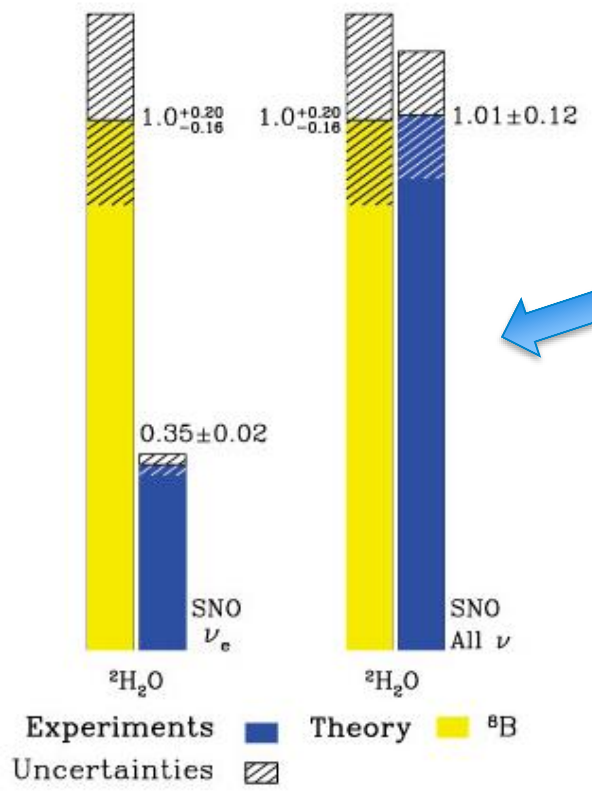
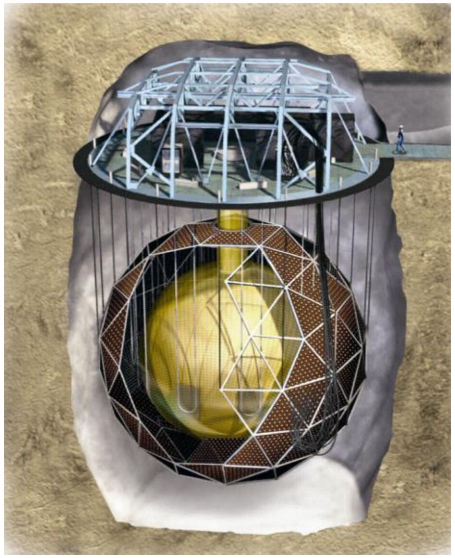
Imperial College London

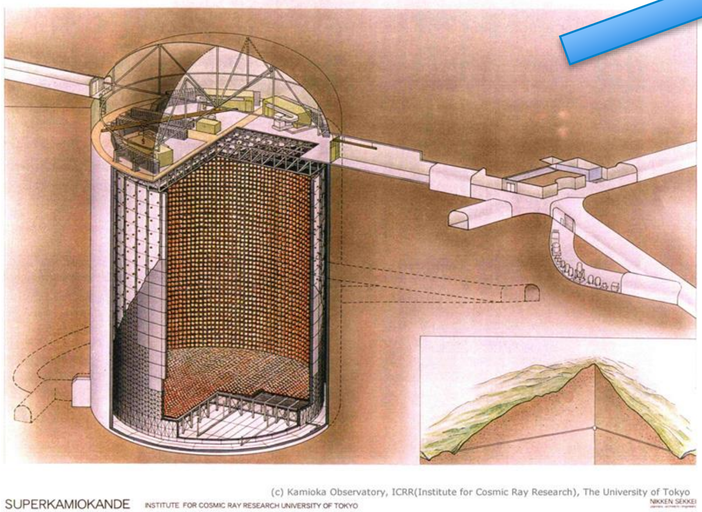
Long-baseline neutrino oscillation physics in Japan

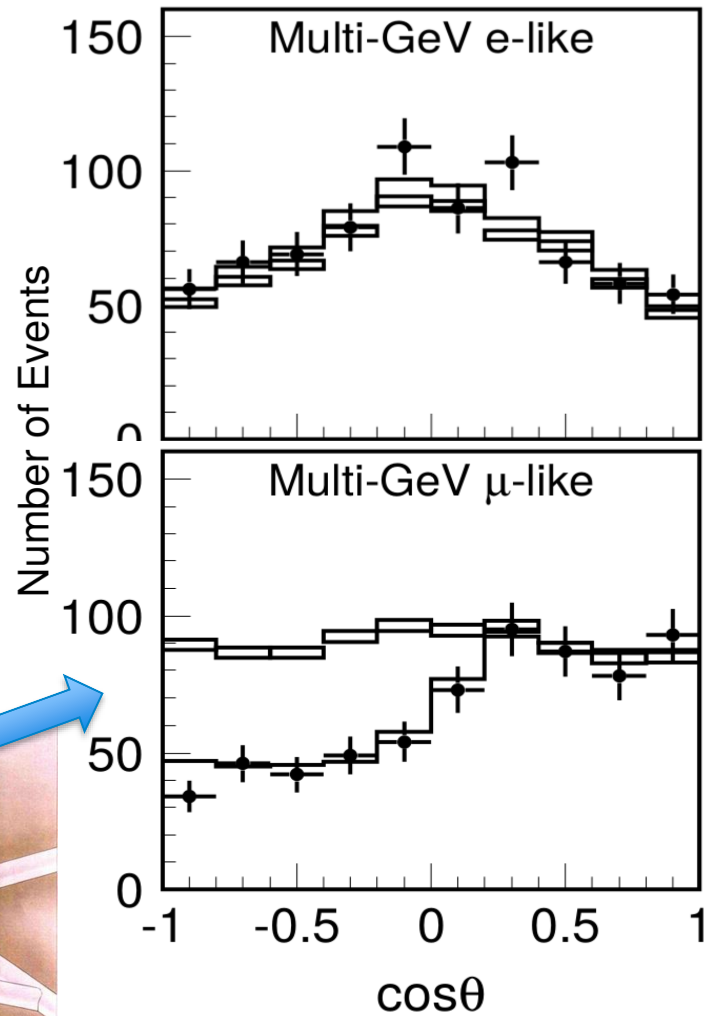
Mark Scott
University of Warwick
10th June 2021

Neutrino Oscillations







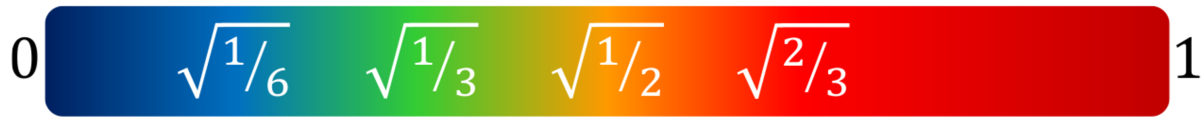


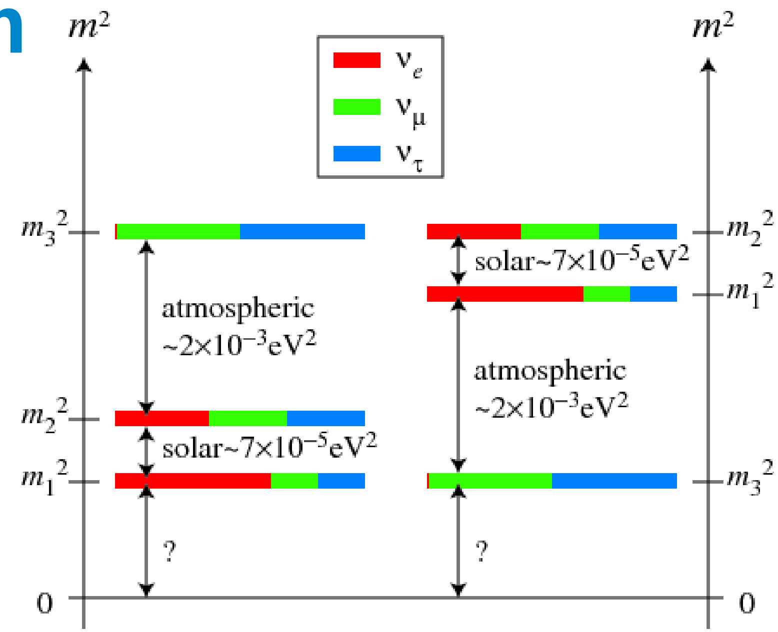
Art McDonald
2015 Nobel

Takaaki Kajita
2015 Nobel

Neutrino Oscillation Formalism

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





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

Atmospheric /Beam | Beam /Reactor | Reactor /Solar

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$\delta = \delta_{CP}$

Neutrino Oscillation Formalism

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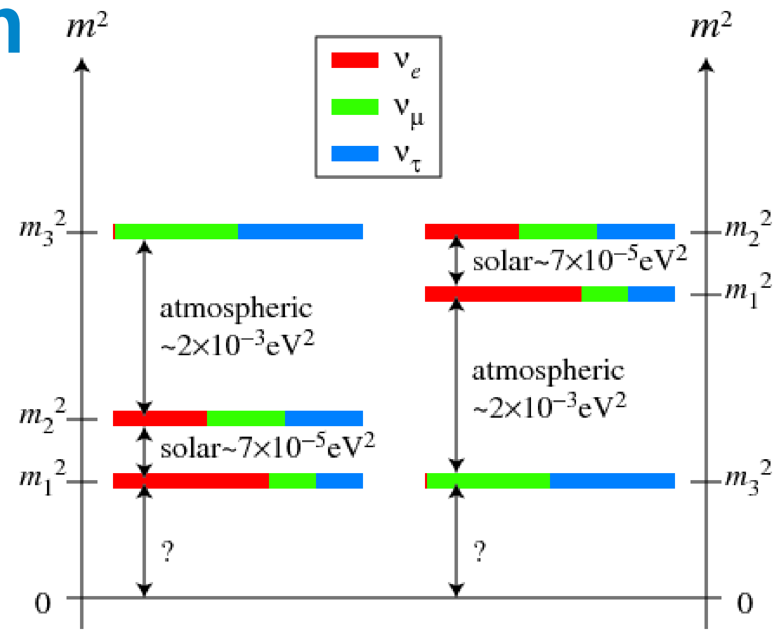
0 $\sqrt{1/6}$ $\sqrt{1/3}$ $\sqrt{1/2}$ $\sqrt{2/3}$ 1



What **do** we know?

- $\theta_{23} = 45.6^o \pm 2.3^o$
- $\theta_{13} = 8.3^o \pm 0.2^o$
- $\theta_{12} = 33.6^o \pm 0.8^o$
- $|\Delta m^2_{32}| = (2.45 \pm 0.05) \times 10^{-3}\ eV^2c^{-4}$
- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ eV^2c^{-4}$

What **don't** we know?

- Is $\theta_{23} == 45^o$ (octant)?
- Is $\Delta m^2_{32} > 0$ (mass ordering)?
- Do neutrinos violate CP-symmetry?
- New physics?

Neutrino Oscillation Formalism

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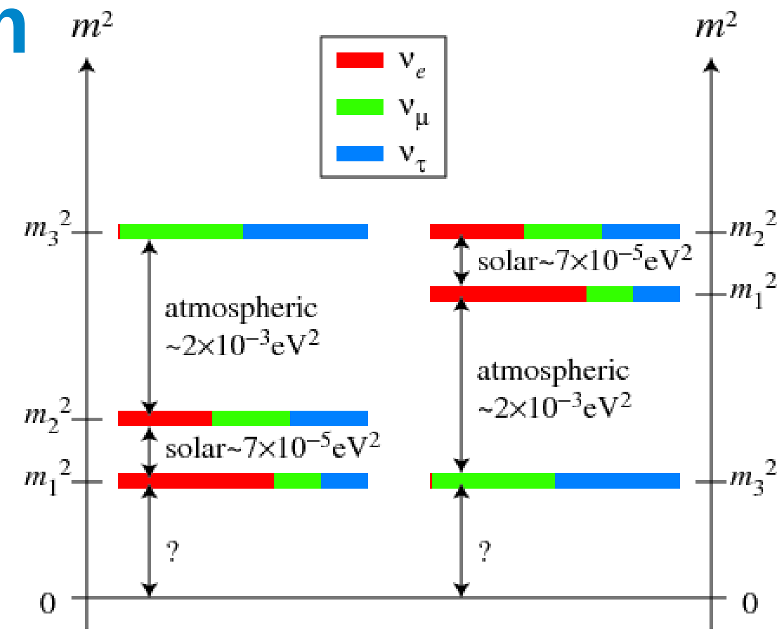

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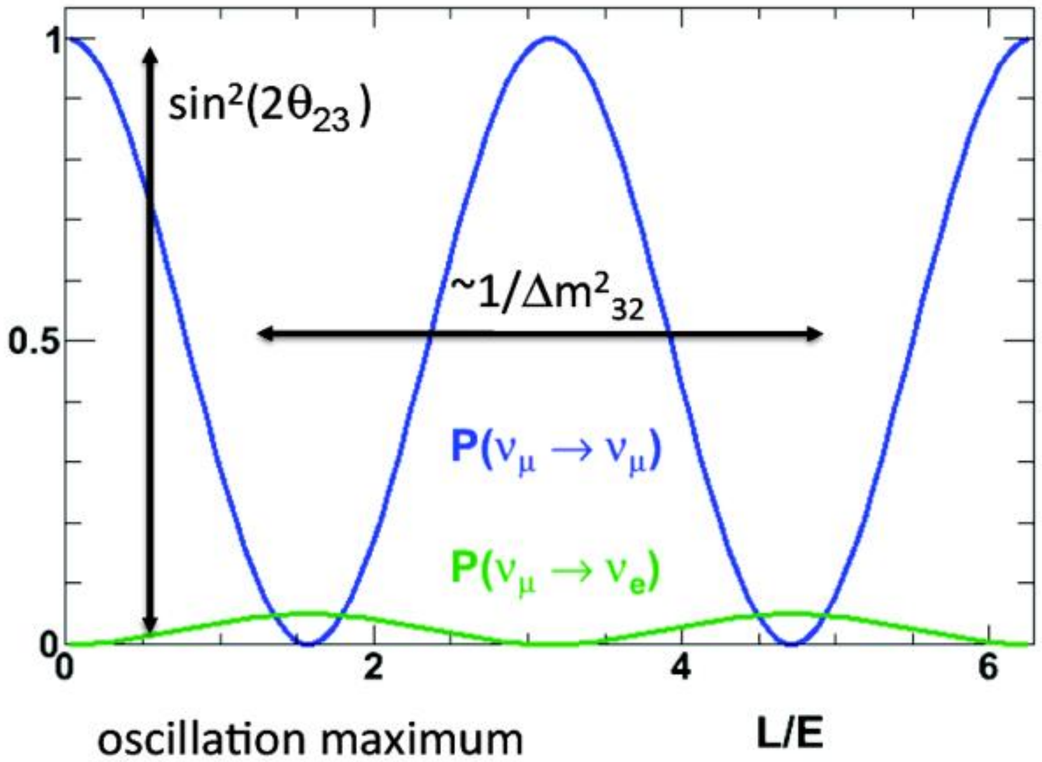
Long-baseline neutrino experiments

- Leading order oscillation probabilities for ν_μ survival and ν_e appearance

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



Long-baseline neutrino experiments

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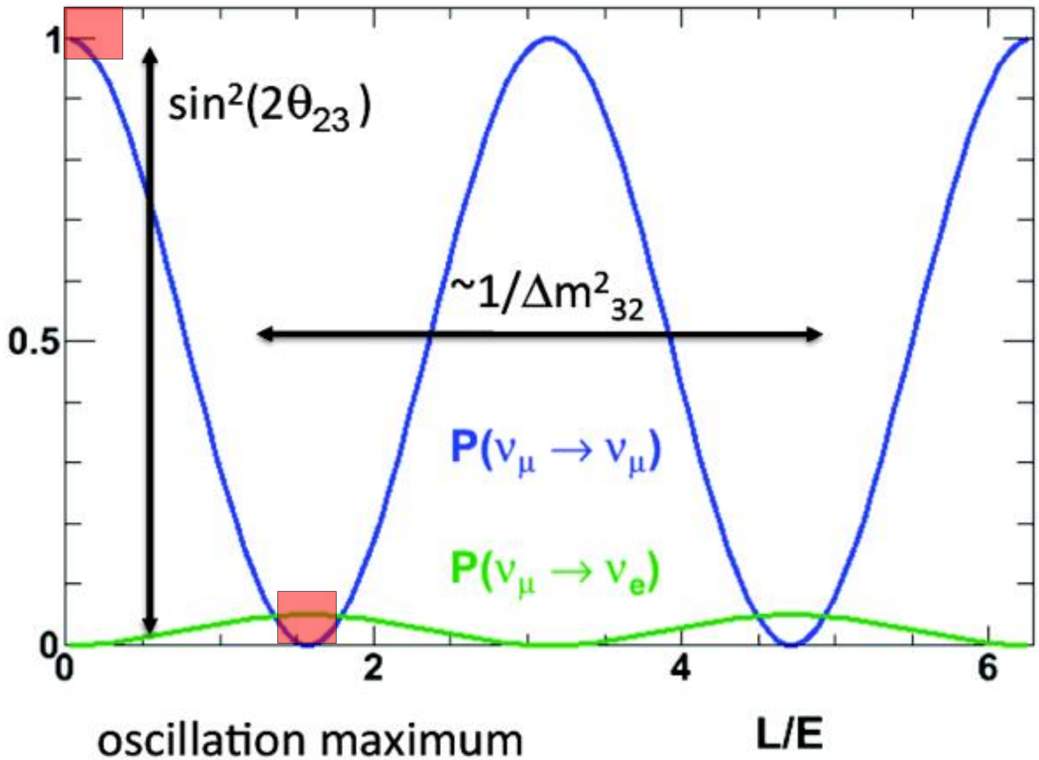


- Need to sample spectrum at different values of L/E
- Build two detectors
- One close to neutrino source
- Other at maximal oscillation

CP violation in neutrino oscillation

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}\left(1-2\sin^2\theta_{13}\right)\right)$$

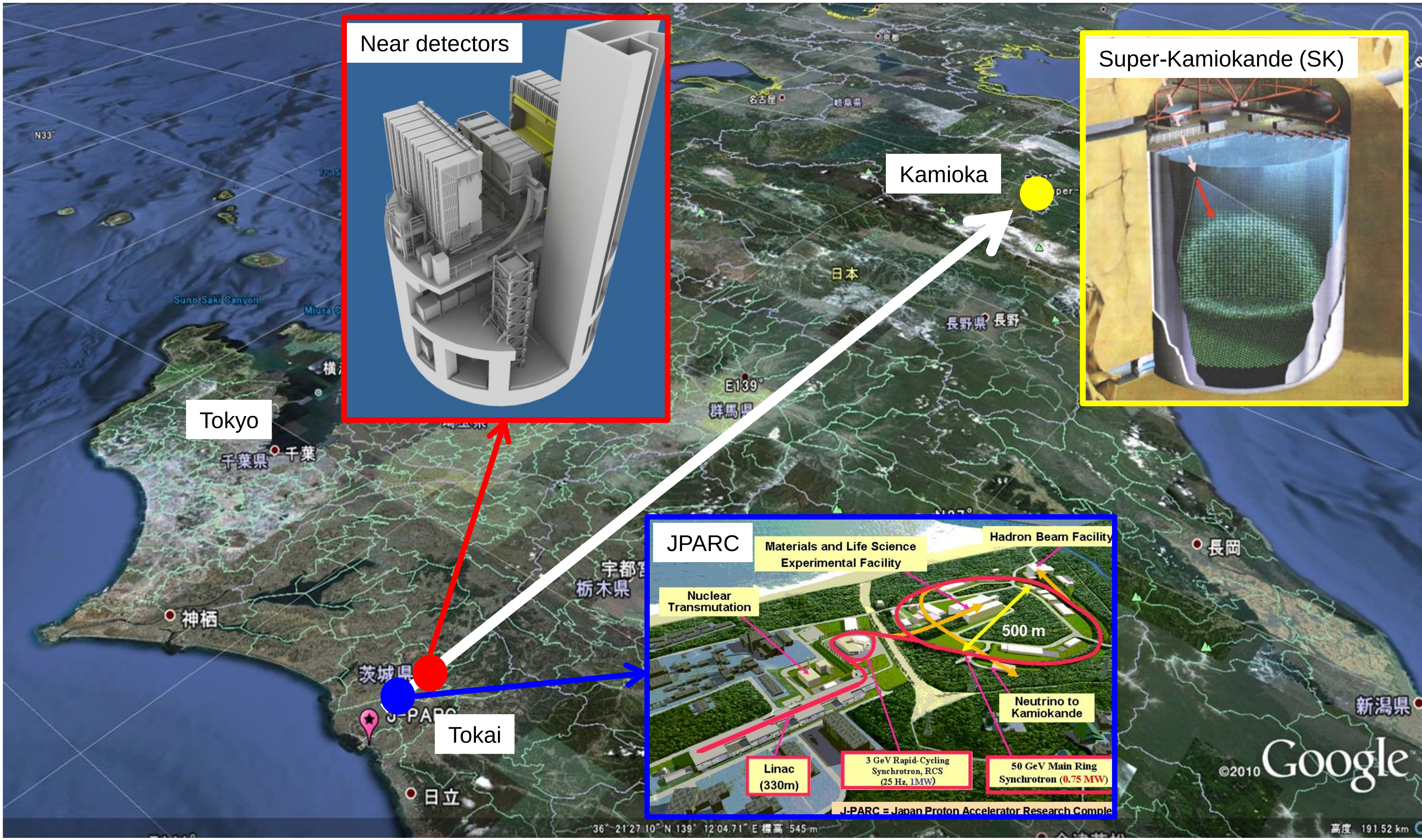
Leading including matter effect

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

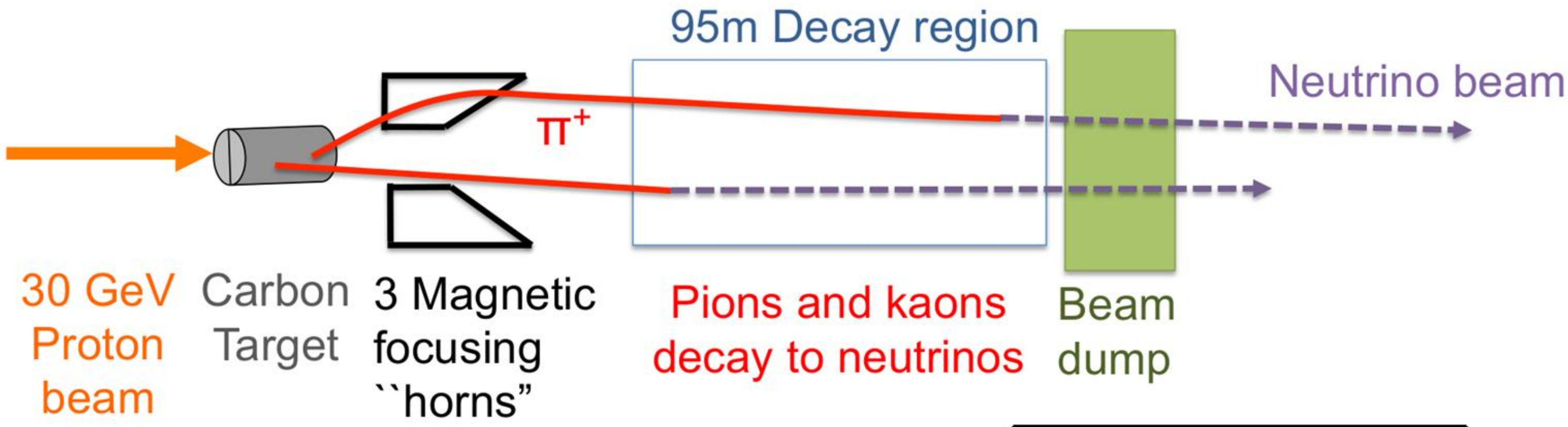
CP violating

- Probability for ν_e appearance around the oscillation maximum, including CP-violating term
  - $\delta \rightarrow -\delta$ when switching from neutrinos to antineutrinos
- Can measure δ_{CP} by comparing rate of electron neutrino appearance to rate of electron antineutrino appearance
  - Can also use absolute rate for neutrinos/antineutrinos if other oscillation parameters known well enough

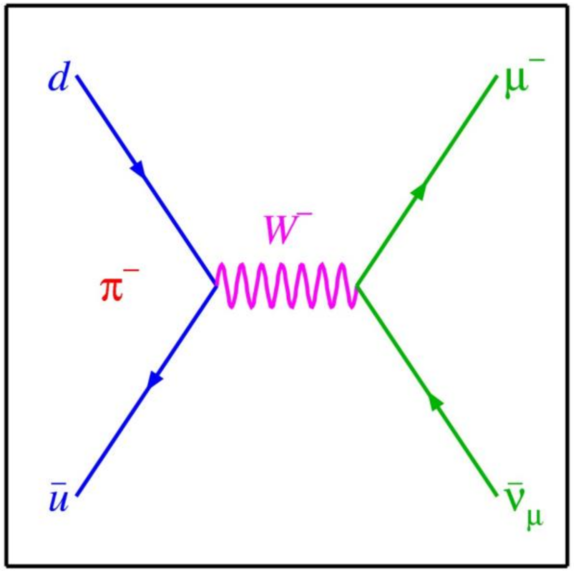
Tokai to Kamioka Experiment – T2K



Neutrino beams

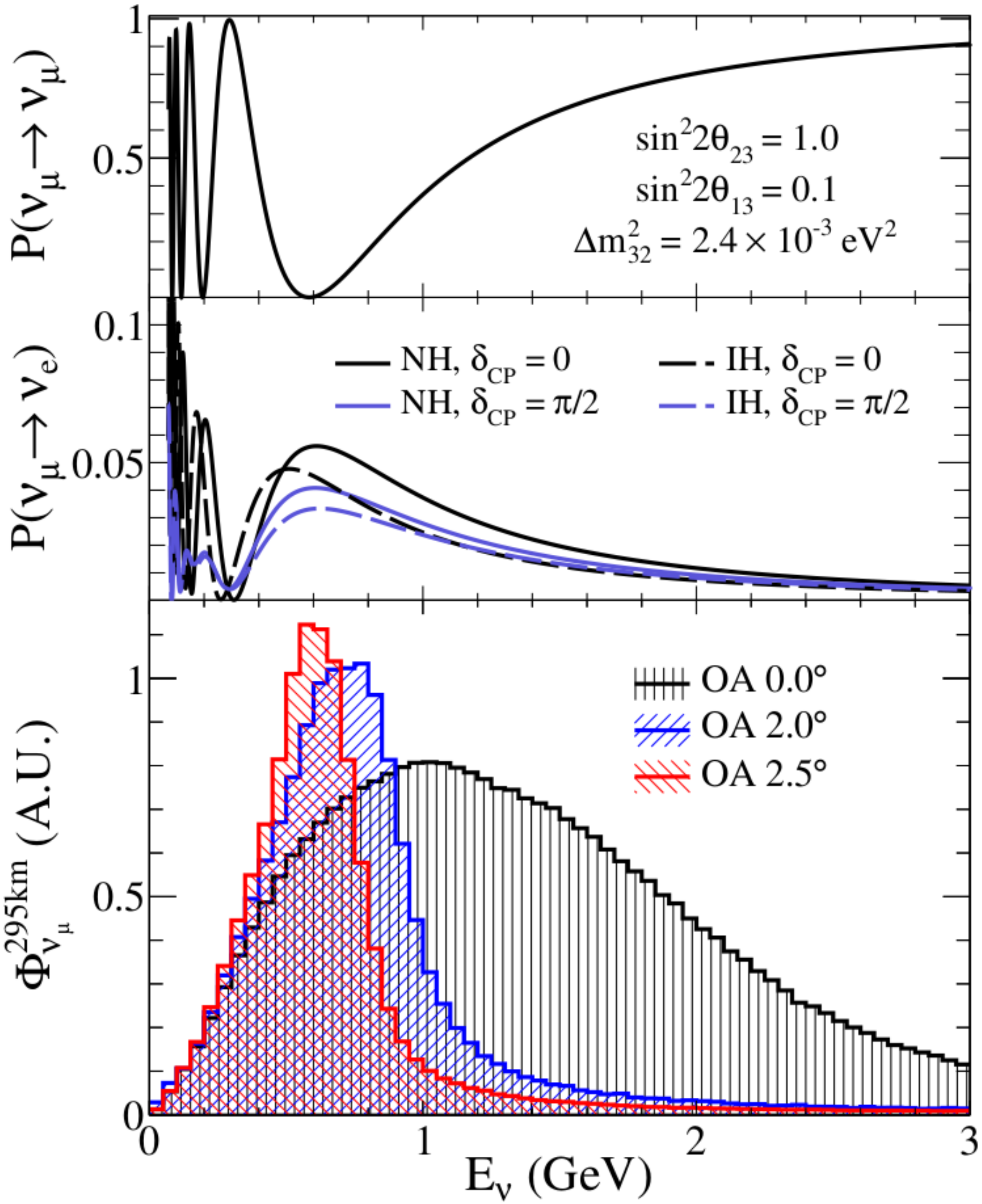


- Proton beam collides with fixed target to produce charged mesons
- Focus positive or negative mesons to produce neutrino-dominated or antineutrino-dominated beam
- Wait for pions to decay into neutrinos

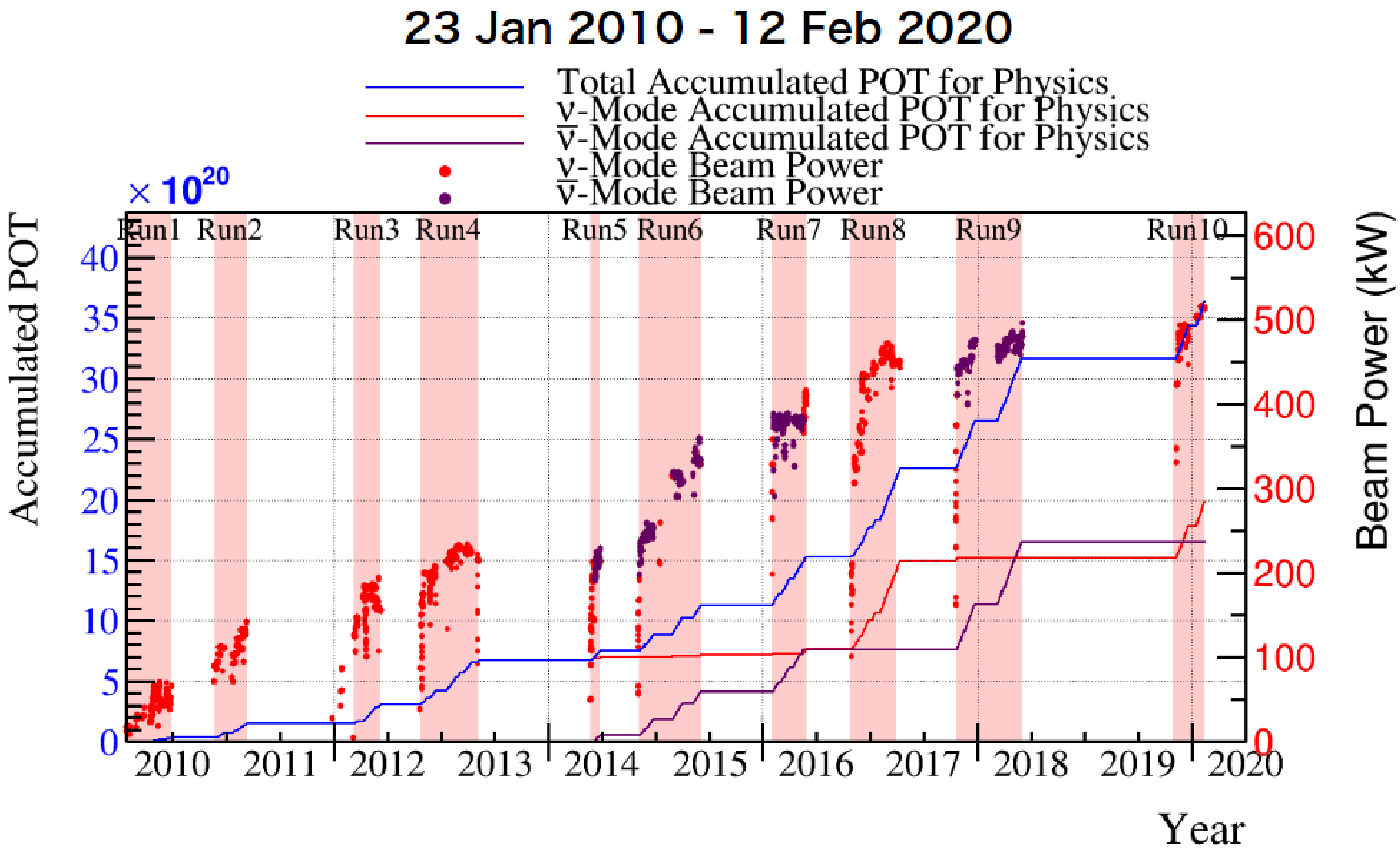


Off-axis beams

- Two-body pion decay
  - Angle and energy of neutrino directly linked
- Moving off axis:
  - Lower peak energy
  - Smaller high energy tail
  - Less energy spread
- T2K is at 2.5° off-axis



Integrated POT (Full T2K - up to Run 10)



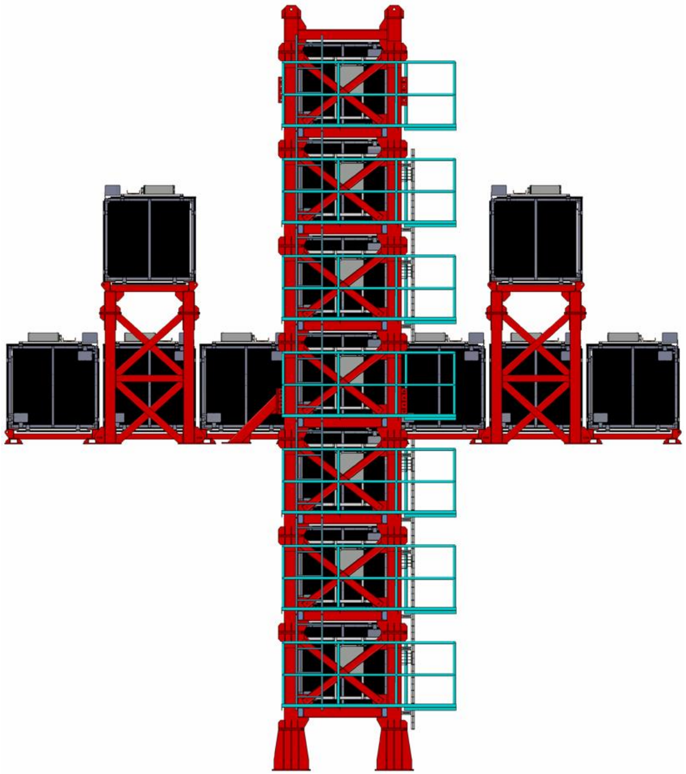
23 Jan 2010 - 12 Feb 2020

POT Total : 3.64059×10^{21}
(maximum power 522.627 kW)

ν mode : 1.99006×10^{21} (54.7%)

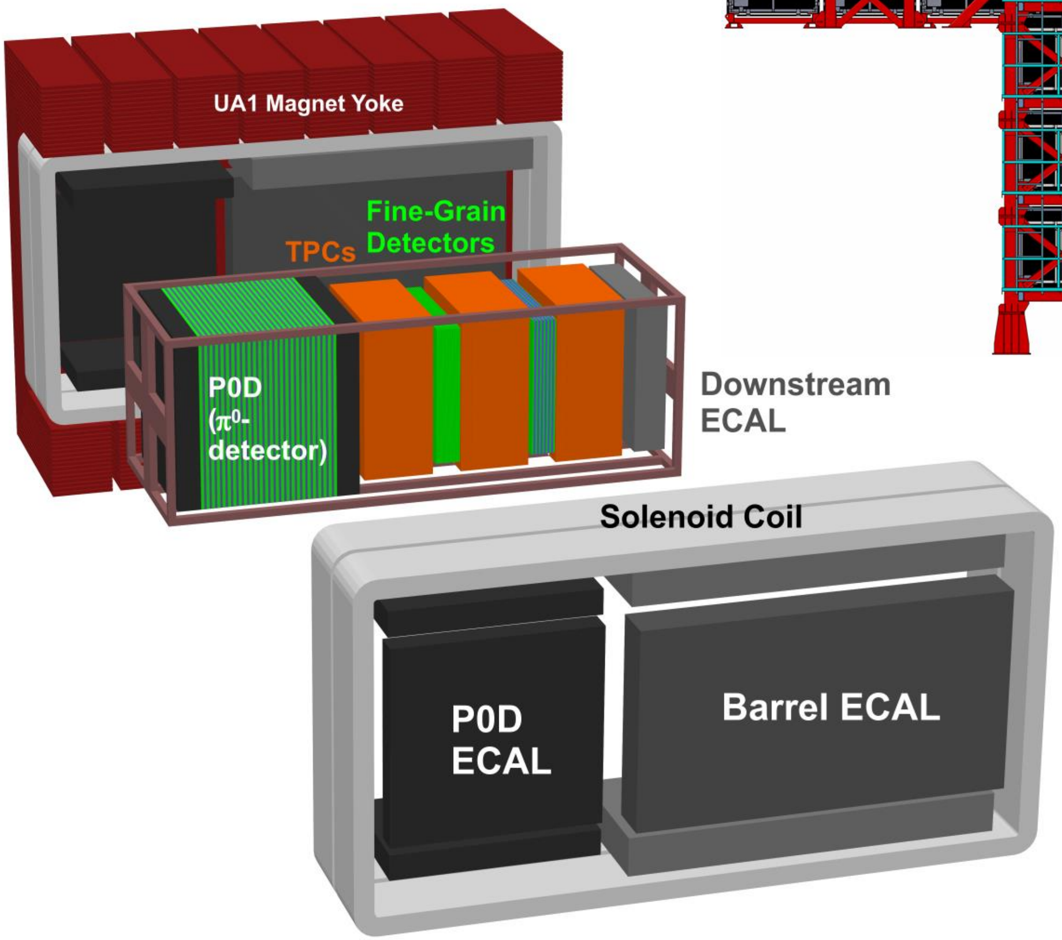
$\bar{\nu}$ mode : 1.65053×10^{21} (45.3%)

Near detectors



INGRID

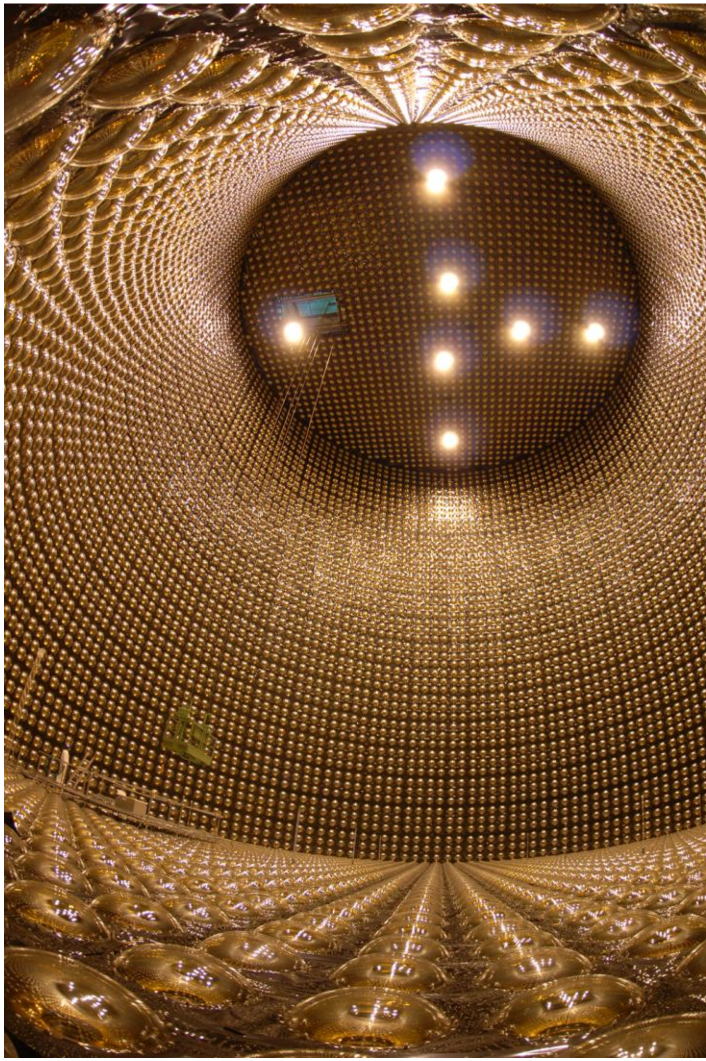
- Measure direction of neutrino beam
- Ensure stable beam operation
- Tune neutrino flux prediction



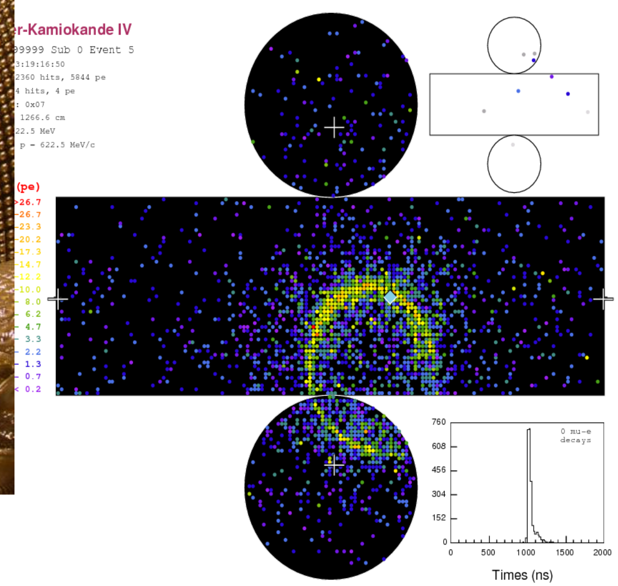
ND280

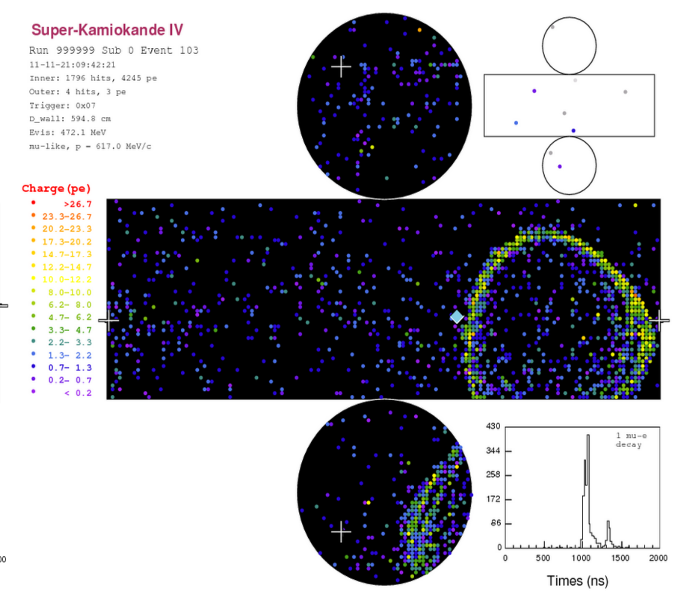
- Measure neutrino flux and cross section before oscillation
- UA1 magnet allows separation of neutrino and antineutrinos
- Oscillation analysis focuses on muon (anti-)neutrino samples

Super-Kamiokande



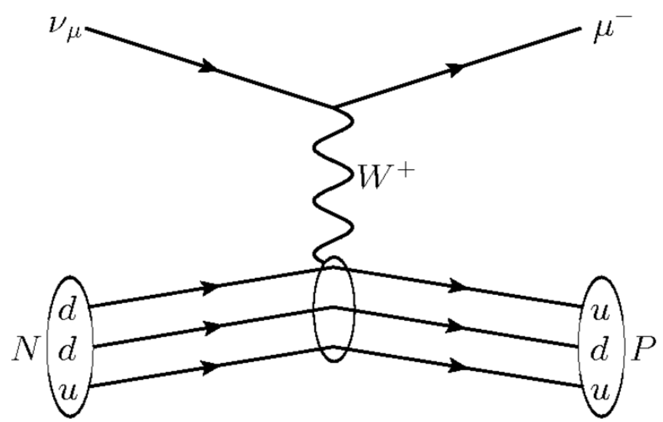
- 40,000 tons of ultra pure water
- 11,000 photo-multiplier tubes (PMTs)
- 1km overburden
- Separate electrons and muons by ring shape
  - Mis-ID <1%
  - No sign selection



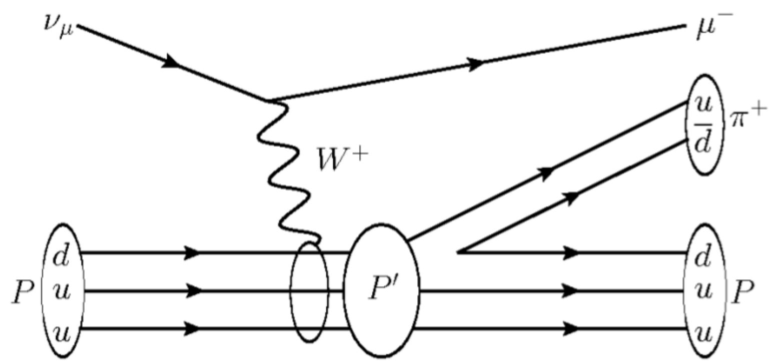


Neutrino interactions

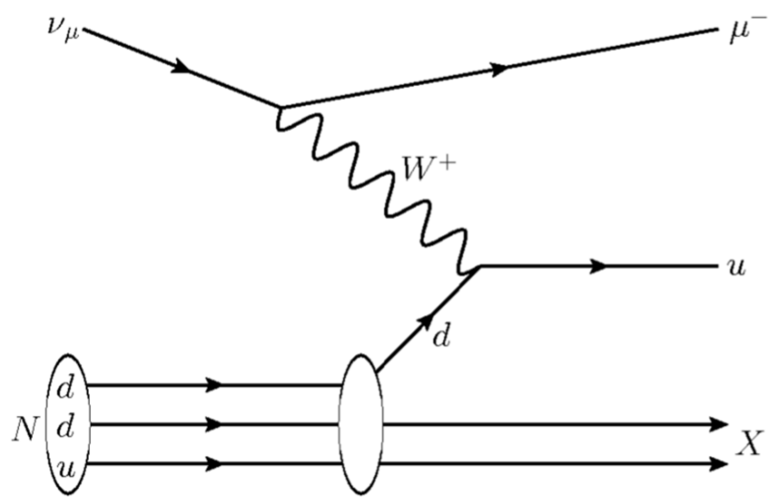
- Three principal types of neutrino interaction
- Occur as both charged current (CC) and neutral current processes



Quasi-elastic (CCQE)

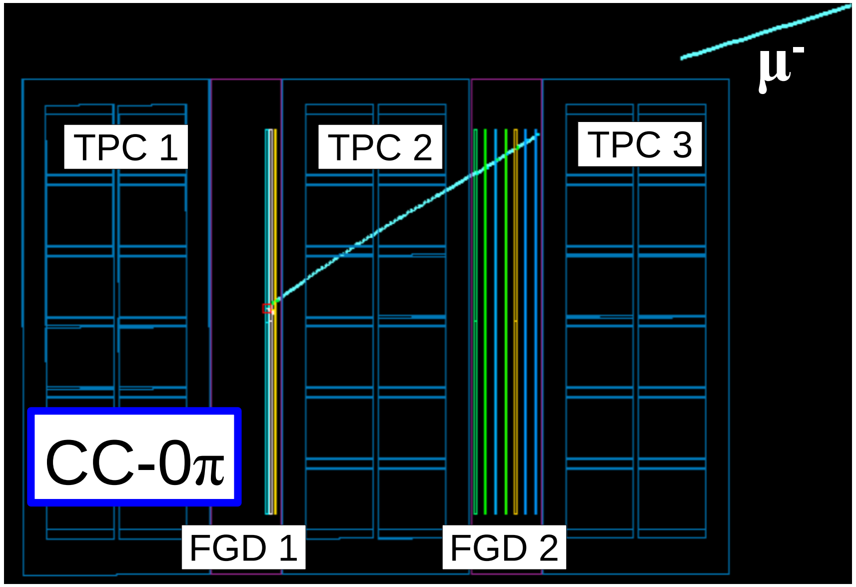


Single pion production



Deep inelastic scattering / Multi-pion production

ND280 data



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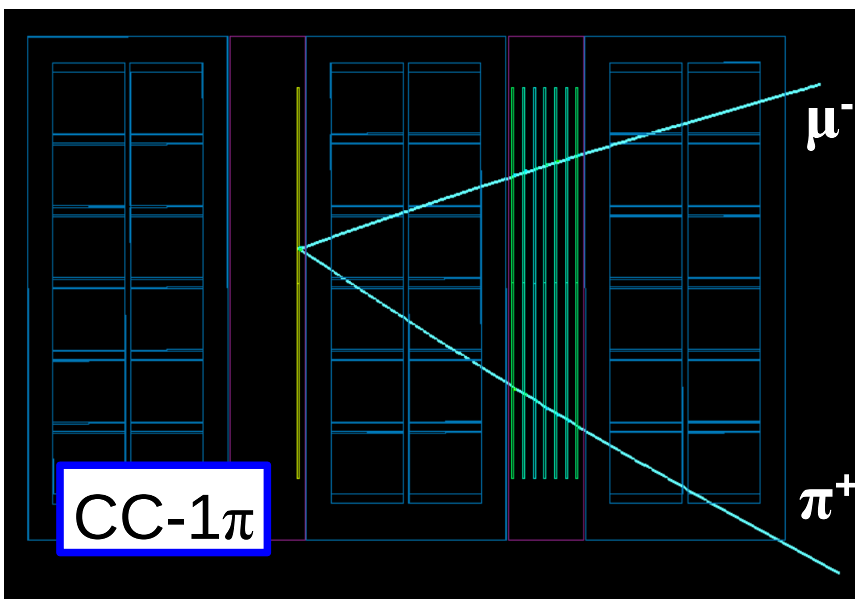
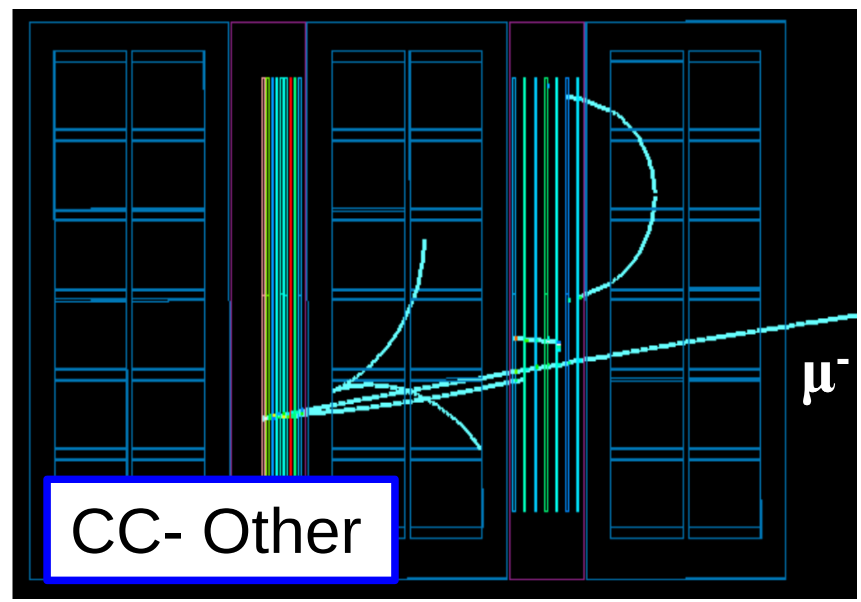
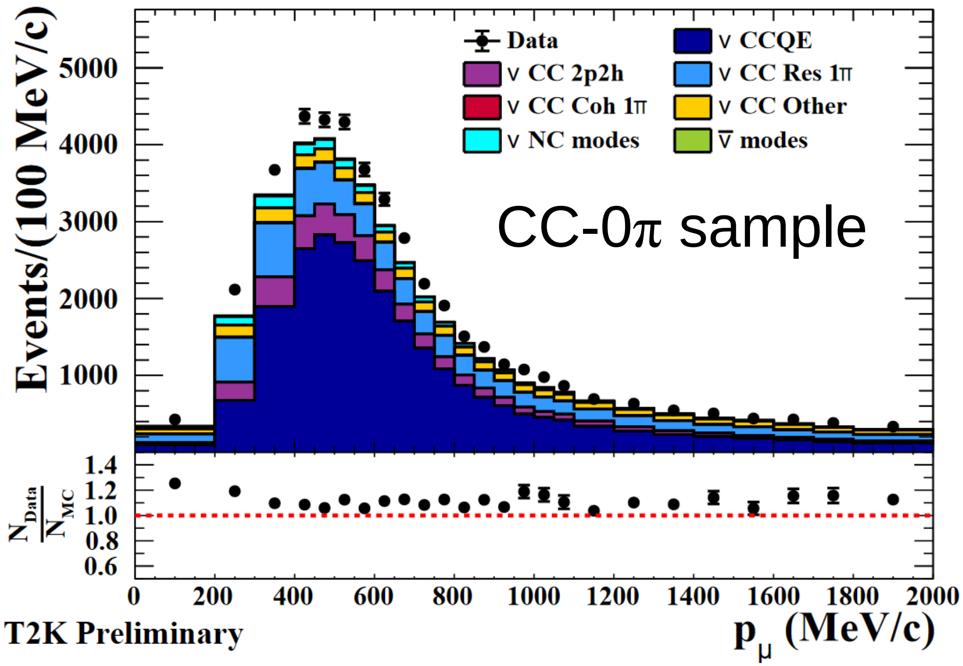
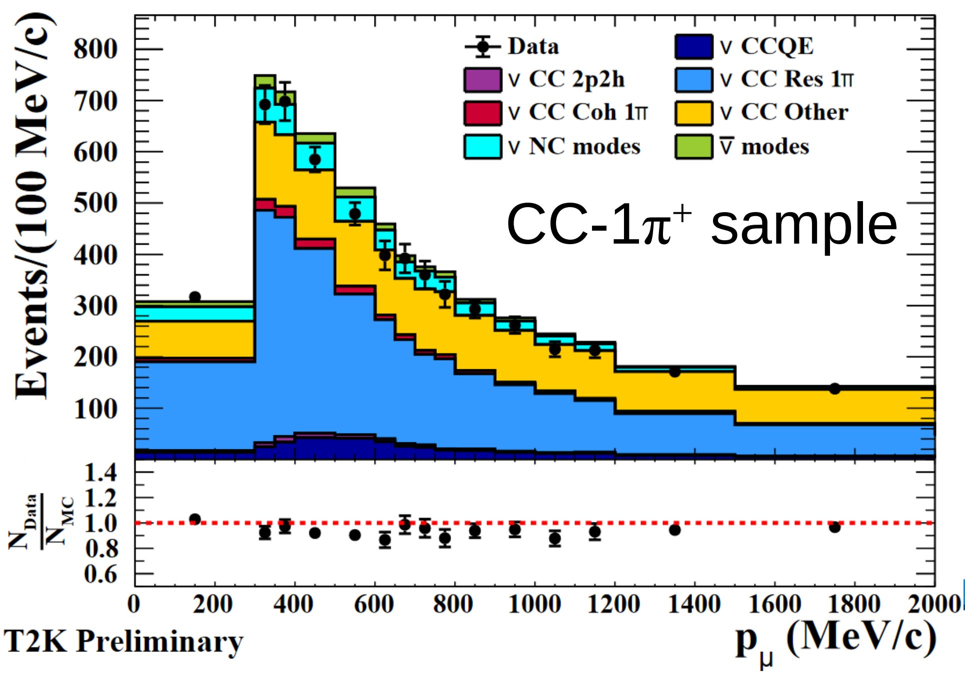


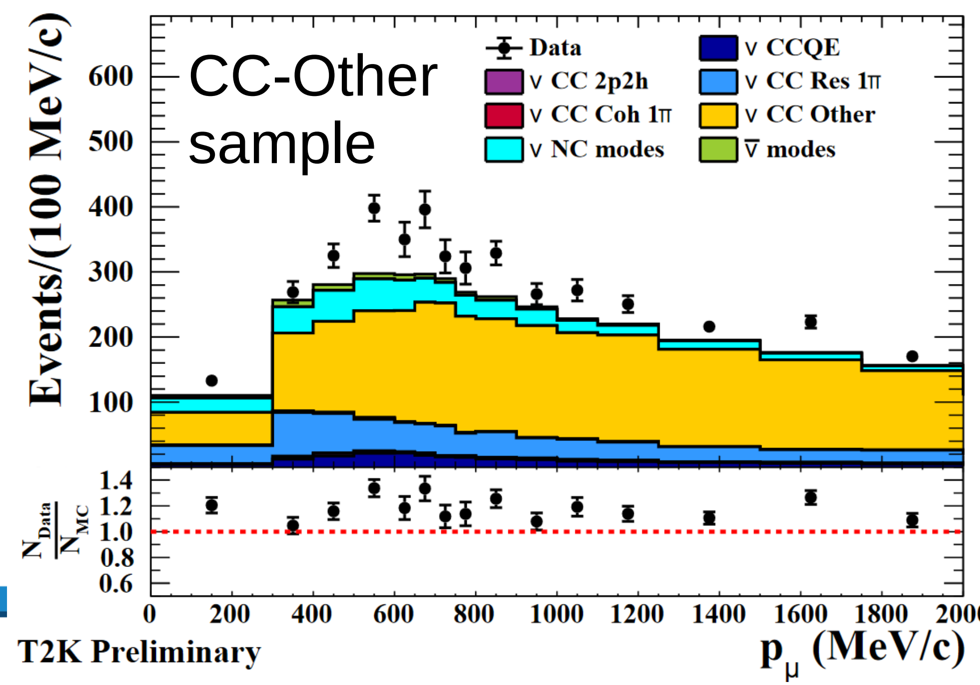


ND280 event samples

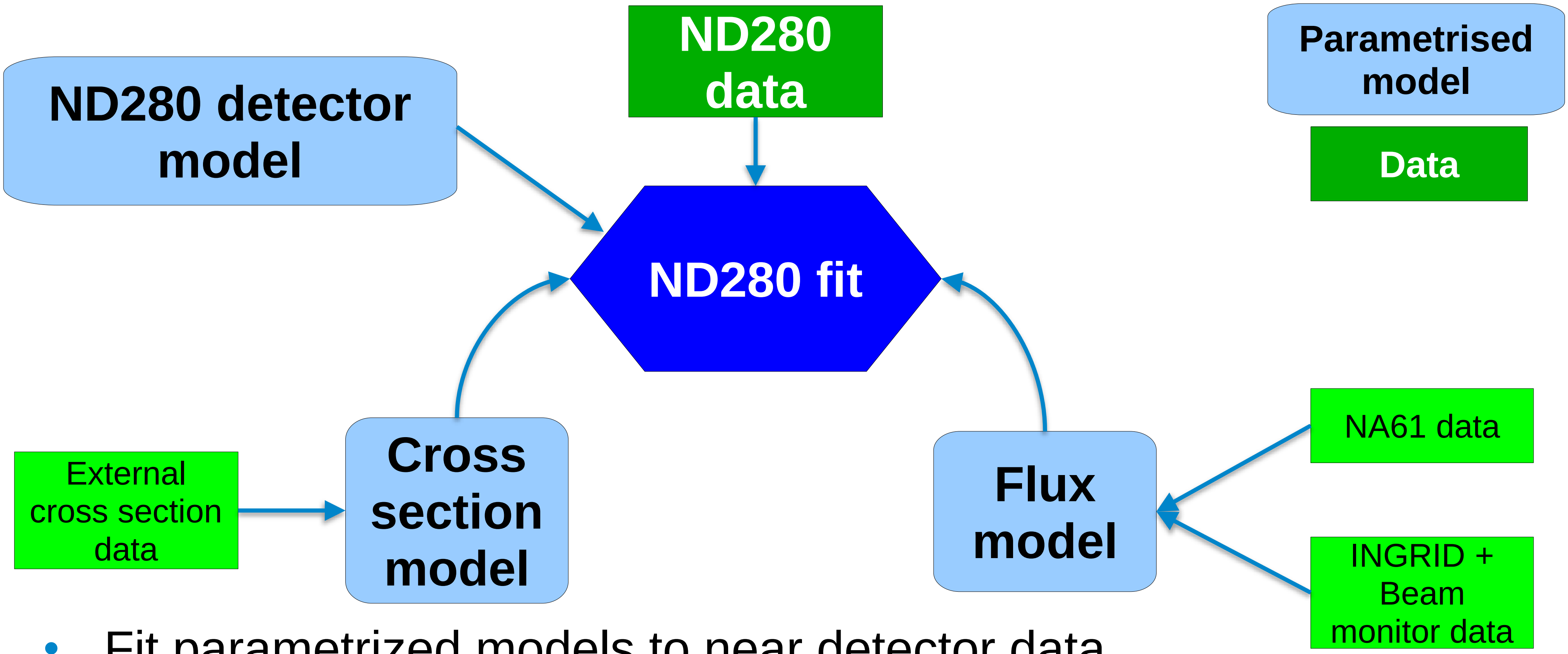


- Select highest momentum, muon-like, negative (positive) track as neutrino (antineutrino) candidate
- Count the number of tagged charged or neutral pions



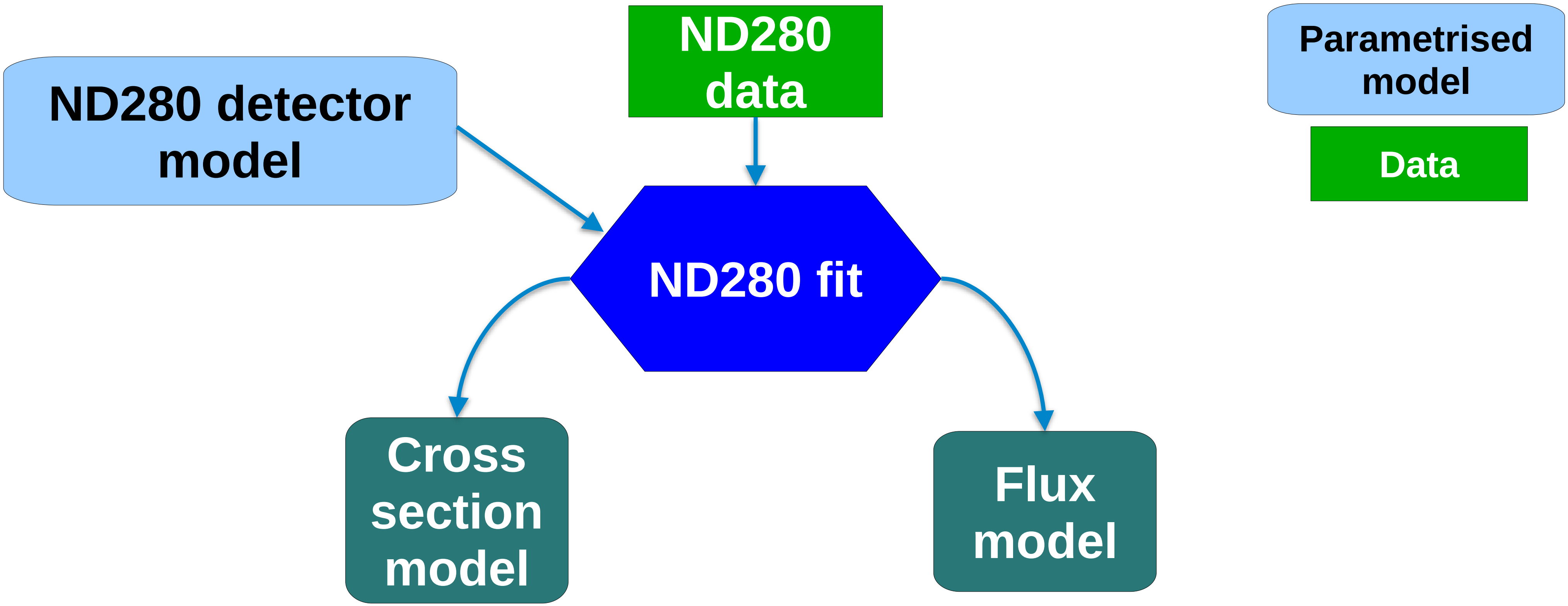


Near detector analysis



- Fit parametrized models to near detector data
  - Two separate analysis, Markov Chain MC and Minimisation, Bayesian and Frequentist methods

Near detector analysis

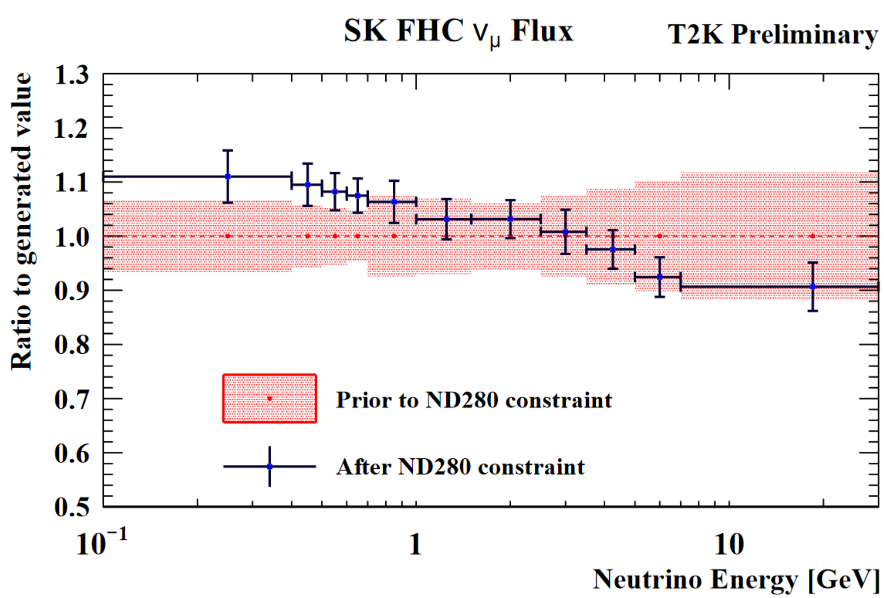


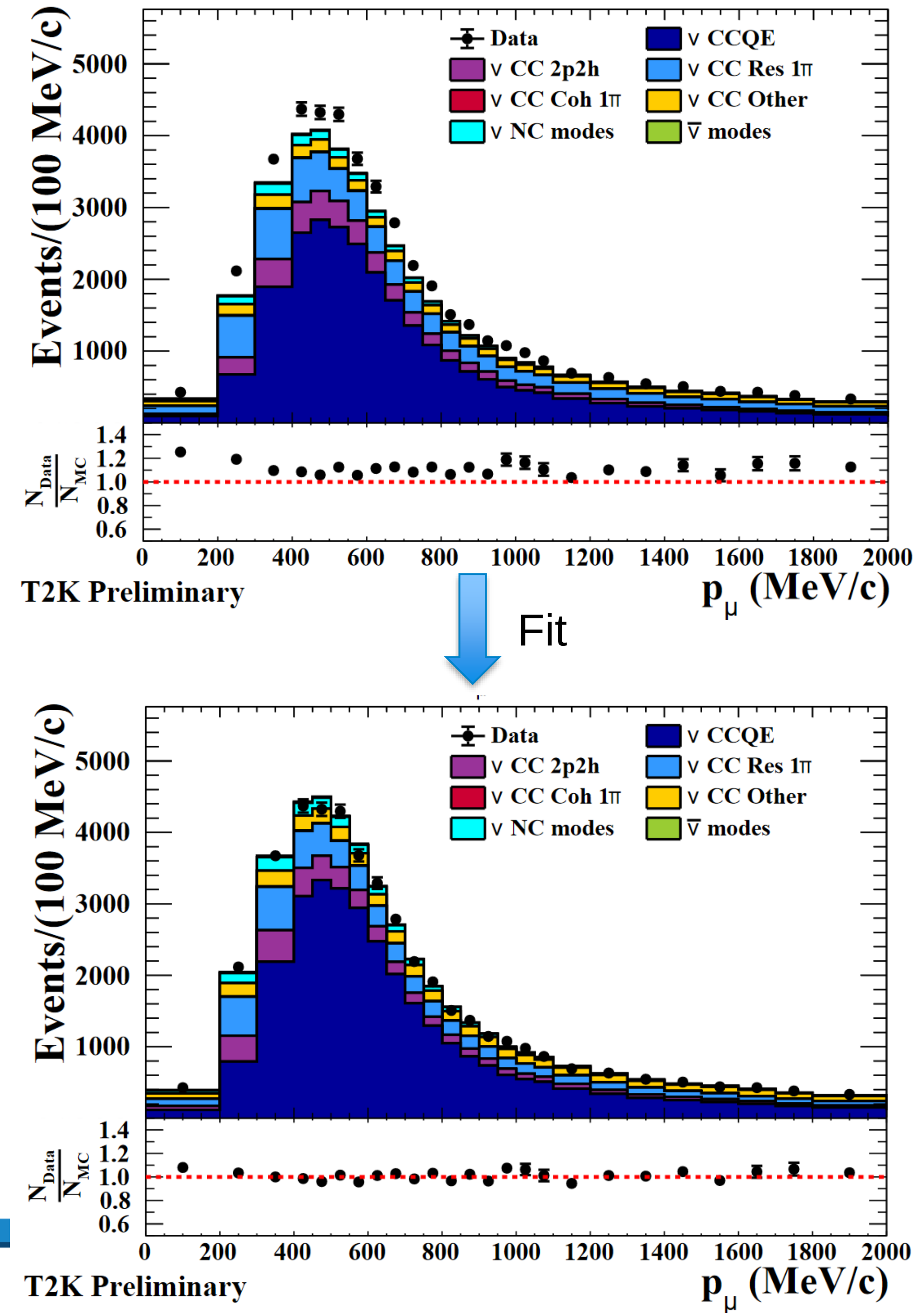
- Produces tuned flux and cross-section models
- Use models to predict unoscillated event rate at Super-K

Near detector fit results

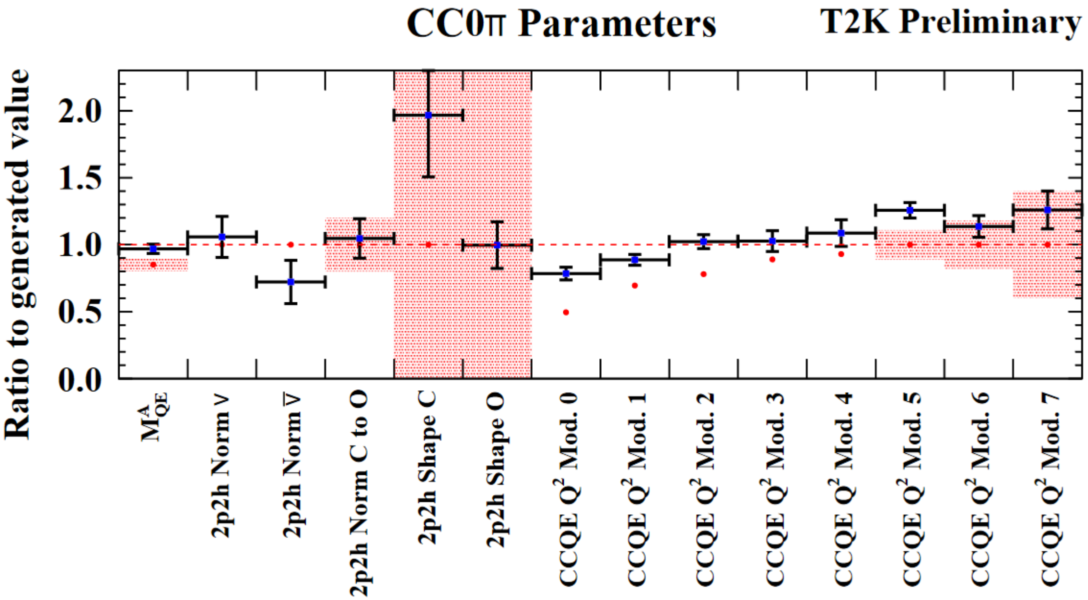
- Charged-current, zero-pion sample shown on right
  - Prefit on top, postfit on bottom

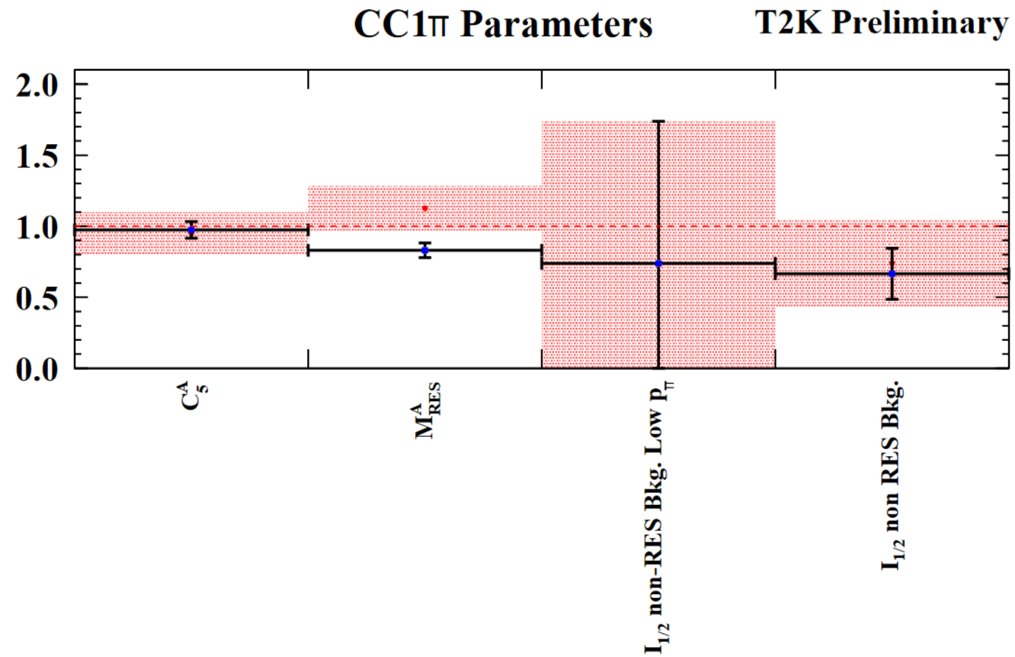
- Tuned muon neutrino flux at Super-K shown below
  - Prior in red, fit result in blue

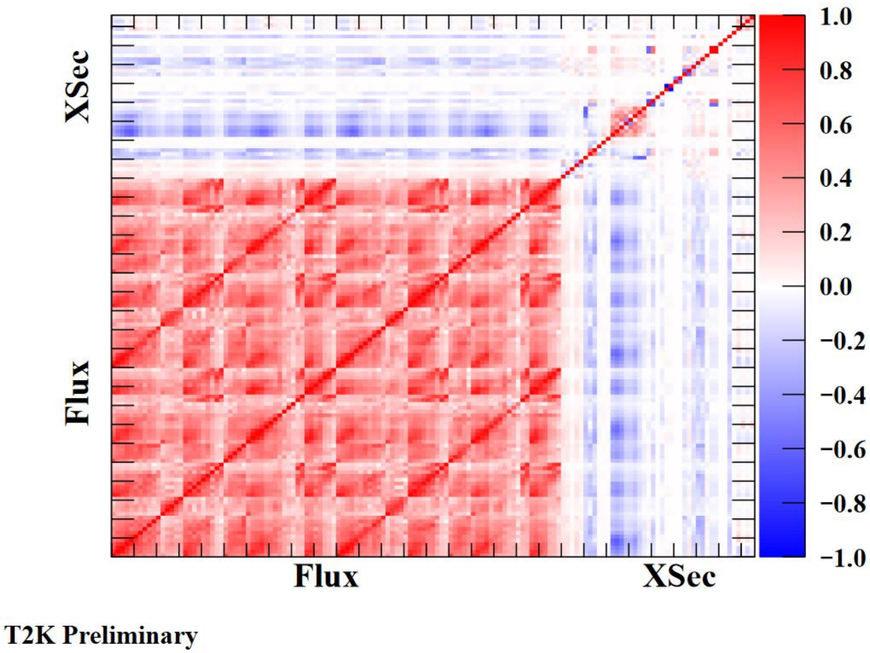


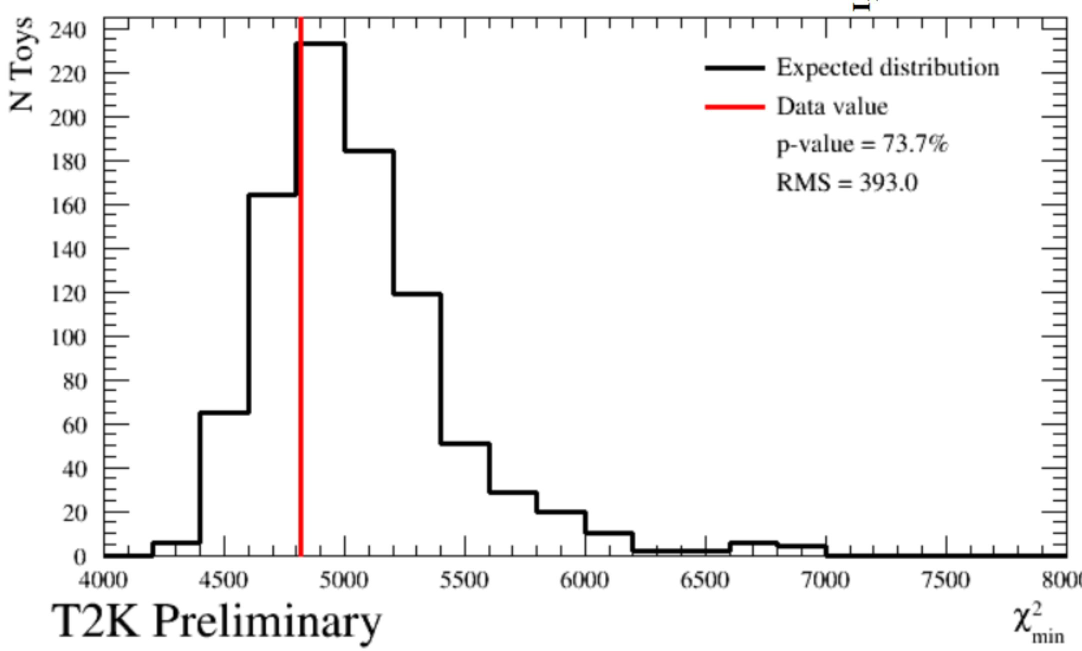


Near detector fit results

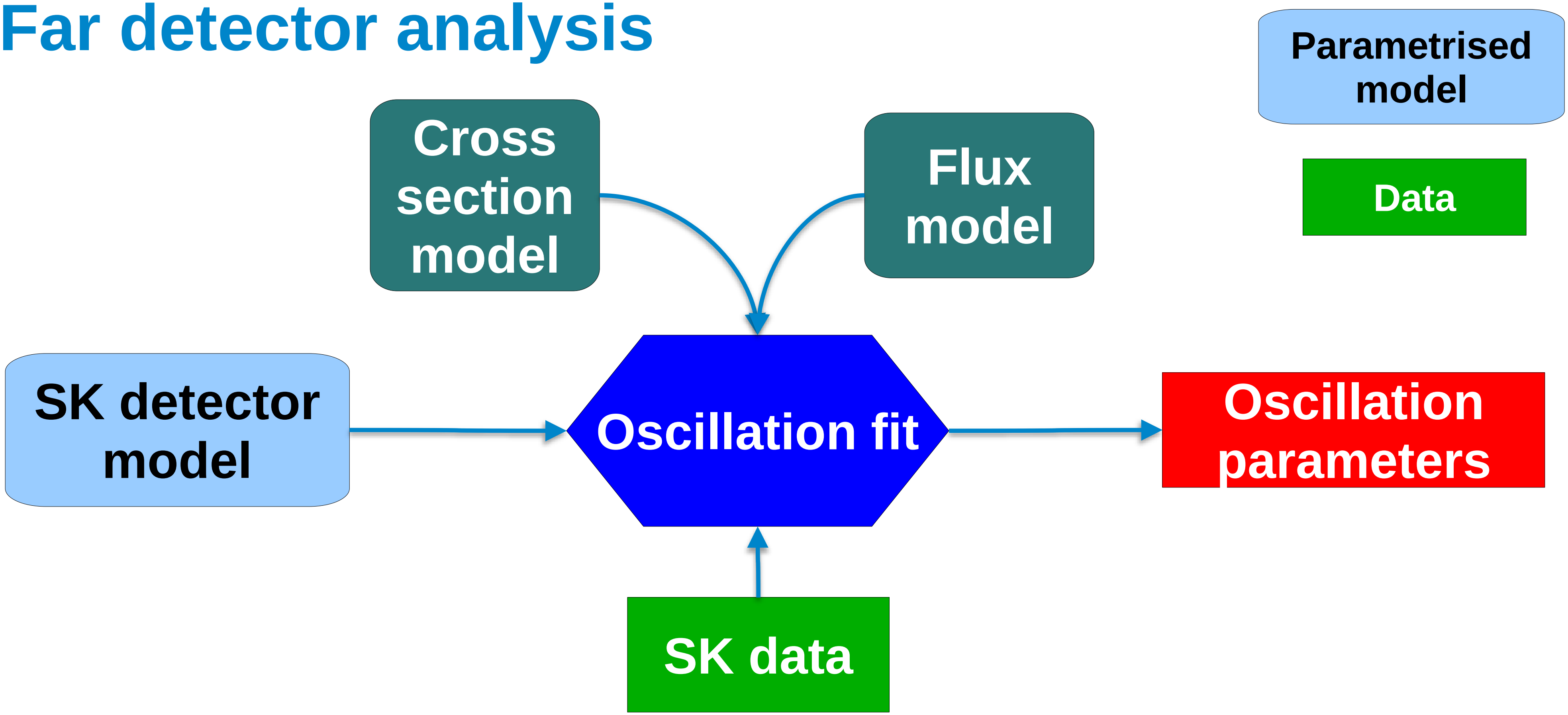








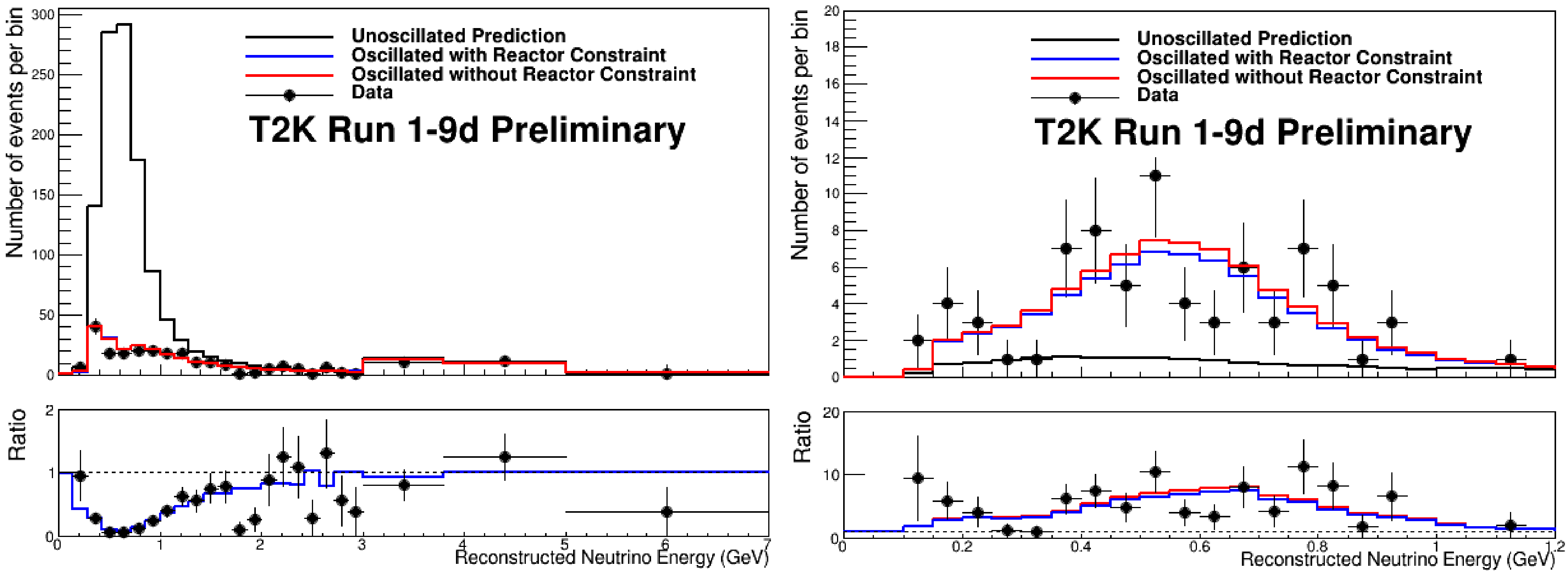
Far detector analysis



- Apply oscillation parameters to prediction from tuned models
- Fit to data, marginalizing over nuisance parameters
  - Three separate analyses, using Markov Chain MC and Minimisation, and Bayesian and Frequentist methods

What T2K measures

2018 Data



- Muon-like neutrino candidates (left), electron-like candidates (right)

What T2K measures

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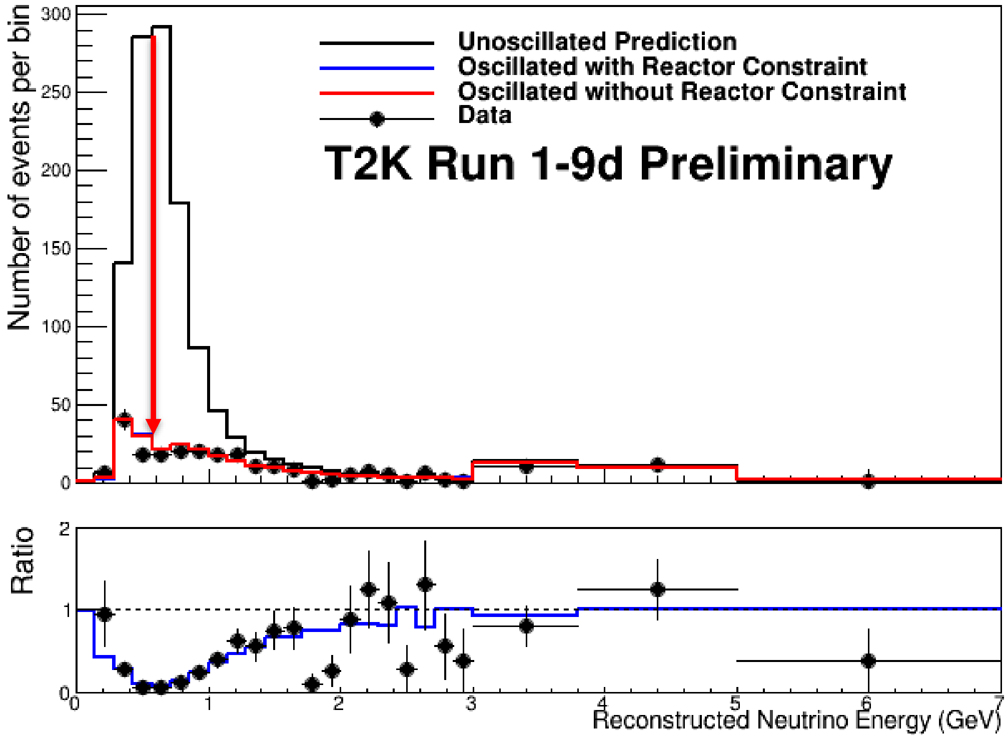

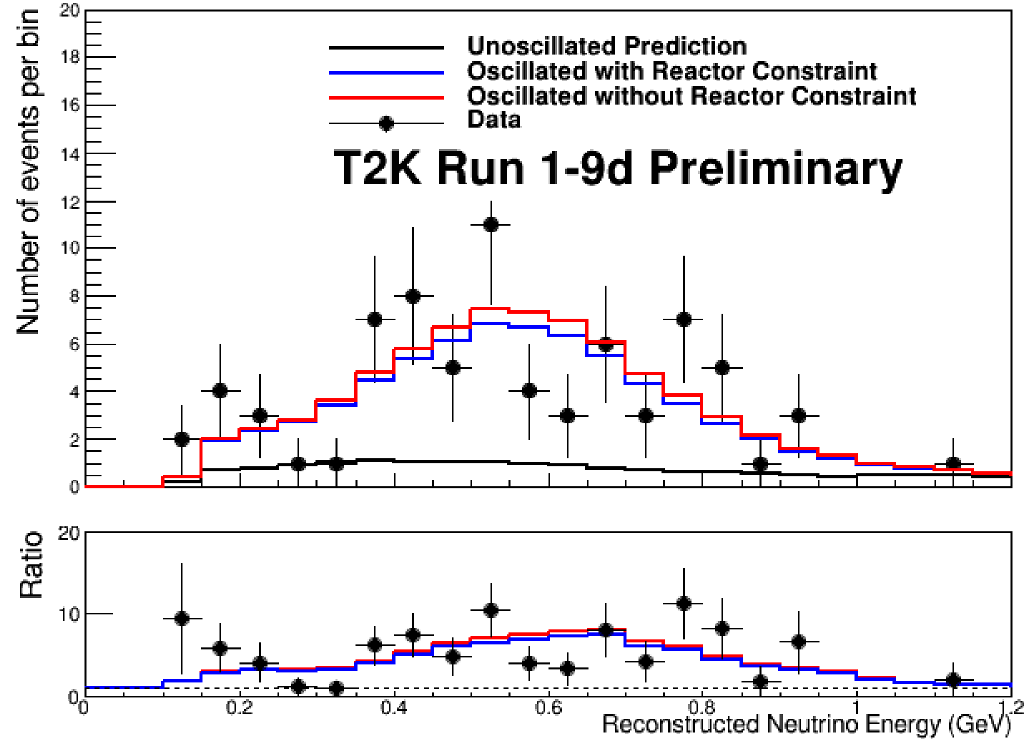

- Muon-like neutrino candidates (left), electron-like candidates (right)
- Suppression in muon neutrino sample driven by $\sin^2\theta_{23}$, Δm^2_{23}

What T2K measures

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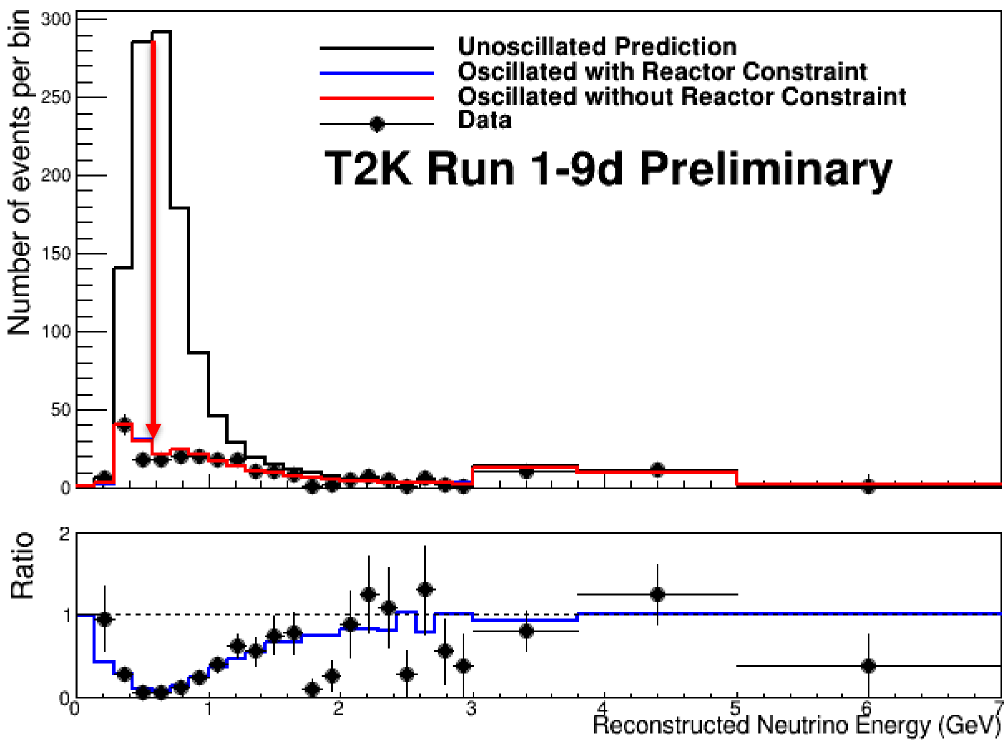
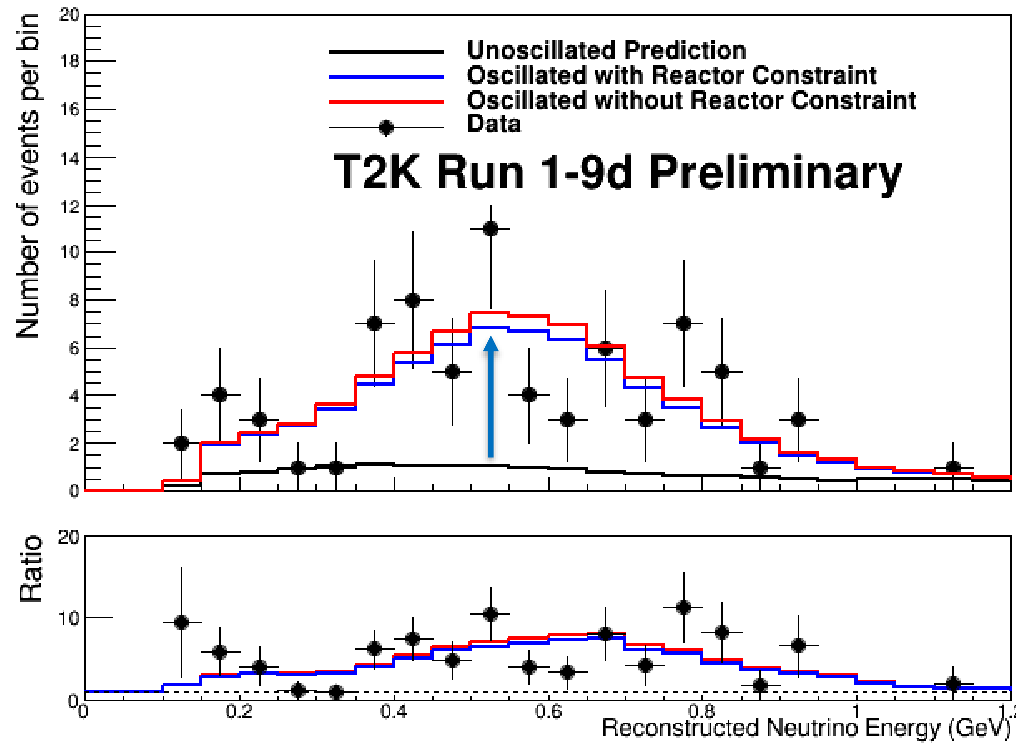
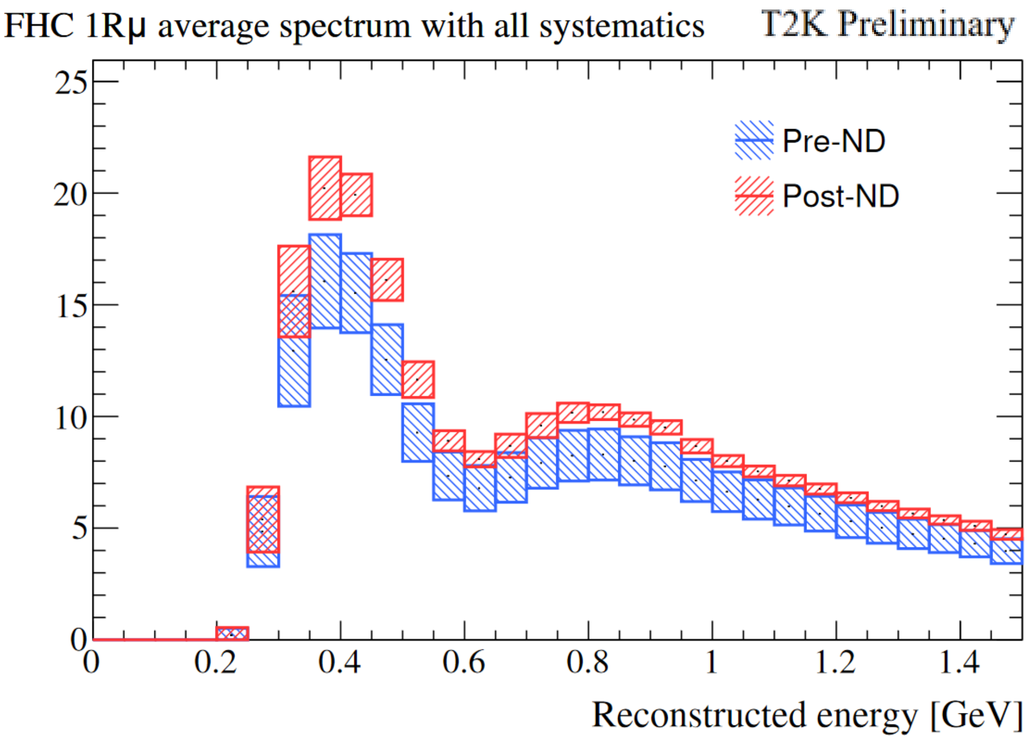
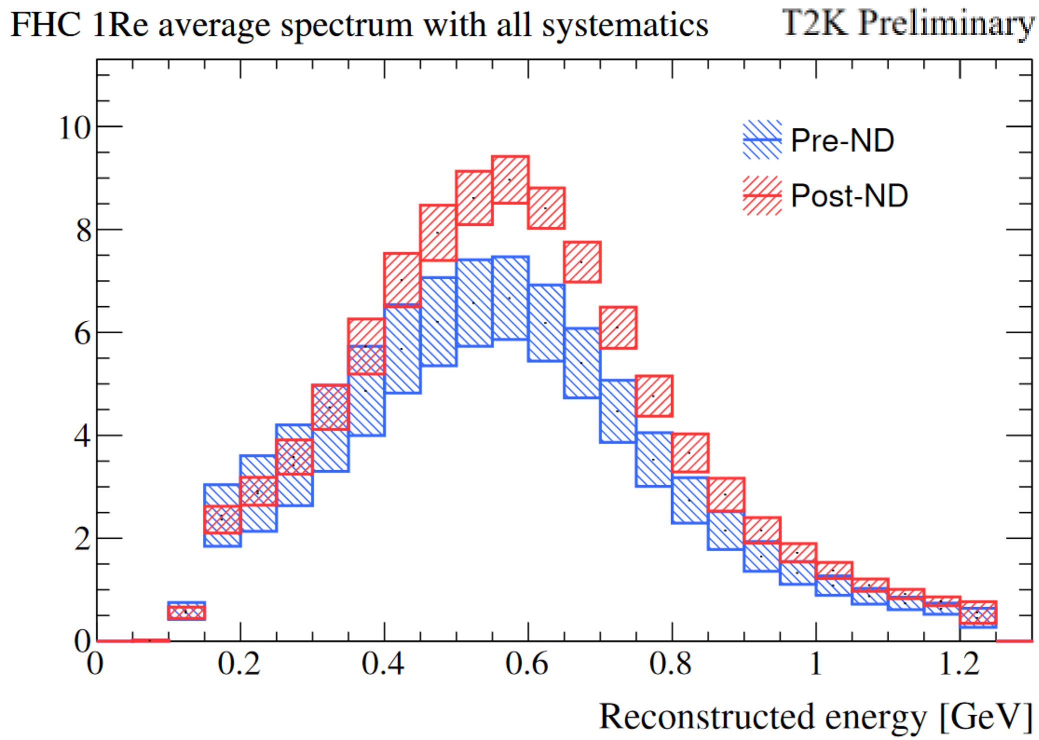




- Muon-like neutrino candidates (left), electron-like candidates (right)
- Suppression in muon neutrino sample driven by $\sin^2\theta_{23}$, Δm^2_{23}
- Increase in electron neutrino sample driven by $\sin^2\theta_{13}$, δ_{CP}

Effect of near detector fit on SK prediction





- Far detector single ring, muon-like sample on left, single ring electron-like sample on right
- ND280 fit result (red) increases predicted event rate, changes shape of spectrum and reduces systematic uncertainty

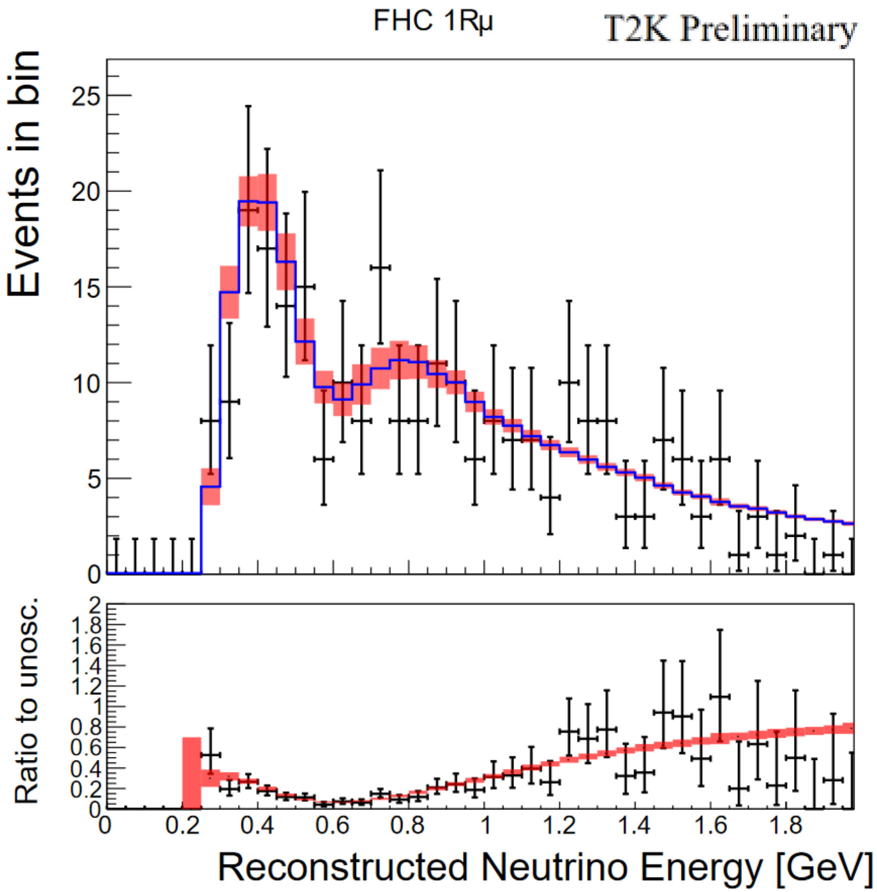
T2K systematic errors

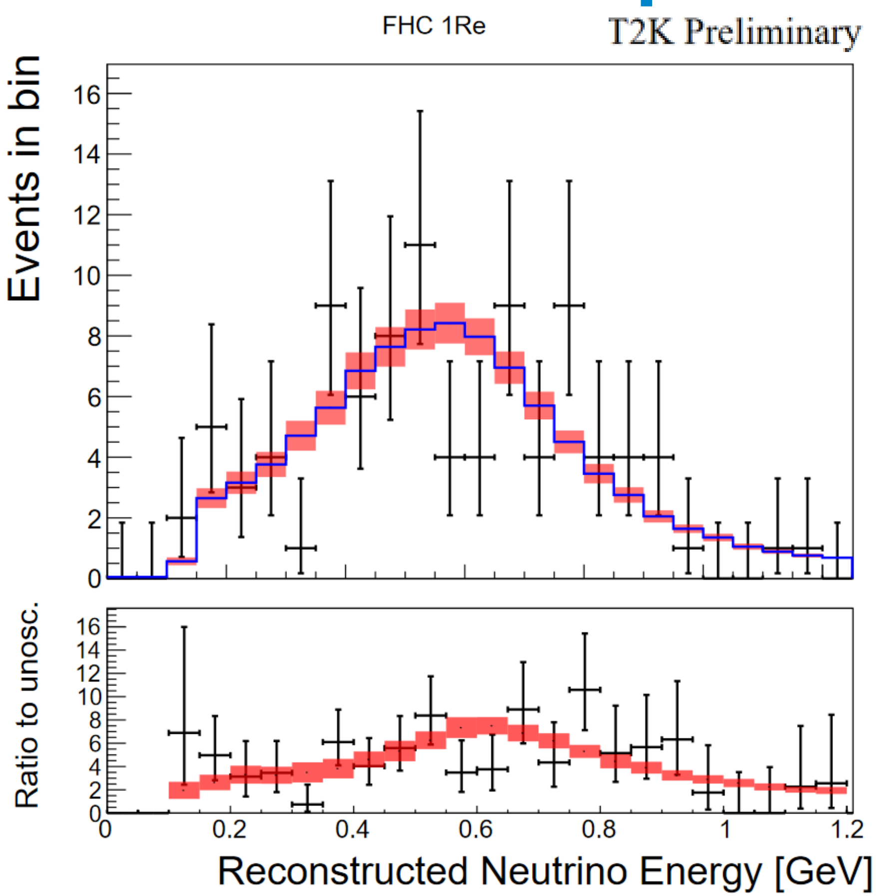
T2K Preliminary

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

- Uncertainty on predicted SK event rate after ND280 fit
  - Flux and cross-section uncertainties are correlated so the combination gives a smaller uncertainty than the individual parts
  - Final column is error on rate of neutrino events compared to antineutrino events in the electron-like samples – critical for CP violation search

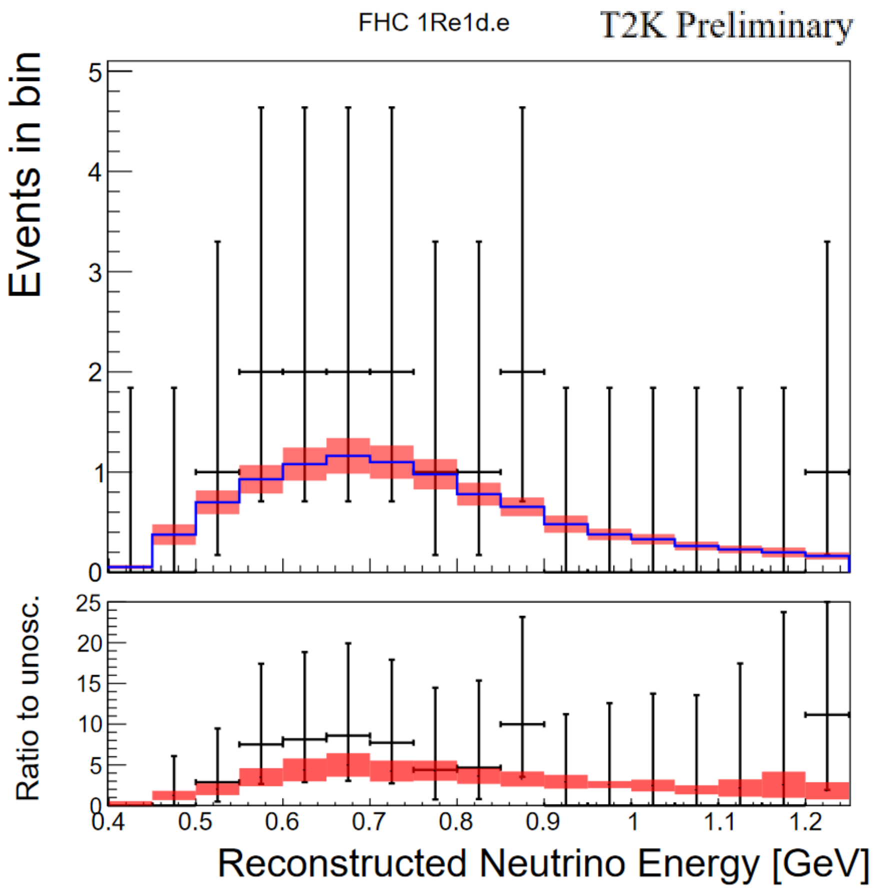
Latest Results – Neutrino mode beam samples

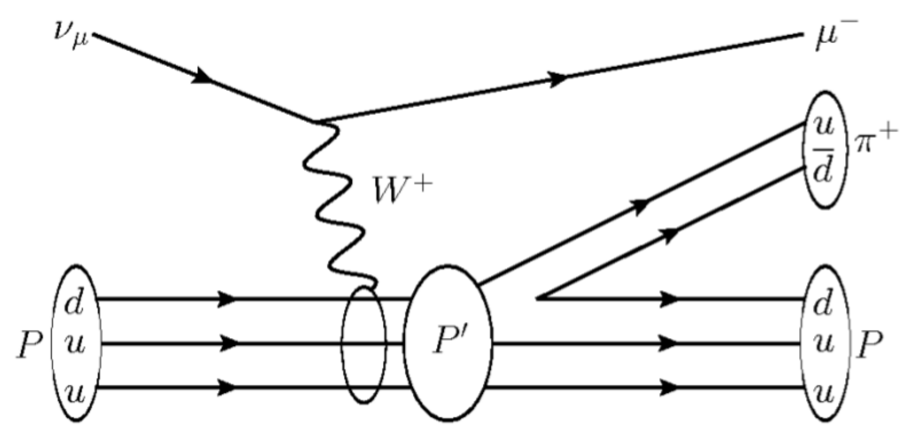




- Neutrino beam mode, muon-like CC-0π candidates (left), electron-like CC-0π candidates (right)
- Prediction (blue histogram) and RMS error (red band) after fit to data

Latest Results – Neutrino mode beam samples

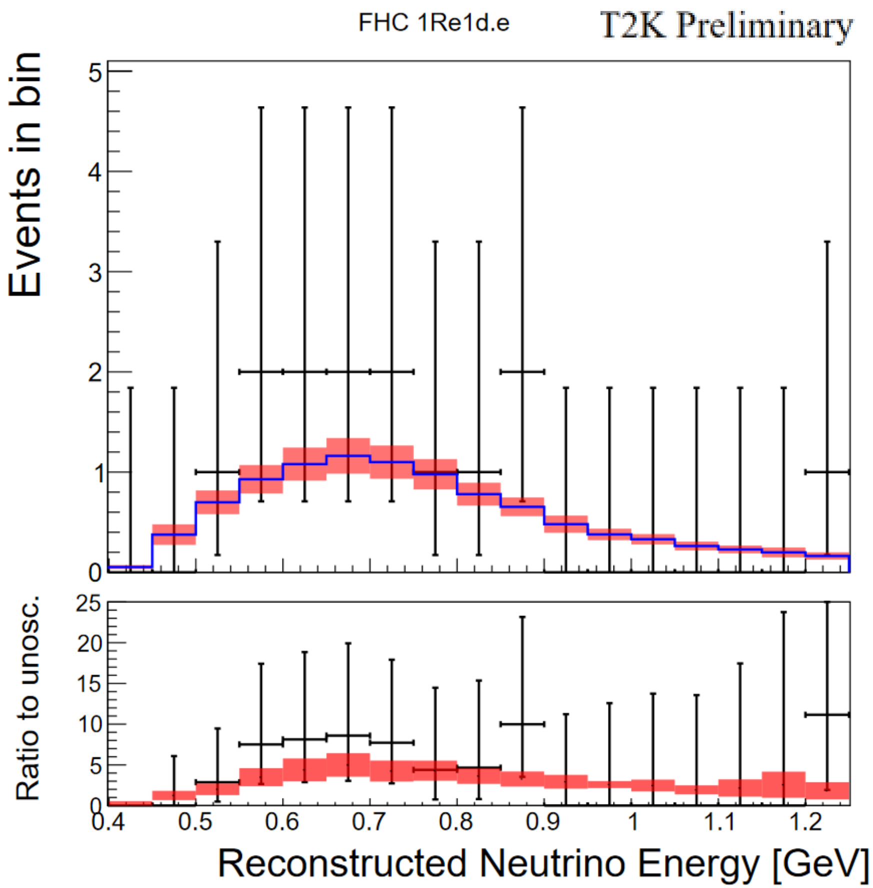


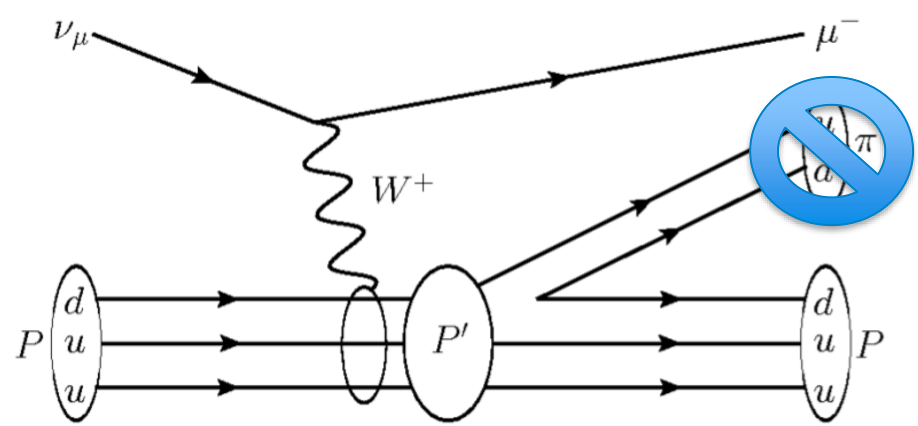


CC-1π sample

- CC-1π sample only in neutrino beam mode

Latest Results – Neutrino mode beam samples

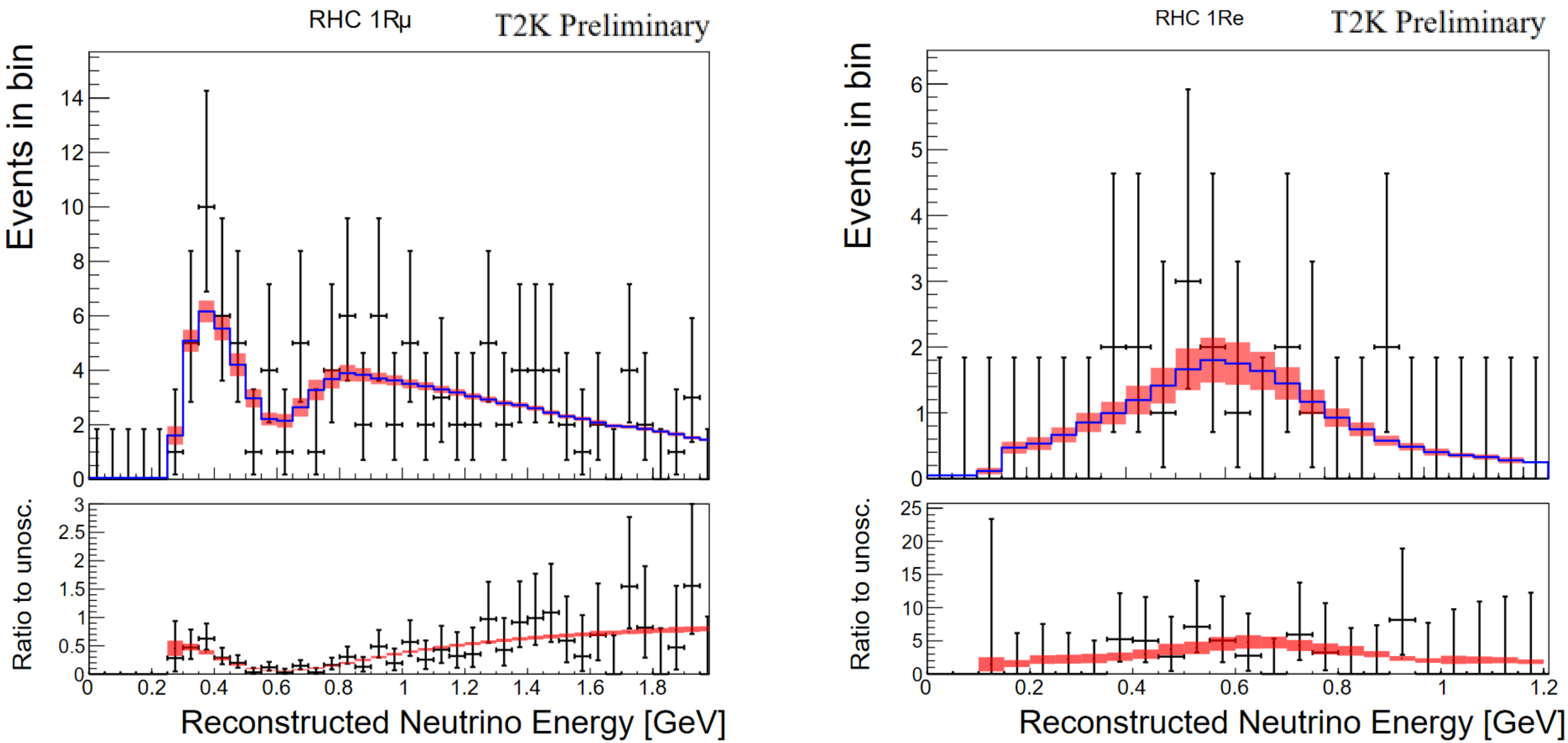




CC-1π sample

- CC-1π sample only in neutrino beam mode
- Use Michel electron tag to locate pion – below Cherenkov threshold

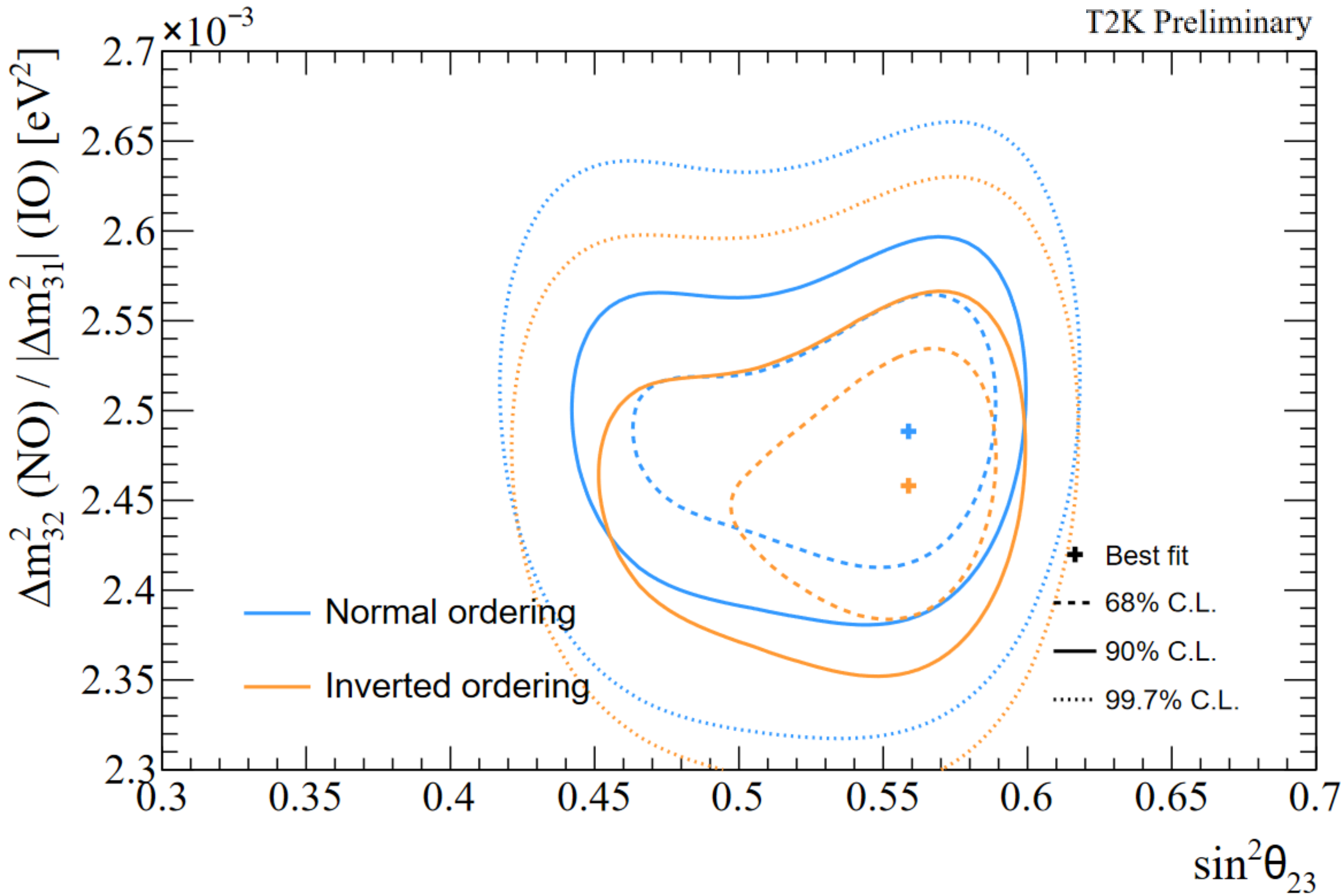
Latest Results – Antineutrino beam mode



- Antineutrino beam mode, muon-like CC-0π candidates (left), electron-like CC-0π candidates (right)
- Prediction (blue histogram) and RMS error (red band) after fit to data

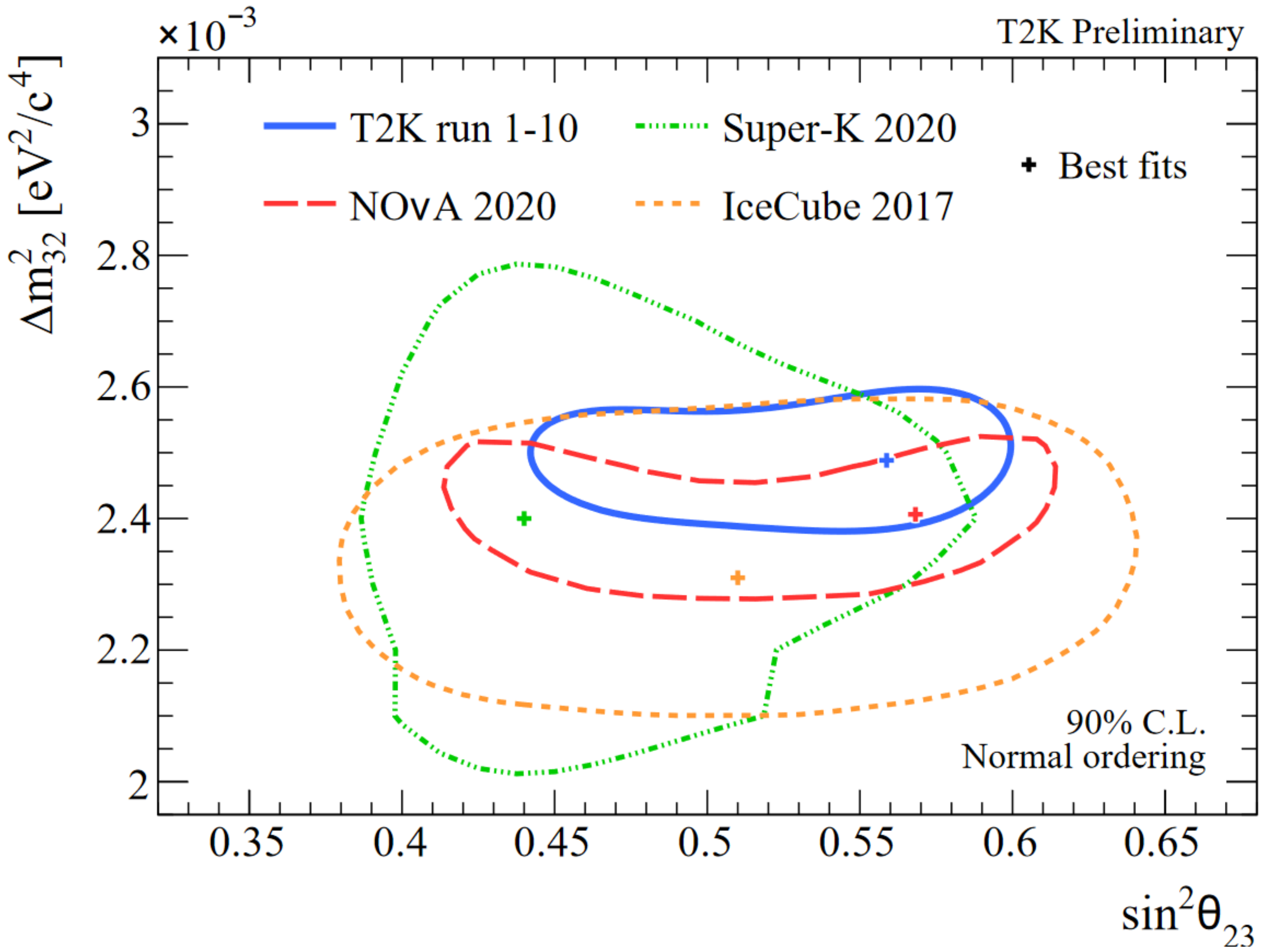
Disappearance parameters

- T2K data shows preference for upper octant
- Best-fit point at non-maximal mixing, though maximal mixing still within 1σ
- Fits include reactor constraint on $\sin^2(\theta_{13})$

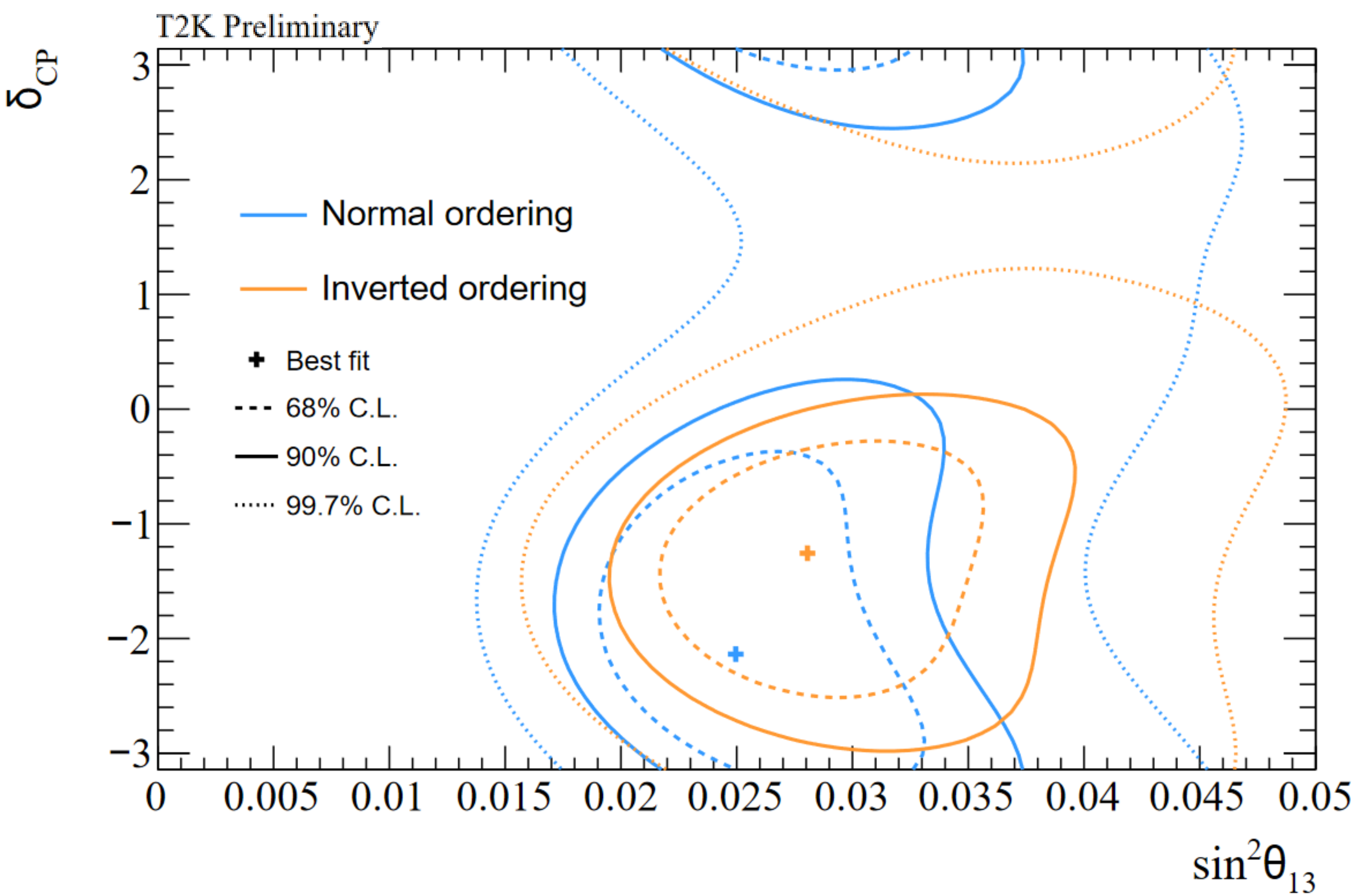


Disappearance parameters – global comparison

- 90% confidence level contours
- Normal mass ordering assumed
- All experiments in agreement

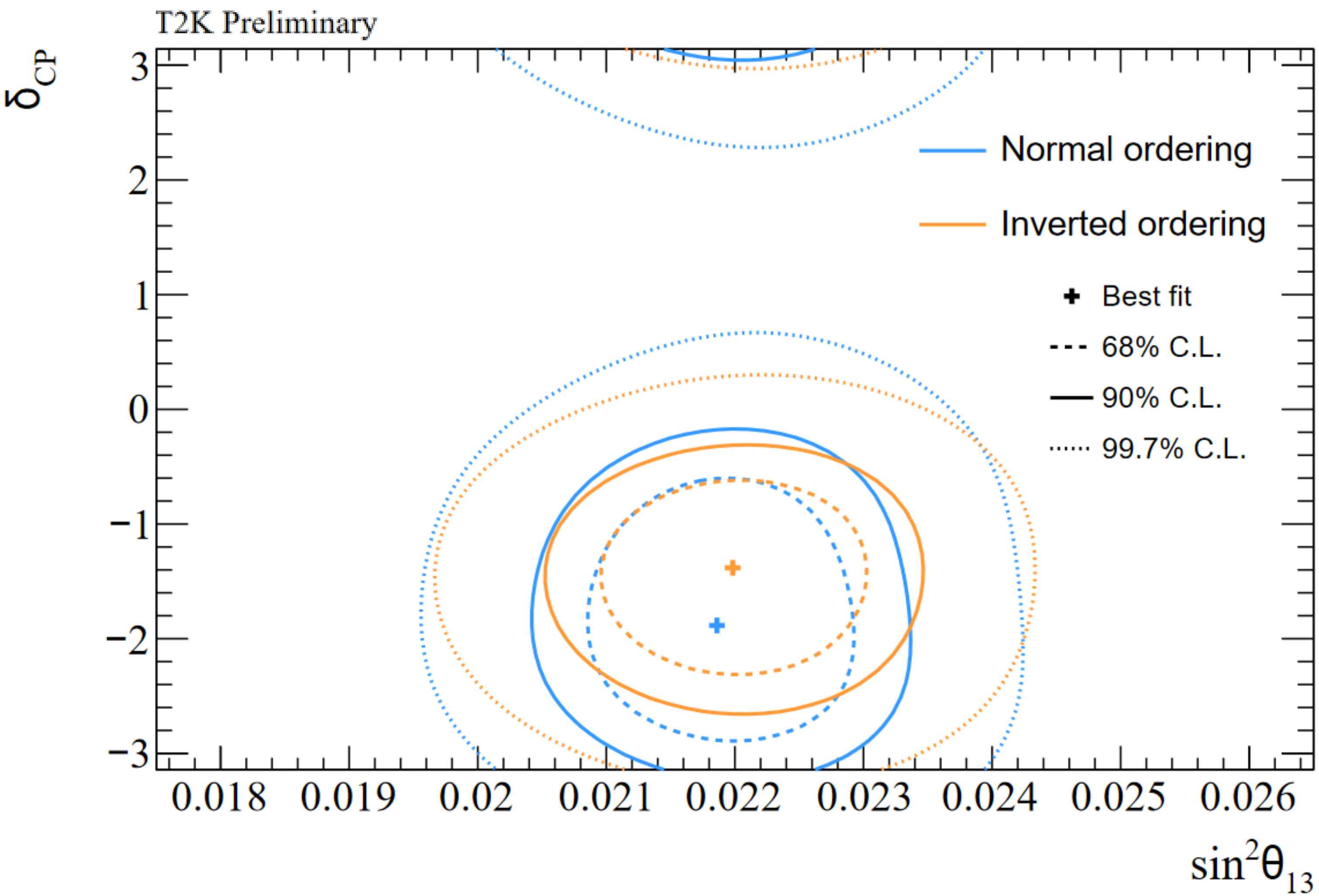


Appearance parameters – without reactor



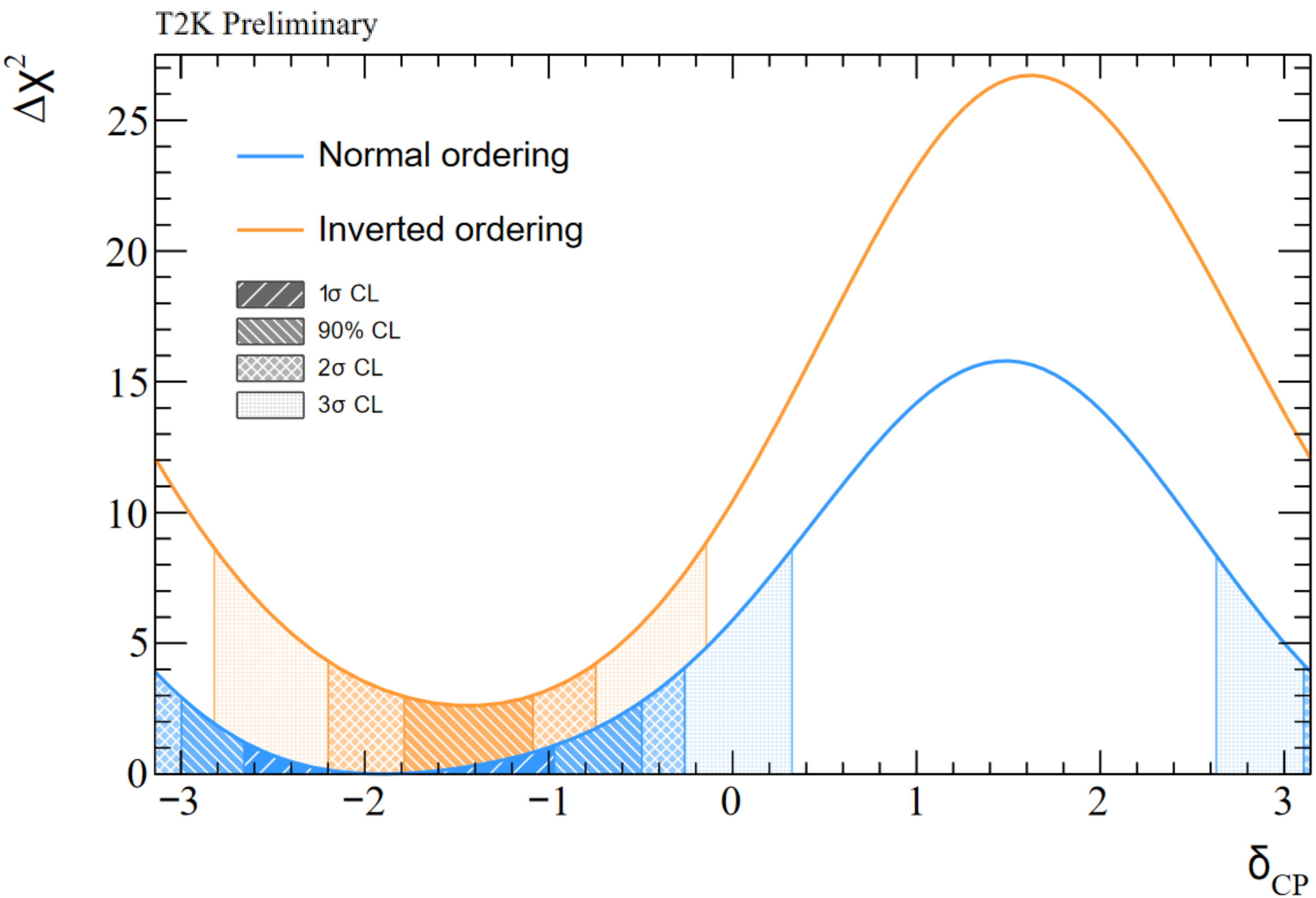
- Fit **without** reactor constraint on $\sin^2(\theta_{13})$
- T2K best-fit point near maximal CP-violation
- Fully consistent with reactor measurements

Appearance parameters – with reactor



- Fit **with** reactor constraint on $\sin^2(\theta_{13})$
- T2K best-fit point nearer maximal CP-violation
- Regions of δ_{CP} space outside 2σ contour

δ_{CP} contour



- Fit **with** reactor constraint on $\sin^2(\theta_{13})$
- Likelihood with respect to global minimum
- Using Feldman-Cousins method to ensure coverage
- $\delta_{CP} = \pi/2$ excluded at >3σ

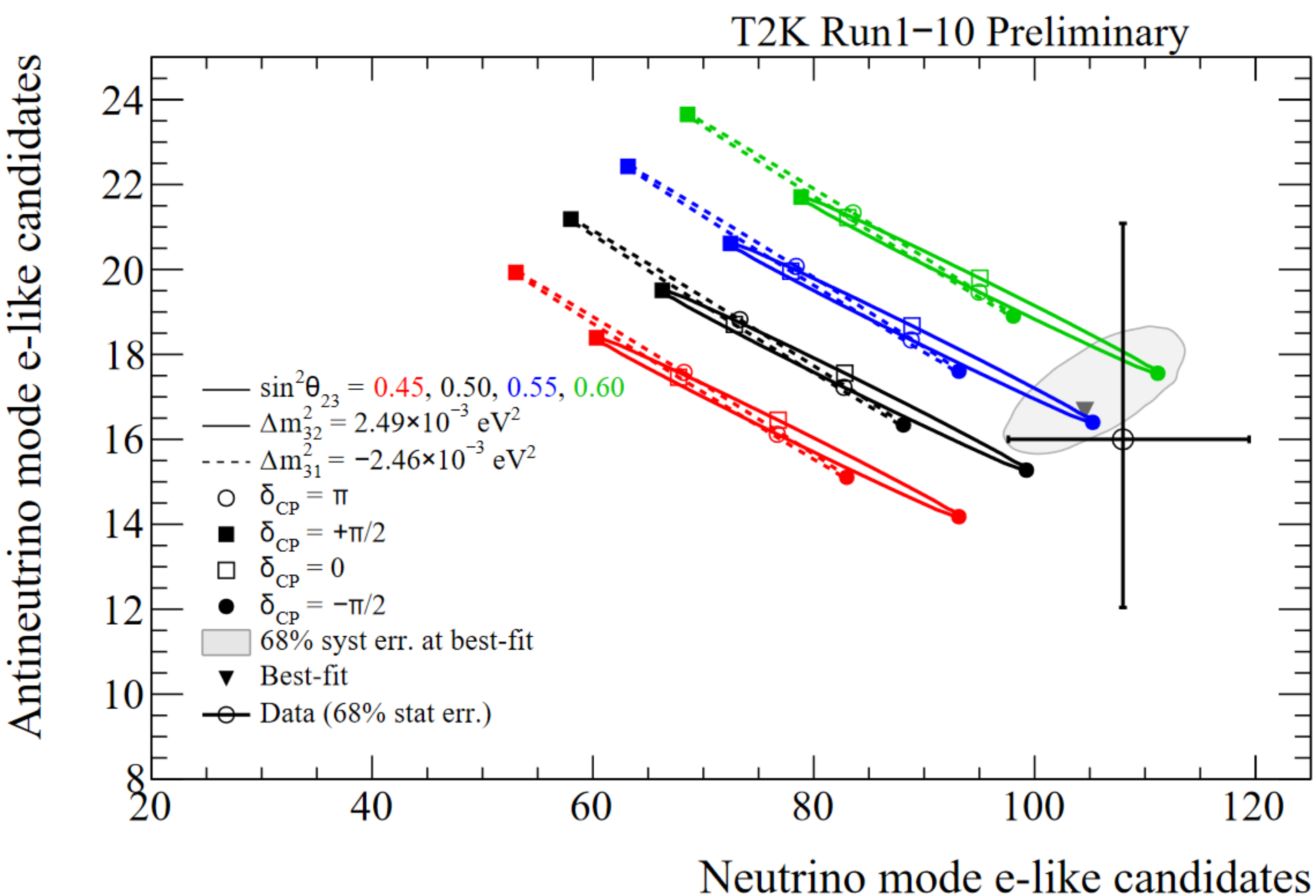
Mass Ordering and θ_{23} Octant

- Table shows posterior probability for various hypotheses
  - Bayesian approach
  - Marginalising over other oscillation parameters
  - A flat prior is used for δ_{CP}, $\sin^2\theta_{23}$, $|\Delta m^2_{23}|$ and mass ordering
  - Solar parameters and $\sin^2 2\theta_{13}$ use Gaussian prior from PDG

- T2K data prefer the upper octant and normal mass ordering

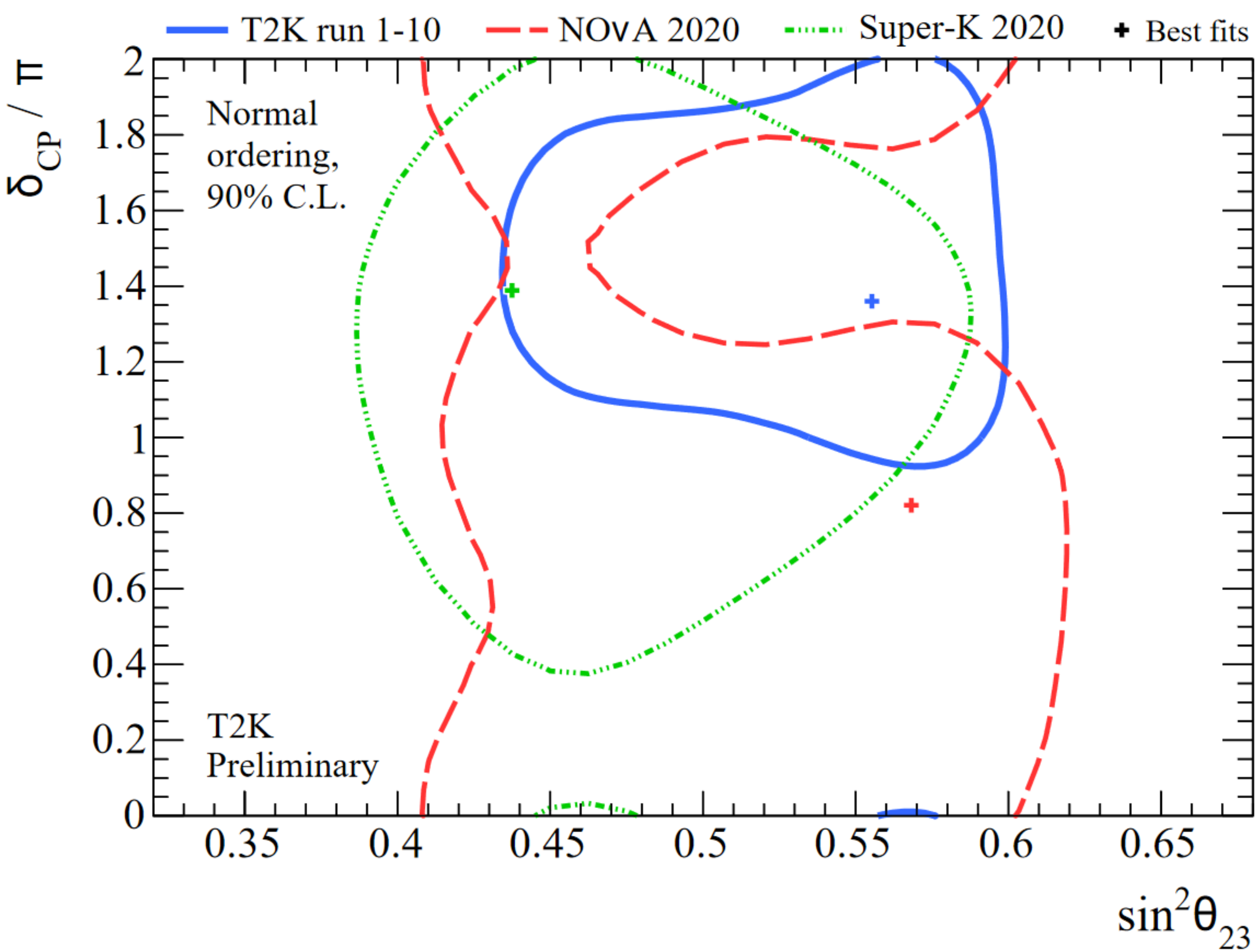
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Normal ordering	0.19	0.65	0.83
Inverted ordering	0.03	0.14	0.17
Column total	0.21	0.79	1.00

T2K bi-event rate



- T2K data consistent with Pontecorvo-Maki-Nakagawa-Sakata prediction
- Shaded area shows systematic uncertainty on prediction

δ_{CP} global comparison



- Fit **with** reactor constraint on $\sin^2(\theta_{13})$
- Assuming Normal mass ordering
- Experiments ~agree at 90% C.L.
  - Need more data!

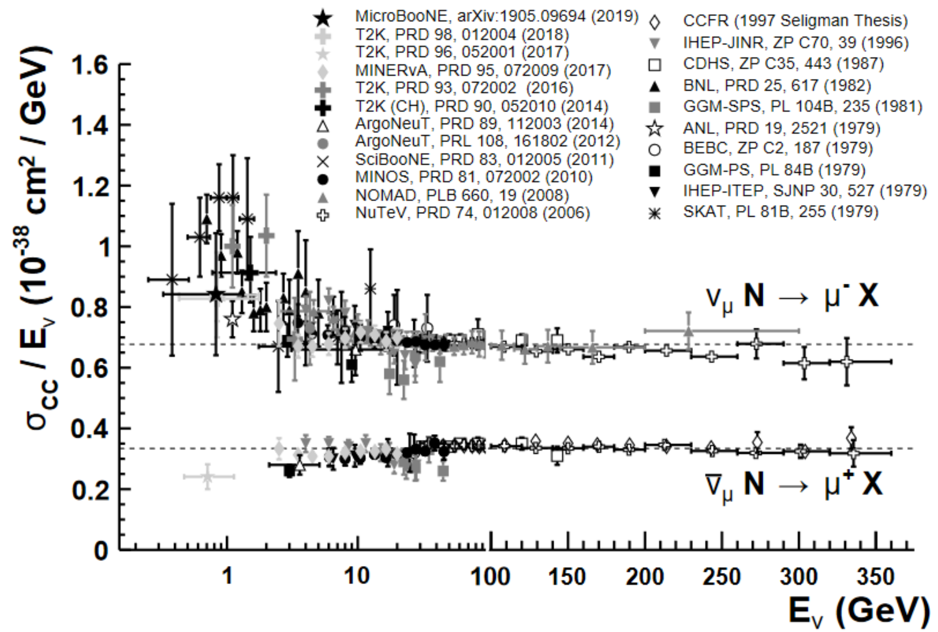
Robustness checks

Neutrino cross section error

- Neutrino cross-section is ~largest source of uncertainty

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

- World data is imprecise around 1 GeV neutrino energy
- Multiple, plausible models exist, however:
  - Monte Carlo simulation based on a single model



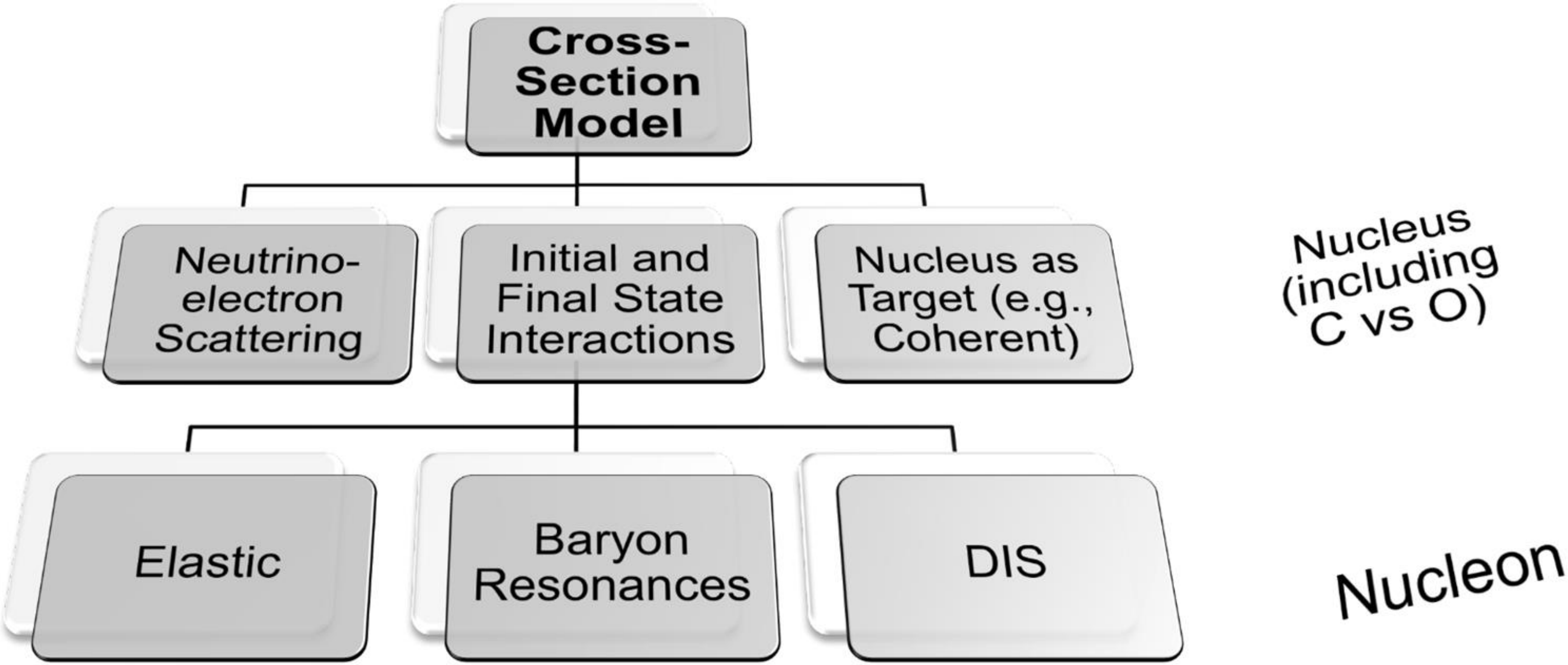
G. Zeller, PDG Neutrino Cross Sections 2019

Simulated data studies

- Use information about simulated interactions to produce mock data based on a different neutrino interaction model
  - Detailed description can be found here: https://arxiv.org/abs/2101.03779

- Pass mock data through near and far detector fitters
  - Tune nominal interaction model to try and match mock data model
  - Extract oscillation parameter contours and compare to our expectation
  - Use results to add additional uncertainties to oscillation contours from real data fit

T2K cross-section model

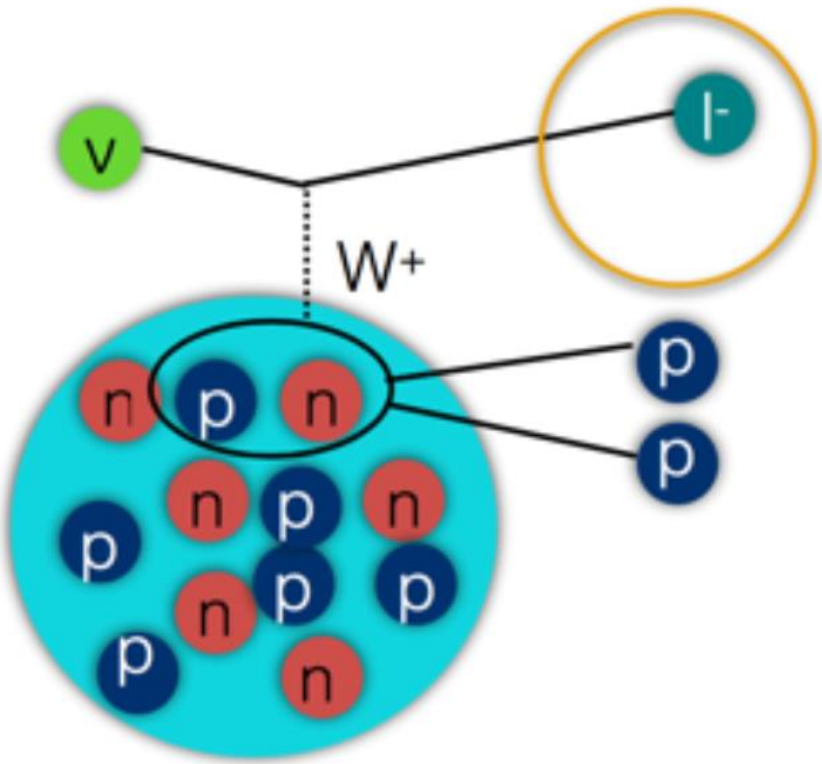


- Many unknowns!

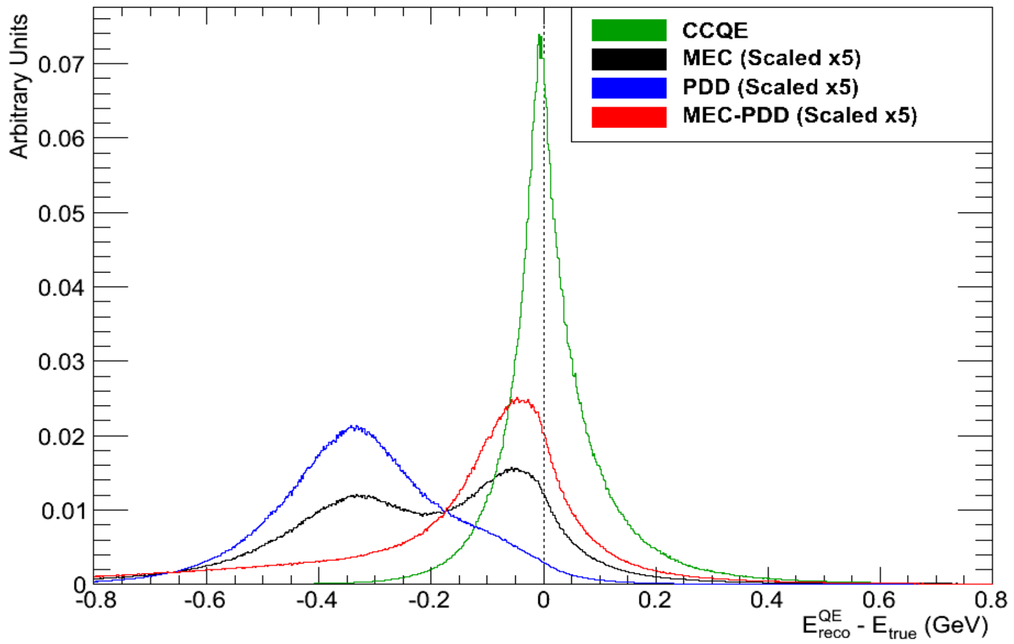
Image from K. McFarland

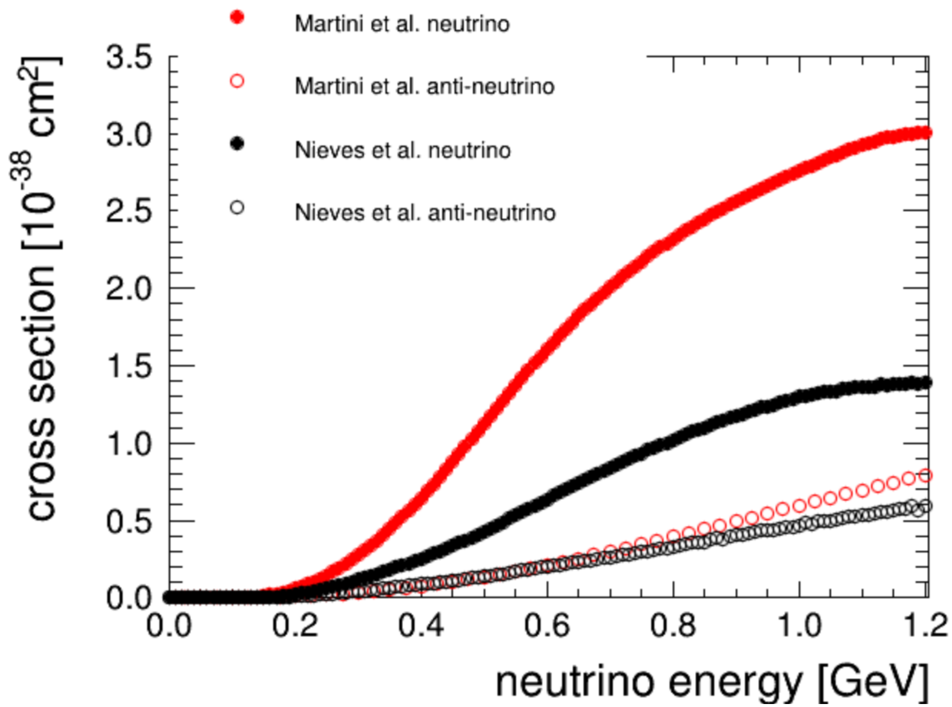
Example: 2p-2h events

- Lepton kinematics give energy
- Extra protons below detector threshold – missed energy
- If we get the model wrong
  - Biased energy reconstruction
  - Incorrect relationship between reconstructed and true neutrino energy



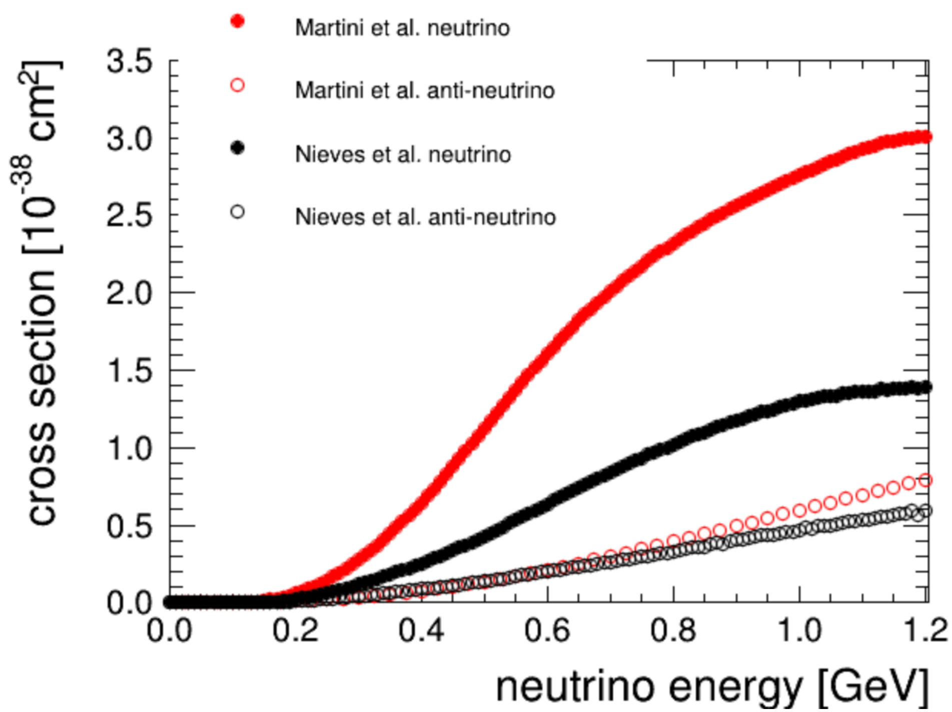
2p-2h event reconstruction

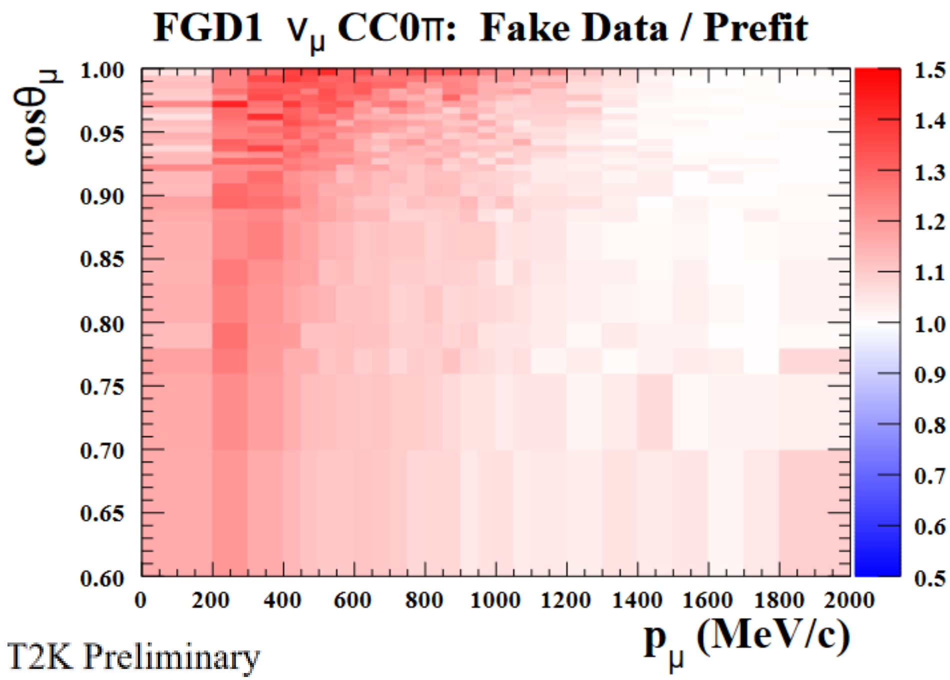




- Biased energy affects oscillation measurements
- Multiple possible models – Martini and Nieves are two examples
  - Different predicted rates for neutrinos and anti-neutrinos
  - ‘CP-violating’ uncertainty

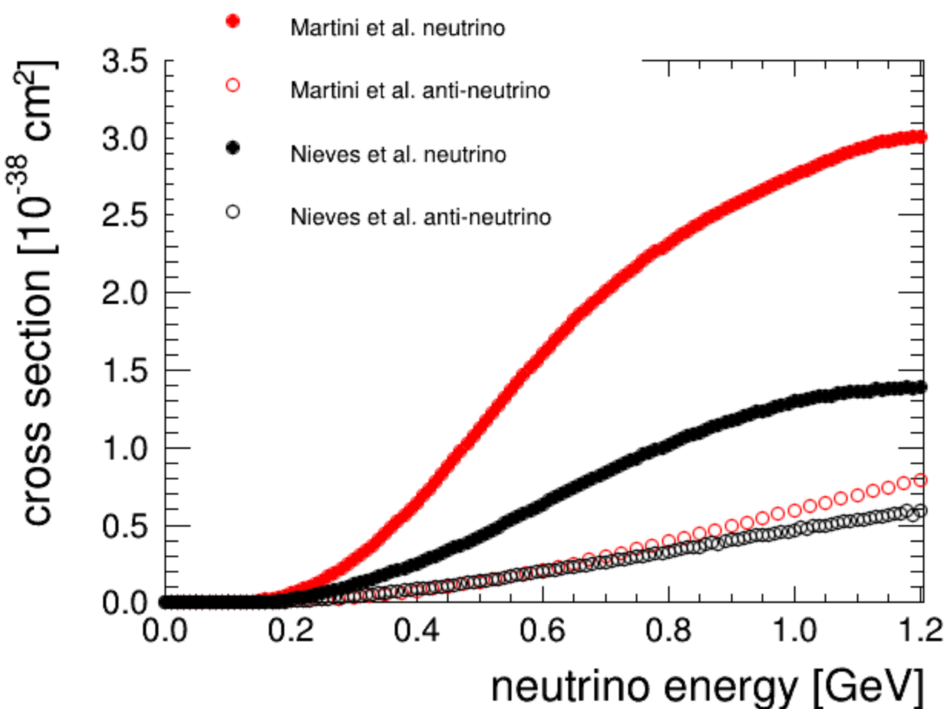
The Martini 2p2h simulated data study

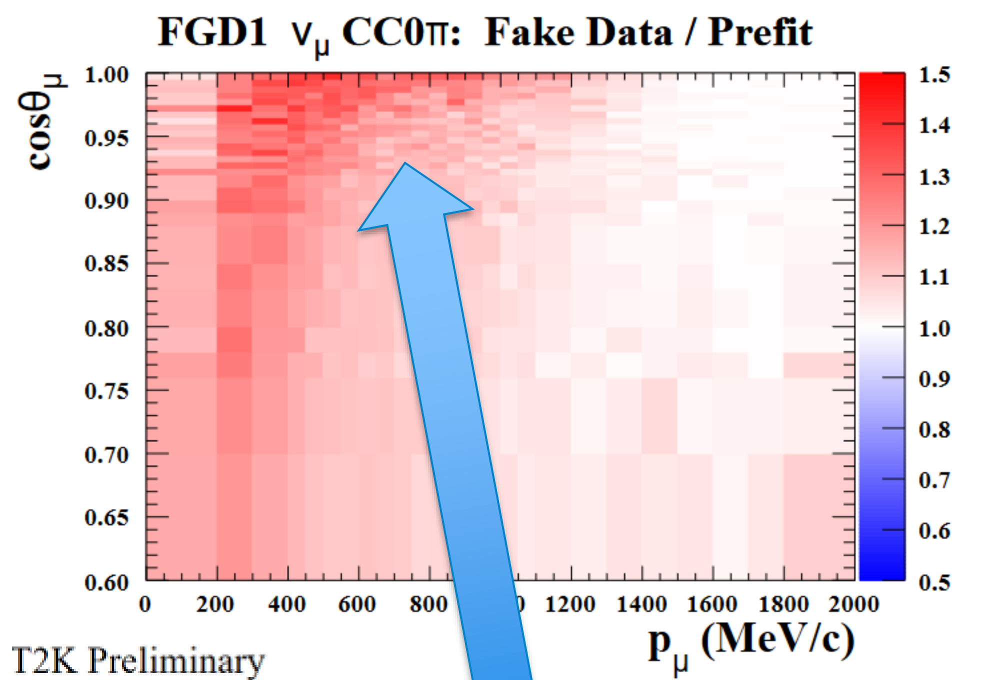




- Model applied to ND280 nominal MC prediction
- FGD1 CC0π sample shown

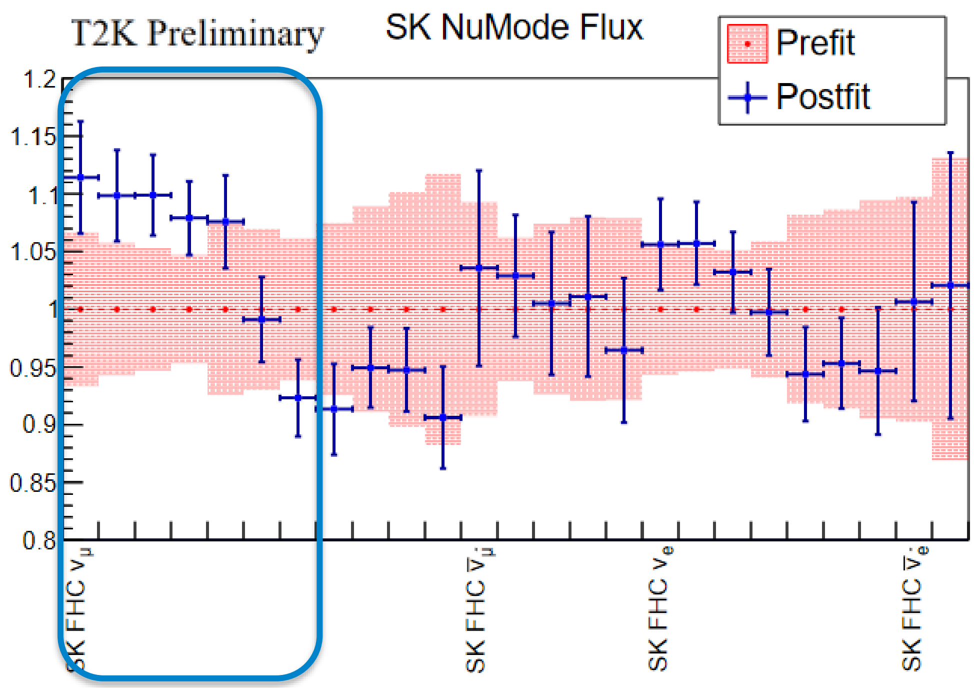
The Martini 2p2h simulated data study

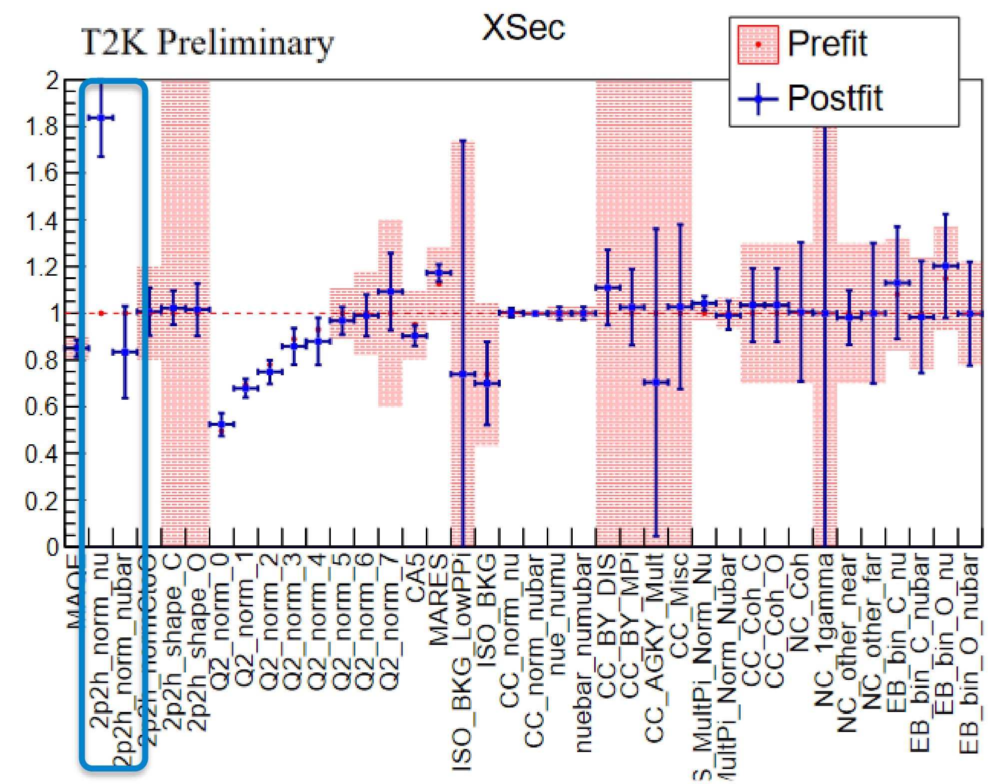




- Model applied to ND280 nominal MC prediction
- FGD1 CC0π sample shown
- Increase in normalization with larger increase at larger neutrino energies

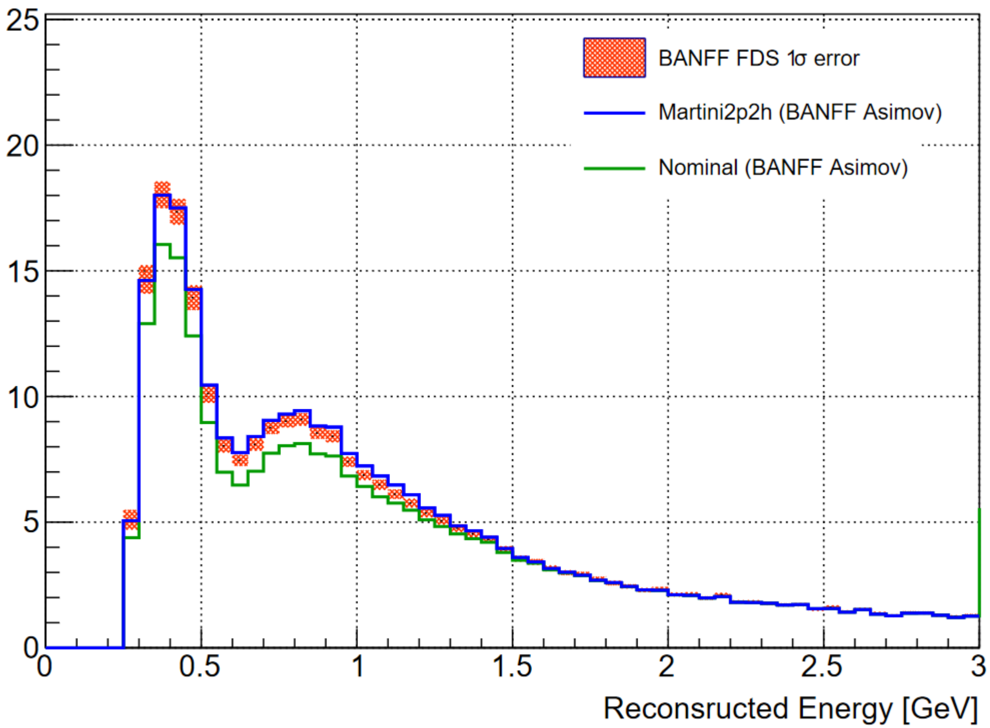
Martini 2p2h ND280 fit

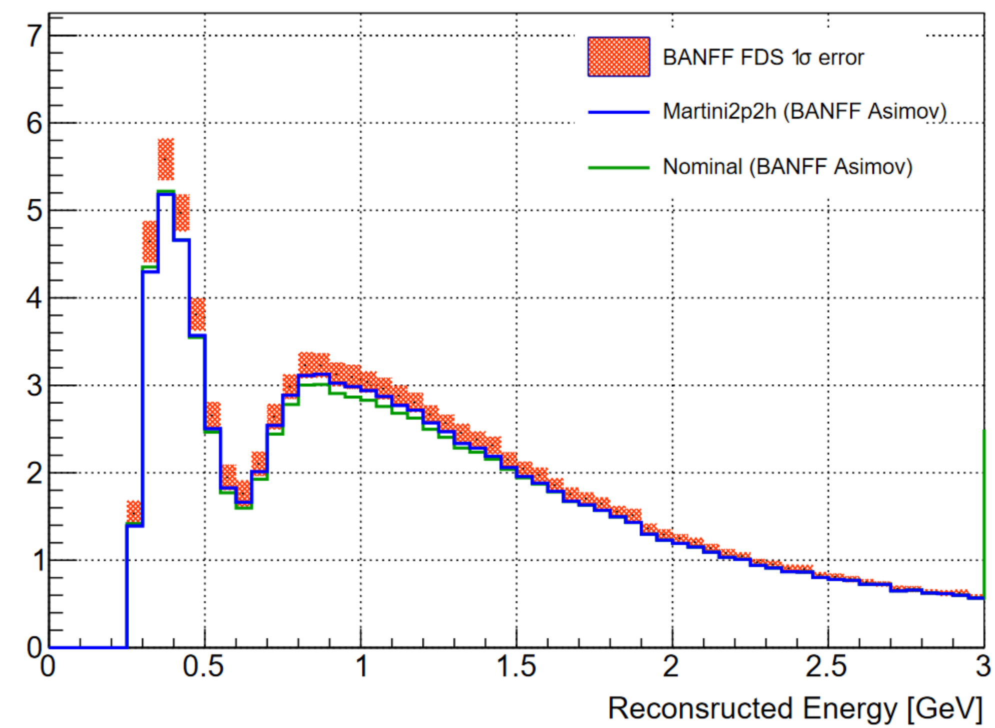




- Changes in flux and 2p2h normalization
  - Normalisation change expected, larger cross-section
  - Energy dependence – only flux parameters allow this in current model

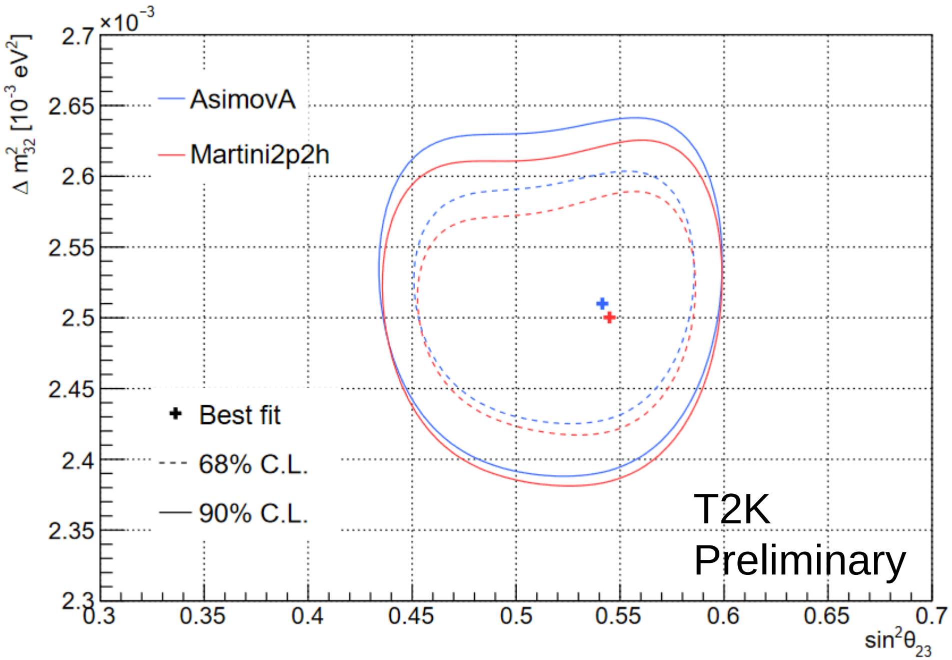
Martini 2p2h at SK

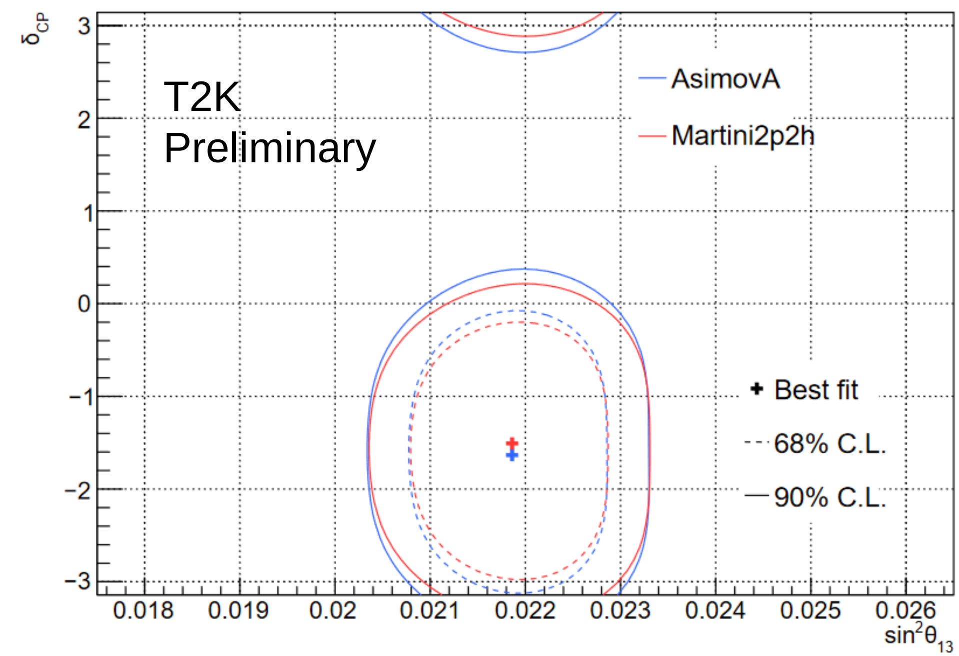




- See that Martini model (compare nominal MC to simulated data) increases neutrino event rate (left), but not antineutrino (right)
- ND280 fit (red shading) under-predicts neutrino data but over-predicts antineutrino data

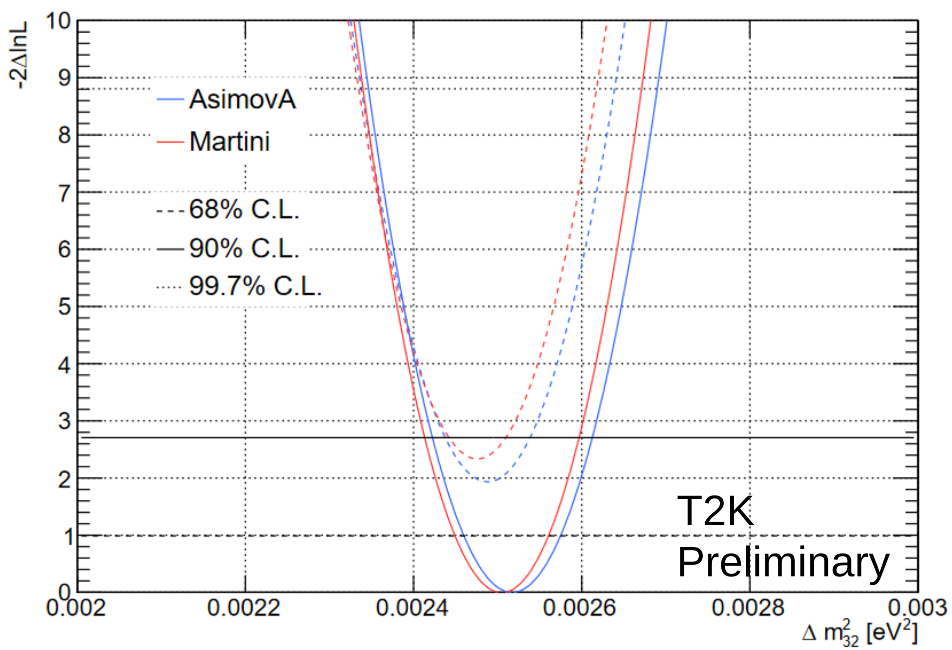
Martini 2p2h at SK – 2D contours

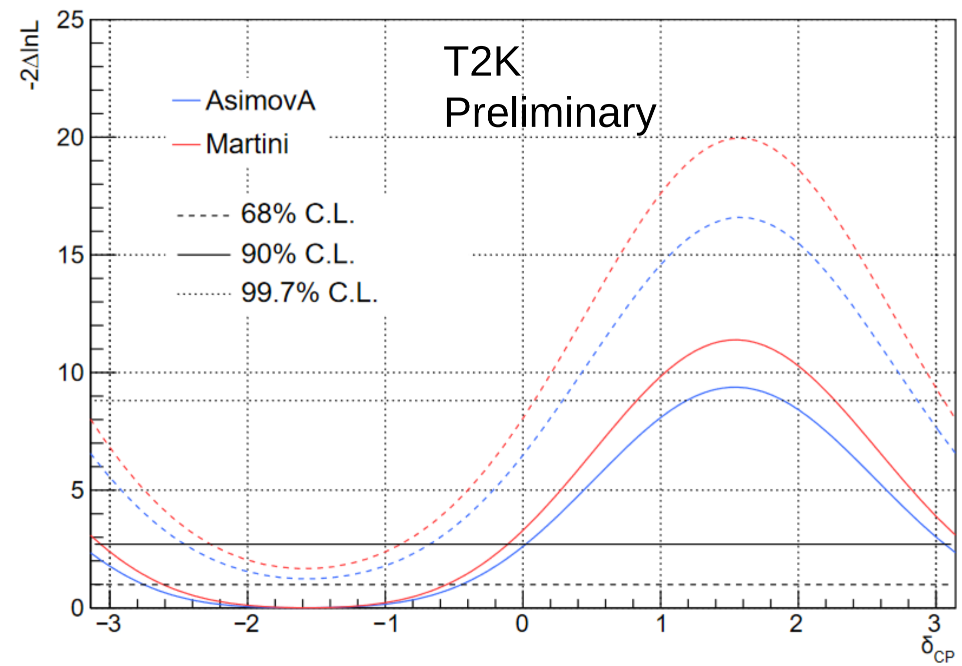




- Disappearance contour shifts to lower values of Δm^2_{32}
  - Bias in energy reconstruction
- Contour shrinks for δ_{CP} – $\sin^2\theta_{13}$
  - Relative rate of neutrino and antineutrino events changes

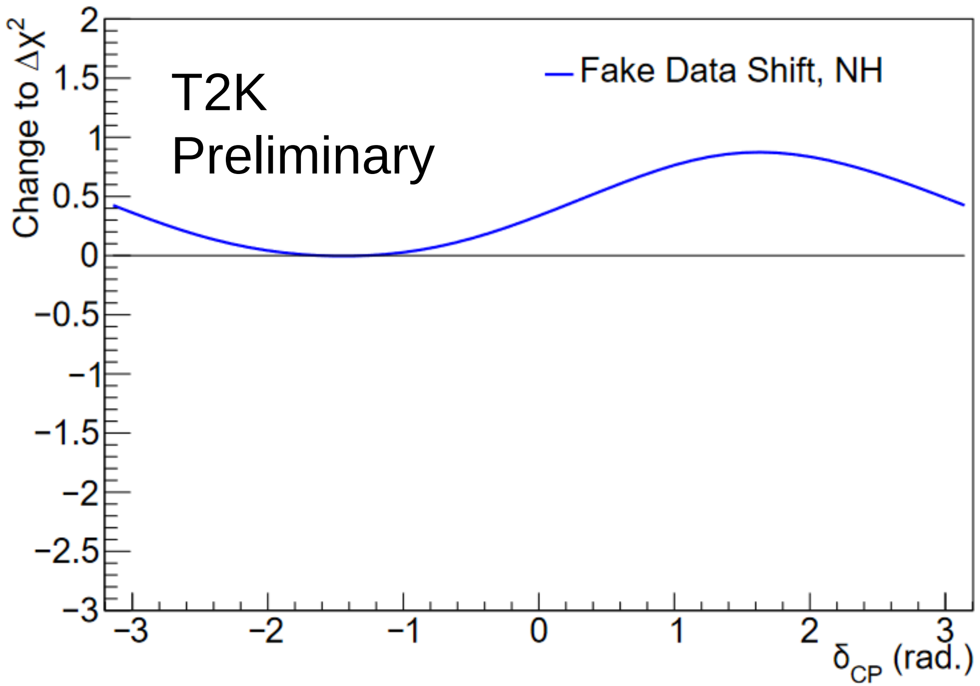
Martini 2p2h at SK – 1D contours

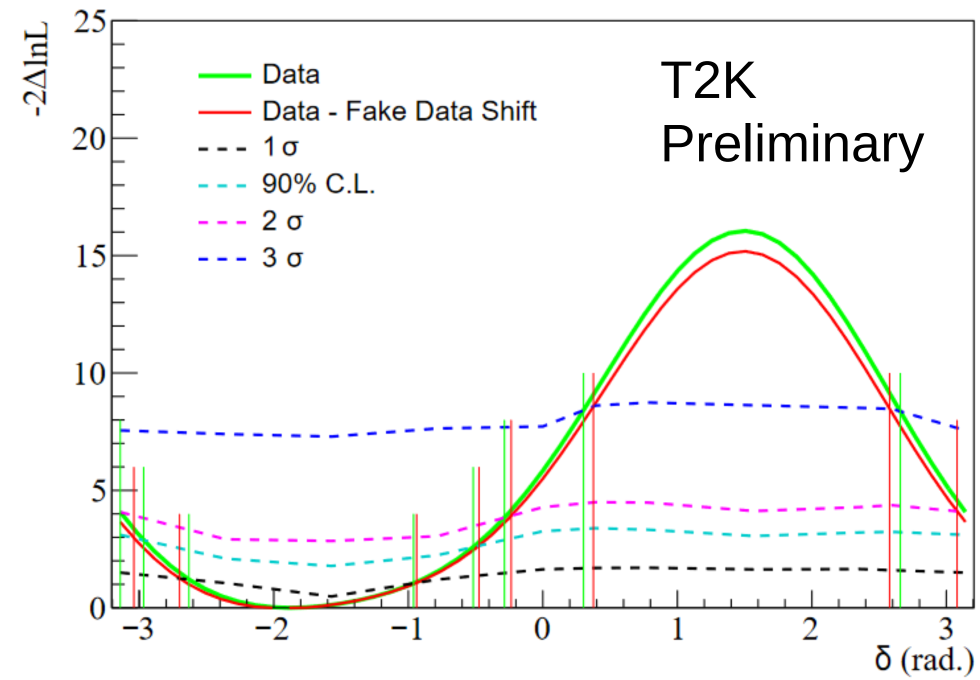




- ΔX^2 for δ_{CP} changes by ~2 units at maximum
  - Apply change in ΔX^2 to data to assess effect
- Δm^2_{32} likelihood is ~Gaussian
  - Apply fractional shift in best fit point as an additional systematic

Martini 2p2h at SK – Assessing δ_{CP}

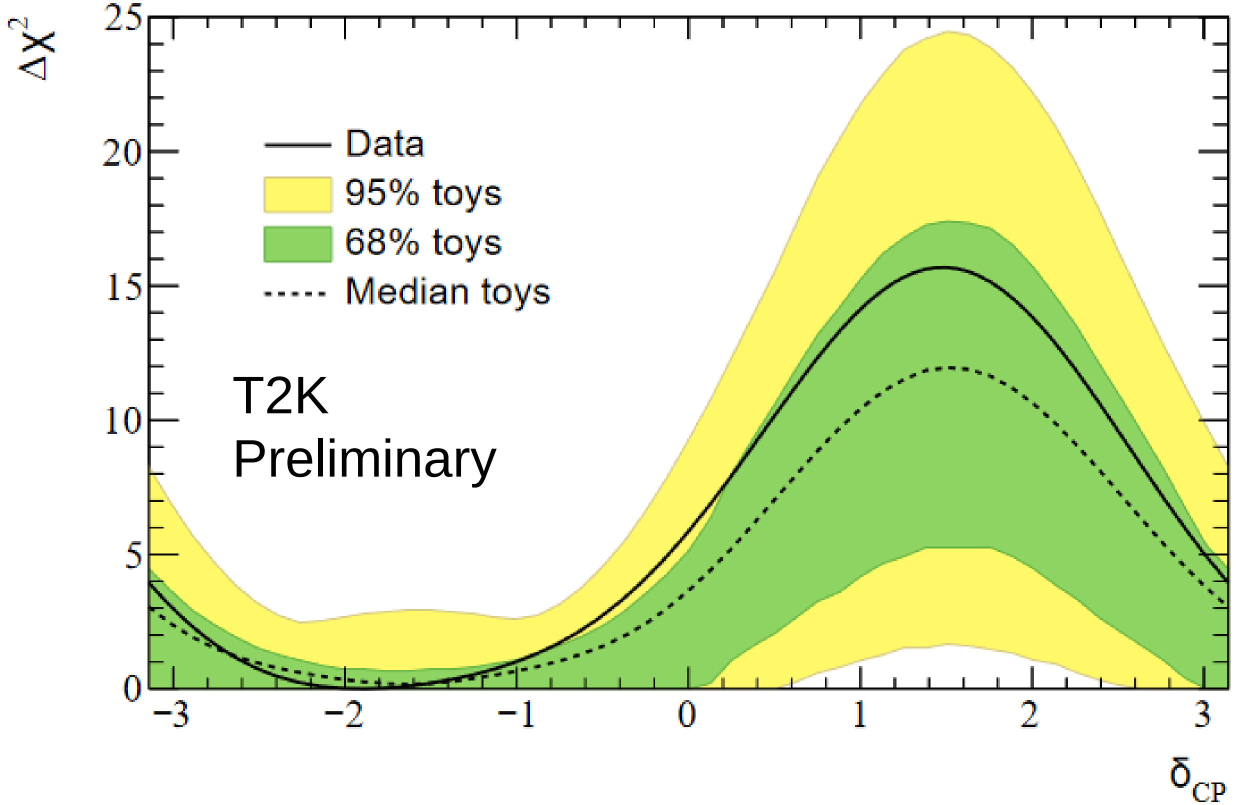




- Change in ΔX^2 on left
- Nominal data ΔX^2 (green) and corrected data ΔX^2 (red) on right
  - Feldman-Cousins 3δ (blue) and 2δ (magenta) critical values
  - Negligible effect – **true for all interaction models studied**

Likelihood of δ_{CP} result

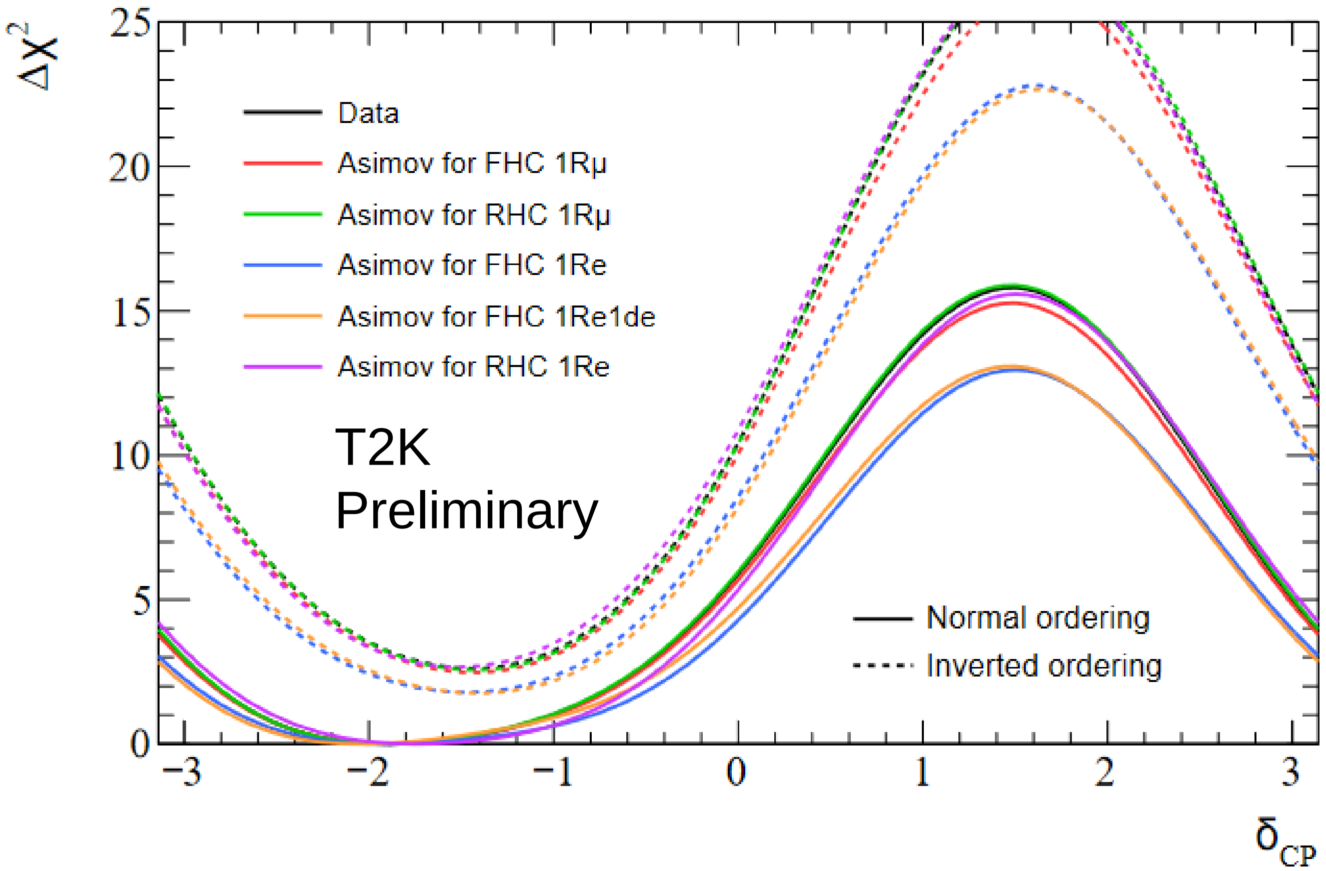
- Use marginalisation 'toy' experiments to check how unlikely our data result is
  - Randomly vary nuisance parameters according to their prior
- Coloured regions contain stated fraction of toys
  - Data result within ~1σ of median



Contribution to δ_{CP} result

- Can also replace individual data samples with nominal MC expectation
  - 'Asimov'

- See that better-than-expected exclusion comes from neutrino mode electron-like samples
  - Both equally



Where next?

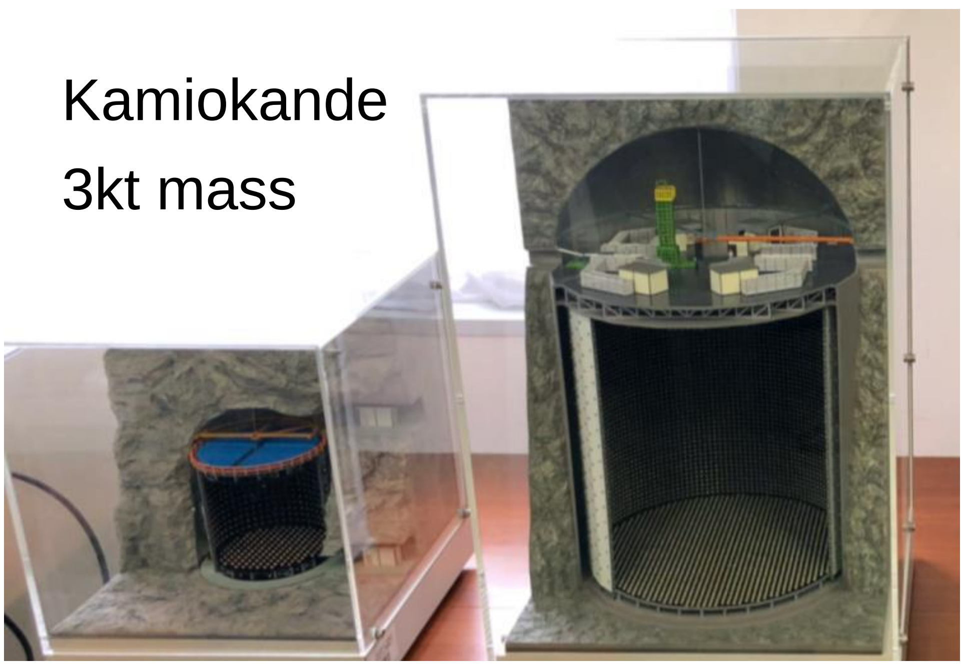
Water Cherenkov detectors in Kamioka

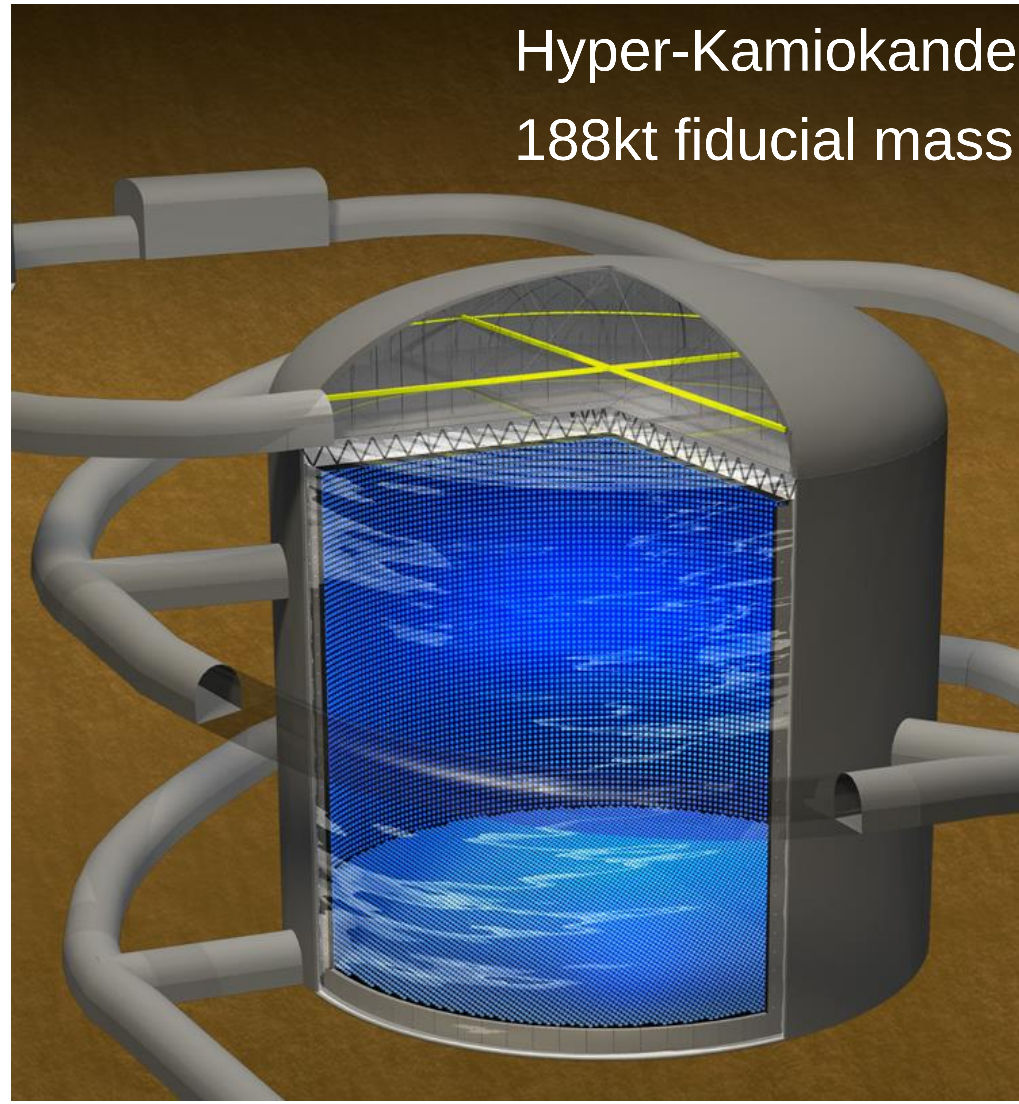
Super-Kamiokande

22.5kt fiducial mass

Kamiokande

3kt mass





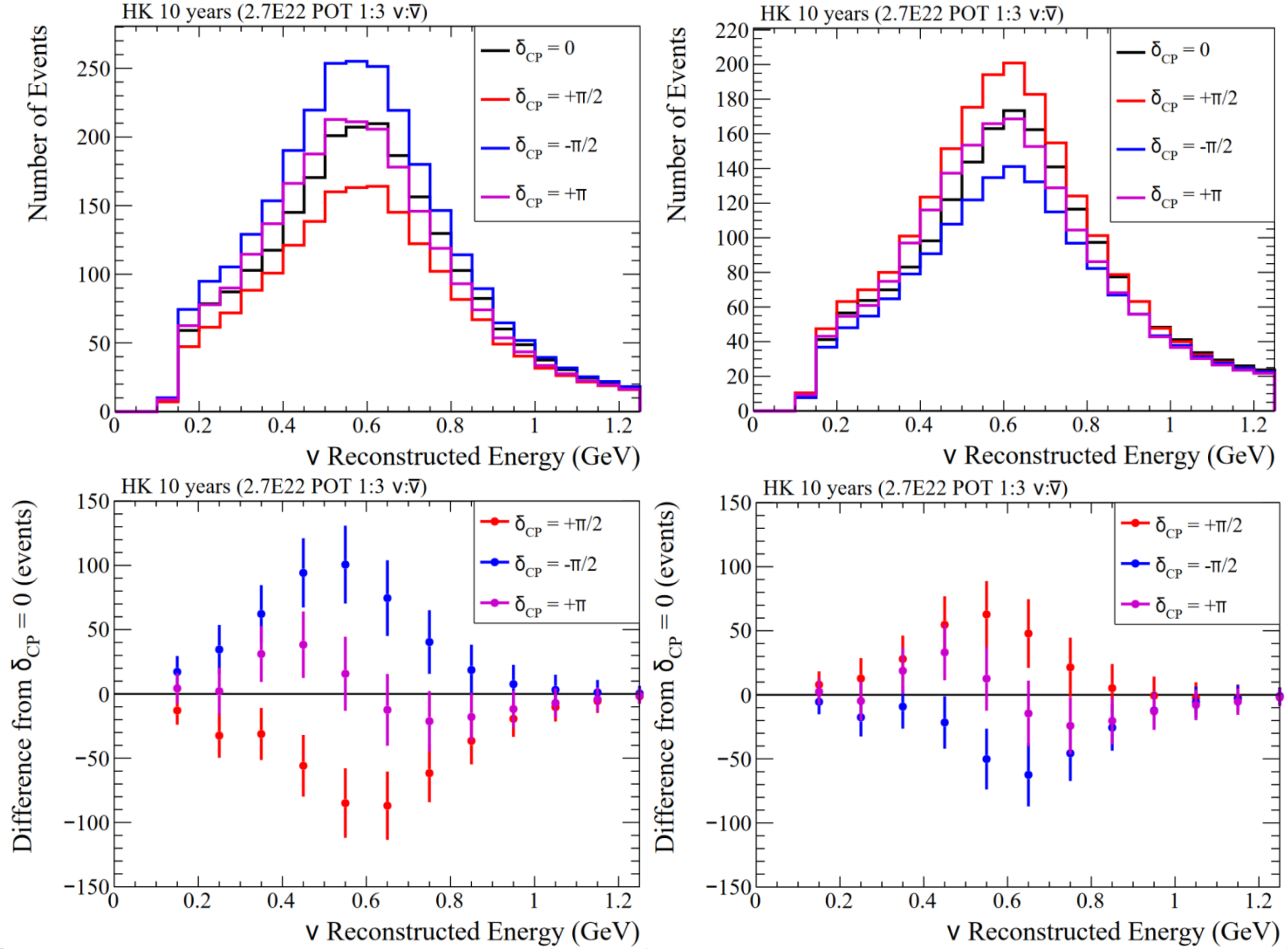
Hyper-Kamiokande electron-like event samples

- Expect approx:
  - 2300 ν_e events
  - 1900 $\bar{\nu}_e$ events
  - Assuming $\sin(\delta_{CP}) = 0$

- Difference between neutrino and antineutrino rates gives δ_{CP}

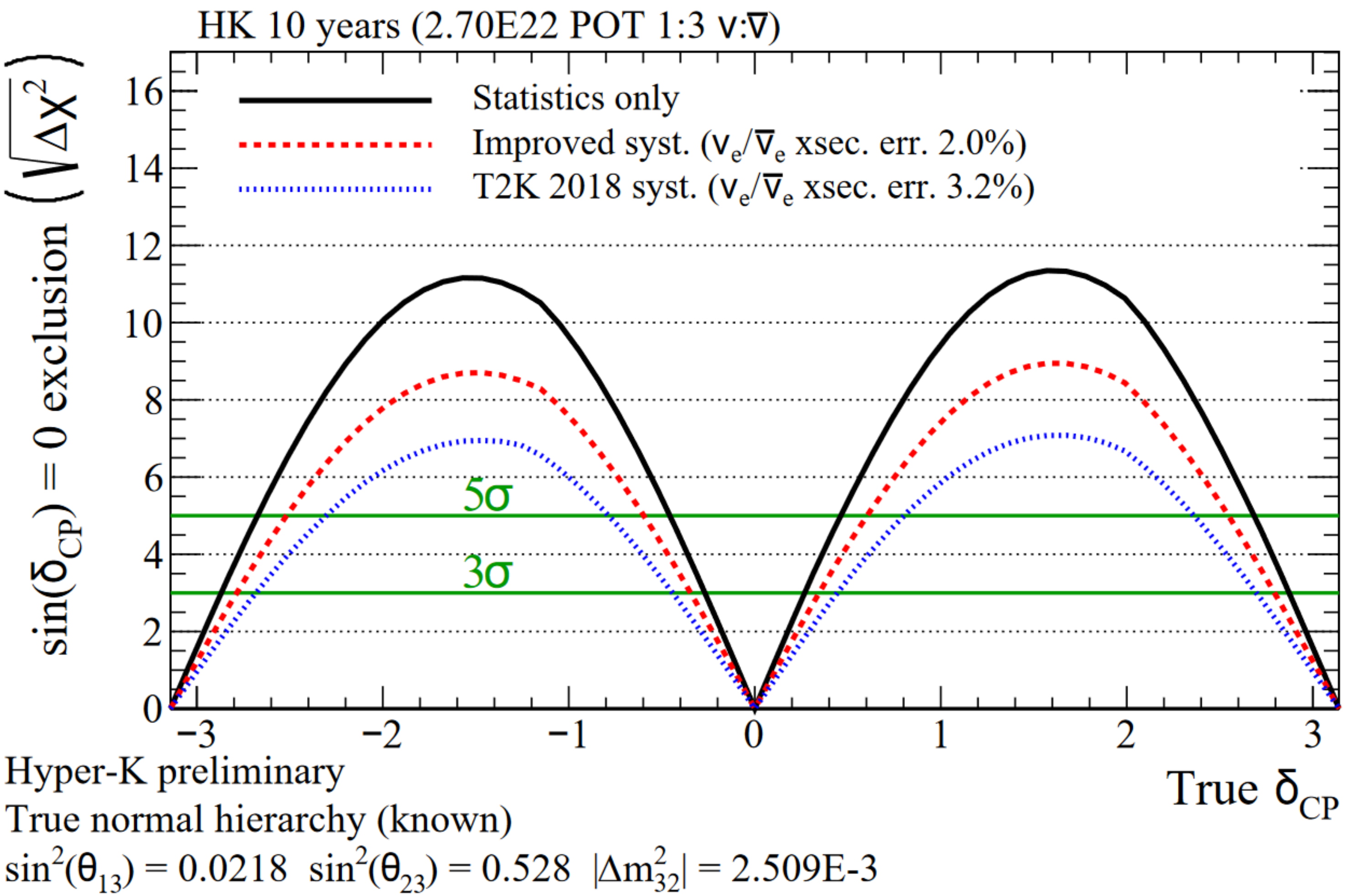
Neutrino beam

Antineutrino beam



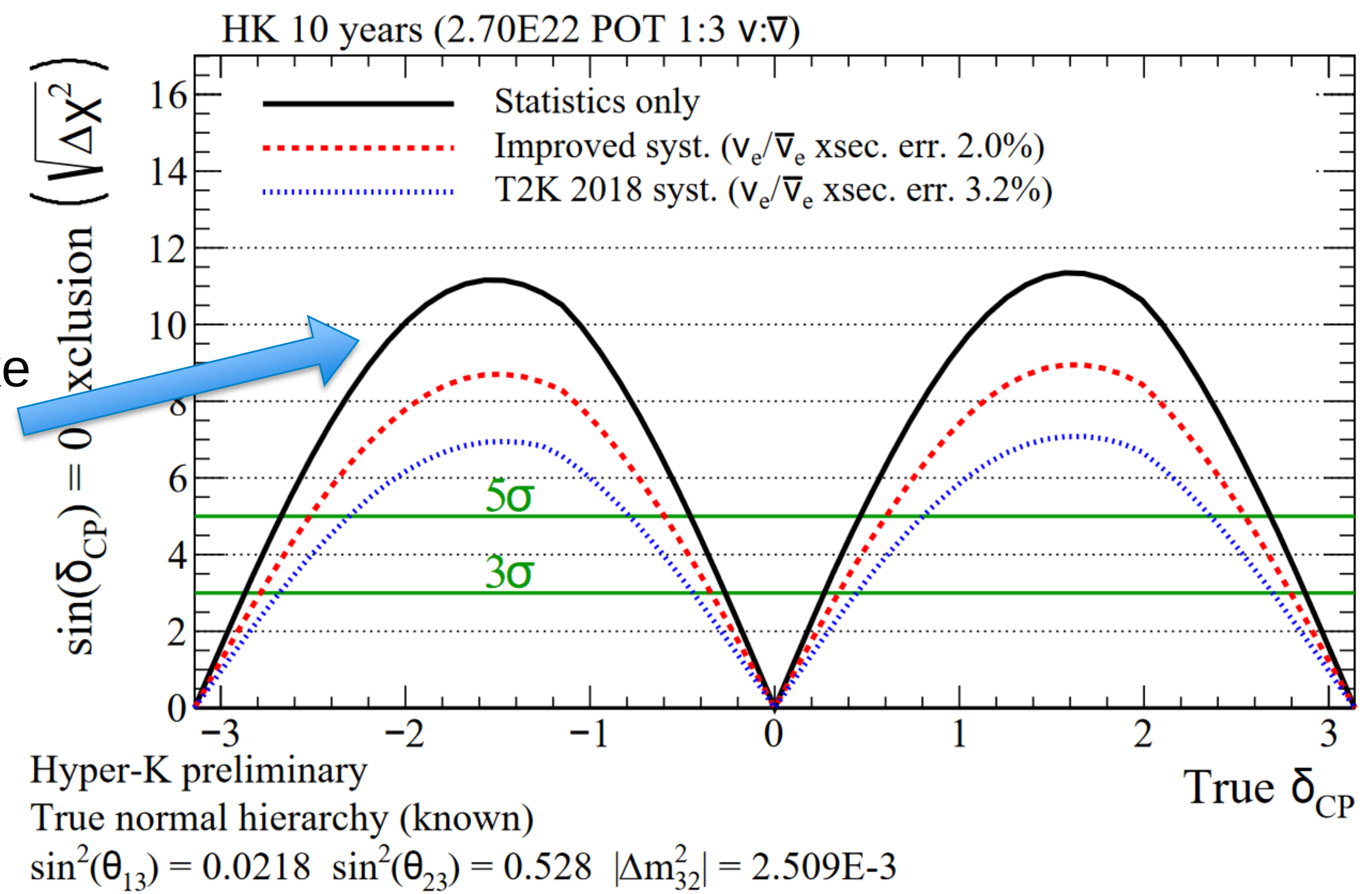
CP violation sensitivity

- Ability to exclude CP conservation versus true value of δ_{CP}



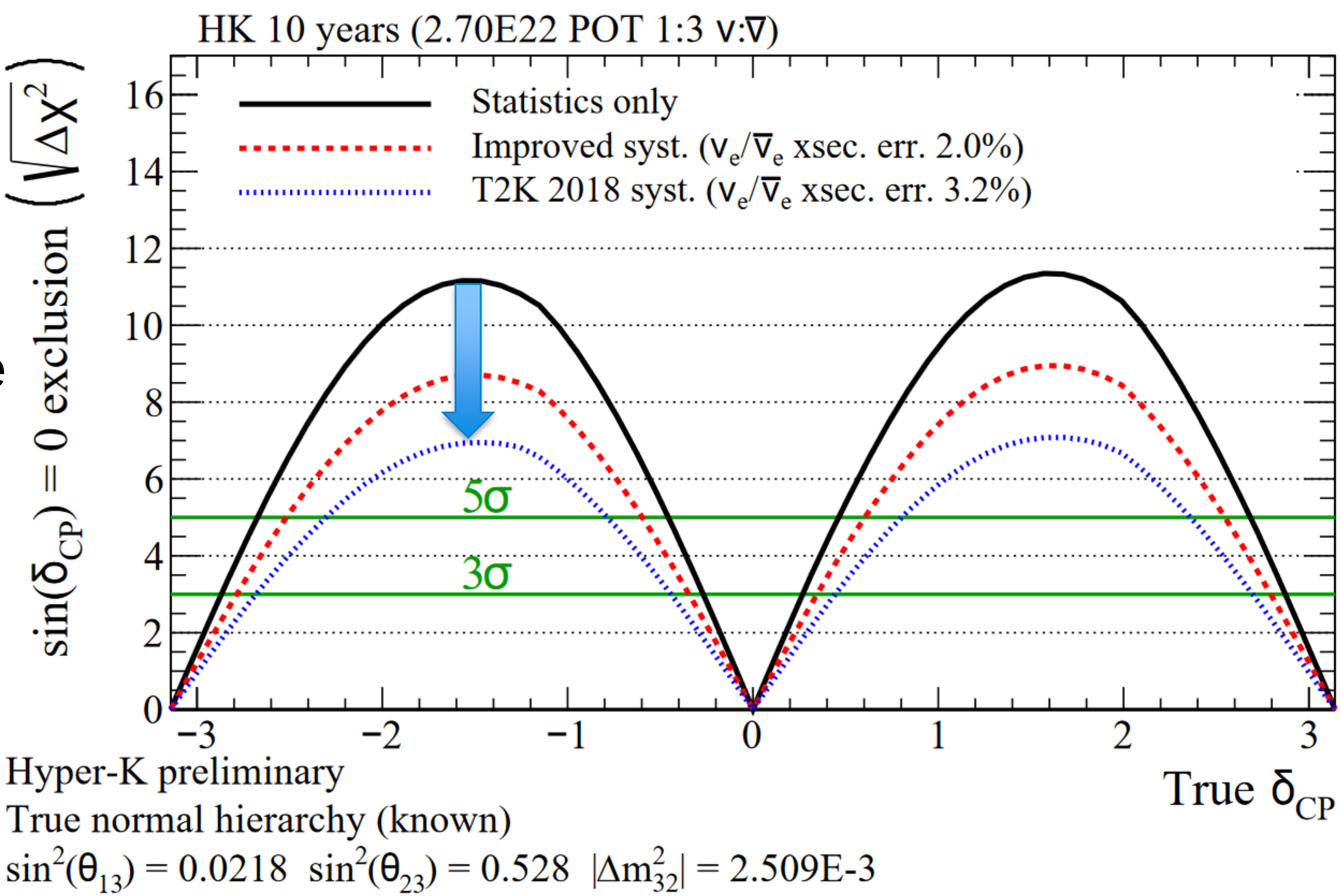
CP violation sensitivity

- Ability to exclude CP conservation versus true value of δ_{CP}
- Large electron-like samples provide high statistics



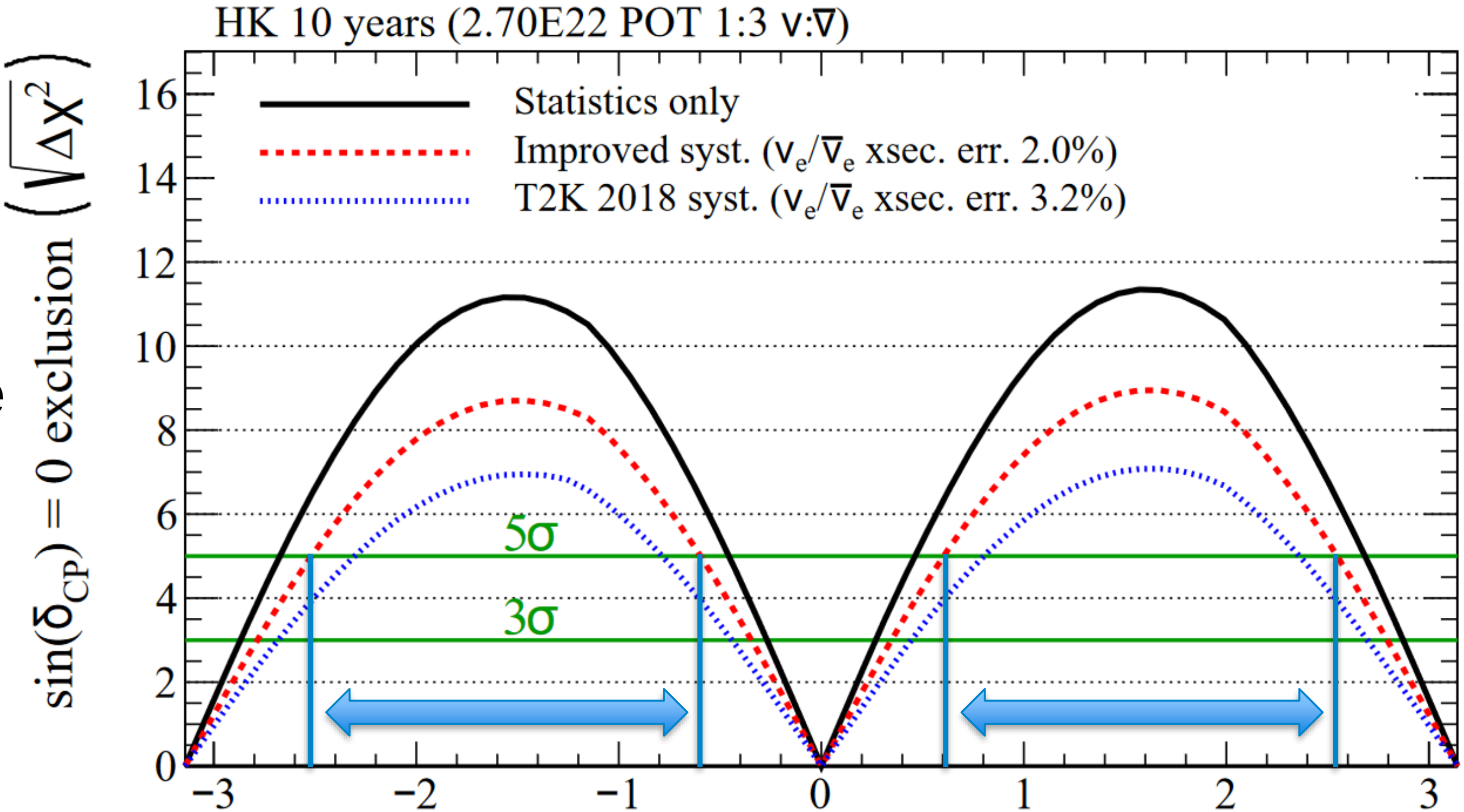
CP violation sensitivity

- Ability to exclude CP conservation versus true value of δ_{CP}
- Large electron-like samples provide high statistics
- Limited by systematics



CP violation sensitivity

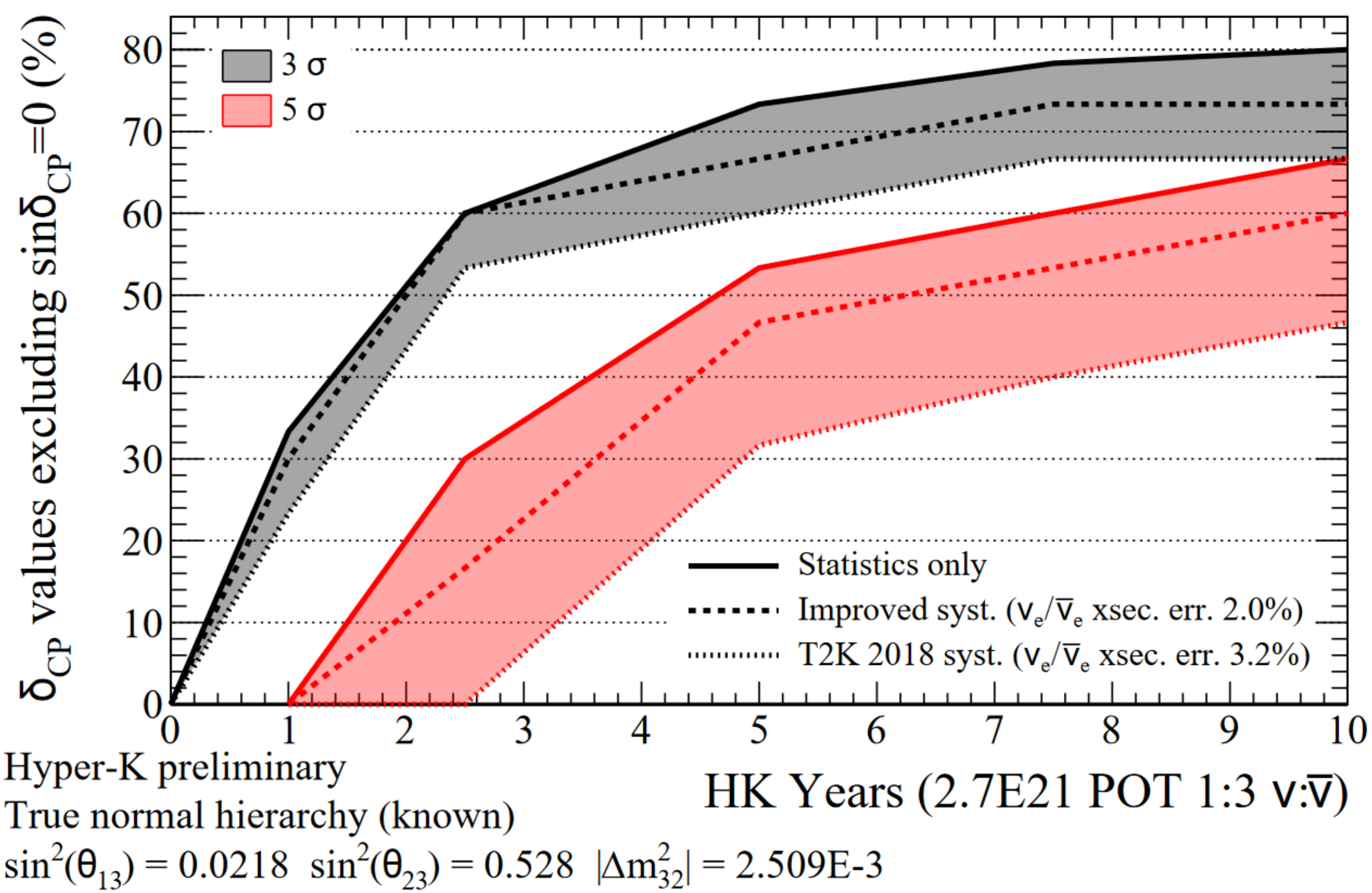
- Ability to exclude CP conservation versus true value of δ_{CP}
- Large electron-like samples provide high statistics
- Limited by systematics
- **Can exclude 60% of true δ_{CP} values at 5σ**



Hyper-K preliminary
True normal hierarchy (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3$

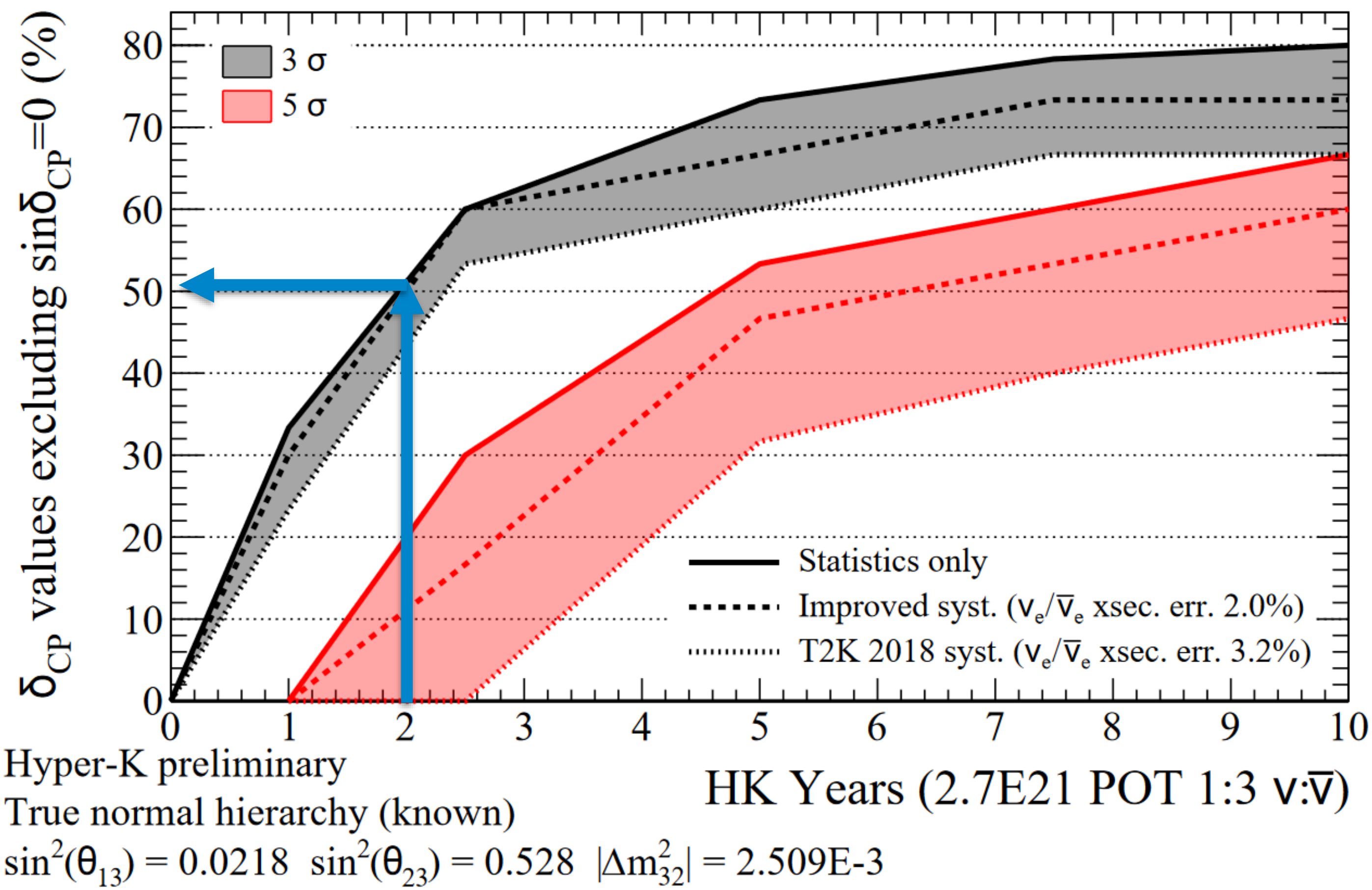
CP violation sensitivity over time

- Percentage of true δ_{CP} values where CP conservation can be excluded as a function of running year



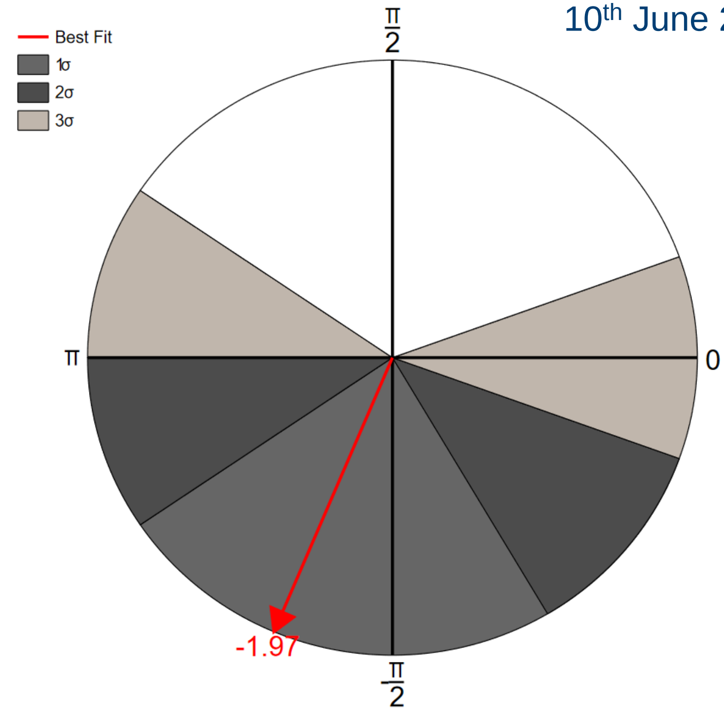
CP violation sensitivity over time

- Percentage of true δ_{CP} values where CP conservation can be excluded as a function of running year
- Can achieve 3σ CP violation result over significant regions of δ_{CP} after 2 years operation

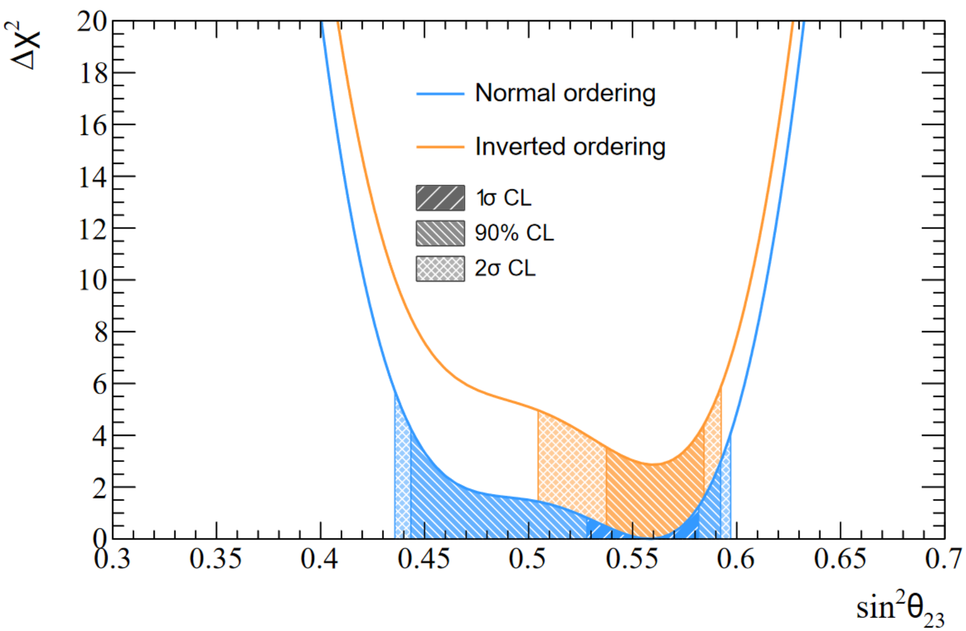


Summary

- T2K has measured neutrino oscillation parameters with 3.64×10^{21} POT
  - Approaching 2σ exclusion of CP conservation
  - Preference for upper octant and normal mass ordering



- Detailed studies of neutrino interaction model robustness
  - Essential for future experiments
- Next generation experiment, HK, will give 5σ sensitivity to CP violation over large range of true δ_{CP} values
  - Systematics limited!



Backup Slides

SK detector systematics

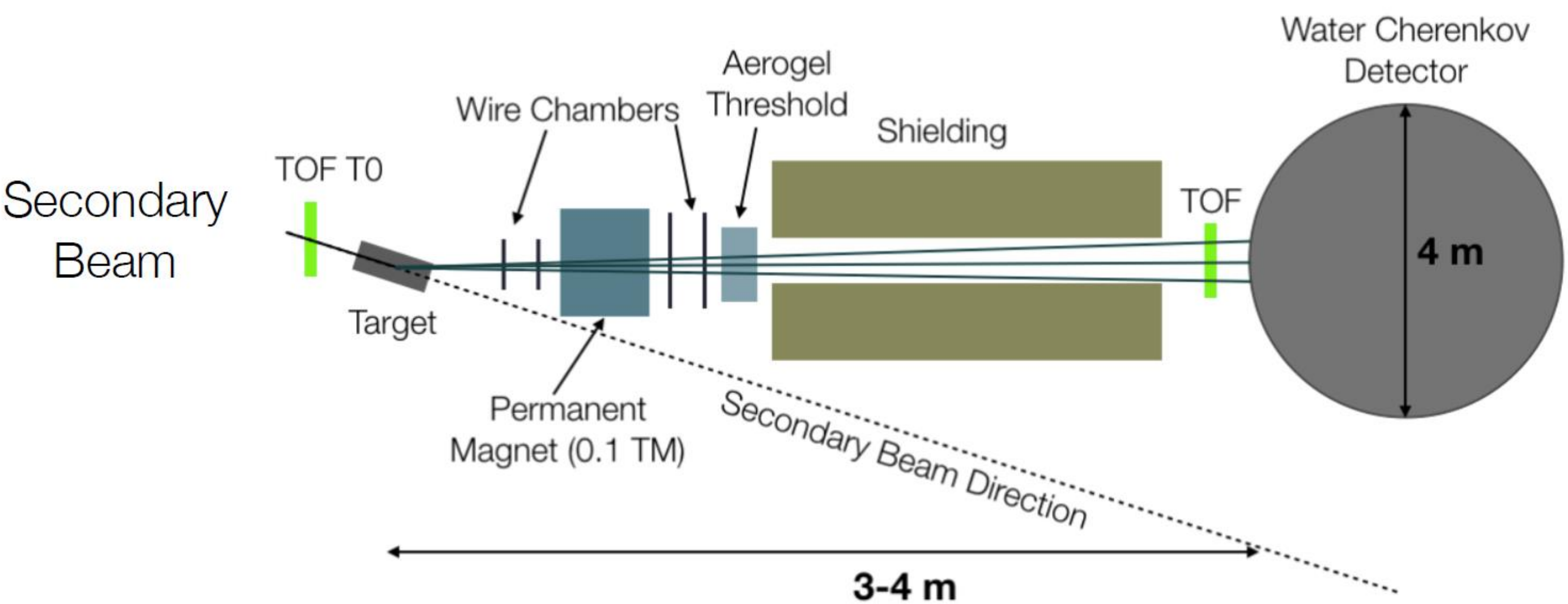
- Understanding detector systematics and pion scattering crucial for future (+current) experiments

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

- Particularly necessary for higher energy events
  - Multi-pion samples at far detector
  - Atmospheric neutrinos
- Table shows effect on rate of events, but must understand energy spectrum shape for precision measurements

Water Cherenkov Test Experiment

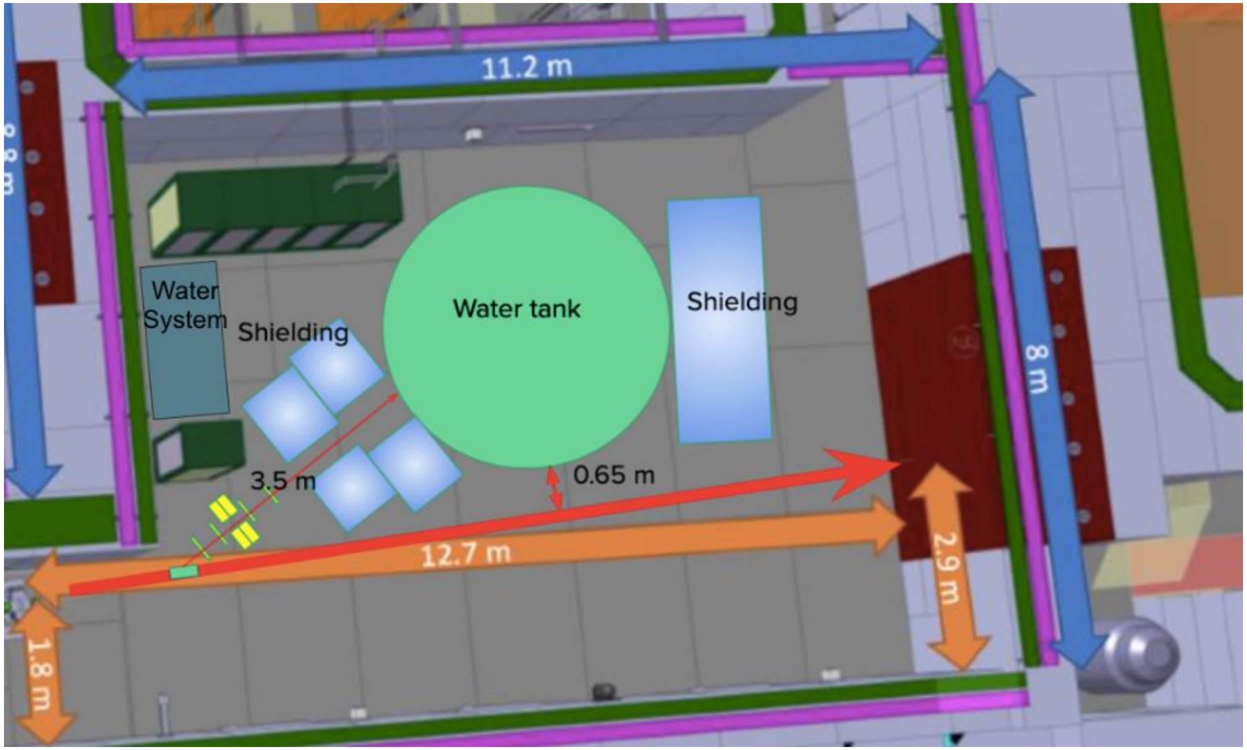
- Goal: study detector systems and detector response to pions, muons, electrons and protons from 200 MeV/c up to 1000 MeV/c
  - Understand detector calibration needed for IWCD/HK
  - Physics: Cherenkov profile, secondary interactions, neutrons
- Use tertiary production target and spectrometer upstream of detector



Experimental area

- We are proposing to use the T9 beam line in the East Area
  - Enough space for 4m by 4m tank and tertiary beamline

- Tertiary beam for pions/protons

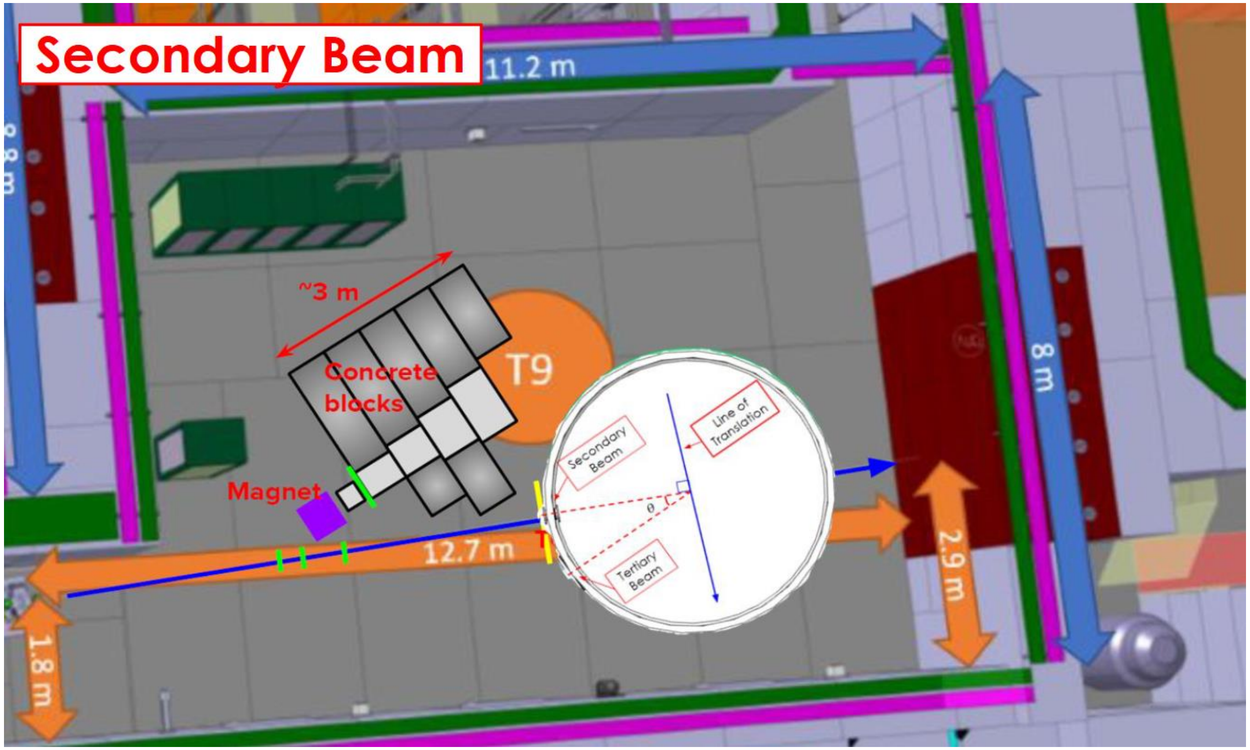


Imperial College London

Experimental area

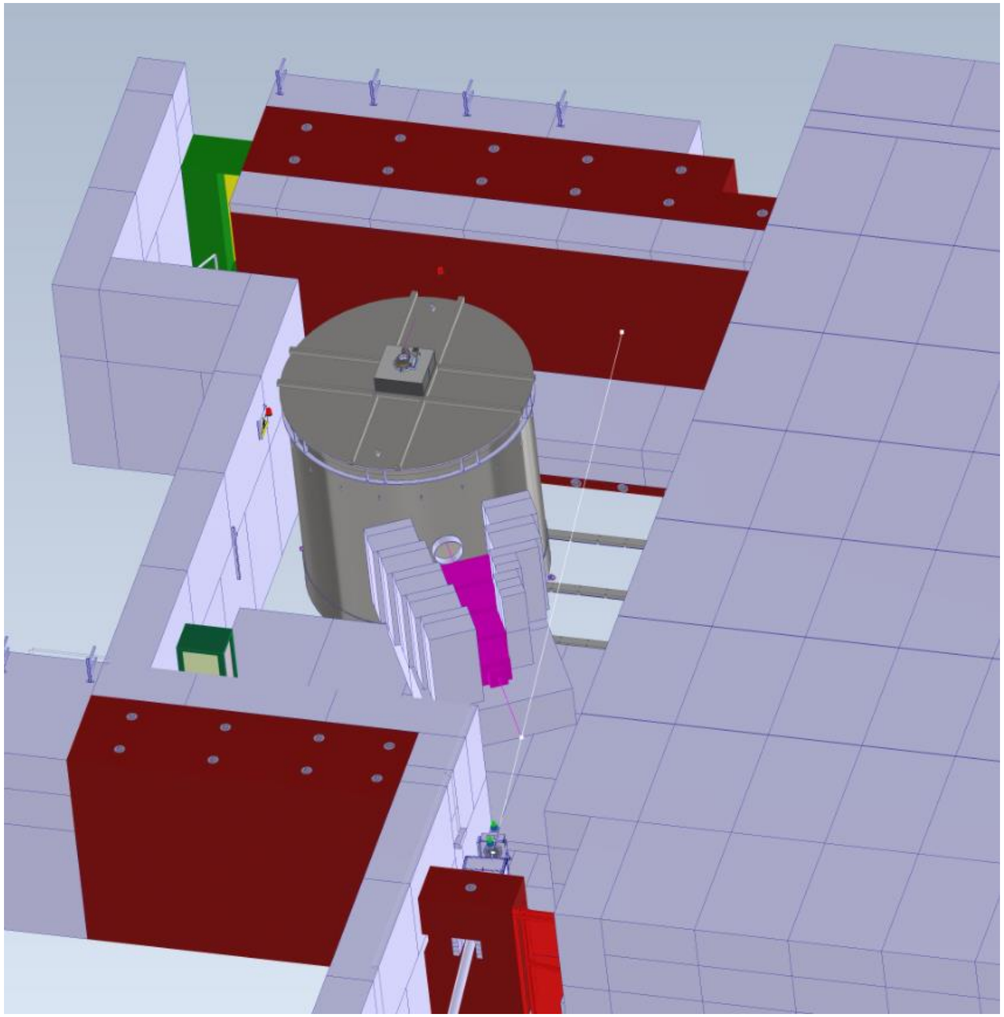
- We are proposing to use the T9 beam line in the East Area
  - Enough space for 4m by 4m tank and tertiary beamline

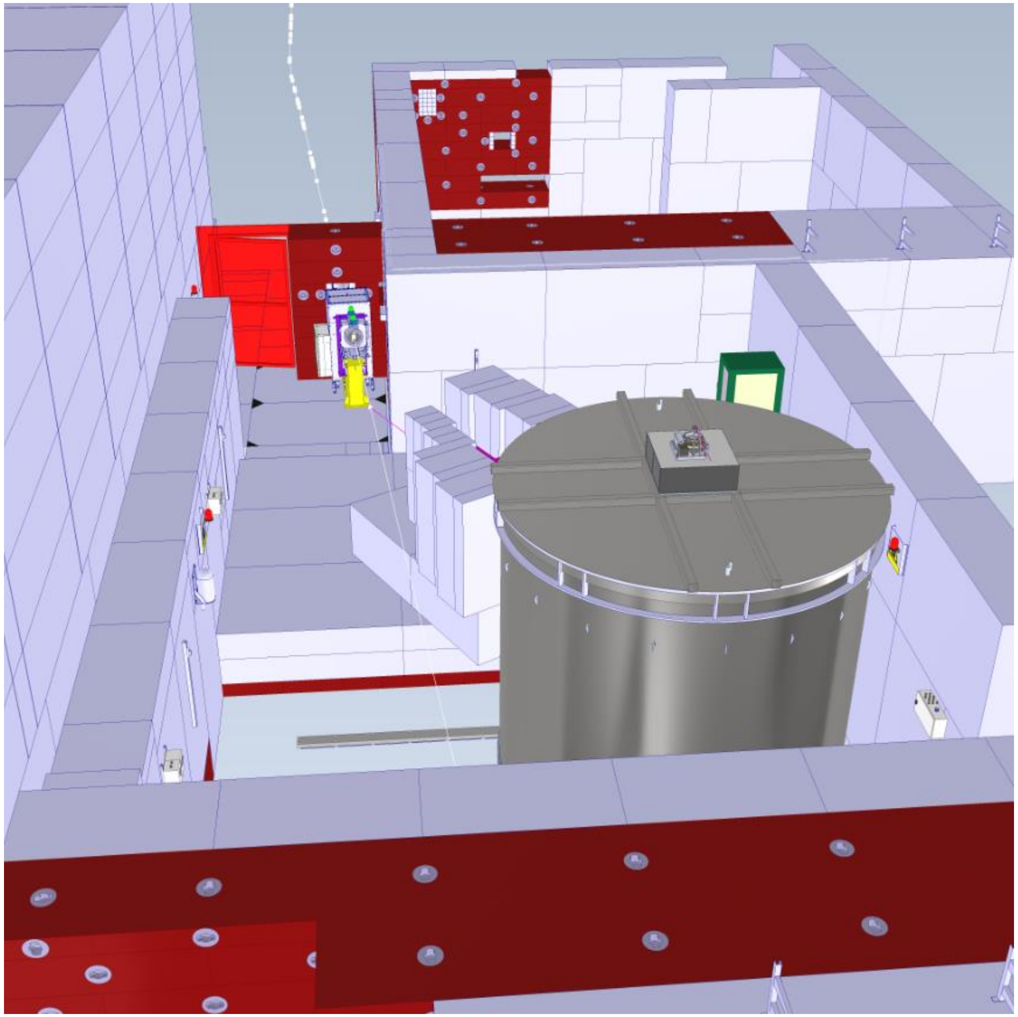
- Tertiary beam for pions/protons
- Secondary beam for low momentum electrons and muons
- Planned for early 2023



Imperial College
London

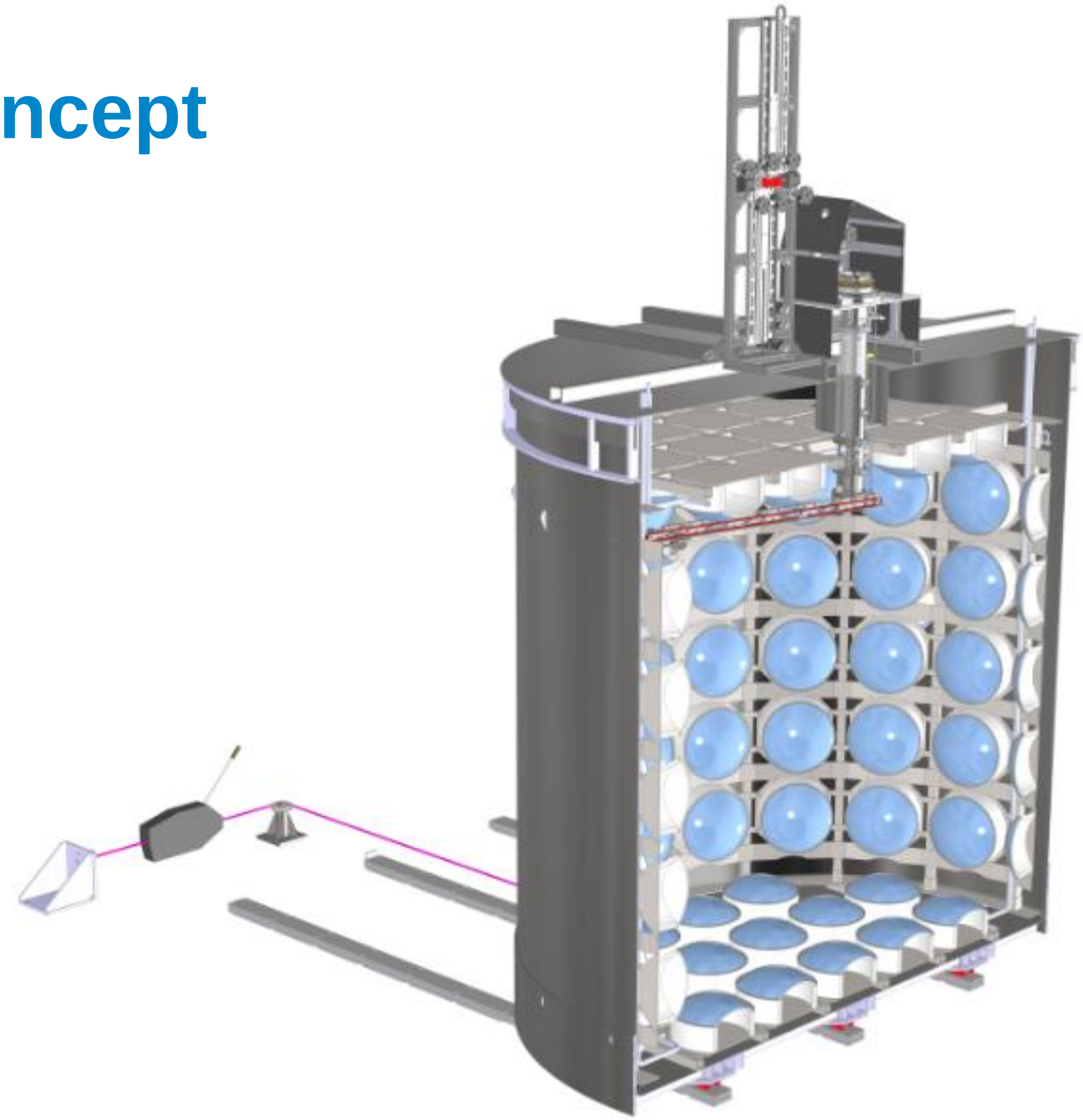
WCTE at CERN T9 beamline





WCTE Detector concept

- Instrumented with multi-PMT modules being developed for Hyper-K
- Integrated calibration system on detector lid
- Total mass ~50 tons



Best fit parameter values

Parameter	Best fit			
Data	T2K only		T2K + reactor	
Hierarchy	Normal	Inverted	Normal	Inverted
$\sin^2(2\theta_{13})$	0.109	0.120	0.0855	0.0860
$\sin^2(\theta_{13})$	28.0×10^{-3}	31.0×10^{-3}	21.9×10^{-3}	22.0×10^{-3}
δ_{CP}	-2.22	-1.29	-1.97	-1.44
Δm^2_{32} (NH)/$\lvert\Delta m^2_{31}\rvert$ (IH) [$\mathrm{eV}^2/\mathrm{c}^4$]	2.495×10^{-3}	2.463×10^{-3}	2.494×10^{-3}	2.463×10^{-3}
$\sin^2(\theta_{23})$	0.467	0.466	0.561	0.563
$-2 \ln L$	597.72	598.56	598.05	600.49

- Global best fit (above) and Feldman-Cousins intervals for δ_{CP} (bottom left) and $\sin^2\theta_{23}$ (bottom right)

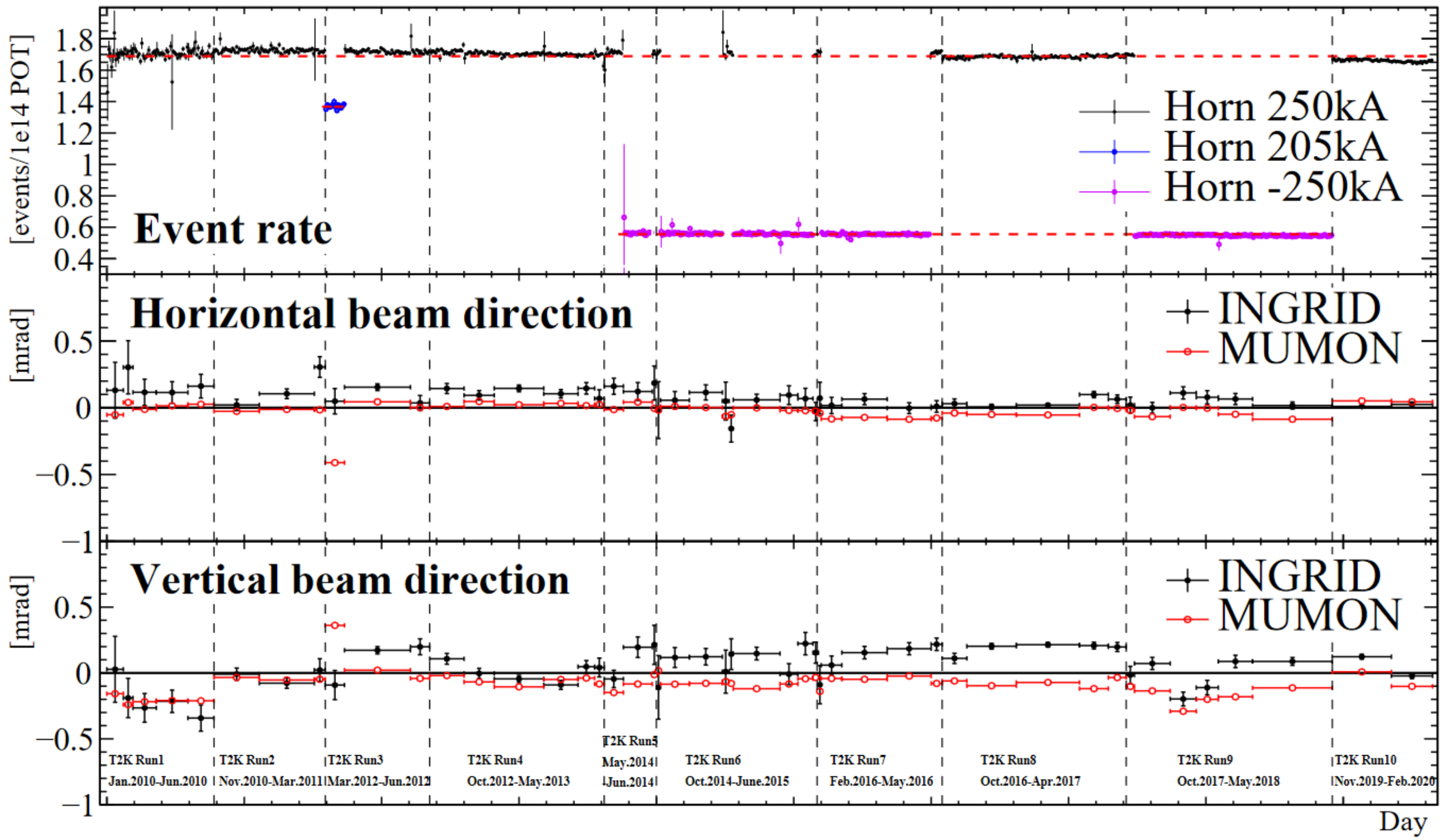
δ_{CP}

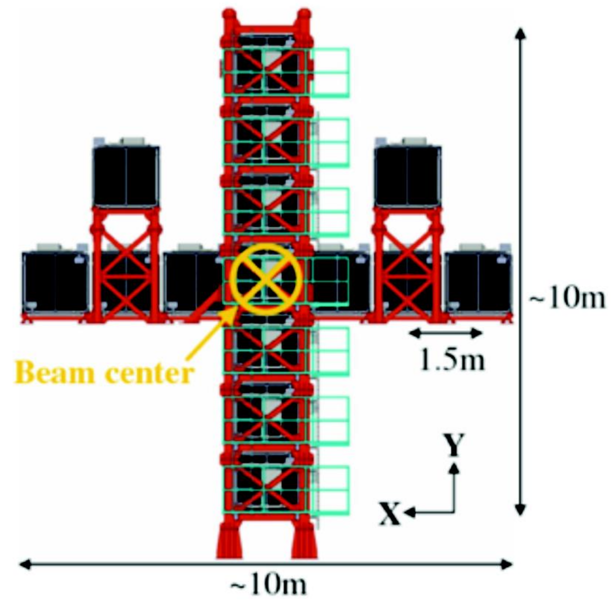
Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.66, -0.97]$	
90%	$[-3.00, -0.49]$	$[-1.79, -1.09]$
2σ	$[-\pi, -0.26] \cup [3.11, \pi]$	$[-2.20, -0.75]$
3σ	$[-\pi, 0.32] \cup [2.63, \pi]$	$[-2.82, -0.14]$

$\sin^2\theta_{23}$

Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.528, 0.582]$	
90%	$[0.443, 0.592]$	$[0.537, 0.584]$
2σ	$[0.436, 0.597]$	$[0.505, 0.593]$

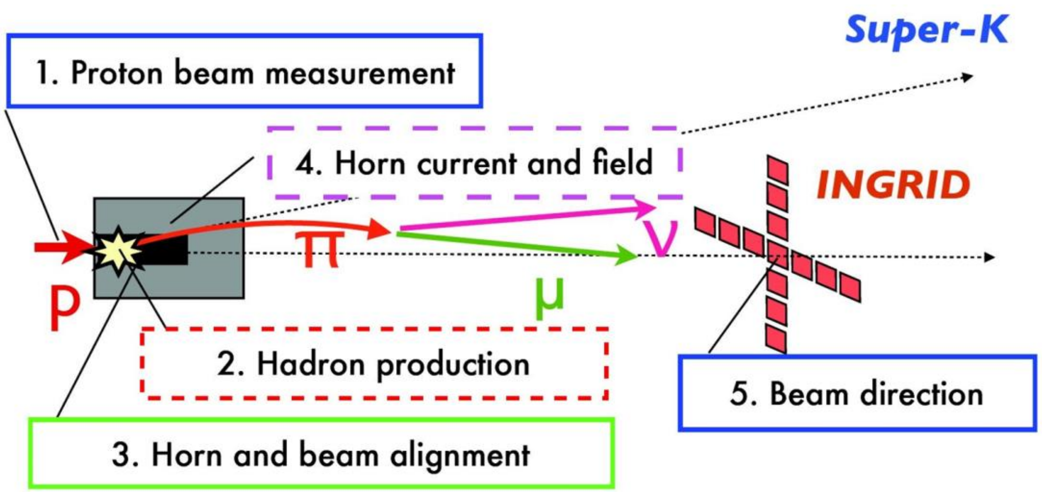
Beam stability

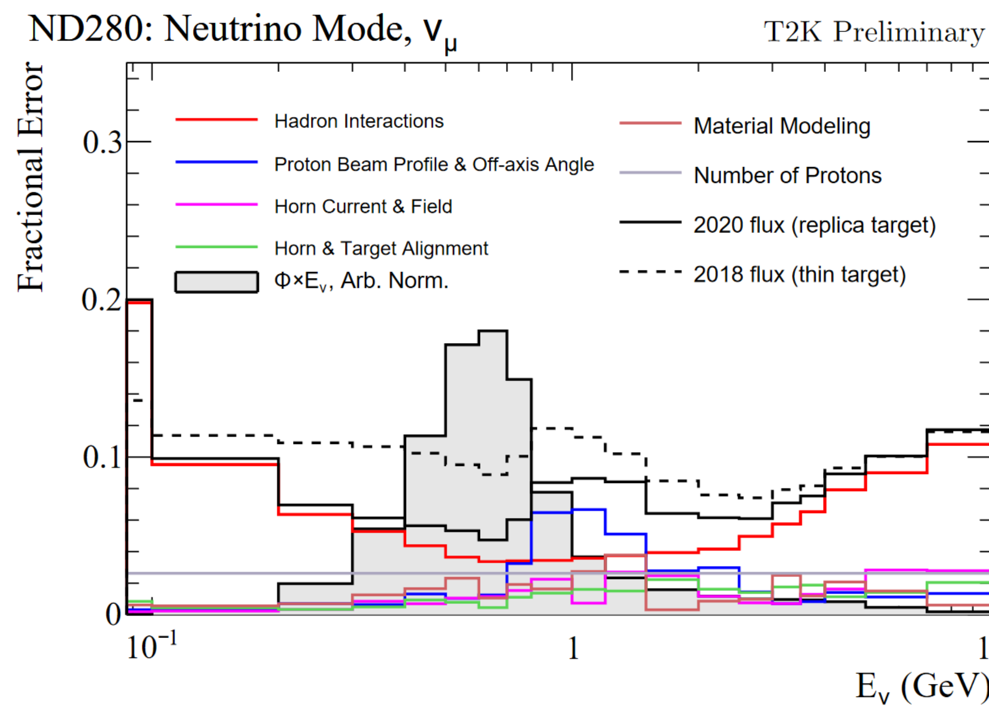


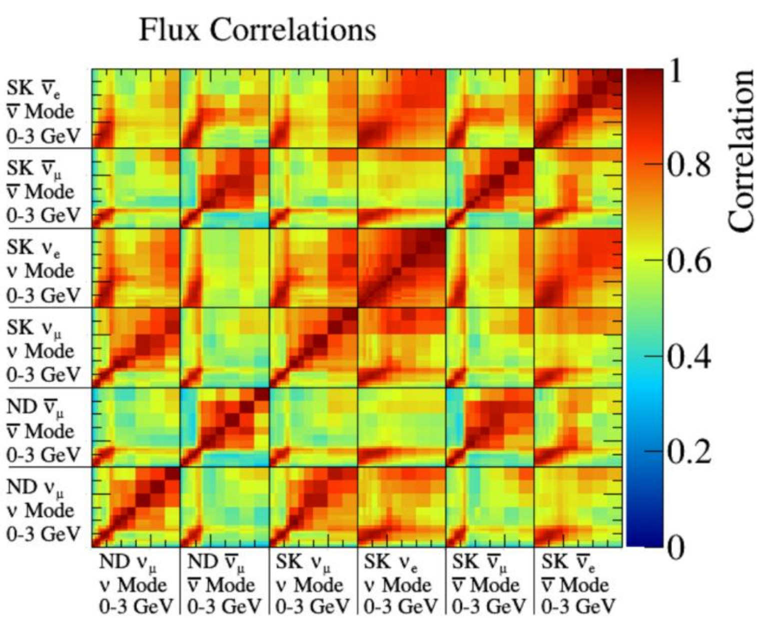


- INGRID and muon monitors measure beam centre position
- Very stable neutrino beam over full run

T2K flux model



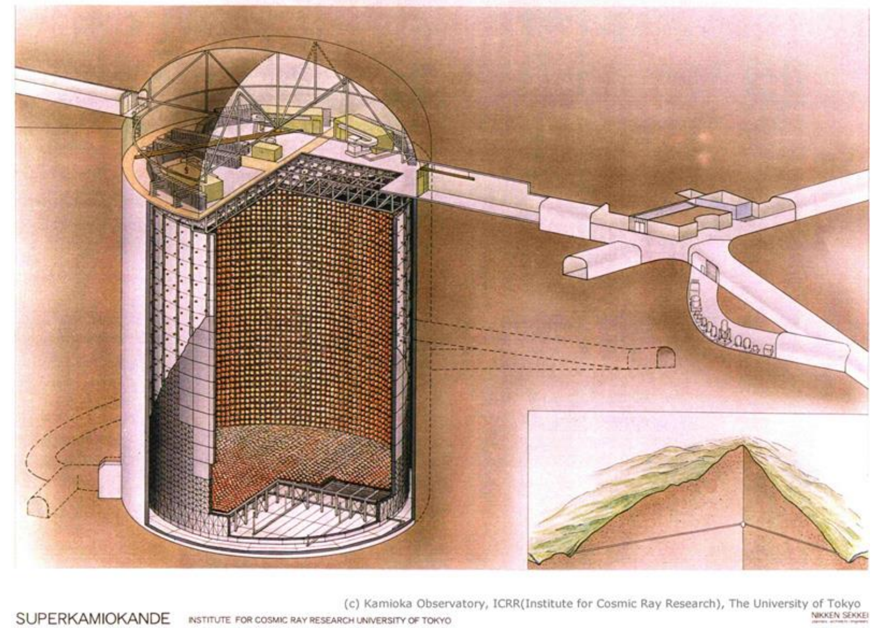


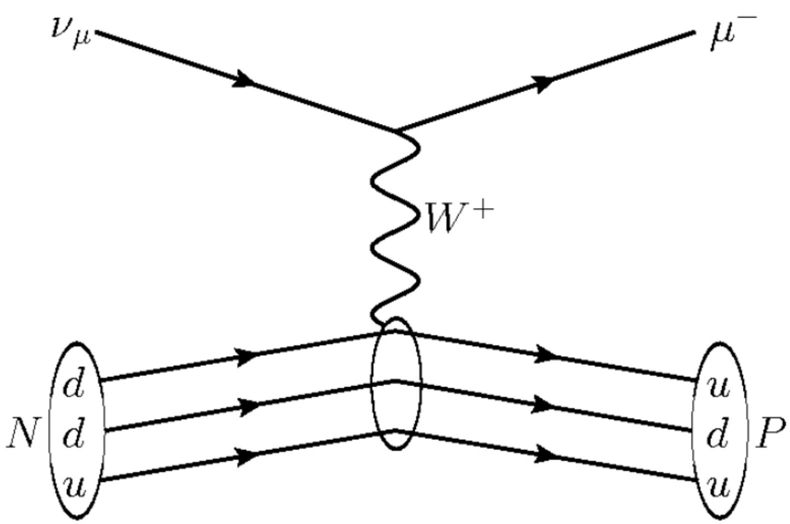


- Parametrised in neutrino energy and flavour
- Parameter uncertainties calculated by varying underlying systematics
- Performed simultaneously for near and far detector
- Correlates near and far flux parameters

Super-Kamiokande detector

- Signal in far detector:
- Measure rate of muon-like and electron-like events
- CCQE interactions are 'golden' channel



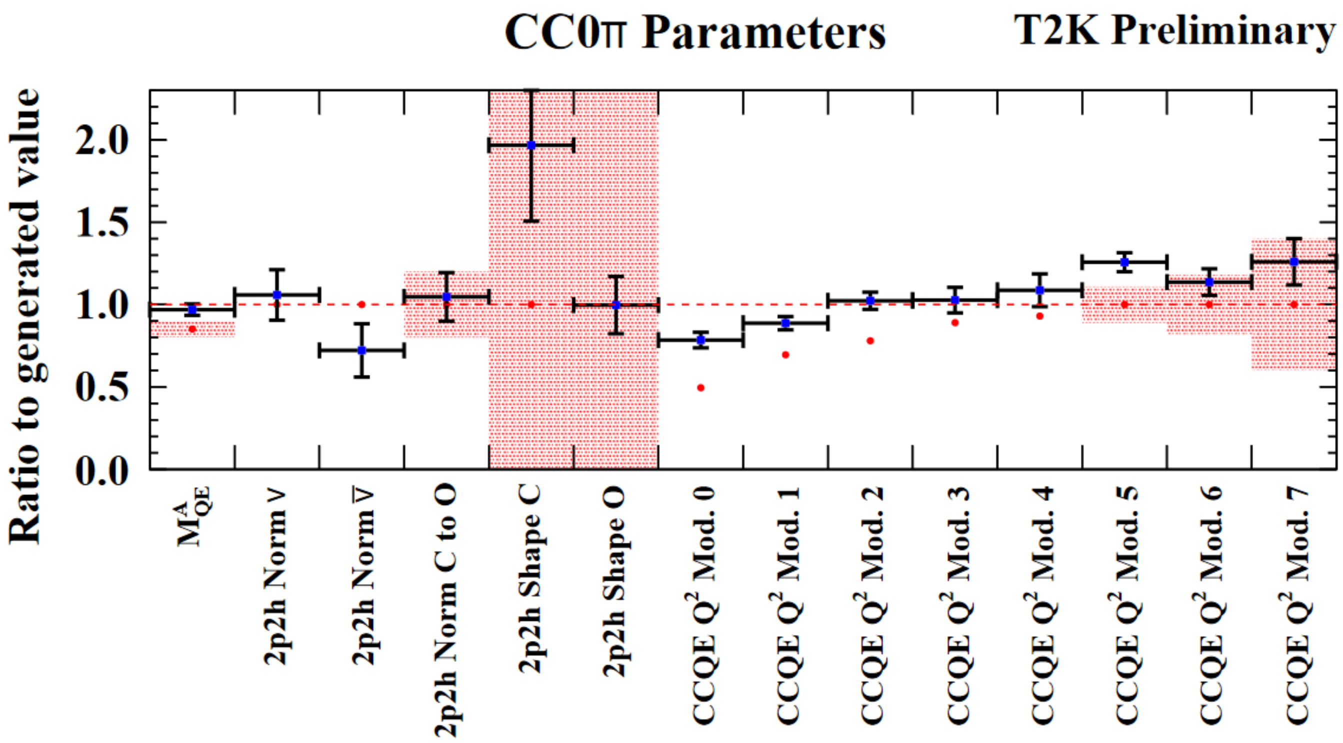


(a) CC QES interaction

- Assume nucleon at rest – 2-body process
- Can calculate neutrino energy from observed muon kinematics

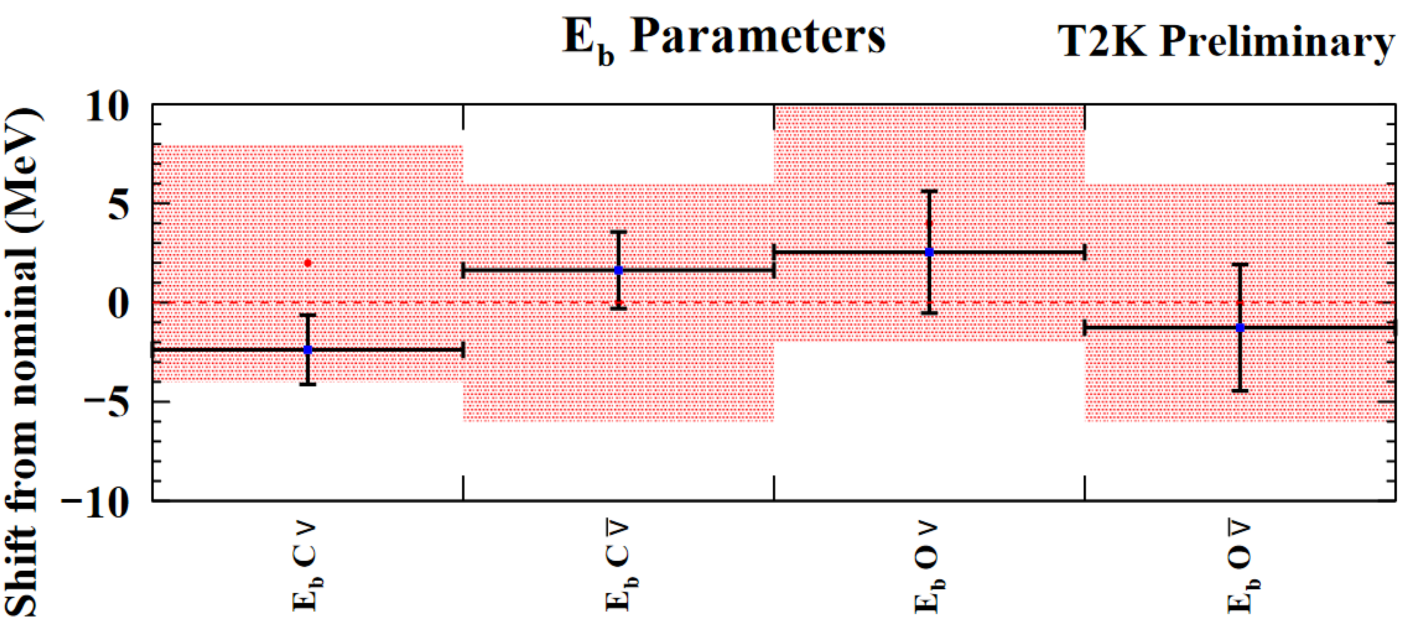
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

Cross-section model – CC 0π



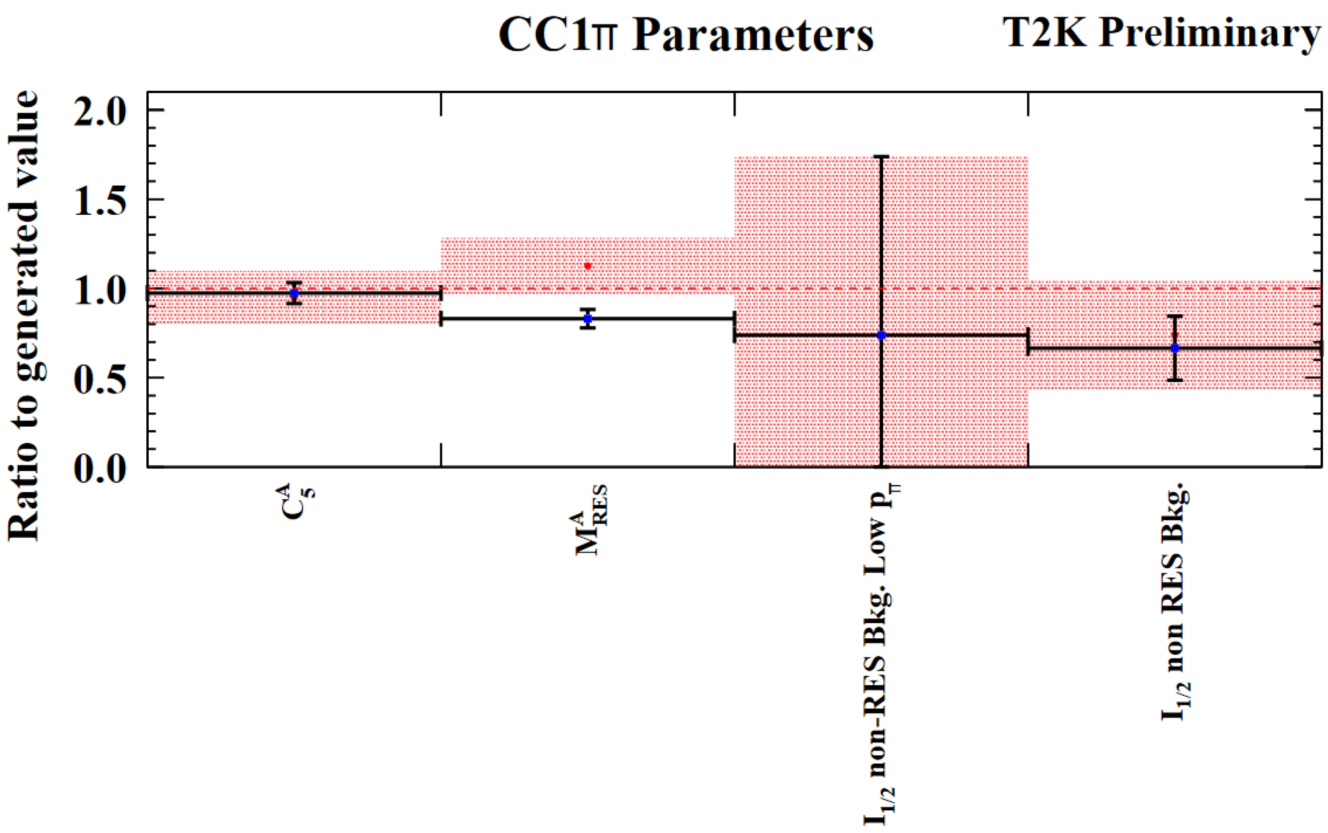
- Axial mass parameter
- 2p2h normalisation
  - Different for neutrinos and antineutrino
- 2p2h shape – difference between true and reconstructed neutrino energy
  - Different for carbon and oxygen
- Q^2 normalization parameters

Cross-section model – Binding energy



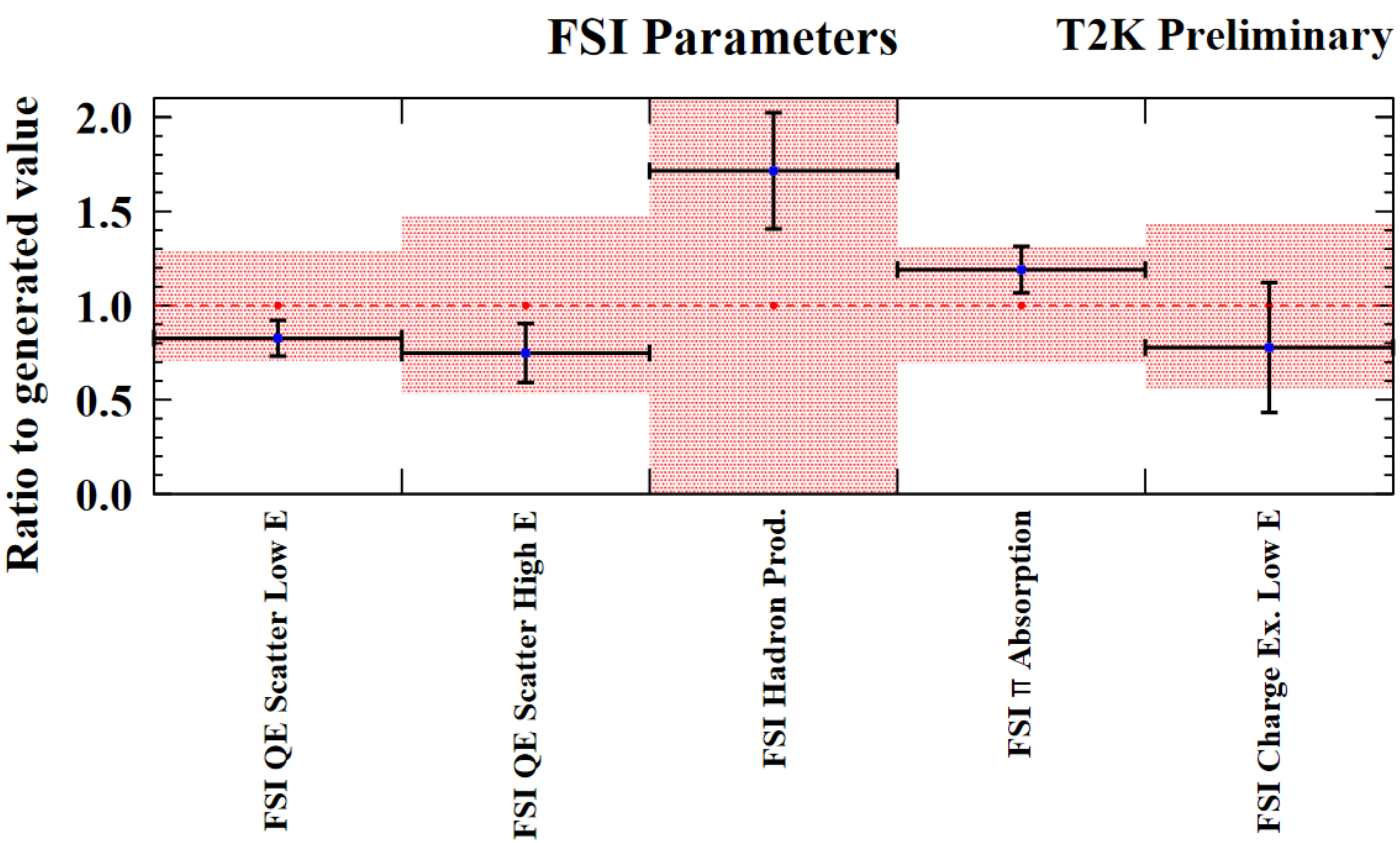
- Affects CC 0π events
- Shifts momentum of outgoing lepton
- New modelling allows this to be constrained by near detectors
  - Previously was a large uncertainty on oscillation measurement

Cross-section model – CC 1π



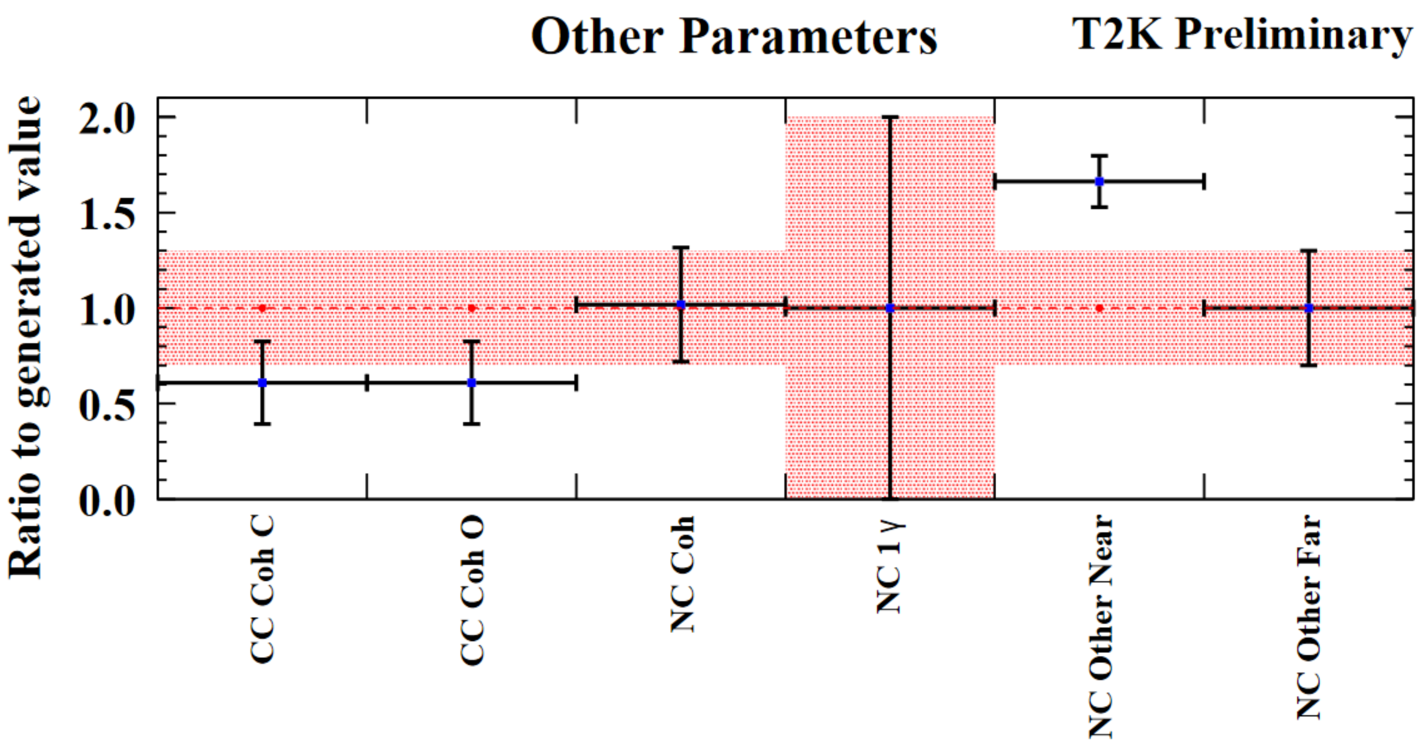
- CA5 – normalisation for the resonant form factor
- Axial mass parameter
- I=1/2 background norm.
  - Low momentum and high momentum pions

Cross-section model – Pion Final State Interactions



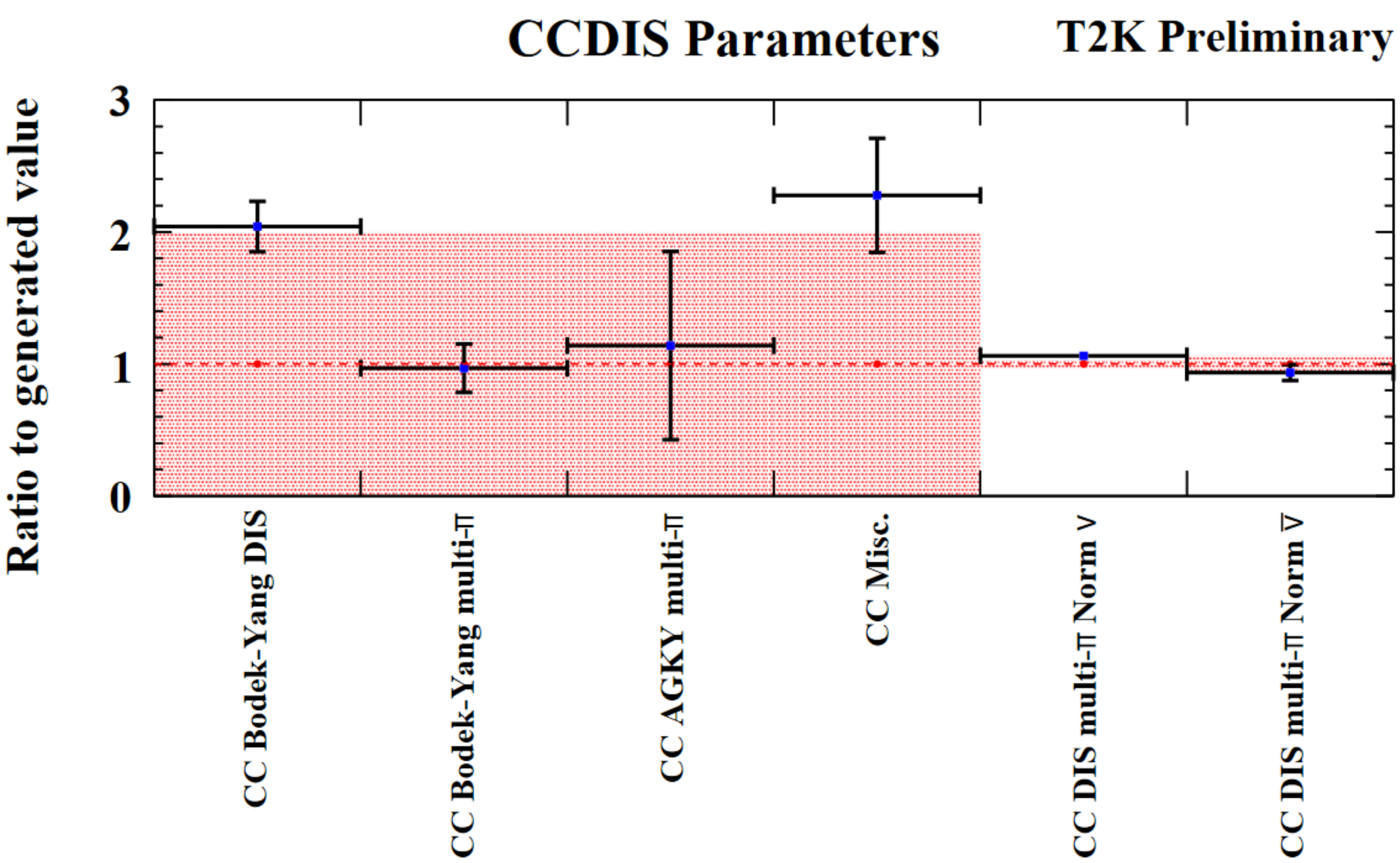
- Microscopic final state interaction cross-section parameters
- Alter charge, kinematics and presence of pions in final state of neutrino interaction

Cross-section model – CC Other



- CC coherent pion production normalization
  - Separate for carbon and oxygen
- NC coherent normalization
  - Not fit at near detector
- NC other normalization
  - Not extrapolated to far detector

Cross-section model – CC DIS



- Bodek-Yang correction uncertainty
  - Separate for DIS and multi-pion production events
- AKGY multi-pion production model uncertainty
- Miscellaneous events
- DIS/multi-pion normalization uncertainties

SK event selection – 0π samples

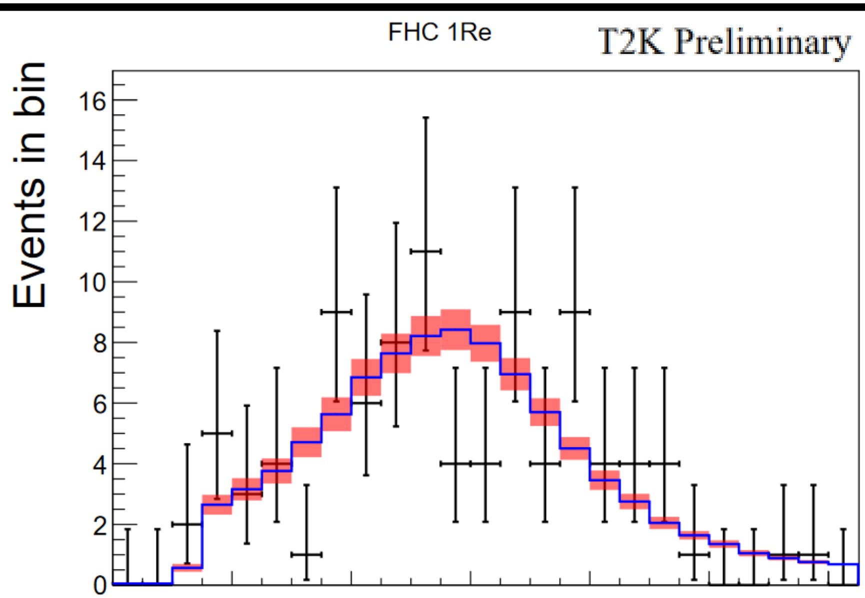
Look for fully contained, single ring events inside SK fiducial volume, then:

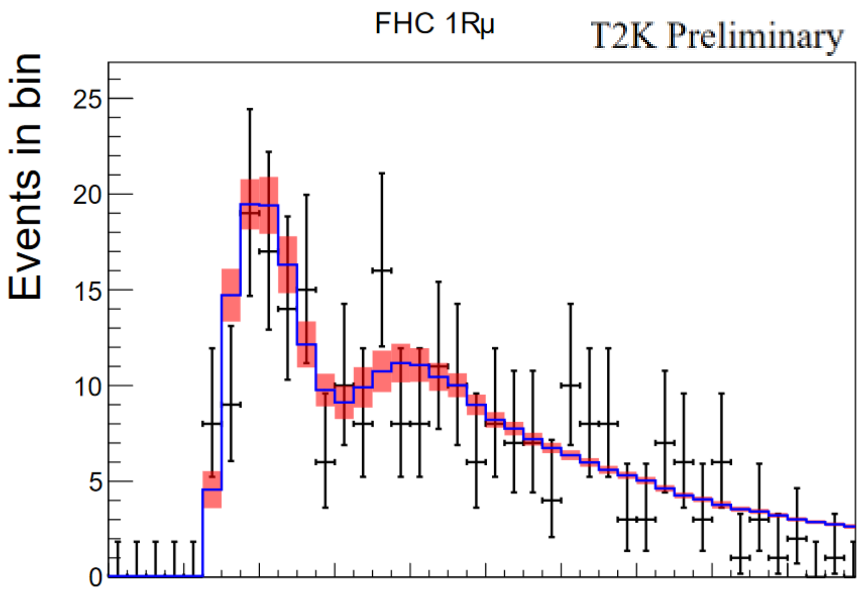
If electron-like ring:

- Visible energy > 100 MeV
- Reconstructed energy < 1250 MeV
- Not identified as π^0
- No decay electrons

If muon-like ring:

- Reconstructed momentum > 200 MeV/c
- At most 1 decay electron



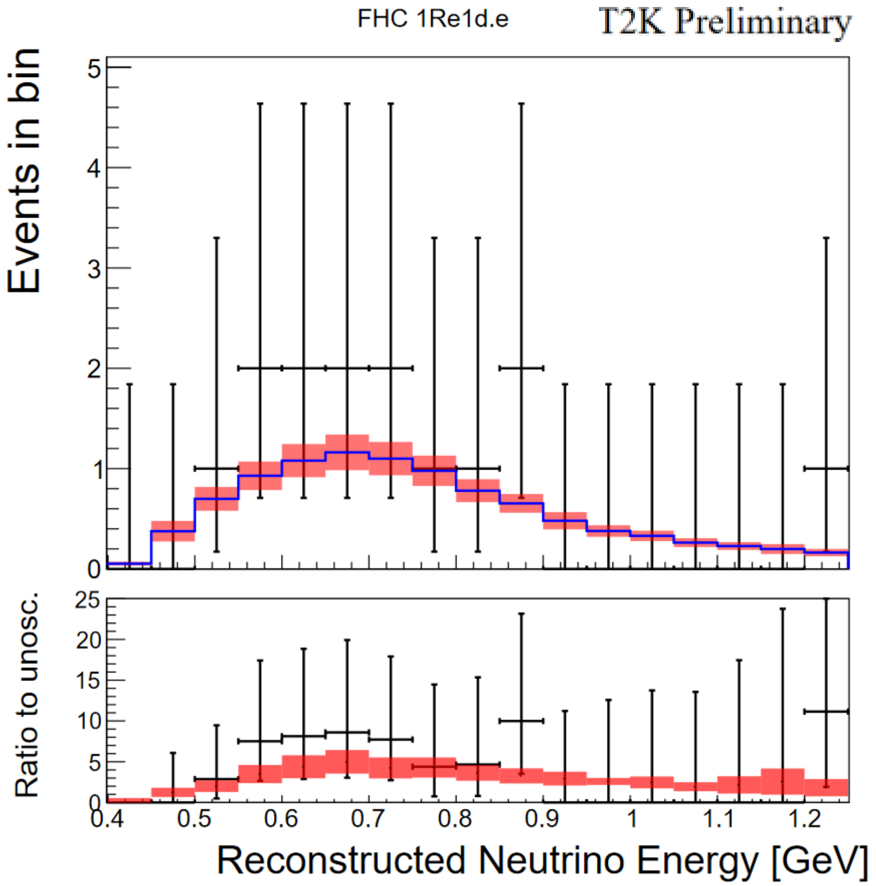


SK event selection – e-like single pion sample

Look for fully contained, single ring events inside SK fiducial volume, then:

If electron-like ring:

- Visible energy > 100 MeV
- Reconstructed energy < 1250 MeV
- Not identified as π^0
- **One** decay electrons



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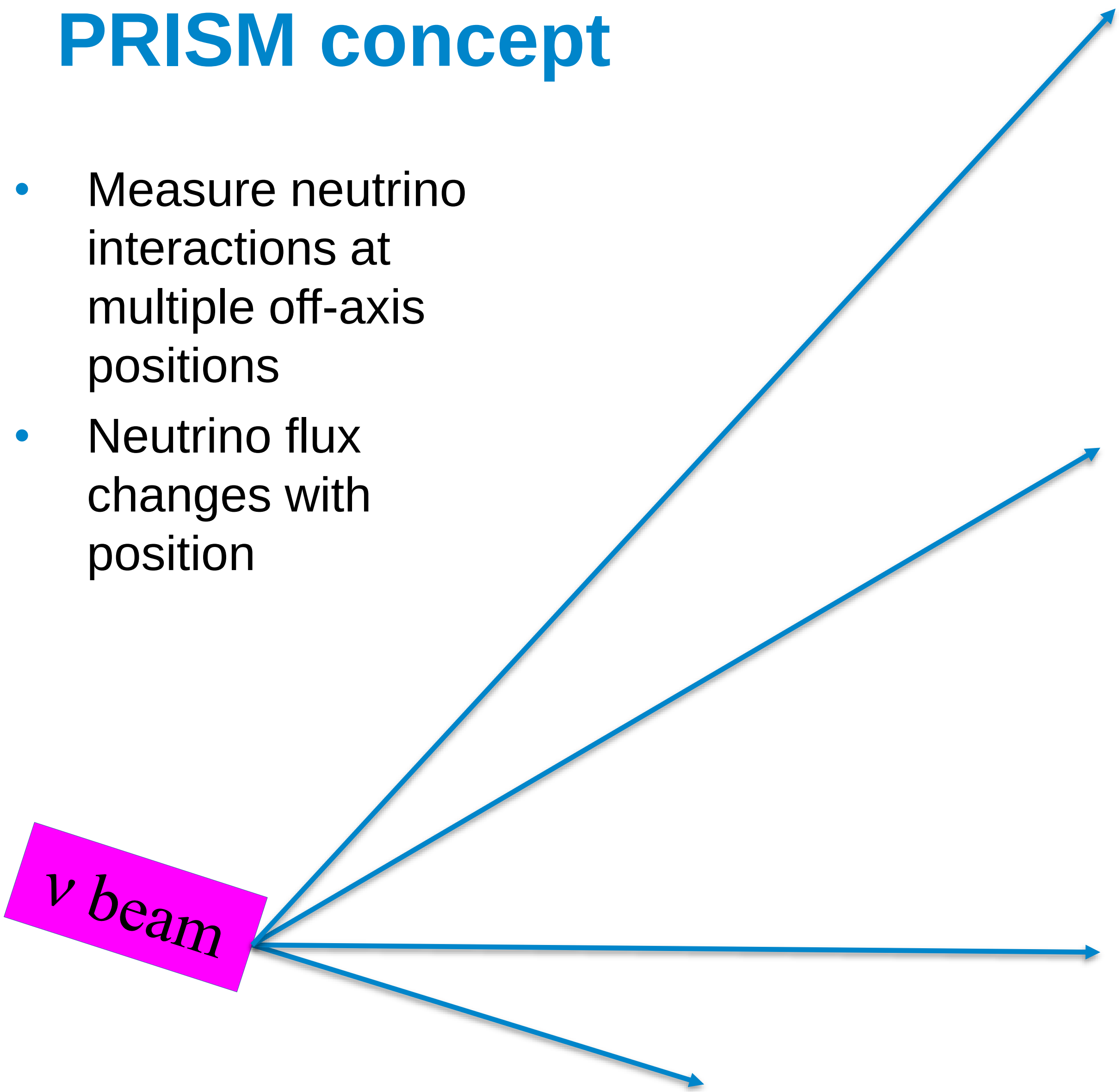
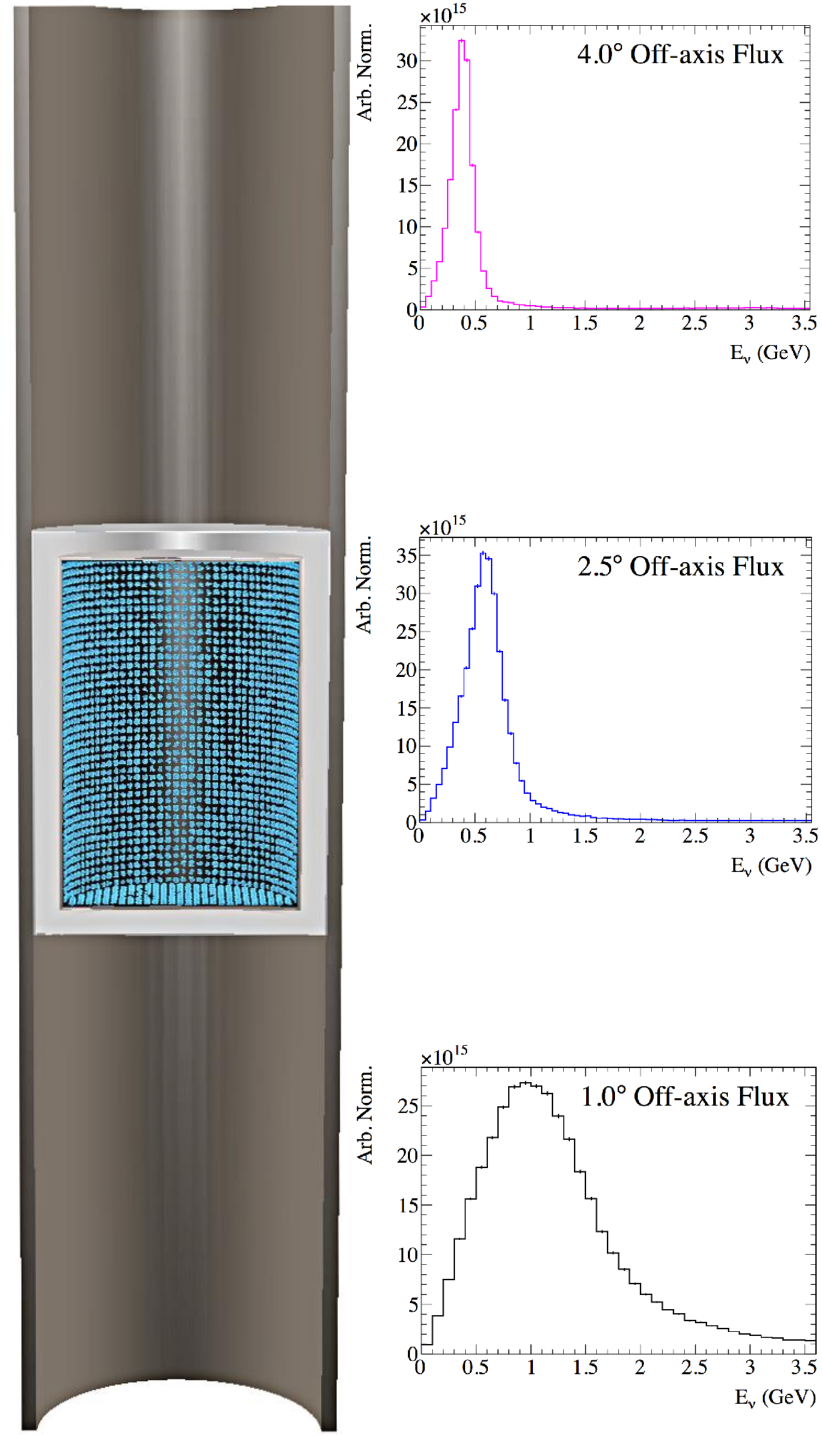
PRISM concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position





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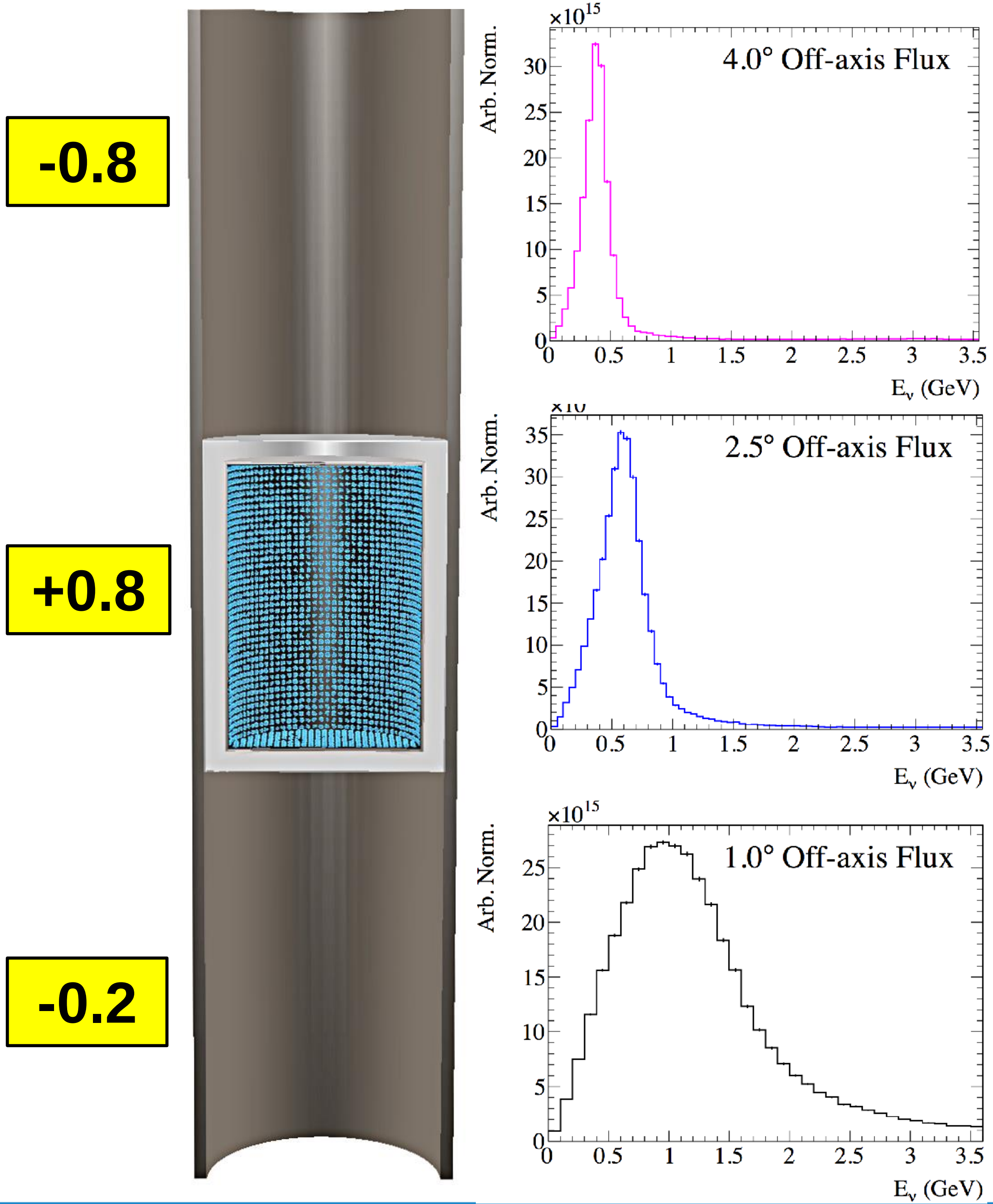
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’



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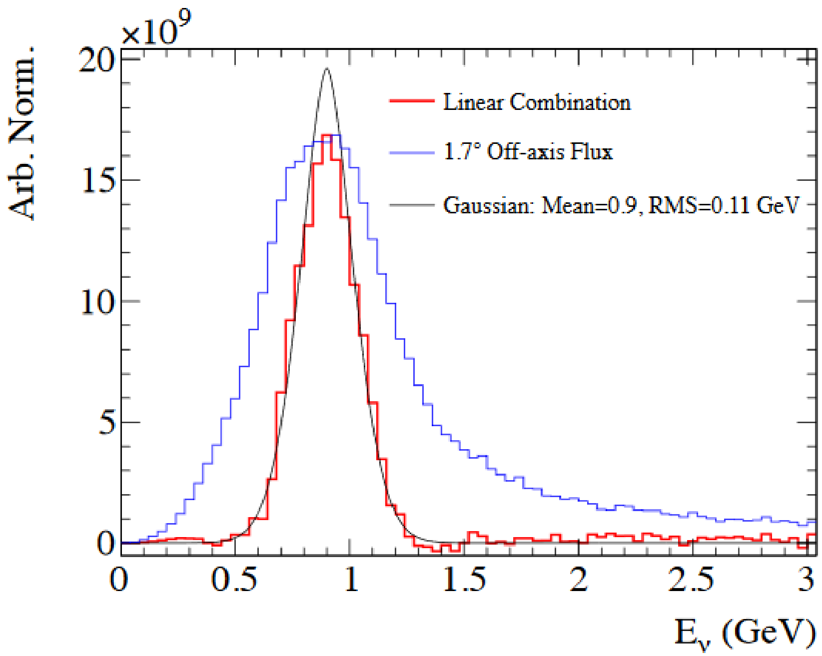
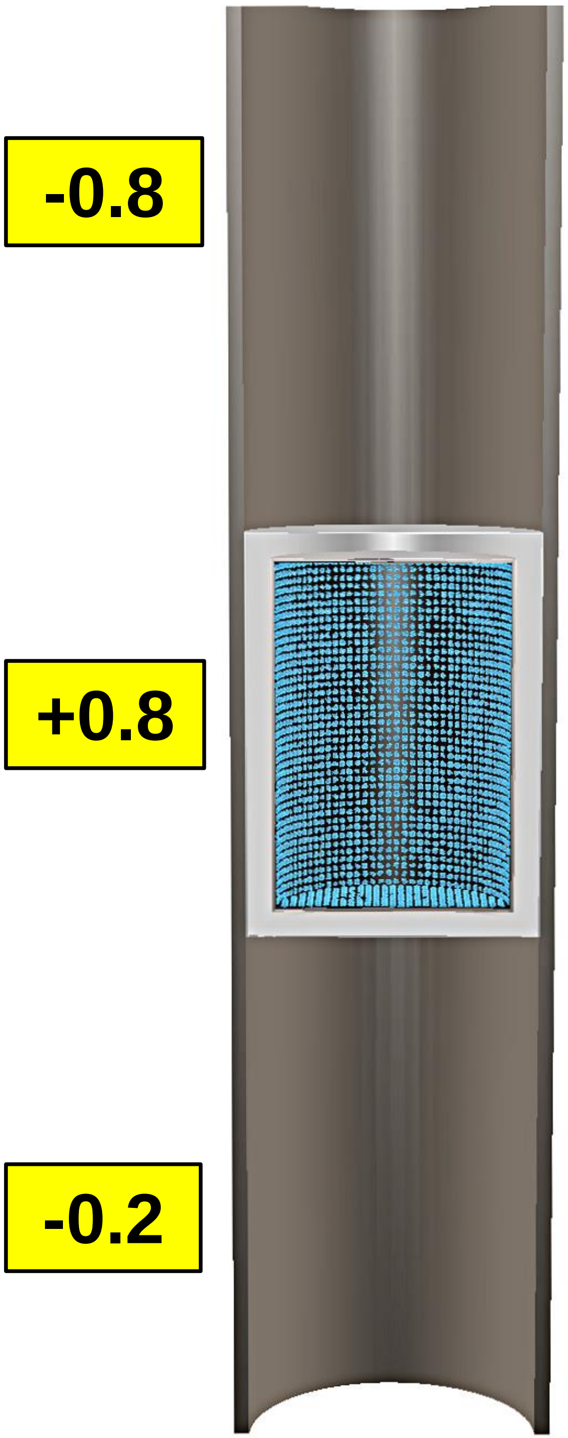
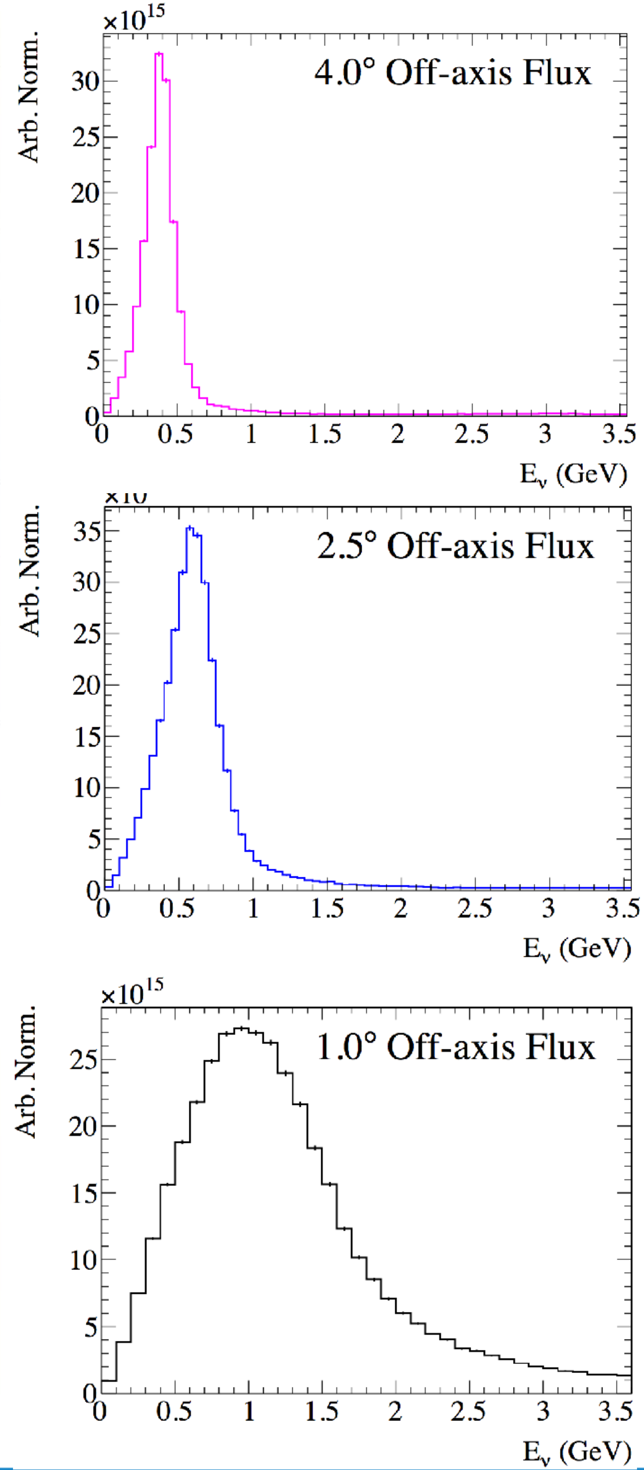
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution



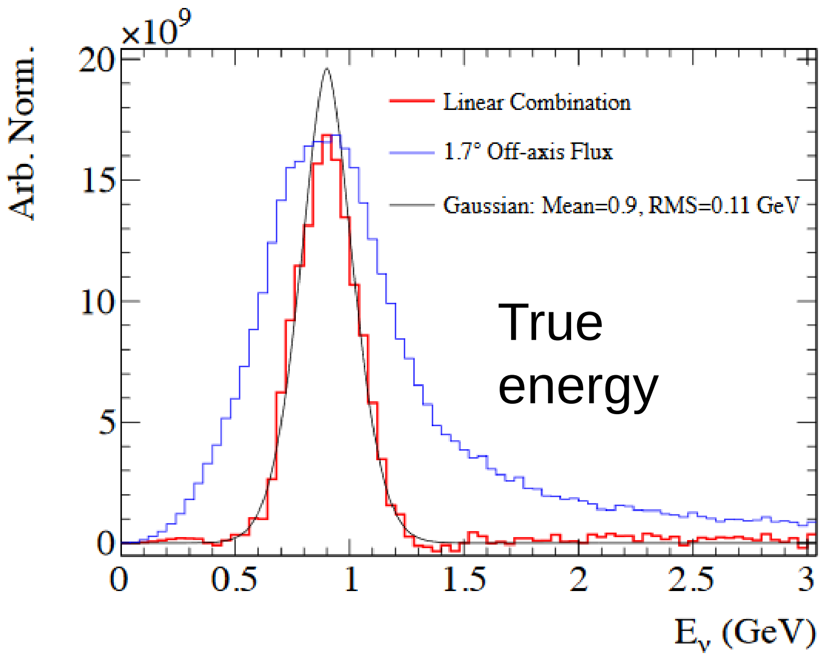


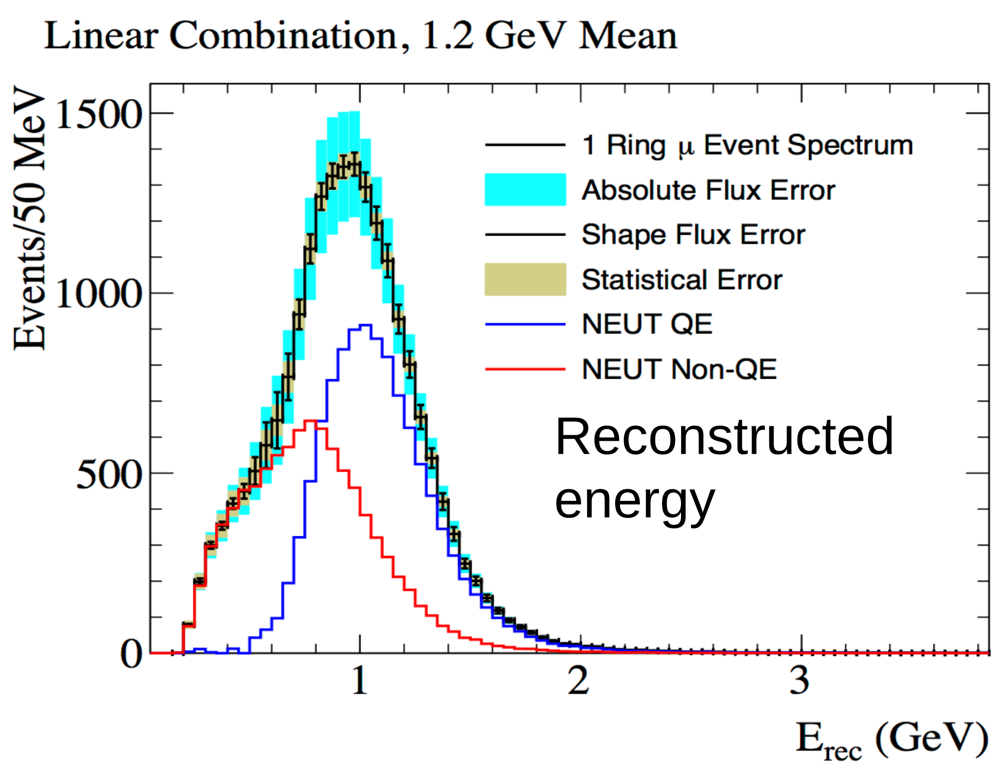


PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution

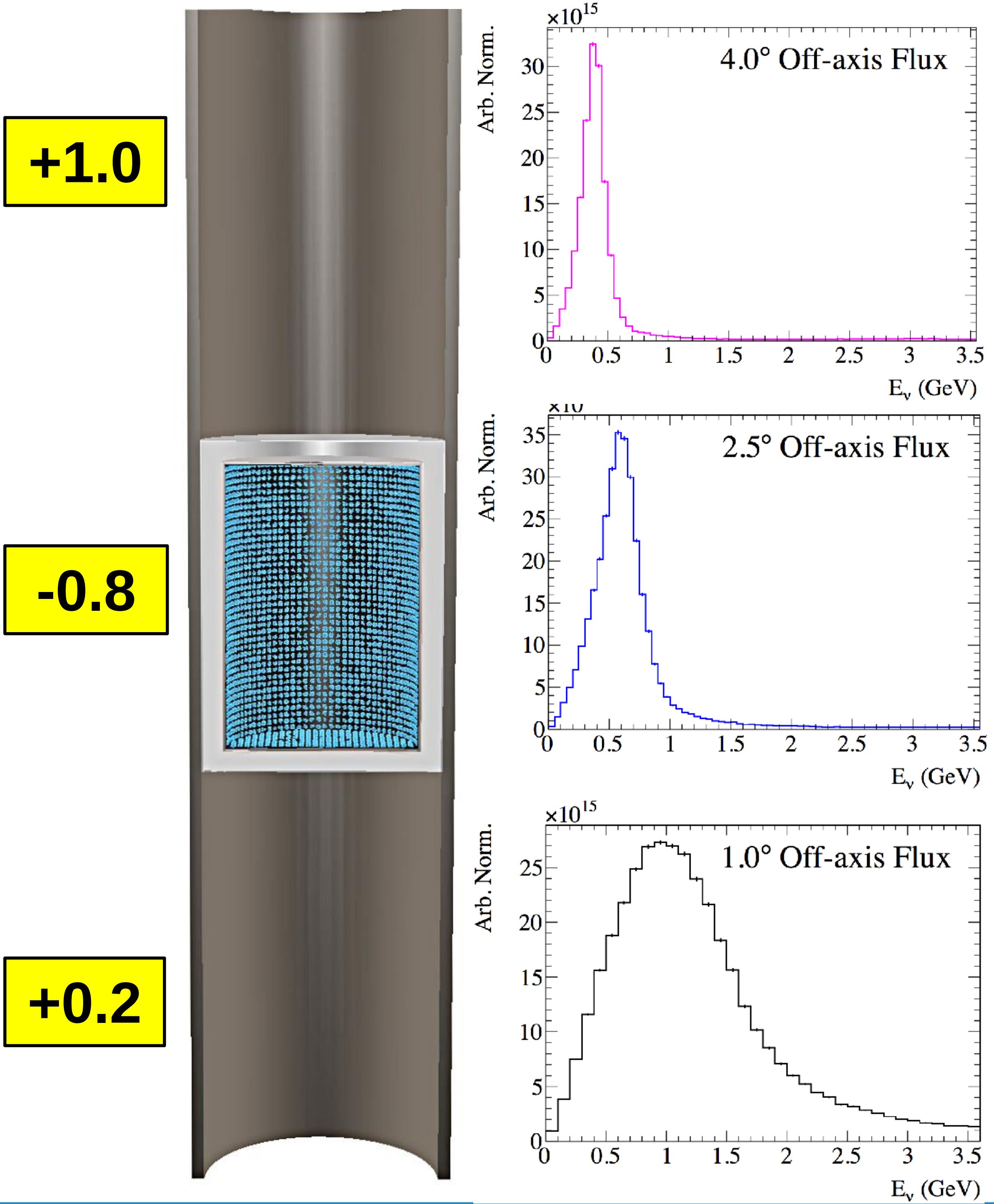
- Measure at a known energy
- Map out true-reco relationship
- Energy range determined by off-axis range





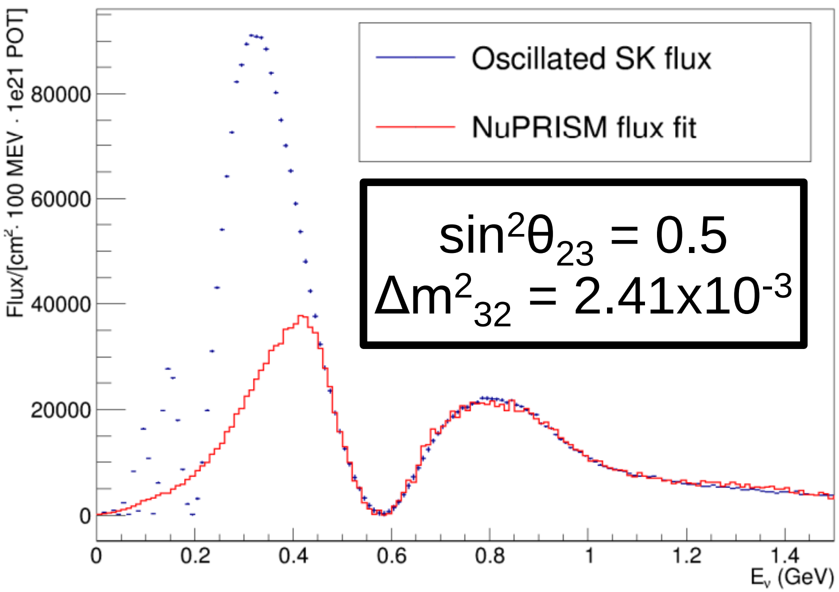
PRISM benefits - 3

- Can have different linear combination



PRISM benefits - 3

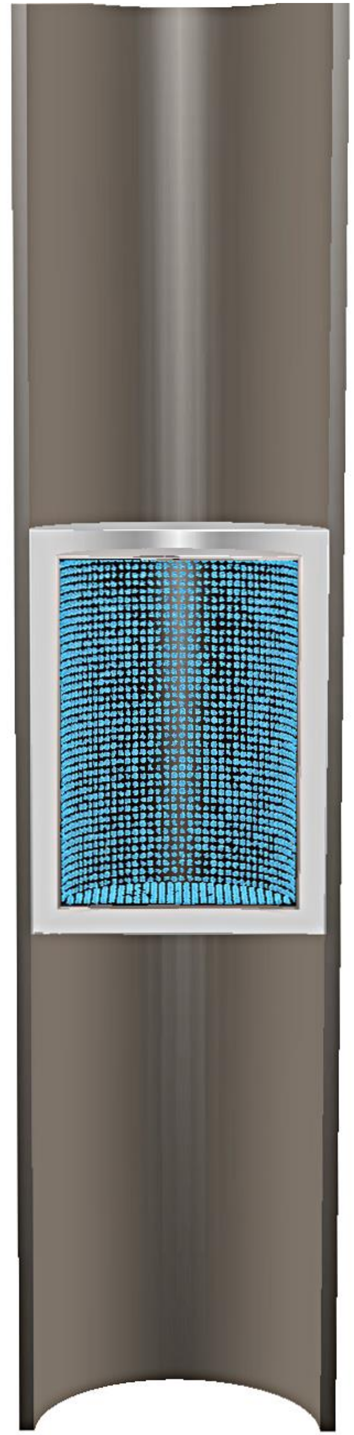
- Can have different linear combination
- Recreate oscillated flux using near detector data

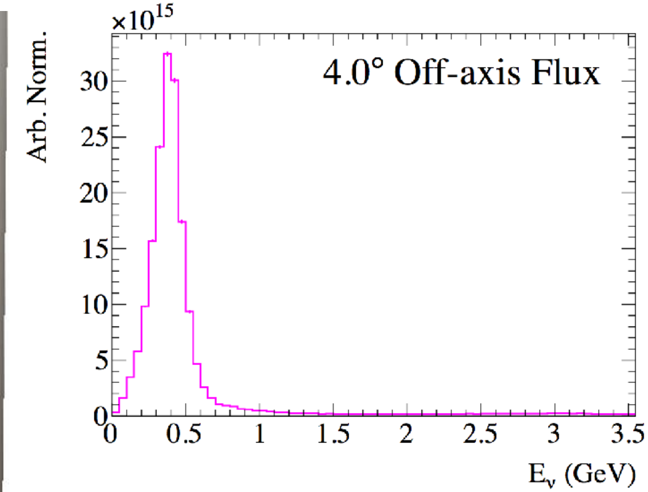


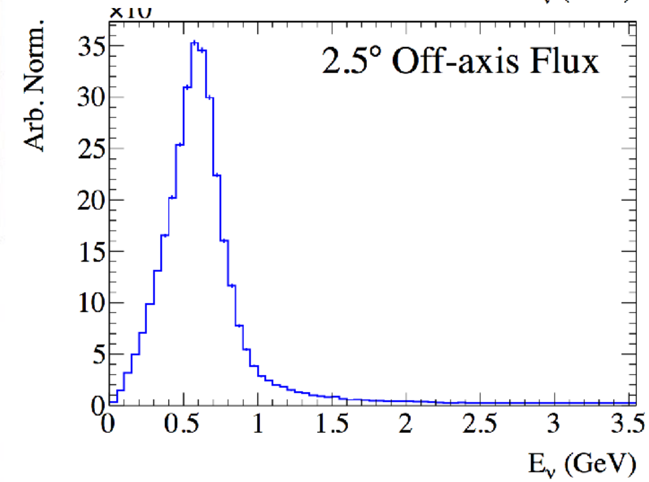
+1.0

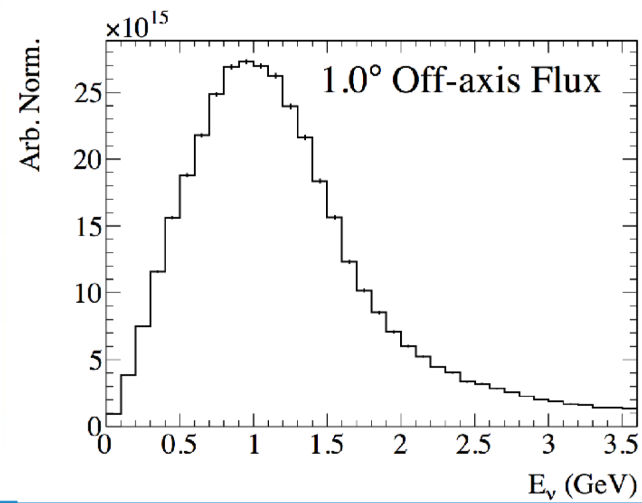
-0.8

+0.2



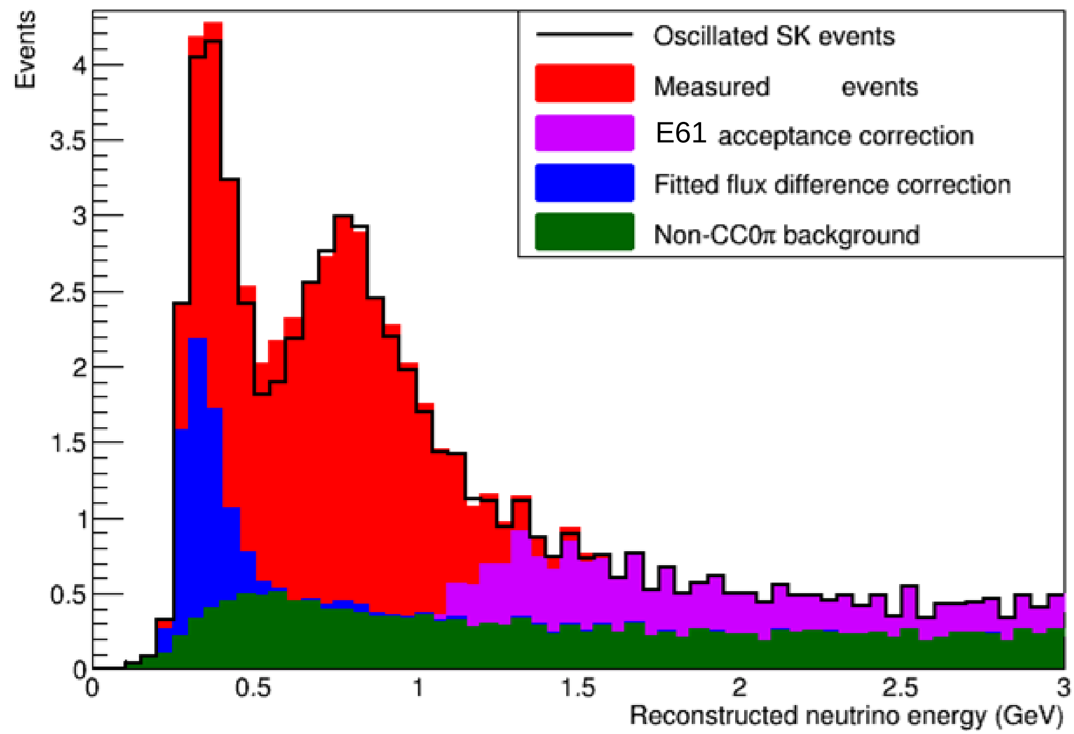


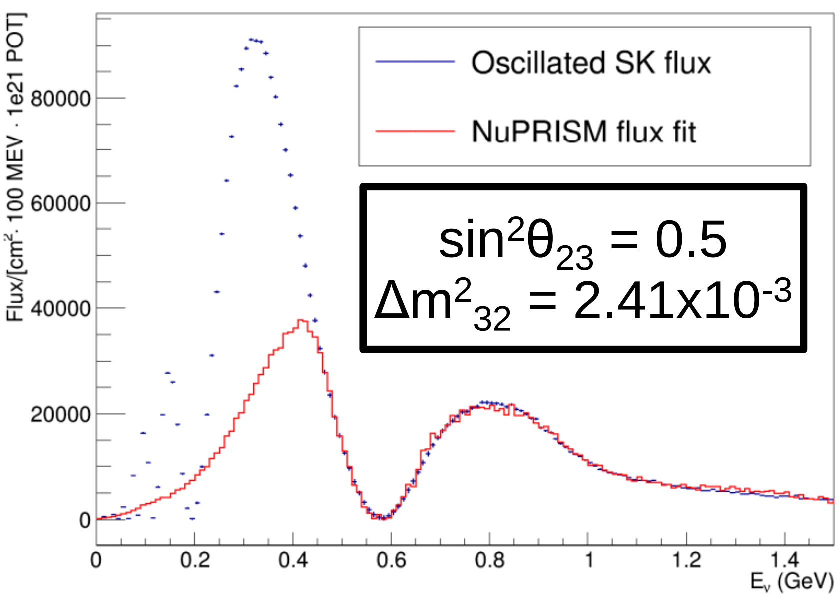




PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data





- Use data to directly predict oscillated spectrum (red)
- Backgrounds (green) can be measured in-situ
- Oscillation analysis minimally dependent on neutrino interaction model

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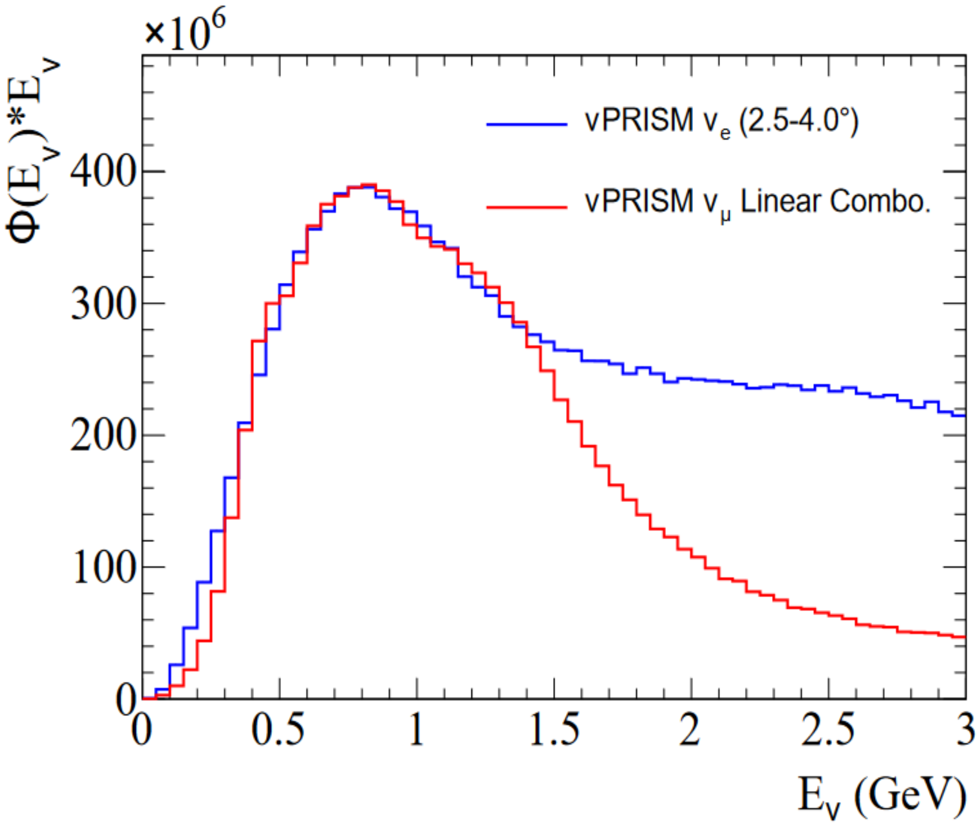
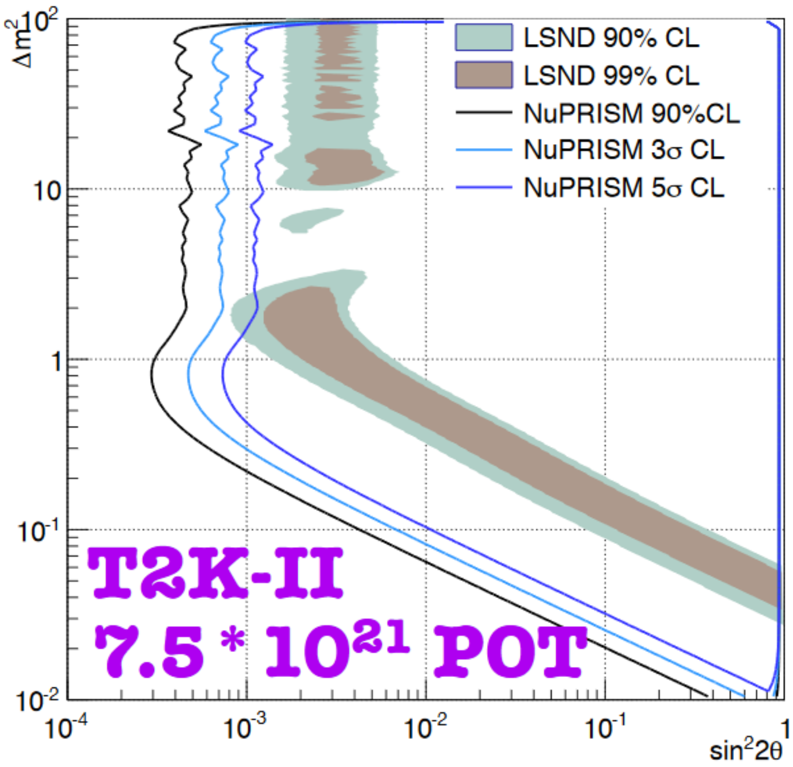
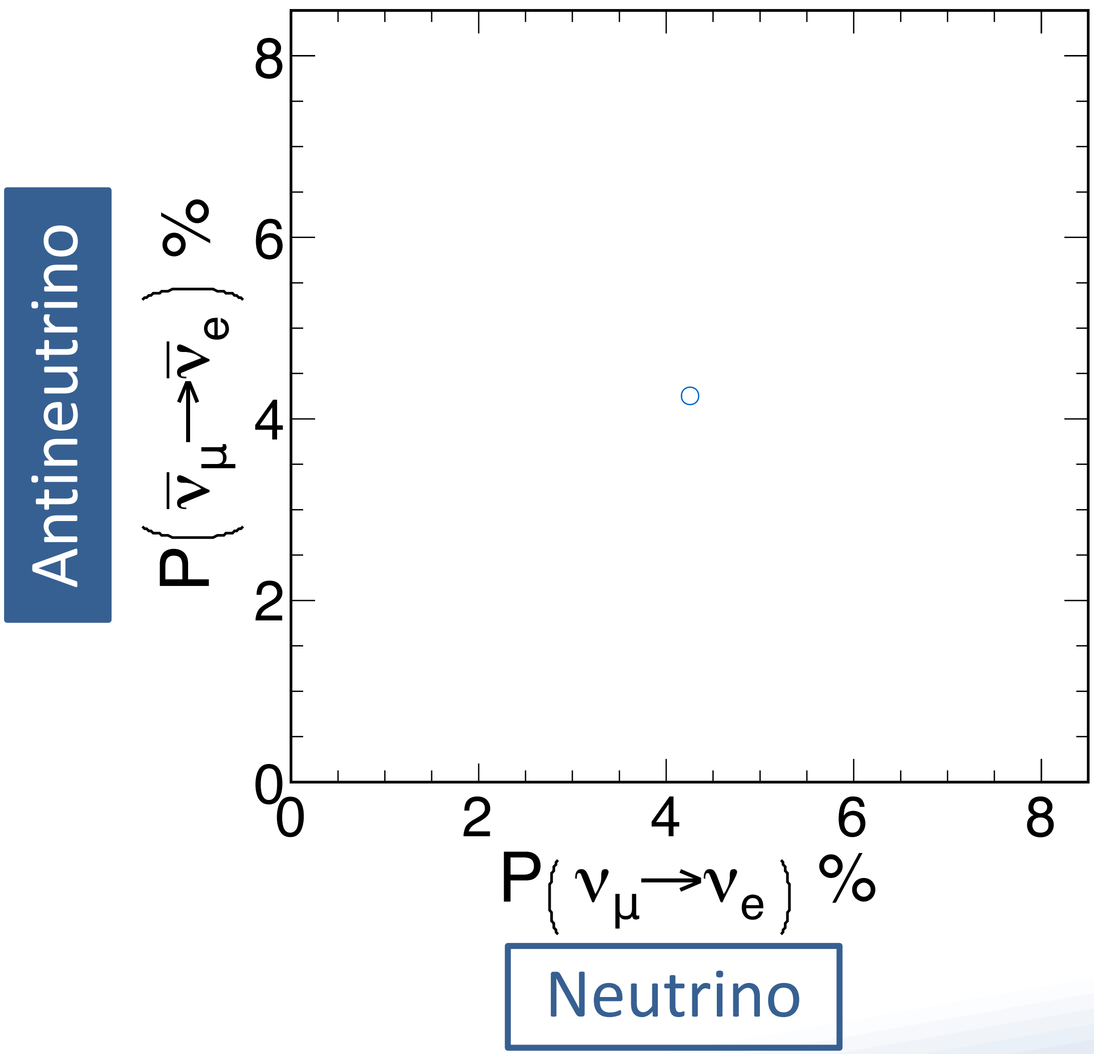
PRISM benefits - 4





- Fit ND ν_e flux
  - Directly measure electron/muon cross-section ratio
- Sterile neutrino searches
  - >5σ exclusion of LSND
  - Oscillation vs off-axis angle

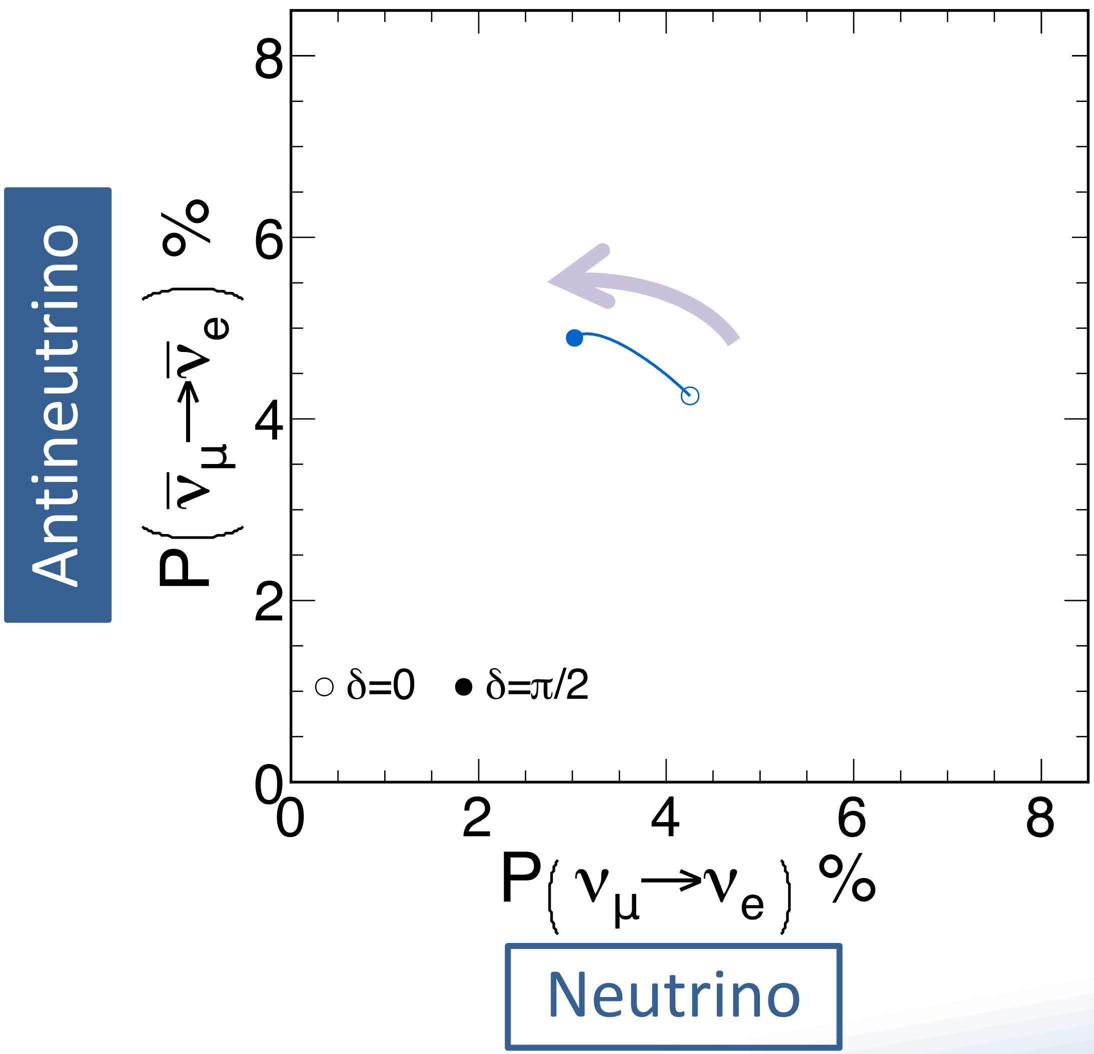
1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?



Vacuum and no CP violation: neutrinos and antineutrinos are the same

Slides by A. Himmel

1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?



CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Slides by A. Himmel

1. Is the mass hierarchy "normal" or "inverted?
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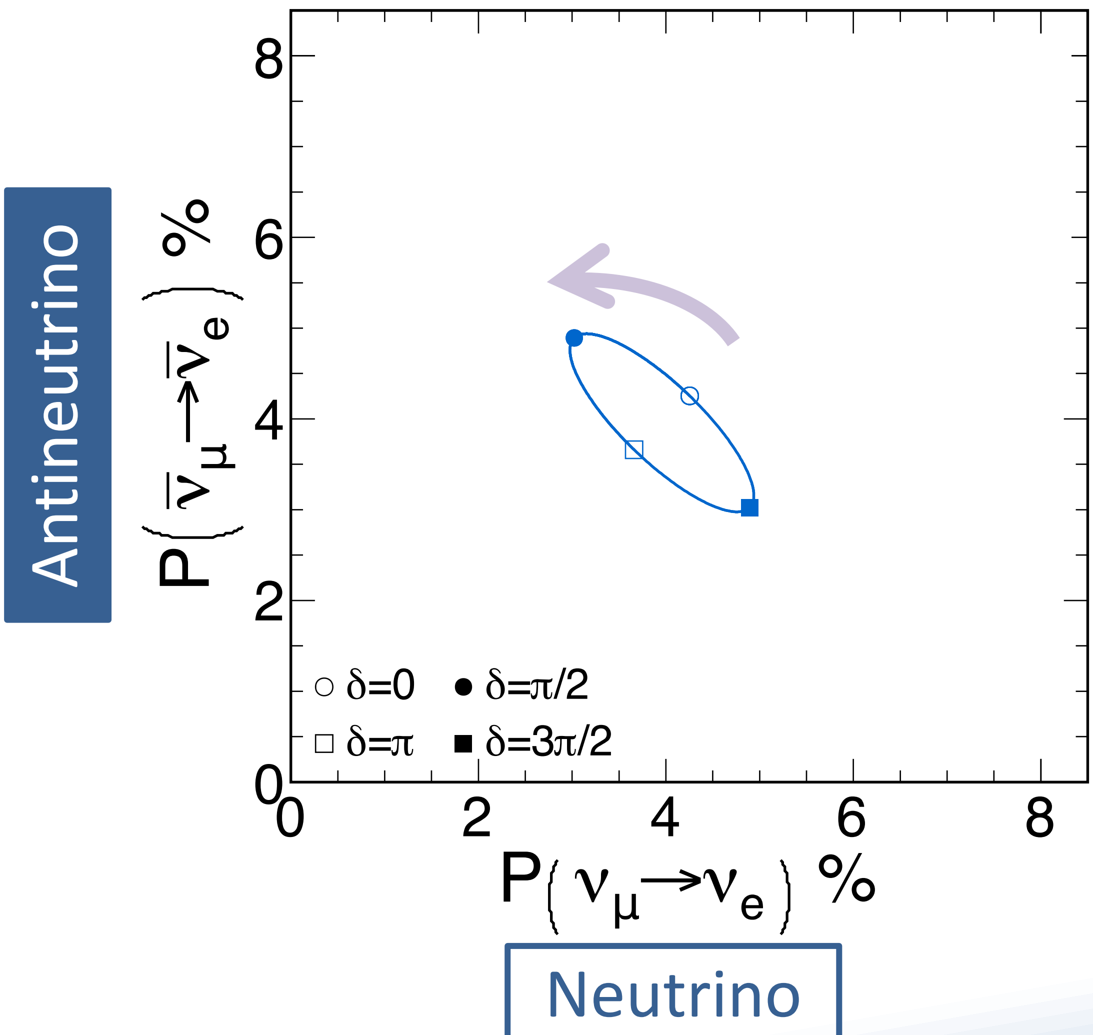
3. What is the "octant" of θ_{23}?



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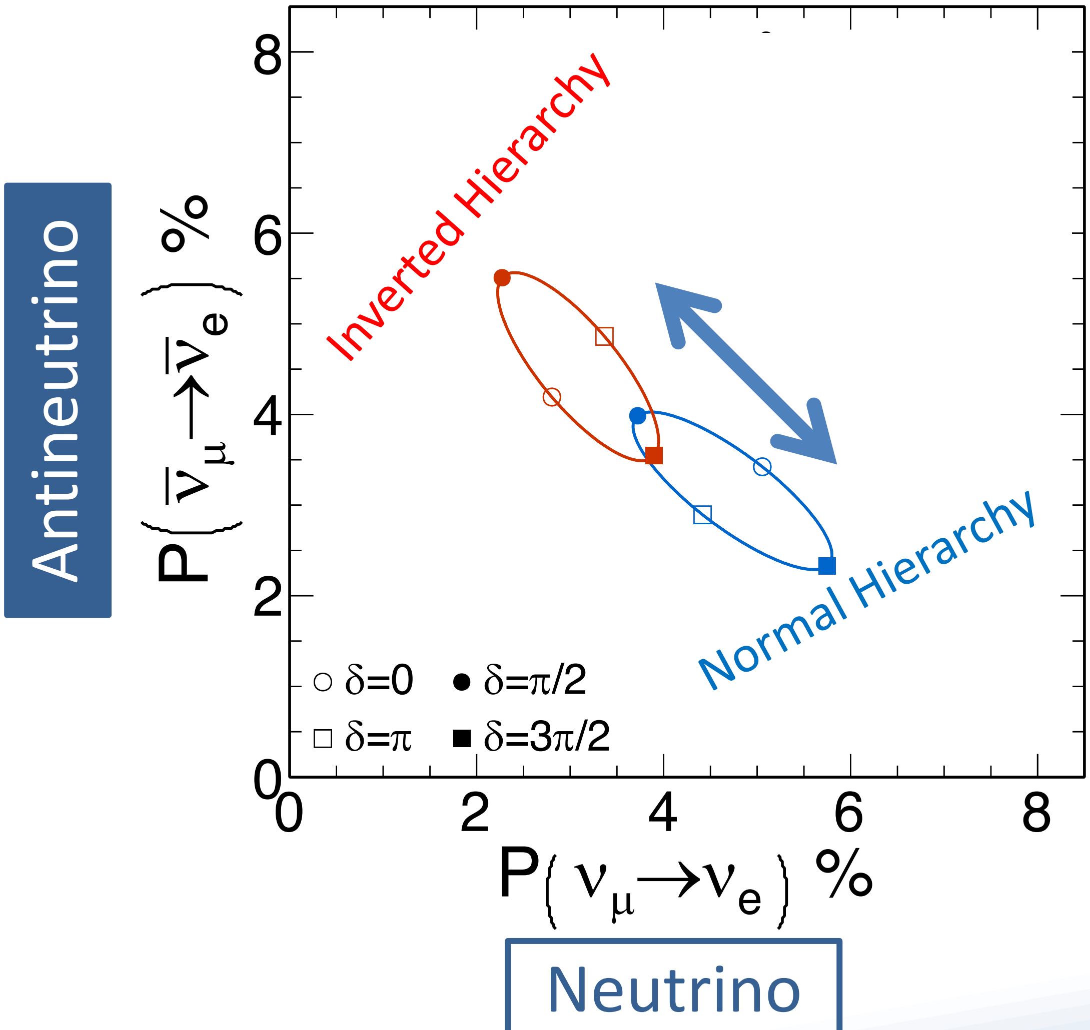

Matter effects also introduce opposite neutrino-antineutrino effects.

Slides by A. Himmel

1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
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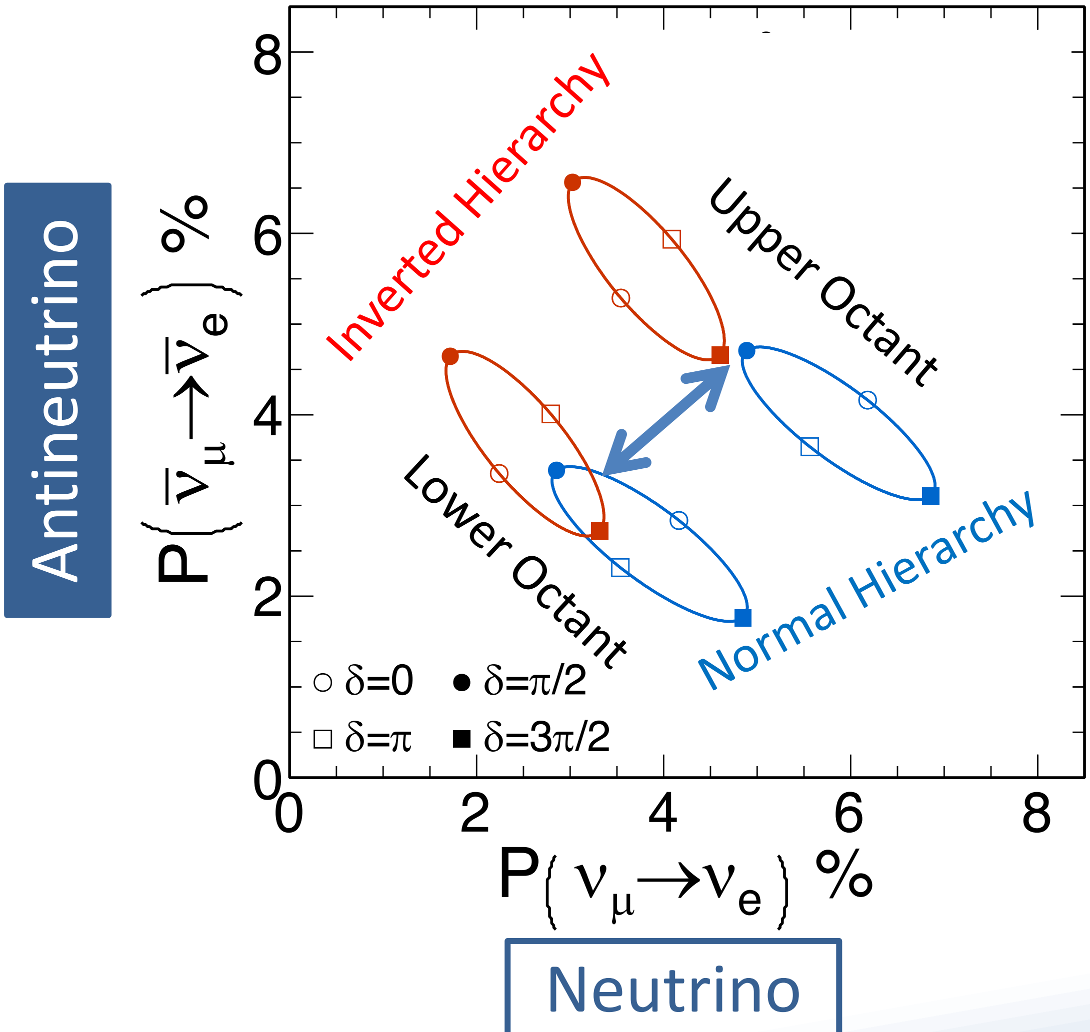

The octant creates the *same* effect in neutrinos and antineutrinos.

Slides by A. Himmel