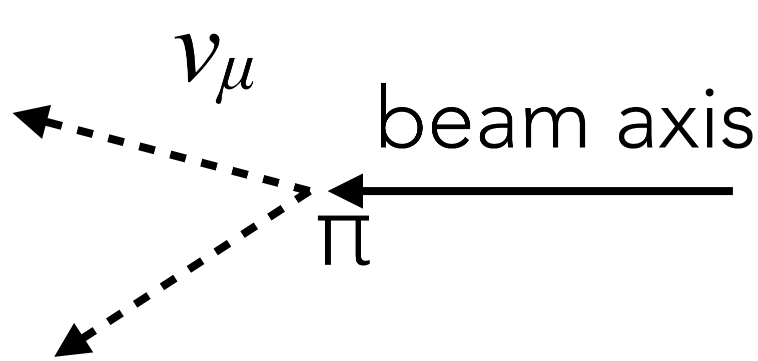
NuPRISM



- New concept to exploit the variation of neutrino energy with off-axis angle
- Data taken at different angles can directly predict neutrino interactions with arbitrary neutrino fluxes including effects from oscillation







- Probe critical neutrino interaction modelling systematics
- Initial phase on surface with large off-axis angle for precision ν_e/ν_μ measurements granted Stage 1 status at J-PARC

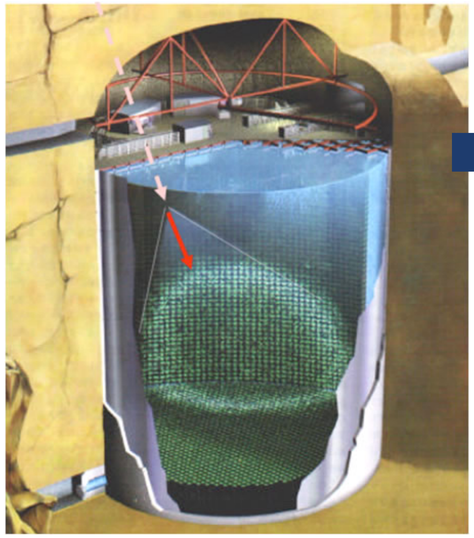
$$N(\nu_\mu \rightarrow \nu_e) = \Phi_\nu(E_\nu) \times \sigma_\nu(E_\nu) \times \varepsilon(E_\nu) \times P(\nu_\mu \rightarrow \nu_e; E_\nu)$$

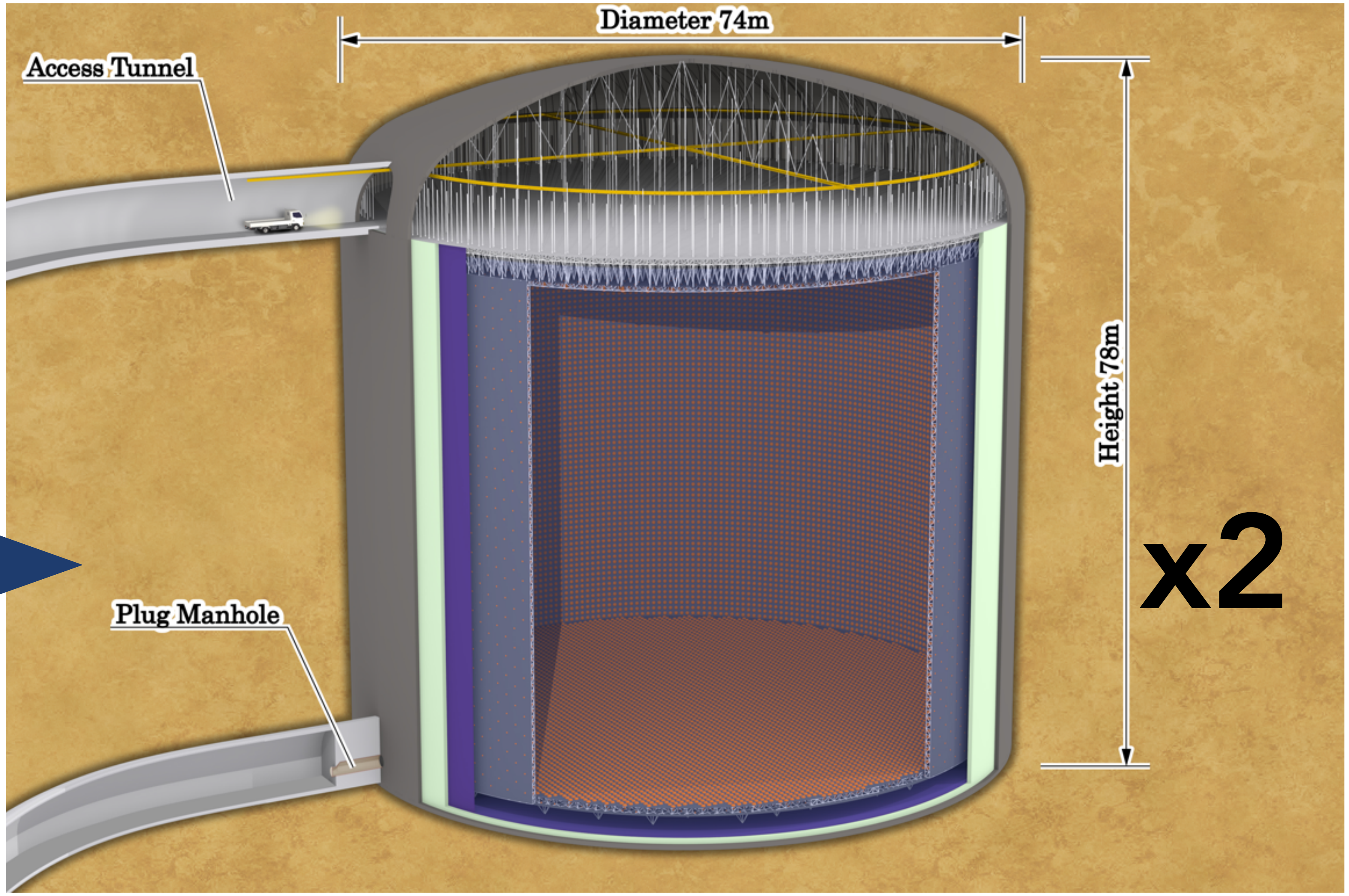
NEUTRINO ECONOMICS

Detector upgrades

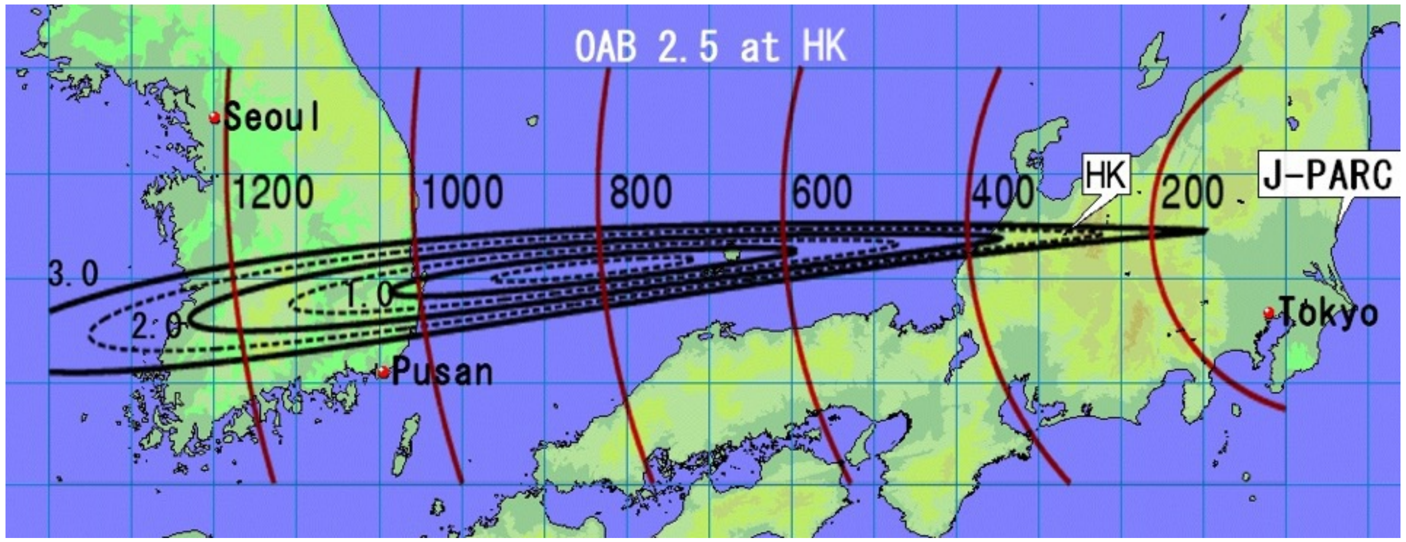
- Super-Kamiokande → Hyper-Kamiokande

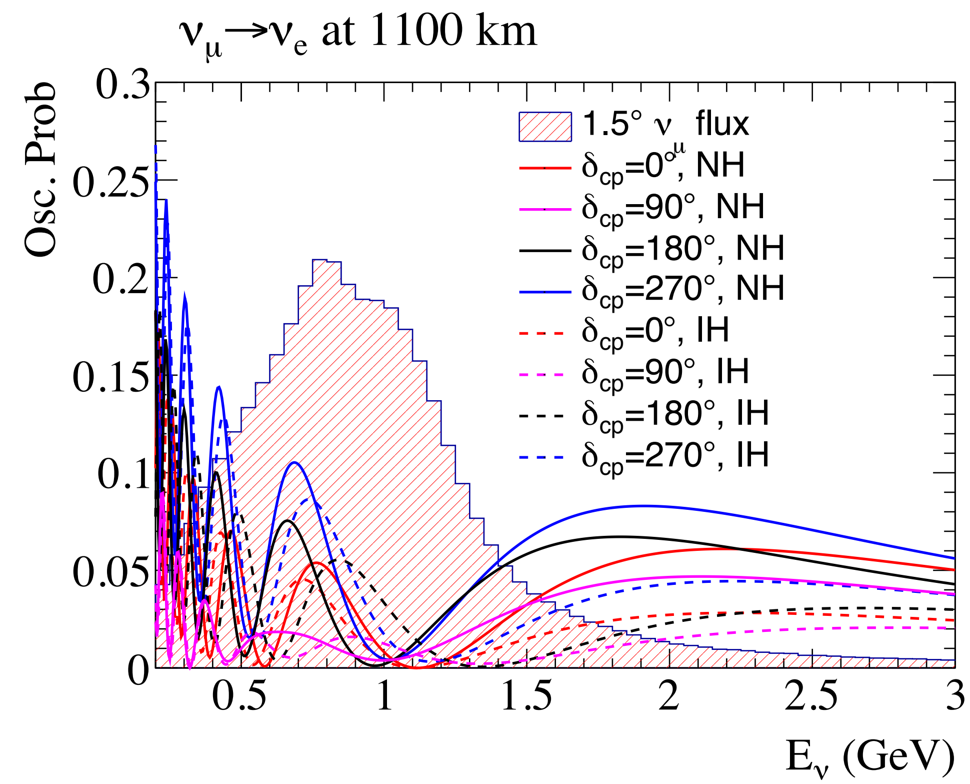
$$N \propto \Phi_\nu \times \boxed{V \times \rho \times \epsilon} \times \sigma$$

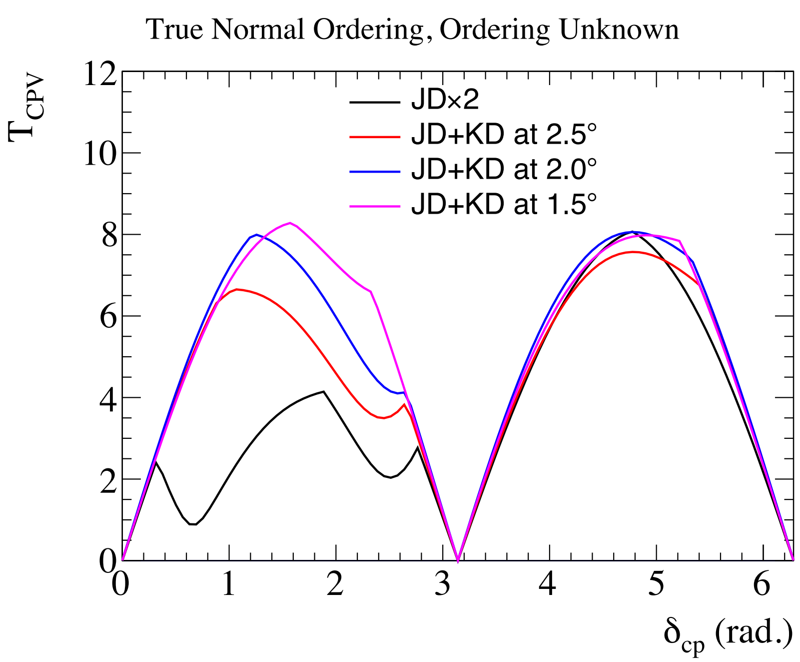


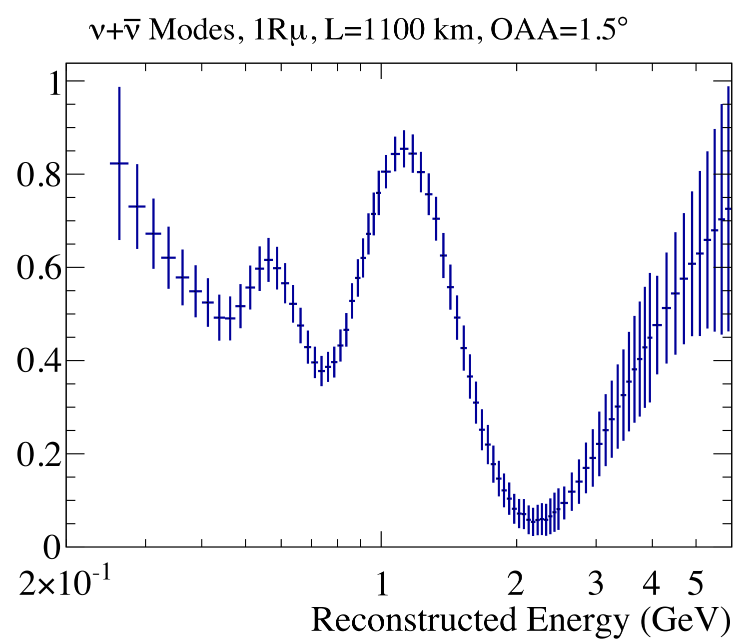


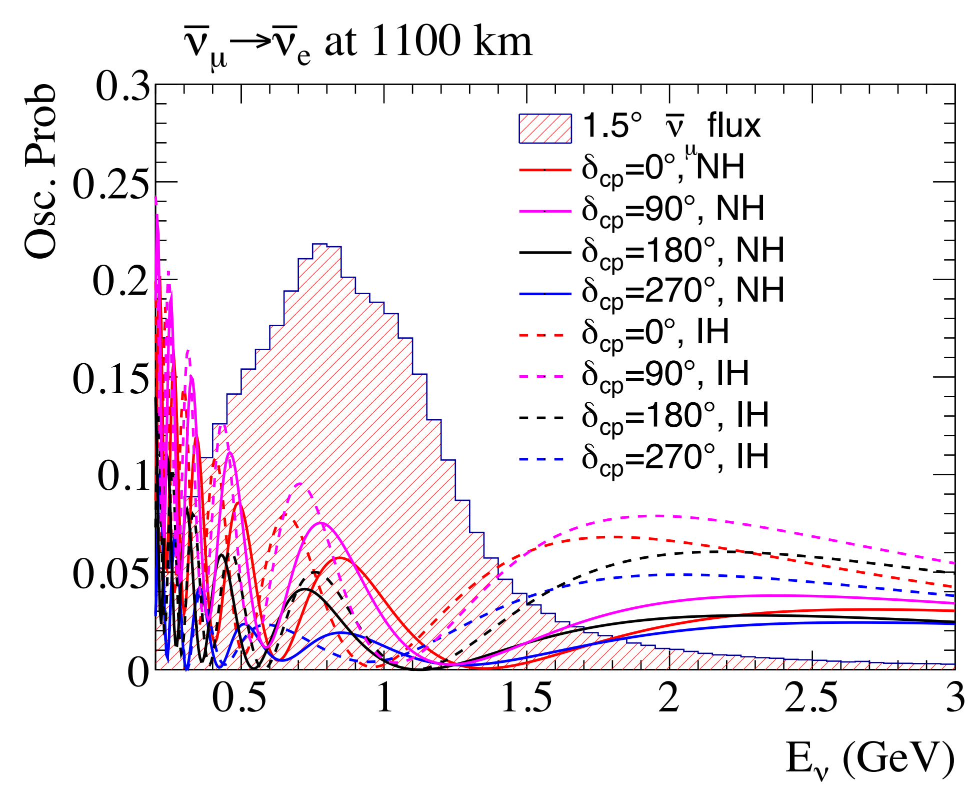
TOKAI-TO-KAMIOKA AND BEYOND











- Reviving a great idea in light of favorable new circumstances . . . ..

https://arxiv.org/pdf/1611.06118.pdf

ELUCIDATING CPV

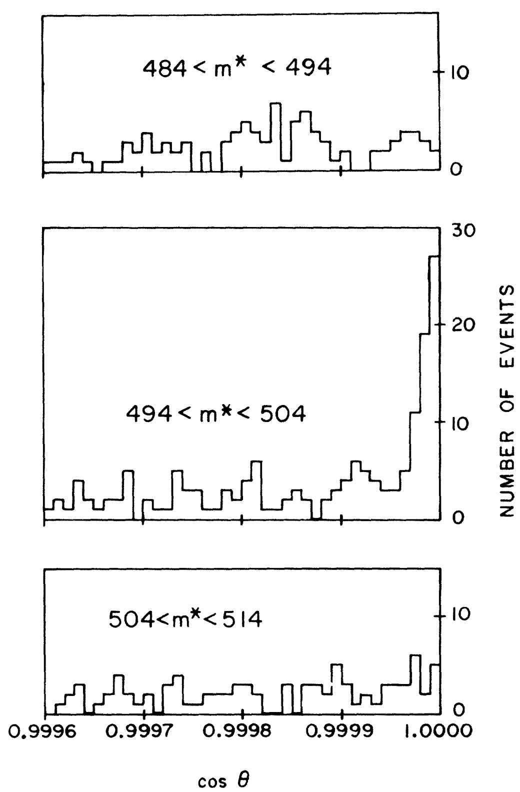


FIG. 3. Angular distribution in three mass ranges for events with cos θ > 0.9995.

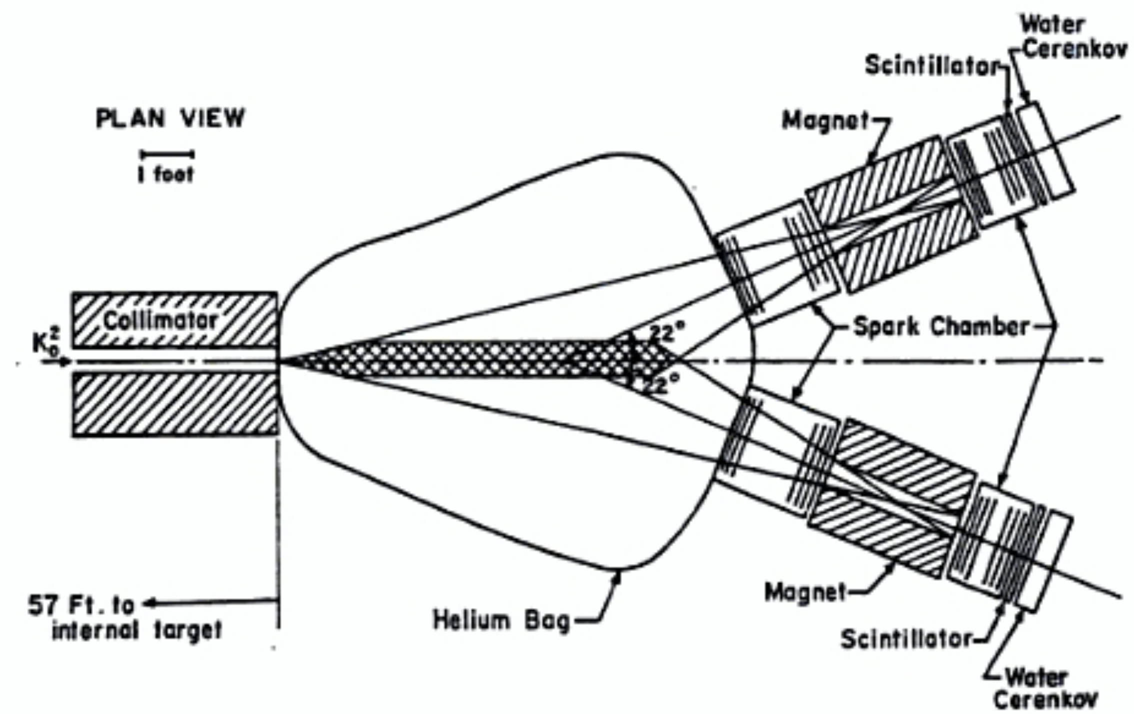
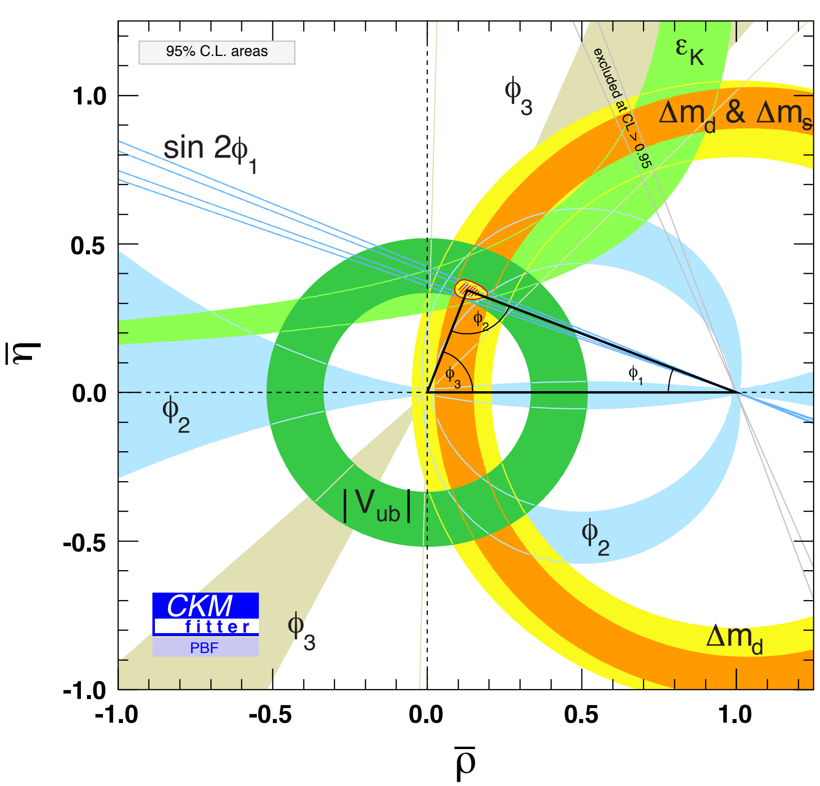
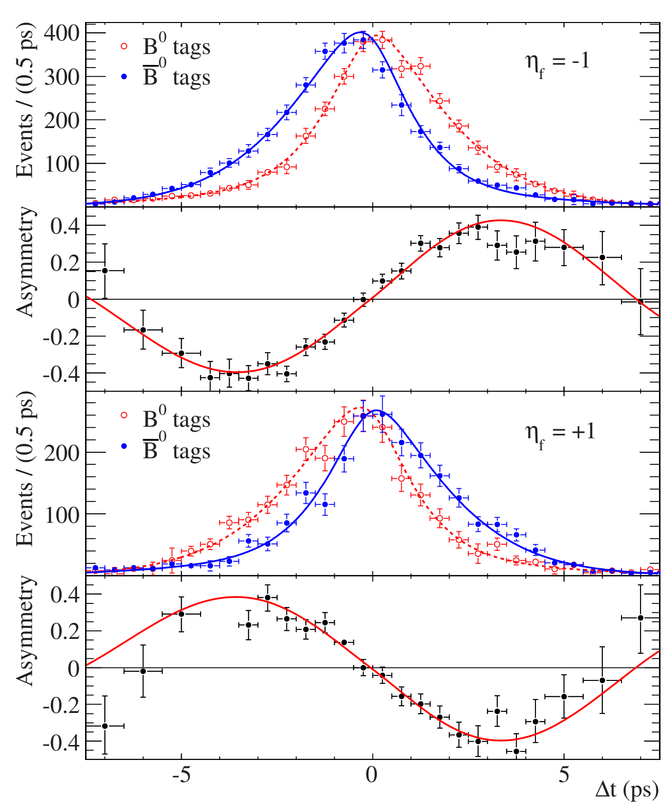


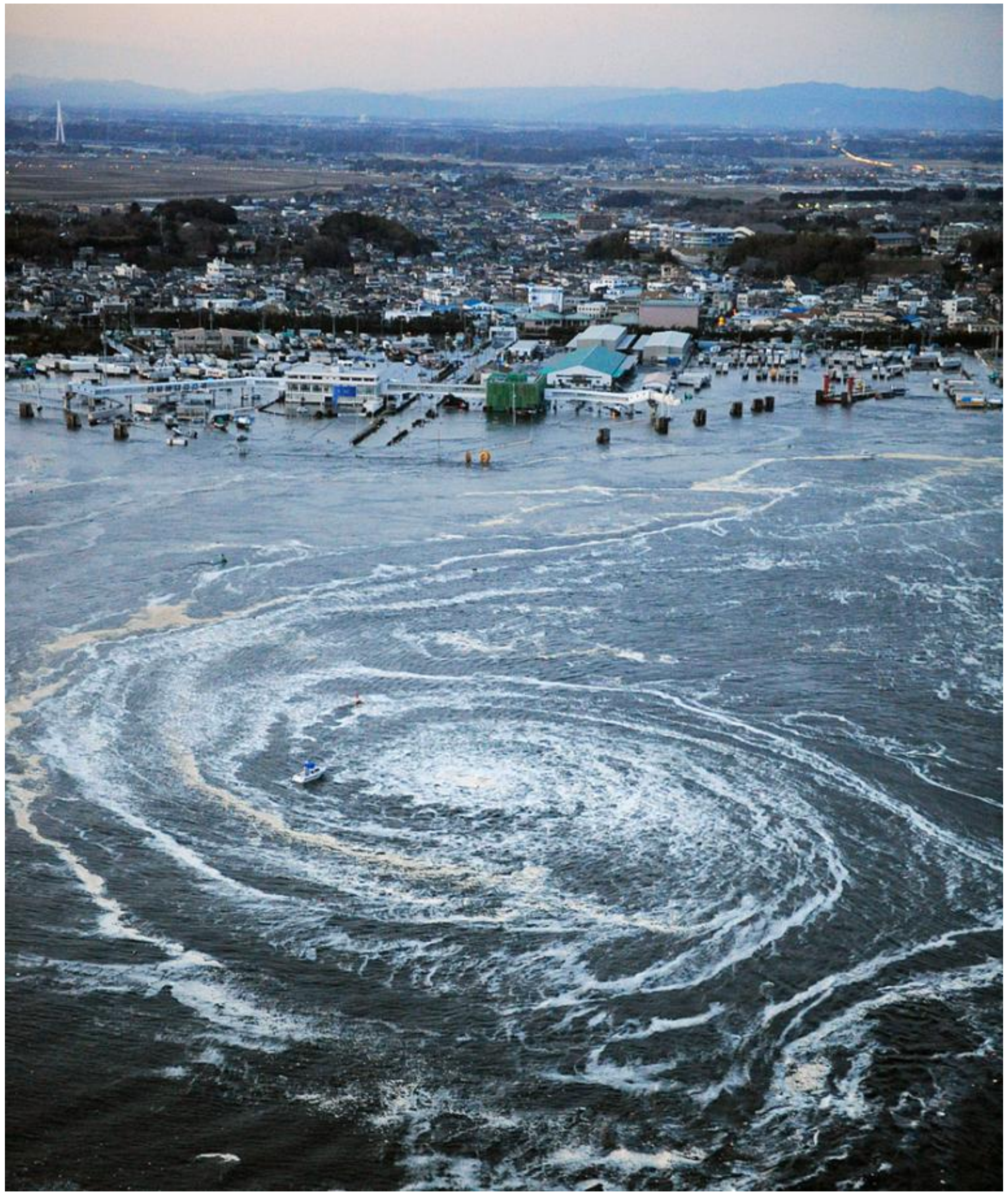
Fig. 9a. Set-up used to detect $K_2 \to \pi^+\pi^-$.





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

3/11 EARTHQUAKE



Oarai:
(~15 km south of J-PARC)

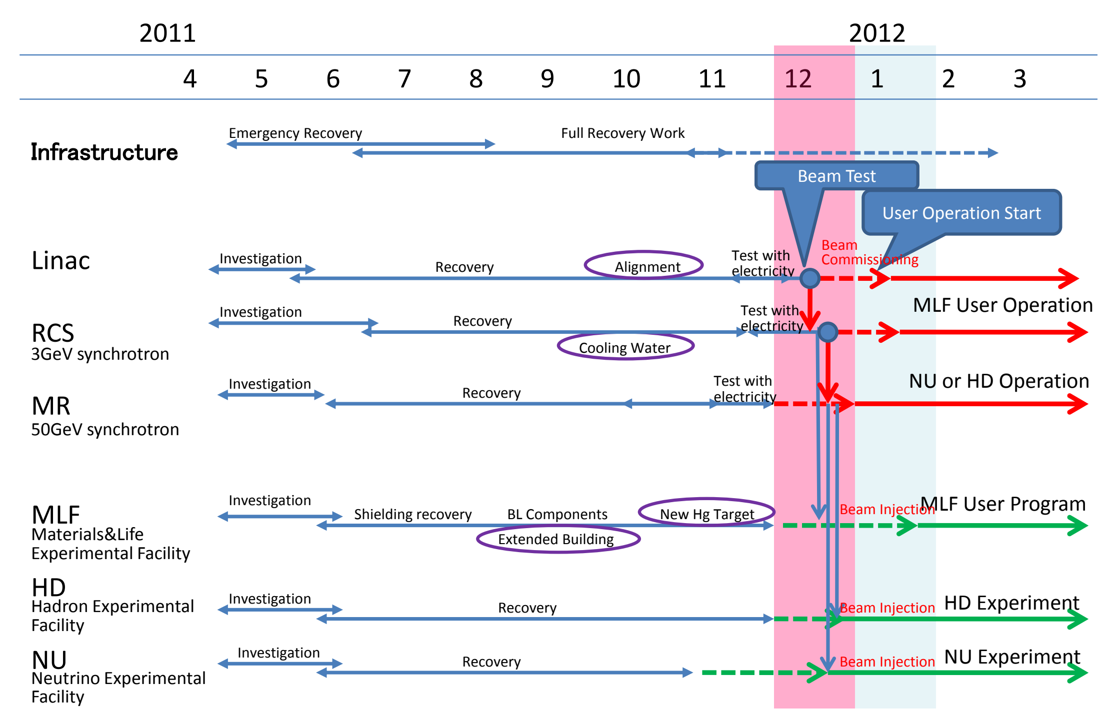
Damage on J-PARC site

- Barely one year after the start of operations . . . . .

RESTART OF ACCELERATOR

- May 2011:
  - "User program will be started with beam time of about 50 days . . within FY2011"

J-PARC Recovery Schedule （@2011.5.20）



- Translation: "We're putting this bad boy back together in six months and sending you beam by the end of the year"

- 9 Dec. 2011: First beam from LINAC
- 25 Dec. 2011: extraction to neutrino beam line

Happy New Year !

January 2012

J-PARC Director, Shoji Nagamiya

Gerry:

Thank you very much for many years of inspiration, precious and firm guidance!

Your impact is greater than you can imagine!

Look forward to/require more!