NEUTRINO OSCILLATION AT T2K: SEARCH FOR CP VIOLATION

Kirsty Duffy, Fermilab

Fermilab Neutrino Seminar, 28th September 2017

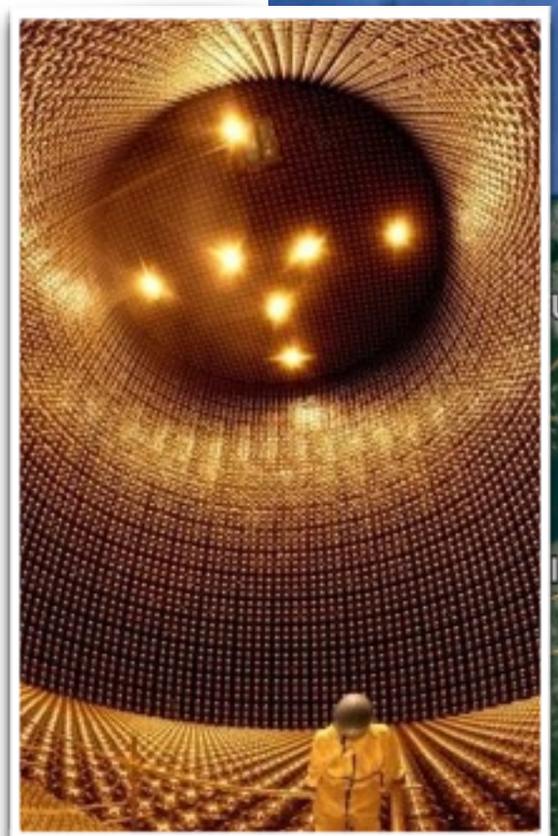
T2K has collected data in both neutrino- and antineutrino-beam running, and in 2016 released its first results using both neutrino and antineutrino data. This provided the first sensitivity to δ_{CP} from a single experiment.

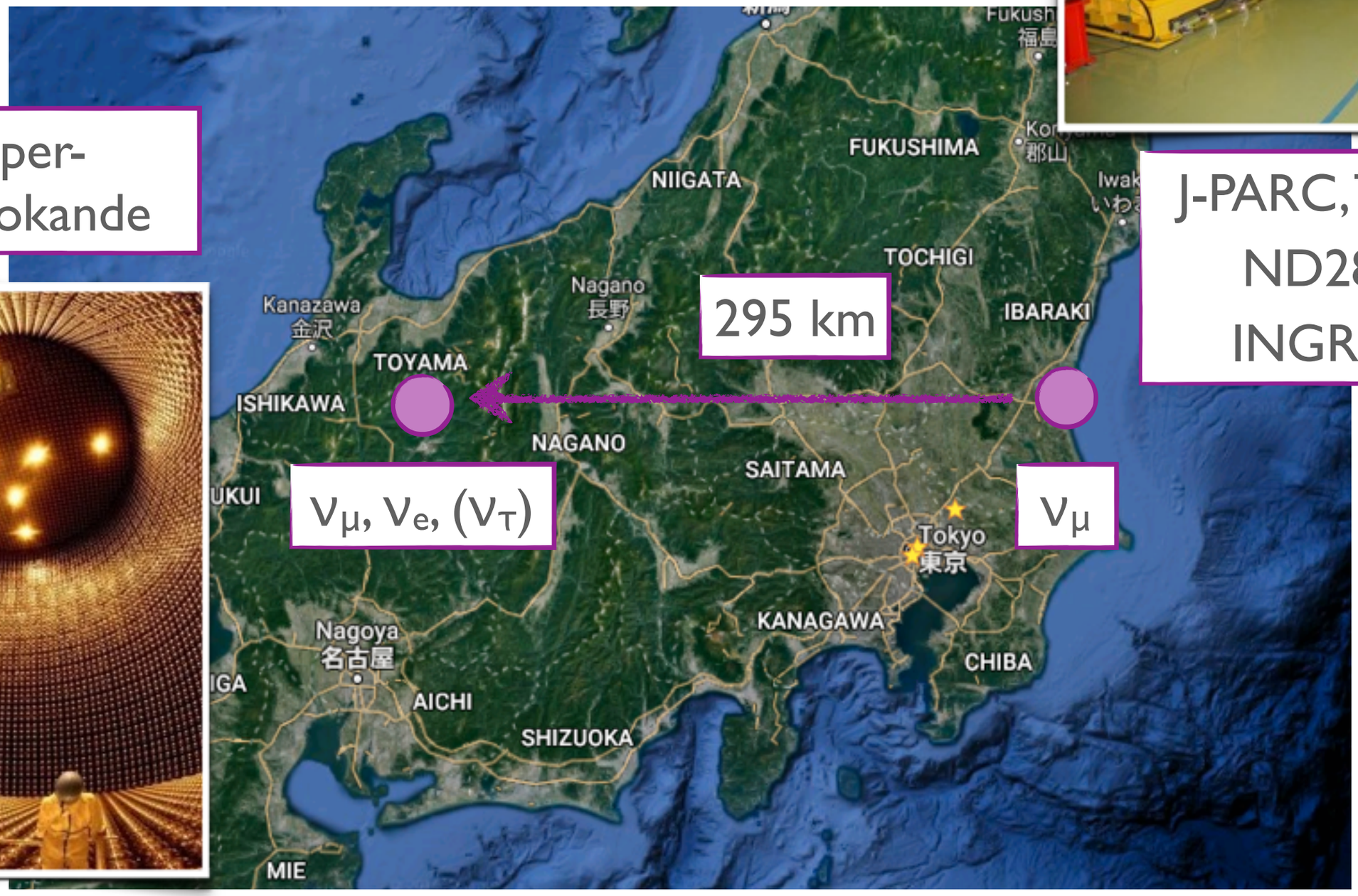
Substantial improvements have been made to the T2K analysis since these results, focusing in two areas: the far detector reconstruction, and the neutrino interaction model uncertainties.

In the last year, T2K has doubled its neutrino-mode data set. I will present the newest results including this new data and analysis improvements.

THE T2K EXPERIMENT

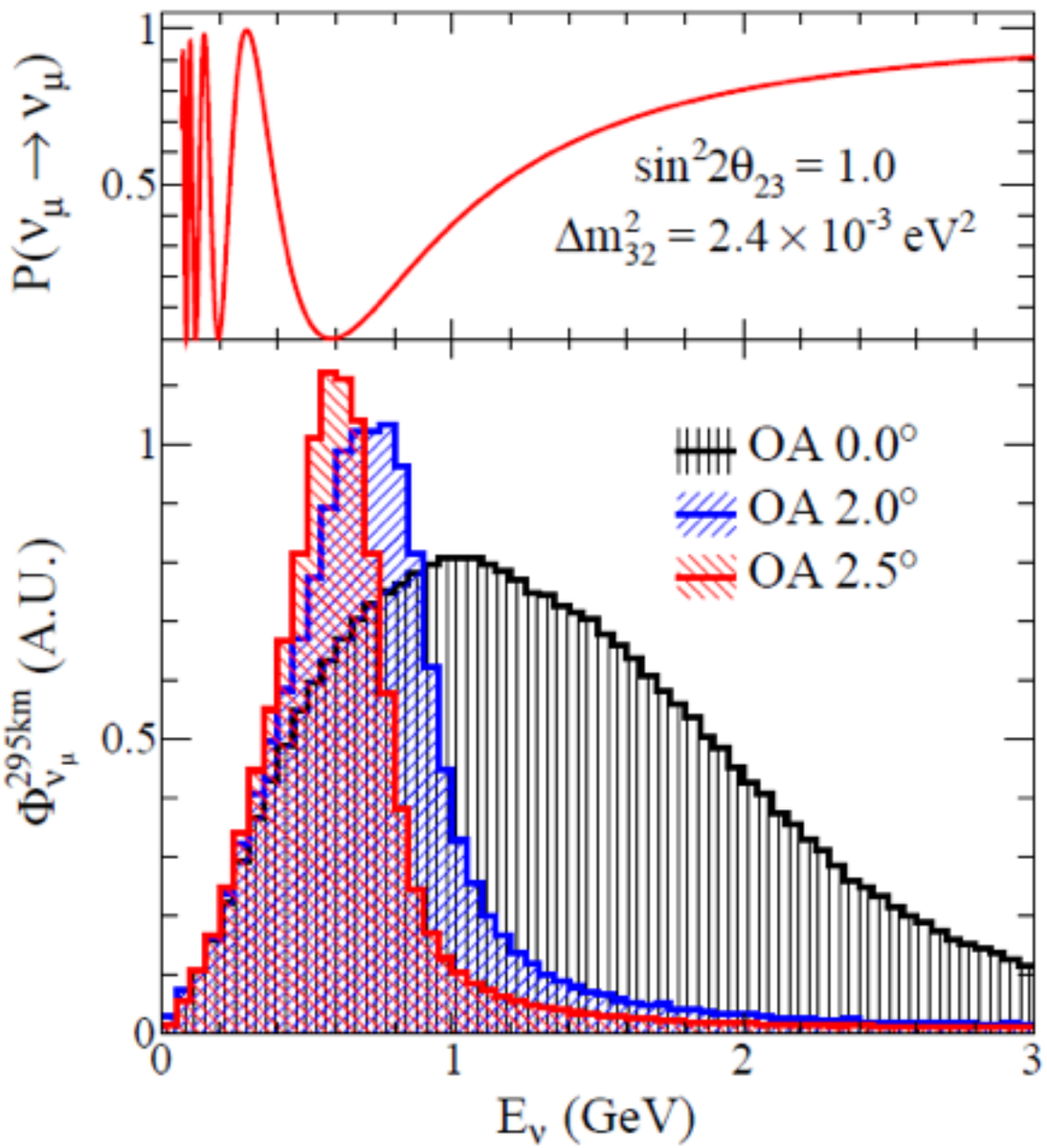
Super-Kamiokande

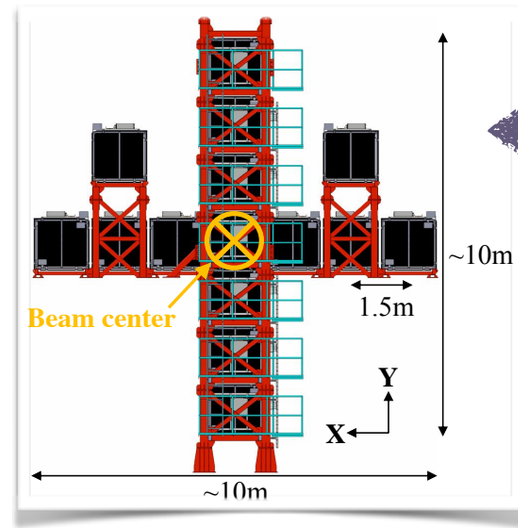




J-PARC, Tokai
ND280
INGRID

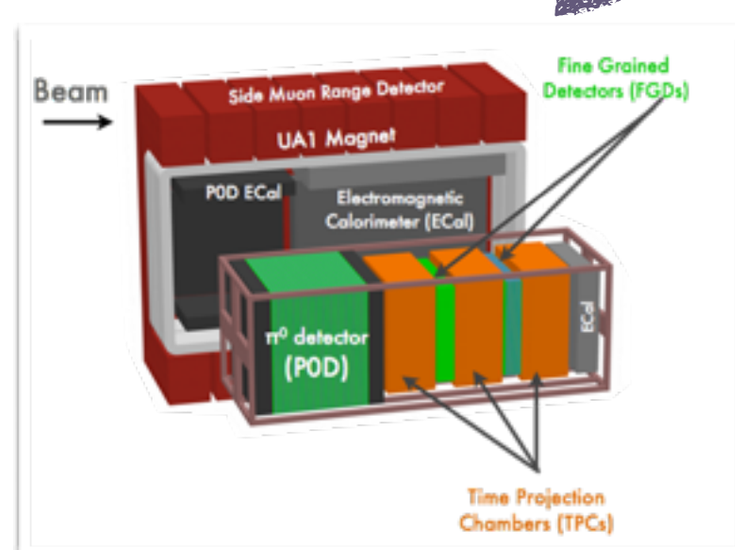
OFF-AXIS BEAM

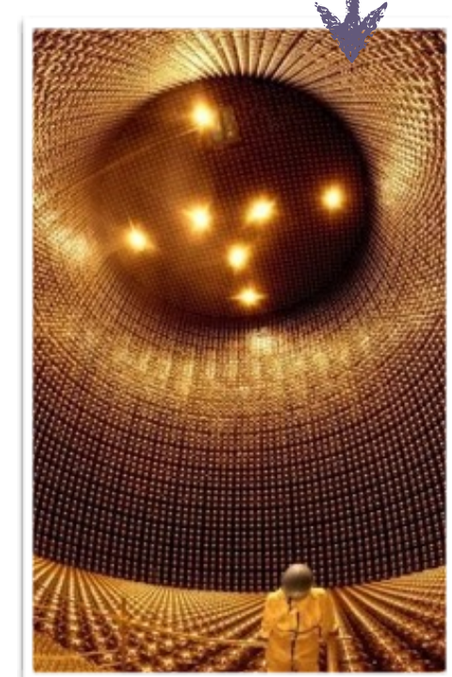




On axis: INGRID

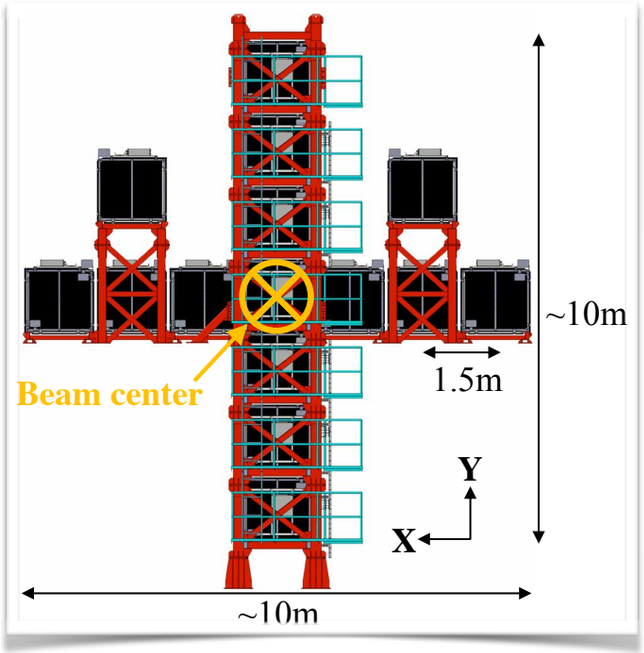
Off axis (2.5°): ND280, Super-K





T2K NEAR DETECTORS

Both near detectors also used for cross-section measurements

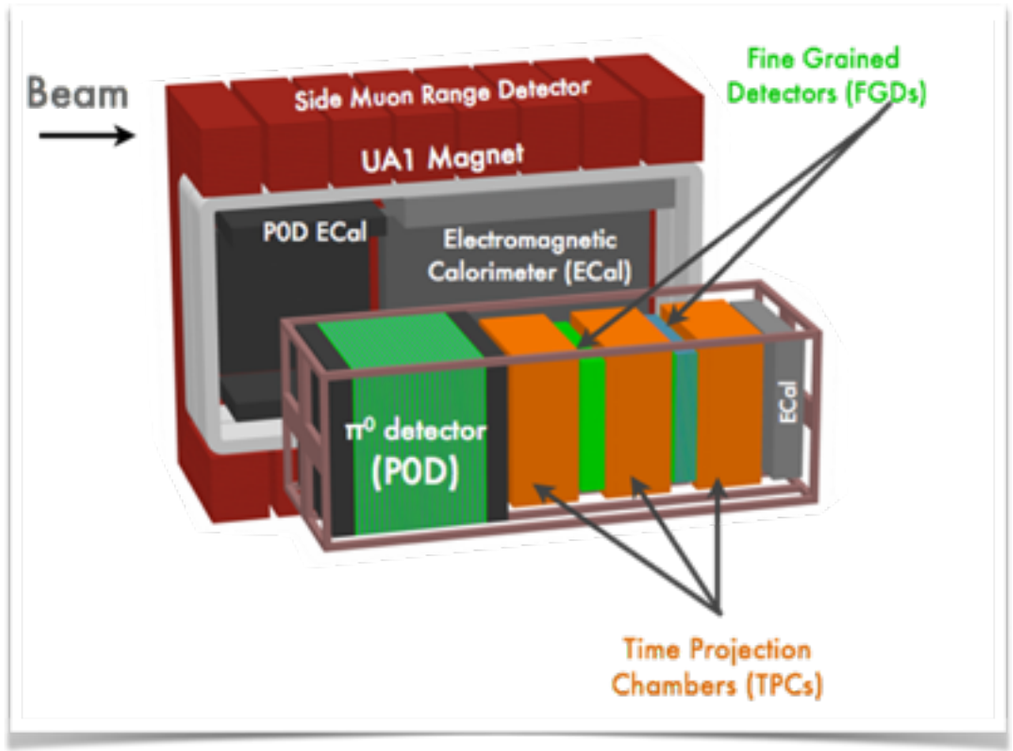


INGRID (on axis)

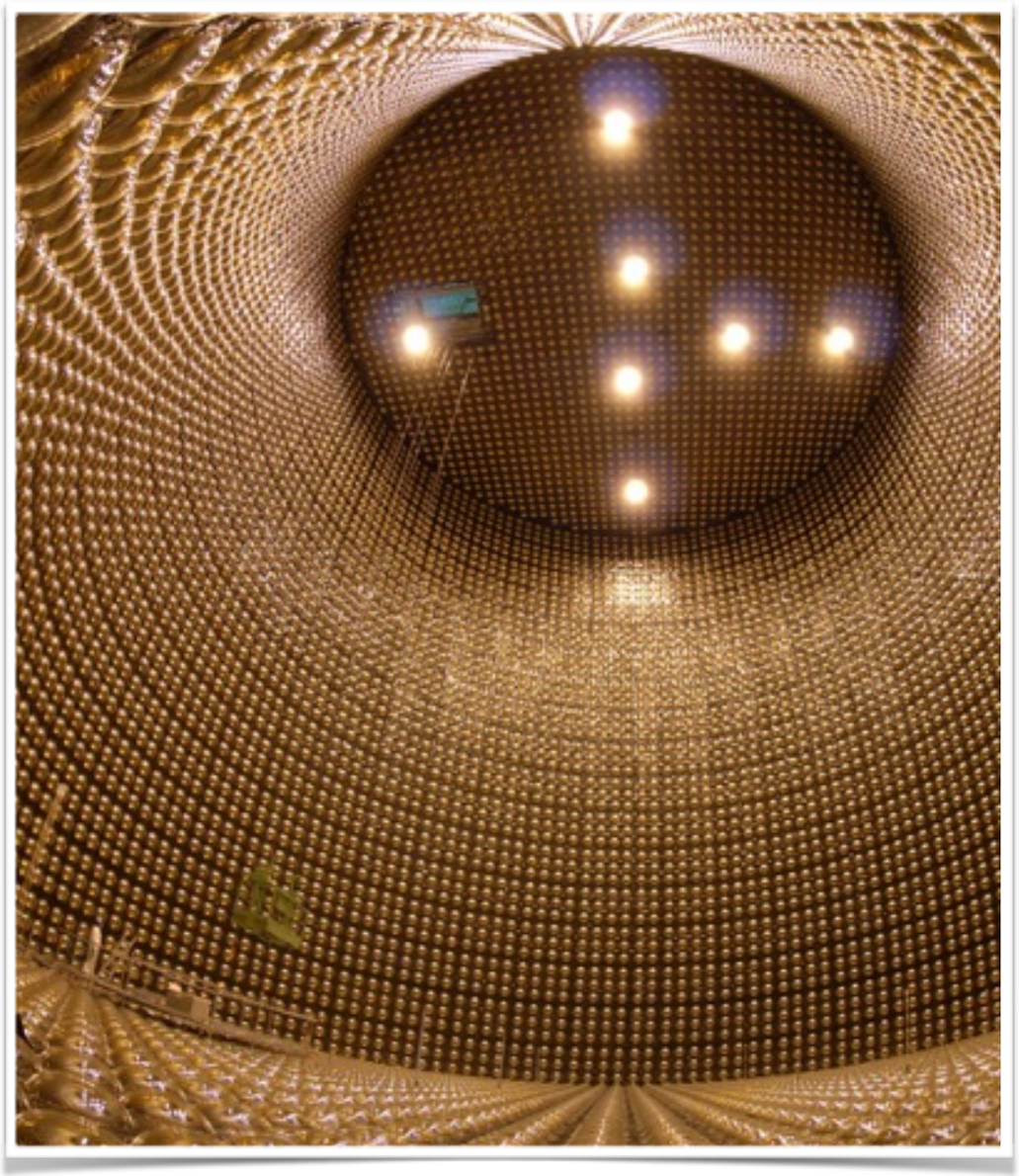
- 7+7 array of iron/scintillator detectors
- Used **indirectly** in oscillation analysis: measure beam stability, estimate flux uncertainty before ND280 fit

ND280 (off axis)

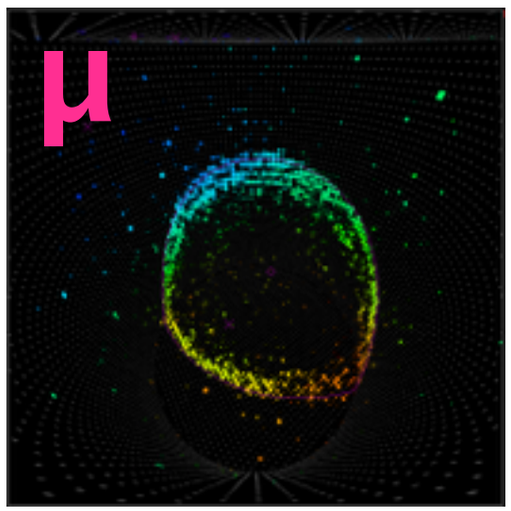
- Used directly in oscillation analysis to reduce flux and cross-section uncertainties
- **F**ine-**G**rained **D**etectors: scintillator **targets** for neutrino interactions, excellent vertexing
- **T**ime-**P**rojection **C**hambers: very good **momentum resolution** and **PID**

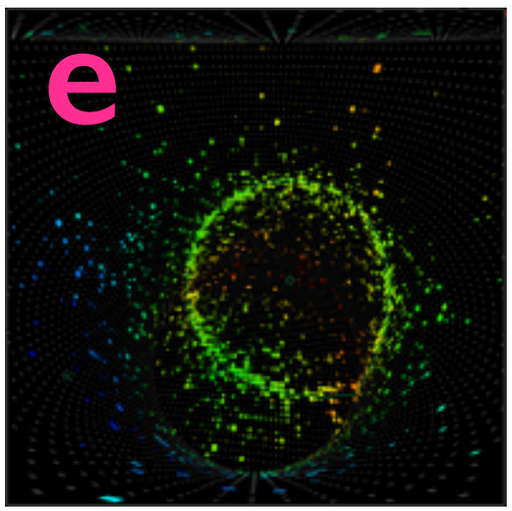


T2K FAR DETECTOR: SUPER-K



- 50 kton water Cherenkov detector
- Lepton flavour identification from pattern of Cherenkov light from charged particle → 0.7% of μ misidentified as e
- No magnetic field





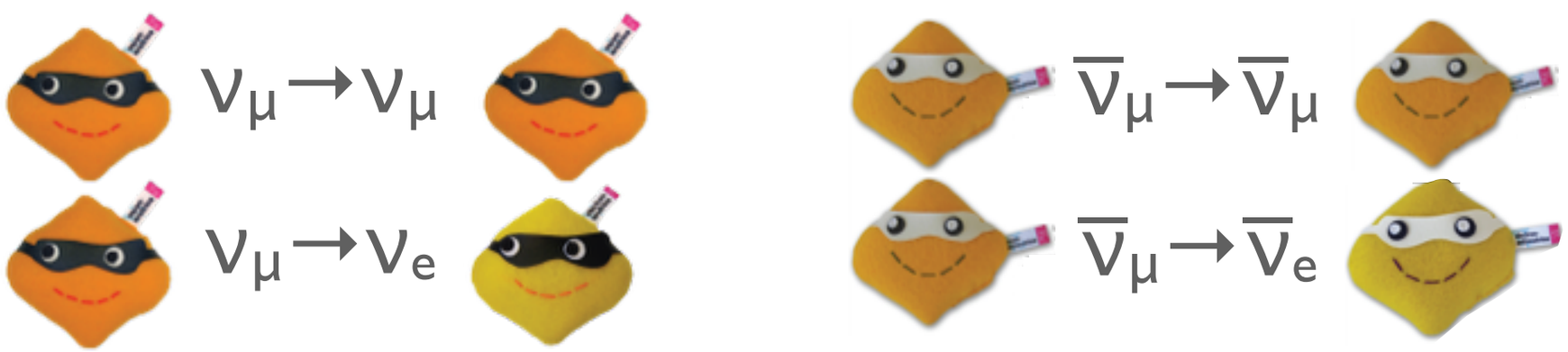
NEUTRINO OSCILLATION AT T2K

T2K neutrino beam can be run in two configurations:
neutrino mode and **antineutrino mode**

Beam composed of mostly ν_μ

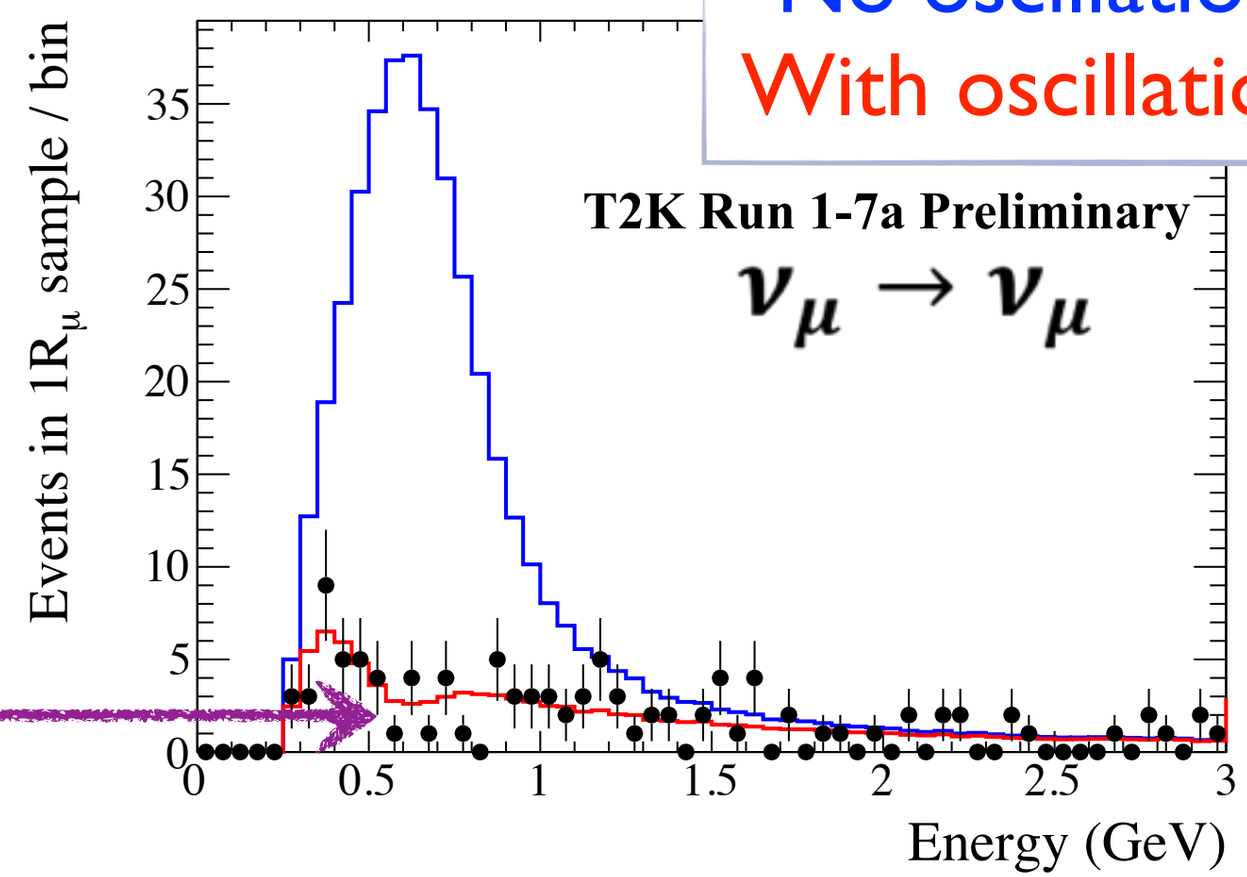
Beam composed of mostly $\bar{\nu}_\mu$

Measure neutrino oscillation in four channels:



DISAPPEARANCE CHANNEL

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32}L}{4E} + (\text{solar, matter effect terms})$$

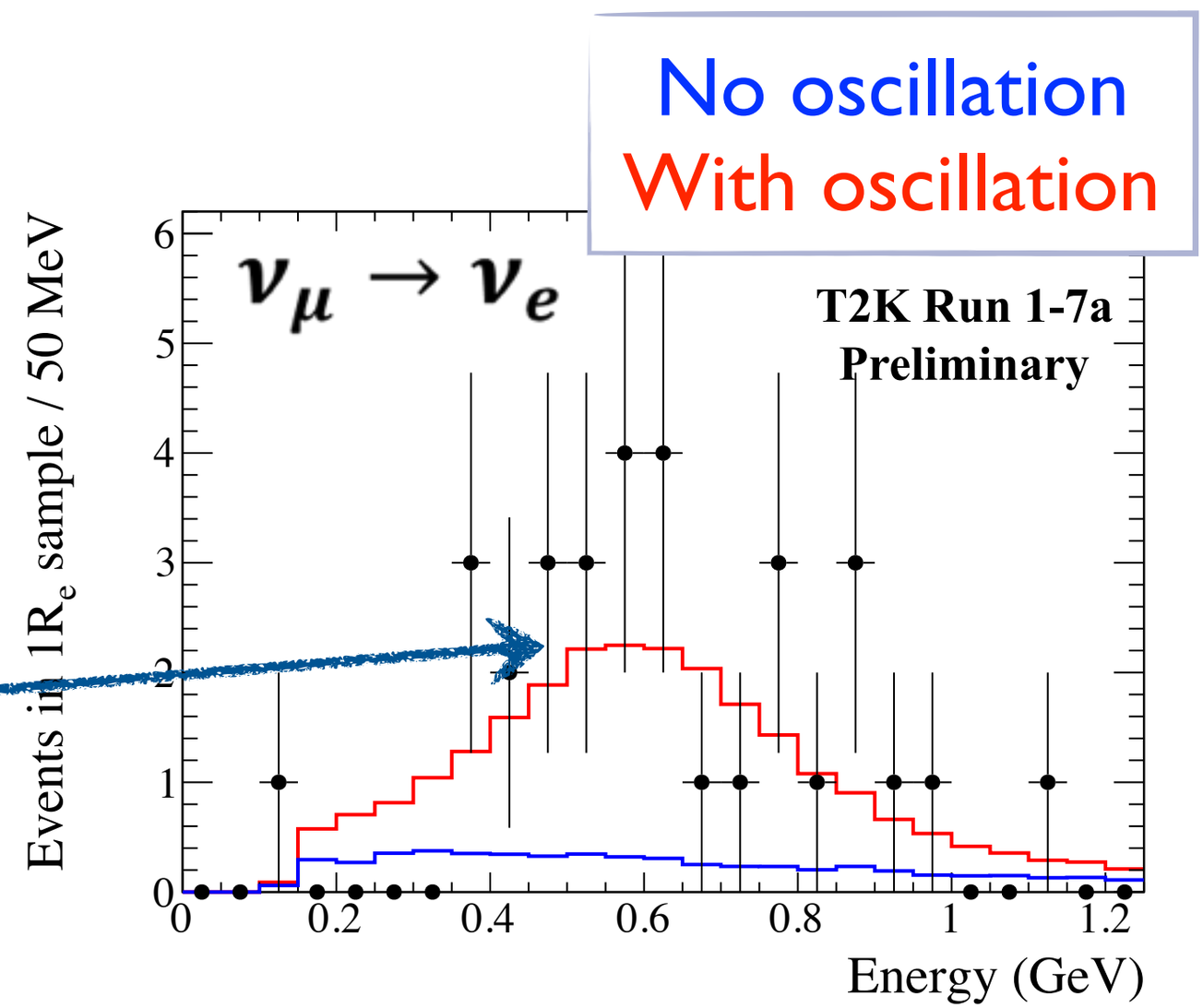


Location of dip: Δm^2_{32}
Depth of dip: $\sin^2 2\theta_{23}$

APPEARANCE CHANNEL

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$
$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$
$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$
$$+\,(\text{CP-even, solar, matter effect terms})$$

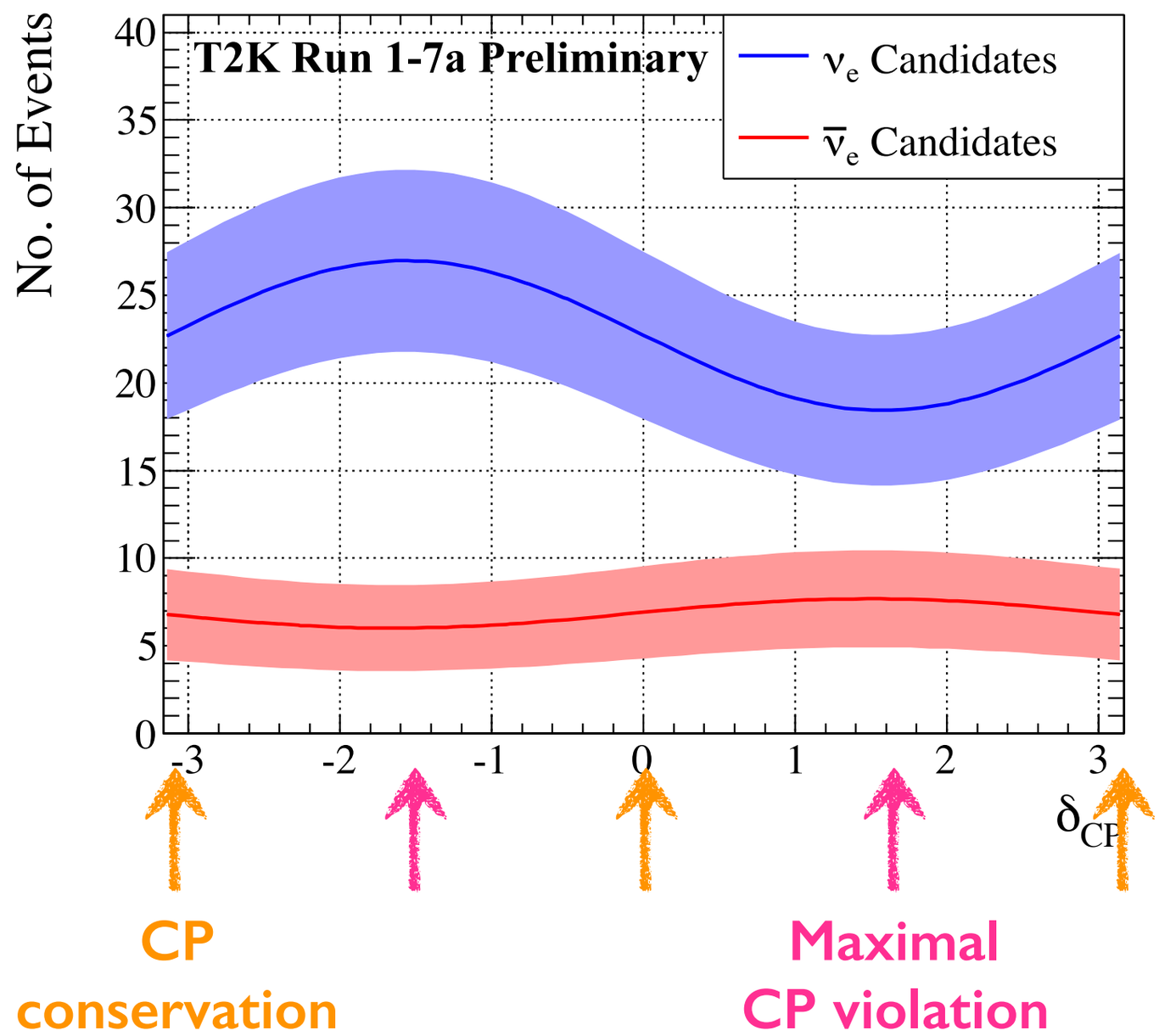
Magnitude of peak:
$\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}



EFFECT OF THE CP PHASE

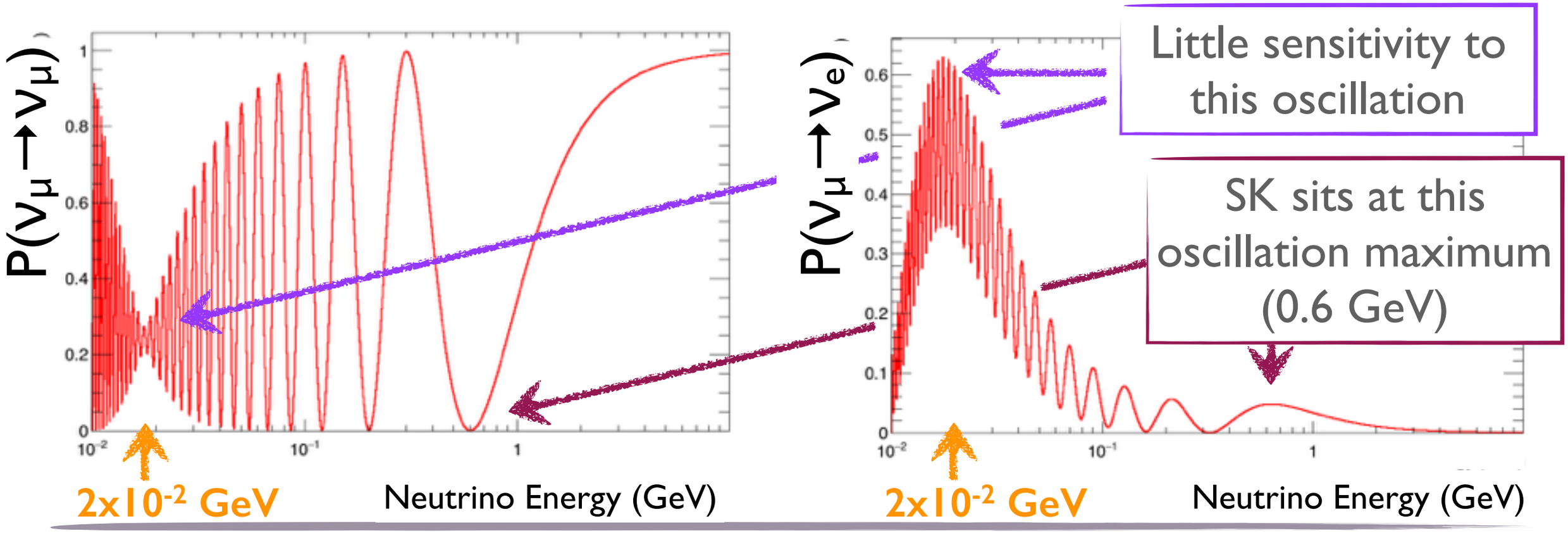
$$P(\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$
$$(+)-\left[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\right.$$
$$\left.\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\right]$$
$$+\,(\text{CP-even, solar, matter effect terms})$$

$\sin\delta_{CP}$ occurs in ν_e and $\bar{\nu}_e$ appearance probability with opposite sign

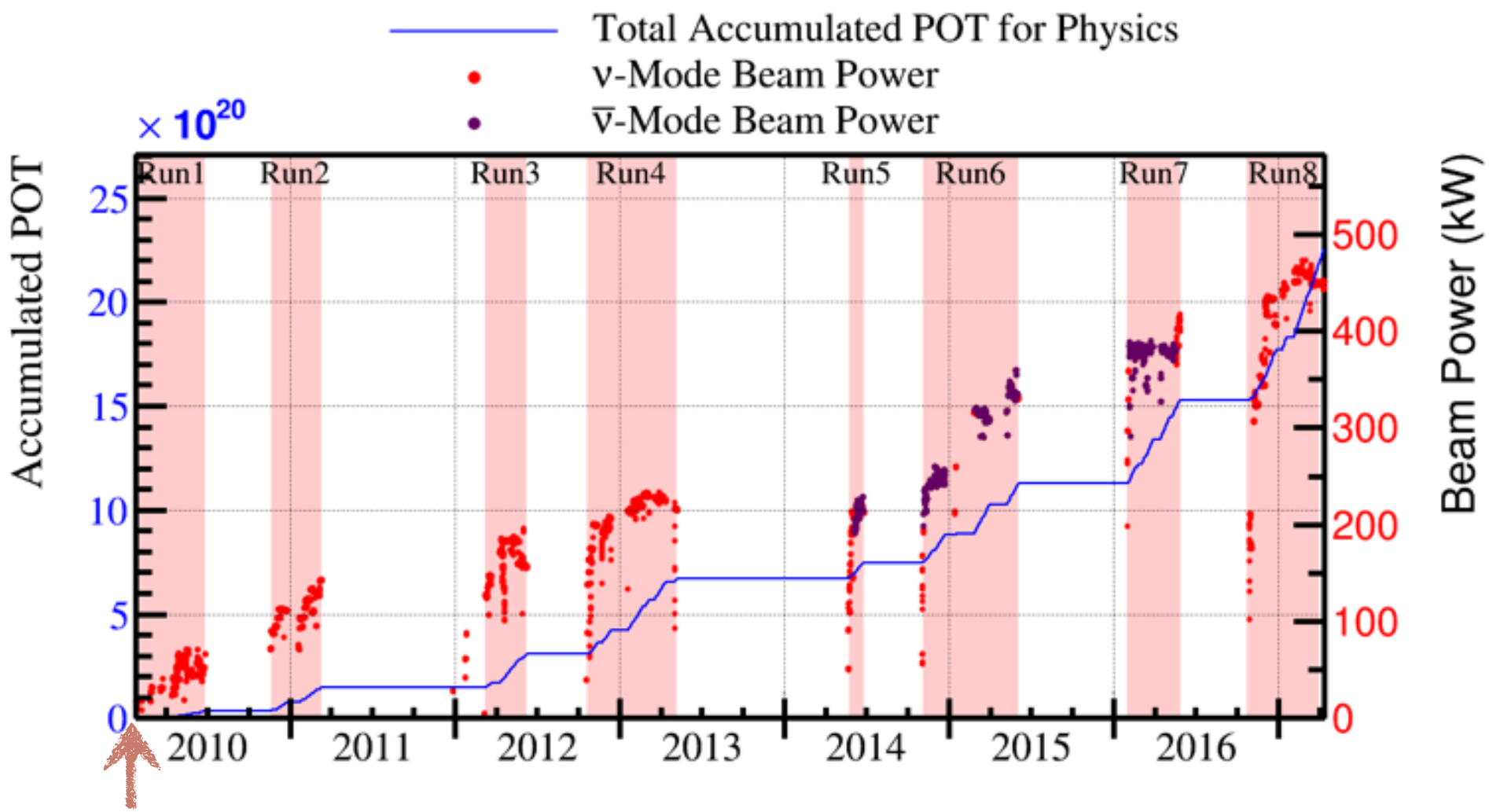


WHAT ABOUT THE SOLAR PARAMETERS?

- T2K baseline and energy are chosen to coincide exactly with first oscillation maximum according to Δm^2_{32} oscillations
- Solar parameters (Δm^2_{21} and $\sin^2\theta_{12}$) are also important, but are already better-constrained by solar neutrino experiments than T2K's sensitivity



T2K DATA-TAKING



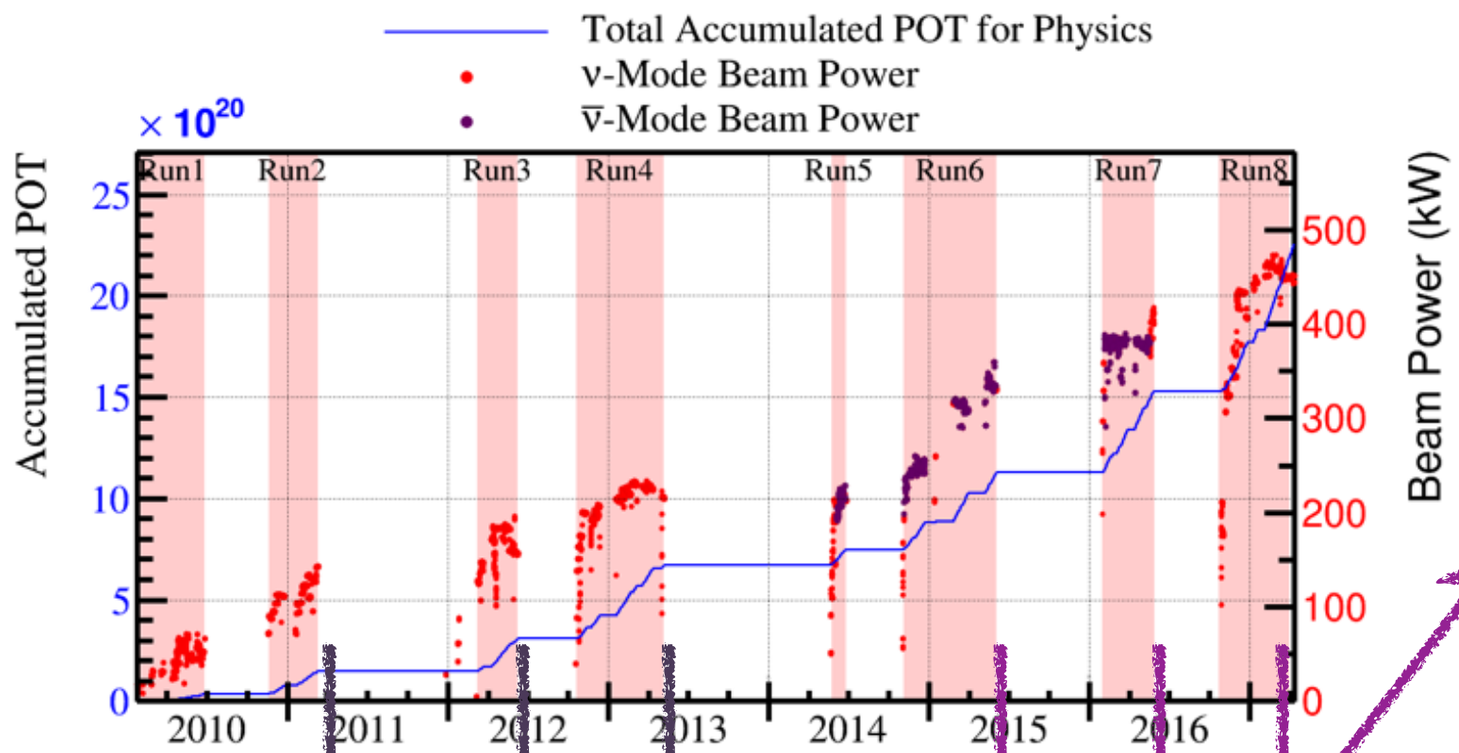
Beam start: January 2010

Antineutrino-mode beam since mid-2014

Total protons on target (POT) ($\times 10^{20}$):
14.93 ν-mode
7.62 ν̄-mode

~ 29% of expected total for T2K

T2K MEASUREMENTS



Today: Updated joint fit $\nu_\mu + \nu_e + \bar{\nu}_\mu + \bar{\nu}_e$

ν_e appearance: 2.5σ

ν_e appearance: 3.1σ

ν_e appearance: 7.3σ

Joint fit: $\nu_\mu + \nu_e$

Joint fit: $\nu_\mu + \nu_e + \bar{\nu}_\mu + \bar{\nu}_e$

ν_μ disappearance

ν_μ disappearance

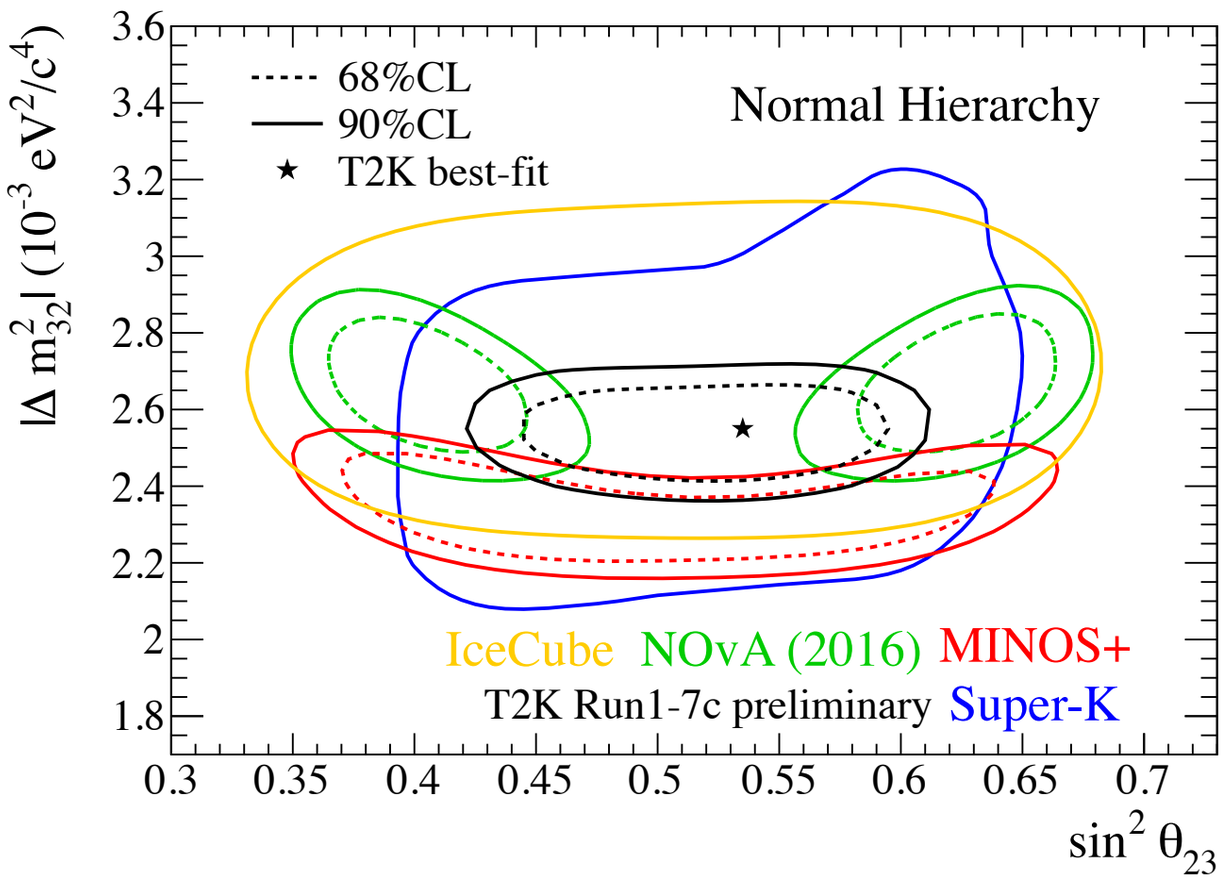
ν_μ disappearance

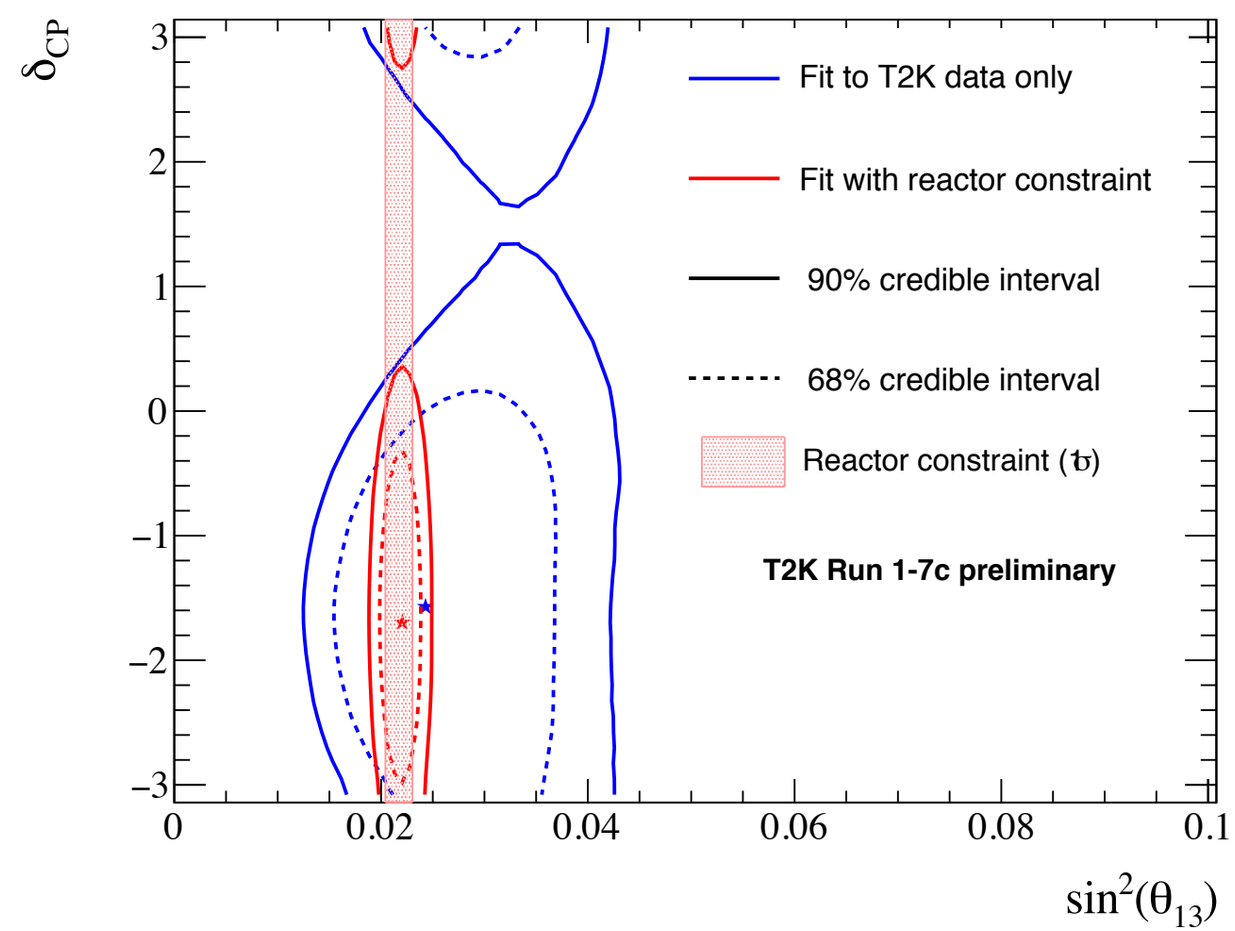
$\bar{\nu}_\mu$ disappearance

$\bar{\nu}_e$ appearance search

PREVIOUS T2K RESULTS: WINTER 2016/2017

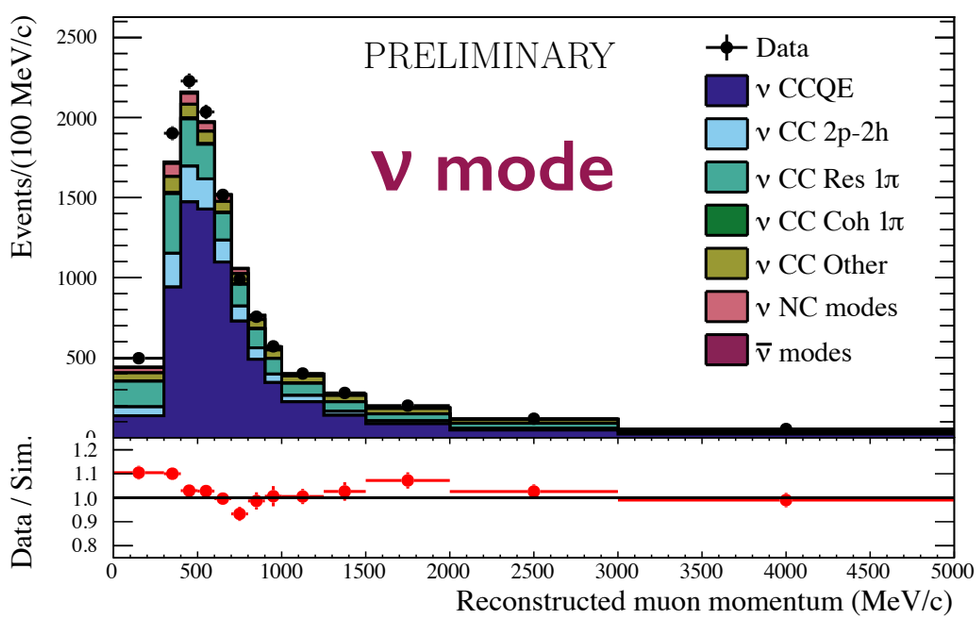
Joint fit of neutrino and antineutrino appearance and disappearance

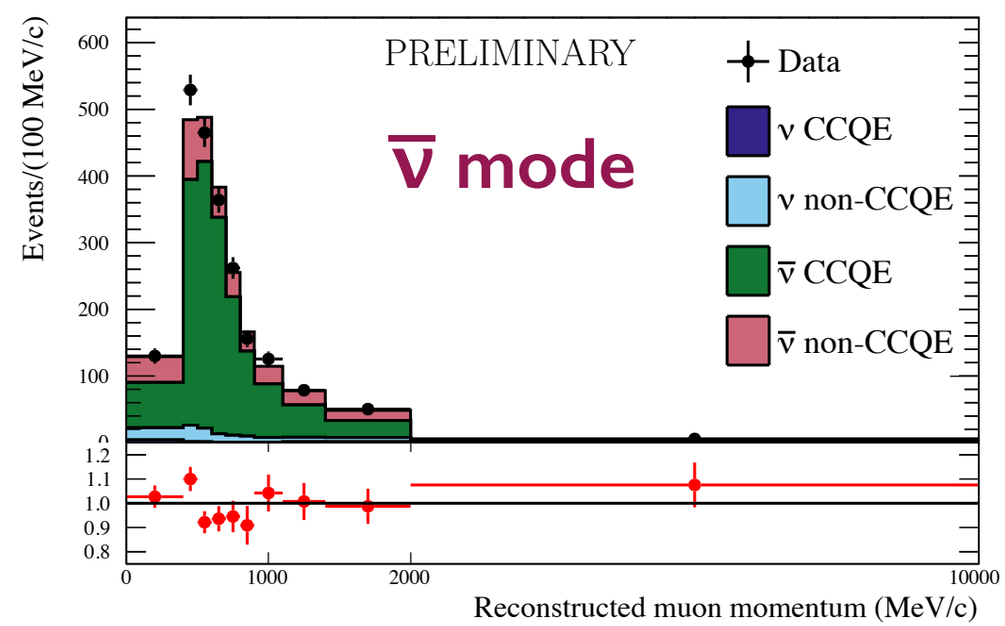




OSCILLATION ANALYSIS IN A NUTSHELL: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$

Measure $\overset{(-)}{\nu}_\mu$ charged-current (CC) events in ND → Propagate prediction from ND to FD → Measure $\overset{(-)}{\nu}_\mu$ CC events in FD → Infer oscillation parameters from differences between measured and predicted FD energy spectrum





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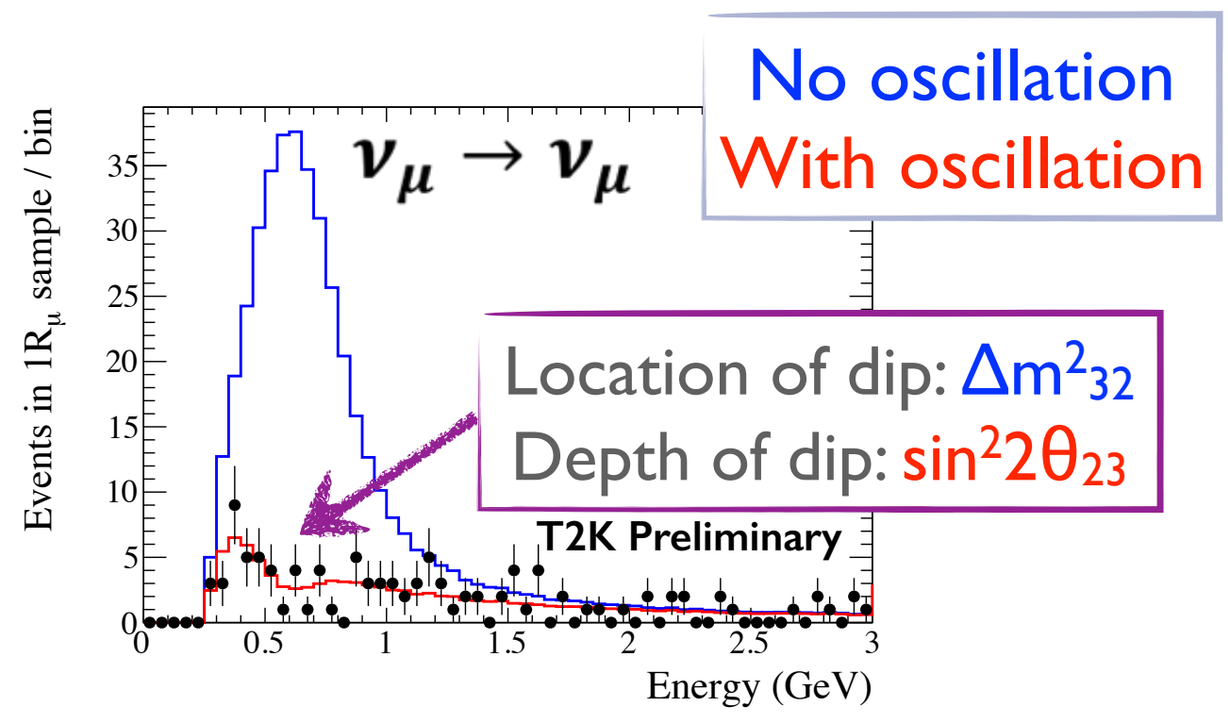

OSCILLATION ANALYSIS IN A NUTSHELL: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

Measure $\overset{(-)}{\nu}_\mu$ CC events in ND → Use ND candidates to predict beam backgrounds in the FD → Measure $\overset{(-)}{\nu}_e$ CC events in FD → Interpret any FD excess over prediction as $\overset{(-)}{\nu}_e$ appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$
$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$
$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$
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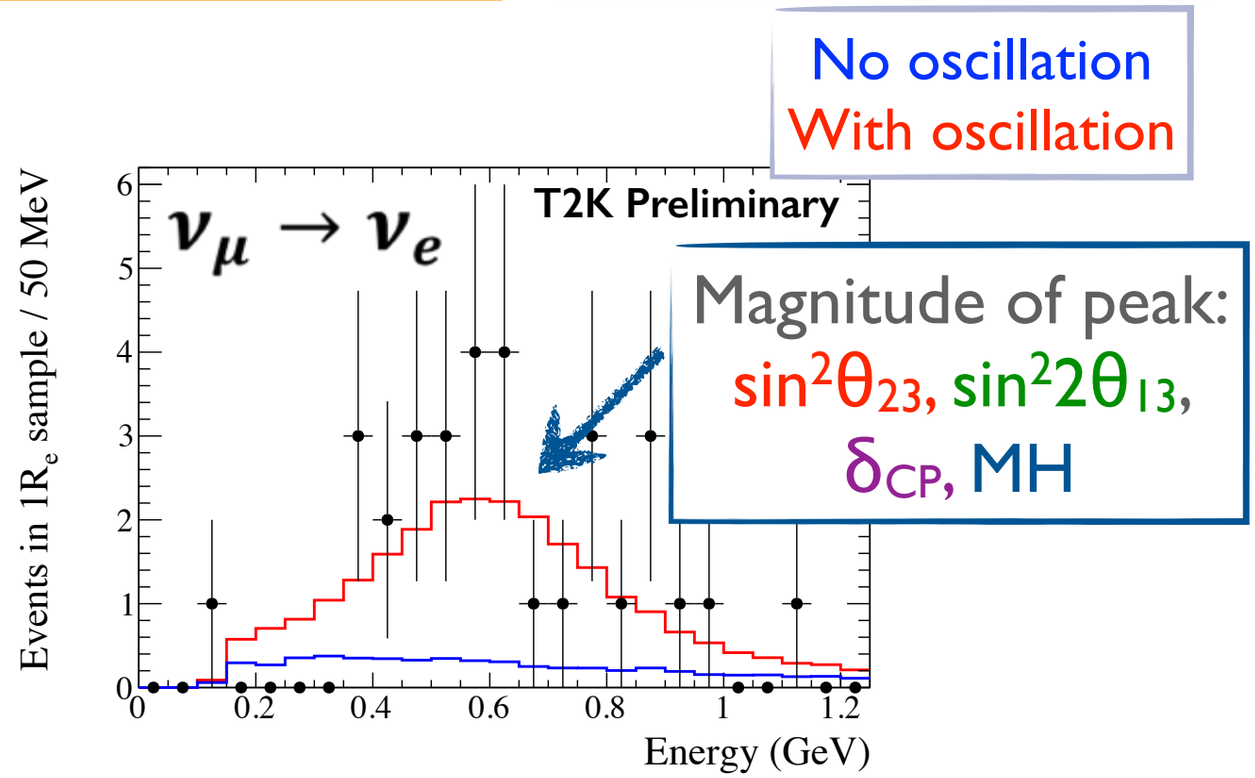


SYSTEMATIC UNCERTAINTIES

The number of measured events in the near detector ND280 depends on:

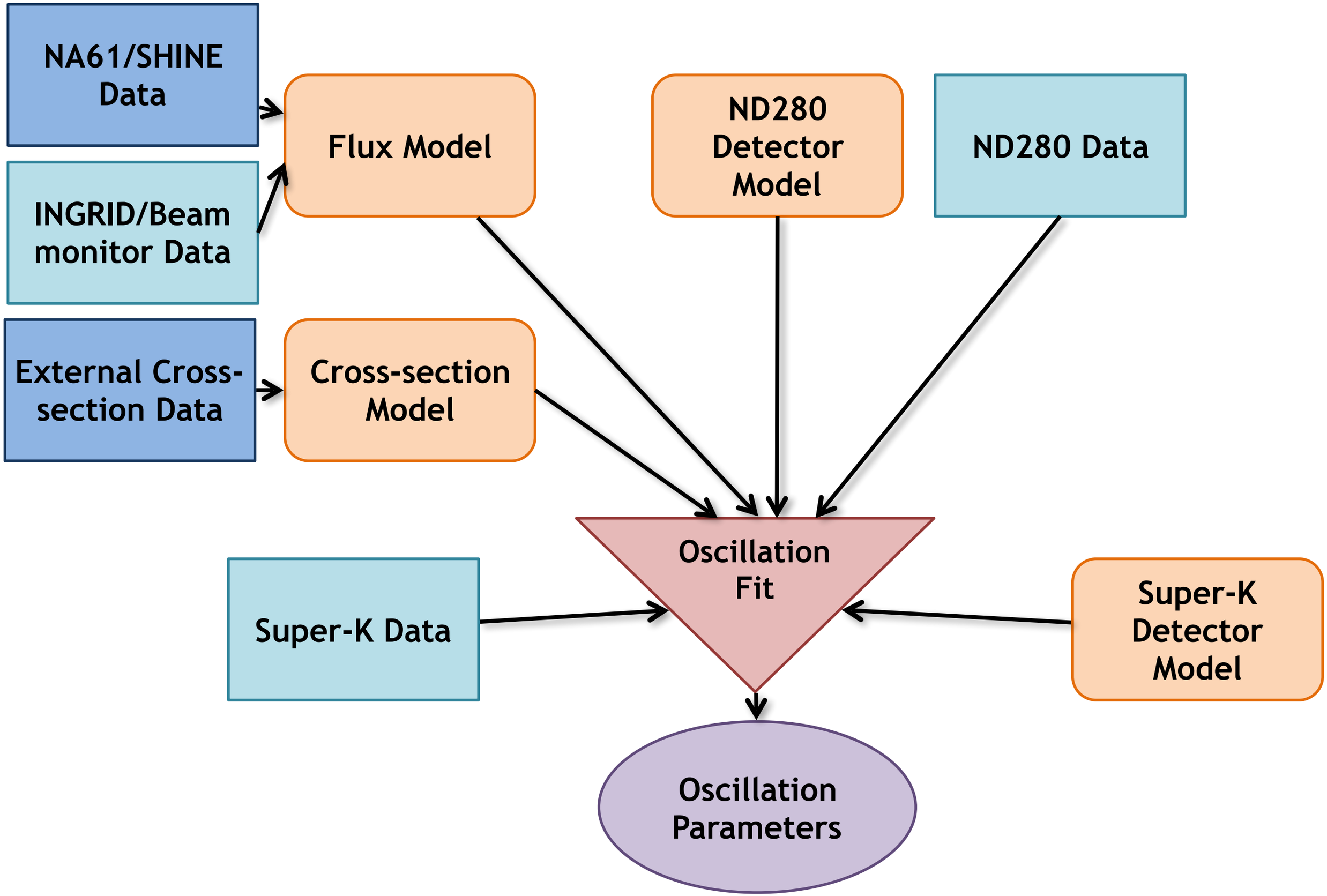
$$N_{ND} \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\varepsilon_{ND}$$

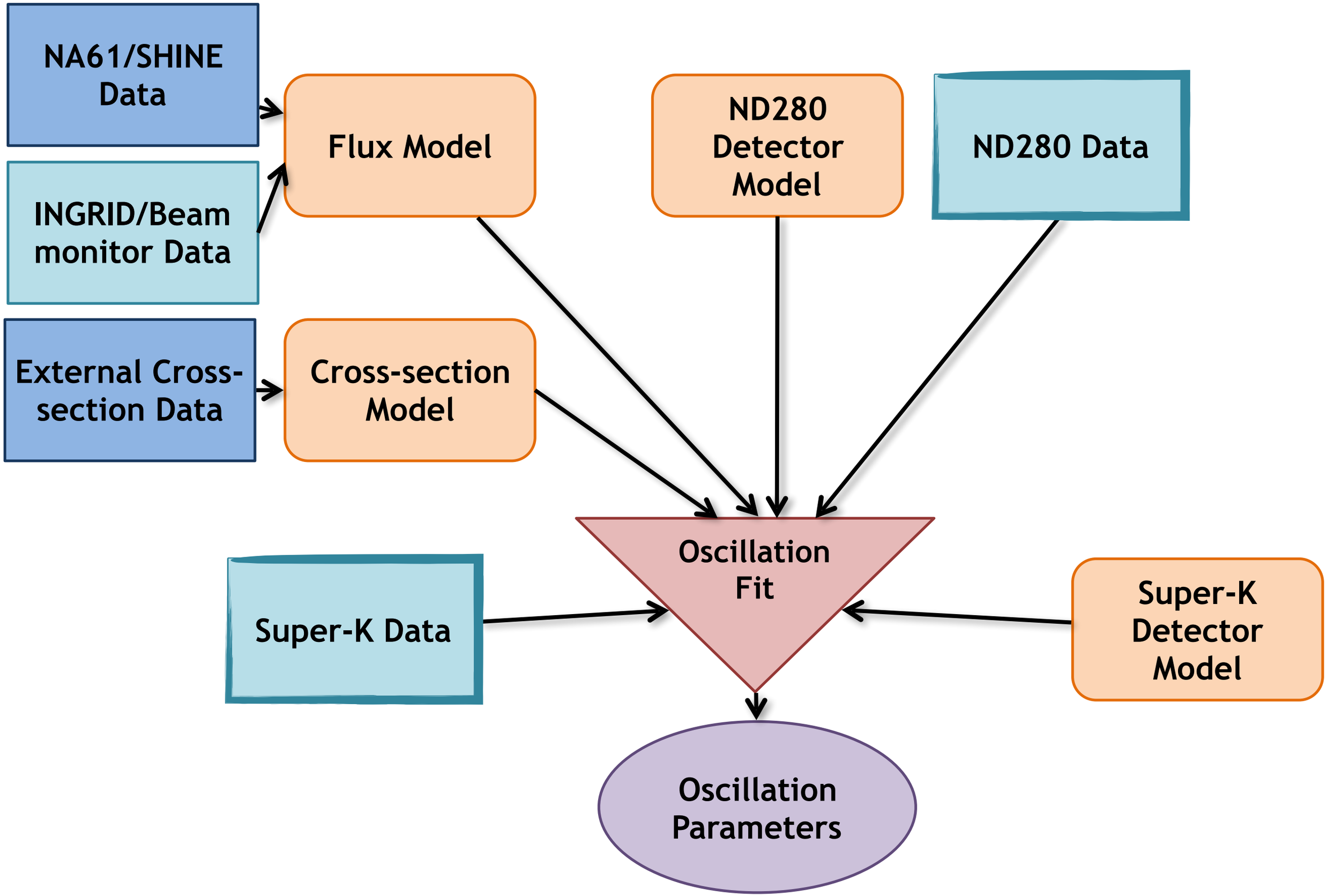
- $\Phi_{ND}(E_\nu)$: Neutrino flux prediction
- $\sigma(E_\nu)$: Neutrino cross section model
- ε_{ND}: Near detector selection, efficiency

The number of measured events in the far detector depends on:

$$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\varepsilon_{FD}P(\nu_\alpha \rightarrow \nu_\beta)$$

- $\Phi_{FD}(E_\nu)$: Neutrino flux prediction
- $\sigma(E_\nu)$: Neutrino cross section model
- $\varepsilon_{FD}P(\nu_\alpha \rightarrow \nu_\beta)$: Far detector selection, efficiency


NA61/SHINE Data
INGRID/Beam monitor Data
External Cross-section Data
Flux Model
Cross-section Model
ND280 Detector Model
ND280 Data
Oscillation Fit
Super-K Data
Super-K Detector Model
Oscillation Parameters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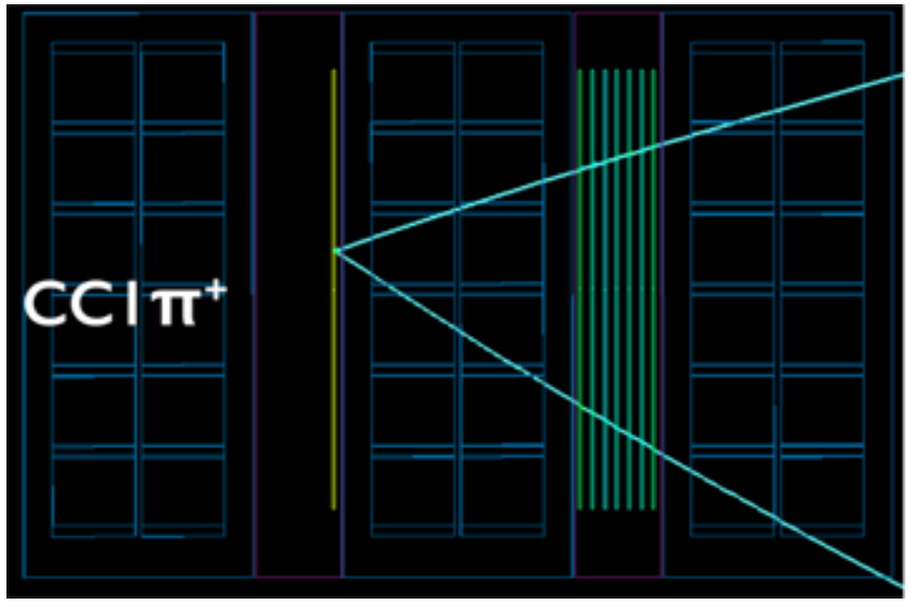
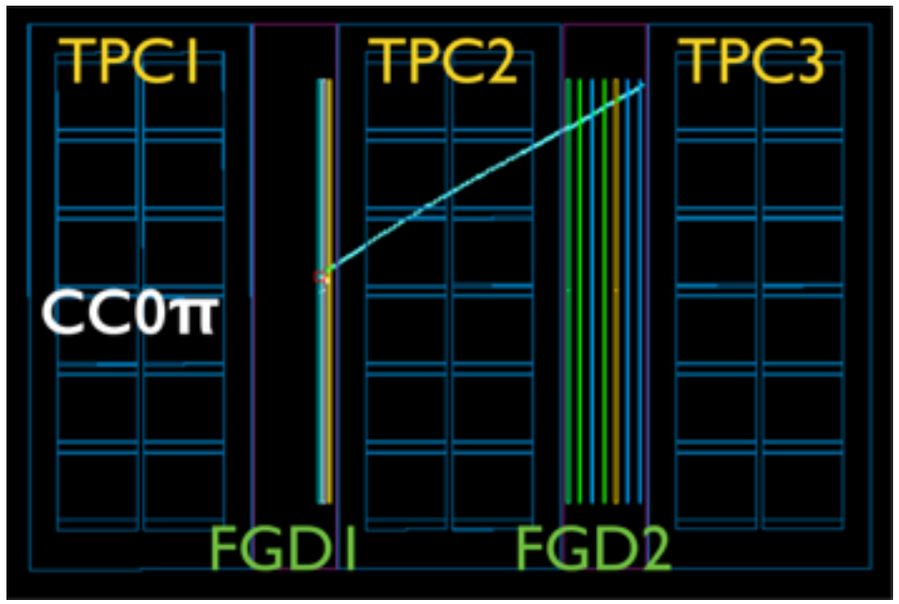
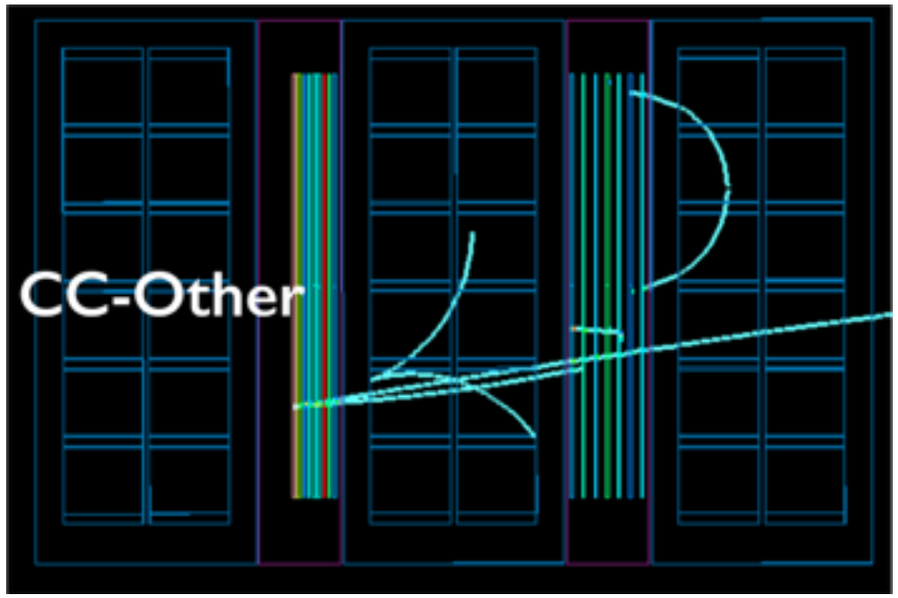
Oscillation Parameters

ND280 DATA SELECTION

- Since 2016, include separate data sets with interactions in FGD1 (carbon target) and FGD2 (water target)
- Neutrino-mode samples separated by number of charged pions:
  CC 0π, CC 1π, CC Other

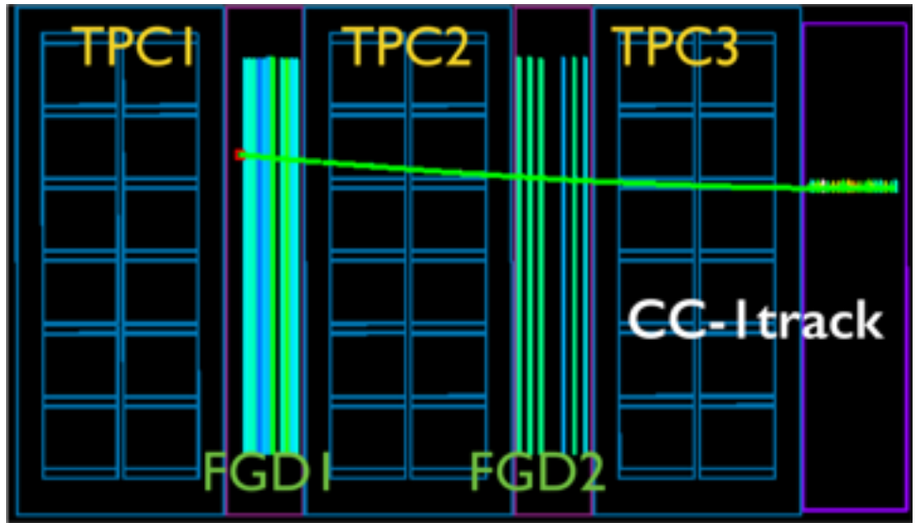


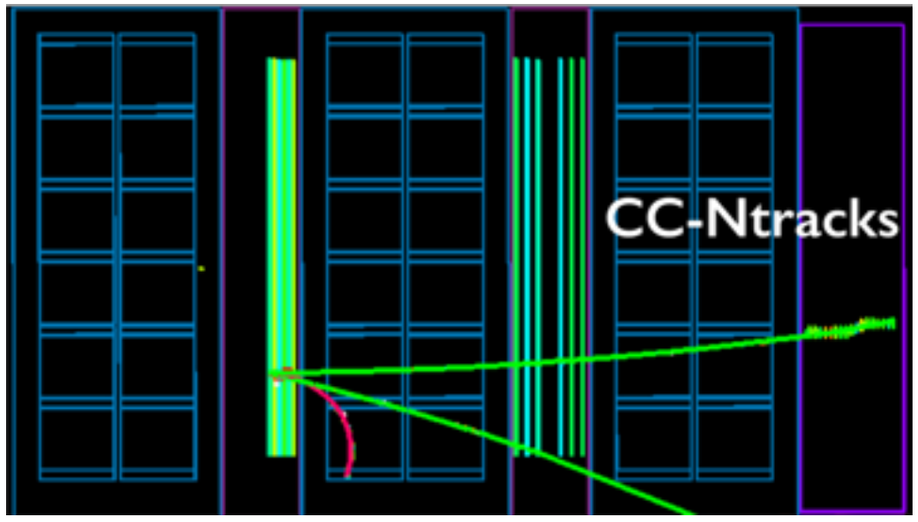




ND280 DATA SELECTION

- Since 2016, include separate data sets with interactions in FGD1 (carbon target) and FGD2 (water target)
- Neutrino-mode samples separated by number of charged pions: CC 0π, CC 1π, CC Other
- Antineutrino-mode samples separated by number of TPC tracks: CC 1Track, CC NTrack
  - Antineutrino-mode: also include separate samples for μ^+ and μ^- candidates





ND280 DATA SELECTION

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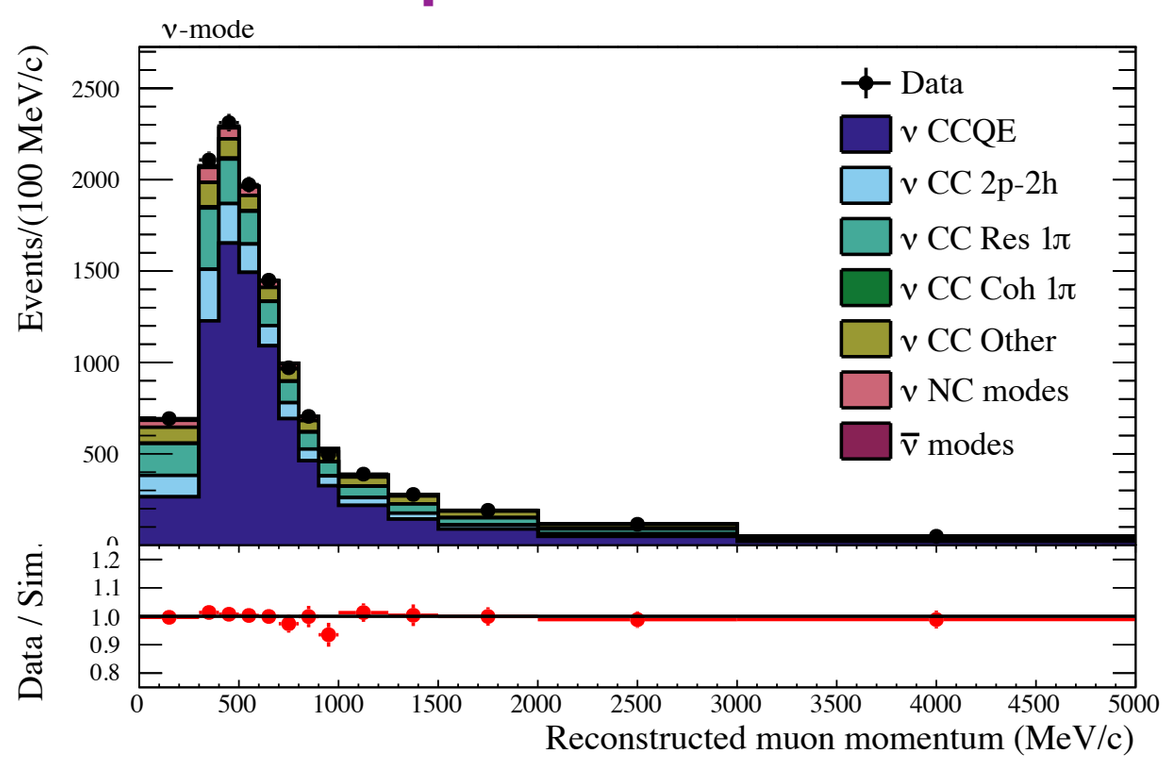
  - Antineutrino-mode: also include separate samples for μ^+ and μ^- candidates

eg. ν-mode FGD1 CC 0π, post-fit p-value: 0.47



PRELIMINARY

SK DATA SELECTION

Five samples are selected at SK:

Neutrino mode

- **$1R_\mu$**: 1 muon-like ring, ≤1 decay electron (CCQE)
- **$1R_e$**: 1 electron-like ring, 0 decay electrons (CCQE)
- **$1R_e1\pi$**: 1 electron-like ring, 1 decay electron (CC1π)

Antineutrino mode

- **$1R_\mu$**: 1 muon-like ring, ≤1 decay electron (CCQE)
- **$1R_e$**: 1 electron-like ring, 0 decay electrons (CCQE)

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + X$$
$$\downarrow$$
$$e^-(e^+) + \bar{\nu}_e(\nu_e) + \nu_\mu(\bar{\nu}_\mu)$$

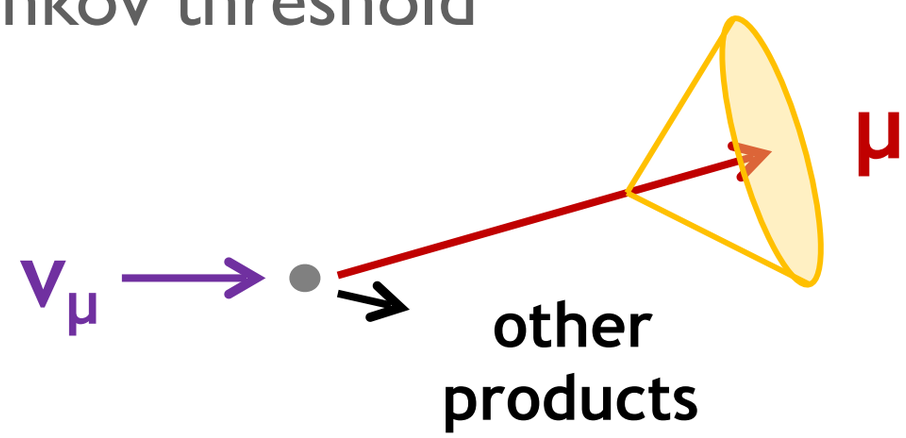
$$\nu_e(\bar{\nu}_e) + N \rightarrow e^-(e^+) + X$$

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$
$$\downarrow$$
$$\mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$

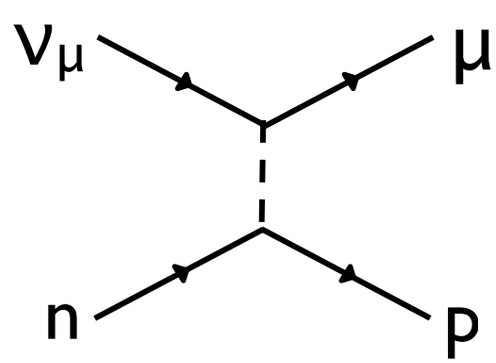
detected particles

SUPER-K EVENT SELECTION: 1-RING SAMPLES

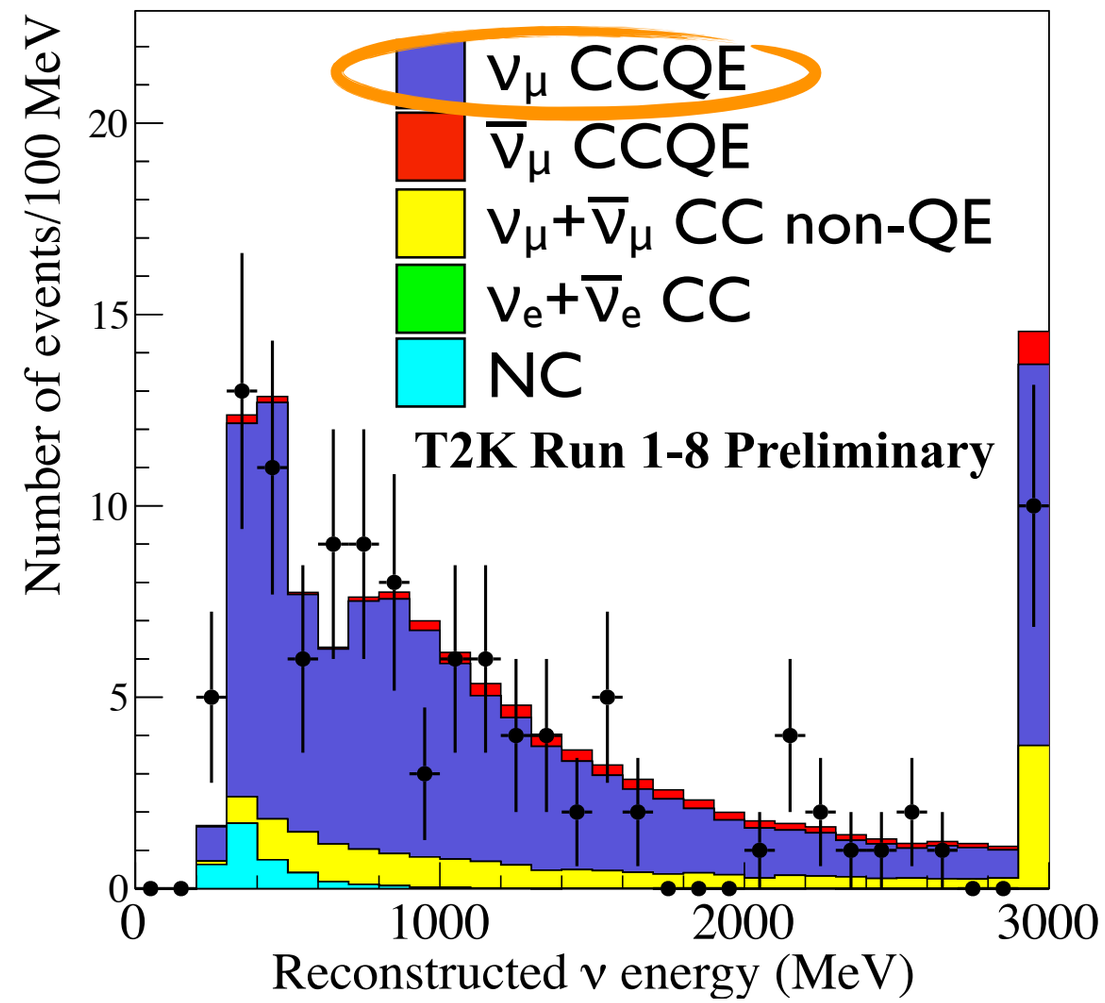
Select events with only 1 reconstructed ring → 1 charged particle above Cherenkov threshold



Mostly Charged-Current Quasielastic (CCQE) scattering → reconstruct neutrino energy from muon kinematics



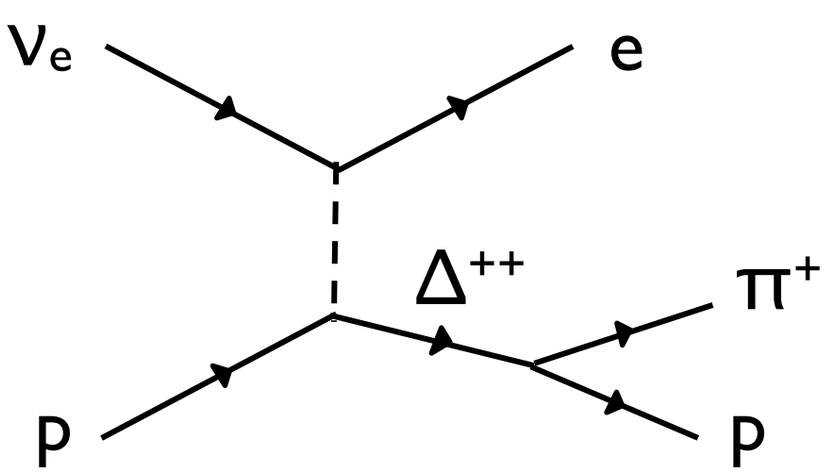
$$E^{QE}{}_{\nu} = \frac{m_p{}^2 - (m_n - E_b)^2 - m_\mu{}^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

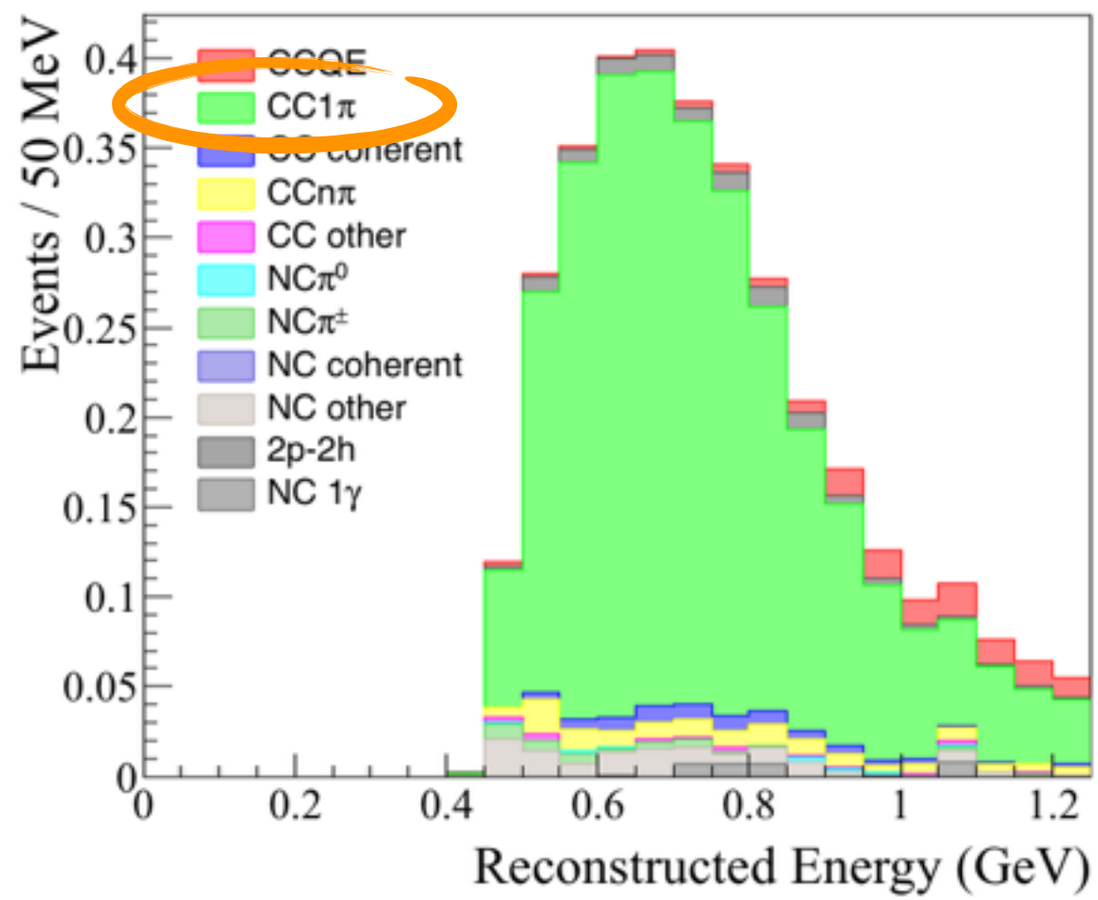


SUPER-K EVENT SELECTION: $1R_e1\pi$ SAMPLE

- Same event selection as $1R_e$ but also require that all events have 1 decay electron (in addition to the original electron ring)

Mostly Charged-Current single pion production (CC1π)





NEW SK RECONSTRUCTION ALGORITHM: FITQUN

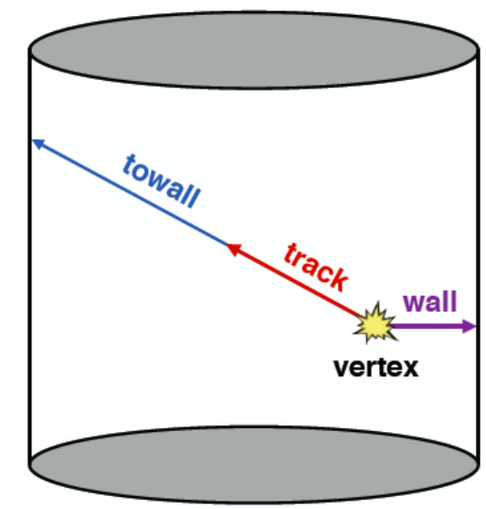
- This year, the event reconstruction at SK has been updated to use a new algorithm: **fiTQun** (previous T2K analyses used reconstruction algorithm **APFit**)

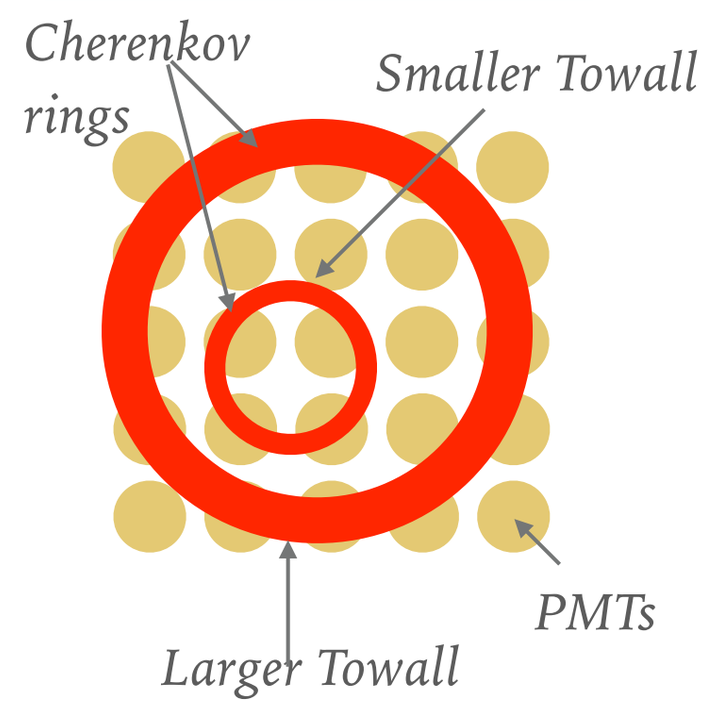
- Improved efficiency and purity (more signal events selected for a given POT!)

MC Prediction	fiTQun Selection		APFit Selection	
Sample	Candidates	Purity	Candidates	Purity
ν mode $1R_\mu$	261.6	79.7%	268.7	68.1%
ν mode $1R_e$	69.5	81.2%	56.5	81.4%
ν mode $1R_e1\pi$	6.9	78.8%	5.6	72.0%
$\bar{\nu}$ mode $1R_\mu$	62.0	79.7%	65.4	70.5%
$\bar{\nu}$ mode $1R_e$	7.6	79.7%	6.1	63.7%

EXPANDED FIDUCIAL VOLUME

- APFit fiducial volume: reconstructed vertex > 2m from detector wall
- fiTQun: cut on two variables
  - Distance of vertex from wall **(Wall)**
  - Distance to the wall along the particle trajectory **(Towall)**
    - Larger **Towall** = finer sampling of ring
- Optimise cuts for each sample individually, accounting for systematic and statistical errors





SK DATA SAMPLES

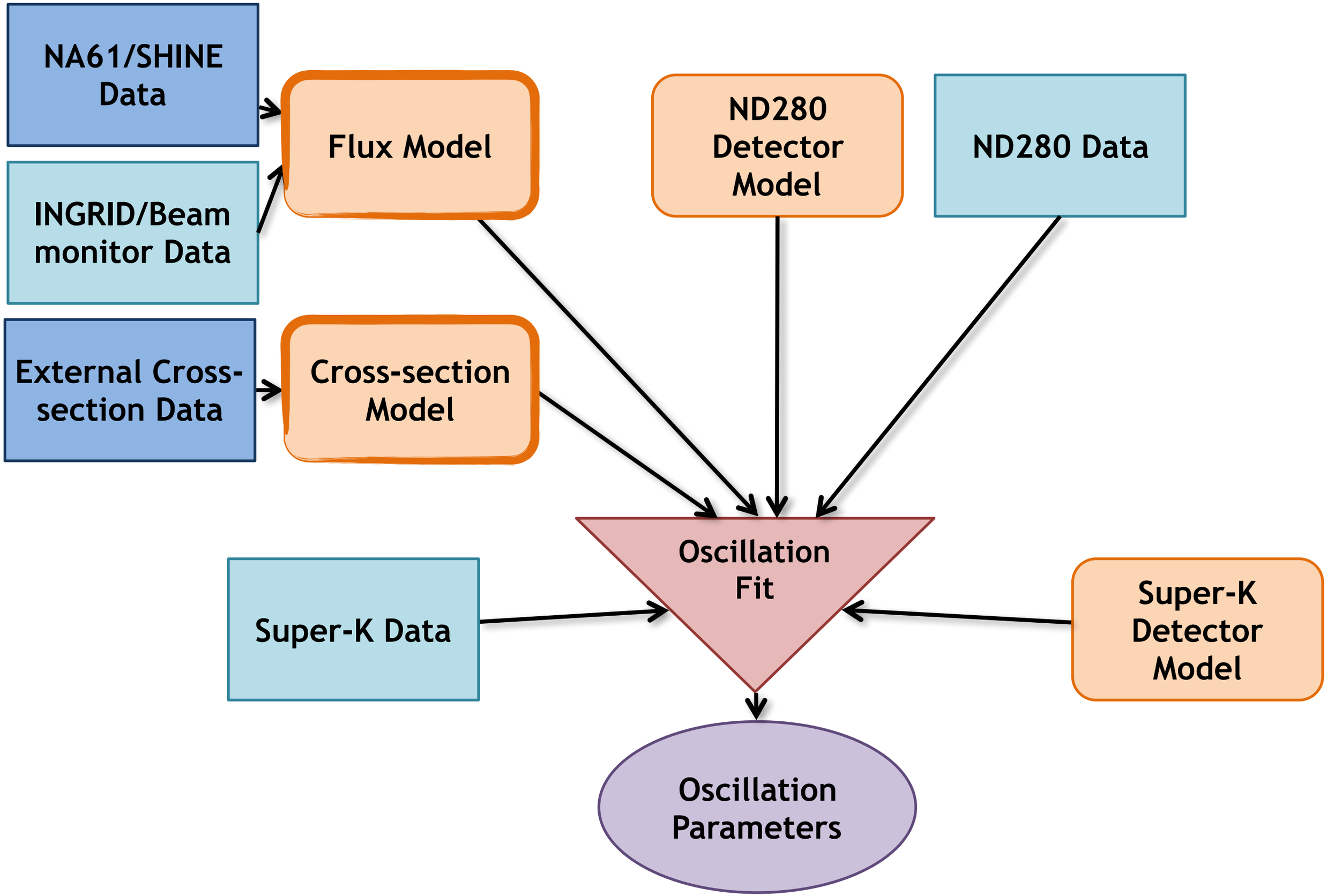
Sample	Predicted Rates				Observed Rates
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	
ν mode $1R_\mu$	267.8	267.4	267.7	268.2	240
ν mode $1R_e$	73.5	61.5	49.9	62.0	74
ν mode $1R_e1\pi$	6.92	6.01	4.87	5.78	15
$\bar{\nu}$ mode $1R_\mu$	63.1	62.9	63.1	63.1	68
$\bar{\nu}$ mode $1R_e$	7.9	9.0	10.0	8.9	7

- The number of observed events are largely in line with predictions after oscillations
  - Number of events in electron-like samples most consistent with $\delta_{CP}=-\pi/2$ hypothesis
  - Number of events in muon-like ν-mode sample below prediction (consistent within systematic and statistical uncertainties)

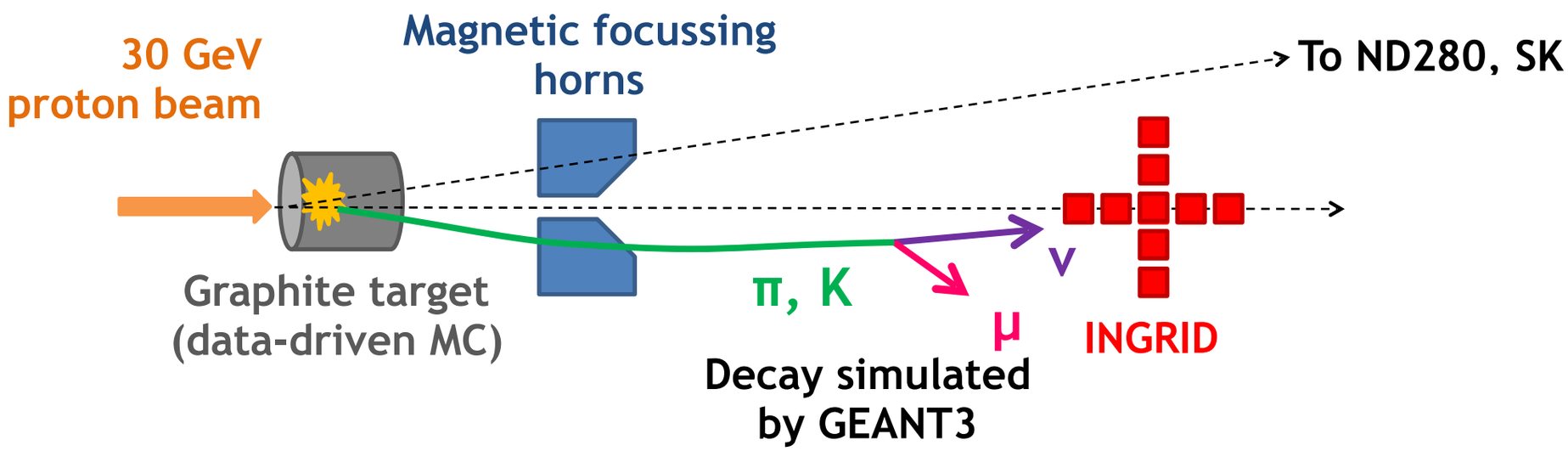
SK DATA SAMPLES

	Predicted Rates				Observed Rates
Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	
ν mode $1R_\mu$	267.8	267.4	267.7	268.2	240
ν mode $1R_e$	73.5	61.5	49.9	62.0	74
ν mode $1R_e1\pi$	6.92	6.01	4.87	5.78	15
$\bar{\nu}$ mode $1R_\mu$	63.1	62.9	63.1	63.1	68
$\bar{\nu}$ mode $1R_e$	7.9	9.0	10.0	8.9	7

- 15 events observed in $1Re1\pi$ sample, with prediction ~5-7
  - p-value for upward or downward fluctuation in one sample: 2.5%
  - p-value for upward or downward fluctuation in at least one of five samples: 11.9%


NA61/SHINE Data
INGRID/Beam monitor Data
External Cross-section Data
Flux Model
Cross-section Model
ND280 Detector Model
ND280 Data
Oscillation Fit
Super-K Data
Super-K Detector Model
Oscillation Parameters

NEUTRINO FLUX PREDICTION



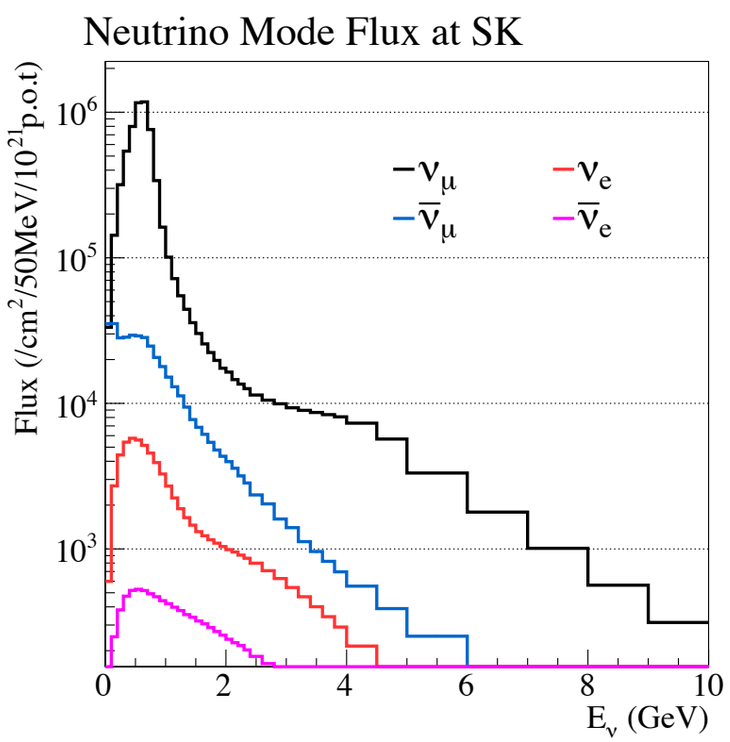
Data-driven flux prediction based on external or in-situ measurements of:

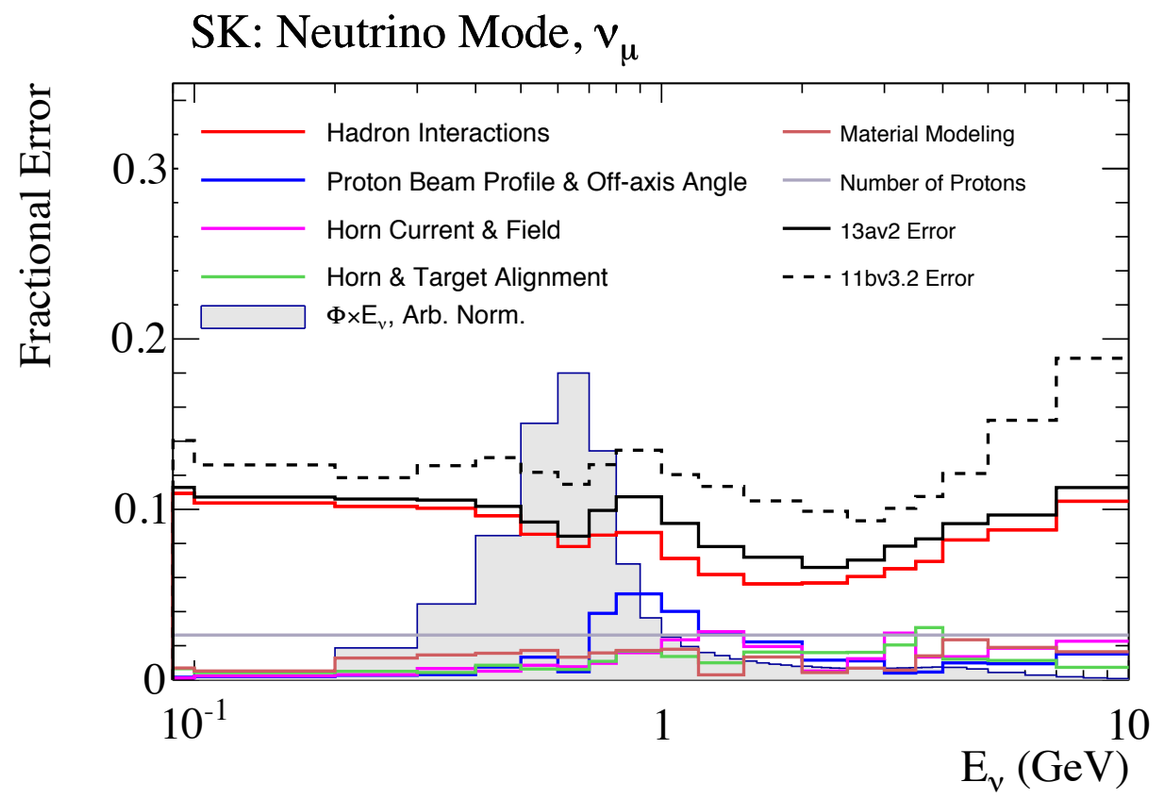
- 30 GeV proton beam
- Alignment and off-axis angle
- Pion and Kaon production

NA61/SHINE

INGRID measures beam direction and stability to within 0.4 mrad
(1 mrad = 2% shift in peak of off-axis neutrino energy distribution)

NEUTRINO FLUX PREDICTION





- Flux prediction uncertainty is **8-12%**
- Dominant source of uncertainty: **hadron interactions in target**
- NA61/SHINE data taken with **replica T2K target** is being incorporated — expect reduction of flux uncertainty

NEUTRINO INTERACTION MODEL

- In recent years, T2K has used an improved neutrino interaction model:
  - CCQE model: chosen by studying data from T2K, MINERvA, and MiniBooNE (Phys. Rev. D93 (2016) 072010): **relativistic Fermi gas with corrections:**
    - **Valencia 2p-2h multi-nucleon scattering process** (Phys. Rev. C83 (2011) 045501)
    - **Long-range correlations** in nucleus (calculation technique: **Valencia random phase approximation, RPA** Phys. Rev. C vol. 70 p. 055503 (2004))
  - Recently improved pion production model with tuning to scattering data on hydrogen and deuterium

NEUTRINO INTERACTION MODEL

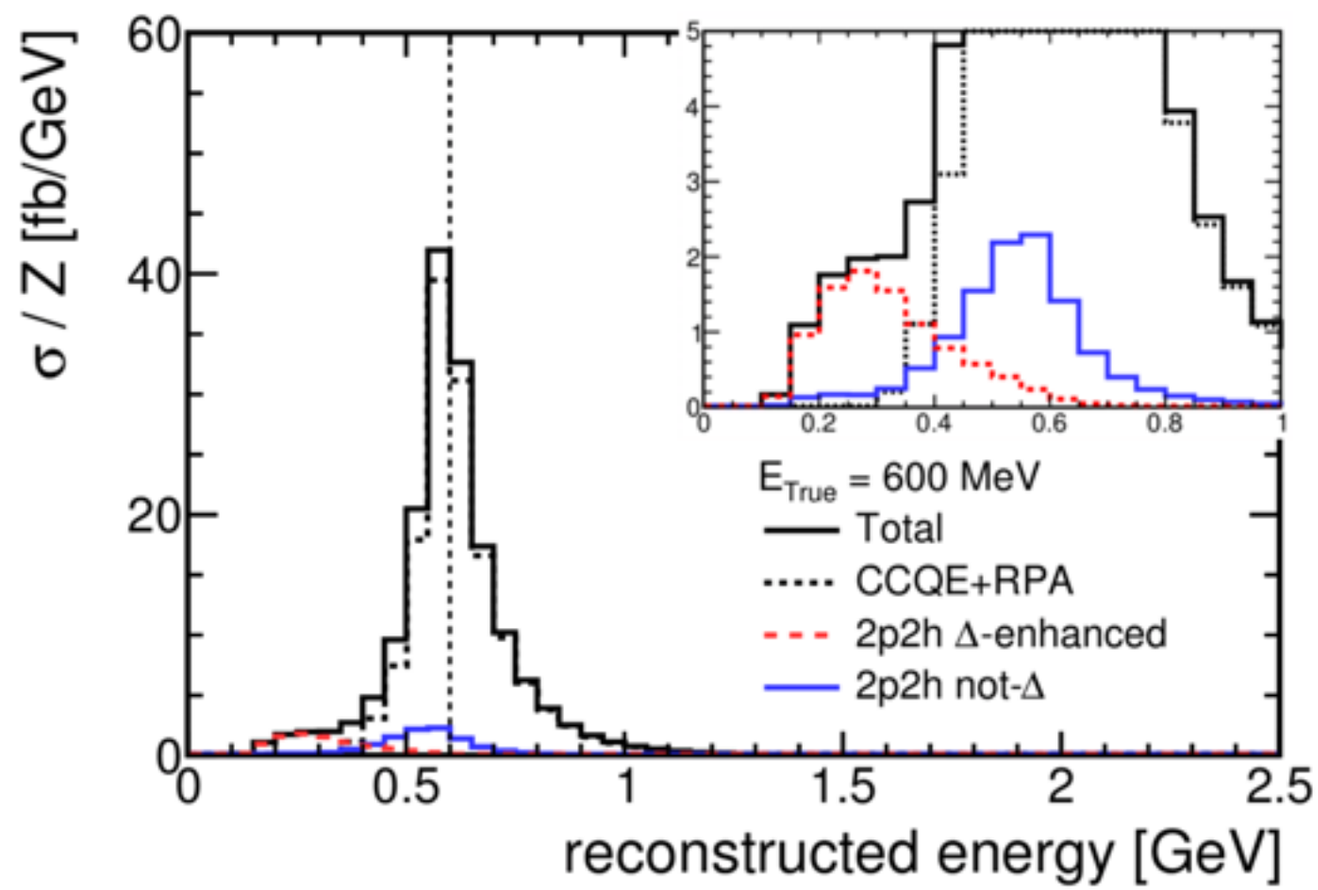
- In recent model:
  - CCQE ections, chosen E (Phys. Rev. D93 (2

New in this analysis: improved 2p-2h and RPA uncertainties

  - Valencia 2p-2h multi-nucleon scattering process (Phys. Rev. C83 (2011) 045501)
  - Long-range correlations in nucleus included in CCQE model (calculation technique: random phase approximation, RPA)
  - Pion production model with tuning to scattering data on hydrogen and deuterium

2P-2H MODELLING UNCERTAINTY

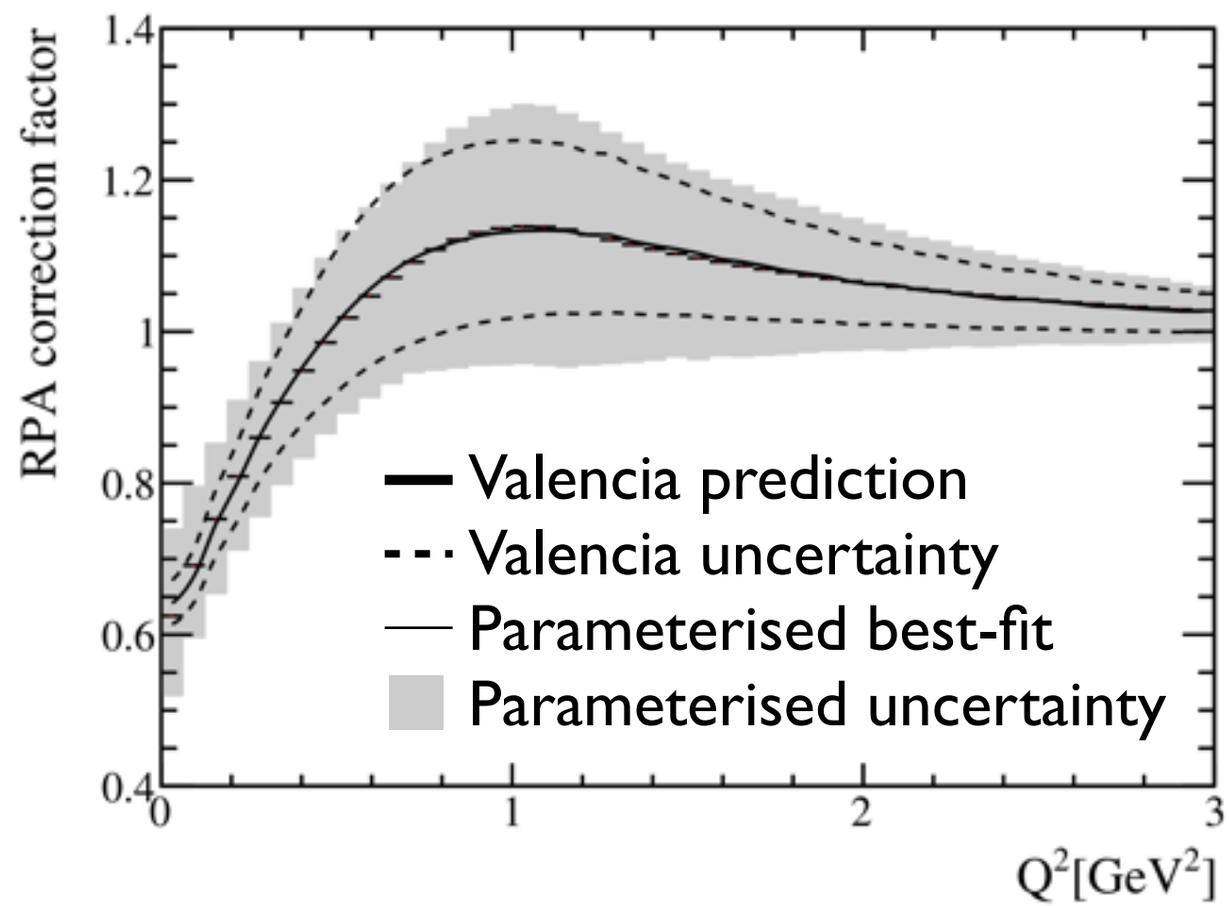
- 2p-2h processes produce events with biased reconstructed energy
- Bias largest in processes involving coupling to a Δ resonance
- Model the reconstruction error: allow strength of 2p-2h cross section to vary between all Δ-enhanced and all not-Δ-enhanced
- Also allow normalisation for 2p-2h to vary separately for neutrinos and antineutrinos (cover other 2p-2h models)

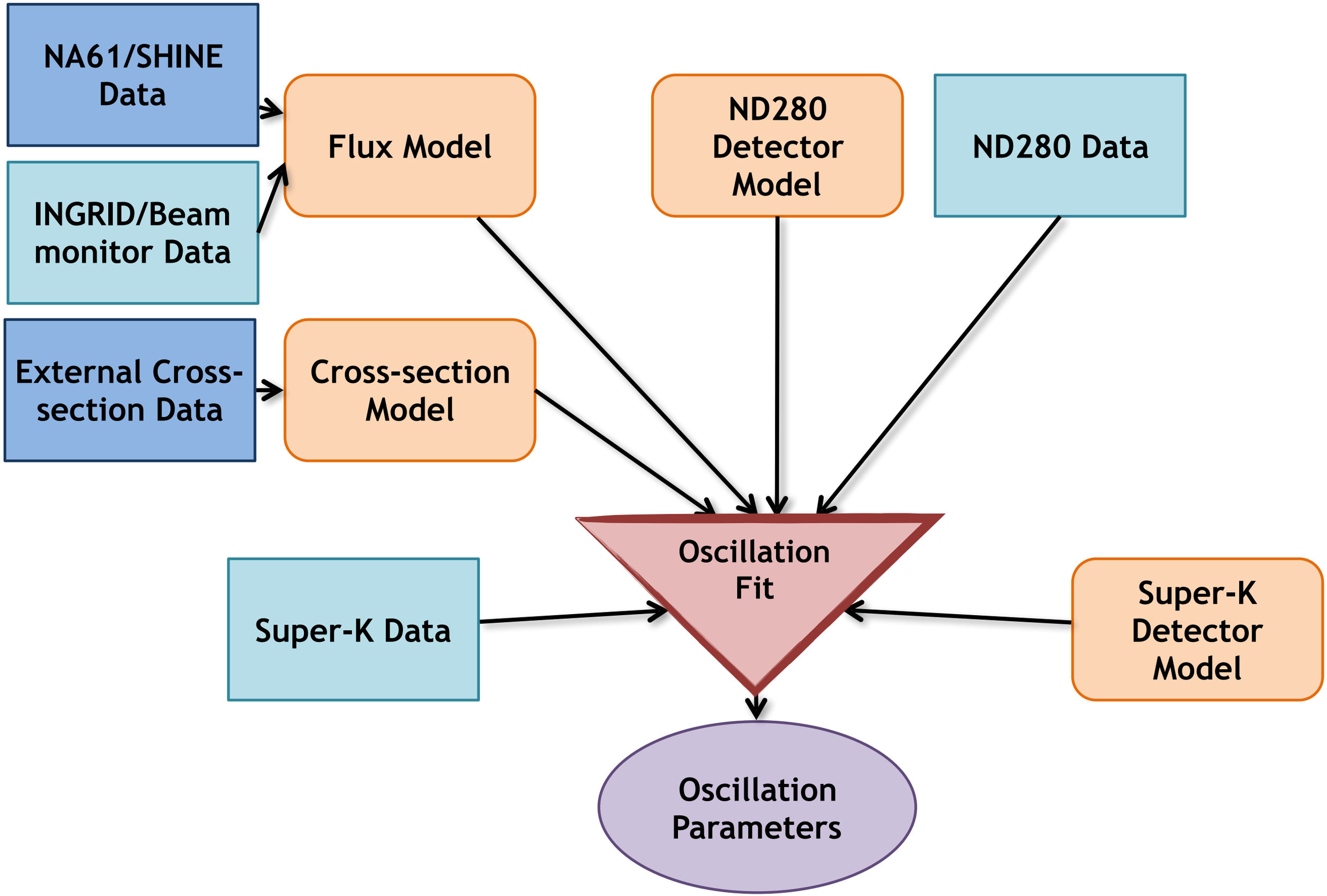


RPA CORRECTION UNCERTAINTY

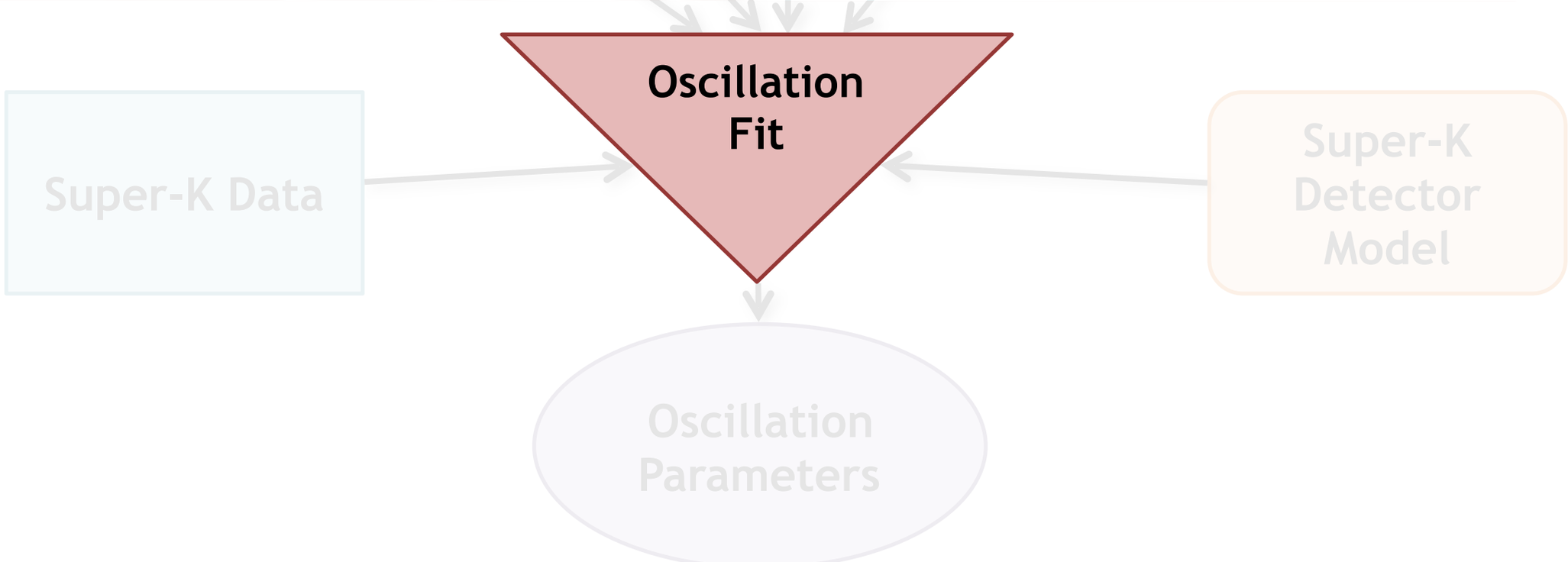
- Correction for long-range correlations in the nucleus modifies Q^2 dependence of CCQE cross section
- Parameterise this correction using a polynomial in Q^2
- Apply uncertainties on parameters to cover theoretical RPA correction uncertainty

$$f(Q^2) = \begin{cases} A + B(Q^2) + p_2(Q^2)^2 + p_3(Q^2)^3, & Q^2 < U \\ (C-1)\exp(-D(Q^2 - U)), & Q^2 > U. \end{cases}$$




NA61/SHINE Data
INGRID/Beam monitor Data
External Cross-section Data
Flux Model
Cross-section Model
ND280 Detector Model
ND280 Data
Oscillation Fit
Super-K Data
Super-K Detector Model
Oscillation Parameters

- Oscillation in the PMNS framework
  - Flat priors in $\sin^2\theta_{23}$, δ_{CP}, and Δm^2_{32} (including mass hierarchy)
  - Gaussian priors on solar parameters: $\sin^2 2\theta_{12} = 0.846 \pm 0.021$, $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
  - Two fits with two treatments of θ_{13}:
    - Flat prior on $\sin^2\theta_{13}$
    - Reactor constraint: $\sin^2 2\theta_{13} = 0.0857 \pm 0.0046$



OSCILLATION FIT

Two approaches: **Bayesian** and **hybrid frequentist-Bayesian**

- Simultaneous fit to ND280 and SK data using MCMC
- Credible intervals

- Fit ND280 data, propagate to SK and fit SK data with constraints on flux and cross-section parameters
- Confidence intervals

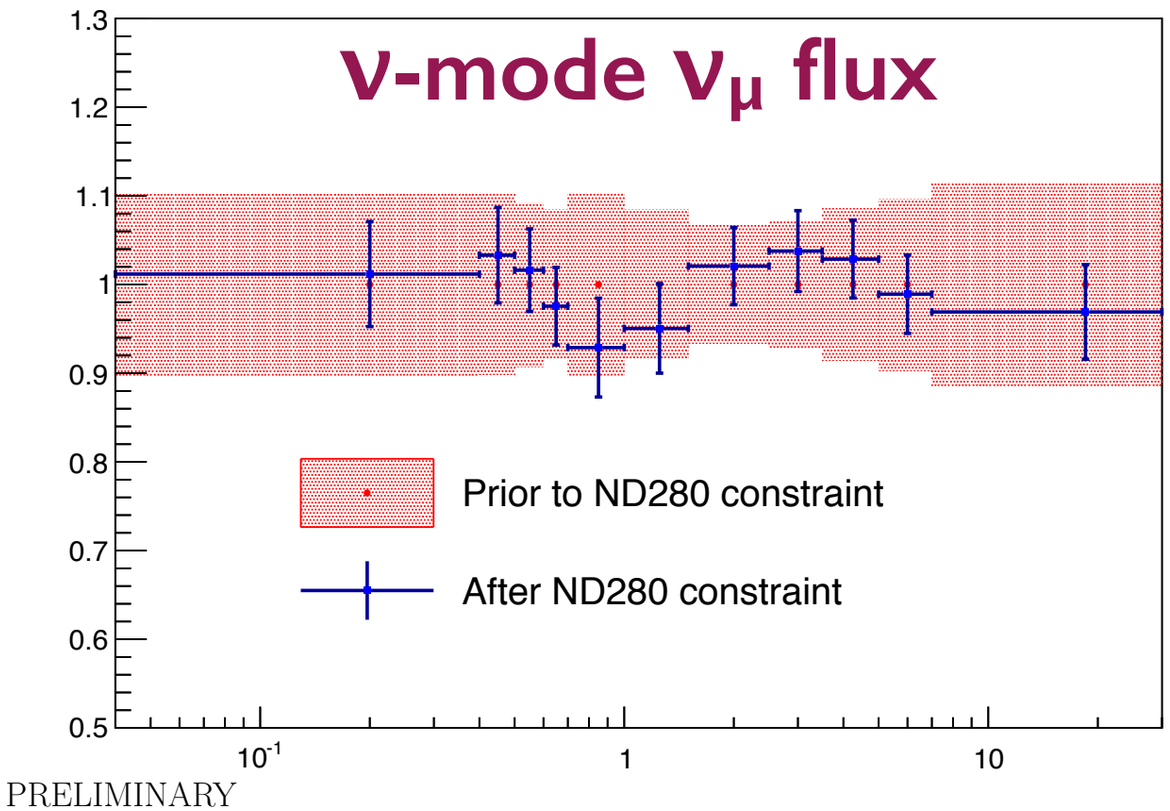
Both use binned likelihood, marginalised over nuisance parameters:

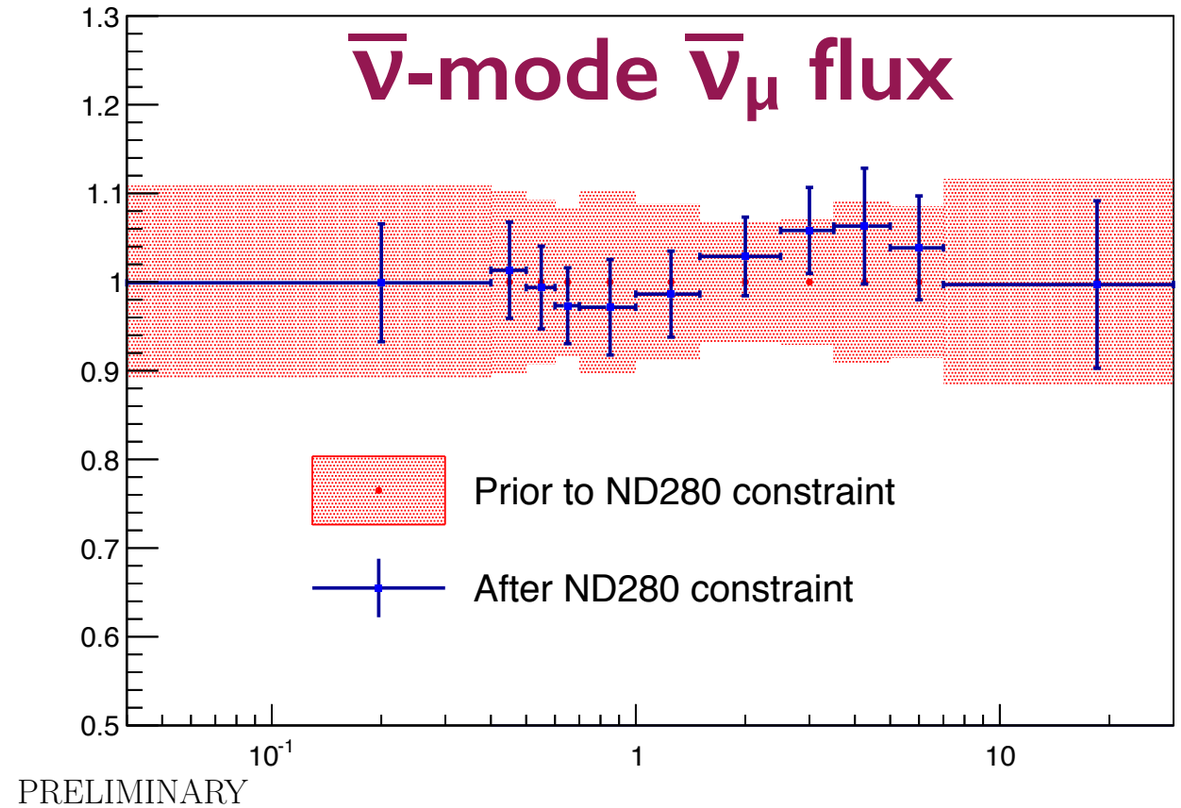
$$P(\vec{o}|D) = \int \prod_{SK,ND280bins} \mathcal{L}_{Poisson,bin}(\vec{o},\vec{s}) \times \pi_{osc.}(\vec{o}) \times \pi_{syst.}(\vec{s}) d\vec{s}$$

"Interesting" oscillation parameters: $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, Δm^2_{32}, δ_{CP}

Systematic parameters, $\sin^2\theta_{12}$, and Δm^2_{21}

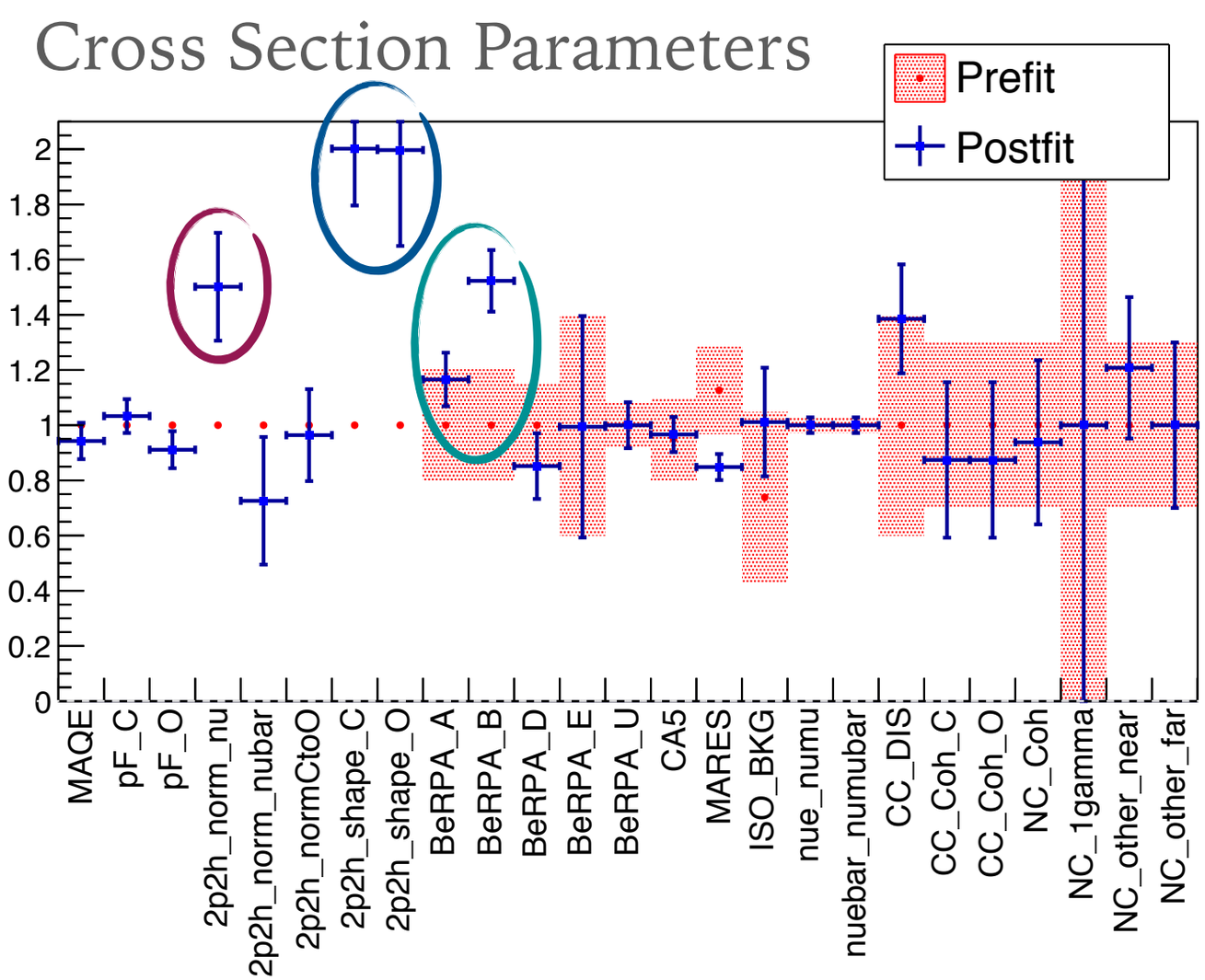
FITTED FLUX PARAMETERS





- Fitted flux parameters consistent with pre-fit predictions
- Contrast to 2016 results (flux parameters increased by ~10-15%)

FITTED CROSS-SECTION PARAMETERS



- 2p-2h normalisation for neutrinos increased by ~50%
- 2p-2h shape shifted so that Δ-enhanced component is maximal
- RPA parameters for $Q^2<1\,GeV^2$ increased, enhancing cross section in that region

SYSTEMATIC UNCERTAINTY

Uncertainty on number of events(%)	ν mode			$\bar{\nu}$ mode		ν-mode/$\bar{\nu}$-mode
	$1R_\mu$	$1R_e$	$1R_e1\pi$	$1R_\mu$	$1R_e$	$1R_e$
SK Detector	1.9	3.0	16.7	1.5	4.2	1.6
SK FSI+SI+PN	2.2	3.0	11.4	2.0	2.3	1.6
ND280 const. flux + xsec	3.2	3.2	4.1	2.7	2.9	2.5
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.0	2.6	2.6	0.0	1.5	3.0
NC1γ	0.0	1.1	0.3	0.0	2.6	1.5
NC Other	0.3	0.1	1.0	0.3	0.3	0.2
Total	**4.4**	**6.1**	**20.9**	**3.8**	**6.5**	**4.8**

Systematic uncertainties after ND280 constraint (in hybrid frequentist-Bayesian approach)

Large uncertainty due to SK detector modelling and pion interactions in the nucleus and detector for CC1π-dominated sample

SYSTEMATIC UNCERTAINTY

Uncertainty on number of events(%)	ν mode			$\bar{\nu}$ mode		ν-mode/$\bar{\nu}$-mode
	$1R_\mu$	$1R_e$	$1R_e1\pi$	$1R_\mu$	$1R_e$	$1R_e$
SK Detector	1.9	3.0	16.7	1.5	4.2	1.6
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$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.0	2.6	2.6	0.0	1.5	3.0
NC1γ	0.0	1.1	0.3	0.0	2.6	1.5
NC Other	0.3	0.1	1.0	0.3	0.3	0.2
Total	**4.4**	**6.1**	**20.9**	**3.8**	**6.5**	**4.8**

Systematic uncertainties after ND280 constraint (in hybrid frequentist-Bayesian approach)

Uncertainty due to flux and cross-section parameters constrained at ND280 ~3-4%

Other parameters to account for interactions not measured at ND280 (ν_e and NC)

SYSTEMATIC UNCERTAINTY

Uncertainty on number of events(%)	ν mode			$\bar{\nu}$ mode		ν-mode/$\bar{\nu}$-mode
	$1R_\mu$	$1R_e$	$1R_e1\pi$	$1R_\mu$	$1R_e$	$1R_e$
SK Detector	1.9	3.0	16.7	1.5	4.2	1.6
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$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.0	2.6	2.6	0.0	1.5	3.0
$NC1\gamma$	0.0	1.1	0.3	0.0	2.6	1.5
NC Other	0.3	0.1	1.0	0.3	0.3	0.2
Total	**4.4**	**6.1**	**20.9**	**3.8**	**6.5**	**4.8**

Systematic uncertainties after ND280 constraint (in hybrid frequentist-Bayesian approach)

Total uncertainty generally ~4-7% (except CC1π sample)

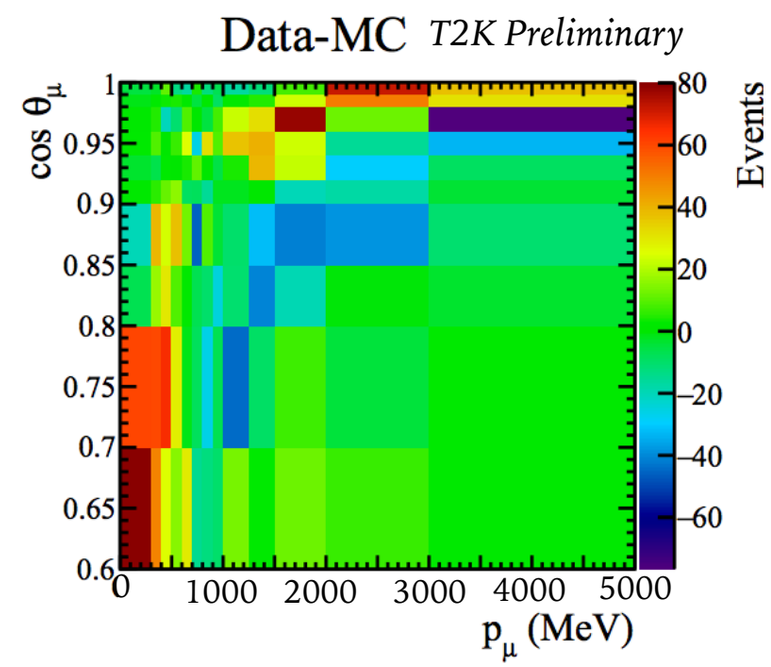
Error on ν-mode/$\bar{\nu}$-mode 1Re ratio 4.8% (impacts ability to measure δ_{CP})

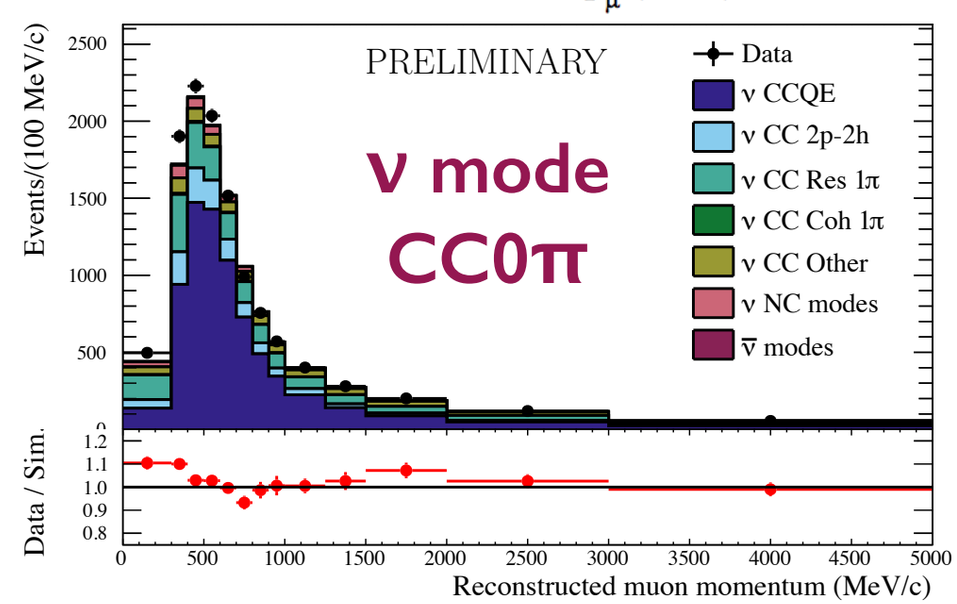
ROBUSTNESS OF T2K RESULTS

- Neutrino interaction model can have a large effect on T2K results
- Uncertainties on systematic parameters well-motivated from external /T2K data and theory
- **What about effects we haven't considered/parameters not included?**
- Check effect on oscillation analysis using fake data:
  1. Generate "fake data" (systematically varied Monte Carlo) at ND280 and SK
  2. Fit with current fitting model
  3. Check for biases in fitted oscillation parameters

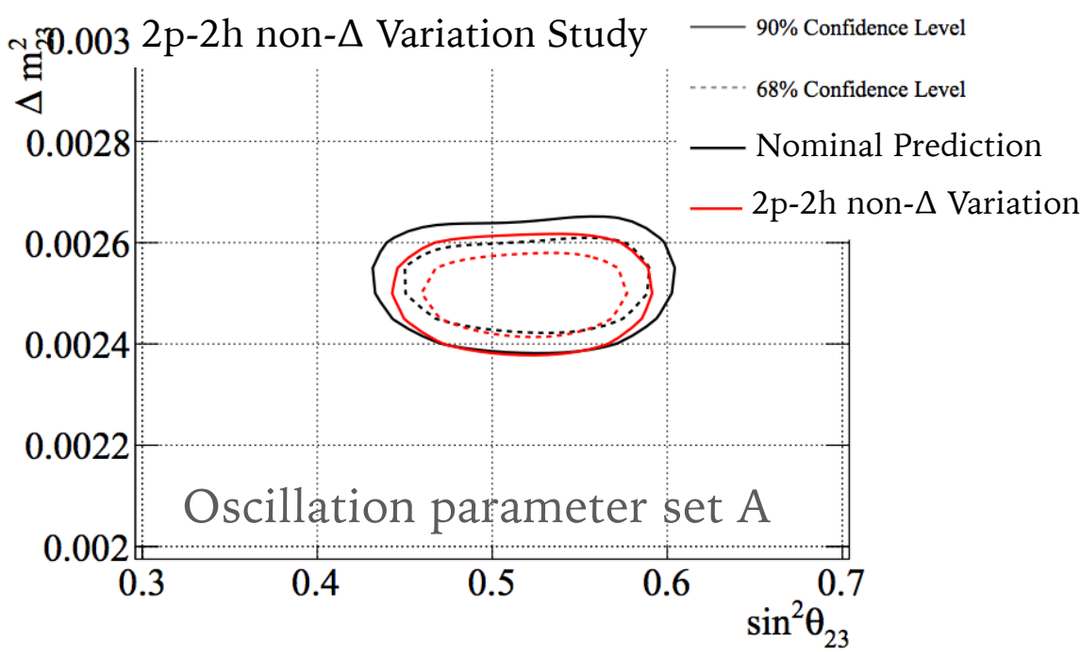
AN EXAMPLE: ND280 DATA-DRIVEN VARIATION

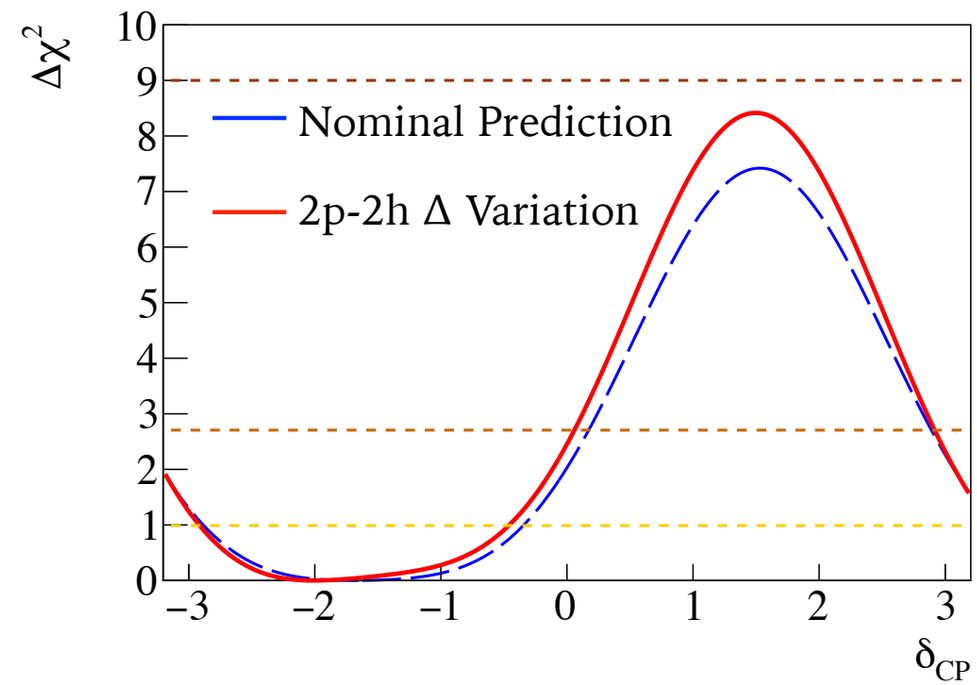
- Excess of data over prediction in CC0π sample prior to ND280 fitting
- Create three fake data sets assuming excess is entirely due to either:
  - CCQE (not shown)
  - 2p-2h Δ-enhanced (not shown)
  - **2p-2h non-Δ-enhanced (next slide!)**





AN EXAMPLE: ND280 DATA-DRIVEN VARIATION





- Δm^2_{32} biased towards lower values
- $\sin^2\theta_{23}$ biased towards maximal disappearance → smaller contours than when fitting nominal prediction

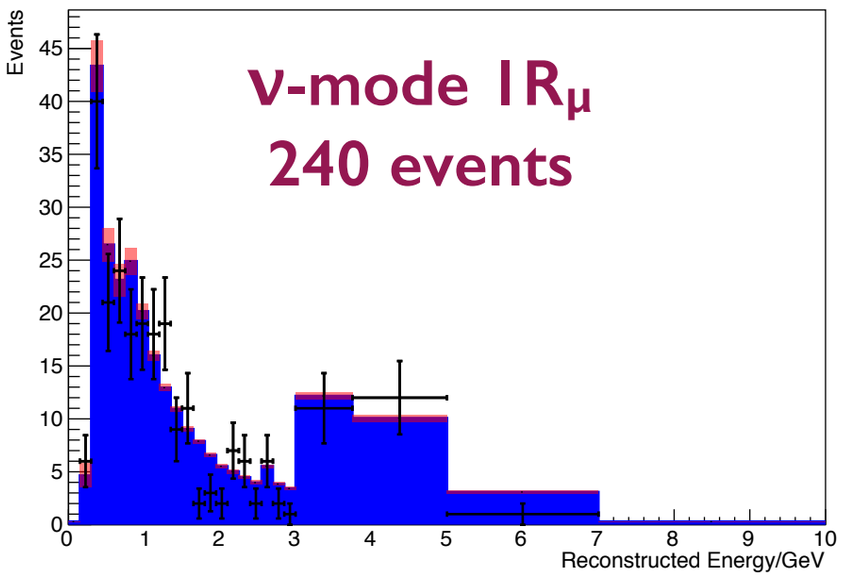
- Very little effect on δ_{CP}
- Normal-hierarchy 2σ confidence interval changes by 2.3%

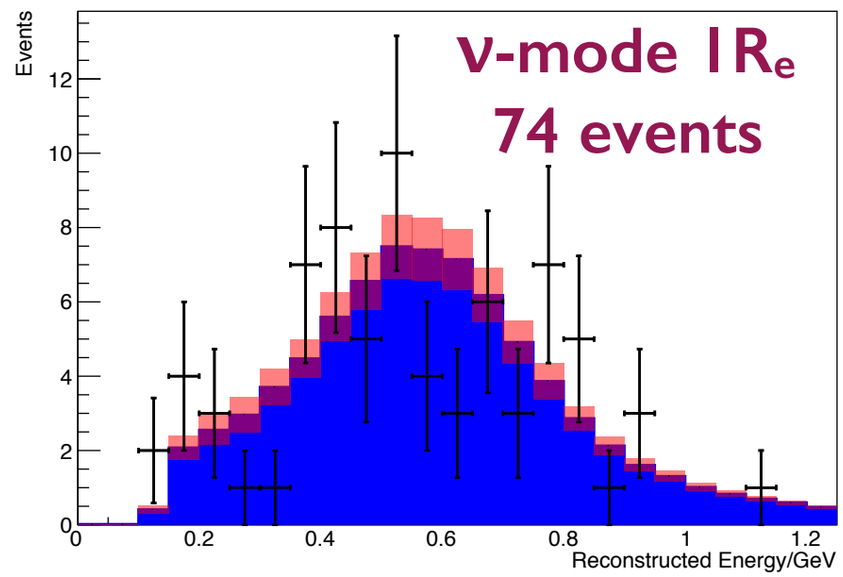
ROBUSTNESS OF T2K RESULTS: DISCUSSION

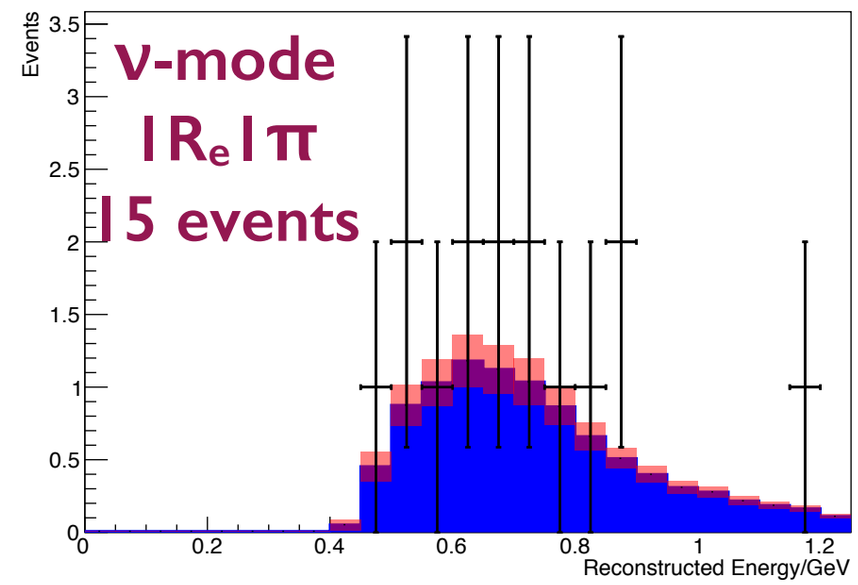
- Fake data checks are ongoing and final results are pending. This is just one example (also check theoretically-motivated differences and data-MC discrepancies elsewhere in T2K and other experiments)
- We are investigating whether these variations represent a physical effect that should be included as a systematic uncertainty
- Contours in $\sin^2\theta_{23}$—Δm^2_{32} are presented with the caveat that **systematic uncertainties might be updated**
- **There seems to be little effect on the δ_{CP} result**
- In the future, 1p-1h vs 2p-2h systematic effects will be addressed by the use of 4π (coverage) ND280 samples, proton kinematic information, and (eventually) near detector upgrades designed to target interaction modelling issues

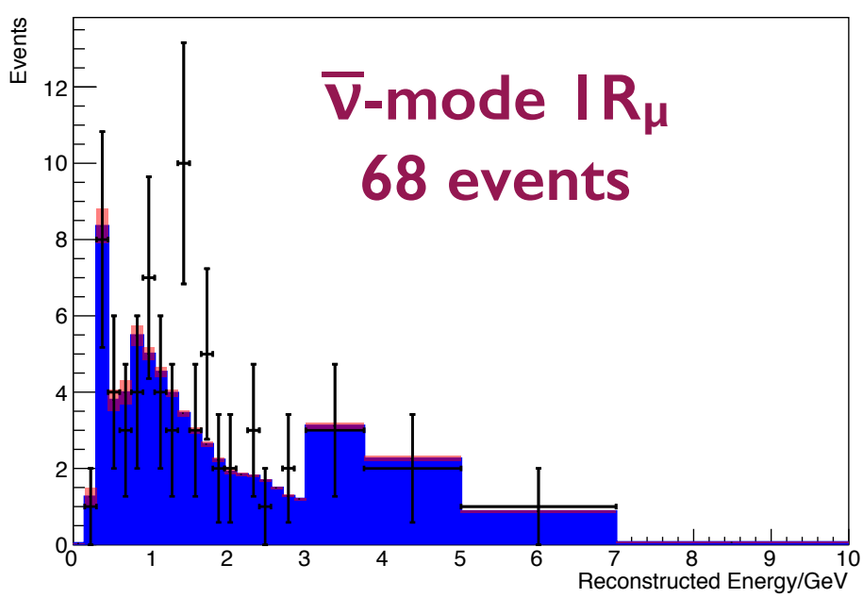
FIT RESULTS

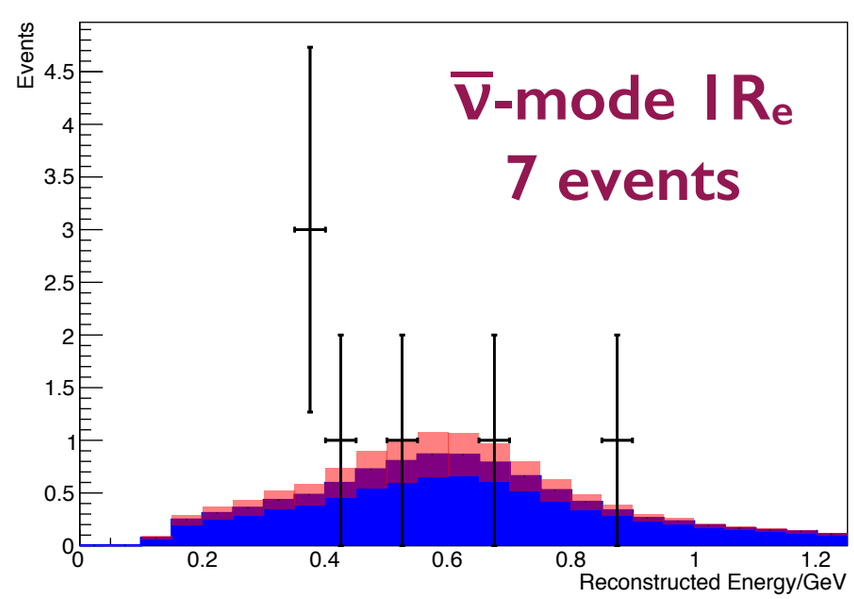
P-value
T2K-only 0.42
T2K+reactor 0.41



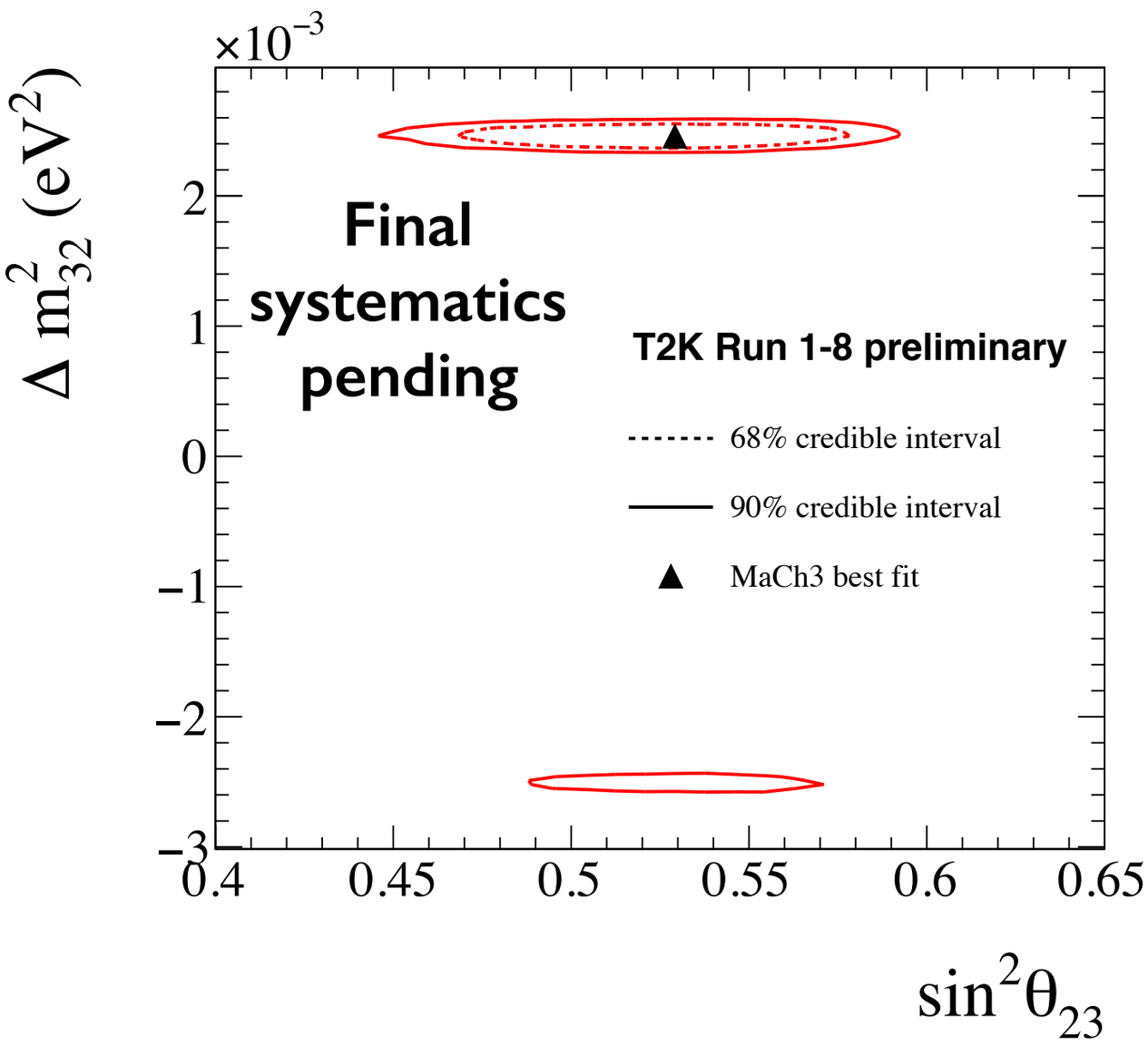








MEASUREMENT OF $\sin^2\theta_{23}$ AND Δm^2_{32}



Including reactor constraint on $\sin^2 2\theta_{13}$

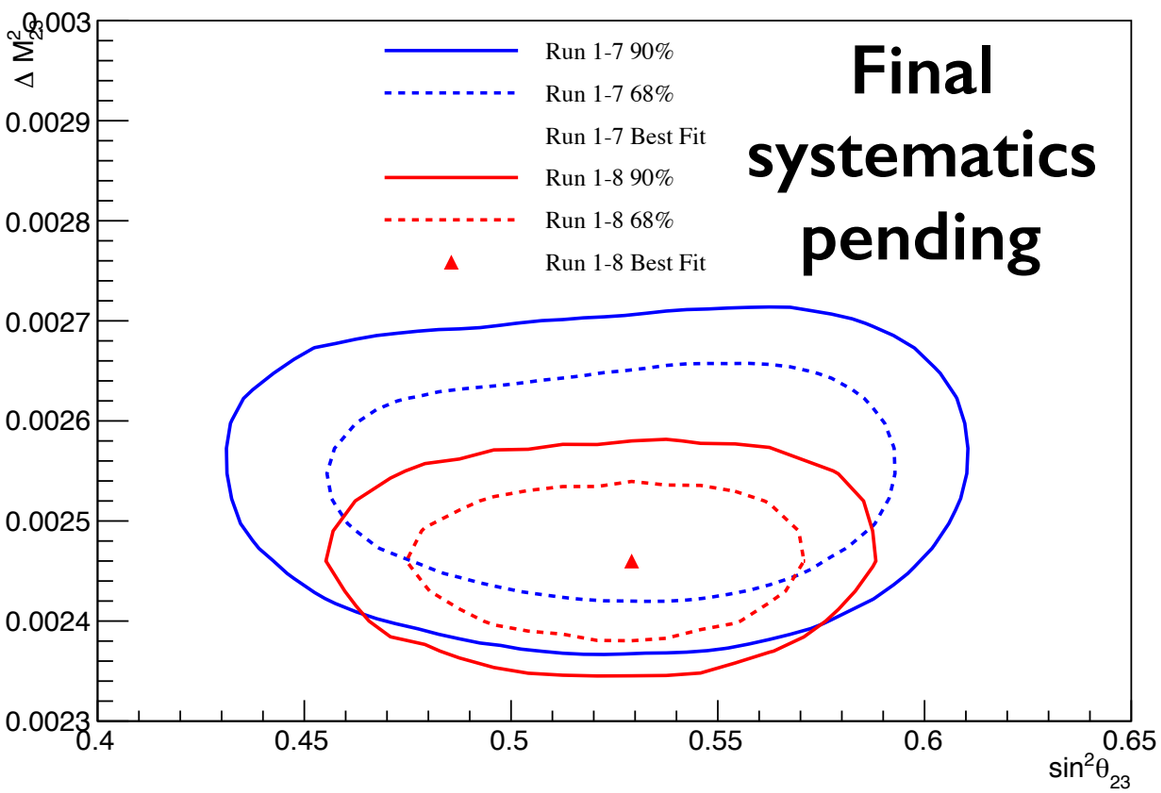
Results (pending final systematics) continue to favour maximal disappearance

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
IH ($\Delta m^2_{32} < 0$)	0.03	0.11	0.13
NH ($\Delta m^2_{32} > 0$)	0.19	0.67	0.87
Sum	0.22	0.78	1

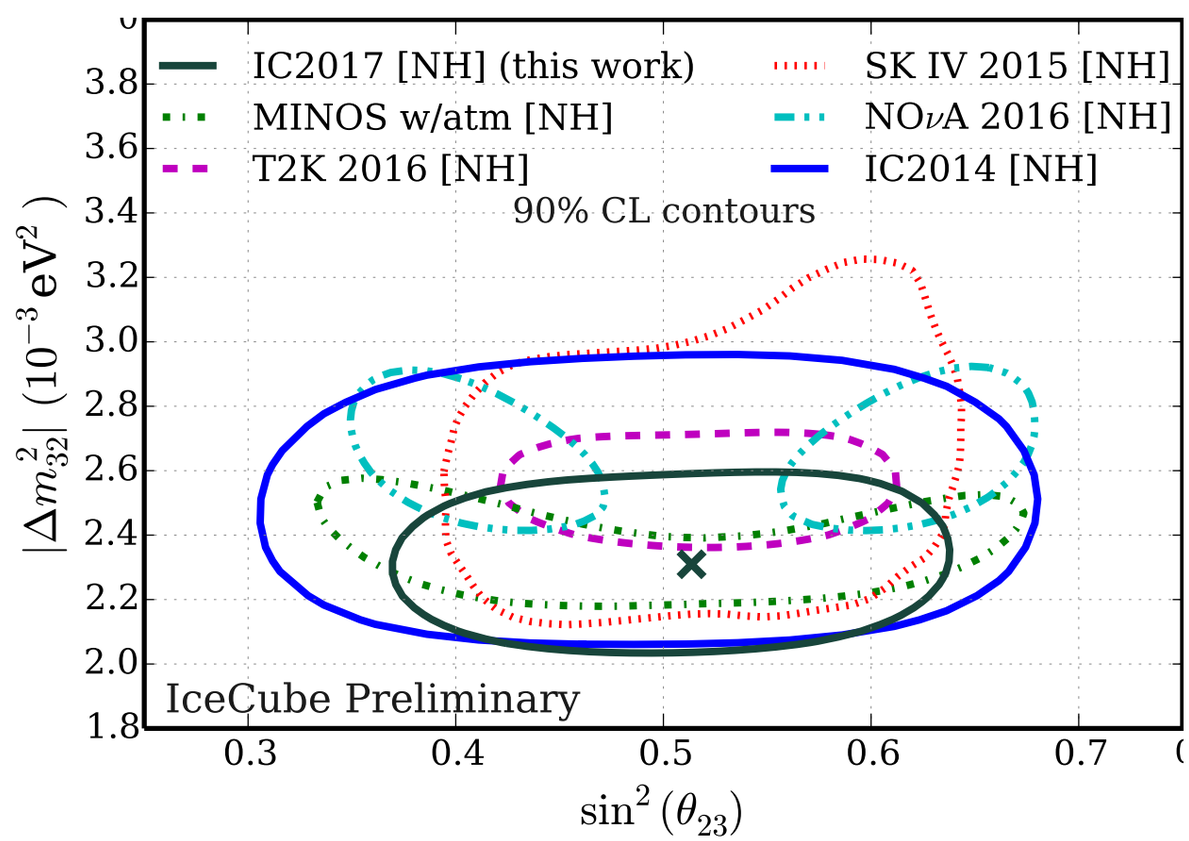
Posterior probability: **mildly** favour upper octant and normal hierarchy

MEASUREMENT OF $\sin^2\theta_{23}$ AND Δm^2_{32}

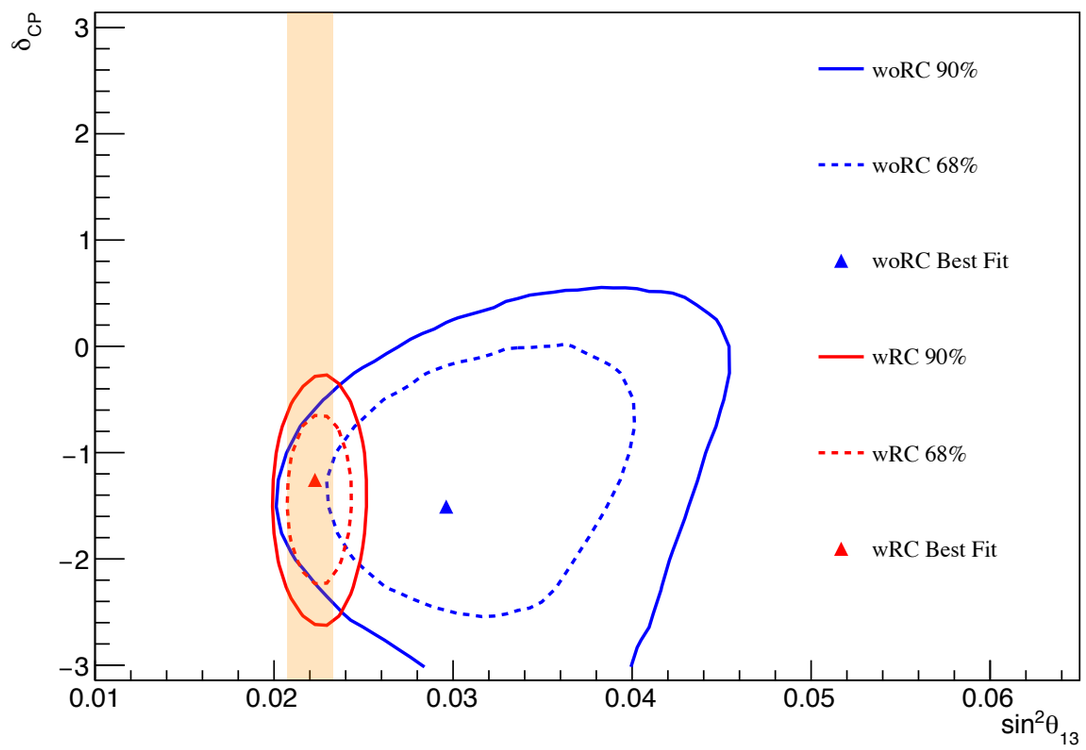
Comparison with winter 2016/2017 results



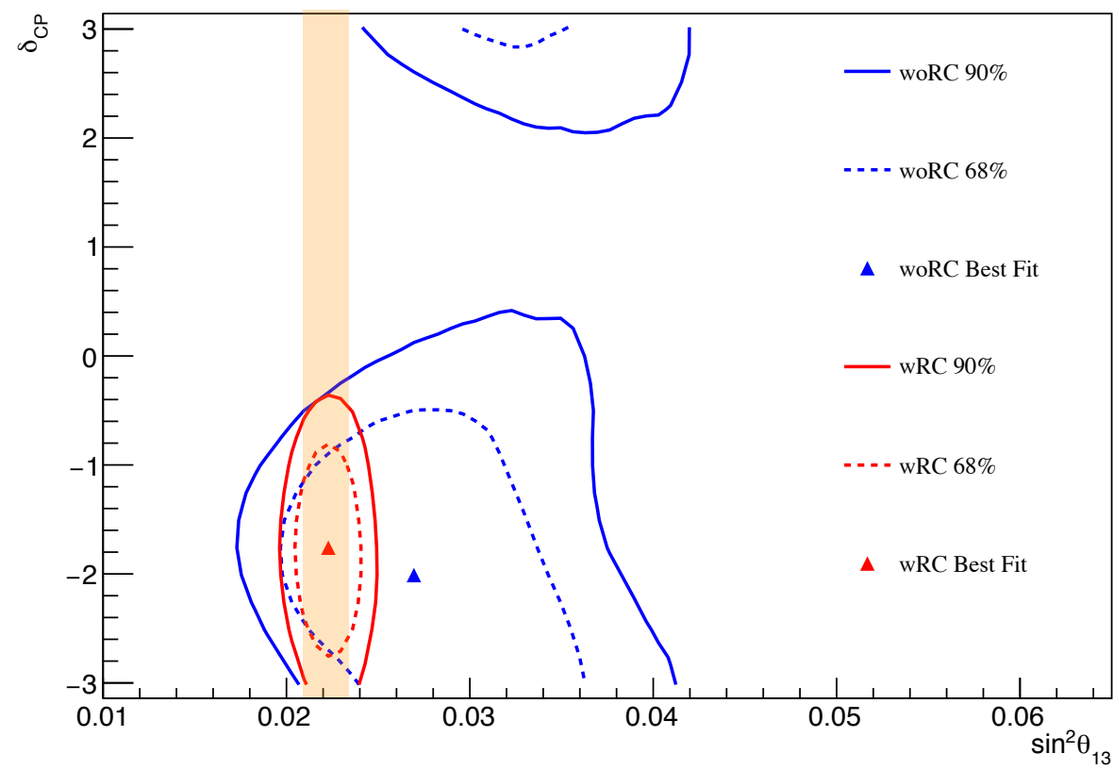
Winter 2016/2017 comparison with other experiments (fixed-hierarchy confidence levels)



MEASUREMENT OF $\sin^2\theta_{13}$ AND δ_{CP}



Normal Hierarchy



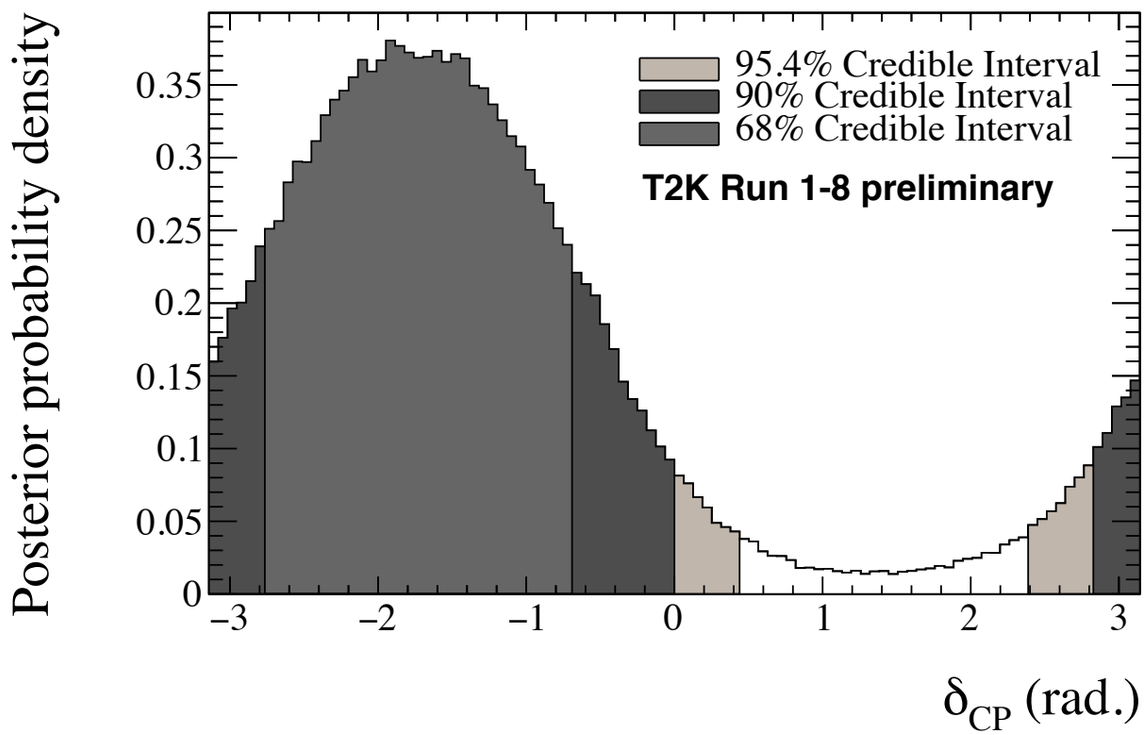
Inverted Hierarchy

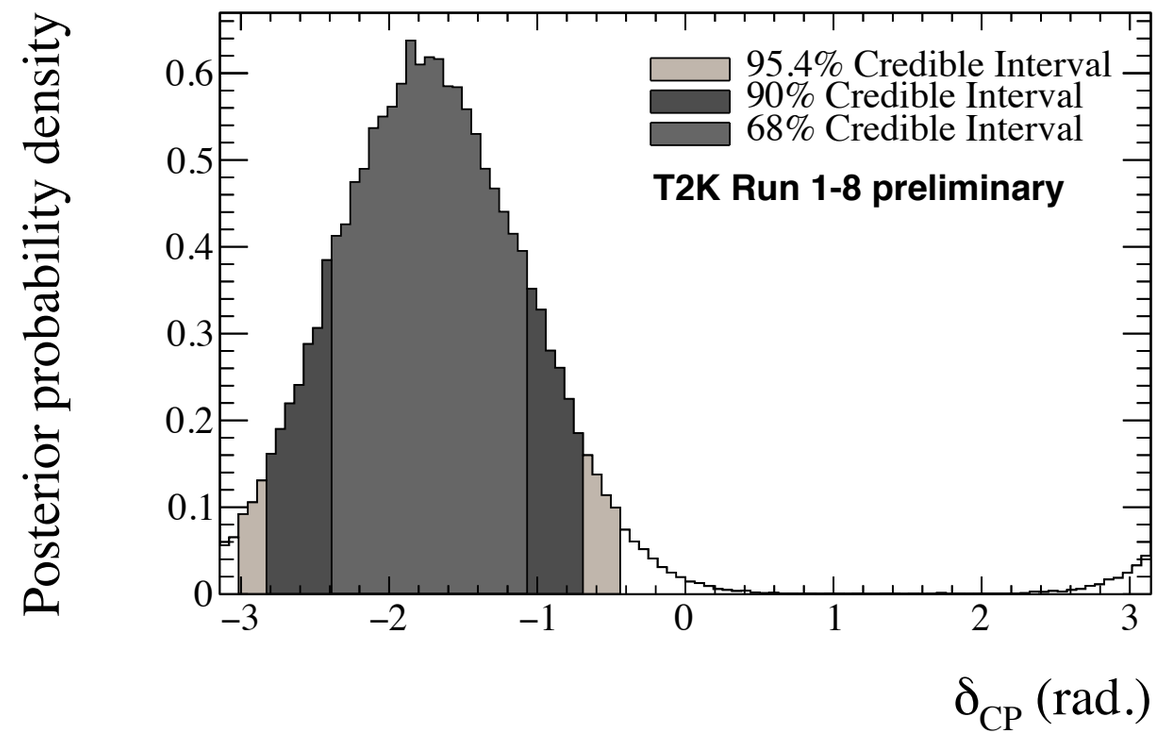
T2K only

With reactor constraint

Reactor constraint: $\sin^2 2\theta_{13} = 0.0857 \pm 0.0046$

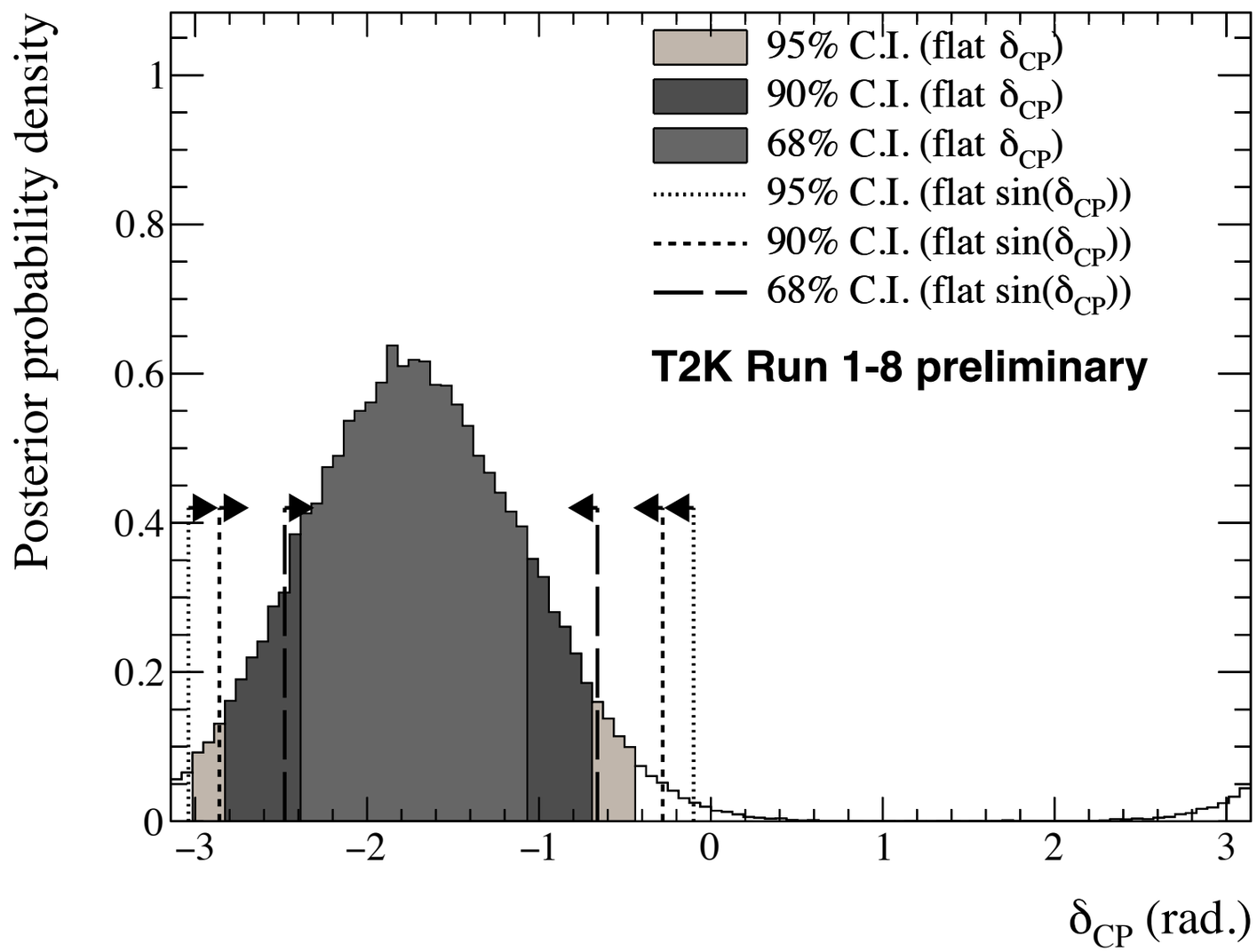
WHAT CAN WE SAY ABOUT δ_{CP}?





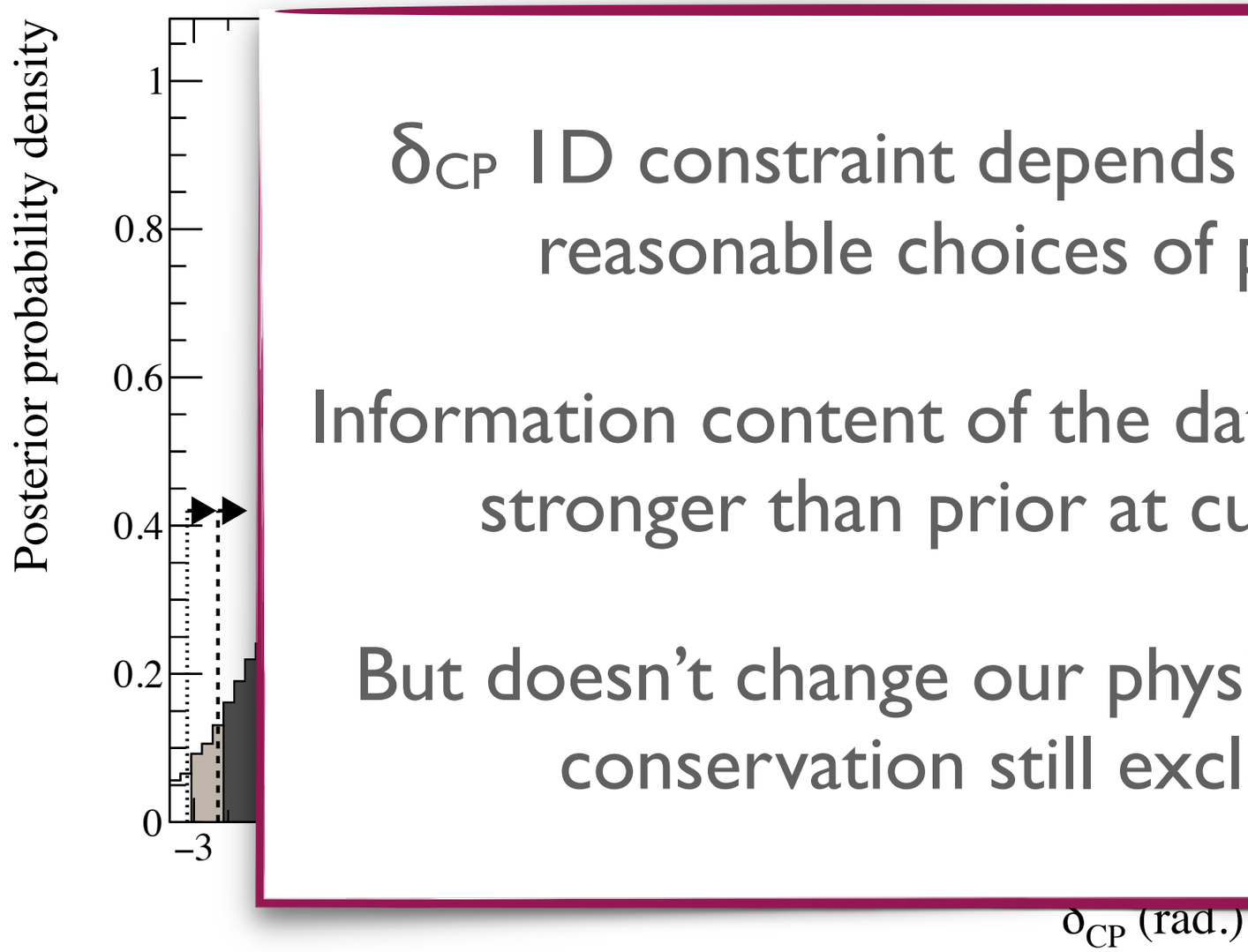
T2K Only		T2K+Reactor
-π — 0.00 & 2.82 — π	90% δ_{CP}	-2.76 — -0.63
-π — 0.44 & 2.39 — π	95% δ_{CP}	-3.02 — -0.44

WHAT CAN WE SAY ABOUT δ_{CP}? PRIOR CONSTRAINT



- The fit uses an uninformative (flat) prior on δ_{CP}
- Ideal for making a parameter measurement
- **But** CP-violating terms in oscillation probability ~ $\sin\delta_{CP}$
- When looking for CP violation, flat prior (and plotting) in $\sin\delta_{CP}$ might be more appropriate

WHAT CAN WE SAY ABOUT δ_{CP}? PRIOR CONSTRAINT



- The fit uses an uninformative

rameter

ns in

~ $\sin\delta_{CP}$

nd

ght be

more appropriate

δ_{CP} 1D constraint depends on prior (for two reasonable choices of prior on δ_{CP})

Information content of the data is not significantly stronger than prior at current statistics

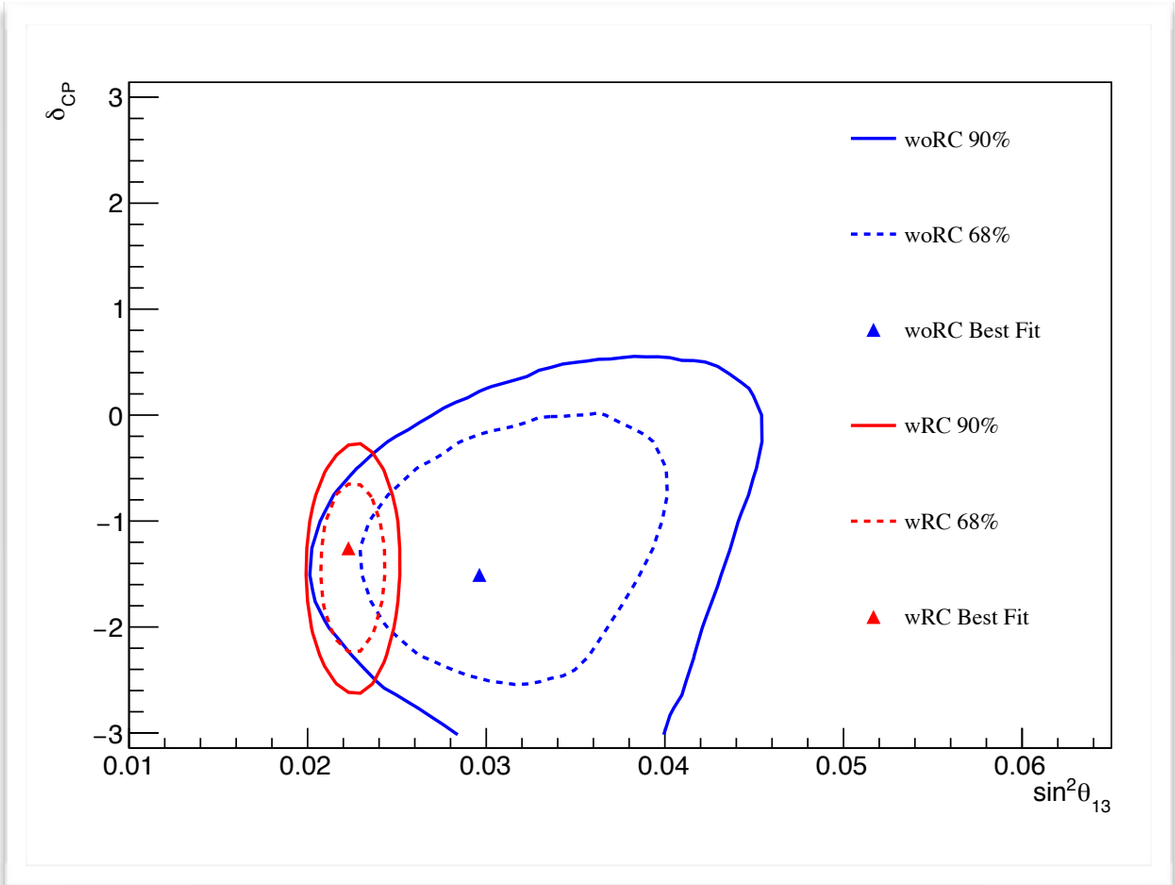
But doesn't change our physics conclusions: CP conservation still excluded at 95%

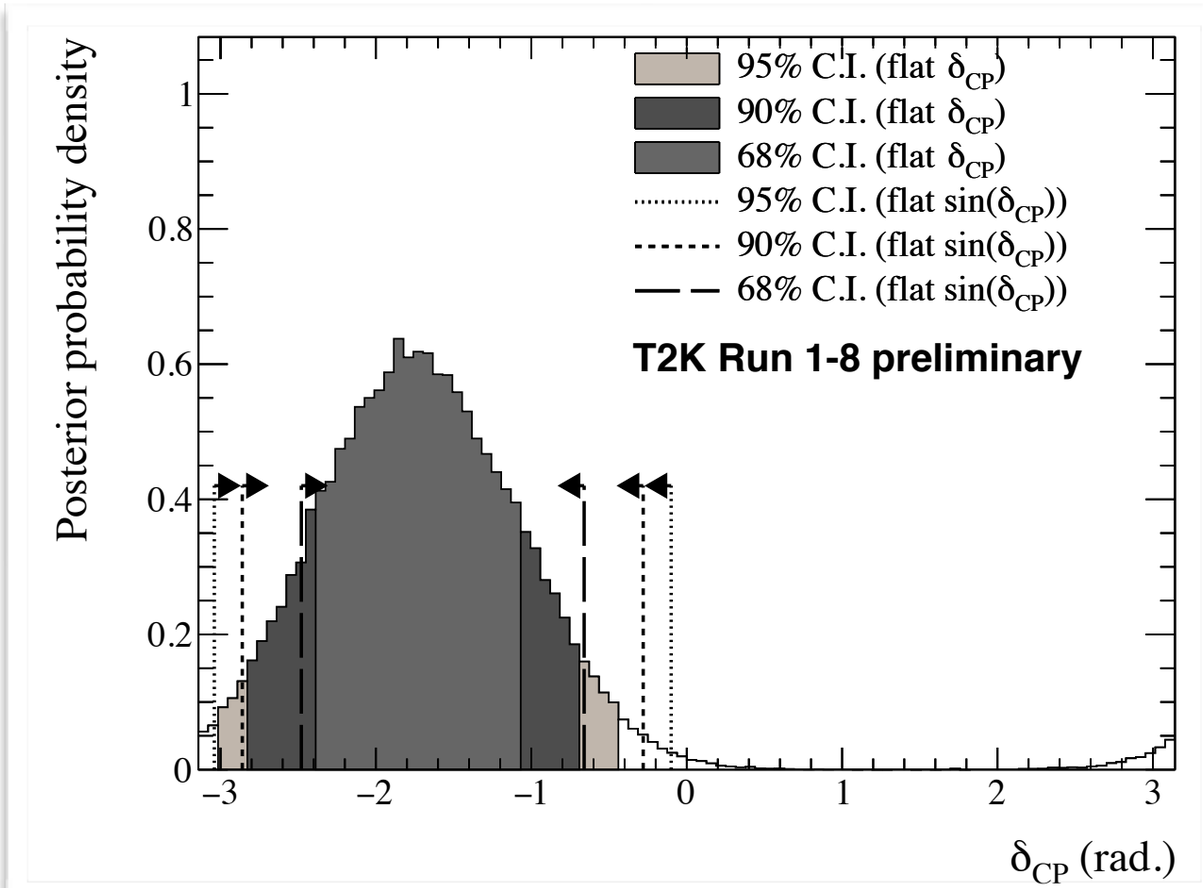
WHAT'S NEXT?

- This result is an exciting first step towards discovering lepton-sector CP violation and provides a hint towards the neutrino mass hierarchy
- Need larger statistics for more precise measurements
- Also vital to decrease systematic uncertainty and understand nuclear effects
  - Neutrino interaction measurements on different nuclear targets
  - Hadron production measurements

SUMMARY

- T2K has doubled neutrino-mode statistics since 2016
- Other new updates to oscillation analysis:
  - Improved Super-K reconstruction → effective ~30% increase in statistics
  - Improved uncertainties on neutrino interaction model (2p-2h and RPA)
- CP-conserving values of δ_{CP} are excluded at 2σ/95.45% in both credible and confidence intervals (confidence intervals not shown)
- T2K prefers the normal hierarchy and upper octant (but not statistically significant)
- Higher statistics from longer T2K running and eventual combination with NOvA, as well as improved interaction models and measurements, mean there is a bright future ahead for precision neutrino physics and searching for CP violation!


δCP
3
2
1
0
−1
−2
−3
0.01
0.02
0.03
0.04
0.05
0.06
sin²θ13
woRC 90%
woRC 68%
woRC Best Fit
wRC 90%
wRC 68%
wRC Best Fit

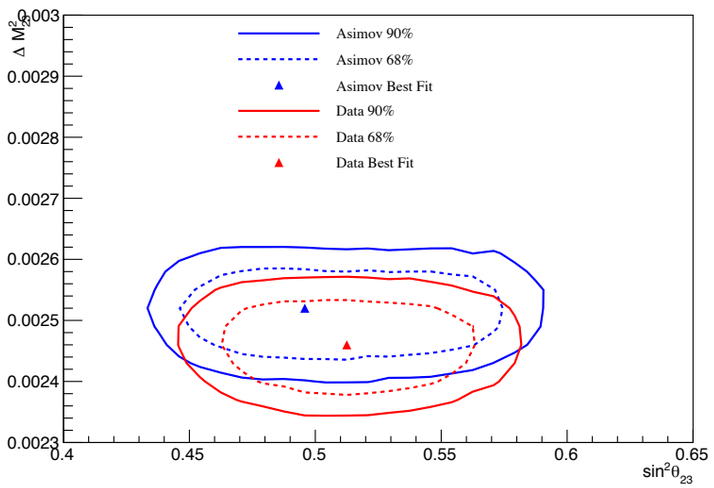

Posterior probability density
1
0.8
0.6
0.4
0.2
0
−3
−2
−1
0
1
2
3
δCP (rad.)
95% C.I. (flat δCP)
90% C.I. (flat δCP)
68% C.I. (flat δCP)
95% C.I. (flat sin(δCP))
90% C.I. (flat sin(δCP))
68% C.I. (flat sin(δCP))
T2K Run 1-8 preliminary

THANK YOU

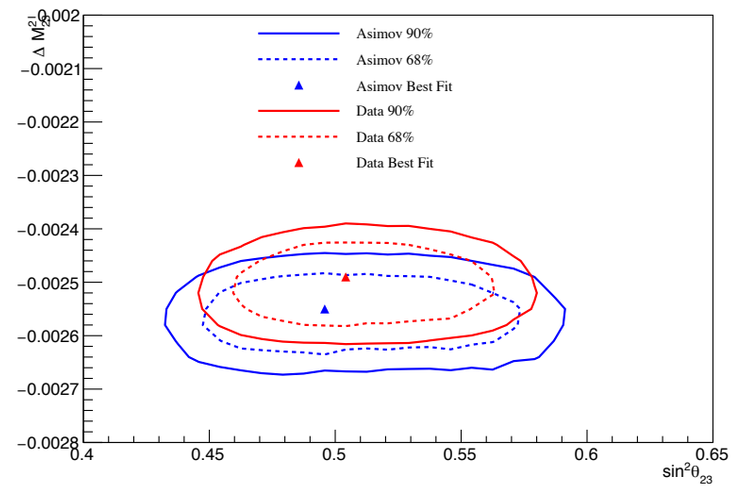
SUPPLEMENTARY

OSCILLATION PARAMETER SENSITIVITIES

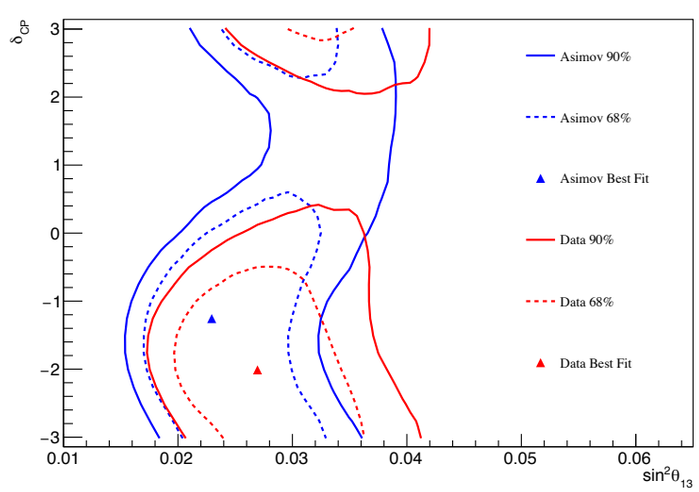
T2K only



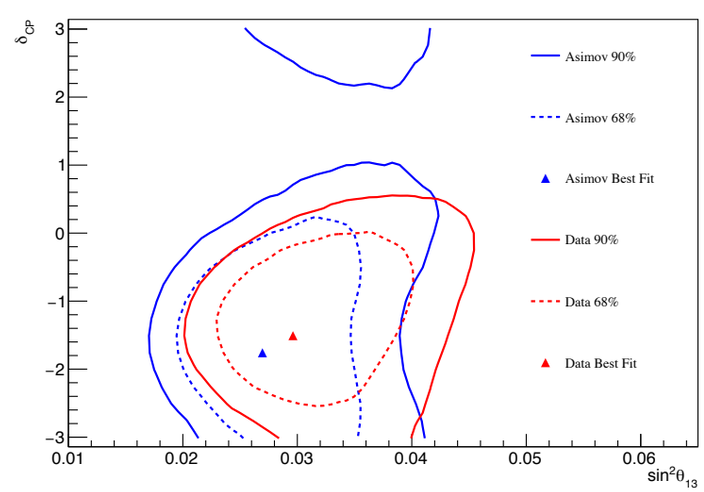
(a) $\sin^2\theta_{23}$–Δm^2_{32}: normal hierarchy



(b) $\sin^2\theta_{23}$–Δm^2_{32}: inverted hierarchy



(c) $\sin^2\theta_{13}$–δ_{CP}: normal hierarchy

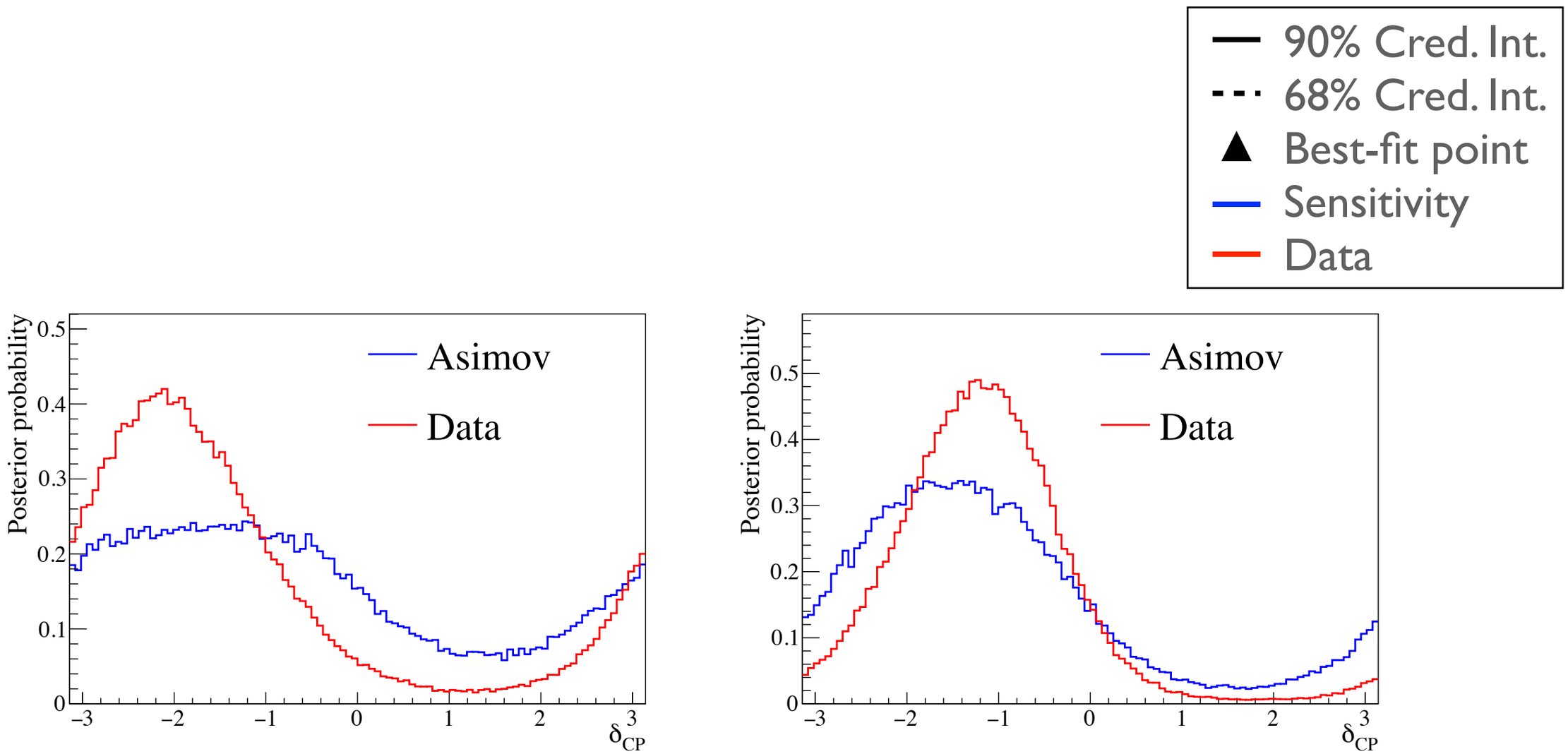


(d) $\sin^2\theta_{13}$–δ_{CP}: inverted hierarchy

- 90% Cred. Int.
- 68% Cred. Int.
- Best-fit point
- Sensitivity
- Data

OSCILLATION PARAMETER SENSITIVITIES

T2K only

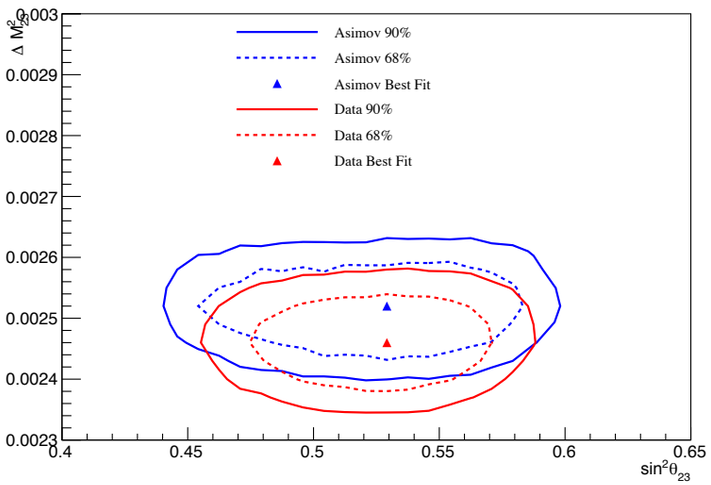


Normal Hierarchy

Inverted Hierarchy

OSCILLATION PARAMETER SENSITIVITIES

T2K+Reactor



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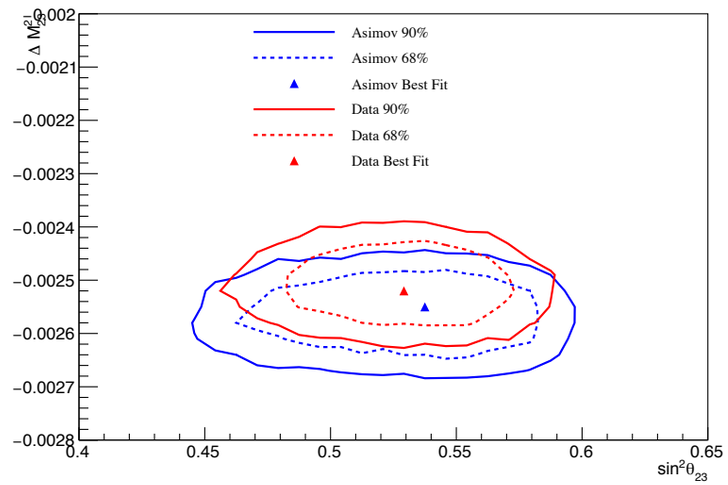

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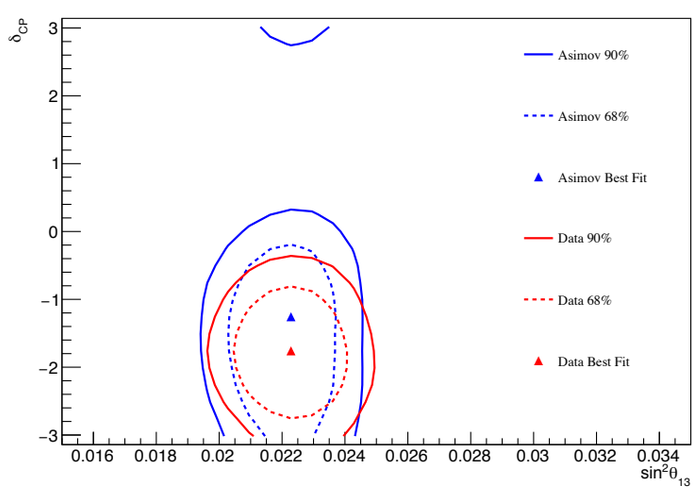

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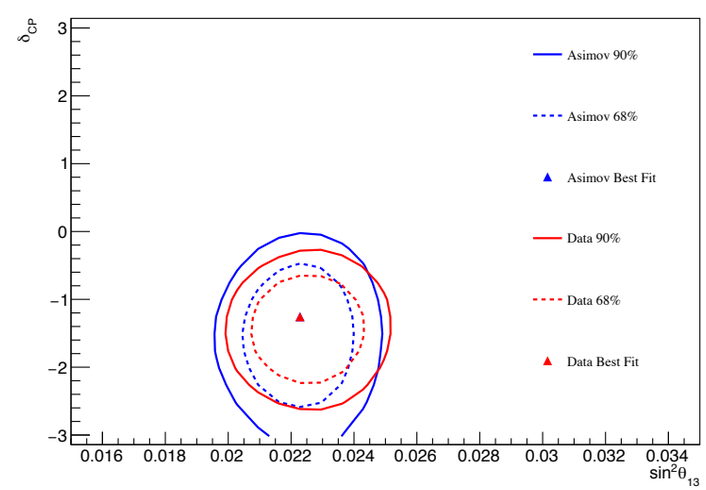

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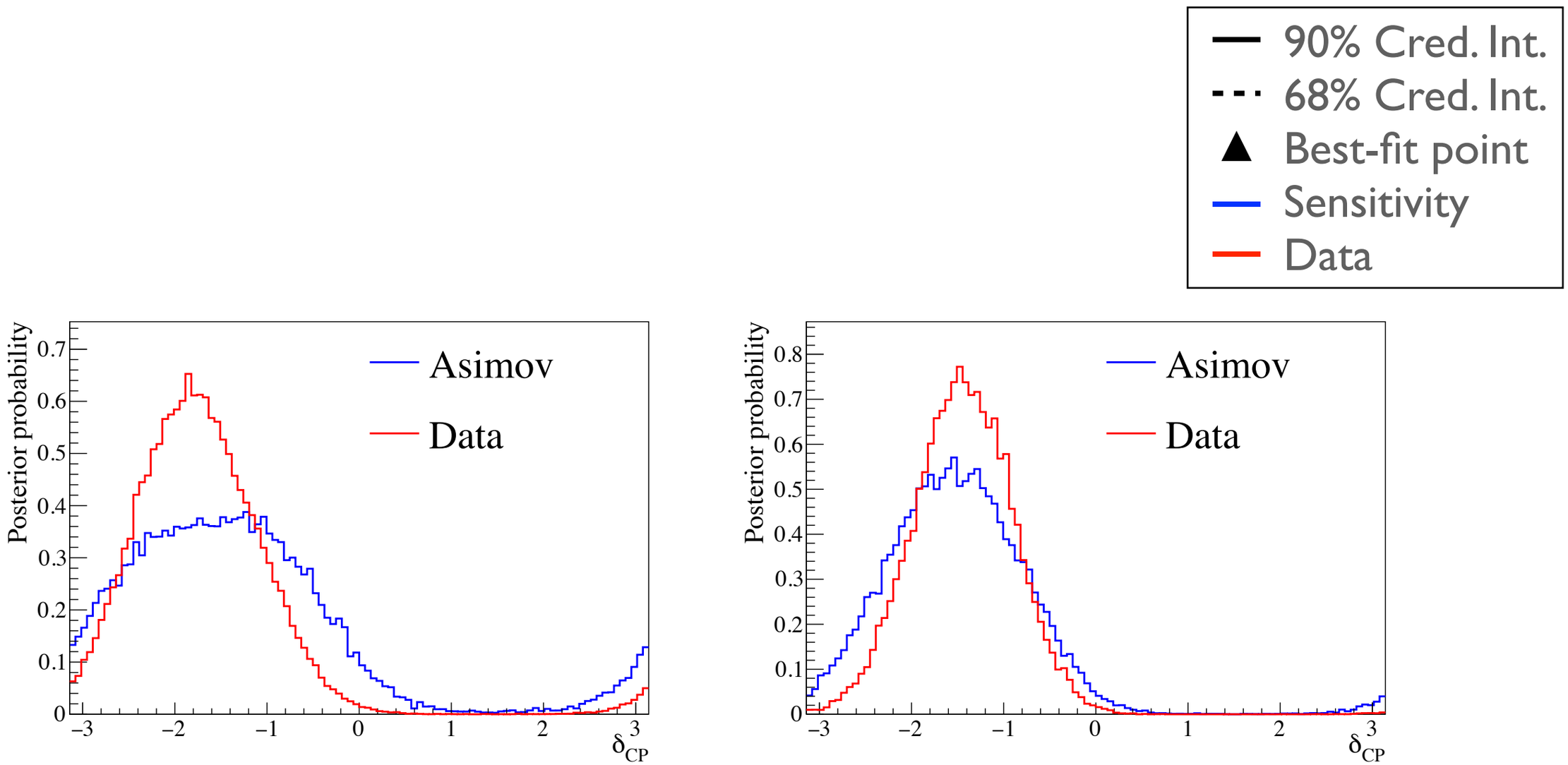
T2K+Reactor

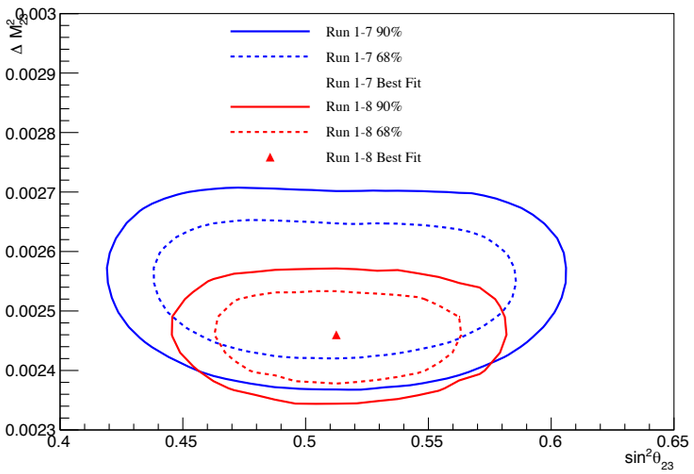


Normal Hierarchy

Inverted Hierarchy

COMPARISON TO 2016 RESULTS

T2K only



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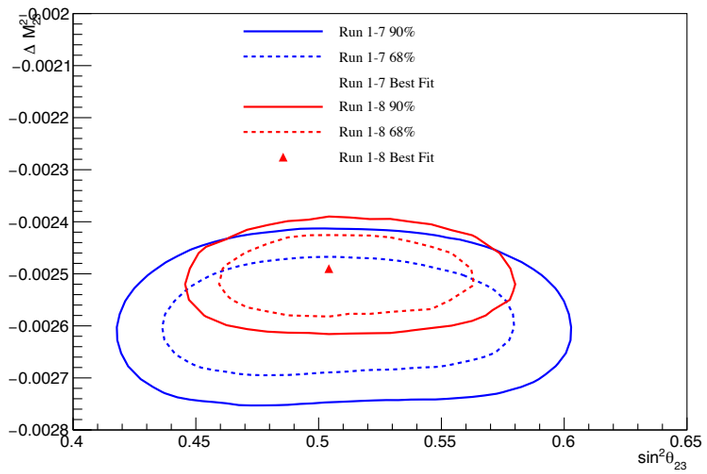

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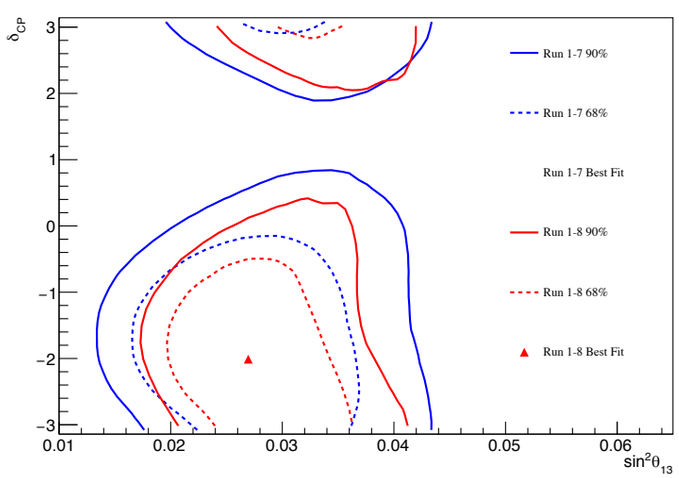
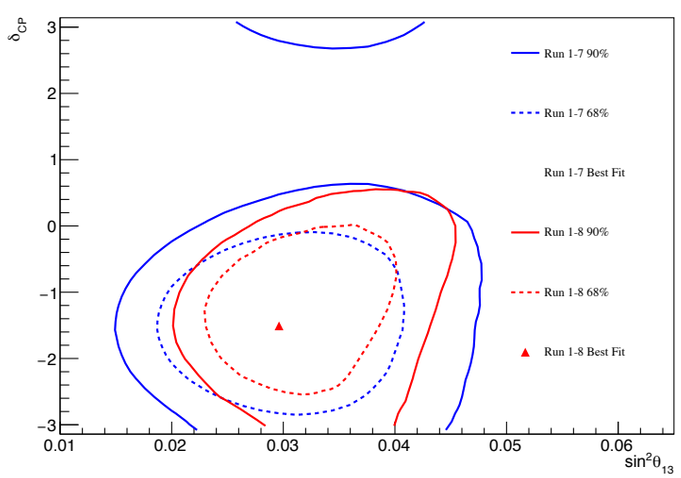


(c) $\sin^2\theta_{13}$–δ_{CP}: normal hierarchy



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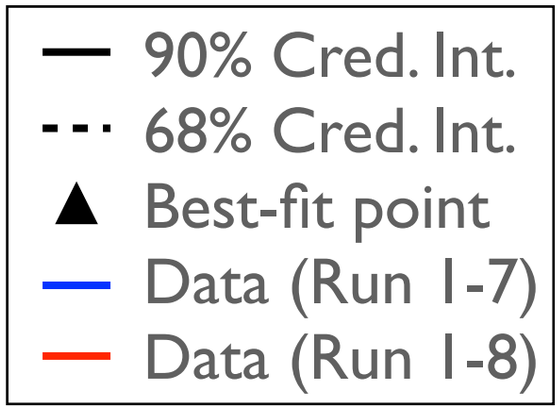
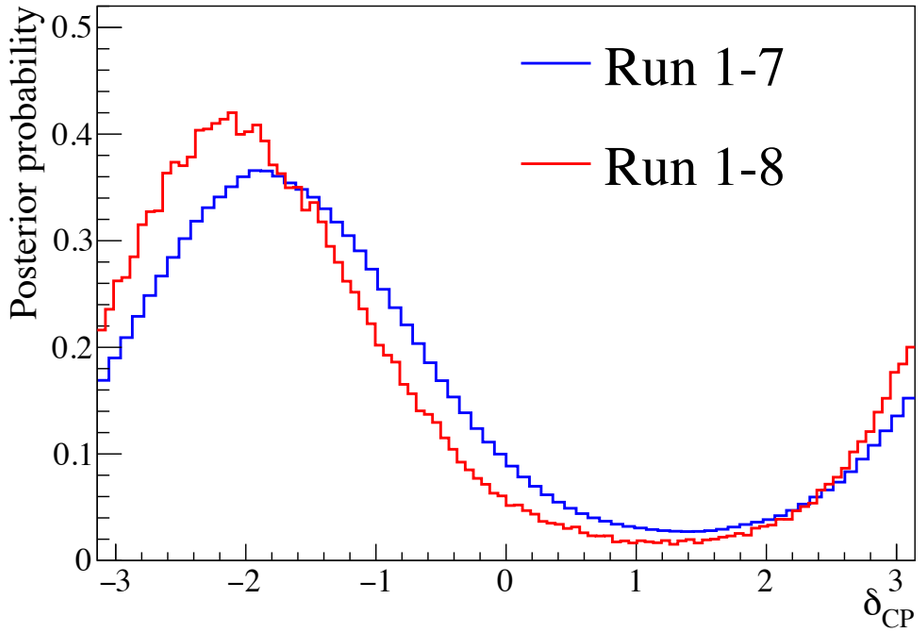
- Data (Run 1-8)

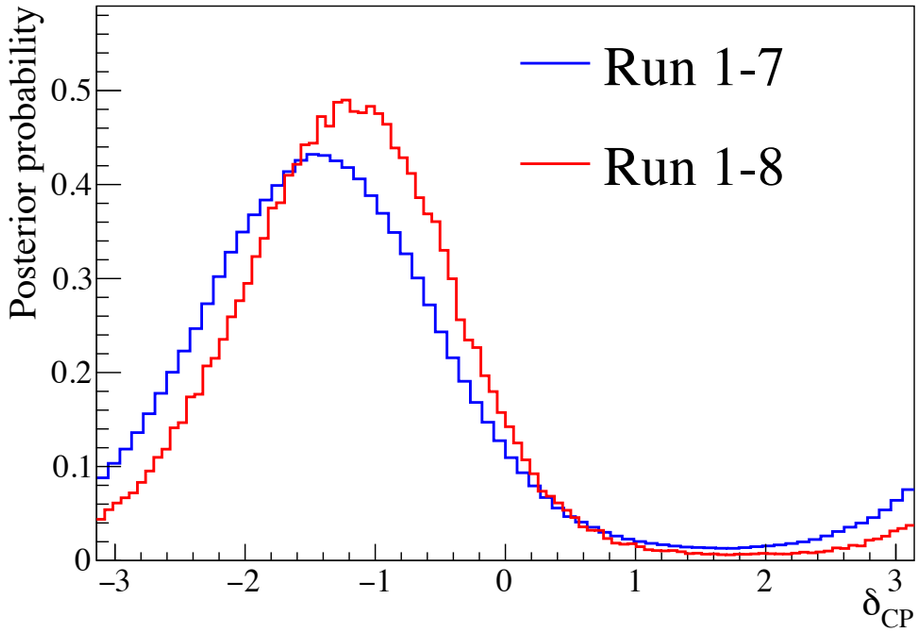
COMPARISON TO 2016 RESULTS

T2K only





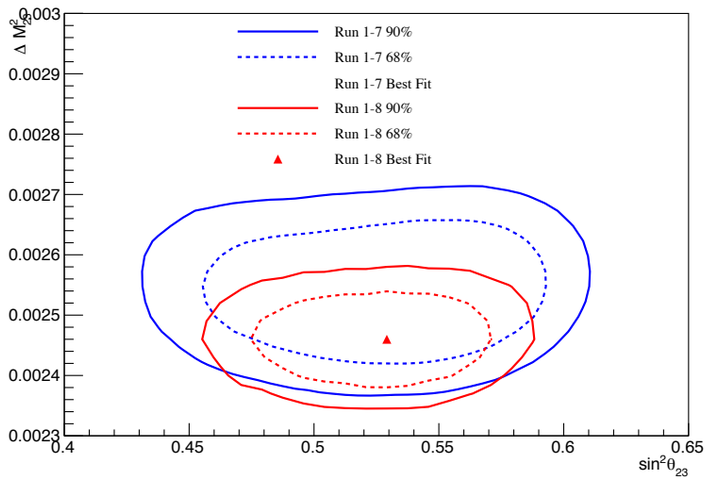
Normal Hierarchy



Inverted Hierarchy

COMPARISON TO 2016 RESULTS

T2K+Reactor



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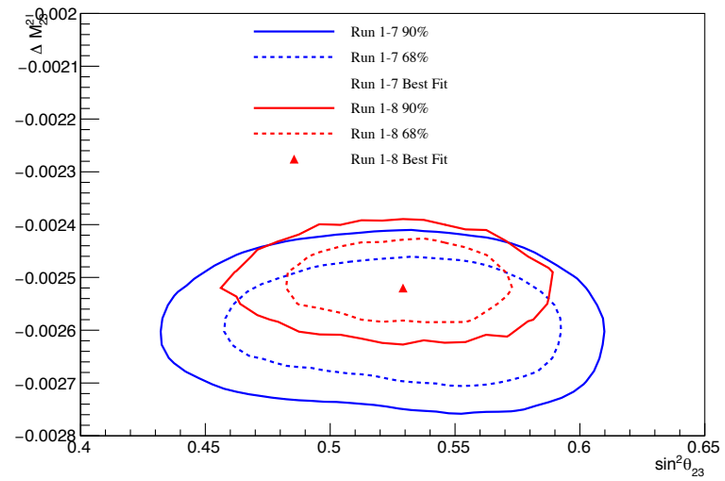
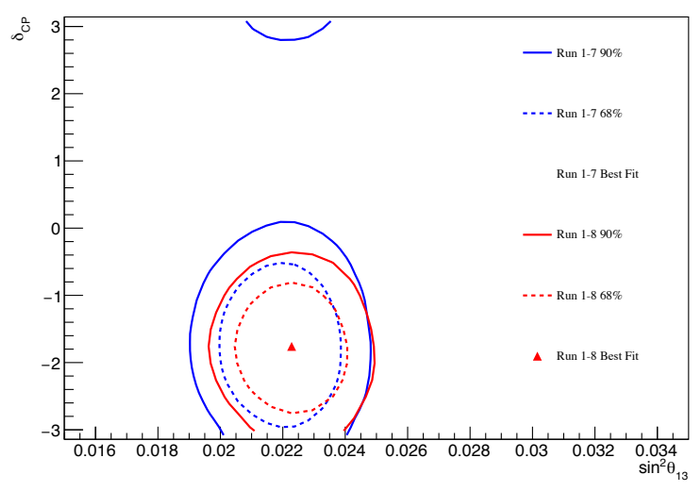
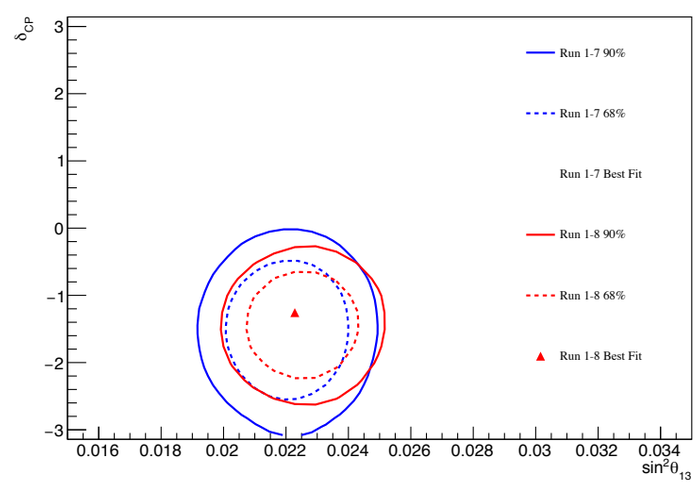


(b) $\sin^2\theta_{23}$–Δm^2_{32}: inverted hierarchy



(c) $\sin^2\theta_{13}$–δ_{CP}: normal hierarchy



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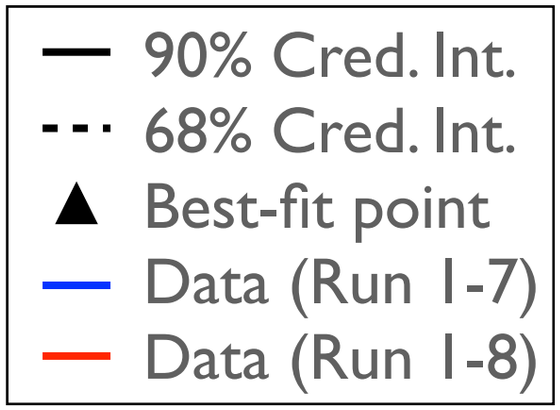
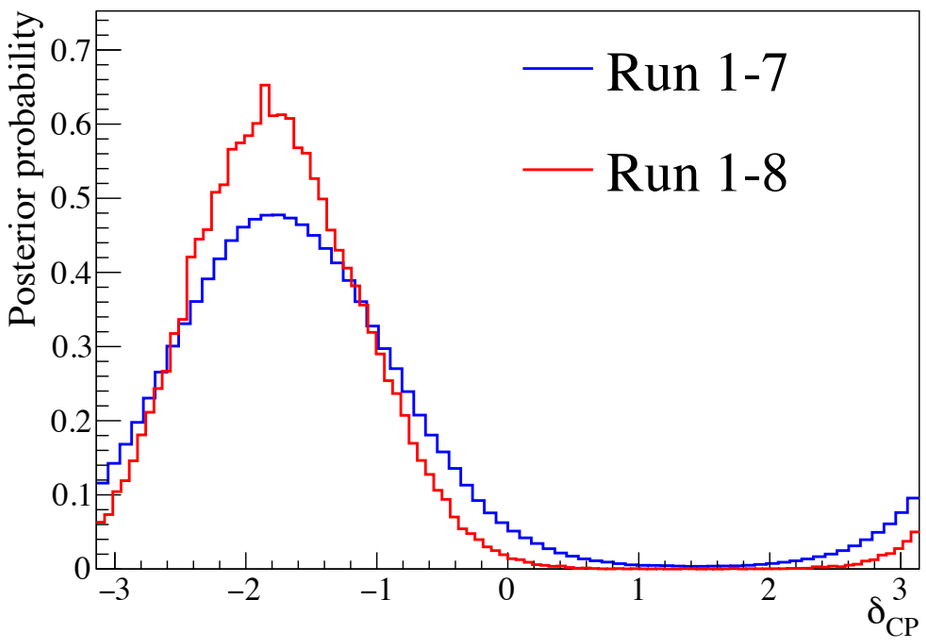
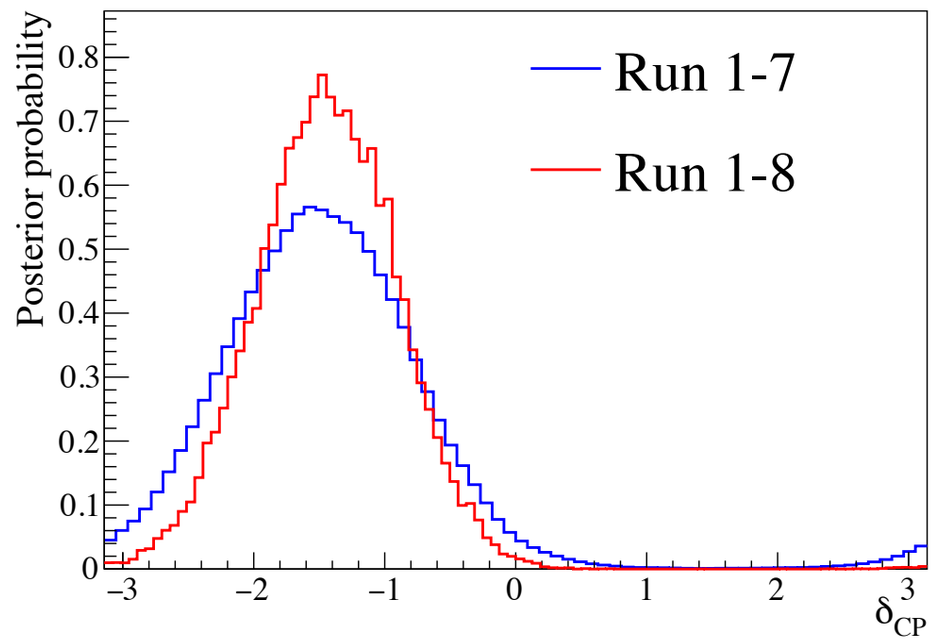
COMPARISON TO 2016 RESULTS

T2K+Reactor





Normal Hierarchy

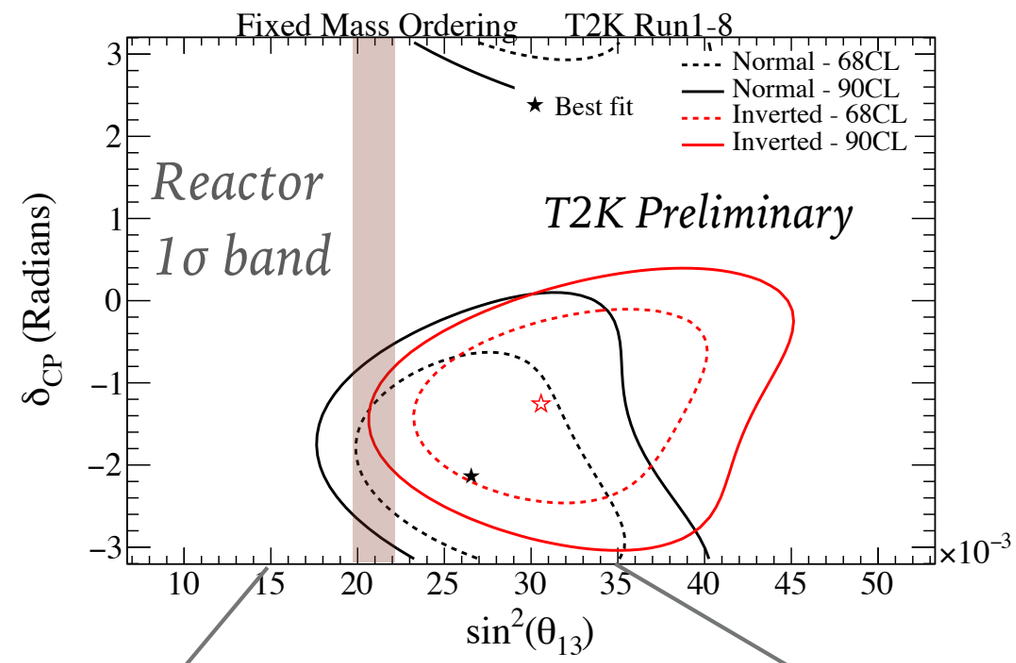


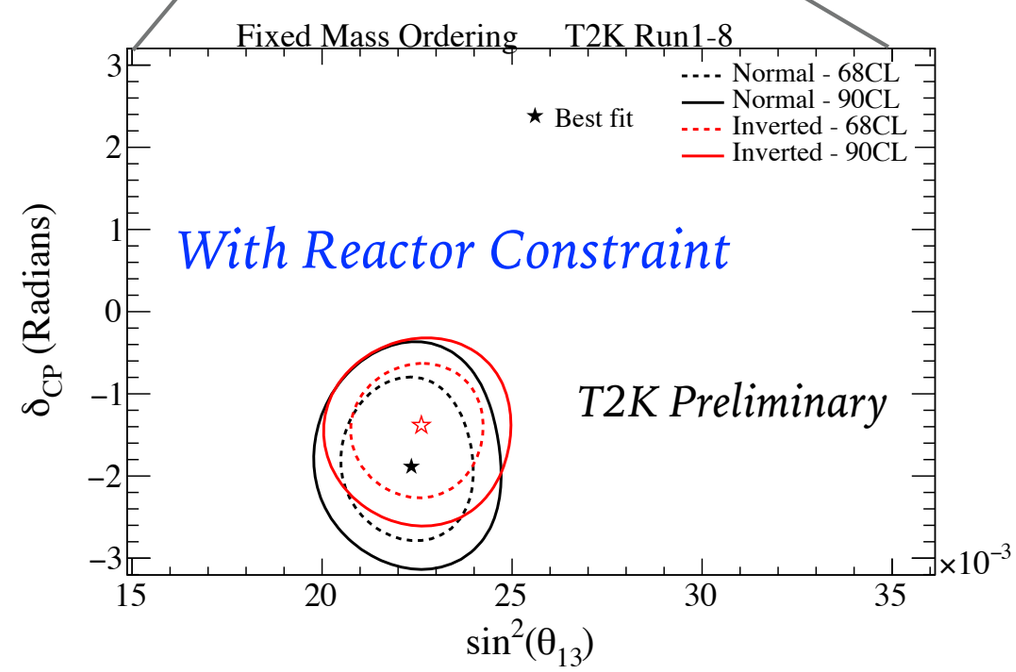
Inverted Hierarchy

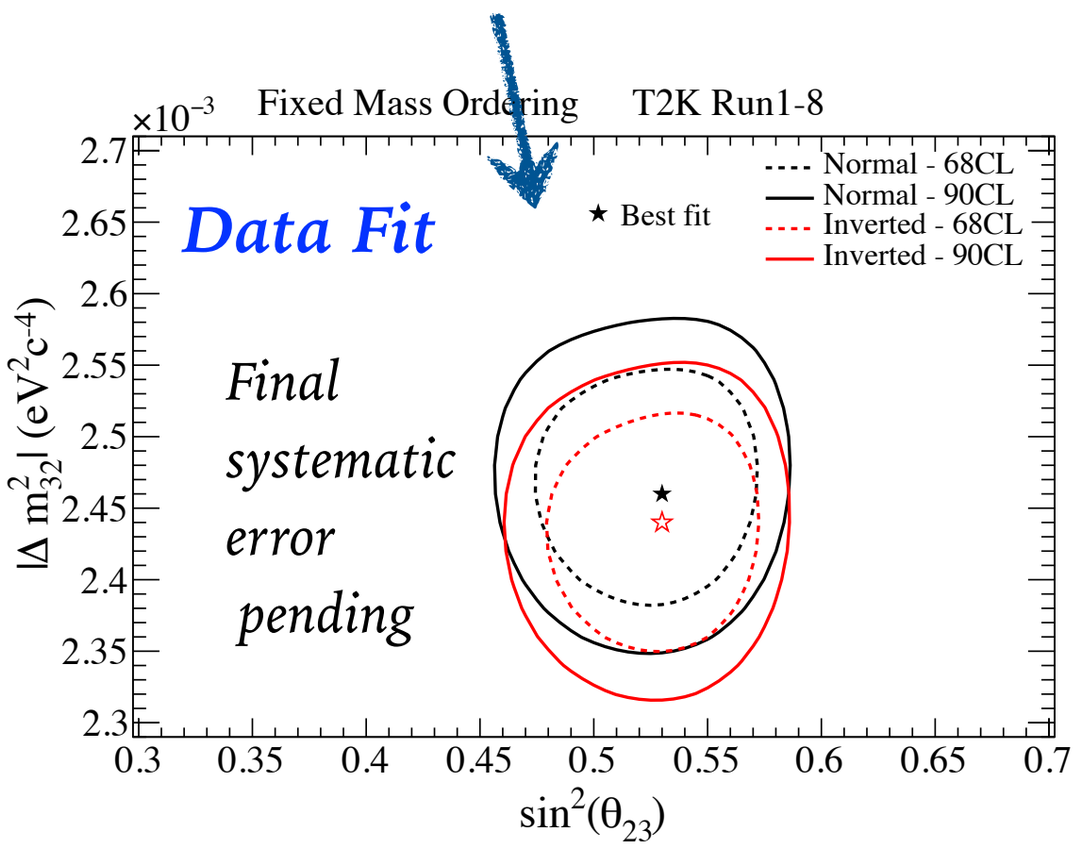
CONFIDENCE INTERVALS

$\sin^2\theta_{13}$—δ_{CP}

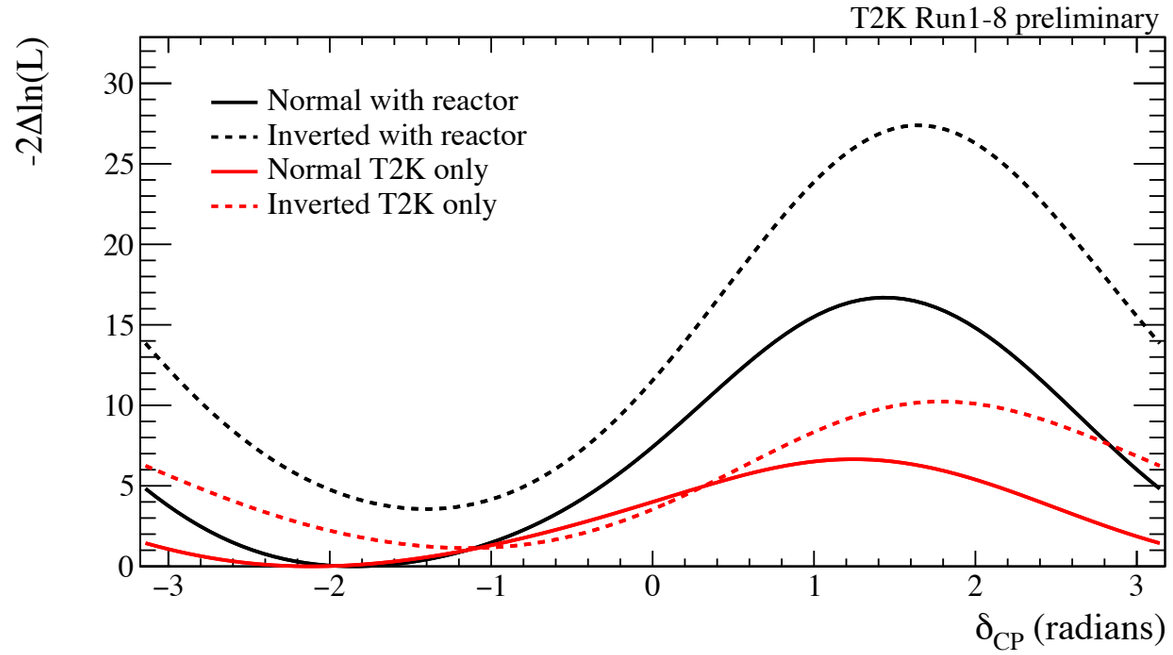
$\sin^2\theta_{23}$—Δm^2_{32}
(with reactor constraint)

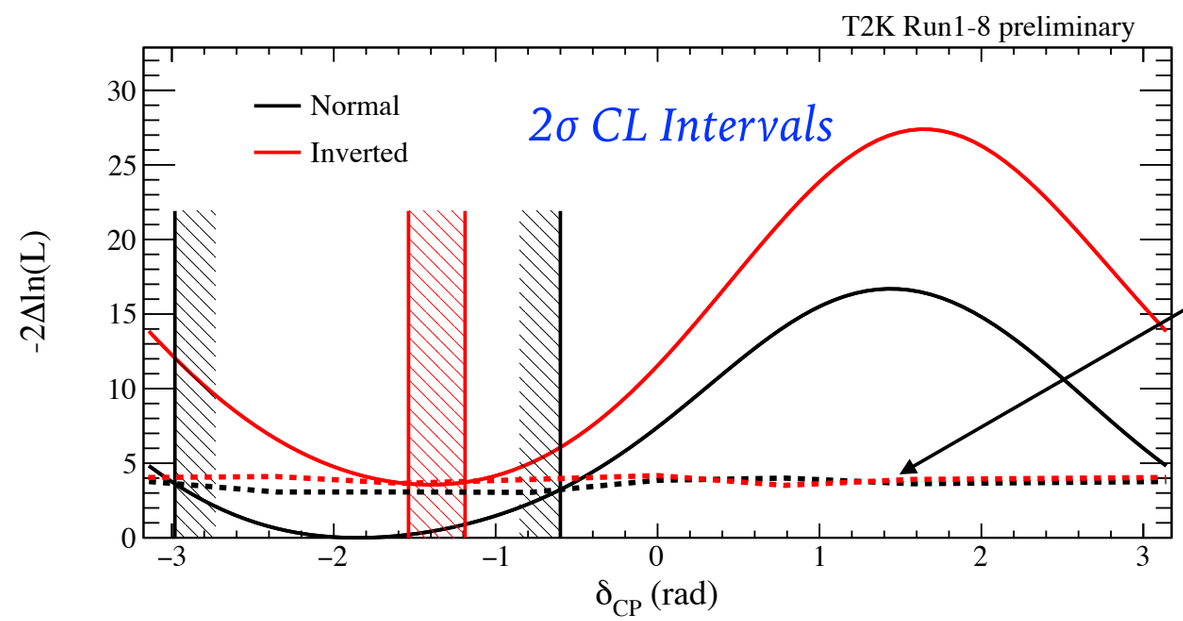






CONFIDENCE INTERVALS

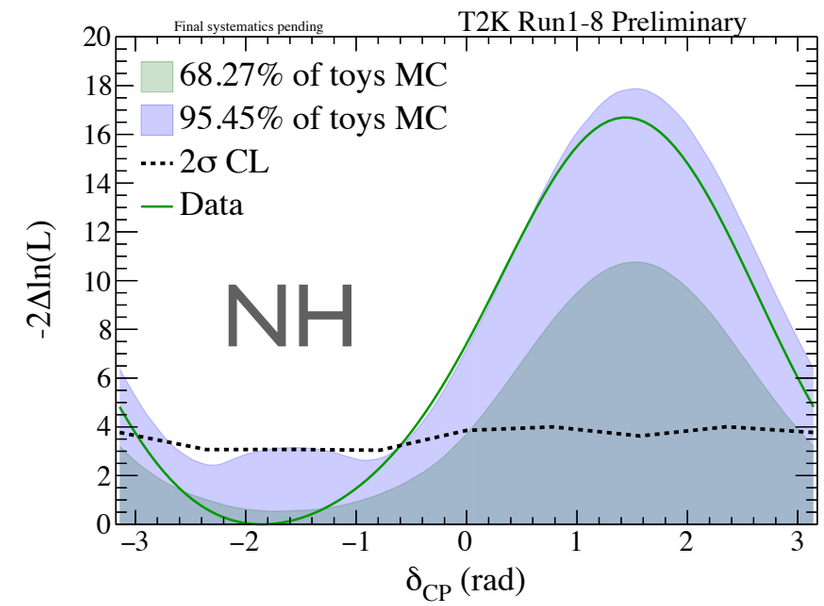


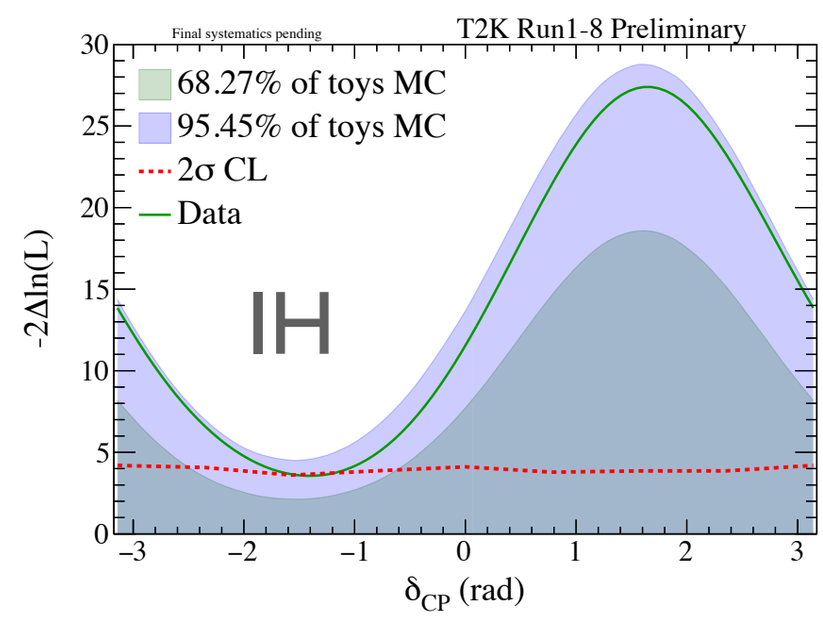


critical $\Delta\chi^2$ values for 2σ confidence level

MEASURED CONSTRAINT COMPARED TO SENSITIVITY (FREQUENTIST)

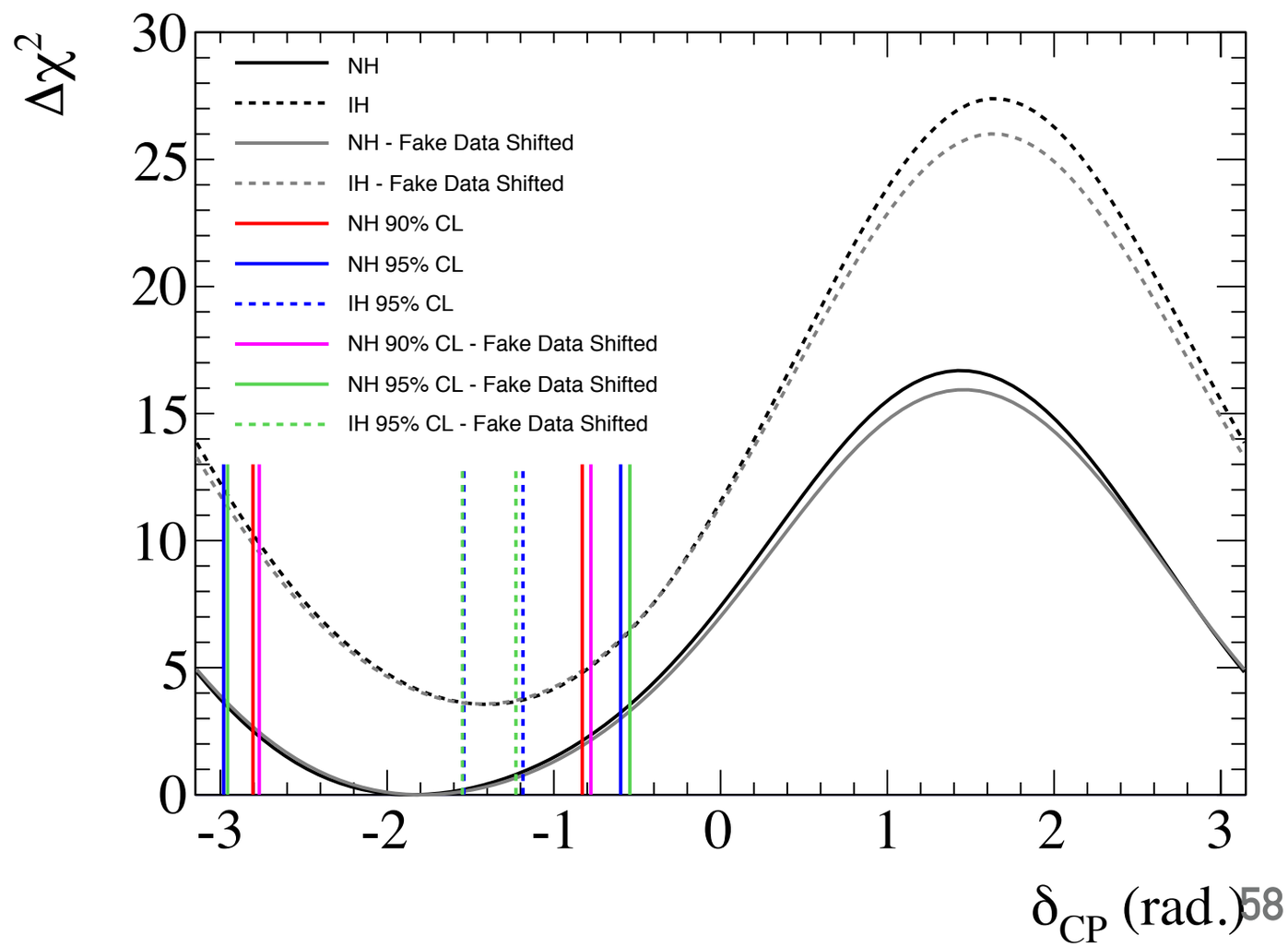
- Data constraint on δ_{CP} is stronger than sensitivity. Is that reasonable?
- Run many toy experiments with statistical and systematic fluctuations
- Input δ_{CP}=-π/2, normal hierarchy
- Data constraint falls within range for 95.45% of experiments for most δ_{CP} points
- 30% of experiments exclude δ_{CP}=0 at 2σ
- 25% of experiments exclude δ_{CP}=π at 2σ



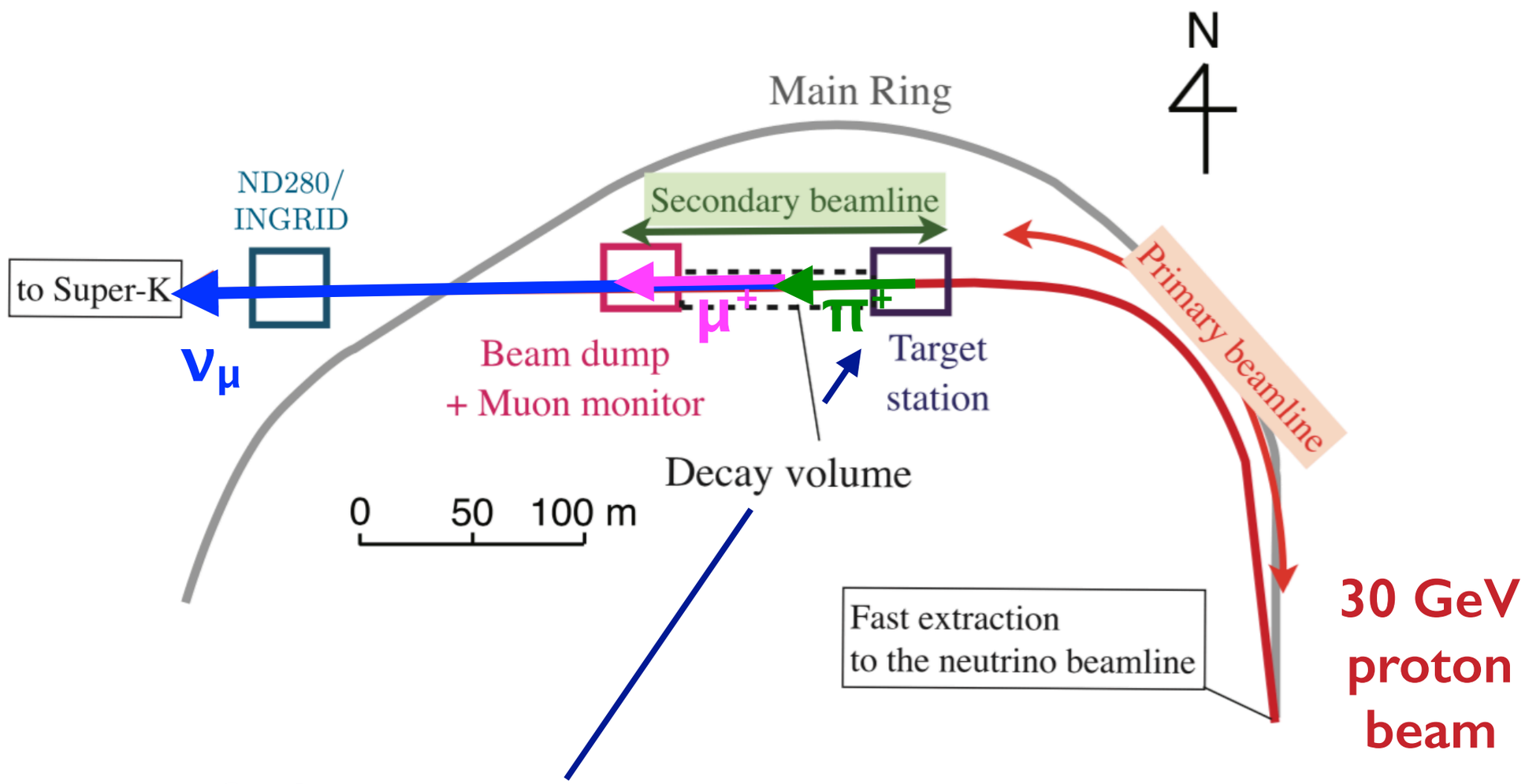


ROBUSTNESS OF RESULTS: CP PHASE

- Figure shows change in 90% and 95% confidence intervals comparing the default T2K input model and the ND280 data-driven variation (2p2h Δ-enhanced)
- No significant change in confidence intervals

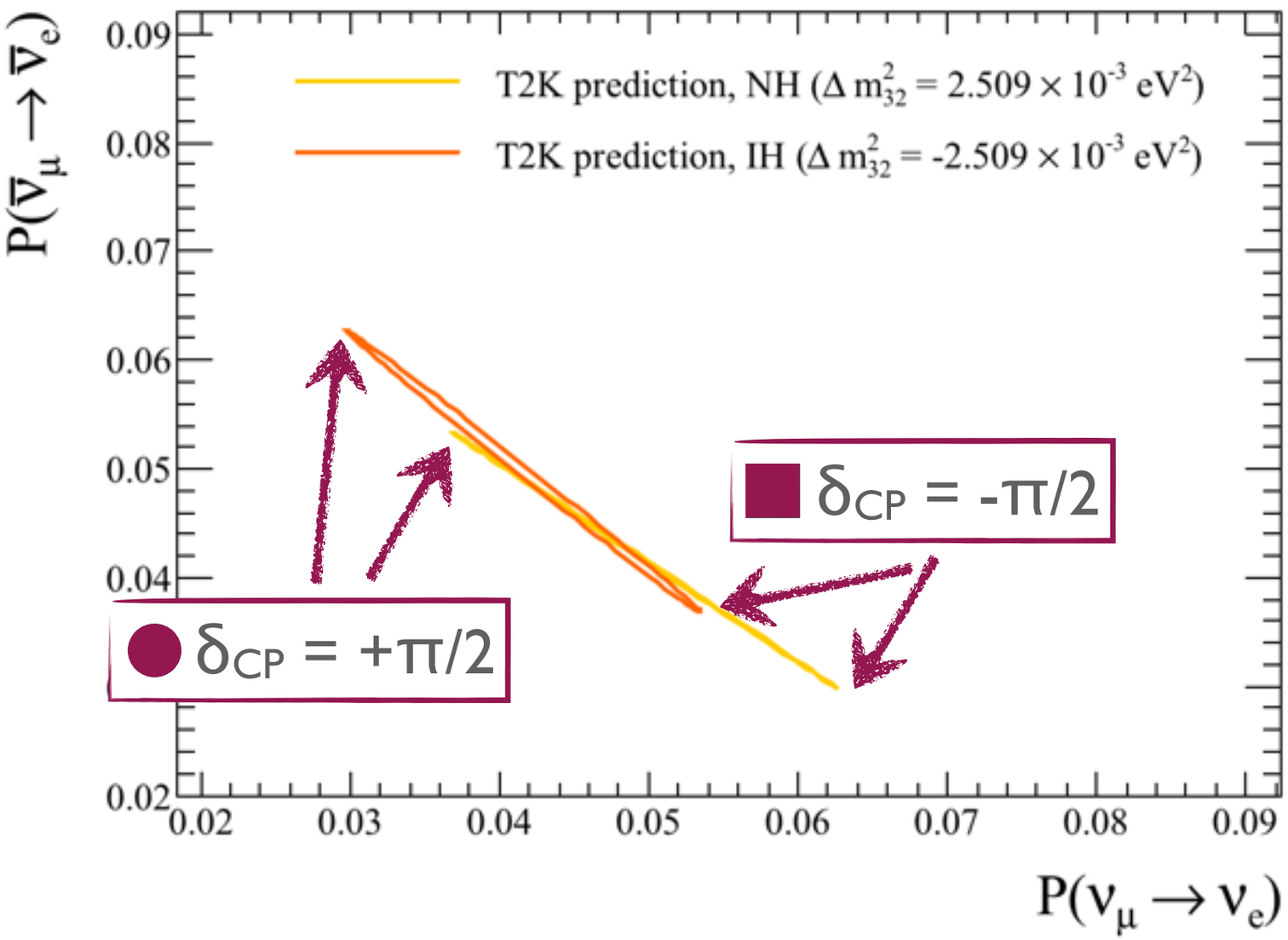


J-PARC NEUTRINO BEAM LINE



Pions are focused by 3 electromagnetic horns
Target installed in 1st horn

APPEARANCE: WHAT DO THE OSCILLATION PARAMETERS DO?



Predicted oscillation probabilities at T2K, assuming:

$\sin^2\theta_{23} = 0.528$
$\sin^2\theta_{12} = 0.304$
$\sin^2\theta_{13} = 0.0217$
$\Delta m^2_{32} = \pm 2.509 \times 10^{-3}$ eV^2
$\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2
$E_\nu = 0.6$ GeV
L = 295 km
Earth density = 2.6 g/cm^3

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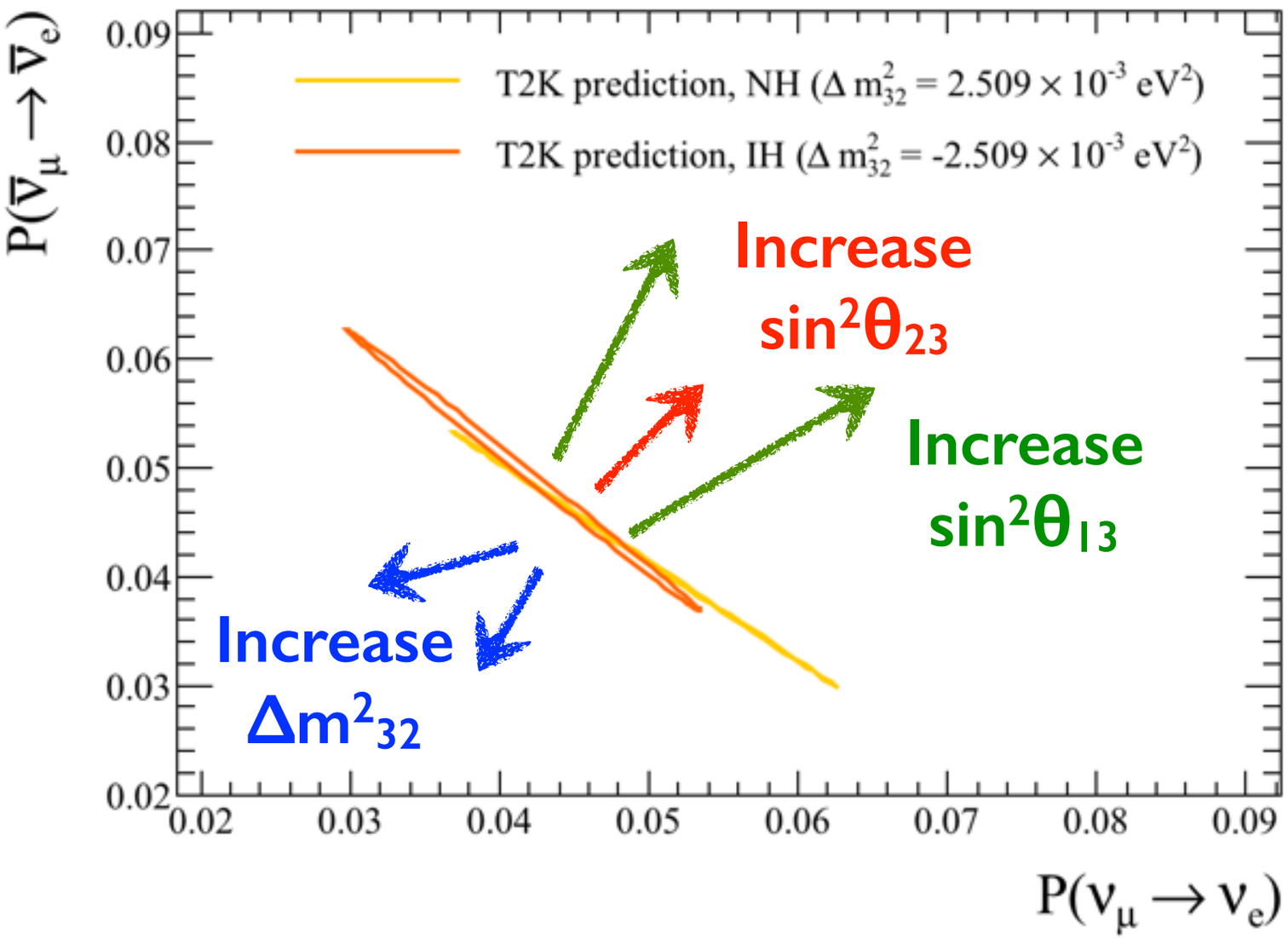

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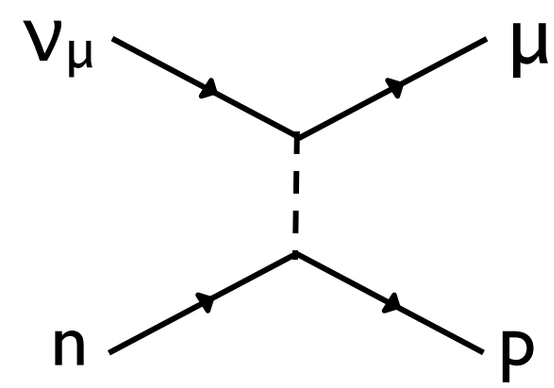
NEUTRINO INTERACTION MODEL

- Energy reconstruction at SK assumes all interactions that produce a single Cherenkov ring are CCQE

Quasi-elastic



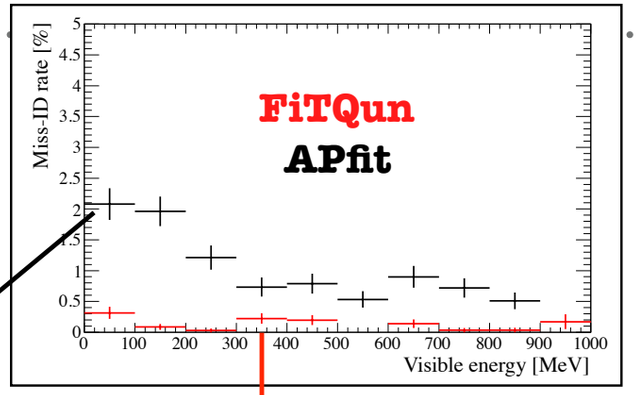
- Non-CCQE interactions: bias in reconstructed energy
  - **Major worry: interactions that mimic CCQE**
    - Neutrino scatters on a correlated pair of nucleons (2p-2h)
    - Neutrino scatter produces a pion, which is re-absorbed in the nucleus
    - Neutrino scatter produces a pion, which is absorbed in the detector

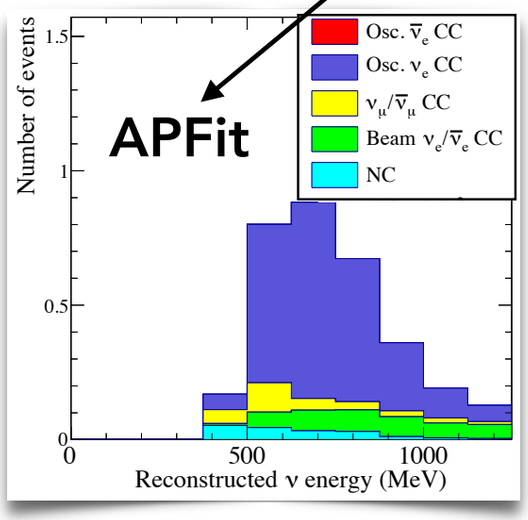
NEW SK RECONSTRUCTION ALGORITHM: FITQUN

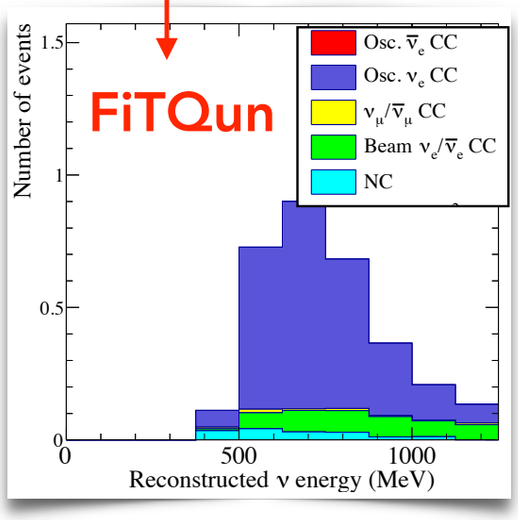
- Previous T2K analyses used reconstruction algorithm **APFit**
- This year, the event reconstruction at SK has been updated to use a new algorithm: **fiTQun**
  - **fiTQun** uses a charge and time likelihood for a given ring(s) hypothesis
  - Maximises likelihood for each event
  - Complete charge and time information in the likelihood leads to improved event reconstruction

ADVANTAGES OF FITQUN

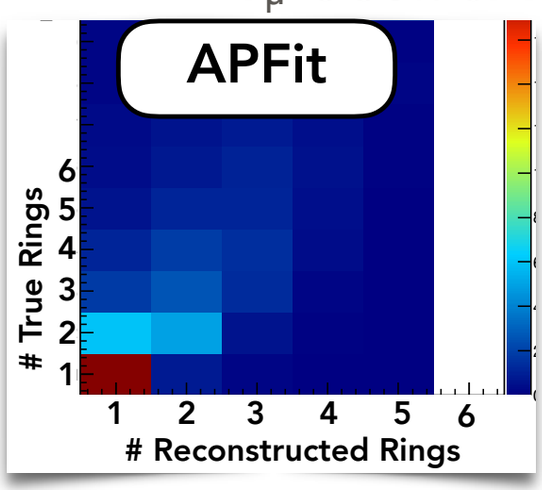
Improved particle ID reduces μ^- contamination of 1-ring CCπ^+ sample

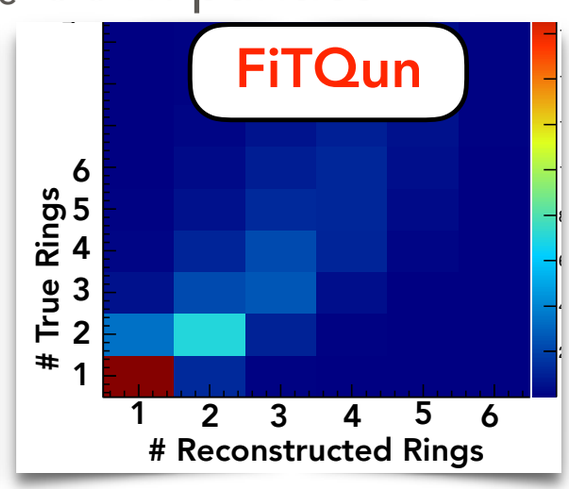




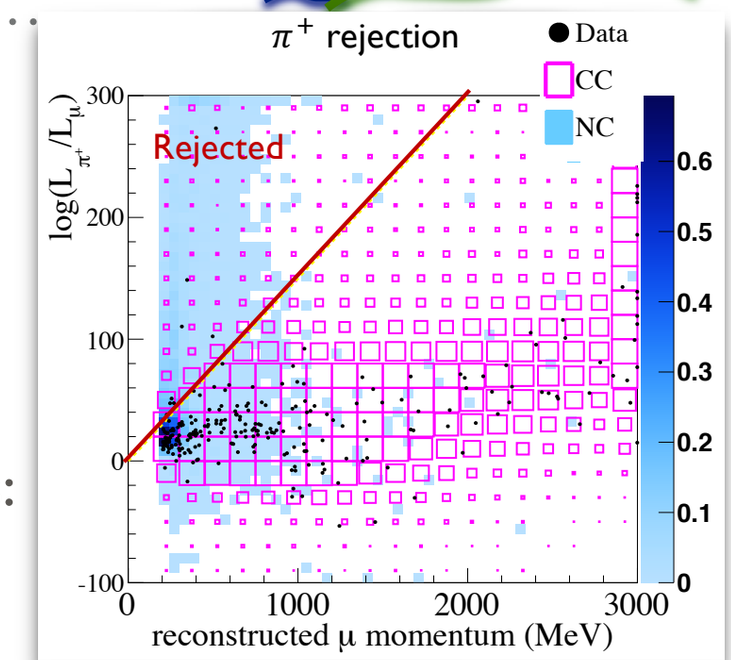


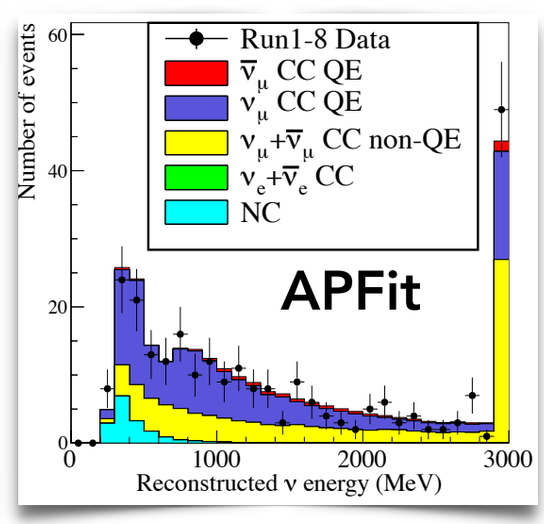
Improved ring counting increases ν_μ-CC0π & ν_e-CC1π purities

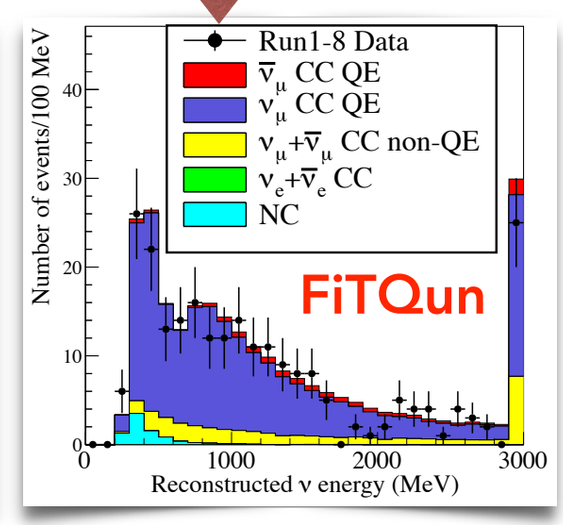




Unlike APFit, FiTQun can distinguish muons from charged pions:







Note: FiTQun π^0 rejection has been applied to "APFit" results since 2013

IMPROVEMENTS FROM APFIT TO FITQUN

MC Prediction	fiTQun Selection		APFit Selection	
Sample	Candidates	Purity	Candidates	Purity
ν mode $1R_\mu$	261.6	79.7%	268.7	68.1%
ν mode $1R_e$	69.5	81.2%	56.5	81.4%
ν mode $1R_e1\pi$	6.9	78.8%	5.6	72.0%
$\bar{\nu}$ mode $1R_\mu$	62.0	79.7%	65.4	70.5%
$\bar{\nu}$ mode $1R_e$	7.6	79.7%	6.1	63.7%

- $1R_\mu$ (CCQE): improvement in efficiency and purity
  - Reduction of NCπ and CCπ backgrounds

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- $1R_\mu$ (CCQE): improvement in efficiency and purity
  - Reduction of NCπ and CCπ backgrounds
- $1R_e$ (CCQE): efficiency increases (due to new fiducial volume)
- $1R_e1\pi$ (CC1π): improvement in efficiency and purity
  - Reduced contamination from muon rings (improved PID)