NEUTRINO PHYSICS RESULTS FROM T2K

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for the T2K Collaboration

Neutrino Oscillation Workshop
Ostuni, 10 September 2018

Neutrino physics results from T2K

- The open questions in neutrino oscillations
- T2K's goals and approach
- About T2K
- T2K oscillation analysis
- Neutrino interactions
- Plans for the future
- Conclusion

Open questions in neutrino oscillations

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\Delta_{32}\left(\sin^2\theta_{23} - \frac{\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta_{CP}}{2\sin\theta_{13}}\Delta_{21}\right)$$

$$P(\nu_\mu \to \not\nu_\mu) \approx \sin^2(2\theta_{23})\Delta_{32}$$

$$P(\nu_e \to \not\nu_e) \approx \sin^2(2\theta_{13})\Delta_{32}$$

θ_{13}

$\sin(2\theta_{23}) \sim 1$

$\sin^2(\theta_{23}) \sim 0.5$

δ_{CP}

$$\text{where } \Delta_{ij} \equiv \sin^2\frac{\Delta m^2_{ij} L}{4E}$$

- Oscillation depends on:
  - Mixing angles: θ_{12}, θ_{23}, θ_{13}
    - Is $\sin^2 2\theta_{23}$ maximal or not? If not, what is the octant (< or >45°)?
  - Mass splitting: $|\Delta m^2_{32,31}| \sim \Delta m^2_{atm}$, Δm^2_{21}
    - What is the mass hierarchy?
      - $\Delta m^2_{32,31} > 0$: Normal, <0 Inverted
  - Is there CPV in neutrino oscillations?
    - In standard PMNS model with Dirac neutrinos, parametrized by one CP violating phase δ
    - Causes neutrino vs. antineutrino appearance (but not disappearance) rates to differ

T2K: Physics goals

- T2K's major physics goals:
  - Search for $\nu_\mu \rightarrow \nu_e$ appearance (found!) and measure precisely (underway)
  - Measure ν_μ disappearance precisely (done, improving)
  - Search for CP violation using antineutrino beam (initial results, more underway)
  - Measure neutrino interaction cross-sections (some done, others underway)
  - Searches for exotic physics (underway)

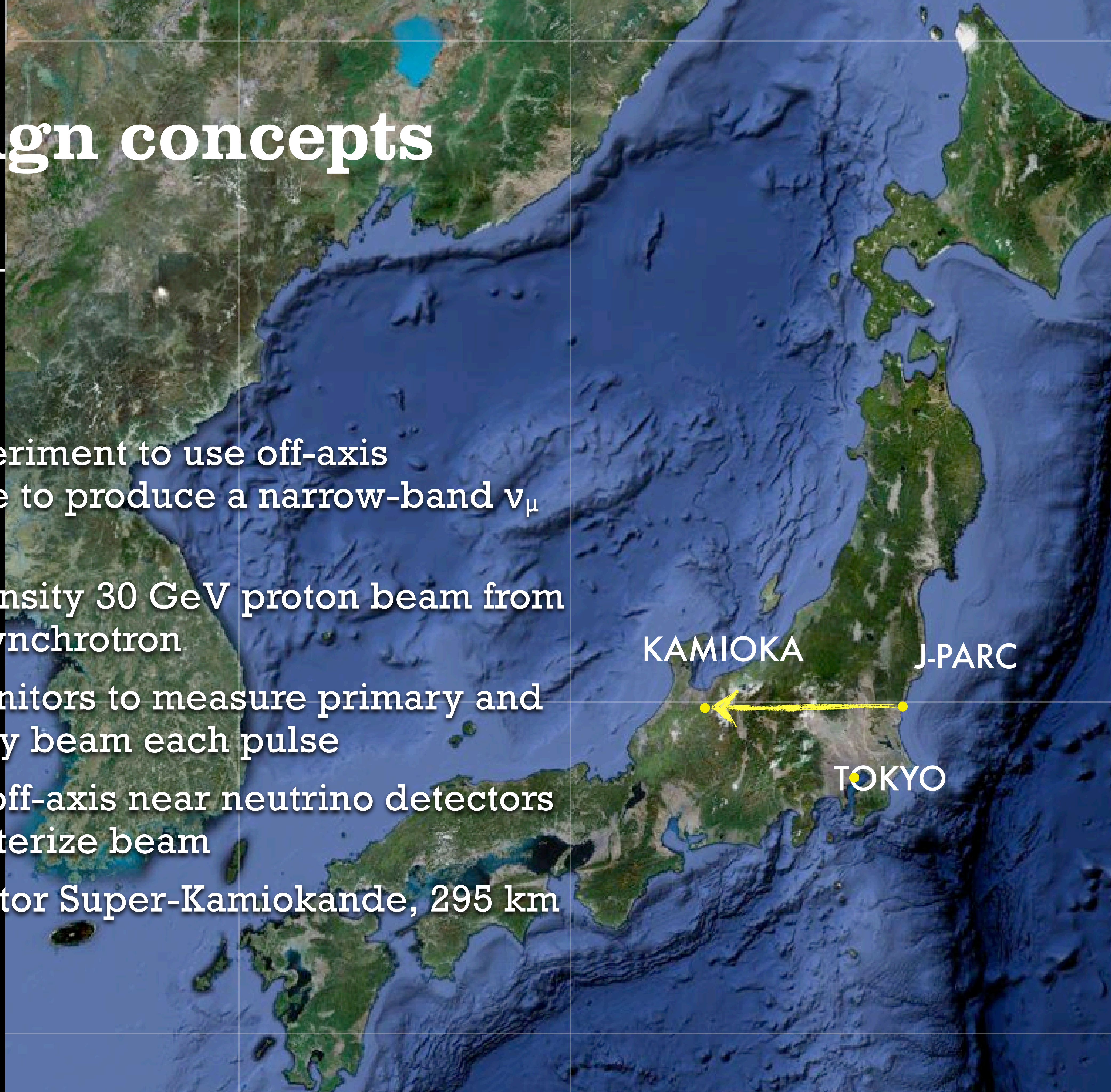

T2K is...
Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.
France
CEA Saclay
LLR E. Poly.
LPNHE Paris
Germany
Aachen U.
Italy
INFN, U. Bari
INFN, U. Naples
INFN, U. Padua
INFN, U. Rome
Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U. of Science
Yokohama National U.
Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.
Russia
INR
Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid
Switzerland
ETH Zurich
U. Bern
U. Geneva
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. London
Royal Holloway U. London
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick
Texas
U. of Houston
USA
Boston U.
Colorado St U.
Duke U.
Louisiana State U.
Michigan St. U.
SLAC
Stony Brook U.
U. C. Irvine
U. of Colorado
U. of Pittsburgh
U. Rochester
U. Washington
Vietnam
IFIRSE
IOP, VAST
T2K Breakthrough Prize Celebration, 2016

Two approaches to measuring θ_{13}:

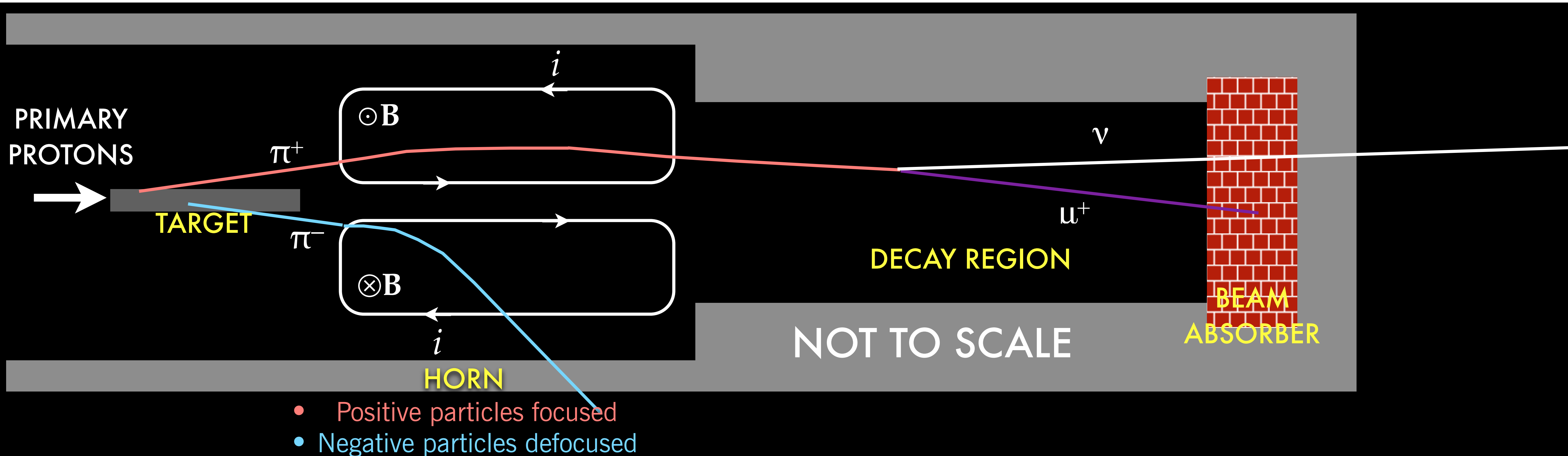
- Search for $\nu_\mu \rightarrow \nu_e$ in long-baseline accelerator measurements:
  - Present: T2K, NOvA
  - Future: Hyper-Kamiokande, DUNE
- Search for $\bar{\nu}_e$ disappearance at nuclear reactors
  - Daya Bay, RENO, Double Chooz

T2K design concepts

- Design:
  - First experiment to use off-axis technique to produce a narrow-band ν_μ beam
  - High-intensity 30 GeV proton beam from J-PARC synchrotron
  - Beam monitors to measure primary and secondary beam each pulse
  - On- and off-axis near neutrino detectors to characterize beam
  - Far detector Super-Kamiokande, 295 km baseline

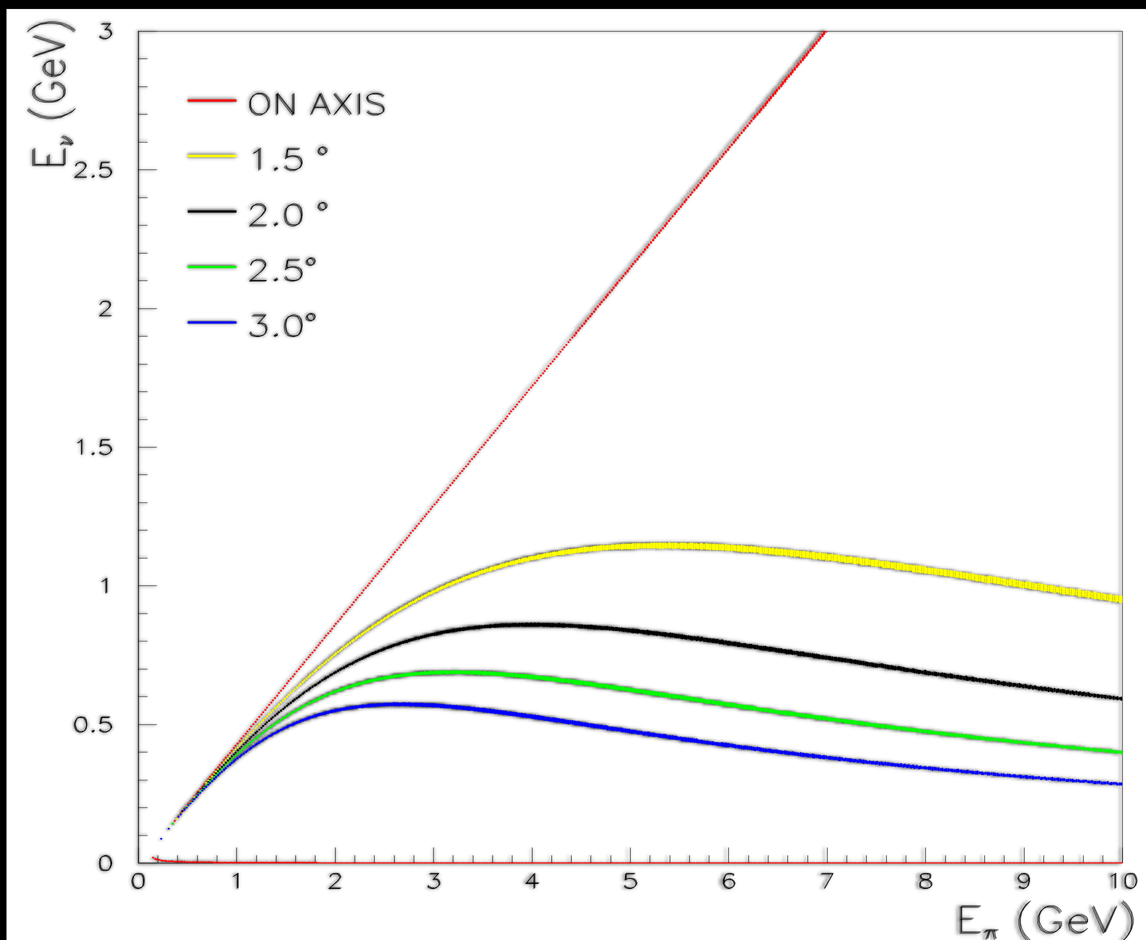


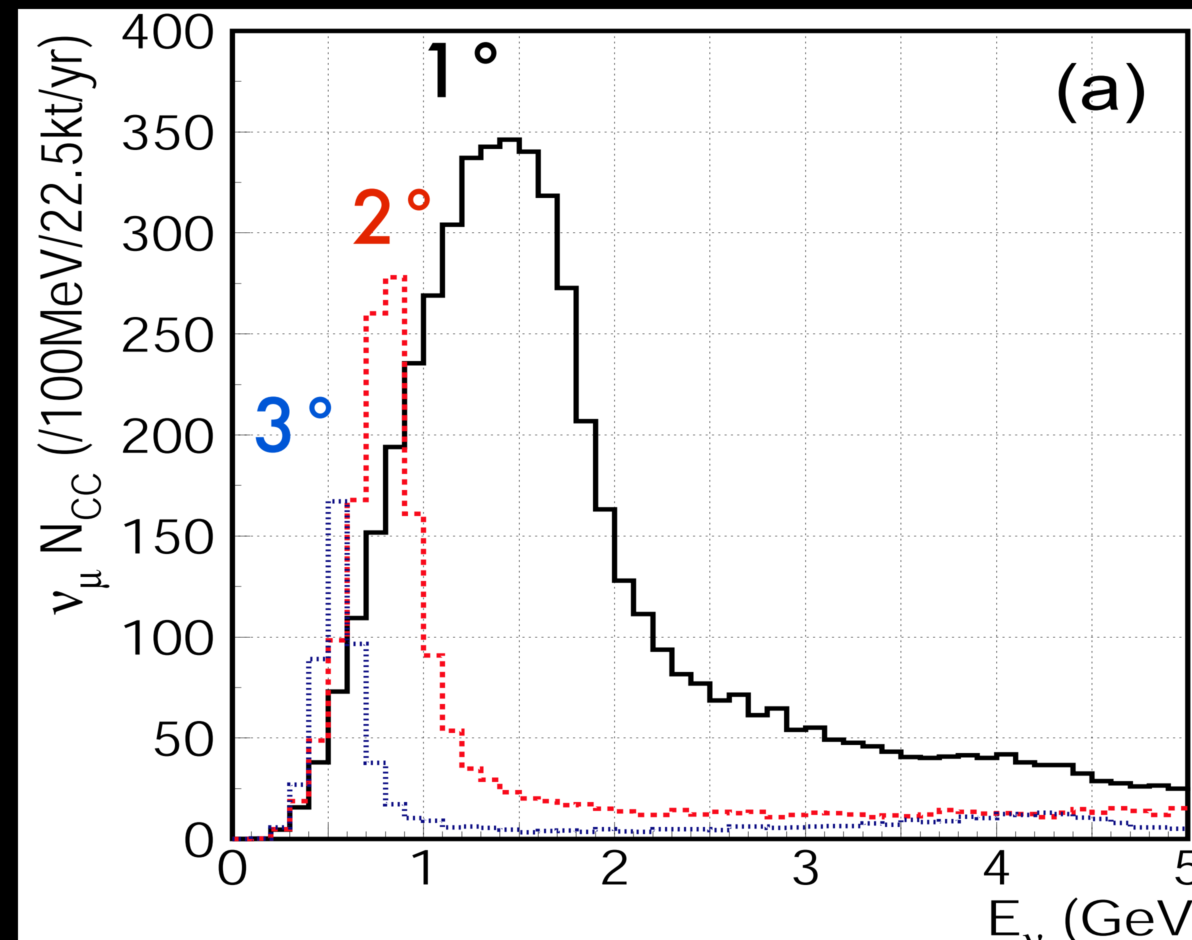
Accelerator-based neutrino beam principle



- Horn current direction determines whether π^+ (for ν beam) or π^- (for $\bar{\nu}$ beam) focused
  - Forward horn current (FHC): neutrino mode
  - Reverse horn current (RHC): antineutrino mode
- Neutrino beam properties:
  - Predominantly ν_μ, with ν_e contamination at the ~1% level from muon, kaon decays.
  - Wrong-sign contamination is relatively higher in antineutrino mode
  - Neutrino energies from <0.4 GeV to >4 GeV
    - Even "narrow-band" beams tend to have tails to high energy
  - Fluxes have significant systematic errors

Off-axis beam technique

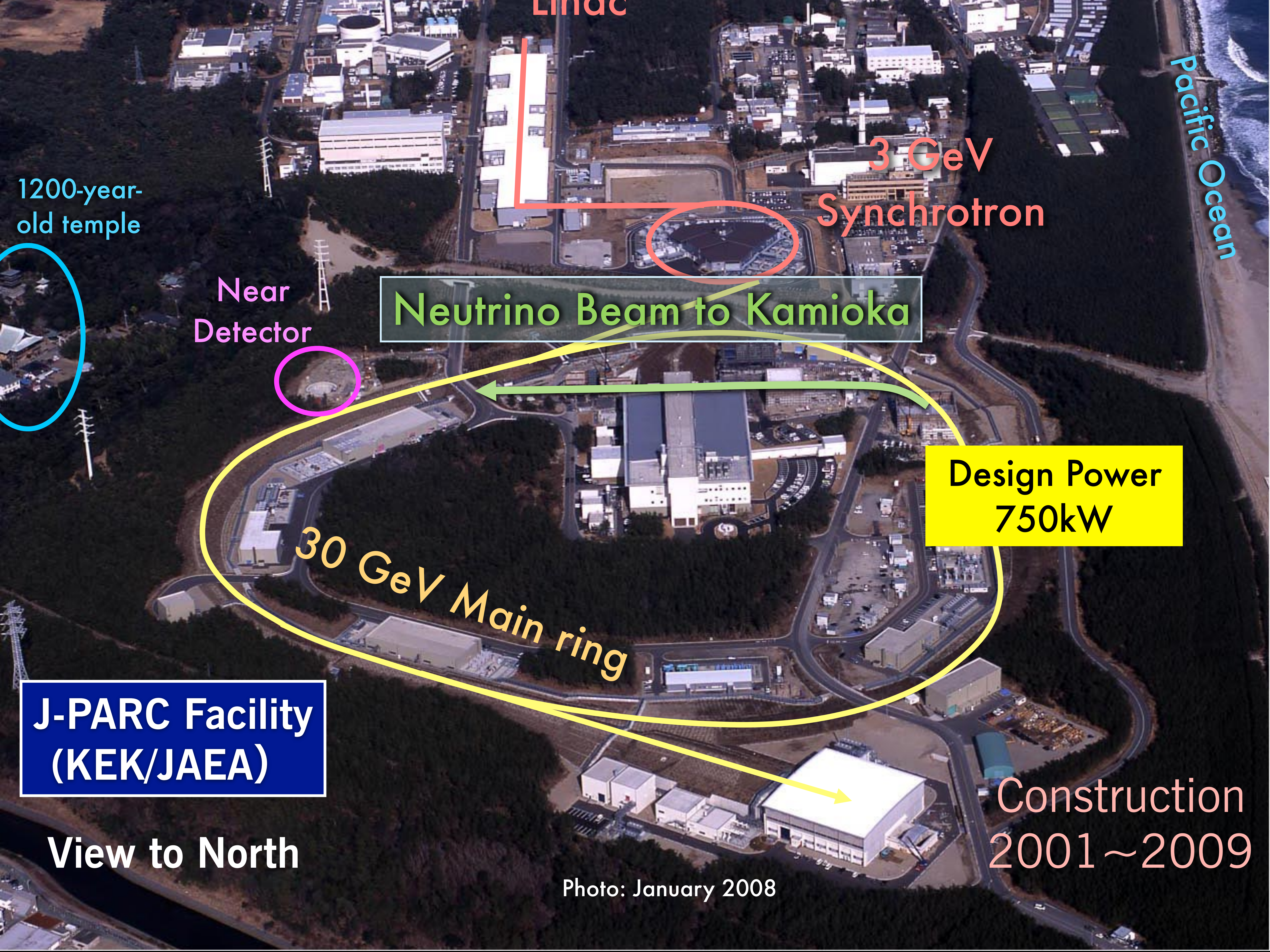




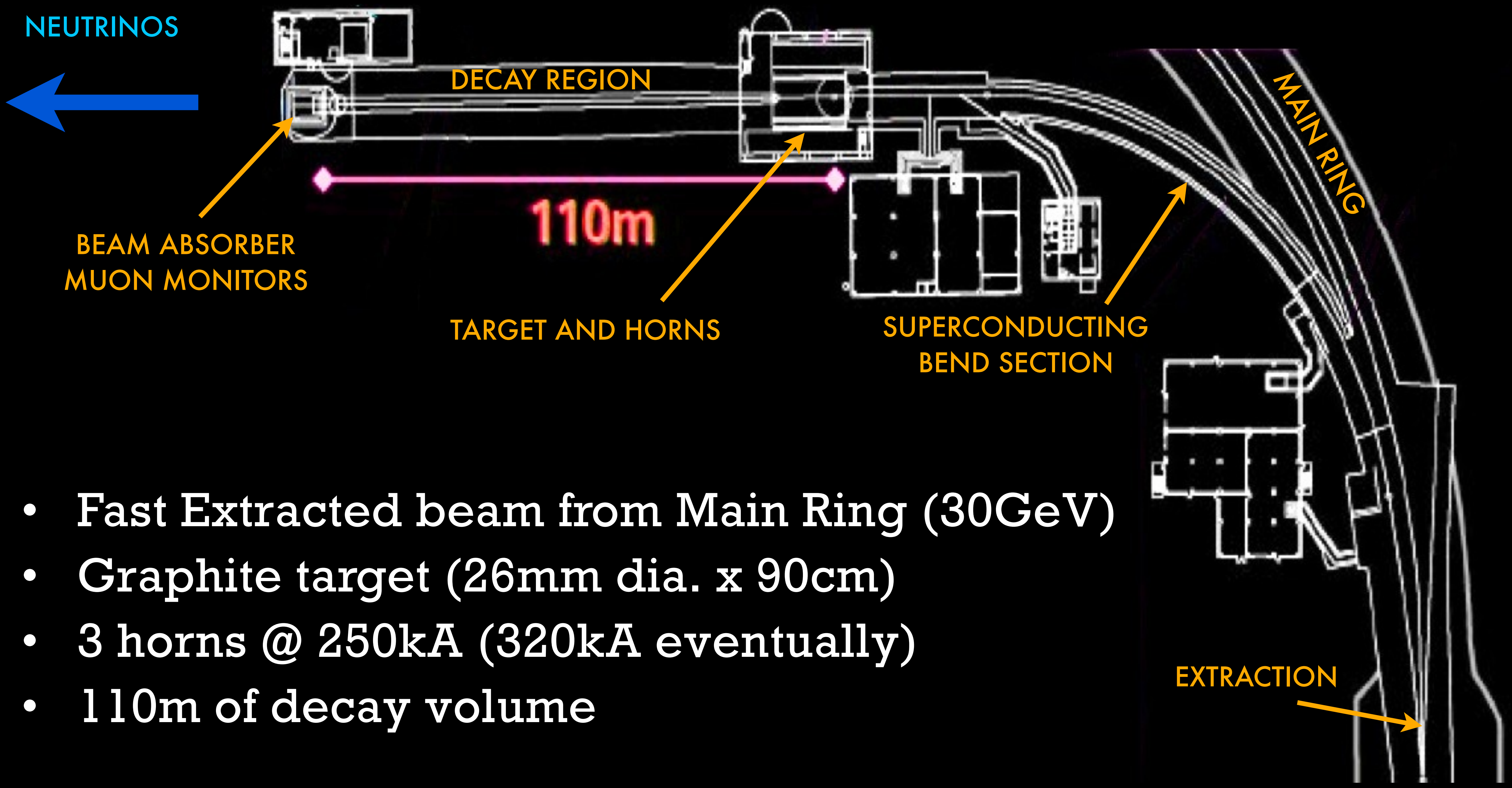
- For wide range of pion momenta, E_ν depends more on decay angle than E_π
- Exploit to make narrow-band ν_μ beams by going off-axis
- At 295 km baseline, first oscillation maximum is at 570 MeV for $\Delta m^2 = 2.4 \cdot 10^{-3}$ eV^2 $\Rightarrow$ T2K wants 2.5° off-axis angle

The facilities and experiment

- J-PARC accelerator
- Neutrino beam facility
- Near detector complex
- Far detector: Super-Kamiokande
- Operations and data collection so far

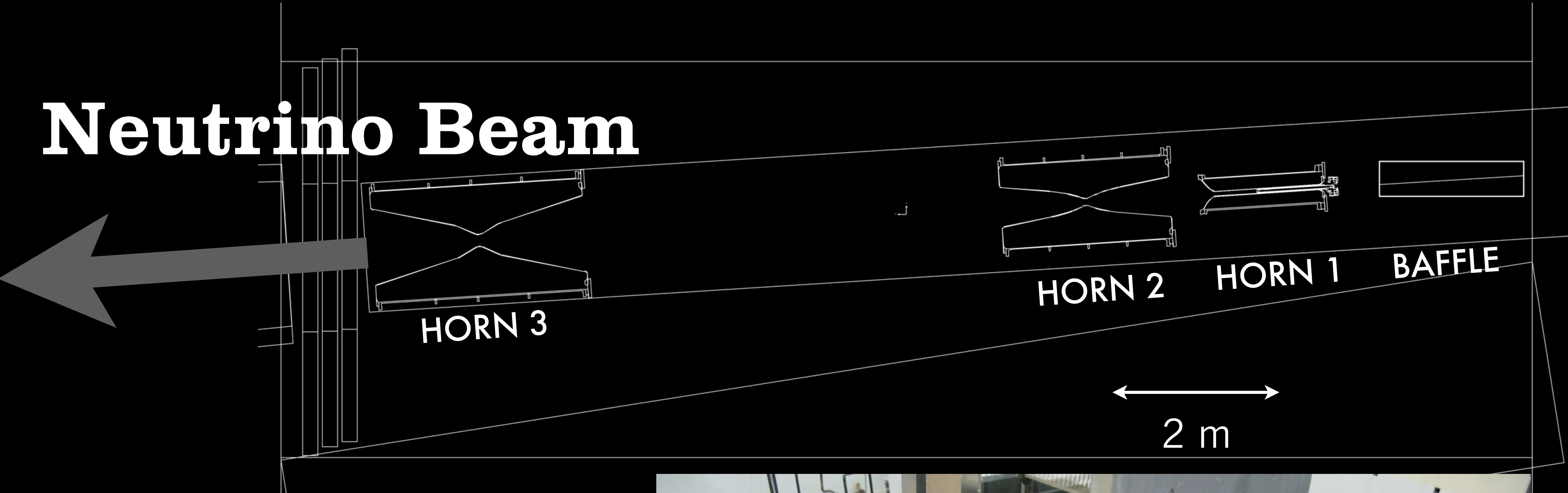

Linac
3 GeV
Synchrotron
Pacific Ocean
1200-year-
old temple
Near
Detector
Neutrino Beam to Kamioka
Design Power
750kW
30 GeV Main ring
J-PARC Facility
(KEK/JAEA)
View to North
Photo: January 2008
Construction
2001~2009

Neutrino Beam



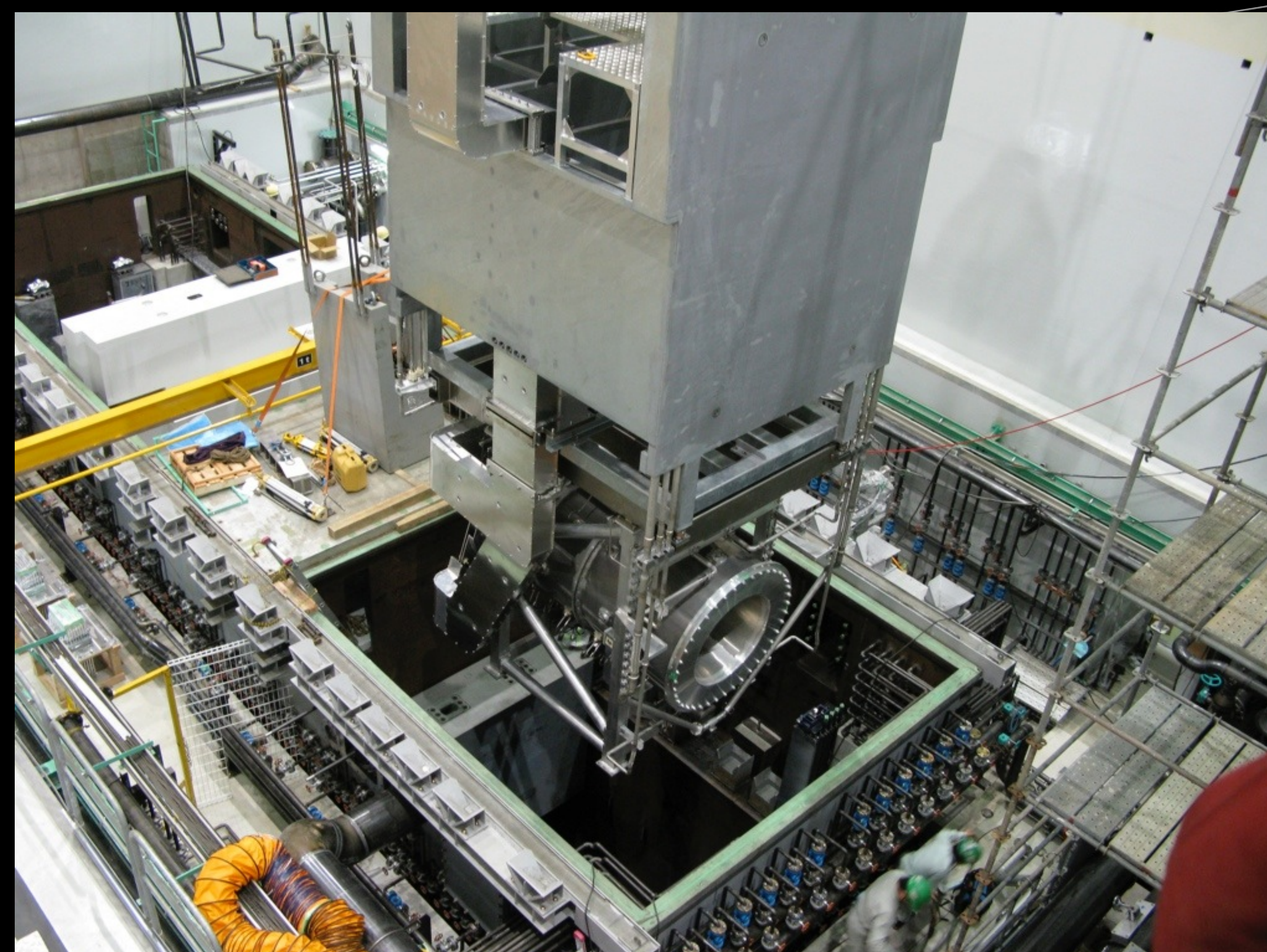
- Fast Extracted beam from Main Ring (30GeV)
- Graphite target (26mm dia. x 90cm)
- 3 horns @ 250kA (320kA eventually)
- 110m of decay volume

Neutrino Beam



Target Station building: three horns in helium vessel

(Horn 3 shown during installation)



Neutrino beam: the decay tunnel and absorber

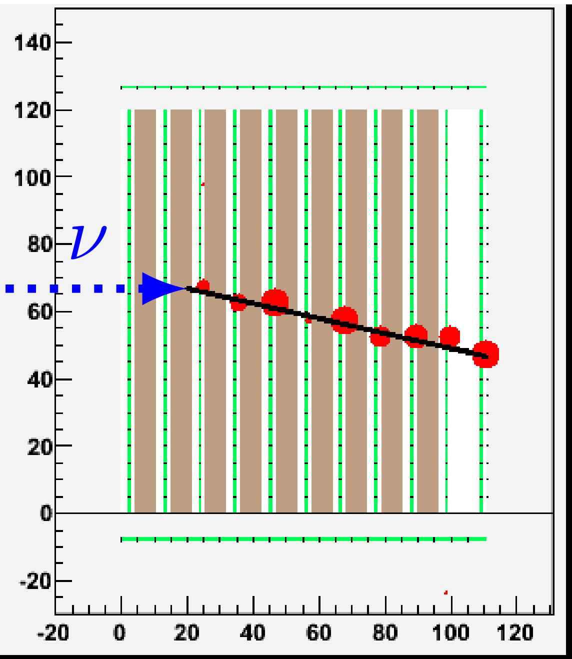
Decay tunnel

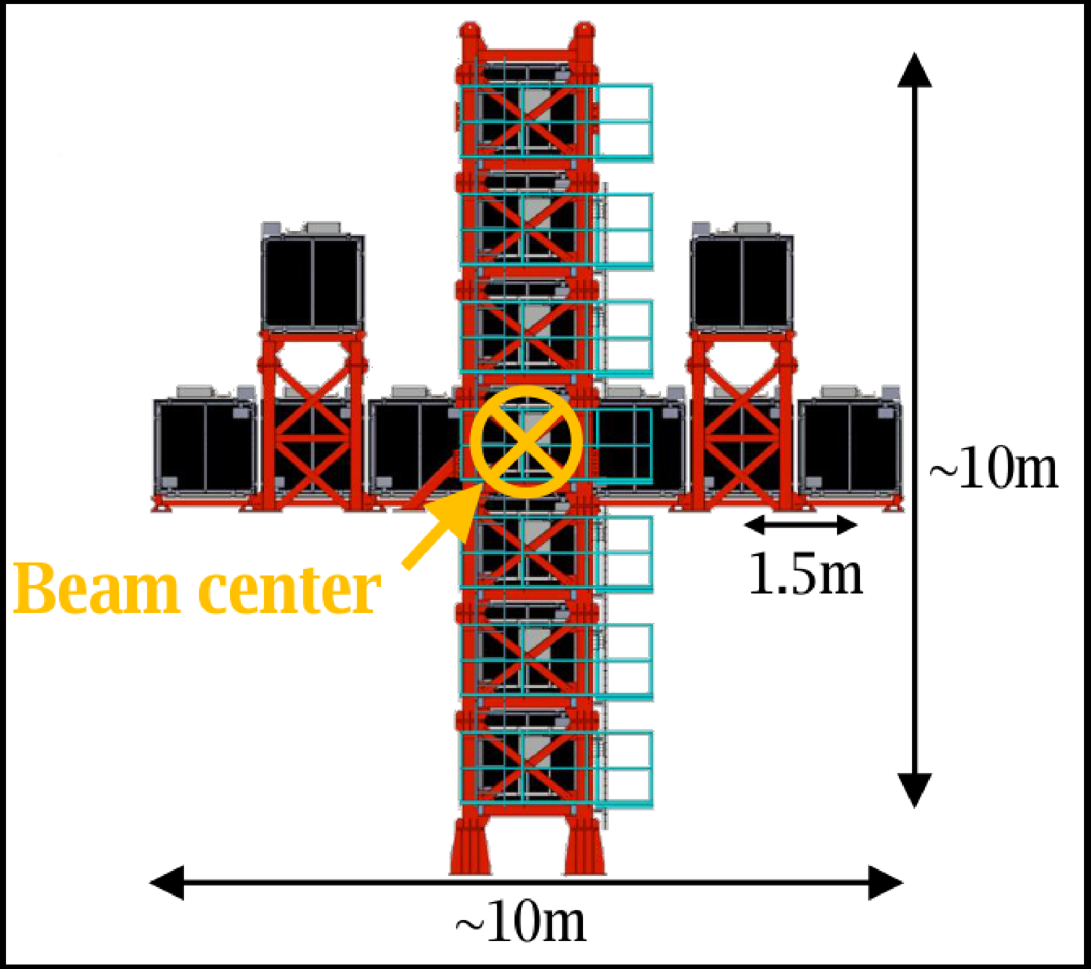
Absorber

Muon monitor

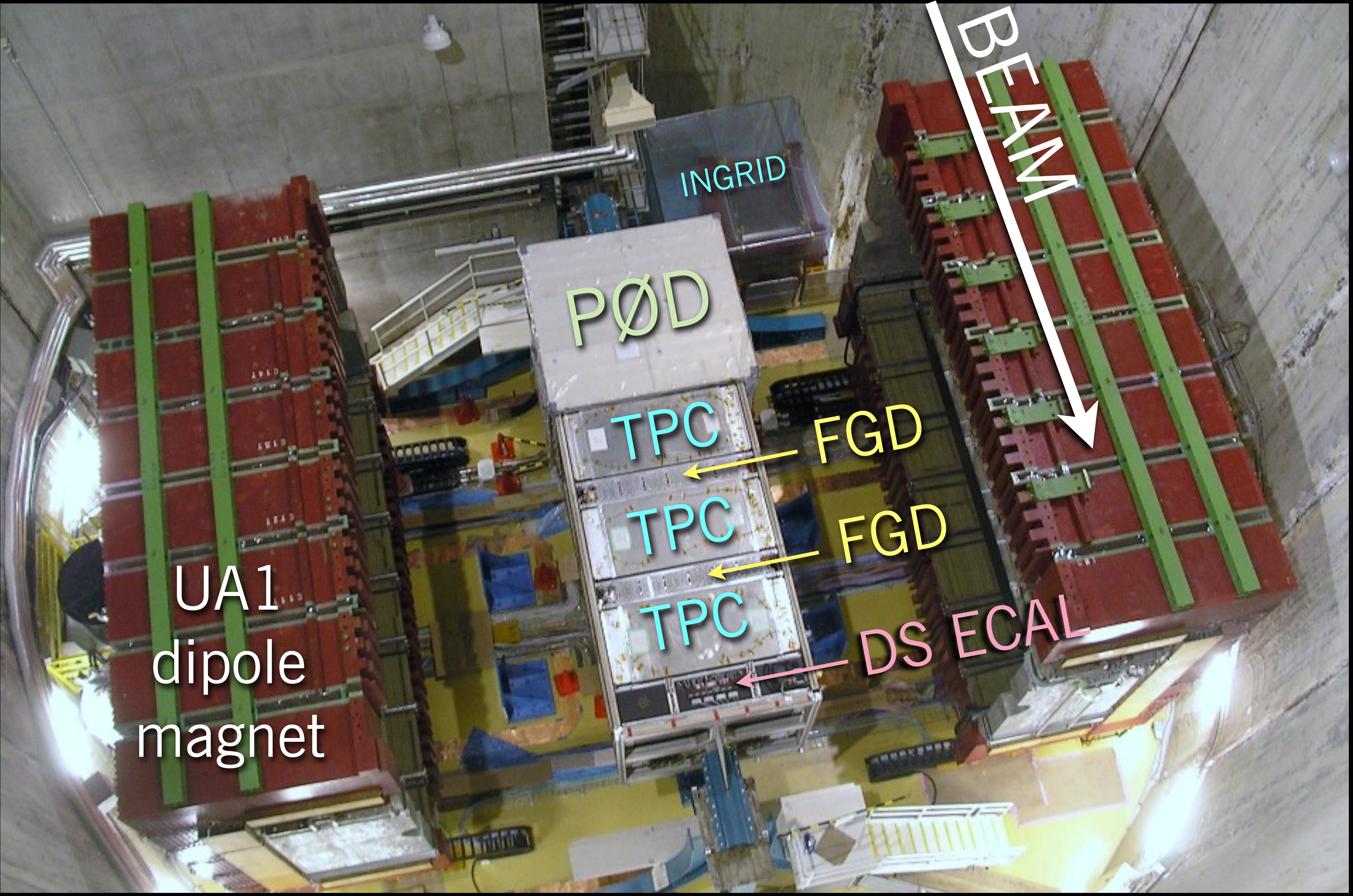
280m on-axis near detector: INGRID

- Array of 9-ton iron-scintillator neutrino detectors in cross shape centered on beam axis
- Designed to show neutrino beam profile, event rate, and precise measure of beam center/off-axis angle





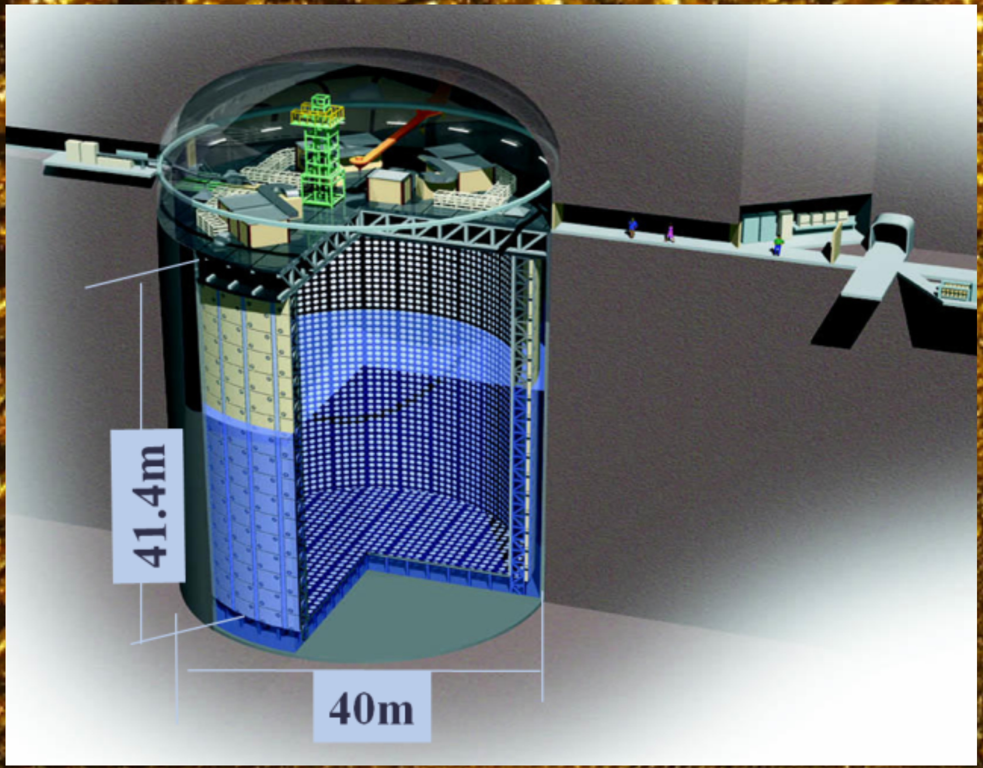
Off-axis Near Detector (ND280)



- PiØ Detector (PØD): optimized for π^0 detection, includes H_2O target
- Tracker: 2 Fine-Grained Detectors (FGD), H_2O target, 3 TPCs: measure fluxes before oscillation
- ECAL: surrounding P0D and Tracker, measure EM activity
- Side Muon Range Detector: in the magnet yokes, identify muons

Super-Kamiokande

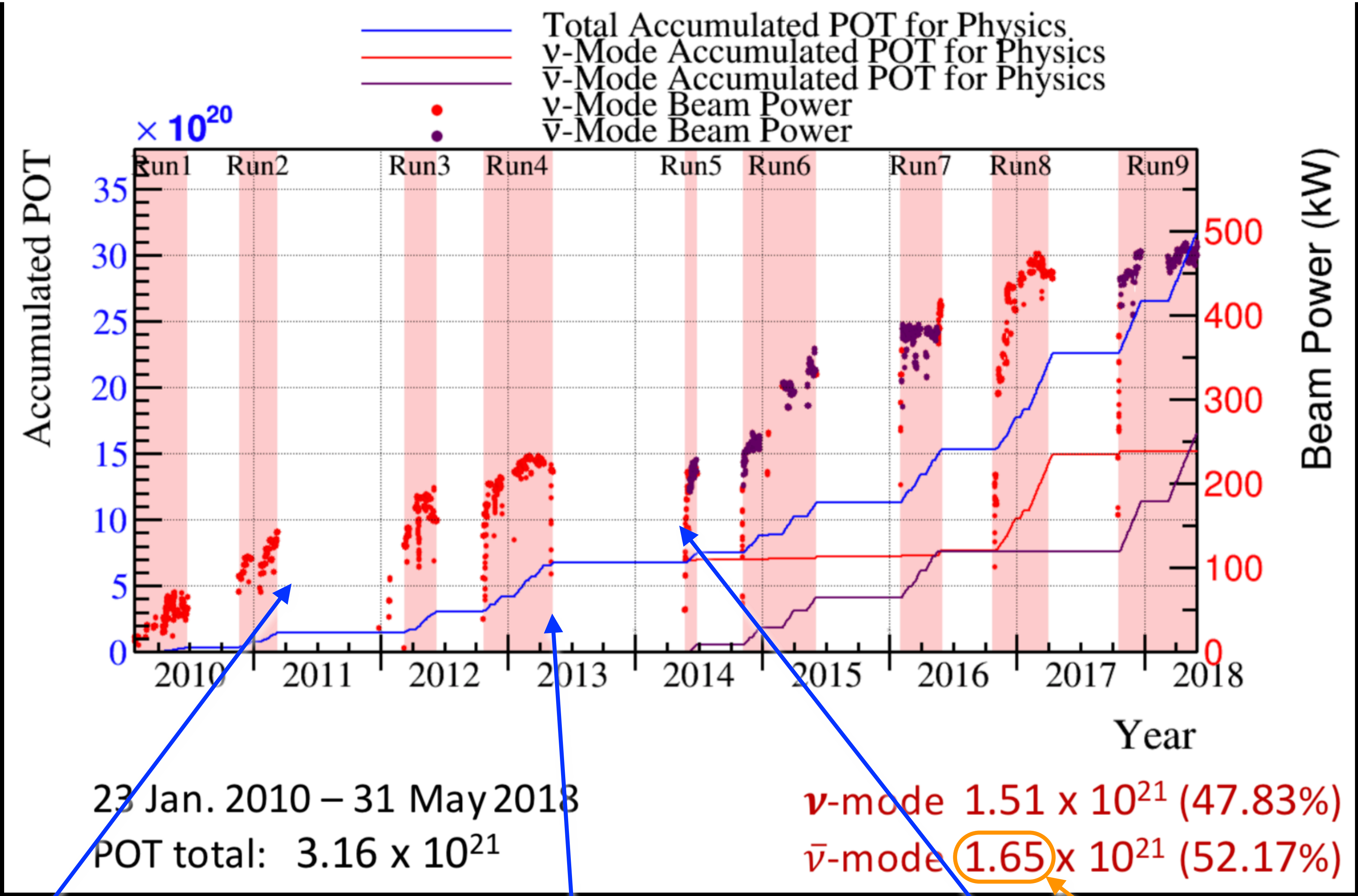
- 50 kt water Cherenkov
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector



- Originally commissioned 1997
- Undergoing refurbishment now (tank is open)
- Expect recommissioning around end of 2018
- Gadolinium doping to begin next year

Neutrino physics runs

- Beam delivery since 2010
- 3.16×10^{21} protons on target so far
- Steadily increasing beam power:
  - Have exceeded 500 kW
  - Steady running now at 485 kW



Analyzed 1.12×10^{21}

March 2011: Great East Japan Earthquake

May 2013: Hadron hall radiation incident

June 2014: First antineutrino mode data

Neutrino oscillation analysis

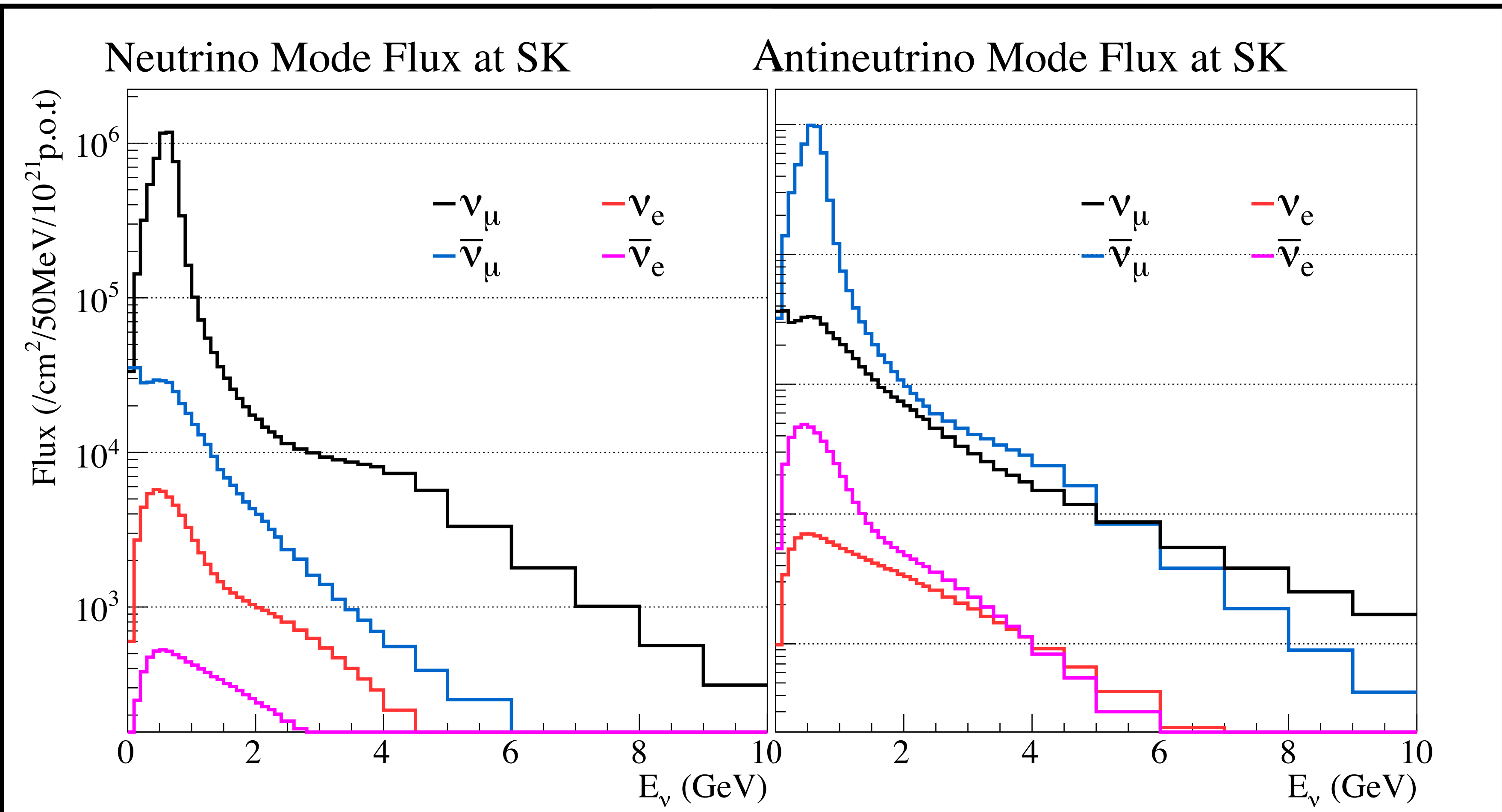
- Event rates depend on
  - Oscillation parameters **o**: $\Delta m^2_{32,31}$, θ_{12}, θ_{13}, θ_{23}, δ_{CP}, MH
  - Nuisance parameters **x**: flux, cross-sections, detector effects, oscillation priors from external data (*e.g.* Δm^2_{21})

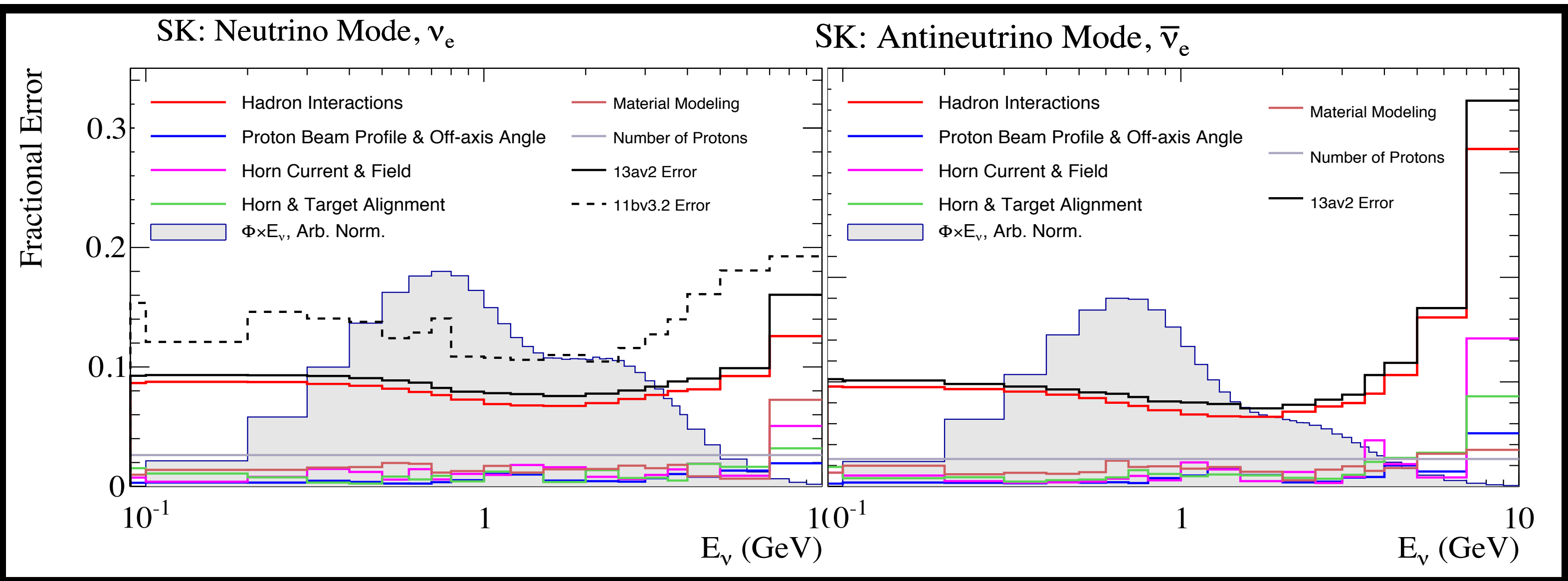
$$R(\vec{x},\vec{o}) = \int \Phi(E_\nu,\vec{x}) \times \sigma(E_\nu,\vec{x}) \times \epsilon(\vec{x}) \times P(\vec{o}:\nu_\mu \to \nu_{e,\mu})dE_\nu$$

- To fit, use:
  - Flux predictions from MC and external data
  - Near-detector fits to constrain flux and interaction model
  - Event predictions at SK
  - Event reconstruction and selection at SK
- Obtain combined fit of all oscillation parameters using all data channels

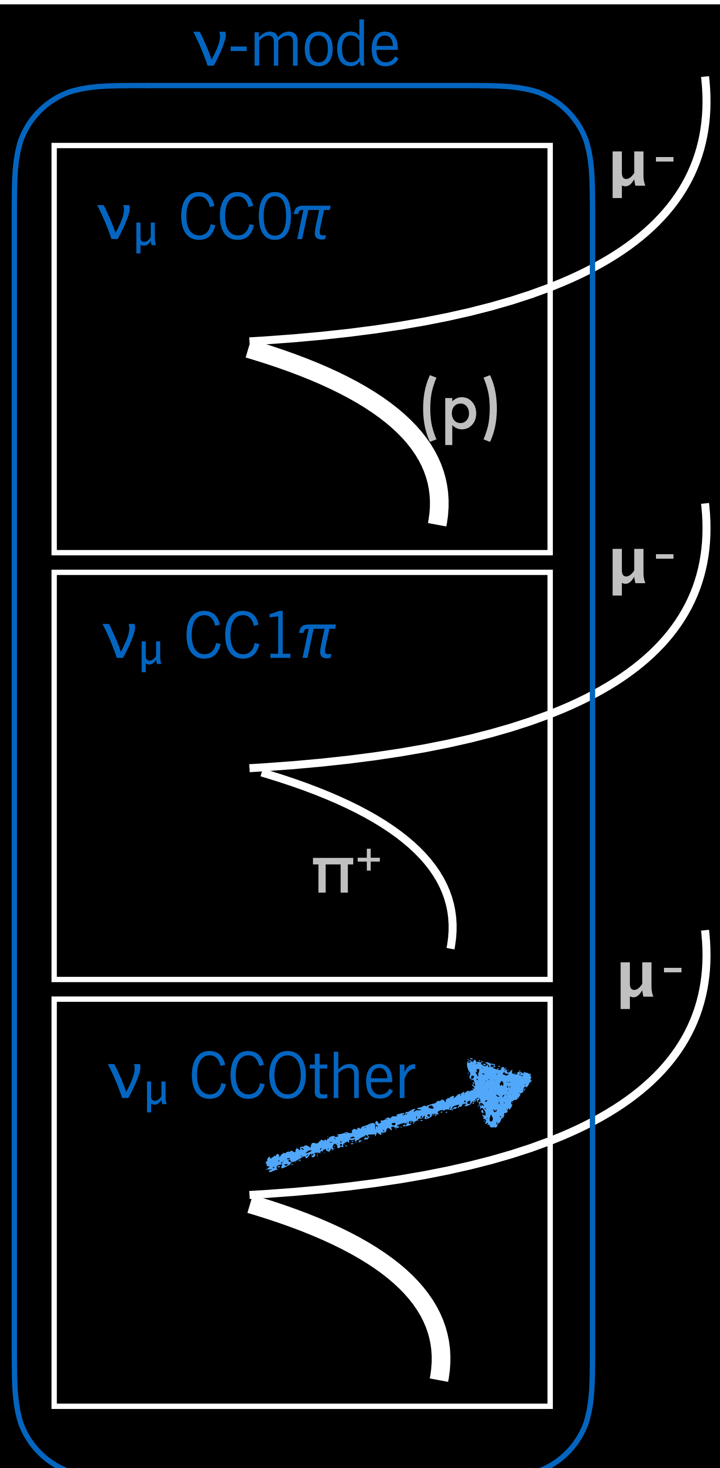
Neutrino beam flux predictions

- *A priori* prediction of un-oscillated flux at Super-Kamiokande
- Uses hadron production data from NA61/SHINE
- Hadron production uncertainties still dominate — but new NA61 replica target data will improve this soon (see talk by Matej Pavin)
- Absolute flux errors are <10% over most neutrino energies
- Use near detector constraint to improve event rate prediction at SK further

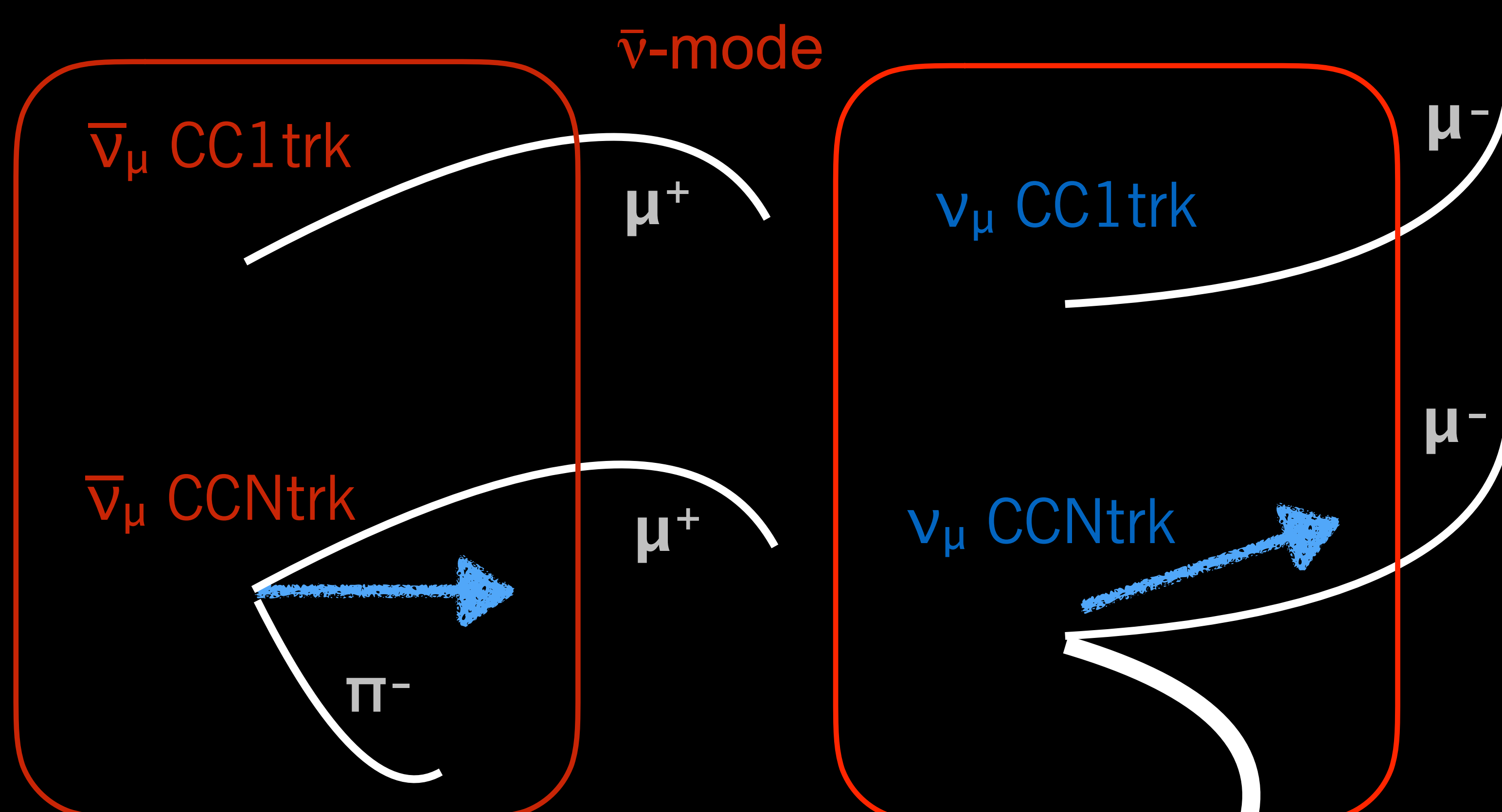




Near-detector samples used in oscillation fit

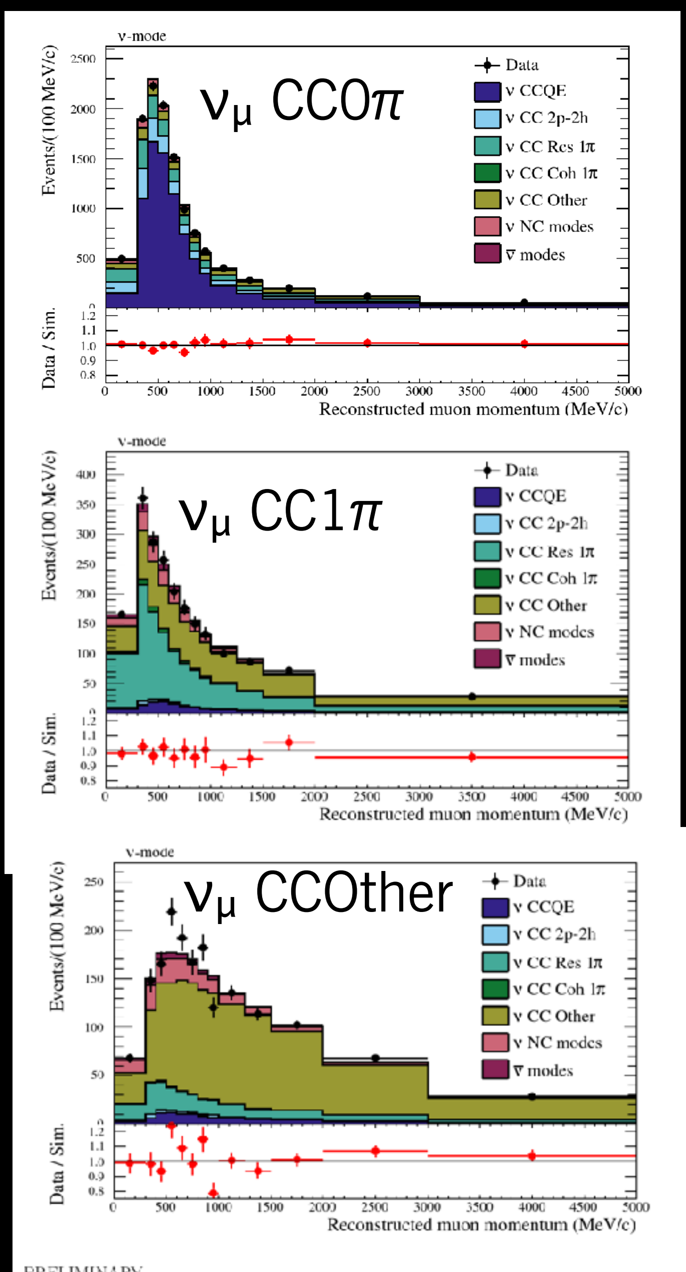


- 14 total samples
- **Neutrino mode:** sort by pion multiplicity; C and O fine-grained detectors
- **Antineutrino mode:** sort by muon charge and number of tracks; C and O fine-grained detectors
    - Wrong-sign backgrounds constrained with ND280 magnetic field

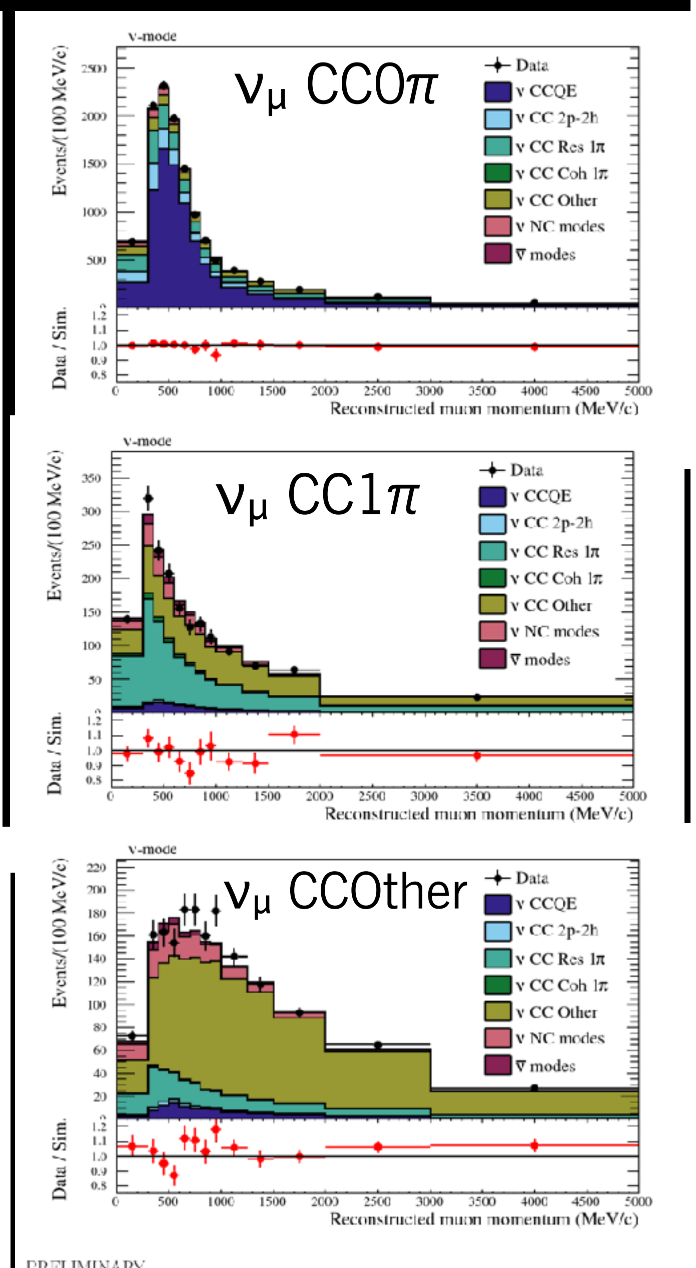


ND280 data for oscillation analysis

ν-mode

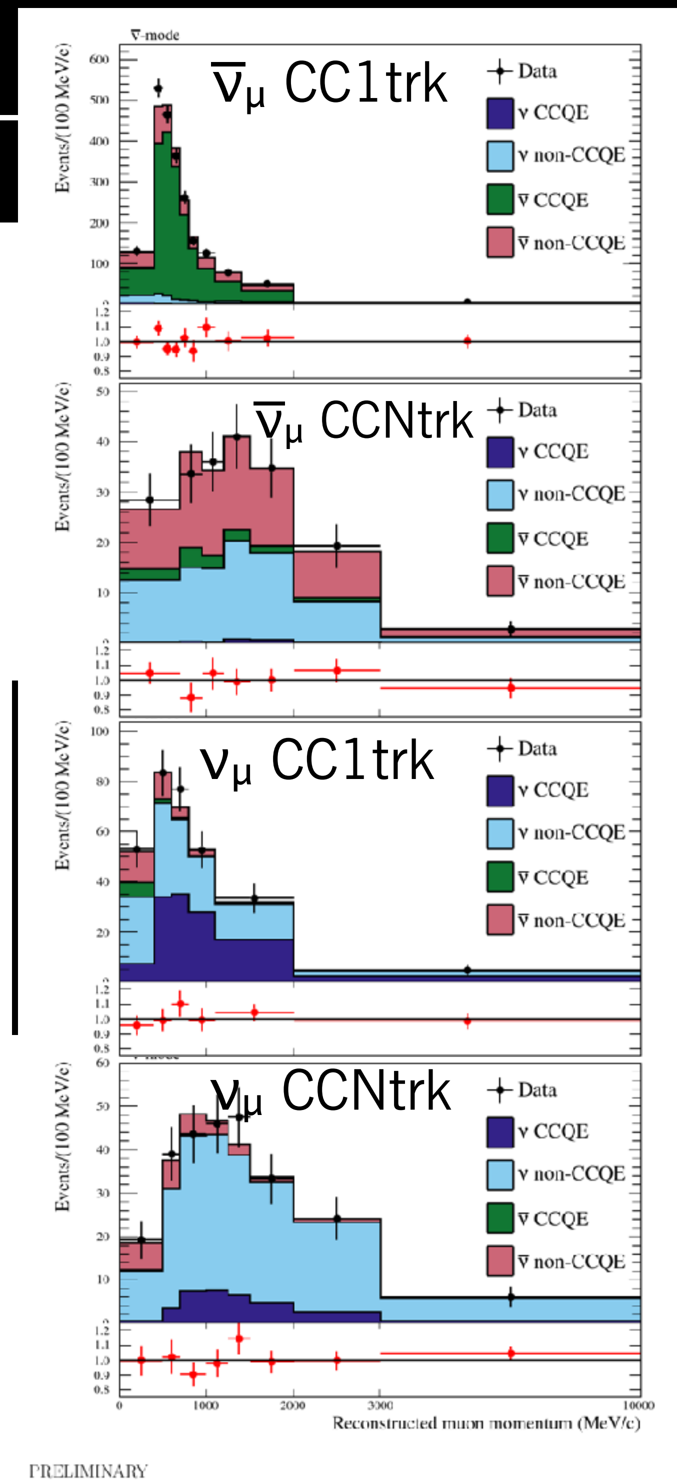


FGD1
(carbon)

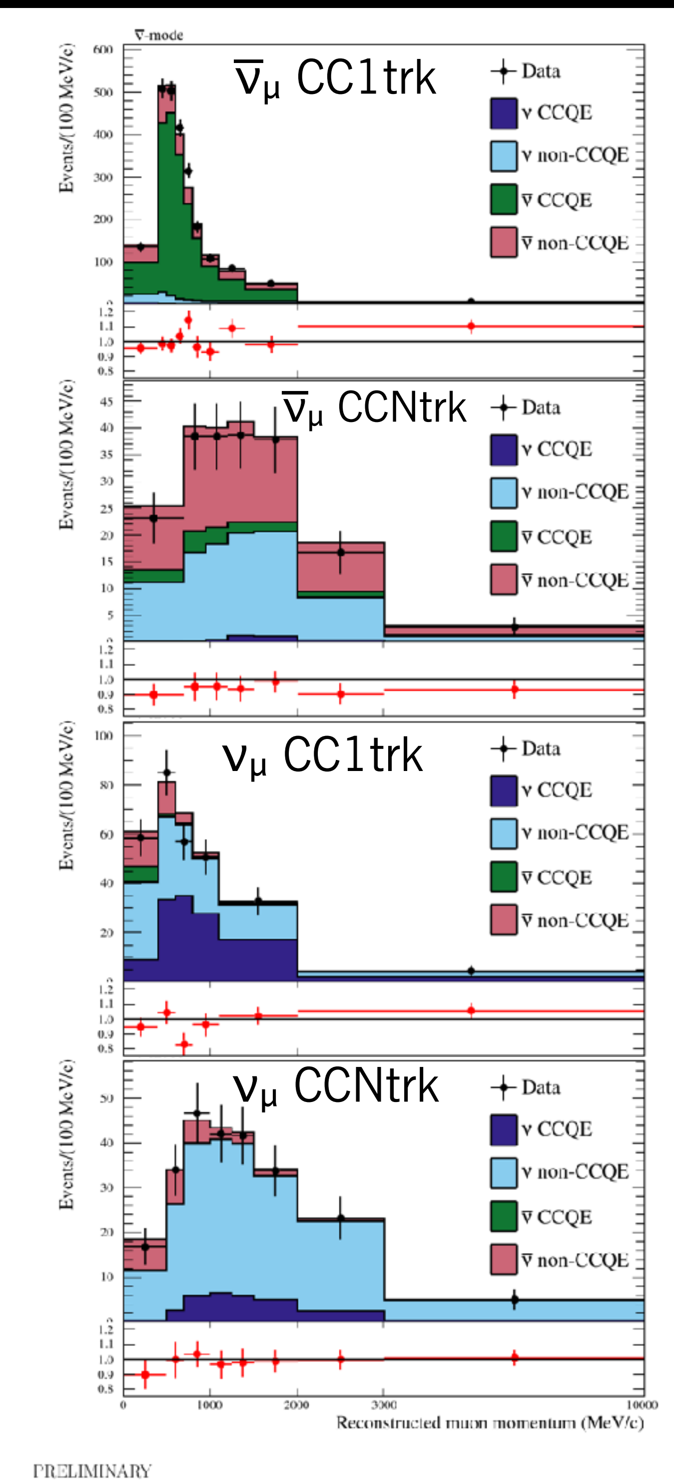


FGD2
(carbon & oxygen)

ν̄-mode



FGD1
(carbon)



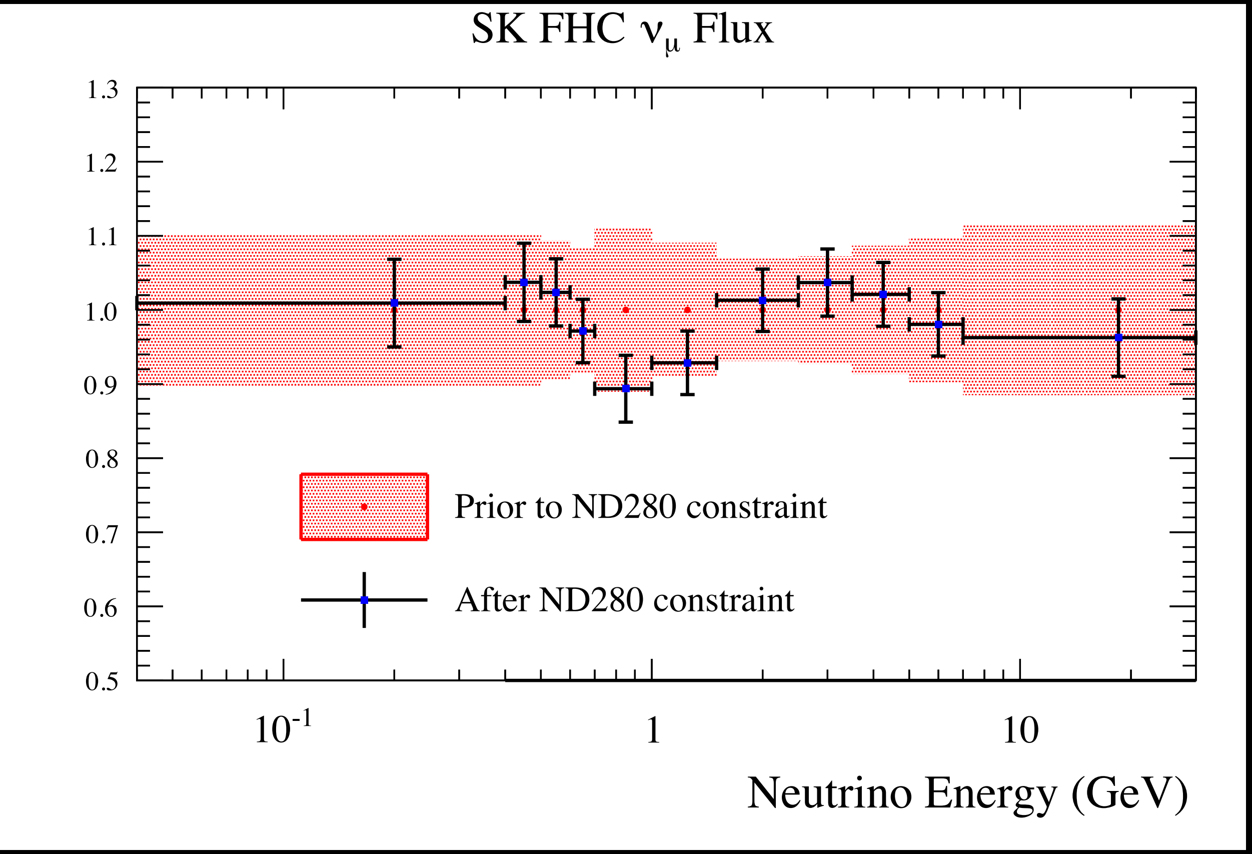
FGD2
(carbon & oxygen)

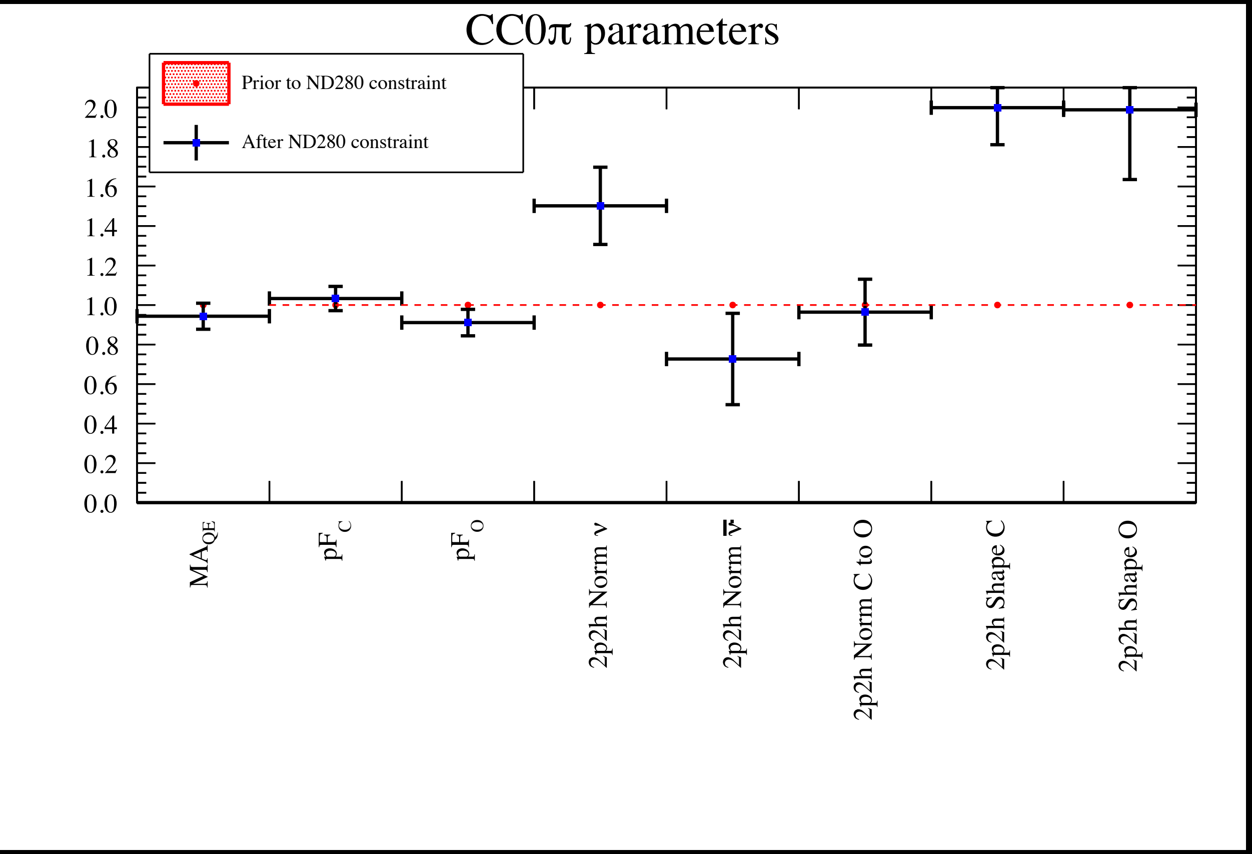
Highlights of T2K's neutrino interaction model

- Relativistic Fermi Gas (RFG) with dipole form factor
- 1p1h (scattering off single nucleon) uses Random Phase Approximation parameters from Valencia group, applied to our RFG model
- 2p2h (scattering off correlated nucleon pairs) model also from Valencia group (Nieves *et al.*).
- Single- and multi-pion uses models by Rein and Sehgal normalized to match D_2 bubble chamber (resonant, non-resonant) and MINERvA (coherent) data
- Deep Inelastic Scattering through PYTHIA 5.9
- FSI via Salcedo Oset and Bertini cascade models, tuned to external pion-nucleon scattering data
- We fit parameters for all these models (and flux model) to the ND280 data

Fitting the ND280 data

- Fitted flux and cross-section parameters vs. pre-fit (shown for one sample and channel only: ν_μ CC0π)
- Note improvement in flux error; higher 2p2h (scattering off correlated nucleon pairs) vs raw model by Nieves *et al*



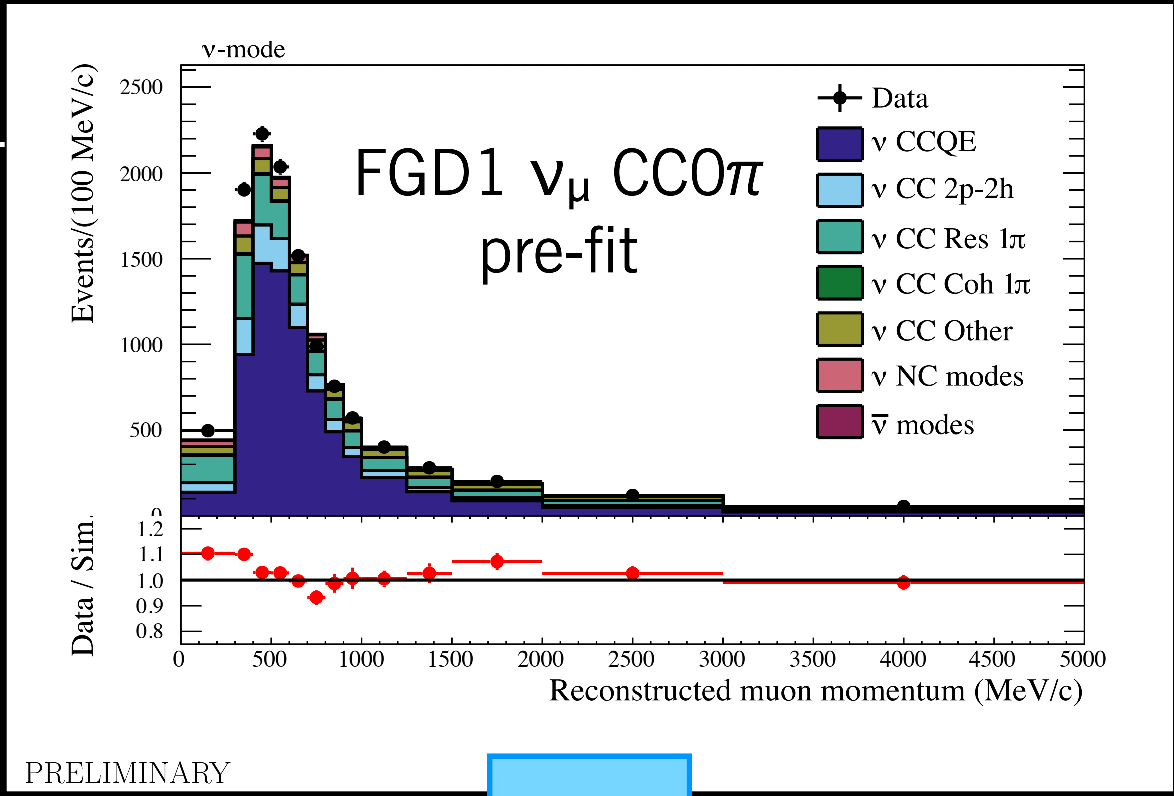


Fitting the ND280 data

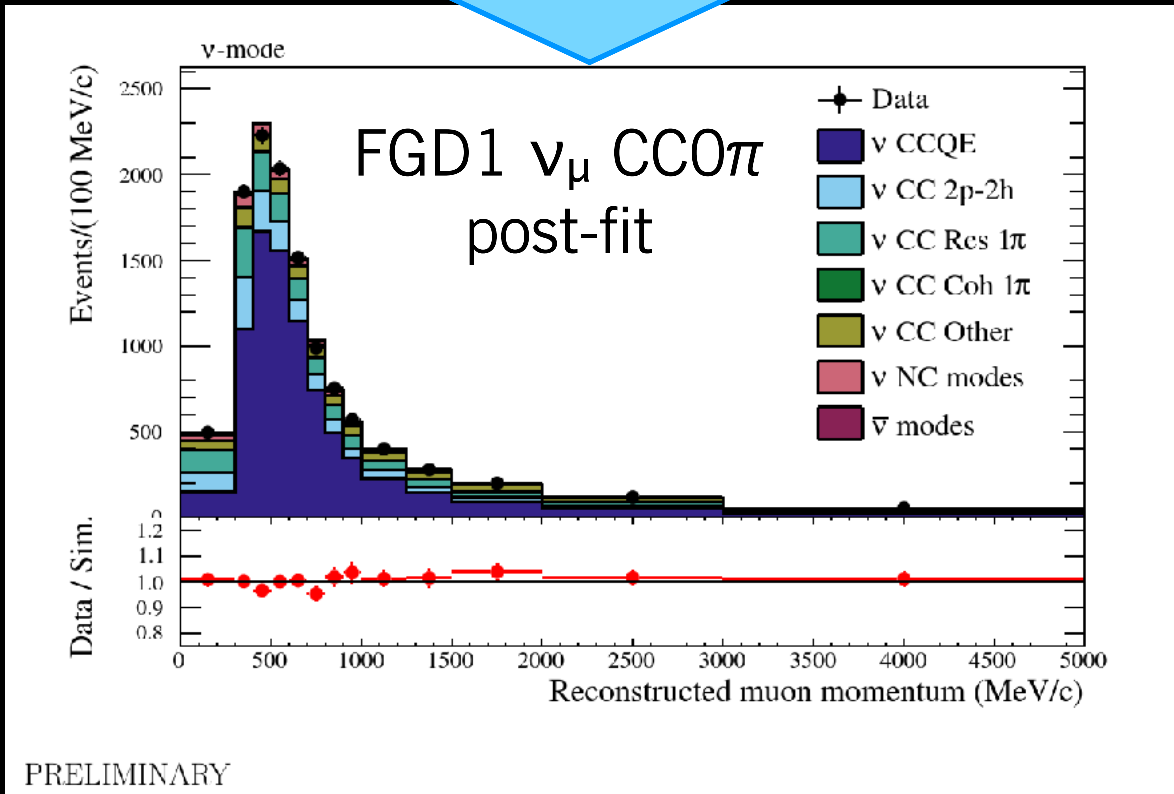
- Data fit result reduces error on SK event rate predictions to about 5-9% depending on channel

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	ν̄-mode	ν-mode	ν̄-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

Percentage error on event rate by error source and sample. Final column is the percentage error on the ratio of FHC/RHC events in the one-ring e sample.

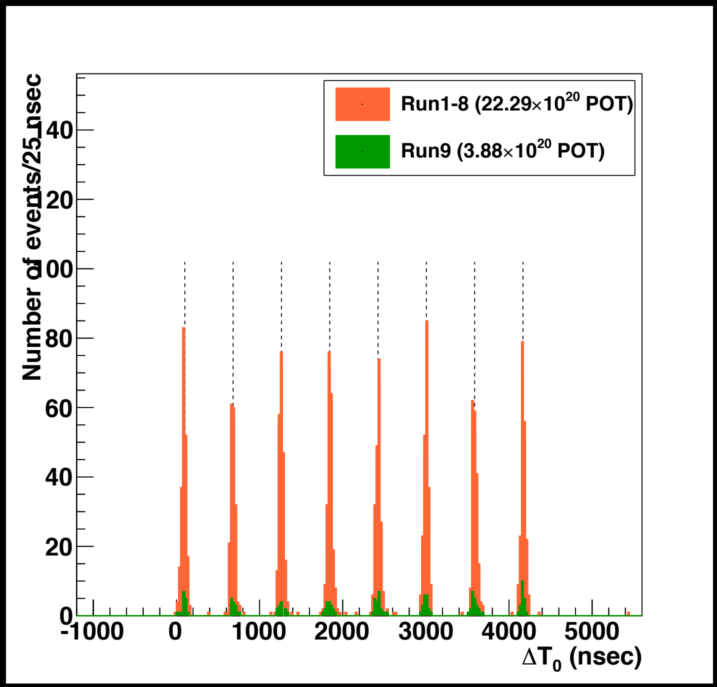


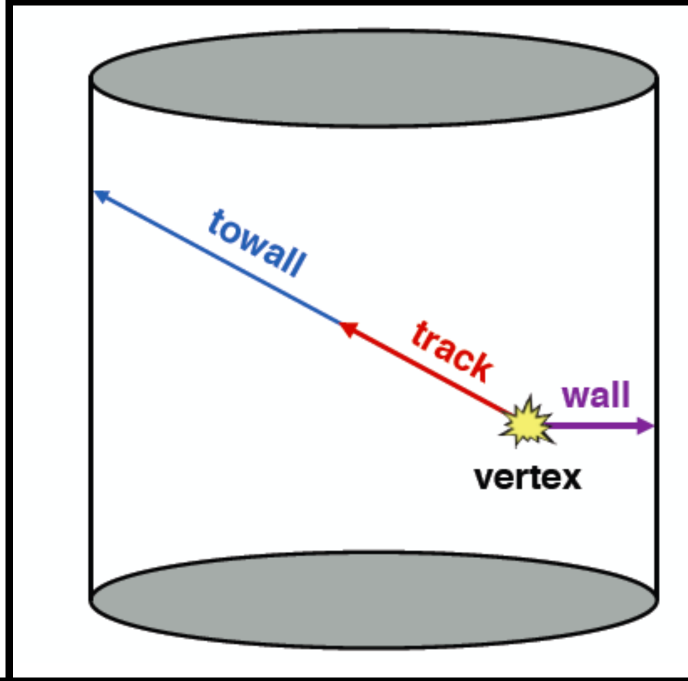
Data fit



Looking at the far-detector data

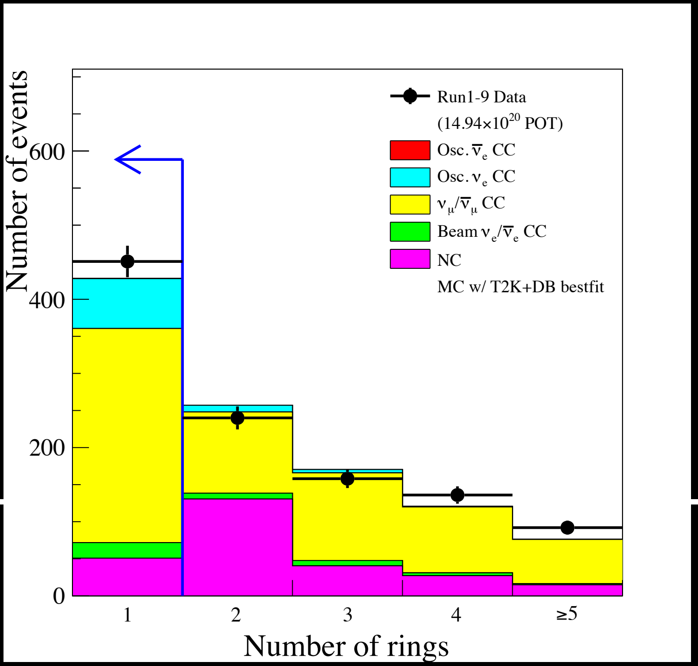
- Two main channels, by final state particles:
  - Charged-Current Quasi-Elastic (CCQE) samples: look for final state with a lepton and nucleon but no pions
  - $CC\pi^+$ (ν_e only): one charged pion in final state: mostly resonant CC interactions
- Selection criteria:
  - Within beam time window
  - Fully-contained (minimal outer-detector activity)
  - Fiducial cuts: cut on *wall* (distance from reconstructed vertex to detector wall) and *towall* (distance to wall along track direction).
    - Cut values optimized for each sample (at right)
    - New likelihood-based reconstruction (fiTQun) introduced 2017: allows 22% more signal to pass fiducial cuts than before





Sample	Towall Cut	Wall Cut
CCQE 1-Ring e-like FHC	170 cm	80 cm
CCQE 1-Ring μ-like FHC	250 cm	50 cm
$CC1\pi$ 1-Ring e-like FHC	270 cm	50 cm
CCQE 1-Ring e-like RHC	170 cm	80 cm
CCQE 1-Ring μ-like RHC	250 cm	50 cm

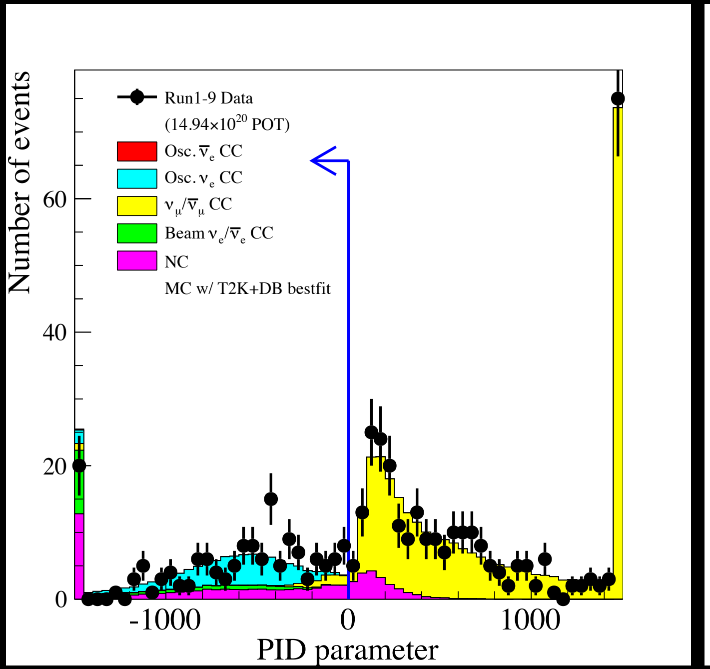
Event selections at SK

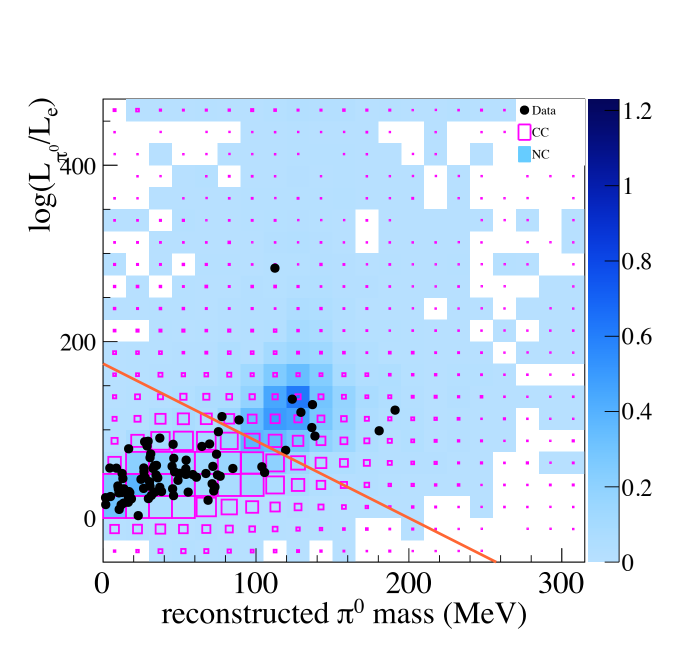


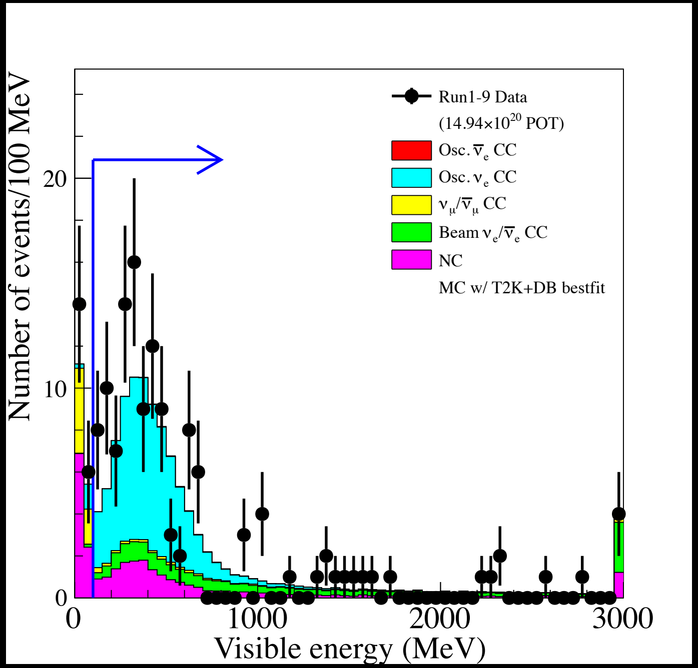
ν_e CCQE selections

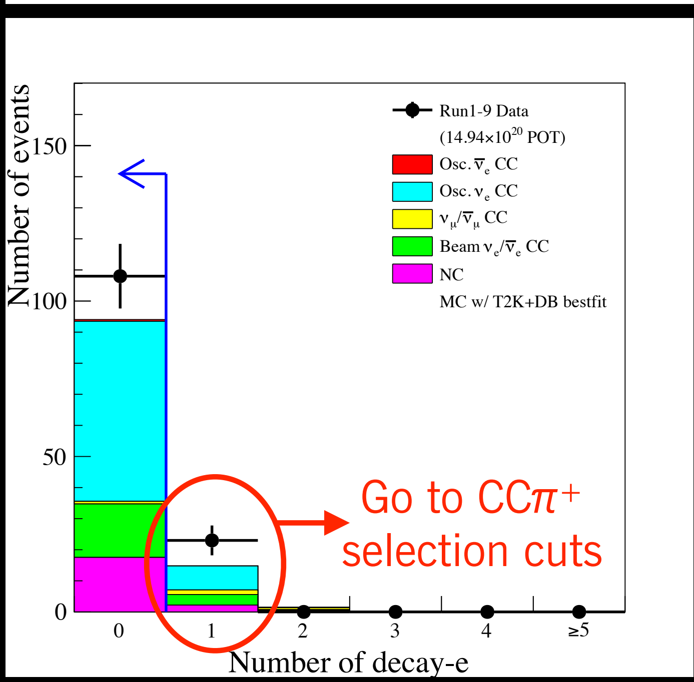
Starting from fully-contained fiducial events, select different samples based on:

- Number of rings (oscillation samples all require **one ring** for now)
- Ring particle-ID likelihood ratios: electron vs. muon, electron vs. π^0
- Visible energy >30 MeV
- Reconstructed energy <1.25 GeV
- Number of decay electrons:
  - <2 for $\nu_\mu/\bar{\nu}_\mu$ CCQE
  - <1 for $\nu_e/\bar{\nu}_e$ CCQE
  - =1 for ν_e CCπ^+ (sample added last year; adds 10% to expected statistics for appearance)









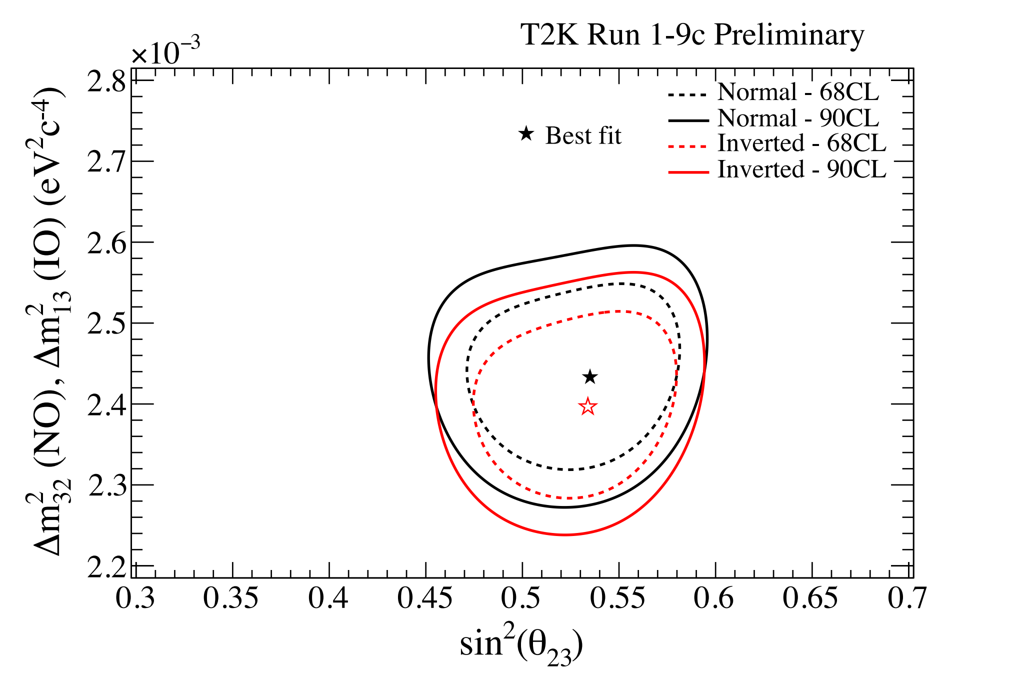
Statistics at SK

SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC μ CCQE	268.5	268.2	268.5	268.9	243
RHC μ CCQE	95.5	95.3	95.5	95.8	102
FHC e CCQE	73.8	61.6	50.0	62.2	75
FHC e CC1π^+	6.9	6.0	4.9	5.8	15
RHC e CCQE	11.8	13.4	14.9	13.2	9

- Observed events at SK in runs through 2017, vs. ND data-tuned predictions under oscillation hypothesis using NH, 2016 PDG θ_{13}, and $\theta_{23}=45°$.
  - ν-mode POT (FHC) : 1.49×10^{21}
  - $\bar{\nu}$-mode POT (RHC) : 1.12×10^{21}
- 15 events in CC1π sample, max-CPV prediction is 6.9
  - *p*-value for up/down fluctuation this big in one of 5 samples is ~5%
  - in a single sample it's ~1%

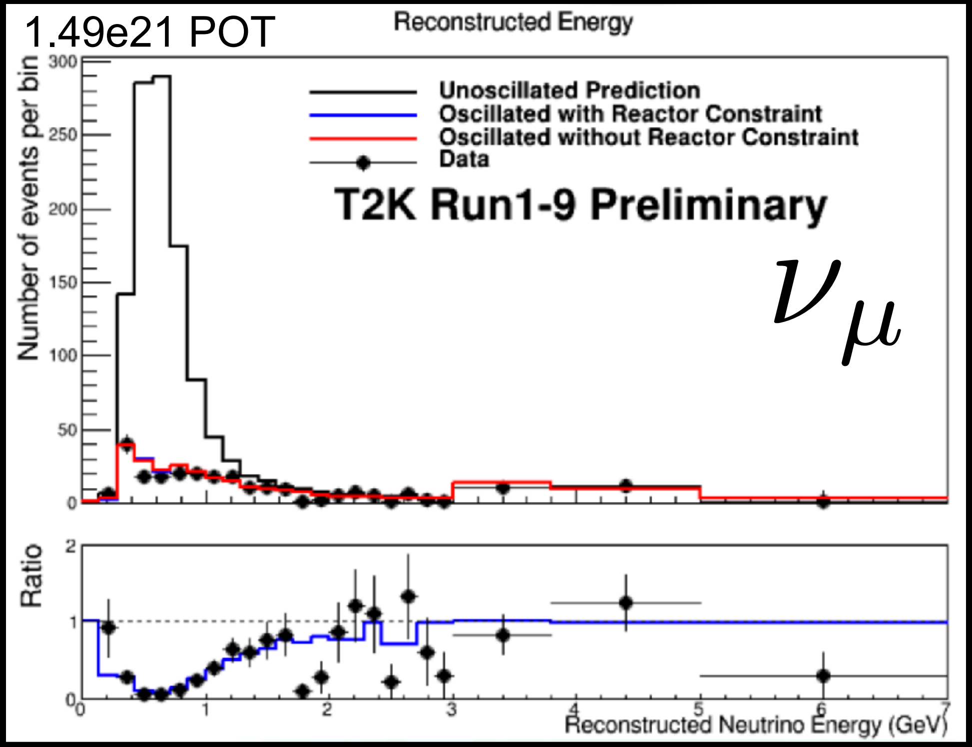
ν_μ, $\bar{\nu}_\mu$ disappearance: Precision era of Δm^2_{atm}, θ_{23}

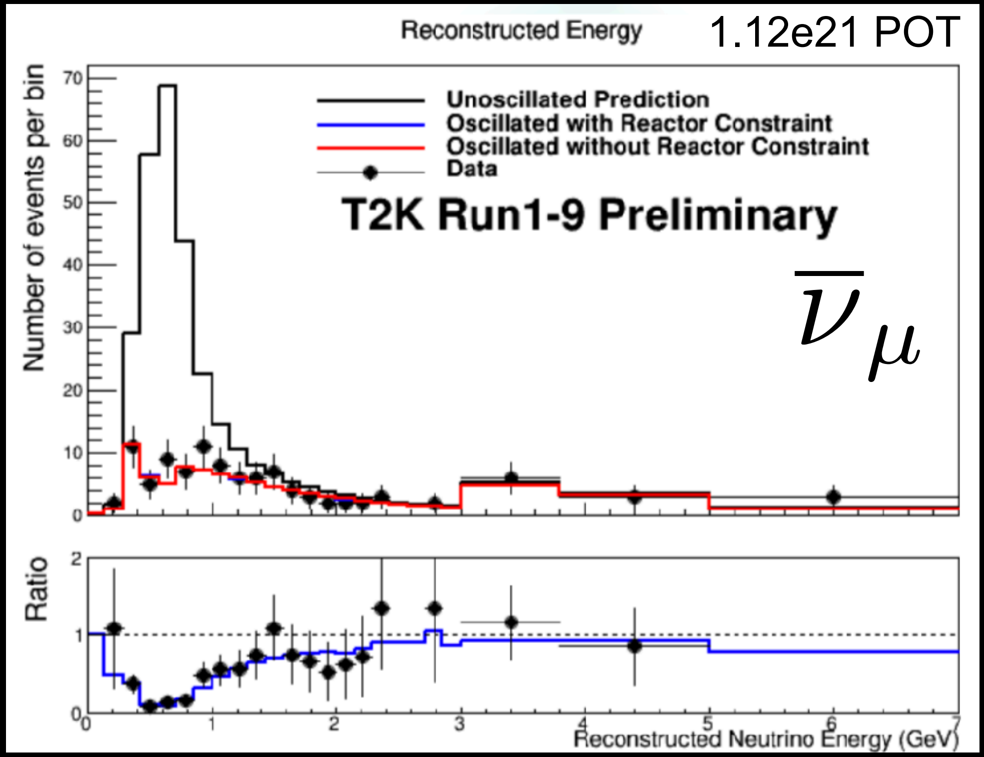
- T2K continues to favor maximal mixing (θ_{23}=45°)



Updated to correct a bug in systematic error implementation. Contour changes are small.

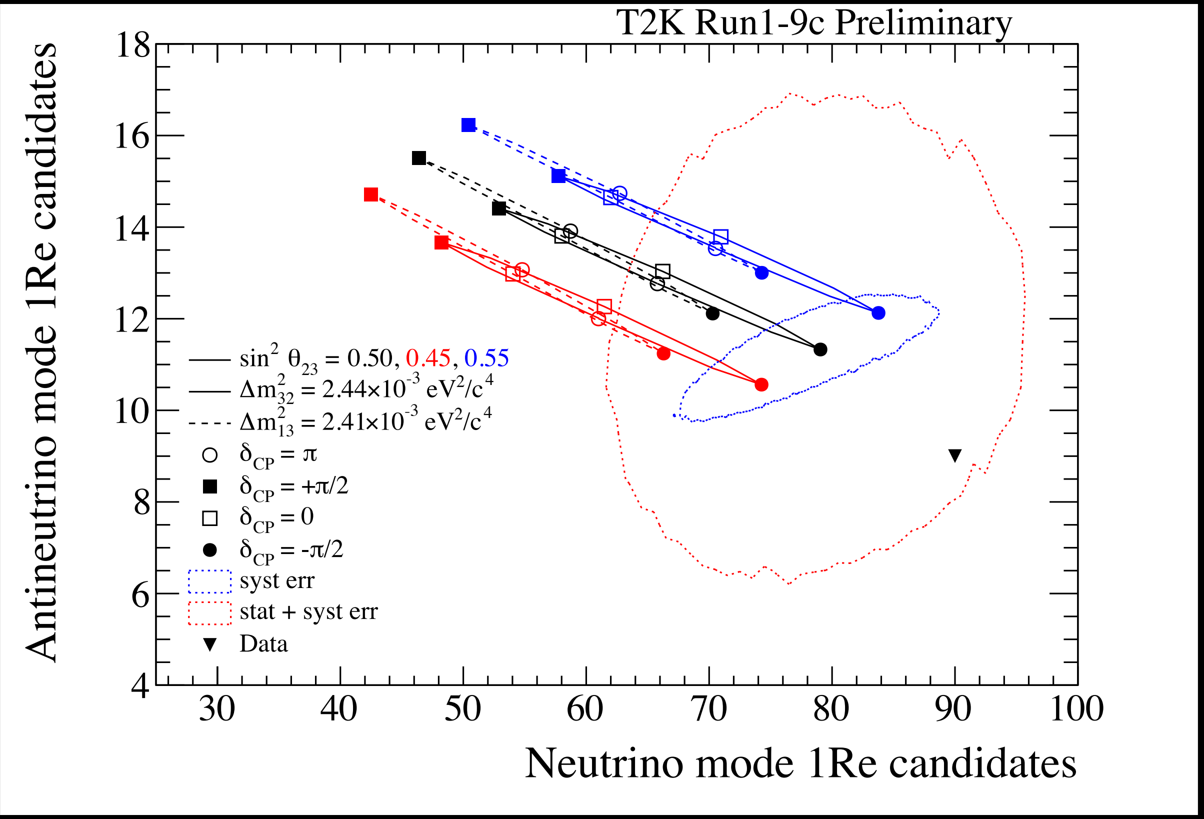
Data through Run 9c: 2.62 x 10²¹





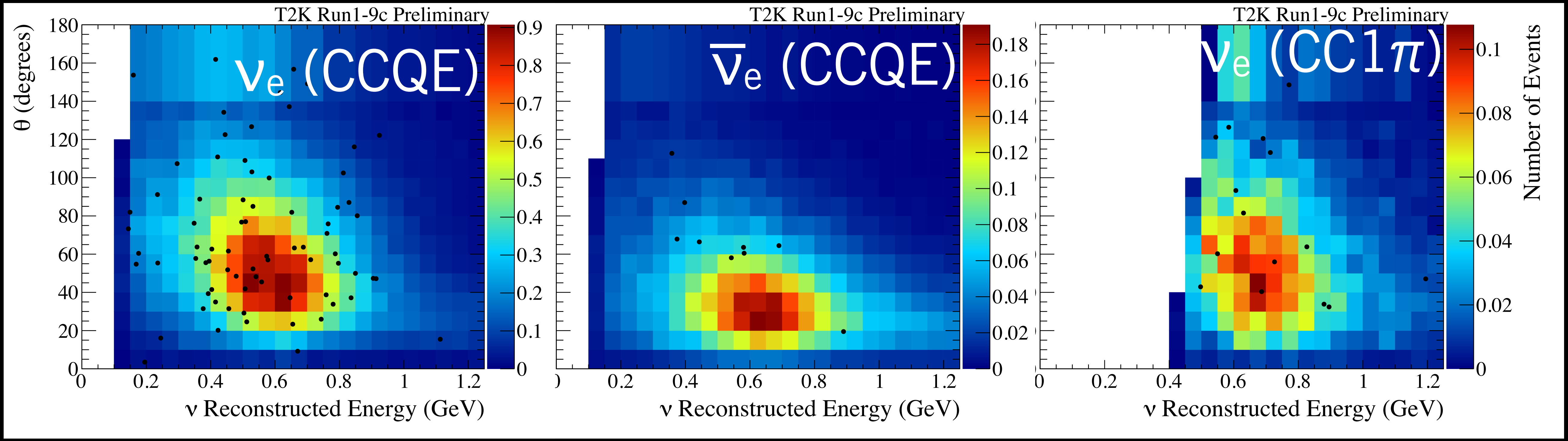
Electron (anti)neutrino appearance: event counting

- Bi-event rate plot shows T2K's sensitivity (in single-bin counting analysis) to CPV and hierarchy
- Dashed lines are 68% C.L. for systematic (blue) and total error (red)
- Data shown as black inverted triangle



SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC e CCQE	73.8	61.6	50.0	62.2	75
FHC e CC1π^+	6.9	6.0	4.9	5.8	15
RHC e CCQE	11.8	13.4	14.9	13.2	9

Electron (anti)neutrino appearance

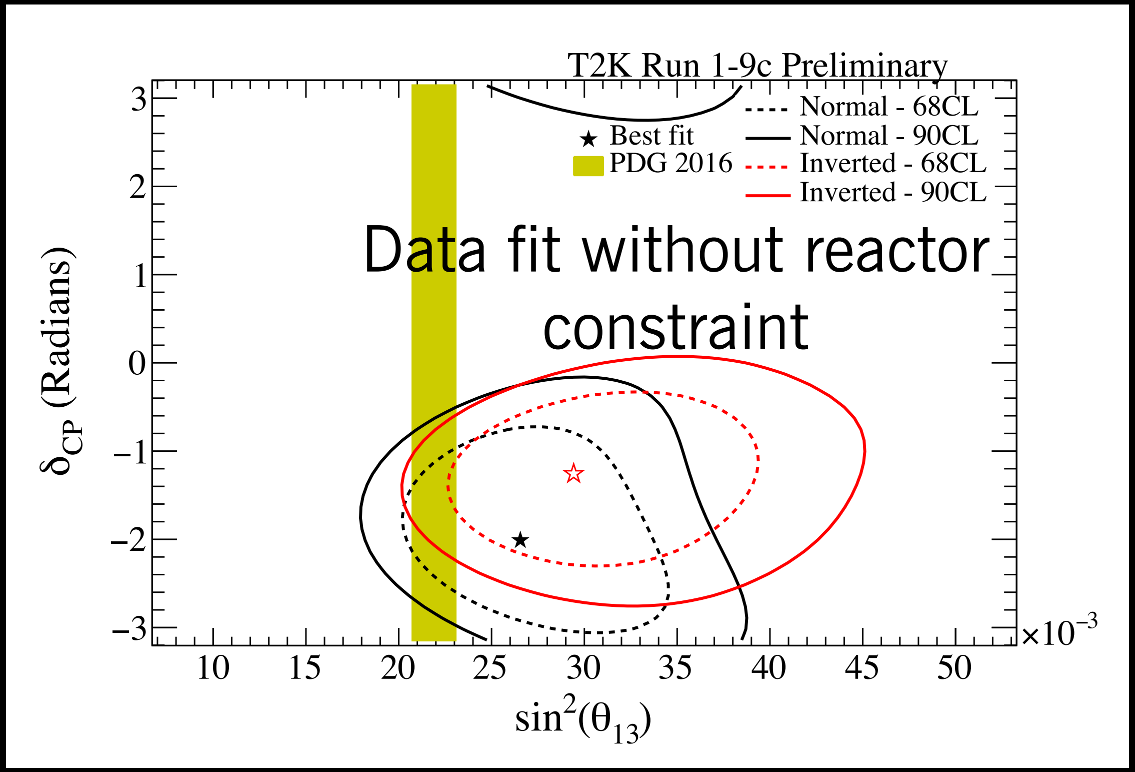


- But… of course much more information is available in the reconstructed energy, angle of lepton.
- Note that antineutrinos are not especially signal-like in these variables

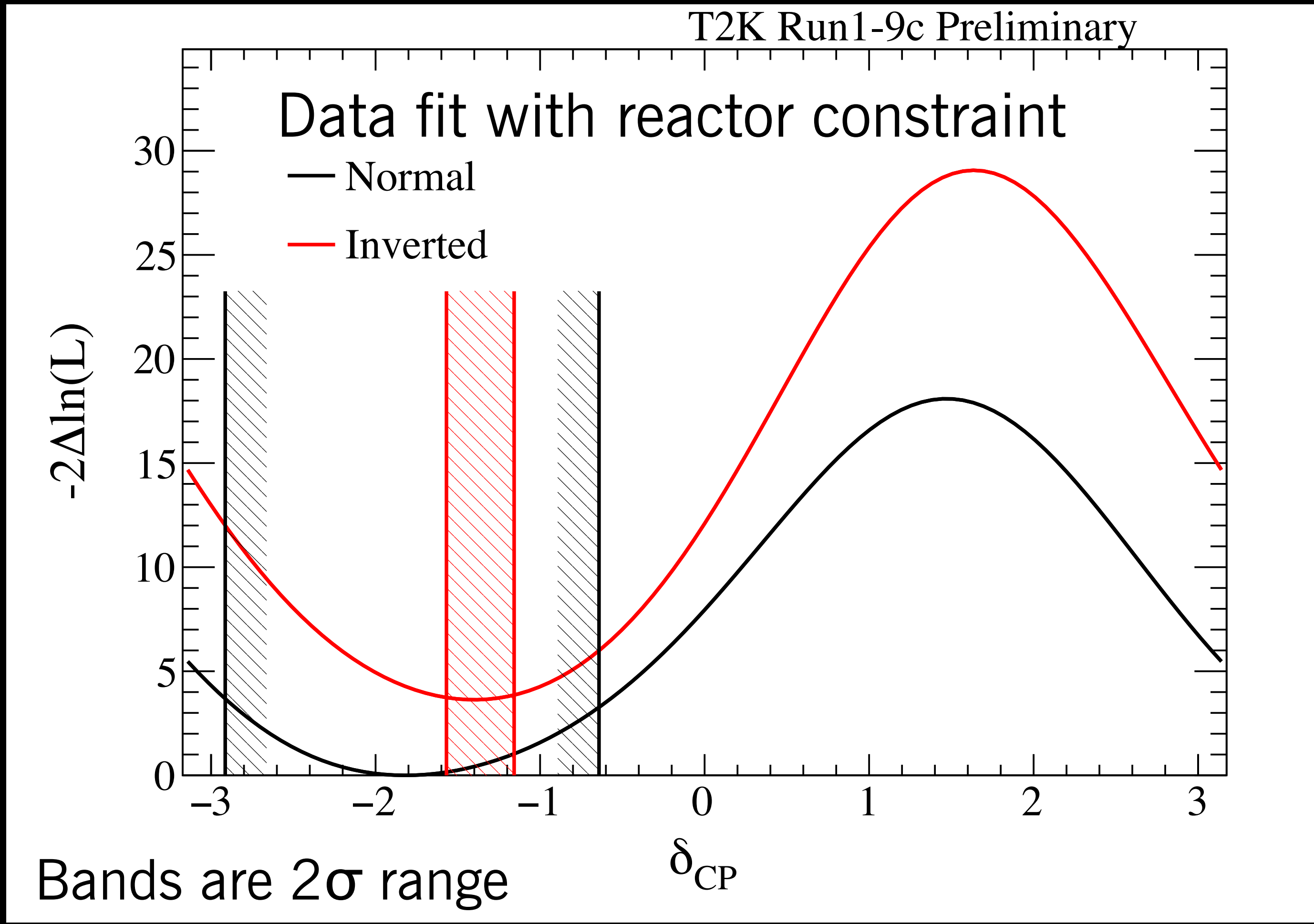
Oscillation fits

- Binned-likelihood oscillation fits to all far-detector samples simultaneously
- Marginalize over all nuisance parameters
- Two oscillation fits:
  - Fit for θ_{13} using T2K data
  - Use 2016 (reactor data only) PDG value as a constraint

T2K CP analysis



- Consistent with reactor measurements of θ_{13}
- CP-conserving values outside of 2σ region for both hierarchies
- (not strong yet) preference for normal hierarchy

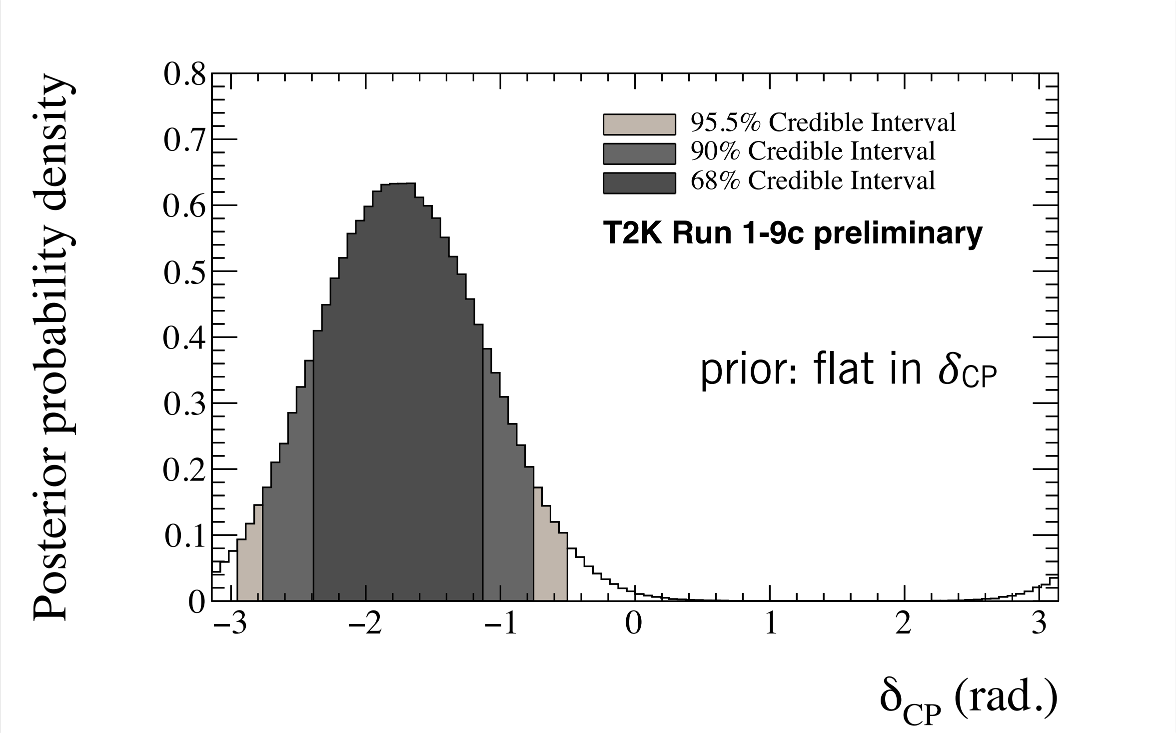


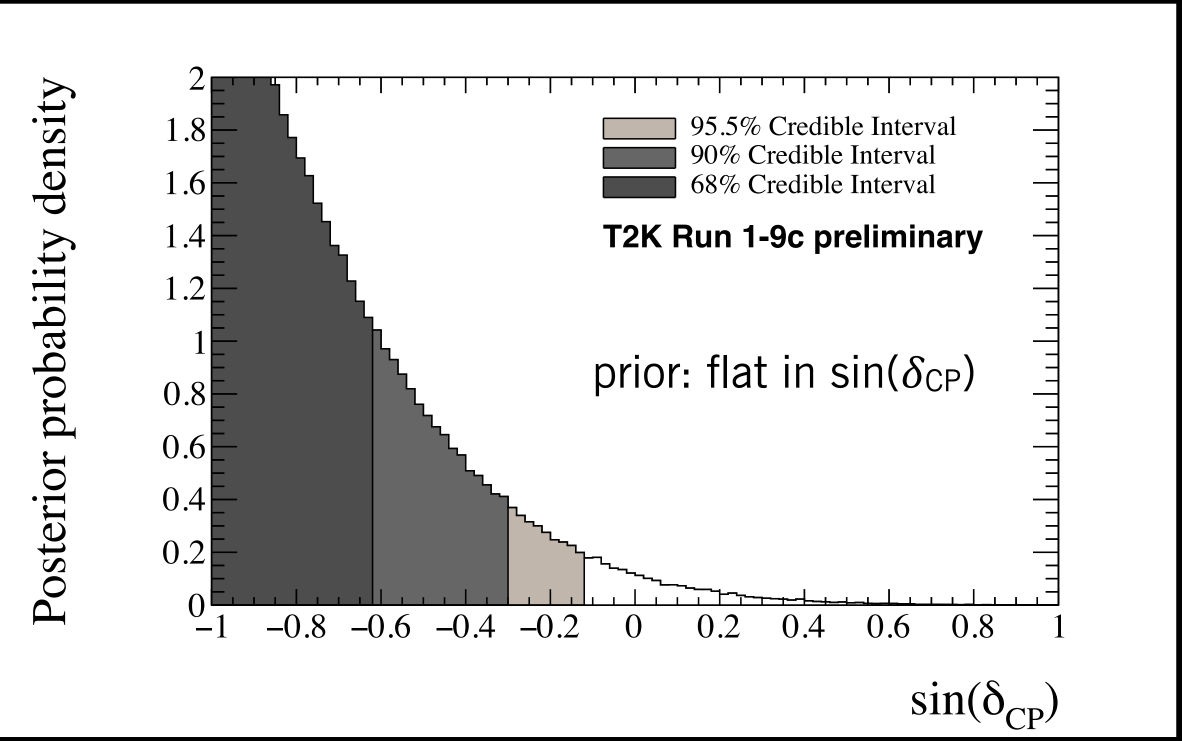
Bayesian analysis: posterior probabilities

- CP conservation disfavored at 2σ, independent of choice of prior
- Bayes factor for NH/IH is 7.9

Posterior prob. by hierarchy, octant

	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31} < 0$)	0.023	0.089	0.112
SUM	0.227	0.773	1



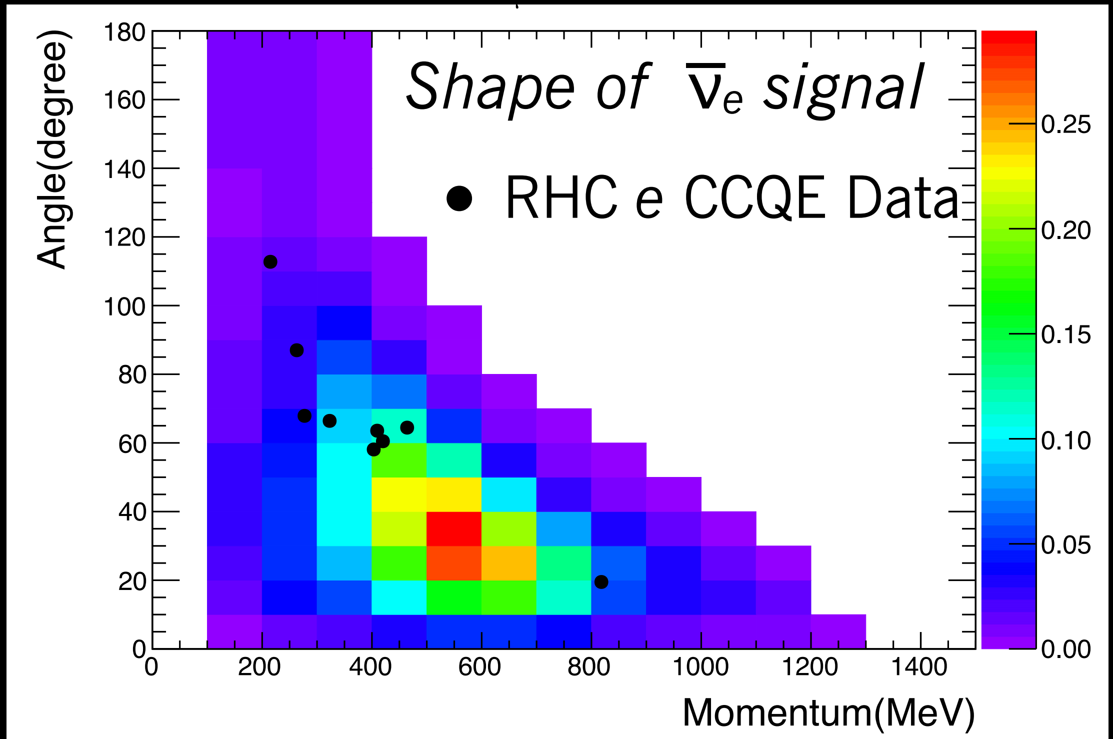


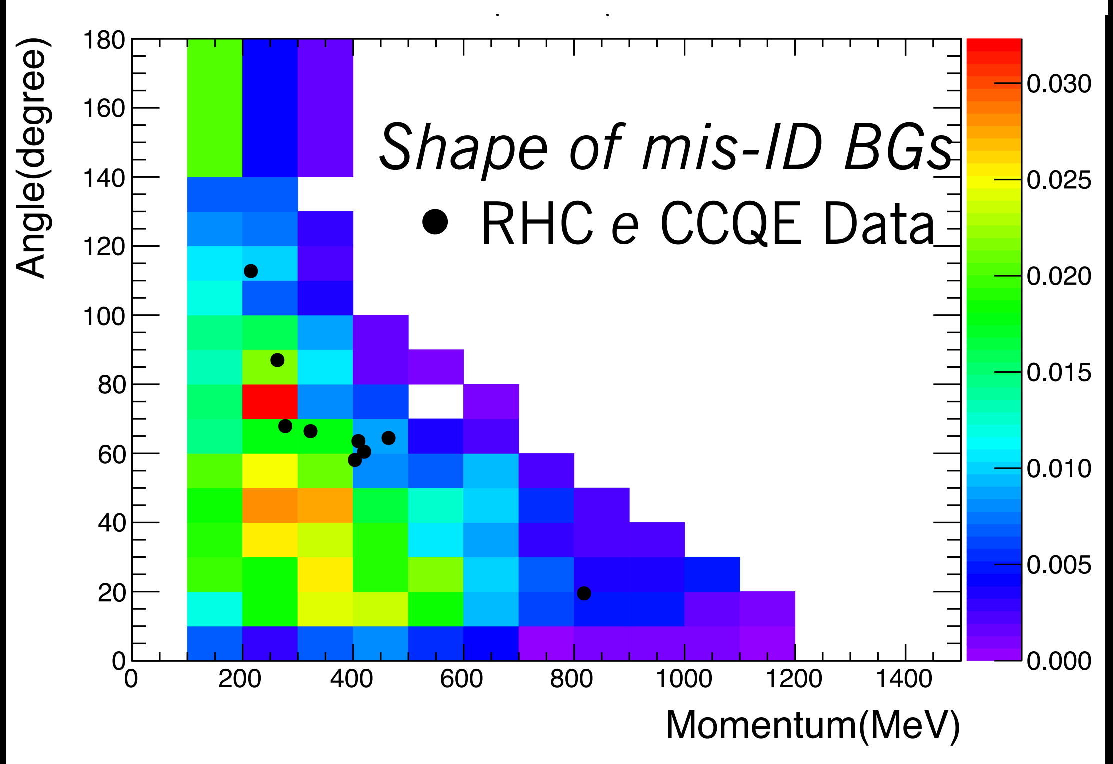
Electron antineutrino appearance search

Data through Run 9c:
2.62×10^{21}
Neutrino 2018 results

- Test hypothesis of appearance (expect 11.8 events) and no appearance (expect 6.5 events)
  - Observe 9 events
- No strong statistical statement yet

HYPOTHESIS	P-VALUE
NO appearance	p=0.233
PMNS appearance	p=0.0867

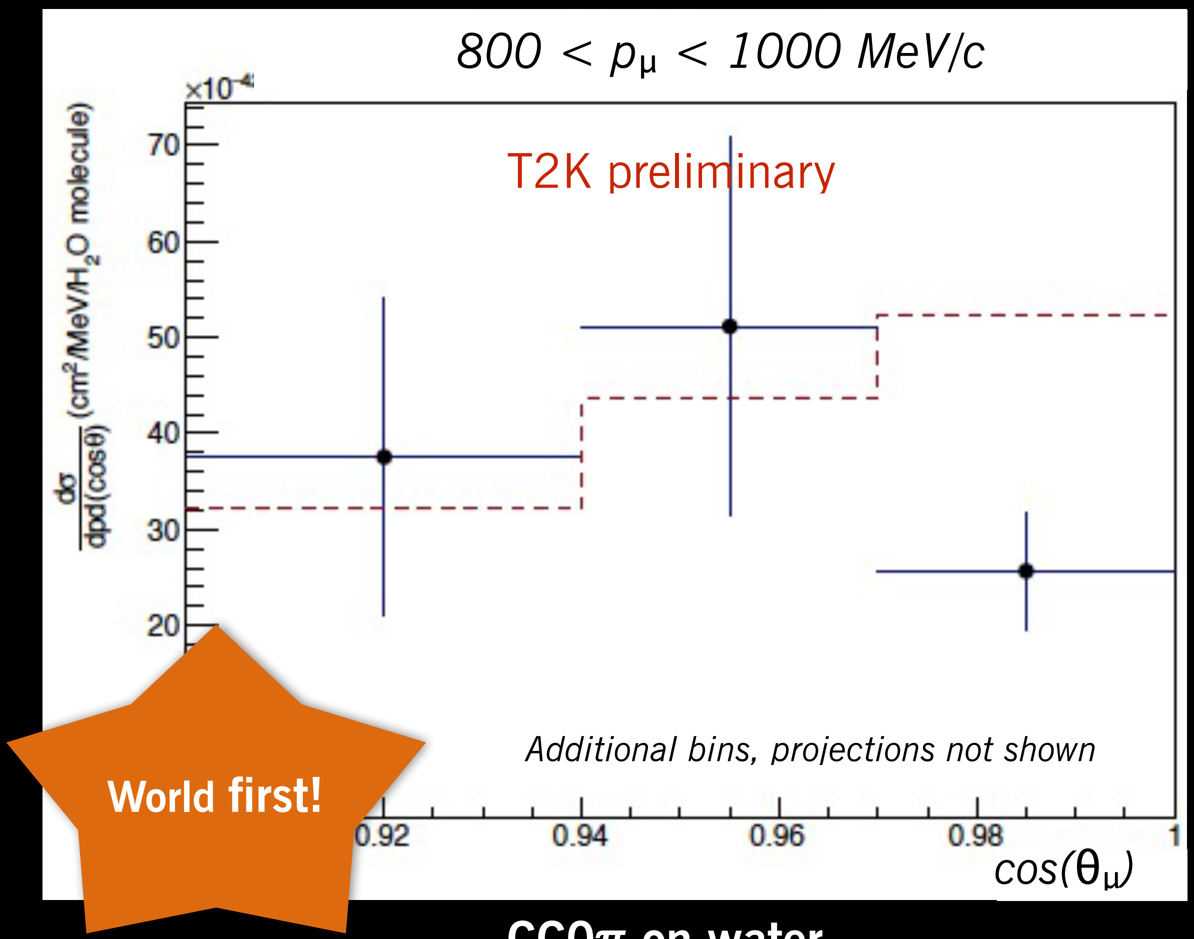




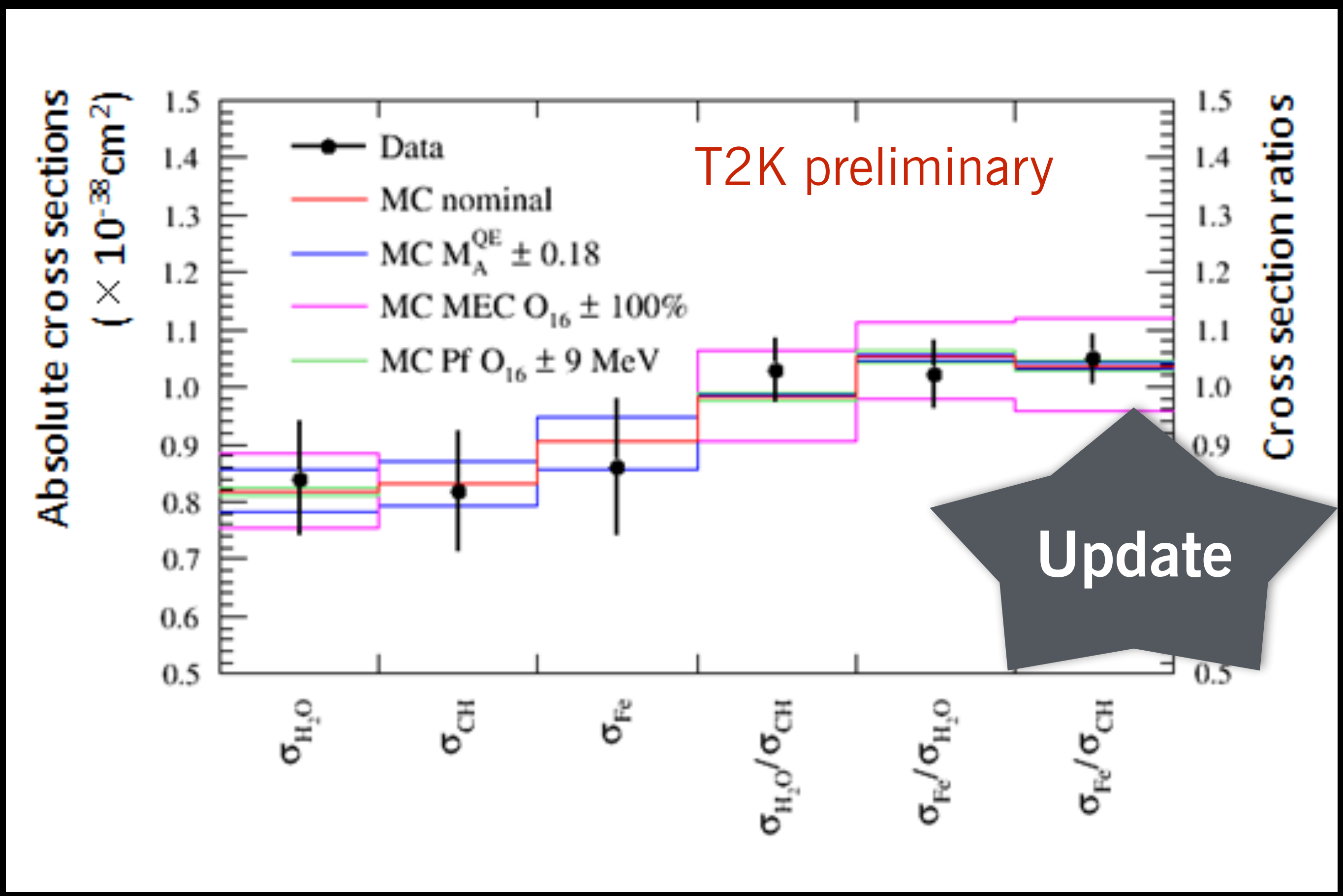
Neutrino interaction cross-sections

- See Margherita's talk on Wednesday afternoon!
- Some highlights here:

T2K Cross-sections 2018 Highlights



CC0π on water, antineutrinos, off-axis flux



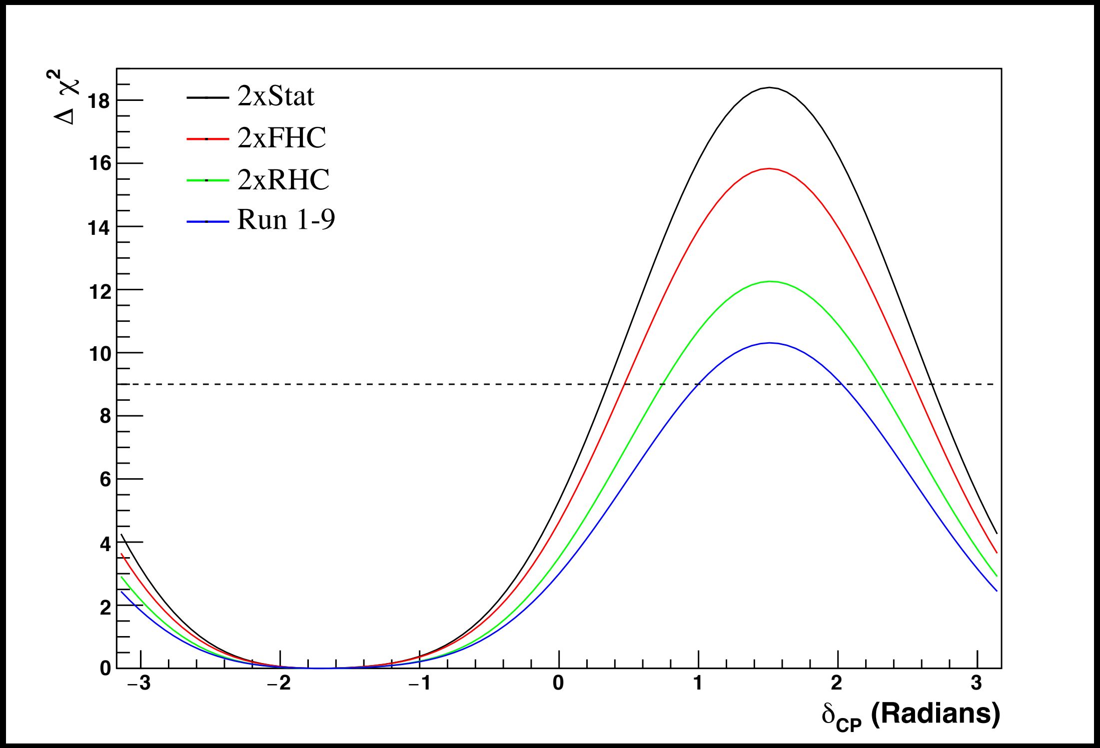
CC inclusive, multiple targets neutrinos, on-axis flux

- Extensive work within collaboration to test and mitigate model dependence in cross section results for users (experiment and theory)

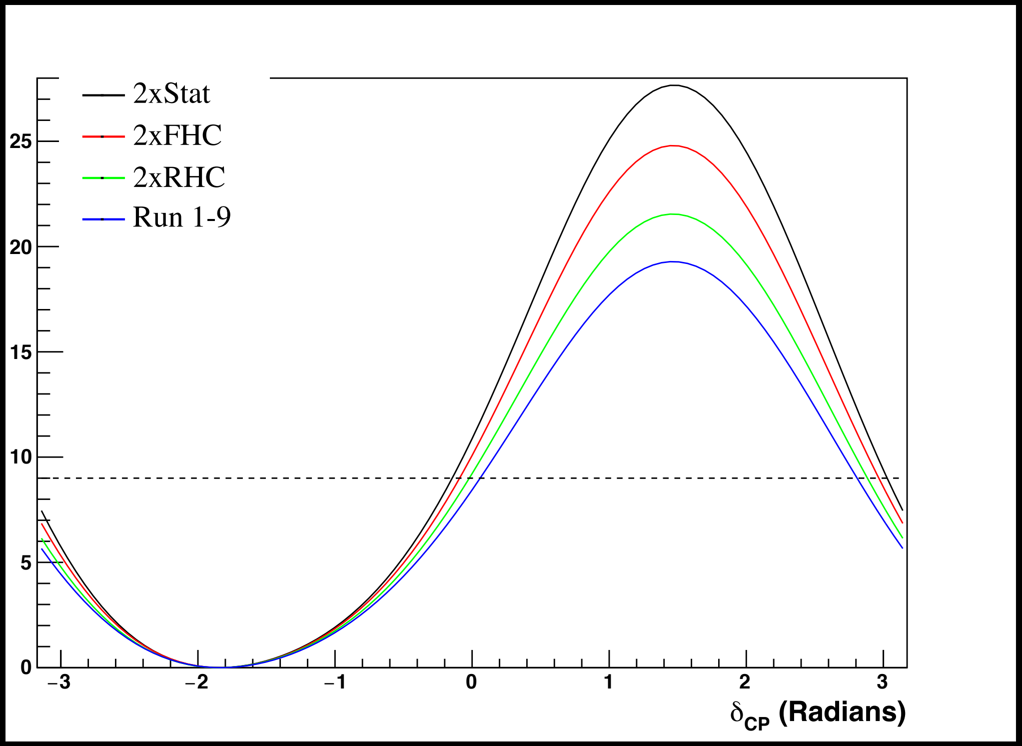
T2K's future

- Very near future: analysis with full RHC data from 2018 ($1.12 \rightarrow 1.63 \times 10^{21}$ POT)
- Near-ish future: double RHC data to 3.2×10^{21} POT in two years after SK refurbishment, then double FHC
  - In addition to conventional sensitivity with projected POT, explore "hybrid" sensitivity that projects ahead using existing results for POT on tape but average expectation with a particular set of oscillation parameters for future data
  - May approach 3σ exclusion of CP-conserving values

Conventional Sensitivity

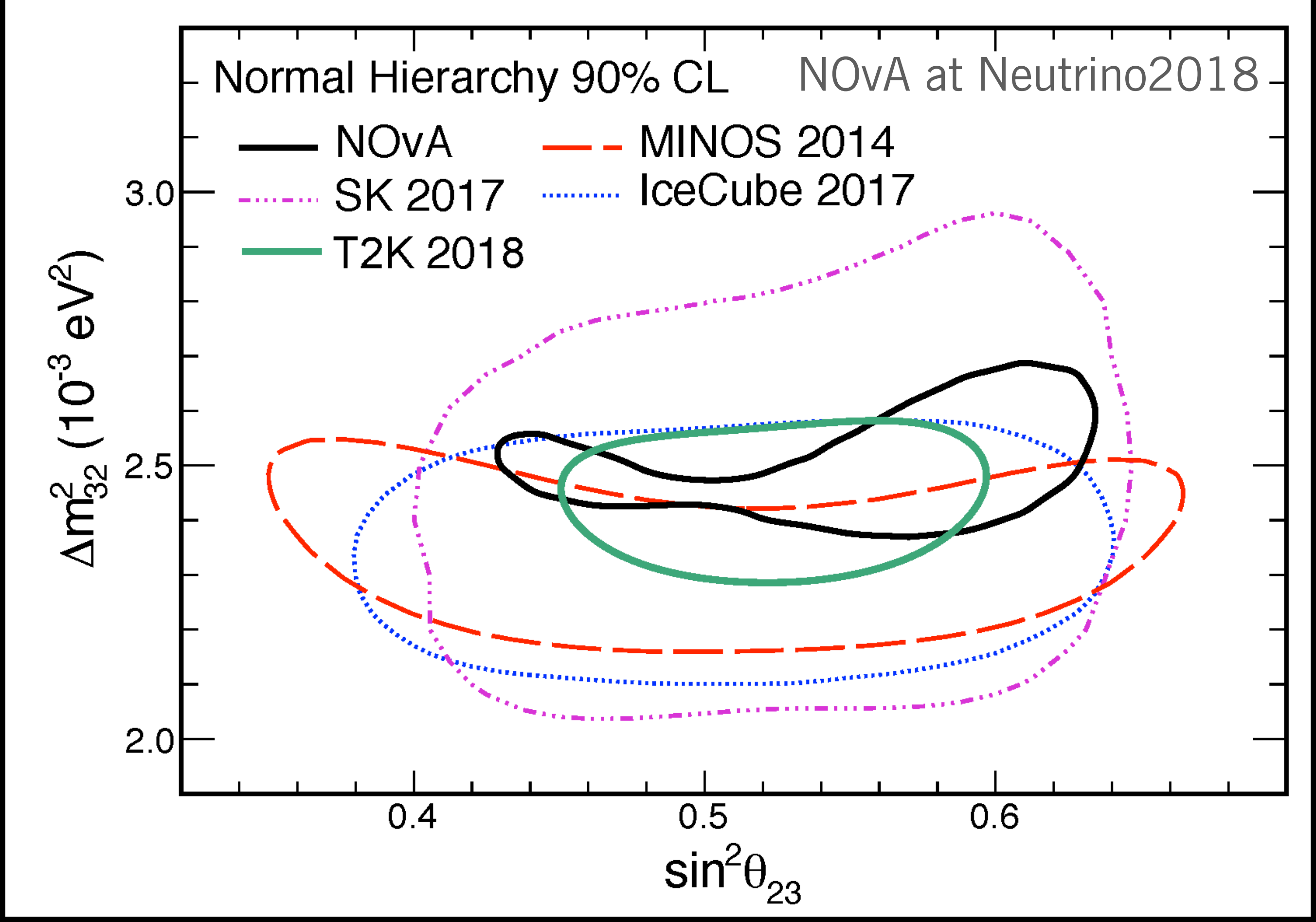


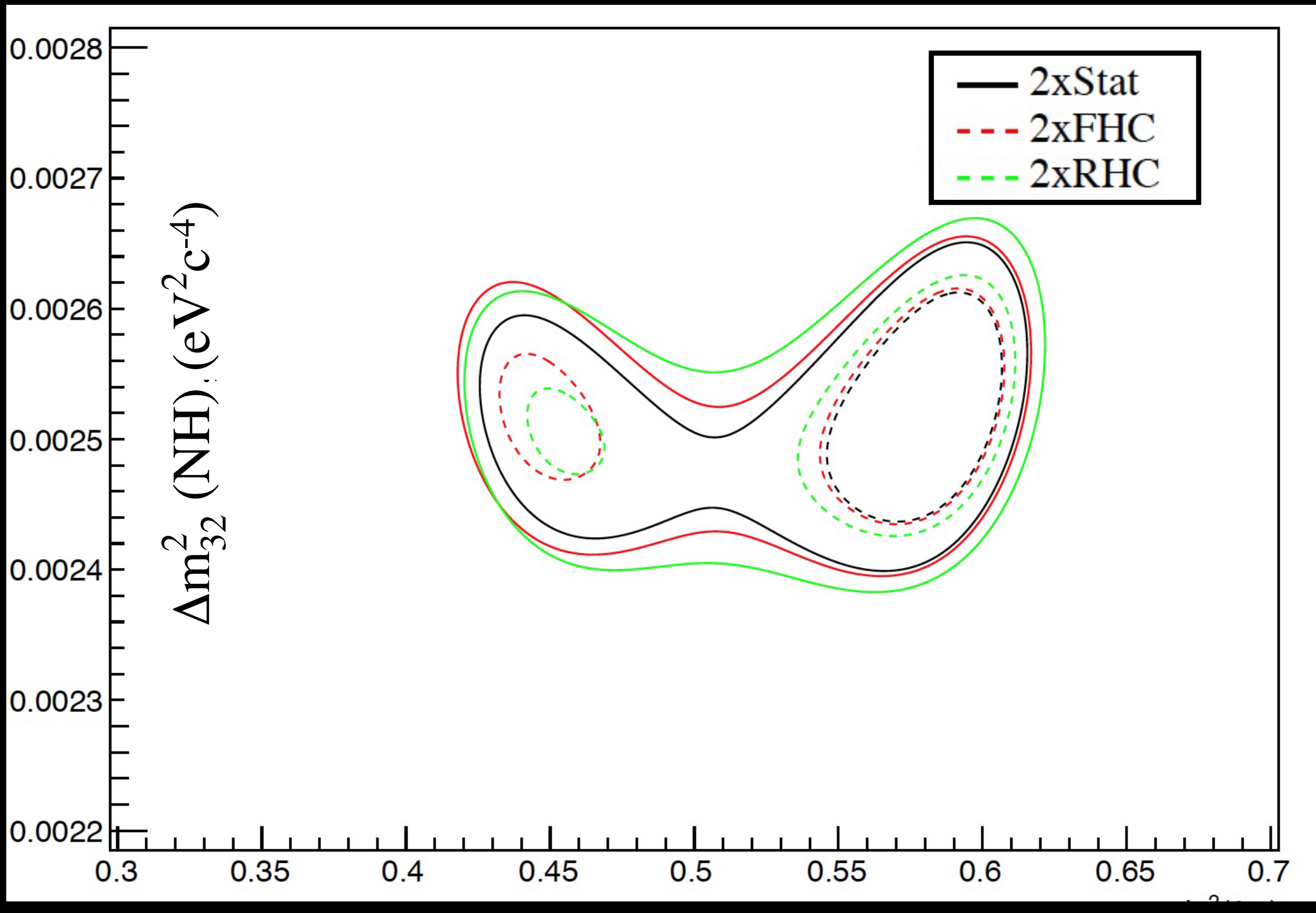
Hybrid with existing data



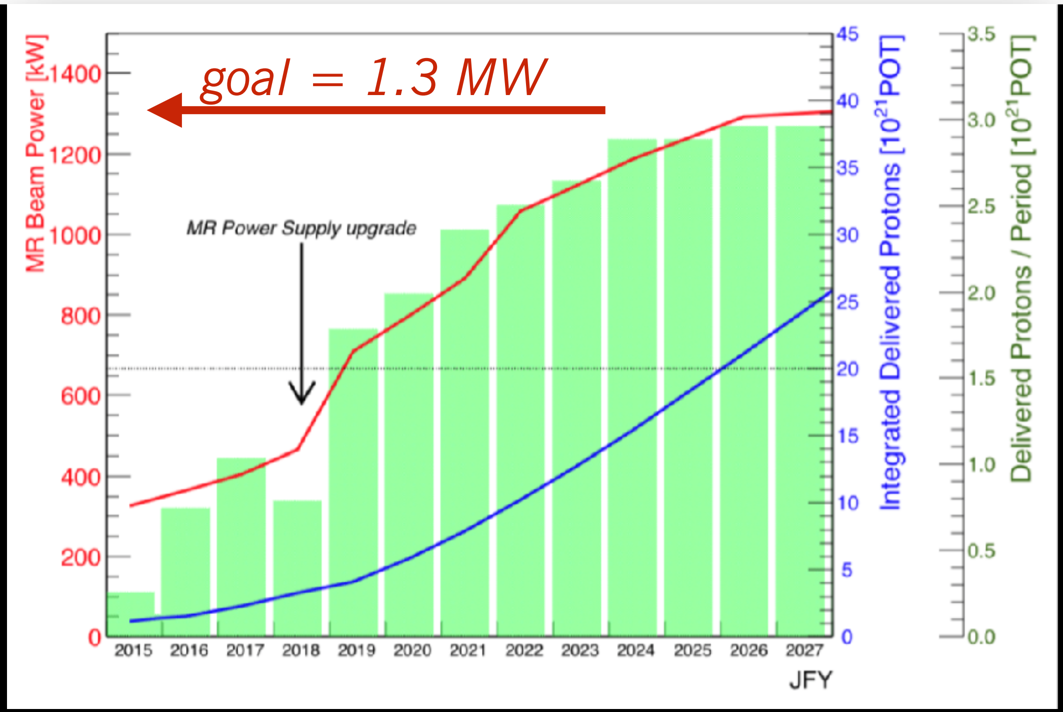
T2K's future

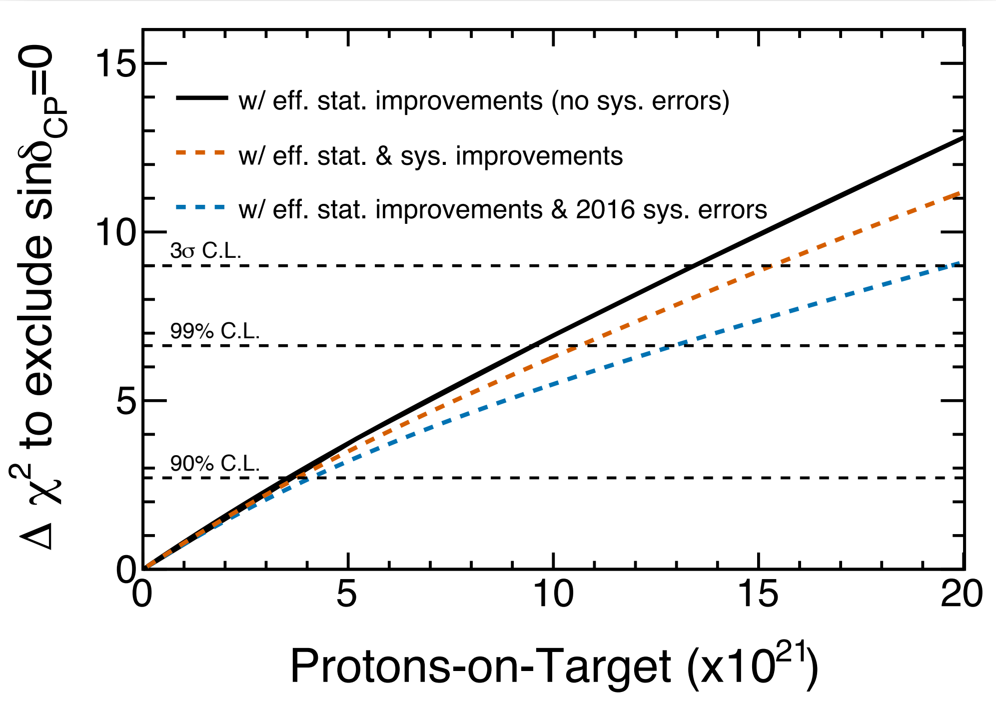
- Disappearance picture is changing rapidly
- Doubling T2K statistics will make a real impact on sensitivities





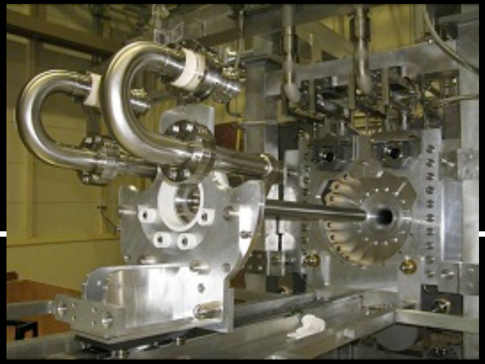
T2K's longer-term future: T2K-II

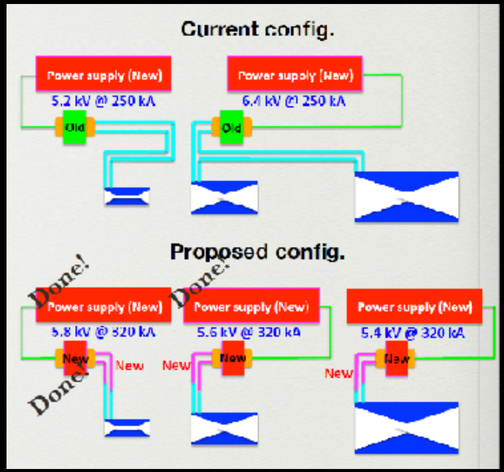


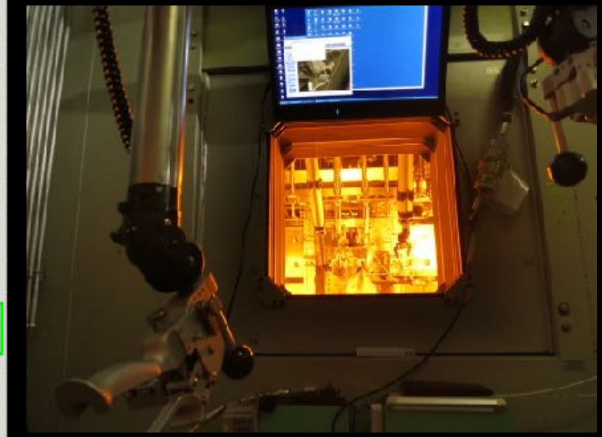


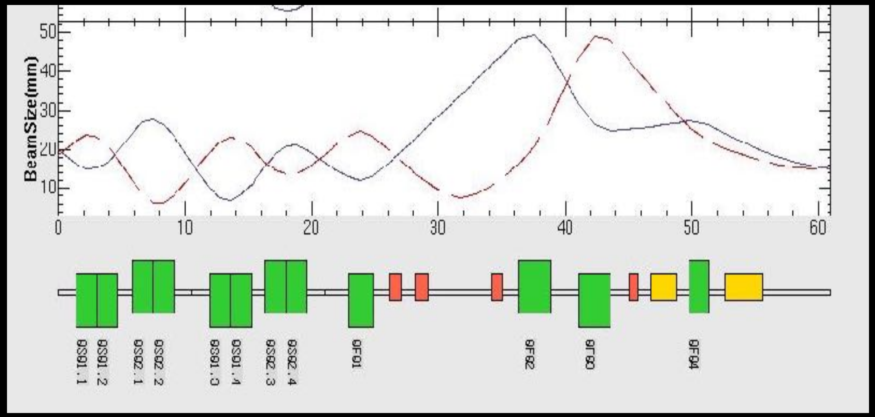
- T2K's long term goal is the pursuit of CP violation in the neutrino sector.
- In 2016, T2K phase 2 run extension given Stage-1 status by KEK/J-PARC.
- Proposal to collect 20×10^{21} POT by ~2026 (arXiv:1609.04111 [hep-ex]).
- With 20×10^{21} POT, T2K has up to 3σ (median) CPV sensitivity
  - Increased efficiency goal close to achieved already
  - Sensitivity improves beyond 3σ with reduced systematic errors.
- T2K initiated Near Detector upgrade project in January 2016 in collaboration with CERN

Neutrino beam upgrades







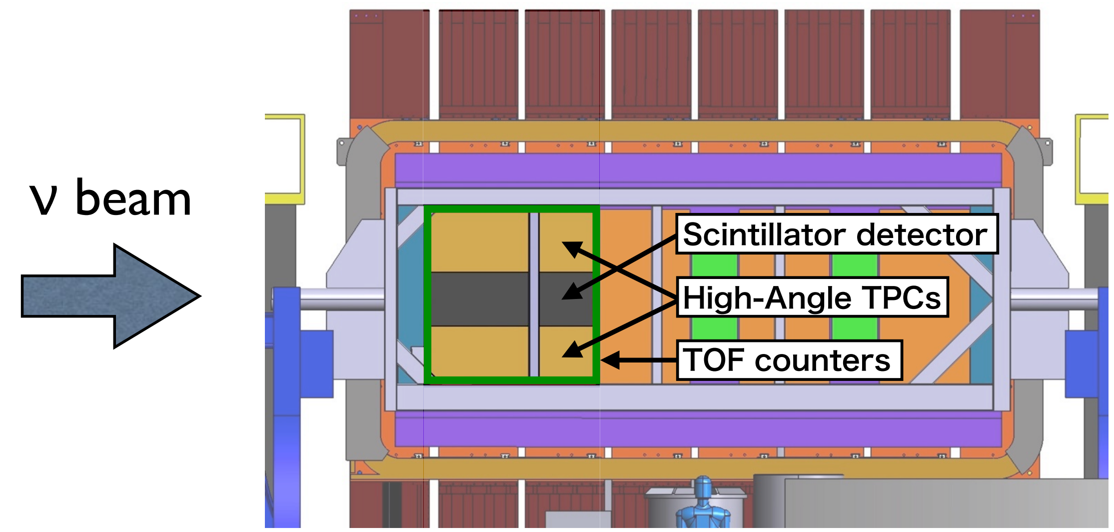


- Main Ring power supply upgrade approved by MEXT
    - MR-PS upgrades will allow 750 kW operation, with eventual upgrades to 1.3 MW
- Beamline improvements needed in:
    - target station
    - horns & horn power supplies
    - remote maintenance
    - apertures in magnet/beam ducts
    - activated water handling
    - many more…
- Aim to complete work when MR-PS upgrade is done → **2021**
- TDR has been submitted to KEK-IPNS Director for review in June 2018

ND280 upgrade

- T2K phase 2 goal: reduce systematics to ~4%
- Requirements for upgraded detector:
    - Full polar angle acceptance
    - Fiducial mass of a few tons
    - High efficiency for short tracks
    - Good timing information to determine track direction
- Strong collaboration of experts from Europe (incl. CERN neutrino group), Russia, Japan, USA
- WAGASCI collaboration has become part of T2K: see Margherita's talk
- Submitted proposal to CERN SPSC
    - supported as a Neutrino Platform project, http://cds.cern.ch/record/2299599
    - Had detector beam tests this summer
    - TDR expected by the end of 2018
- **Aiming for installation in 2021**

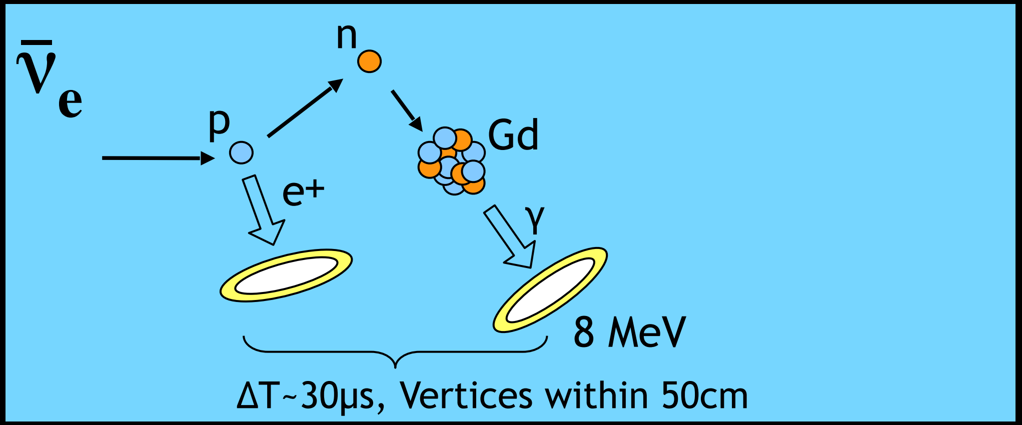
ND280 upgrade configuration

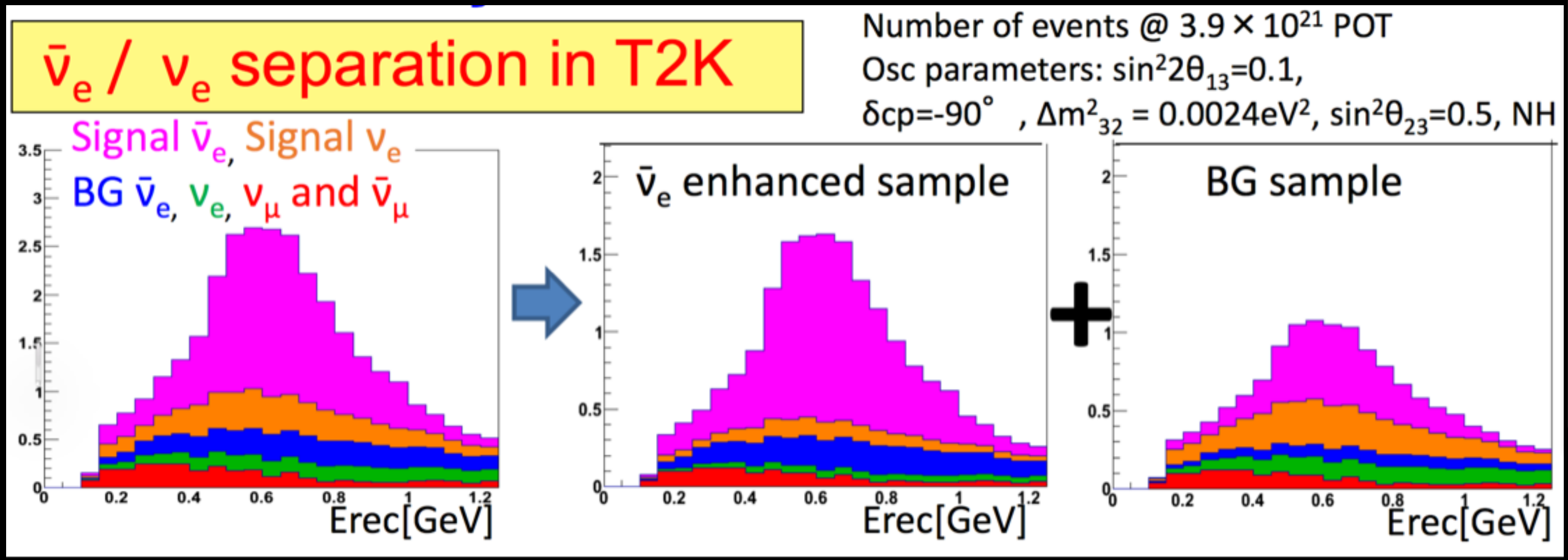


- Replace (most of) P0D with **Scintillator Detector** + **2 High-Angle TPCs** + **TOF**
    - Improve acceptance for large angle tracks
- Keep current "tracker" [2 FGDs + 3 TPCs] (& upstream part of P0D) as well as ECal, magnet & SMRD
    - For keeping continuity and forward acceptance

Far detector upgrade

- Additional SK data samples under study
  - $CC1\pi^{\pm}$ and $NC\pi^0$, in both FHC and RHC data
- SK-Gd project
  - Initiative to add Gd to SK water
    - enhance neutron detection capability
    - improves low energy antineutrino detection
    - could provide wrong-sign background constraint in T2K $\bar{\nu}$ data
  - Repairs to SK tank **ongoing now!**
  - Load $Gd_2(SO_4)_3$ in stages up to 0.2%





Conclusions

- T2K reporting oscillation results on data collected through 2017
  - CP conservation disfavored at ~2σ
  - Normal hierarchy slightly favored
- Expect to see results on 2018 data very soon (45% more antineutrino data)
- Recent improvements in the far-detector analysis have increased event yield by >30%; more to come
- Far-detector improvements underway; near-detector in next few years
- Aiming for 8x more data by 2027