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Oscillation results and plans from the T2K experiment

Patrick Dunne for the T2K Collaboration

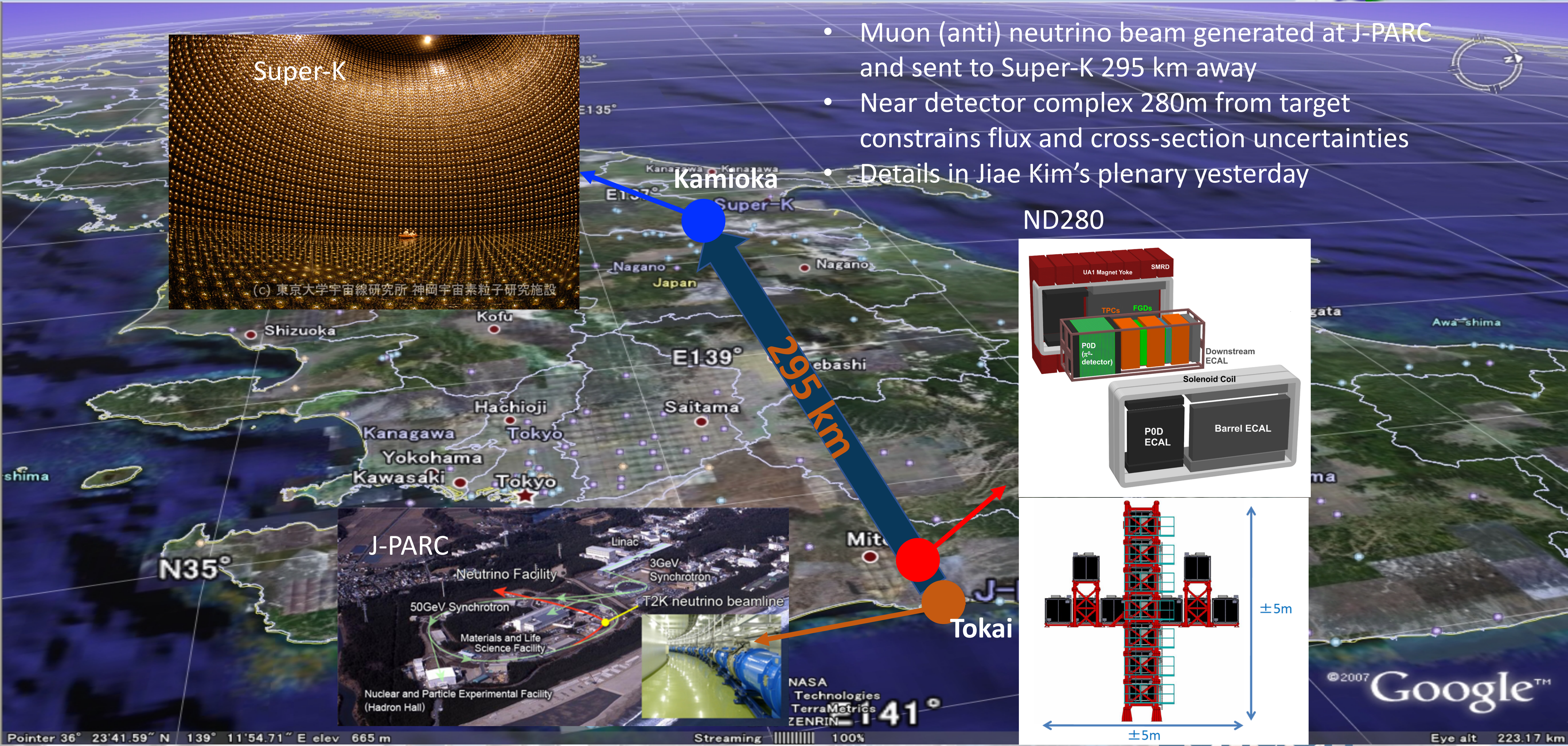
NUFACT 2017

Outline

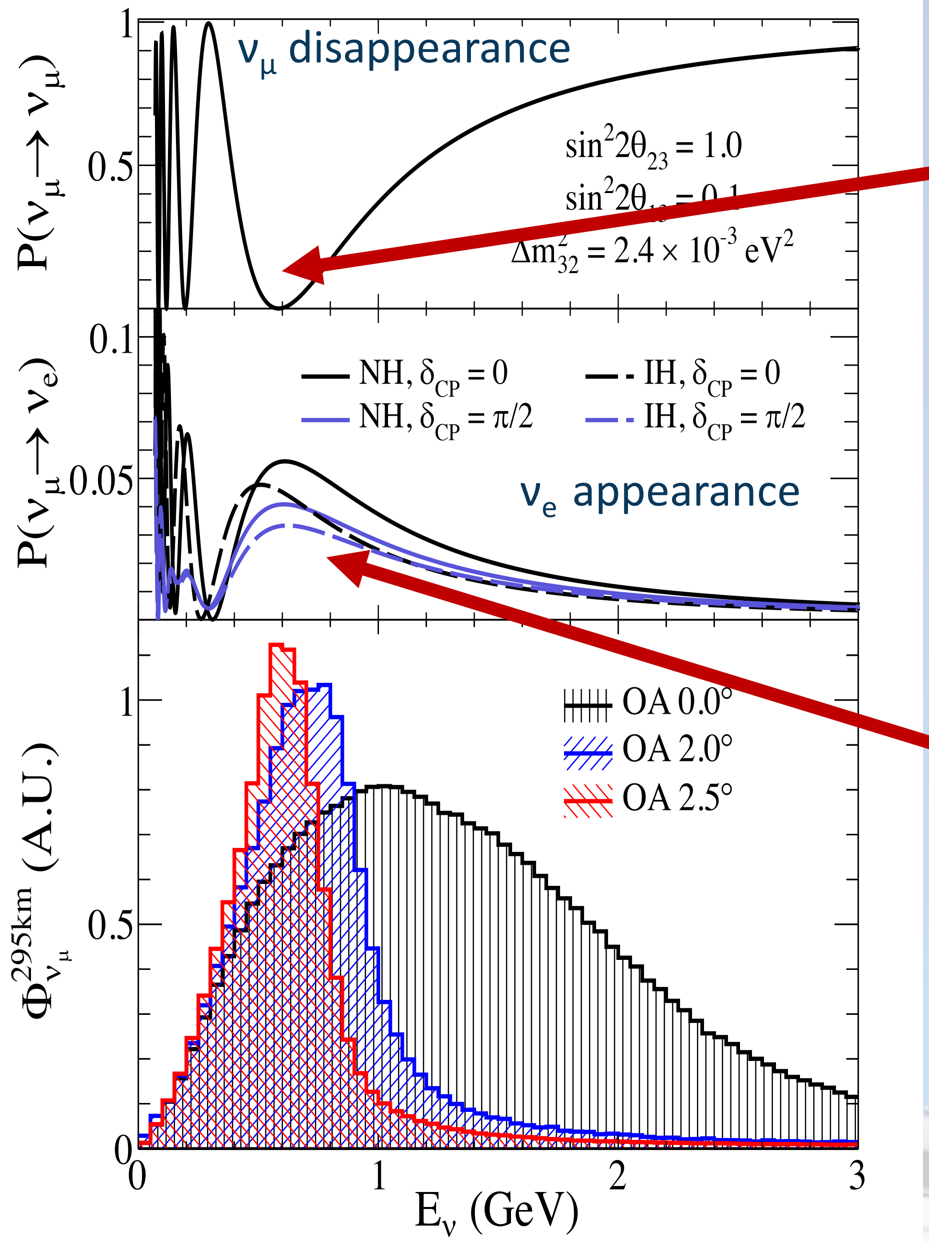
- The T2K Experiment
- Structure of T2K oscillation analysis
- New results from data to date
- Future prospects

The T2K Experiment

- Muon (anti) neutrino beam generated at J-PARC and sent to Super-K 295 km away
- Near detector complex 280m from target constrains flux and cross-section uncertainties
- Details in Jiae Kim's plenary yesterday

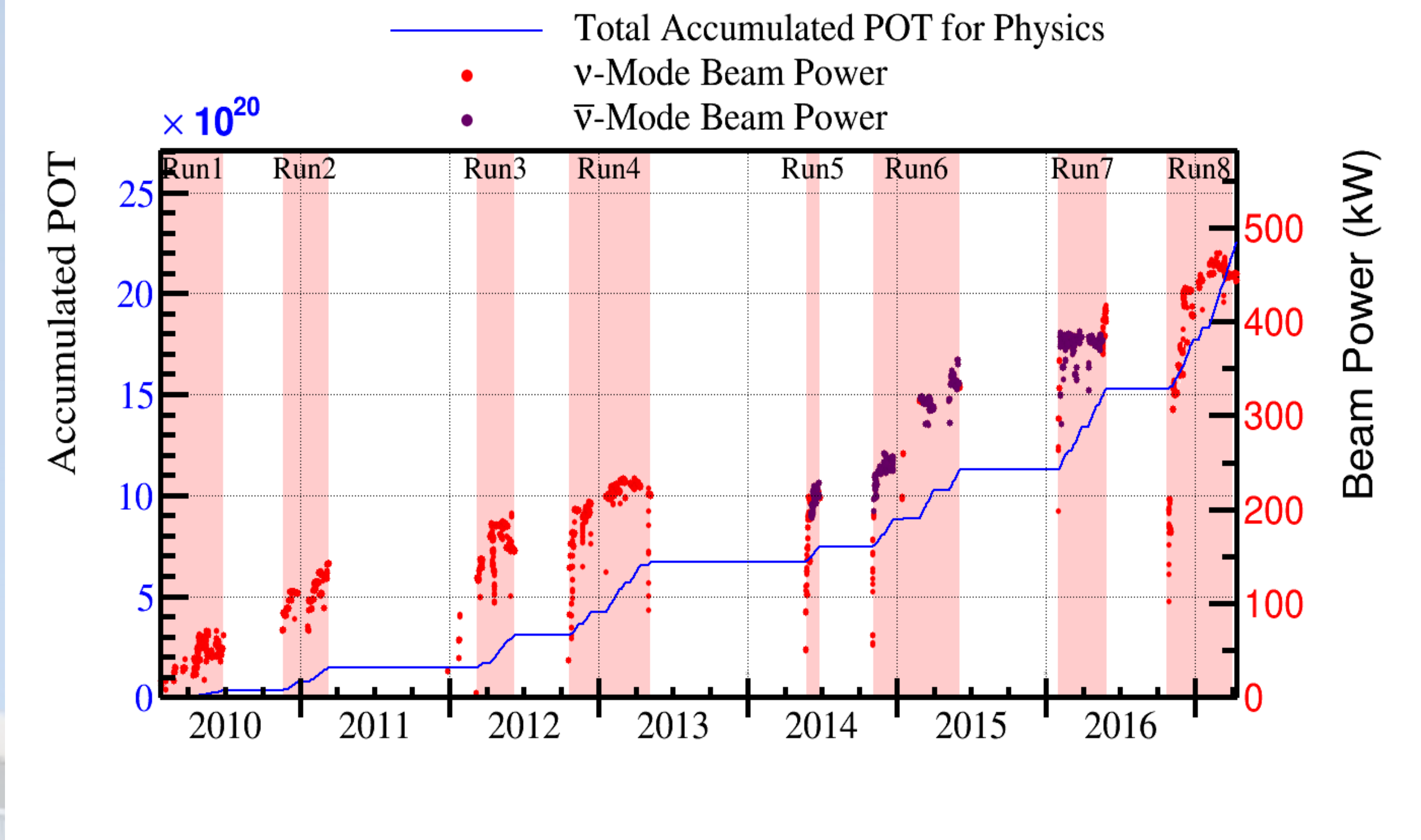


Neutrino oscillations at T2K



- Muon (anti)neutrino disappearance
  - Location of dip determined by Δm^2_{23}
  - Depth of dip determined by $\sin^2(2\theta_{23})$
- Electron (anti)neutrino appearance
  - Leading term depends on $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$ and Δm^2_{23}
  - Sub-leading dependance on δ_{CP}
    - $\delta_{CP} = \pi/2$: fewer neutrinos, more anti-neutrinos
    - $\delta_{CP} = -\pi/2$: more neutrinos, fewer anti-neutrinos
  - Matter effects give dependence on mass hierarchy

Beam operation

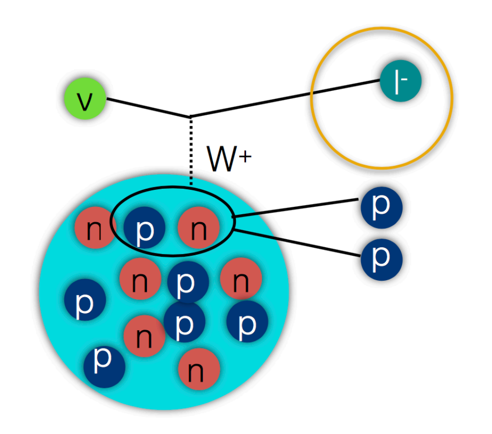


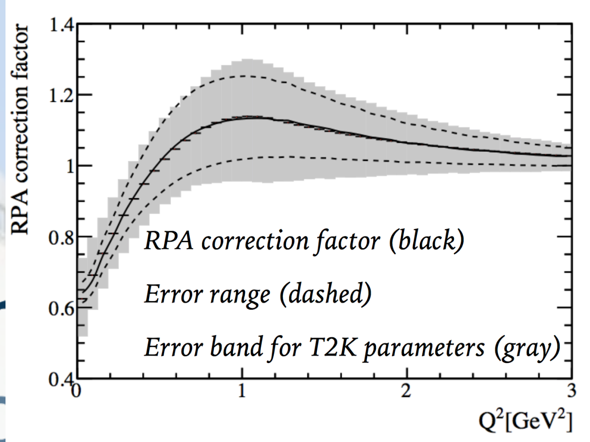
- Accumulated 14.7×10^{20} protons-on-target (POT) in neutrino mode and 7.6×10^{20} POT in antineutrino mode
  - 29% of approved T2K-I POT
- Previous results used 7.5×10^{20} POT ν-mode, 7.5×10^{20} POT $\bar{\nu}$-mode
  - Phys. Rev. Lett. 118 (2017) no. 15, 151801
- Operated at stable beam power of 470 kW this year
  - Enabled doubling ν-mode data

Changes for this year

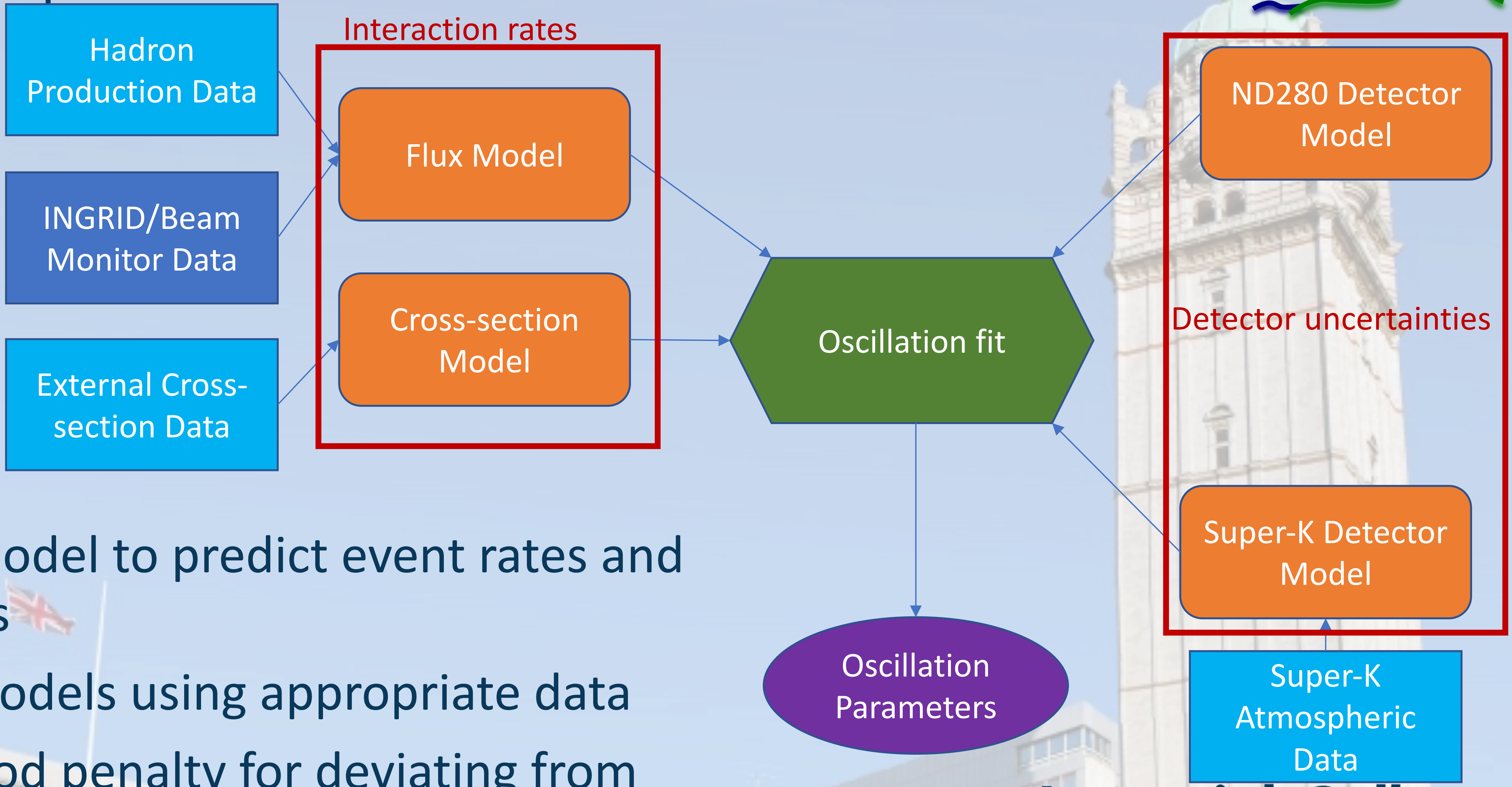
- New fiTQun SK reconstruction algorithm has been used
  - Allows ~20% increase in fiducial volume (FV)
- This year we added a sample targeting CC1pi interactions
  - Require one electron ring and an additional decay electron
  - Last summer's analysis used 4 samples all targeting CCQE
- Cross-section model updated
  - Improved uncertainties to multi-nucleon interactions (2p2h) and long range nucleon correlations (RPA)
  - Details in Keigo Nakamura's talk yesterday

$$\nu_e + N \to e^- + \pi^+ + X$$
$$\downarrow$$
$$\mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_\mu$$



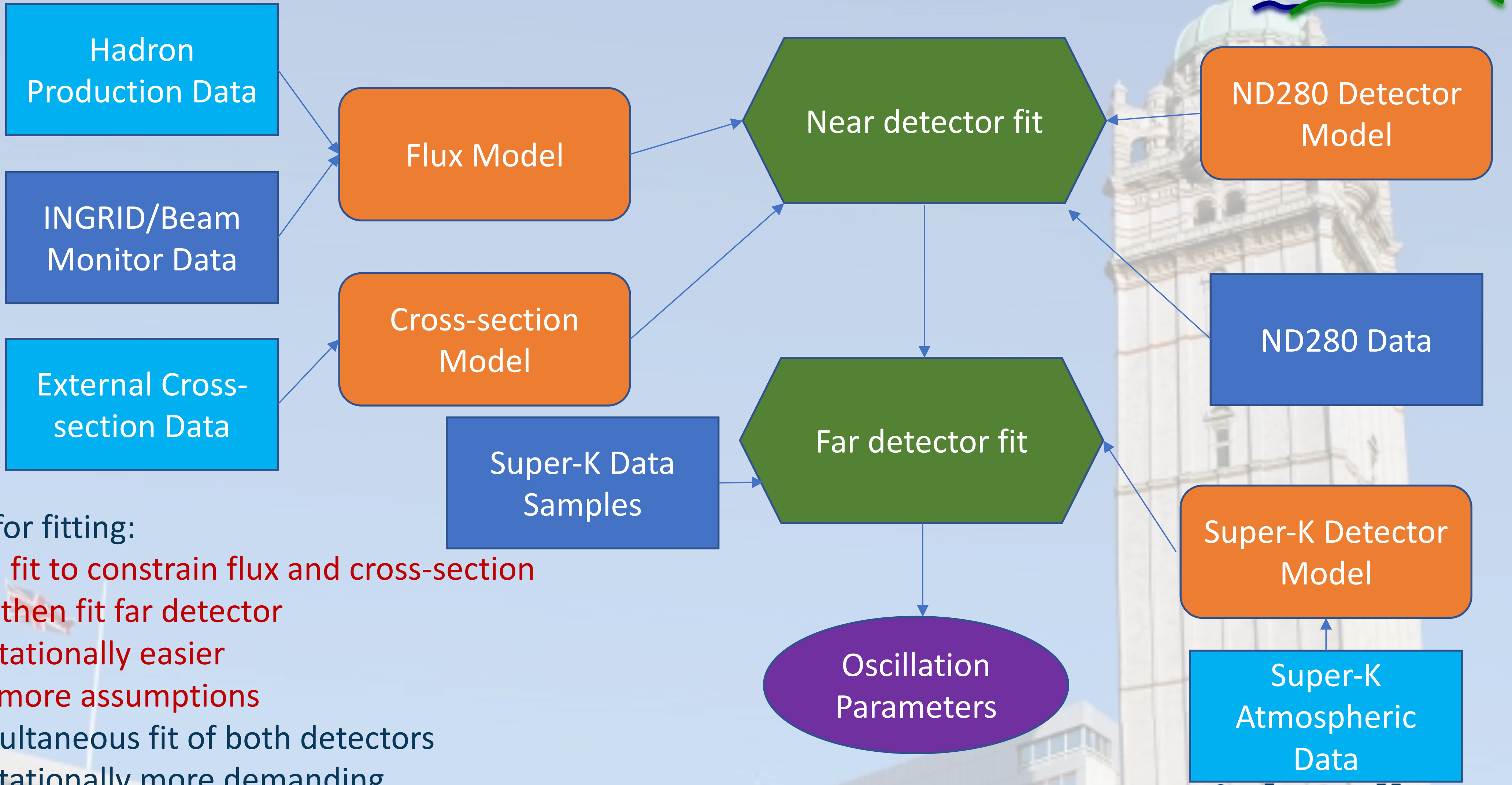


Event rate prediction framework



- Construct model to predict event rates and distributions
- Constrain models using appropriate data
- Add likelihood penalty for deviating from these constraints to fit

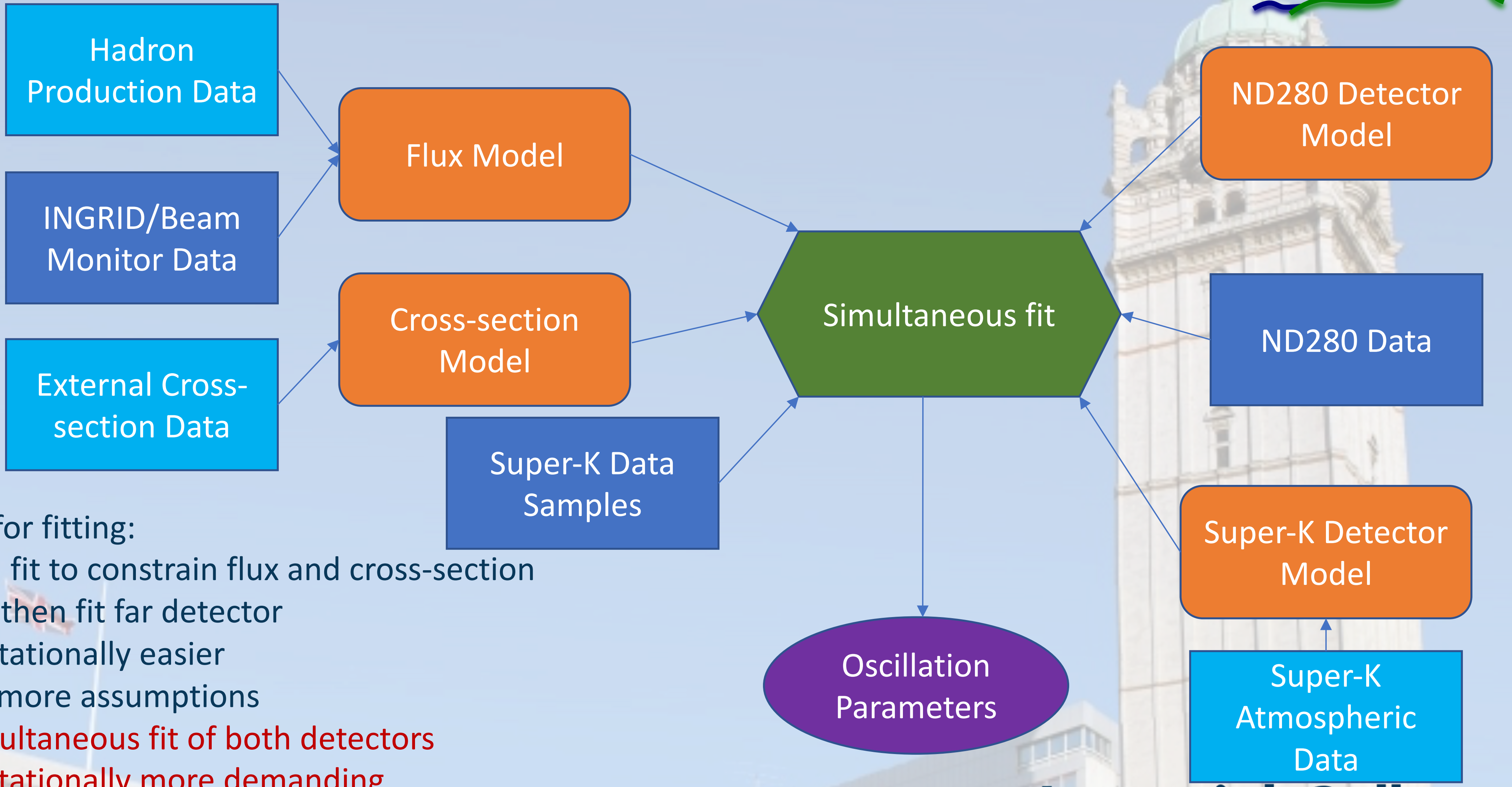
Fitting to data



Two approaches used for fitting:

1. Use ND data fit to constrain flux and cross-section models first then fit far detector
   - Computationally easier
   - Makes more assumptions
2. Perform simultaneous fit of both detectors
   - Computationally more demanding
   - Makes fewer assumptions

Fitting to data



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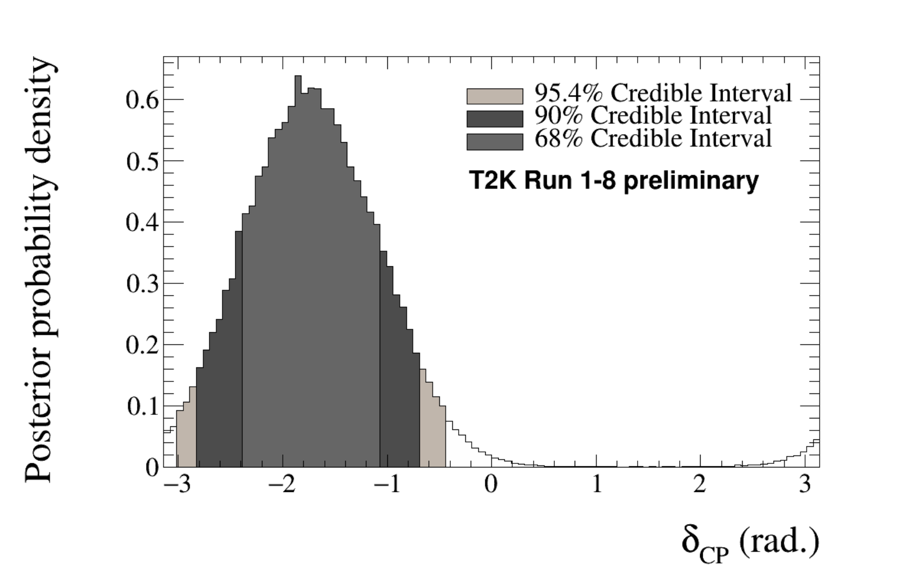
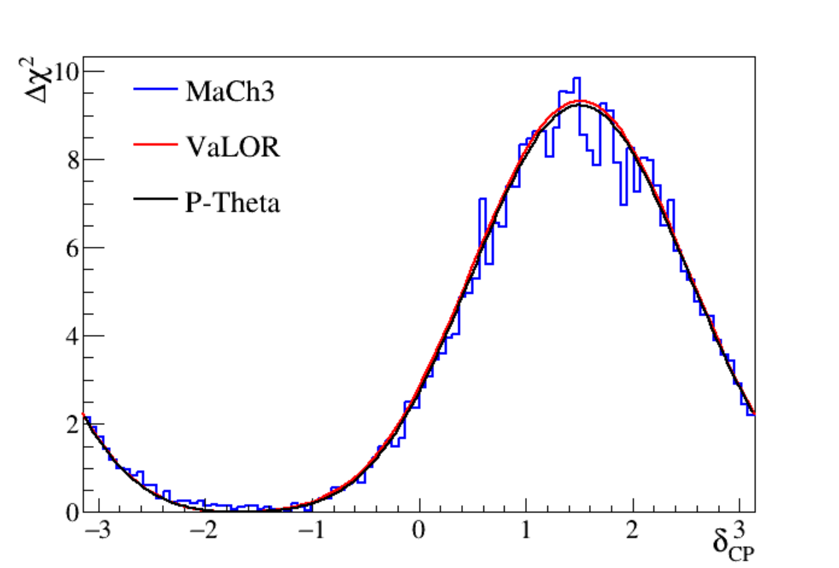
T2K analyses: Bayesian vs Frequentist

- T2K has three separate analysis frameworks: two frequentist, one Bayesian
- Bayesian analysis does joint near/far detector fit, frequentist analyses fit near detector first and propagate
- All three able to construct frequentist confidence intervals for comparisons
  - Very good agreement is seen





Bayesian analysis shows posterior probability density	Frequentist analyses show $\Delta\chi^2$
(high values mean more likely this is the "correct" parameter value)	(low values mean better agreement with the data for this parameter value)

Predicted and observed Super-K event rates

Sample	Predicted Rates				Observed Rates
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	
CCQE 1-Ring e-like ν-mode	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like ν-mode	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like $\bar{\nu}$-mode	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like ν-mode	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like $\bar{\nu}$-mode	63.1	62.9	63.1	63.1	68

- Other oscillation parameters at previous best fits: maximal θ_{23}
- Number of events observed generally agrees with oscillated predictions
  - e-like sample rates are most consistent with $\delta_{CP} = -\pi/2$ hypothesis
  - μ-like sample rates consistent within statistical and systematic errors
  - CC1π rate shows large upwards fluctuation
    - p-value for fluctuation of this size in at least 1 of 5 samples: 11.9%

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Size of systematic uncertainties

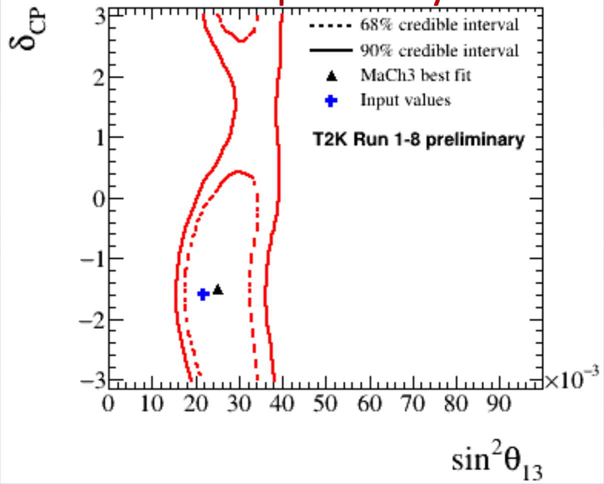
	% Errors on predicted event rates, Osc. Parameters as for rates					
	1R μ-like		1R e-like			
Error Source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	ν-mode/$\bar{\nu}$-mode
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.39
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic Error	4.40	3.76	6.10	6.51	20.94	4.77

- Total error in the 4-7% range (except CC1pi)
- Errors constrained by ND280 contribute 3-4% uncertainties
- Error on ν-mode /$\bar{\nu}$-mode ratio 4.8%
    - important for CP violation

Sensitivities

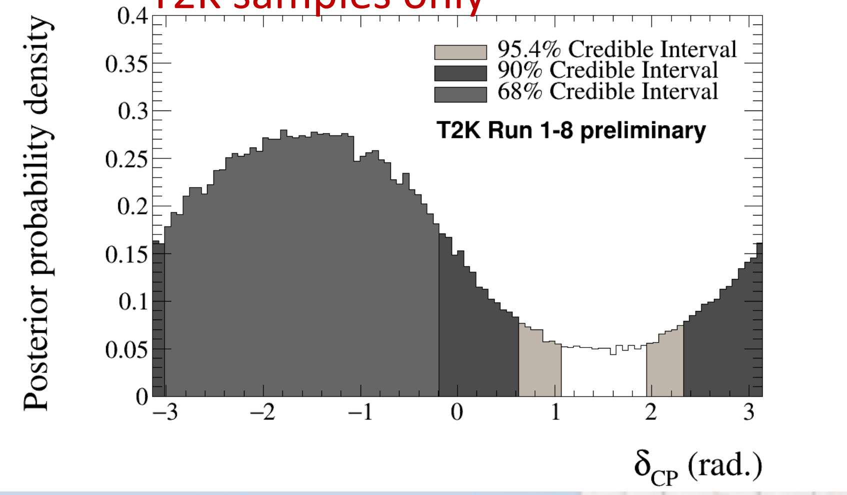
Set A sensitivity

T2K samples only



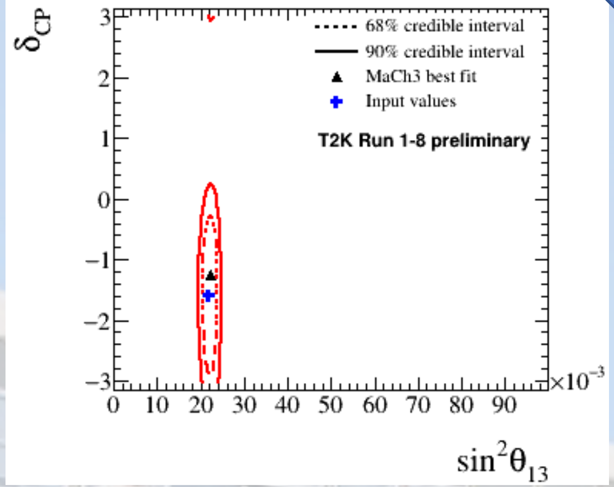
Integrate out $\sin^2\theta_{13}$ dependence

T2K samples only



Impose reactor constraint on $\sin^2(2\theta_{13})$ (PDG 2016)

T2K +reactor constraint



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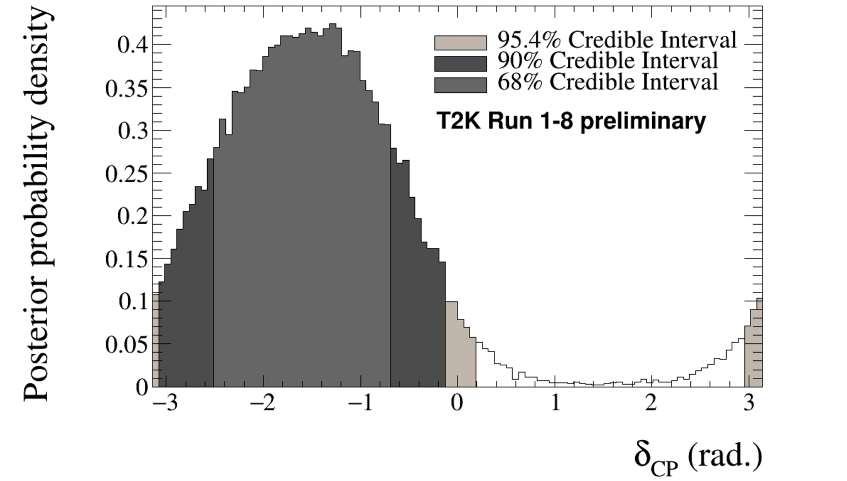
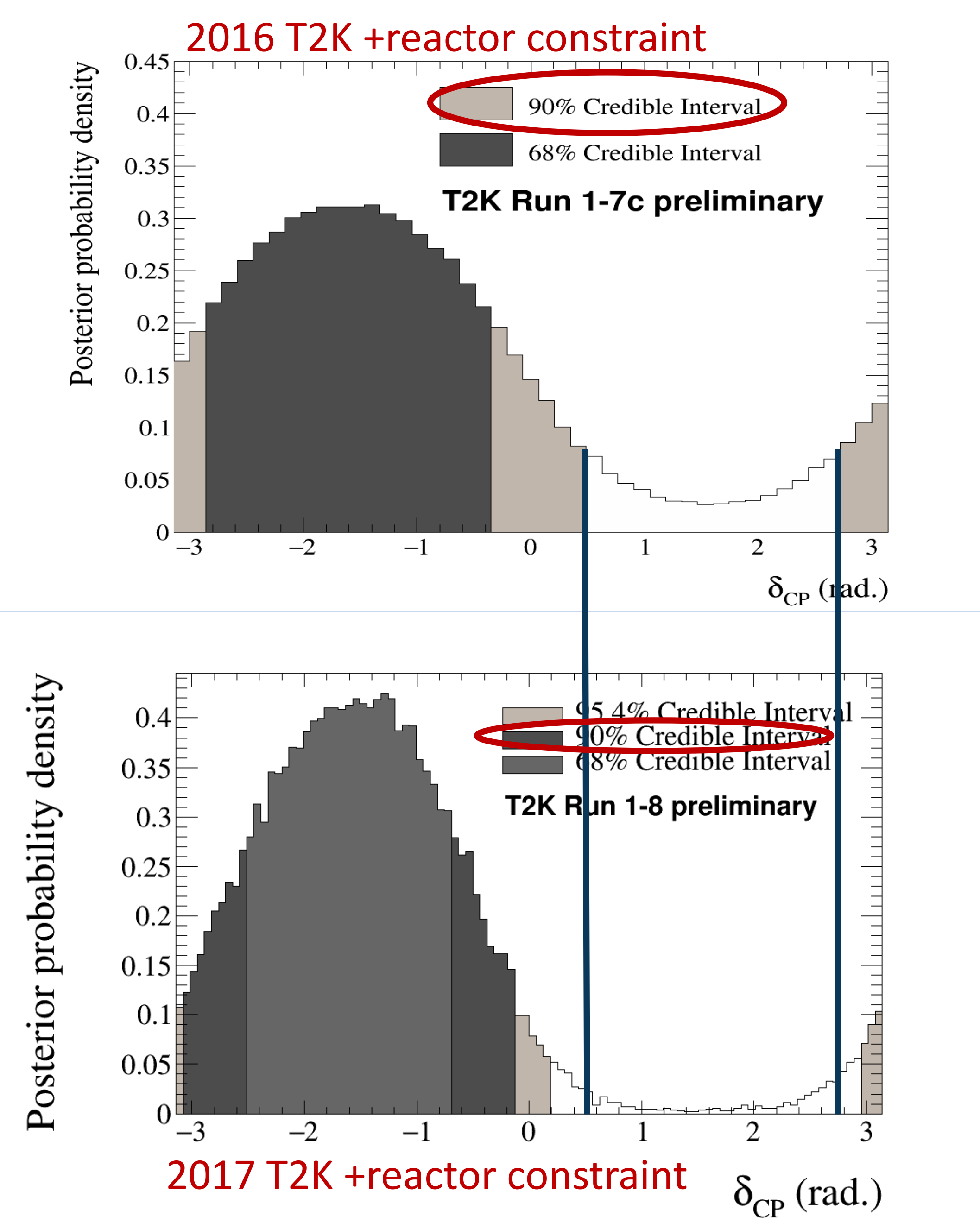
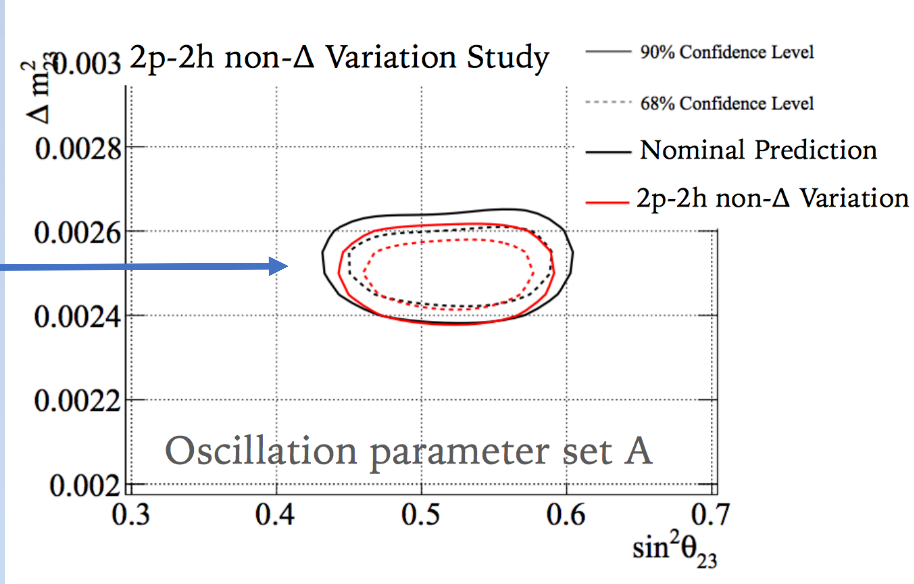


Comparison to Summer 2016 sensitivity



Fake data

- Check robustness of results to neutrino interaction model by using our model to fit ``fake data" generated with two methods
  1. `Data-driven': assign differences between current model and ND280 data to one interaction mode and refit
     - Effect seen on $\sin^2\theta_{23}$ and Δm^2_{23}
  2. Model choices: generate data using other models implemented in generator but not used in oscillation analysis and refit



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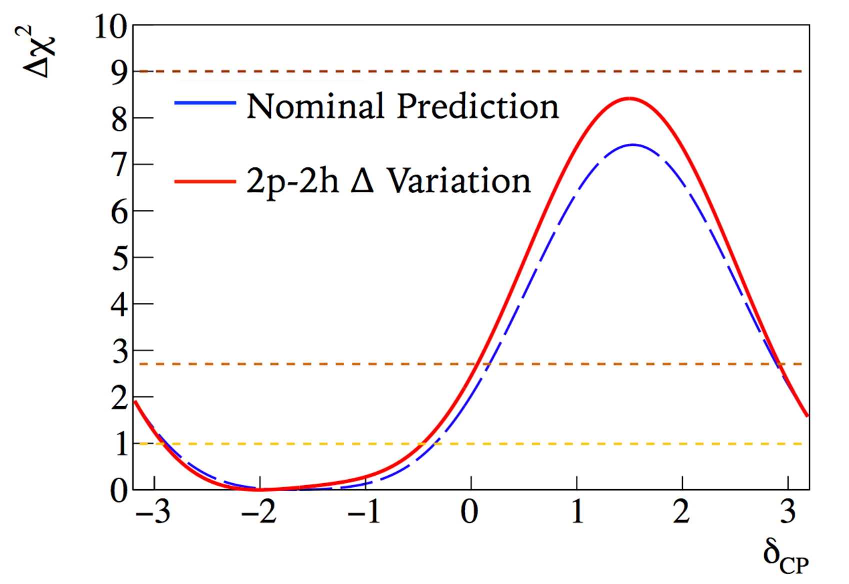
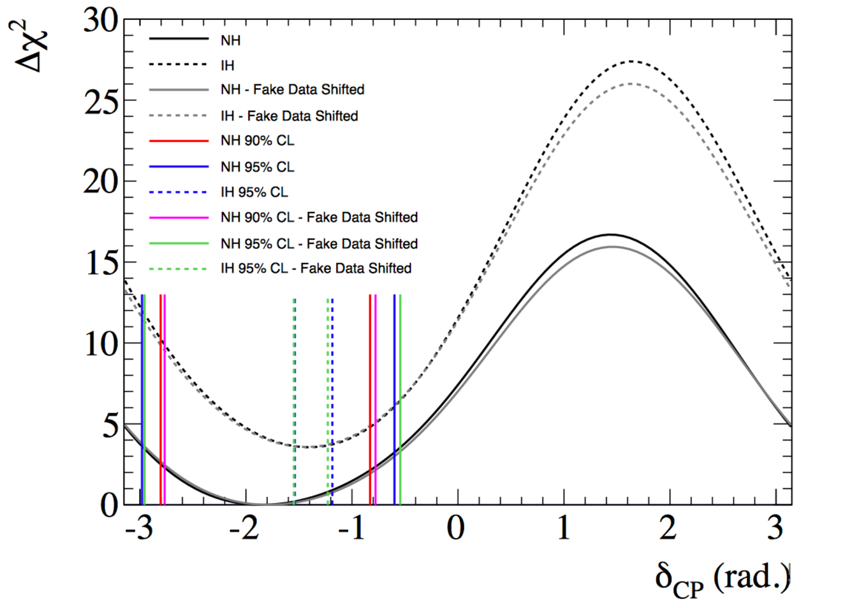
Impact on δ_{CP}

- Need to check how changes to $\Delta\chi^2$ from fake data studies affect statements on δ_{CP}
- Take $\Delta\chi^2$ difference observed in fake data study (top plot) and shift observed $\Delta\chi^2$ in data (bottom plot) by that amount
- Impact on δ_{CP} intervals is small
- $\sin^2\theta_{23}$ and Δm^2_{23} results presented with caveat that the systematic error model may be updated





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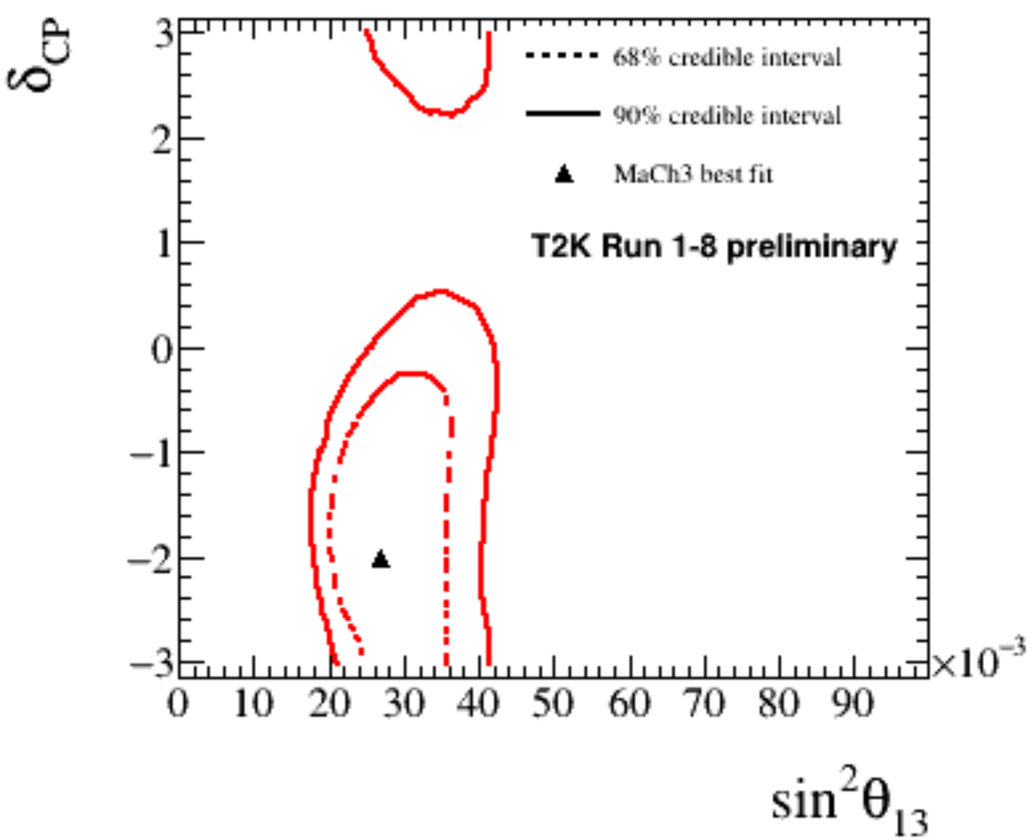
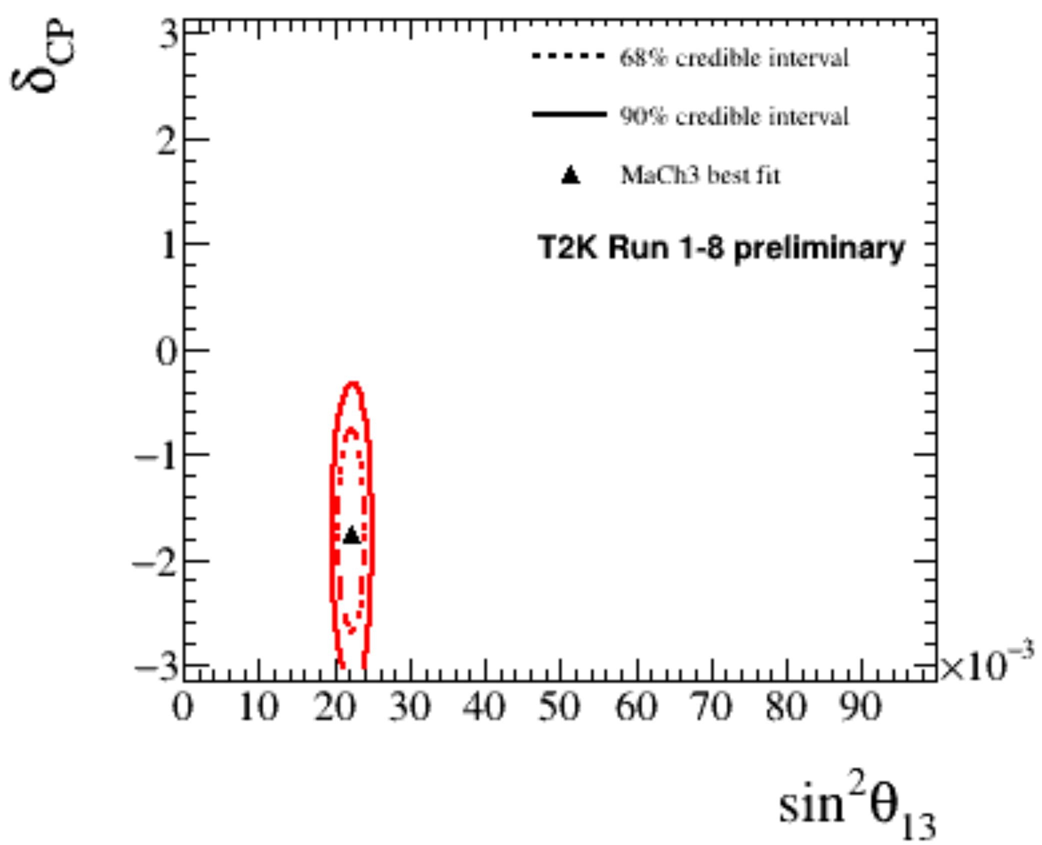
Data results

Appearance parameter constraints

T2K data only



T2K +reactor constraint



- T2K value for $\sin^2\theta_{13}$ is consistent with PDG 2016 average (0.0219)

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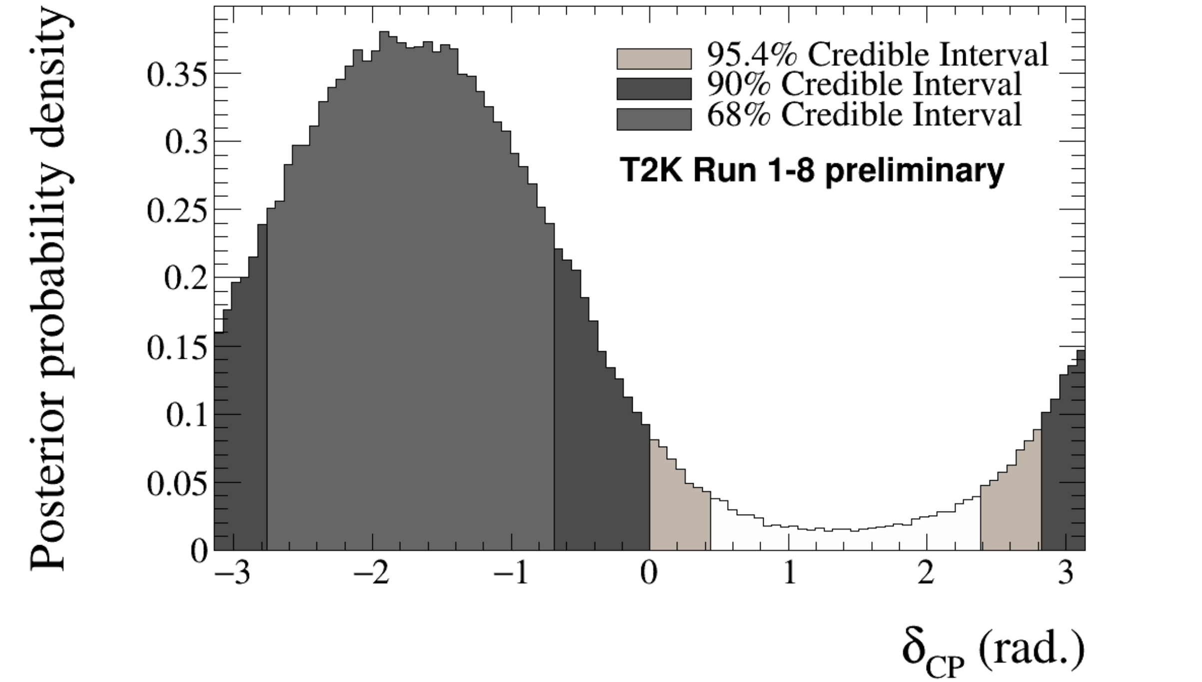
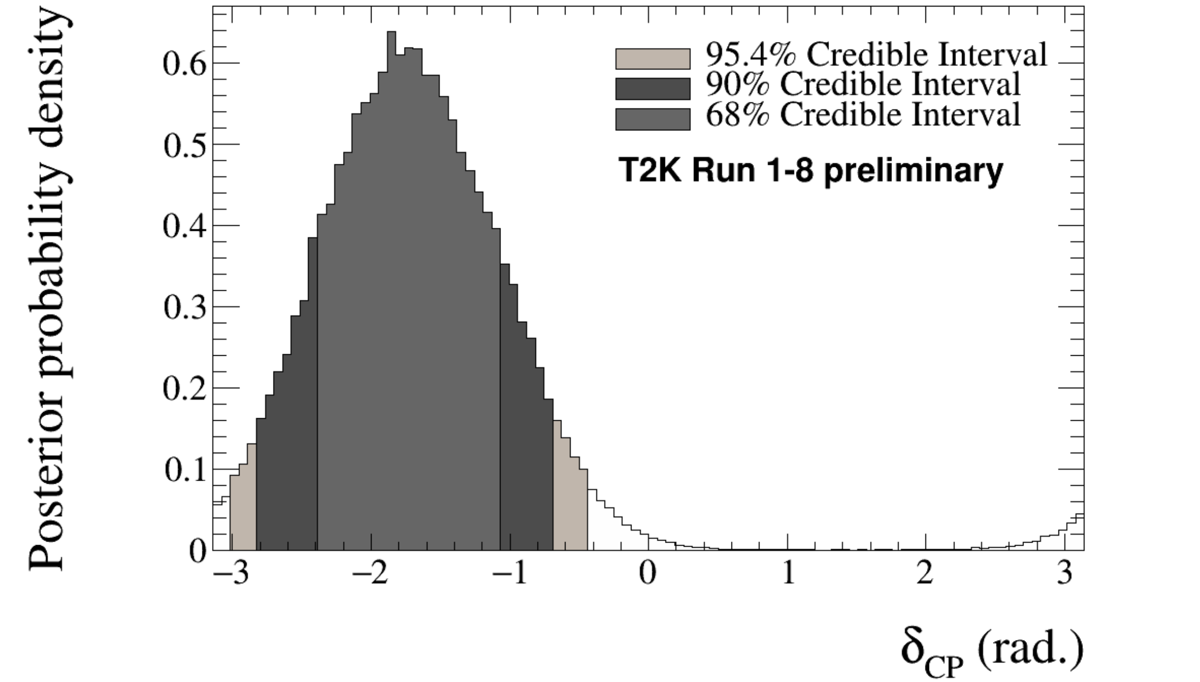
δ_{CP} Constraint

T2K data only

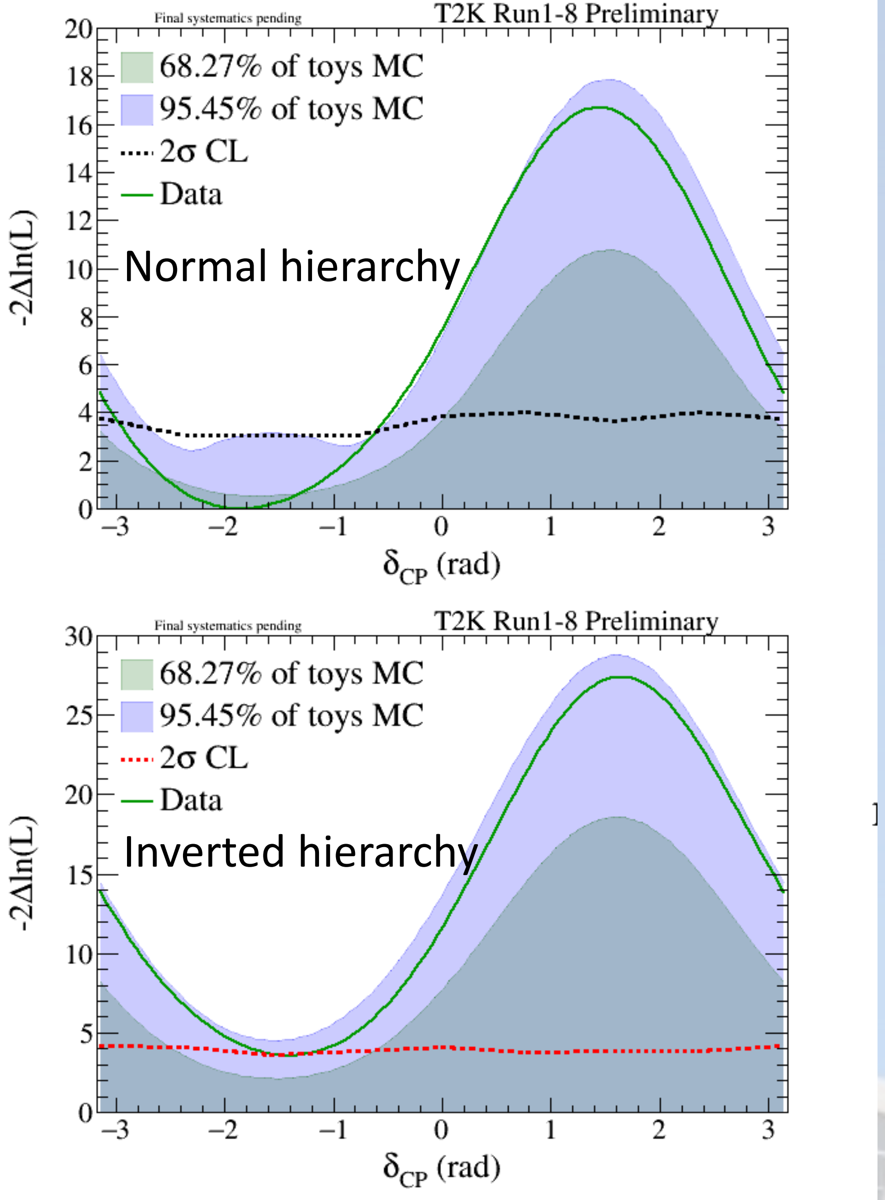


T2K +reactor constraint



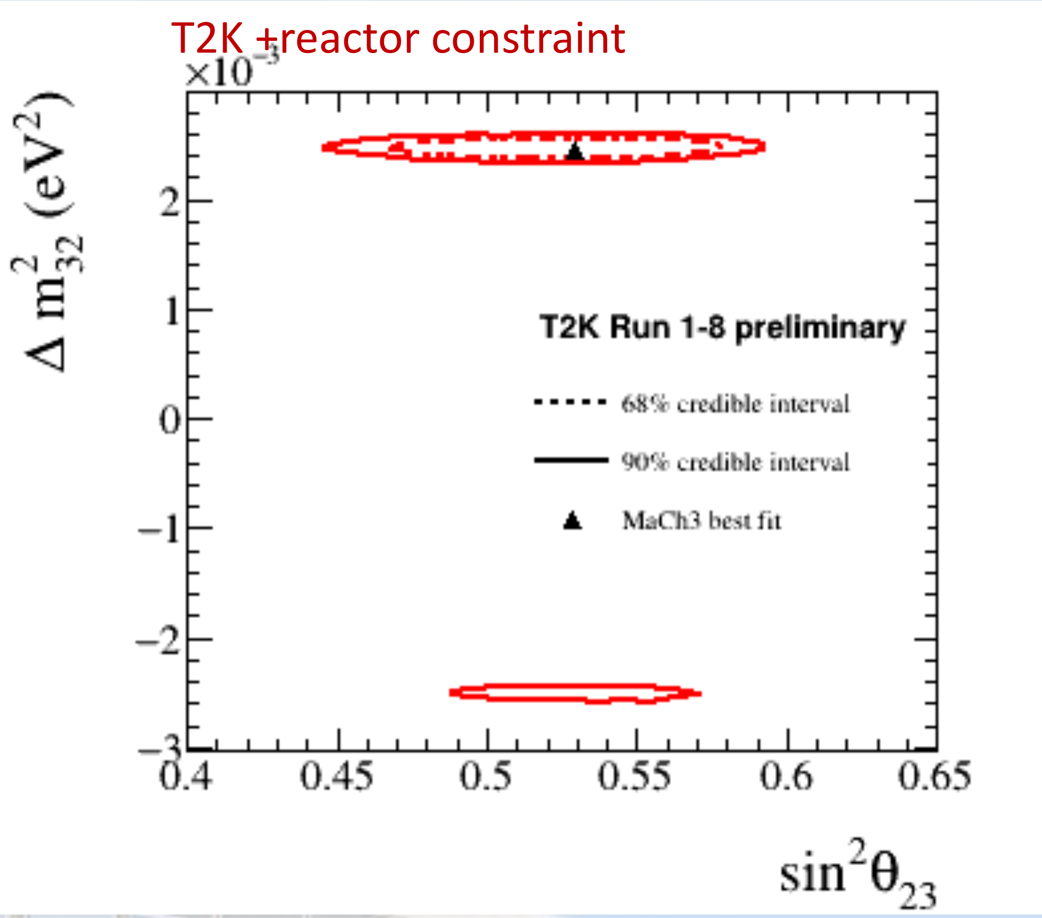
- CP conserving values outside 2σ (95.4%) interval for T2K+reactor constraint

Constraint vs sensitivity



- Observed constraint stronger than predicted sensitivity
- Studied how likely this was to happen
- Generated many toy data sets with statistical and systematic fluctuations around $\delta_{CP}=-\pi/2$, normal hierarchy (NH)
- Ran fits to these spectra to determine δ_{CP} constraint
- Observed constraint falls within 95.45% for most δ_{CP} points
- 30% of experiments exclude $\delta_{CP} = 0$ at 2σ
- 25% of experiments exclude $\delta_{CP} = \pi$ at 2σ

Octant and hierarchy preferences



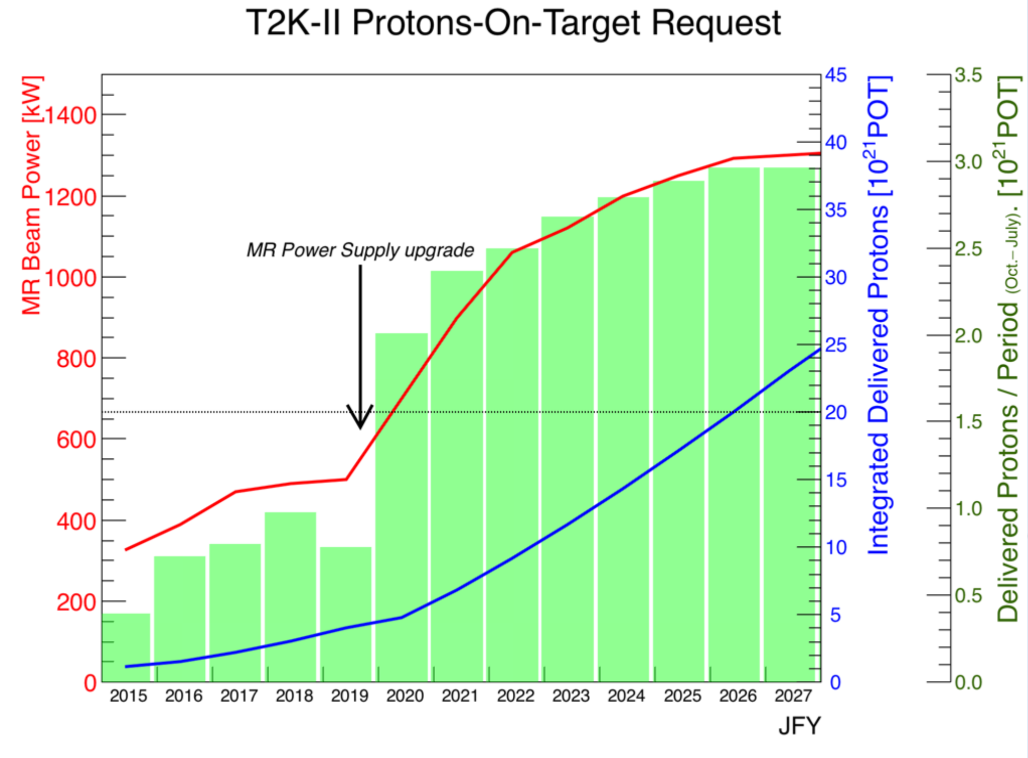
- Bayesian framework has natural way to express preference for binary choices: Bayes factors
  B=P(option 1)/P(option 2)
- Bayes factor for NH vs IH: 6.6
- Bayes factor for upper vs lower octant: 3.6
- Both classified as "substantial/positive" on Jeffreys/Kass & Rafferty scale but not yet decisive
- Systematics may change due to fake data studies

Posterior probabilities (T2K + reactor constraint)			
	$\sin^2\theta_{23}<0.5$	$\sin^2\theta_{23}>0.5$	Sum
NH ($\Delta m^2_{23}>0$)	0.193	0.674	0.868
IH ($\Delta m^2_{23}<0$)	0.026	0.106	0.132
Sum	0.219	0.781	

Future plans

T2K-II

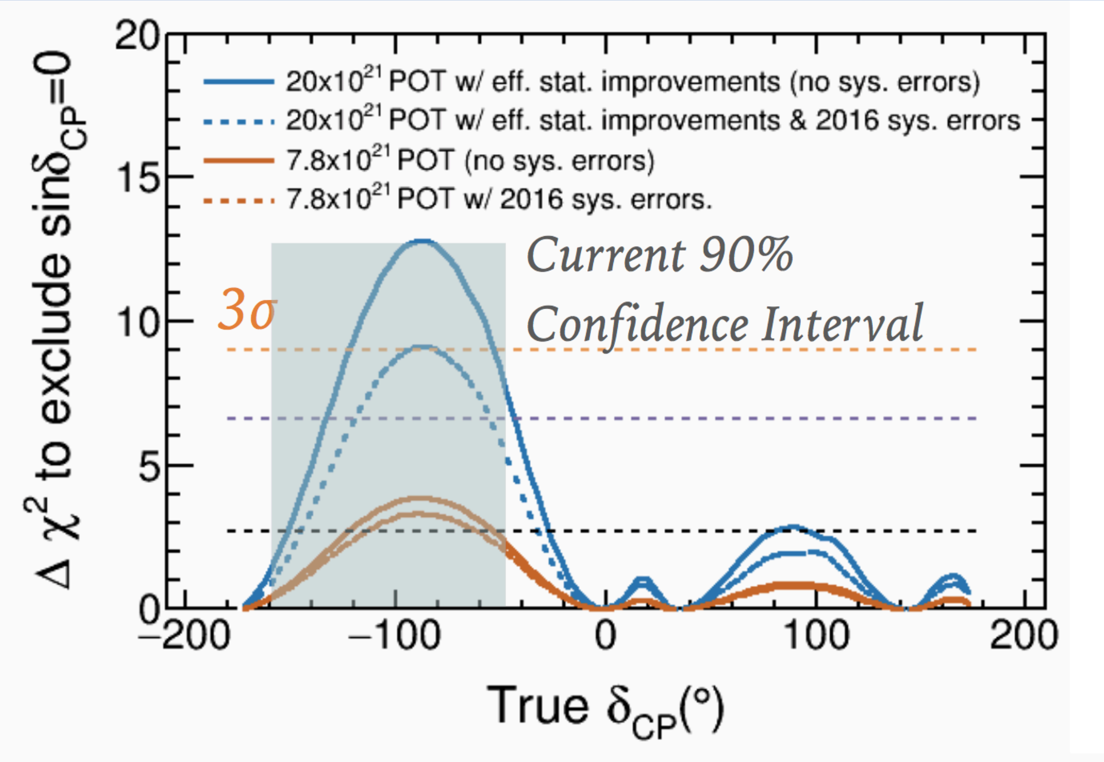
- T2K target POT is 7.8×10^{21}
- T2K-II is a proposal to extend target to 20.0×10^{21} POT by ~2026
  - Upgrade Main Ring power supply to increase from 0.4->1 Hz running
  - Beam power increase up to 1.3 MW

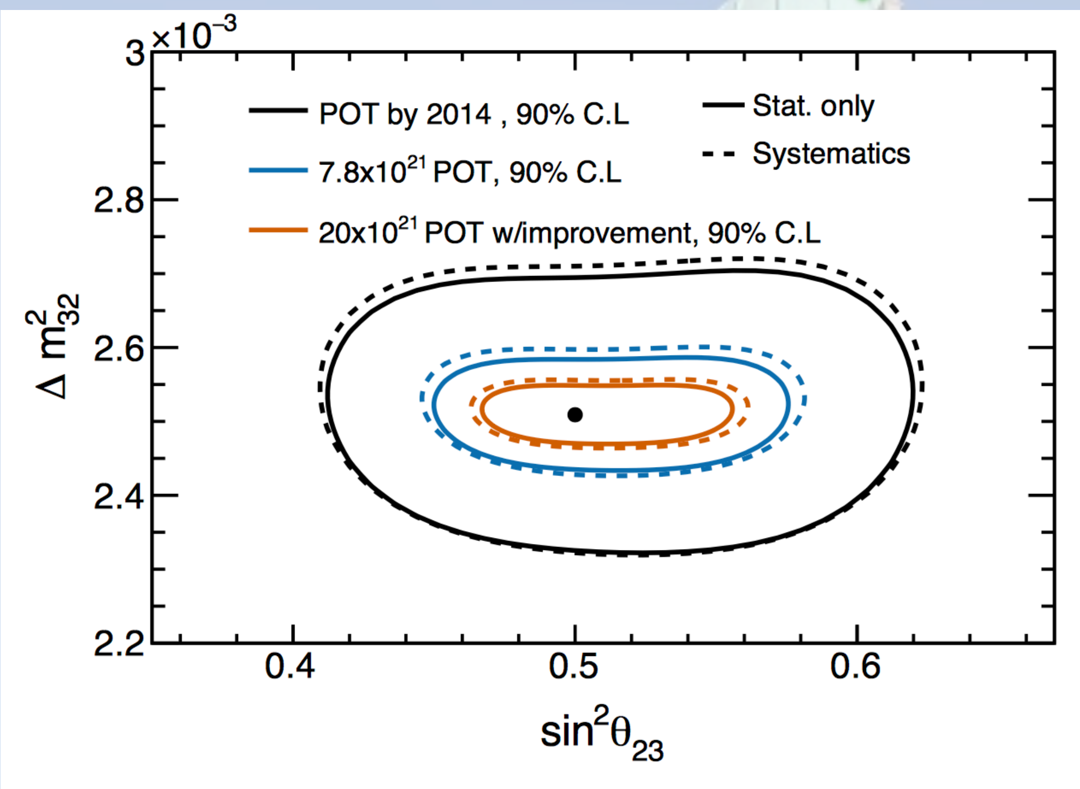


Other beam and detector upgrades

- Neutrino horns will run at 320 kA from next year
  - Reduces wrong sign contamination in antineutrino mode
- ND280 will be upgraded to improve high-angle acceptance
  - More similar to SK improving cross-section constraint
- SK will be refurbished during Summer 2018 to allow Gd addition in 2019/2020
  - Gd enables neutron tagging

T2K-II sensitivity





- If current preferred δ_{CP} is true T2K-II has potential for 3σ discovery
- Size of systematic uncertainties has large effect on sensitivity

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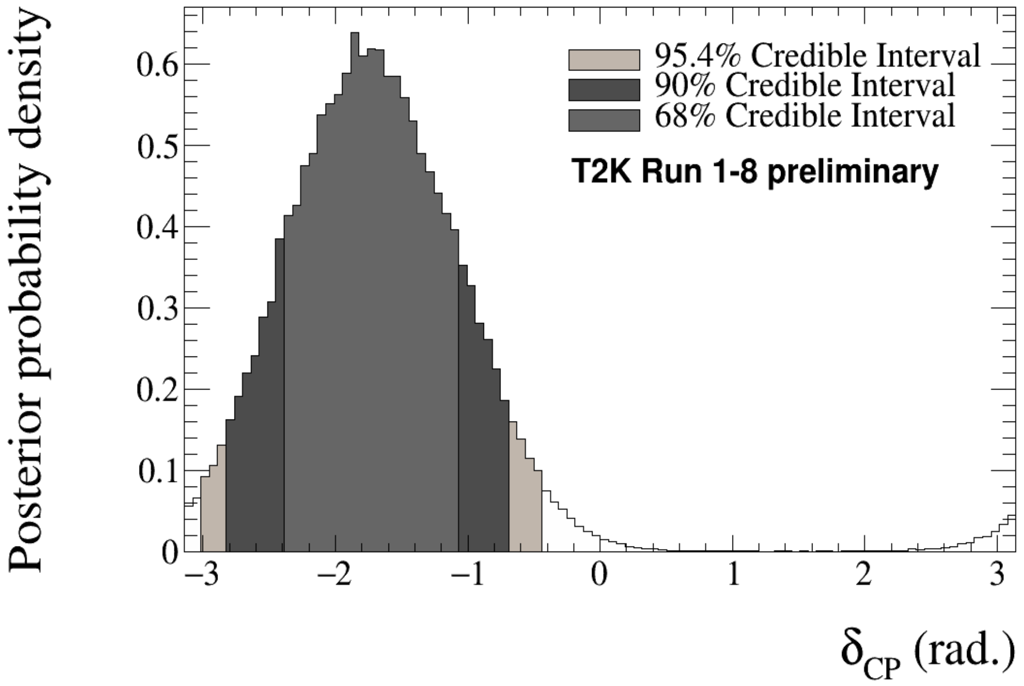
Summary

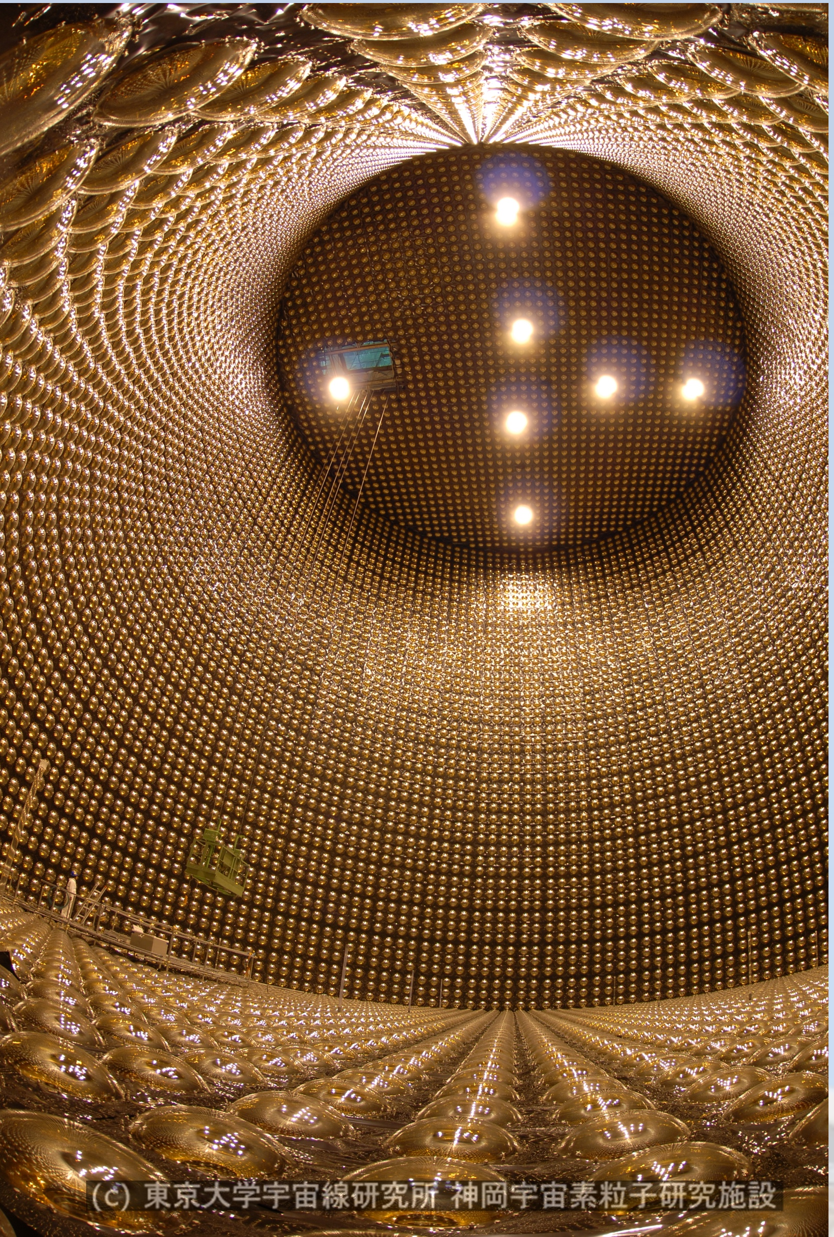
- T2K neutrino mode data has doubled since Summer 2016
- SK reconstruction improved and additional samples added
  - Increases number of events per POT by ~30%
- With new analysis CP conserving values of δ_{CP} are excluded at 2σ in both Bayesian and frequentist frameworks
- T2K-II proposal plans to collect 20×10^{21} POT
  - Gives 3σ sensitivity to favourable δ_{CP} values
  - Actively looking for new groups to join
- Exciting program of oscillation physics to look forward to!

T2K +reactor constraint

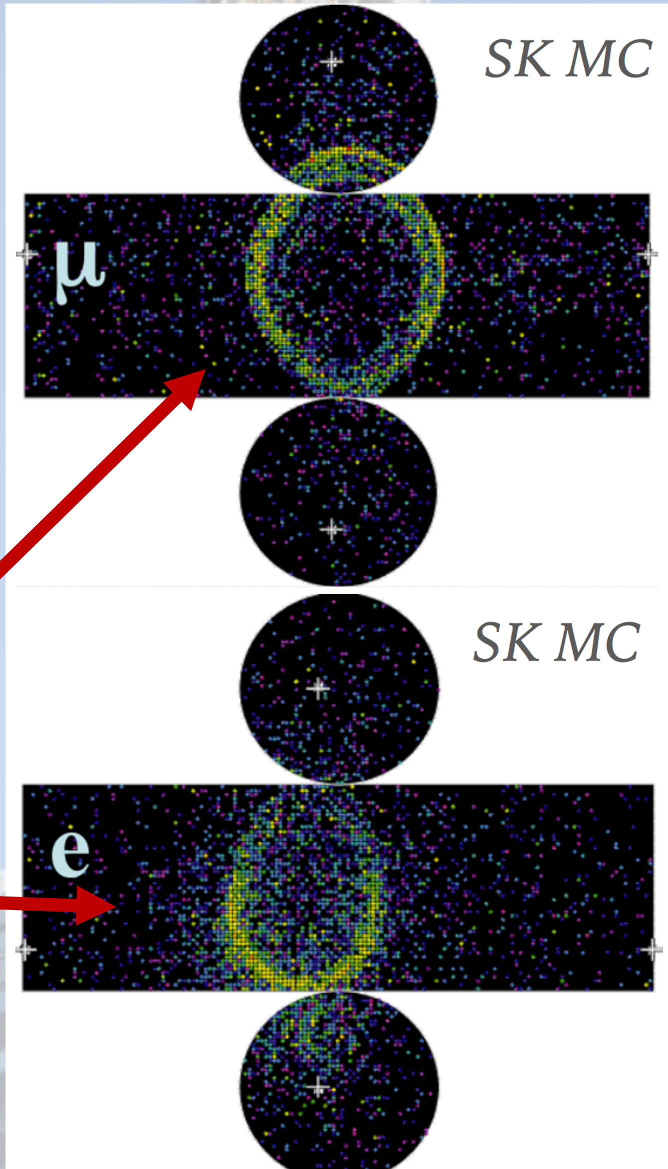


Backup

Super-K



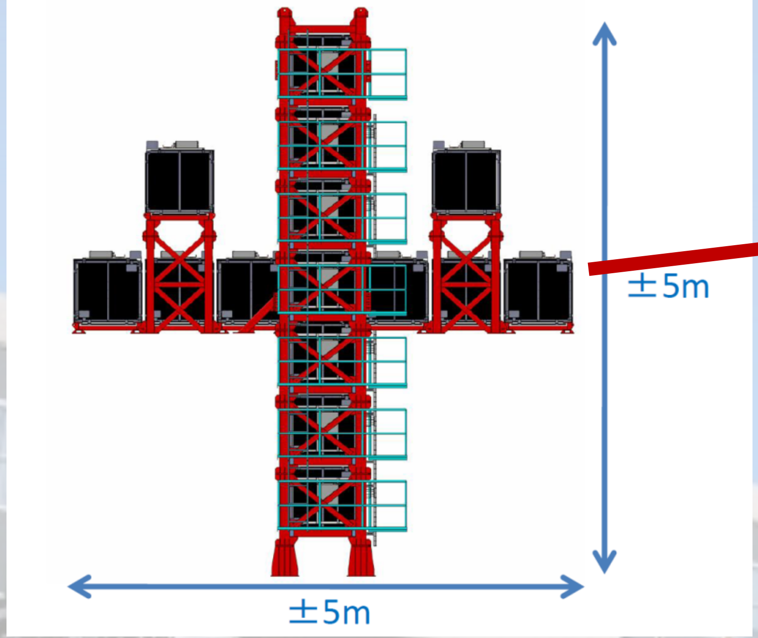
- 50 kton water-Cherenkov detector
- 11,000 20” PMT inner detector
  - 40% photo-coverage
- 2,000 8” PMT outer detector
  - Cosmic veto/exiting particles
- Not magnetised
- Particle ID via Cherenkov ring pattern:
  - Muons produce sharp rings
  - Electrons scatter more → fuzzier rings

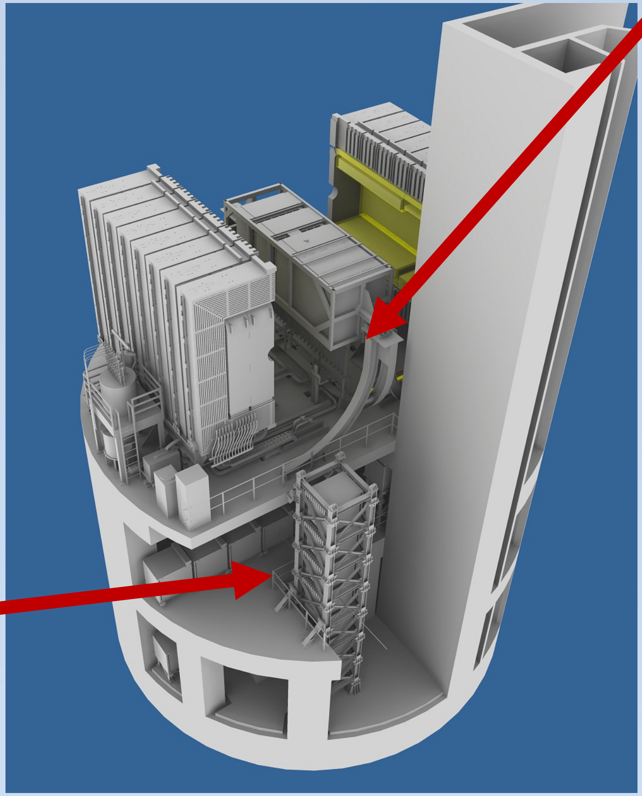


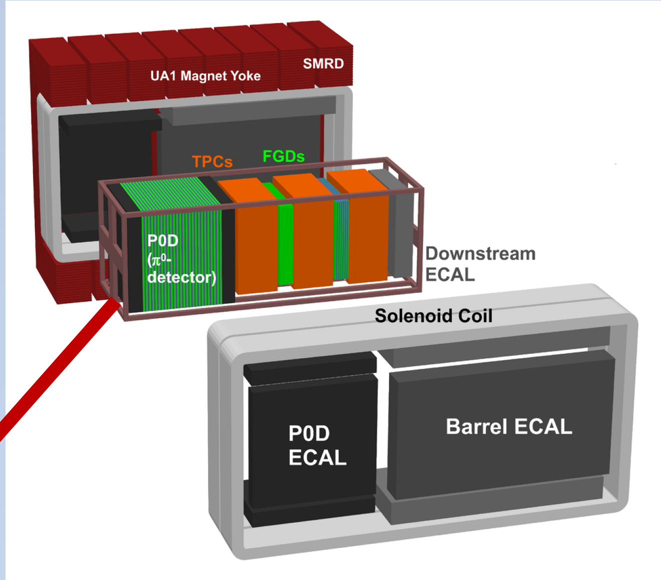
Near detectors

INGRID

- On-axis detector
- Monitors beam direction and constrains flux
- Design beam direction tolerance 1 mrad
- Achieved <0.5 mrad



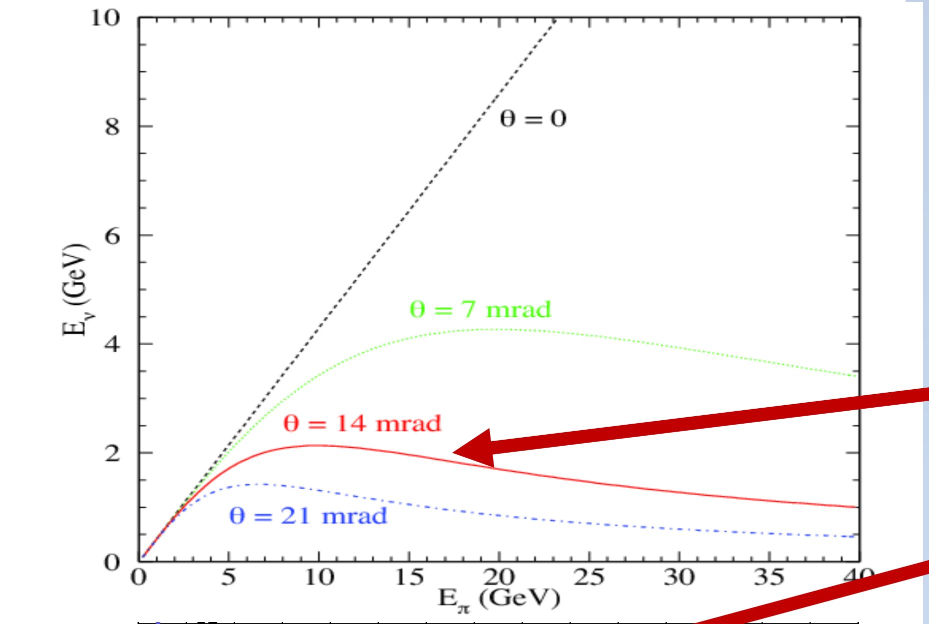


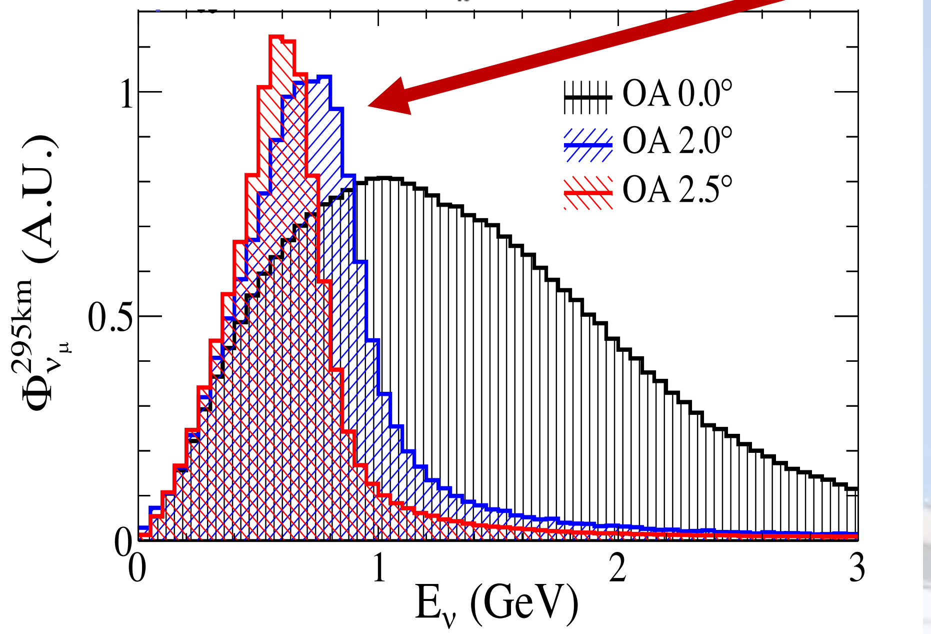


ND280

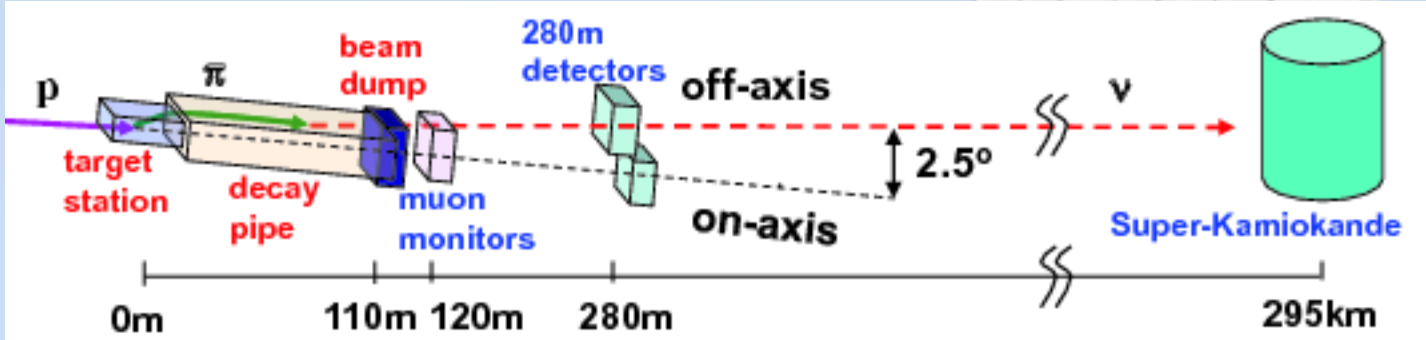
- 2.5° off-axis (same as Super-K)
- Two fine-grained detector (FGD) targets
  - FGD1 – Active carbon target
  - FGD2 – Active carbon and passive water layers
- Magnet + three TPCs
  - Particle charge + momentum from curvature
  - Particle ID From dE/dx – 0.2% mis-ID rate
- Constrains cross-section and flux uncertainties

Off-axis beam concept



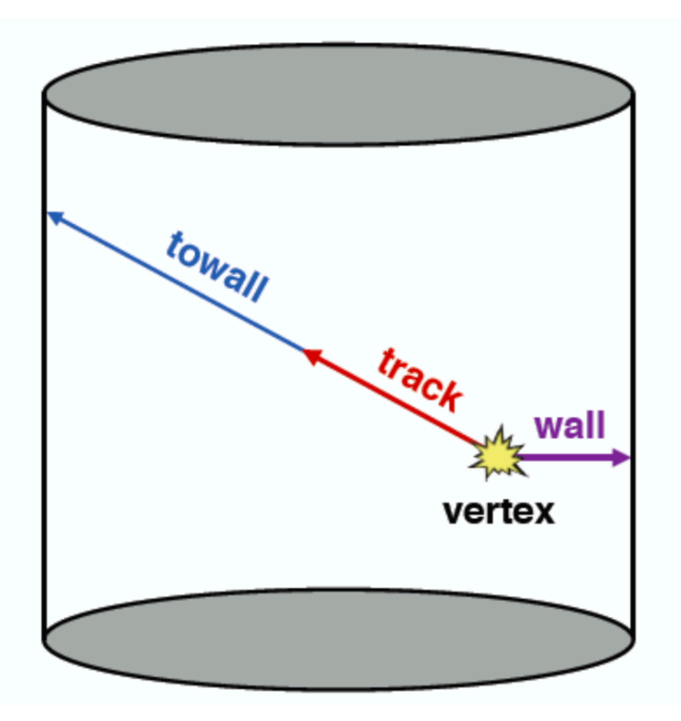


- Want as much flux as possible at oscillation peak (~0.6 GeV)
- Use 2.5º off-axis beam:
  - Off-axis phase space gives maximum energy for neutrinos from pion decay at a given angle
  - Gives narrower peak in flux
  - Removal of high-energy component suppresses NC backgrounds



Changes for this year – SK reconstruction

- Previous T2K analyses used “APFit” Super-K reconstruction algorithm
- For this result fiTQun algorithm has been used
  - For each event chooses event kinematic/topology hypothesis that maximises likelihood
  - Full charge and time information in likelihood leads to improved signal/background discrimination
- Improved reconstruction performance enables increased fiducial volume
  - Previously required vertices to be >2m from detector wall
  - Now optimise cut on “wall” and “towall” for each sample to minimise statistical and systematic errors
  - Provides ~20% increase in fiducial volume (FV)



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Changes since last summer – SK samples

- Last summer's result used 4 Super-K samples
  - Neutrino mode:
    - 1 μ-like ring, ≤1 decay electron
    - 1 e-like ring, 0 decay electrons
  - Antineutrino mode:
    - 1 μ-like ring, ≤1 decay electron
    - 1 e-like ring, 0 decay electrons
  - All four samples target charged-current quasi-elastic (CCQE) interactions

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

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

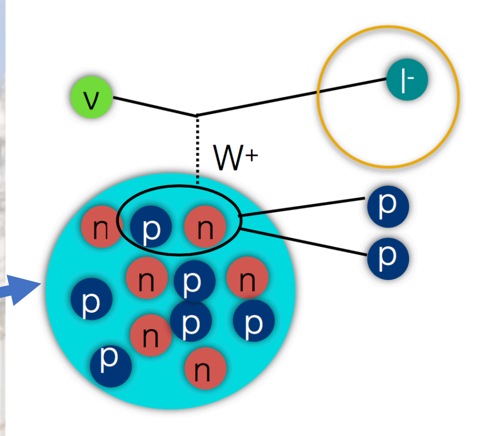
- This year we also include neutrino mode sample targeting CC1π interactions
  - Neutrino mode: 1 e-like ring, 1 decay electron
  - No antineutrino mode due to π^- absorption

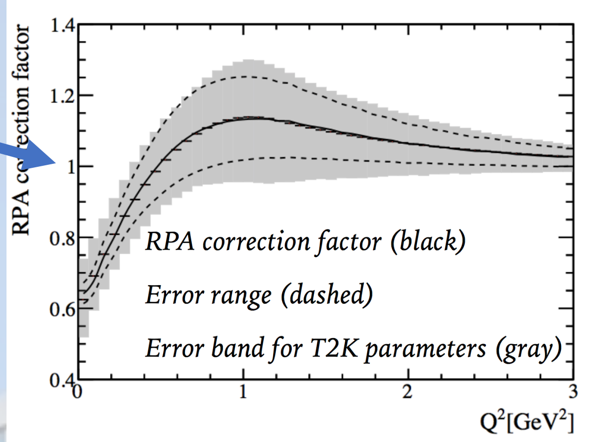
$$\nu_e + N \to e^- + \pi^+ + X$$
$$\downarrow$$
$$\mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_\mu$$

- Combination of new sample and increased FV equates to 30% increase in event rate for same POT in neutrino mode

Changes to model this year – Cross section

- NEUT neutrino interaction MC generator has been significantly improved in recent years:
  - New tune of pion production model to external hydrogen and deuterium data
  - Inclusion of multi-nucleon scattering processes: Valencia 2p-2h model (Phys. Rev. C83 (2011) 045501)
  - Improvements to the CCQE model: Included the effect of long-range nucleus correlations (calculated using random phase approximation, RPA)
- This analysis includes new parametrisations of the uncertainties on 2p-2h and RPA modelling





more on ν_μ disappearance

- ν_μ disappearance probability in vacuum

$$P(\nu_\mu \to \nu_\mu) = 1 - (c_{13}^4 \ \sin^2 2\theta_{23} + s_{23}^2 \ \sin^2 2\theta_{13}) \sin^2 \Delta_{atm}$$
$$+\left\{ c_{13}^2 \,(c_{12}^2 - s_{13}^2 \ s_{23}^2) \sin^2 2\theta_{23} + s_{12}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} - c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{23} \ \sin 2\theta_{12} \ \cos\delta \right\}$$
$$\times \left\{ \frac{1}{2} \sin 2\Delta_{solar} \ \sin 2\Delta_{atm} + 2 \sin^2 \Delta_{solar} \ \sin^2 \Delta_{atm} \right\}$$
$$-\left\{ \sin^2 2\theta_{12} \,(c_{23}^2 - s_{13}^2 \ s_{23}^2)^2 + s_{13}^2 \ \sin^2 2\theta_{23} \,(1 - c_\delta^2 \ \sin^2 2\theta_{12}) \right.$$
$$+2 s_{13} \ \sin 2\theta_{12} \ \cos 2\theta_{12} \ \sin\theta_{23} \ \cos 2\theta_{23} \ c_\delta$$
$$-\frac{1}{2} c_{13} \ \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \ \cos\delta \ s_{23}^2 \ s_{12}^2$$
$$\left. + \sin^2 2\theta_{23} \ c_{13}^2 \ (c_{12}^2 - s_{13}^2 \ s_{12}^2) + s_{13}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} \right\} \times \sin^2 \Delta_{solar} \qquad (26)$$

$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$
$$c_\delta = \cos\delta$$
$$\Delta_{atm} = \frac{\Delta m_{13}^2 \ L}{4 \ E_\nu}$$
$$\Delta_{solar} = \frac{\Delta m_{21}^2 \ L}{4 \ E_{/nu}}$$

T2K: L = 295 km, E_ν peaks at ~ 0.6 GeV -> $\sin^2\Delta_{solar}$ ~ 0, $\sin 2\Delta_{atm}$ ~ 0

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

Leading-term Next-to-leading

ν_μ disapp. probability depends on $\sin^2 2\theta_{13}$ $\sin^2\theta_{23}$ to second order

-> Can be used in combination with known $\sin^2 2\theta_{13}$ to resolve the θ_{23} octant

ν_e appearance probability with 1st order matter effect

$$P(\nu_\mu \to \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2s_{13}^2\right)\right)$$

Leading including matter effect

$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP conserving

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP violating

$$+4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

Solar

$$-8c_{13}^2 s_{13}^2 s_{23}^2(1-2s_{13}^2)\frac{aL}{4E}\cos\Delta_{32}\sin\Delta_{31}$$

Matter effect (small)

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}$$

replace δ by $-\delta$ and a by $-a$ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

T2K

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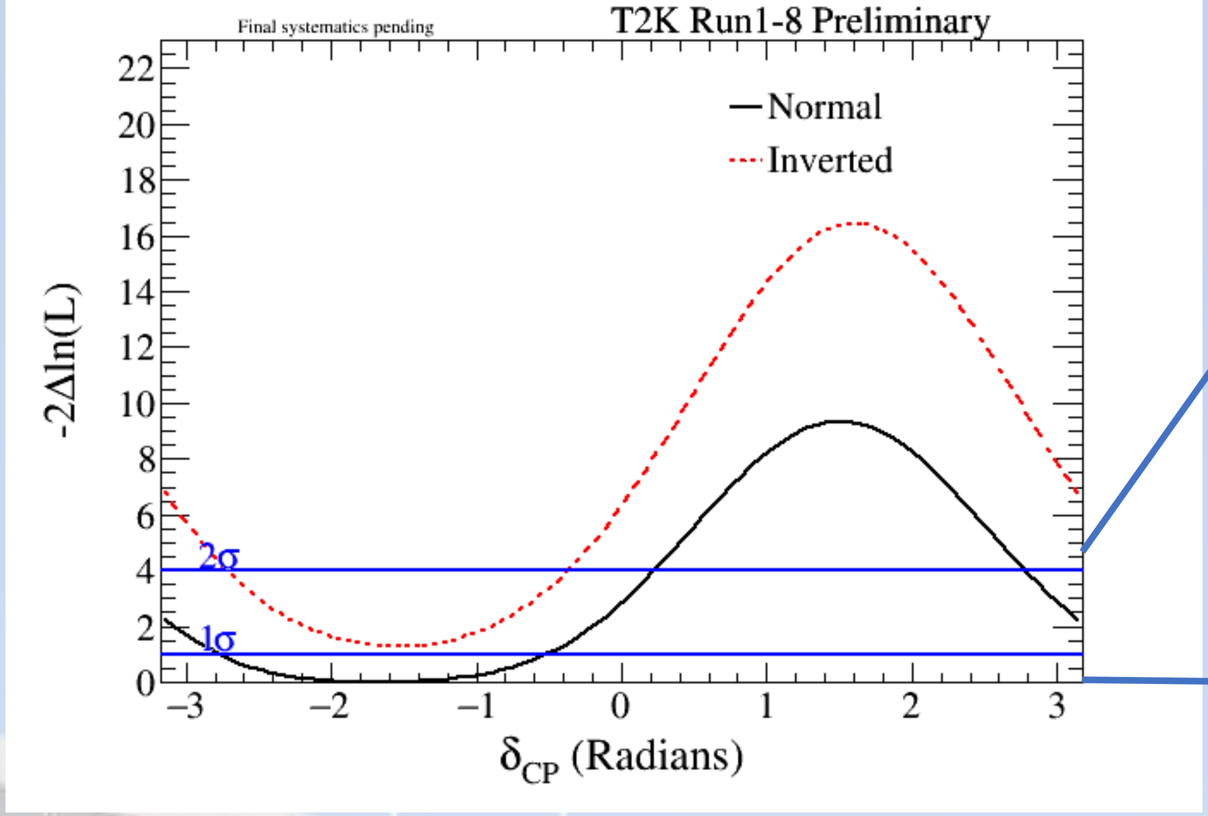
Oscillation parameters used for predictions

- Evaluated sensitivity by fitting spectrum expected for certain oscillation parameters if no statistical or systematic fluctuations
- Define two sets of oscillation parameter values:

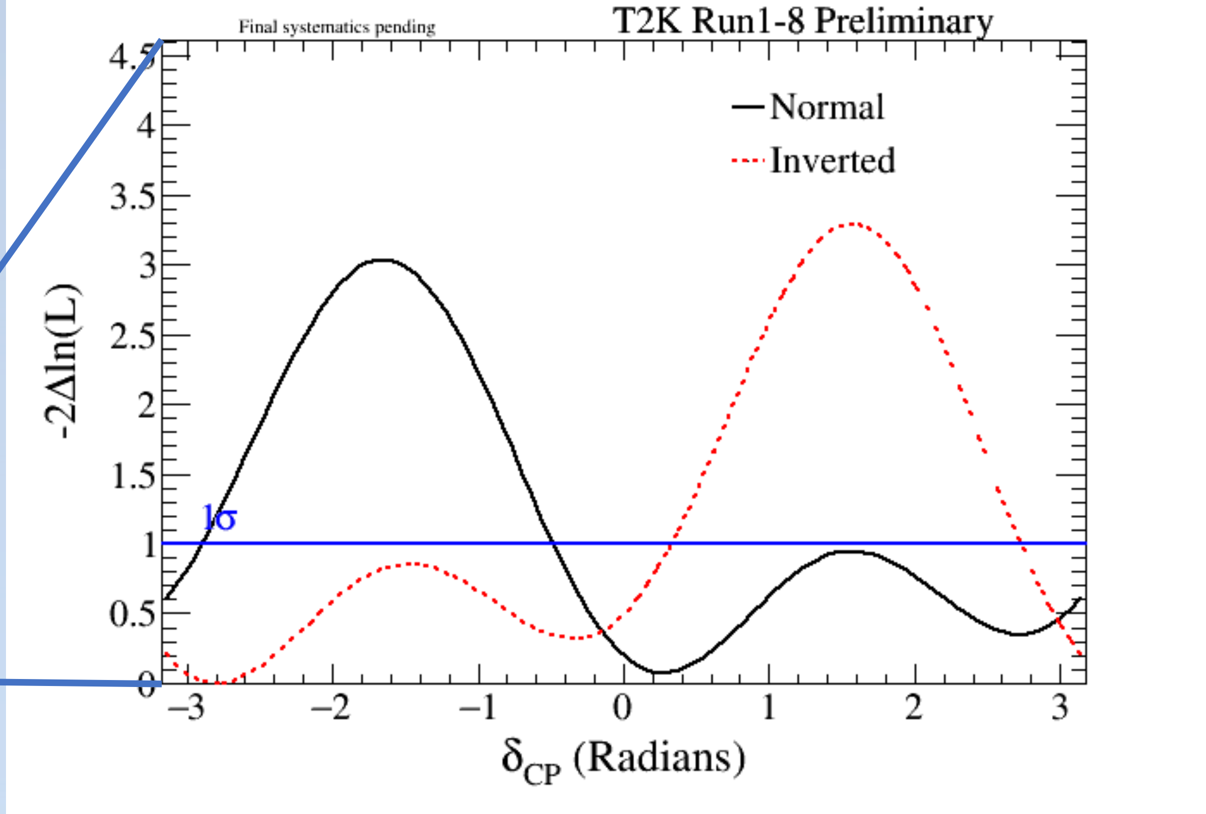
	Set A	Set B
$\sin^2\theta_{12}$	0.304	0.304
$\sin^2\theta_{23}$	0.528	0.45
$\sin^2\theta_{13}$	0.0219	0.0219
Δm^2_{12}	7.53×10^{-5} eV^2	7.53×10^{-5} eV^2
Δm^2_{23}	2.509×10^{-3} eV^2	2.509×10^{-3} eV^2
δ_{CP}	-1.601	0

Set B sensitivity

Set A: $\sin^2\theta_{23}$=0.528, δ_{CP} = -1.601



Set B: $\sin^2\theta_{23}$=0.45, δ_{CP} = 0



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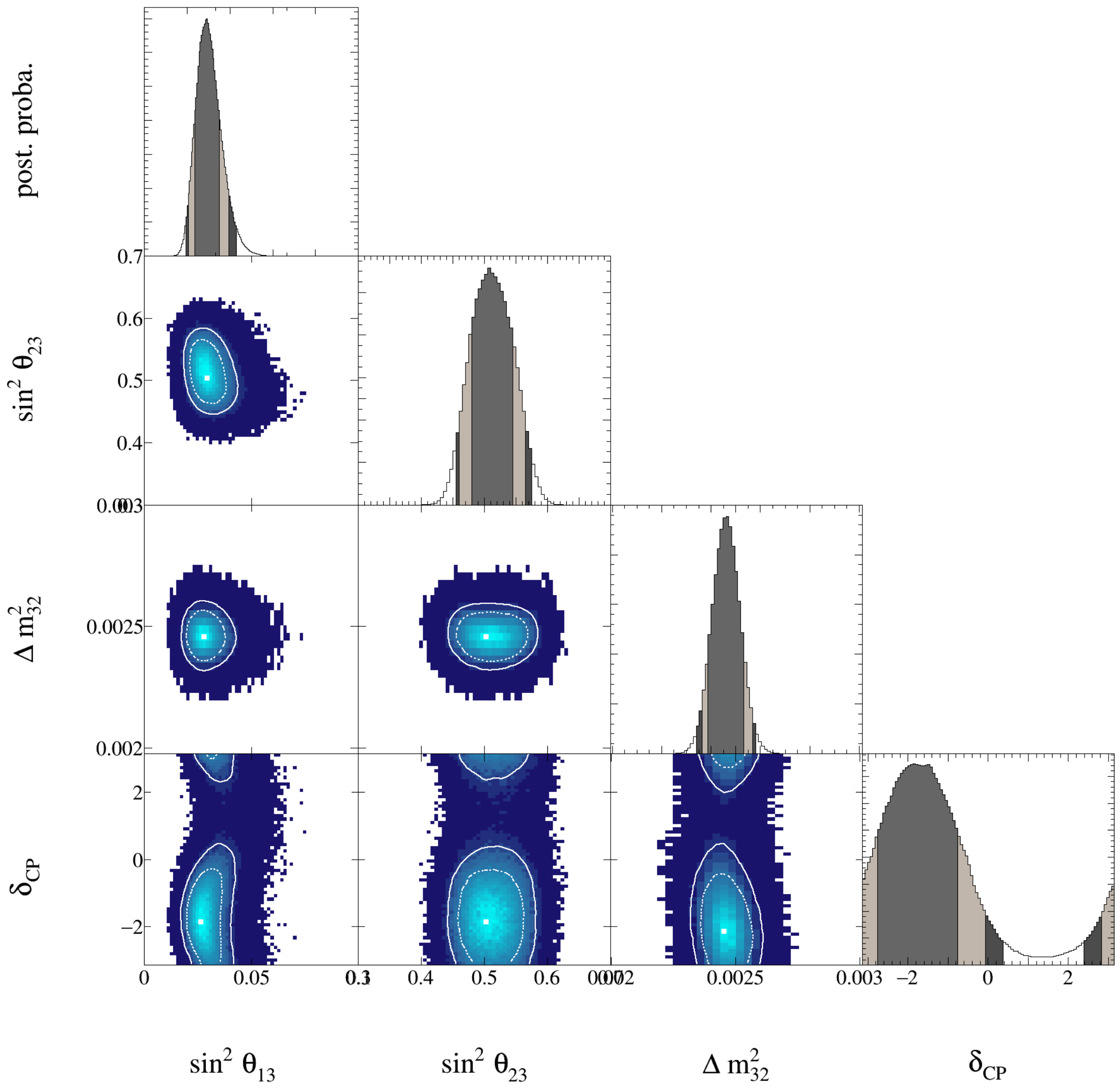
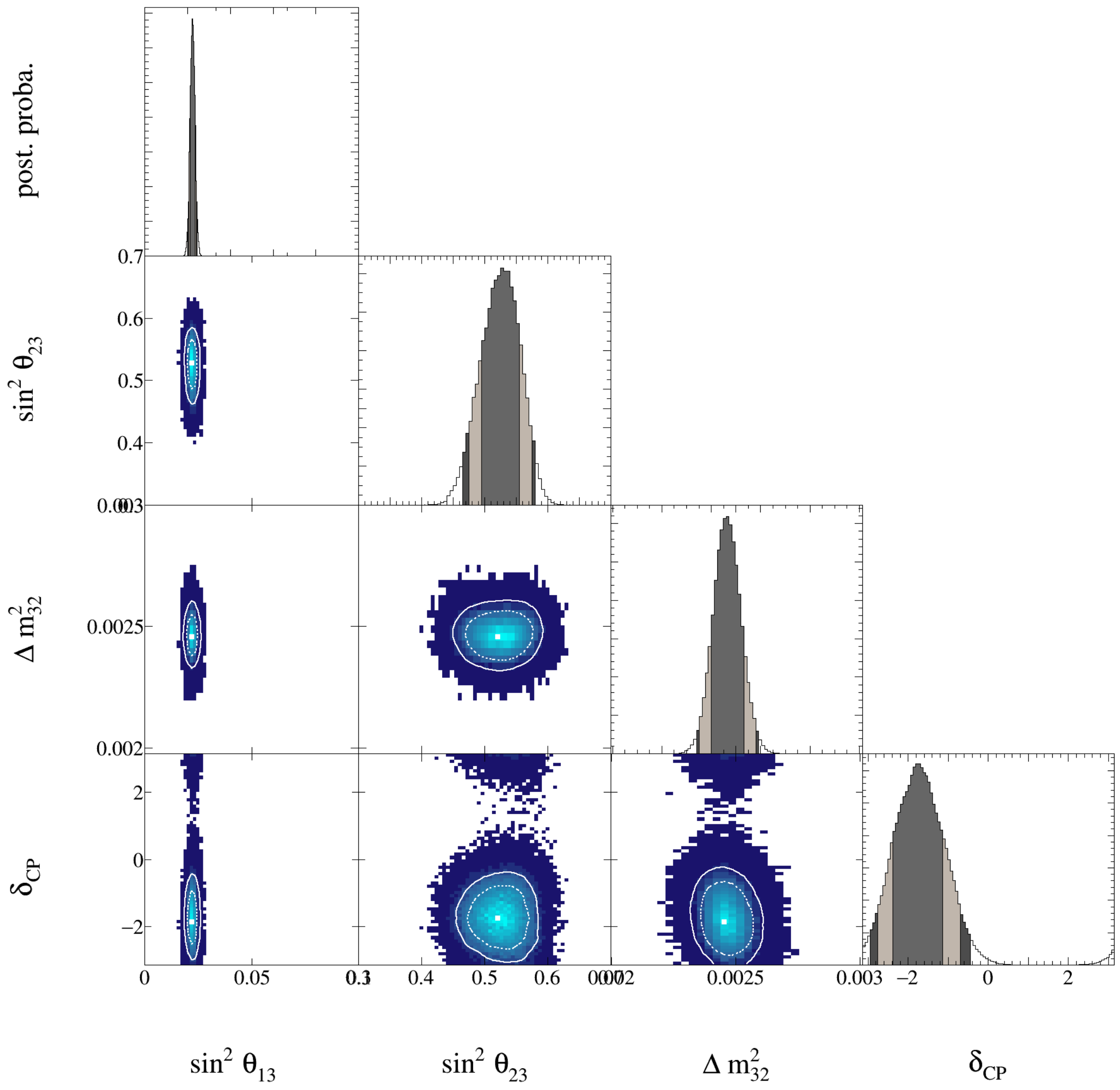
Triangle plots

T2K data only

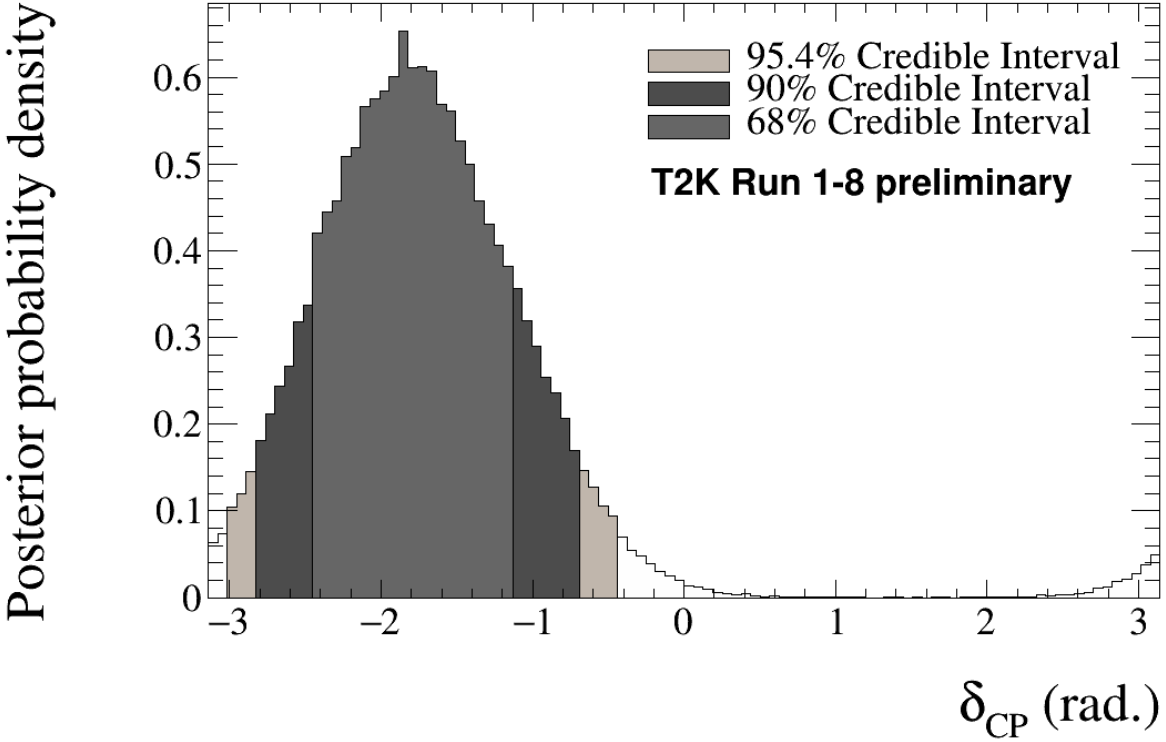


T2K +reactor constraint

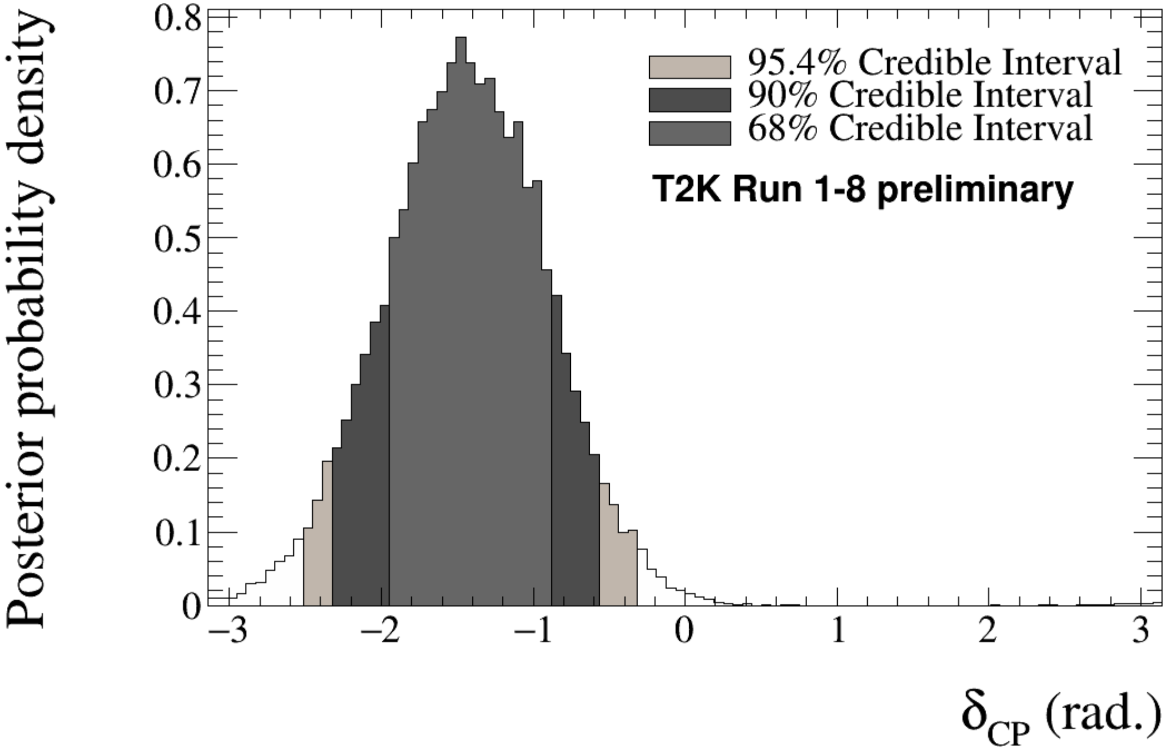


Dcp split by hierarchy- T2K+reactor

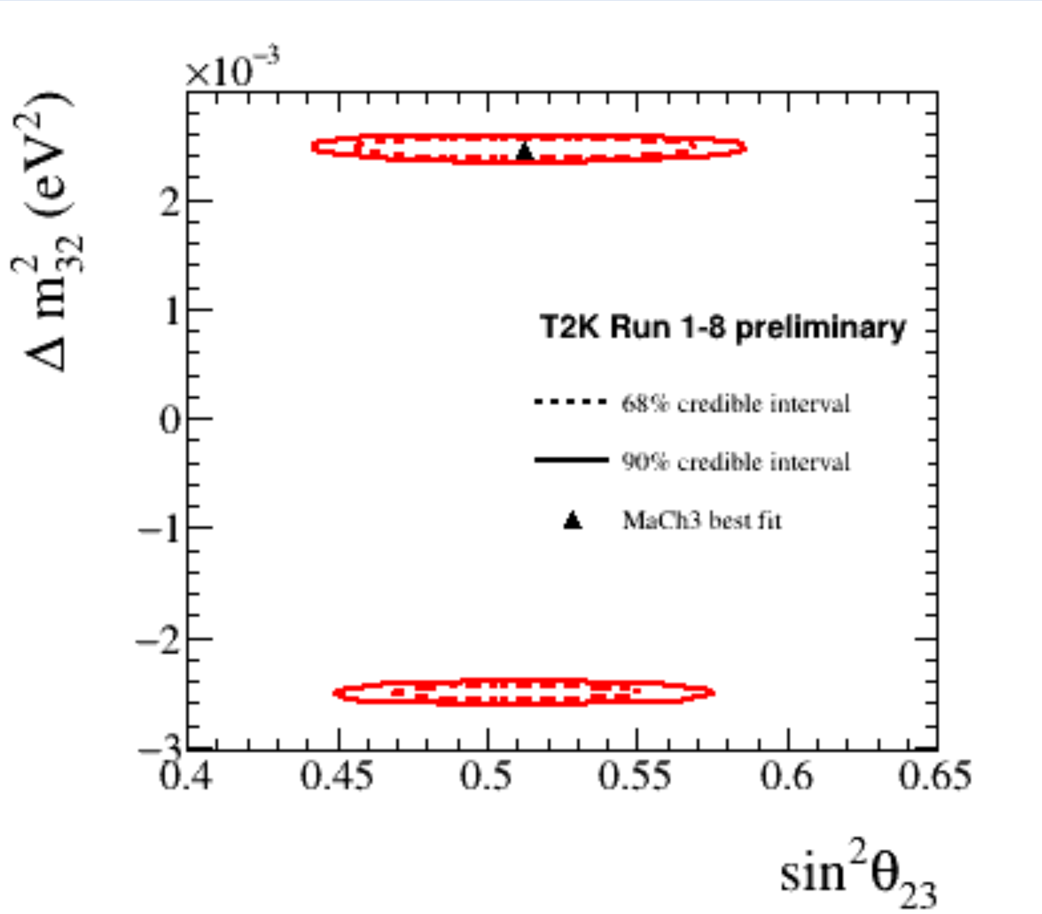
Normal hierarchy



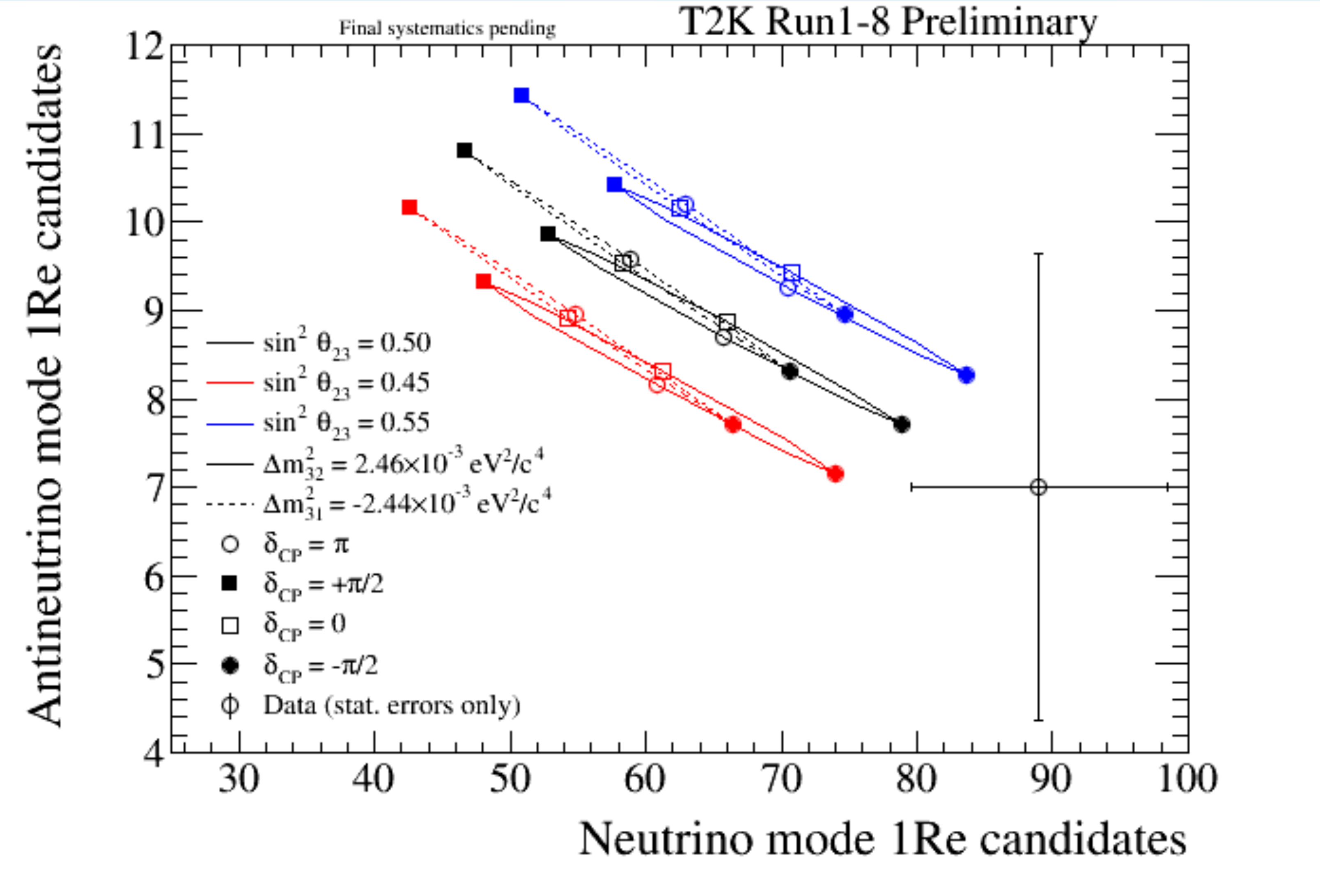
Inverted hierarchy

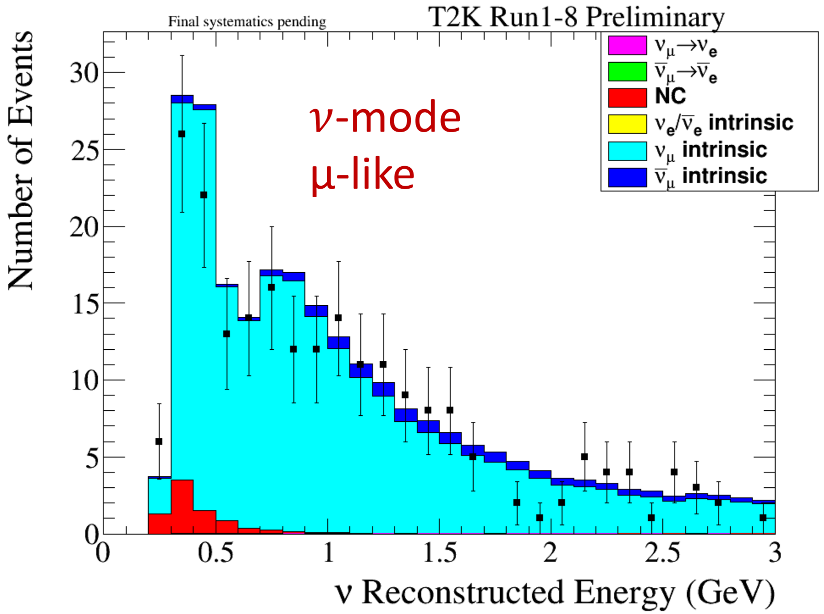


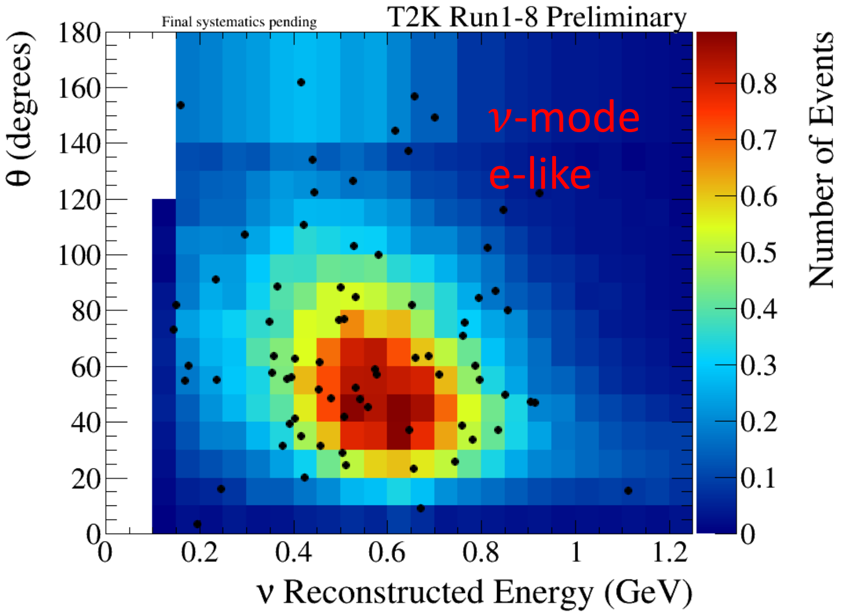
T2K data only disappearance parameters

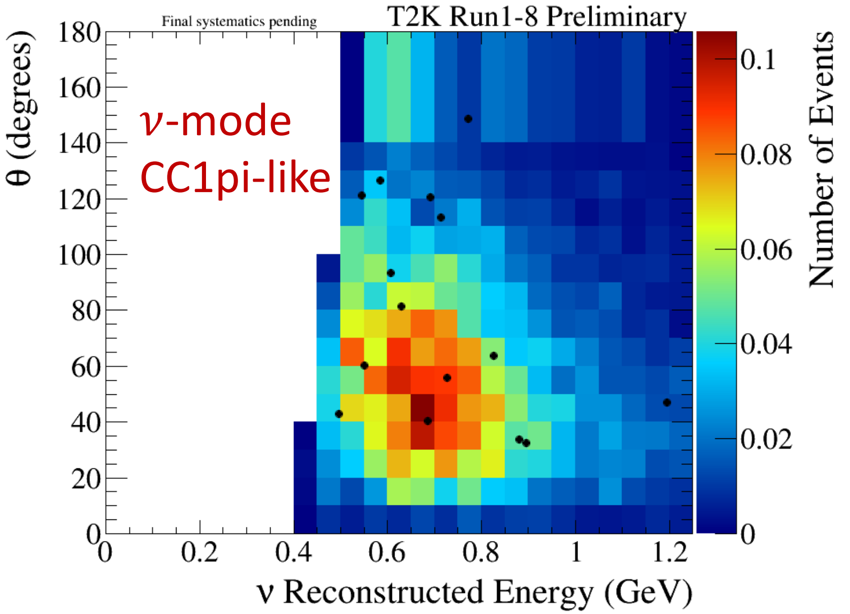


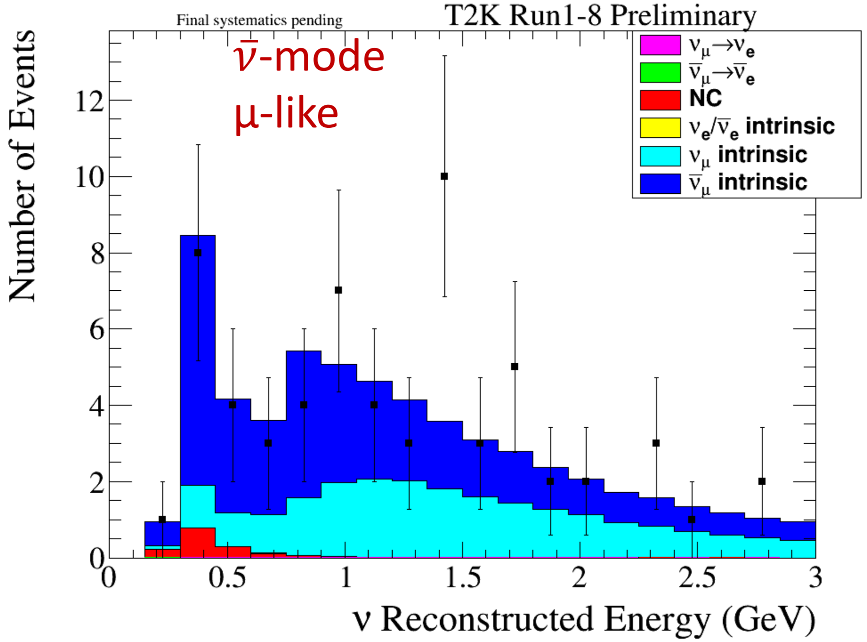
Biprobability plots




Final systematics pending
T2K Run1-8 Preliminary
ν-mode
μ-like
$\nu_\mu \rightarrow \nu_e$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
NC
$\nu_e/\bar{\nu}_e$ intrinsic
ν_μ intrinsic
$\bar{\nu}_\mu$ intrinsic
Number of Events
ν Reconstructed Energy (GeV)


Final systematics pending
T2K Run1-8 Preliminary
ν-mode
e-like
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)


Final systematics pending
T2K Run1-8 Preliminary
ν-mode
CC1pi-like
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)


Final systematics pending
T2K Run1-8 Preliminary
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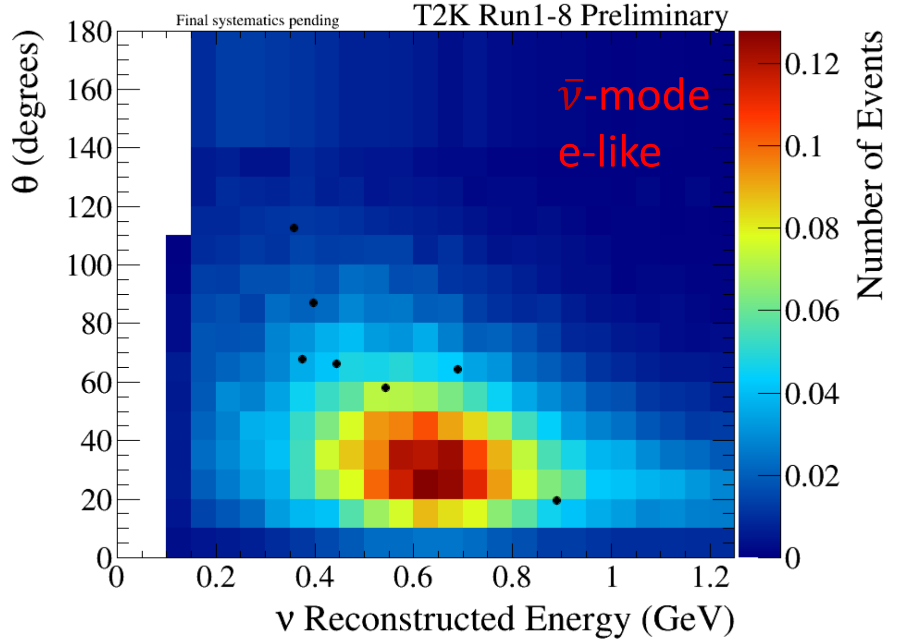
μ-like
$\nu_\mu \rightarrow \nu_e$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
NC
$\nu_e/\bar{\nu}_e$ intrinsic
ν_μ intrinsic
$\bar{\nu}_\mu$ intrinsic
Number of Events
ν Reconstructed Energy (GeV)


Final systematics pending
T2K Run1-8 Preliminary
$\bar{\nu}$-mode
e-like
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)

Plan to deal with fake data

- Investigating further to see if differences seen between data and MC are a physical effect we should include an uncertainty for
- δ_{CP} results not affected
- $\sin^2\theta_{23}$ and Δm^2_{23} results presented with caveat that the systematic error model may be updated
- In future we plan to address ambiguity between interaction modes with:
  - Use of 4π acceptance samples at ND280 to better match SK acceptance
  - Studies of hadronic recoil system through proton reconstruction
  - Near detector upgrades to improve model constraints