Latest oscillation results from T2K

Mark Scott for the T2K Collaboration
TAUP 2017

Neutrino oscillation

- Neutrinos have two sets of eigenstates – flavour and mass
  - Interact through flavour states
  - Propagate in mass states

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

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

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

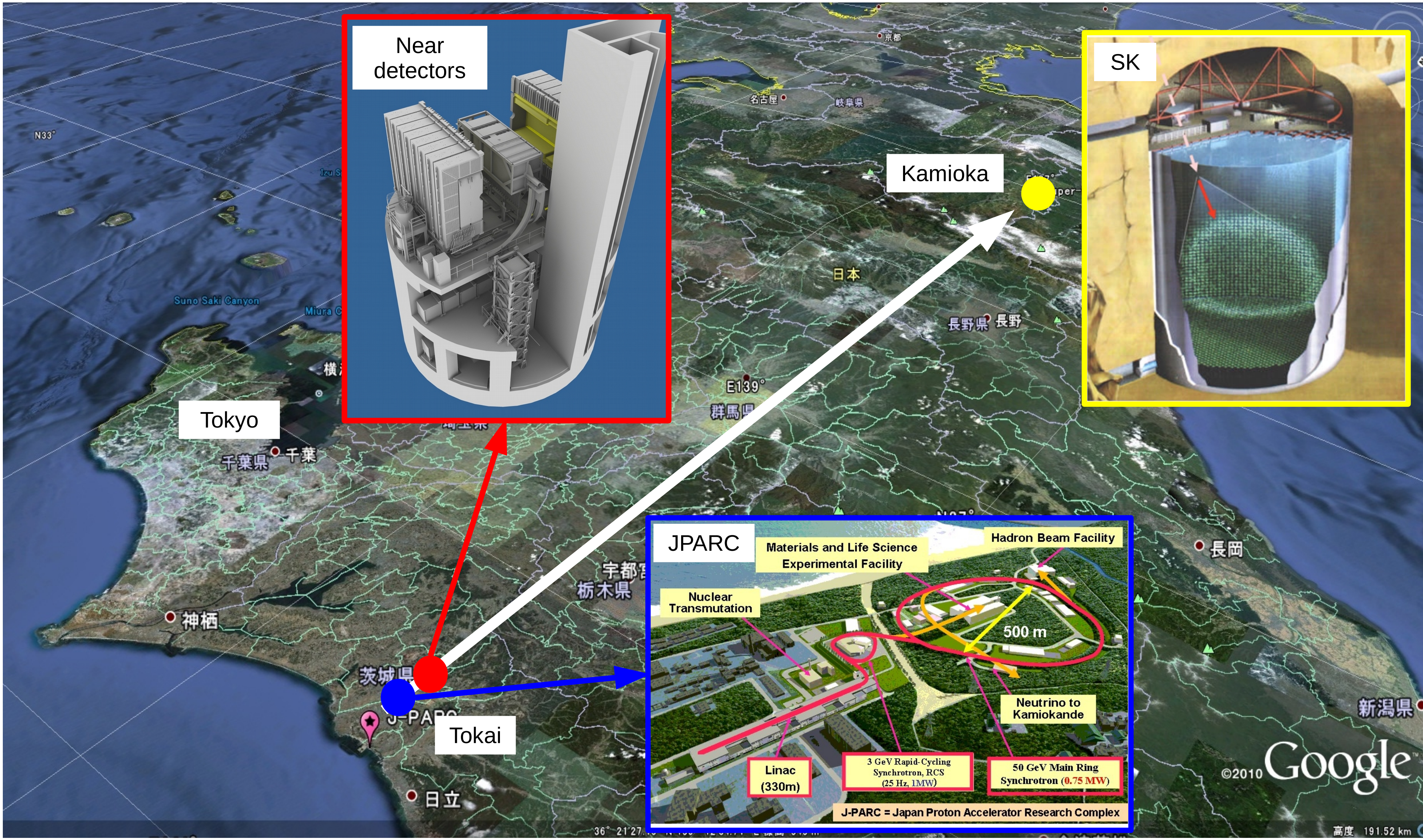
Atmospheric /Beam — Beam /Reactor — Reactor /Solar

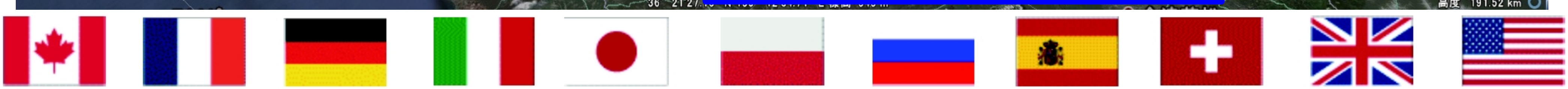
$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$\delta = \delta_{CP}$

Unanswered questions:

$\delta_{CP} \neq 0$? $\quad \Delta m^2_{32} < 0$? $\quad \theta_{23} > 45^{o}$?

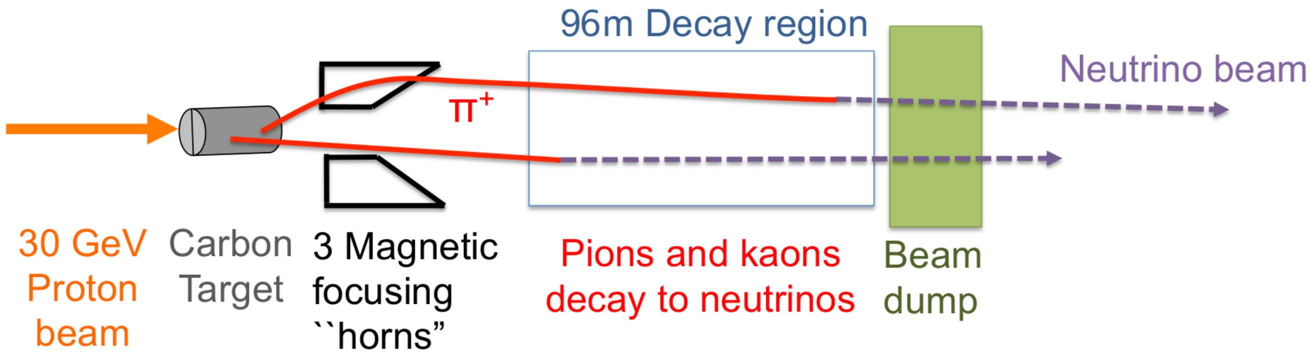
Tokai to Kamioka (T2K) experiment



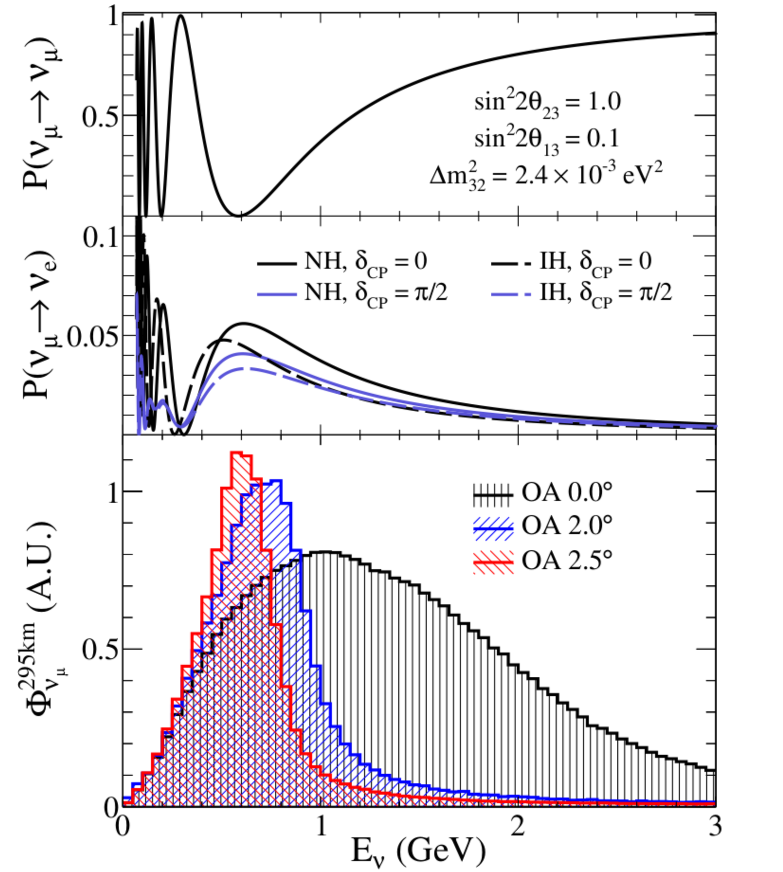


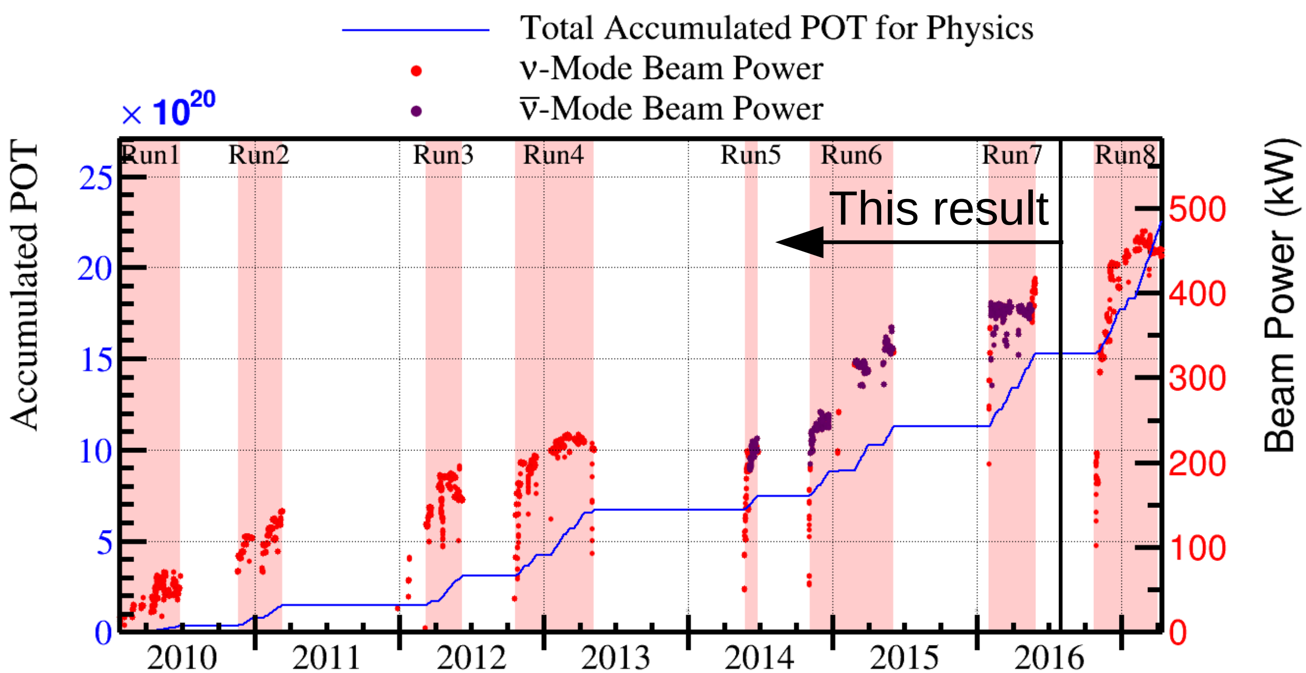
11 countries, 60 institutions, ~500 collaborators

The T2K neutrino beam



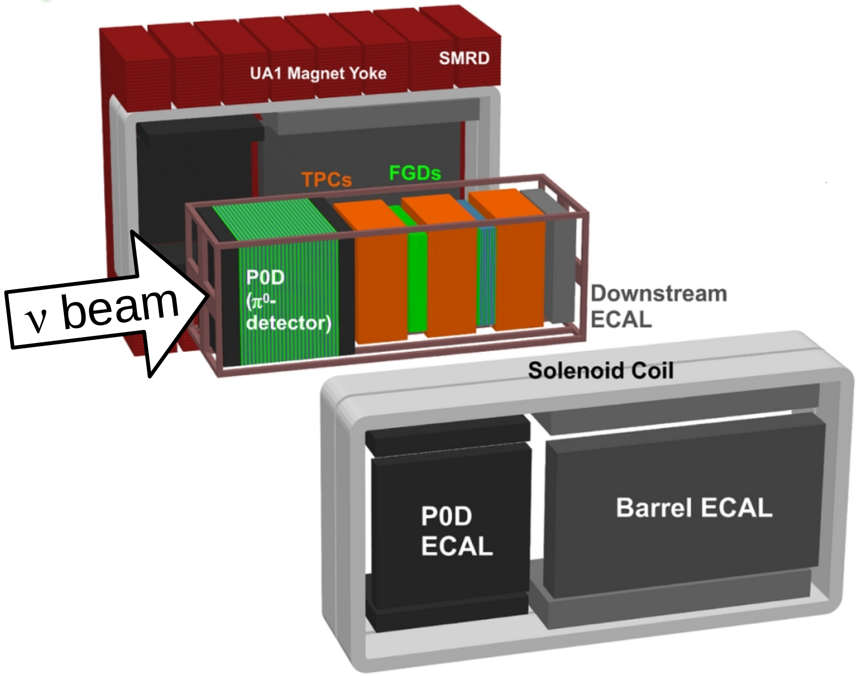
- Conventional neutrino beam
- T2K is an **"off-axis"** experiment
  - 2.5°, tuned to maximal disappearance at SK





- POT: Protons On Target
- Total POT for latest result (runs 1-7):
  - Neutrino beam mode:
    - 7.48×10^{20} POT
  - Anti-neutrino mode:
    - 7.47×10^{20} POT

T2K detectors



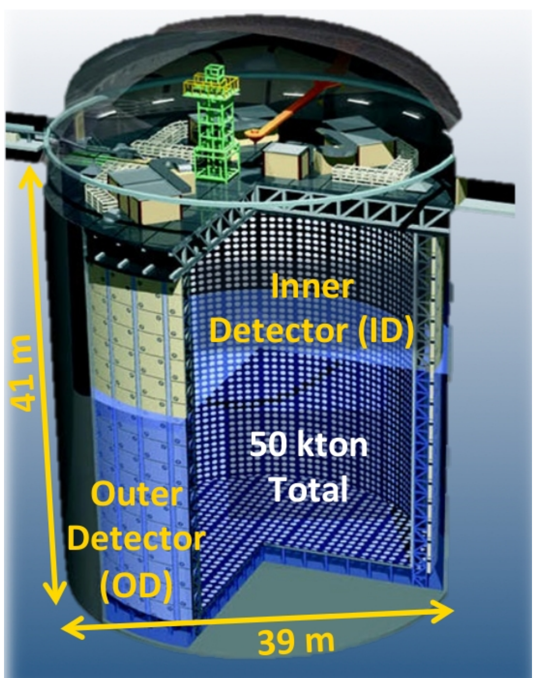
Near, Off-axis detector (ND280)

Two fine-grained detectors (FGDs)

- FGD1 – Fully active carbon target
- FGD2 – Active carbon and passive water layers

Magnet + three TPCs

- Particle charge + momentum via curvature
- Particle ID from dE/dx - 0.2% mis-ID rate



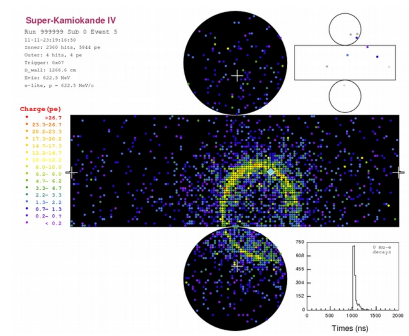
Super-Kamiokande (SK)

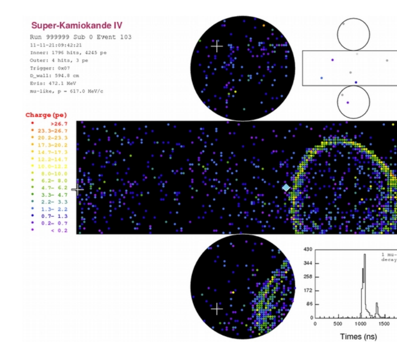
Large water-Cherenkov detector

- ~11,000 20” PMTs in inner detector
- 22.5 kT fiducial volume

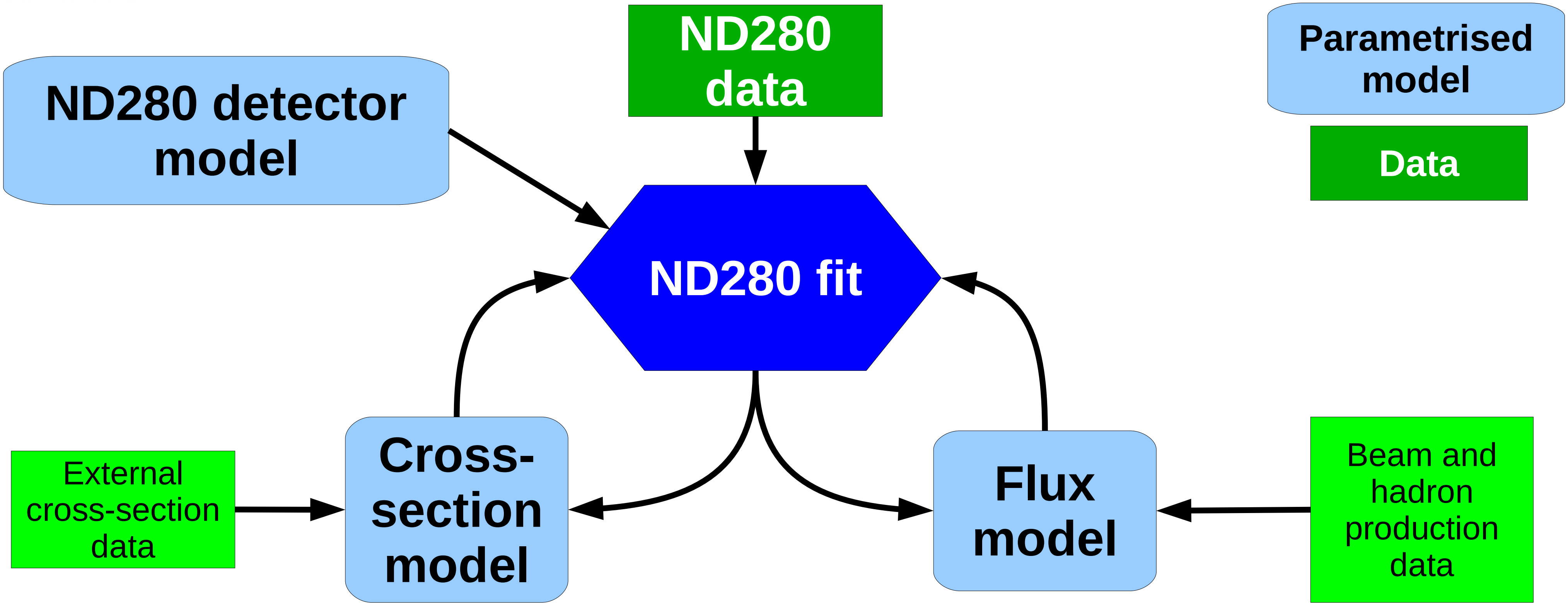
Separate electrons and muons by ring shape

- Mis-ID <1%
- No sign selection





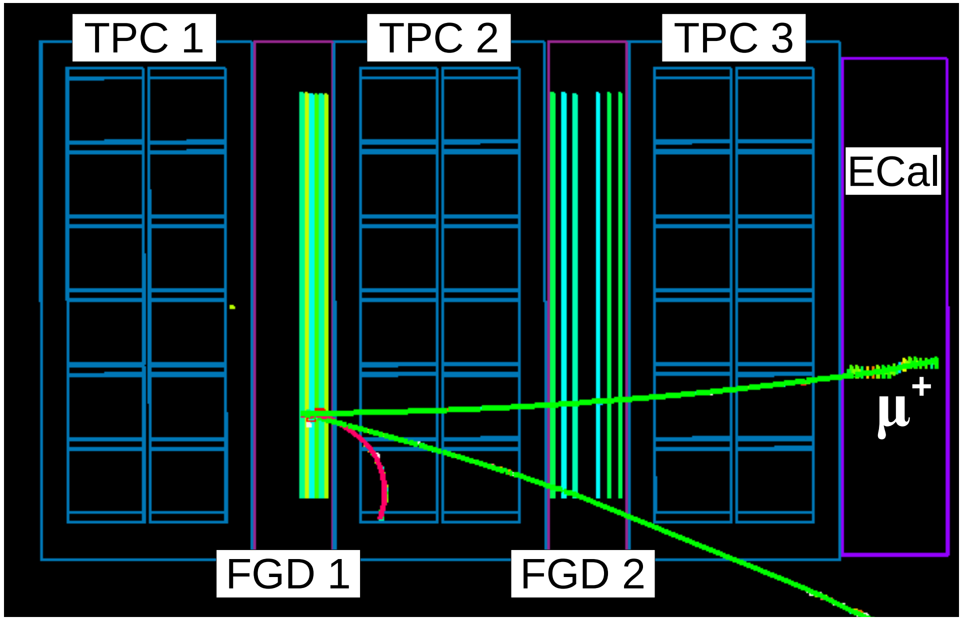
T2K near detector analysis



Detectors measure interaction rate:

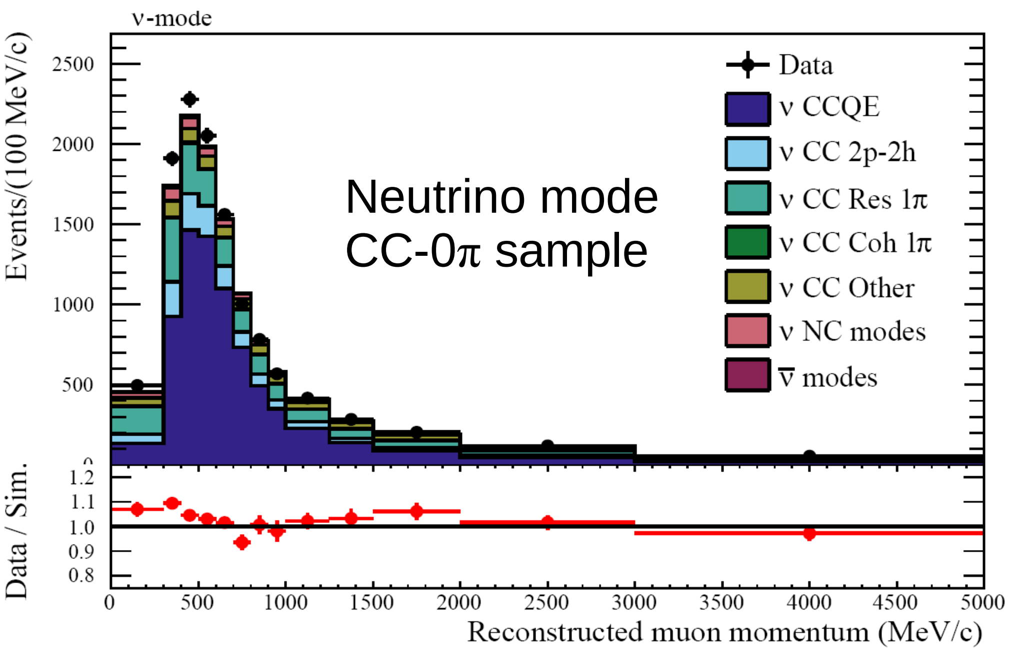
- Flux * Cross section → Neither is known to better than 10%
- Joint fit of models to ND280 data allows constraint on rate
- Produce tuned, correlated, flux and cross-section models

ND280 data

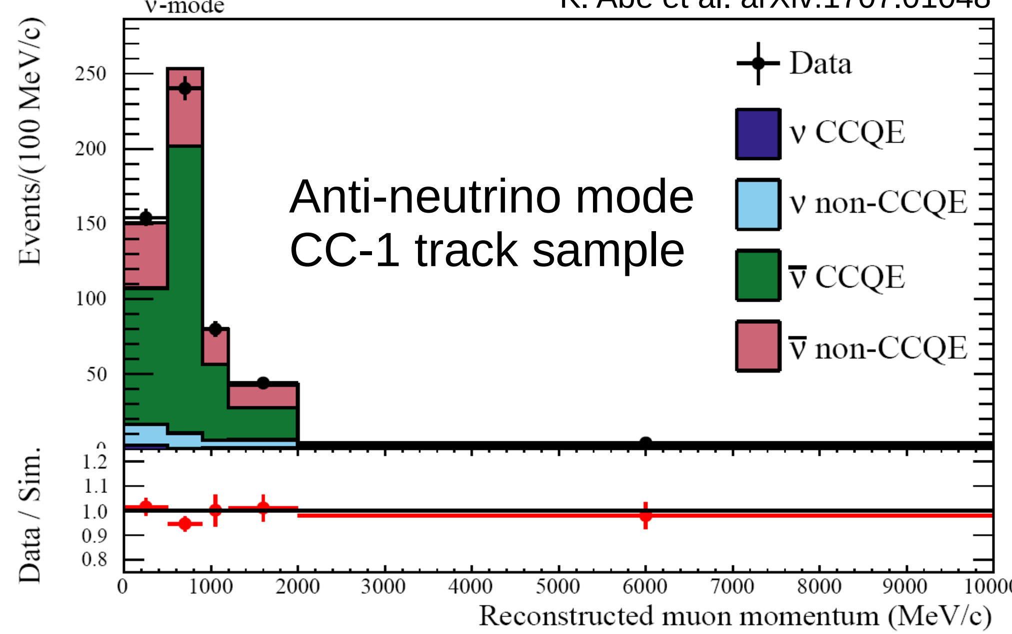


Selection:

- Identify highest momentum muon-like track
  - Charge differentiates neutrino from anti-neutrino
- Separate by number of tagged pions
  - Anti-neutrino samples separated into 1-track and N-track
- Select ν and anti-ν events in anti-ν beam to constrain wrong-sign backgrounds

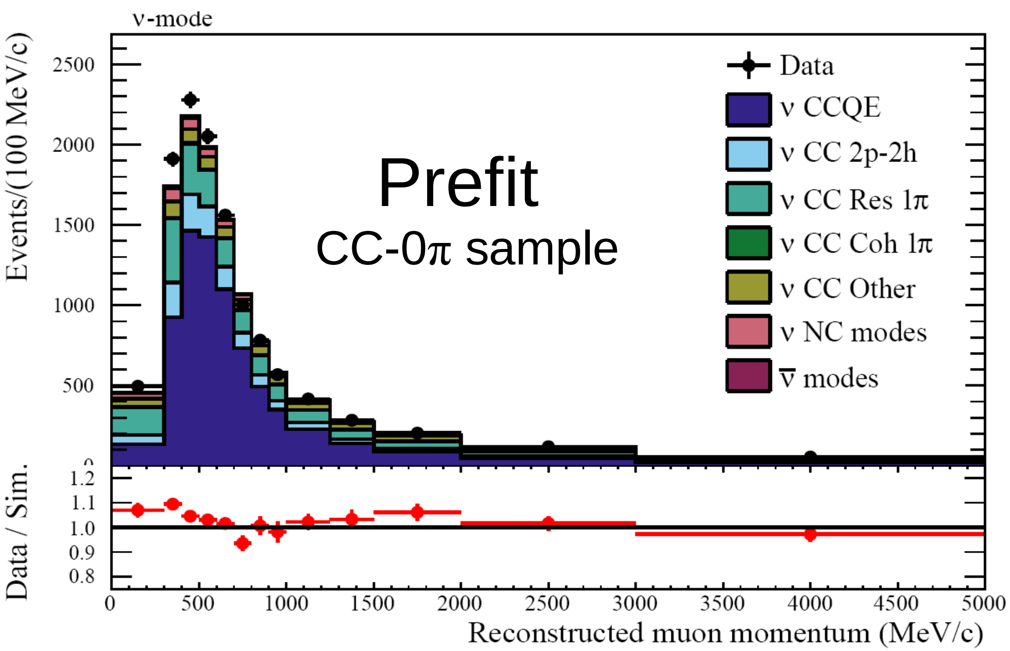


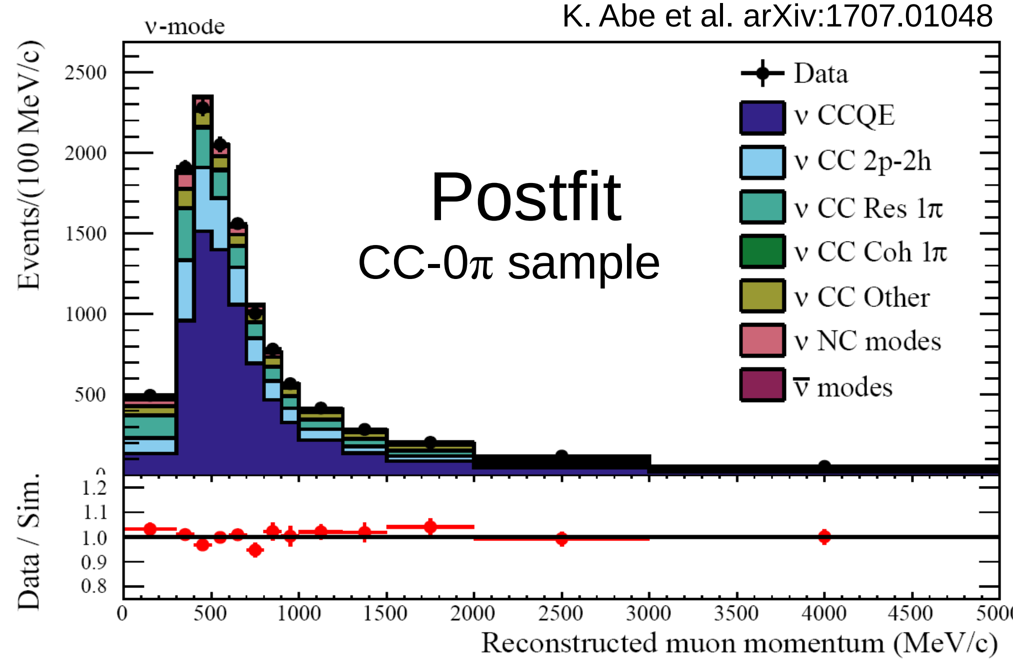
K. Abe et al. arXiv:1707.01048



ND280 fit

K. Abe et al. arXiv:1707.01048

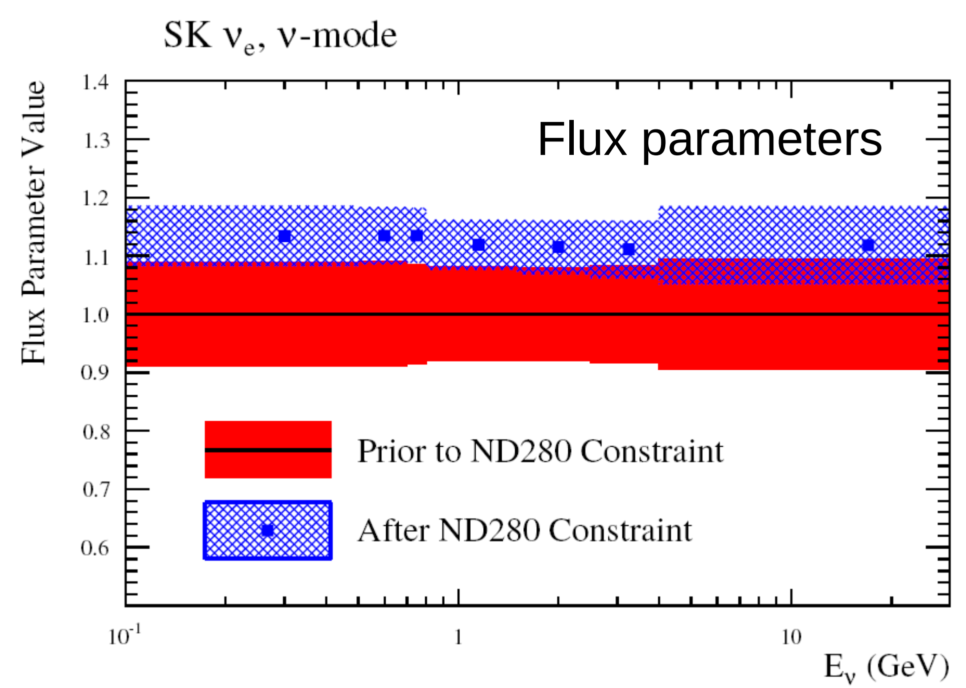




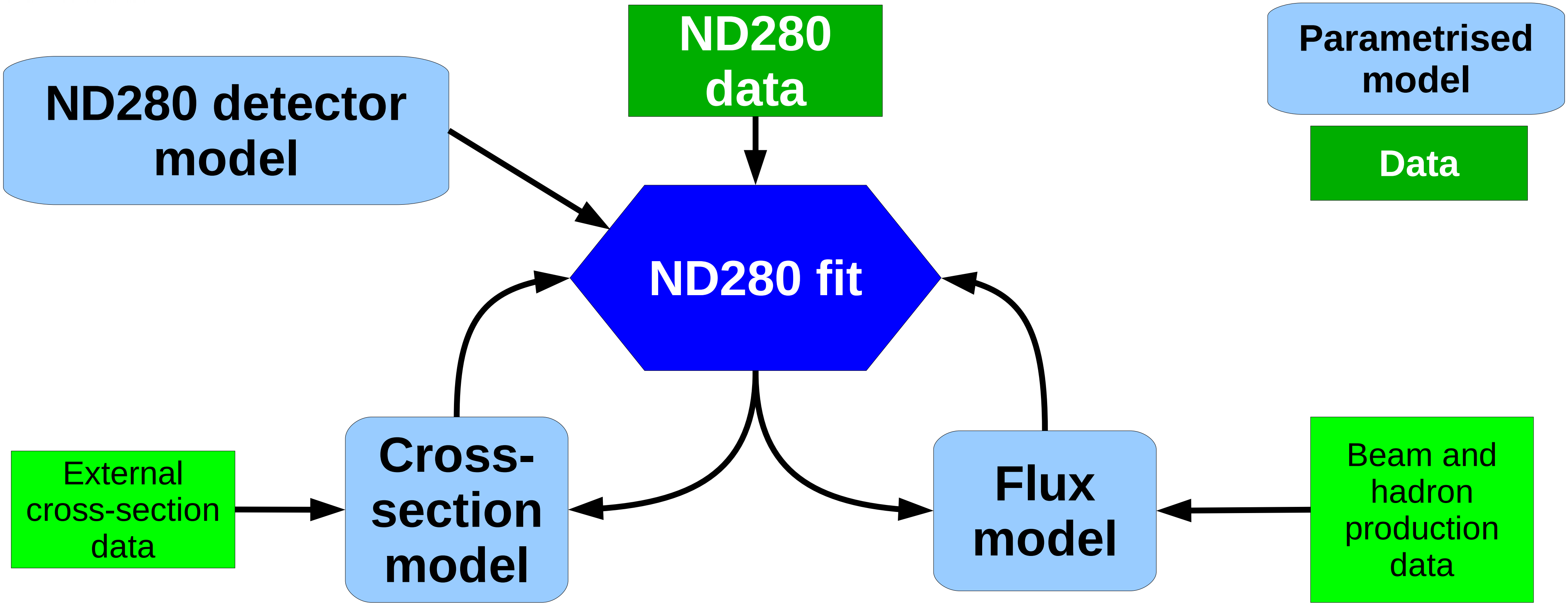
Model parameters shifted from prior values

Fit only as good as the input models:

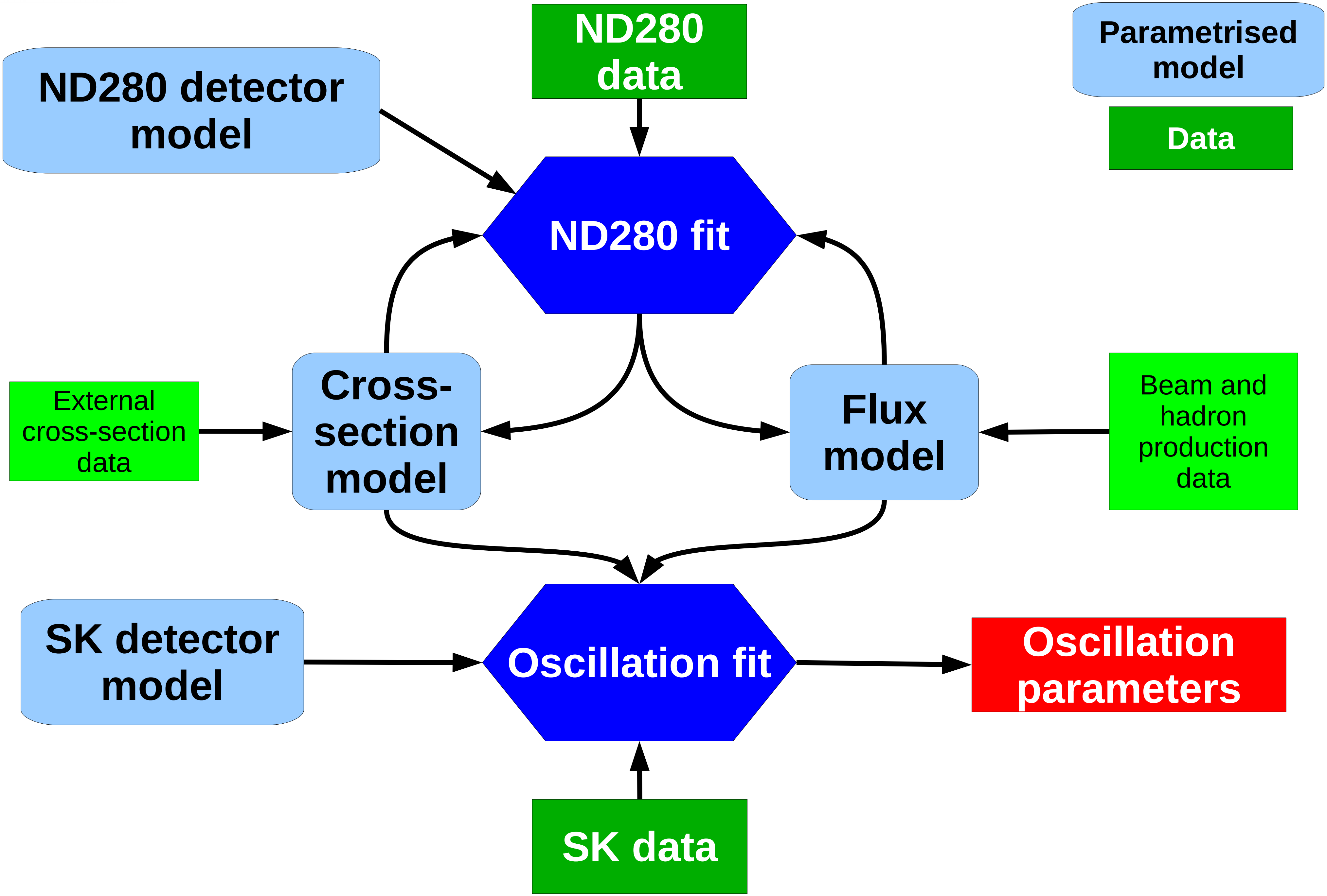
- Test model dependence using ND280 fit
- Choice of interaction model has small effect on this analysis



T2K oscillation analysis



T2K oscillation analysis



SK event selection

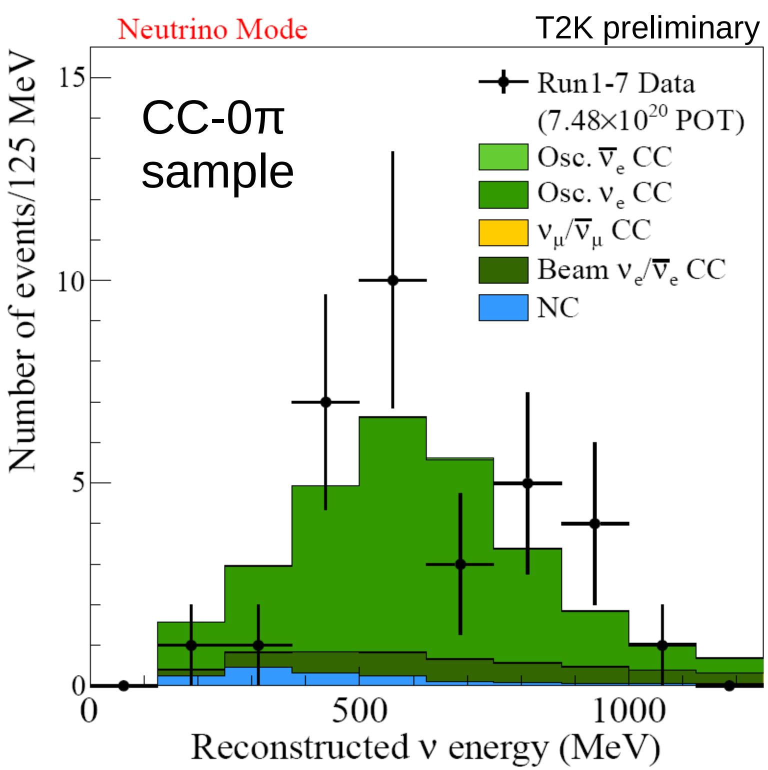
Look for fully contained, single ring events inside SK fiducial volume, then:

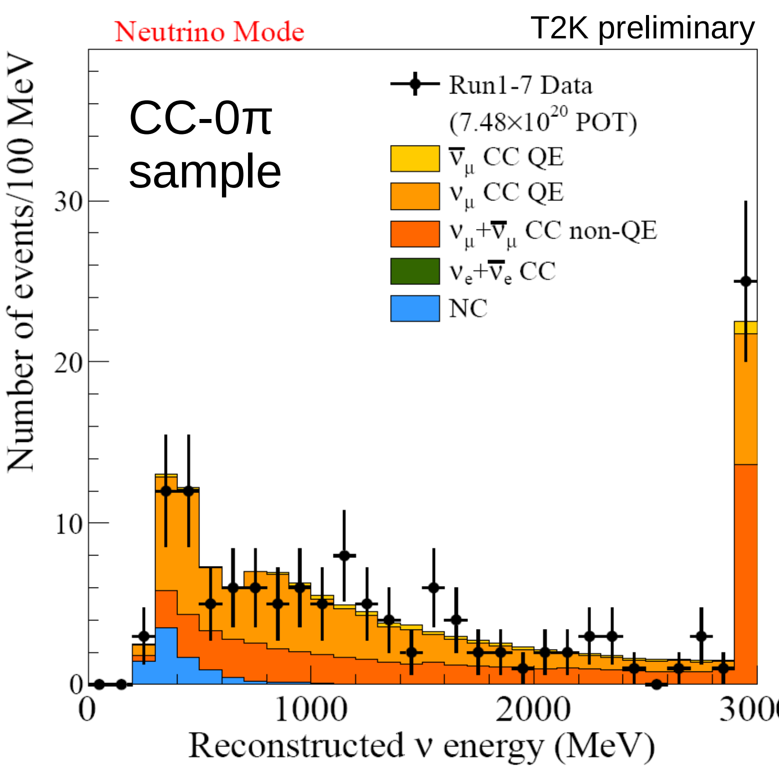
If electron-like ring:

- 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

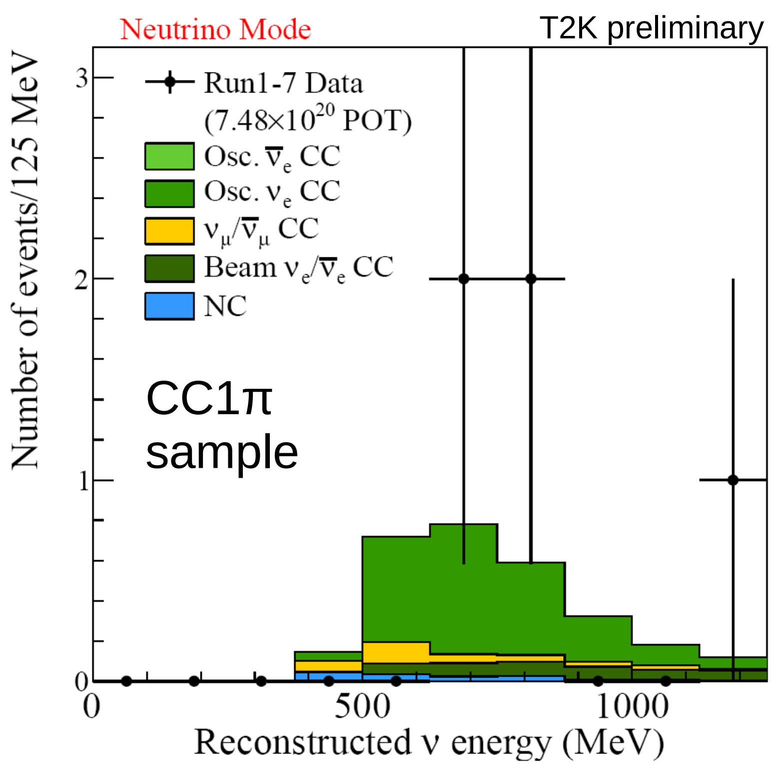
Look for fully contained, single ring events inside SK fiducial volume, then:

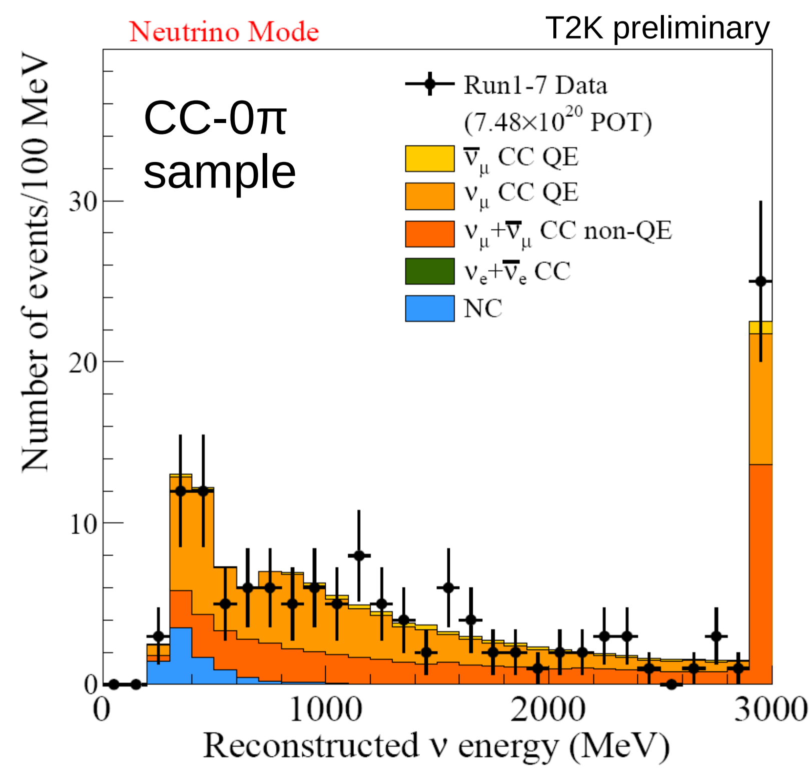
If electron-like and neutrino mode beam:

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

If muon-like ring:

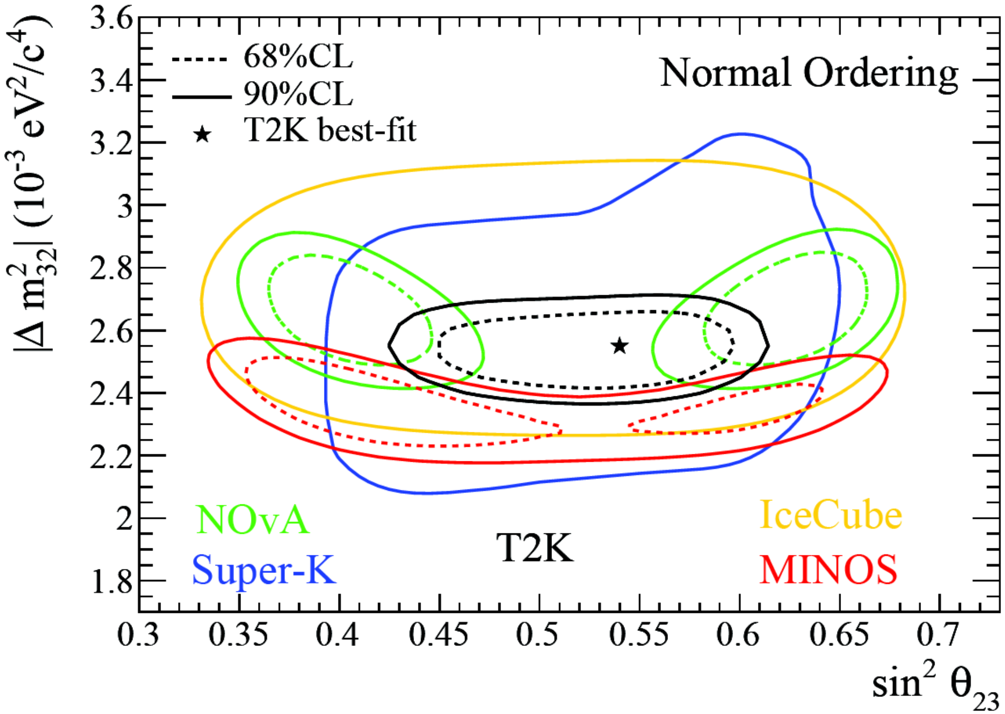
- Reconstructed momentum > 200 MeV/c
- At most 1 decay electron

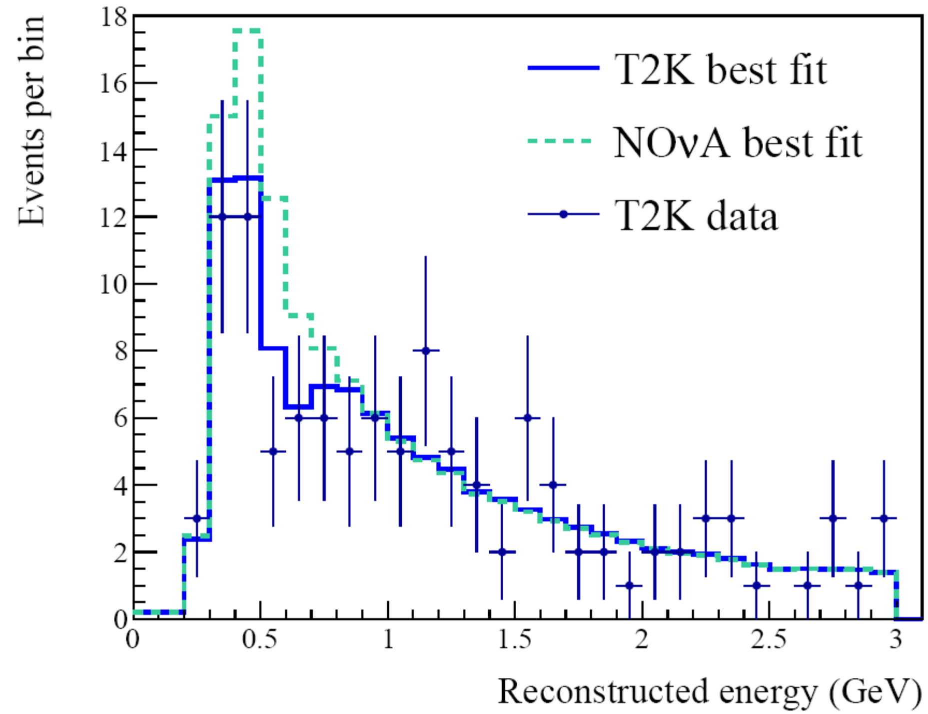




Disappearance results

K. Abe et al. arXiv:1707.01048

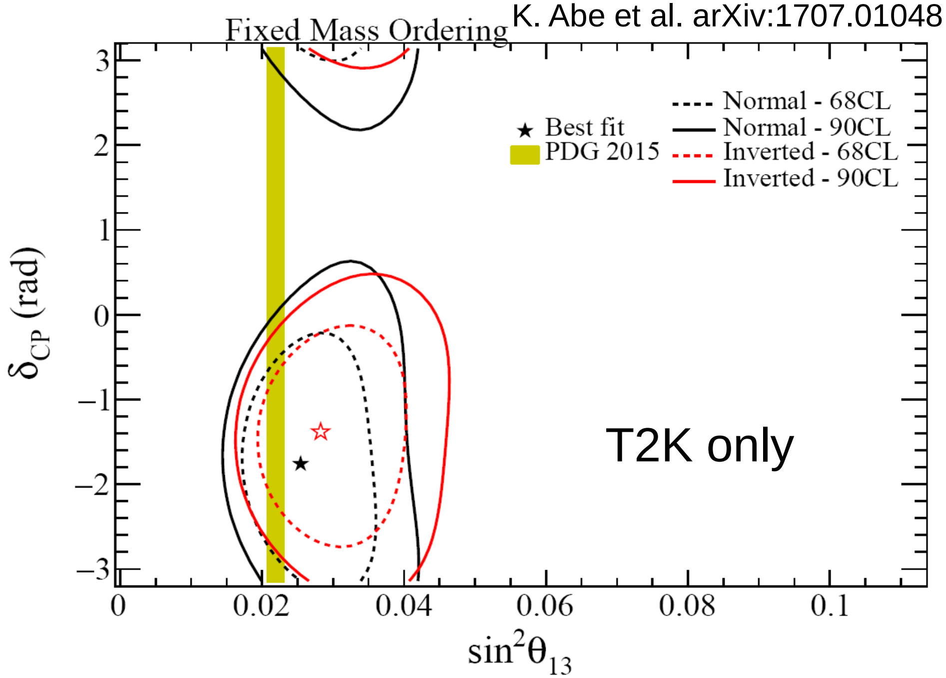


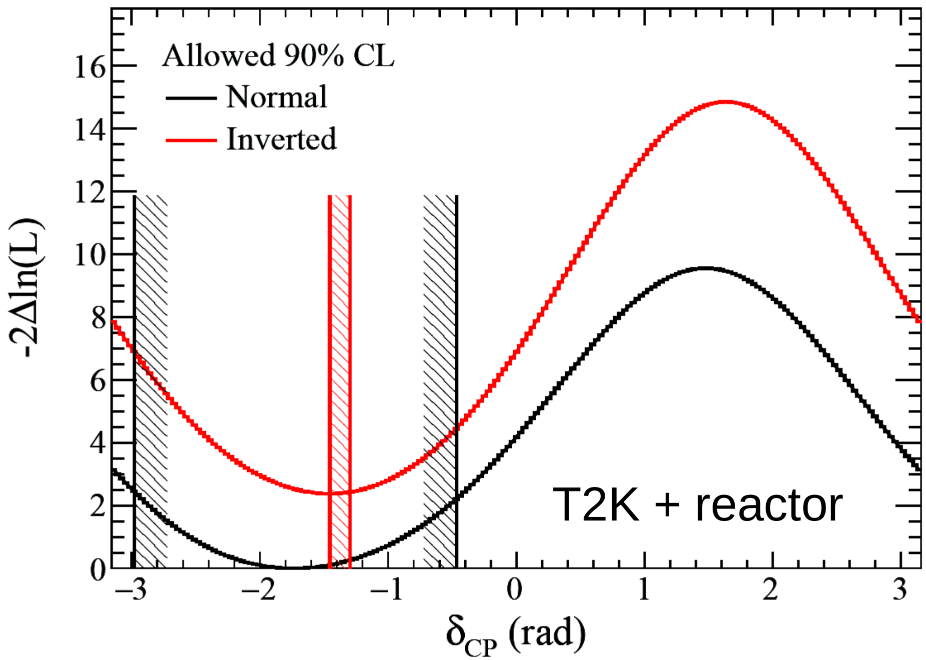


- Maximise a likelihood: $\mathcal{L} = \mathcal{L}_{\text{Data}} * \mathcal{L}_{\text{Flux}} * \mathcal{L}_{\text{XSec}} * \mathcal{L}_{\text{SK detector}}$
- Fit results on left, best-fit reconstructed neutrino energy spectra on right
- Best fit point
  - $\sin^2\theta_{23} = 0.55^{+0.05}_{-0.09}$
  - $\Delta m^2_{23} = (2.54 \pm 0.08) \times 10^{-3} (eV^2/c^4)$
- T2K data favours more disappearance than NOvA

Appearance results

K. Abe et al. arXiv:1707.01048





- Data fit without (top) and with (bottom) constraint on $\sin^2\theta_{13}$ from reactor measurements
  - T2K $\sin^2\theta_{13}$ in agreement with reactor value
  - T2K data alone excludes some region of δ_{CP} parameter space at 90% C.L.
- CP conservation excluded at 90% C.L.
- Data consistent with PMNS oscillations within 2σ

Conclusions

- With 1.5 x 10^{21} POT T2K has measured:
  - $\Delta m^2_{23} = (2.54 \pm 0.08) \times 10^{-3} (eV^2/c^4)$
  - $\sin^2\theta_{23} = 0.55^{+0.05}_{-0.09}$
    - Consistent with maximal mixing
  - $\sin^2\theta_{13} = 0.027^{+0.007}_{-0.006}$ (fit without reactor constraint)
  - $\delta_{CP} = -1.728^{+0.85}_{-0.81} (rad)$
    - CP conservation excluded at 90% CL
- Many other results: non-PMNS oscillation, cross sections, exotic physics...
- Neutrino dataset doubled in Run 8:
  - New results to be announced soon!

Thank you!

Other T2K results

New results published in the last year:

Physics	Title	Journal / Status
PMNS oscillation	Sensitivity of the T2K accelerator-based neutrino experiment with an Extended run to 20×10^{21} POT	arXiv:1607.08004 (2016)
Cross-section	First measurement of the muon neutrino charged current single pion production cross section on water with the T2K Near Detector	Phys. Rev. D 95, 012010 (2017)
PMNS oscillation	Combined Analysis of Neutrino and Antineutrino Oscillations at T2K	Phys. Rev. Lett. 118, 151801 (2017)
Cross-section	Measurement of coherent $\pi+$ production in low energy neutrino-carbon scattering	Phys. Rev. Lett. 117, 192501 (2017)
Exotic	Search for Lorentz and CPT violation using sidereal time dependence of neutrino flavor transitions over a short baseline	Phys. Rev. D 95, Rapid Communications 111101 (2017)
PMNS oscillation	Updated T2K measurements of muon neutrino and antineutrino disappearance using 1.5×10^{21} protons on target	Accepted in PRD Rapid Communications arXiv:1704.06409

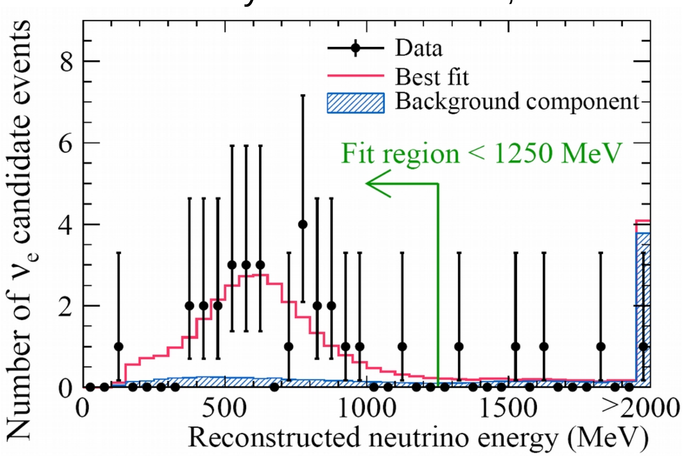
All publications, conference talks etc. at
http://t2k-experiment.org/for-physicists/

Supplementary slides

Why study neutrinos?

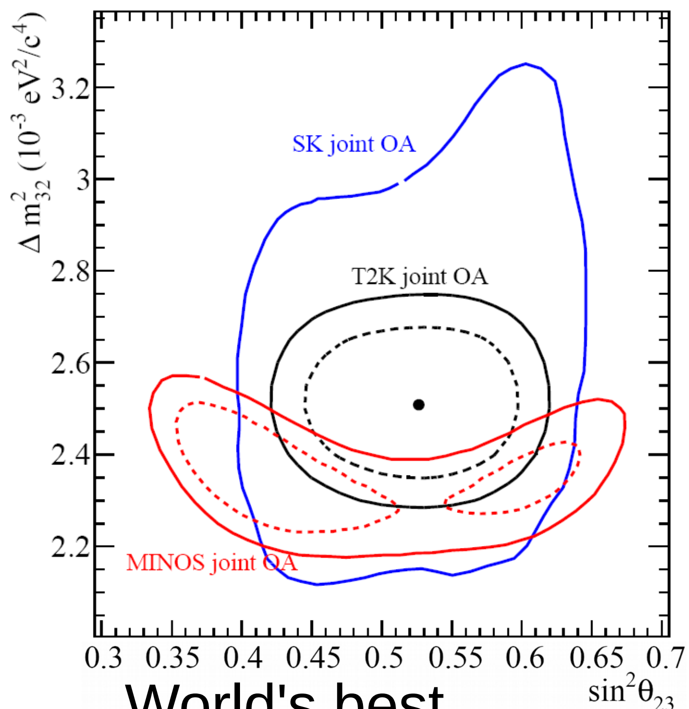
- How are neutrino masses generated, and why are they so small?
- How does neutrino mass fit into the Standard Model?
- Do neutrinos violate CP?

K. Abe et al. Phys. Rev. Lett. 112, 061802

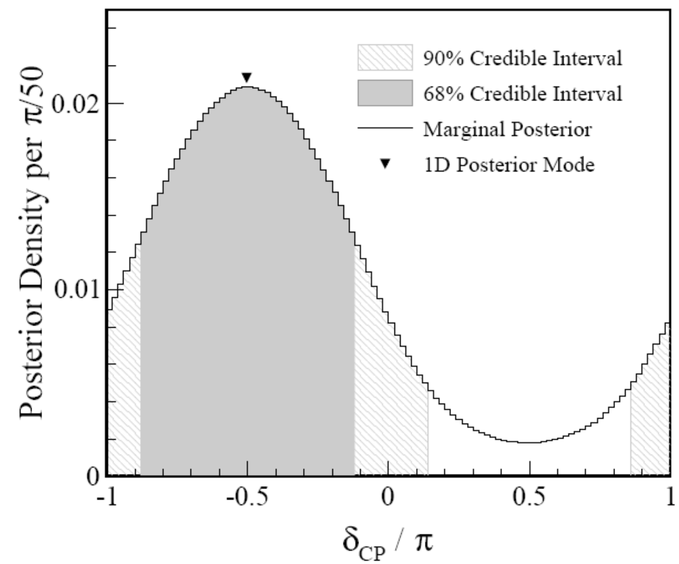


First observation of electron neutrino appearance

K. Abe et al. Physical Review D 91.7 (2015): 072010

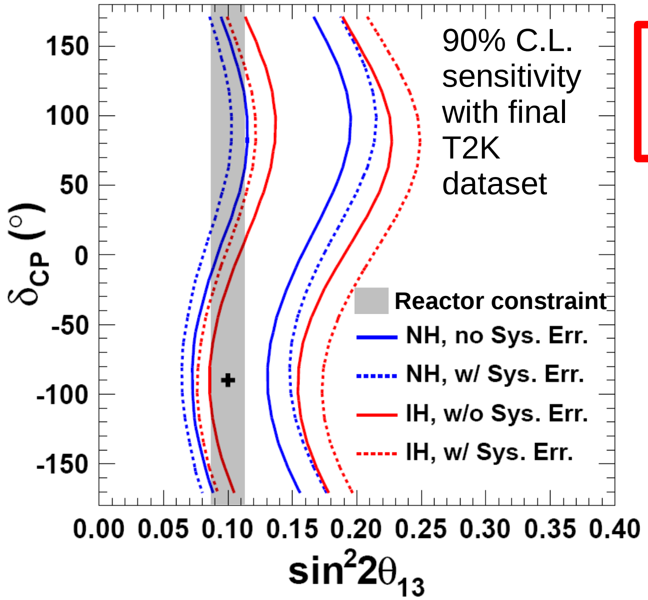


World's best measurement of θ_{23}



First T2K constraint on δ_{CP}

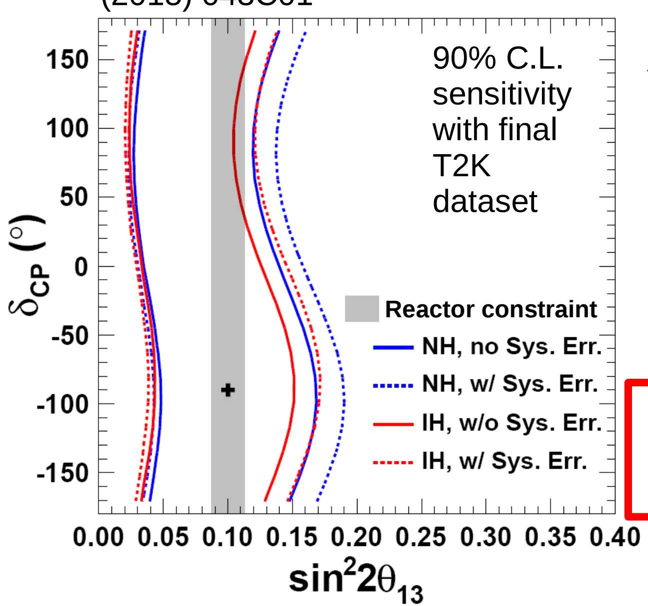
Why study anti-neutrinos?



Neutrino only

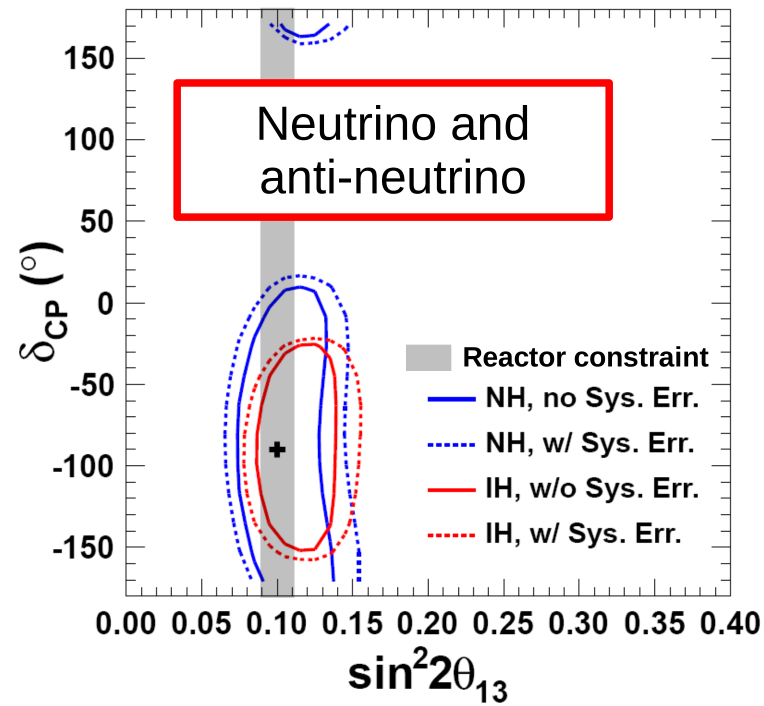
- δ_{CP} = -90°
- $\sin^2 2\theta_{13}$ = 0.1

Prog. Theor. Exp. Phys. (2015) 043C01



Anti-neutrino only

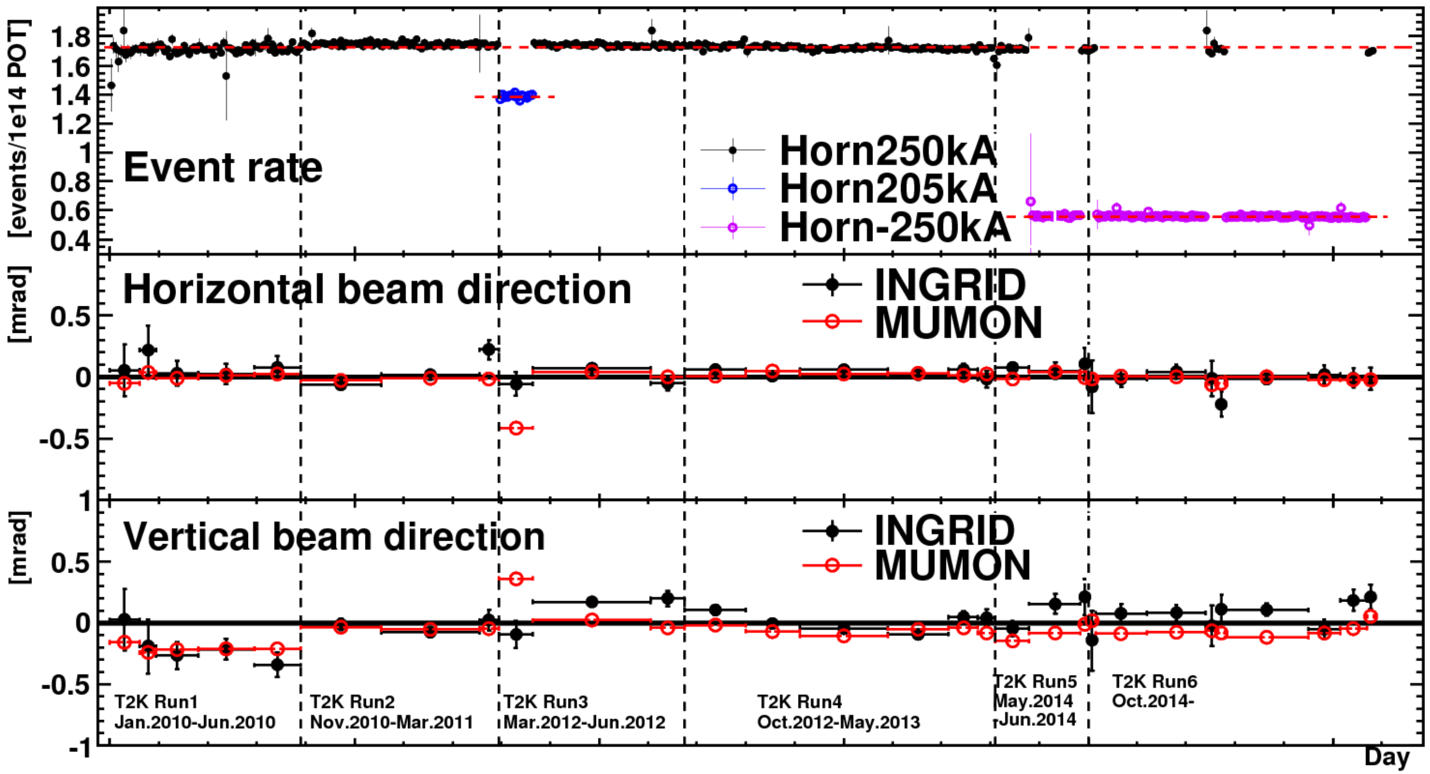
- Can constrain δ_{CP} using T2K data only
- Reactor measurement of $\sin^2 2\theta_{13}$ over-constrains PMNS framework



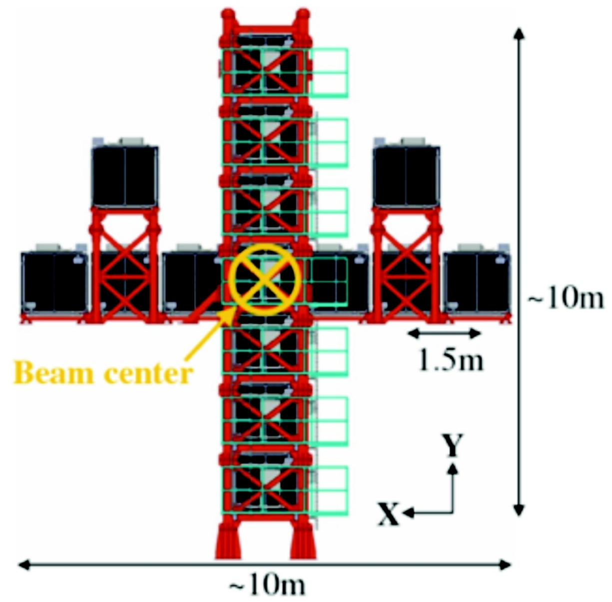
Neutrino and anti-neutrino

- Test CPT symmetry
- Search for non-standard interactions with matter

Beam stability

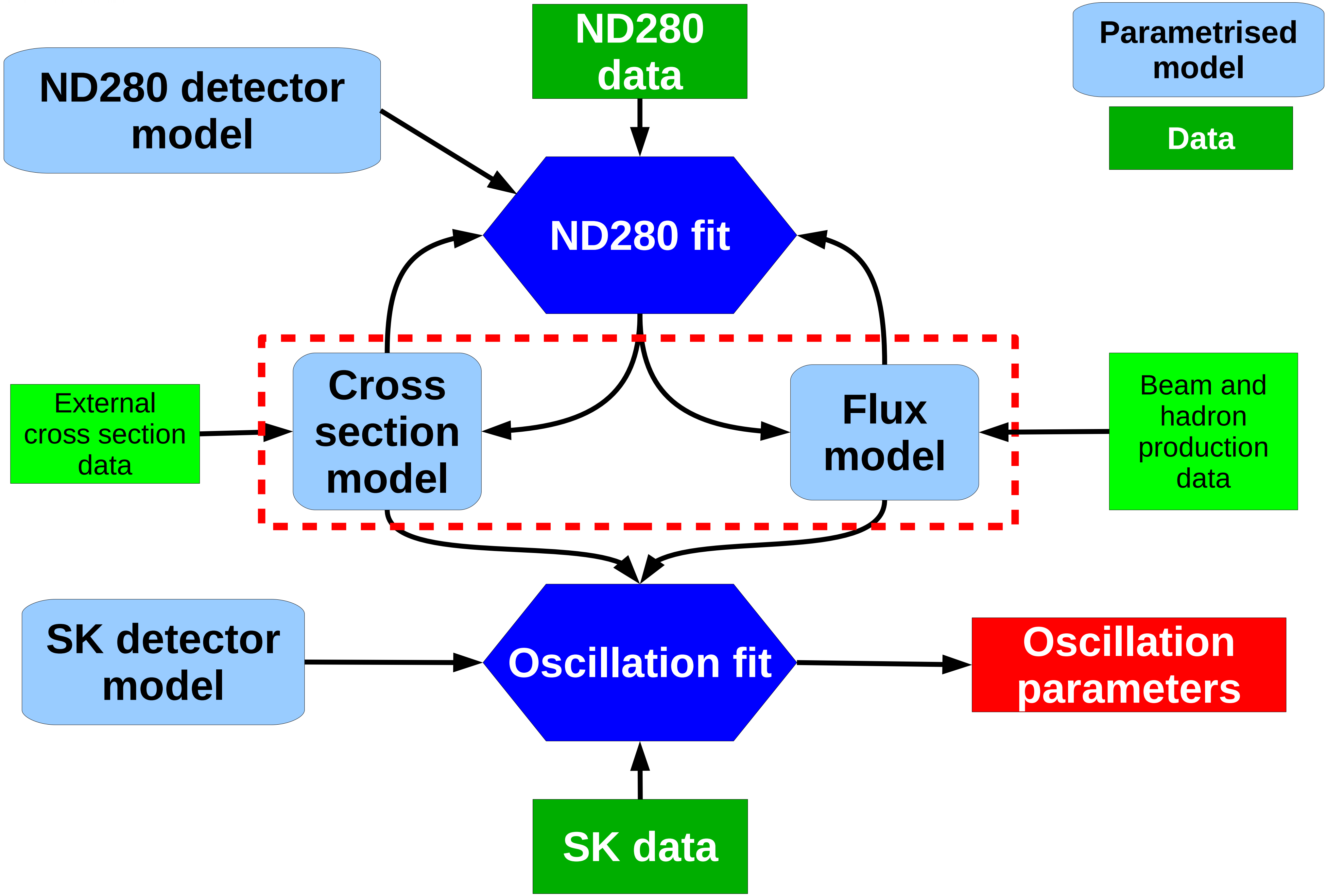


INGRID on-axis detector monitors beam stability

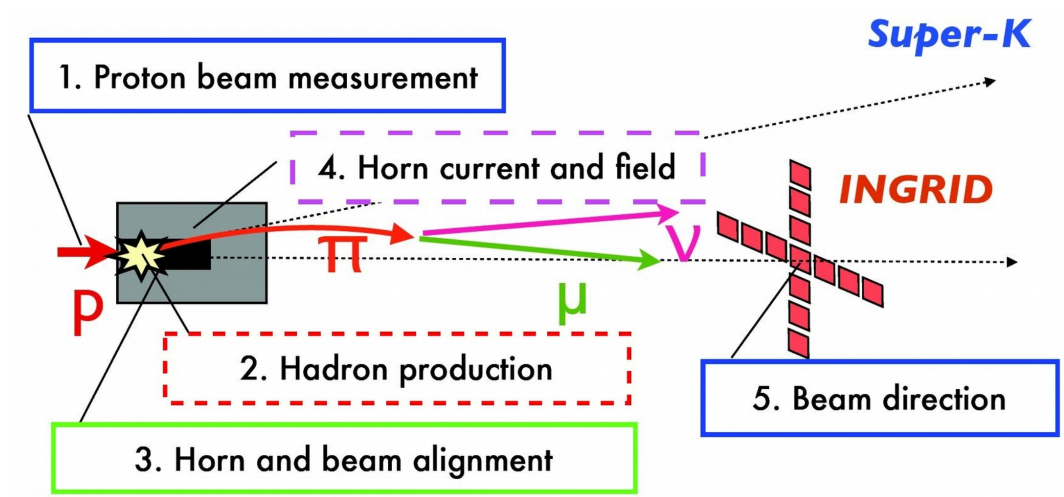


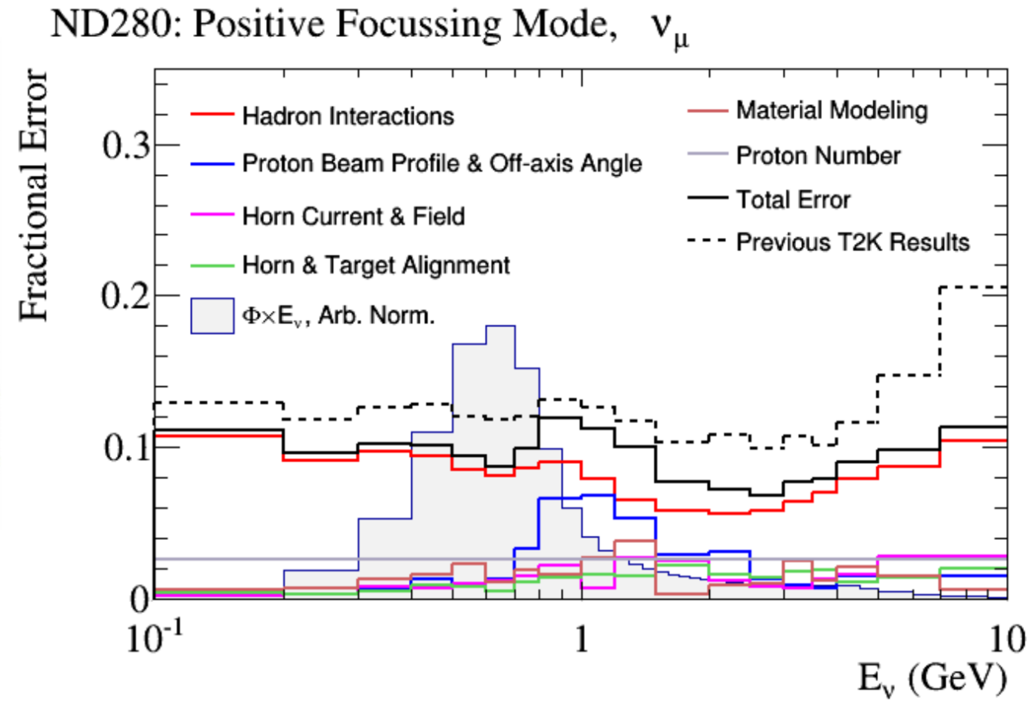
Beam rate and direction very stable across T2K running period

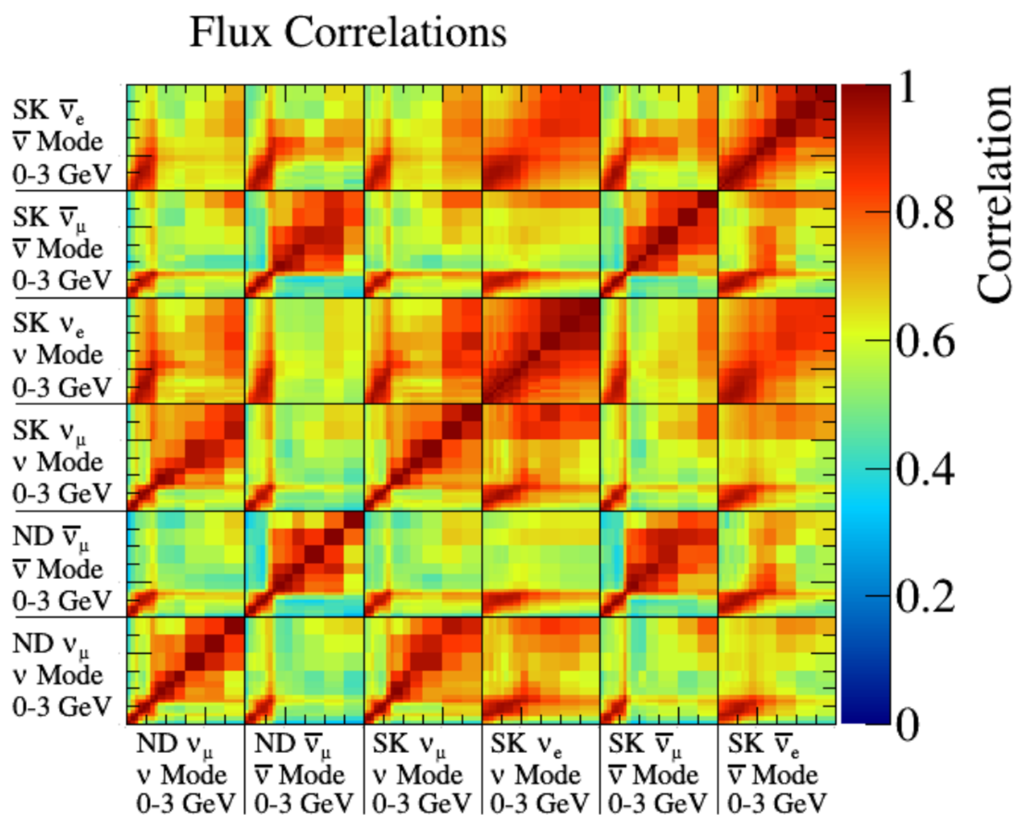
T2K oscillation analysis



T2K flux model





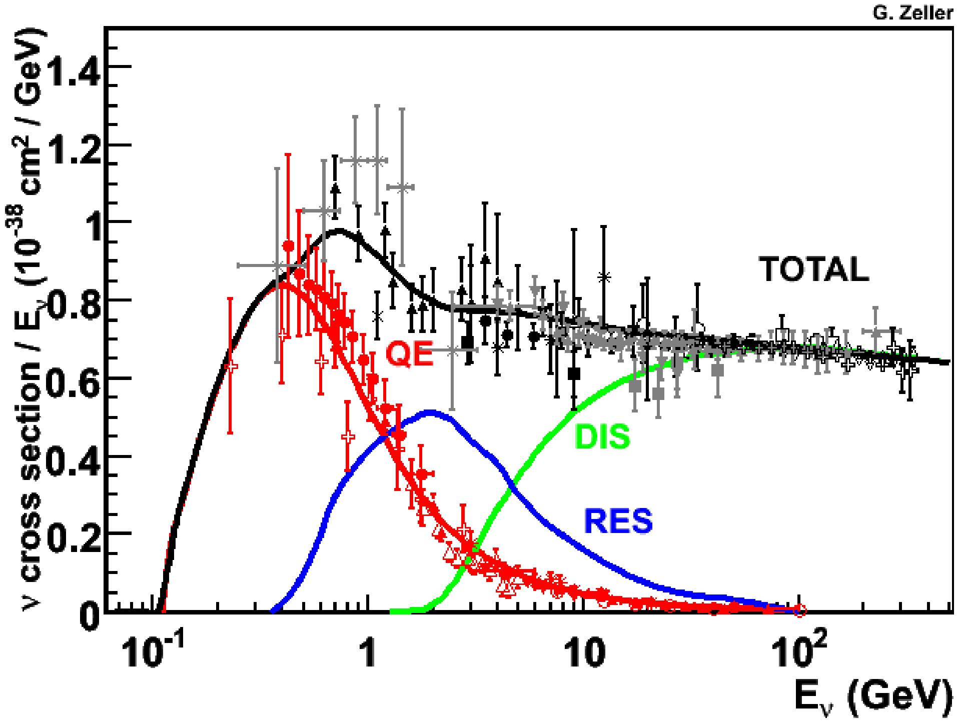


- Parametrised in neutrino energy and flavour
  - Parameter uncertainties calculated by varying underlying systematics
  - Performed simultaneously for near and far detector
  - Correlates near and far flux parameters

Neutrino cross sections

Neutrino cross sections have ~10% uncertainty:

- Effect of nucleus is large!
- Cannot calculate from first principles
- Existing data has large uncertainties



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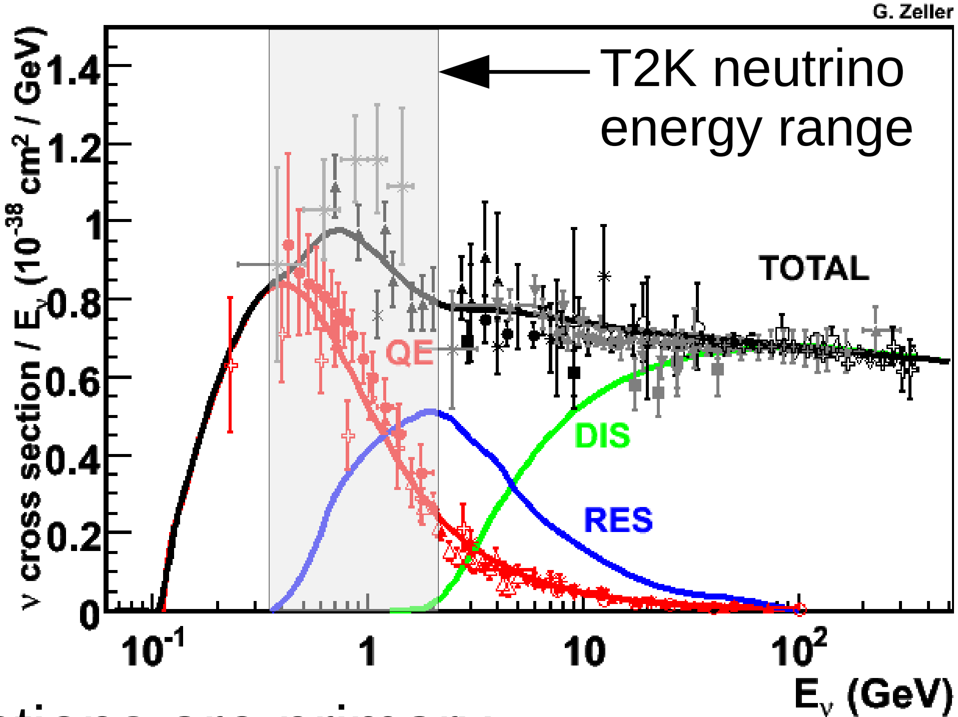
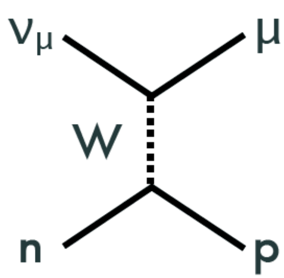


Charged current quasi-elastic interactions are primary signal

- But, other interactions mimic CCQE
  - 2p-2h, pion absorption, detector effects
- Need to understand multiple interaction modes over range of neutrino energies

Charged current quasi-elastic (CCQE)

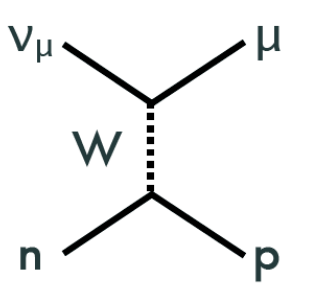


Cannot directly measure neutrino flux – known to ~10% level at T2K

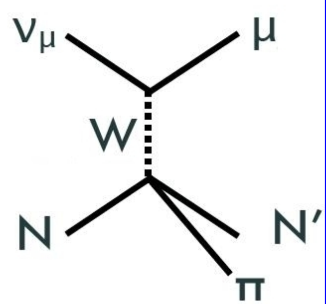
T2K cross section model

- NEUT neutrino interaction generator

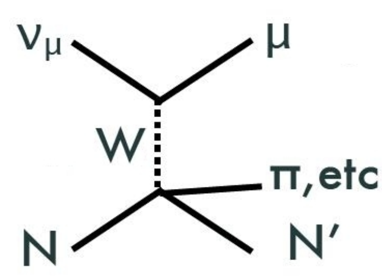
Charged current quasi-elastic

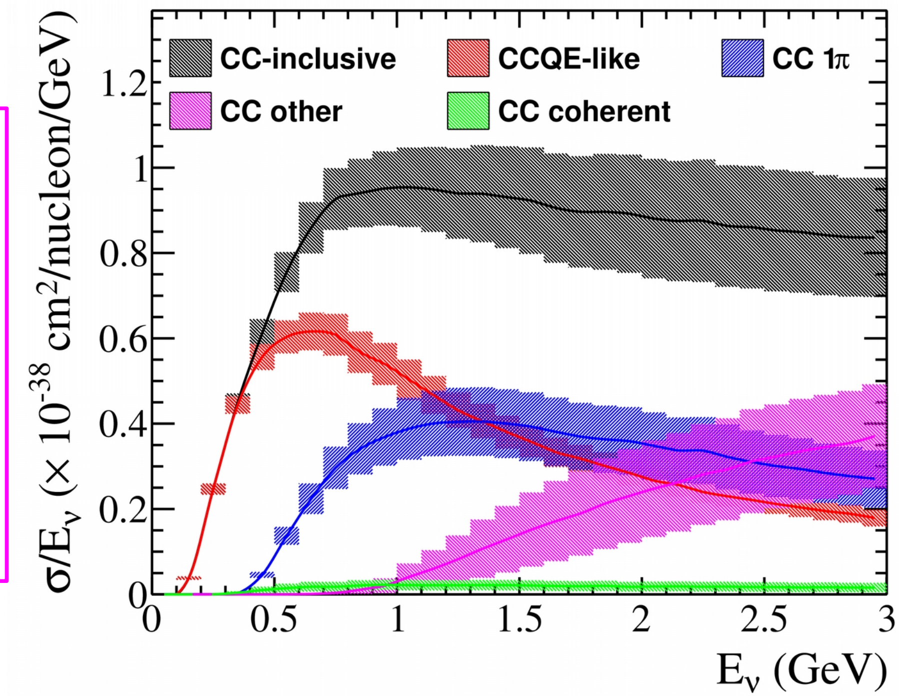


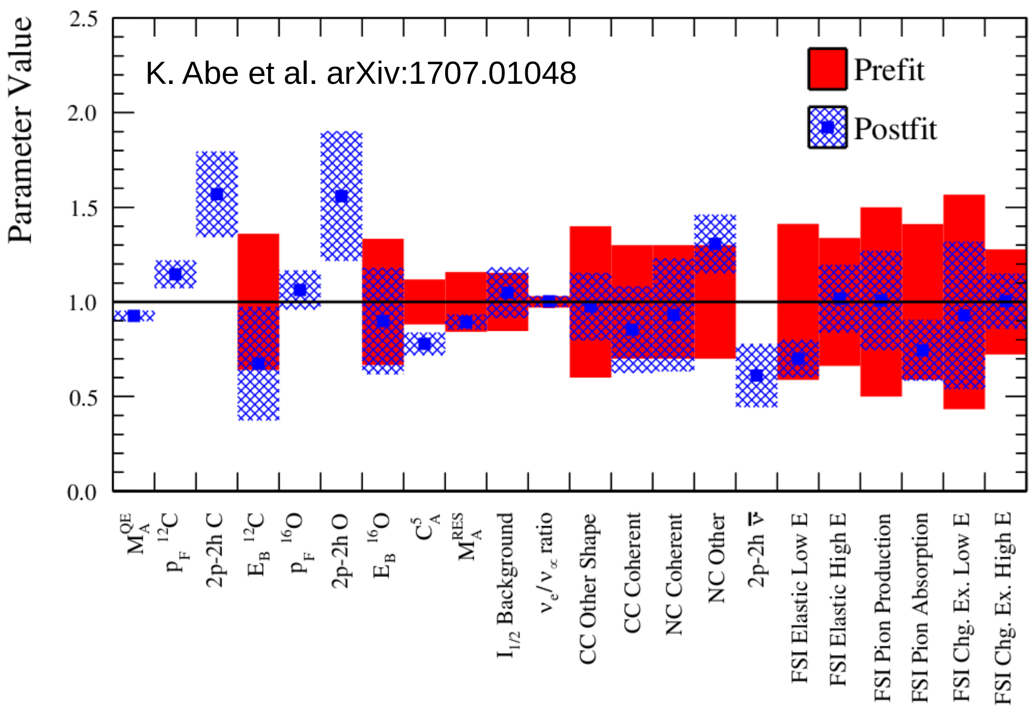
Charged current single pion



Charged current deep inelastic scattering



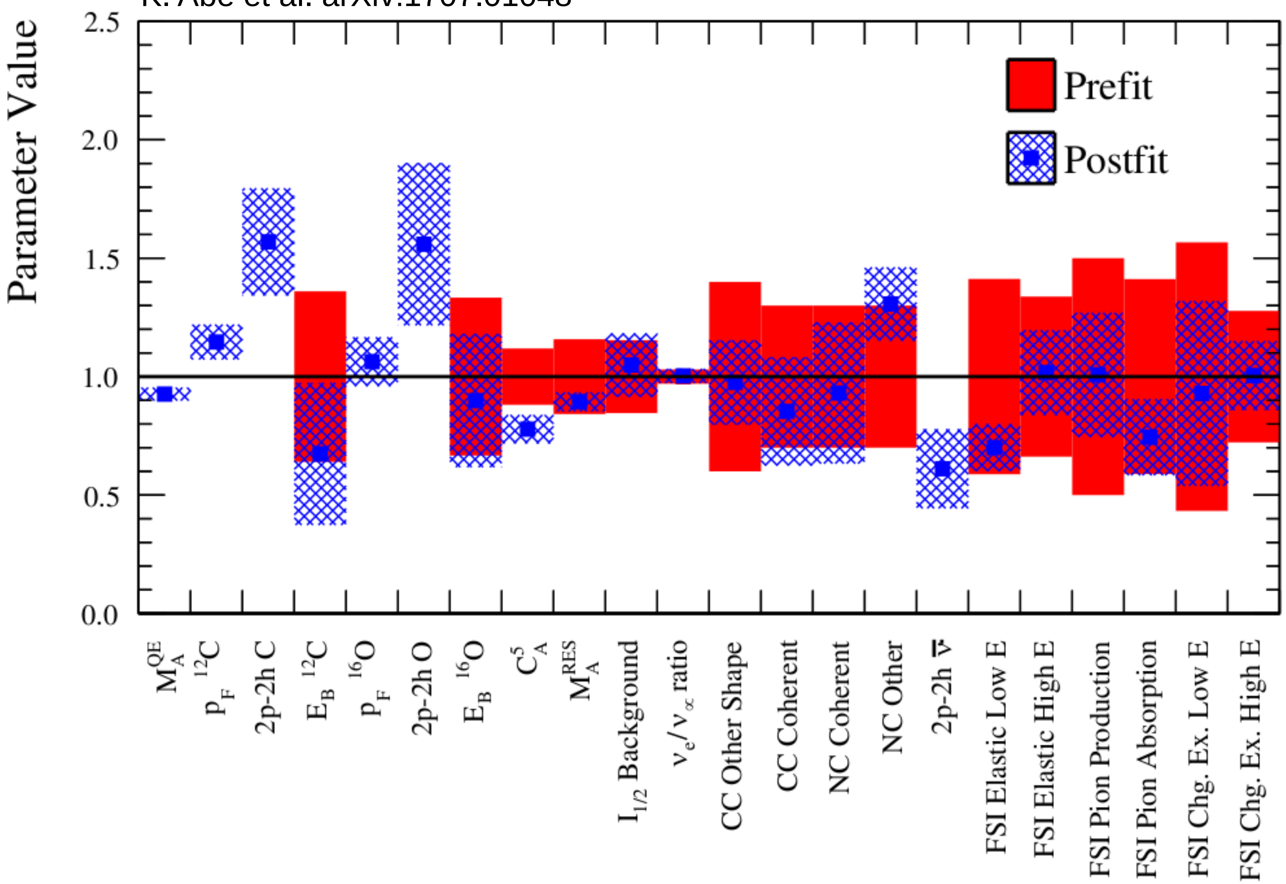




- Cross section is parametrised
  - CC Quasi-Elastic
    - Nuclear model
    - 2p2h
  - CC Single Pion
  - CC Multi-Pion / DIS
  - NC
  - Pion Final State Interactions

Model parametrisation

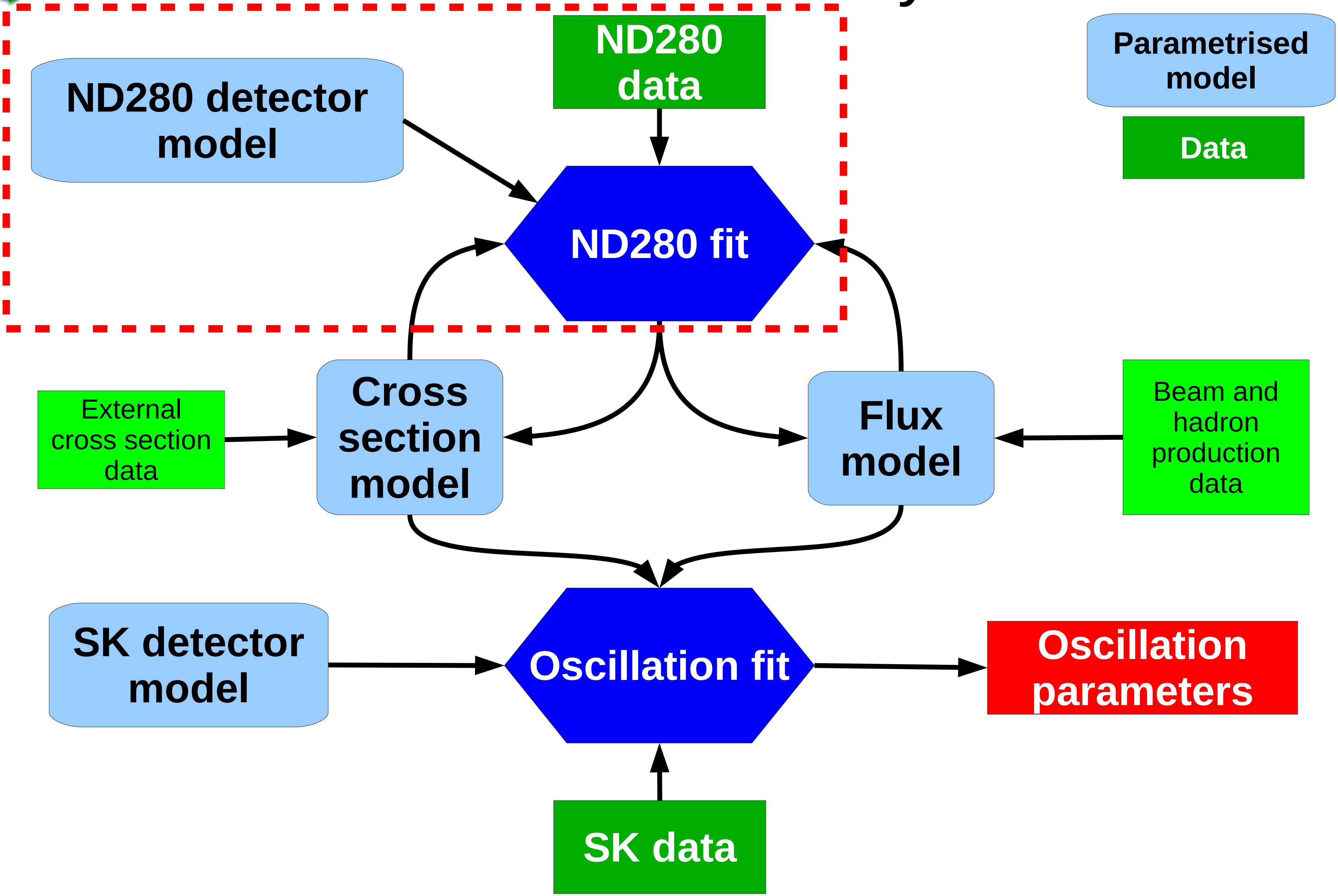
K. Abe et al. arXiv:1707.01048



- CCQE:
  - Nuclear model
    - Separate for C/O
    - Binding energy (Eb)
    - Fermi mom. (pF)
    - 2p2h normalisation, ν and $\bar{\nu}$
  - Axial mass parameter
- Single pion
  - CA5 – normalisation resonant form factor
  - Axial mass parameter
  - I=1/2 background norm.

- Multi-pion/DIS – parameter to alter normalisation as function of energy
- CC coherent pion production normalisation
- NC coherent normalisation
- NC other normalisation
- Microscopic final state interaction cross-section parameters

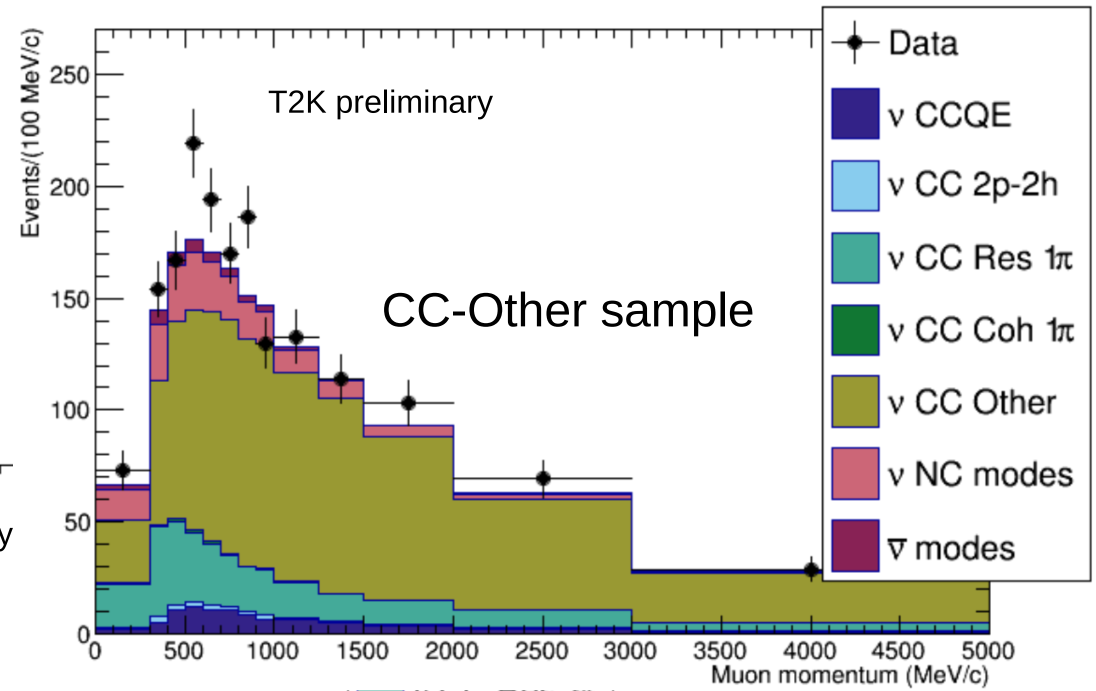
T2K oscillation analysis

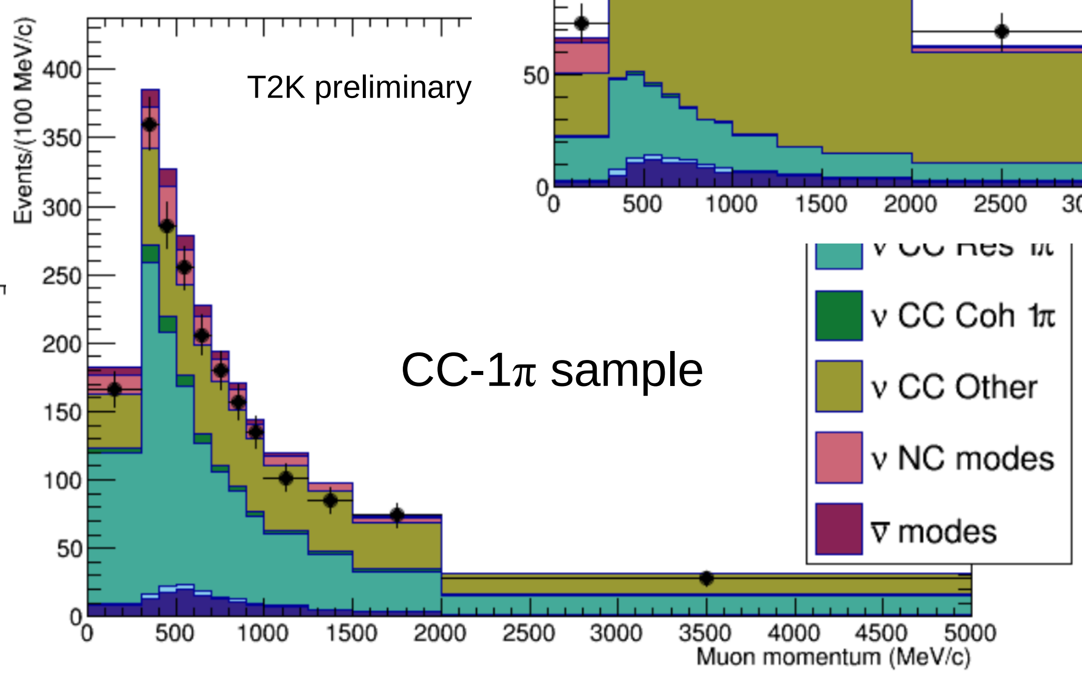


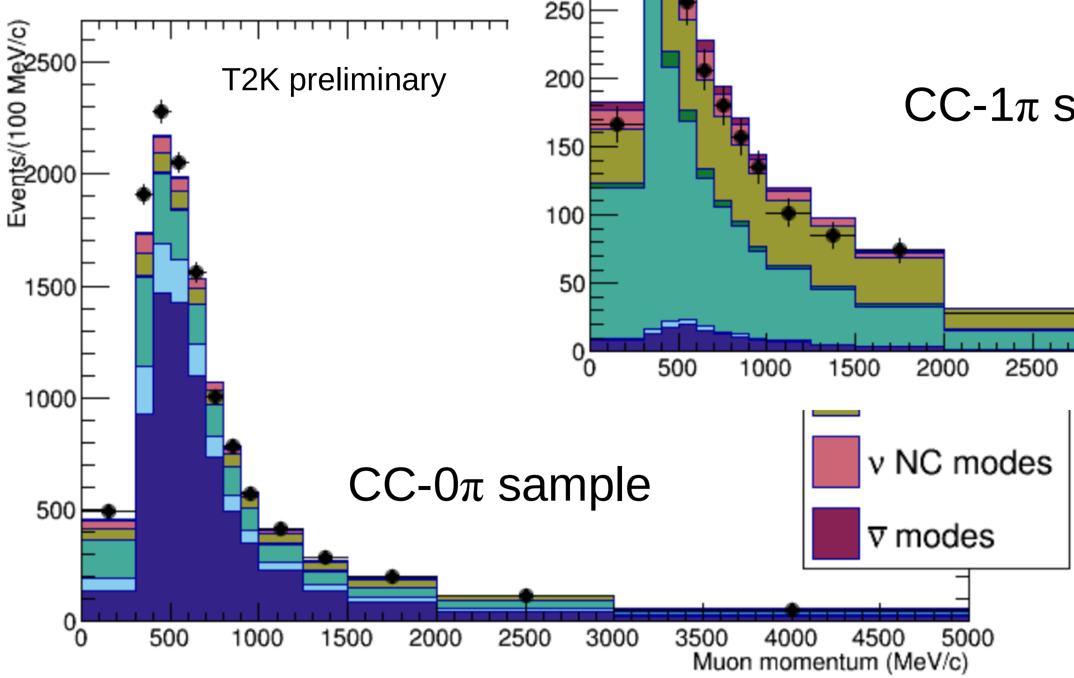
ND280 neutrino samples

Selection:

- Identify highest momentum muon-like track
- Separate by number of tagged pions
- No proton information (yet) – poorly understood model



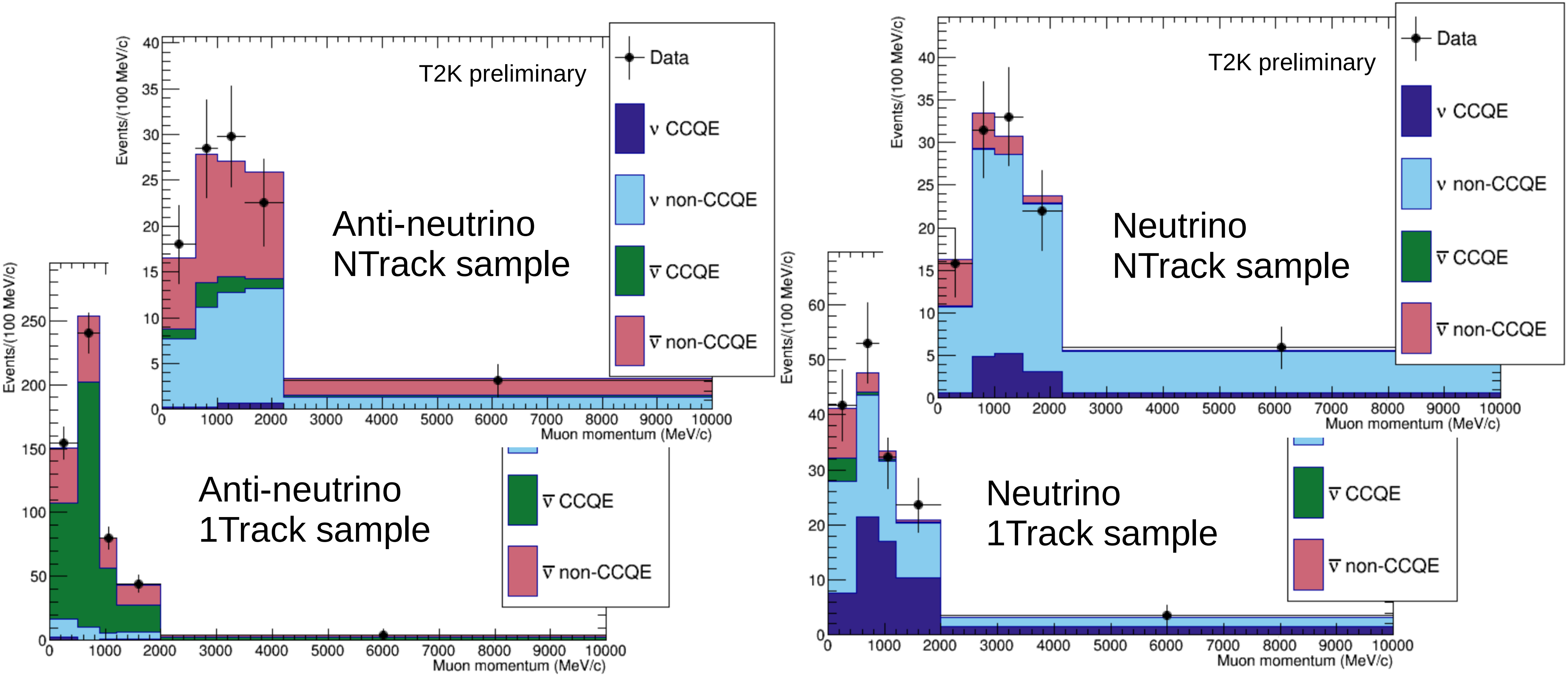




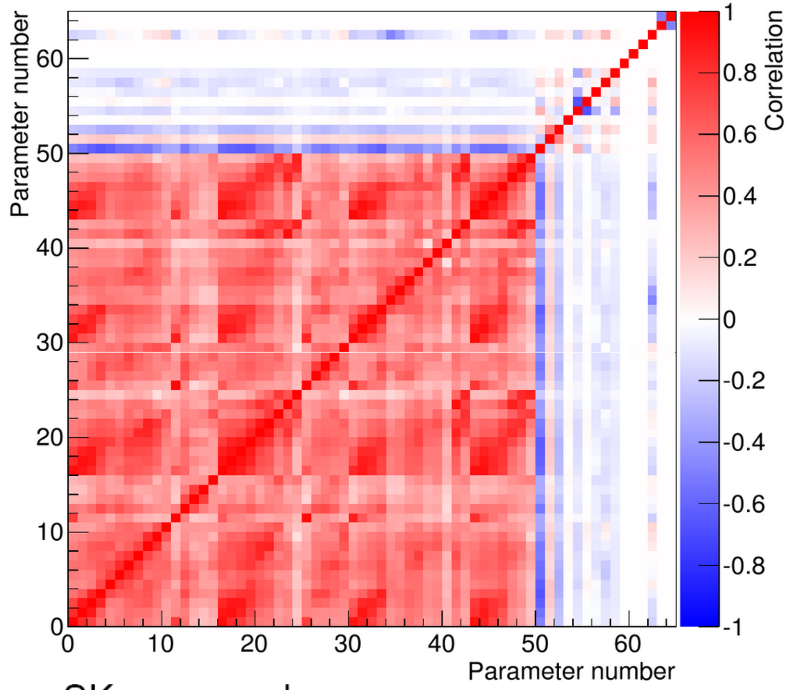
ND280 anti-neutrino samples

Selection:

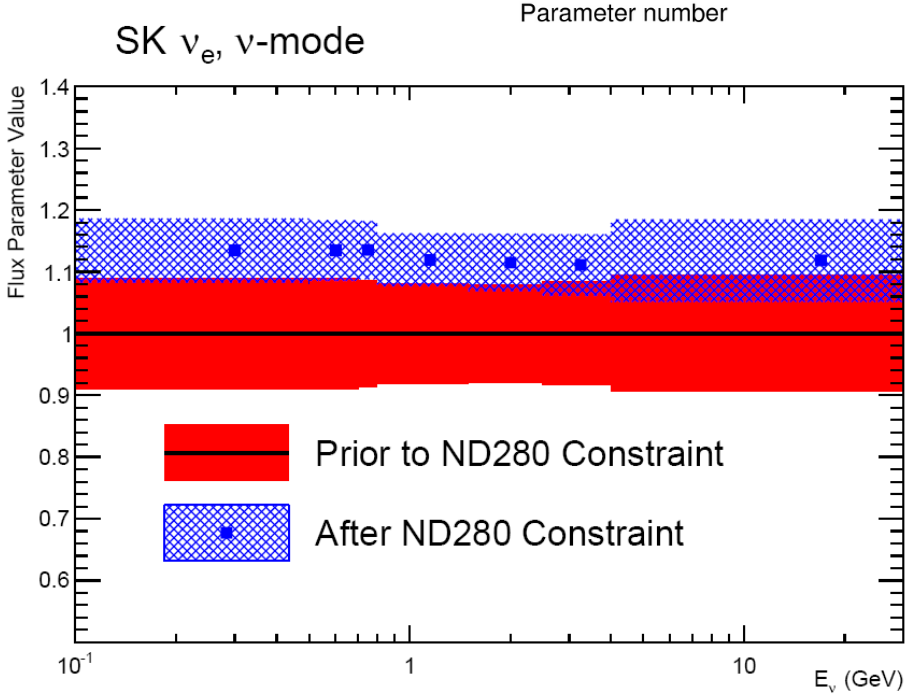
- Identify highest momentum muon-like track
  - Charge determines neutrino or anti-neutrino → select both to constrain wrong-sign background
- Separate by number of tracks



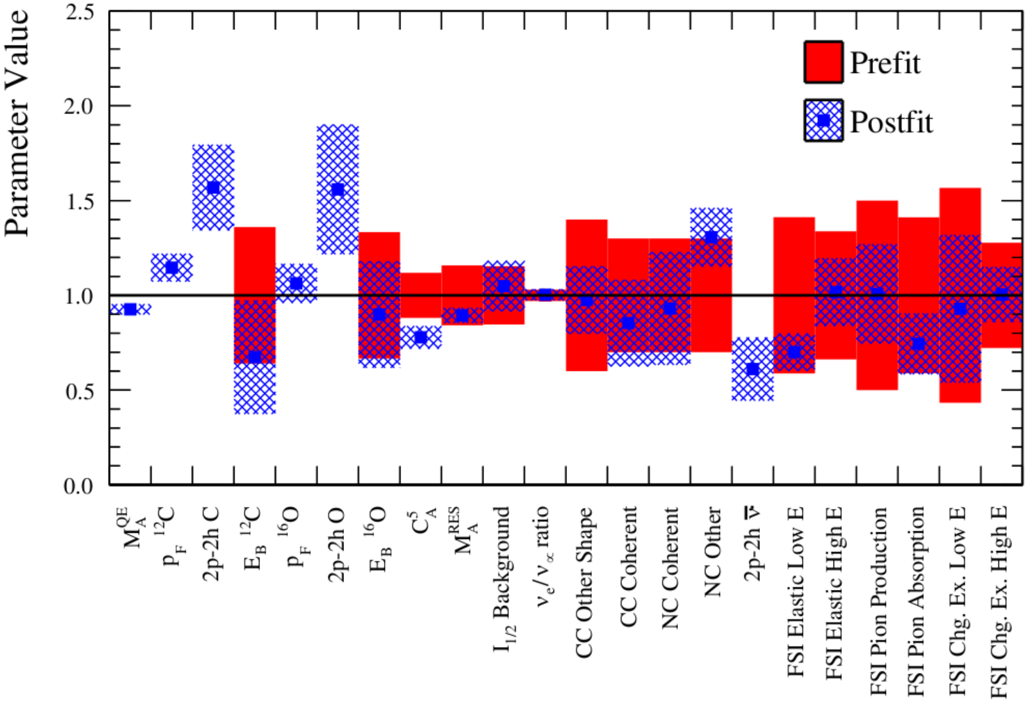
ND280 fit output



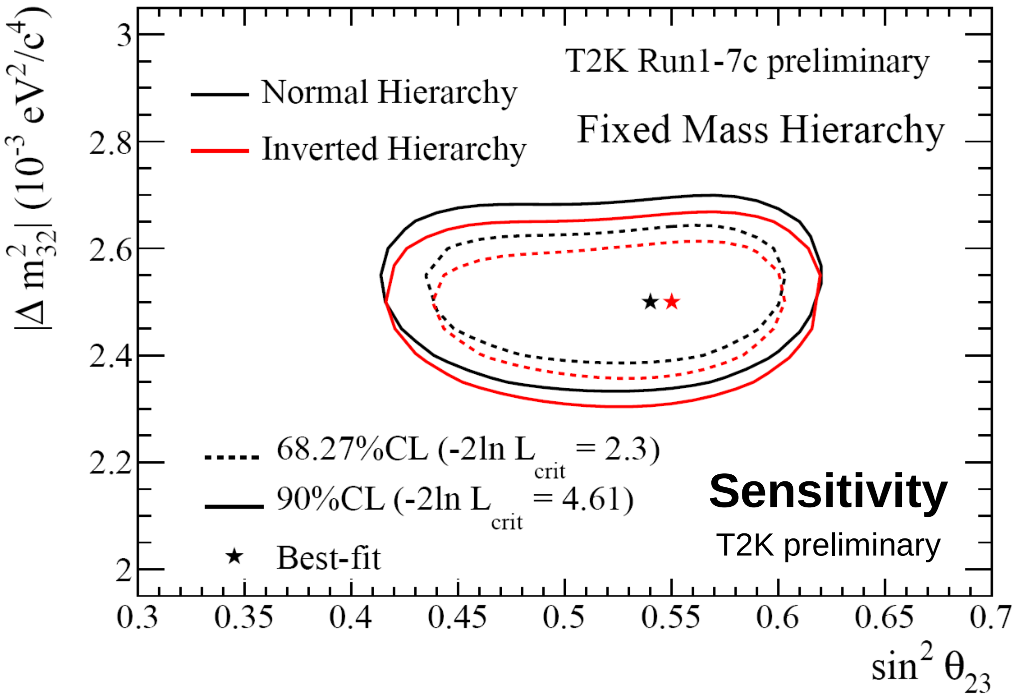
- Fit anti-correlates flux and cross-section uncertainties
  - Reduces rate uncertainty at SK
- Fitted parameters applied directly to MC to make SK prediction
  - MC model does propagation
  - Uncertainties taken from fit

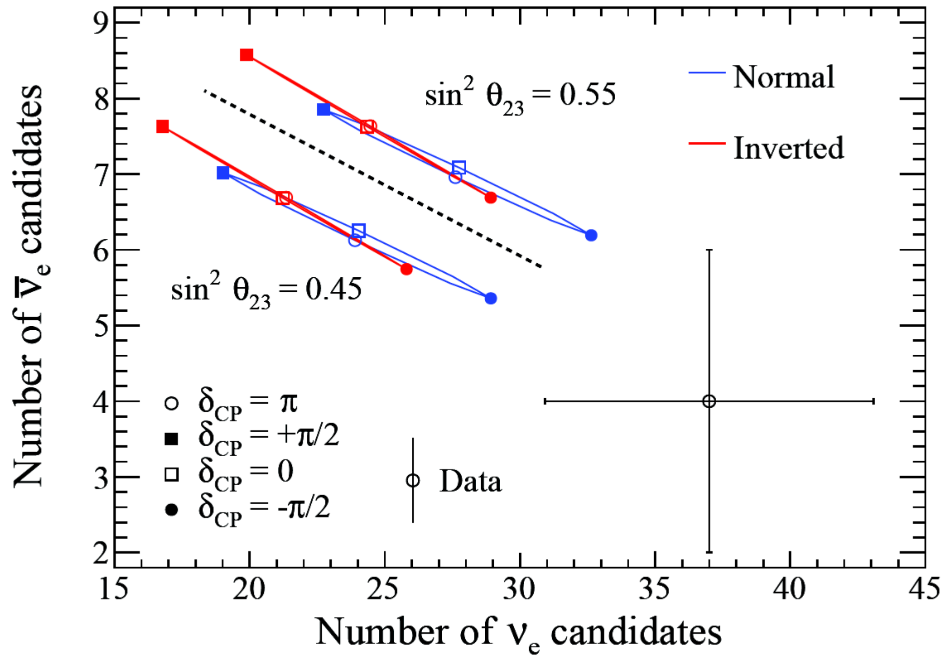


K. Abe et al. arXiv:1707.01048



Sensitivity and expectations





- Expected disappearance sensitivity on left
  - Observed contours similar
- Appearance candidate events on right
  - Expectation given by coloured ovals
  - Observe more CP violation than prediction
  - Calculated as less than a 2σ fluctuation of expectation

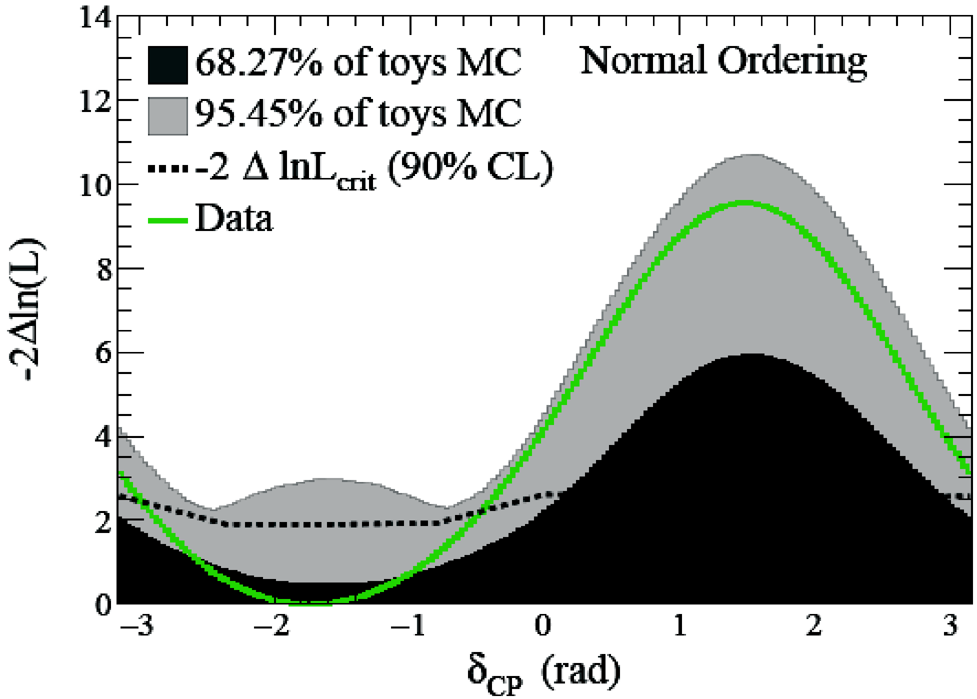
Data fluctuation

K. Abe et al. arXiv:1707.01048

TABLE XXVI. The fraction of toy experiments for which $\delta_{CP} = 0, \pi$ and normal and inverted ordering are excluded at 90% and 2σ confidence is shown for different true values of δ_{CP} and mass ordering. 10,000 toy experiments are used for each set of values.

δ_{CP}	Ordering	90% CL	2σ CL
True: $\delta_{CP} = -\pi/2$ — normal ordering			
0	Normal	0.243	0.131
π	Normal	0.216	0.105
0	Inverted	0.542	0.425
π	Inverted	0.559	0.436
True: $\delta_{CP} = 0$ — normal ordering			
0	Normal	0.104	0.0490
π	Normal	0.130	0.0591
0	Inverted	0.229	0.137
π	Inverted	0.205	0.122
True: $\delta_{CP} = -\pi/2$ — inverted ordering			
0	Normal	0.124	0.0515
π	Normal	0.102	0.0413
0	Inverted	0.290	0.194
π	Inverted	0.308	0.207

- Fraction of toy fits that exclude given set of parameters at a given confidence level
- >20% for T2K best-fit parameters



- 10,000 toy throws fit
- Grey-scale area shows regions containing 68% and 95% of the toy likelihood contours
- Data in green falls within the 95% region for all values of δ_{CP} and mass hierarchy

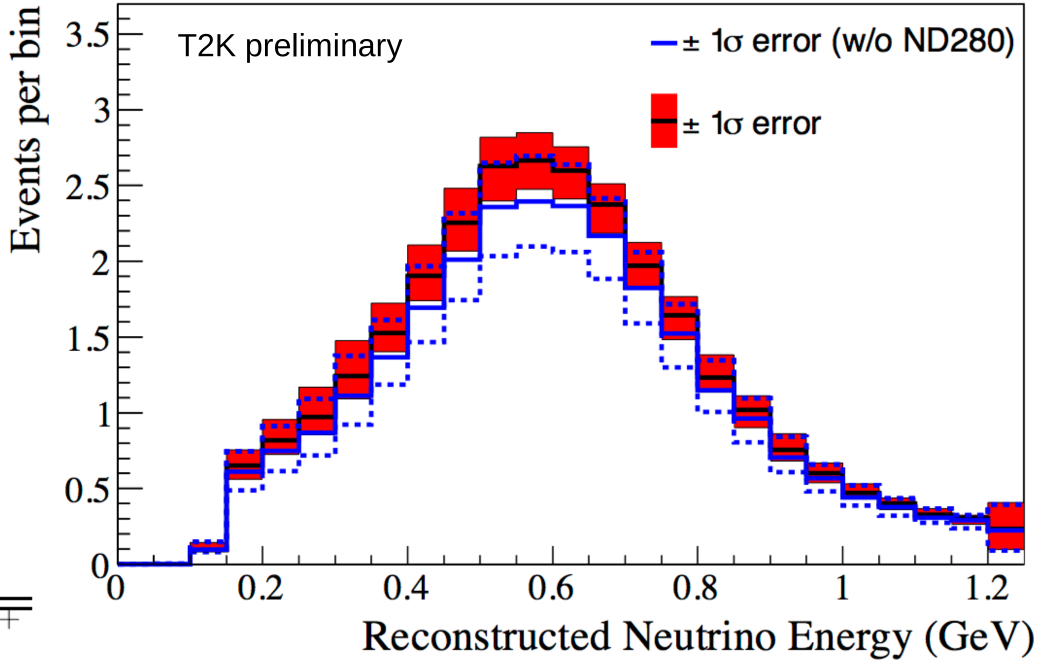
Systematic uncertainty

Electron-like, neutrino beam, single ring sample on right

ND280 fit reduces flux and cross-section systematics from ~11% to ~4%

K. Abe et al. arXiv:1707.01048

Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$	ν_e CC1π^+ $\delta N/N$
Flux (w/ ND280 constraint)	3.7%	3.6%	3.6%
Cross section (w/ ND280 constraint)	5.1%	4.0%	4.9%
Flux+cross-section			
(w/o ND280 constraint)	11.3%	10.8%	16.4%
(w/ ND280 constraint)	4.2%	2.9%	5.0%
FSI+SI+PN at SK	2.5%	1.5%	10.5%
SK detector	2.4%	3.9%	9.3%
All			
(w/o ND280 constraint)	12.7%	12.0%	21.9%
(w/ ND280 constraint)	5.5%	5.1%	14.8%



Major systematics:

- Final state and secondary interactions (FSI + SI)
- SK detector uncertainties
- Cross-section
  - 2p-2h model
  - ν_e / ν_μ ratio

Fake data studies

- Neutrino cross-sections need to be well understood to measure oscillation parameters
  - Many models exist that can fit current cross-section data
  - Tension between these data sets – unknown unknowns

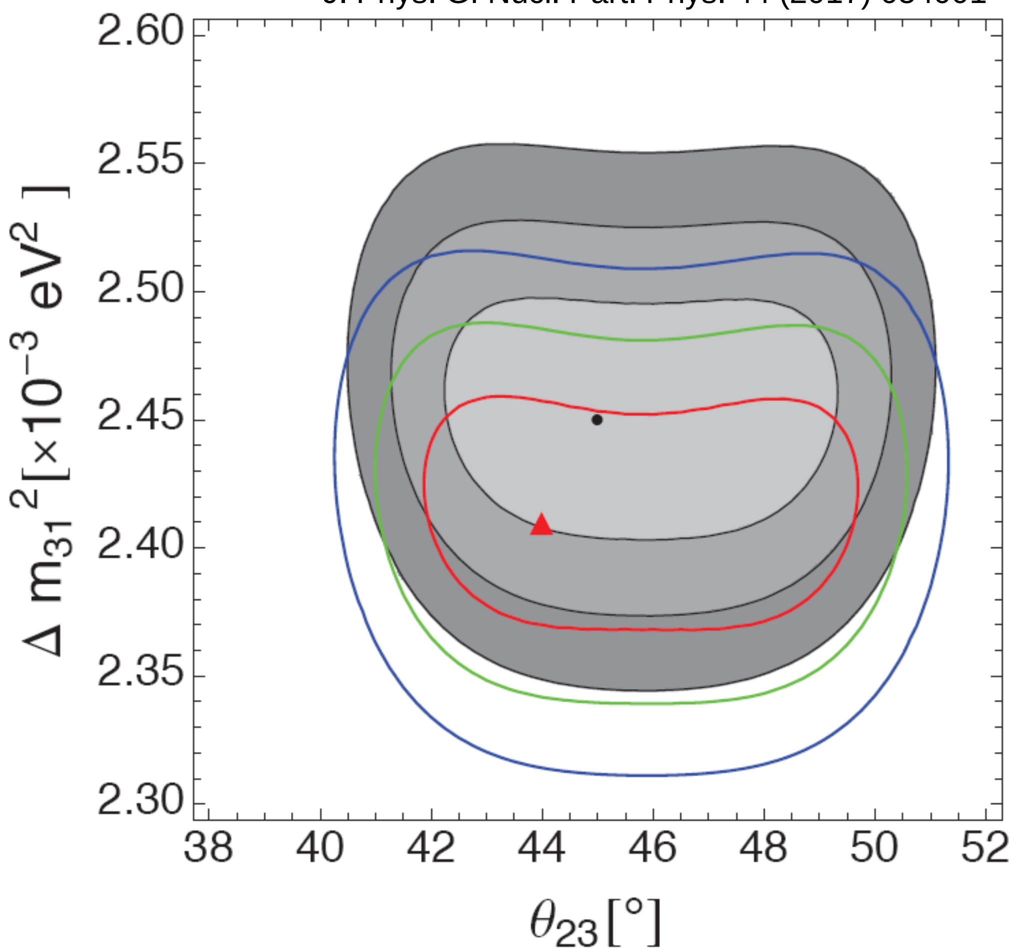
- Near detector data used to constrain the predicted MC rate at the far detector
  - Constraint on parameters (T2K), energy spectrum (NOvA)
  - Near and far detectors can have different acceptances
  - Definitely see different neutrino flux (oscillation + decay pipe)
    - MC tuned to different phase space than far detector samples
  - This can lead to biased oscillation measurements

- At T2K we study these biases using fake data
  - Allows study of effect of model variations that are hard to parametrise

Phenomenology studies

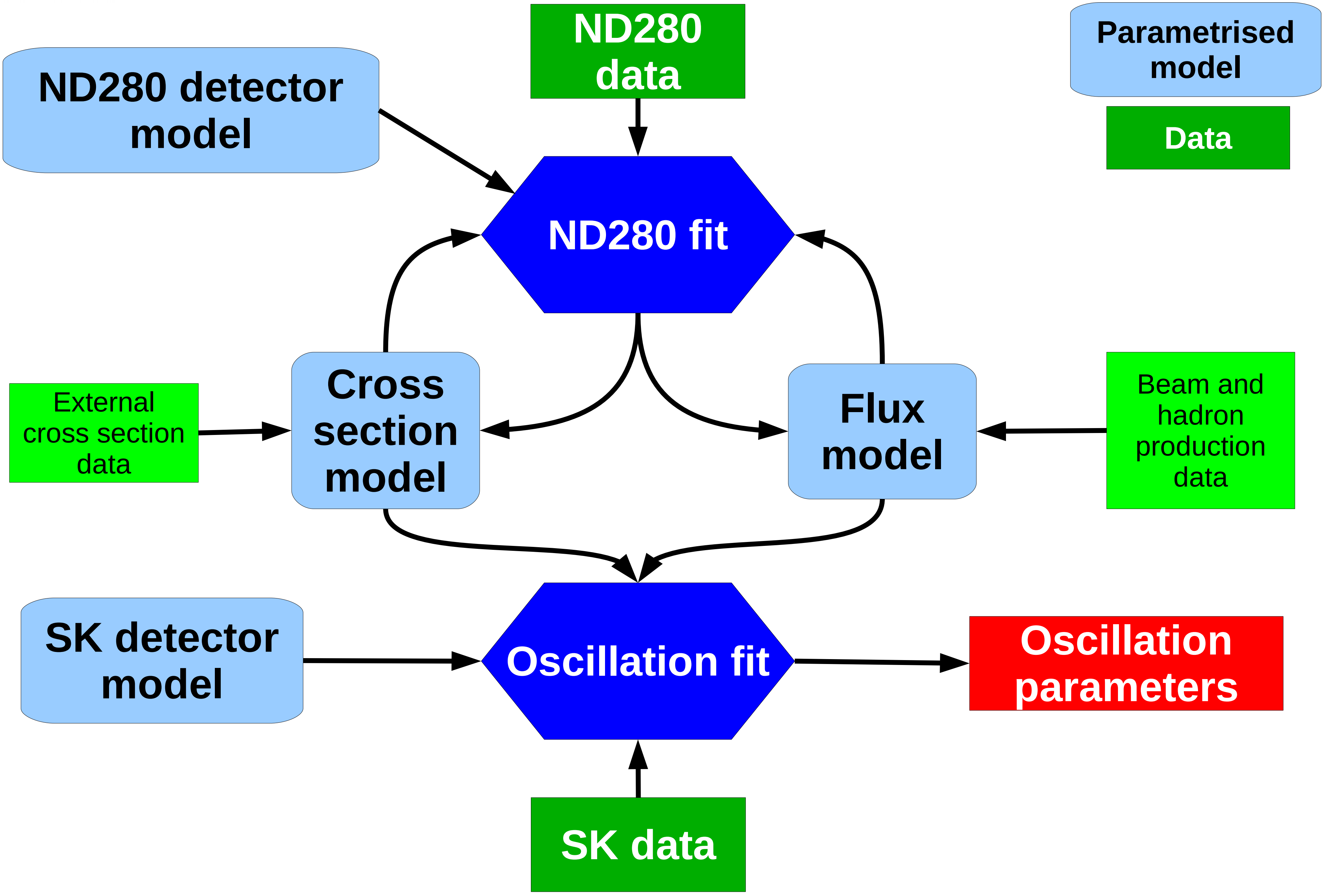
- Fake data studies used in phenomenology community – Virginia Tech studies below:
- GLoBES based oscillation analysis
  - Uses matrices to extrapolate from near to far detector
  - Matrices encode effect of model choice on measurement
- Plot shows effect of using correct (shaded) or incorrect (coloured) nuclear model to generate matrices
- Shifts best fit oscillation point by ~1σ

J. Phys. G: Nucl. Part. Phys. 44 (2017) 054001

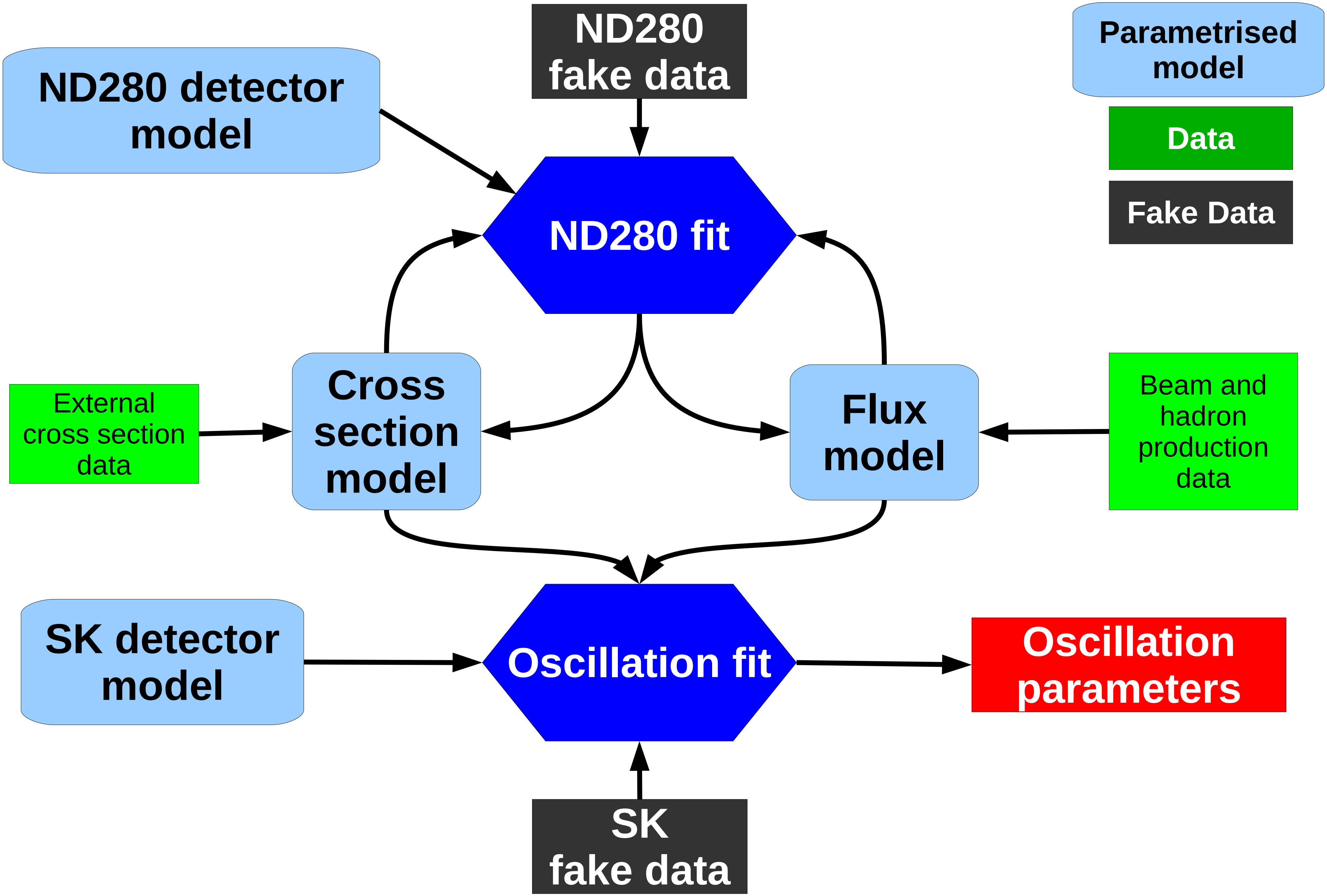


- Analysis criticised for being too simplistic – don't fit all samples at far detector, over-simple detector, flux and cross-section models
- T2K has performed similar studies using full analysis machinery

T2K oscillation analysis



T2K oscillation analysis



Procedure at T2K

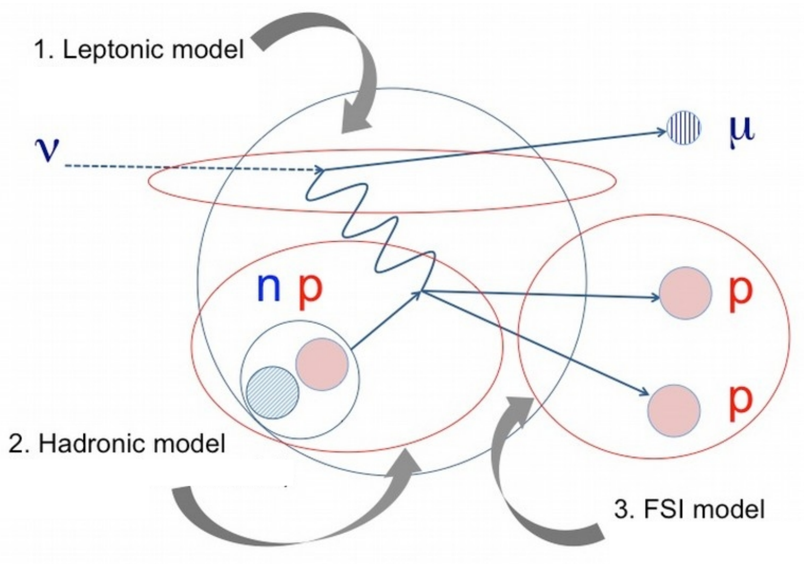
- Generate fake data at SK and ND280
  - Apply event selections to nominal MC to create event samples
  - Weight events in sample by ratio of old cross-section model to the new model, as a function of some set of variables
    - Assumes selection efficiency does not change when cross-section model changes
    - Must ensure it's possible to reweight nominal MC to new model
- Fit fake data at ND280 with nominal MC and nominal cross-section parametrisation
- Extrapolate to SK to make new far detector prediction with new parameter central values and constraints
- Perform oscillation fit to SK fake data using extrapolated prediction
- Compare results to nominal oscillation fit

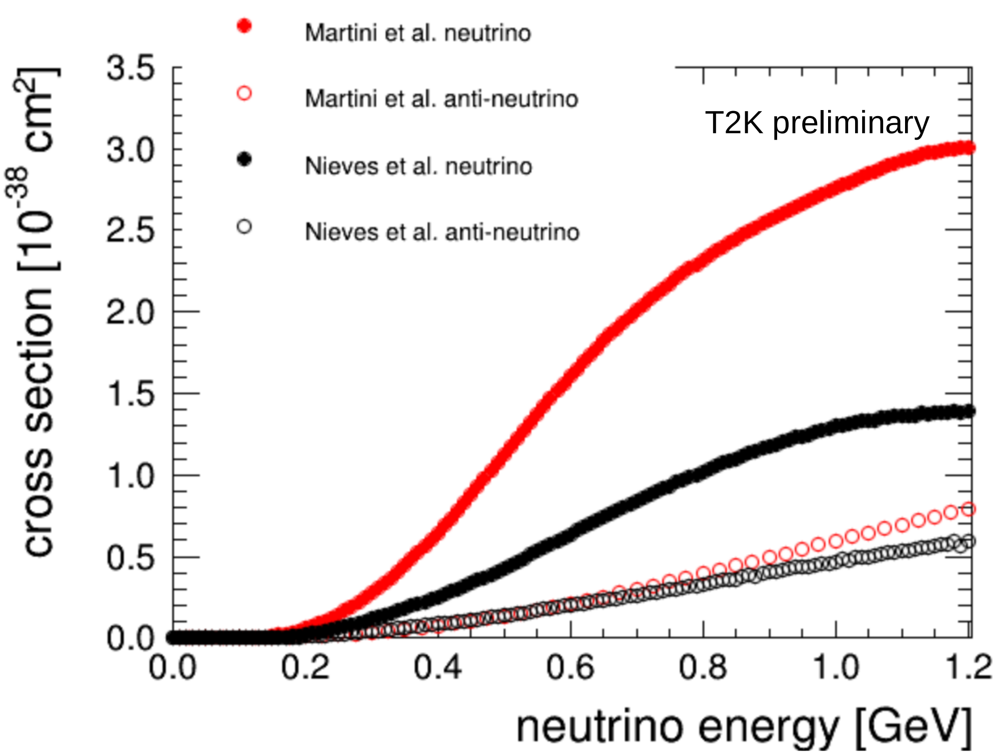
T2K fake data studies

- Fake data studies at T2K performed as part of 2016 oscillation analysis
- Ran fits to five fake data sets
  - Spectral function (SF) vs relativistic Fermi gas (RFG) nuclear model
  - 2p2h shape study datasets:
    - PDD-like (like pion-less delta decay process)
    - Non-PDD-like (everything else)
  - Differences between Nieves and NEUT CCQE (1p1h) models
    - Different definitions of binding energy, local Fermi gas versus global Fermi gas
  - **Martini vs Nieves 2p2h**

2p2h interactions

- Neutrinos scatter of correlated pair of nucleons within nucleus - 2p2h
  - CCQE-like
  - Hard to measure or constrain experimentally
  - Make up 10-20% of the T2K CCQE-like event sample

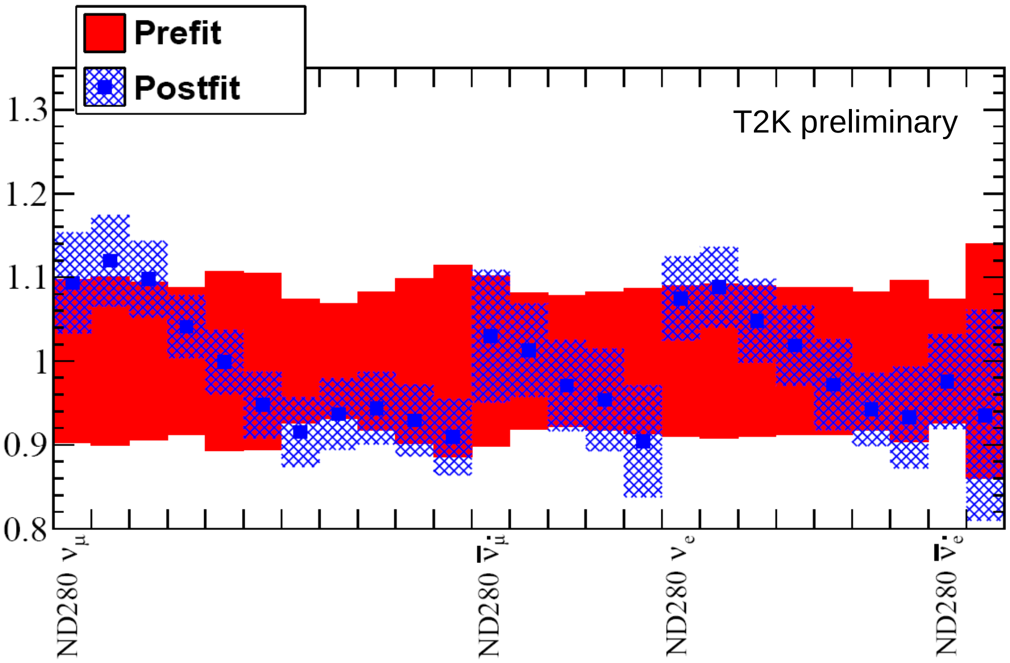


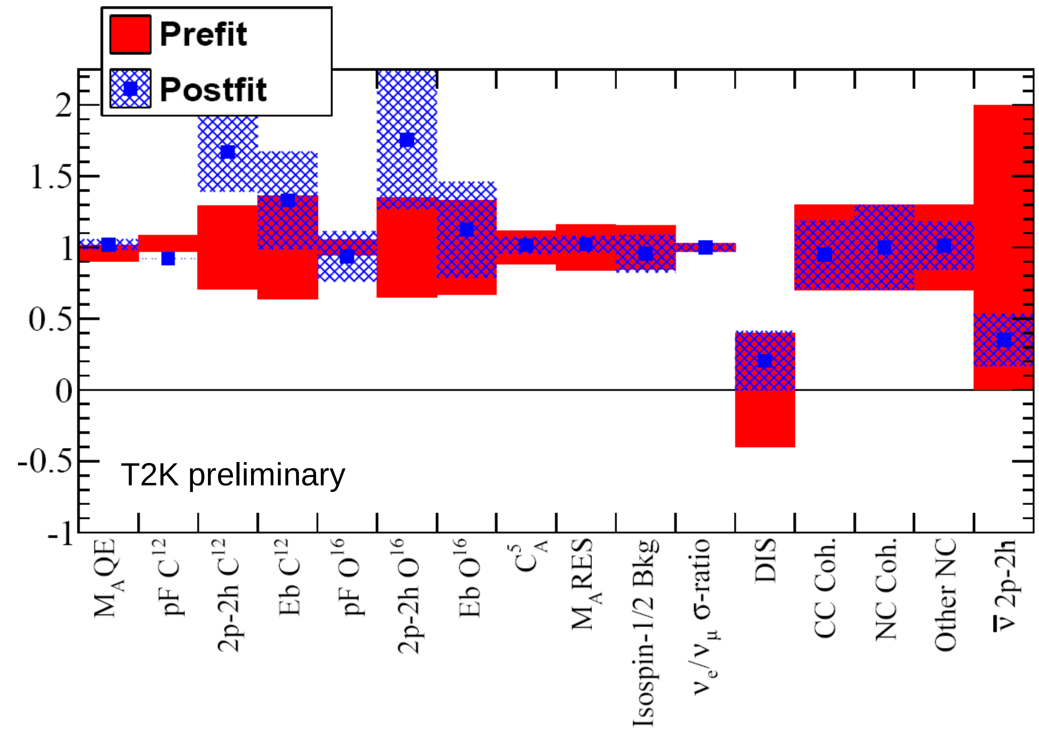


- Study Nieves and Martini models
- Nieves' model included in NEUT
- To study Martini model, weight 2p2h events by Martini-Nieves cross-section ratio as function of neutrino energy and lepton angle (left)

Martini ND280 fit

- Fit results shown below:

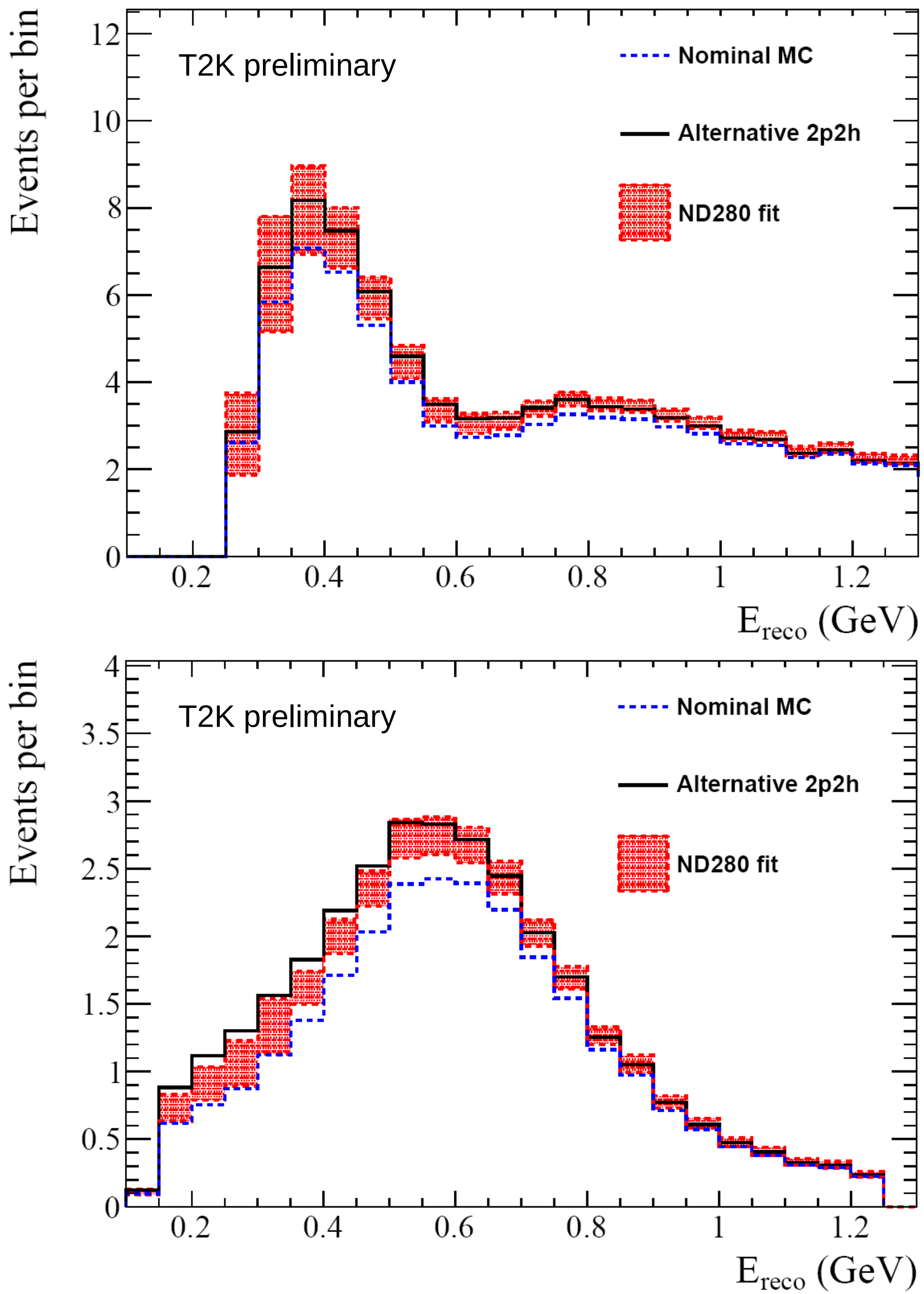




- See change in flux and cross-section parameters
  - Martini 2p2h cross-section ~2 times the nominal NEUT value – 2p2h normalisation parameters increase
  - Martini fake data created by weighting as a function of neutrino energy – see effect in flux
  - Anti-neutrino 2p2h cross-section reduced compared to Nieves prediction – CP violating effect

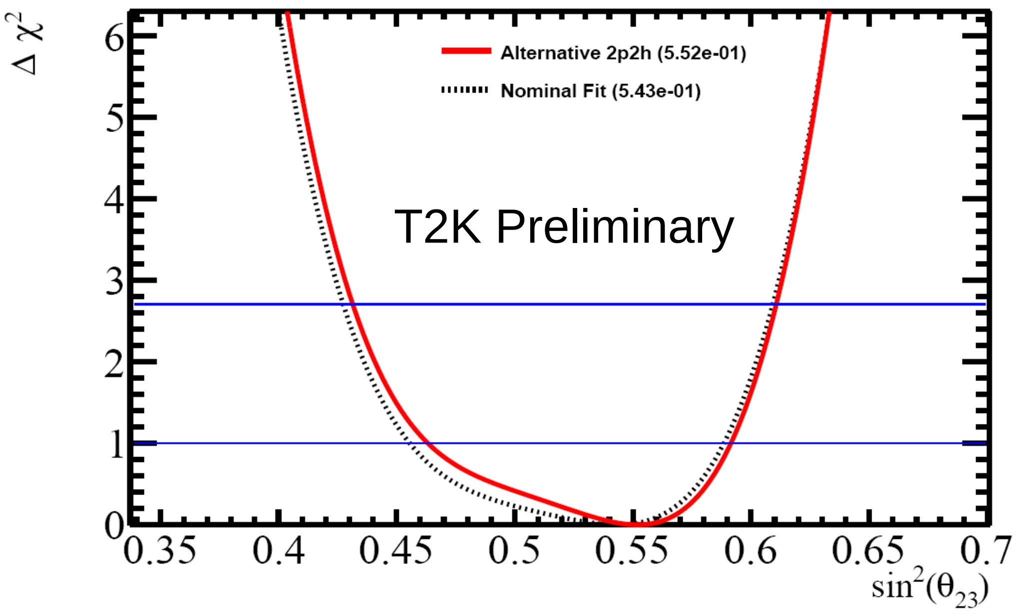
SK spectra

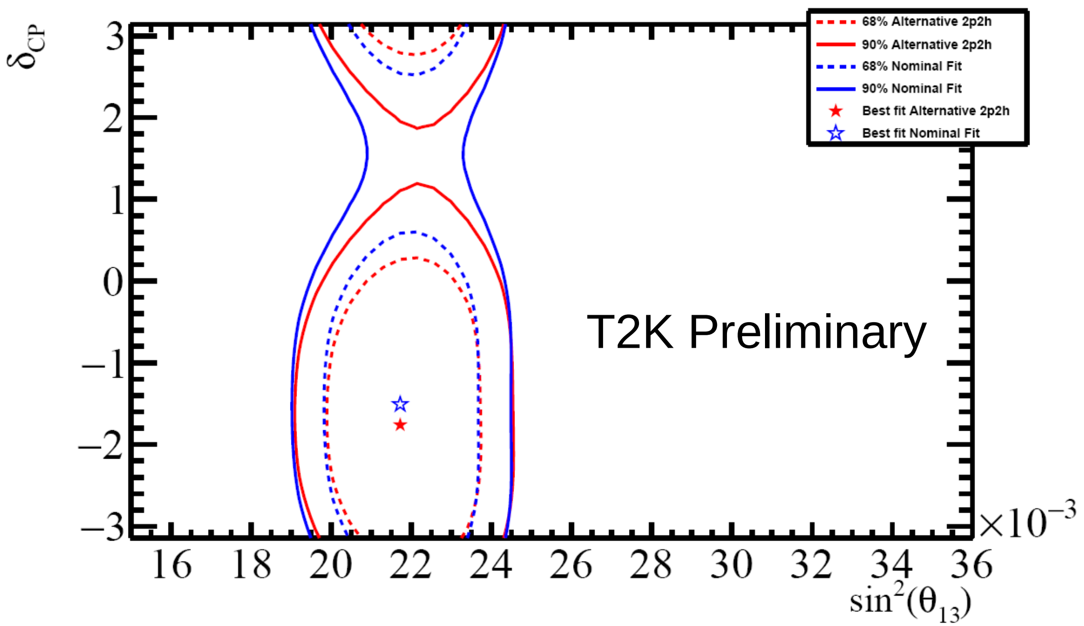
- Plot shows SK muon (top) and electron (bottom) samples for Martini 2p2h fake data
  - Blue = nominal MC
  - Black = fake data
  - Red = extrapolated prediction from ND280 fit
- ND280 prediction matches SK fake data within 1 sigma for muon sample
  - Prediction still not perfect
- ND280 prediction under-shoots fake data in electron sample
  - More than 1-sigma



Martini fake data SK fit

- Fits performed with reactor constraint, assuming maximal disappearance and CP violation and performed at current T2K statistics
  - Red = Martini fake data fit
  - Black/Blue = Nominal fit





- Little affect on $\sin^2\theta_{23}$
- If Martini is correct model, using the Nieves 2p2h model artificially tightens constraints we get on delta CP
- Statistics currently major uncertainty in analyses – affect will become bigger as statistics increase