NEUTRINO OSCILLATION RESULTS FROM THE T2K EXPERIMENT

THIRTEENTH CONFERENCE ON THE INTERSECTIONS OF PARTICLE AND NUCLEAR PHYSICS

PALM SPRINGS, CALIFORNIA

MAY 30TH, 2018

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On behalf of the T2K Collaboration

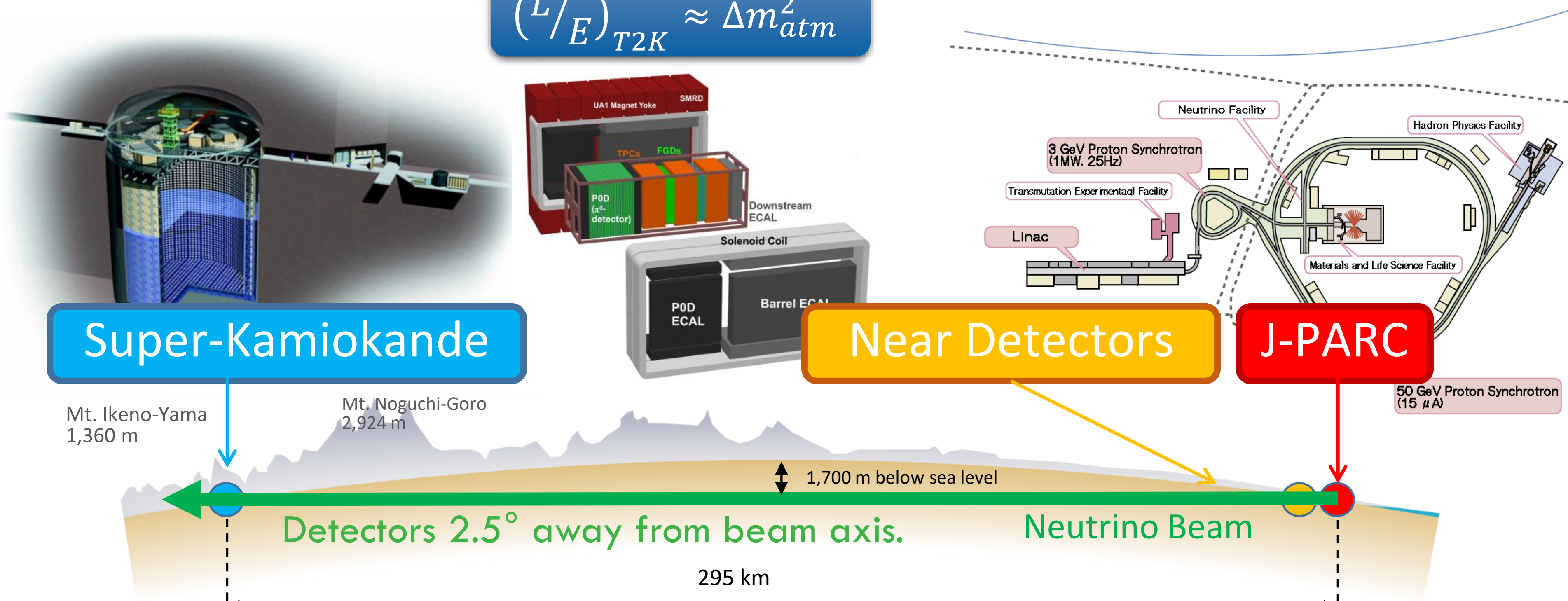
Stony Brook University

THE TOKAI-TO-KAMIOKA EXPERIMENT

- First observation of electron-neutrino appearance in a muon-neutrino beam in 2013
  - Phys. Rev. Lett. 112, 061802 (2014).
- World-leading precision on θ_{23}, Δm^2_{32} and most stringent constraint on leptonic CP violation.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\left({}^{L}/_{E}\right)^{-1}_{T2K} \approx \Delta m^2_{atm}$$



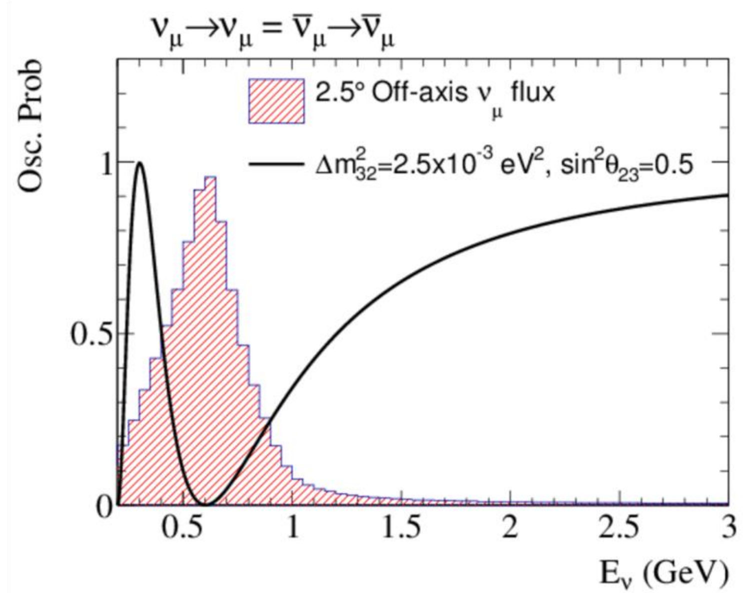
NEUTRINO OSCILLATIONS AT T2K

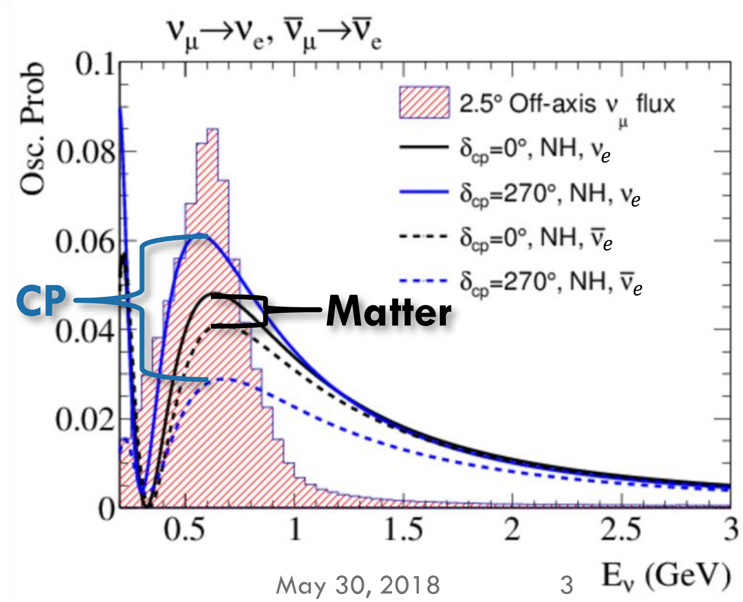
ν_μ Disappearance

- Sensitivity to $|\Delta m^2_{32}|$ and θ_{23}.
- Is $\theta_{23} = 45°$? If not, what octant?
  - Maximal mixing might indicate underlying symmetry.
- Test CPT invariance: $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$?

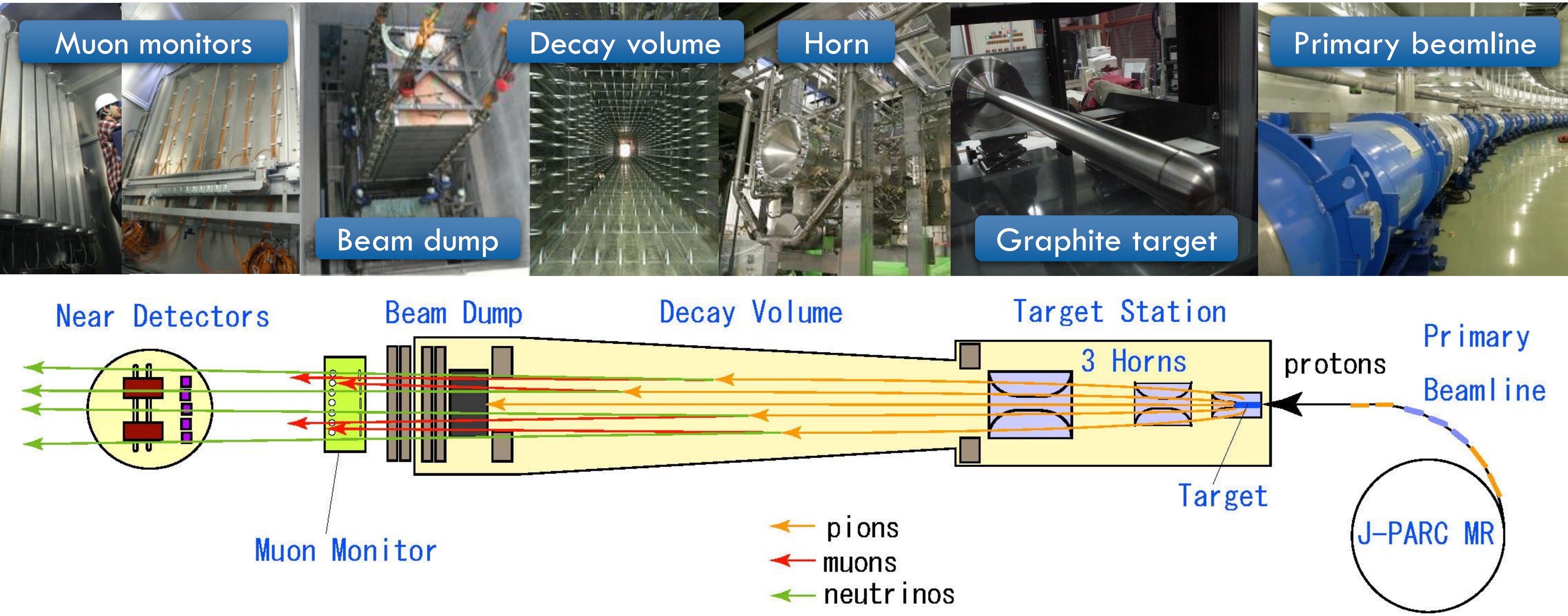
ν_e Appearance

- Sensitivity to θ_{13}, δ_{CP}, θ_{23} octant and mass hierarchy through matter effect.
- If δ_{CP} not 0 or π, CP symmetry is **violated** in lepton sector.
- $P(\nu_\mu \rightarrow \nu_e)$ **enhanced** if hierarchy is **normal** or δ_{CP} ~-π/2
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ **enhanced** if hierarchy is **inverted** or δ_{CP} ~π/2
- With the T2K flux, **matter** effect (∝ E) is smaller than δ_{CP}.
  - Complementarity with NOνA, which has similar $^L/_E$ but larger L and E.



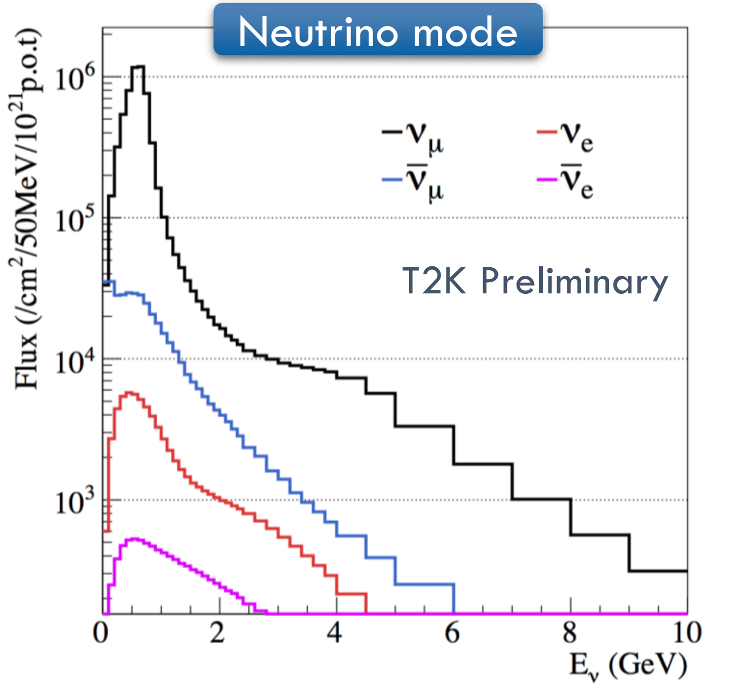


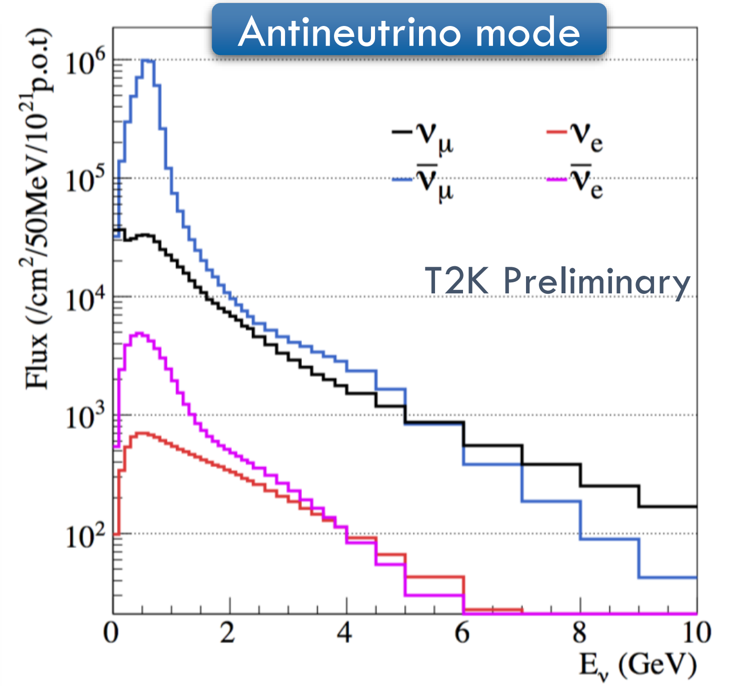
T2K BEAMLINE



- Protons are extracted from the J-PARC 30 GeV Main Ring onto a graphite target via the superconducting primary beamline.
- $\pi^{\pm}$ focused by three magnetic horns and allowed to decay into $\mu^{\pm}$ and $\nu_{\mu}(\bar{\nu}_{\mu})$
  - Horn polarity determines charge of the focused $\pi^{\pm}$ and helicity of neutrinos in the Earth frame.
- Muon detectors downstream of beam dump monitor beamline stability.

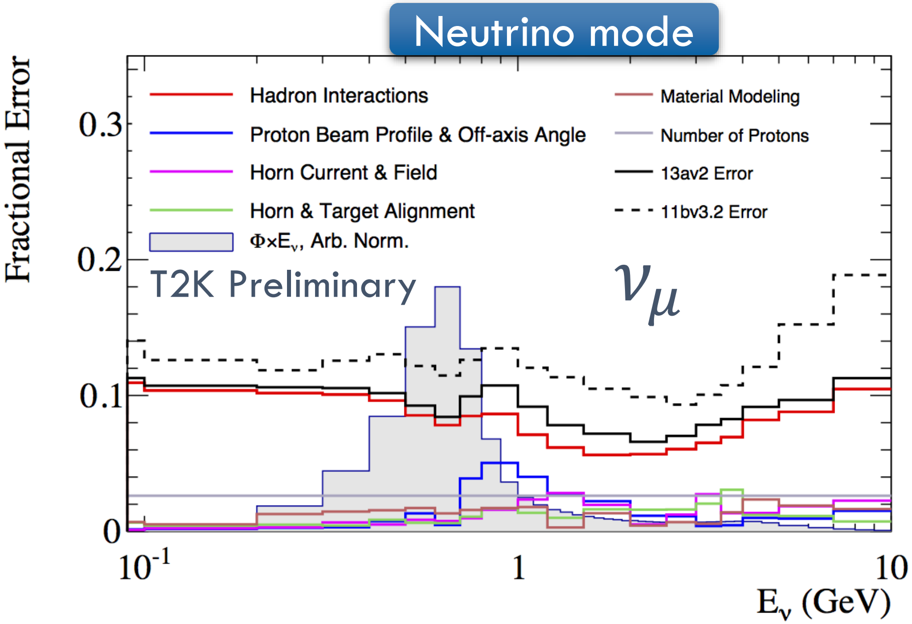
T2K $\nu_\mu(\bar{\nu}_\mu)$ FLUX

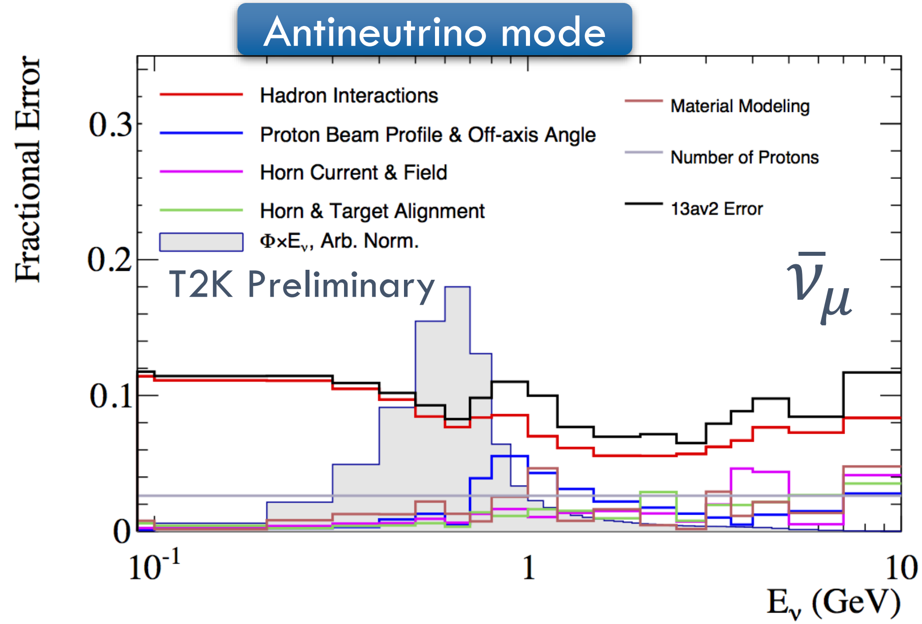




- Very low $\nu_e(\bar{\nu}_e)$ contamination. Less than 1% near oscillation maximum.
  - Irreducible background to $\nu_e(\bar{\nu}_e)$ appearance.
- Wrong sign contamination more significant in antineutrino mode.

FAR DETECTOR $\nu_\mu(\bar{\nu}_\mu)$ FLUX UNCERTAINTIES



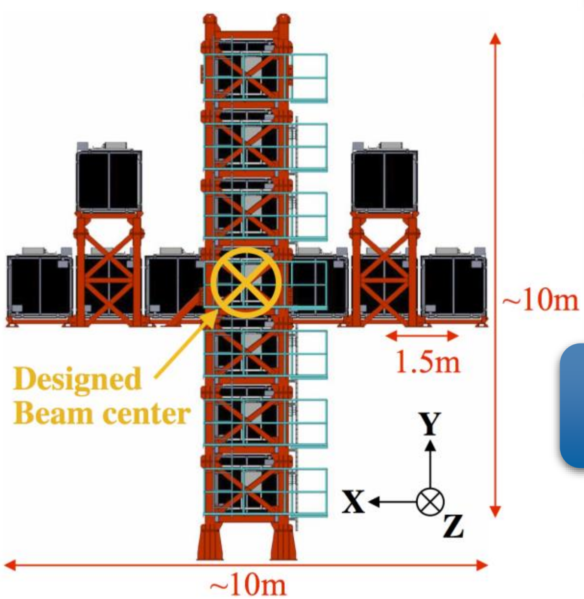


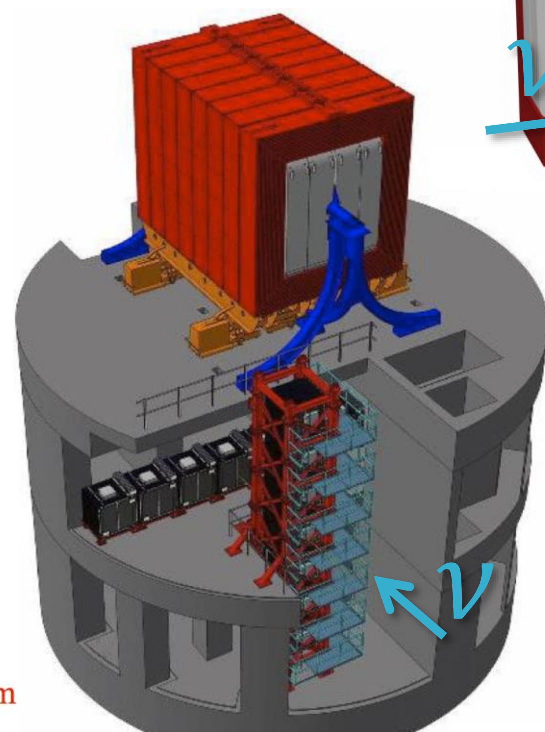
- Flux uncertainties dominated by hadron interaction in the target.
  - Constrained by external measurements at NA61/SHINE.
    - See Y. Nagai's presentation Thursday afternoon.
    - Prior to T2K near detector constraint, absolute flux uncertainties are ~10%.
  - Significant cancellation in near-to-far oscillation analysis extrapolation.

T2K NEAR DETECTOR COMPLEX

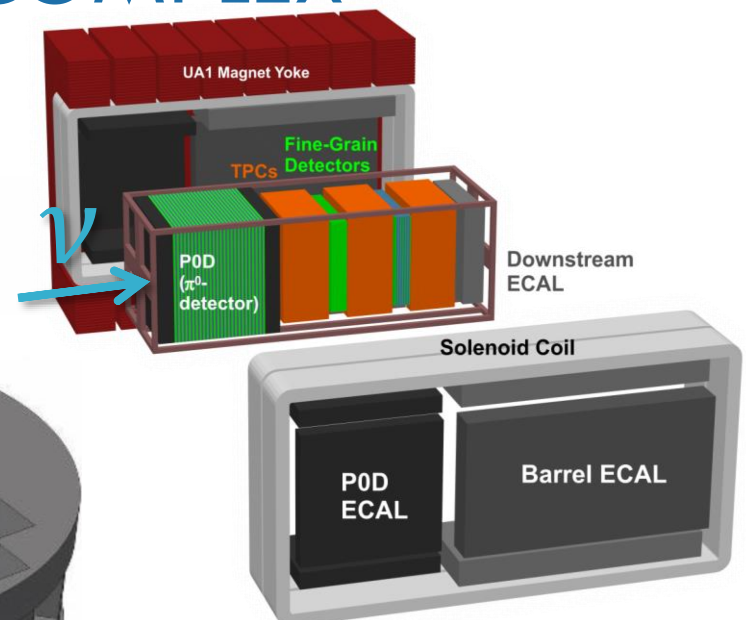
INGRID: on axis

- Plastic scintillator and iron neutrino detectors arranged in a grid perpendicular to beam axis.
- Beam stability monitoring with direction and rate measurements.





Near detector complex, 280 m away from target.

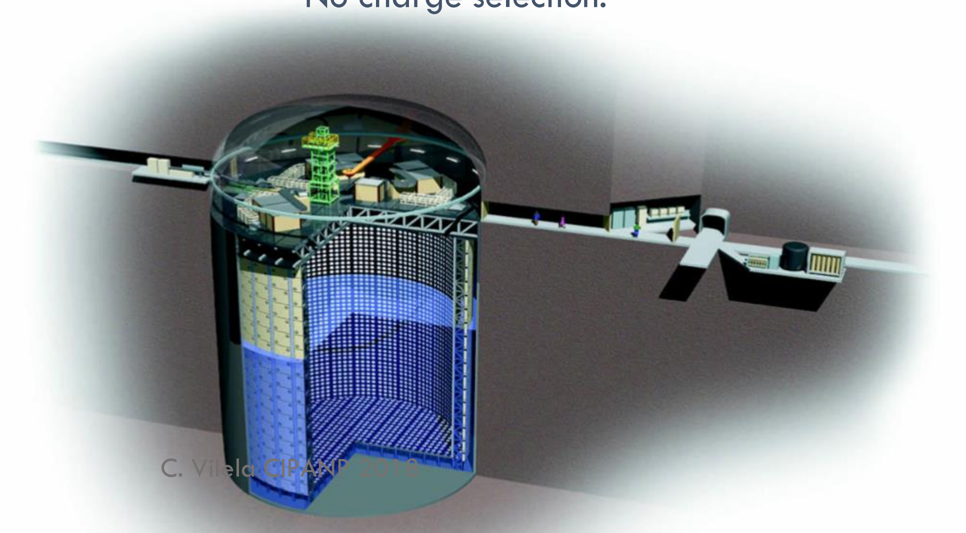


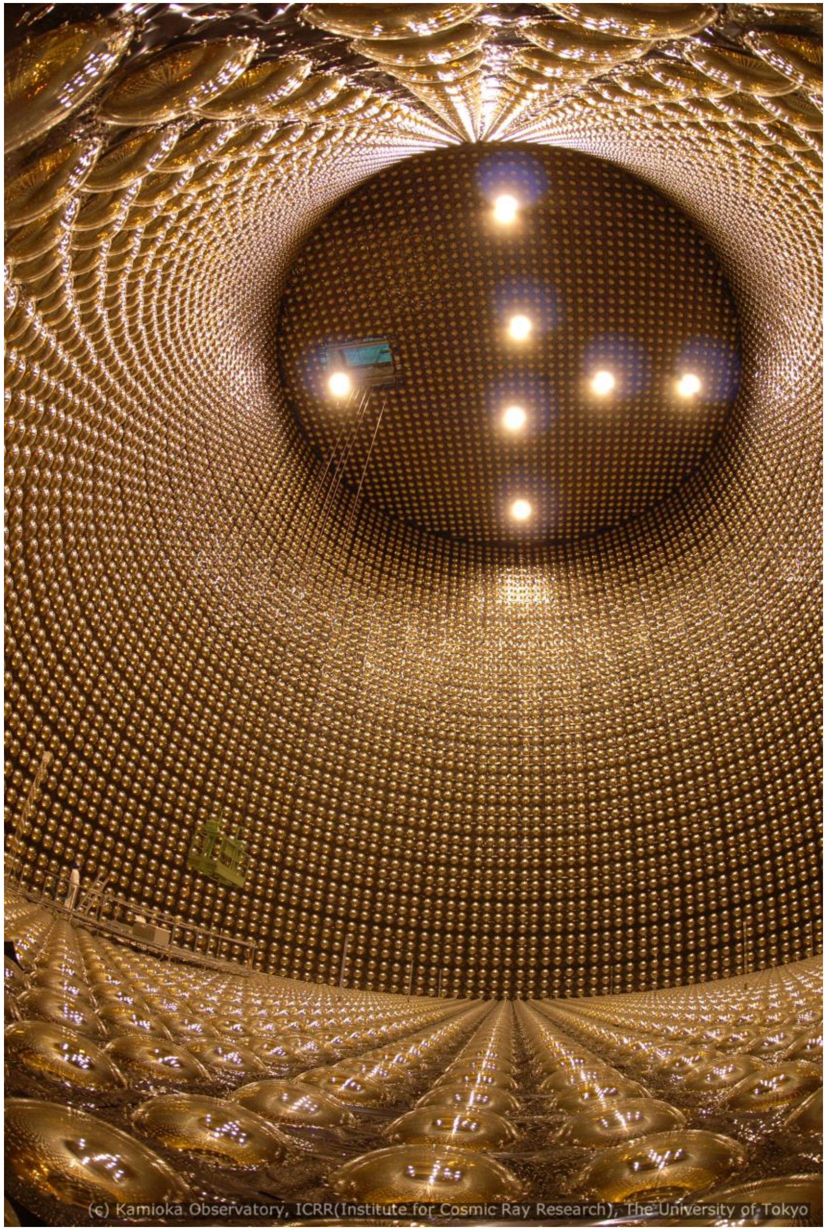
ND280: 2.5° off-axis

- Detectors in 0.2 T field generated by repurposed UA1/NOMAD magnet.
    - Identify μ^-/μ^+ from $\nu/\bar{\nu}$ interactions.
- Dedicated π^0 detector.
- Tracker composed of two plastic scintillator fine-grained detectors (FGDs) and three time projection chambers (TPCs).
- Plastic and **water** targets.

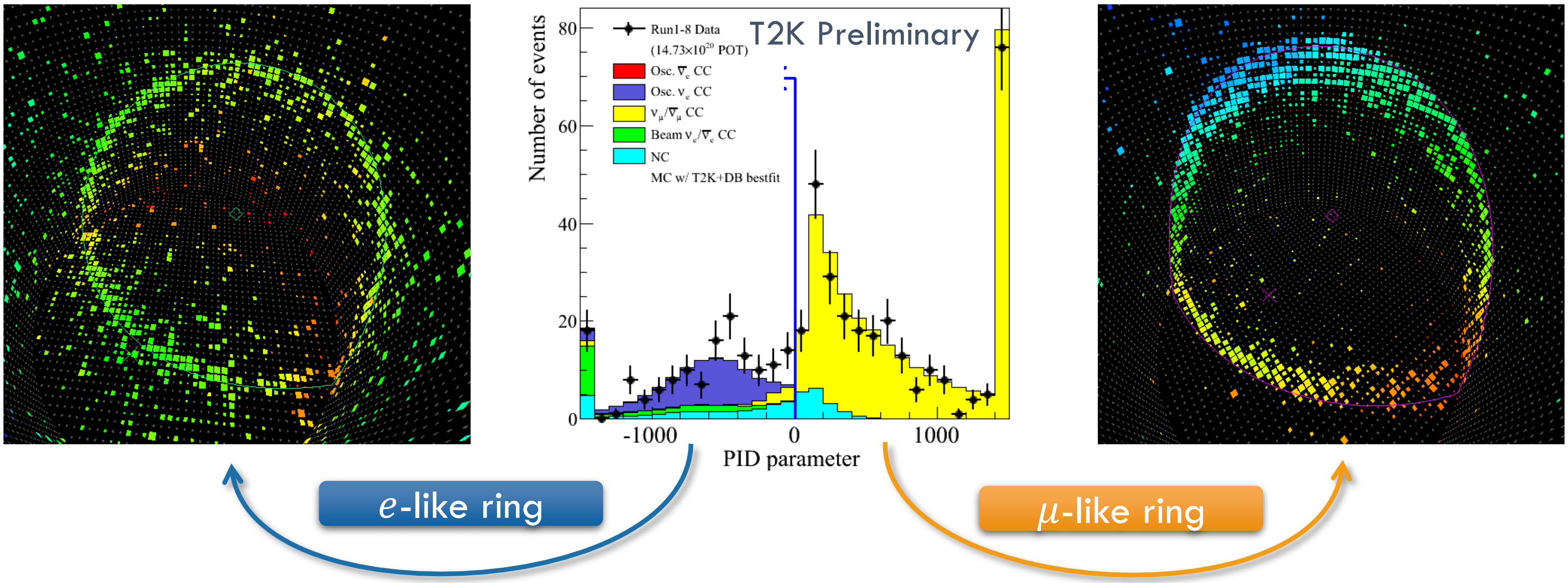
SUPER-KAMIOKANDE

- 50 kiloton water-Cherenkov detector.
- Optically separated outer detector for tagging entering/escaping particles.
- ~11000 20" photomultiplier tubes (PMTs) facing the inner detector giving a photocathode coverage of 40%.
- ~2000 8" PMTs in the outer detector.
- Measure momentum and direction of particles above Cherenkov threshold.
  - Excellent $\mu^{\pm}/e^{\pm}$ separation.
  - No charge selection.

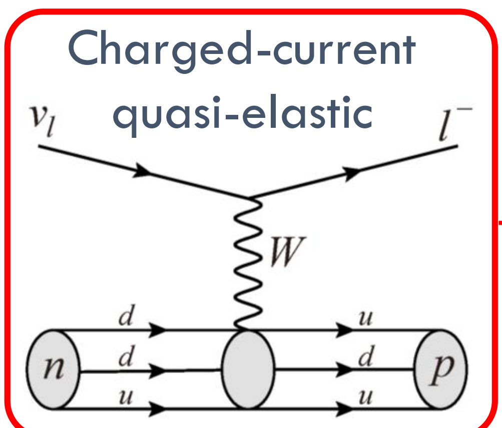


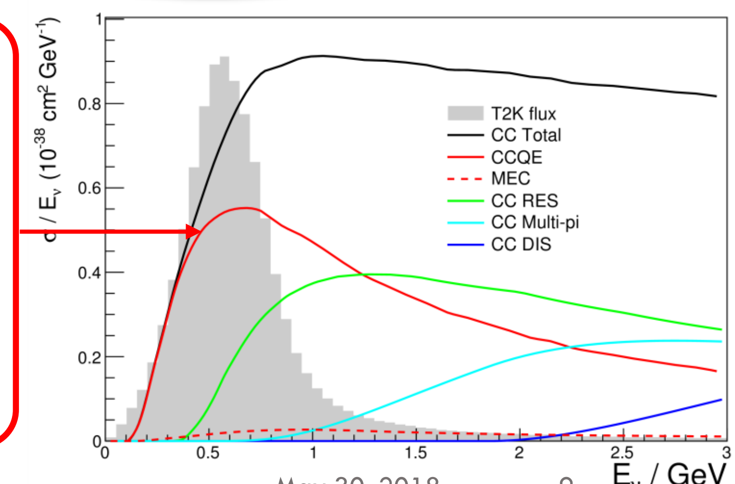


SUPER-KAMIOKANDE SAMPLES

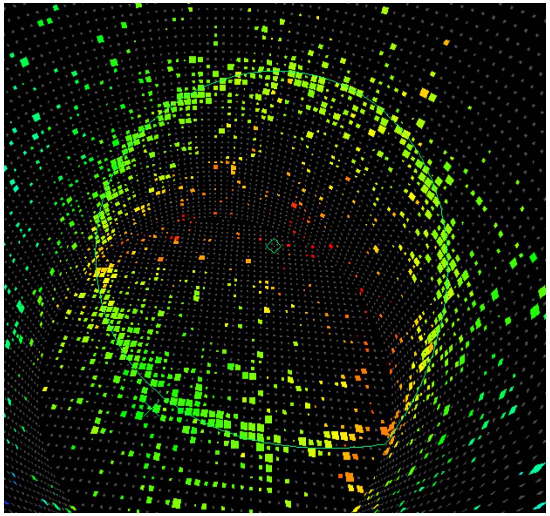


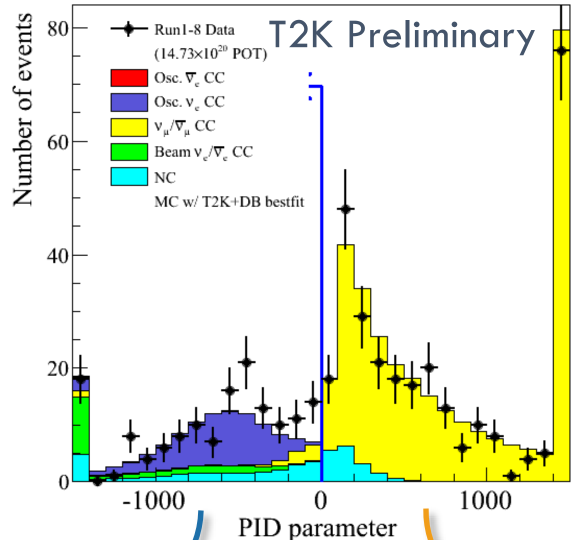
- Hadronic system typically below Cherenkov threshold.
- Signal samples use single-ring events.
- Infer neutrino energy from lepton p and θ_{beam}.

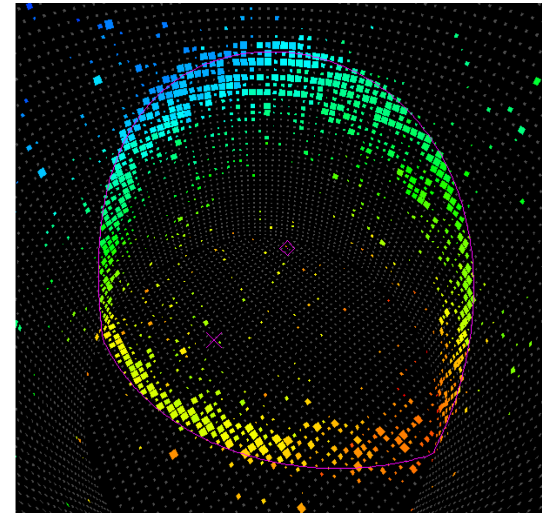




SUPER-KAMIOKANDE SAMPLES





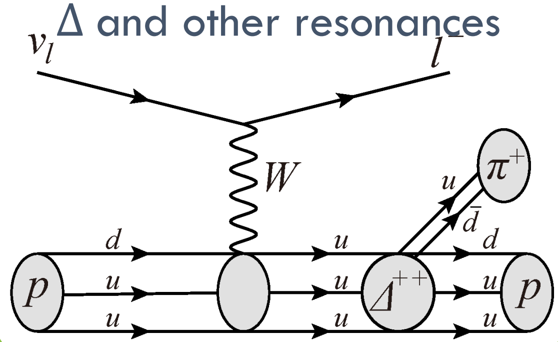


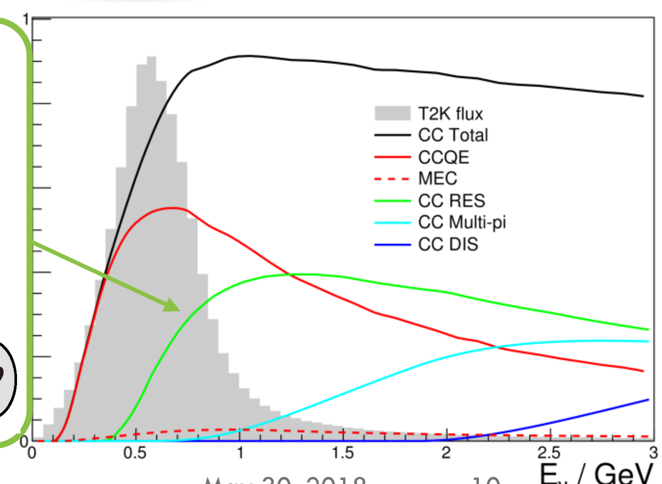
e-like ring

μ-like ring

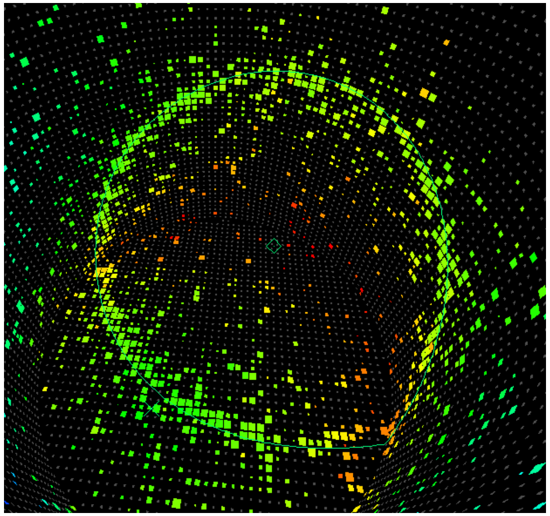
- New sample since summer 2016.
- π^+ below Cherenkov threshold.
  - Infer from μ^+ decay electron.
- Only neutrino mode e-like.

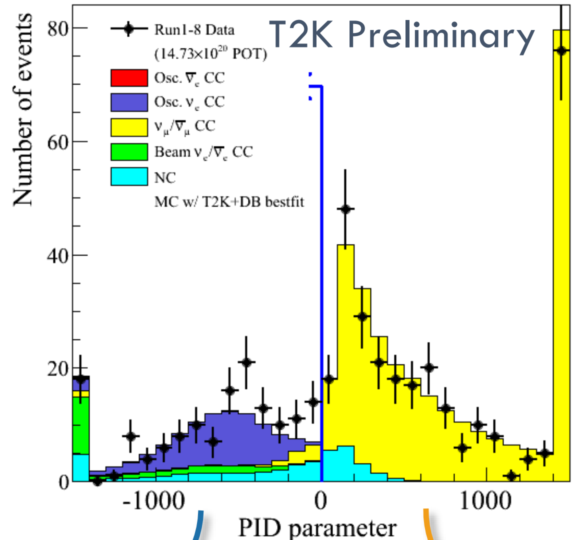
Charged-current
Δ and other resonances

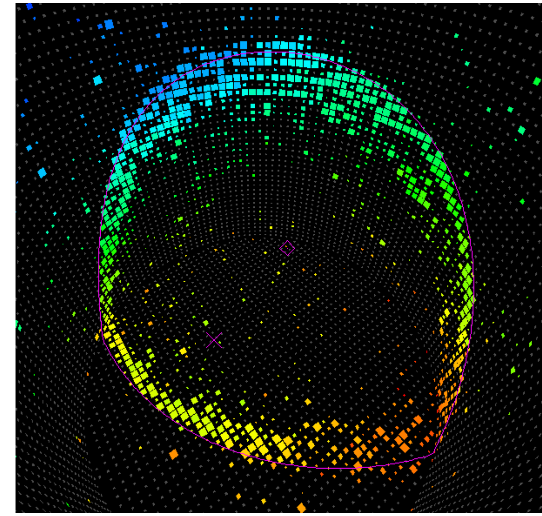




SUPER-KAMIOKANDE SAMPLES







e-like ring

μ-like ring

- Five samples at Super-K, targeting:
  - Charged-current quasi-elastic interactions.
  - Charged-current resonant π production.
- Backgrounds are neutral current π production.
  - $\pi^0 \rightarrow \gamma\gamma$ misidentified as e
  - π^+ misidentified as μ

ν-mode

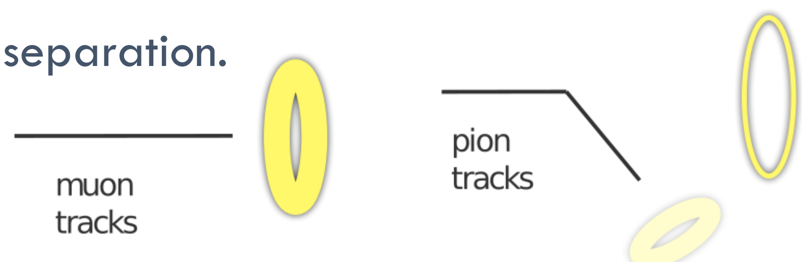
- μ-like, $\leq$1 decay-e
- e-like, 0 decay-e
- e-like, 1 decay-e

$\bar{\nu}$-mode

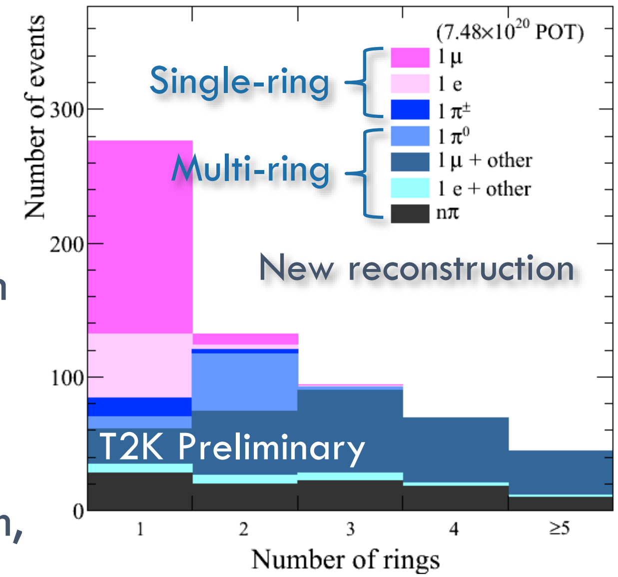
- μ-like, $\leq$1 decay-e
- e-like, 0 decay-e

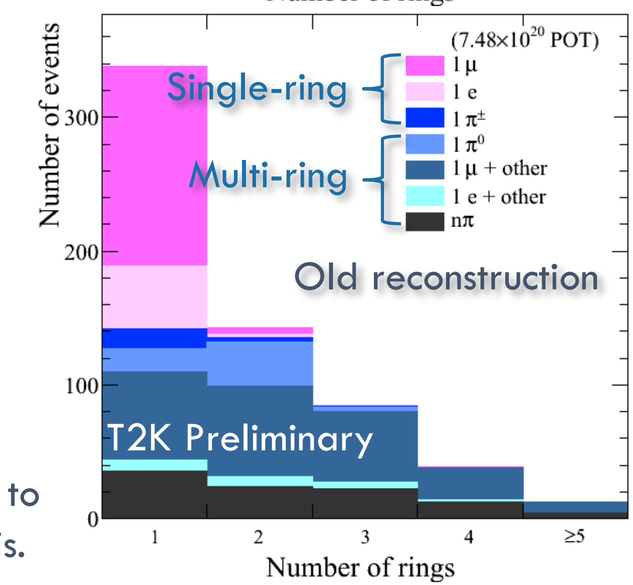
SUPER-K EVENT RECONSTRUCTION

- New event **reconstruction** algorithm for Super-K.
- Previously used only for neutral current π^0 background rejection.
- Maximum-likelihood estimation using all the information in an event, including **unhit** PMTs.
- Likelihood ratios used to compare event hypotheses.
- Improved particle **identification**, ring-counting, momentum, vertex and direction **resolutions**.
- **New** μ / π^+ separation.



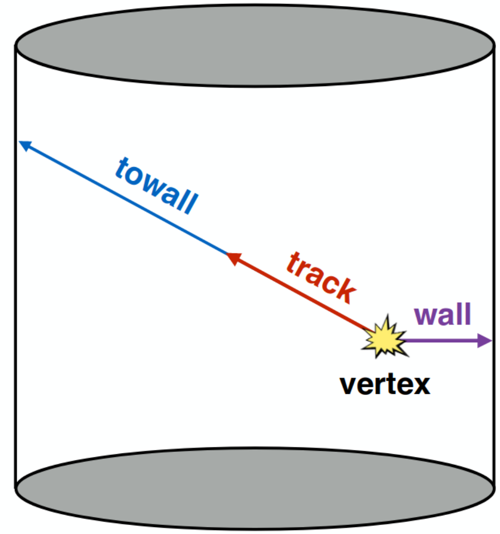
- Optimize **fiducial volume** and **neutral current rejection** criteria for new event reconstruction.
  - Neutral current rejection criteria chosen for optimal sensitivity to oscillation parameters by running simplified oscillation analysis.

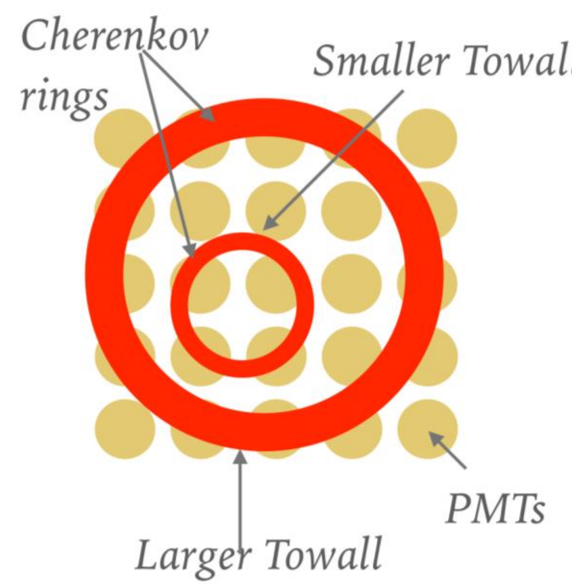




FIDUCIAL VOLUME OPTIMIZATION

- In previous T2K results vertices were required to be > 2 m away from the nearest wall.
- For new event selection, fiducial volume defined as a function of:
  - *wall*: reduces background due to particles entering the detector;
  - *towall*: ensures adequate number of PMTs sample the ring, improving reconstruction quality.
- Both *wall* and *towall* are optimized in a fit to Super-K atmospheric neutrino data, taking into account statistical gains and systematic uncertainties.



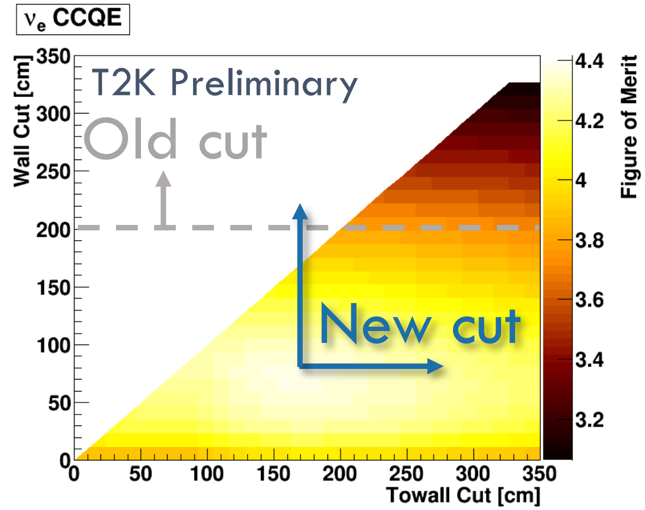


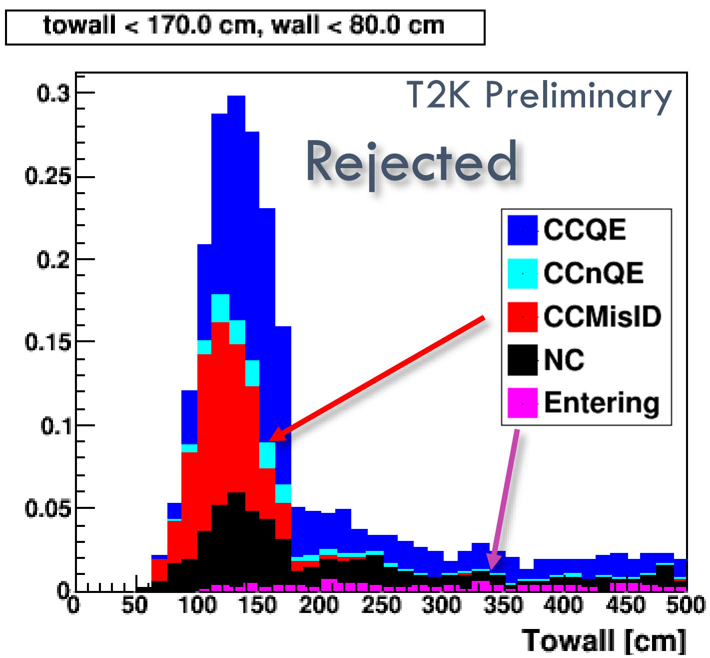
FIDUCIAL VOLUME OPTIMIZATION

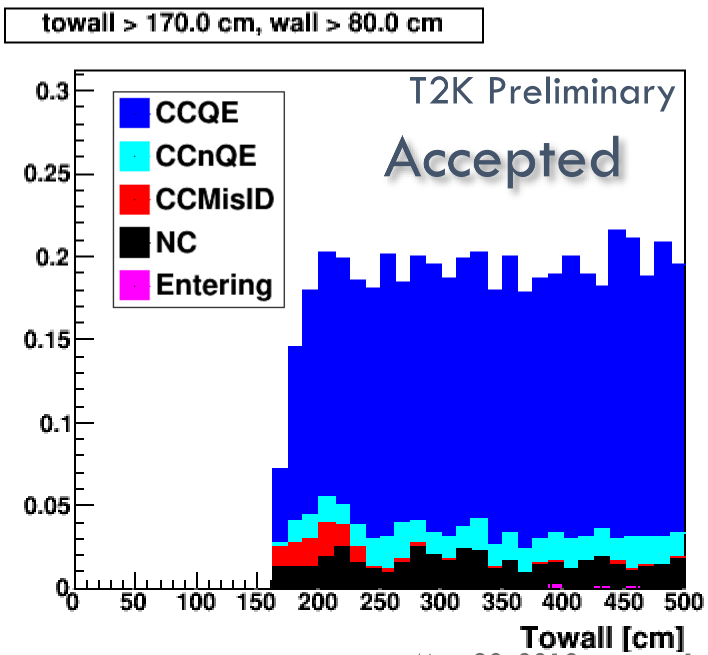
- Optimize figure of merit that enhances events that change significantly under oscillations:

$$FOM = \frac{\left(\frac{\partial \hat{N}}{\partial \theta}\right)^2}{\hat{N} + \sigma_{syst}^2}, \text{ with } \theta = \delta_{CP}, \theta_{23}$$

- Cut points are optimized for each of the five analysis samples separately.







IMPROVEMENTS FROM NEW SELECTION

		New selection		Old selection	
	Sample	Candidates	Purity	Candidates	Purity
ν	μ-like, $\leq$1 decay-e	261.6	**79.7%**	268.7	**68.1%**
	e-like, 0 decay-e	**69.5**	81.2%	**56.5**	81.4%
	e-like, 1 decay-e	**6.9**	**78.8%**	**5.6**	**72.0%**
$\bar{\nu}$	μ-like, $\leq$1 decay-e	62.0	**79.7%**	65.4	**70.5%**
	e-like, 0 decay-e	**7.6**	62.0%	**6.1**	63.7%

- μ-like samples: improved **purity** by reducing neutral current background.

IMPROVEMENTS FROM NEW SELECTION

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- μ-like samples: improved **purity** by reducing neutral current background.
- e-like, 0 decay-e samples: increase **efficiency** by > 20% while keeping previous selection's purity.

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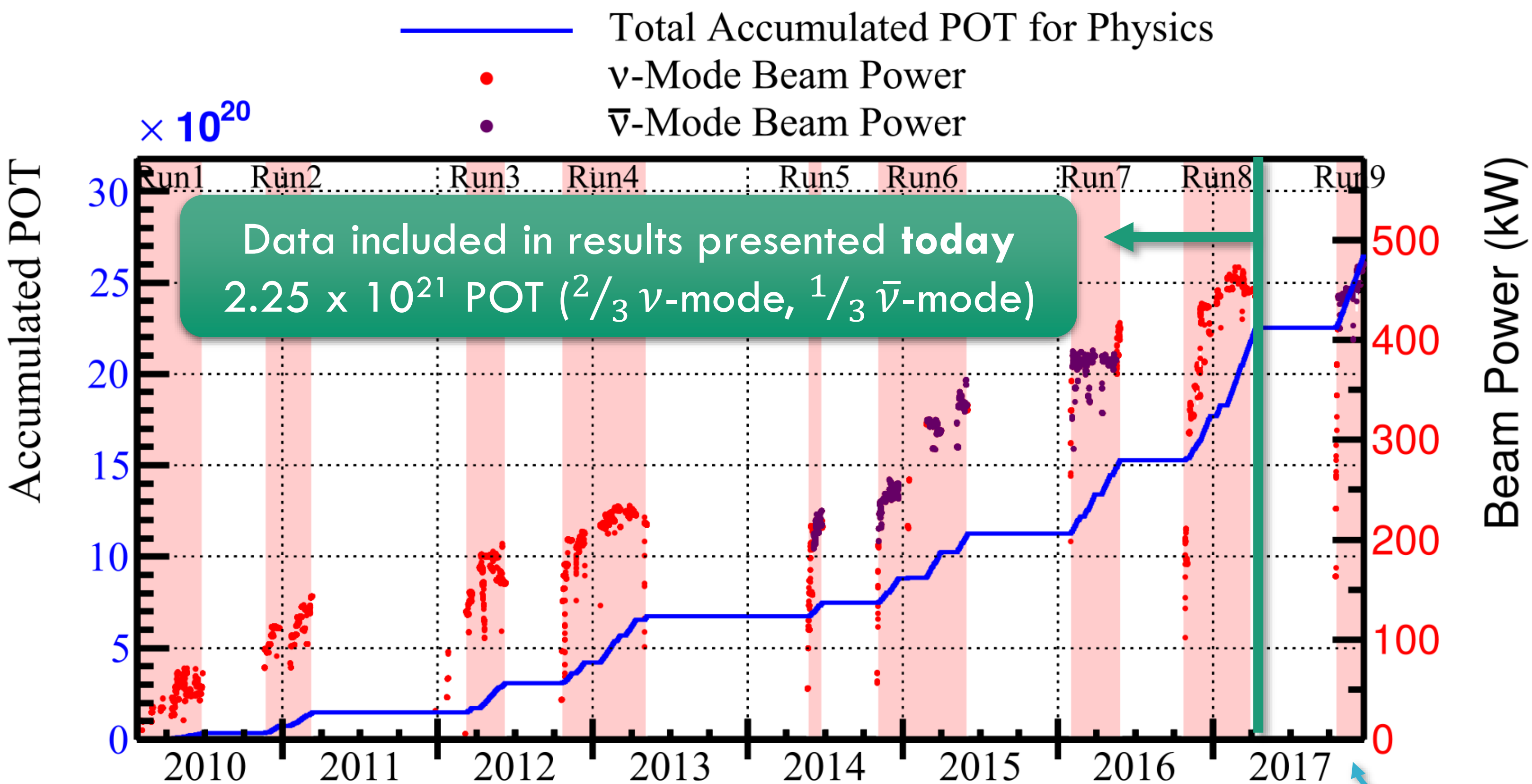
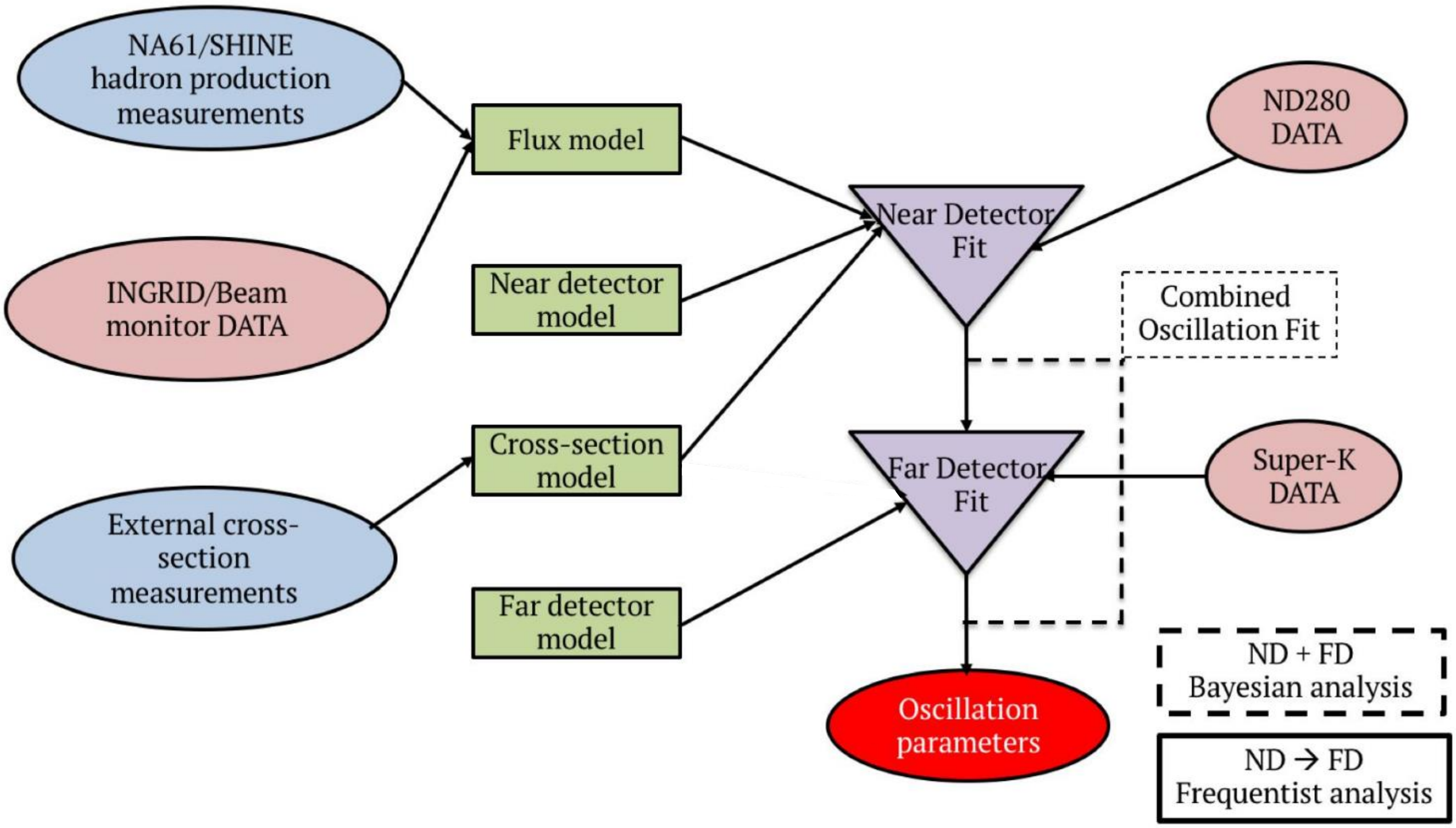
- μ-like samples: improved **purity** by reducing neutral current background.
- e-like, 0 decay-e samples: increase **efficiency** by > 20% while keeping previous selection's purity.
- e-like, 1 decay-e sample: improvement in **purity** from better particle identification and increased **efficiency** from fiducial volume expansion.

DATA TAKING



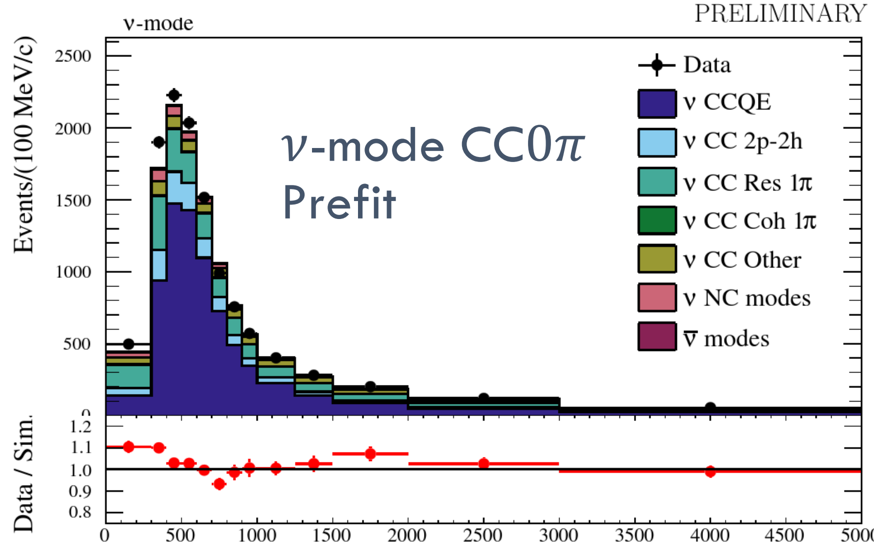
- Stable accelerator operation with 470 kW beam power.
  - Neutrino-mode data doubled in one year of data taking!
- Up to December 2017 a total of 2.65 x 10^{21} protons on target (POT) have been collected.
  - Doubled antineutrino-mode data, in total: 60% in neutrino-mode and 40% in anti-neutrino mode.
  - Keep an eye out for results at **Neutrino** 2018!

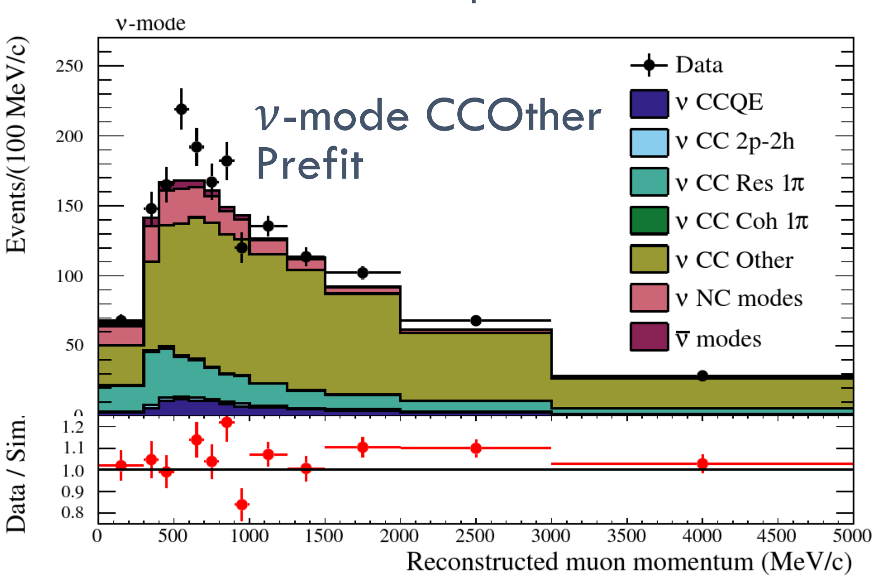
OSCILLATION ANALYSIS STRATEGY

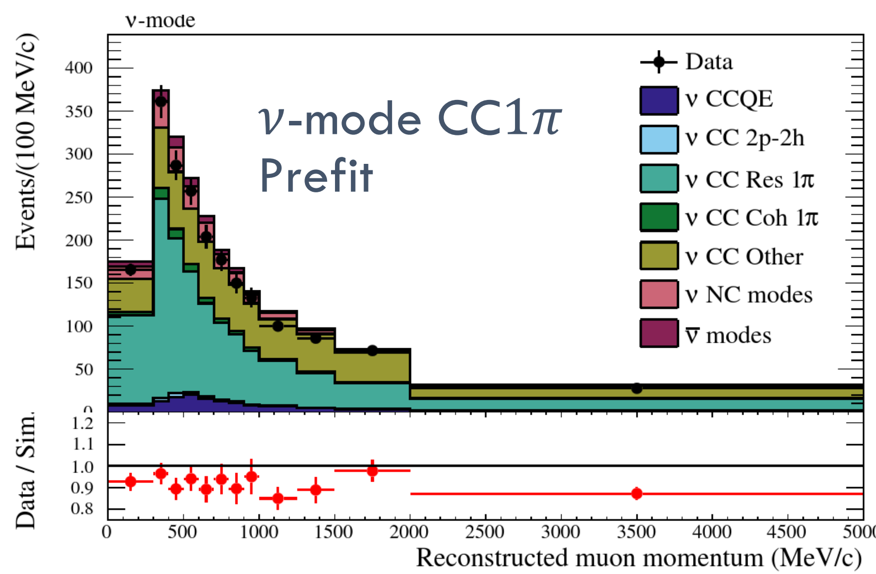


NEAR DETECTOR FIT

- Fourteen near detector samples are used to constrain flux and cross-section model.
  - For ν-mode: charged current with: 0 πs; 1π^+; or other particles.
  - Single-track and multi-track charged current with μ^+ or μ^- for $\bar{\nu}$-mode.
  - Seven samples for each FGD.





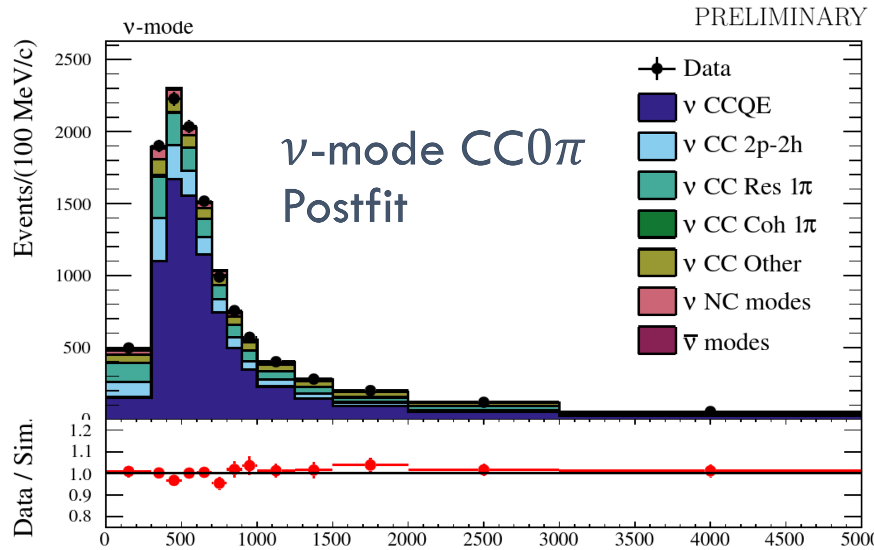


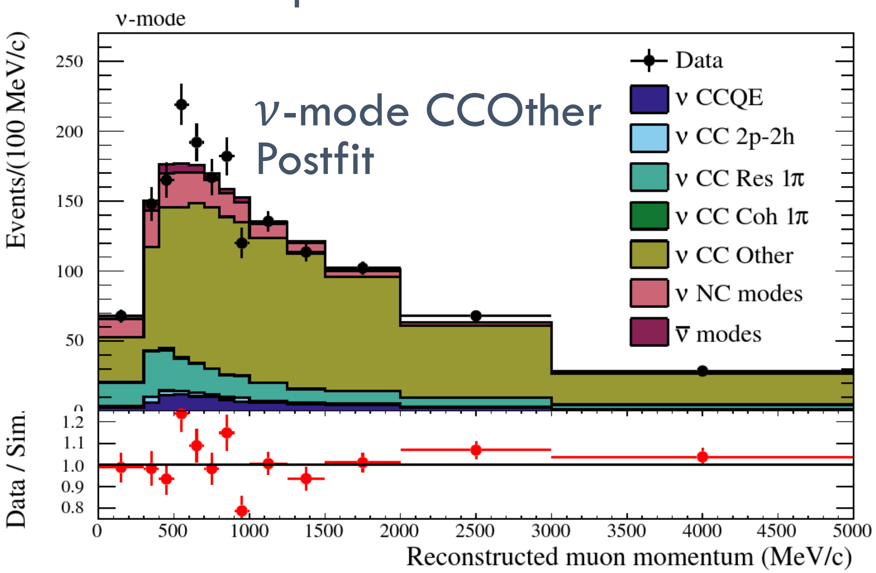
PRELIMINARY

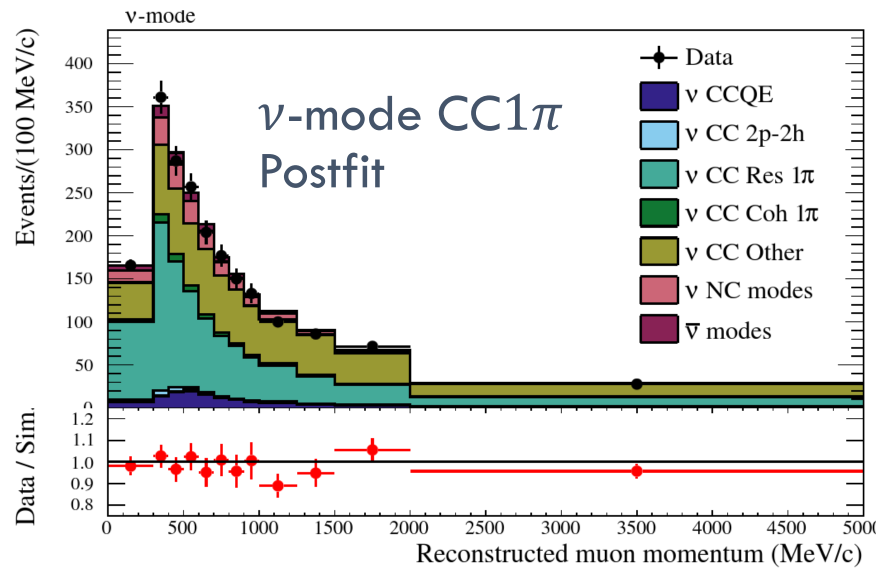
RELIMINARY

NEAR DETECTOR FIT

- After fit to near detector samples, flux and cross-section uncertainties at far detector reduced from ~15% to ~5%.
- Good fit to the data.
  - p-value: 0.47





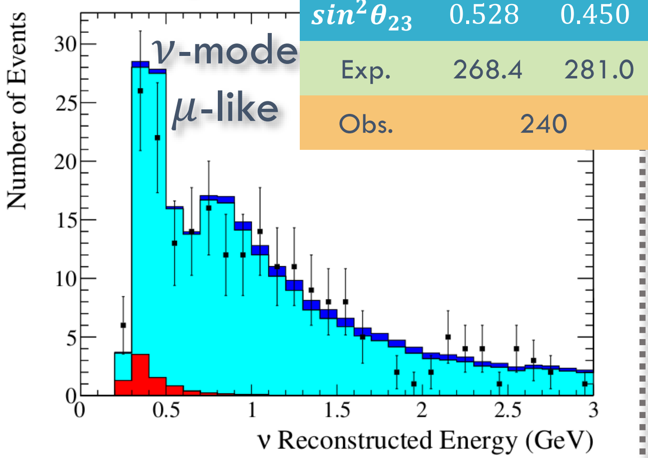


PRELIMINARY

RELIMINARY

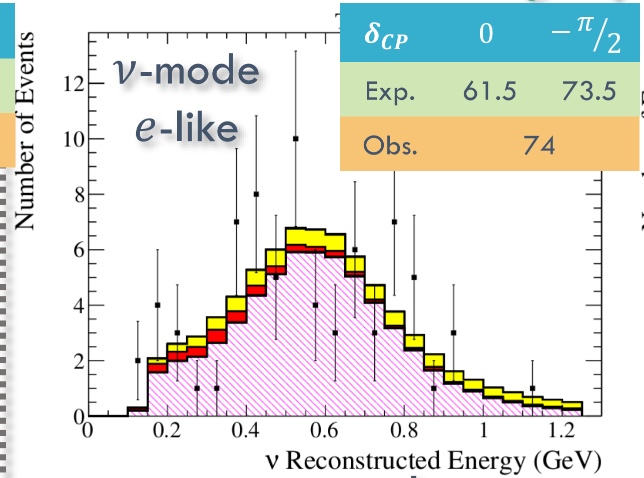
FAR DETECTOR DATA

ν_μ Disappearance

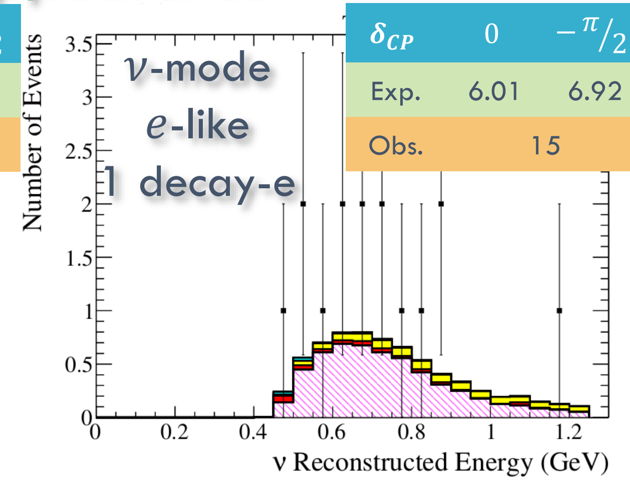


$sin^2\theta_{23}$	0.528	0.450
Exp.	268.4	281.0
Obs.	240	

ν_e Appearance



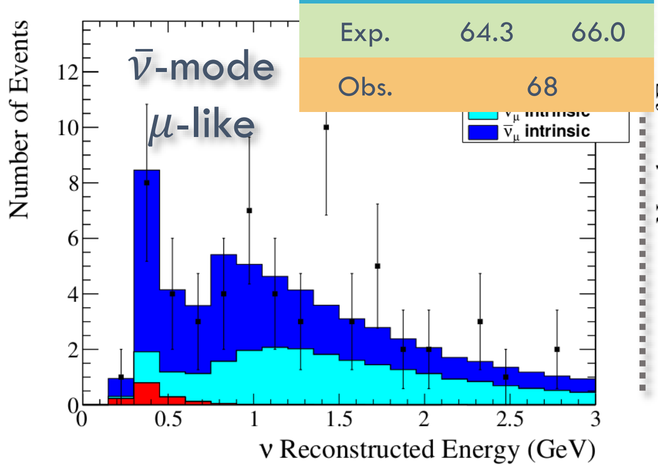
δ_{CP}	0	$-\pi/2$
Exp.	61.5	73.5
Obs.	74	



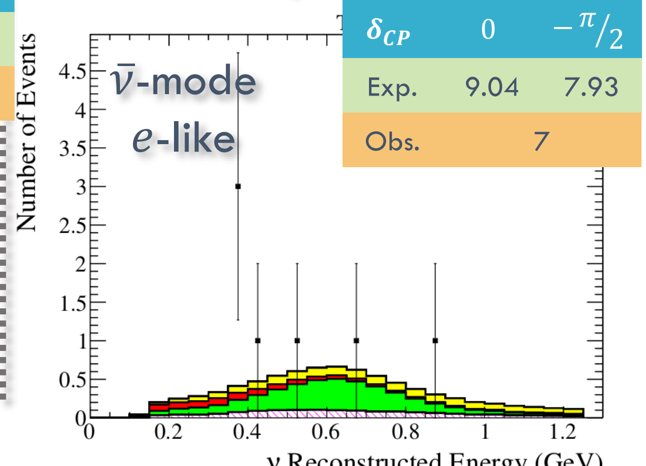
δ_{CP}	0	$-\pi/2$
Exp.	6.01	6.92
Obs.	15	

ν-mode

$\bar{\nu}$-mode



$sin^2\theta_{23}$	0.528	0.450
Exp.	64.3	66.0
Obs.	68	



δ_{CP}	0	$-\pi/2$
Exp.	9.04	7.93
Obs.	7	

- $\nu_\mu \rightarrow \nu_e$
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- NC
- $\nu_e/\bar{\nu}_e$ intrinsic
- ν_μ intrinsic
- $\bar{\nu}_\mu$ intrinsic

p-value = 0.42

T2K Preliminary

SYSTEMATIC UNCERTAINTIES

	% Errors on predicted event rate at Super-K					
	μ-like		e-like			
Error Source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode 1 dcy-e	$\nu/\bar{\nu}$
SK Detector	2.41	2.02	2.85	2.83	13.26	1.47
SK final state and secondary interactions	2.21	1.99	3.03	2.34	11.51	1.57
ND280-constrained flux and cross section	3.25	2.74	3.24	2.90	4.08	2.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.00	0.00	2.64	1.45	2.63	3.04
NC1γ	0.00	0.00	1.08	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.98	0.18
Binding energy	2.42	1.73	7.27	3.70	2.99	3.71
Total Systematic Error	5.07	4.32	8.81	7.02	18.41	5.87

- Largest uncertainties are the Super-K detector modelling and π interaction modelling, both for the e-like events with one decay electron.

SYSTEMATIC UNCERTAINTIES

	% Errors on predicted event rate at Super-K					
	μ-like		e-like			
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- No precise measurement of $\nu_e(\bar{\nu}_e)$ interactions in the near detector.
- Theoretically motivated uncertainty based on Phys.Rev. D86 (2012) 053003.

SYSTEMATIC UNCERTAINTIES

	% Errors on predicted event rate at Super-K					
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- No near detector constraint on neutral current modes.
- Uncertainty based on modelling and external data.

SYSTEMATIC UNCERTAINTIES

	% Errors on predicted event rate at Super-K					
	μ-like		e-like			
Error Source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode 1 dcy-e	$\nu/\bar{\nu}$
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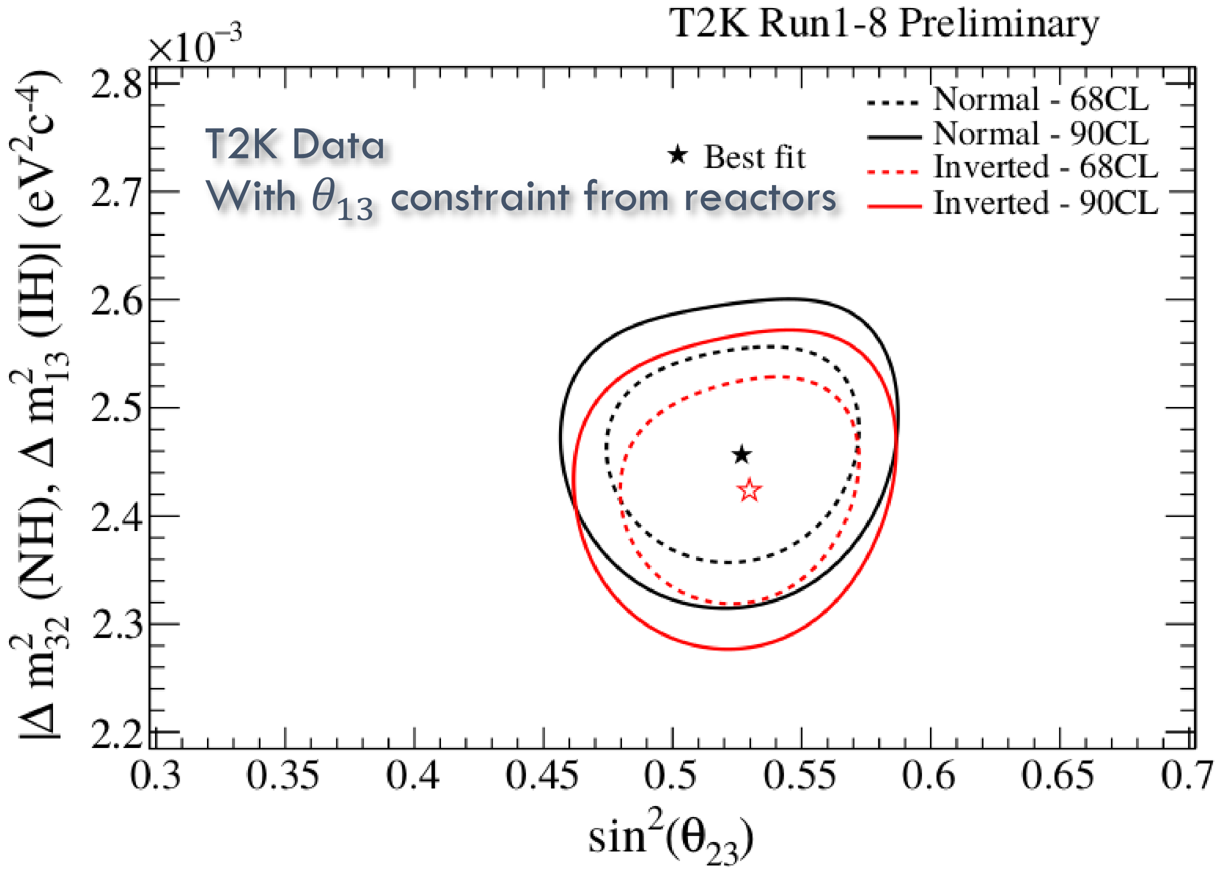
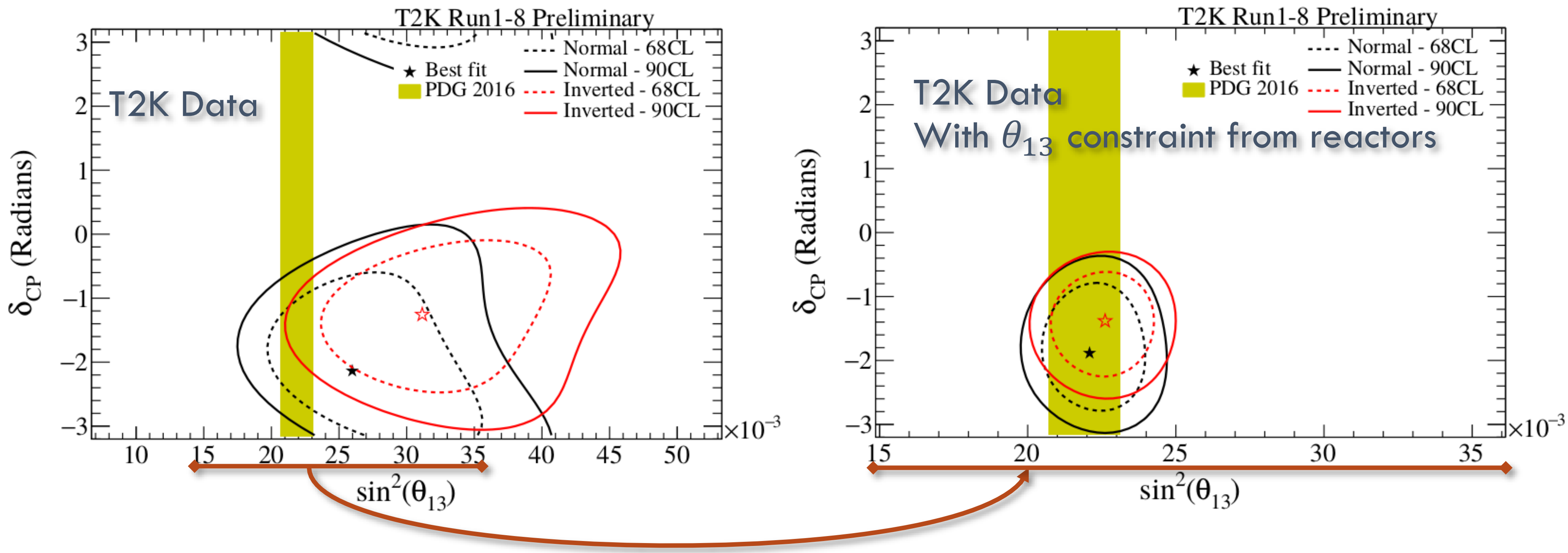
- Binding energy range based on A. Bodek (arXiv:1801.07975), motivated by electron scattering data.
- Size of effect estimated by running oscillation analyses on simulated data.

ATMOSPHERIC PARAMETER CONSTRAINTS



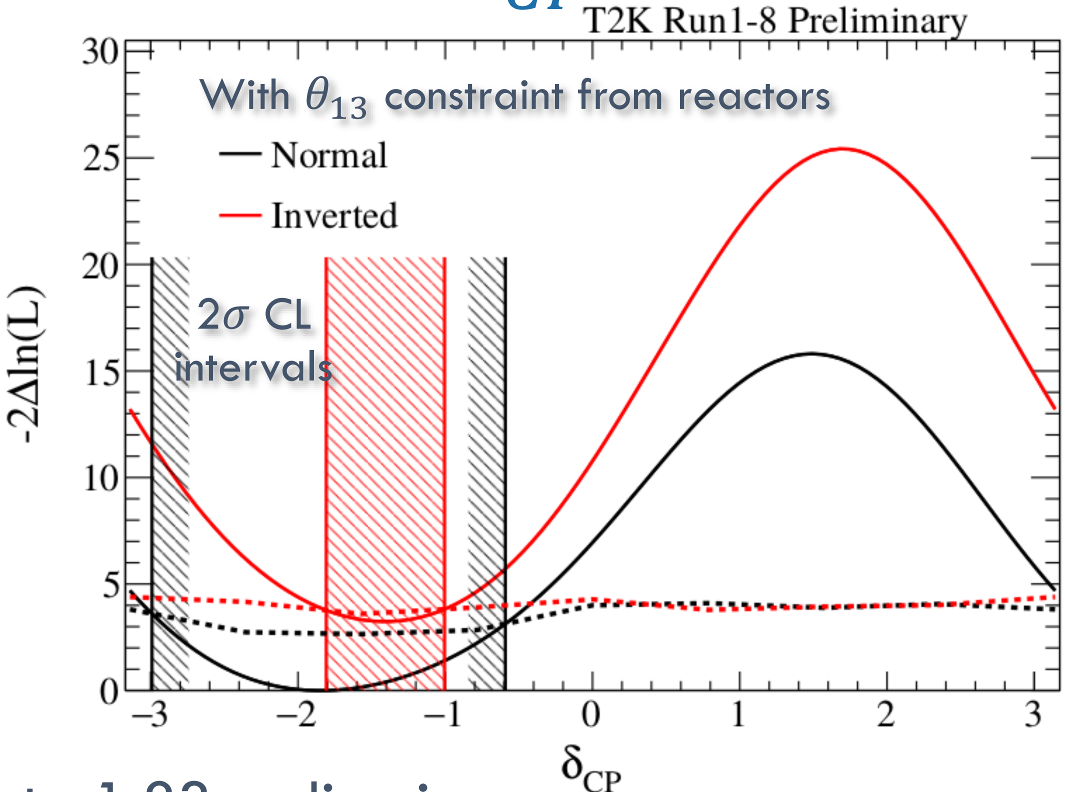
- Fit under normal and inverted hierarchy assumptions separately.
- Apply constraint on θ_{13} from reactor experiments.
- T2K data consistent with maximal mixing.

APPEARANCE PARAMETERS



- Closed contours at 90% CL in δ_{CP} for fit without external θ_{13} constraints.
- T2K best fit consistent with PDG 2016.
  - T2K: $\sin^2\theta_{13} = 0.0279^{+0.0064}_{-0.0048}$ (NH)
  - PDG 2016: $\sin^2\theta_{13} = 0.0210 \pm 0.0011$

CONSTRAINT ON δ_{CP}



- Best-fit point: -1.83 radian in Normal Hierarchy
- CP conserving values are outside of the 2σ CL intervals.

	NH	IH
90% CL	[-2.82, -0.85]	∅
2σ CL	[-2.99, -0.59]	[-1.81, -1.01]

θ_{23} OCTANT AND MASS HIERARCHY

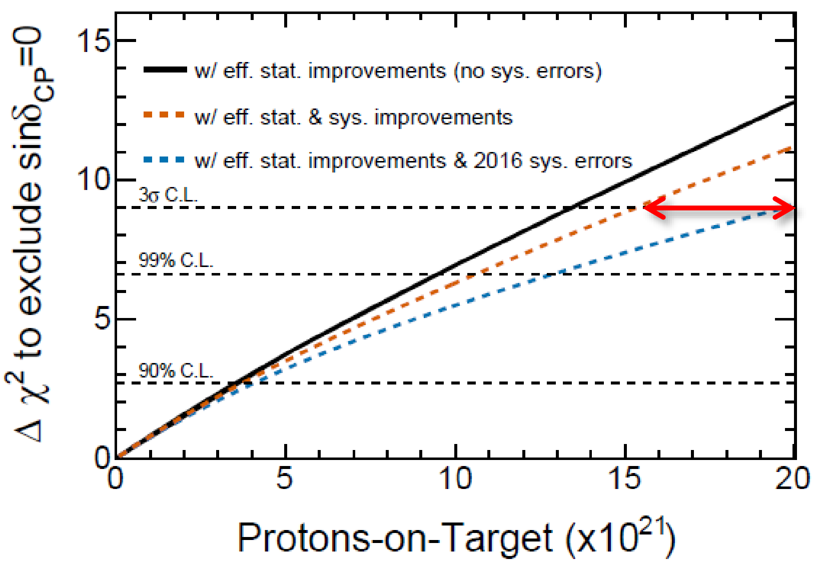
- Look at posterior probability from Bayesian analysis to infer T2K data preference for θ_{23} octant and mass hierarchy.
- Equal prior probability given to all hypotheses.

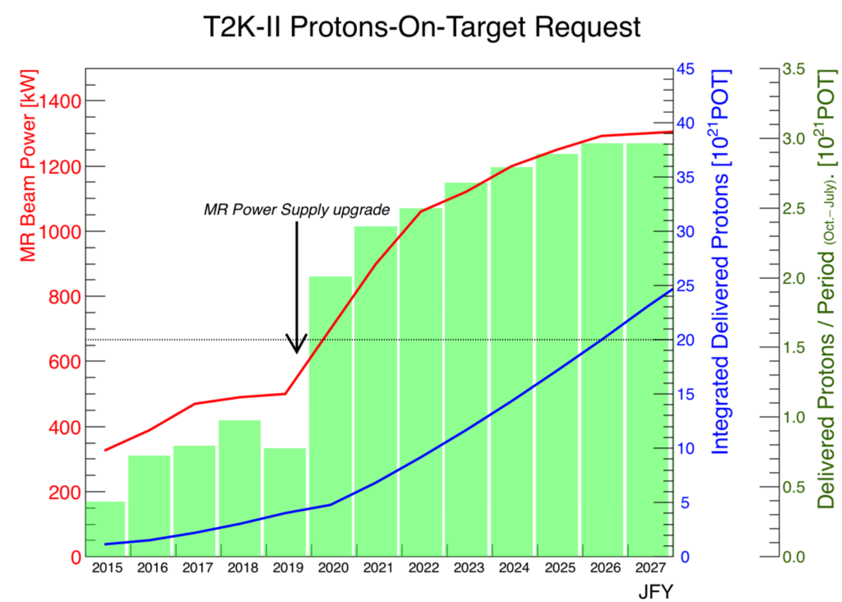
	$sin^2\theta_{23} < 0.5$	$sin^2\theta_{23} > 0.5$	**Sum**
NH ($\Delta m_{32} > 0$)	0.191	0.681	0.872
IH ($\Delta m_{32} < 0$)	0.024	0.104	0.128
Sum	0.216	0.784	

- Data shows weak preference for **normal** hierarchy and **upper** octant.

PLANS FOR AN EXTENDED T2K RUN

- T2K originally approved to take 7.8x10^{21} POT (~2021).
- T2K-II: proposal to extend T2K running to 20x10^{21} POT (~2026). arxiv:1609:04111
- Sensitivity to exclude CP conserving values of δ_{CP} at 3σ within reach if δ_{CP} is near current best fit.
- Analysis improvements foreseen to increase sensitivity by 50% compared to 2016 results.
  - 30% already achieved!
- Systematic uncertainties will play significant role in measurement – expect improvement.





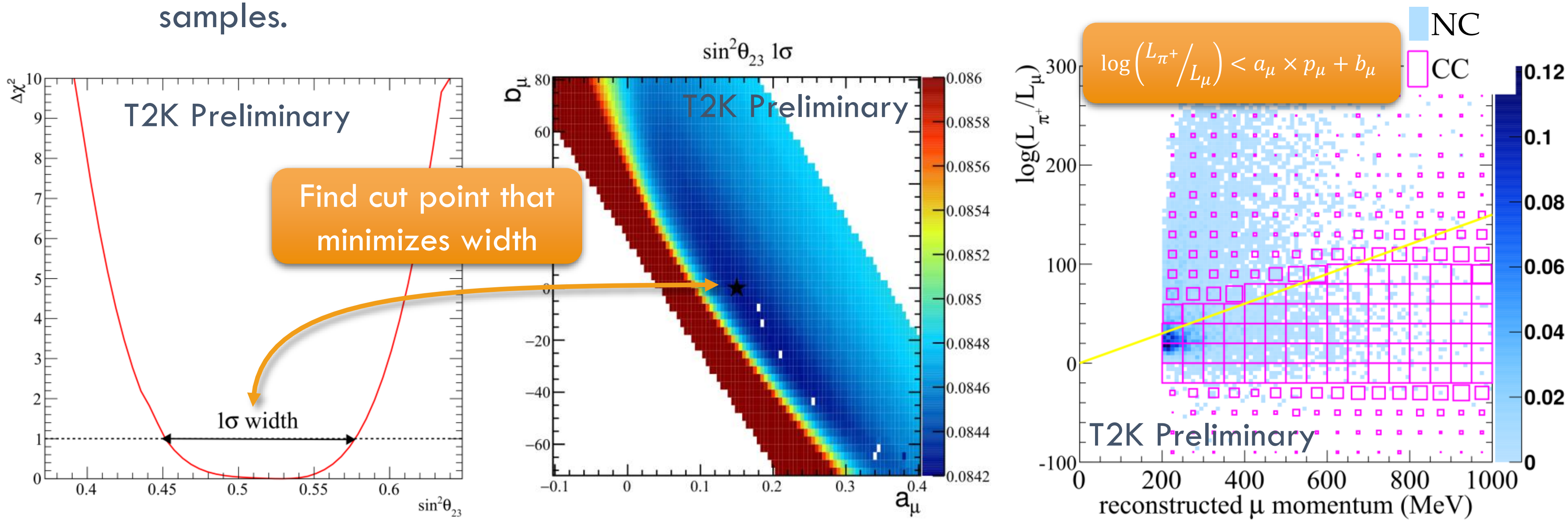
SUMMARY

- Since summer 2016:
  - Doubled neutrino-mode protons-on-target with steady beam operation at 470 kW.
  - New reconstruction algorithm and event selection improved Super-K samples statistics by $> 20\%$.
- With new data and analysis improvements, CP conserving values of δ_{CP} are disfavoured at 2σ.
- Proposal to run T2K until ~2026, accumulating 20×10^{21} POT.
  - Potential to exclude CP conservation in lepton sector at 3σ if δ_{CP} near maximal.
- Expect results with new 2017 antineutrino-mode data soon!

SUPPLEMENTARY

NEUTRAL CURRENT REJECTION

- Optimize selection criterium to reject neutral current π^+events in $\nu_\mu(\bar{\nu}_\mu)$ samples.
  - Large uncertainty on cross section degrades precision on disappearance measurements.
- Run simplified oscillation analysis framework, including systematic uncertainties.
- Choose cut point in $\log\left({}^{L_{\pi^+}}/_{L_\mu}\right)$ vs p_μ that maximizes precision on $\sin^2\theta_{23}$ measurement.
  - Optimal cut point is different for equivalent study with statistical uncertainty only.
- Same procedure for neutral current π^0 rejection cut optimization for appearance samples.



SIMULATED DATA STUDIES FOR E_B

- Generate 2D templates of μ momentum shifts in E_ν vs θ_μ.
  - For each ν species and for carbon and oxygen targets.
    - Carbon: 25^{+18}_{-9} MeV
    - Oxygen: 27^{+18}_{-9} MeV
  - Shifts are applied to 1p1h events.
- Produce simulated data sets using E_B templates and run oscillation analysis fit.
- Setting both C and O E_B to the maximum value considered gives:
  - At the near detector: slight decrease in CCQE cross-section parameters; increased 2p2h contribution.
  - At far detector: significant bias in Δm^2_{32} estimation; small impact on θ_{13}, δ_{CP}.
- Setting E_B to maximum for ν and minimum for $\bar{\nu}$ gives similar results.

δ_{CP} SENSITIVITY

- Data constraint on δ_{CP} is stronger than the average sensitivity.
- Run toy experiments with normal hierarchy and $\delta_{CP} = -\pi/2$.
- Data constraint falls within range for 95.54% of experiments for most δ_{CP} points.
- 30% of experiments exclude $\delta_{CP} = 0$ at 2σ.
- 25% of experiments exclude $\delta_{CP} = \pi$ at 2σ.