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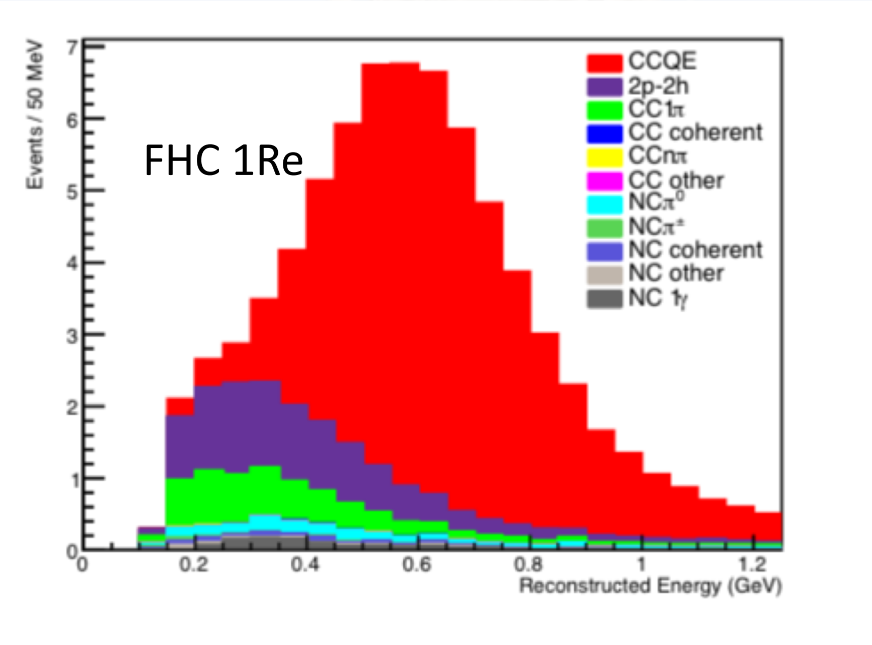
Critical cross-section modeling issues for the oscillation program

Patrick Dunne

for the T2K collaboration

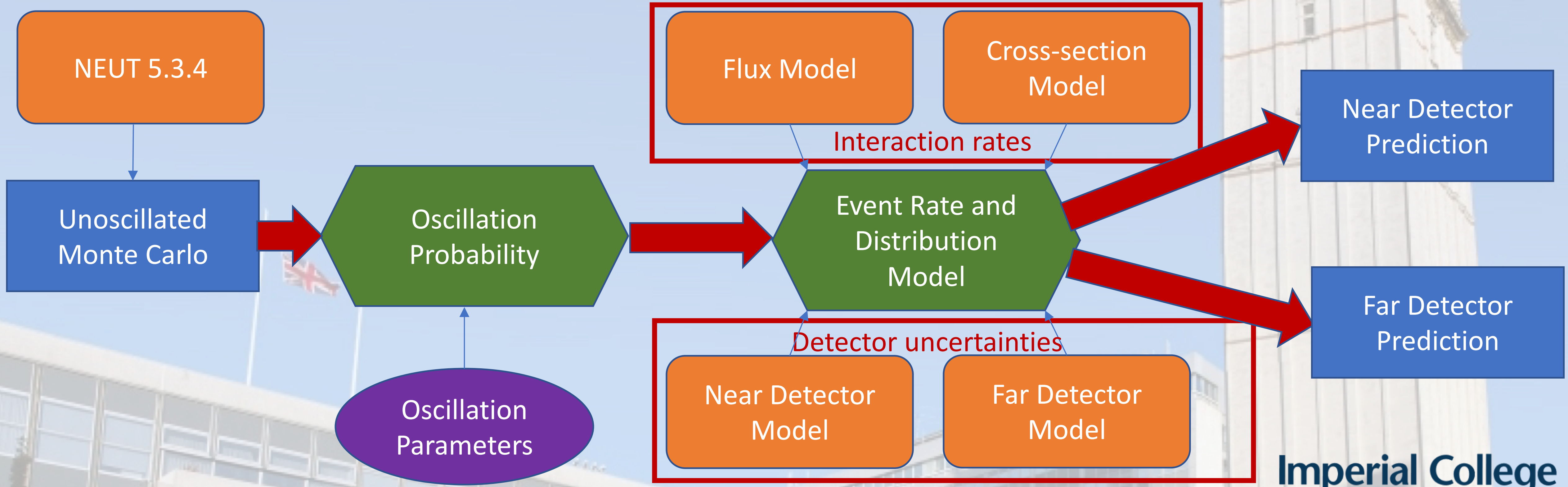
Outline

- How do cross-sections enter oscillation analyses
- Simulated data method – How do we check our model?
- Which interaction modes do we have concerns about?
- What can we do about the concerns in the future?



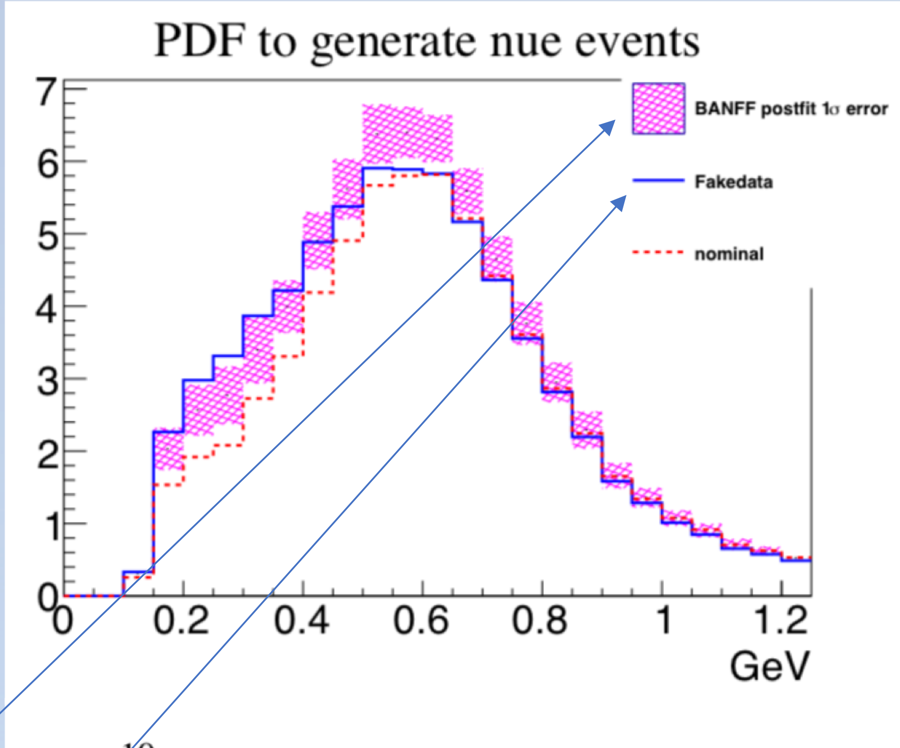
Where do cross-sections enter analysis

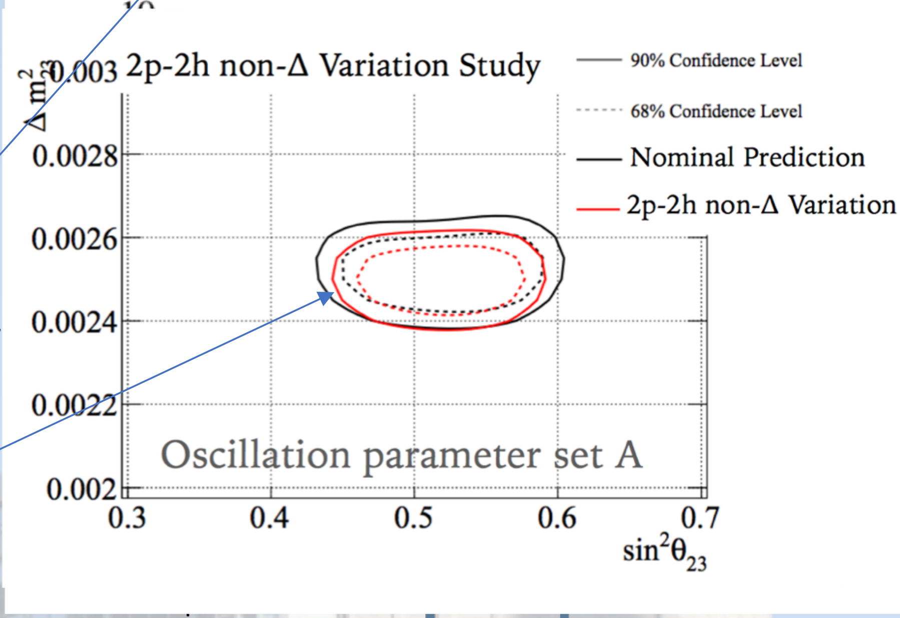
- Apply oscillation effects to Monte Carlo as a function of true E_ν
- Construct model to predict event rates and distributions at near and far detectors
- Need to ensure experiment can constrain non-oscillation elements of model
- Important to allow enough uncertainty to mitigate bias in case of incorrect model choice



Simulated data method

- Check robustness of results to neutrino interaction model by using our model to fit ``simulated data”
- Simulated data are generated in two ways
  1. `Data-driven’: Inflate one interaction mode to account for differences between current model prediction and existing data
  2. Model choices: generate data using other models implemented in generator but not used in oscillation analysis and refit
- Fit simulated ND data, propagate constraint to SK
- Fit SK simulated data using ND constrained xsec model
- Compare fit to simulated data to nominal model Asimov
- If getting the interaction model wrong leads to significantly different constraints: further investigation





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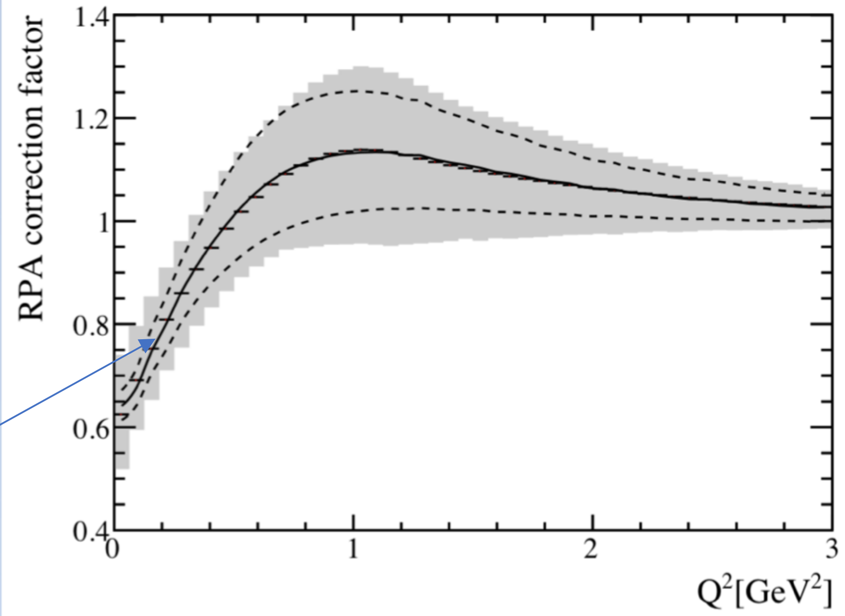
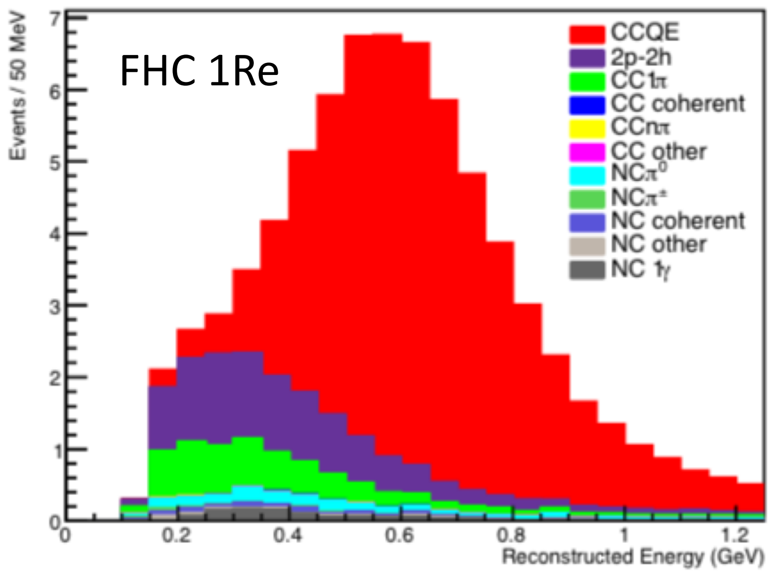
T2K Cross-section Model

- Use Neut 5.3.4
- Separate CC0pi into 1p1h and 2p2h:
  - 1p1h: Assume relativistic fermi gas plus Nieves et al RPA
    - Use effective parametrisation of uncertainty (BeRPA)
  - 2p2h: Assume Nieves et al model
- CC1pi:
  - Generate Rein-Sehgal model for resonant, non-resonant and coherent
  - Reweight to Berger-Sehgal
    - Mostly changes normalisation
- DIS: Modelled using Pythia 5.72





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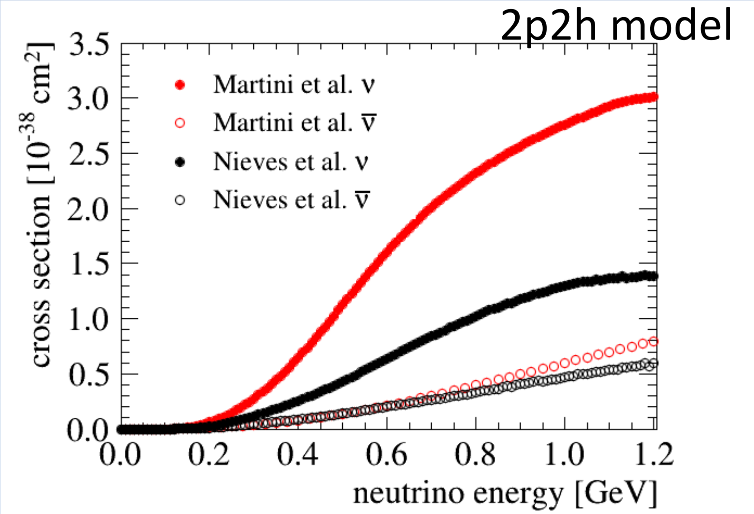
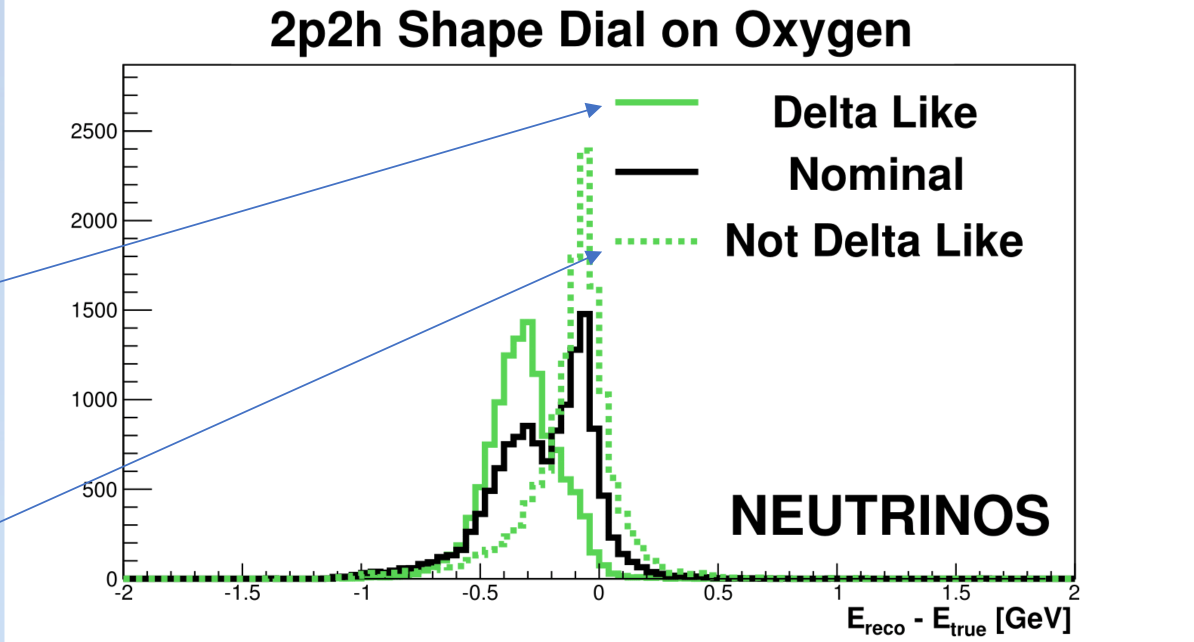
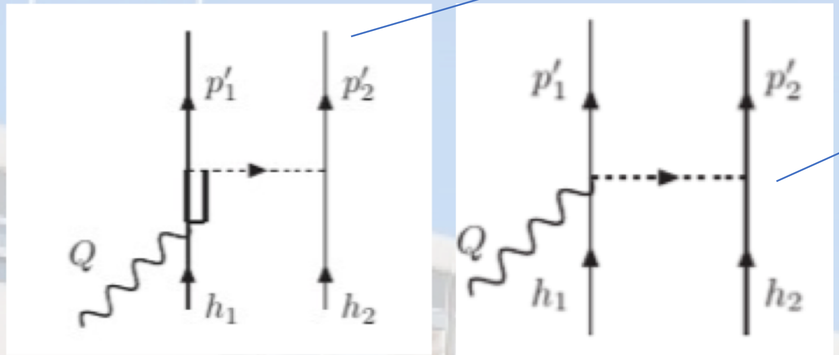
2p2h

- New 2p2h uncertainties for 2017 analysis based on Nieves et al model
- C and O normalisation vary independently
- Shape allowed to vary continuously between totally pionless-delta like and non-pionless-delta like
- Also performed Martini et al 2p2h simulated data study







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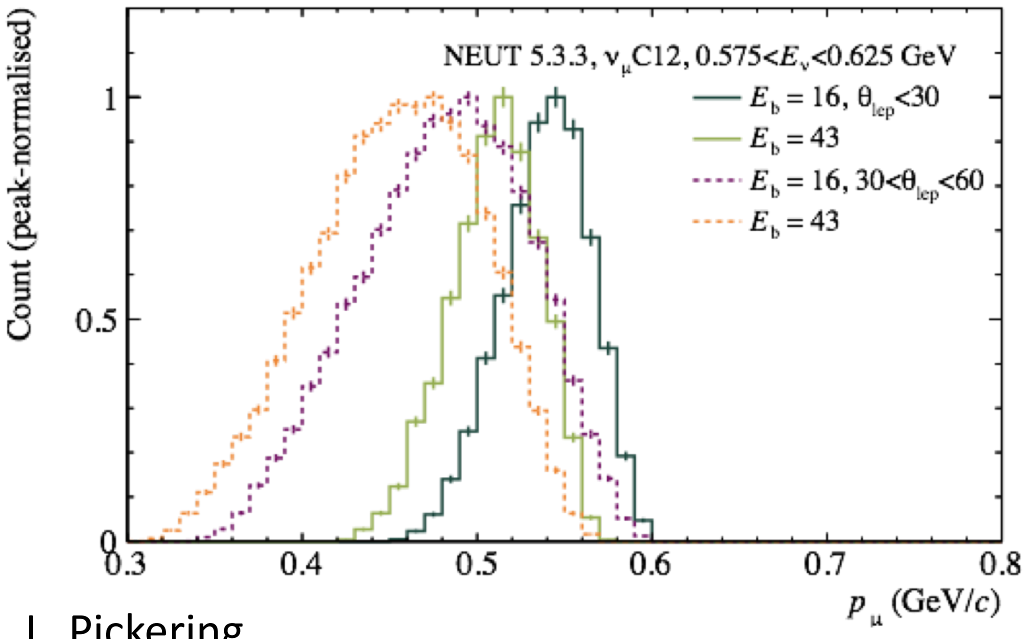
CC0pi issues

Binding Energy like effects (T2K jargon: Eb)

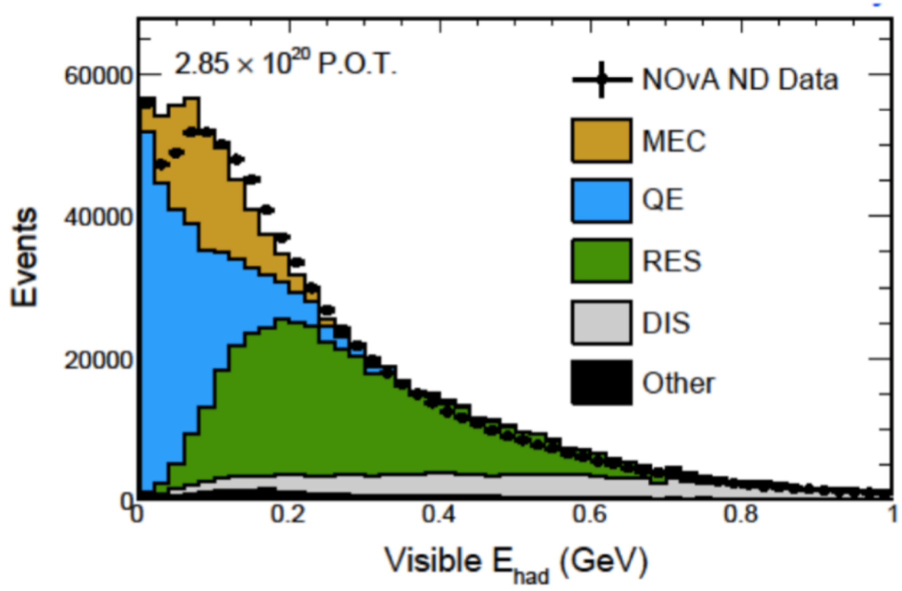
- Most cross-section systematics dealt with using reweighting
- What if the phase space you want to weight up isn't filled in original model?
- Particular problem for Eb as it shifts events up and down in energy
- T2K were unable to add variations for this in time for our analysis release last year
- Eb varied simulated data study is performed
  - Large uncertainty used to cover for several definitions of Eb: (Bodek arXiv:1801.07975)
  - Under study to reduce for future iterations



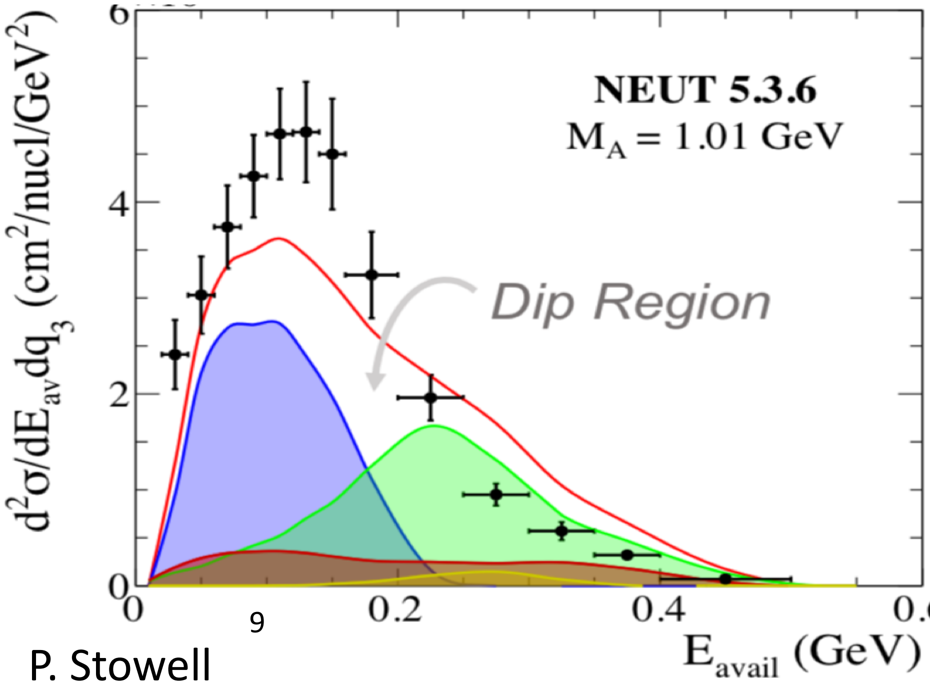
L. Pickering

MINERvA

- MINERvA and NOvA see a discrepancy between GENIE and data in the "dip" region between CCQE and Resonant
  - Both compensate with a procedure to scaling up either 1p1h or 2p2h
- Discrepancy also seen in NEUT when compared to MINERvA data
- 1p1h and 2p2h not disambiguated by ND280
- Comparing increase to 1p1h and 2p2h needed at NuMI energy to that needed at T2K energy gives similar amount at low angles but different (lower for T2K) at high angles
- Studies imply energy dependence of discrepancy is different to our model



"Cross-sections and neutrino oscillations in NOvA", Kirk Bays, *NuFact 2017*



P. Stowell

Non-CC0pi

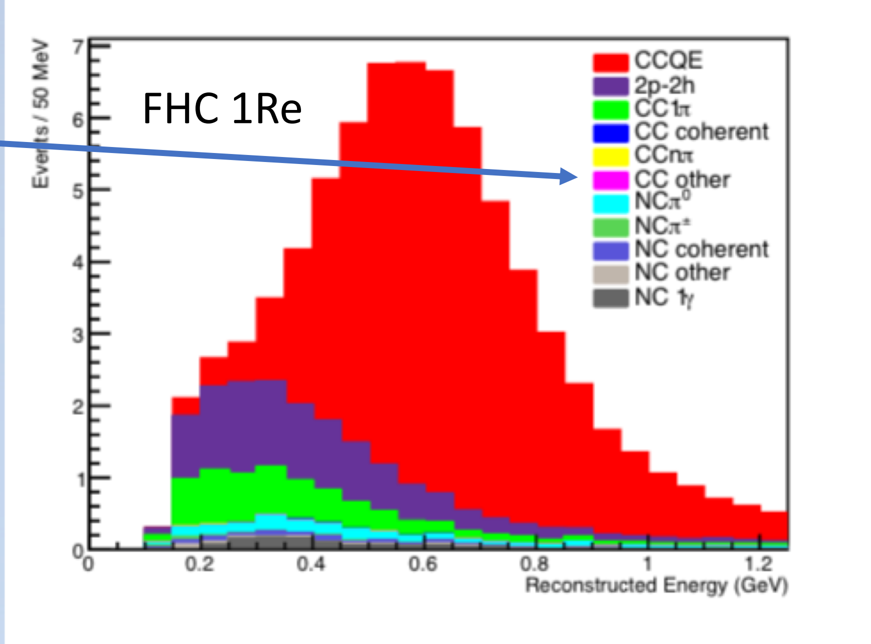
CC1pi

- T2K CC1pi like far detector sample sees more events than expected
  - p-value to see similar fluctuation in one of 5 samples is 12%
- Known deficiencies in CC1pi model: e.g. treatment of multiple resonances
  - New treatment of non-Δ(1232) resonance part (Minoo model) addresses some of these
    - Simulated data study has been performed
  - Simulated data study reweighted SK pion spectrum to match ND280 data-MC difference
  - See S. Dolan's talk for planned CC1pi measurements partly driven by this

	Predicted Rates at SK				Observed Rates
Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	
CCQE 1-Ring e-like ν-mode	73.5	61.5	49.9	62.0	74
CC1pi 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

Additional Processes

- Composed mainly of DIS and other multipion
  - Subdominant component for T2K
- T2K currently treat this with a single energy dependent normalisation uncertainty: $0.4/E_\nu$
- This parameter is starting to be pulled in fits
- Indicates that it may be time for a more advanced treatment
- T2K is considering:
  - Parton distribution function uncertainties
  - Bodek-Yang corrections
  - Hadron multiplicity uncertainties
  - Revisiting overall normalisation uncertainties
  - Work in progress by T2K not yet finalised



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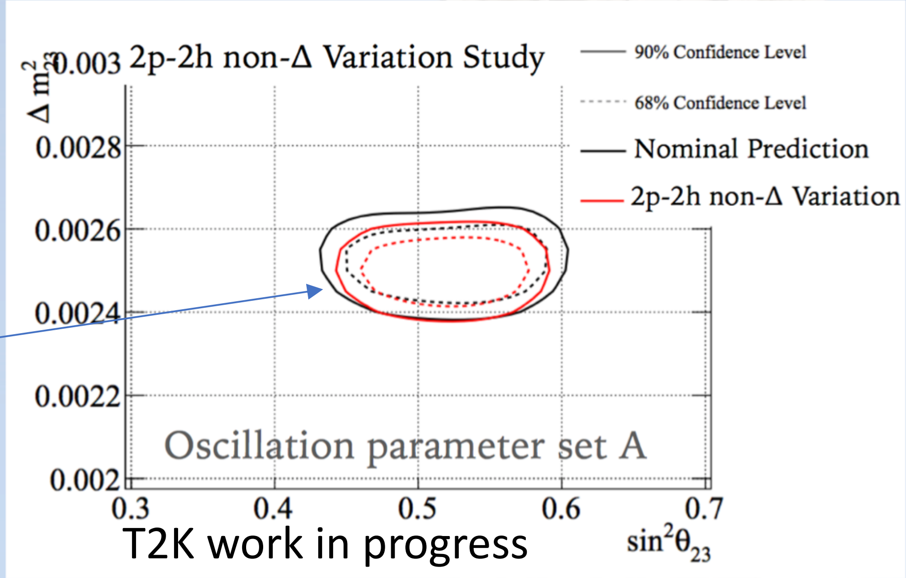
Effects on Analysis

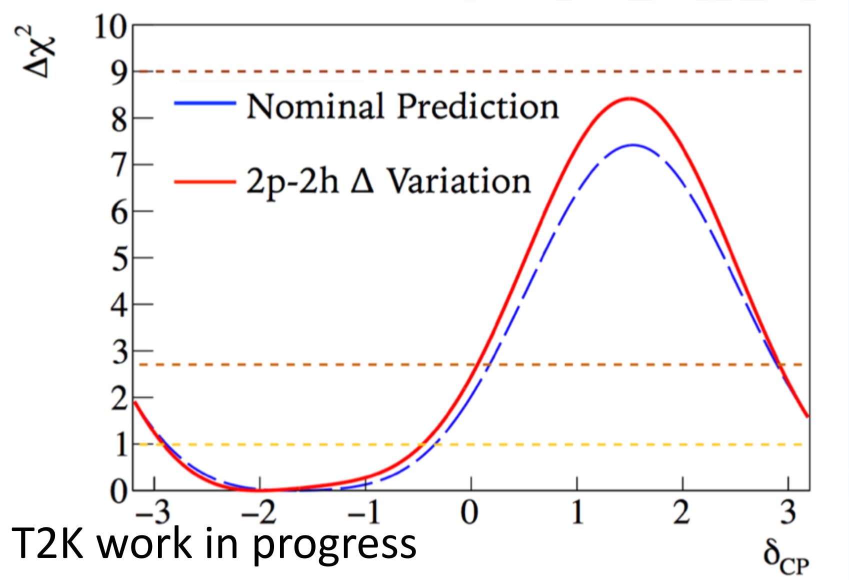
Current status

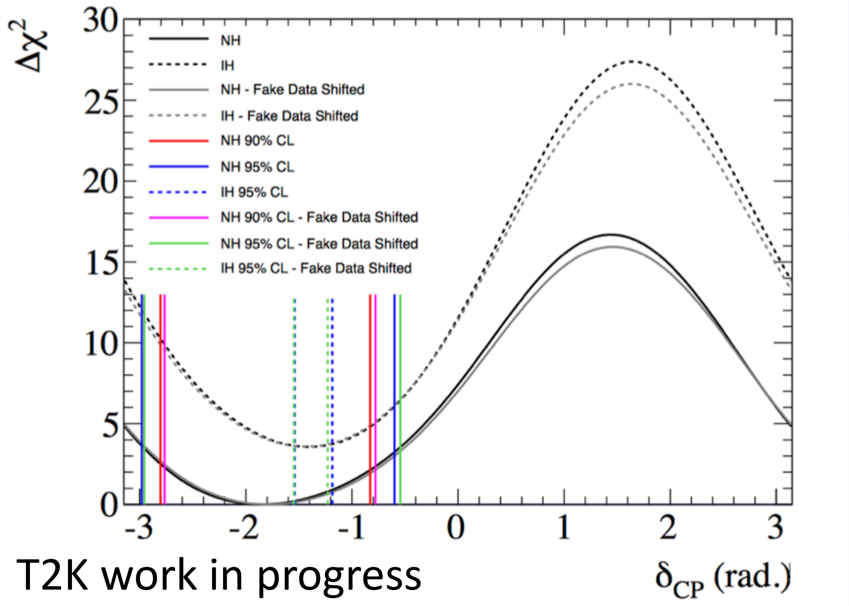
- Several simulated data studies give significant Δm^2_{32} biases
- Indicates that model doesn't have freedom to replicate reco-true energy mapping for these cases
- It is possible for simulated data to show significant bias on θ_{23} as well e.g.
- Additional systematics being added



Impact on δ_{CP}

- Need to check how changes to $\Delta\chi^2$ from simulated data studies affect statements on δ_{CP}
- Take $\Delta\chi^2$ difference observed in simulated data study (top plot) and shift observed $\Delta\chi^2$ in data (bottom plot) by that amount
- Impact on δ_{CP} intervals is small for all simulated data sets
- Statement that CP conserving values are excluded at 95% CL is unaffected

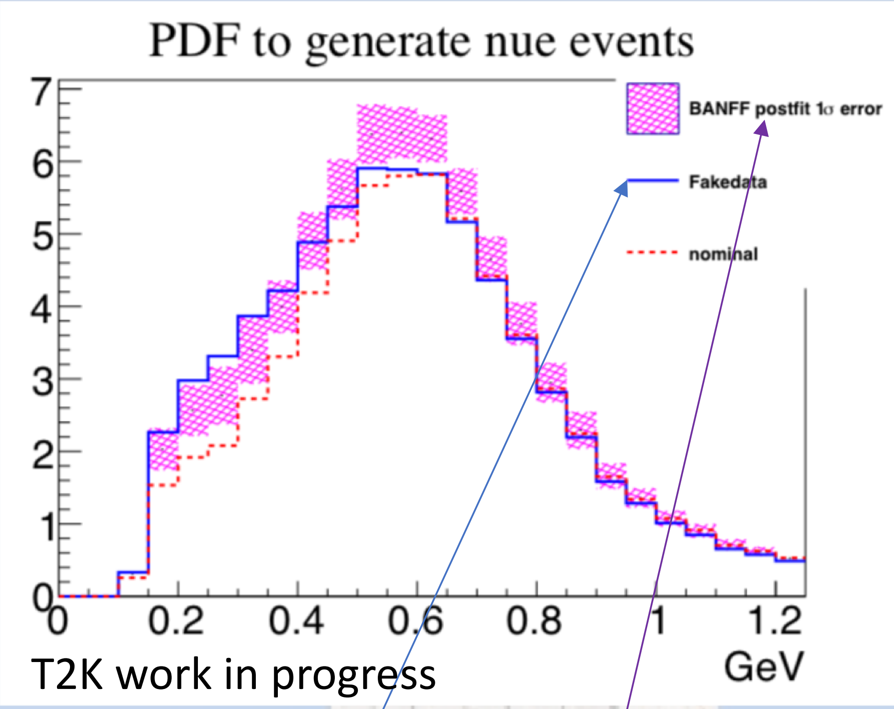




Mitigation plans

General Method:

- Biases caused by inability of model to accommodate different reco to true interaction rate mapping
- Add parameters to model to allow for that variation
  - Most simulated data sets cover known model deficiencies so variations well motivated



- In many cases, e.g. Eb, cannot currently make full theory based variation
- Add freedom to move event weights linearly from 1 to:

$$\frac{Number\ of\ events\ in\ bin\ at\ SK\ in\ SK\ simulated\ data}{Number\ of\ events\ in\ SK\ bin\ predicted\ by\ model\ when\ fit\ to\ ND280\ simulated\ data}$$

- Approximates the missing freedom of the model

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Mitigation plans

- Method on previous slide could be applied generically to a simulated data set
- Additionally in the case of Δm^2_{32} Gaussian smearing of post-fit contours can be done as the parameter is approximately Gaussian
  - Width chosen to be quadrature sum of biases seen in independent simulated data studies

Final sensitivity coming soon!

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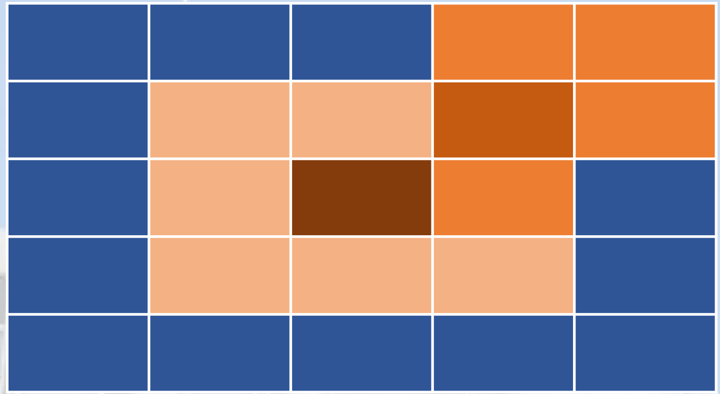
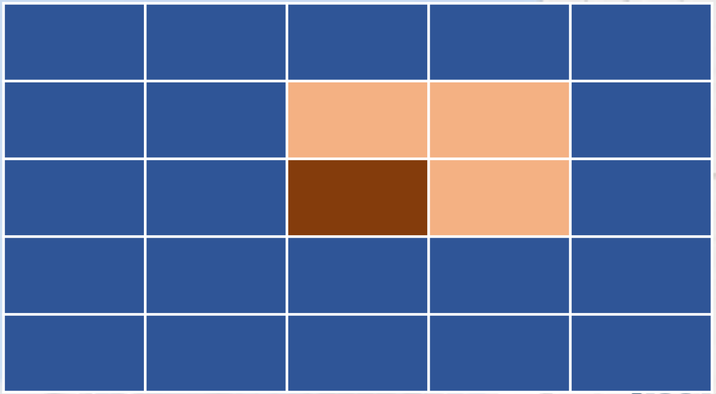
Future

What can we do in future?

- Improve interaction model: better Eb treatment planned for 2019
- A lot of issues involve unobserved hadrons: e.g. inferred kinematics (see S. Dolan)
- Several methods to get better measurements:
- Get a lower threshold detector, e.g. ND280 upgrade (see S. Dolan) or HPTPC
  - Low threshold measurements with several hadrons can constrain high threshold experiments where only highest momentum hadron is seen
- Do novel things with the one we've got, e.g. Vertex activity, Gas/wall analyses

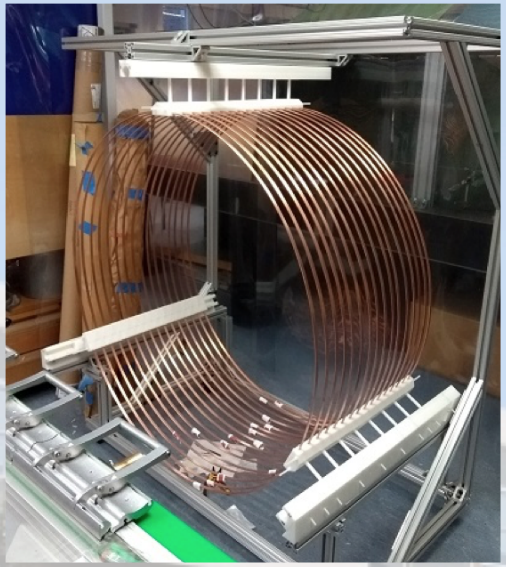


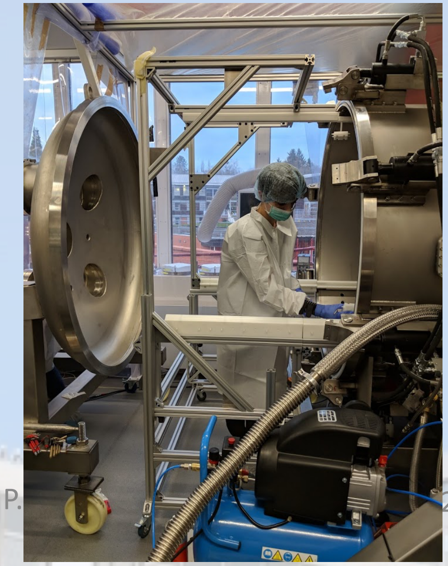
More vertex activity implies more below threshold hadrons

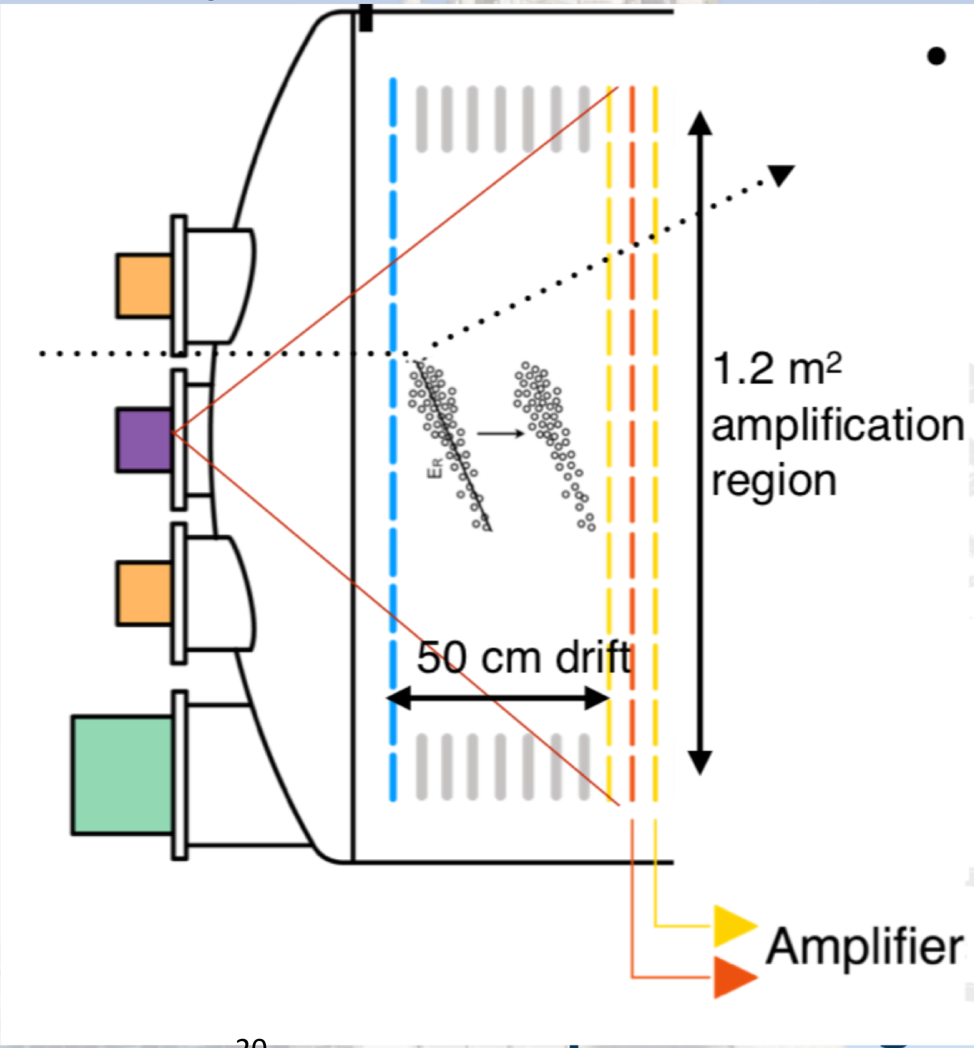


HPTPC

- High pressure gas TPC combines low threshold and acceptable mass
  - Proton momentum threshold ~50 MeV
- Can also switch between target gases
- Optically read out prototype being builtin the UK
  - Design tested before on DMTPC experiment: DOI: 10.1063/1.3700603
  - Beam test due in August: CERN-SPSC-2017-030







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Summary

- We know our model is far from perfect in several areas
  - CC0pi: Inferred kinematics, MINERvA/NOvA discrepancy, theory (Eb)
  - CC1pi: Known deficiencies, improvements expected soon (Minoo model)
  - Other CC: Small contribution with simplistic treatment, will be reviewed
- We try to assess whether this matters using simulated data
- We have a procedure to add an 'effective' uncertainty for problematic simulated data studies
- Better solution is to find ways to incorporate theory driven uncertainties in the analysis

Backup

List of all xsec parameters

CC0pi Inferred Kinematics

- Kinematic energy reconstruction assumes interaction mode and stationary initial nucleon
- System fully specified from lepton kinematics

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

$$E_p^{inferred} = E_\nu - E_\mu + m_p$$

$$\overrightarrow{p}_p^{inferred} = (-p_\mu^x, -p_\mu^y, -p_\mu^z + E_\nu)$$

- If you identify a proton in the event you can compare inferred and measured energy
- $\Delta p = |p^{measured}| - |p^{inferred}|$
- See S. Dolan's talk for more details

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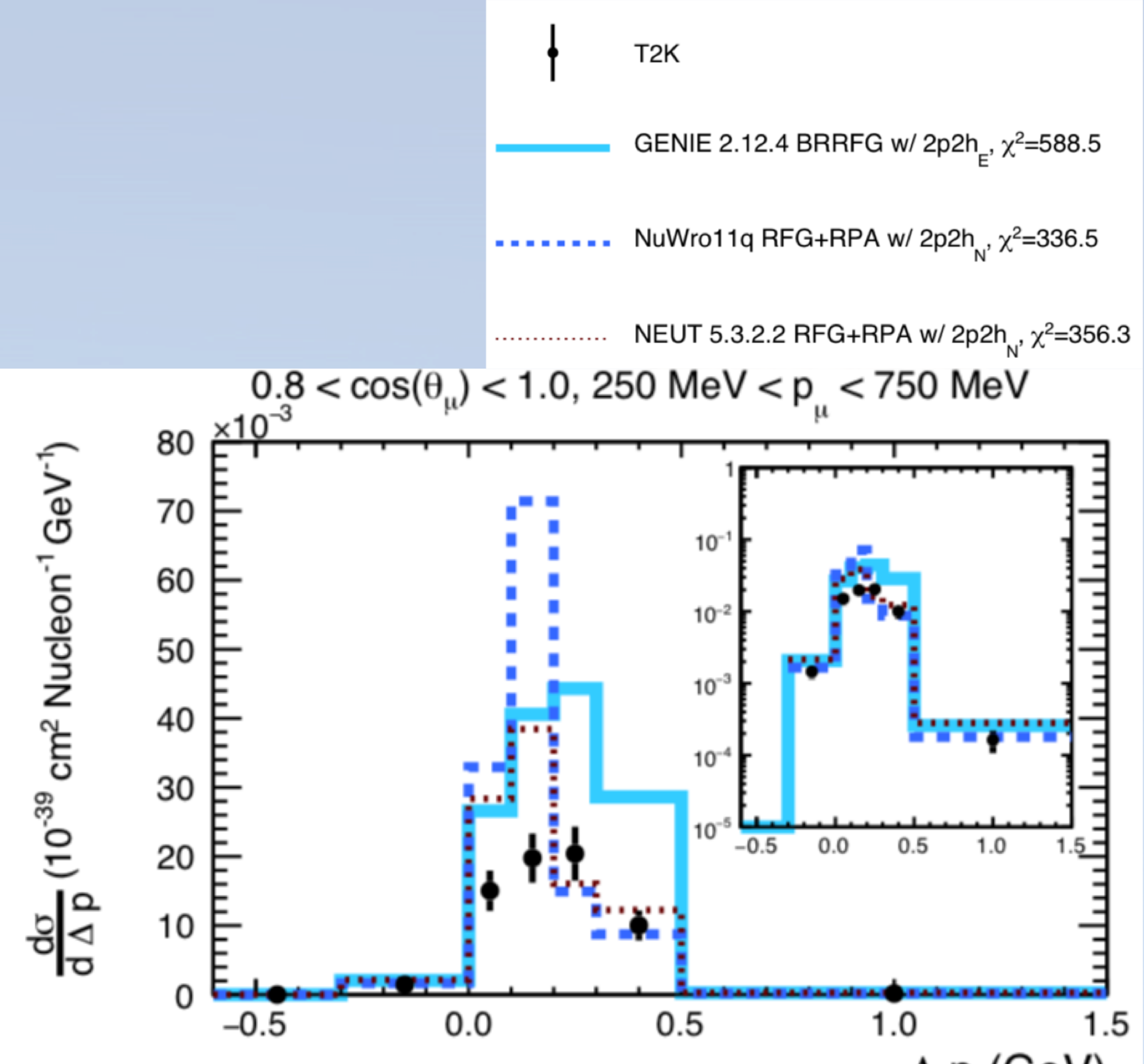
CC0pi Inferred Kinematics

- $\Delta p = |p^{measured}| - |p^{inferred}|$
- RFG+RPA model shows differences with data
- Present when modelled with both NEUT and GENIE
- Need to check this doesn't bias oscillation results
  - Concerning if underlying 1p1h/2p2h models are wrong
  - ND280 data driven, Benhar spectral function and Martini 2p2h model simulated data test robustness to model variations



arxiv:1802.05078

RFG (Relativistic Fermi Gas)
RPA (Random Phase Approximation)

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PMNS matrix

- Ignoring overall phase, general 3x3 unitary matrix can be broken down into 3 rotation matrices and a complex phase

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Oscillation probability in vacuum given by:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$

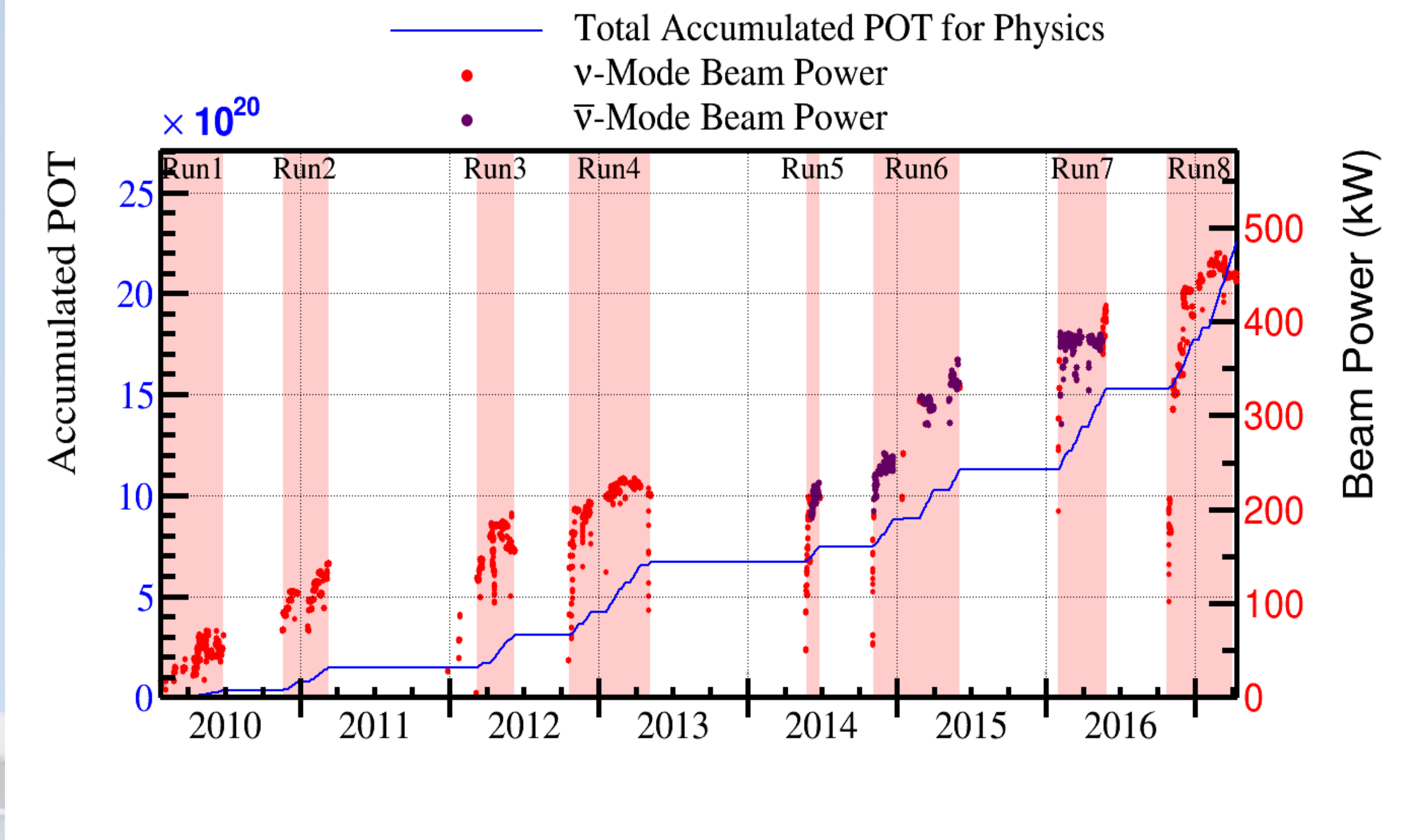
$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$

- Frequency of oscillation set by squared mass difference
- Relevant distance scale for experiment is L/E
- Amplitude of oscillation decided by mixing angles
- CPT symmetry implies $P(\alpha \rightarrow \beta) = P(\bar{\beta} \rightarrow \bar{\alpha})$
- Non-zero complex phase, δ_{CP}, would lead to CP violation

The T2K Experiment

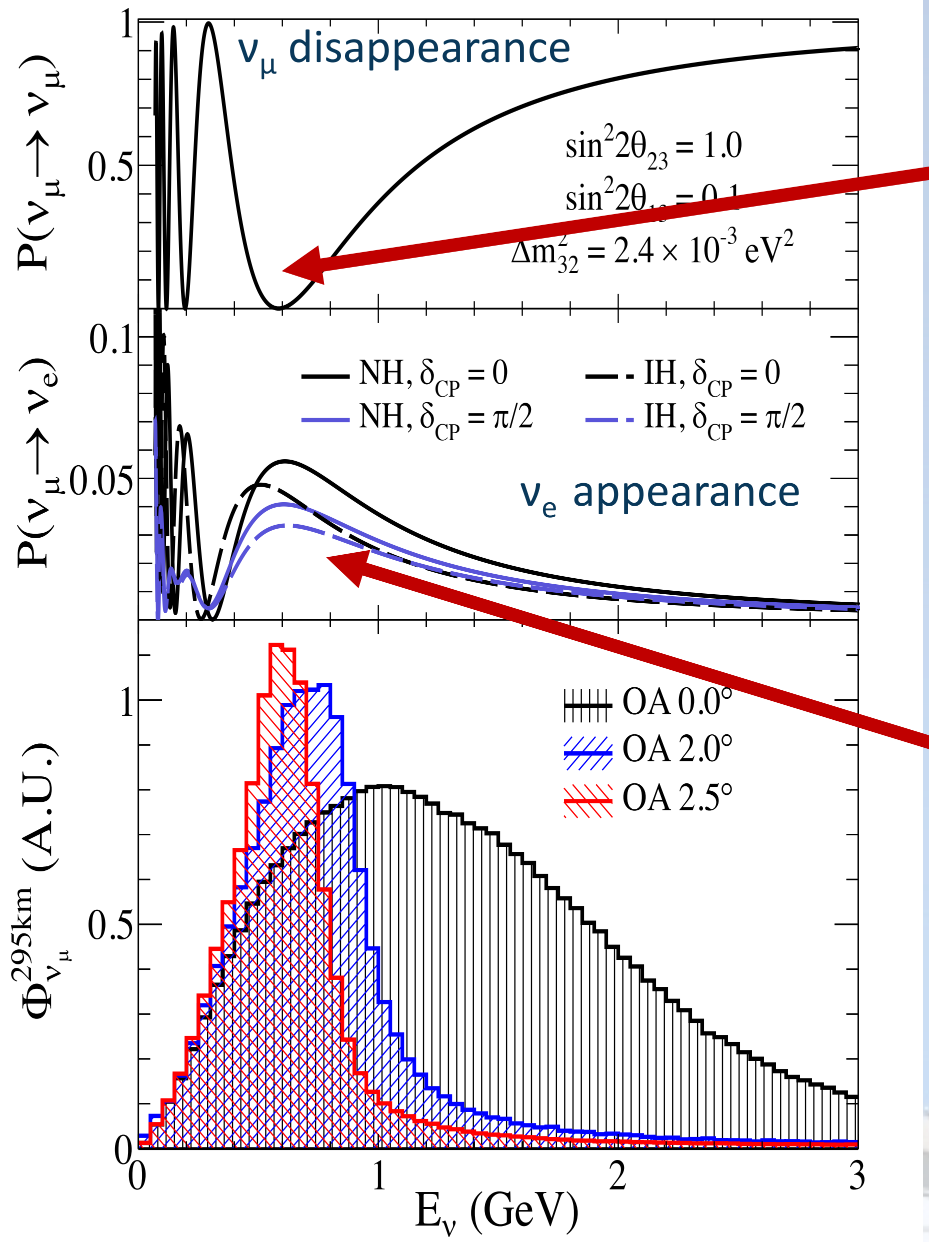
- Muon (anti) neutrino beam generated at J-PARC
- Near detector complex 280m from target measures beam before oscillation
- Beam travels 295 km to 50 kton Super-K detector to be measured after oscillations
- ~500 researchers, 62 institutes, 11 countries

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

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
- For 295km baseline first oscillation maximum is at 0.6 GeV

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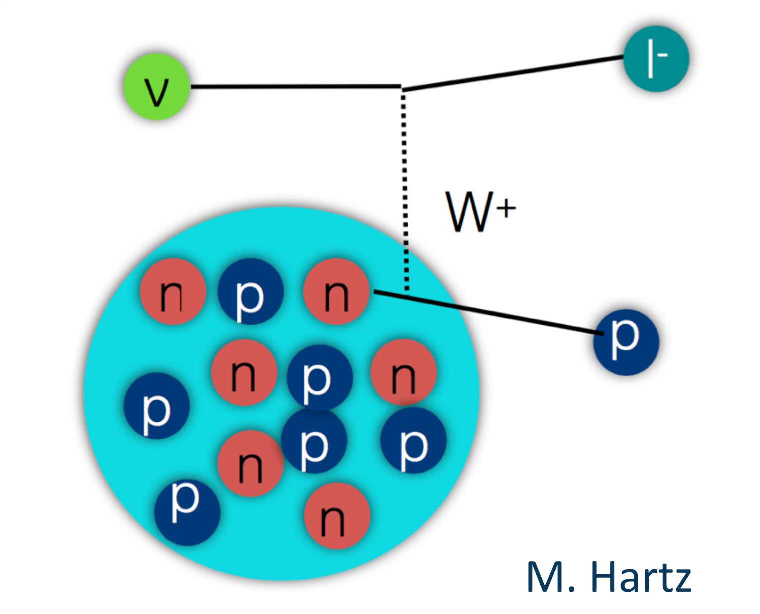
Detecting neutrinos



- Use charged-current neutrino-nucleus interactions
- Detect energetic final state lepton
  - Gives kinematic information and flavour ID
- Oscillation effects vary with E_ν
  - Recoil hadrons often below detection threshold and nuclear effects important so hard to reconstruct
- Construct variable as close to true energy as possible
- Assume quasi-elastic scattering from single bound nucleon (CCQE):

$$E_\upsilon^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

- Only uses particle masses, lepton kinematics and nuclear model

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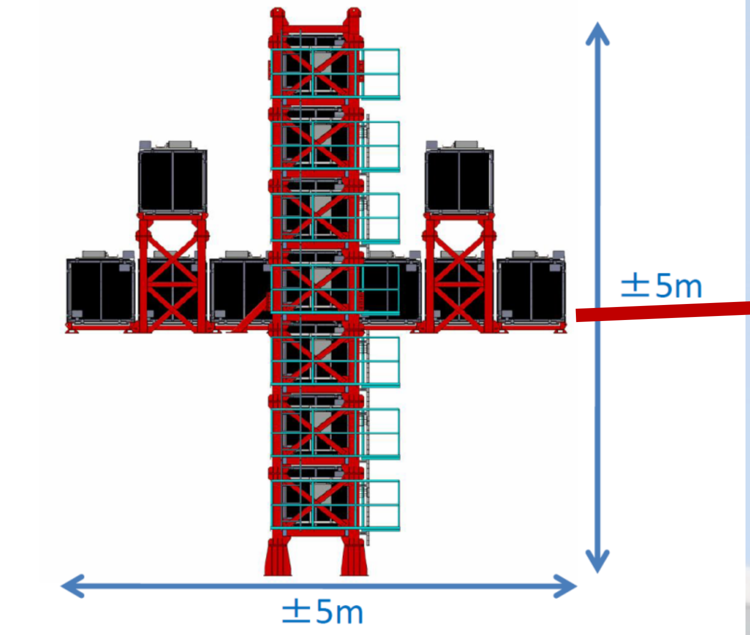
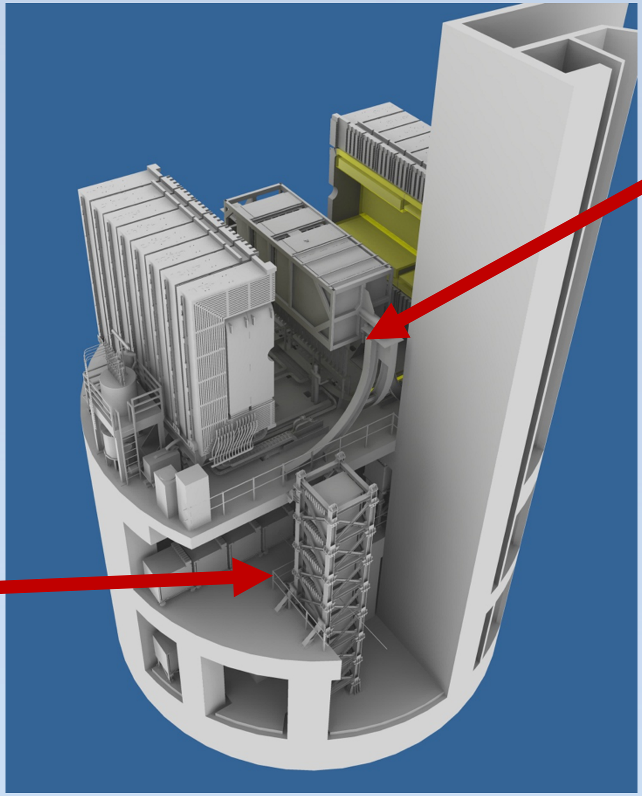
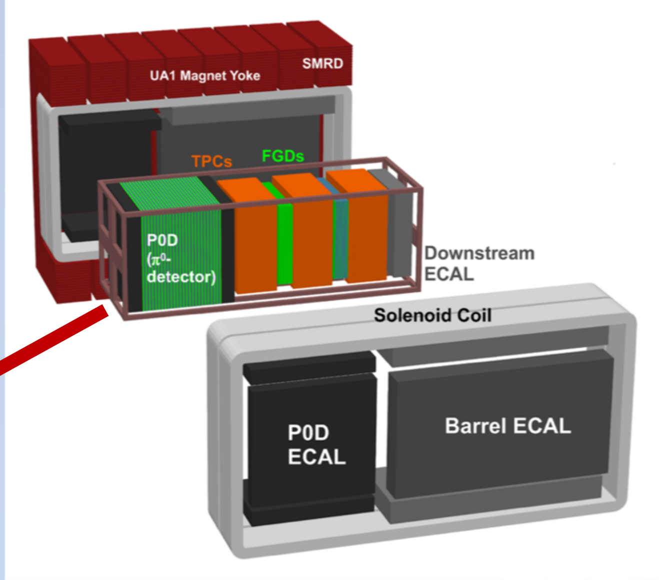
Near detectors

INGRID

- On-axis detector
- Monitors beam direction and constrains flux







ND280

- 2.5^o off-axis (same as Super-K)
- Constrains cross-section and flux uncertainties

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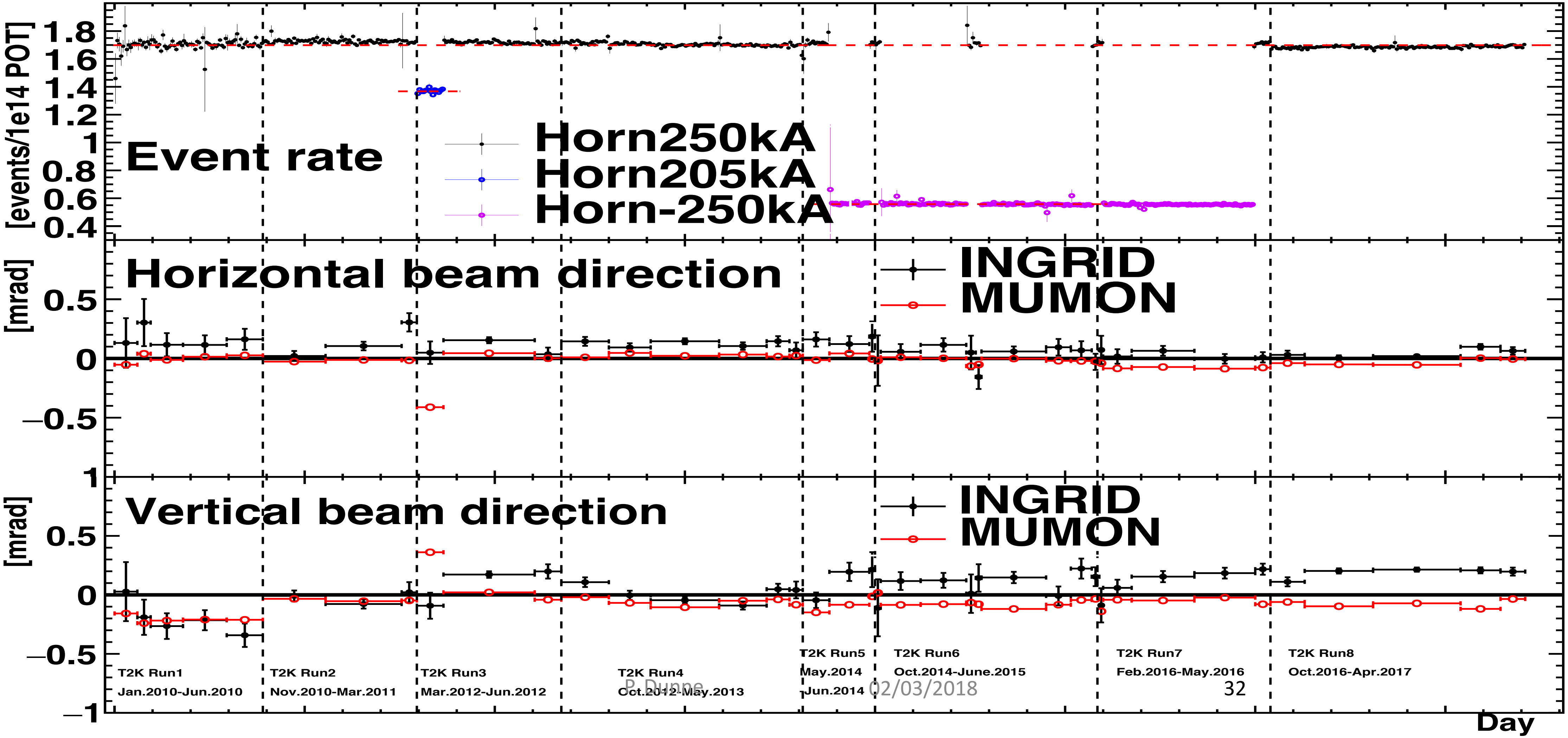
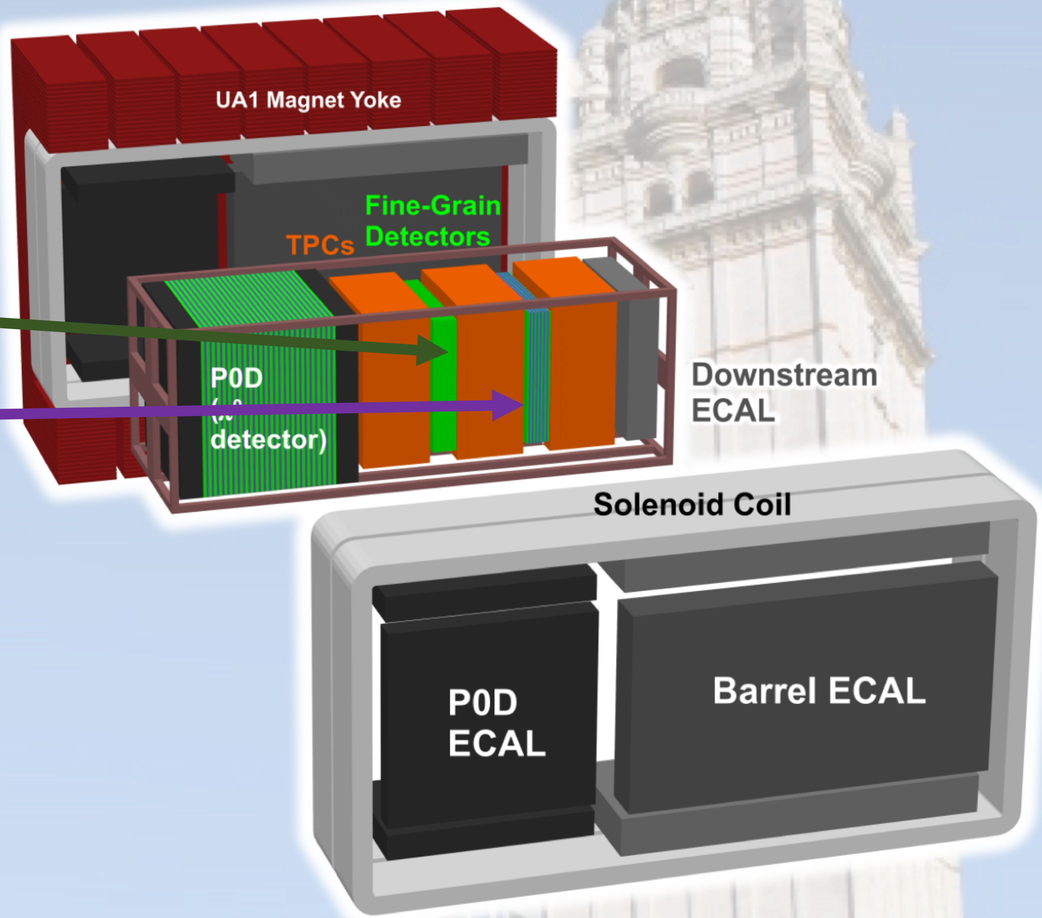
INGRID

- Design beam direction tolerance 1 mrad

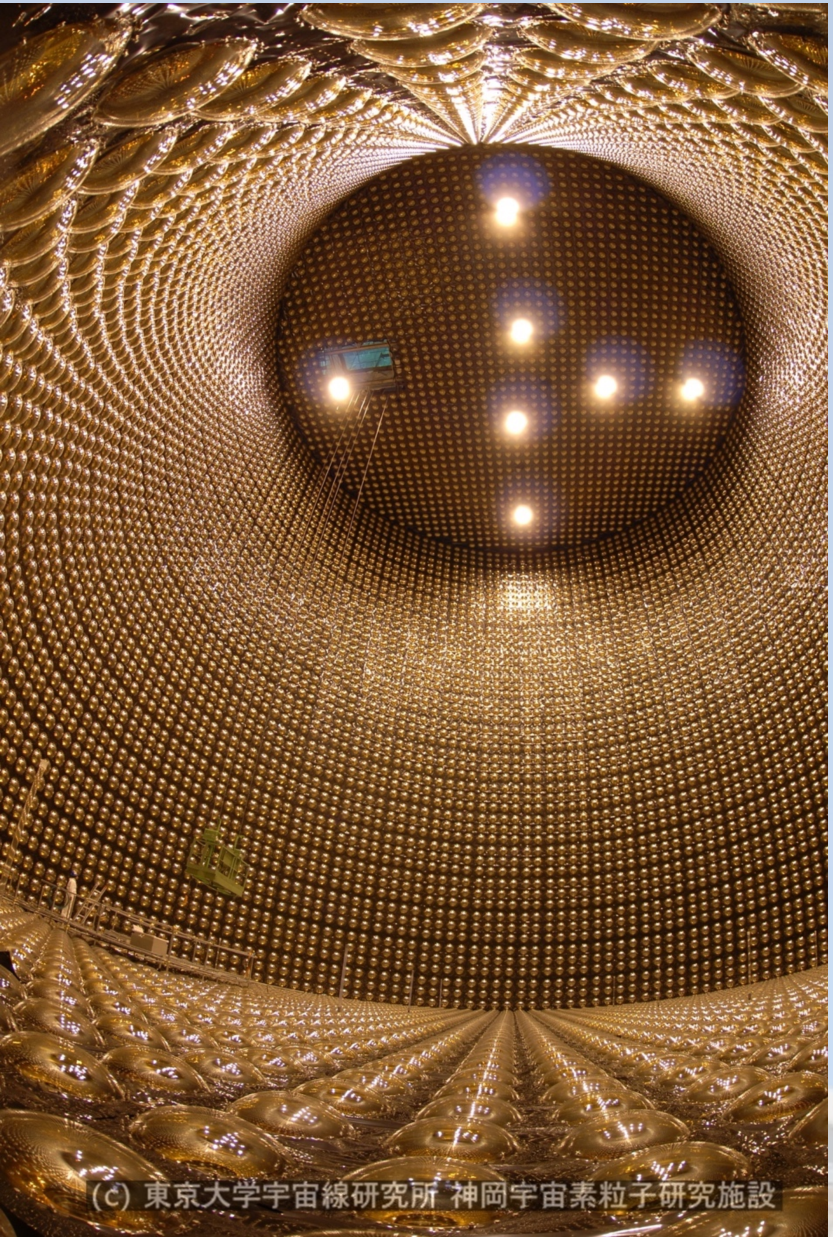


ND280

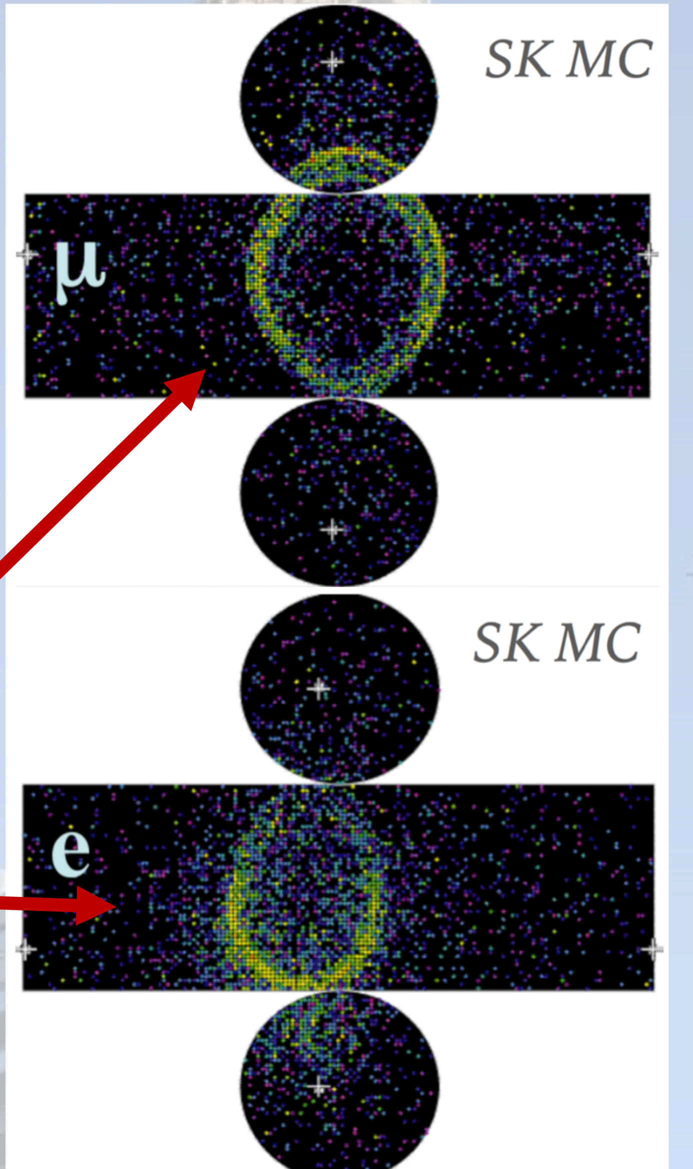
- Measures neutrinos before they oscillate
- Two fine-grained detector (FGD) targets
  - FGD1 – Active carbon target
  - FGD2 – Active carbon and passive water layers (same nucleus as SK)
- Magnet + three TPCs
  - Refurbished 0.2T UA1 magnet
  - Particle charge + momentum from curvature
  - Particle ID From dE/dx – 0.2% mis-ID rate



Super-K



- 50 kt 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



ND280 samples and selection

- ND280 aims to constrain cross-section and flux uncertainties
- Separate samples for FGD1 and FGD2: allows separation of Carbon and Oxygen
- Separate samples by particle content: attempt to isolate interaction modes
- SK is not magnetised so neutrino contamination of antineutrino beam is important to constrain

<table>
<tr><th></th><th colspan="6">FGD1</th><th colspan="6">FGD2</th></tr>
<tr><td>ν events in neutrino mode</td><td colspan="2">CC0pi</td><td colspan="2">CC1pi</td><td colspan="2">CCNpi</td><td colspan="2">CC0pi</td><td colspan="2">CC1pi</td><td colspan="2">CCNpi</td></tr>
<tr><td>$\bar{\nu}$ events in antineutrino mode</td><td colspan="3">CC1track</td><td colspan="3">CCNtrack</td><td colspan="3">CC1track</td><td colspan="3">CCNtrack</td></tr>
<tr><td>ν events in antineutrino mode</td><td colspan="3">CC1track</td><td colspan="3">CCNtrack</td><td colspan="3">CC1track</td><td colspan="3">CCNtrack</td></tr>
</table>

SK samples

- Looking for ν_μ disappearance and ν_e appearance
  - 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

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

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

- Recently we also include neutrino mode sample targeting charged-current interactions with an additional pion
  - Neutrino mode: 1 e-like ring, 1 decay electron
  - Reconstructed energy formula adjusted accordingly

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

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

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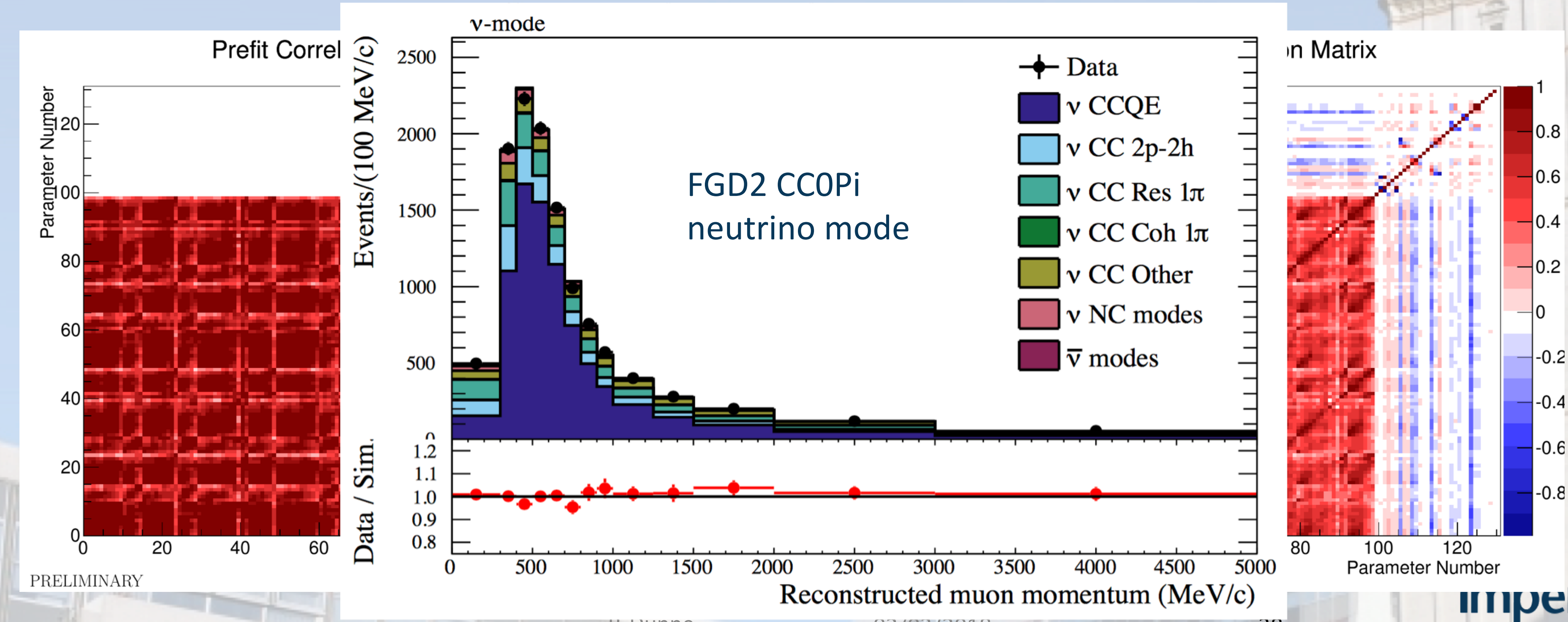
Near Detector Fit Results

Near detector fit results

- Flux and cross-section parameters have similar effects
  - ND Fit leads to significant anti-correlation reducing overall uncertainty
- Fit reproduces data well (p-value 0.47)

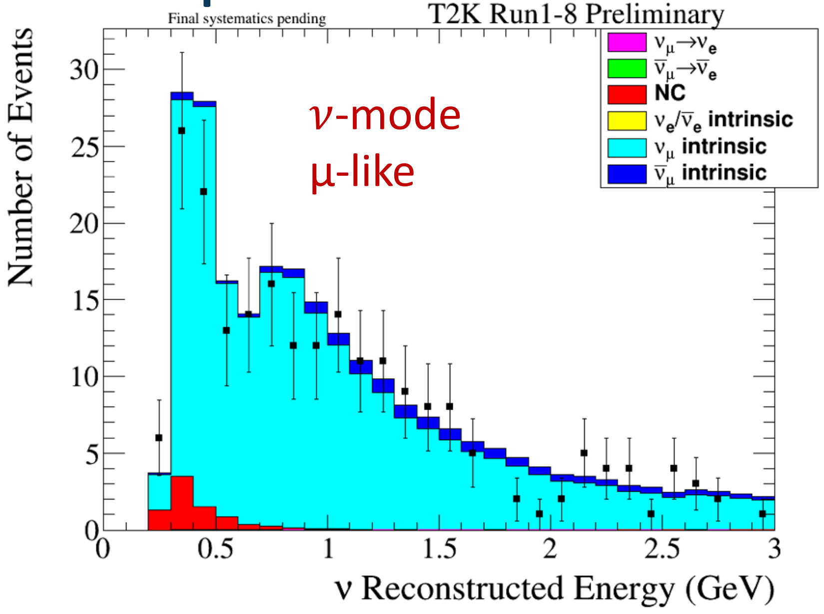


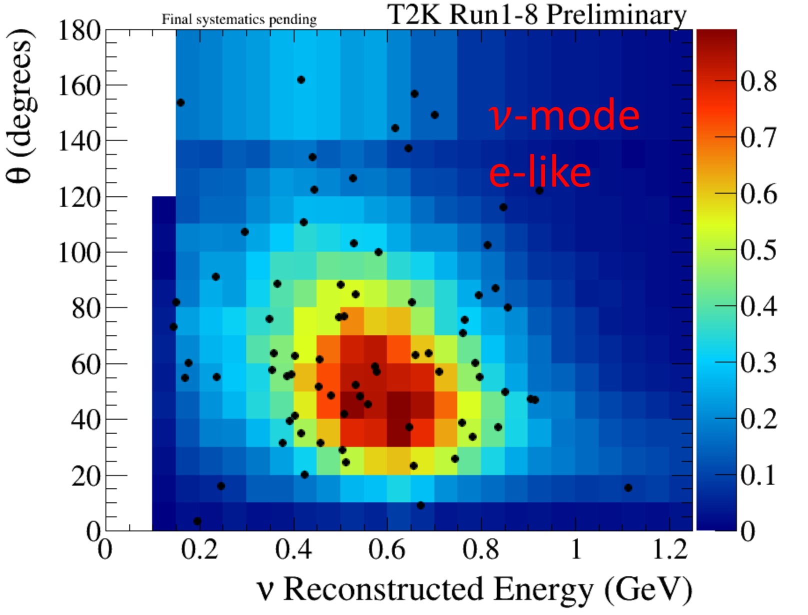
Predicted and observed Super-K event rates

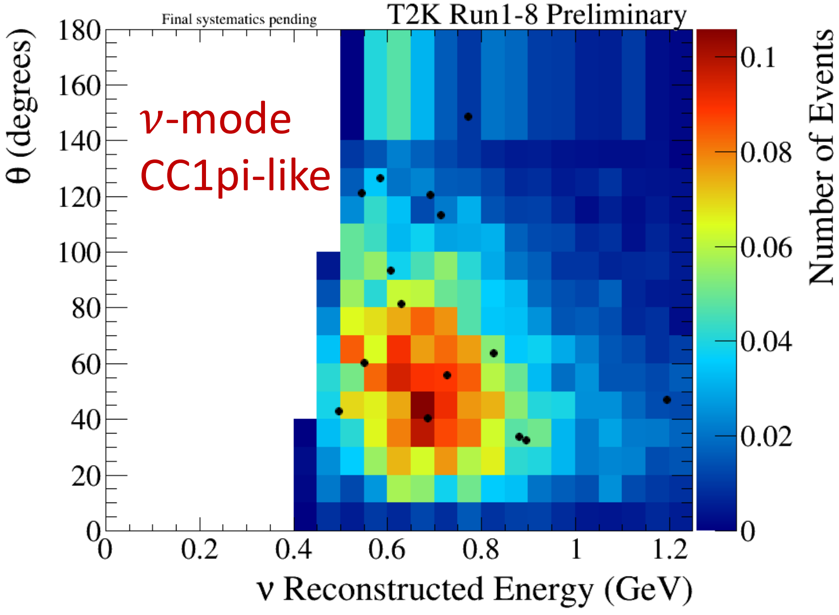
Sample	Predicted Rates				Observed Rates
	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = π/2	δ_{CP} = π	
CCQE 1-Ring e-like ν-mode	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like ν-mode	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like $\bar{\nu}$-mode	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like ν-mode	267.8	267.4	267.7	268.2	240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

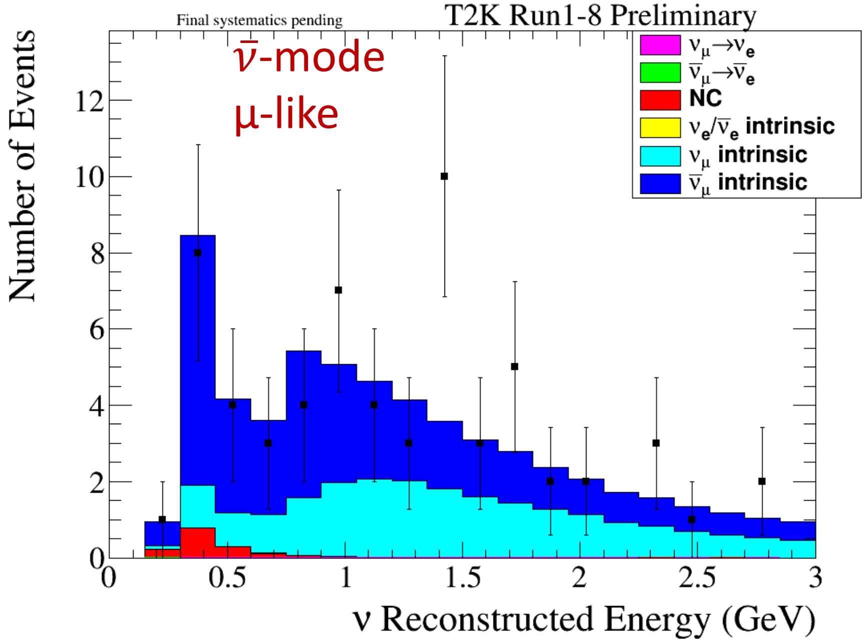
- Other oscillation parameters at set A values: maximal θ_{23}
- Number of events observed generally agrees with oscillated predictions
  - e-like sample rates are most consistent with δ_{CP} = -π/2 hypothesis
  - μ-like sample rates consistent within statistical and systematic errors
  - CC1π rate shows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

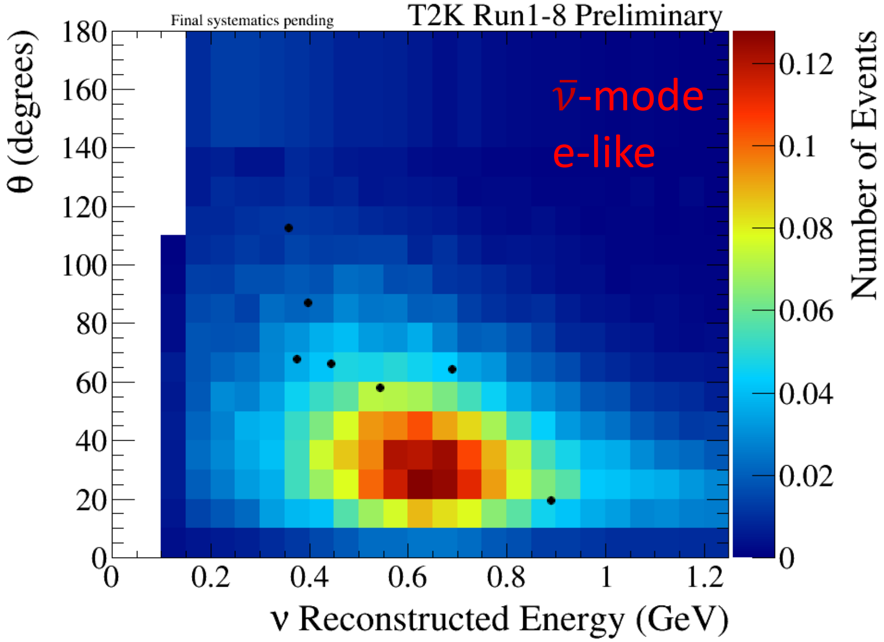
SK spectra


Final systematics pending
T2K Run1-8 Preliminary
$\nu_\mu \to \nu_e$
$\bar{\nu}_\mu \to \bar{\nu}_e$
NC
$\nu_e/\bar{\nu}_e$ intrinsic
ν_μ intrinsic
$\bar{\nu}_\mu$ intrinsic
ν-mode
μ-like
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
$\bar{\nu}$-mode
μ-like
$\nu_\mu \to \nu_e$
$\bar{\nu}_\mu \to \bar{\nu}_e$
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)

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

Far Detector Event Rate Predictions and Uncertainties

Oscillation parameters used for predictions

- Define two sets of oscillation parameter values used for event rate and sensitivity predictions
- Parameters generally at previous T2K 2013 best fit 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

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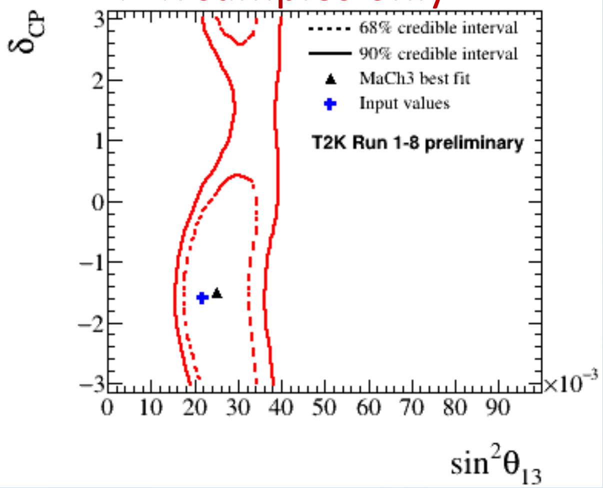
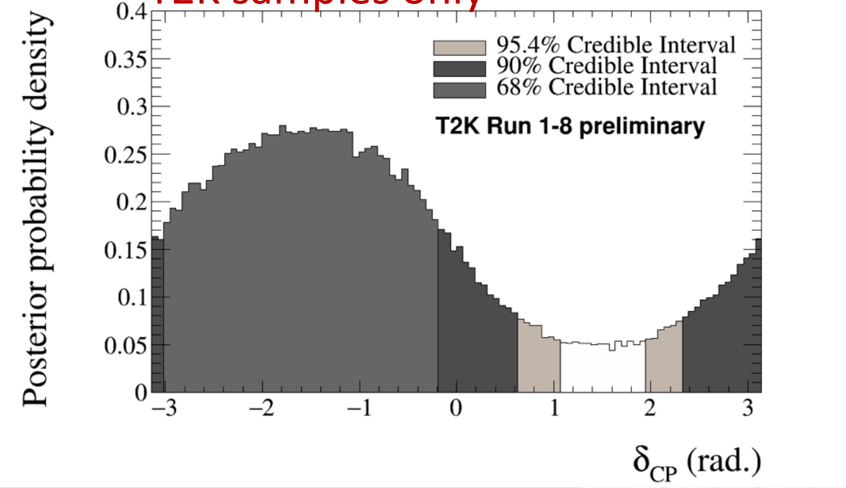
Sensitivities

Set A sensitivity

T2K samples only



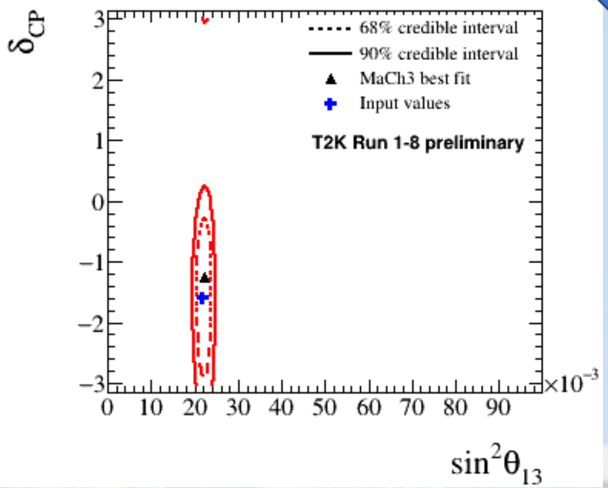
T2K samples only



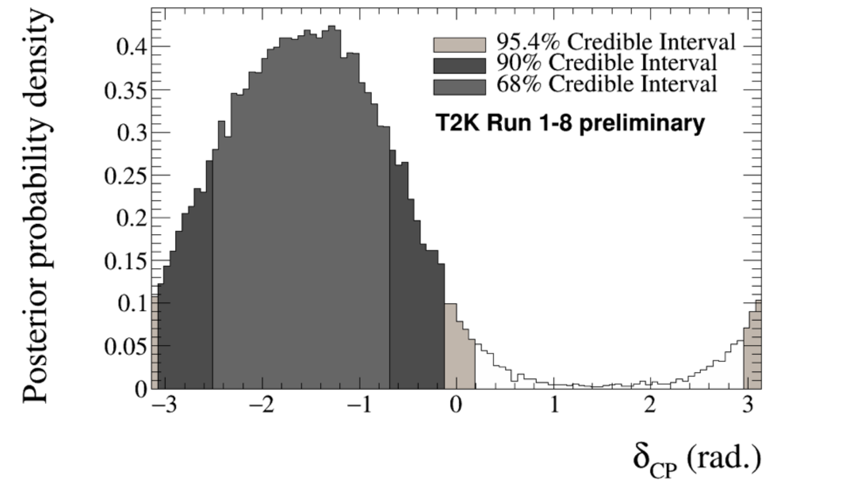
Integrate out $\sin^2\theta_{13}$ dependence

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

T2K +reactor constraint

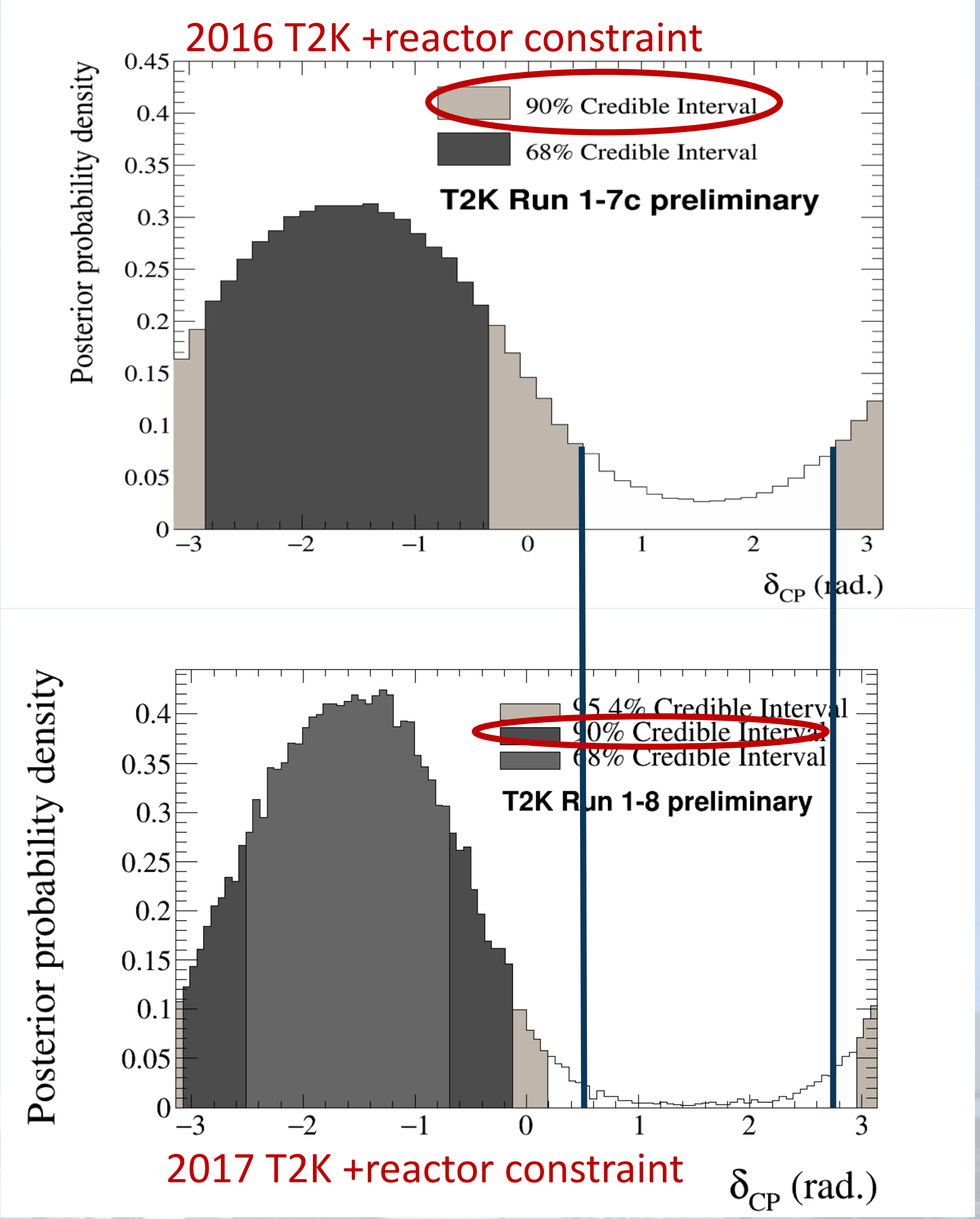


T2K +reactor constraint



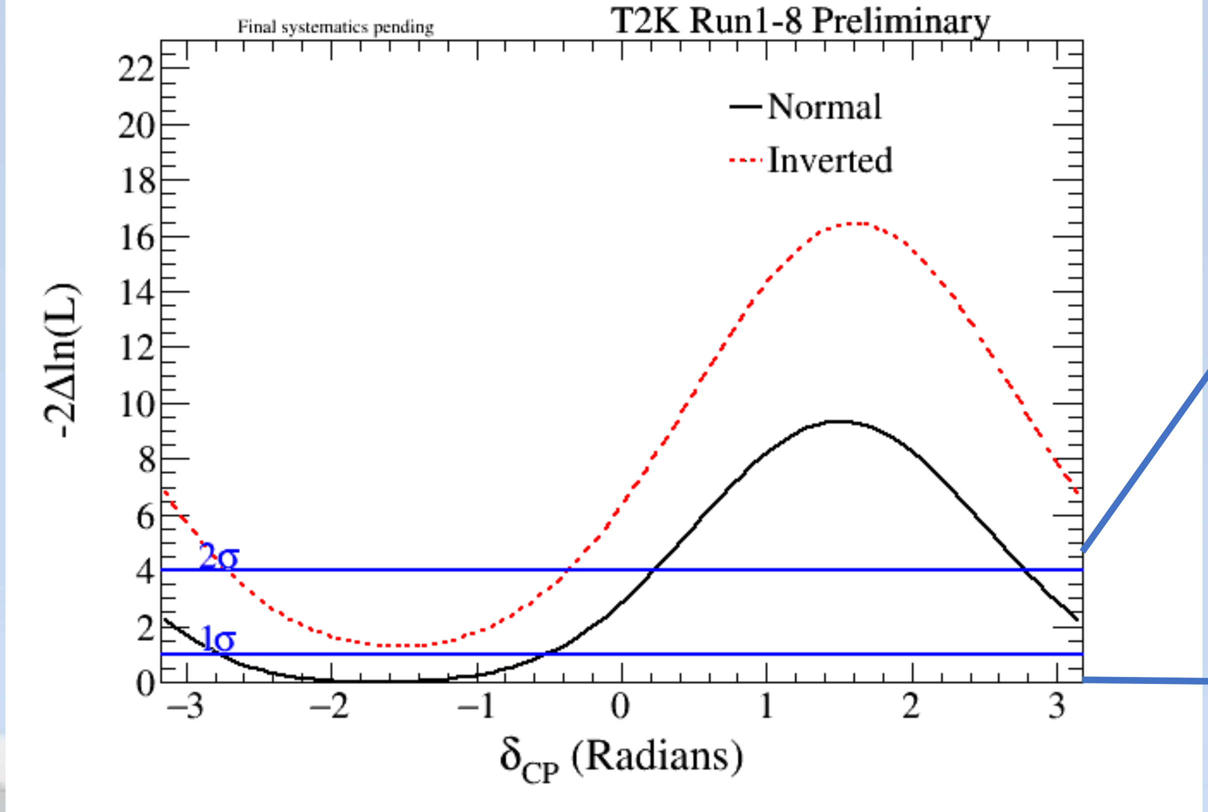
Integrate out $\sin^2\theta_{13}$ dependence

Comparison to Summer 2016 sensitivity

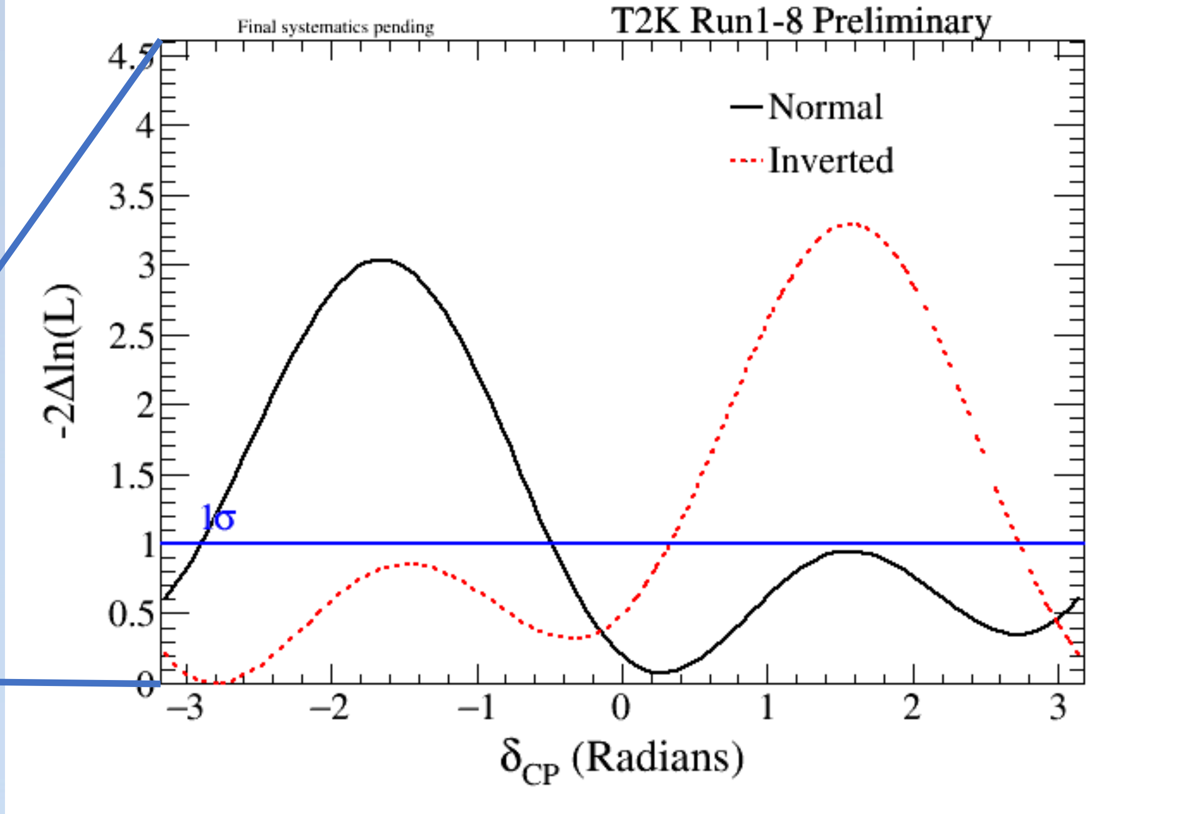


Set A vs Set B sensitivity

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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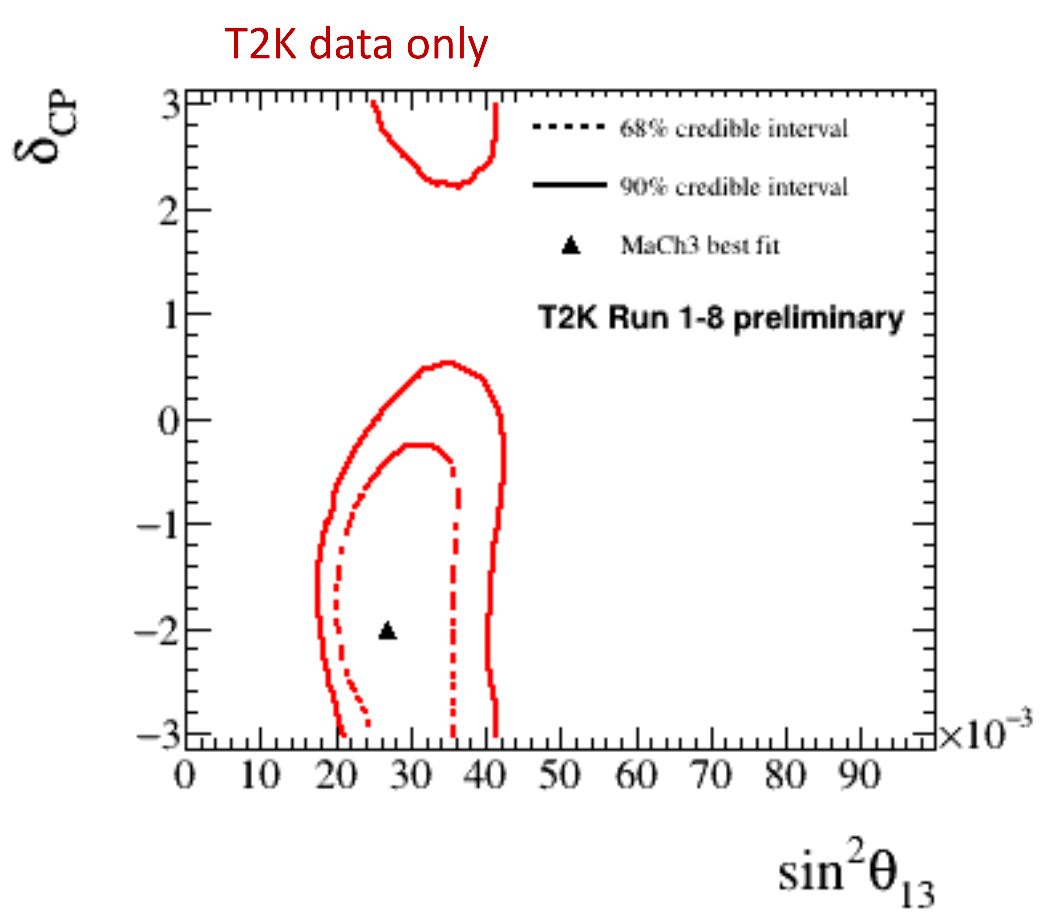
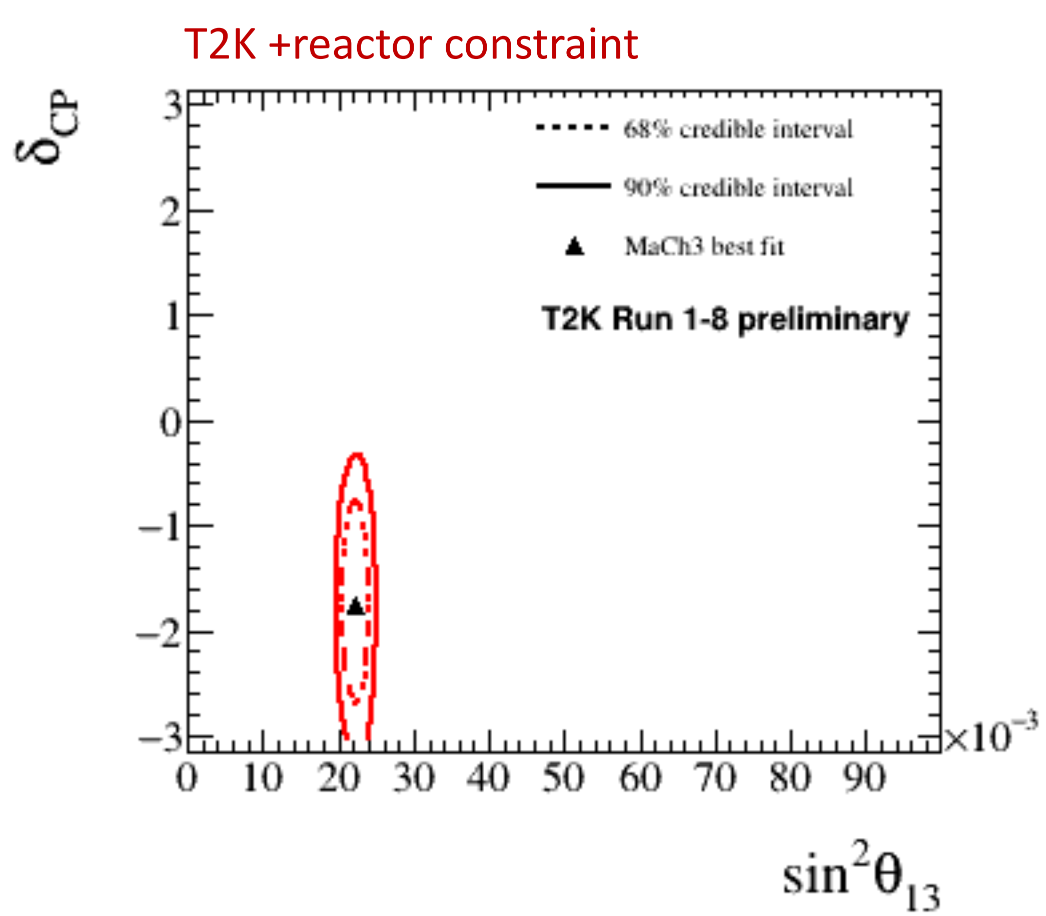
Data results

Appearance parameter constraints





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

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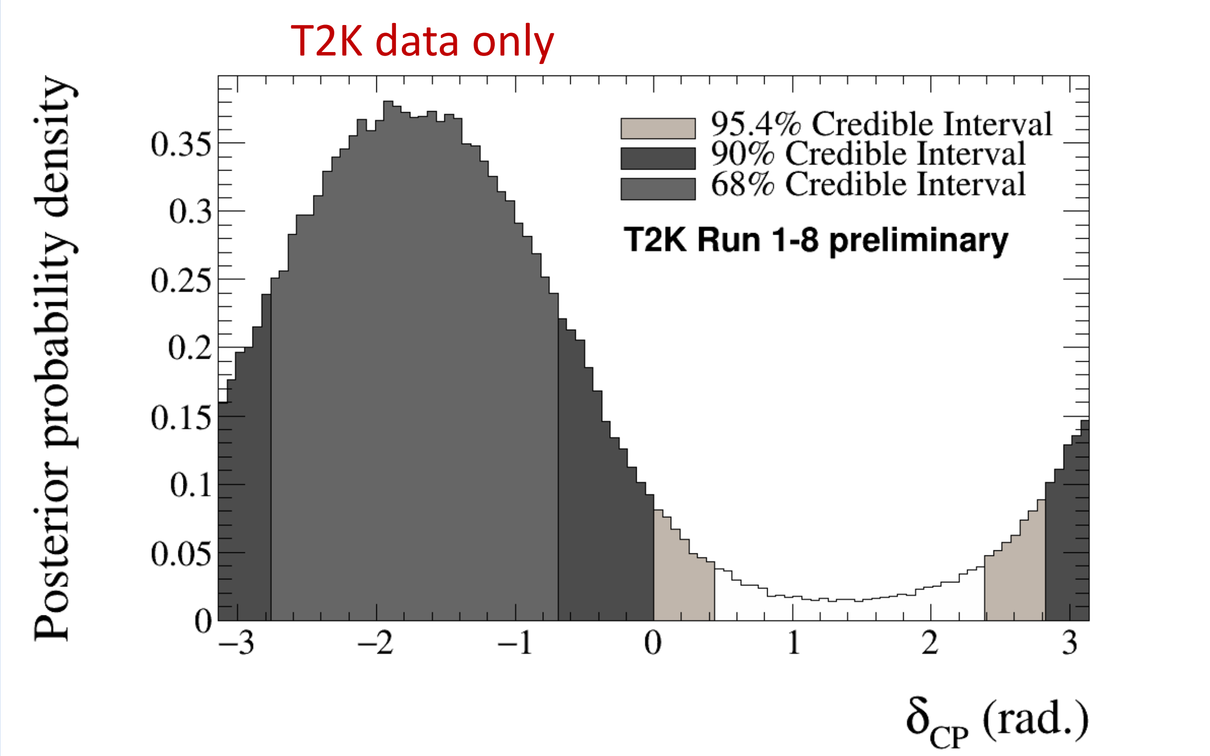
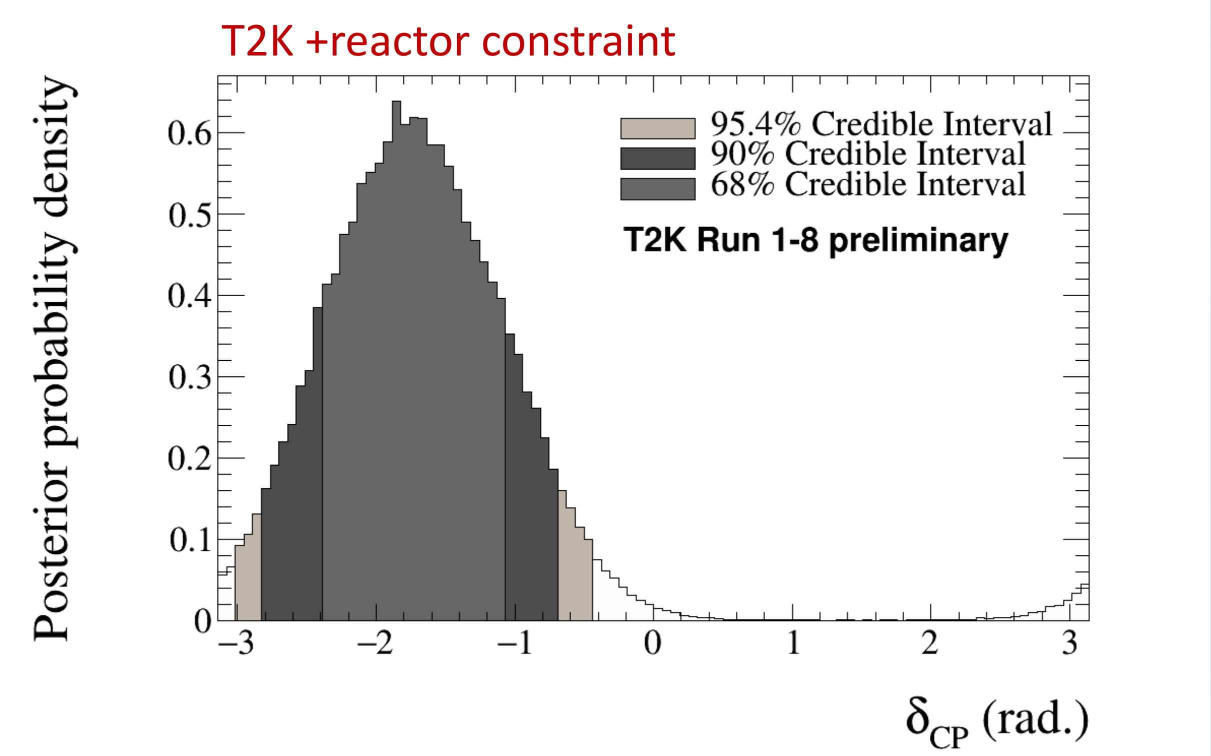
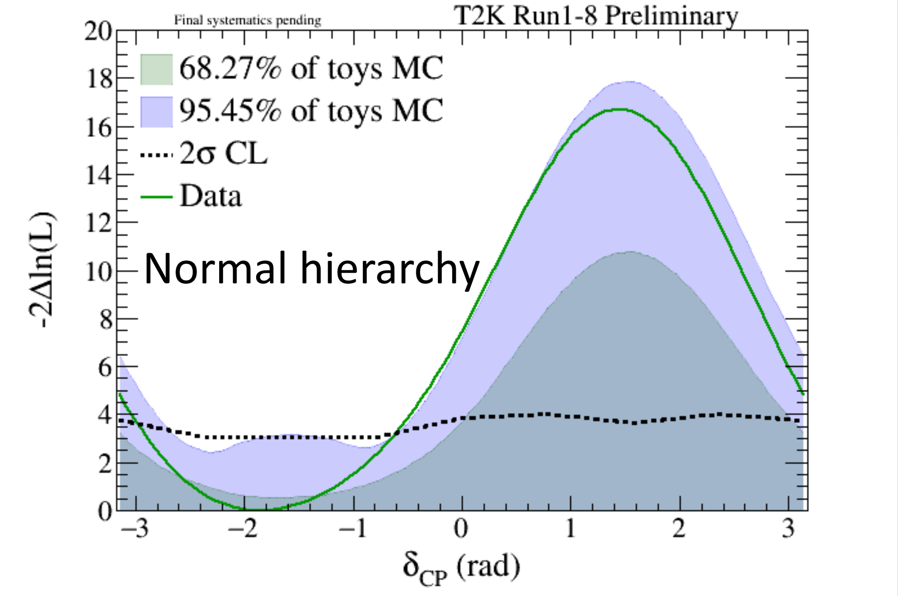
δ_{CP} Constraint

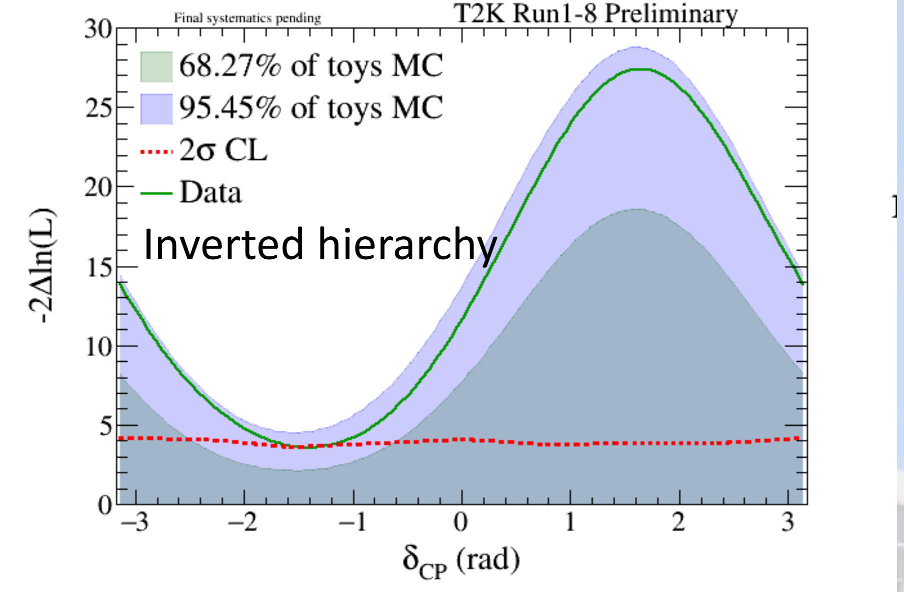




- CP conserving values outside 2σ (95.4%) interval for T2K+reactor constraint

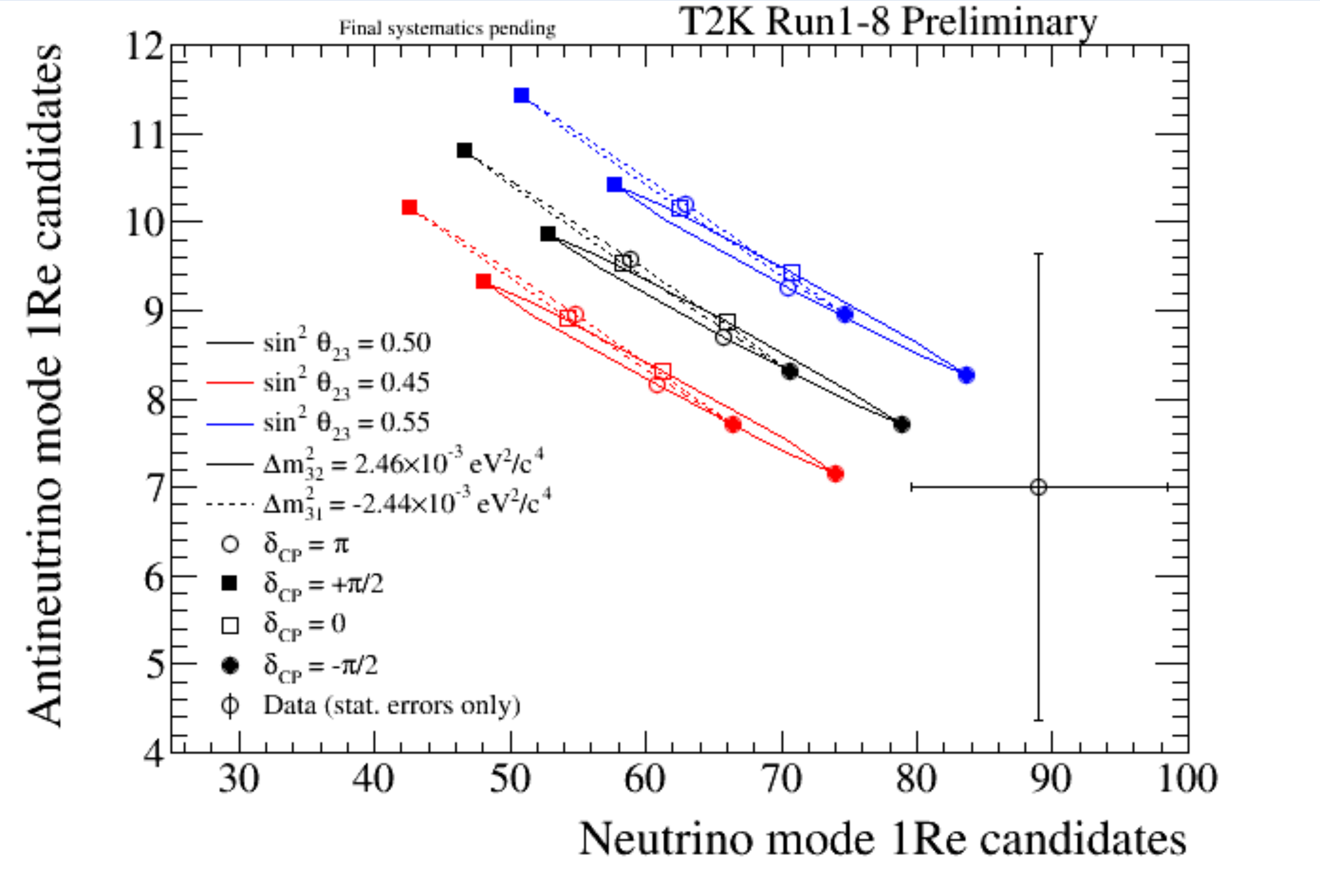
Constraint vs sensitivity





- Observed constraint stronger than predicted sensitivity
- Studied how likely this was to happen
- Generated many toy data sets with statistical and systematic fluctuations around δ_{CP}=-π/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

Biprobability plots



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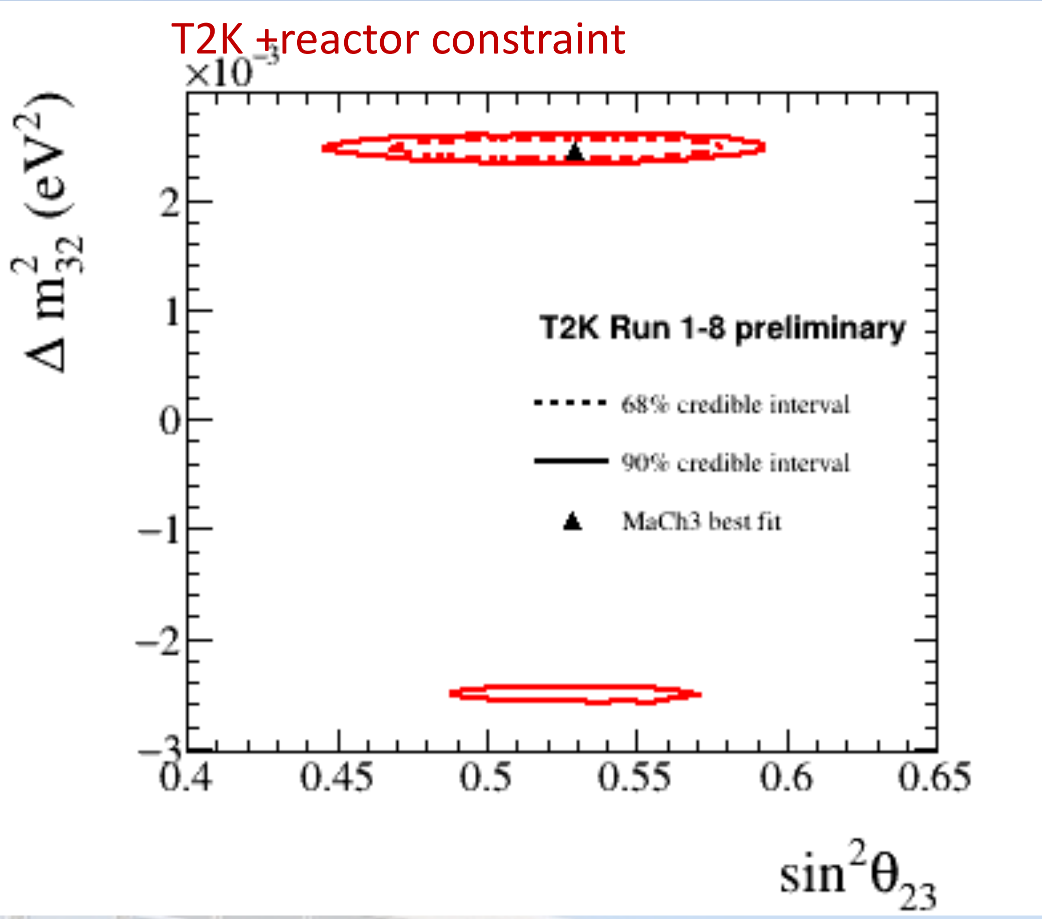
Octant and hierarchy preferences



- Result consistent with maximal $\sin^2\theta_{23}$
- Preference for normal hierarchy
- Systematics may change due to simulated data studies

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

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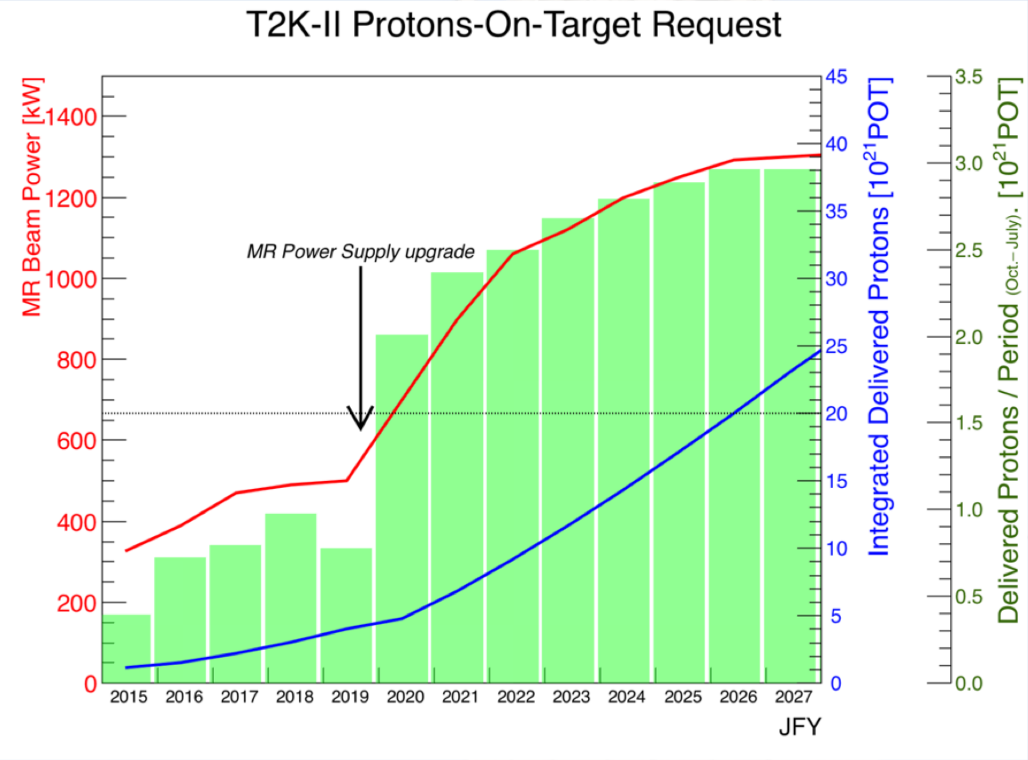
Future plans

T2K-II

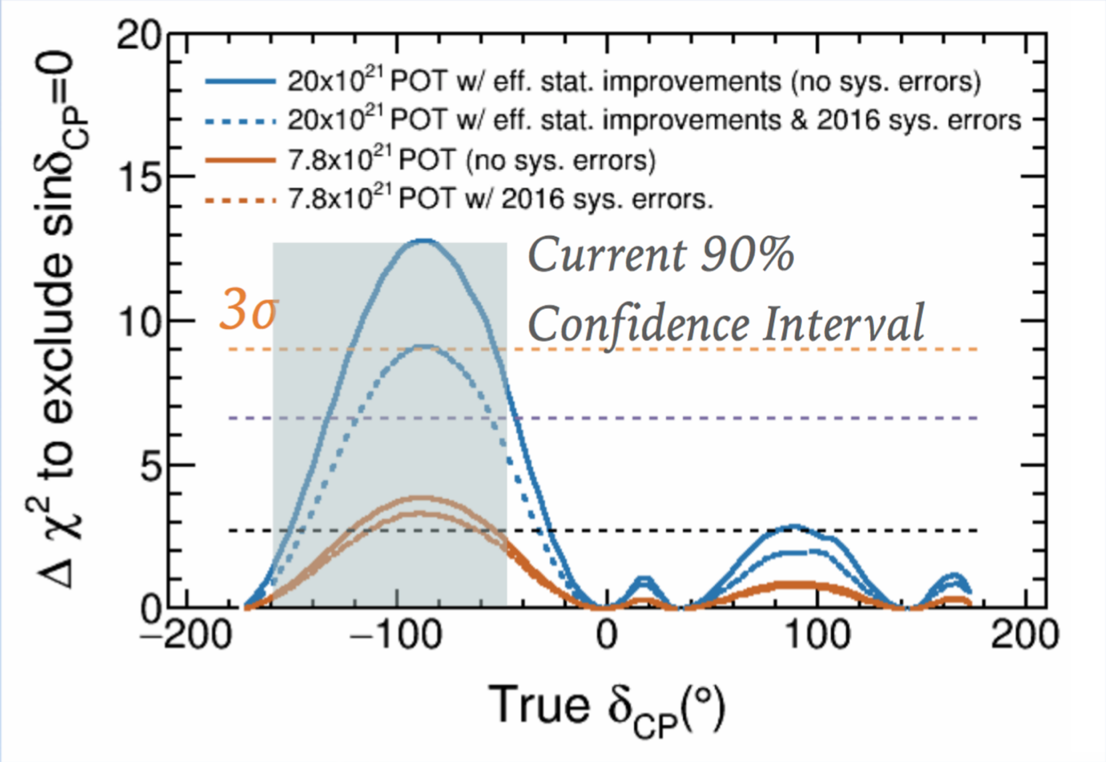
- T2K target protons on target (POT) is 7.8×10^{21}
- T2K-II is a proposal to extend target to 20.0×10^{21} POT by ~2026
  - Upgrade Main Ring power supply to increase from 0.4->1 Hz running
  - Beam power increase up to 1.3 MW

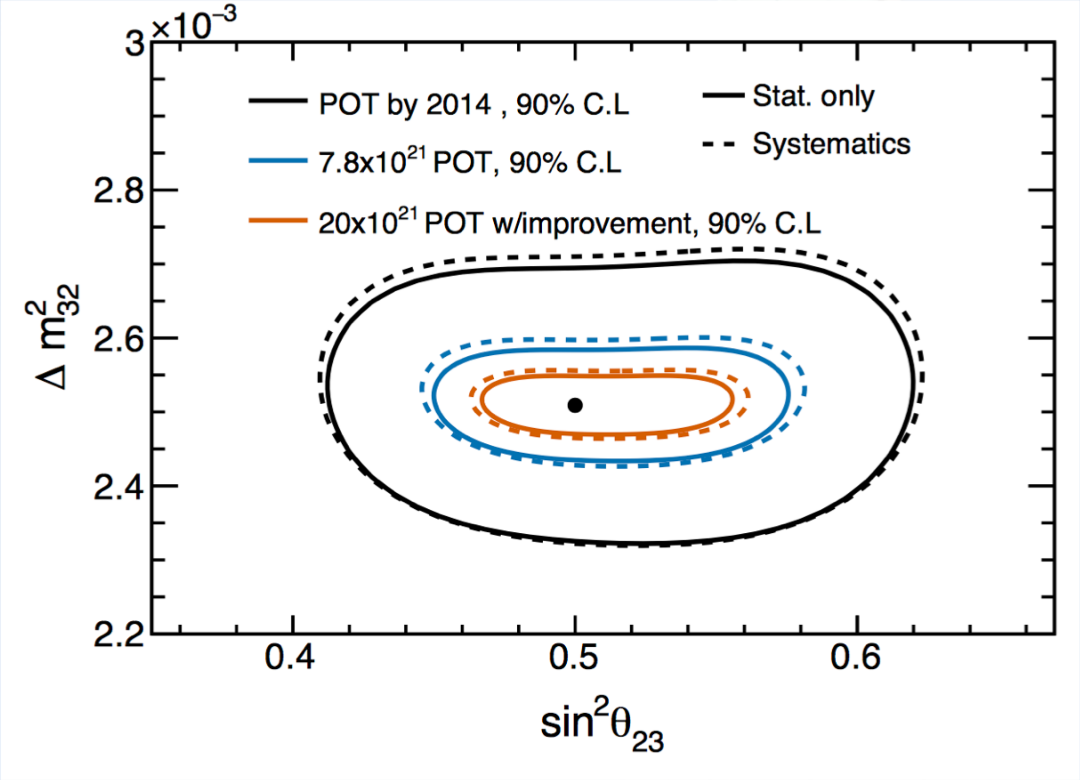


Other beam and detector upgrades

- 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

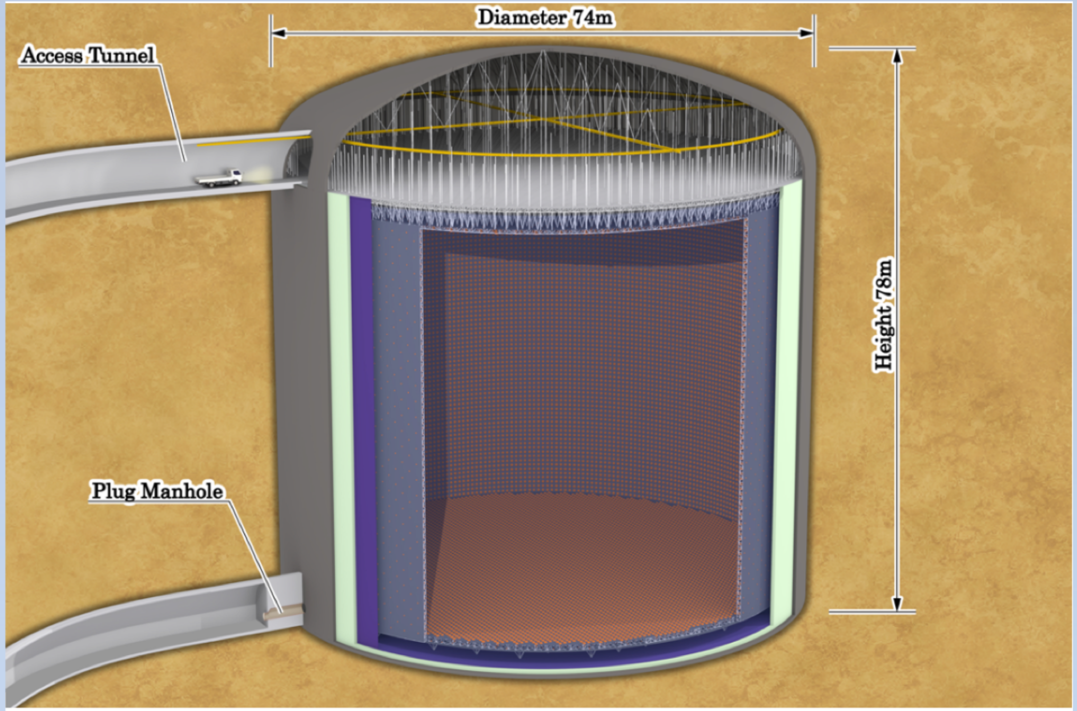


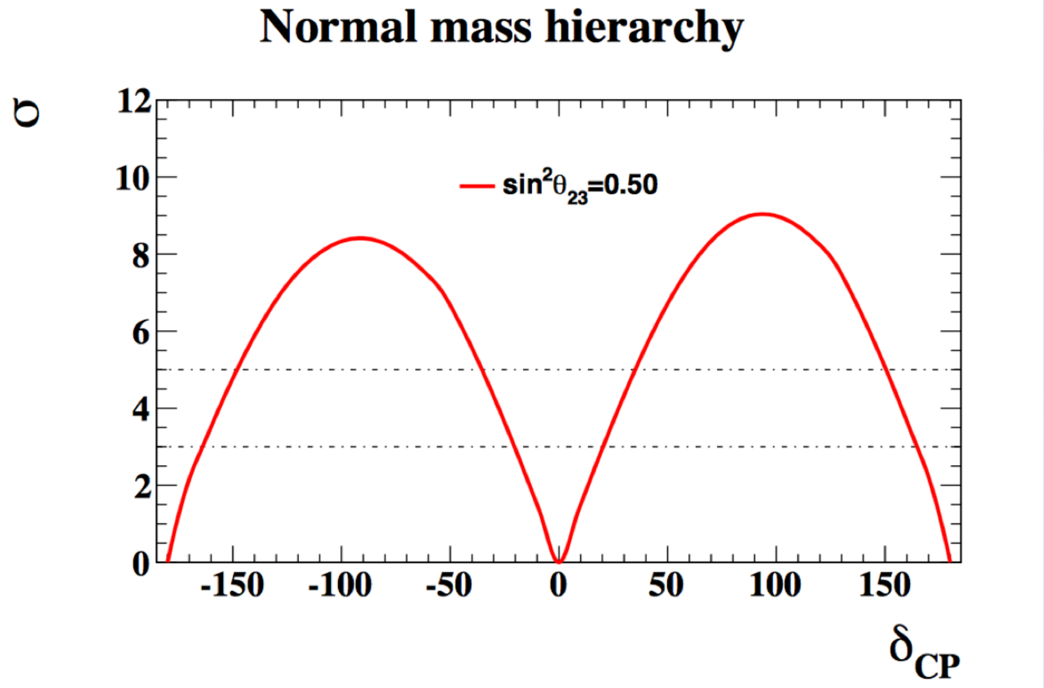


- If current preferred δ_{CP} is true T2K-II has potential for 3σ discovery
- Size of systematic uncertainties has large effect on sensitivity

Hyper-K

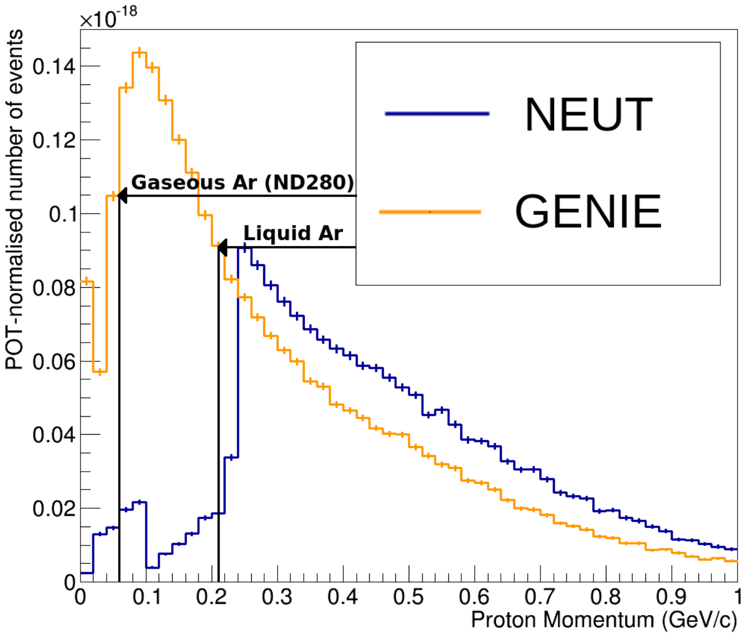
- Larger successor experiment to Super-K
- 187 kton fiducial volume (7x T2K design)
- 1300 kW beam power (2x T2K design)
- Aiming for 5σ δ_{CP} observation unless value is unfavourable
- Possibility to build second tank in Korea at second oscillation maximum
    - Oscillation effects look different
    - Reduces systematic sensitivity and breaks degeneracies
- Also gives world leading proton decay measurements and supernova neutrino sensitivity
- Aim for physics data taking in 2026



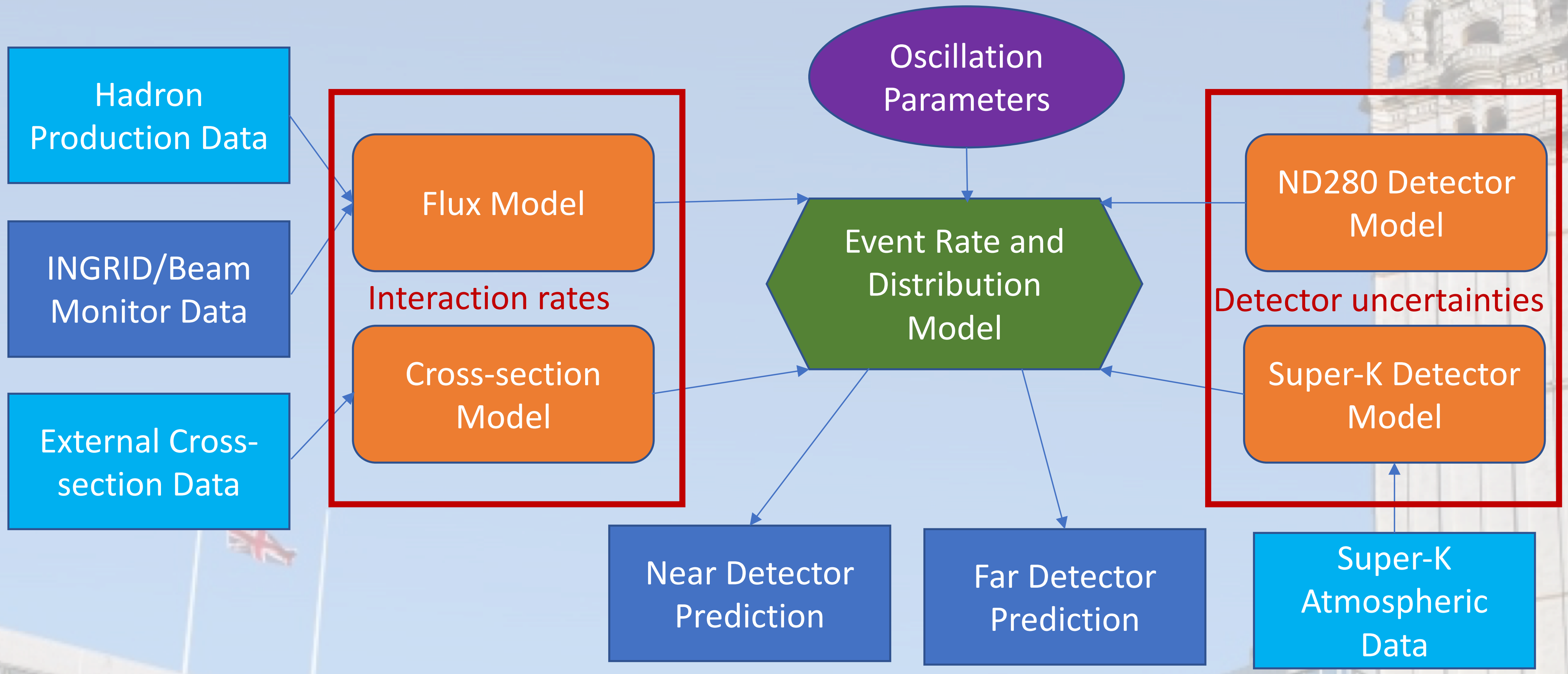


HPTPC – High Pressure TPC

- Reducing systematics key to future oscillation measurements
  - DUNE & HK aim for ~1%
- Current MC generators give different predictions just outside accessible energy range
- Gaseous target has much lower threshold
  - Gas density usually too low for high interaction rate
- Try high pressure gas
- Building 5 bar prototype TPC at RHUL
  - Beam test at CERN planned for next year



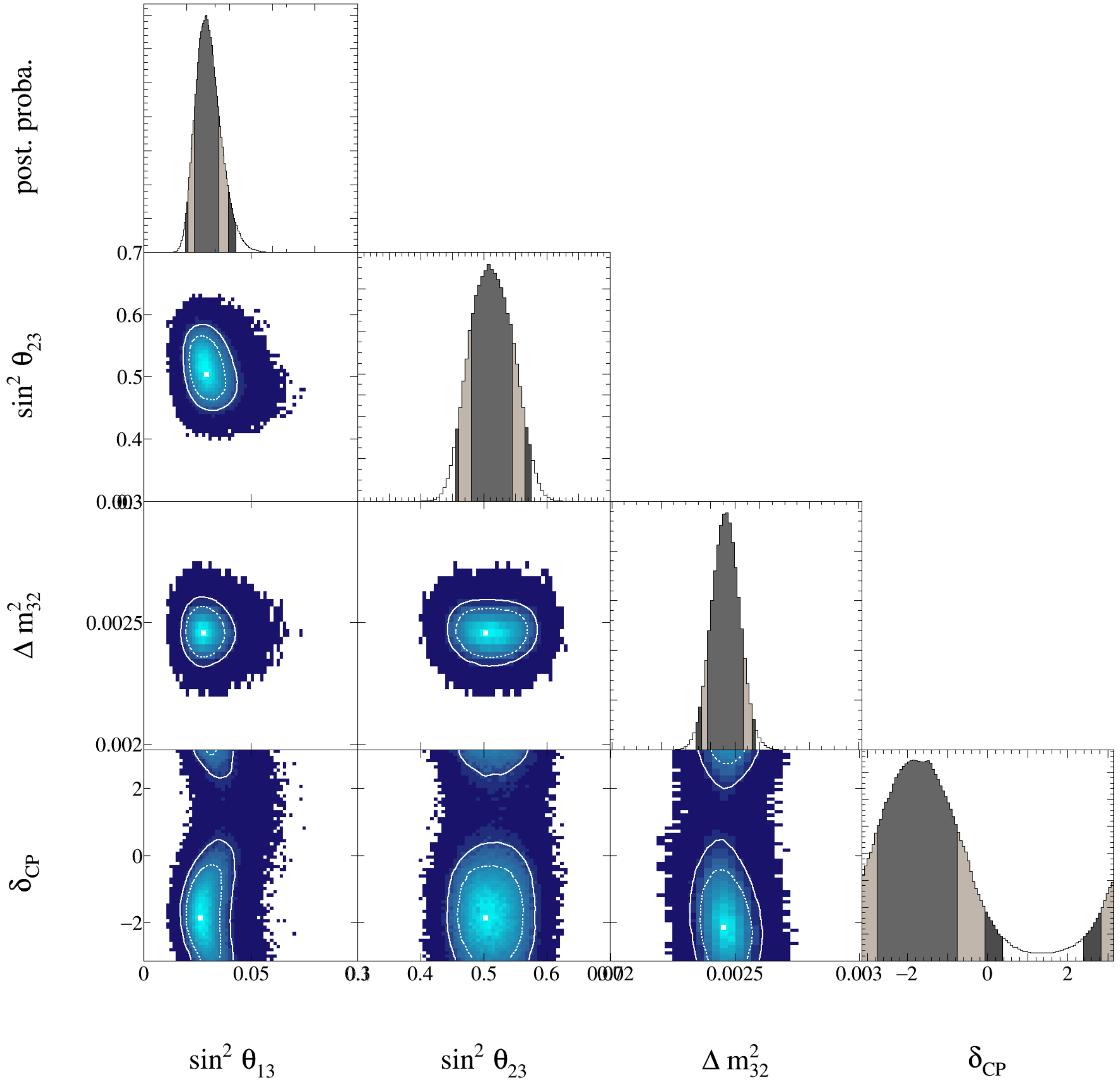
Model constraints



Triangle plots

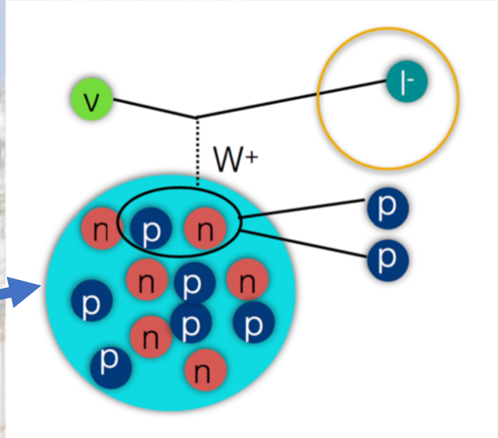
- Markov chain fit used by Bayesian analysis has all values of all parameters for all steps
- Allows study of effect of all combinations of parameters without extra fits

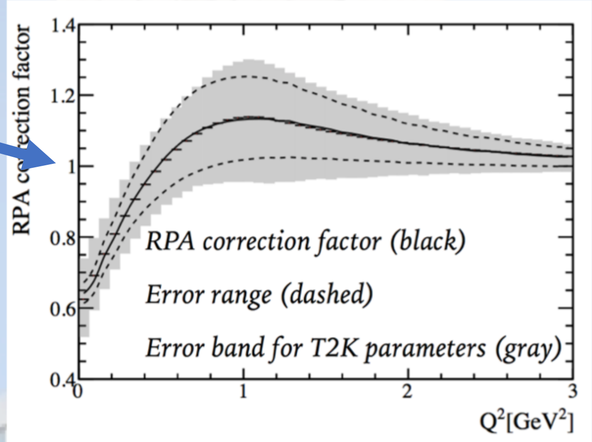
T2K data only



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)
- Analysis now includes new parametrisations of the uncertainties on these processes





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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)

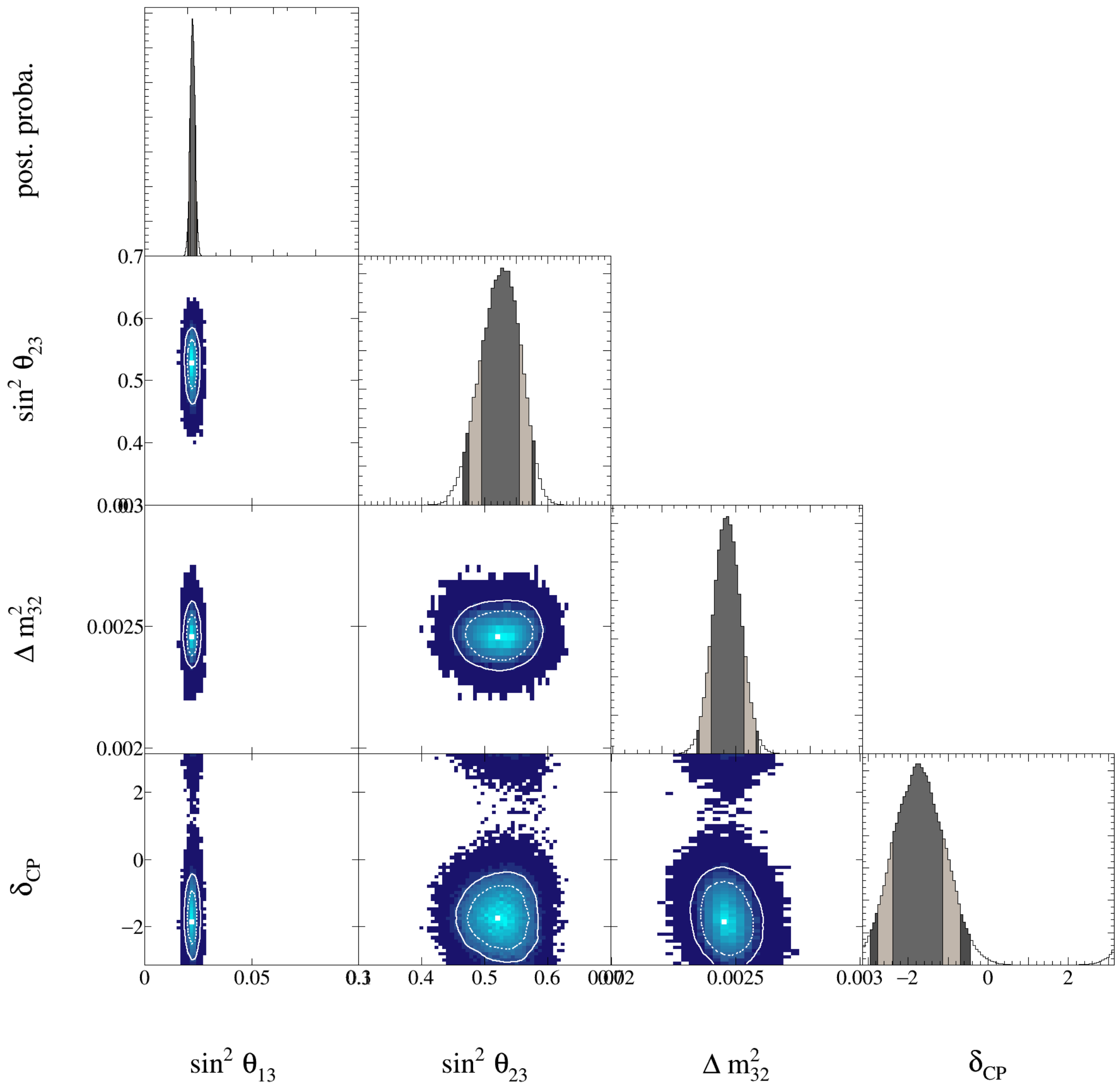
$$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$$

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

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

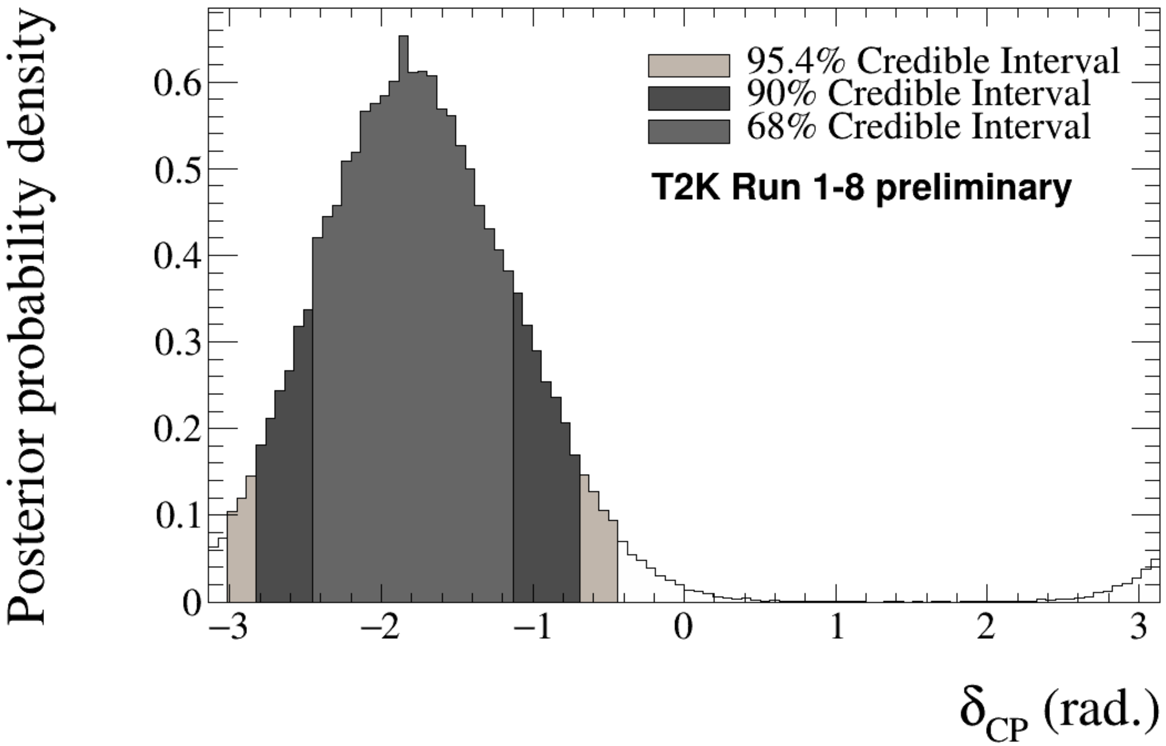
replace δ by $-\delta$ and a by $-a$ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

T2K +reactor constraint

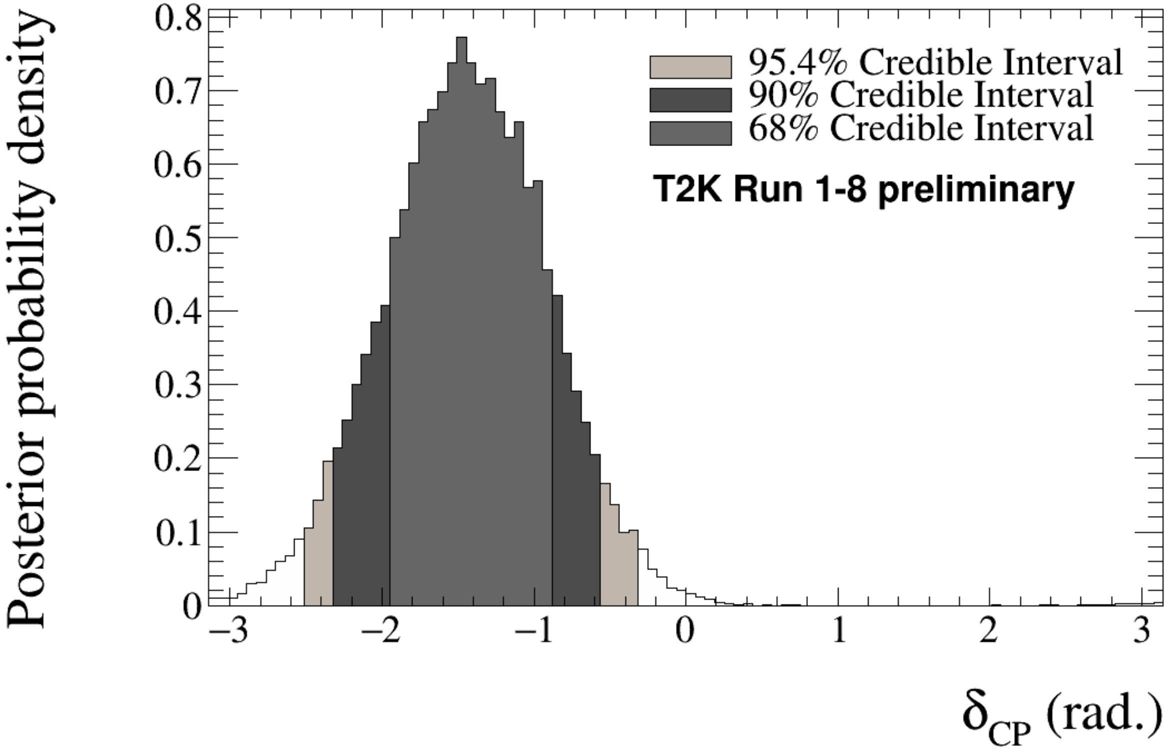


Dcp split by hierarchy- T2K+reactor

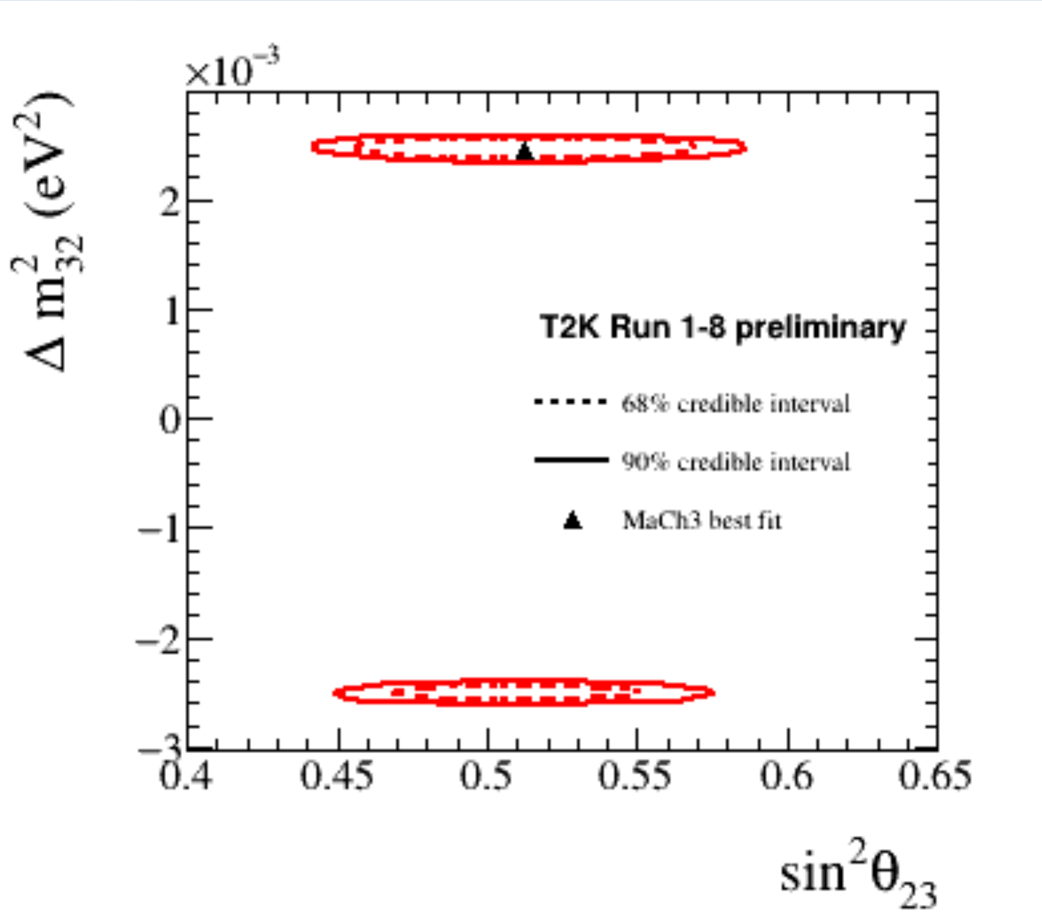
Normal hierarchy



Inverted hierarchy



T2K data only disappearance parameters



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Current status – TN331 not approved version

- Results from last August presented with final systematics pending due to non-neglible biases in ND280 data driven simulated data
- Effect on θ_{13} and δ_{CP} appears very small
- Largish effects on Δm^2_{23} and θ_{23}
- Update:
  - Investigation underway
  - Additional systematics being added to analysis
  - Still not expecting much impact on θ_{13} and δ_{CP}