Recent results from T2K

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La Thuile 2016

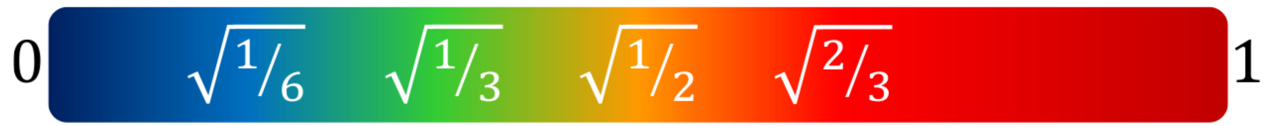
Outline

- Introduction to neutrino physics
- The T2K experiment and oscillation analysis method
- Recent anti-neutrino results from T2K

Neutrino oscillation

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

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



$$P_{\alpha \to \beta} = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E} \right|^2$$

- Experiments sample neutrino flavour states after oscillation
  - Oscillation probability is function of neutrino energy, *E*, and propagation distance *L*
  - *L* is fixed – measuring flavour composition of beam as function of energy probes PMNS mixing matrix *U* and mass splitting

Current knowledge

PDG 2014

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

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

Atmospheric /Beam	Beam /Reactor	Reactor /Solar
$\theta_{23} = 45.8^o \pm 3.2^o$	$\theta_{13} = 8.9^o \pm 0.4^o$	$\theta_{12} = 33.4^o \pm 0.9^o$

- Also have two mass splittings:

  $|\Delta m^2_{32}| = (2.44 \pm 0.06) \times 10^{-3}\ eV^2$

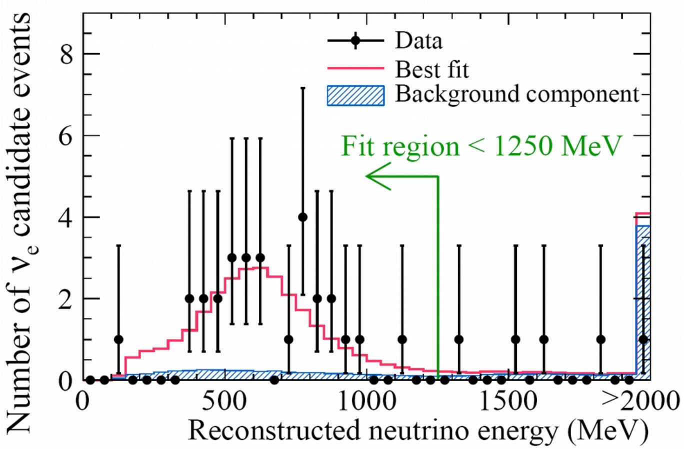
  $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ eV^2$

- Currently don't know:
  - $\delta_{CP} \neq 0$
  - Sign(Δm^2_{32}) - Mass Hierarchy
  - $\theta_{23} > 45^o$ - Octant

Why study neutrinos?

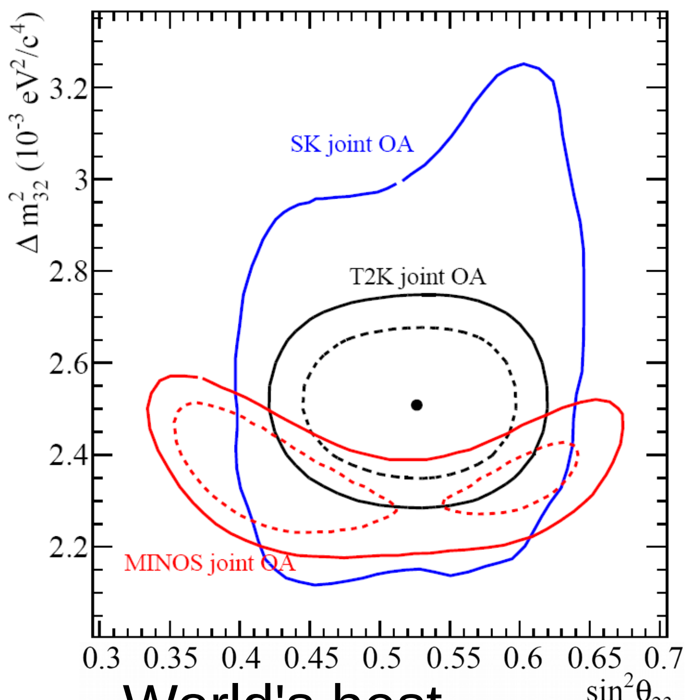
- How are neutrino masses generated, and why are they so small?
- How does neutrino mass fit into the Standard Model?
- Do neutrinos violate CP?

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

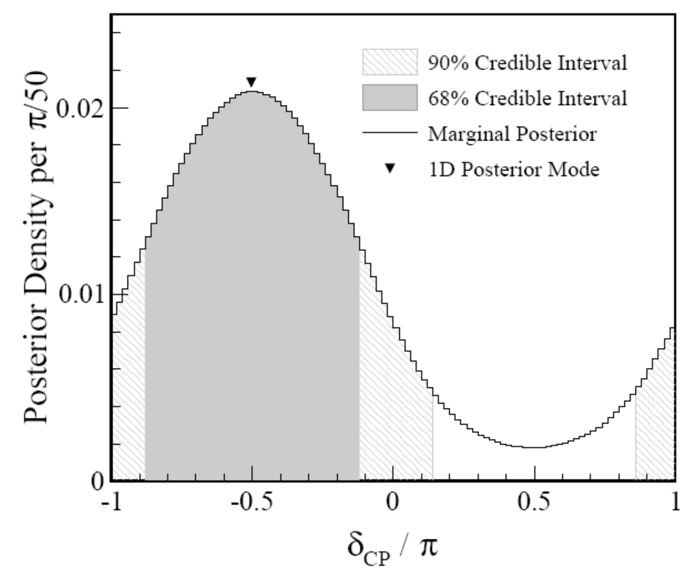


First observation of electron neutrino appearance

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

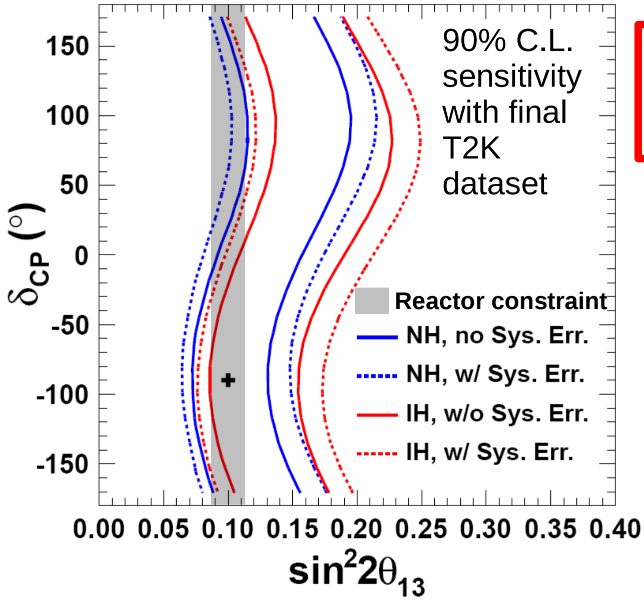


World's best measurement of θ_{23}



First T2K constraint on δ_{CP}

Why study anti-neutrinos?

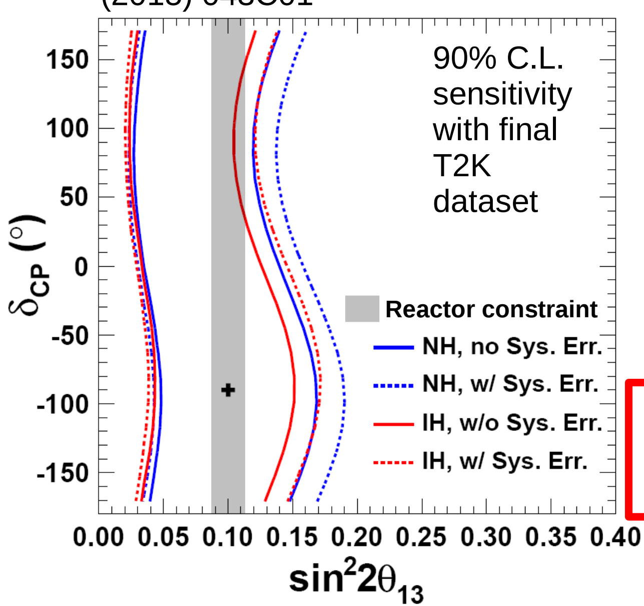


Neutrino only

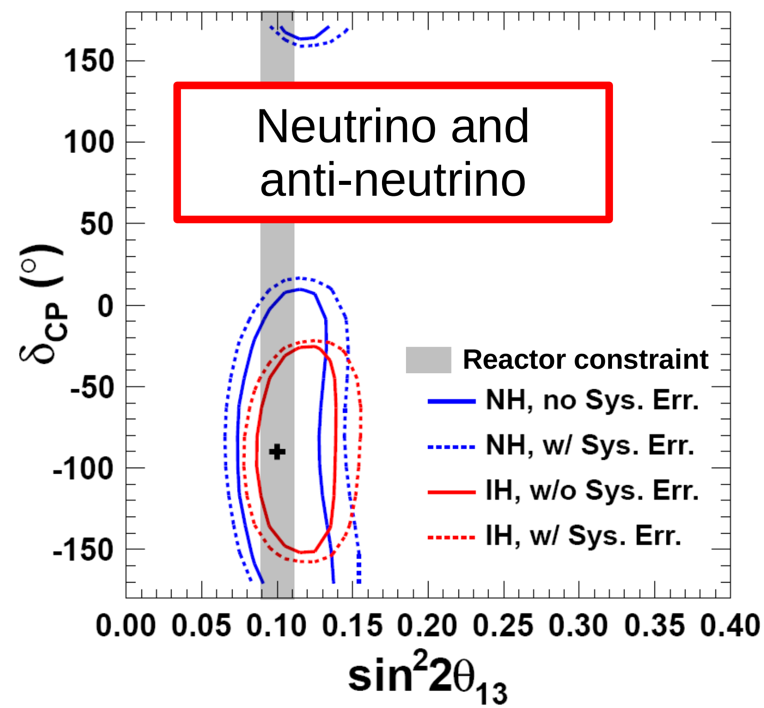
- Can constrain δ_{CP} using T2K data only
- Reactor measurement of $\sin^2 2\theta_{13}$ over-constrains PMNS framework

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

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



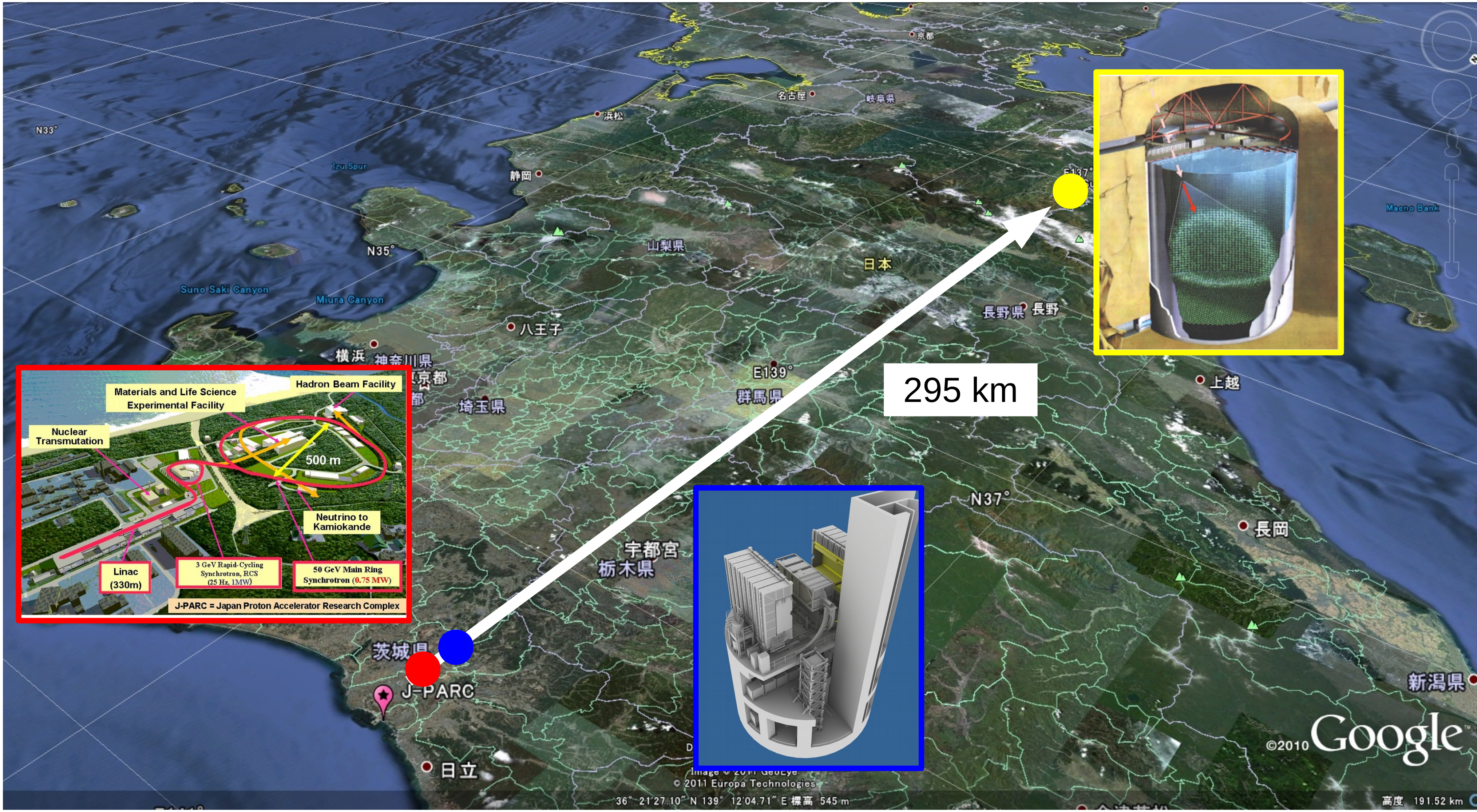
Anti-neutrino only



Neutrino and anti-neutrino

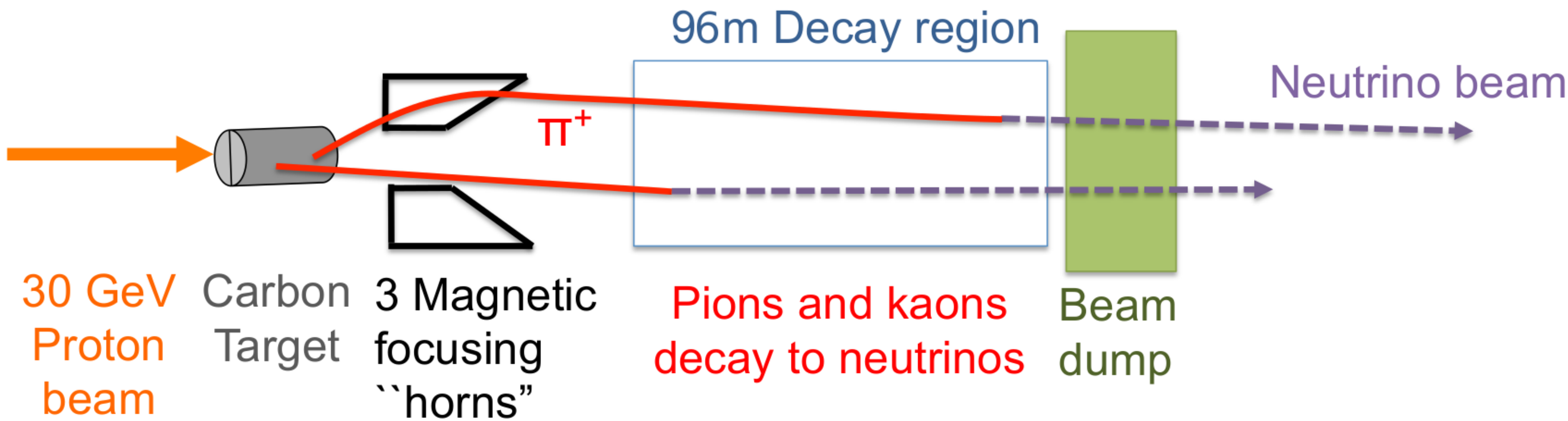
- Test CPT symmetry
- Search for non-standard interactions with matter

Tokai to Kamioka (T2K) experiment

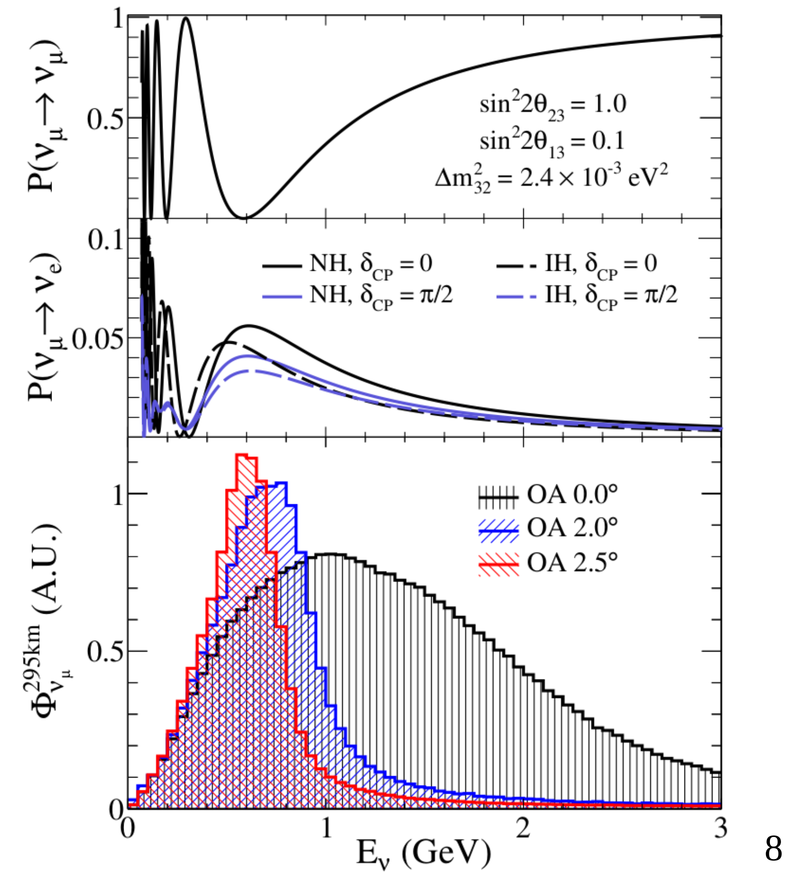


11 countries, 60 institutions, ~500 collaborators

The T2K neutrino beam

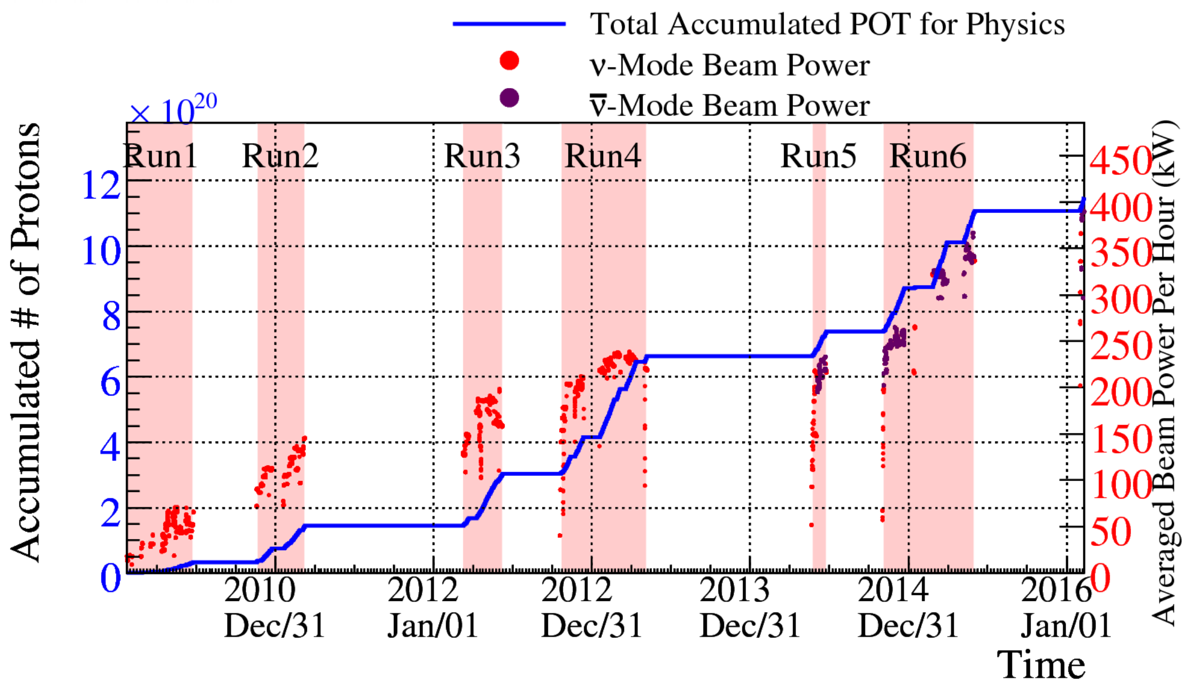


- Protons collide with target → hadrons
- Hadrons focussed by magnetic horns
- Hadrons decay in flight → neutrinos



- T2K is an **"off-axis"** experiment
- Moving away from beam axis changes neutrino energy spectrum
- 2.5° shift tunes neutrino energy to give maximal oscillation at T2K

The T2K neutrino beam

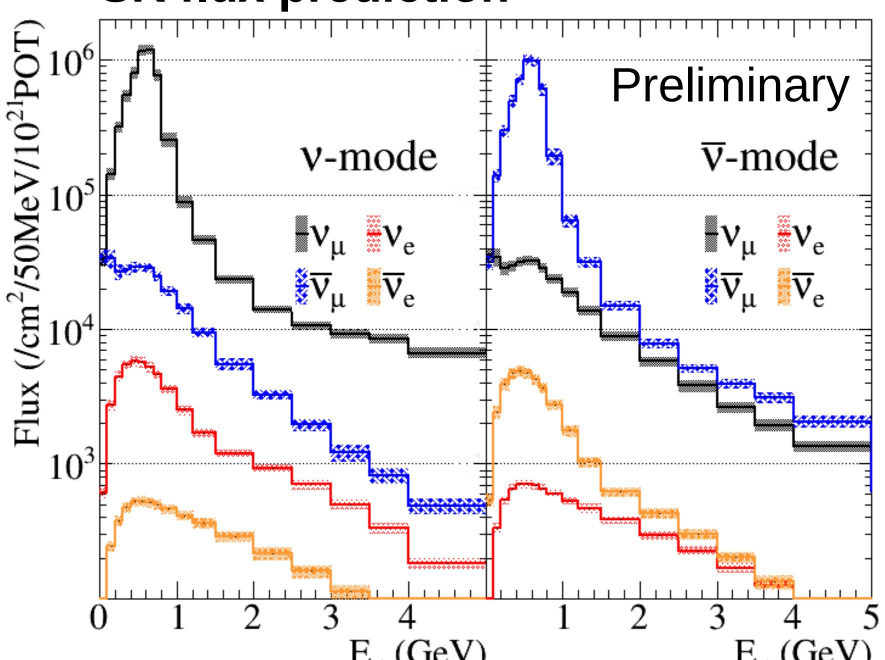


POT: Protons On Target

Total POT for Run 1-6: 11.04×10^{20}

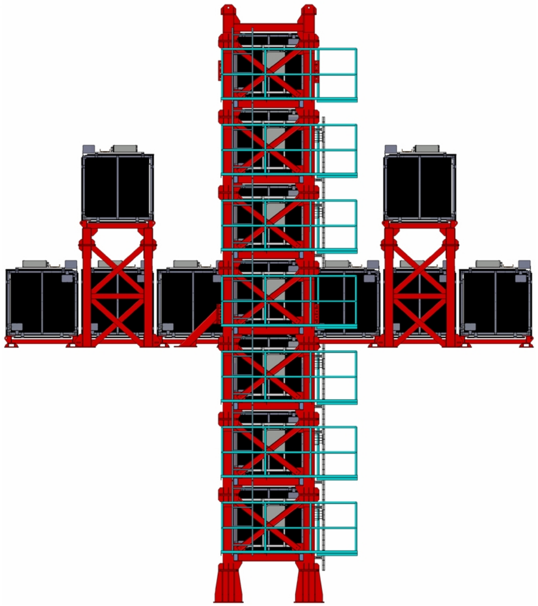
Maximum beam power: ~390kW

SK flux prediction



- Horn polarity changes between neutrino and anti-neutrino beam modes
- Increased “wrong-sign” neutrino component in anti-neutrino mode
  - Neutrino cross section larger than for anti-neutrinos
- No sign selection at far detector – must measure at near detectors

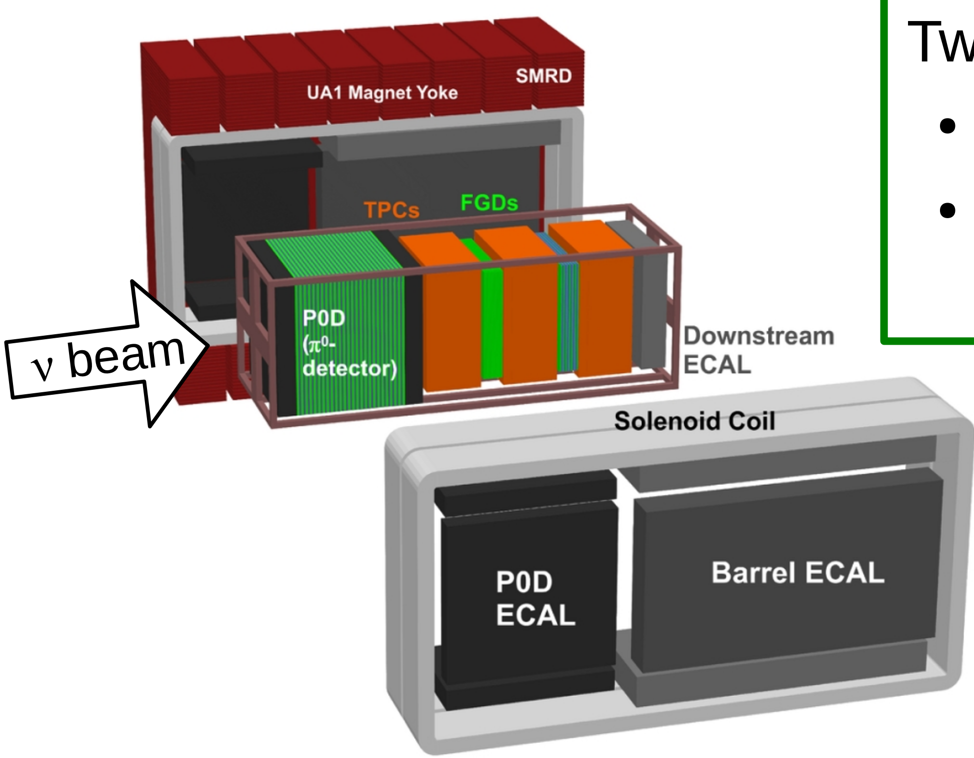
Near detectors at 280m



Interactive Neutrino GRID (INGRID)

- On-axis, iron and plastic scintillator detector
- Measures neutrino beam direction to < 1 mrad

ND280 Off-axis detector (ND280)



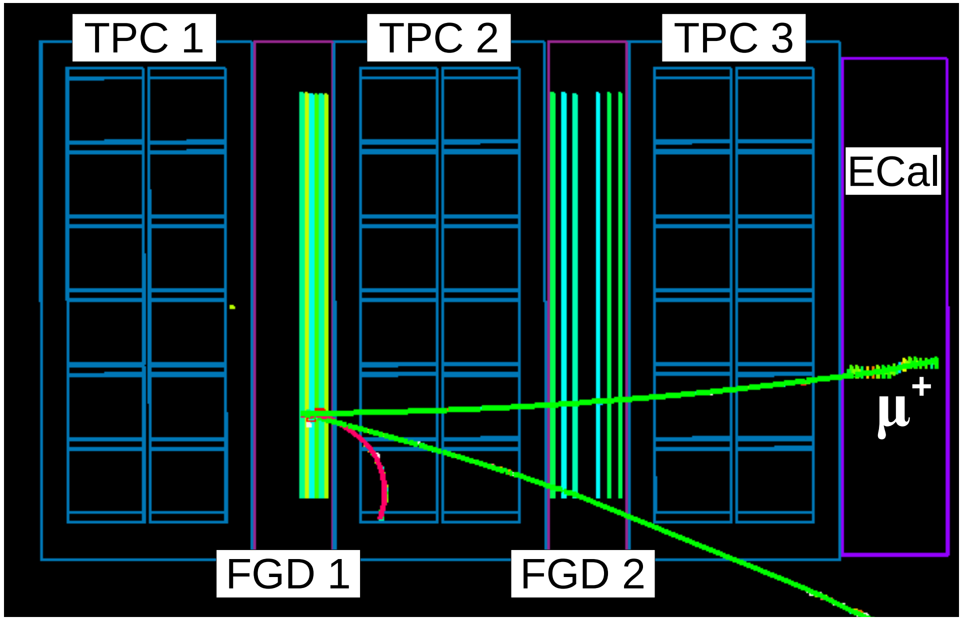
Two fine-grained detectors (FGDs)

- FGD1 – fully active carbon target
- FGD2 – Passive water layers
  - Not used in analysis shown here

Magnet + three TPCs

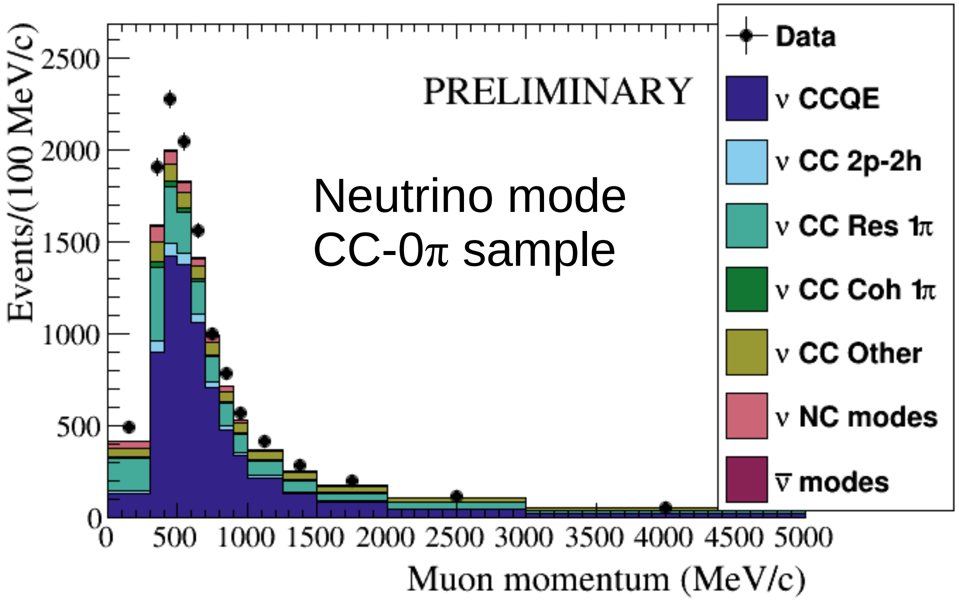
- Particle charge + momentum via curvature
- Particle ID from dE/dx - 0.2% mis-ID rate

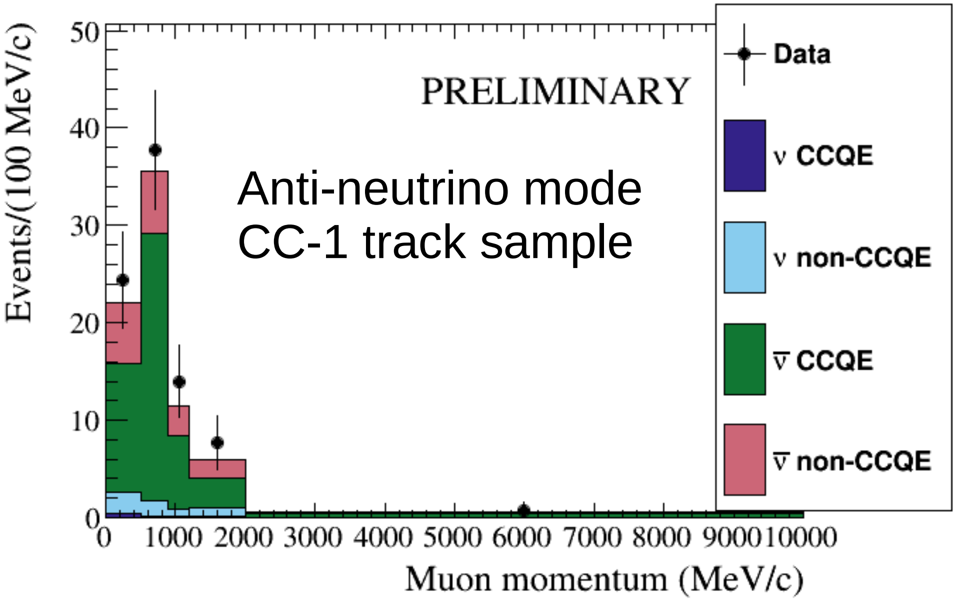
ND280 data



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

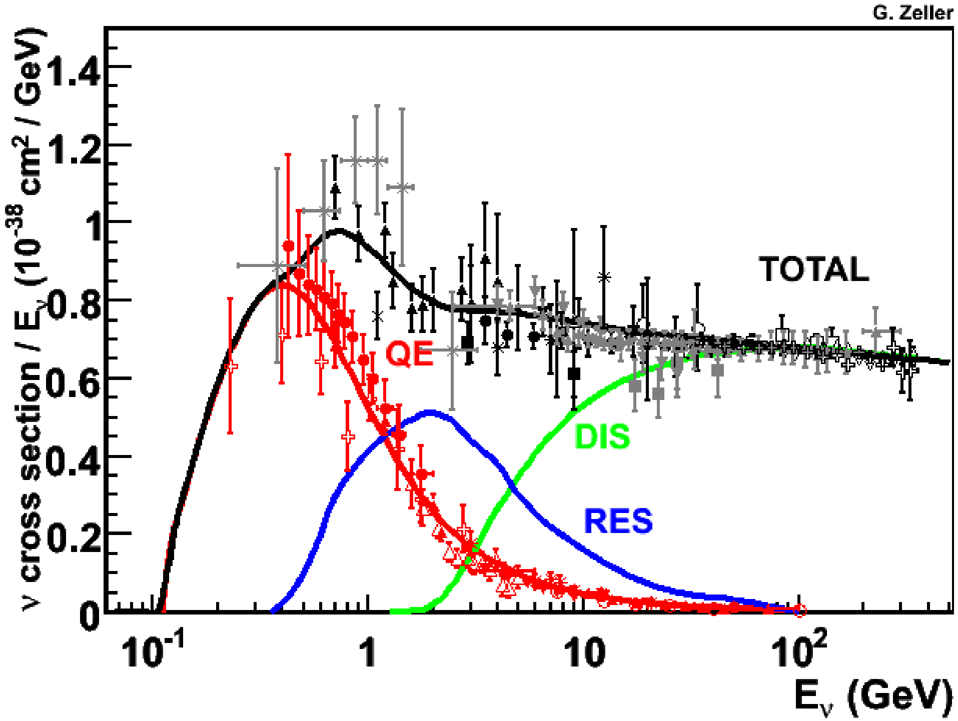




Neutrino cross-sections

Neutrino cross-sections have ~10% uncertainty:

- Nuclear effects are large
- Cannot calculate from first principles
- Existing data has large uncertainties



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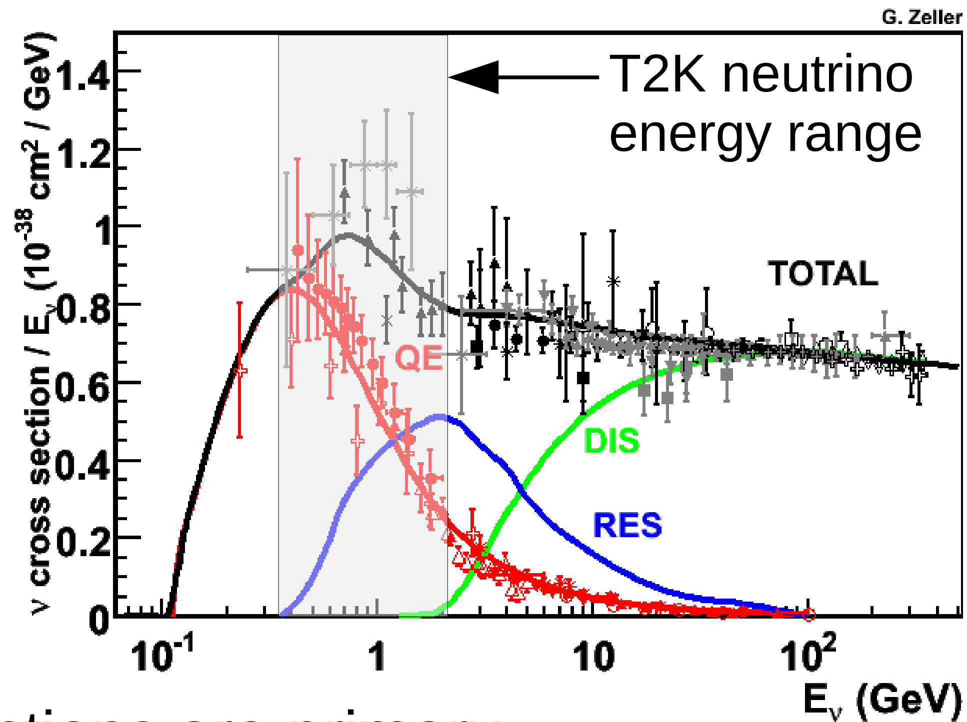
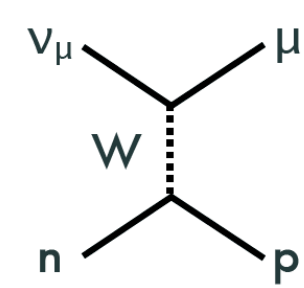


Charged current quasi-elastic interactions are primary signal

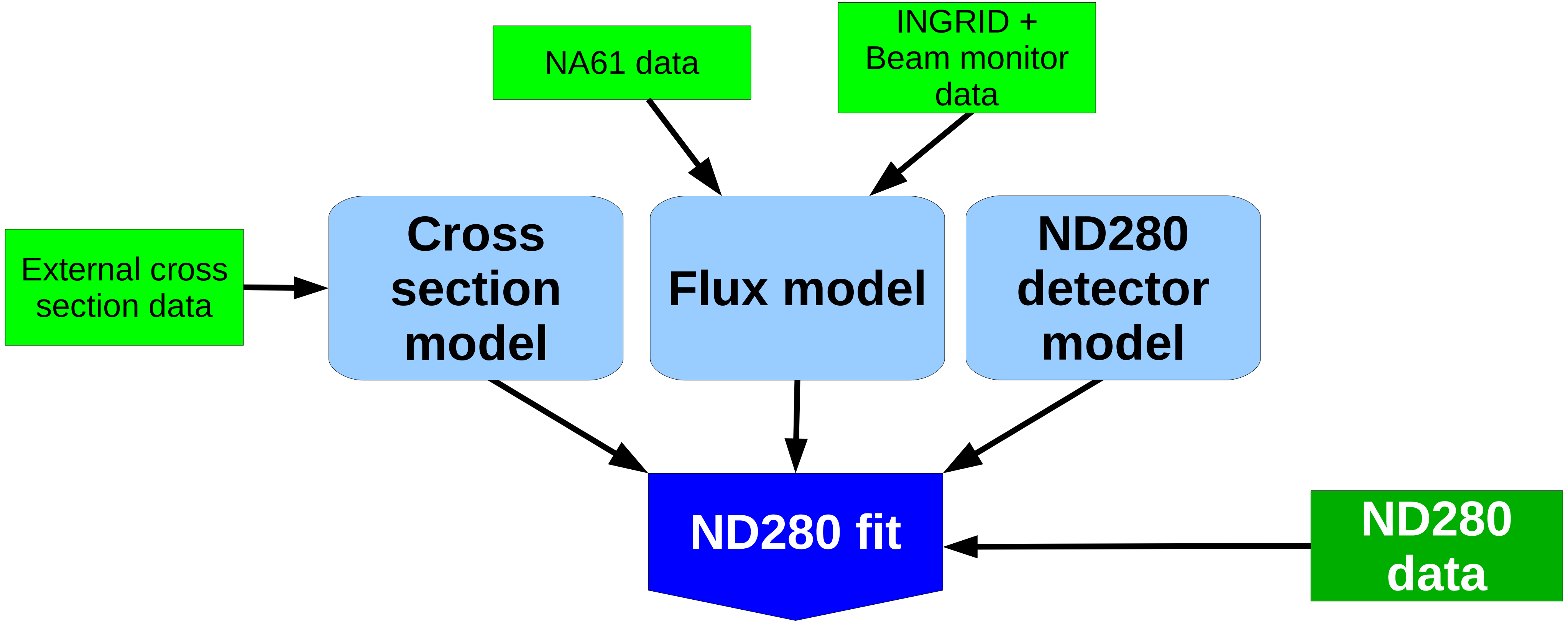
- 2-body interaction → neutrino energy from lepton kinematics
- But, other interactions mimic CCQE
- Need to understand multiple interaction modes over range of neutrino energies

Charged current quasi-elastic (CCQE)



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

T2K oscillation analysis

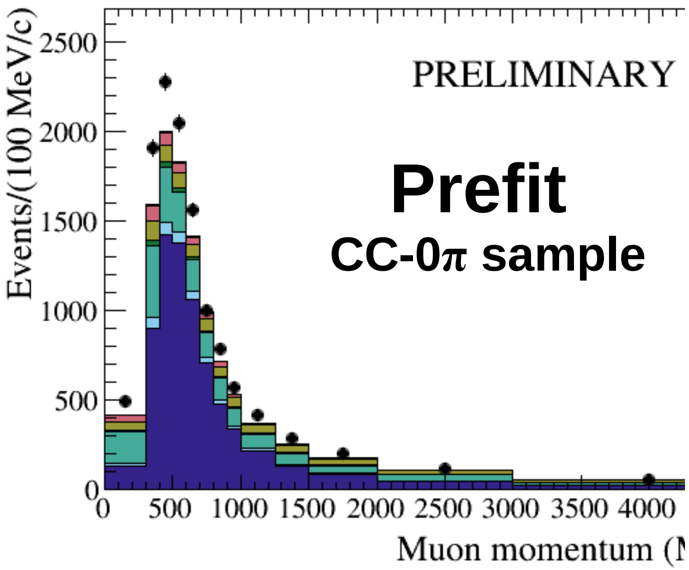


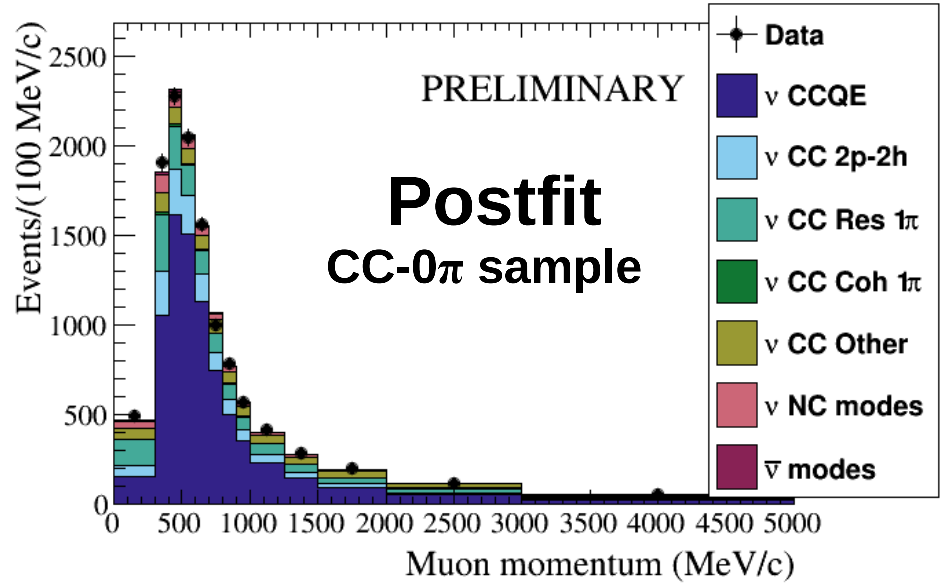
Detectors measure interaction rate:

- Flux * Cross-section → Neither is known to better than 10%
- Joint fit of models to ND280 data allows constraint on rate
- Propagate tuned models to far detector

ND280 fit

Postfit near detector MC agrees much better with data

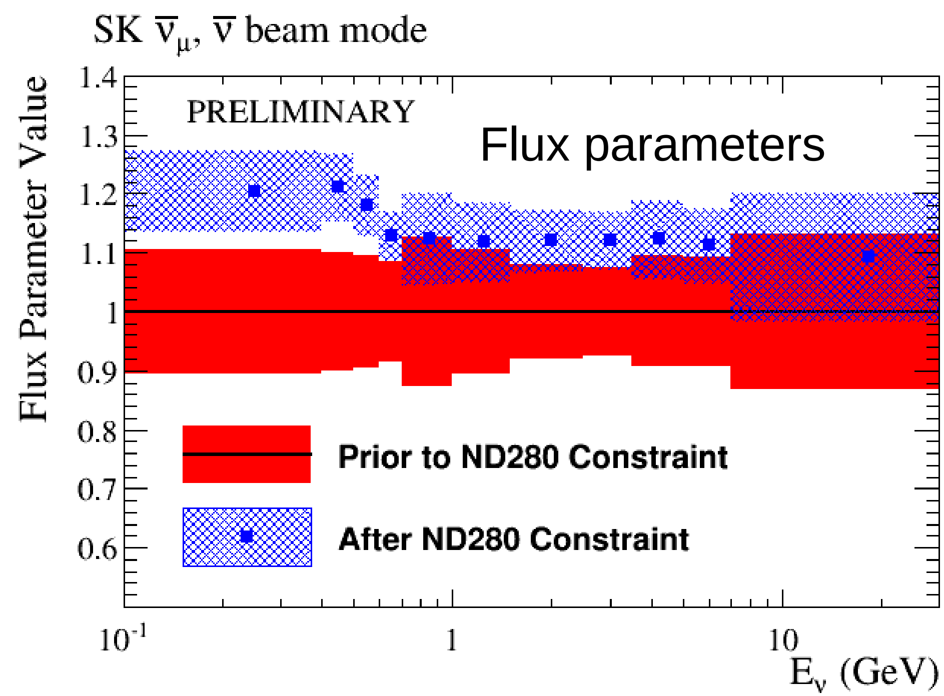




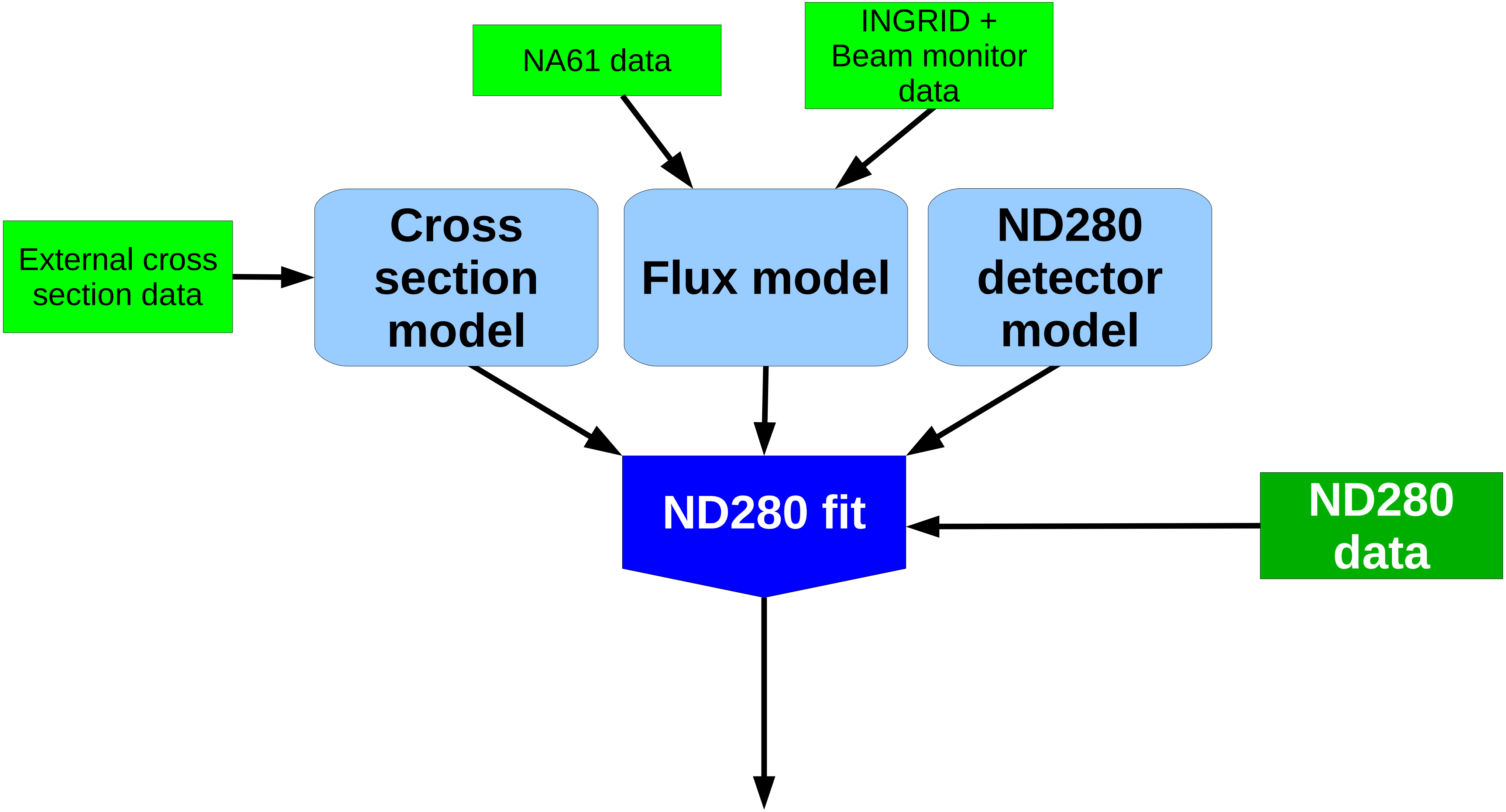
Model parameters shifted from prior values

Fit only as good as the input models:

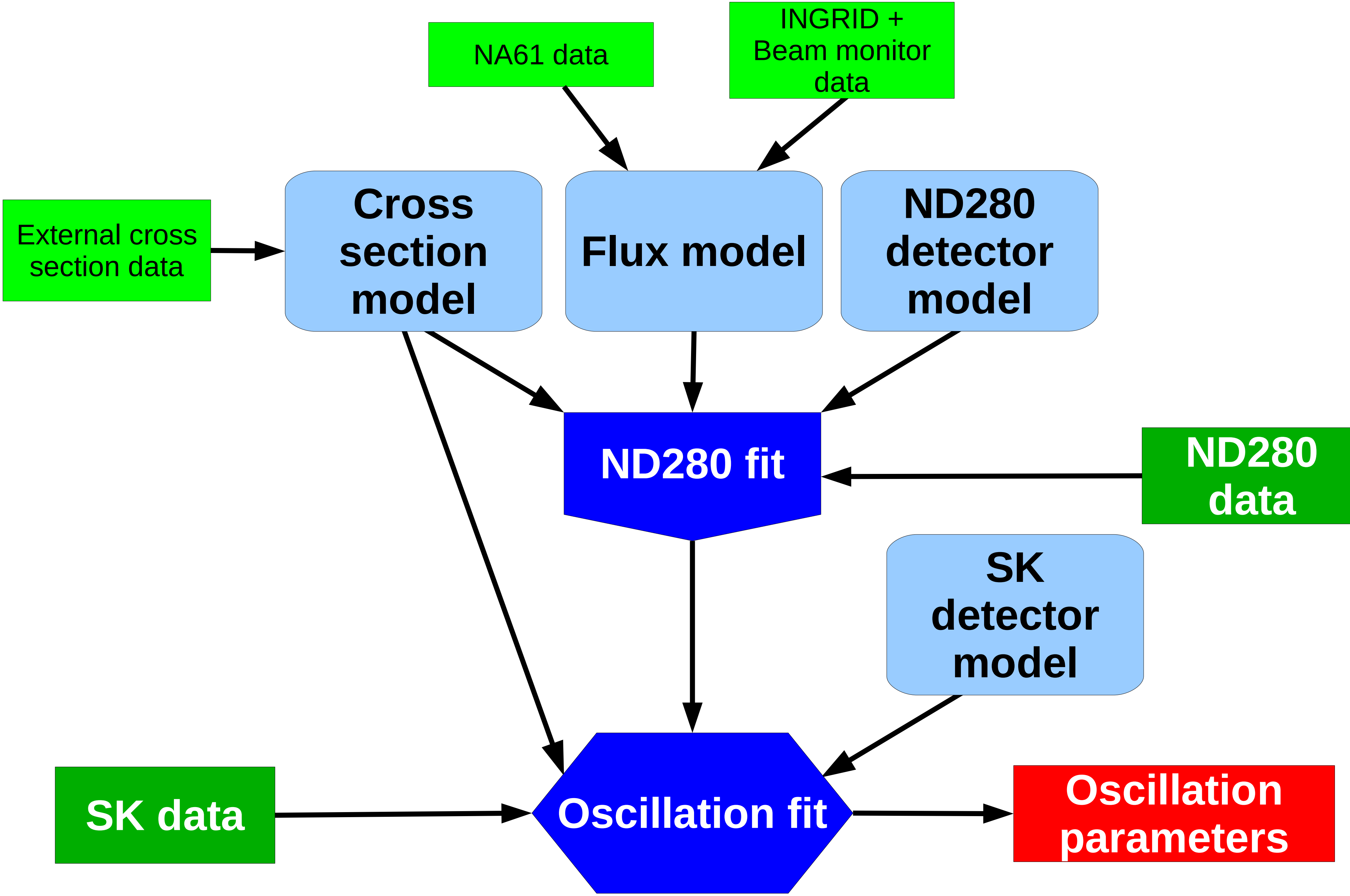
- Test model dependence using ND280 fit
- Choice of interaction model has small effect on this analysis



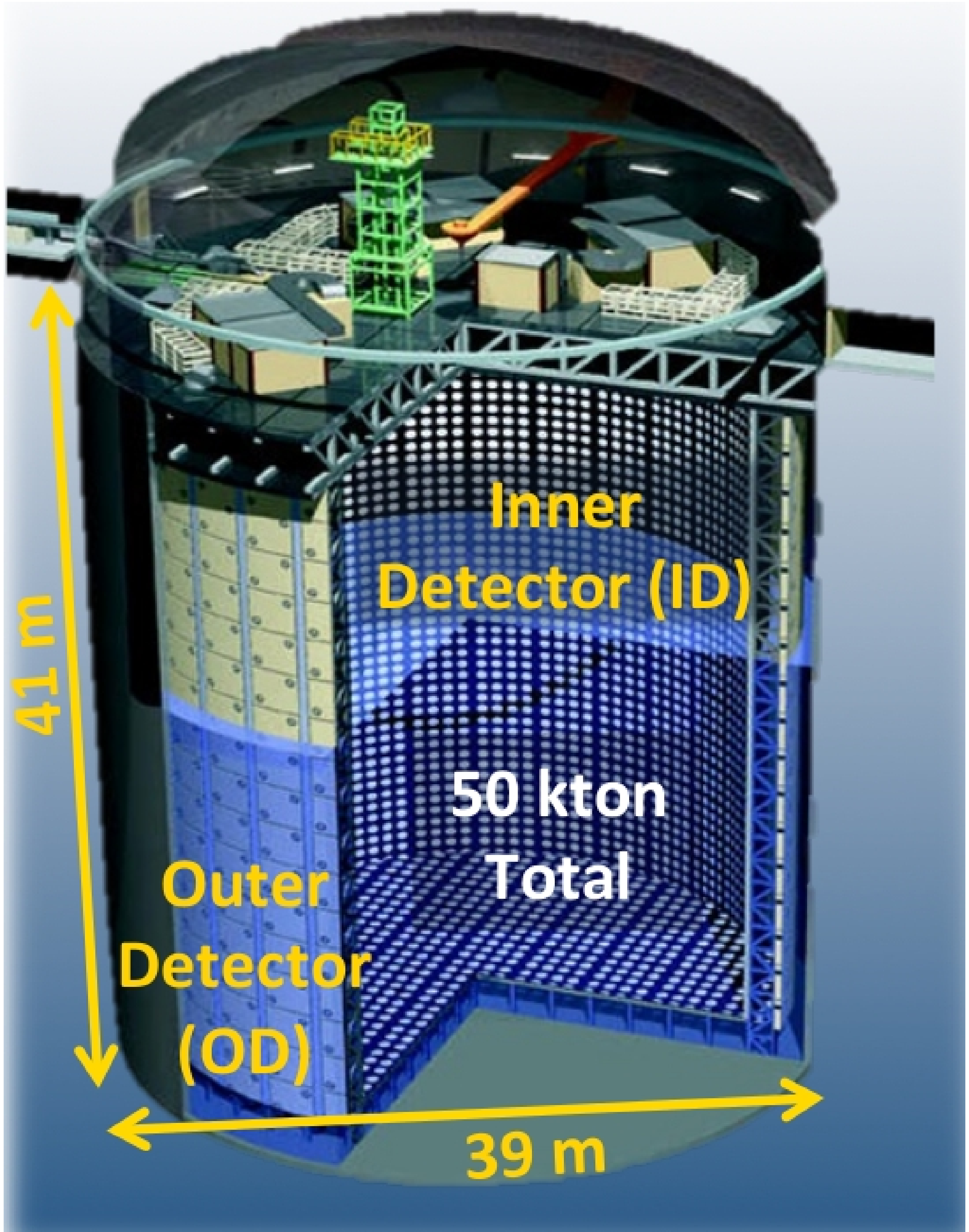
T2K oscillation analysis

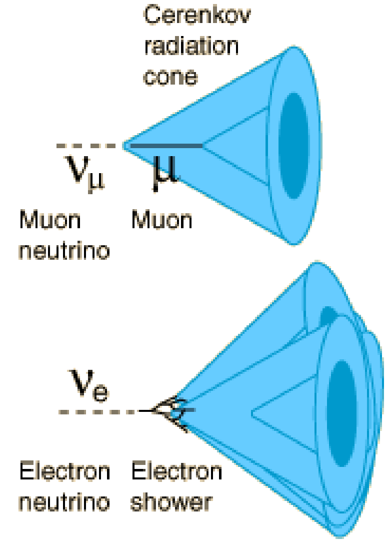


T2K oscillation analysis



Super-Kamiokande





- 50 kT water Cherenkov detector
  - Separate electrons and muons by ring shape
  - Mis-ID <1%

- 22.5 kT fiducial volume
- Inner detector with ~11,000 20” PMTs
  - 40% photo-coverage
- Outer detector with ~2000 8” PMTs
  - Veto exiting/entering events

SK $\bar{\nu}$ event selection

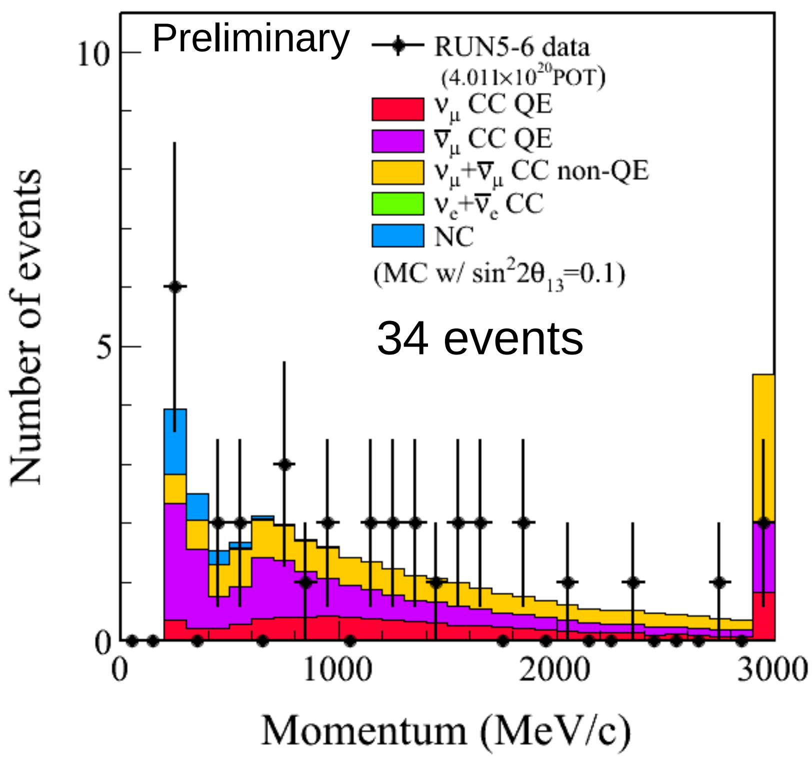
Look for fully contained, single ring events inside SK fiducial volume, then:

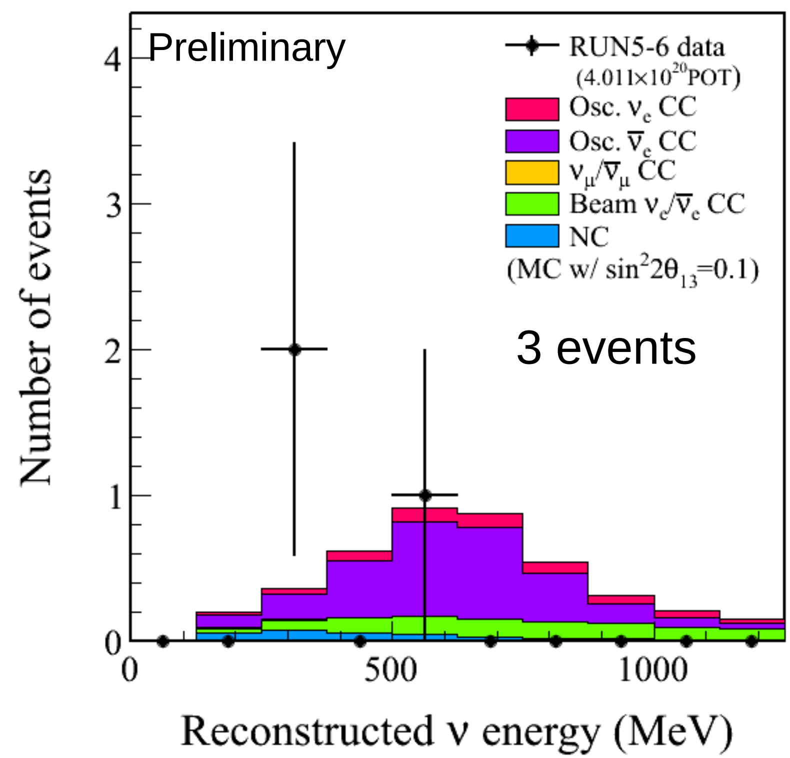
If muon-like ring:

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

If electron-like ring:

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





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

Why?

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

How?

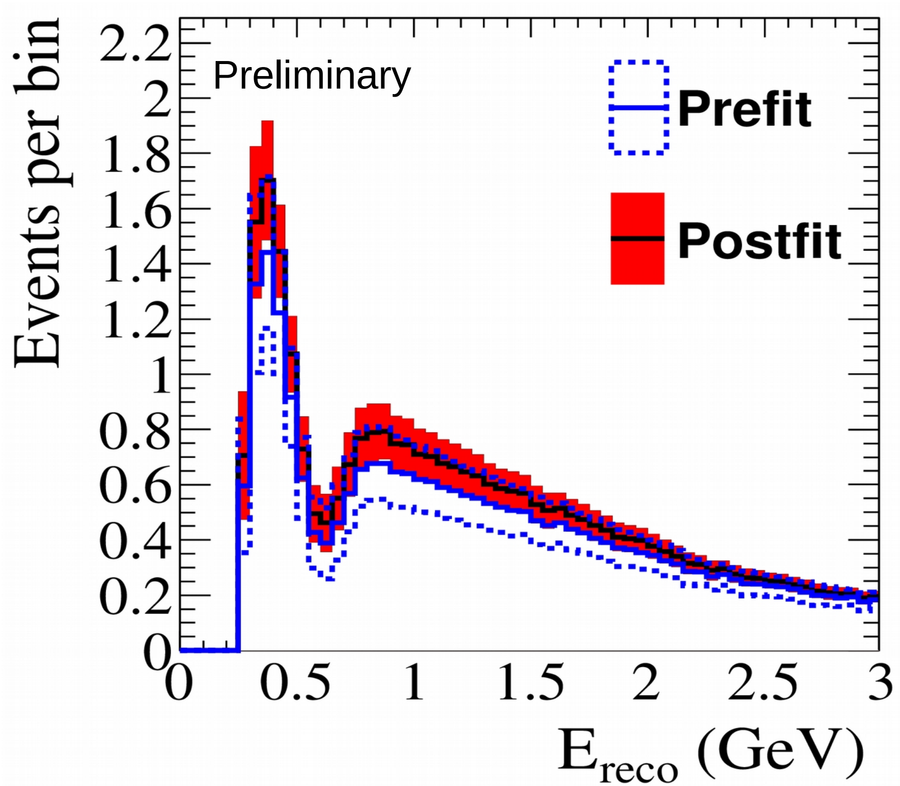
- Maximise a likelihood: $\mathcal{L} = \mathcal{L}_{\text{Data}} * \mathcal{L}_{\text{Flux}} * \mathcal{L}_{\text{XSec}} * \mathcal{L}_{\text{SK detector}}$
- Introduce $\sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}^2_{32}$ to control muon anti-neutrino oscillation

Parameter	ν	$\overline{\nu}$
$\sin^2(\theta_{23})$	0.527	fit 0 – 1
Δm^2_{32} (10^{-3} eV^2)	2.51	fit 0 – 20
$\sin^2(\theta_{13})$	0.0248	
$\sin^2(\theta_{12})$	0.304	
Δm^2_{21} (10^{-5} eV^2)	7.53	
δ_{CP} (rad)	-1.55	

- Fix all oscillation parameters except $\sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}^2_{32}$ using T2K neutrino mode data and PDG 2014

Systematic uncertainty

Systematic		Without ND	With ND measurement
Flux and Cross Section	Common to ND280/SK	9.2%	3.4%
	SK only	10%	
	All	13.0%	10.0%
Final State Interaction/Secondary Interaction		2.1%	
SK Detector		3.8%	
Total		14.4%	11.6%



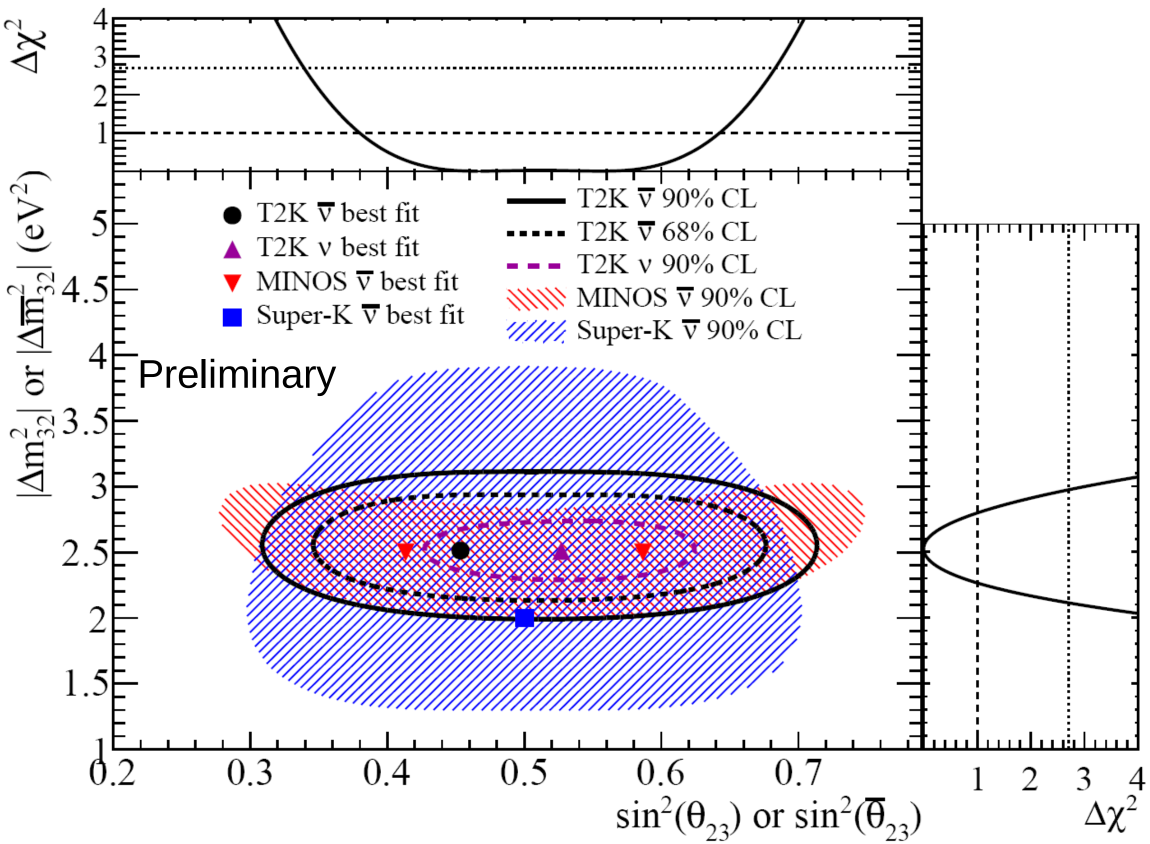
ND280 fit reduces common systematics from 9% → 3%

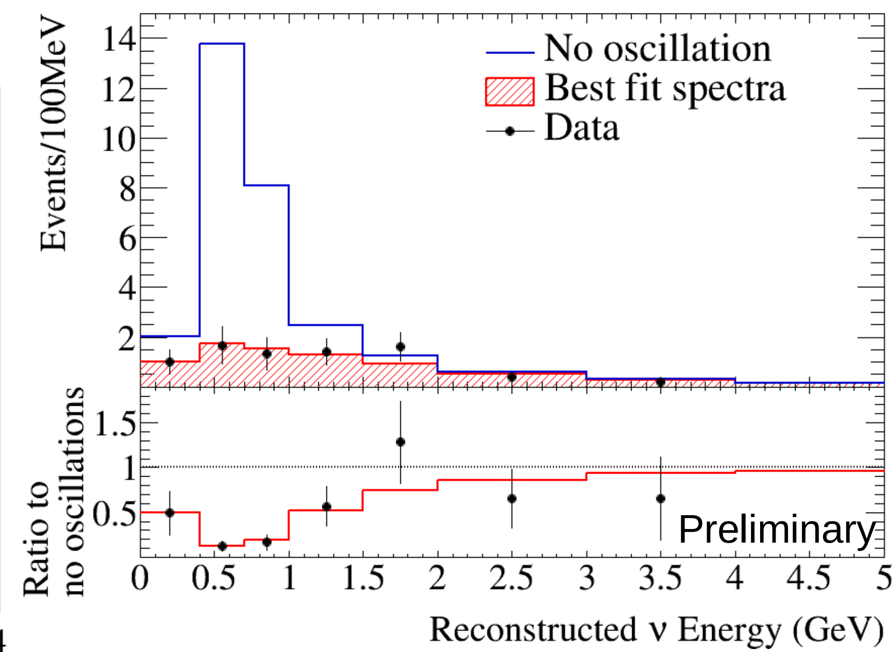
SK only cross-section uncertainty of 10%:

- Current ND280 analysis on carbon target, SK uses water
- Next analysis will reduce this to ~4%

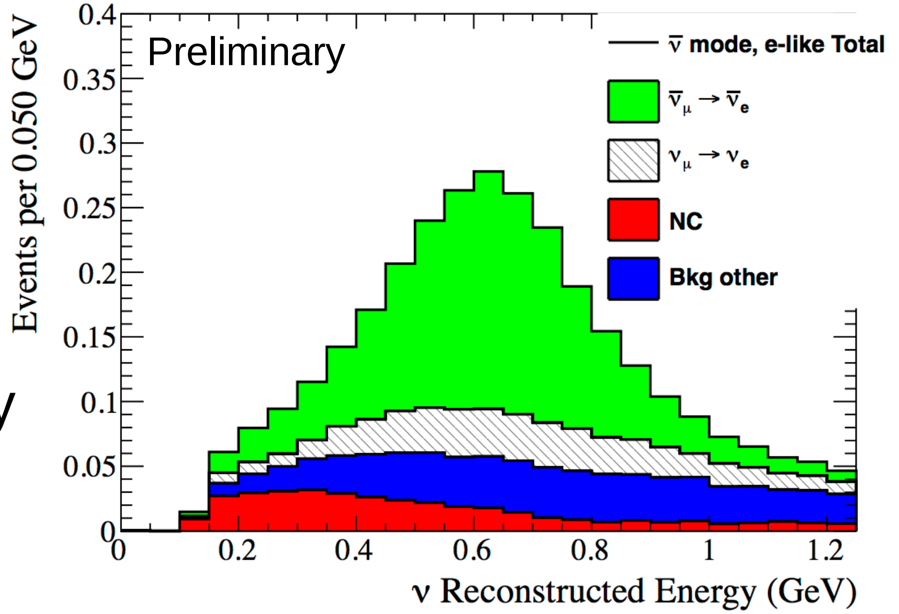
$\bar{\nu}_\mu$ disappearance result

- Clear evidence of oscillation!
  - Best fit point at $\sin^2\bar{\theta}_{23} = 0.45$ and $\Delta\bar{m}^2_{32} = 2.51 \times 10^{-3}$ eV^2
- Completely consistent with T2K neutrino data and previous experiments
- Result statistics limited
  - Taking more anti-neutrino data, significant improvement expected





$\bar{\nu}_e$ appearance



Why?

- Observe anti-neutrino appearance
- Compare to ν_e – constrain δ_{CP}

How?

- Introduce discrete β parameter to modify appearance probability
- $\beta = 0$, null hypothesis, no $\bar{\nu}_e$ appearance
- $\beta = 1$, $\bar{\nu}_e$ appearance with same parameters as ν_e appearance

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{\text{PMNS}}(\bar{\nu}_\mu \to \bar{\nu}_e)$$

Parameter(s)	Treatment	Nominal value
$\sin^2\theta_{23}$	marginalized	0.528
$\sin^2\theta_{13}$	marginalized	0.025
$\sin^2\theta_{12}$	fixed	0.306
$\lvert\Delta m^2_{32}\rvert$ (NH) / $\lvert\Delta m^2_{31}\rvert$ (IH)	marginalized	2.509×10^{-3} eV^2/c^4
Δm^2_{21}	fixed	7.5×10^{-5} eV^2/c^4
δ_{CP}	marginalized	-1.601
Mass Hierarchy	marginalized	NH

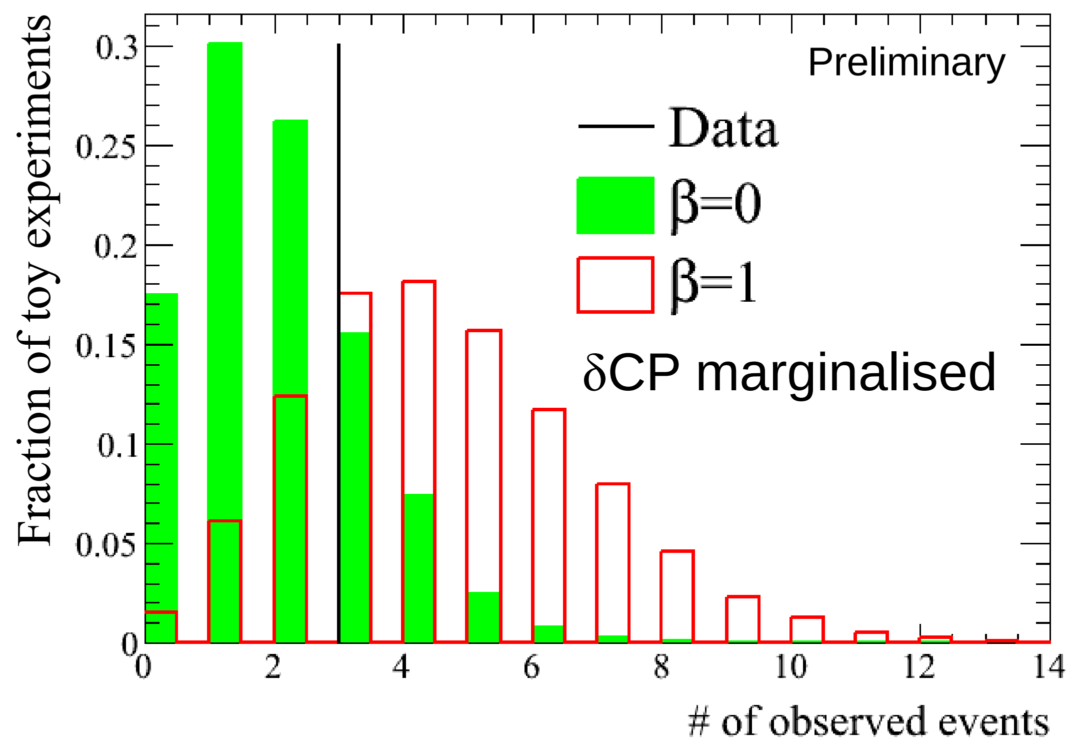
$\bar{\nu}_e$ appearance

Expected event rates for given oscillation parameters

- ~4 if β = 1
- ~1.6 if β = 0
- Observed 3 events in the data

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389
Bkg NC	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826
Total	3.729	4.315	4.851

Observed β = 0 p-value	β = 1 / β = 0 Marginalised likelihood ratio
0.26	1.09



Data do not show evidence for or against $\bar{\nu}_e$ appearance

Conclusions

- With ~4.0 x 10^{20} POT of data T2K has analysed:
  - Muon anti-neutrino disappearance
    - Consistent with neutrino data and past experiments
    - World-leading constraint with ~10% of expected anti-neutrino data
  - Electron anti-neutrino appearance
    - 3 events seen
    - No strong evidence either for or against appearance
- Currently taking more anti-neutrino data
- Next analysis:
  - Near detector fit including water target data → reduce flux and cross section uncertainties significantly
  - Full appearance + disappearance, neutrino + anti-neutrino joint fit

Thank you!

Other T2K results

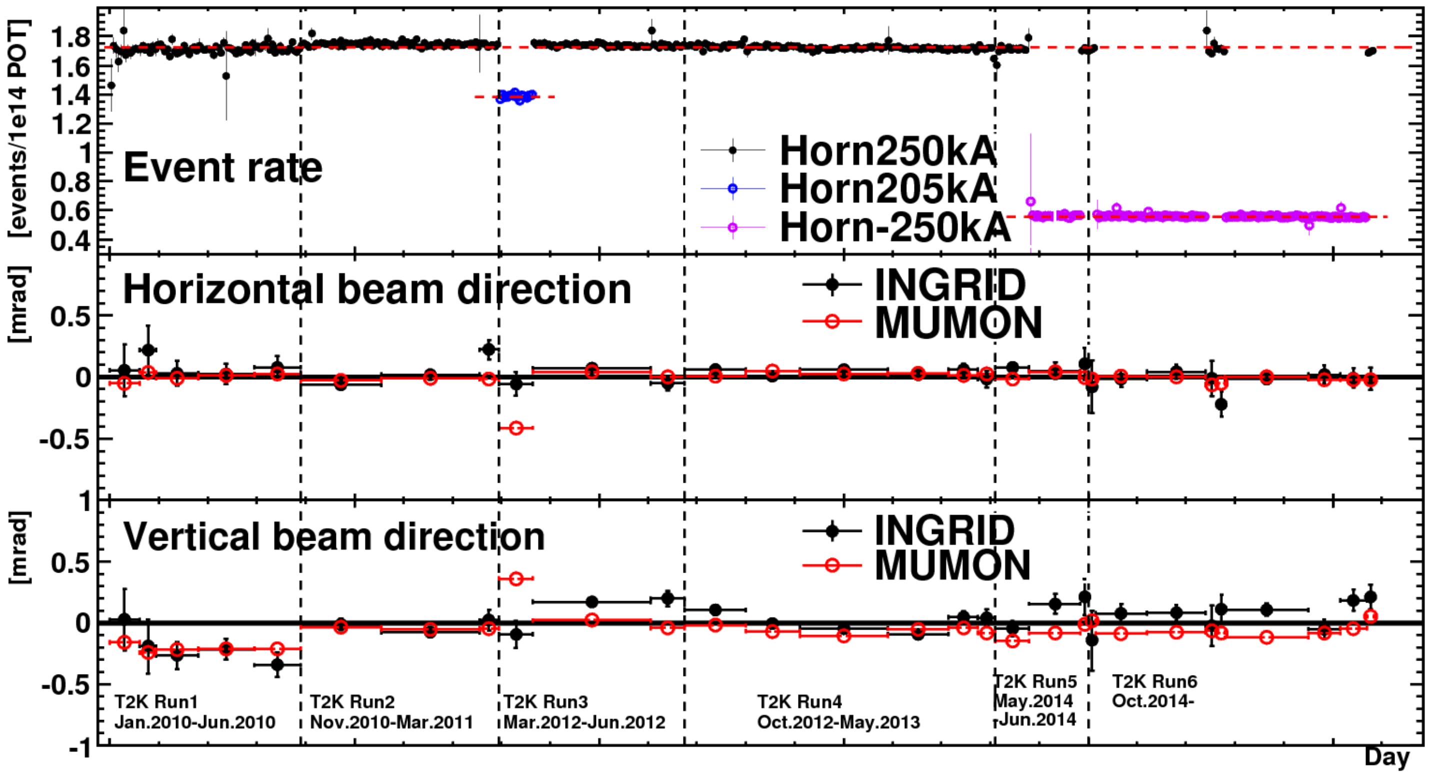
New results published in the last year:

Physics	Title	Journal / Status
Sterile oscillation	Search for short baseline νe disappearance with the T2K near detector	Phys. Rev. D 91, 051102(R) (2015)
PMNS oscillation	Neutrino Oscillation Physics Potential of the T2K Experiment	Prog. Theor. Exp. Phys. 043C01 (2015)
Cross-section	Measurement of the muon neutrino CCQE cross section with ND280 at T2K	Phys. Rev. D 92, 112003 (2015)
Cross-section	Measurement of the electron neutrino charged-current interaction rate on water with the T2K ND280 pi0 detector	Phys. Rev. D 91, 112010 (2015)
Cross-section	Measurement of the muon neutrino charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam	Phys. Rev. D 91, 112002 (2015)
Cross-section	Measurement of the muon neutrino inclusive charged-current cross section in the energy range of 1-3 GeV with the T2K INGRID detector	Accepted by PRD arXiv:1509.06940
Neutrino mass	Upper bound on neutrino mass based on T2K neutrino timing measurements	Phys. Rev. D 93, 012006 (2016)
Cross-section	Measurement of double-differential muon neutrino charged-current interactions on C8H8 without pions in the final state using the T2K off-axis beam	Submitted to journal arXiv:1602.03652

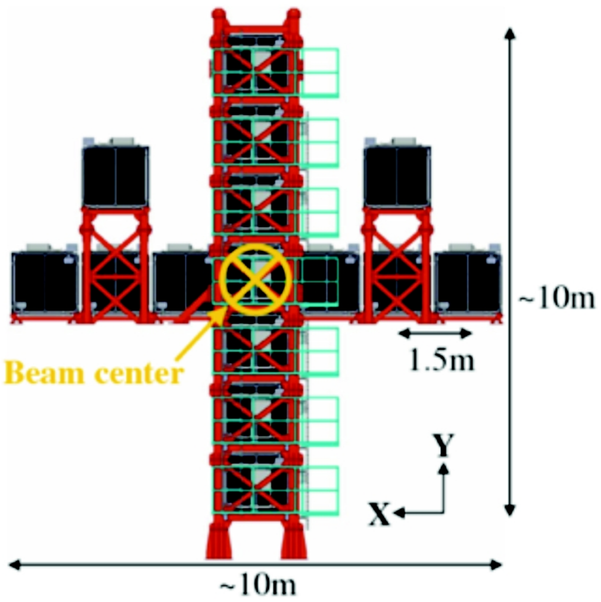
Many more nearing publication – all publications, conference talks etc. at http://t2k-experiment.org/for-physicists/

Supplementary slides

Beam stability

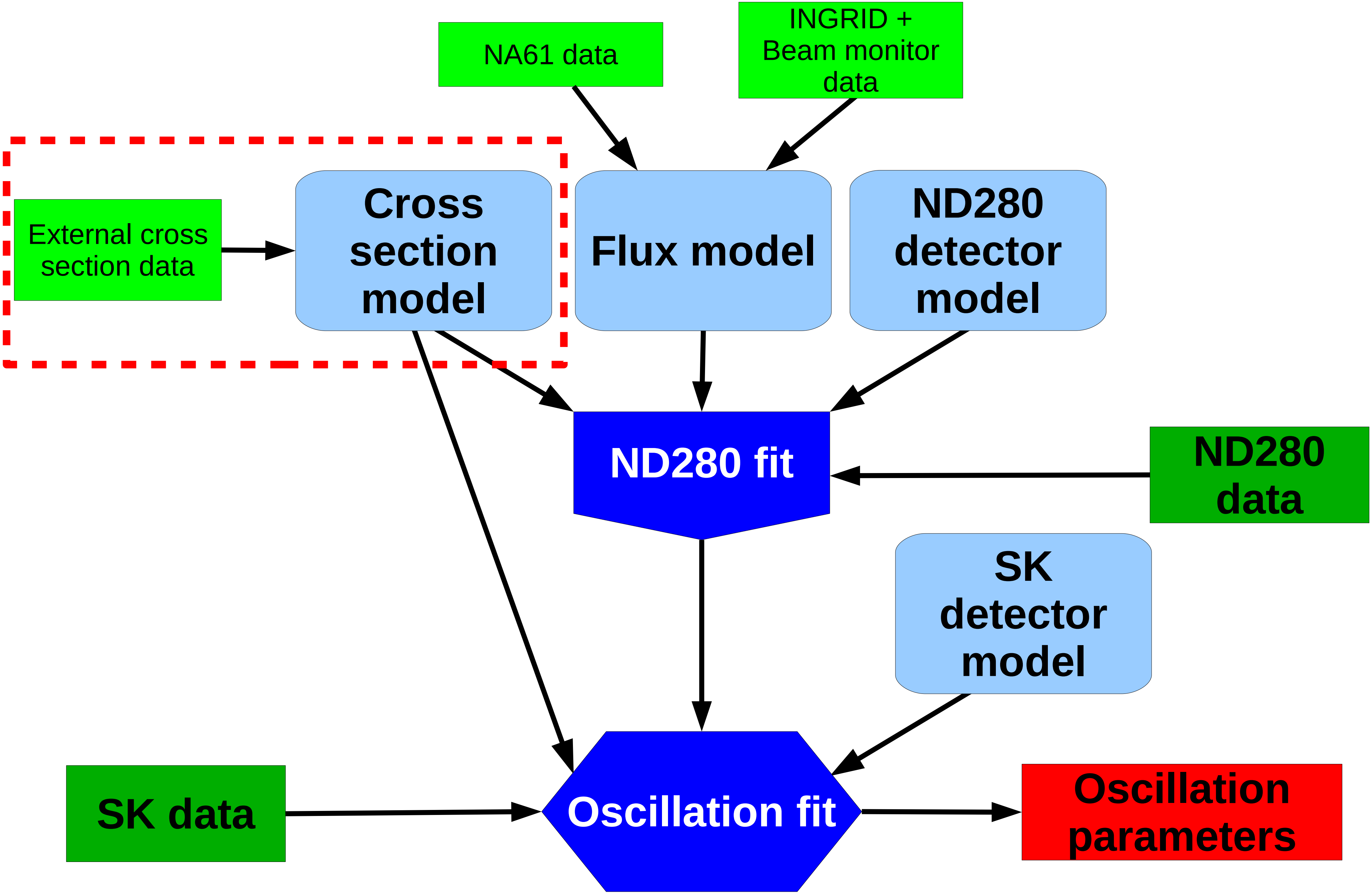


INGRID on-axis detector monitors beam stability



Beam rate and direction very stable across T2K running period

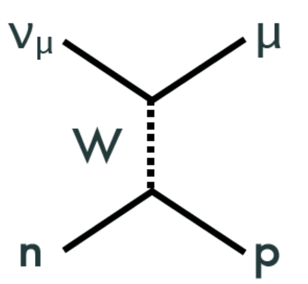
T2K Cross section model



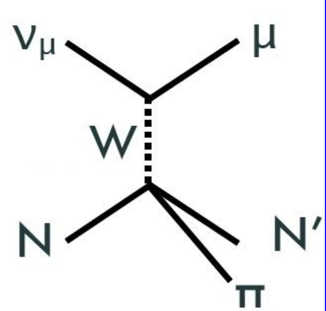
T2K Cross section model

- NEUT neutrino interaction generator

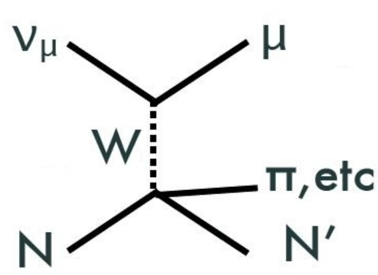
Charged current quasi-elastic

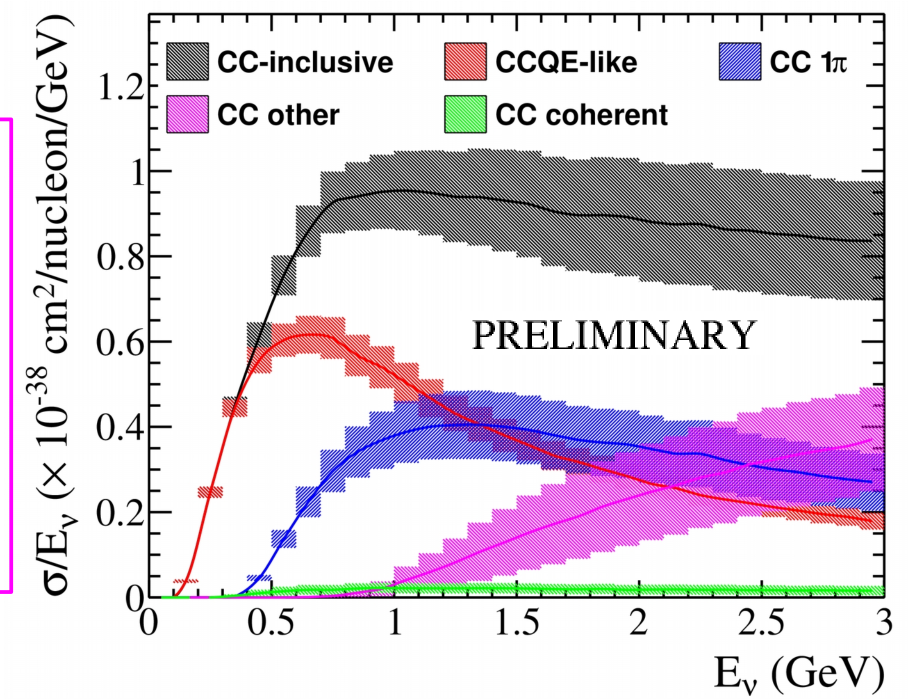


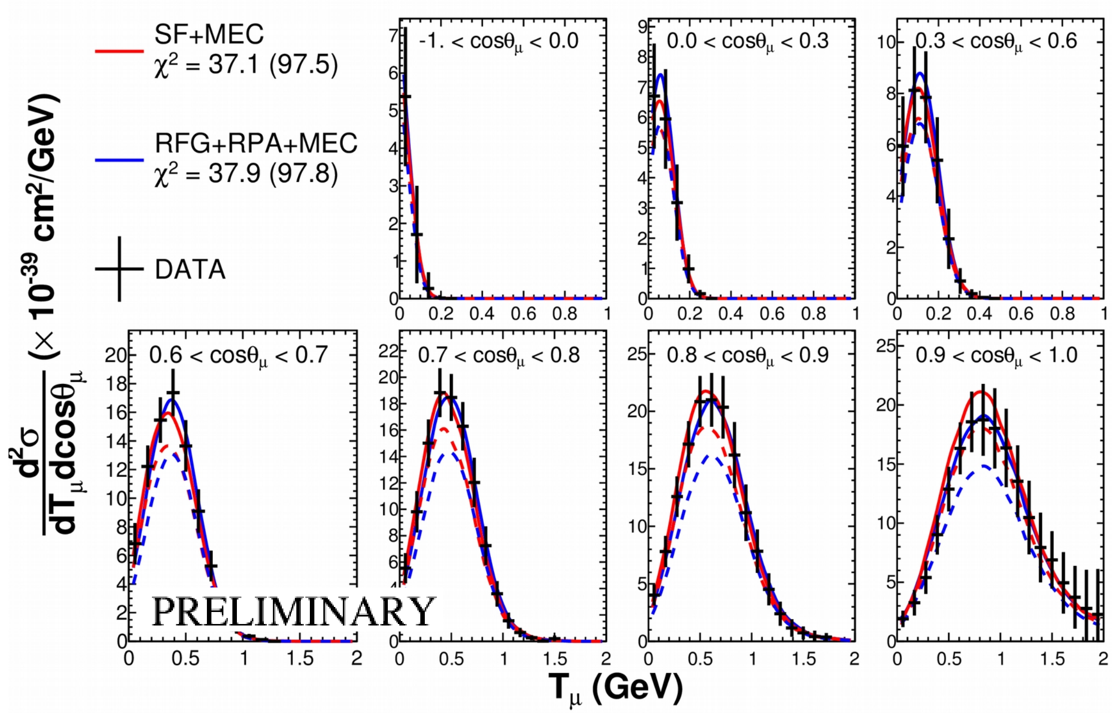
Charged current single pion



Charged current deep inelastic scattering

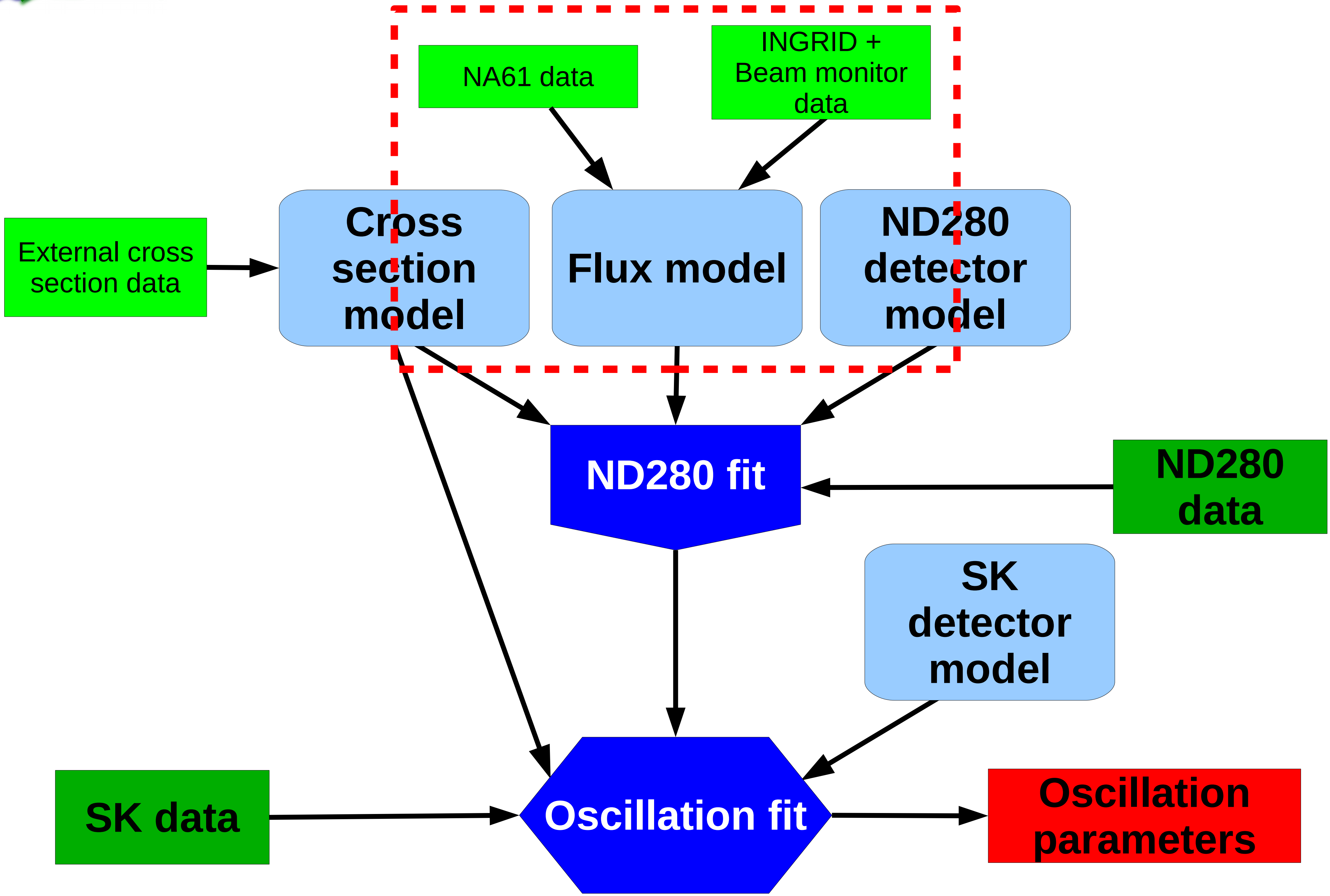




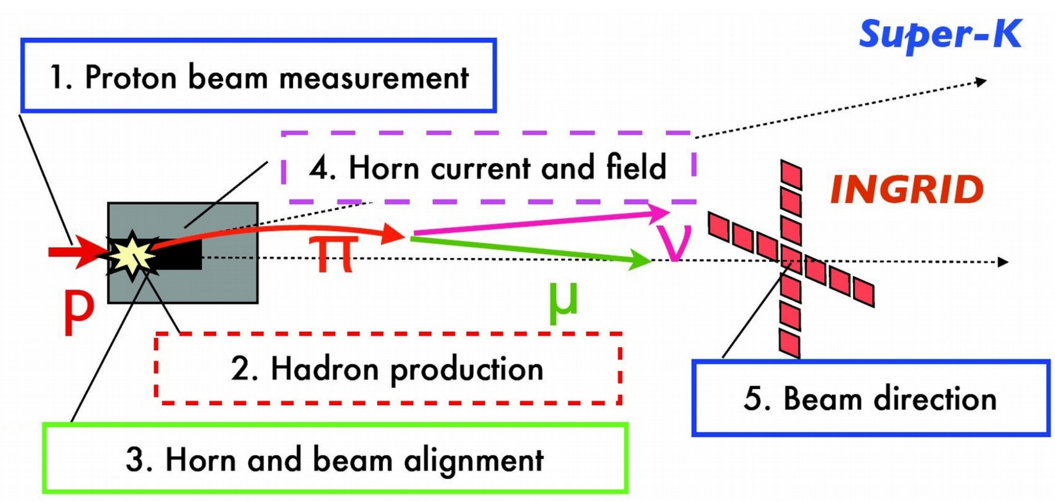


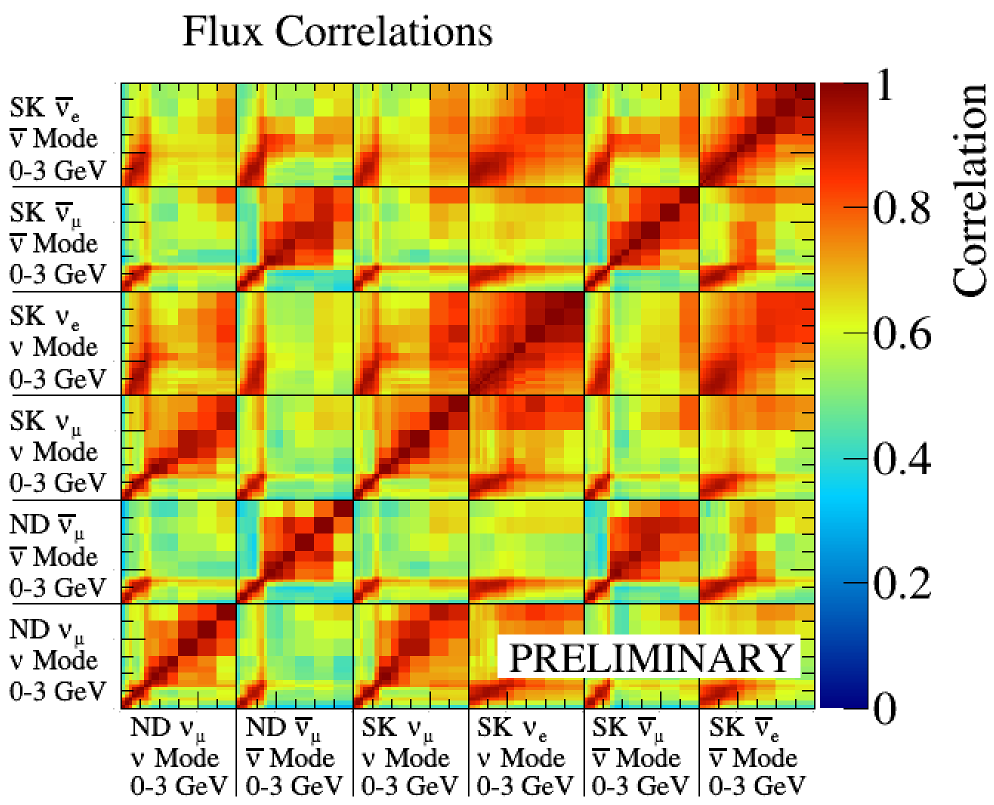
- Cross section is parameterized
- Fit external data (MiniBooNE, Minerva, ANL and BNL) to set parameter values and errors
- Inflate errors to cover tension between datasets

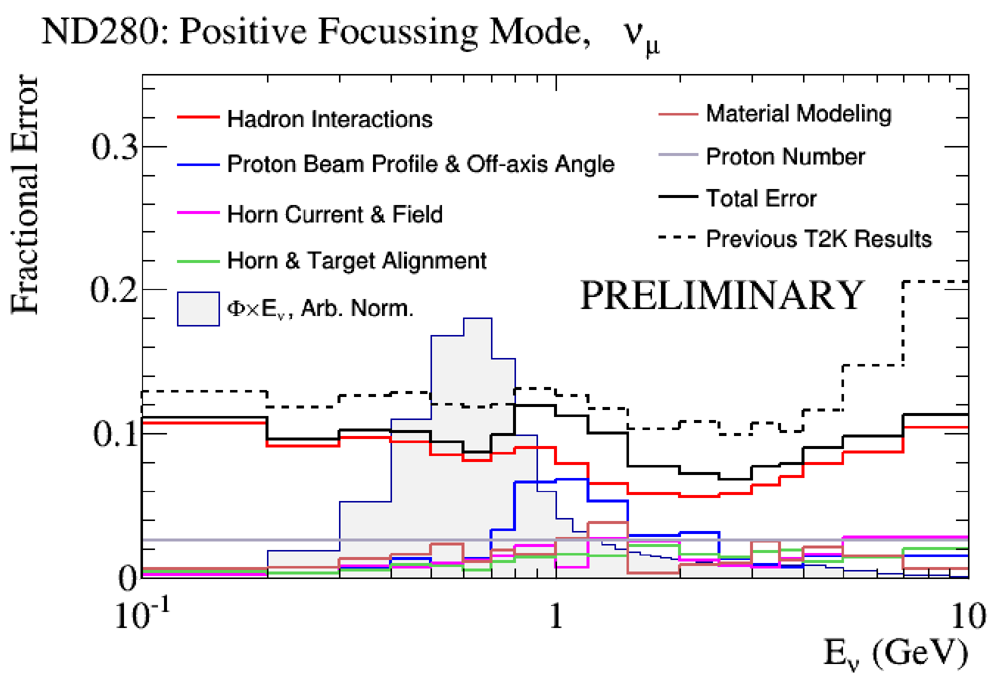
Flux simulation

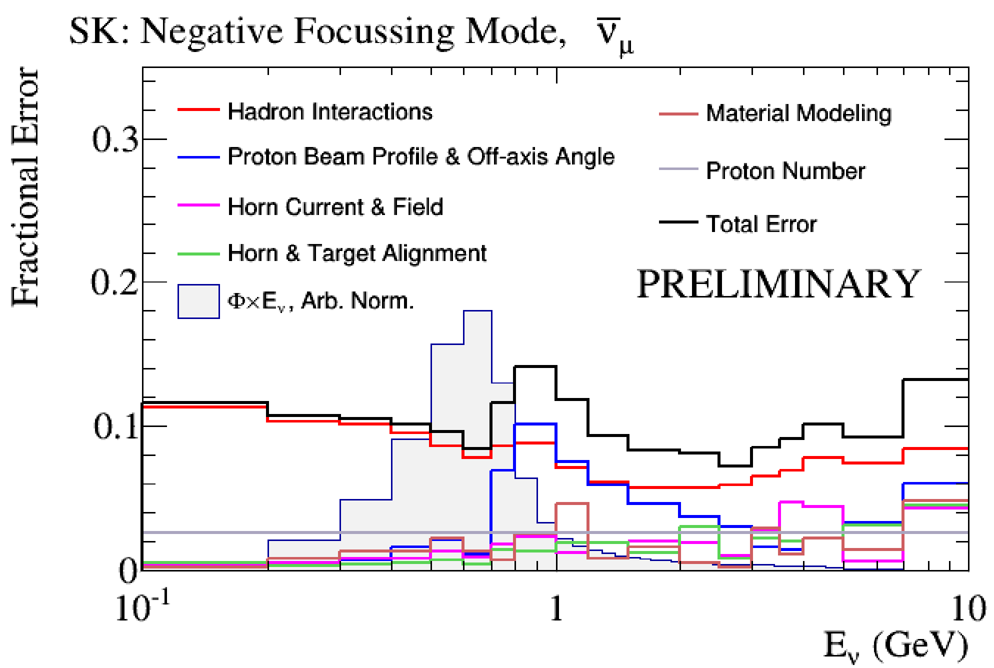


Flux simulation

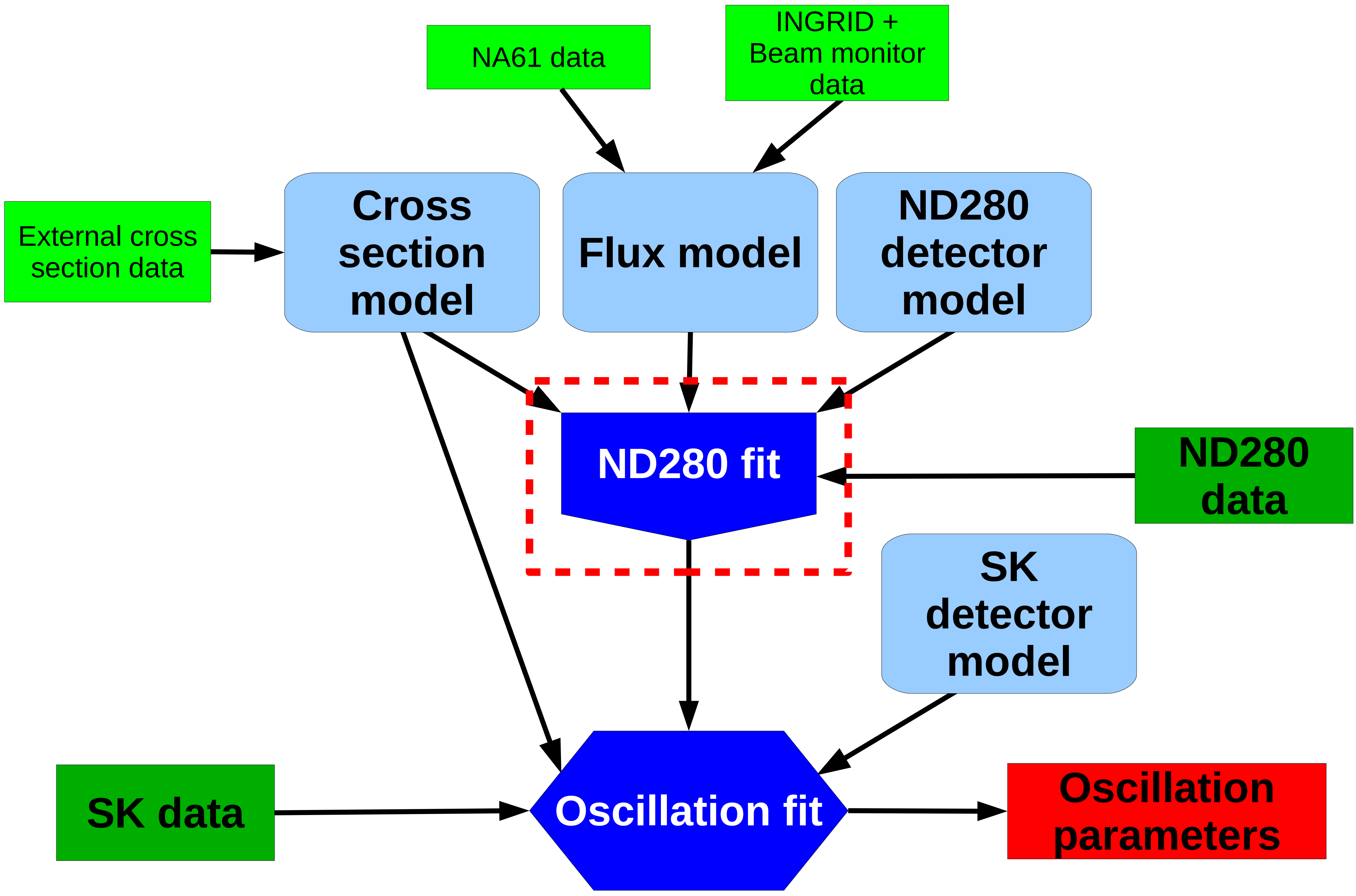








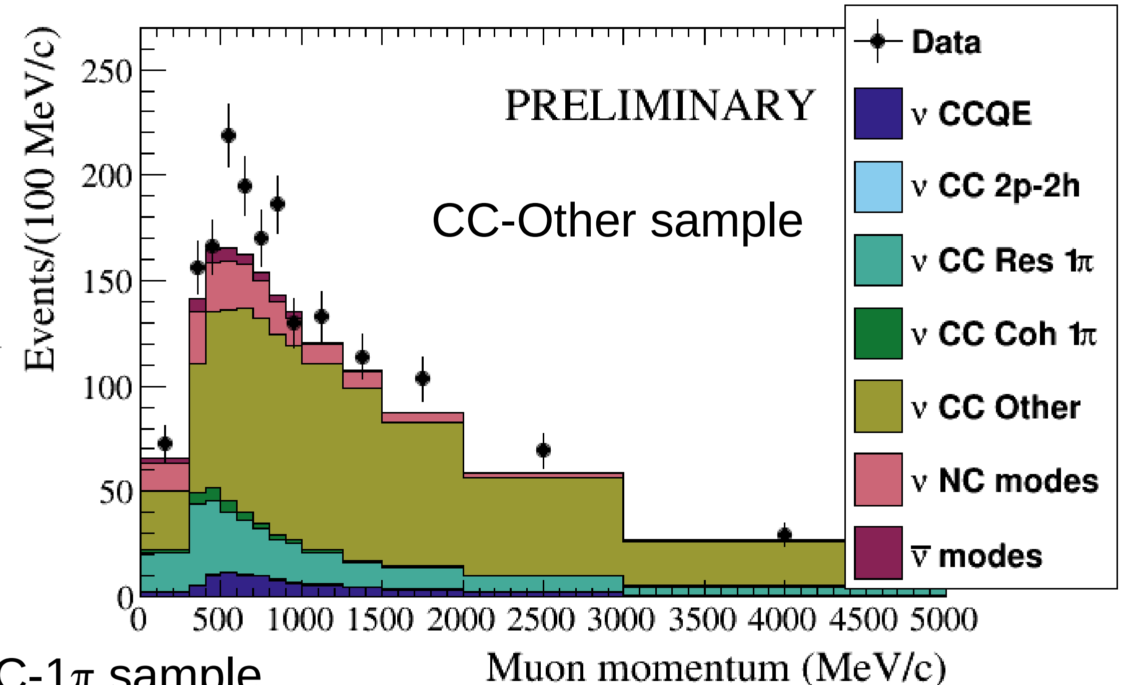
ND280 fit

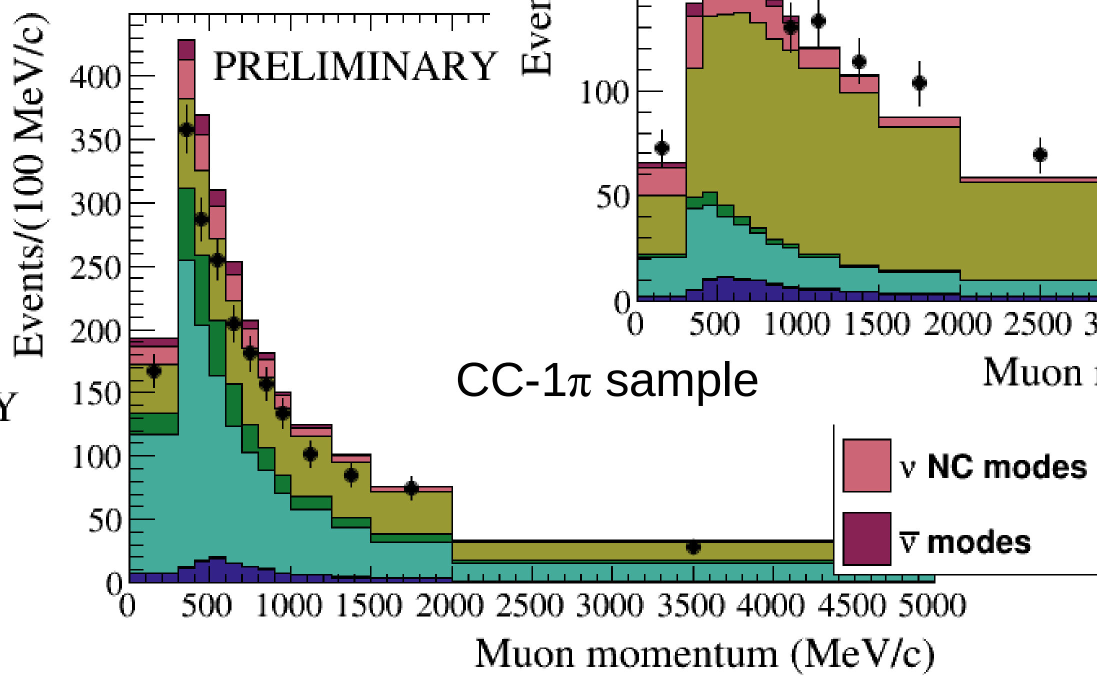

NA61 data
INGRID + Beam monitor data
External cross section data
Cross section model
Flux model
ND280 detector model
ND280 fit
ND280 data
SK detector model
SK data
Oscillation fit
Oscillation parameters

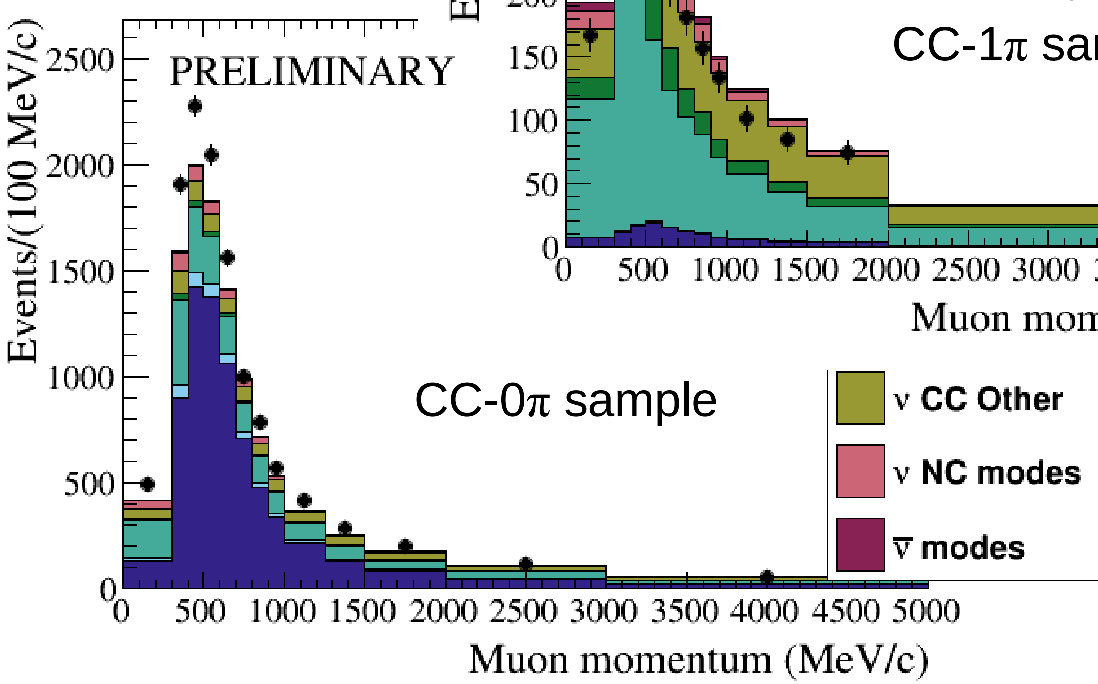
ND280 neutrino samples

Selection:

- Identify highest momentum muon-like track
- Separate by number of tagged pions



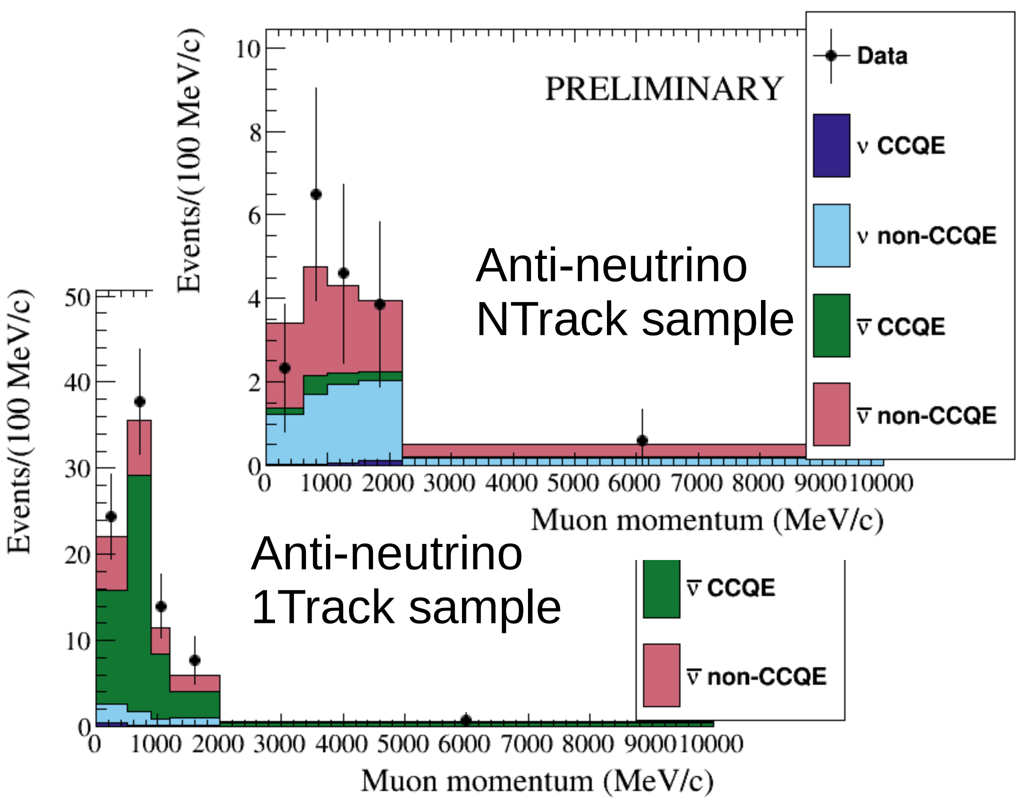


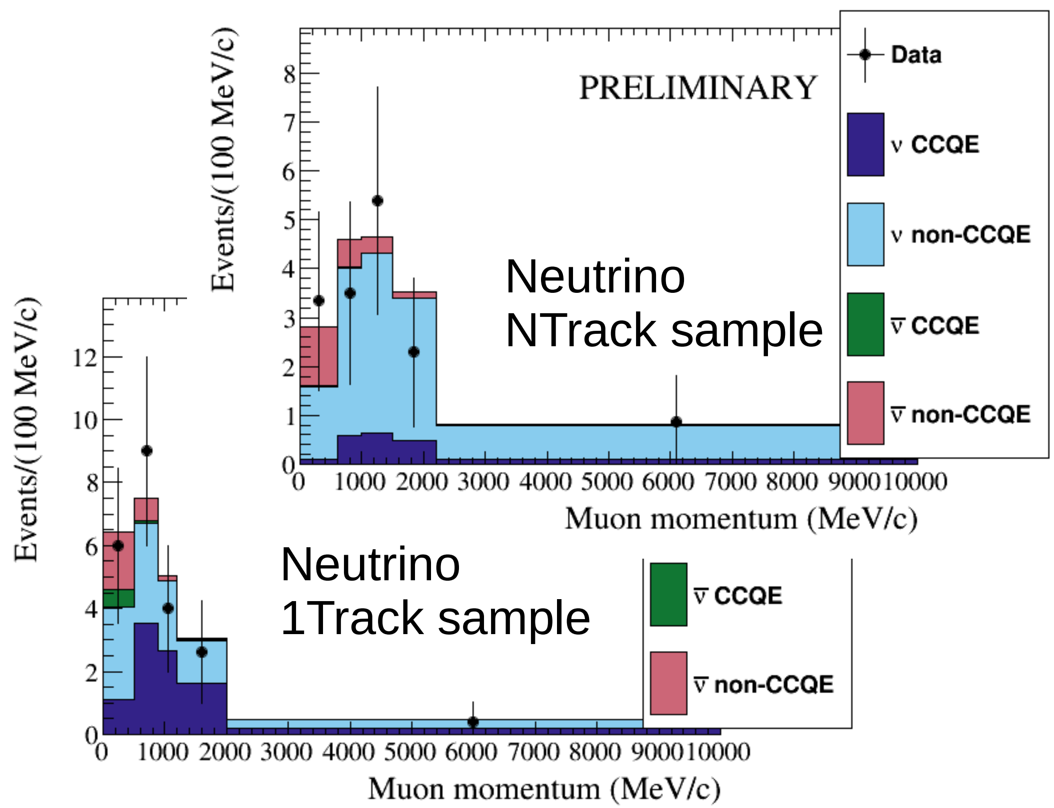


ND280 anti-neutrino samples

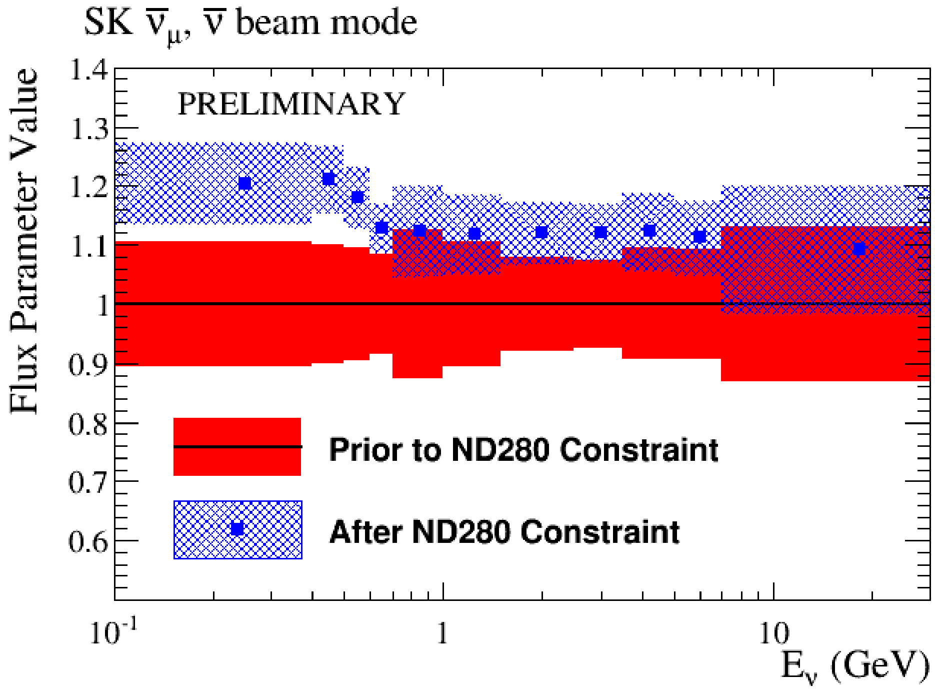
Selection:

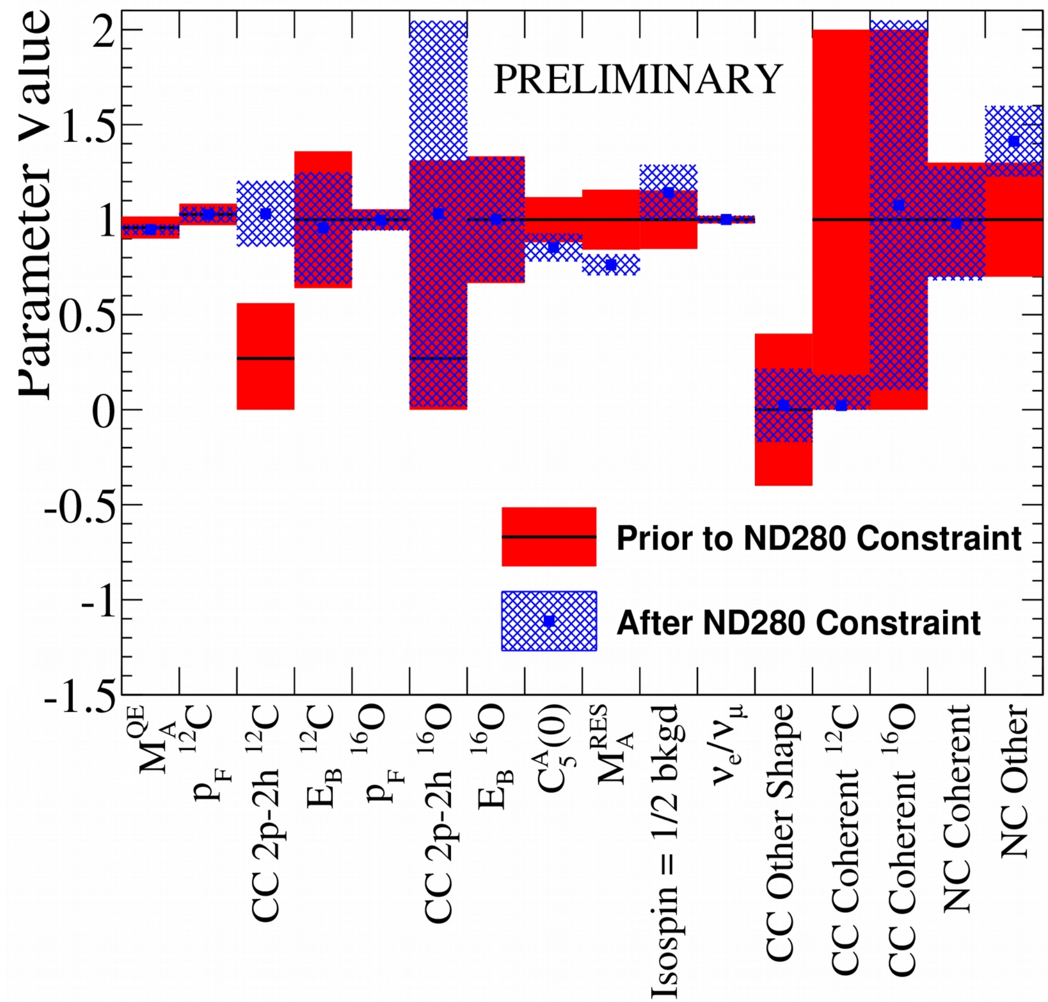
- Identify highest momentum muon-like track
  - Charge determines neutrino or anti-neutrino → select both to constrain wrong-sign background
- Separate by number of tracks





ND280 fit output





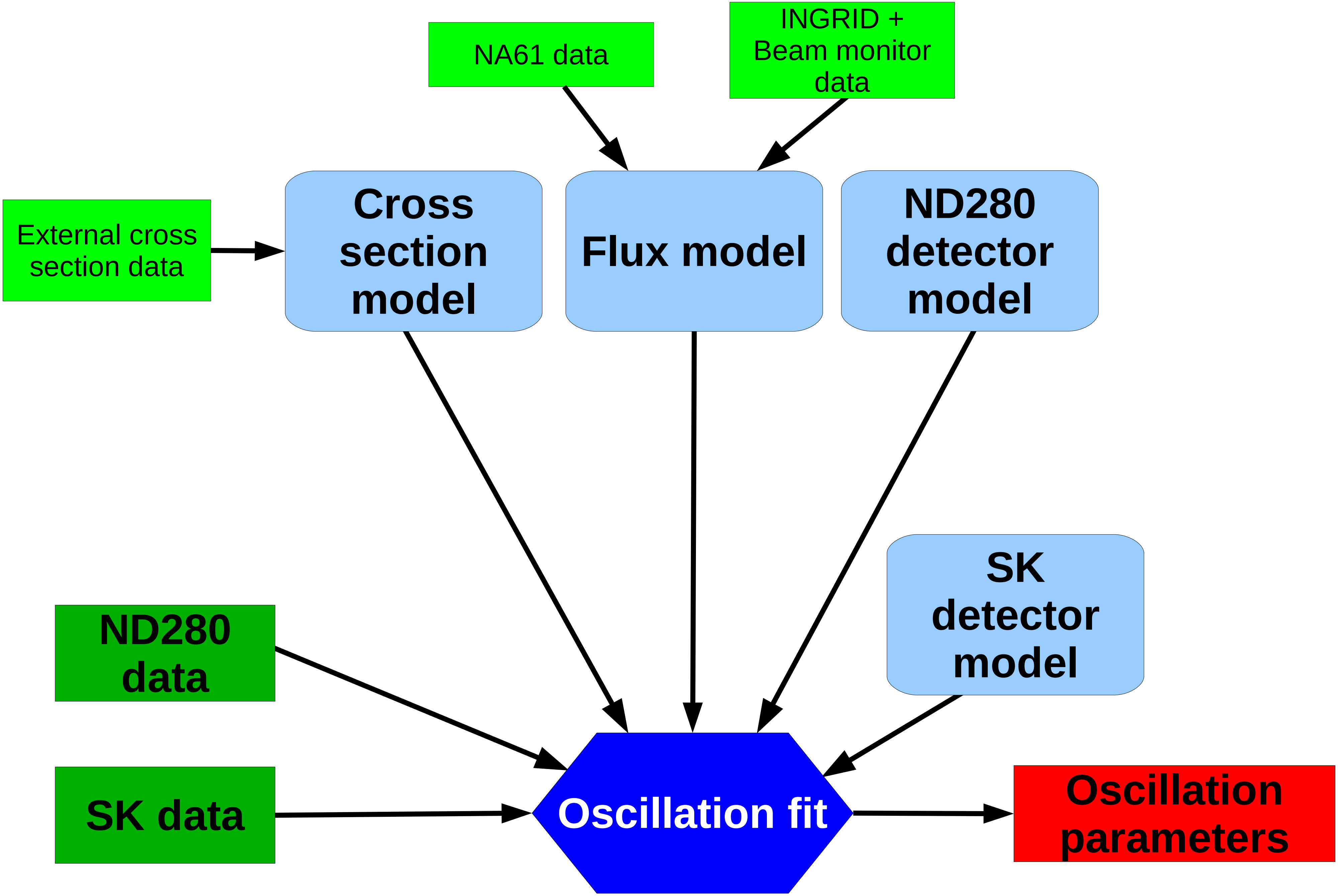
Flux prediction increased

Some cross section parameters moved far from prior values

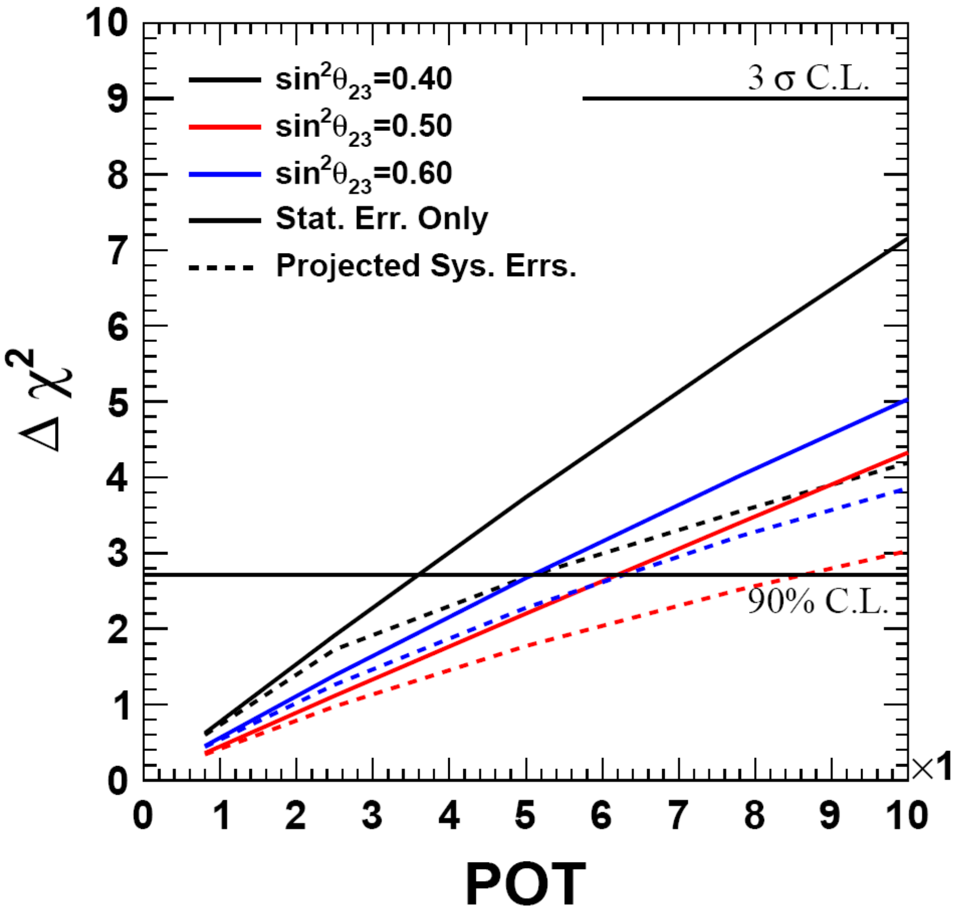
- Multi-nucleon normalisation on carbon
- Resonant pion production axial mass

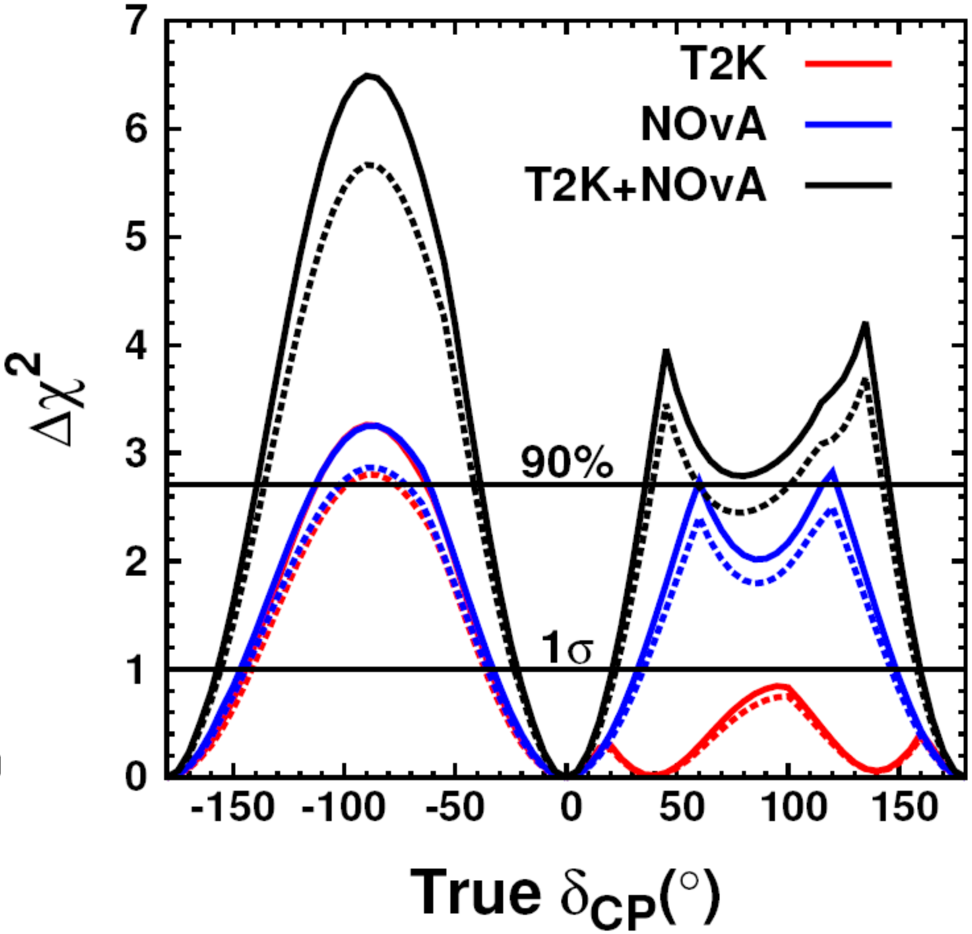
Overall – uncertainty on parameters decreases

MCMC analysis



T2K future sensitivity

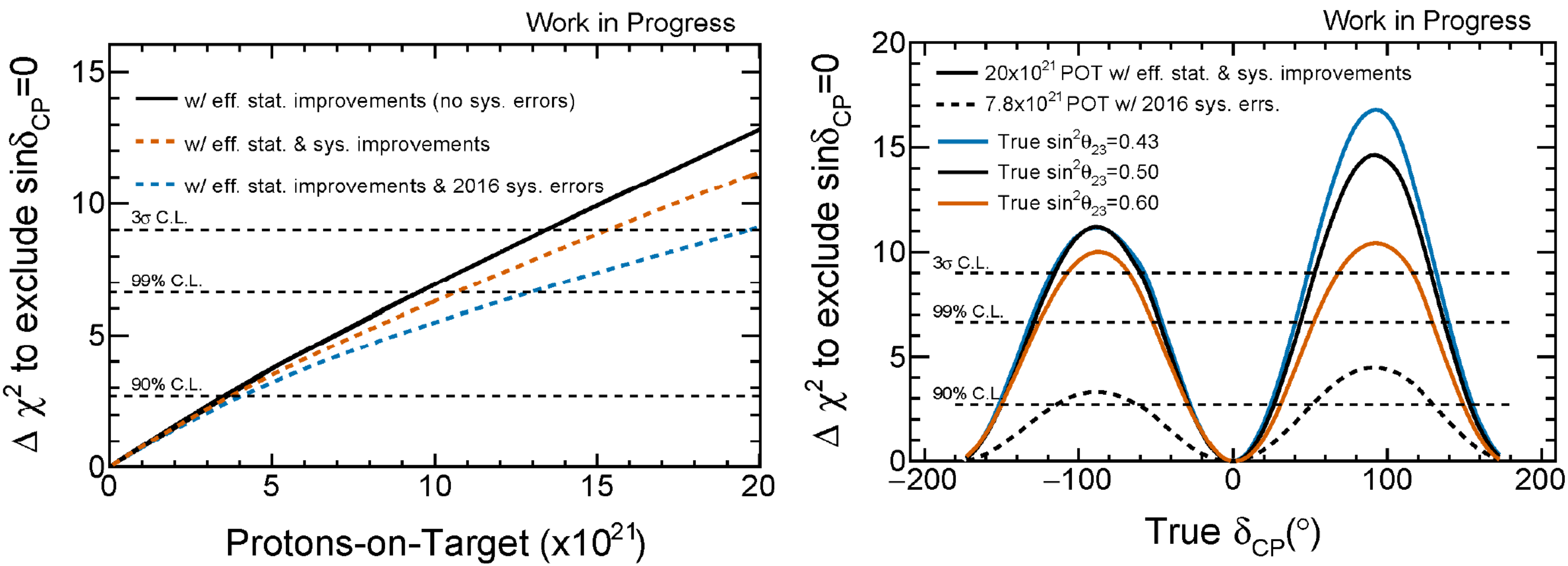




- Plots assume 1:1, ν:$\bar{\nu}$ running, for normal mass hierarchy
- T2K-only, left, assumes δ_{CP} = -90°
- T2K + NOvA reach 90% sensitivity to $\delta_{CP} \neq 0$

T2K Phase 2

- EOI to J-PARC PAC to extend T2K running to collect 20×10^{21} POT



- Expect 50% increase in statistics from new samples and improved reconstruction at SK
- Left plot assumes δ_{CP} = -90° and the normal mass hierarchy
- Right plot assumes known mass hierarchy
- T2K alone can achieve 3σ sensitivity to CP violation in neutrino oscillation