T2K and NuPRISM: An experimental solution to the problems of neutrino interactions in long baseline neutrino experiments

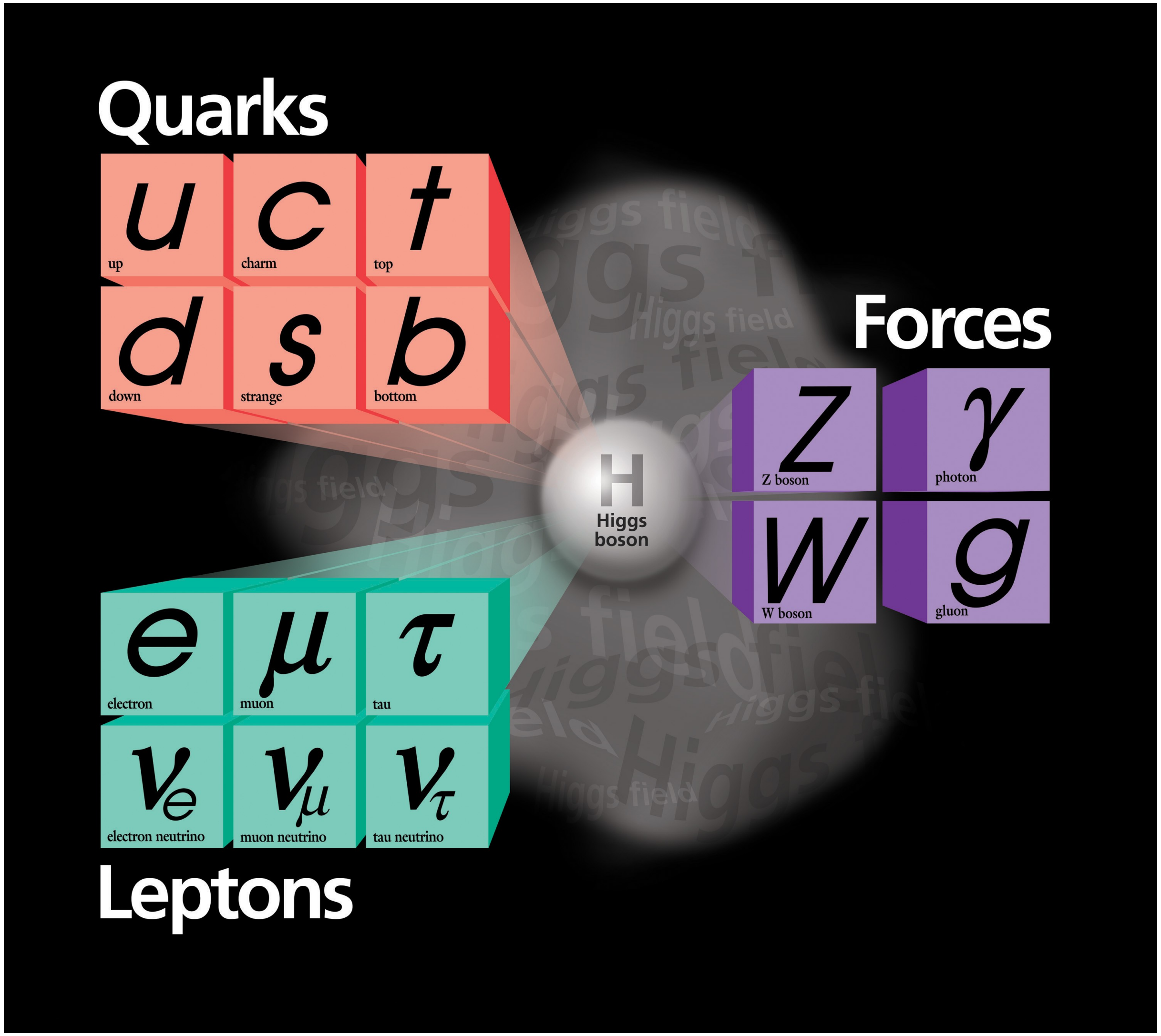
Mark Scott
University of Liverpool
20th July 2016

Outline

- Brief history and physics of neutrino oscillations
- Long baseline neutrino oscillations
  - T2K experiment
  - Oscillation analysis method
  - Latest oscillation results
- NuPRISM
  - Physics concept
  - NuPRISM in oscillations
  - Cross-sections and sterile neutrinos
  - Current status

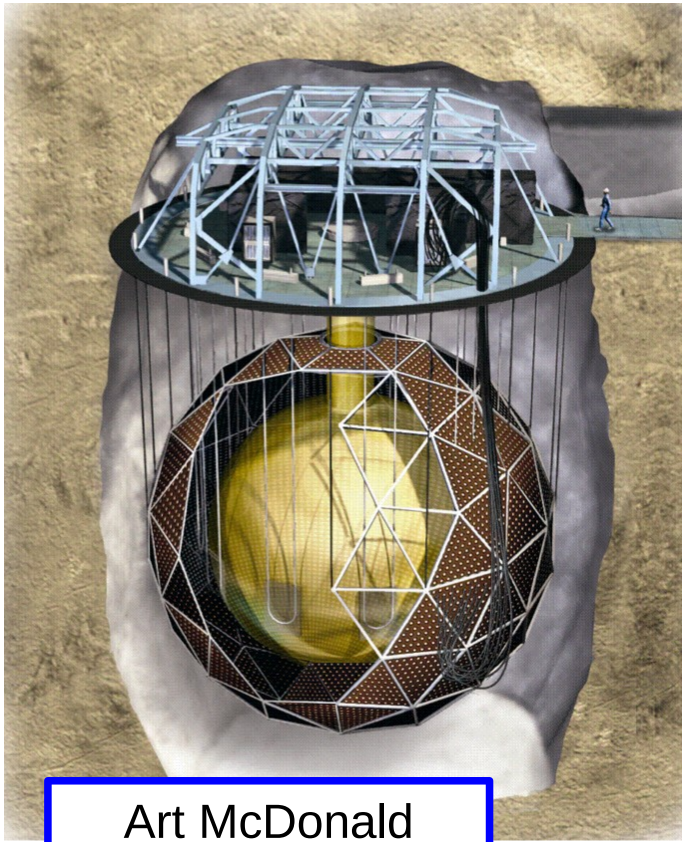
Neutrinos...

- Neutral partner to charged leptons
- 2^{nd} most abundant particle in nature
- Almost zero mass
- Interact very rarely
  - Only through weak force
  - Billions pass through every cm^2 per second

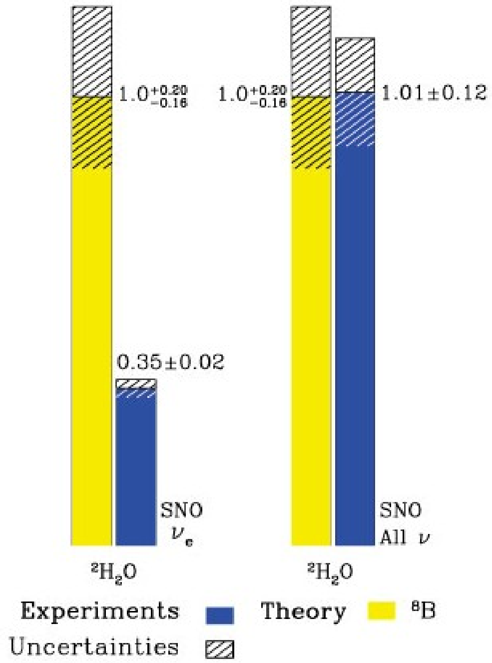


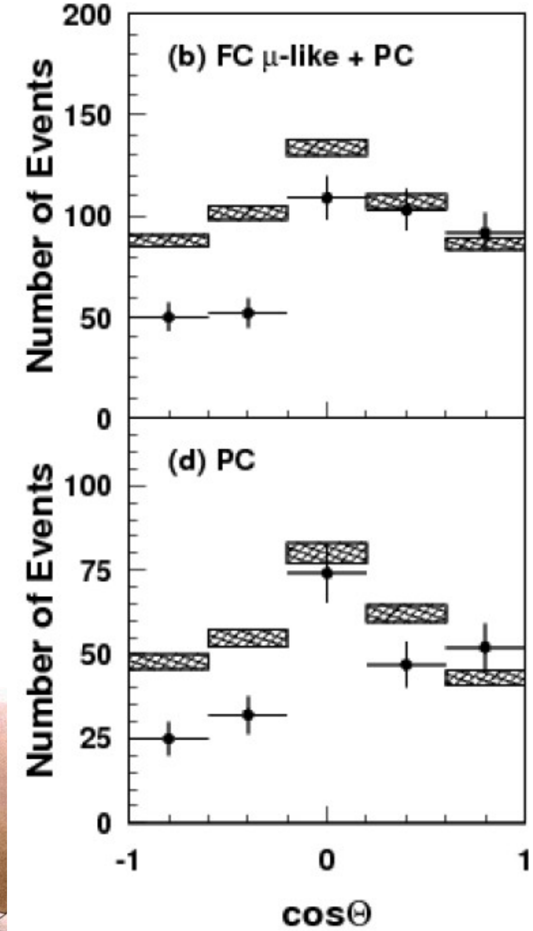
Neutrino oscillation

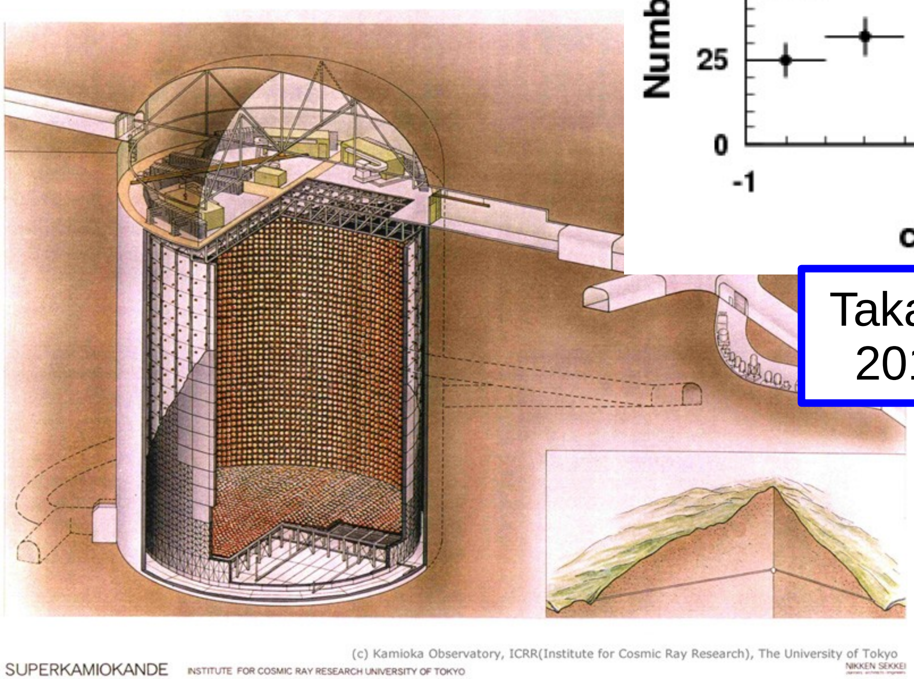
TRIUMF



Art McDonald
2015 Nobel







Takaaki Kajita
2015 Nobel

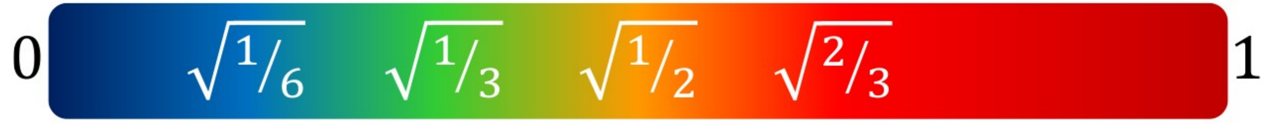
SNO - electron neutrinos made up ~1/3rd total solar neutrino flux

Super-Kamiokande – Atmospheric neutrino rate depends on path length

Neutrino oscillation

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

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

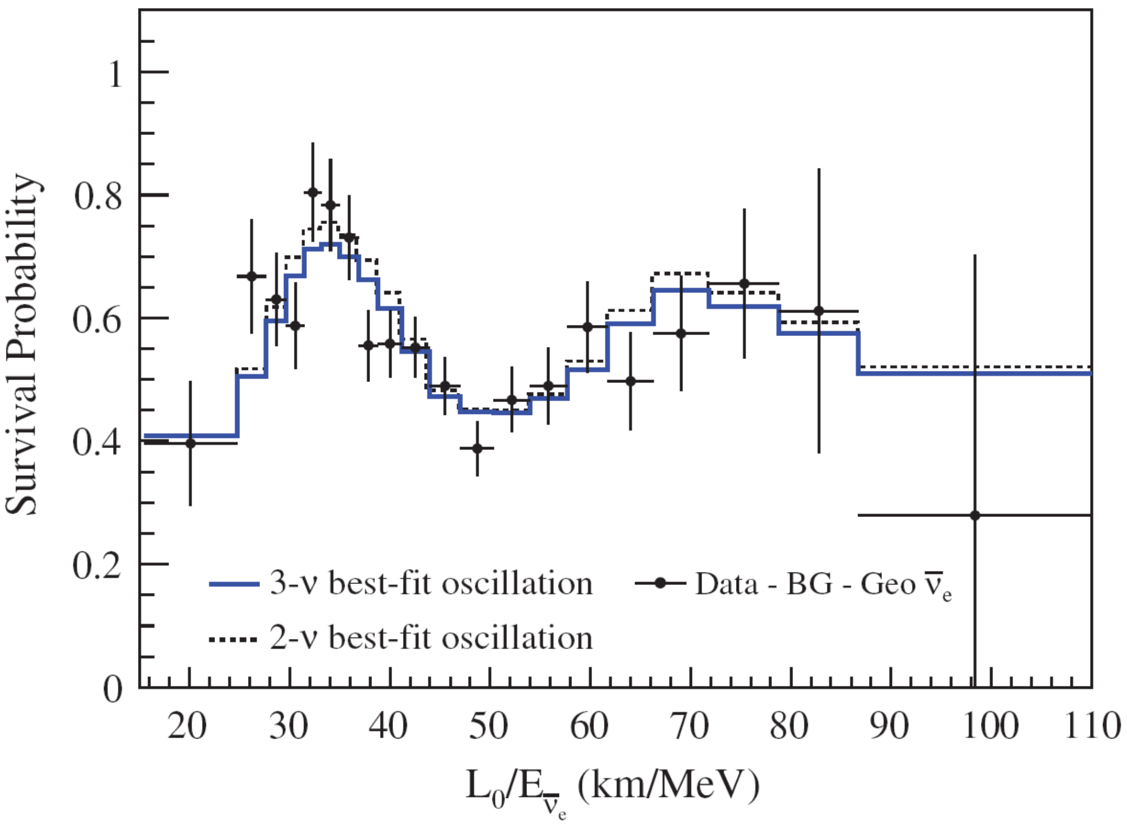


$$P_{\alpha\to\beta} = \left|\langle \nu_\beta | \nu_\alpha(t) \rangle\right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E} \right|^2$$

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

Neutrino oscillation

- KamLAND experiment:
- Surrounded by nuclear reactors
  - Same energy neutrinos
  - Different distances
- Directly measured disappearance and reappearance



- Neutrinos oscillate between the different flavours
  - Neutrinos are massive particles
  - First (and only) experimentally observed BSM physics

What do we know?

TRIUMF

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

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

Atmospheric | Reactor/Beam | Solar

$\theta_{23} = 45.8^o \pm 3.2^o$ $\theta_{13} = 8.51^o \pm 0.23^o$ $\theta_{12} = 33.5^o \pm 0.8^o$

- Also have two mass splittings:

  $|\Delta m^2_{32}| = (2.42 \pm 0.06) \times 10^{-3}\ eV^2$

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

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

How do we measure these parameters?

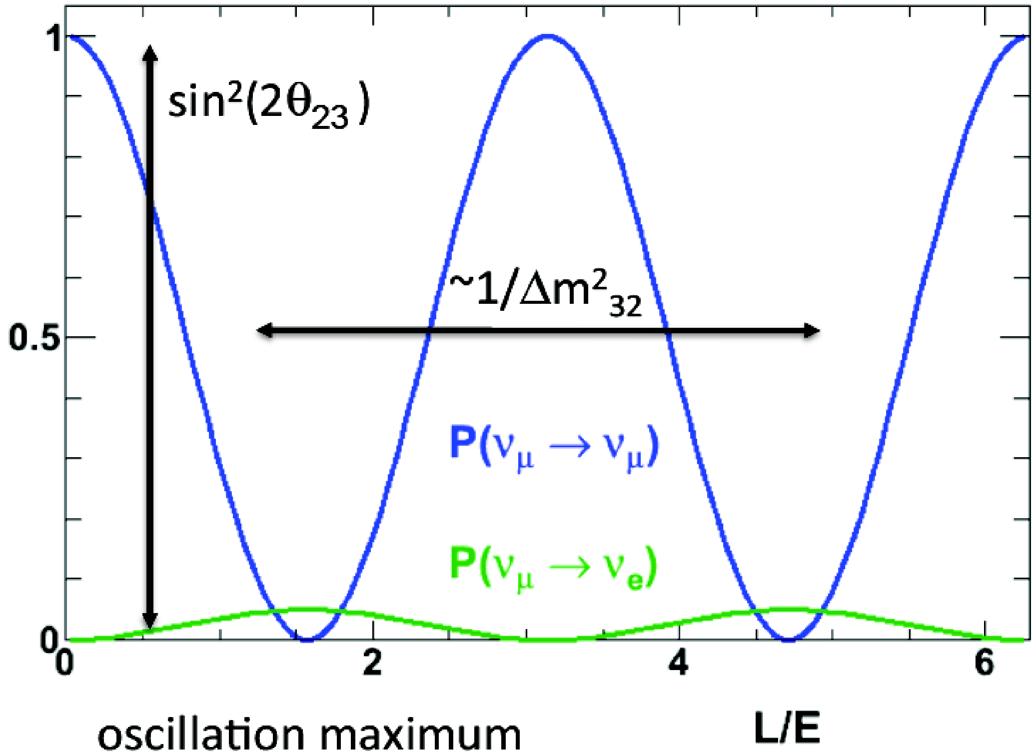
PDG 2015

Measuring neutrino oscillations

- Leading terms for ν_μ disappearance and ν_e appearance

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

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

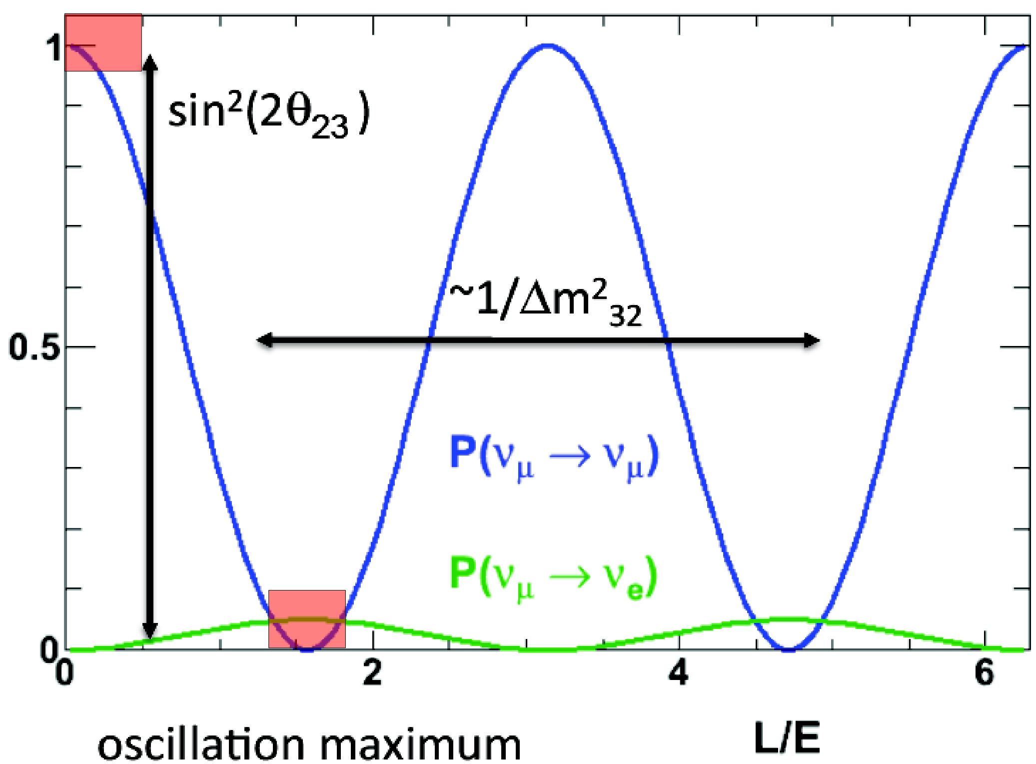


Measuring neutrino oscillations

- Leading terms for ν_μ disappearance and ν_e appearance

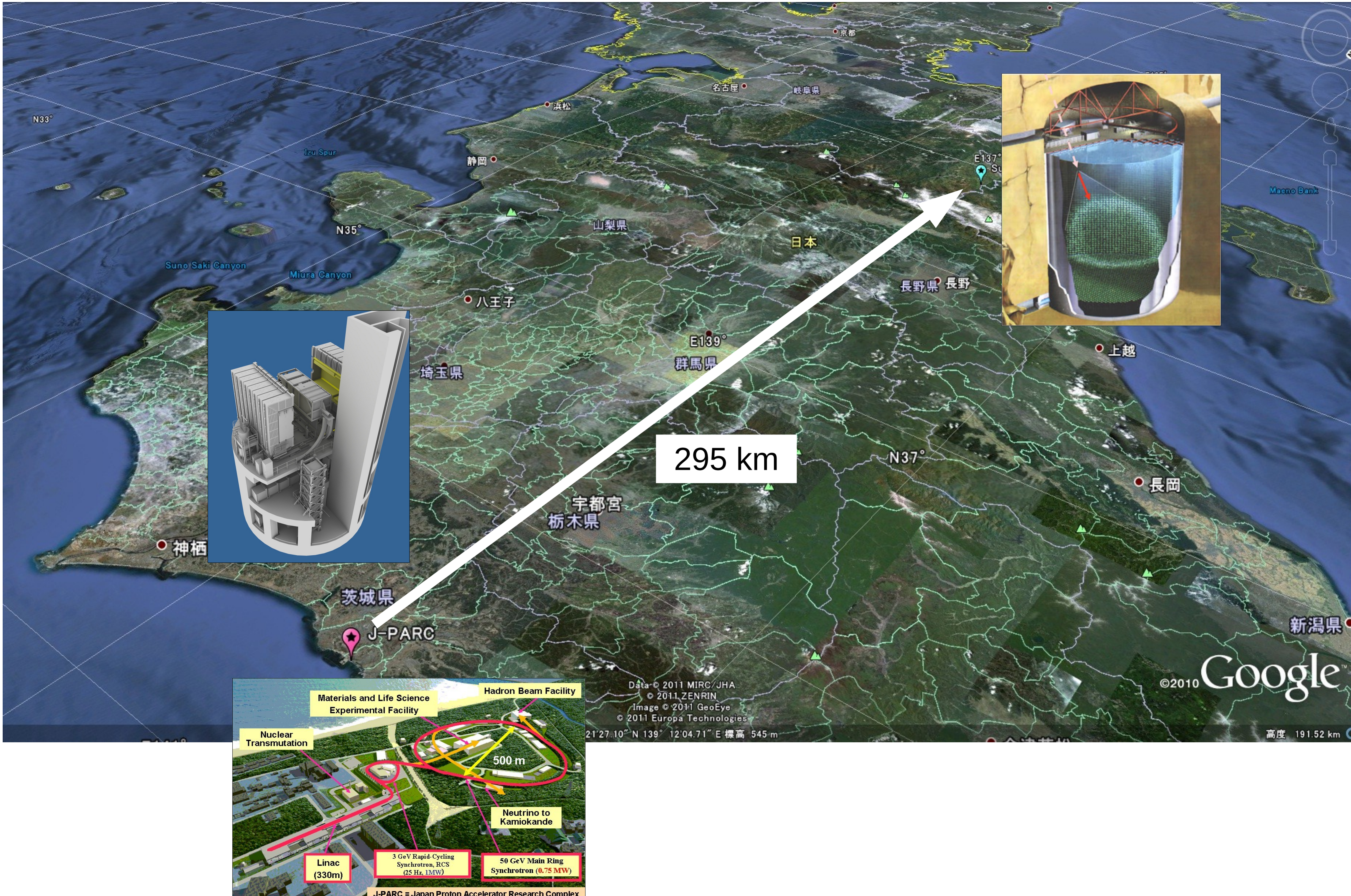
$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

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

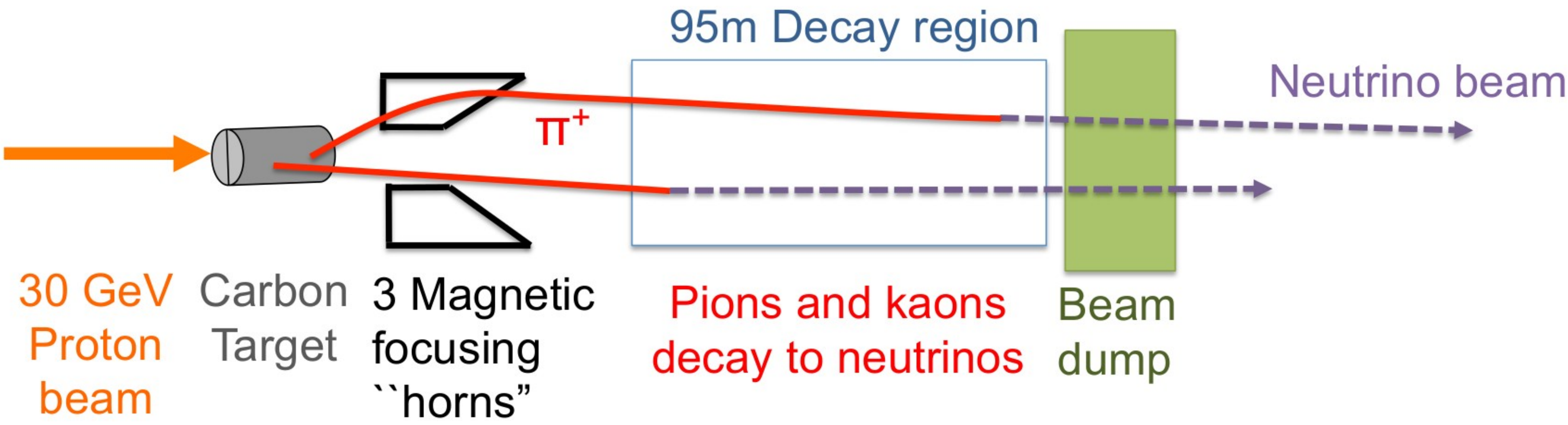


- Need to sample spectrum at different values of L/E
- Build two detectors
  - One close to neutrino source
  - Other at maximal oscillation

Tokai to Kamioka (T2K) experiment

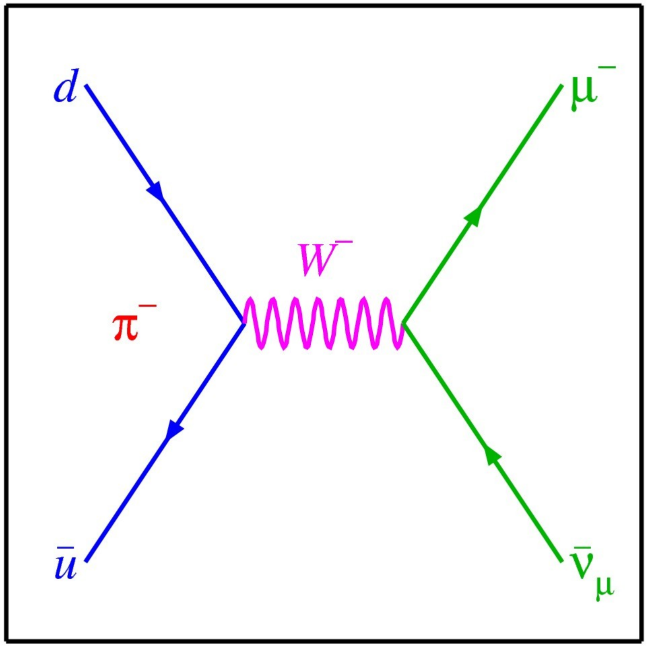


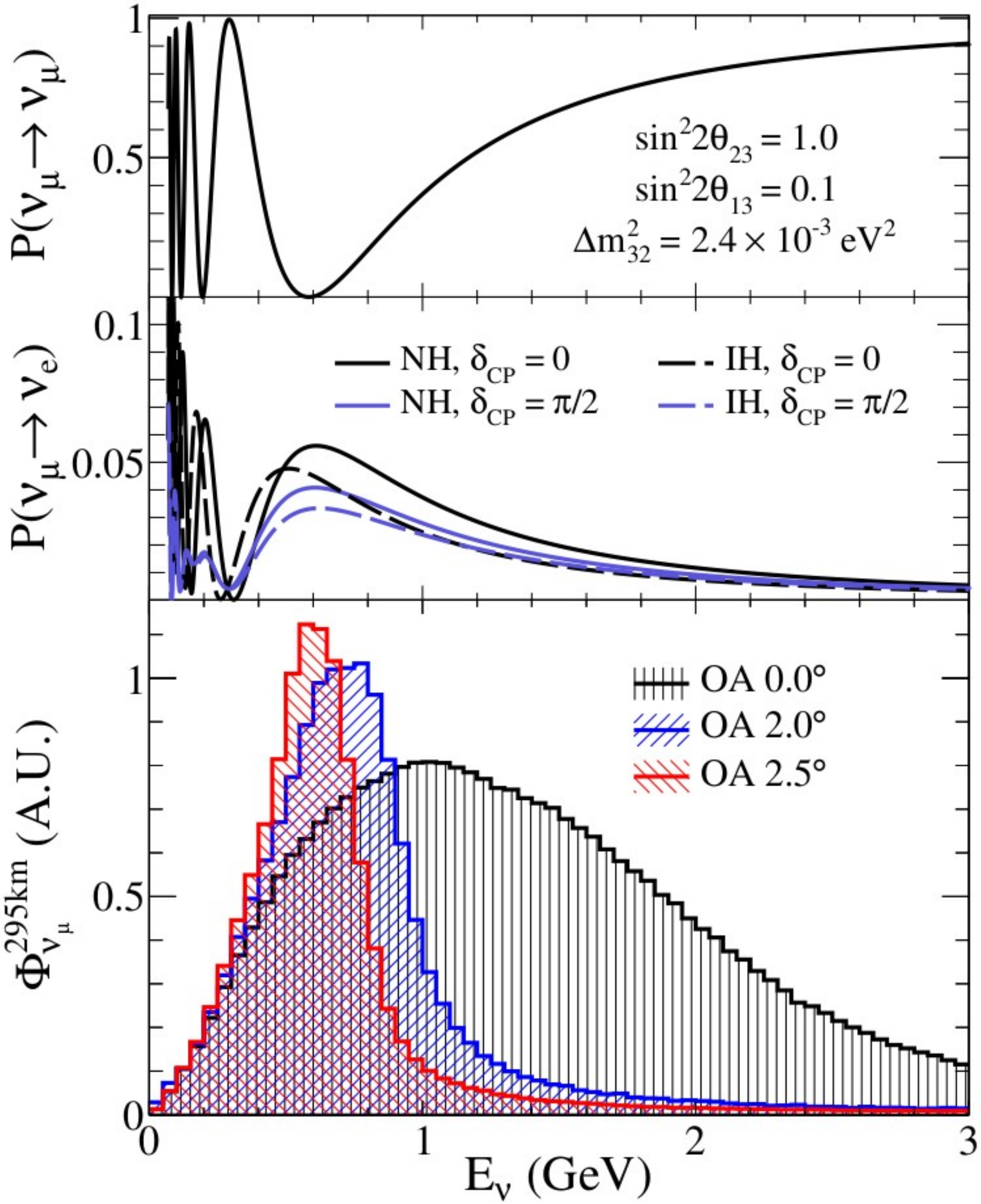
Creating neutrino beams



- Tertiary beam:
  - Protons produce hadrons
  - Hadrons focussed by magnetic horns
  - Hadrons decay in flight
  - Neutrino 'beam'

Off-axis effect



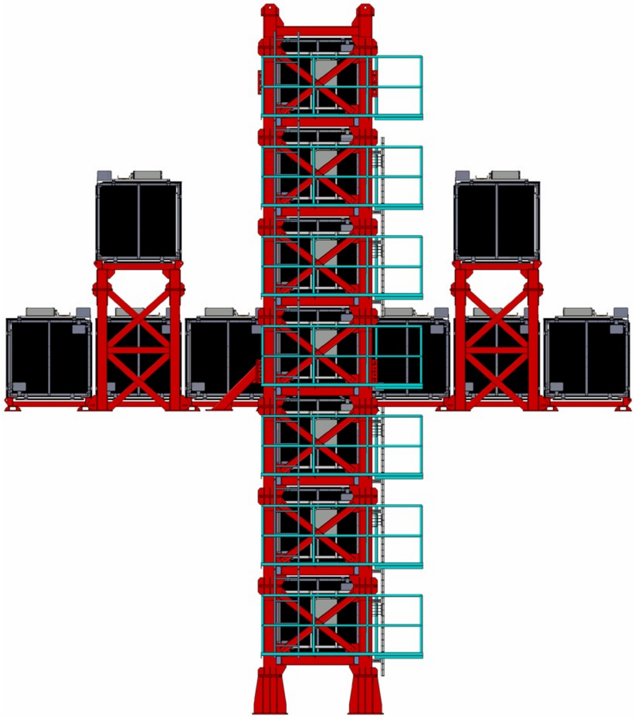


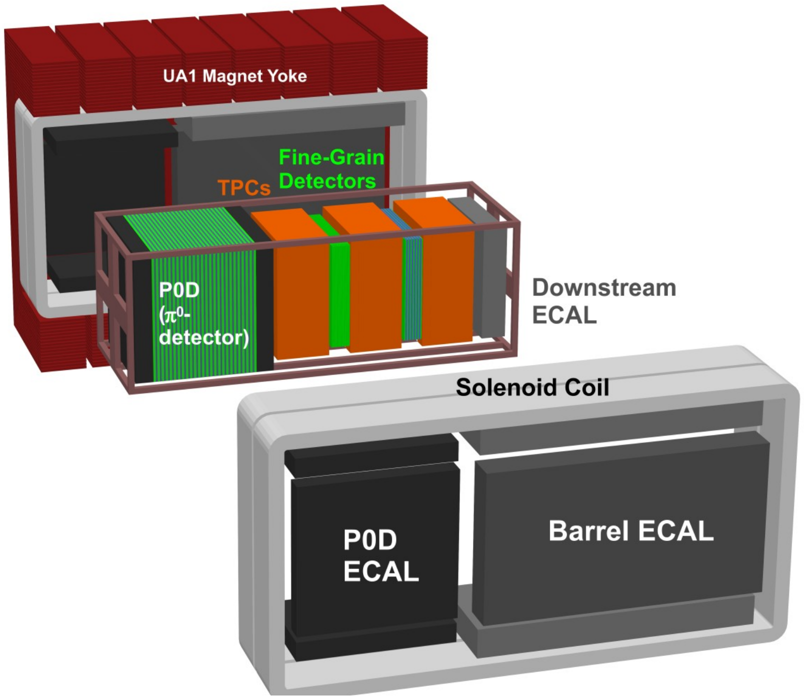
- Two-body pion decay
- Angle and energy of neutrino directly linked
- Moving off axis:
  - Lower peak energy
  - Smaller high energy tail
  - Less energy spread

The Near Detectors at 280m

Interactive Neutrino GRID

- 7 x 7 cross
- Iron and plastic scintillator sheets
- Measures neutrino beam direction to < 1mrad



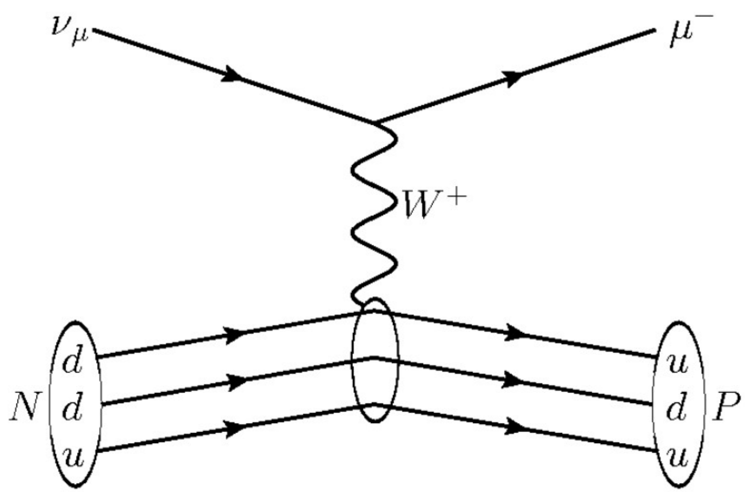


ND280 Off-axis detector

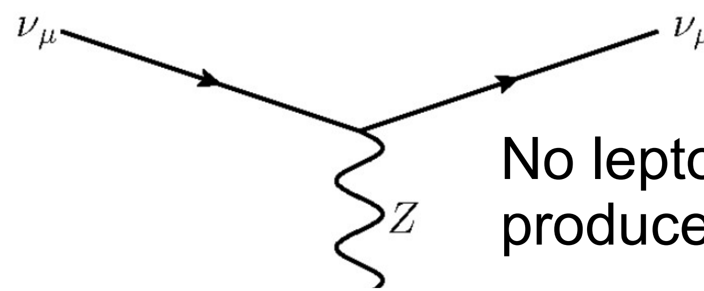
- Fine-grained (FGD) target – vertex reconstruction
- Magnet + TPC – precise momentum, charge and PID
- Characterise neutrino beam

Types of neutrino interaction

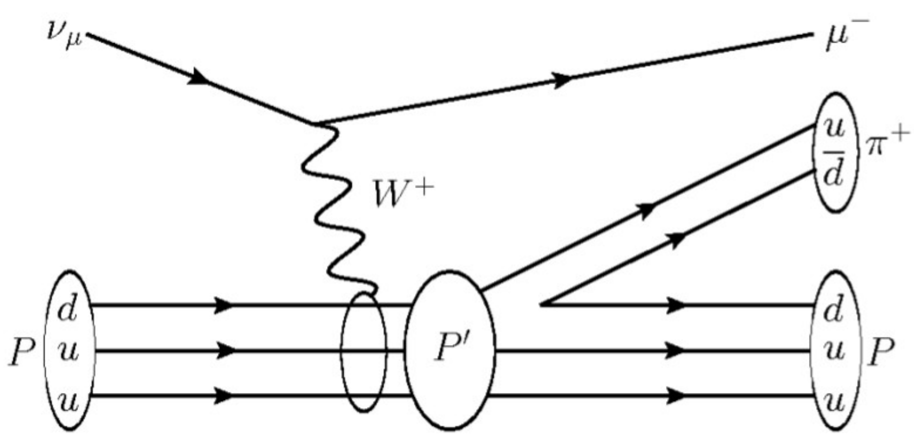
Three principal types of neutrino interaction – occur as both charged current (CC) and neutral current processes



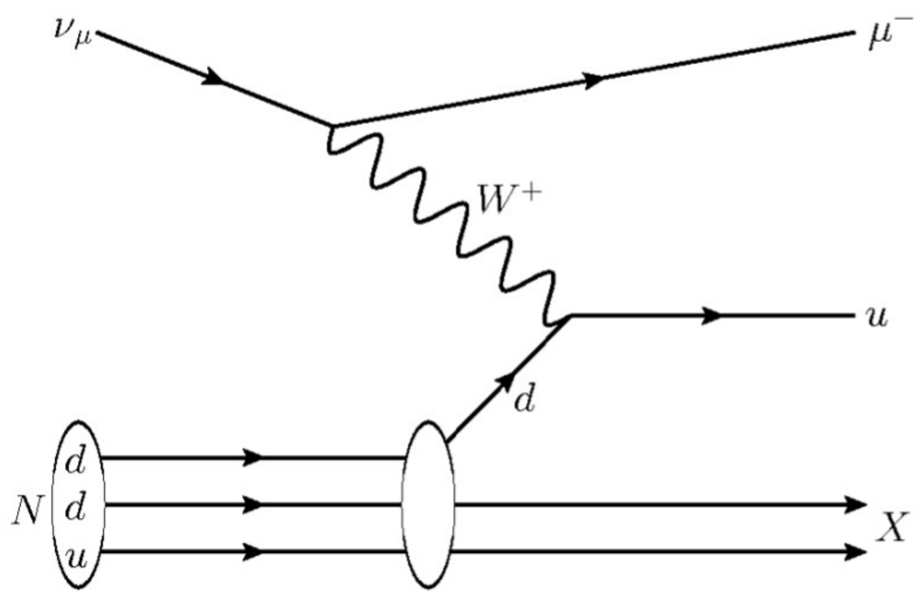
(a) CC QES interaction



No lepton produced

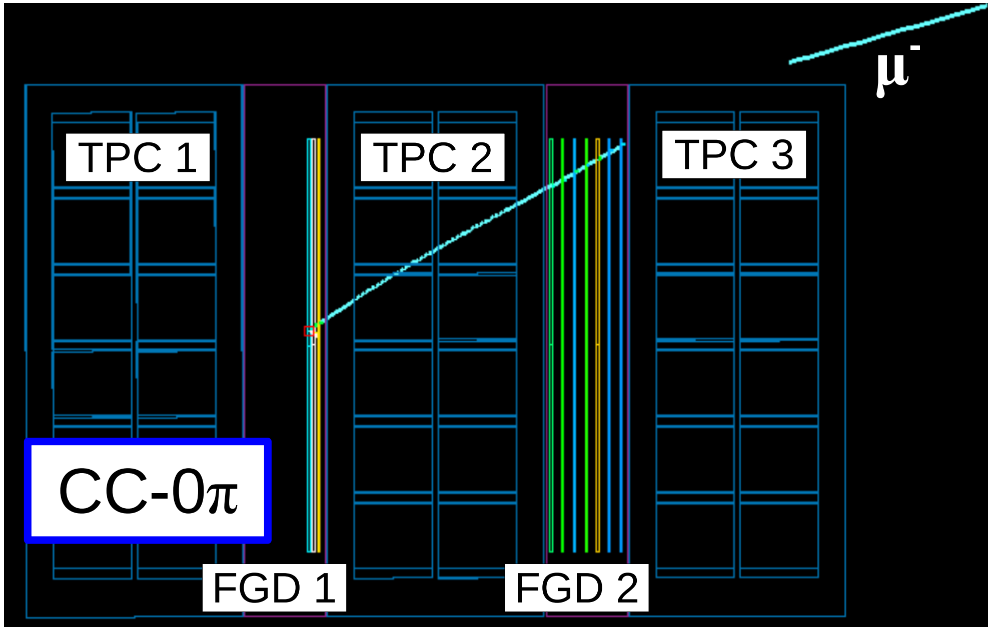


(a) CCRES interaction



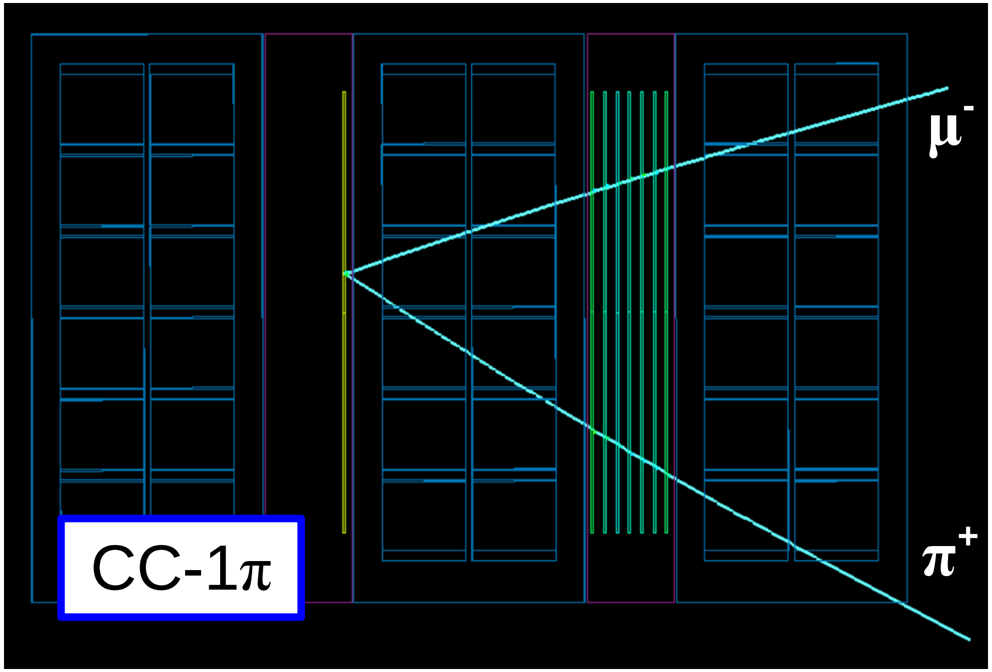
(b) CCDIS interaction

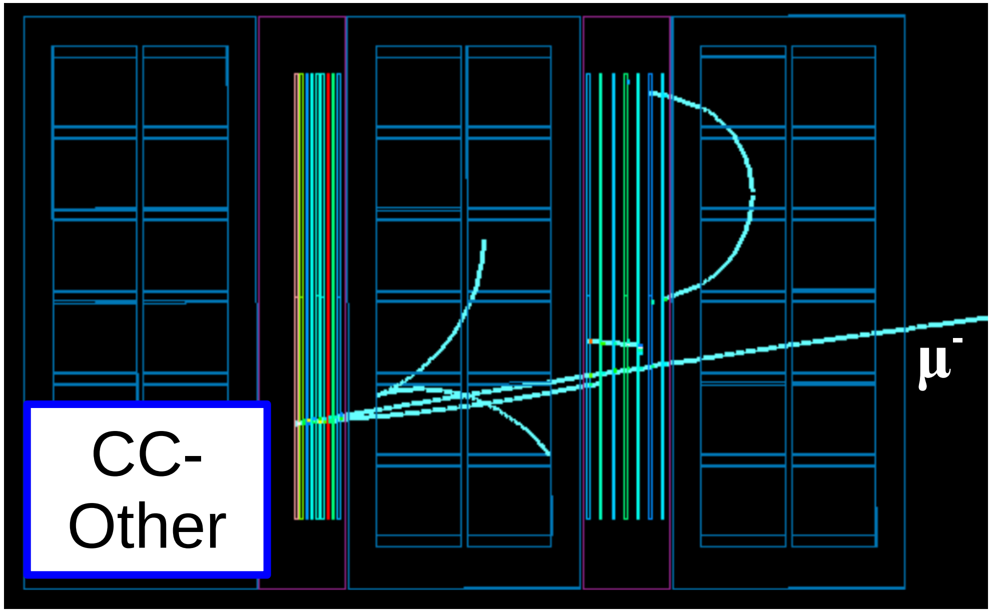
ND280 data



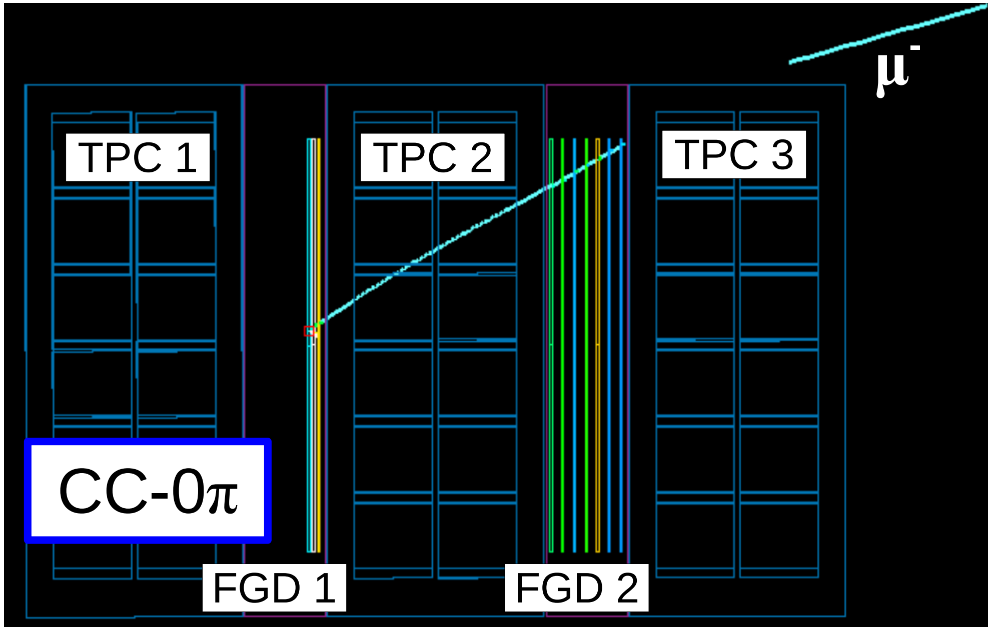
Selection:

- 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



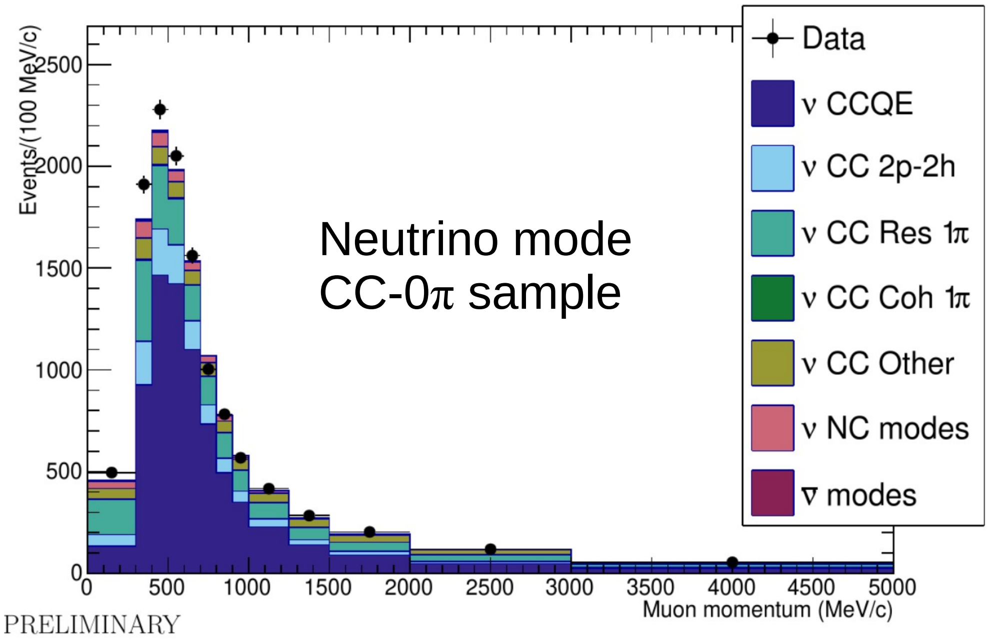


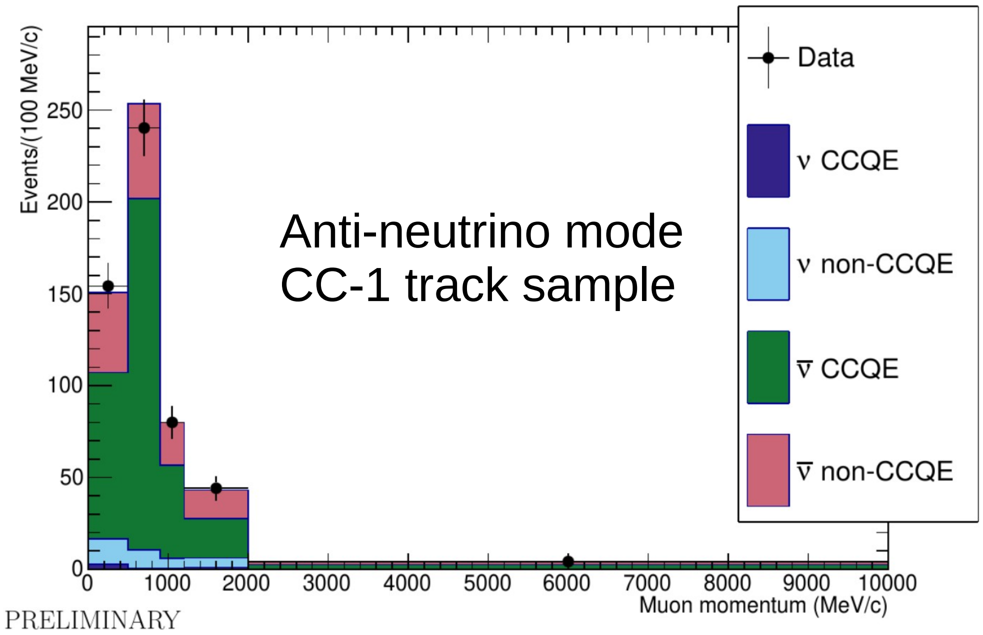
ND280 data



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

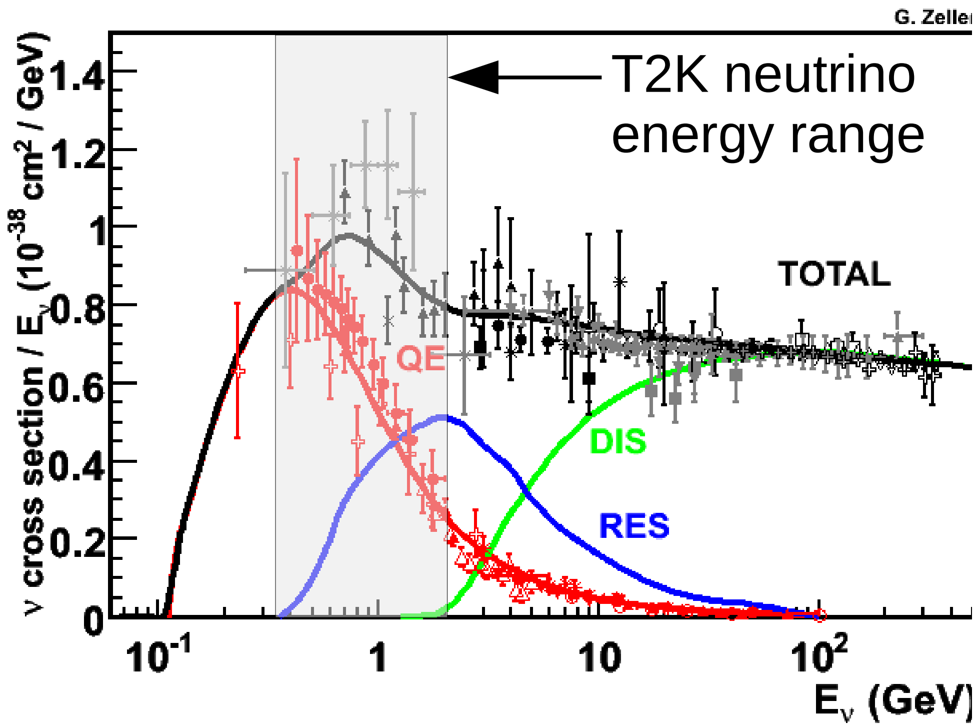




Neutrino cross-sections

Neutrino interaction cross-sections have ~10% uncertainty:

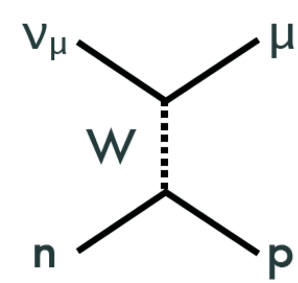
- Nuclear environment has large effect on interaction
  - Cannot calculate from first principles
- Existing data has large uncertainties



Charged current quasi-elastic interactions are primary signal

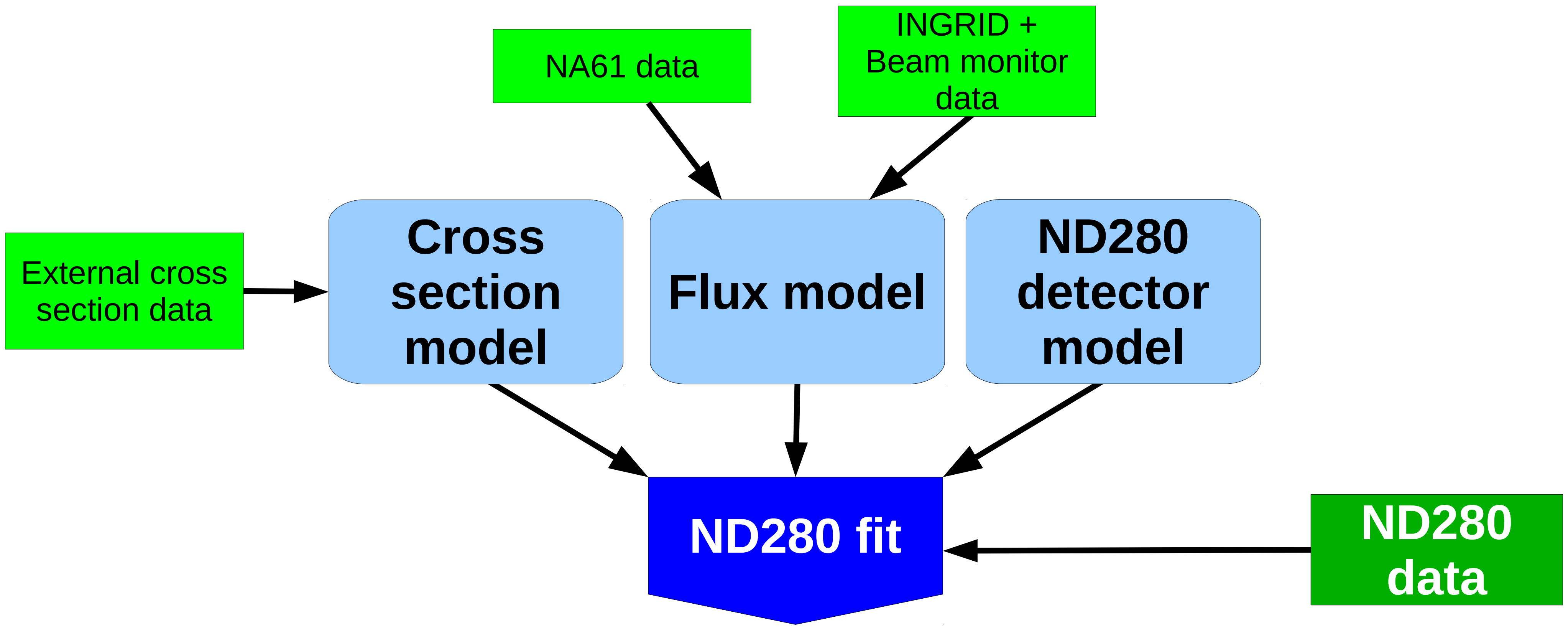
- But, other interactions mimic CCQE
  - Detector effects, final state interactions
- Need to understand multiple interaction modes over range of neutrino energies

Charged current quasi-elastic (CCQE)



Cannot directly measure neutrino flux – known to ~8% level at T2K

T2K near detector analysis

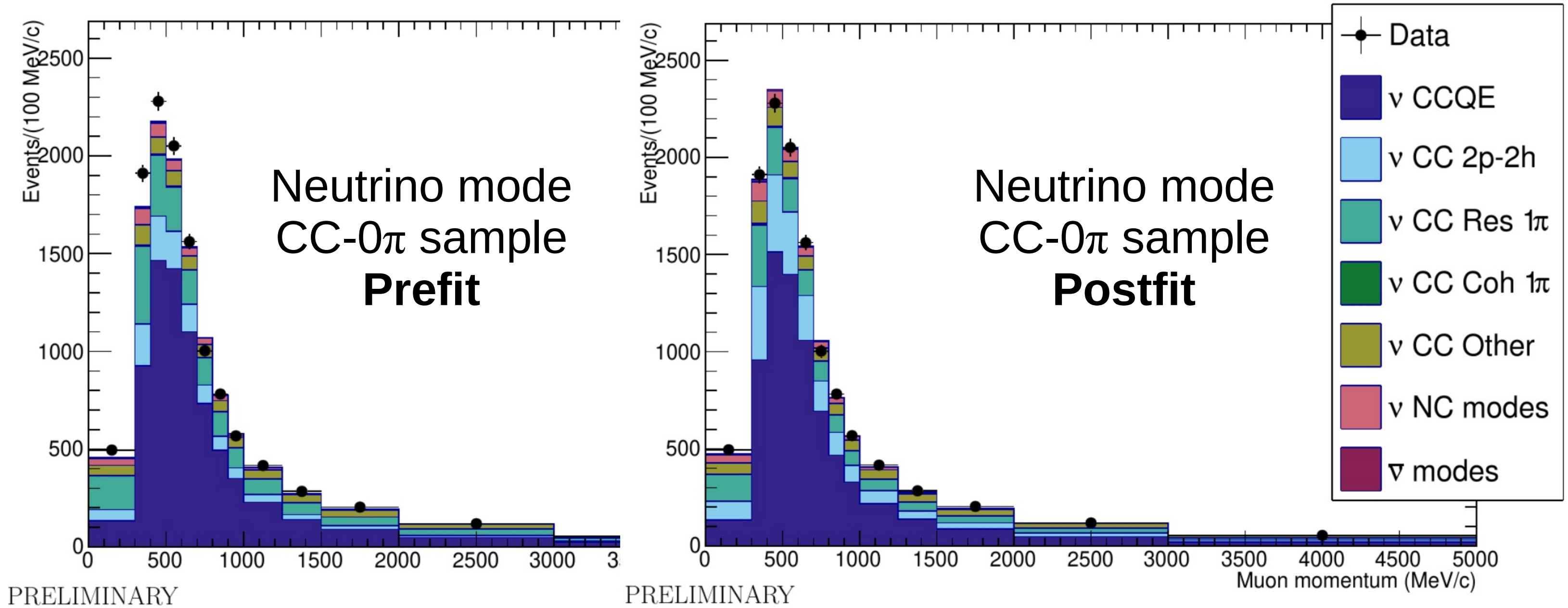


Detectors measure interaction rate:

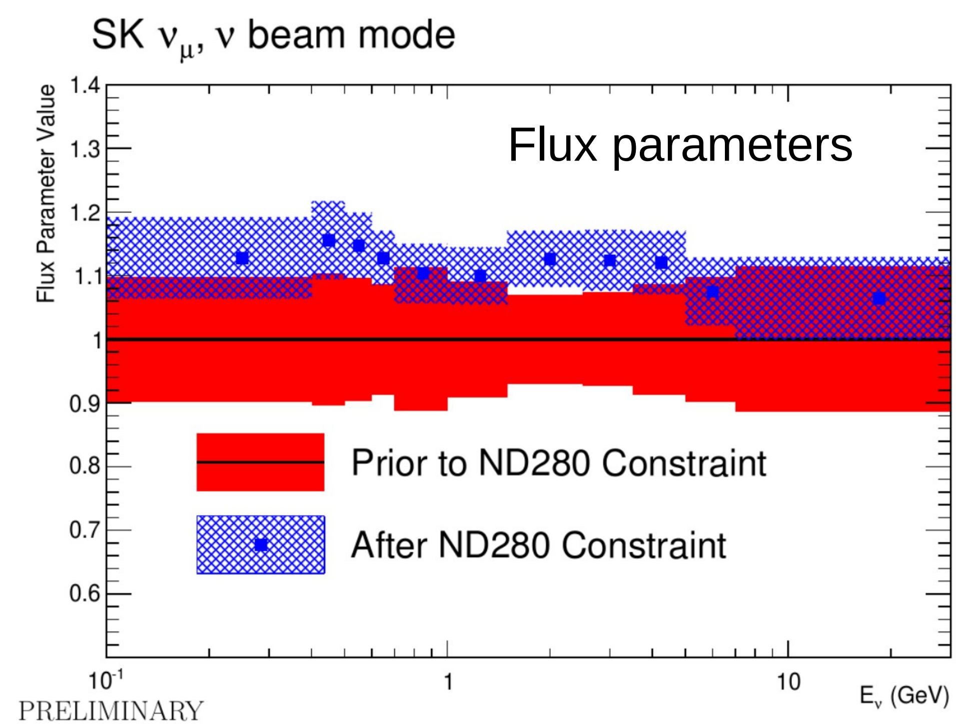
- Flux * Cross-section
- Joint fit of models to ND280 data allows constraint on rate
  - Anti-correlate flux and cross-section uncertainty
- Propagate tuned models to far detector

ND280 fit

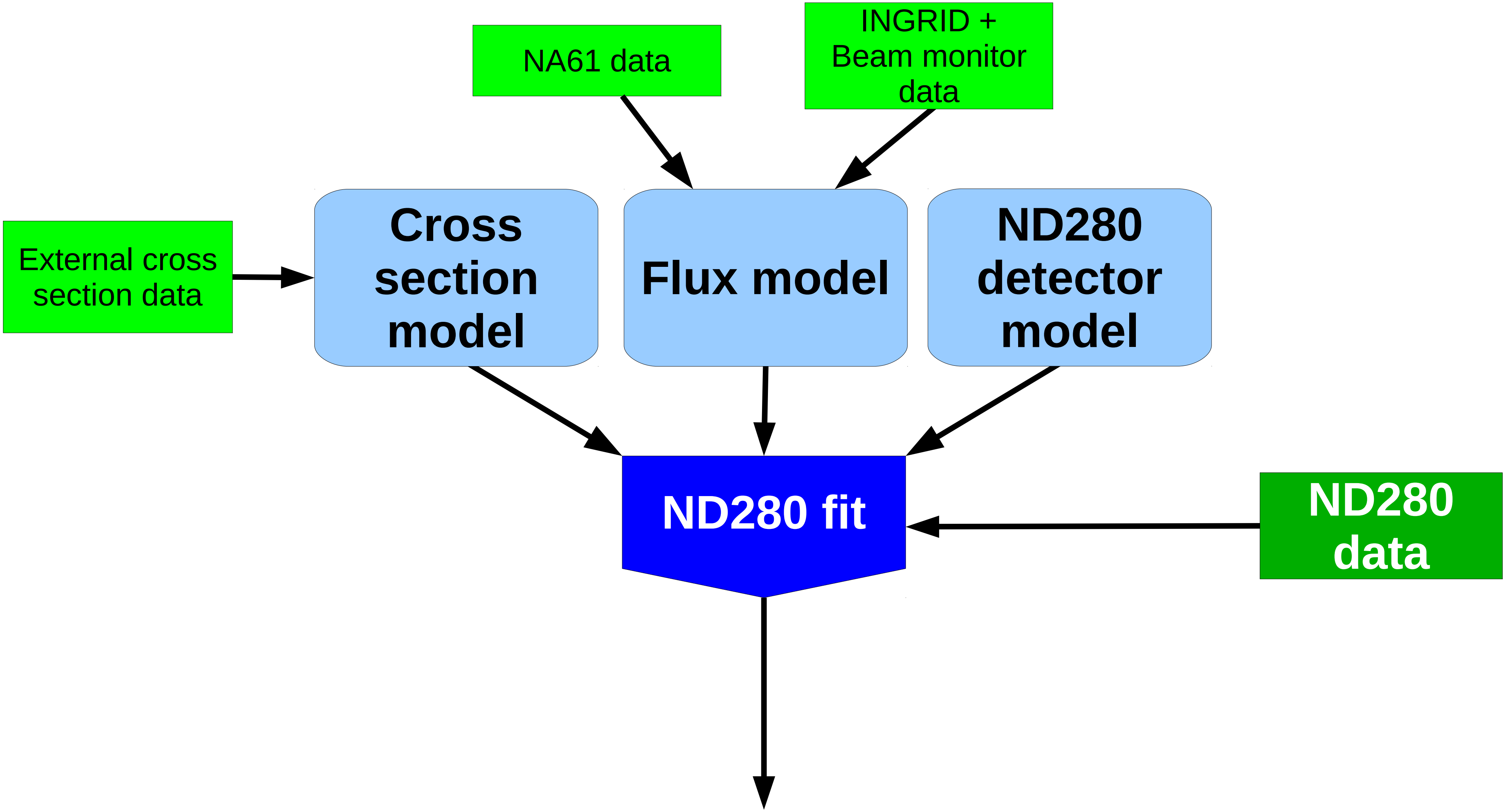
Postfit near detector MC agrees much better with data



- Model parameters shifted from prior values
- Parameter uncertainties reduced
  - Absolute errors smaller
  - Anti-correlated
- Test model dependence using fit
  - More on this later!



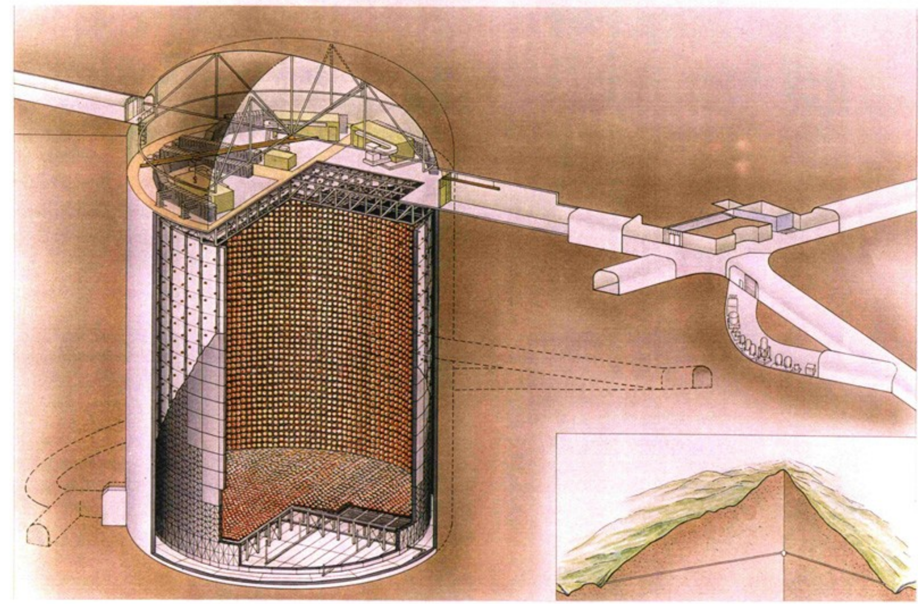
T2K oscillation analysis



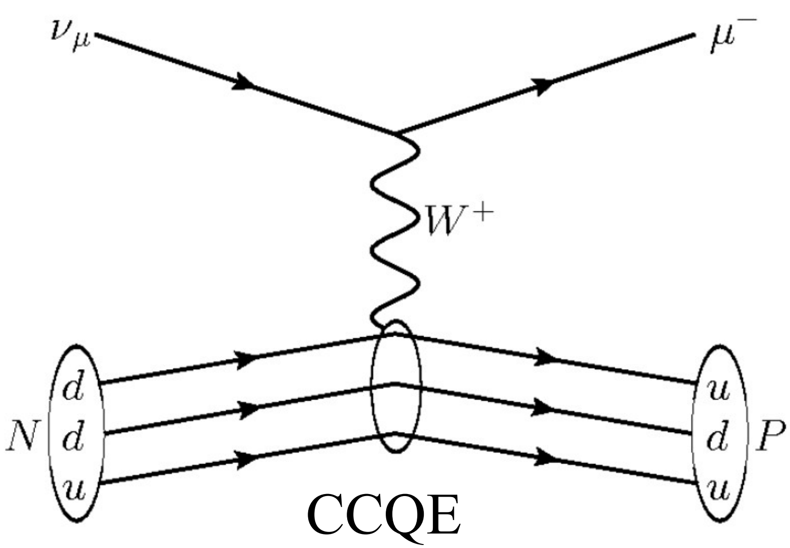
Far detector measurement

Signal in far detector:

- Measure rate of muon-like and electron-like events
- CCQE interactions are 'golden' channel



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO (c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



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

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

SK ν event selection

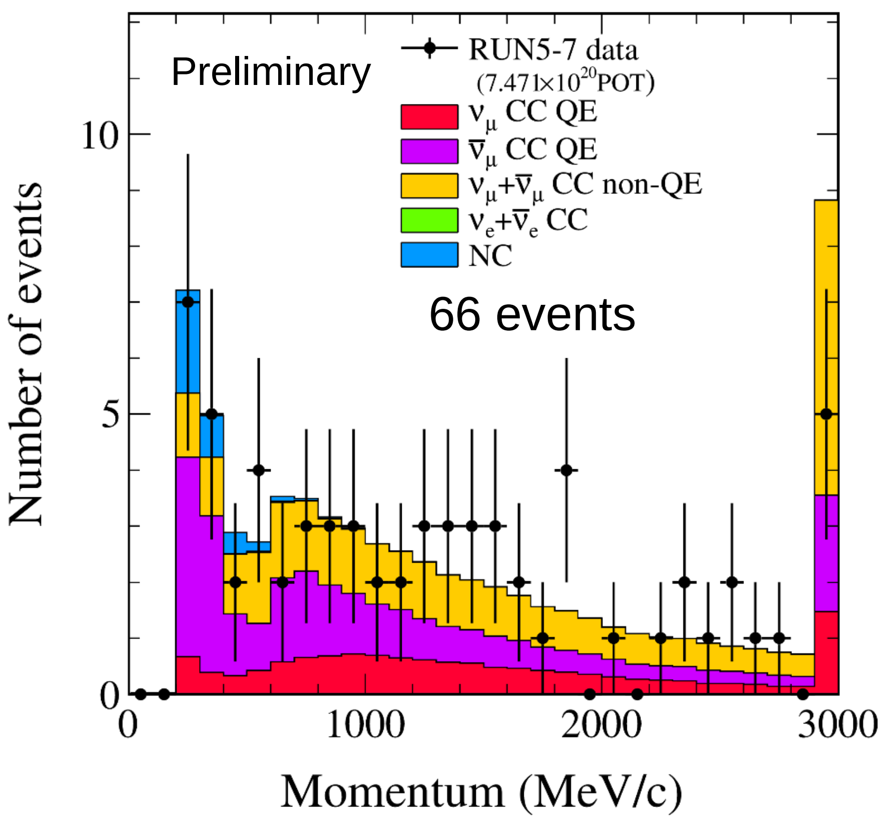
Look for fully contained, single ring events inside SK fiducial volume, then:

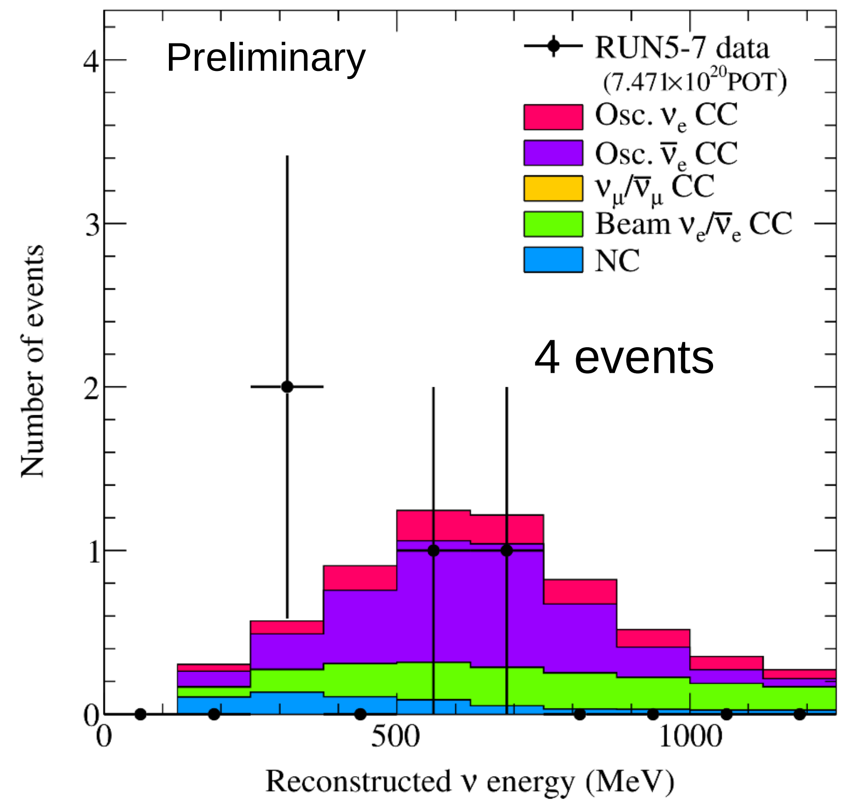
If muon-like ring:

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

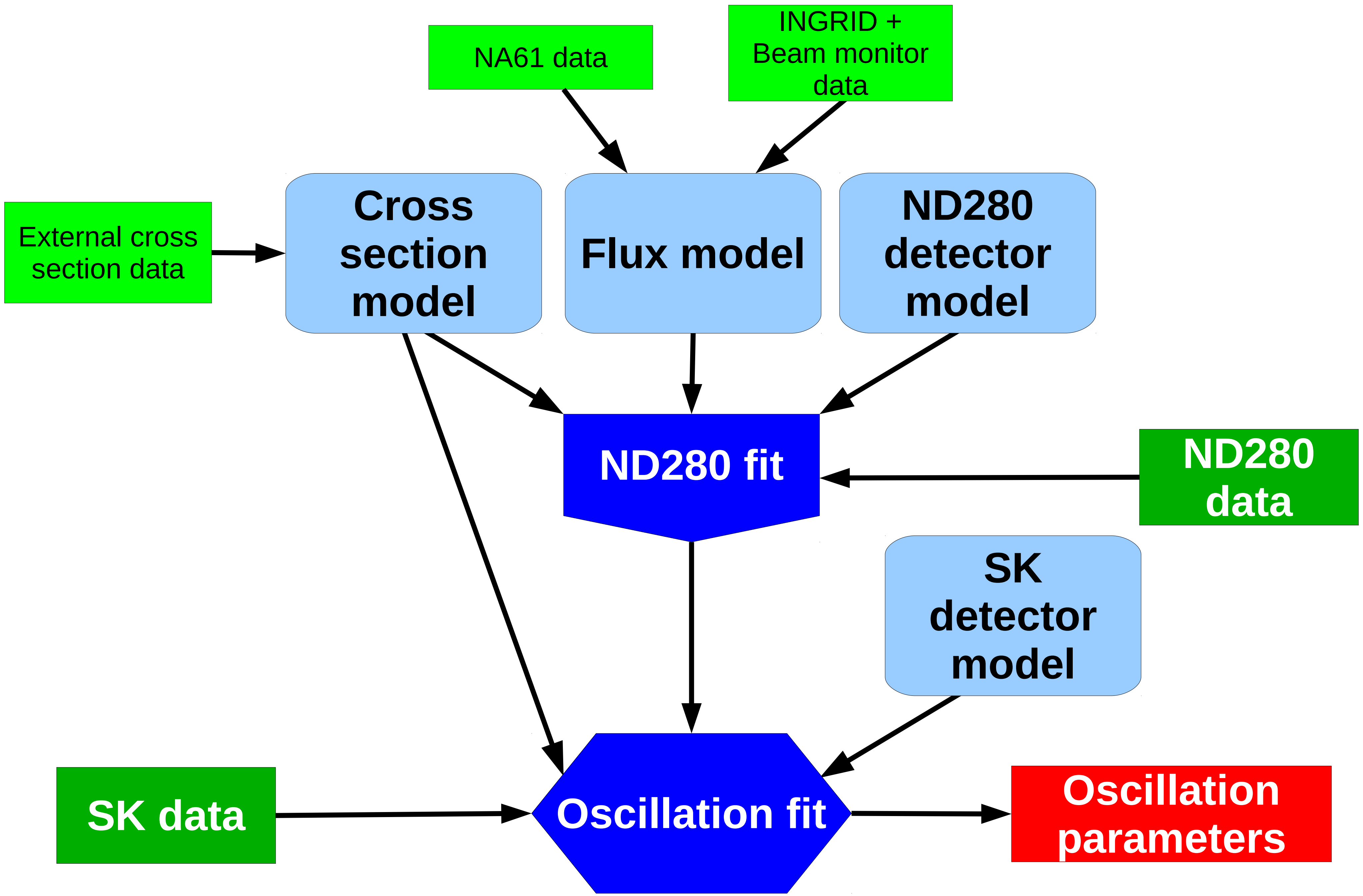
If electron-like ring:

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





T2K oscillation analysis



Joint oscillation analysis

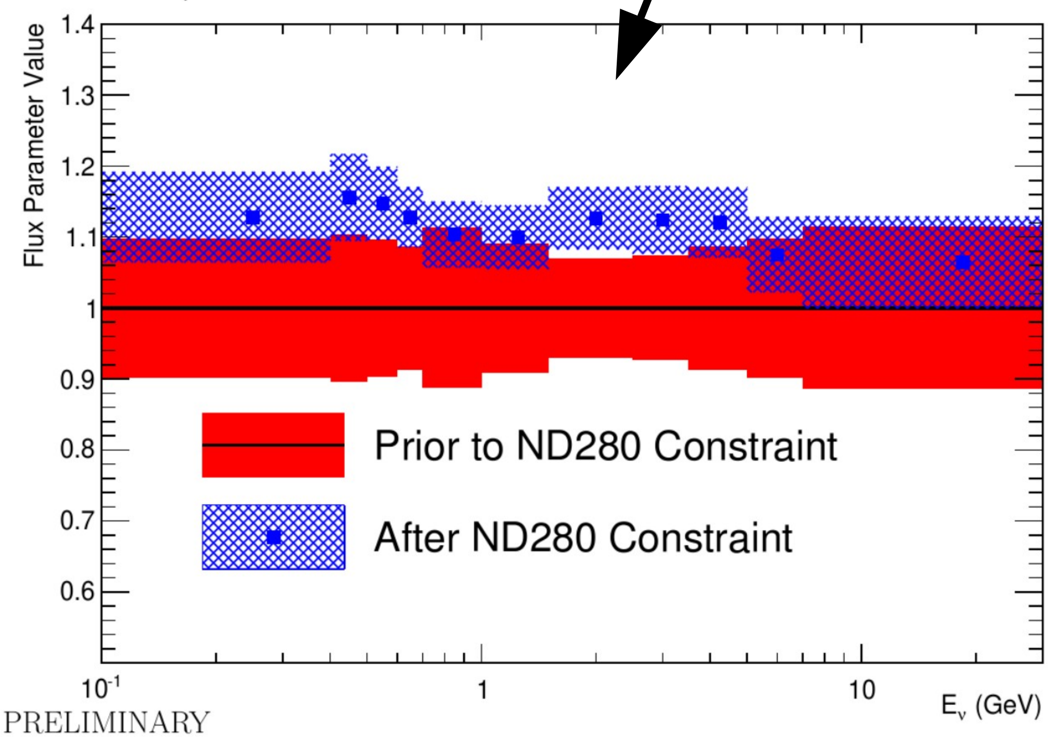
What?

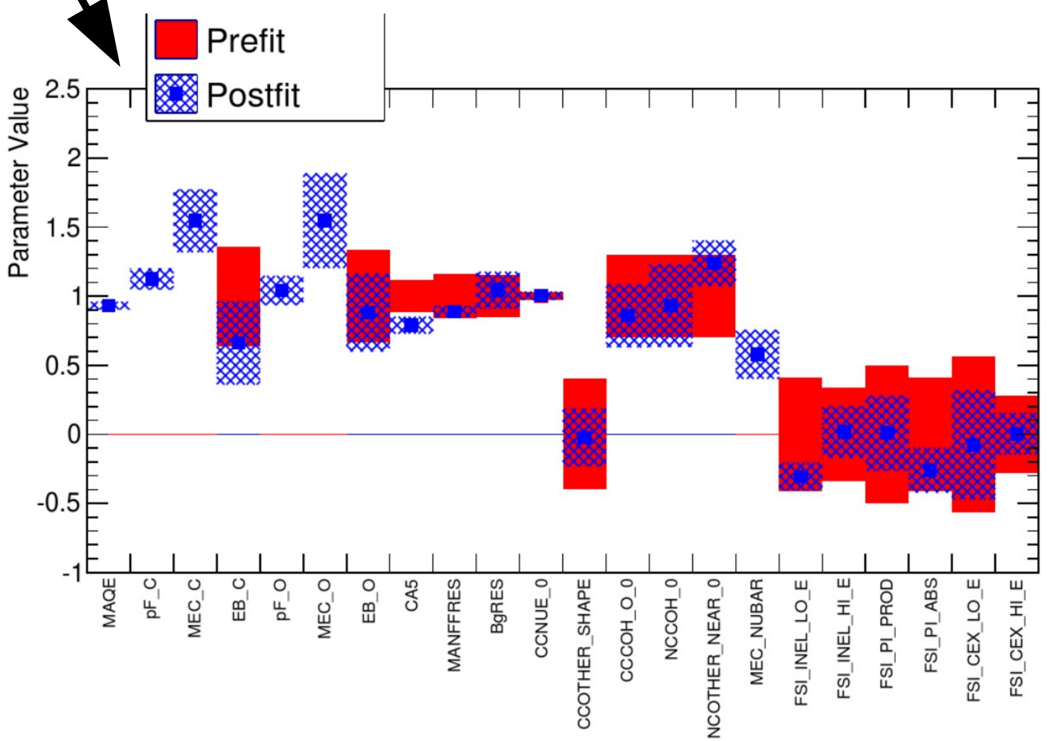
- Fit both electron-like sample and muon-like sample
- Fit both neutrino beam mode and anti-neutrino beam mode data

How?

- Maximise a likelihood: $\mathcal{L} = \mathcal{L}_{\text{Data}} * \mathcal{L}_{\text{Flux}} * \mathcal{L}_{\text{XSec}} * \mathcal{L}_{\text{SK detector}}$
- Prior constraints on flux and cross-section parameters from near detector fit

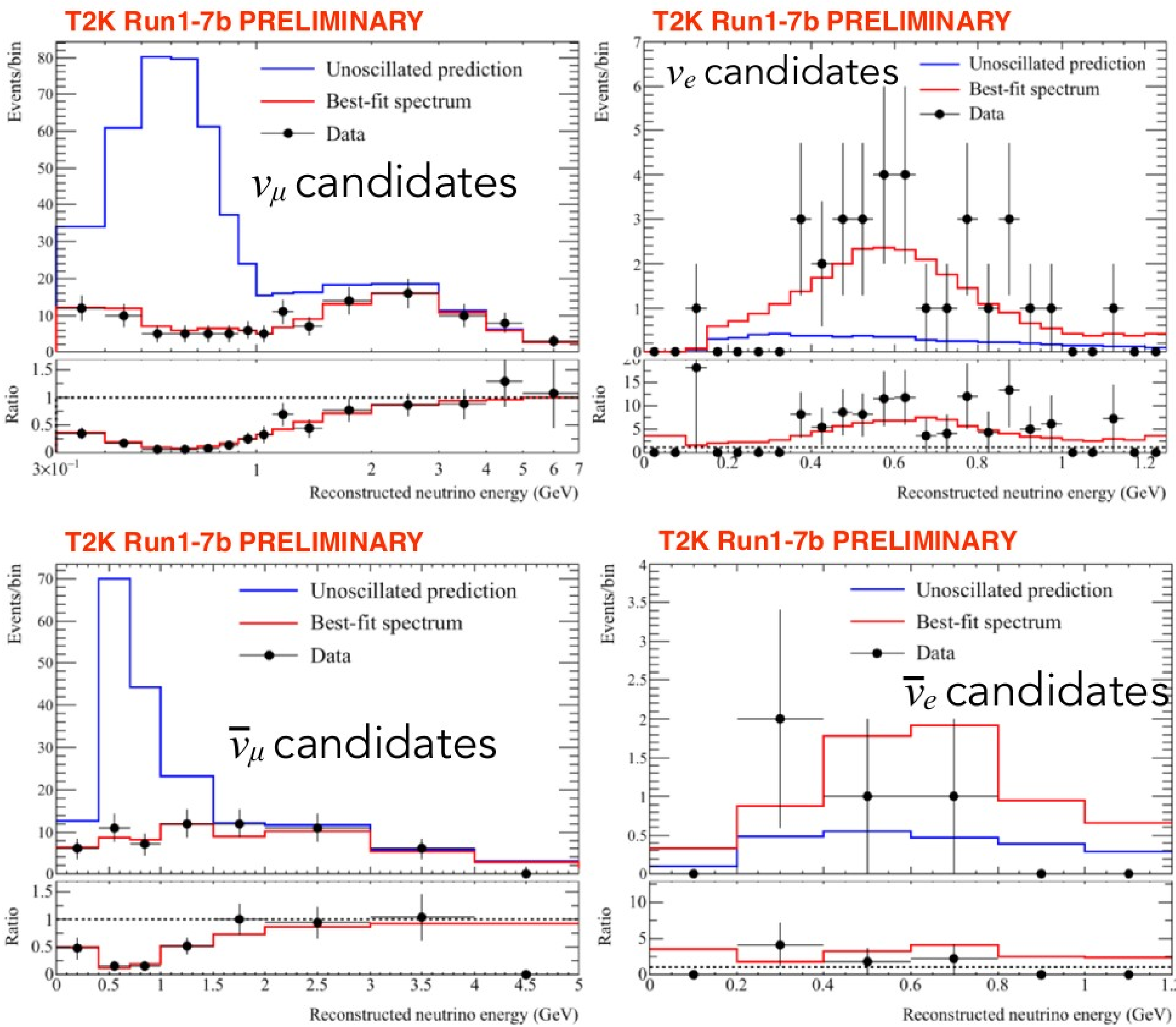
SK ν_μ, ν beam mode





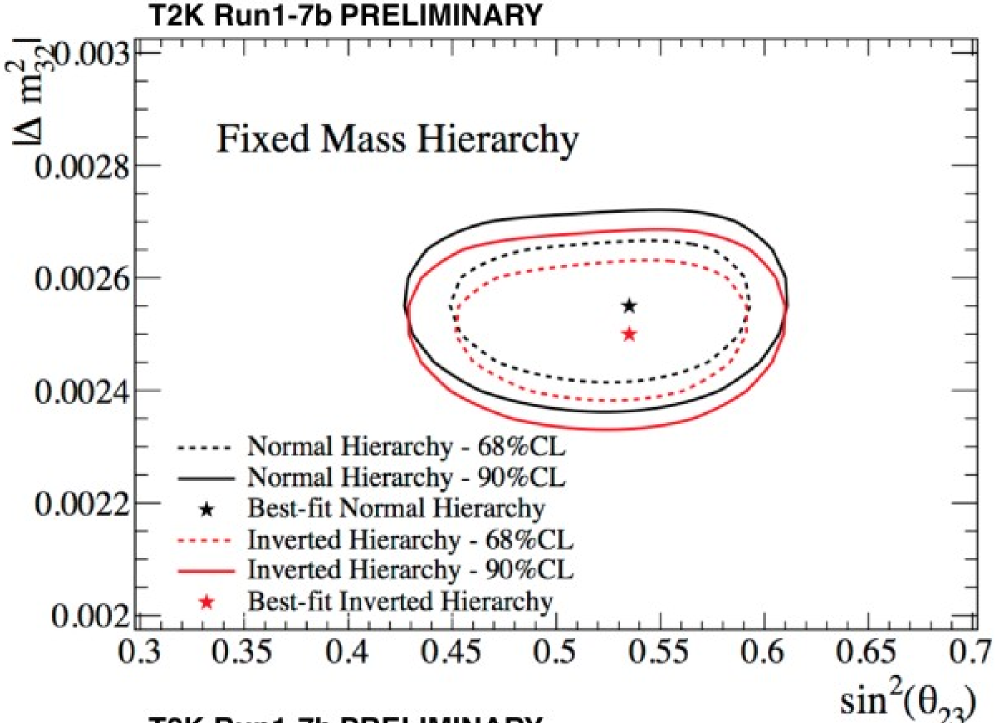
SK data samples

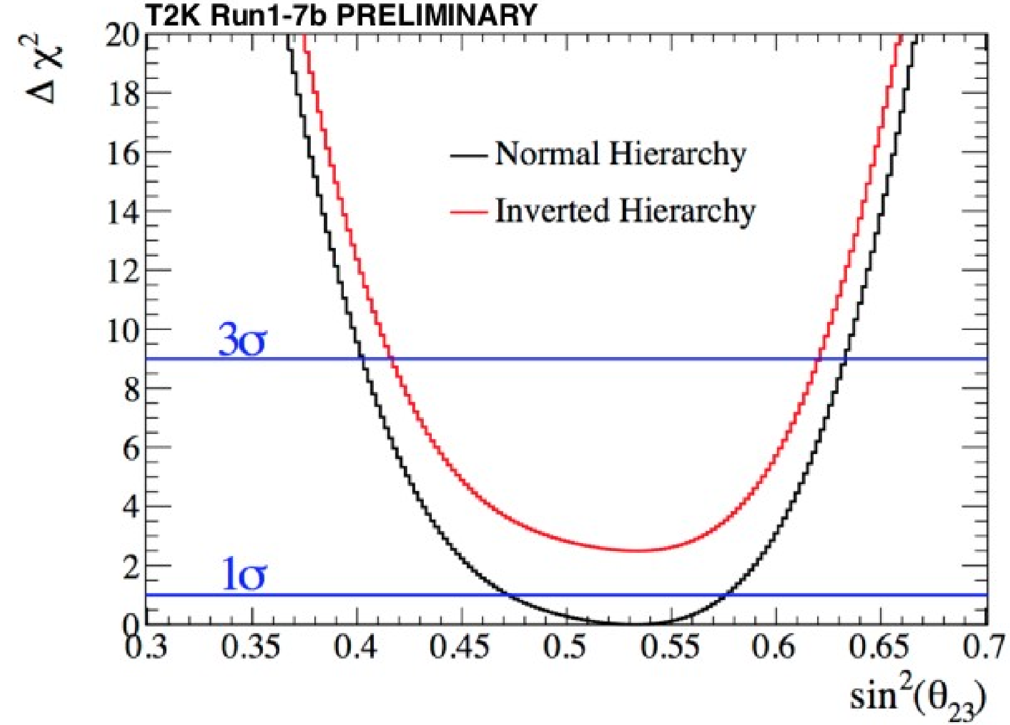
- Data shown with
  - Unoscillated prediction (blue)
  - Best-fit spectrum (red)
- Three independent analyses
  - Bayesian and frequentist
  - All give consistent results

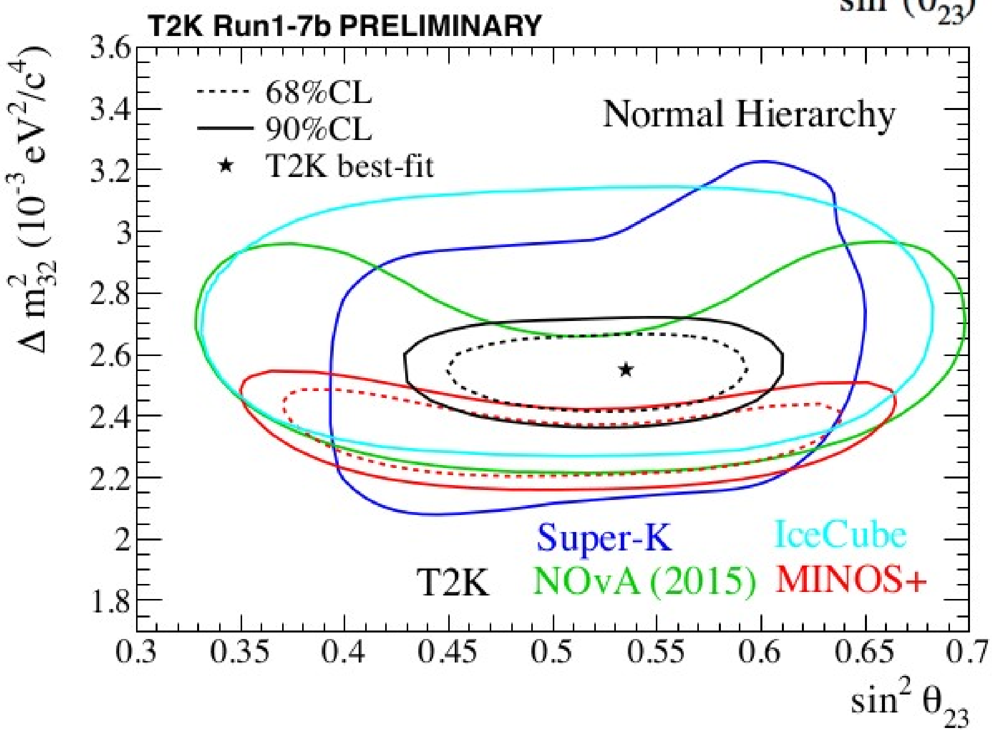


Hiro Tanaka

$\sin^2\theta_{23}$ AND Δm^2_{32}





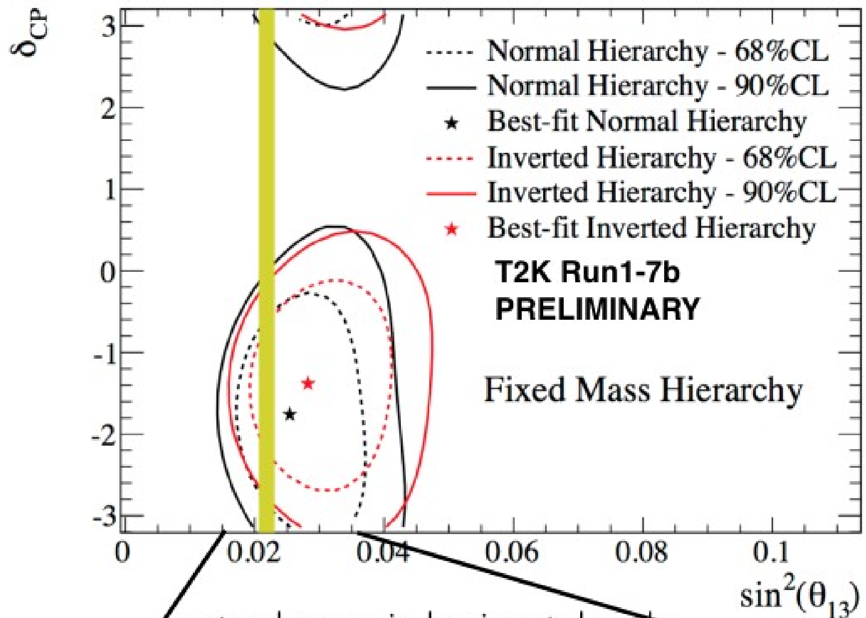


	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$
$\lvert\Delta m^2_{32}\rvert$ ($/10^{-3}eV^2$)	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$

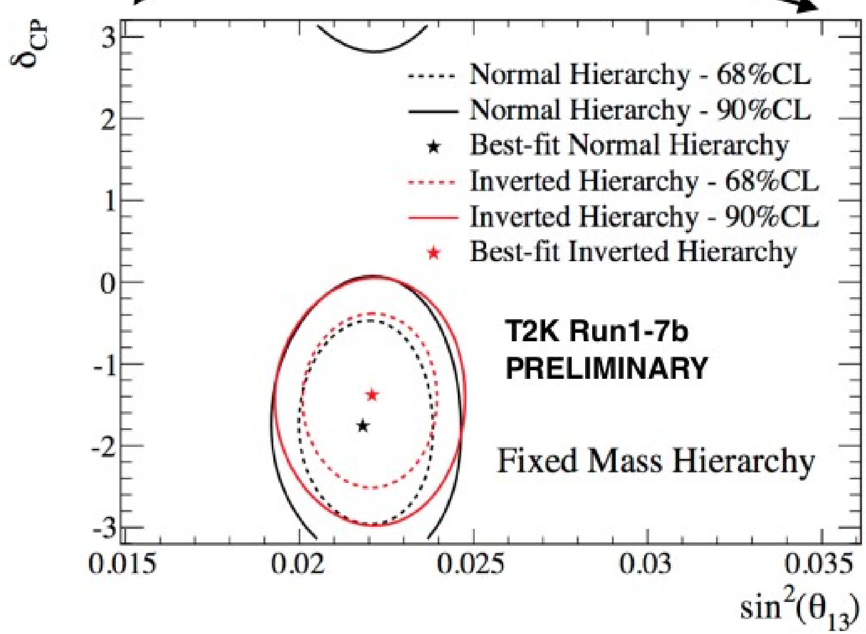
- Results continue to be consistent with maximal mixing/oscillation

Hiro Tanaka

δ_{CP} vs. θ_{13}



note change in horizontal scale

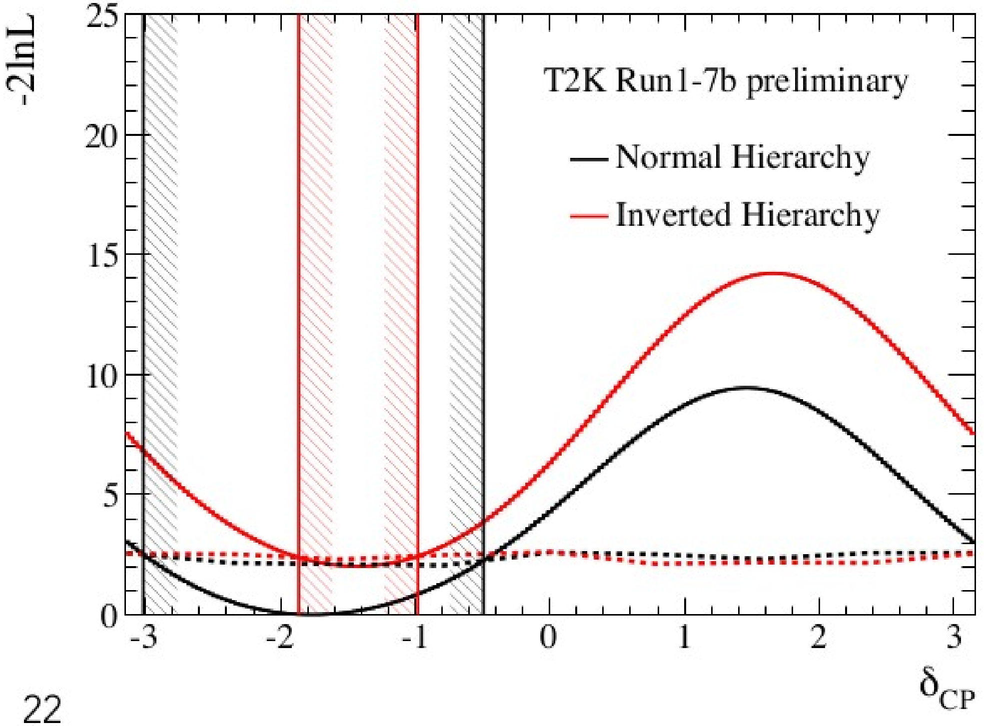


Left: δ_{CP} vs. θ_{13} (fixed $\Delta\chi^2$, fixed hierarchy)

- T2K-only
- T2K with reactor $\sin^2 2\theta_{13}$= 0.085±0.005

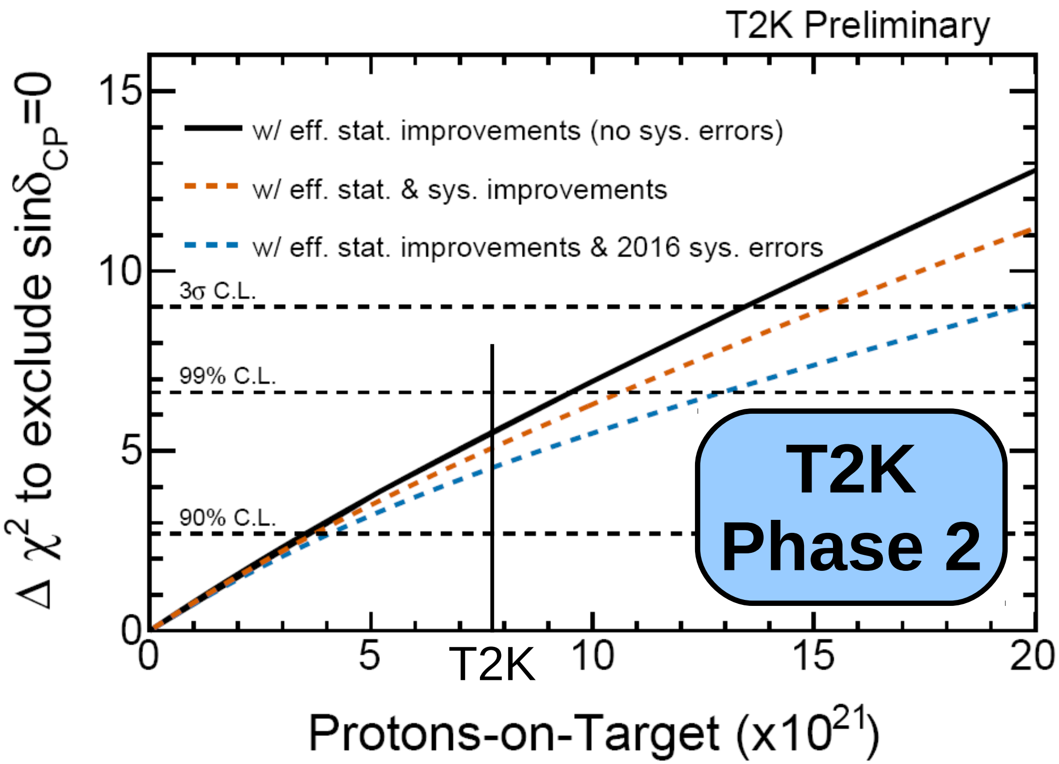
Below: δ_{CP} with Feldman-Cousins critical values and reactor θ_{13}

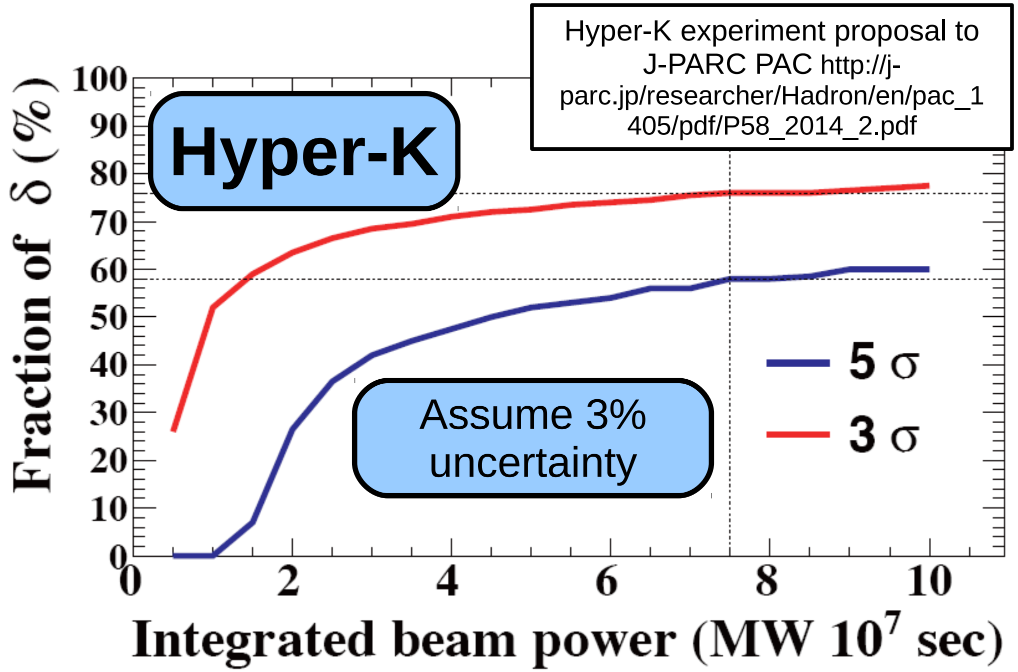
δ_{CP} = [-3.02, -0.49] (NH), [-1.87, -0.98] (IH) @90% CL



Future long-baseline neutrino oscillation measurements

Discovering leptonic CP violation

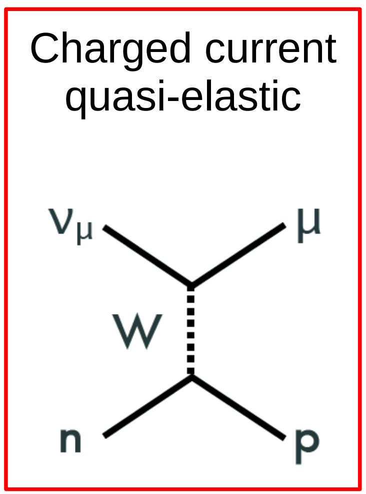


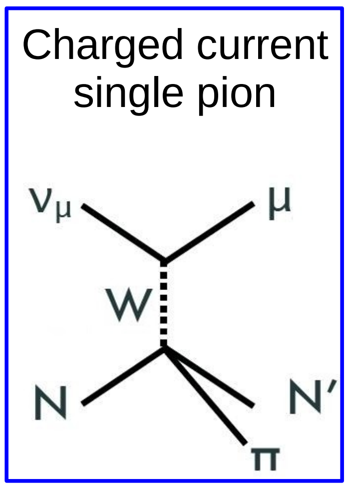


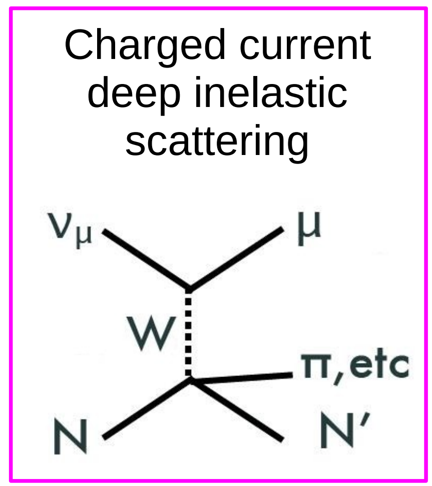
- T2K Phase 2 sensitive to maximal CP violation at 3σ, Hyper-K sensitive at 5σ over range of values of δ_{CP}
- Future long-baseline neutrino oscillation experiments will be systematics limited!

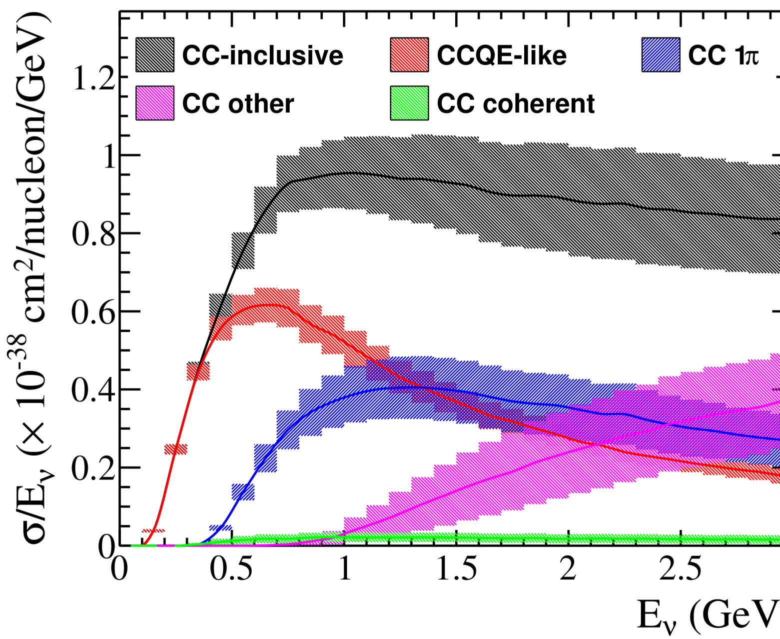
Systematics at T2K

- Uncertainty on δ_{CP} measurement dominated by:
  - Neutrino interaction uncertainties – 3.9%
  - Final state (FSI) and secondary interaction (SI) uncertainties – 3.7%



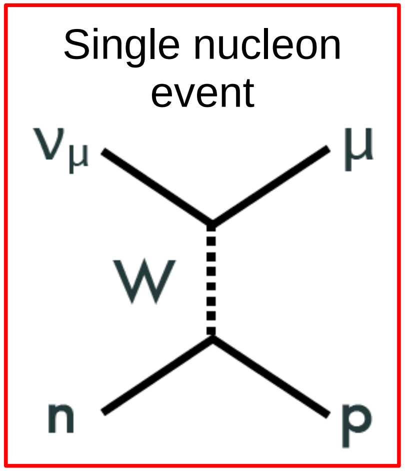


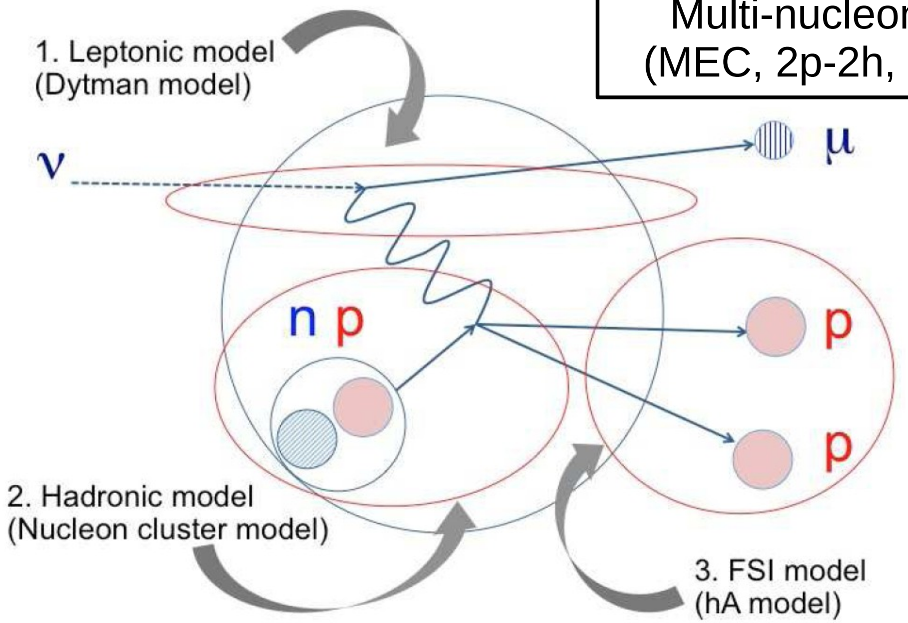




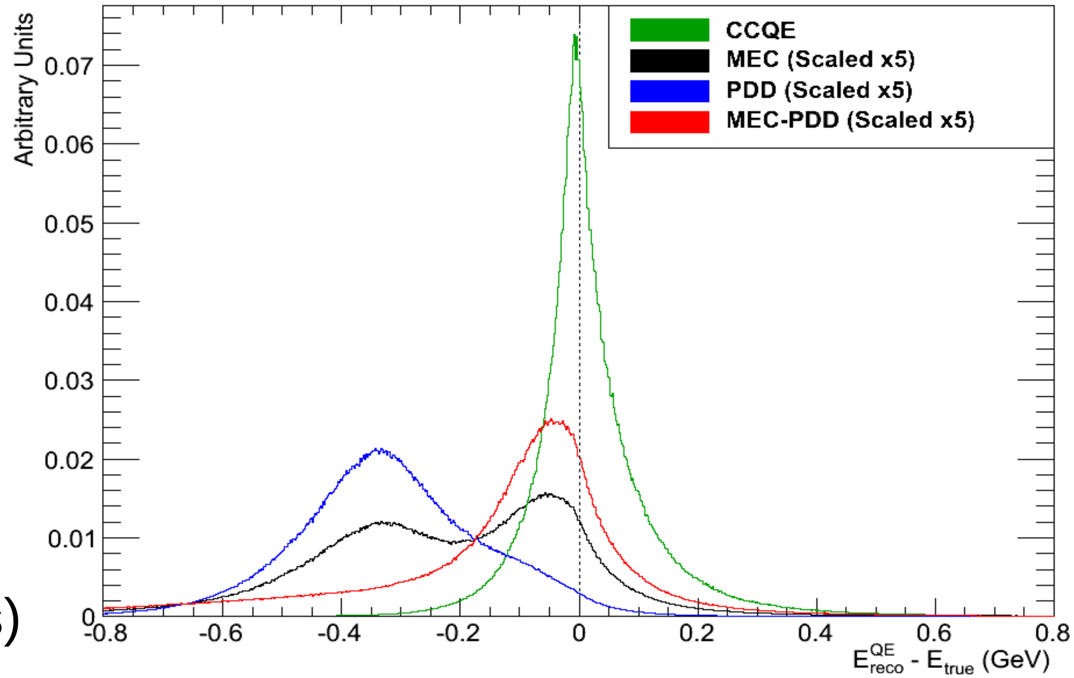
- No clear picture from dedicated cross-section experiments
- Limiting systematic errors from theory
  - Multi-nucleon events...

Multi-nucleon events

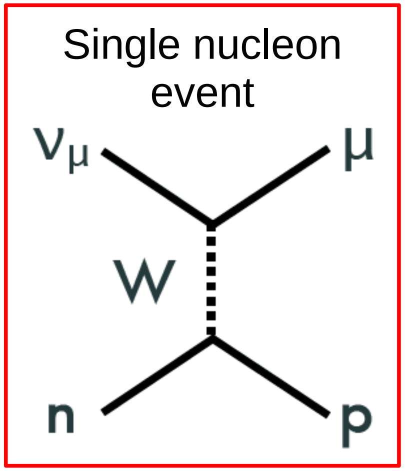


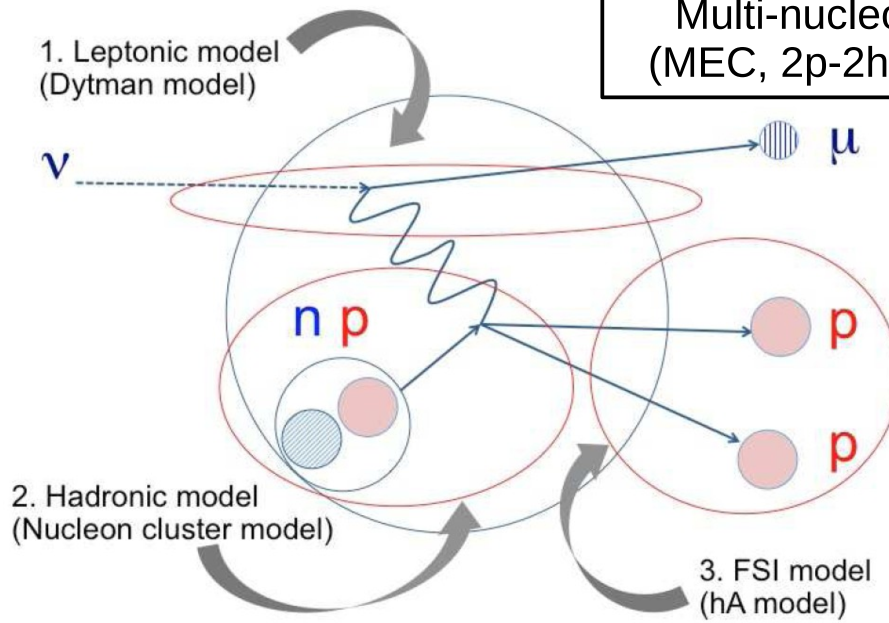


- SK uses lepton kinematics to infer neutrino energy
  - Assumes neutrino scattered from single nucleon at rest
- Multi-nucleon events indistinguishable from single nucleon events at SK
  - Assumption no longer valid
  - Energy reconstruction is **biased**
  - (Also true for calorimetric methods)



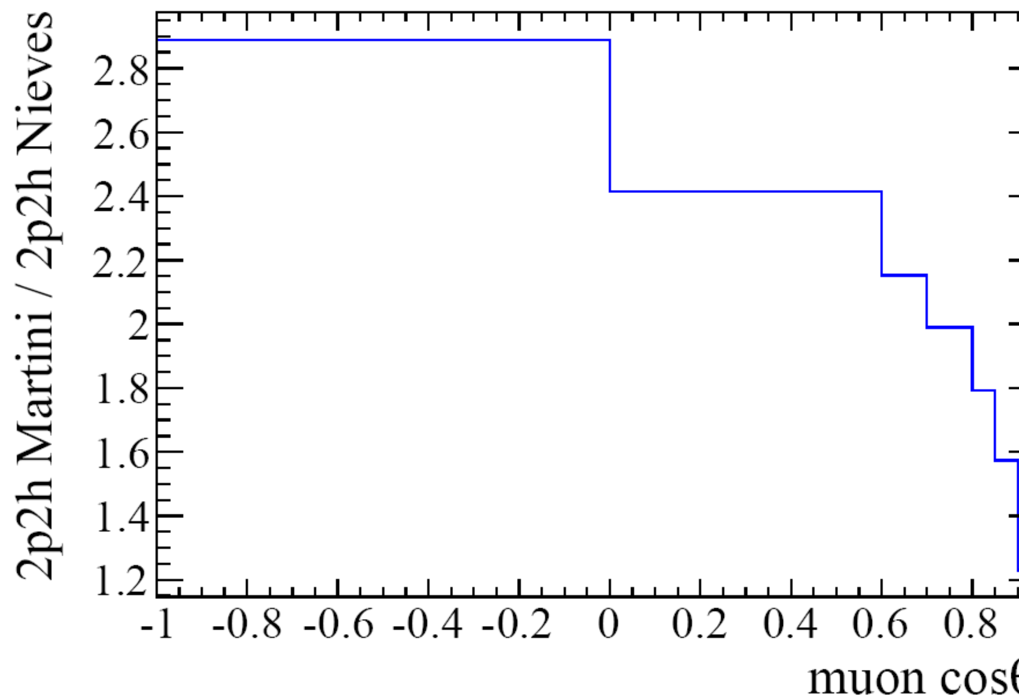
Multi-nucleon events



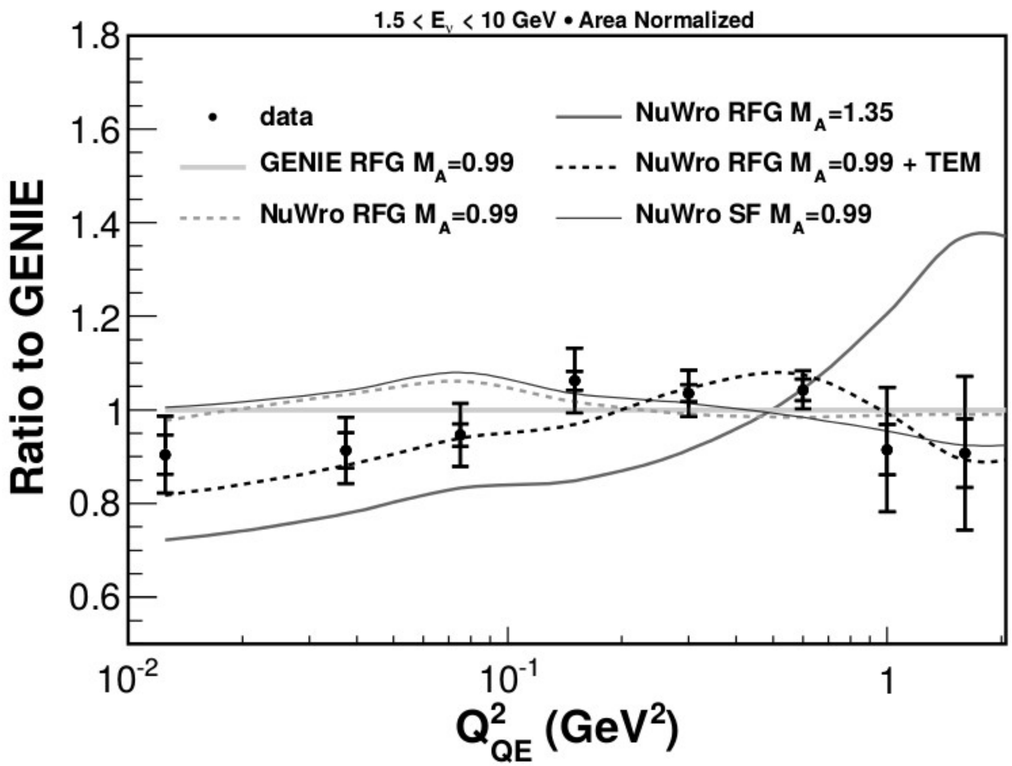


Multi-nucleon event
(MEC, 2p-2h, np-nh...)

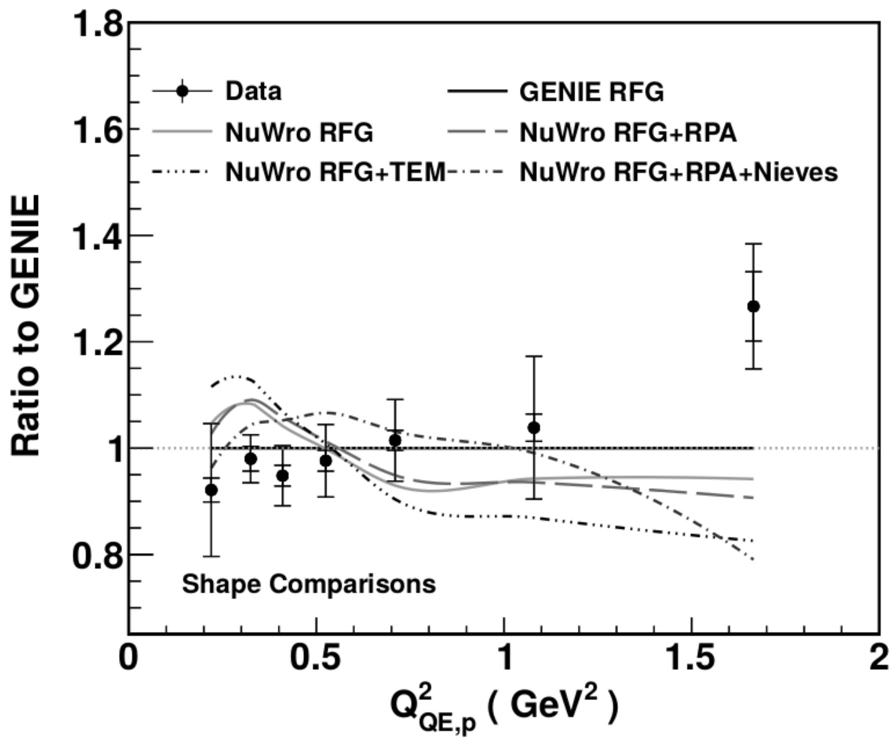
- Many different theoretical models
  - Martini vs Nieves shown on right
  - ~15% of CCQE-like cross-section
  - Can differ greatly in predicted event rates
  - Predict different rates for neutrinos vs anti-neutrinos
  - Hard to separate models experimentally



Cross-section experiments



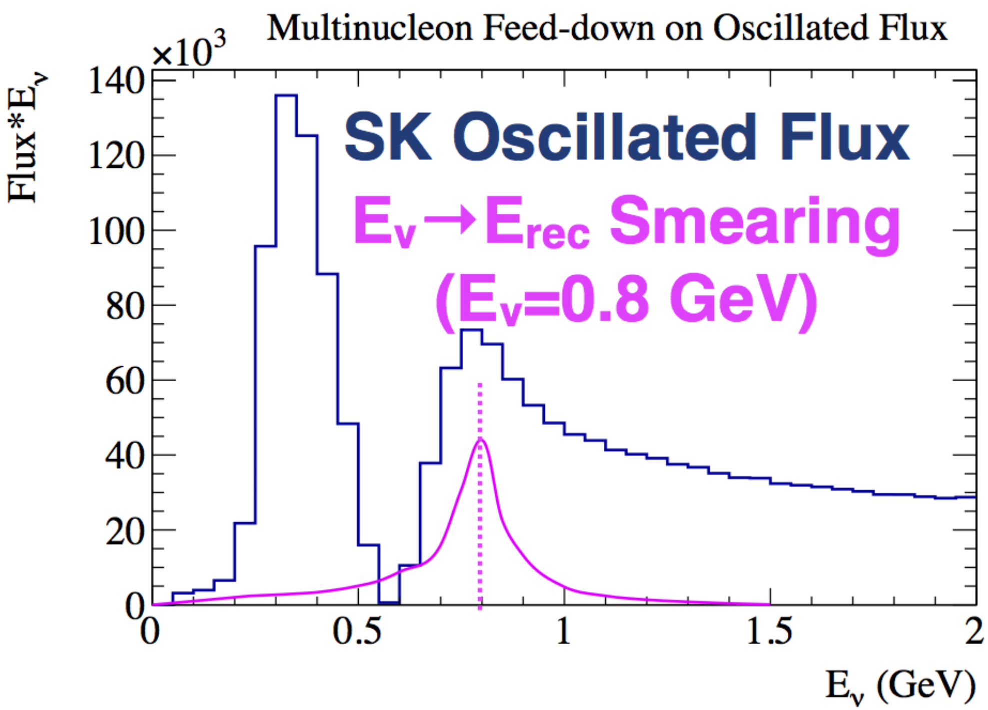
Fiorentini et al. Phys. Rev. Lett. 111, 022502 (2013)
CCQE cross-section using muon kinematics

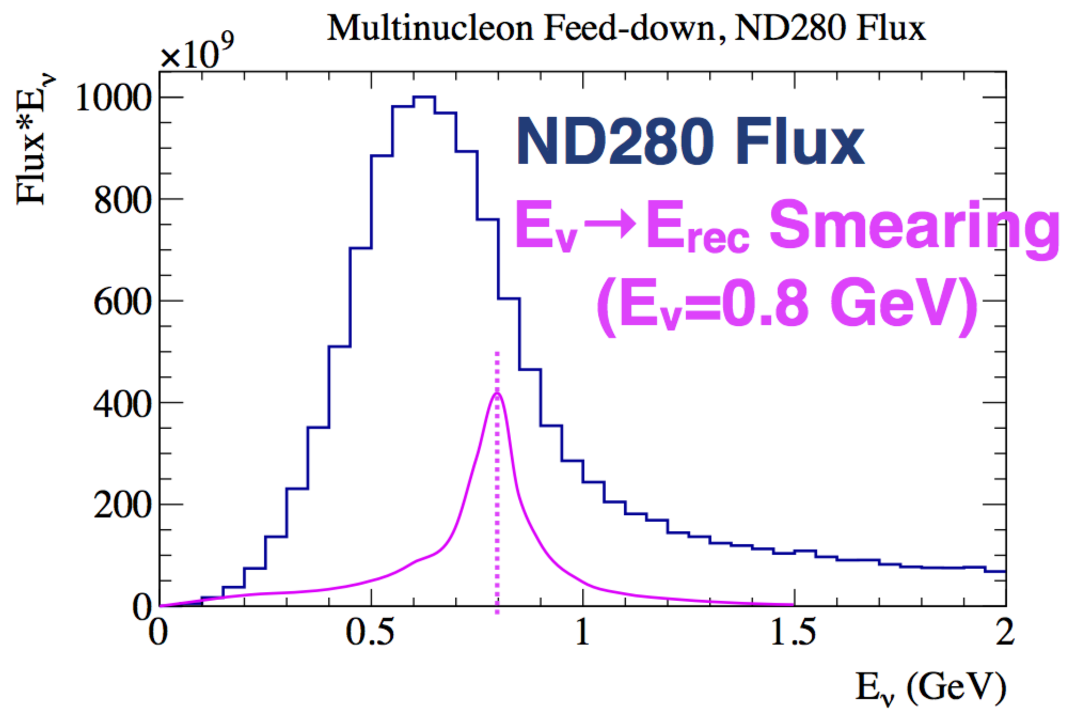


Walton et al. Phys. Rev. D 91, 071301 (2015)
CCQE cross-section using proton kinematics

- MINERvA results for muon CCQE-like cross-sections
  - Neutrino energies from ~1.5 GeV up to 10 GeV
- Ratio to GENIE prediction versus cross-section models
- Muon kinematics weakly prefers TEM model, proton weakly prefers nominal GENIE – no model is consistent with the MiniBooNE and MINERvA data

How does this affect oscillation analyses?

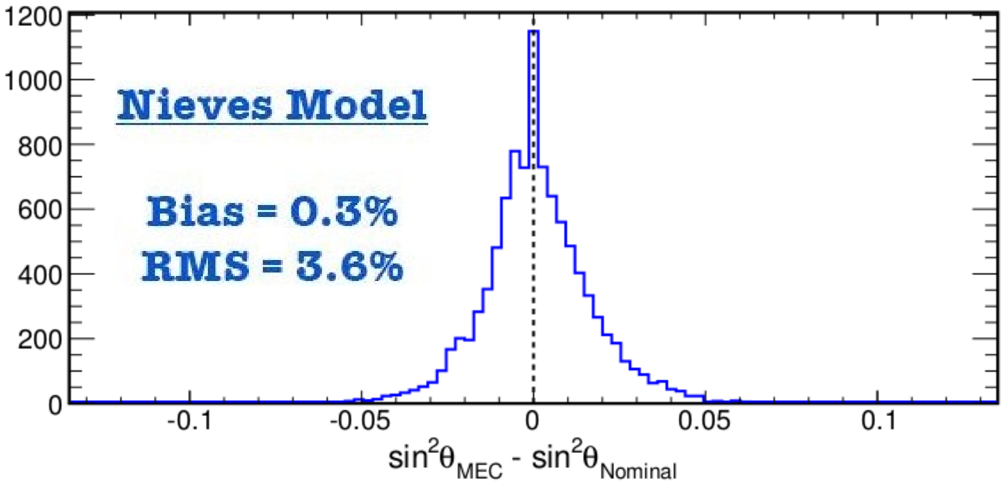


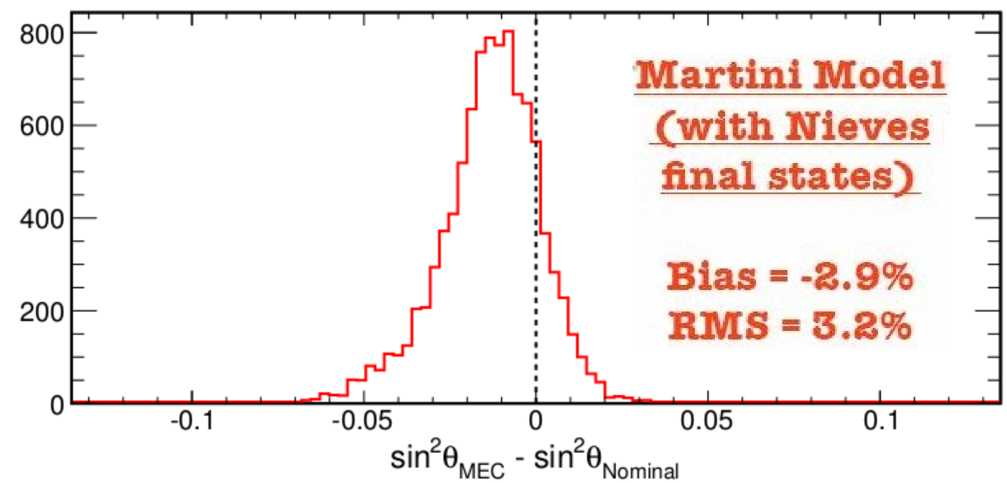


- At maximum oscillation, neutrino flux goes to zero
- Biased energy reconstruction smears multi-nucleon events into oscillation dip
- At near detector, effect of multi-nucleon events 'hidden' under neutrino flux – hard to constrain

T2K multi-nucleon study

- MC-based analysis using full detector simulation, full systematics etc.
- Three fake datasets
  - Nominal NEUT MC
  - NEUT + meson exchange current (MEC) events from Nieves' model - Phys. Rev. C, 83:045501, Apr 2011
  - NEUT + MEC events based on Martini's model - Phys. Rev. C, 81:045502, Apr 2010
- Perform disappearance fit to extract θ_{23} in each case and compare

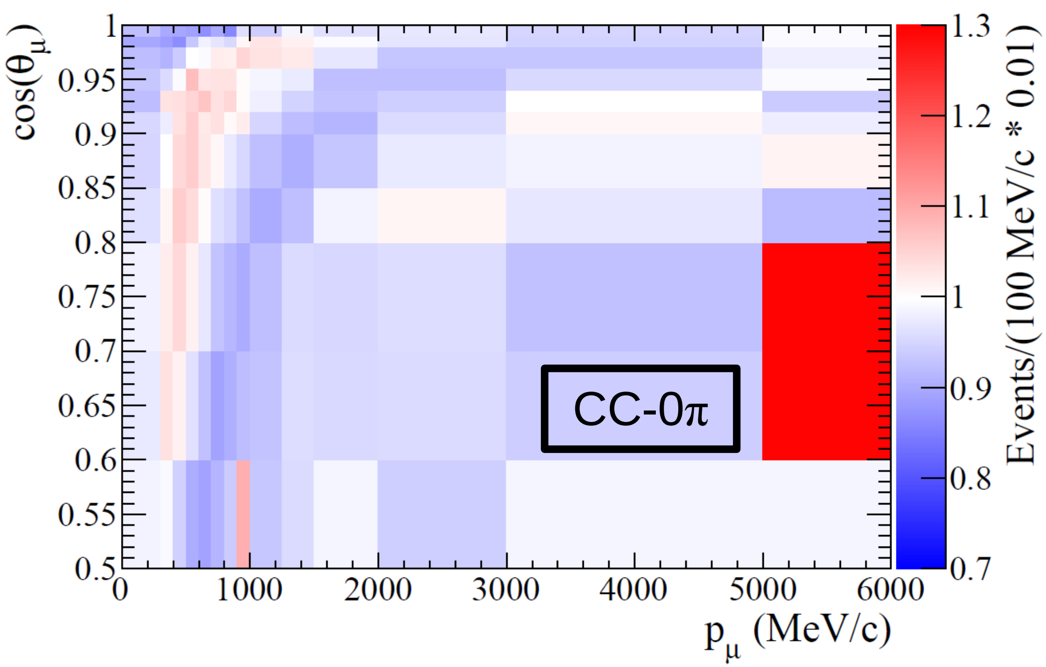


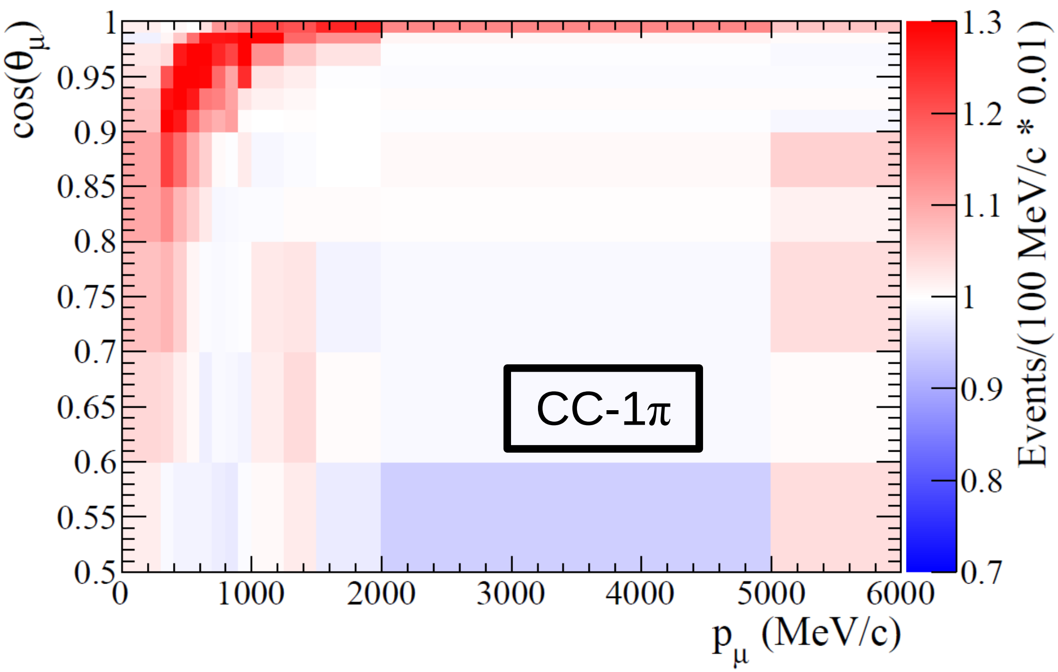


- Models give ~3.5% RMS in $\sin^2\theta_{23}$, Martini model introduces ~3% bias
- More recent studies with other nuclear models show similar effects

T2K fake data studies

- Investigate effect of interaction model choice on latest T2K oscillation results
- MC-based using analysis framework described earlier
  - Create fake data with alternate model
  - Fit near and far detector fake data with nominal model
  - Look at change in best fit oscillation parameters and SK event rates

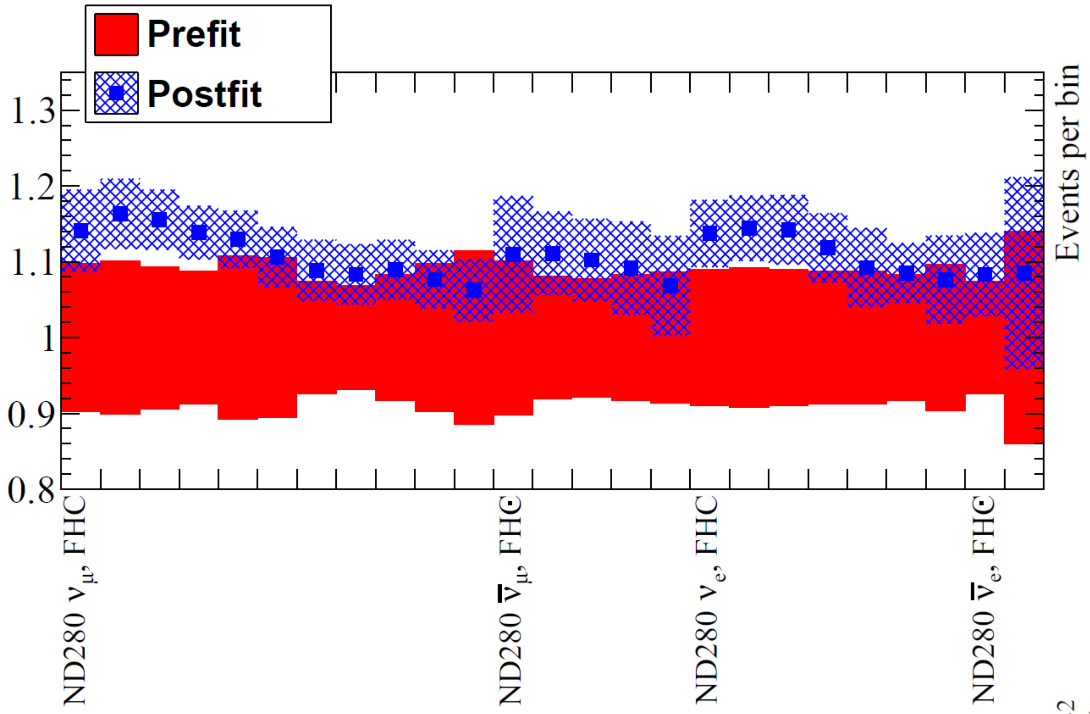


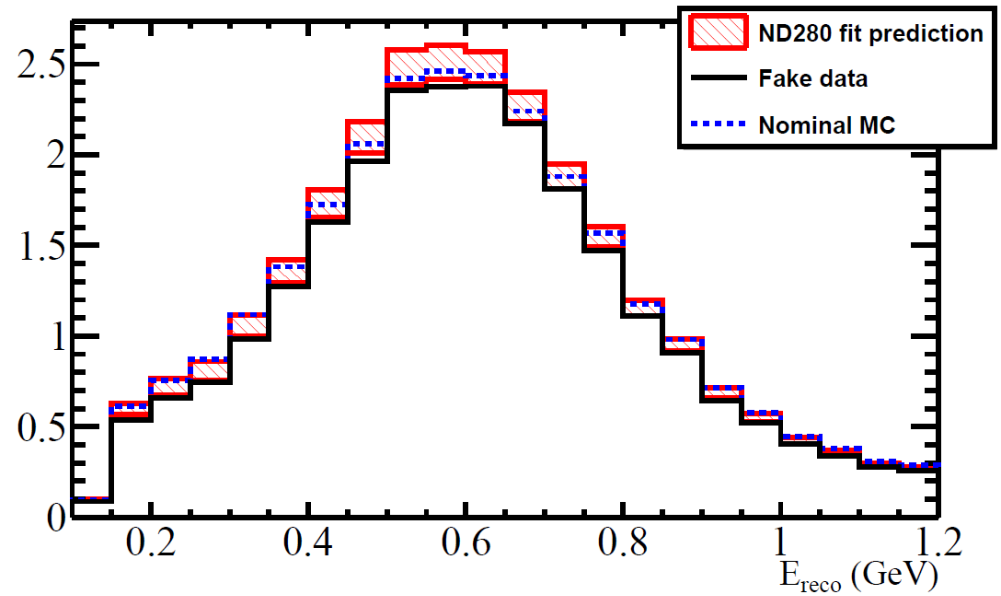


- Fractional change in CC-0π and CC-1π samples at ND280 between Relativistic Fermi Gas (RFG) and Spectral Function (SF) nuclear models

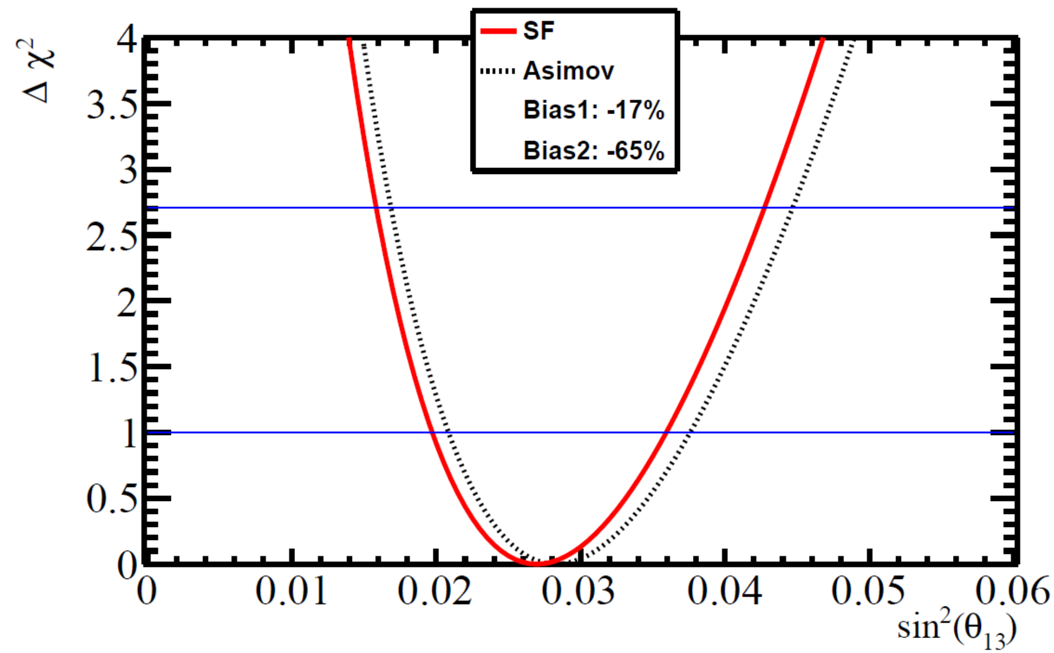
RFG vs SF

- Look at change in best fit model parameters and predicted SK spectrum

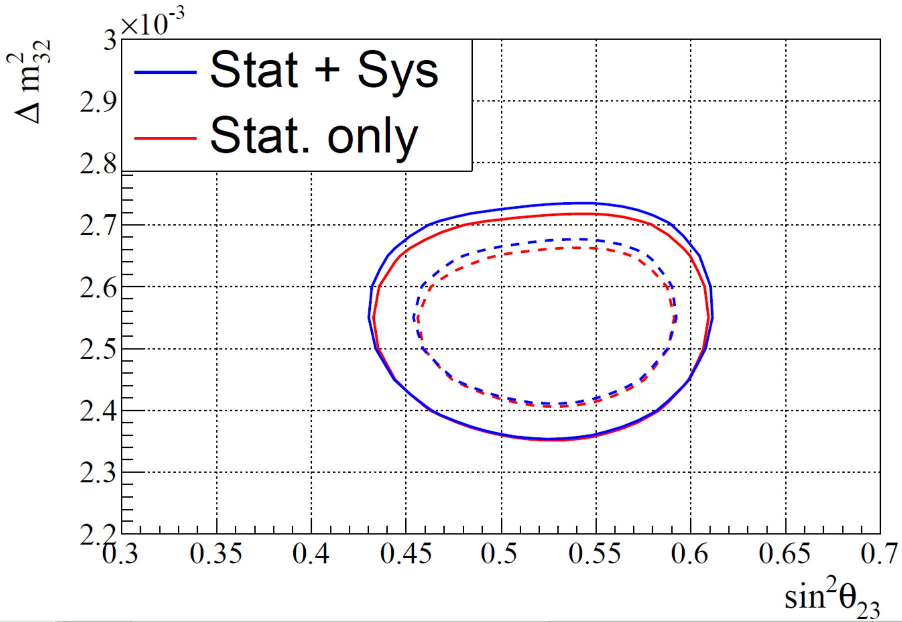


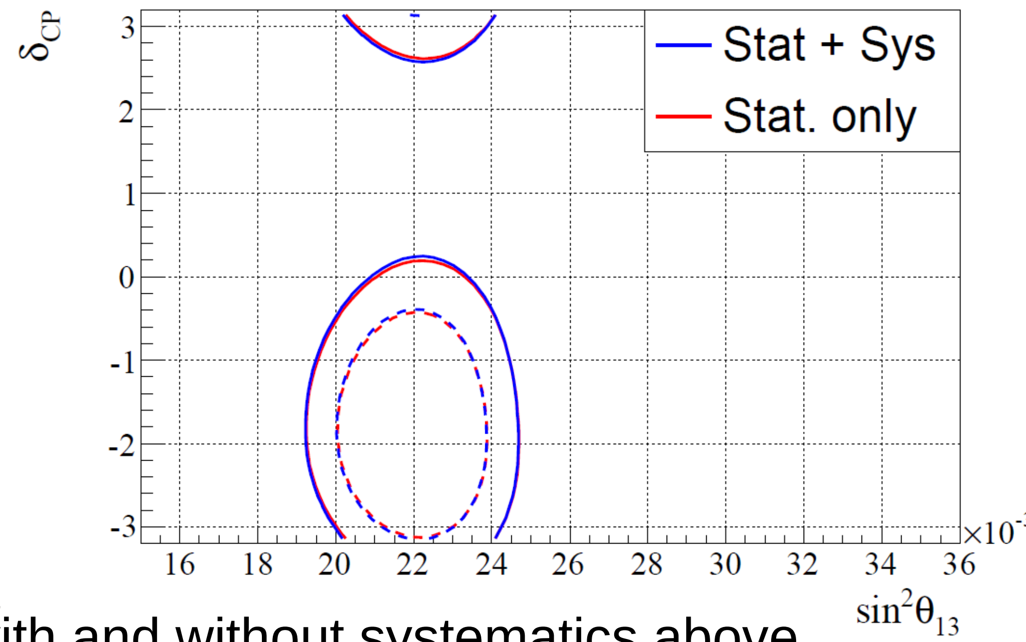


- Significant change in flux parameters (top left)
- ND280 over-predicts SK electron neutrino event rate (top right)
- Shift in best fit of $\sin^2\theta_{13}$ on right – 0.17σ shift in parameter for current uncertainties



Systematics at T2K





- T2K oscillation parameter sensitivity with and without systematics above
- Current analysis dominated by statistical uncertainties - not yet sensitive to effect of nuclear models

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	4.6	3.9	2.8	4.0	1.9
SK Final State & Secondary Interactions	1.8	2.4	2.6	2.7	3.7
ND280 Constrained Flux & Cross-section	2.6	3.0	3.0	3.5	2.4
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.4	2.7	1.5
NC Other Cross-section	0.7	0.7	0.2	0.3	0.2
Total Systematic Error	5.6	5.5	5.7	6.8	5.6
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.2	4.0	0.1

Effect of model choices

- Take fractional change in SK event rate prediction between fake data fits and Asimov samples
- Directly comparable to previous table

T2K Preliminary

Fake data	$1R_\mu$	$1R_e$	RHC $1R_\mu$	RHC $1R_e$	$\frac{1R_e}{\text{RHC } 1R_e}$	$\frac{1R_\mu}{\text{RHC } 1R_\mu}$
SF	3.91	5.58	3.92	3.55	1.18	-0.38
ERPA	0.30	2.19	-1.02	-1.21	3.60	1.14
Martini with $\bar{\nu}$ $2p$-$2h$ parameter	2.86	1.94	1.19	0.69	0.79	2.31
PDD-like $2p$-$2h$	-0.04	-0.72	1.32	3.48	-4.57	-1.24
NonPDD-like $2p$-$2h$	3.31	3.49	3.33	1.39	2.85	0.15
Nieves-NEUT $1p$-$1h$ with ND280 error	2.69	3.37	3.31	3.27	-1.66	-0.53

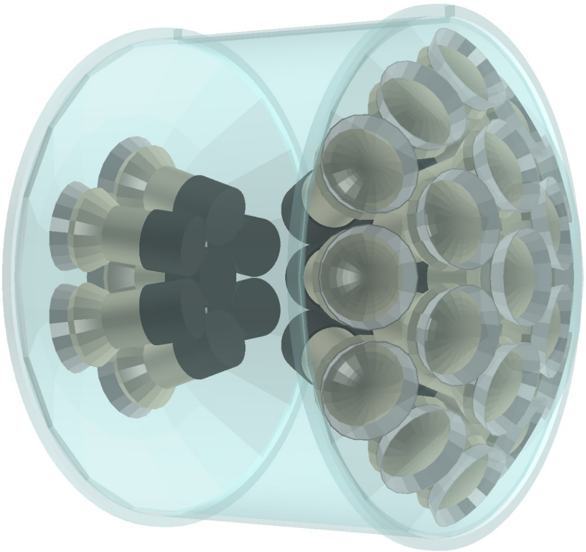
- Electron neutrino / anti-neutrino rate highlighted
  - Direct measure of uncertainty in CP violation measurement
- **Model choice gives shift equal to current systematic uncertainties**

NuPRISM:

An experimental solution to the problems of neutrino interactions in long baseline neutrino experiments

NuPRISM

- Water Cherenkov detector spanning 1° – 4° from the neutrino beam axis
  - 52.5m tall if 1km from neutrino production target
- Instrument movable cylinder:
  - Inner Detector (ID): 8m diameter, 10m tall
  - Outer Detector (OD): 10m diameter, 14m tall
- Same nuclear target and acceptance as far detector
- Smaller near-to-far flux extrapolation uncertainty

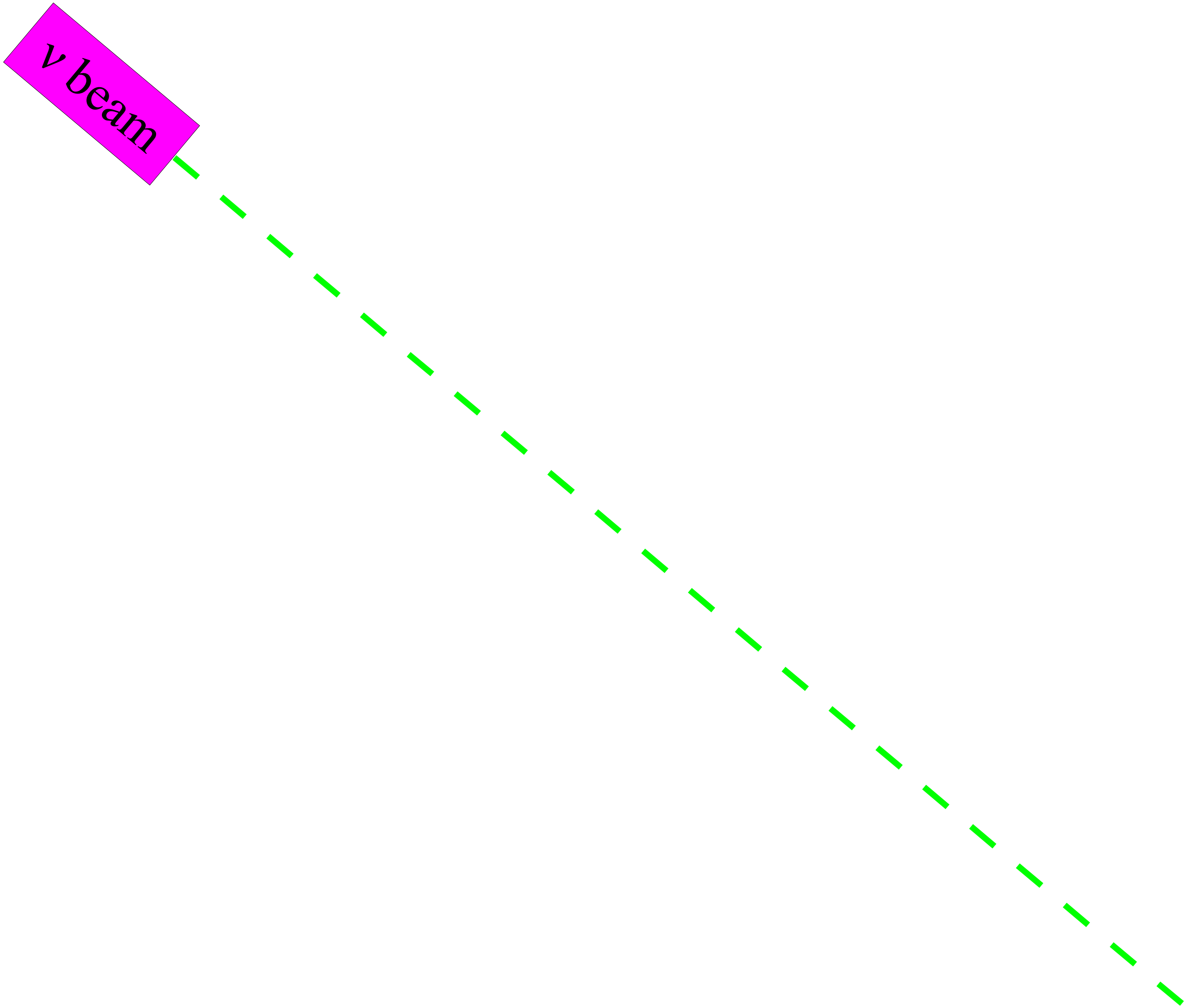


OD: 20” PMT
ID: 8” PMT

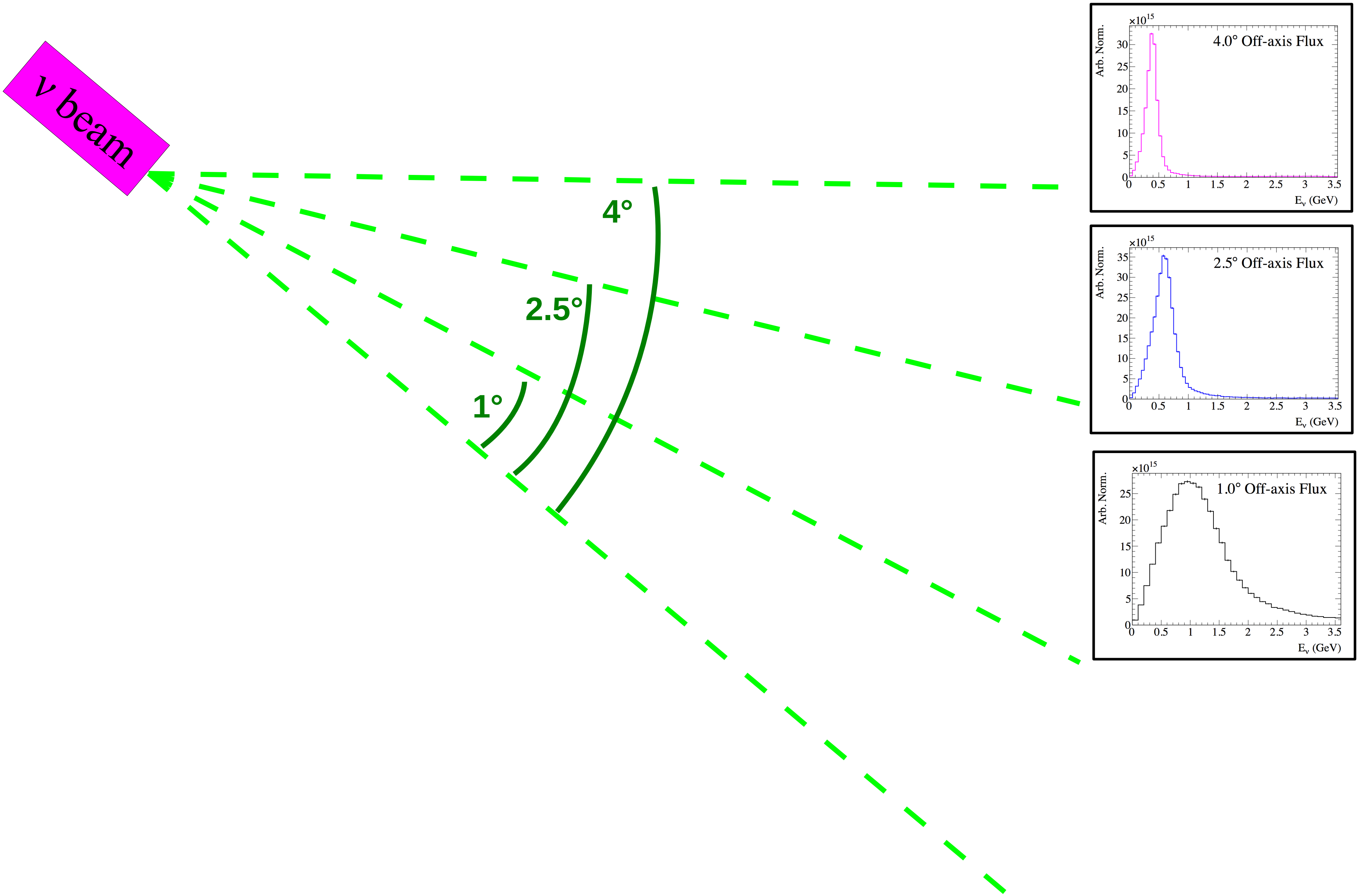
Or

Multi-PMT
for both

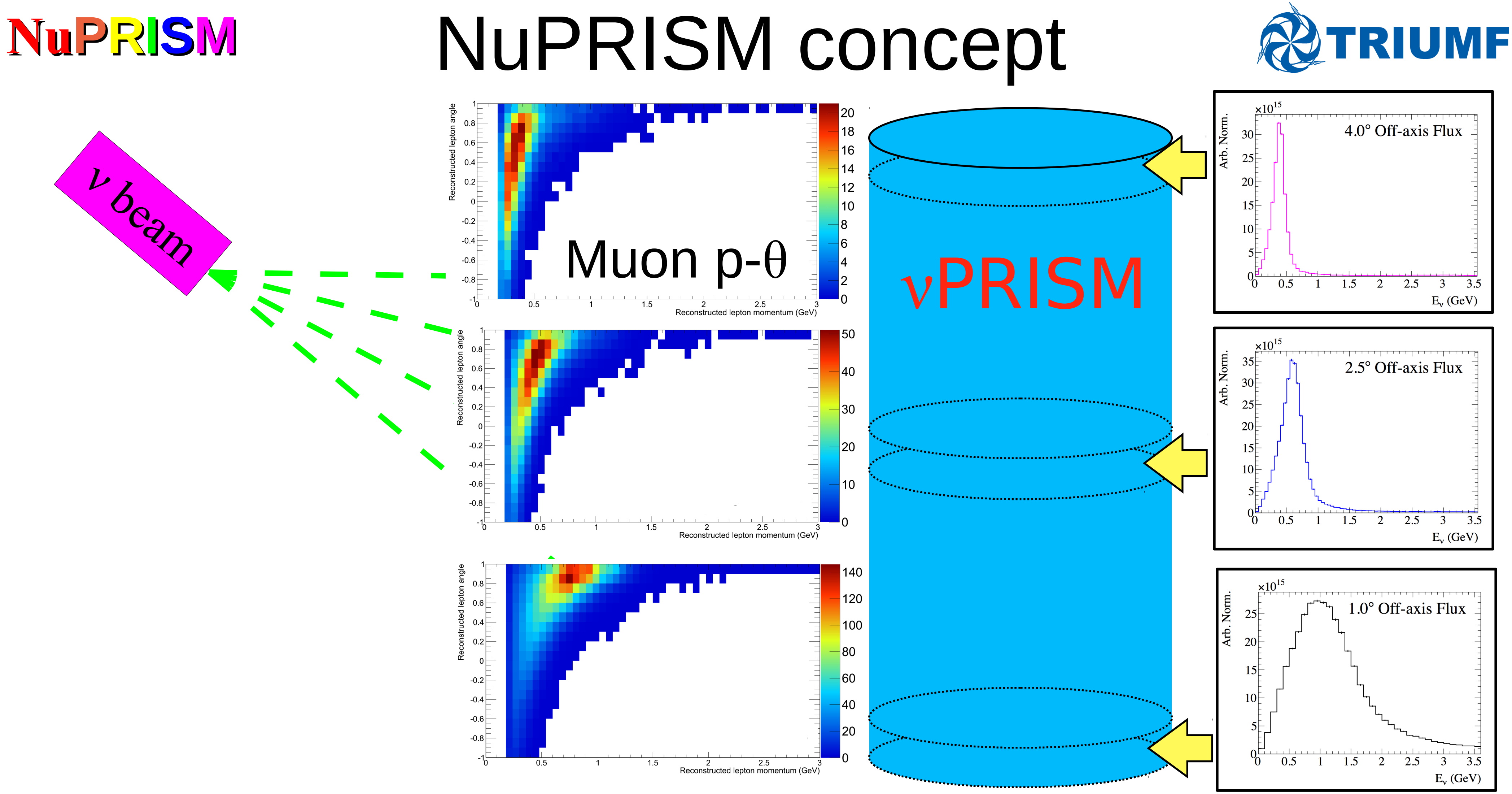
NuPRISM concept



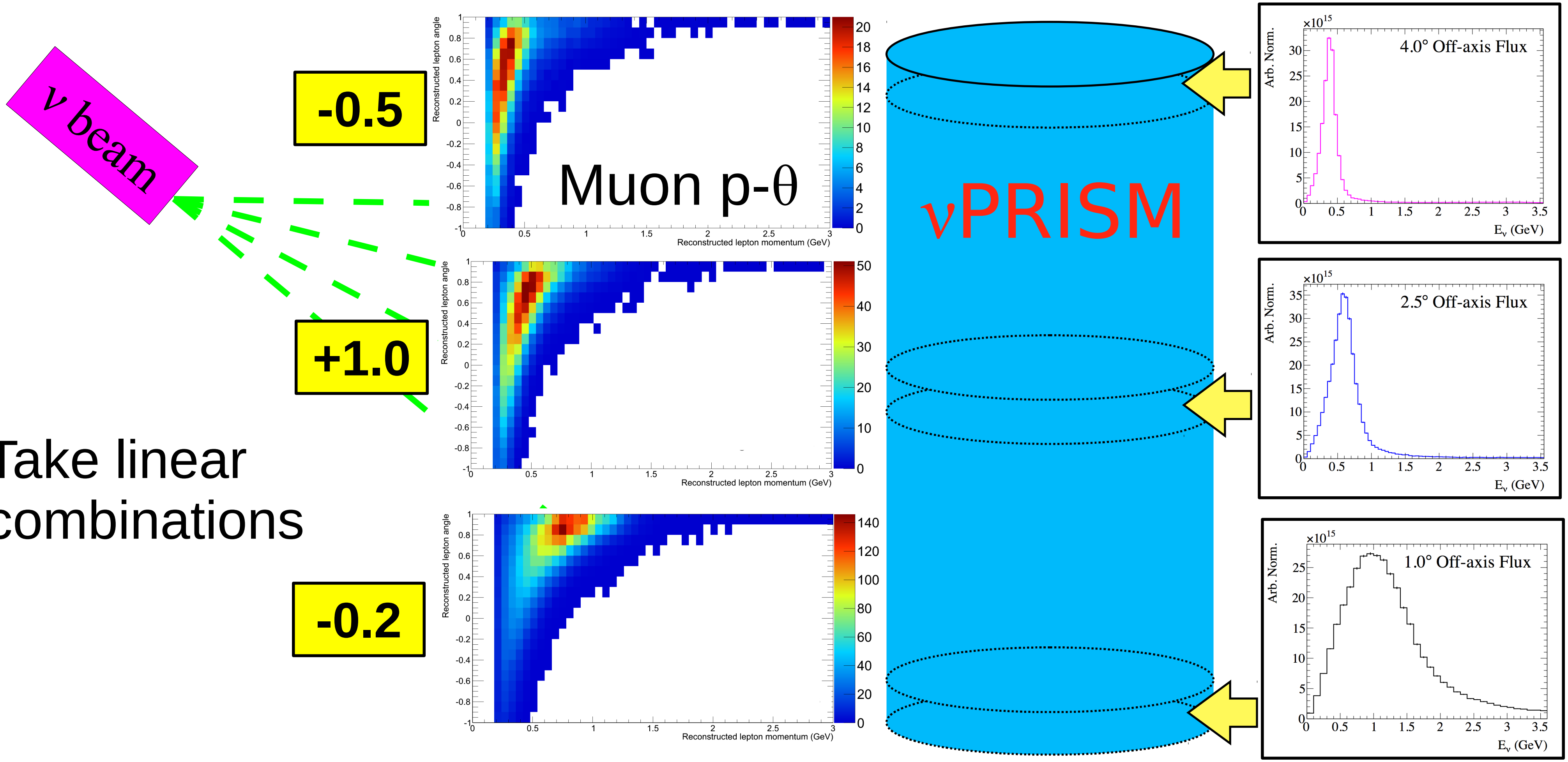
NuPRISM concept



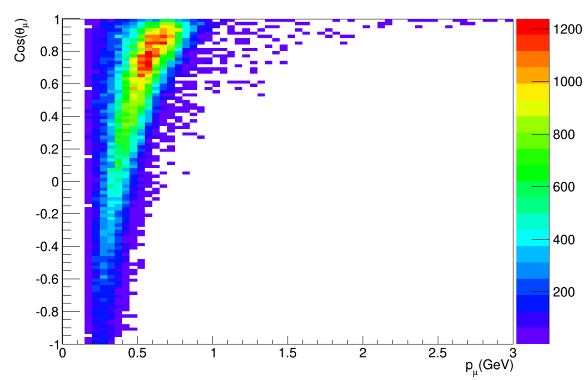
NuPRISM concept

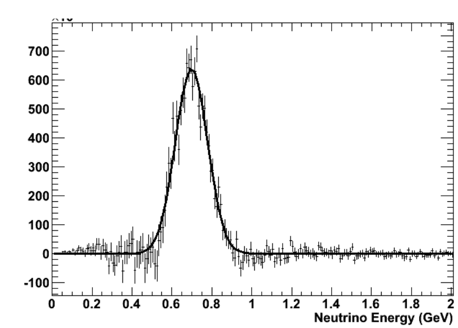


Mono-energetic beams

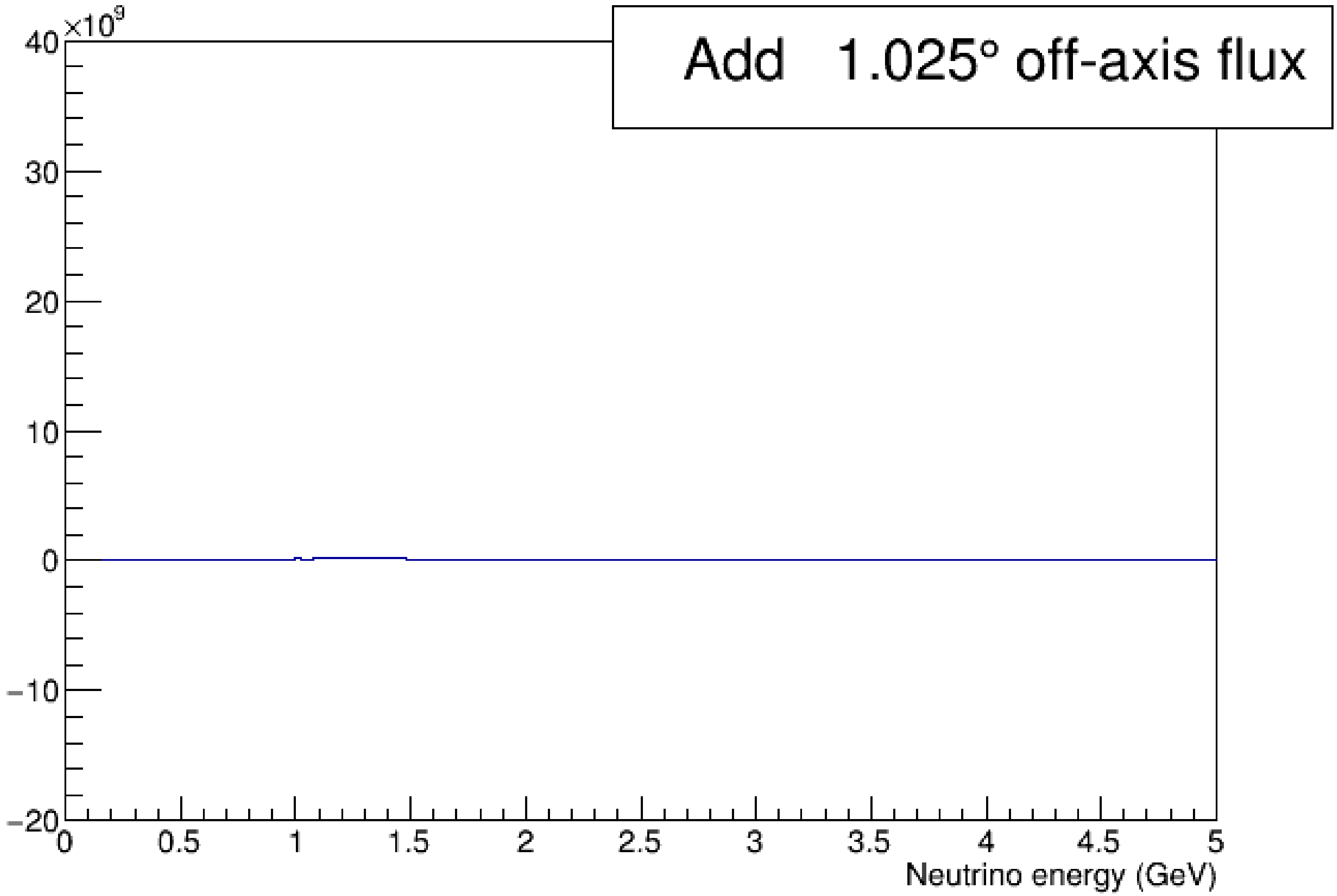


Take linear combinations

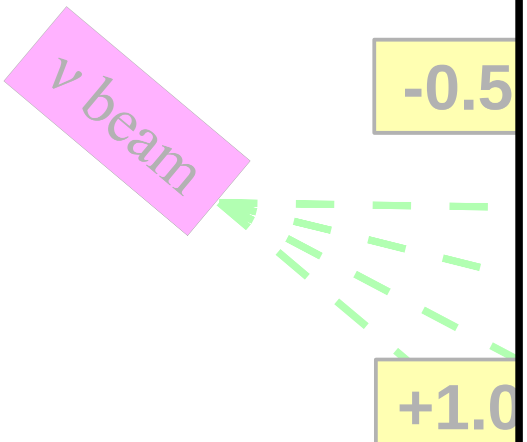


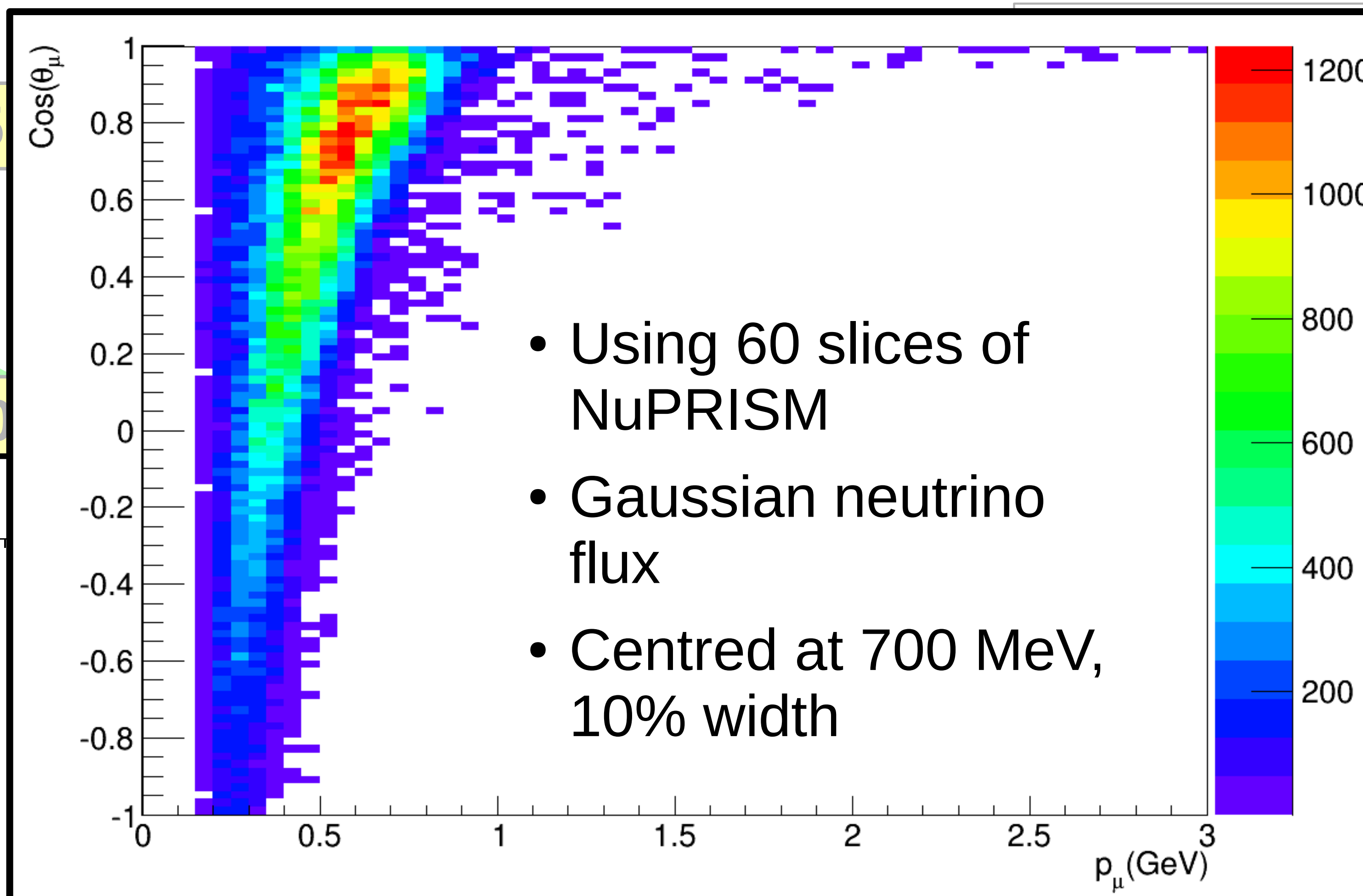


Mono-energetic beams

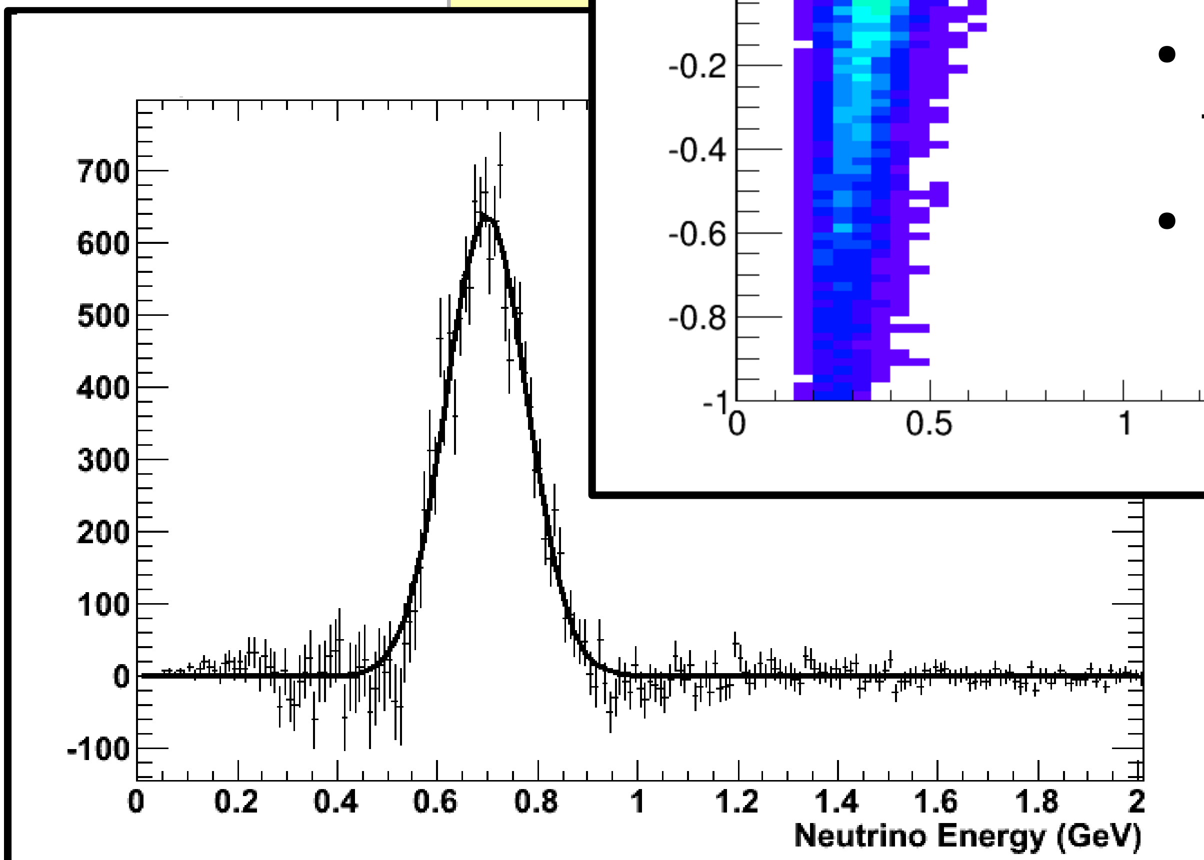


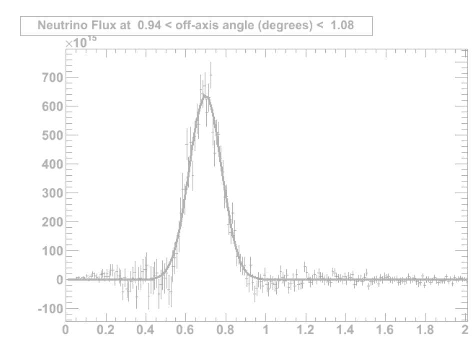
Mono-energetic beams



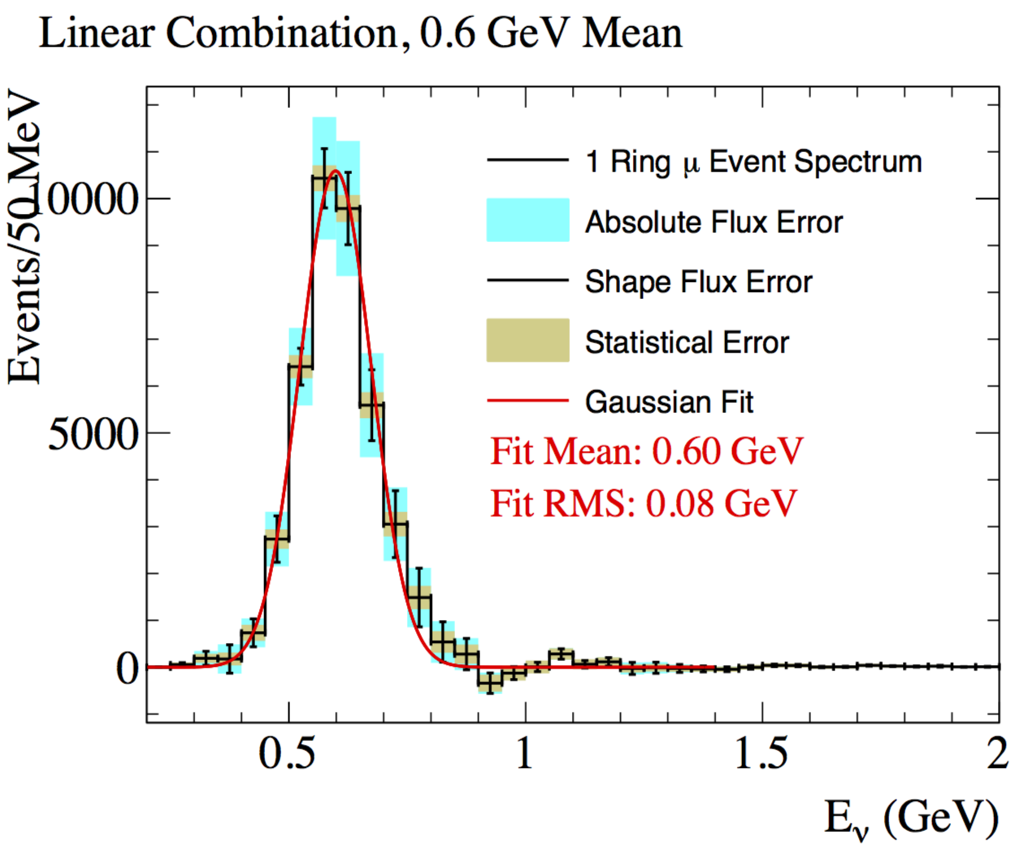


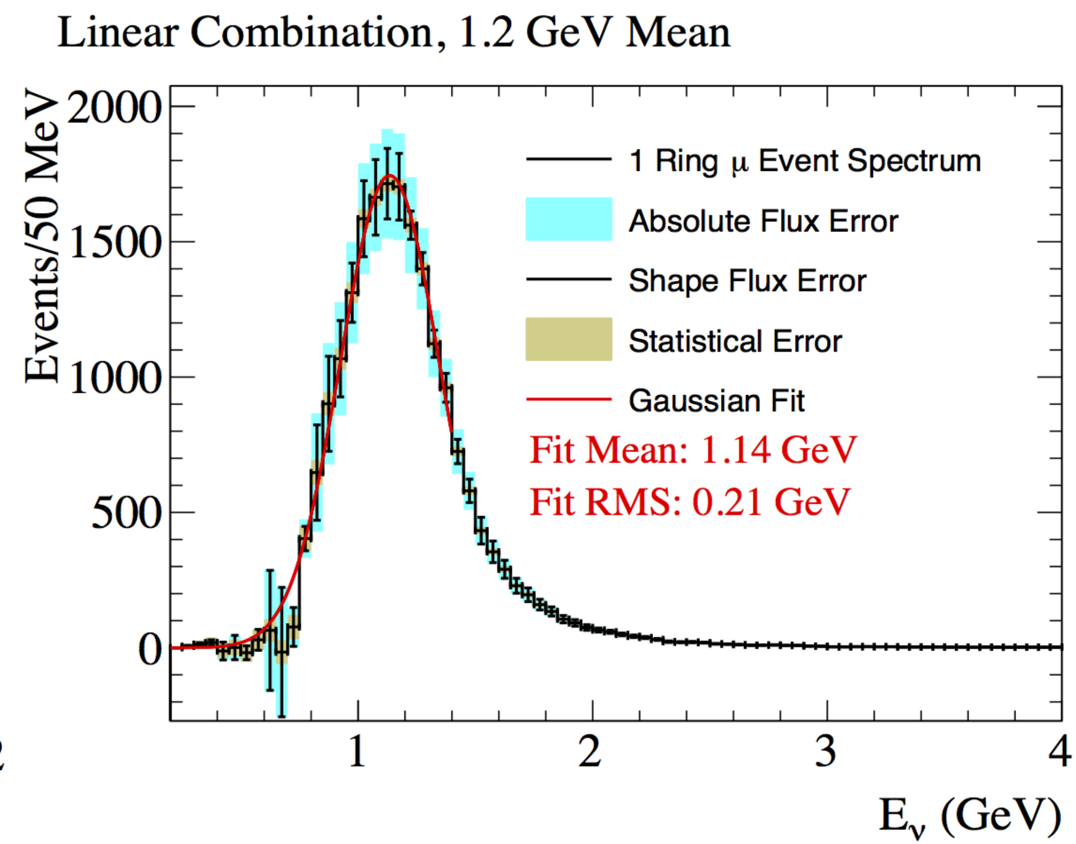
- Using 60 slices of NuPRISM
- Gaussian neutrino flux
- Centred at 700 MeV, 10% width





Mono-energetic beams in practice

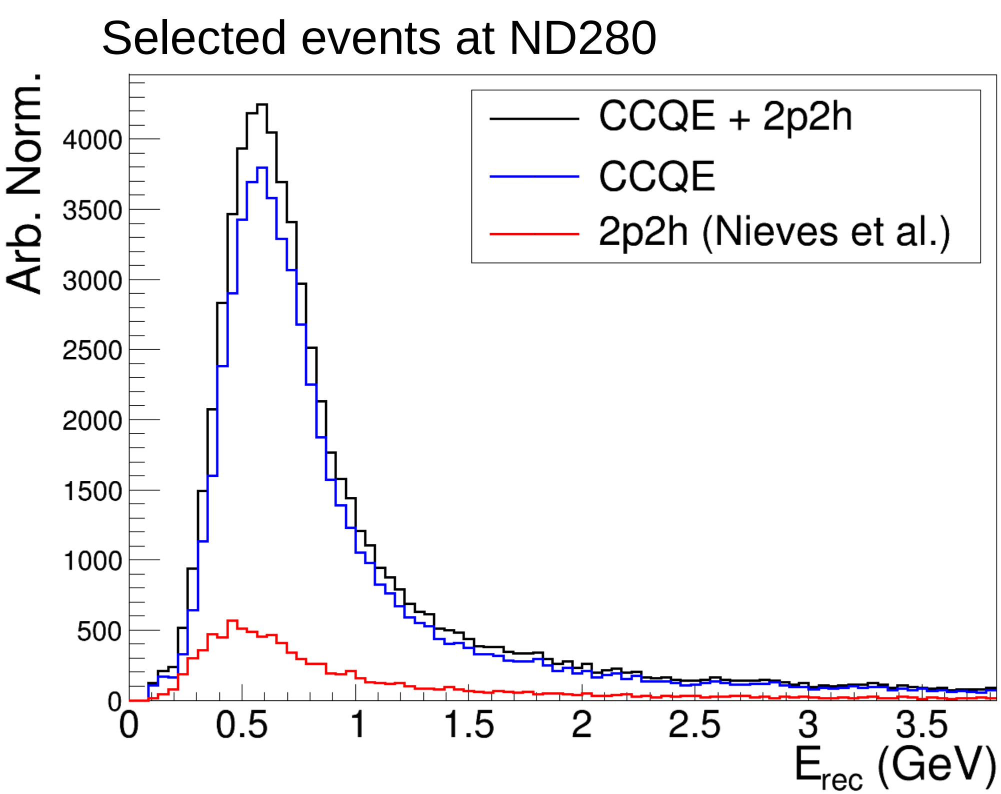


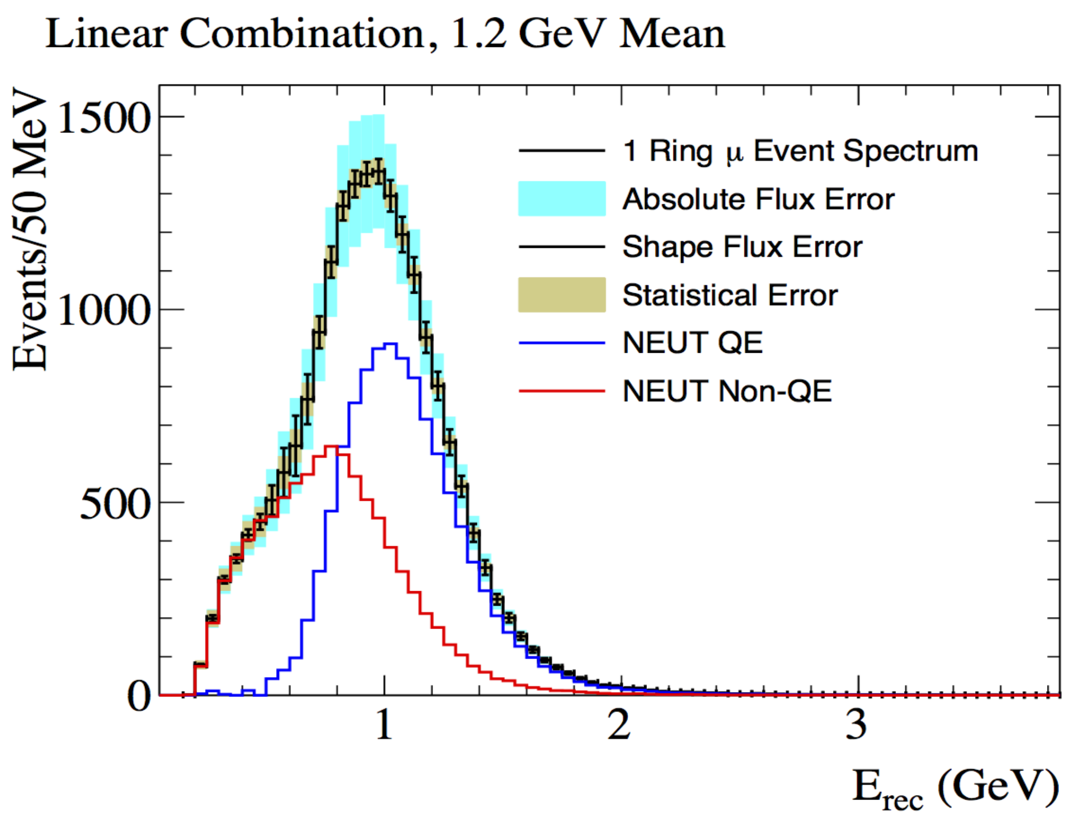


- Gaussian neutrino beams with neutrino energy from 400 MeV → 1200 MeV
  - Determined by off-axis angular span of detector
- Full T2K flux error shown
- High energy tail almost completely cancelled

How can we use them?

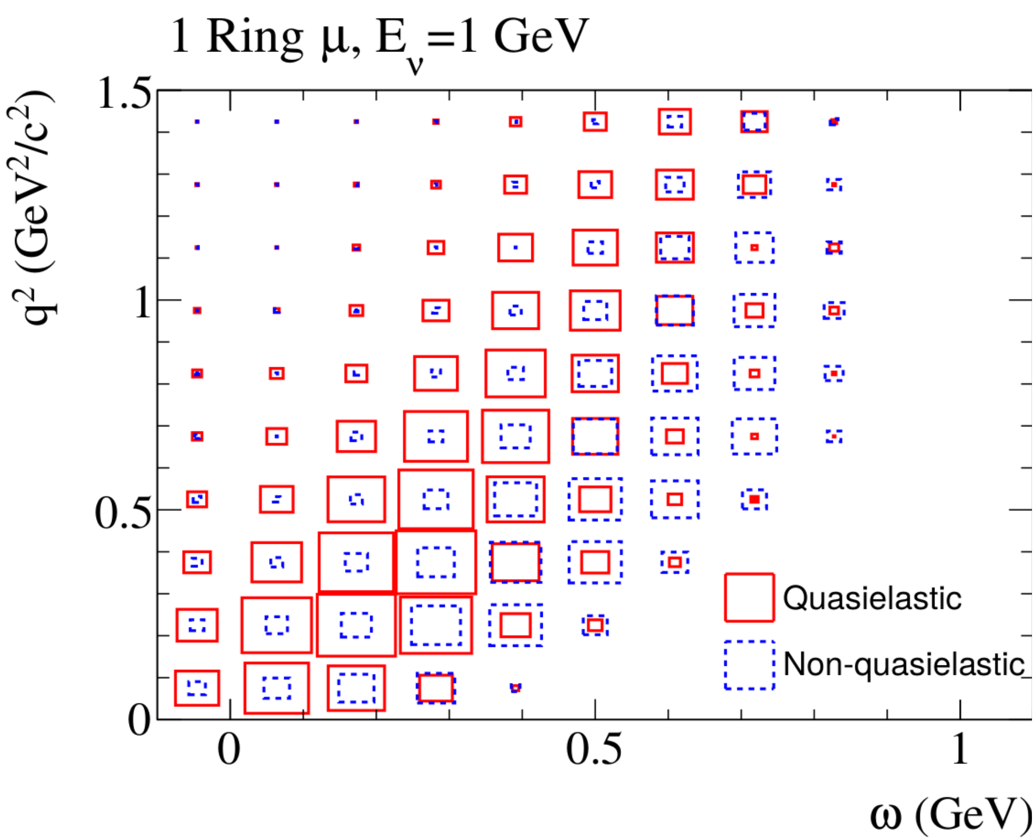
- Provides more information on neutrino interactions
- Clear separation between quasi-elastic (QE) and non-QE events
- Measure in data:
  - As function of true neutrino energy
  - In same detector → highly correlated flux and detector systematics

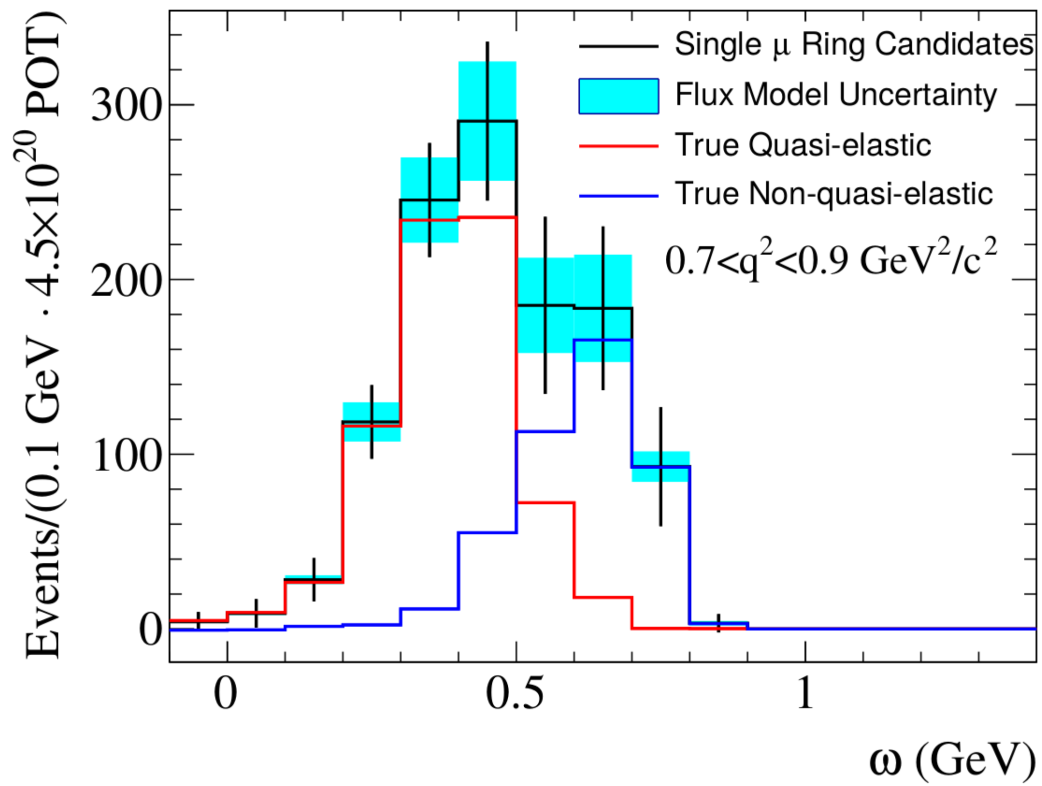




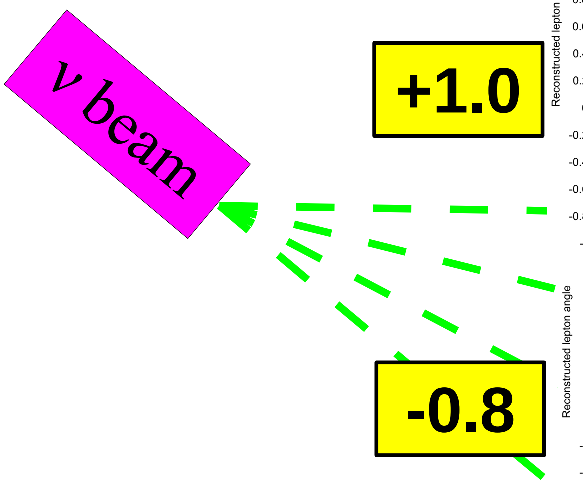
How can we use them?

- Provides more information on neutrino interactions
- Clear separation between quasi-elastic (QE) and non-QE events
- Measure in data:
  - As function of true neutrino energy
  - In same detector → highly correlated flux and detector systematics
  - Can also calculate true Q^2 and ω



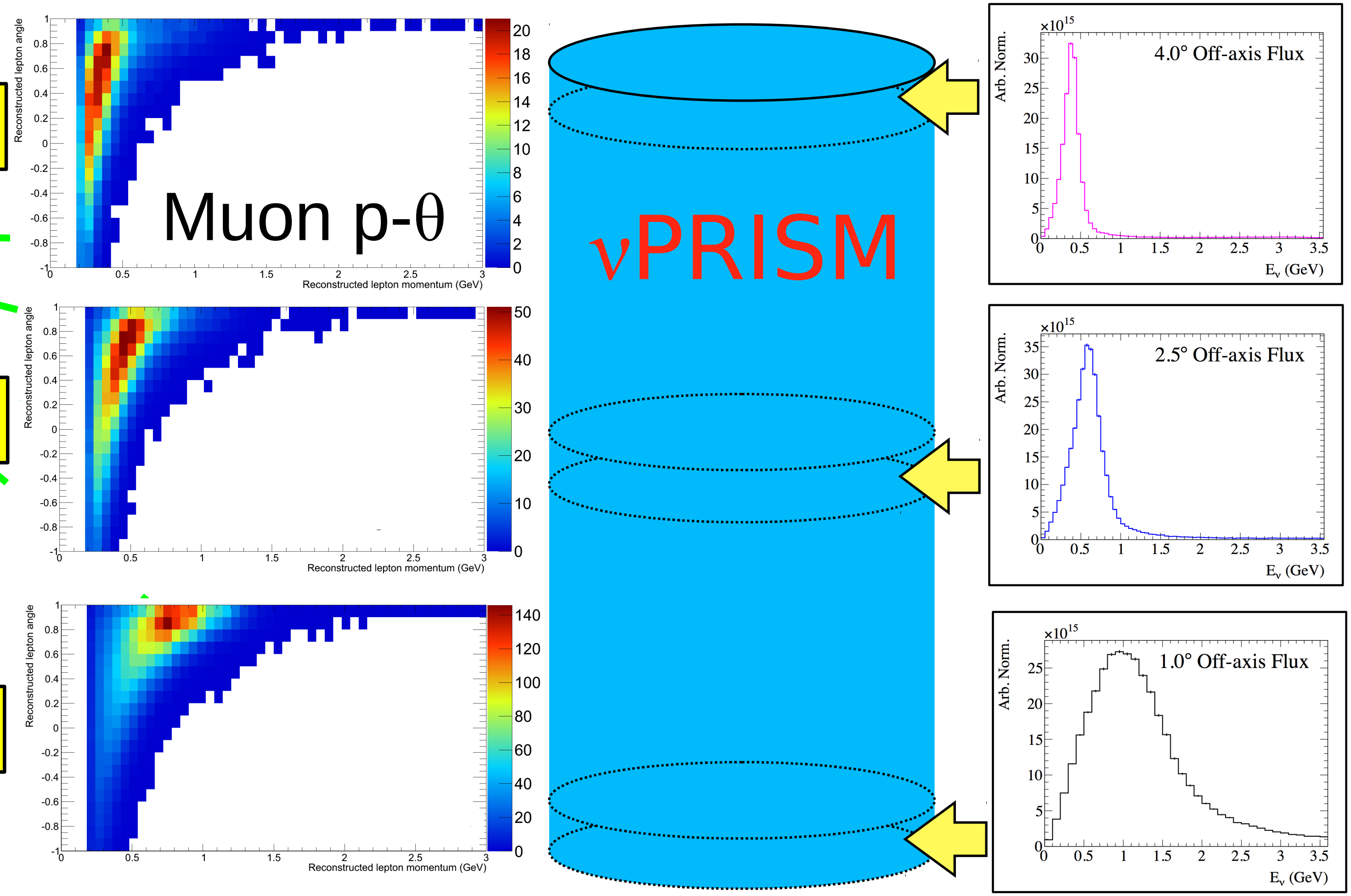


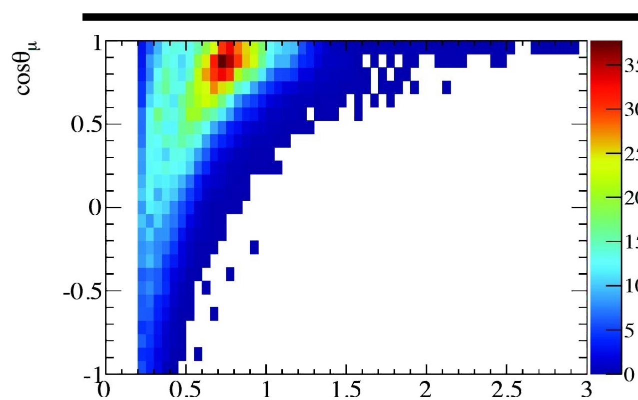
νPRISM detector concept

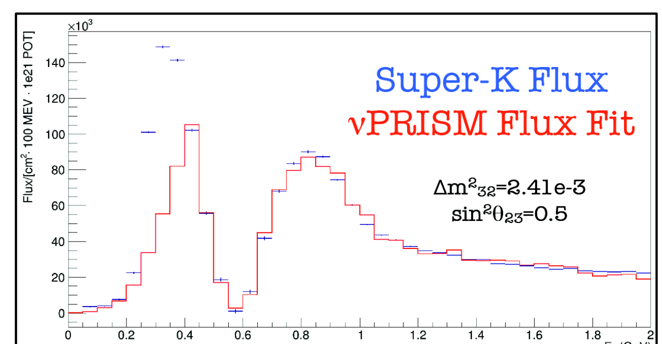


Or take different combinations

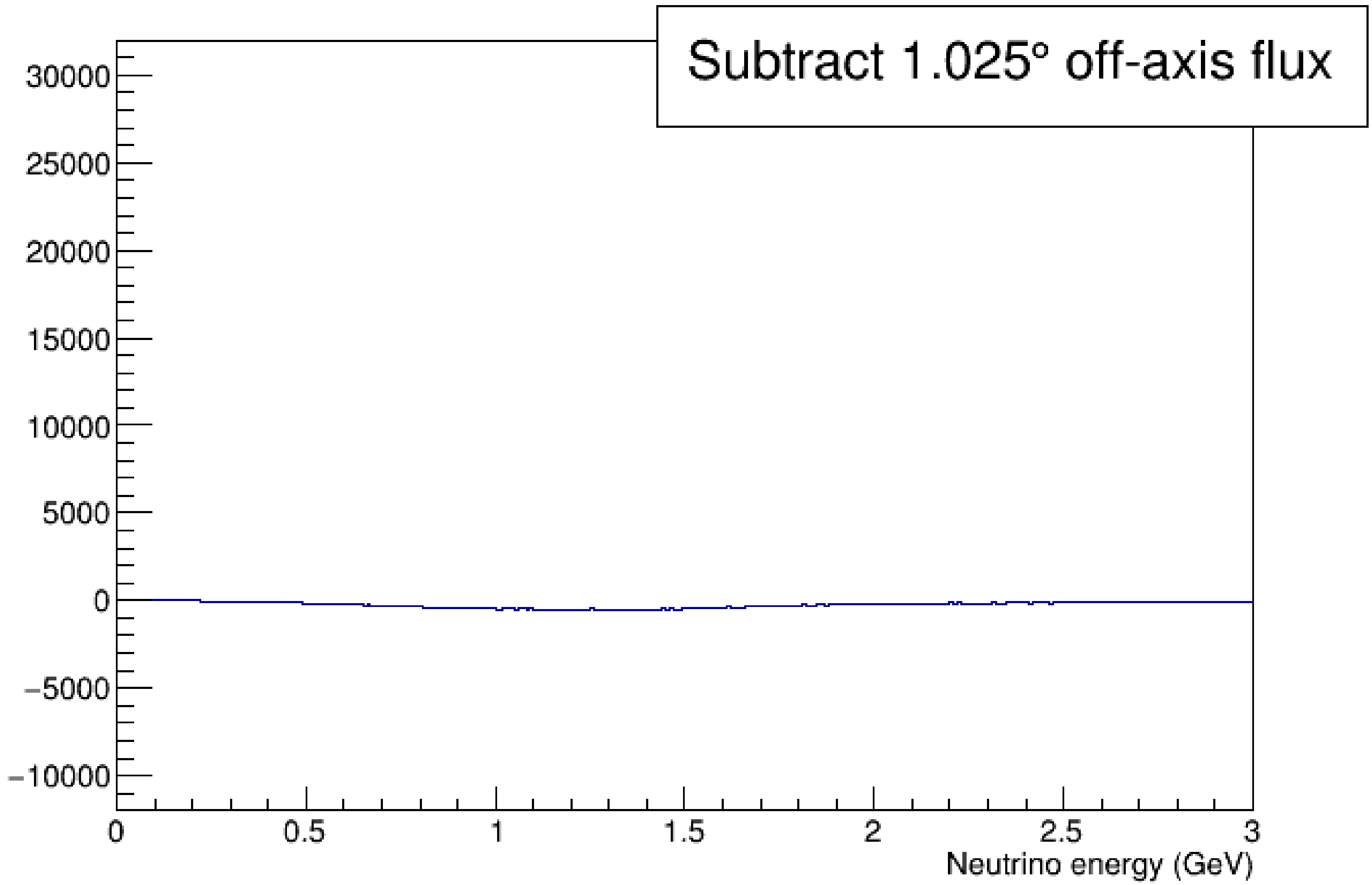
+0.2



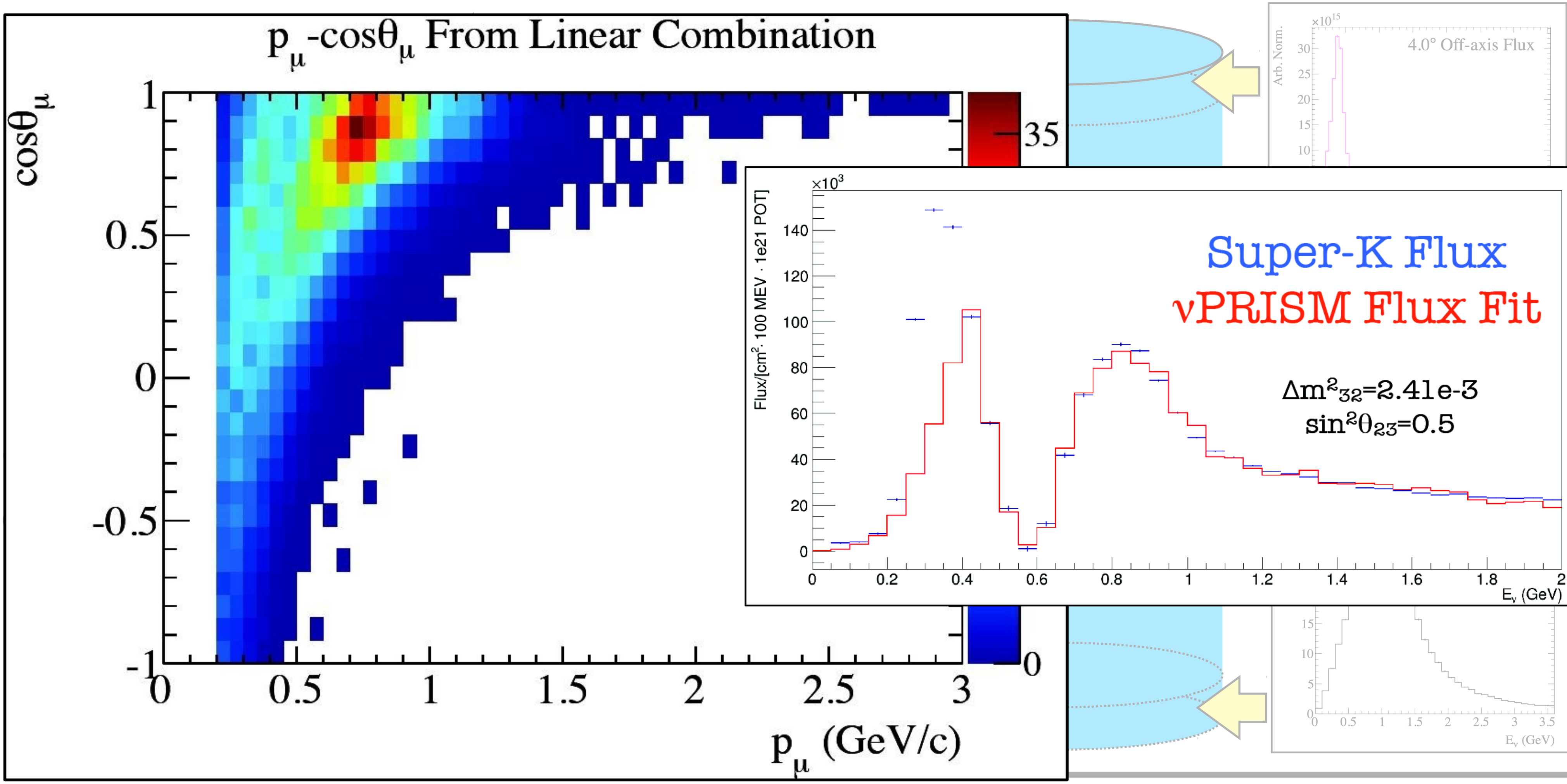


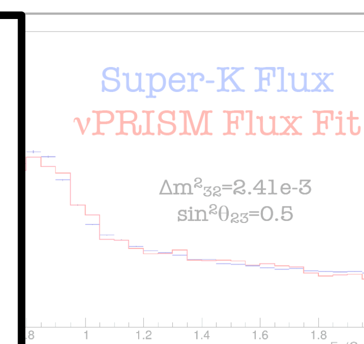


νPRISM detector concept



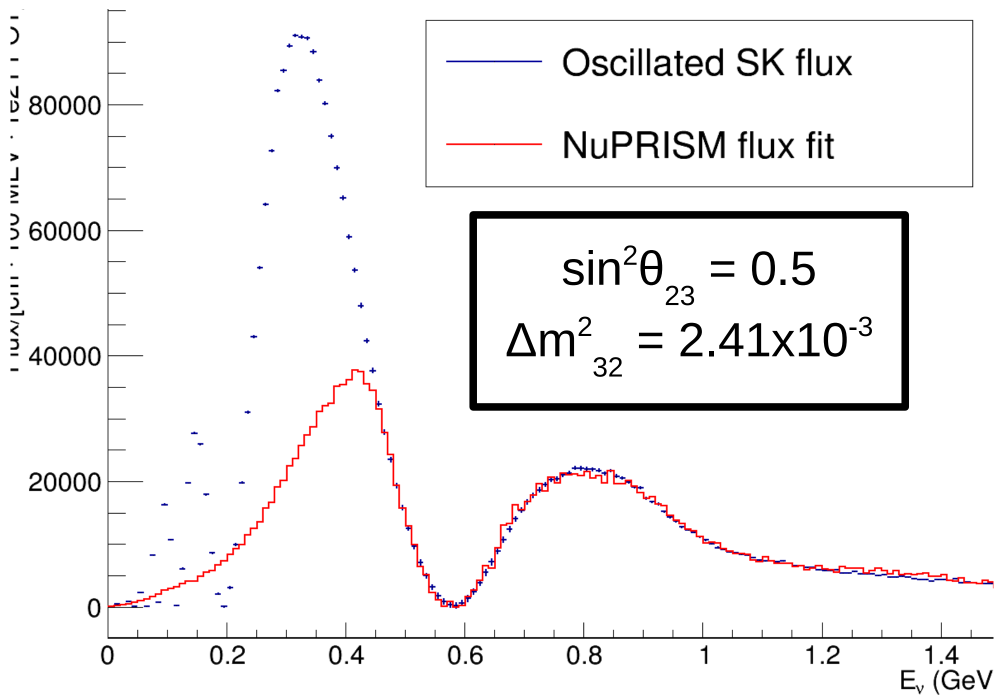
νPRISM detector concept

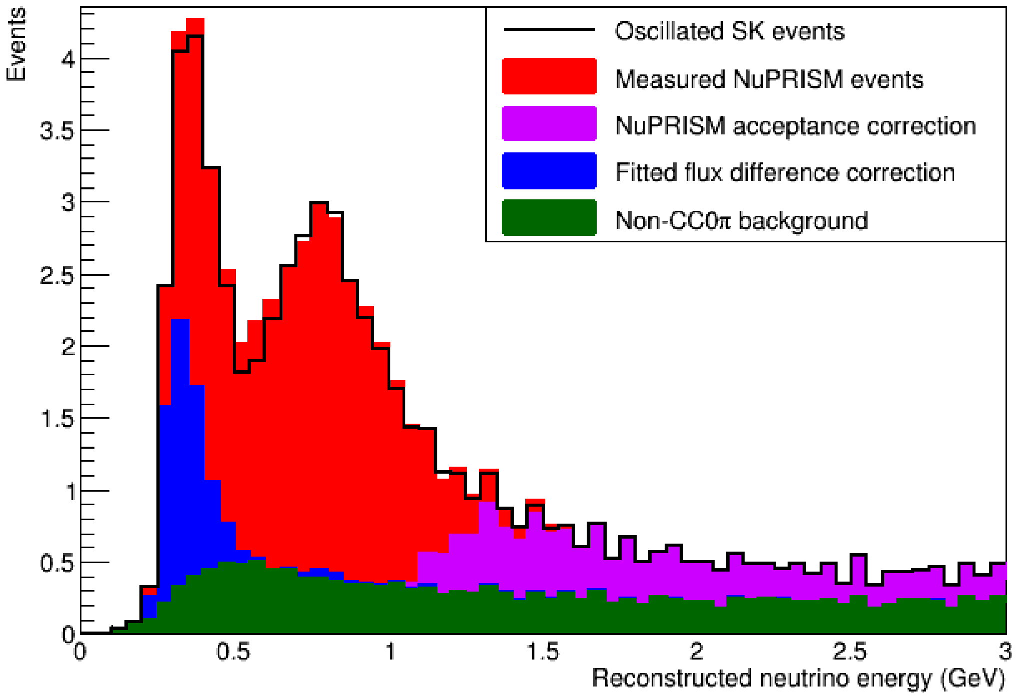




- Recreate oscillated neutrino flux at SK using near detector
- Directly measure muon p-θ for given value of oscillation parameters

ν Oscillation with NuPRISM



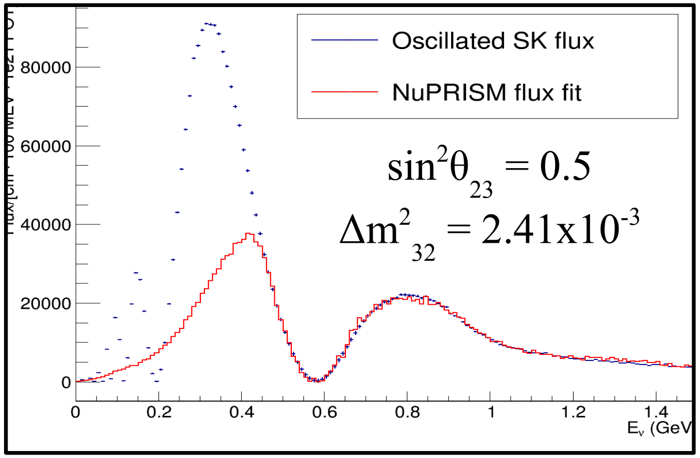


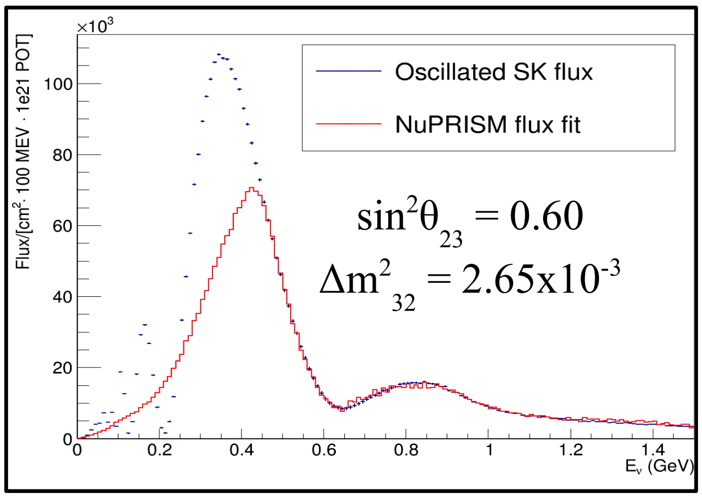
- Event rate = Flux(E_ν) * Cross-section(E_ν) * Efficiency
- NuPRISM and SK have water target – same interaction cross-section
- If fluxes (and efficiency) match:
  - NuPRISM linear combination event rate == **oscillated** SK event rate
  - No cross-section model, no effect from wrong model choice
  - Directly compare to SK data to get oscillation parameters

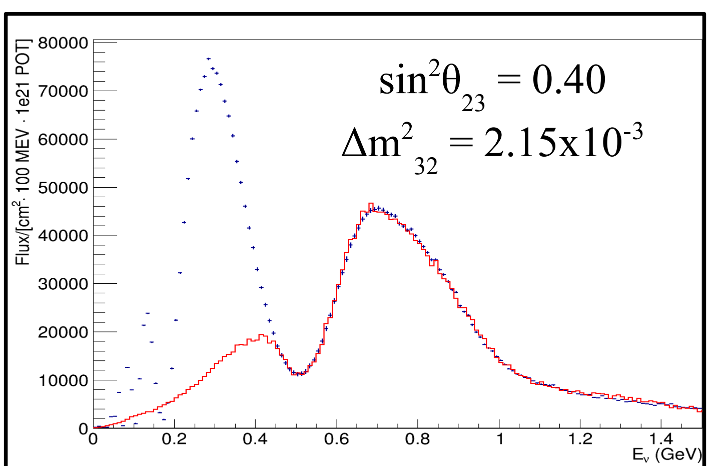
NuPRISM

ν Oscillation with NuPRISM

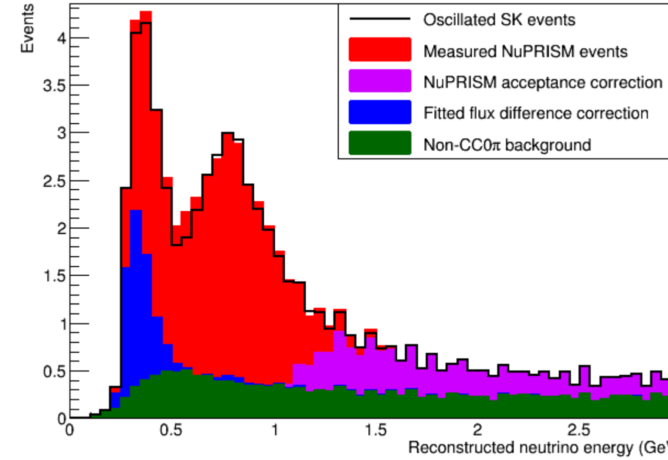
TRIUMF

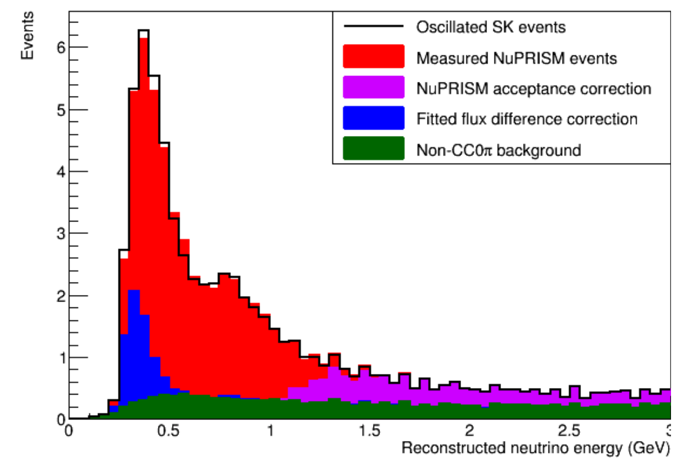


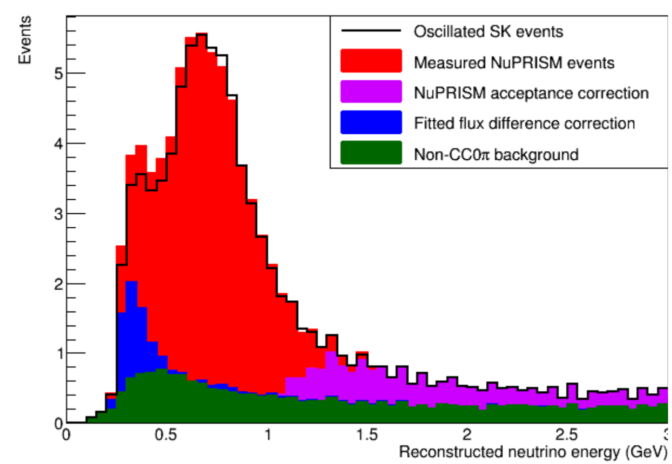




- Red – directly measured in NuPRISM data
- Blue – flux fit difference correction
- Magenta – Acceptance correction
  - NuPRISM only 8m wide
  - Can contain muons up to ~1.2GeV
- Green – SK background correction
  - Cancelation with bkg subtracted at NuPRISM
- **Majority of SK prediction directly measured**

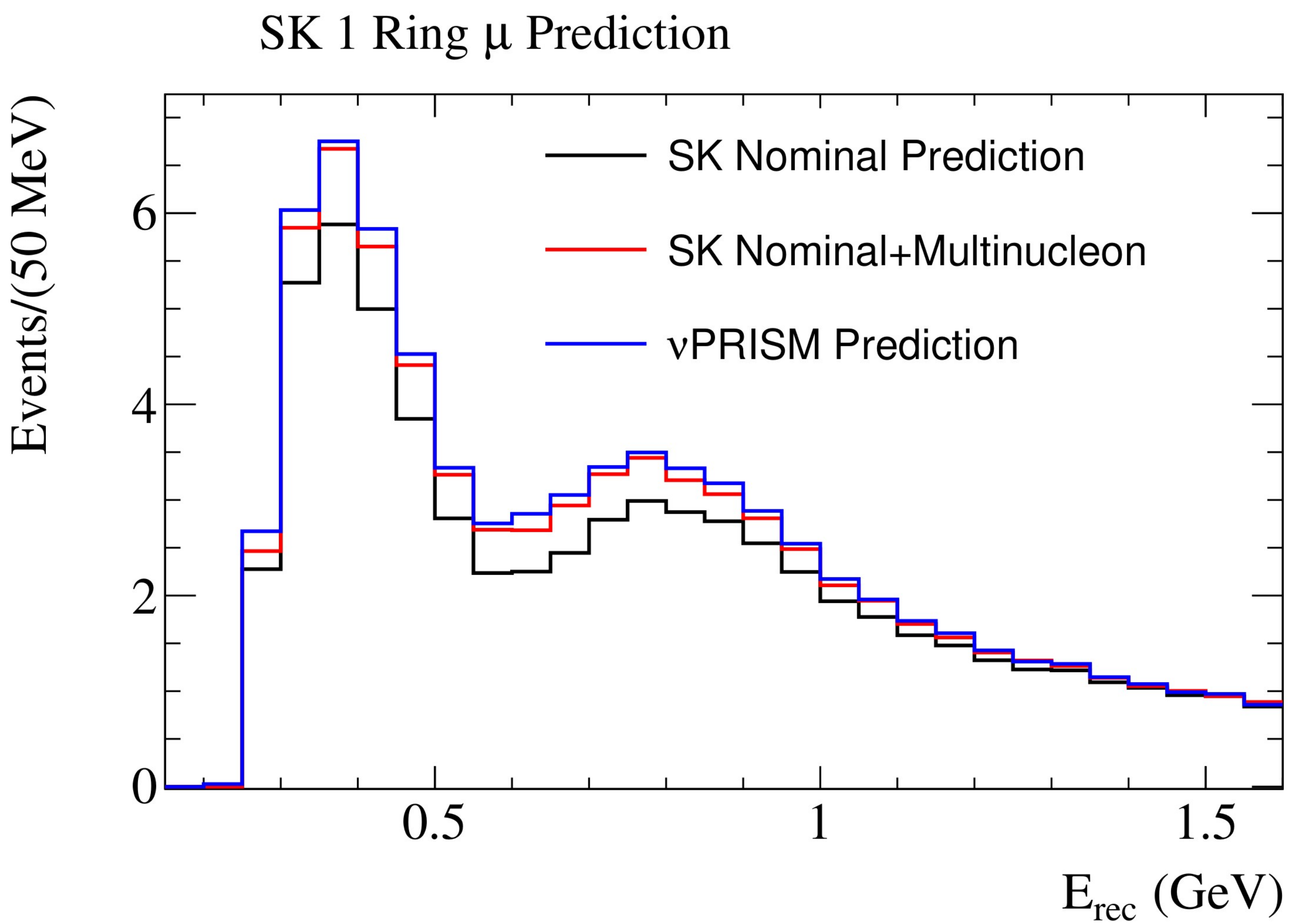






Multi-nucleon events

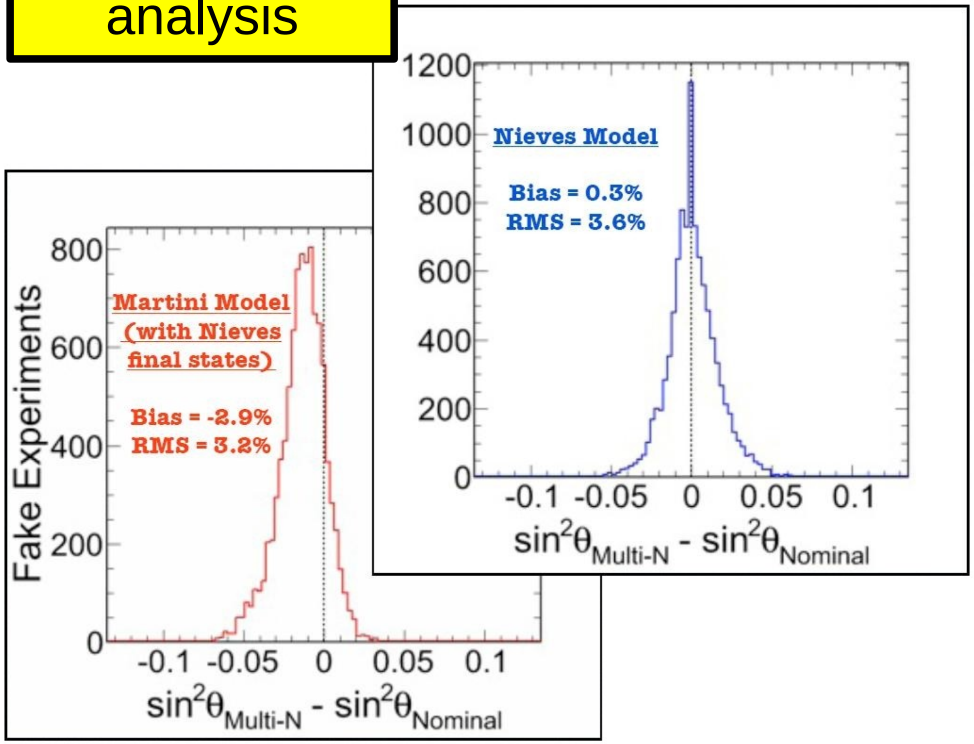
- Add multi-nucleon events to SK and NuPRISM MC to create fake dataset
  - Neutrino interaction model does not include these events
- Redo linear combinations using fake data
- NuPRISM correctly predicts SK event rate!



Effect of multi-nucleon events at νPRISM

NuPRISM

Standard T2K analysis

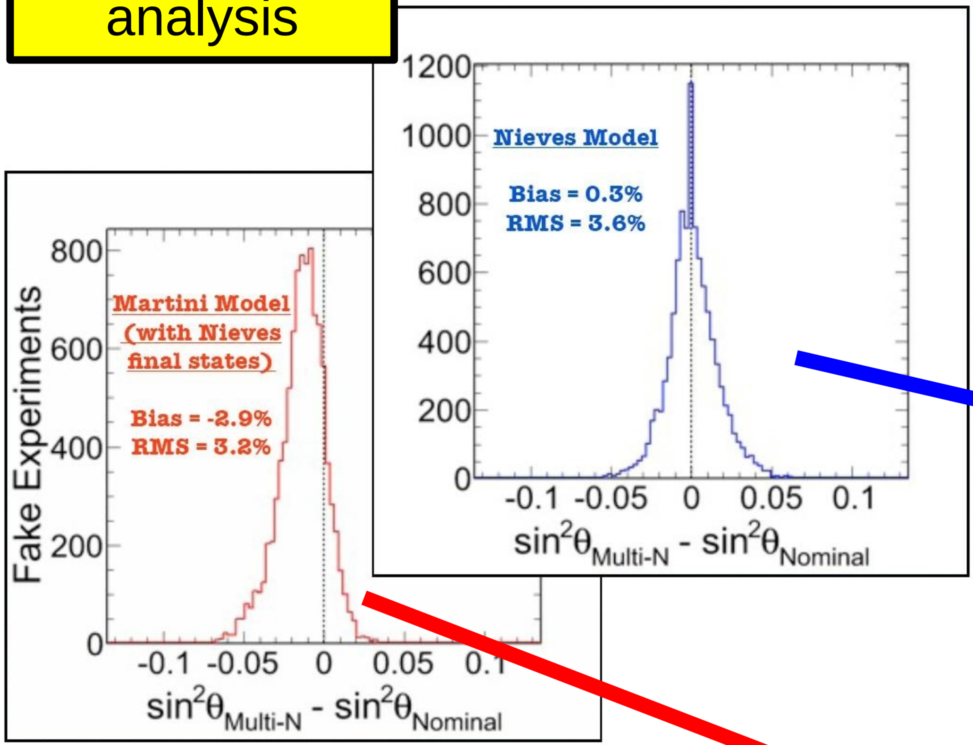


- Add np-nh events (Nieves and Martini models) to T2K fake data
- Perform disappearance fit to extract θ_{23}
- Compare to result from fit to nominal fake data

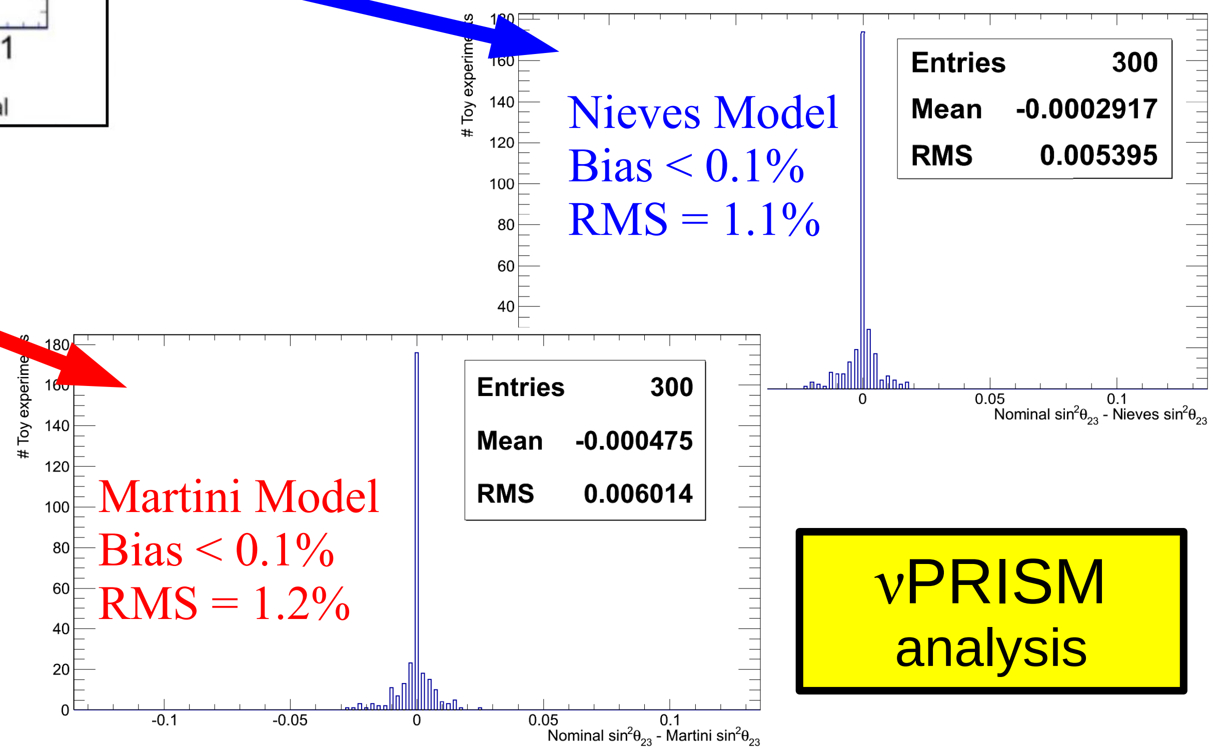
NuPRISM

Effect of multi-nucleon events at νPRISM

Standard T2K analysis



- Add np-nh events (Nieves and Martini models) to T2K fake data
- Perform disappearance fit to extract θ_{23}
- Compare to result from fit to nominal fake data



- Bias and RMS greatly reduced
- νPRISM analysis largely independent of cross section model

νPRISM analysis

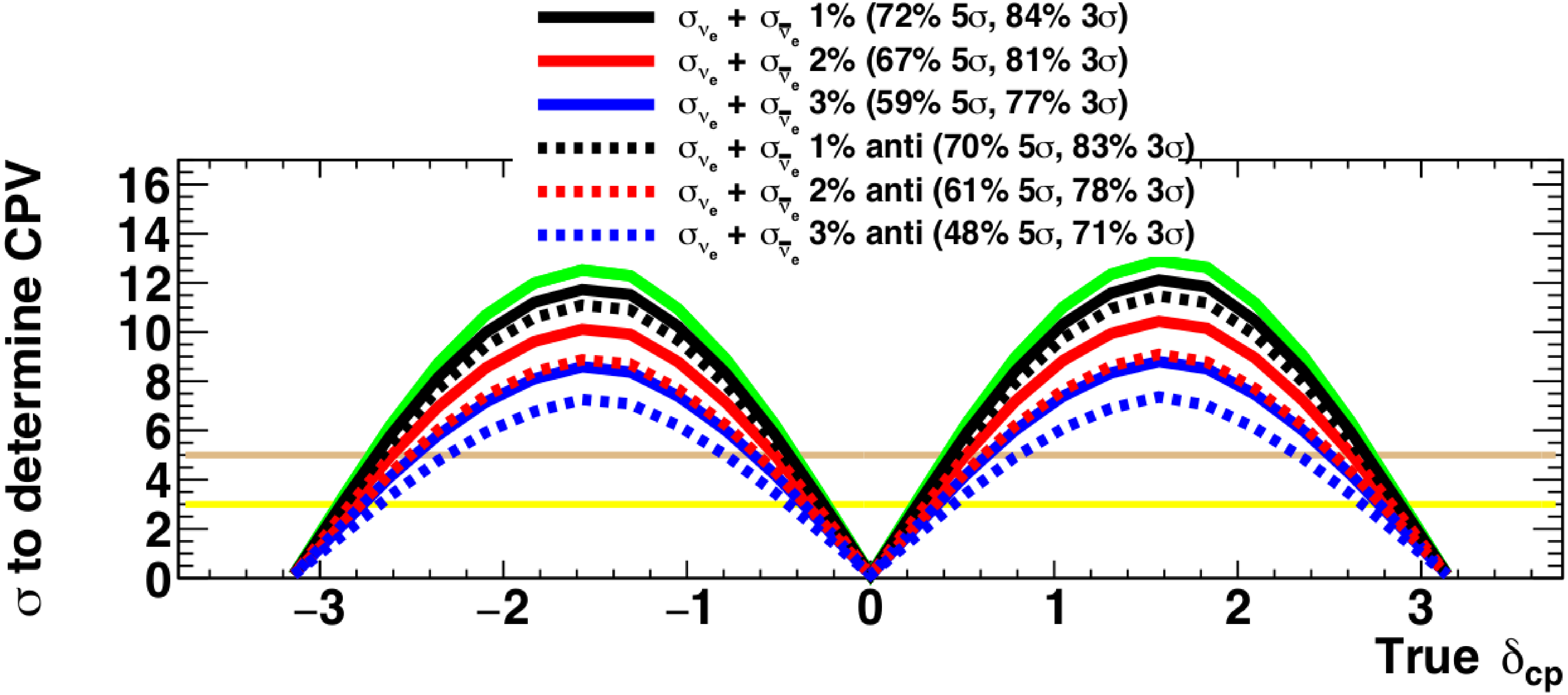
T2K 2016 systematics

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	4.6	3.9	2.8	4.0	1.9
SK Final State & Secondary Interactions	1.8	2.4	2.6	2.7	3.7
ND280 Constrained Flux & Cross-section	2.6	3.0	3.0	3.5	2.4
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.4	2.7	1.5
NC Other Cross-section	0.7	0.7	0.2	0.3	0.2
Total Systematic Error	5.6	5.5	5.7	6.8	5.6
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.2	4.0	0.1

- CP measurement depends on uncertainty on ν_e/anti-ν_e ratio
- Dominant uncertainties from theory
  - Final state interactions (FSI), secondary interactions (SI) – nuclear model extrapolation from pion-nucleus scattering experiments
  - Electron/Muon cross-section ratios – ND280 does not have statistical power to constrain to 3% in region of interest
- ND280 constraint affected by nuclear model uncertainties

ν_e cross-section

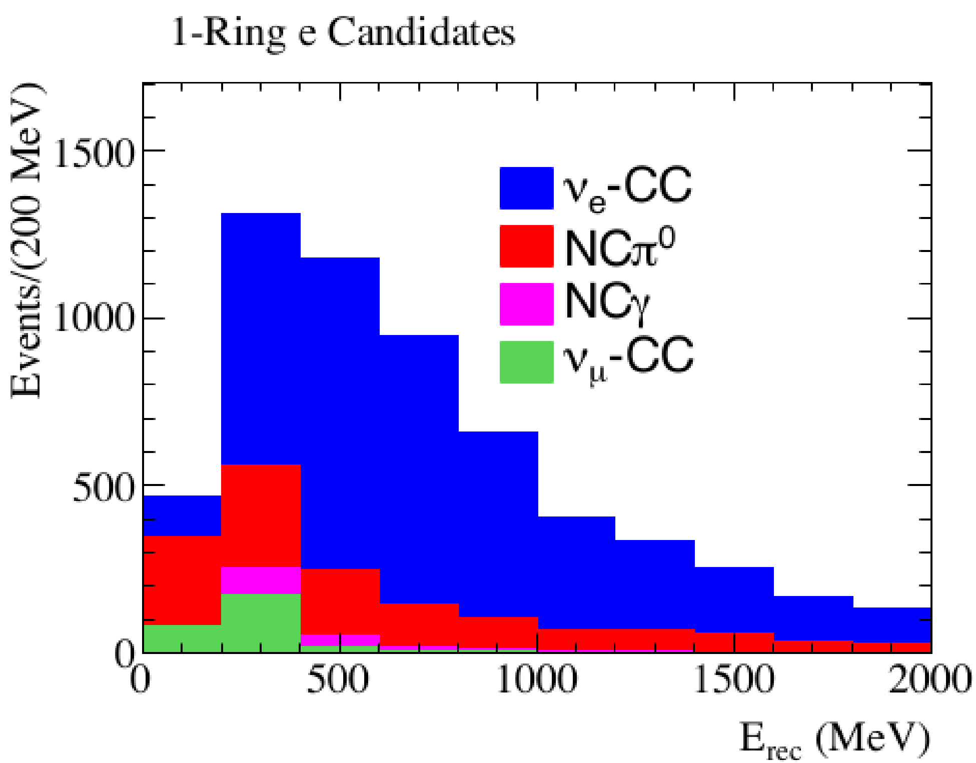
- Current uncertainty based on theory
  - ~3.5% uncertainty on CP violation measurement

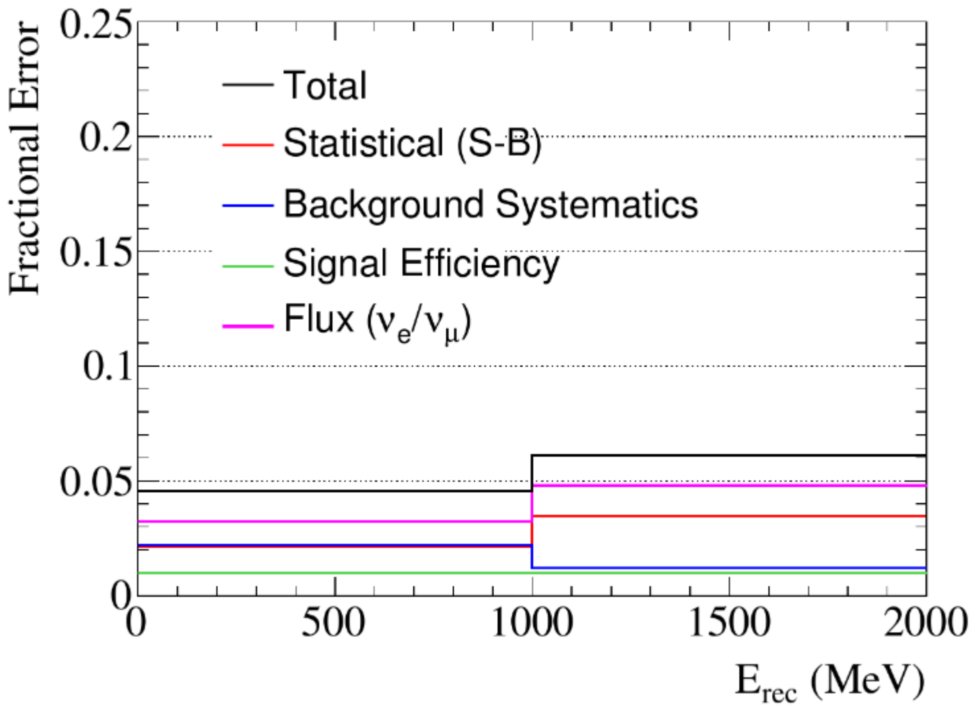


- Hyper-K sensitivity to observe CP violation for various uncertainties on ν_e cross-section
- Significantly degrade sensitivity

ν_e cross-section

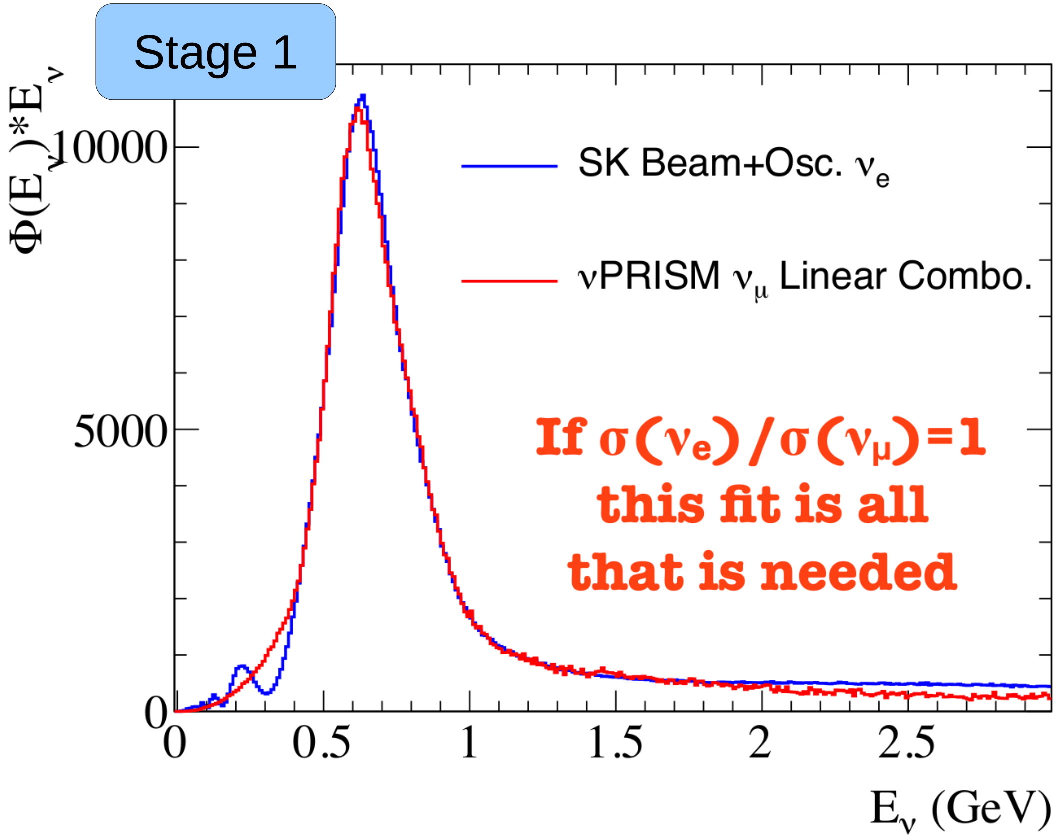
- Current uncertainty based on theory
  - ~3.5% uncertainty on CP violation measurement
- We should measure this!

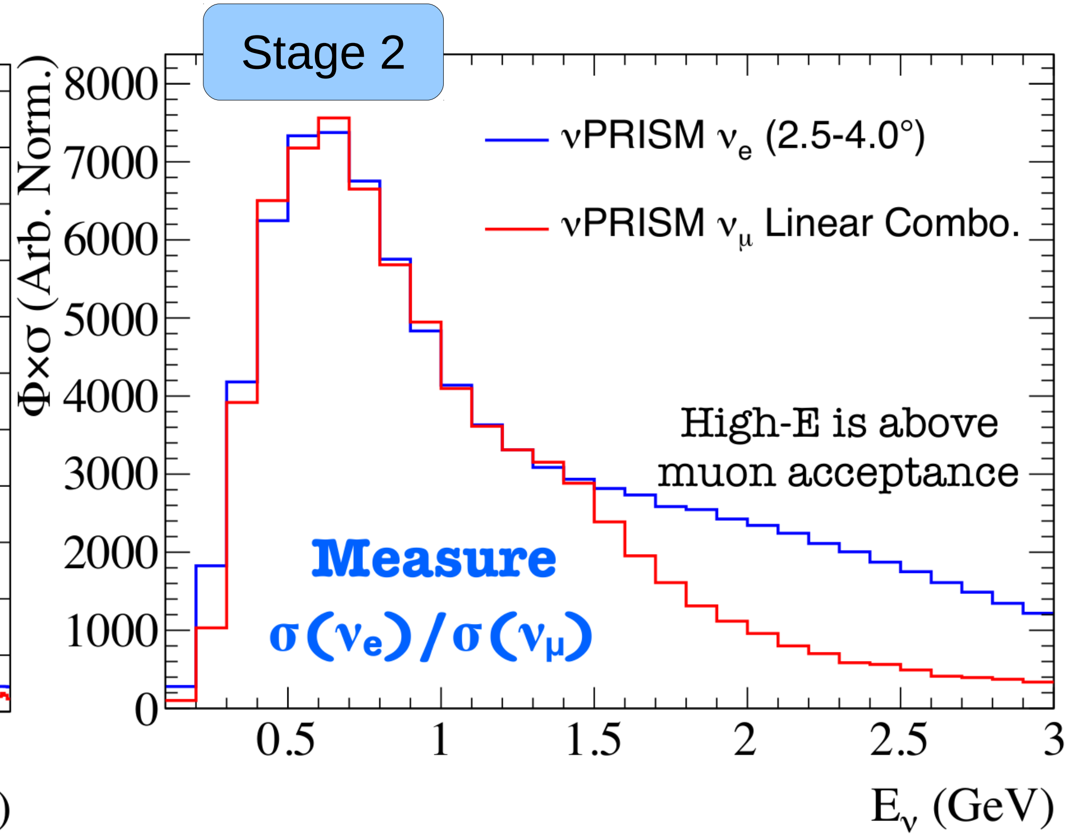




- Expect ~5000 events < 2 GeV per $1e^{21}$ POT at 73% purity
  - Compared to ~500 at ND280 in this energy region
- Conservative error estimate of <5%, dominated by flux ratio uncertainty
  - Replica target data will reduce flux ratio uncertainty

ν_e oscillation at NuPRISM





- 3 stage approach
  - Match SK ν_e appearance flux using NuPRISM ν_μ flux
  - Match NuPRISM instrinsic ν_e flux using NuPRISM ν_μ flux - measure cross-section ratio **with same flux**
  - Measure beam and NC backgrounds using 2.5° NuPRISM flux

NuPRISM

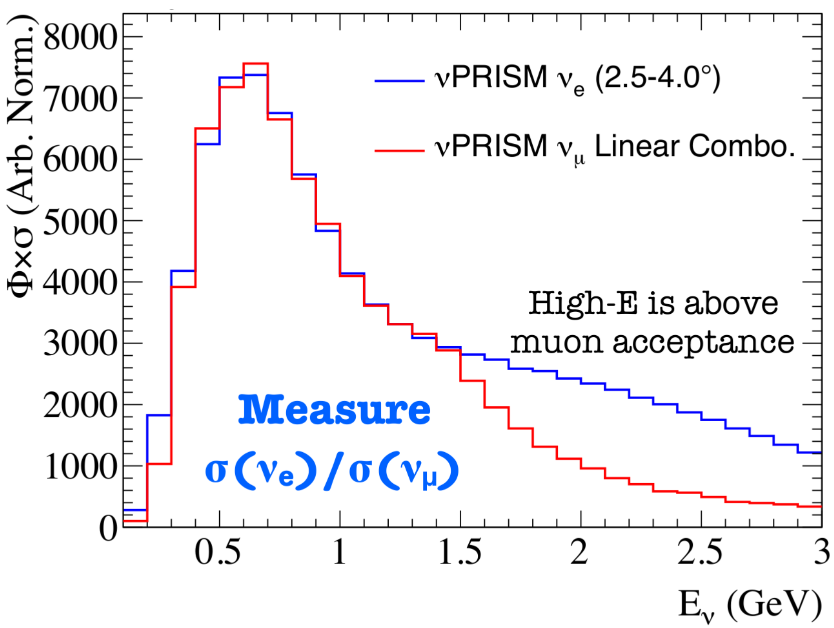
Benefits for ν_e at NuPRISM

TRIUMF

- Water Cherenkov detector, same as SK, so can make high purity electron-neutrino sample
- Going off-axis increases relative fraction of intrinsic electron neutrinos in beam

Off-axis angle (°)	ve Flux 0.3-0.9 GeV	vμ Flux 0.3-5.0 GeV	Ratio ve/vμ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

- Large statistics
- Matching fluxes
  - For appearance signal
    - Nuclear effects
    - FSI, SI
      - All cancel!
  - For cross-section
    - Same interaction modes
    - Same energy dependence
- Dominant, theory driven systematics cancelled out experimentally



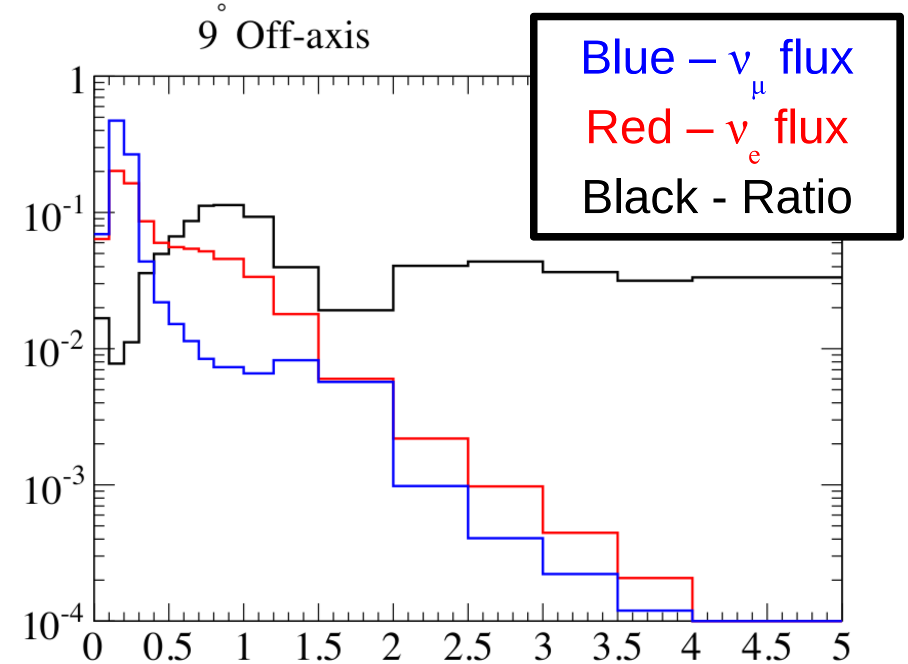
NuPRISM

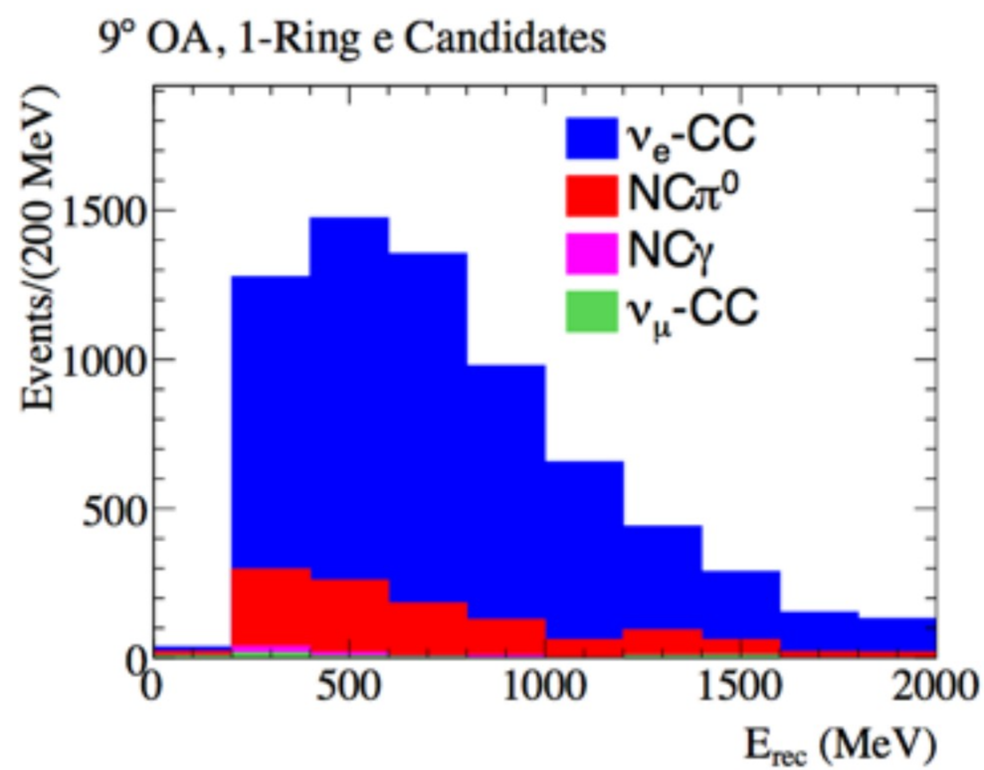
NuPRISM Status

- Updated proposal reviewed at the J-PARC PAC in January 2016:
  - http://j-parc.jp/researcher/Hadron/en/pac_1601/pdf/P61_2016-5.pdf
- Summary of the PAC response:
  - “NuPRISM is an excellent proposal... [but] is intimately related to the T2K extension”
  - “The PAC strongly encourages the continuation of R&D studies in close collaboration with the proponents of the T2K-Phase II proposal”
- ICRR-KEK/IPNS review
  - “the accelerator, beam line, near detector, and intermediate detector upgrades for HK should be realized as soon as possible, and will benefit T2K”
- KEK Project Implementation Plan review concluded that the upgrades for Hyper-Kamiokande have the highest priority
- Working with T2K to put forward joint statement on NuPRISM for T2K-II
- Working with TITUS (an alternative proposal) towards merger of detectors
- Submitted joint CFI Innovation fund request with Canadian IceCube group
  - CAPSTONE (Canadian Advanced PhotoSensor TechnOlogy for Neutrino Experiments), developing a multi-PMT photosensor for NuPRISM and PINGU

NuPRISM Phase 0

- Funding for detector pit available ~2020
  - Want to start before then...
- Fully instrumented detector on surface at ND280 site
  - 9 to 12 degrees off-axis
    - Low enough rate for water Cherenkov
    - Larger fraction of electron neutrinos in beam
    - Electron neutrino energy ~700 MeV
  - Test calibration procedure to reach necessary detector systematic precision
  - High statistics measurement of ν_e / ν_μ cross section





Summary

Oscillation experiments will be limited by systematics not statistics

- Dominant systematics hard to constrain with traditional near detectors

The NuPRISM detector provides a solution

- Same nuclear target and acceptance as SK
- Same signal + background
  - If near and far fluxes match systematics cancel
  - Oscillation analyses independent of interaction model

NuPRISM also enables:

- Unique probe of cross-sections
- Powerful sterile neutrino searches
- Tests of new water Cherenkov technologies

NuPRISM project gaining momentum – NuPRISM Phase 0

New collaborators welcome!

Backup Slides

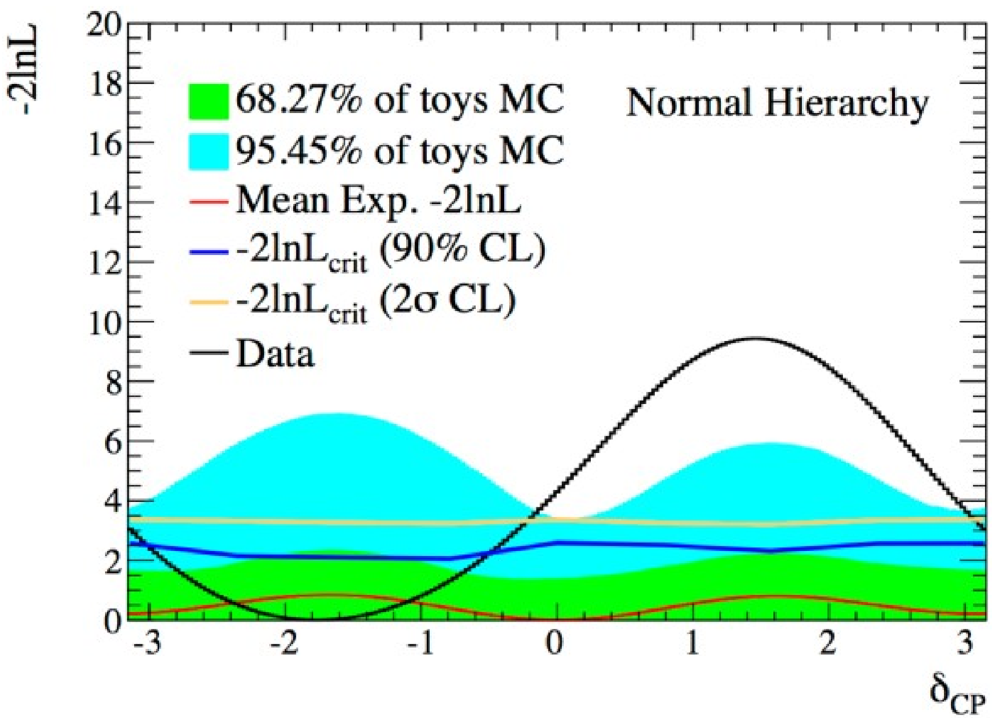
Discussion of T2K results

- Observe
  - more ν_e candidates than predicted
  - fewer $\bar{\nu}_e$ candidates than predicted

in the case of NH, δ_{CP} = -π/2 that induces the largest asymmetry

observed vs. expected number of ν_e and ν_e candidates

		EXPECTED (NH, $\sin^2\Theta_{23}$=0.528)			
	OBS.	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=+π/2	δ_{CP}=π
ν_e	32	27.0	22.7	18.5	22.7
$\bar{\nu}_e$	4	6.0	6.9	7.7	6.8

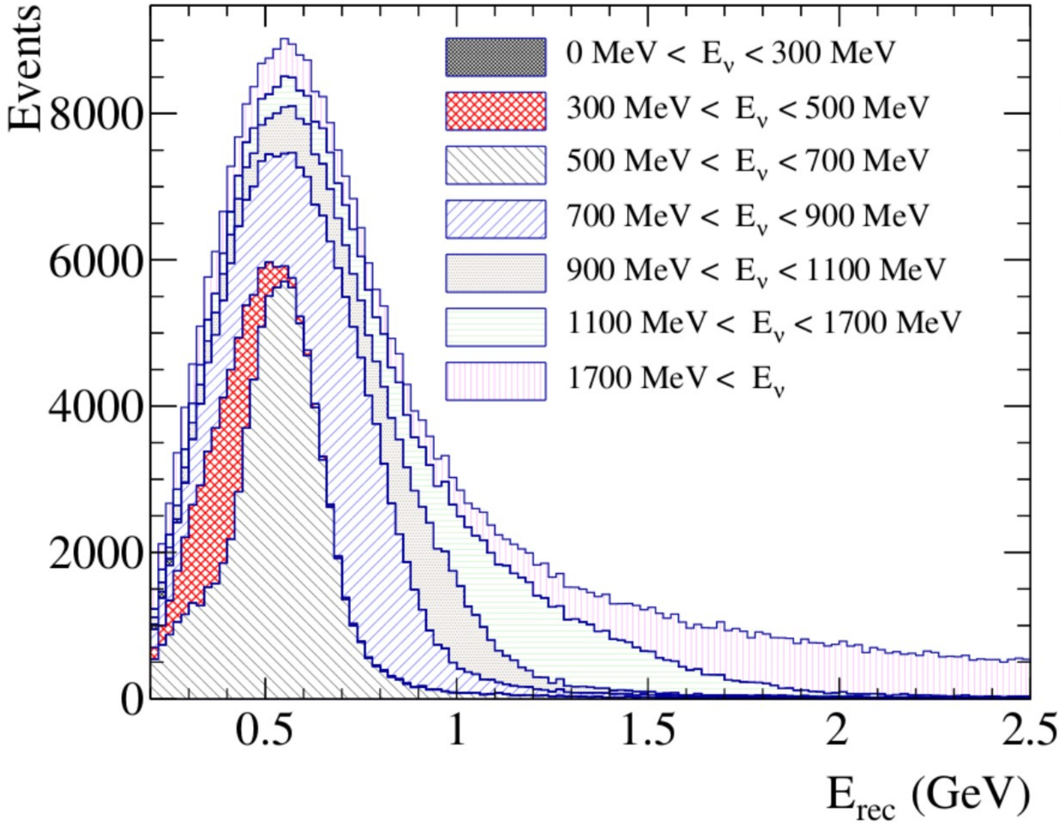


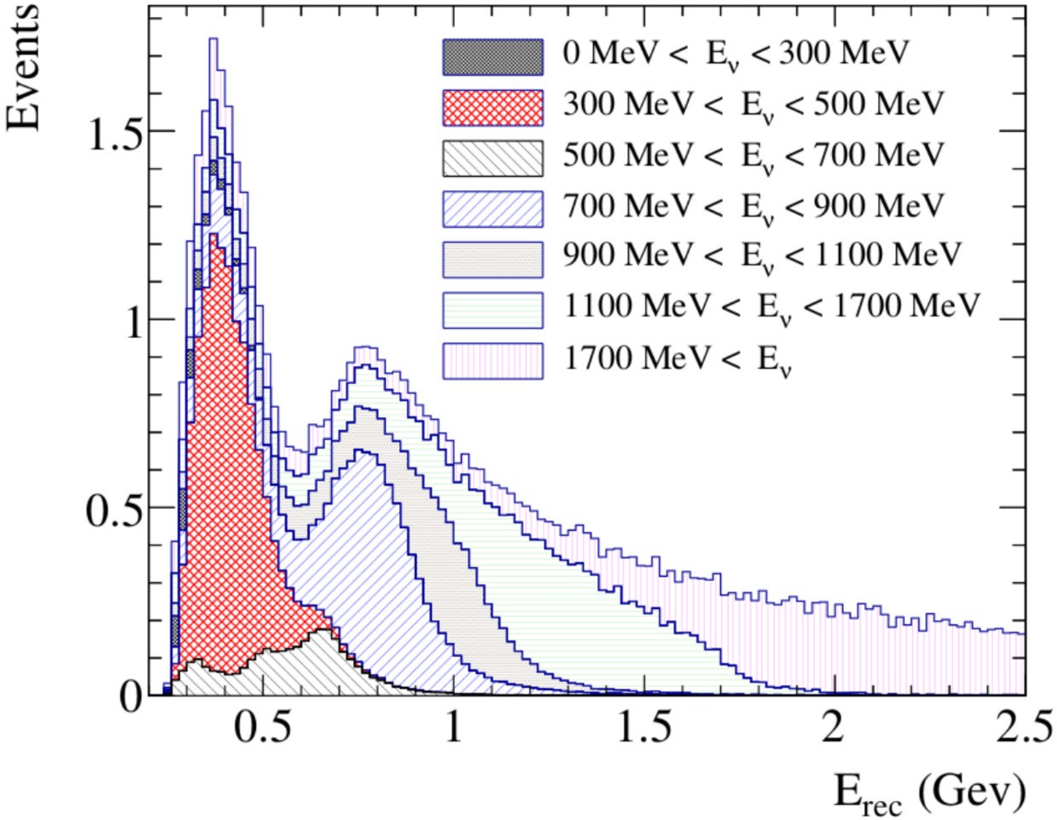
- Toy MC run to assess probability of outcome given a set of "true" parameters
- Below: fraction where δ_{CP} =0 excluded at 90% or 2 σ CL for NH, δ_{CP} = -π/2, 0

	TRUE PARAMETERS	
	δ_{CP}=-π/2, NH	δ_{CP}=0, NH
90%	0.187	0.102
2 σ	0.089	0.047

23

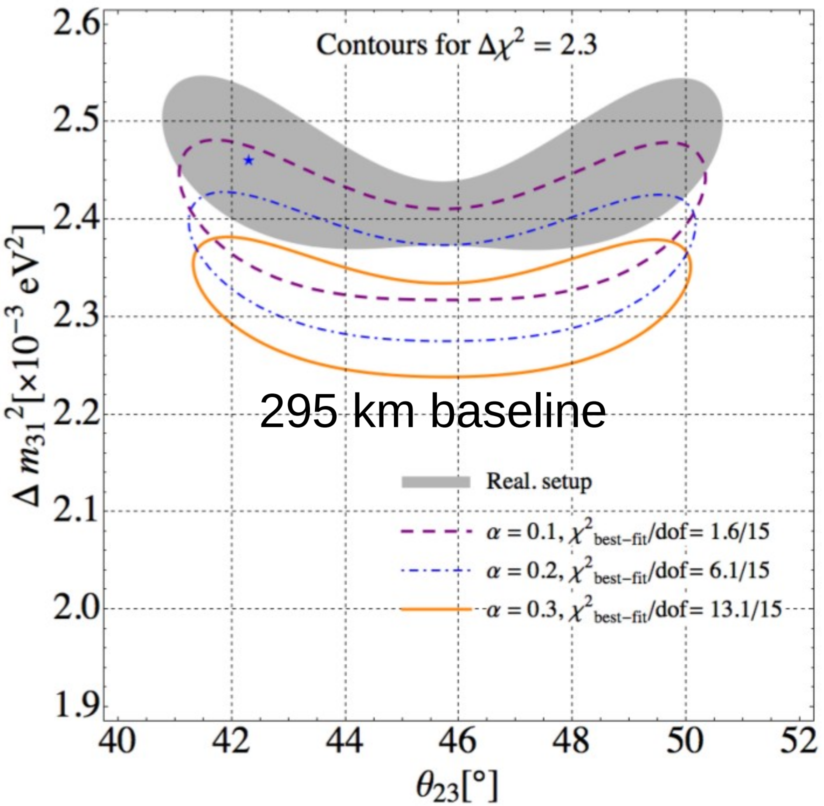
Effect of oscillation on near detector extrapolation

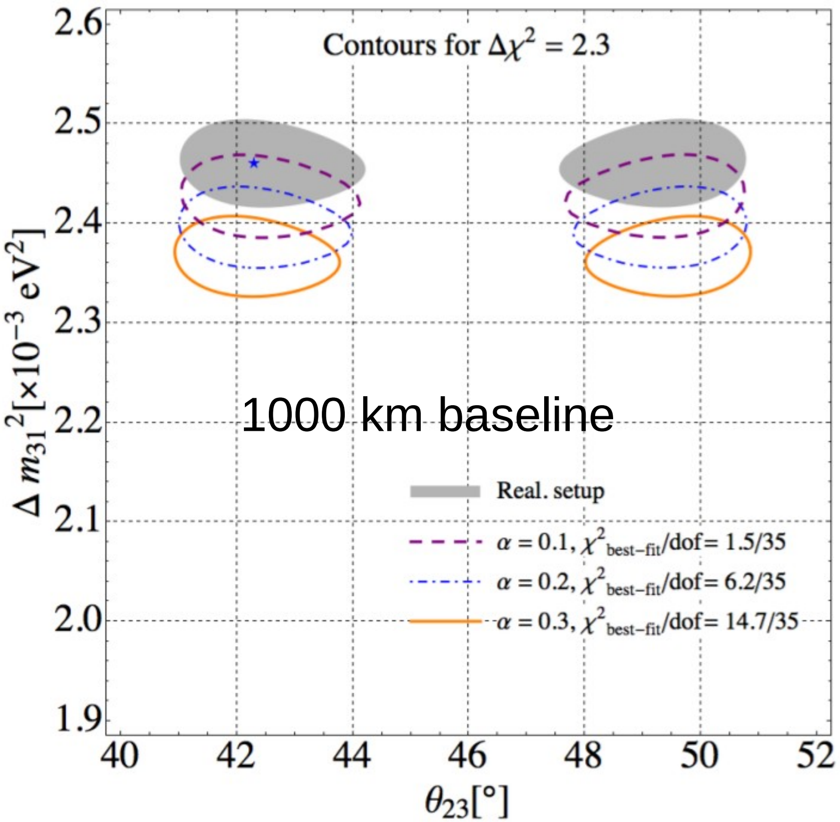




- Near detector event spectrum on left, oscillated far detector spectrum on right
- Near detector tunes to 500 – 700 MeV events, far detector sees higher energy events
  - Can lead to biased tuning

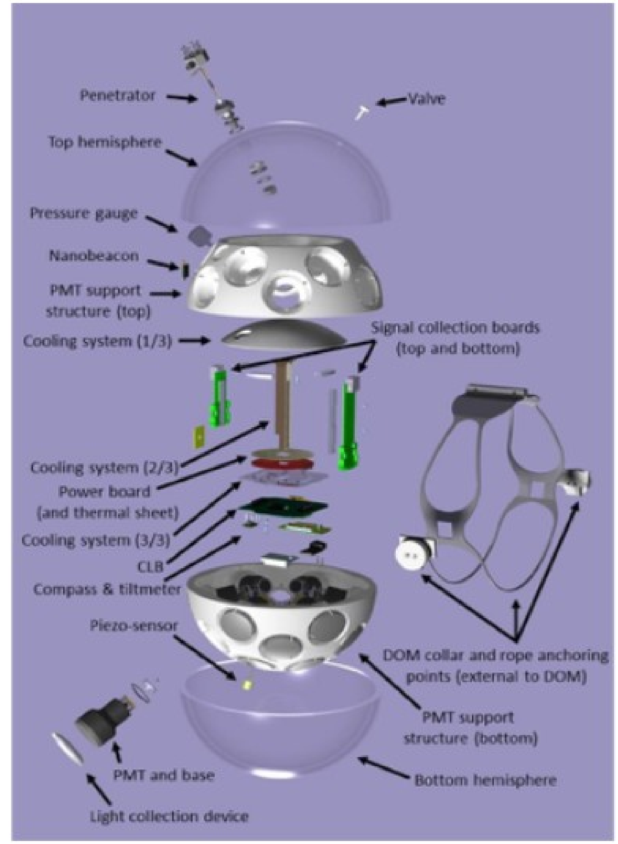
Biases in calorimetric experiments





- Ankowski et al. Phys. Rev. D 92, 073014 (2015)
- Shaded = perfect knowledge of detector
- Coloured lines – amount of 'missing' energy
  - e.g. Incorrectly modelled neutron production rates

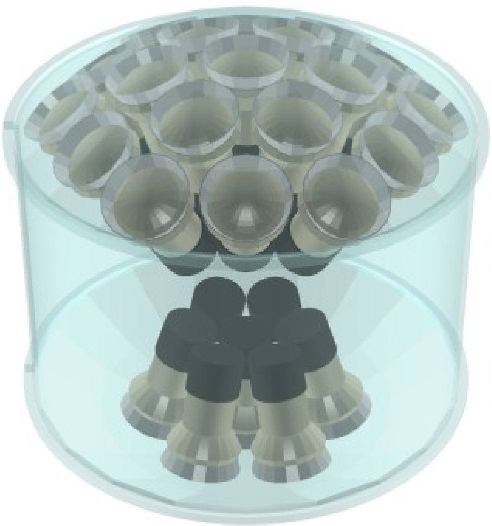
MultiPMTs for Hyper-K

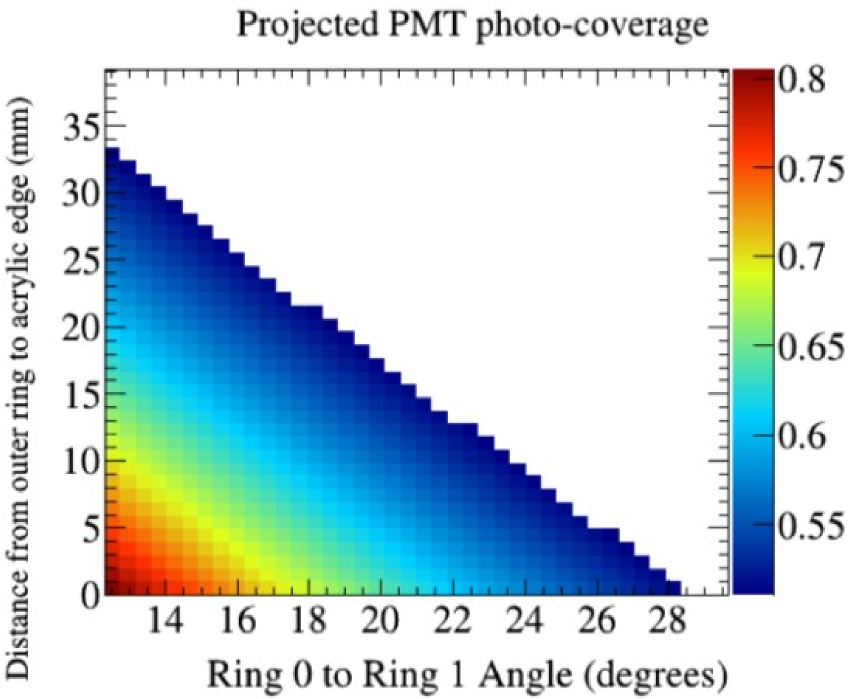


For Hyper-K:

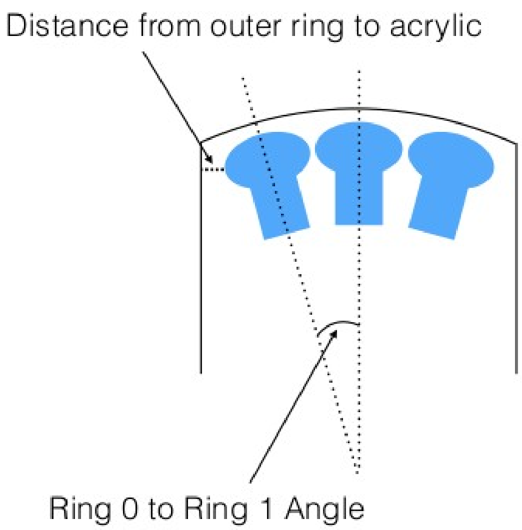
- In standard periphery geometry may need different ID and OD. More flexibility for vessel size, hence filling.
- For initial proof of concept studies: replace 20" photocathode area by same number of mPMT modules with 33 3" PMTs.
- Pressure requirement much less stringent than KM3NeT and IceCube-Gen2 (150 atm (Hyper-K) vs 700 atm): explore cheaper acrylic vessel over Benthos glass sphere.
- Start with same 3" PMTs as KM3NeT.

mPMT for νPrism

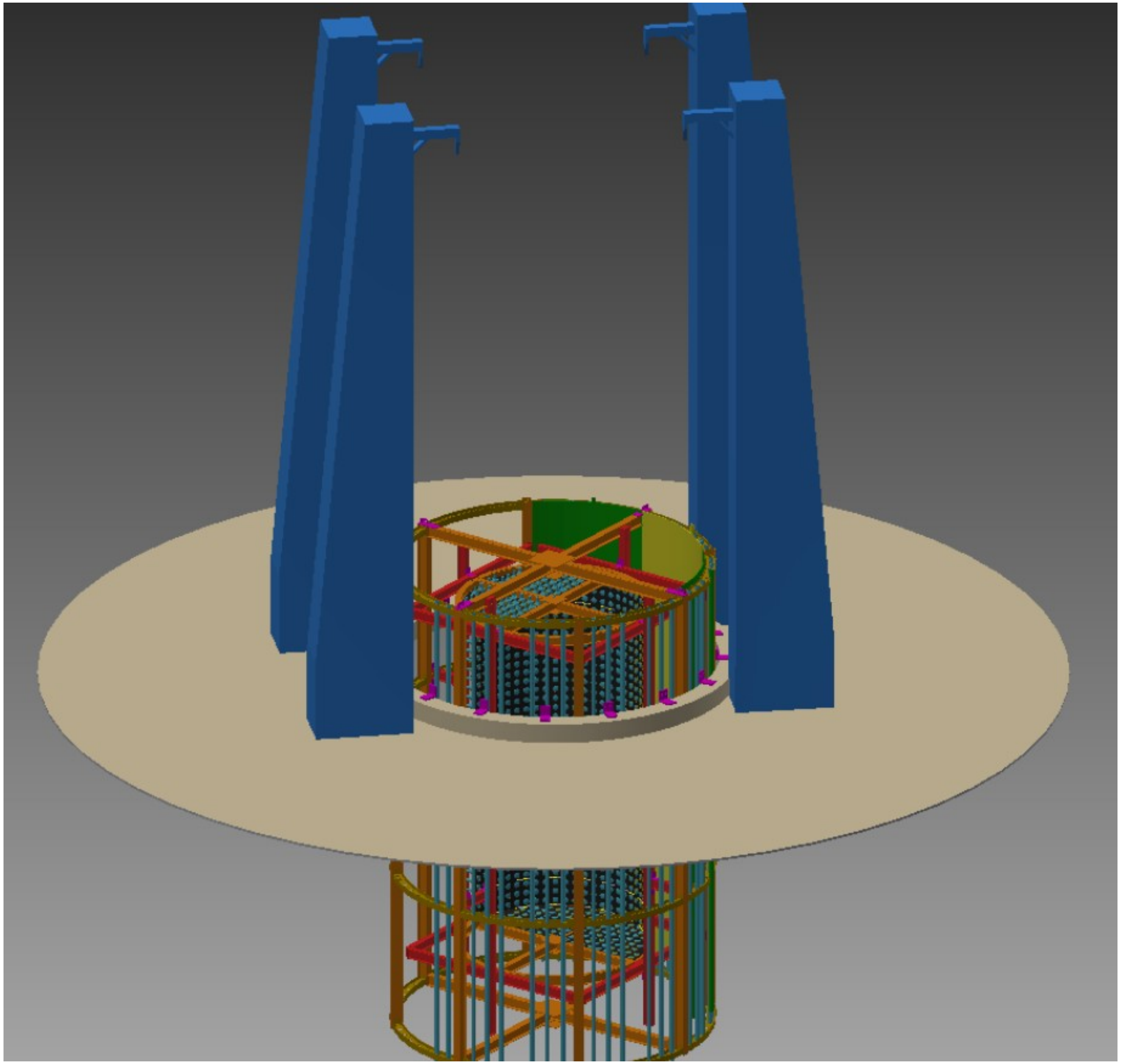


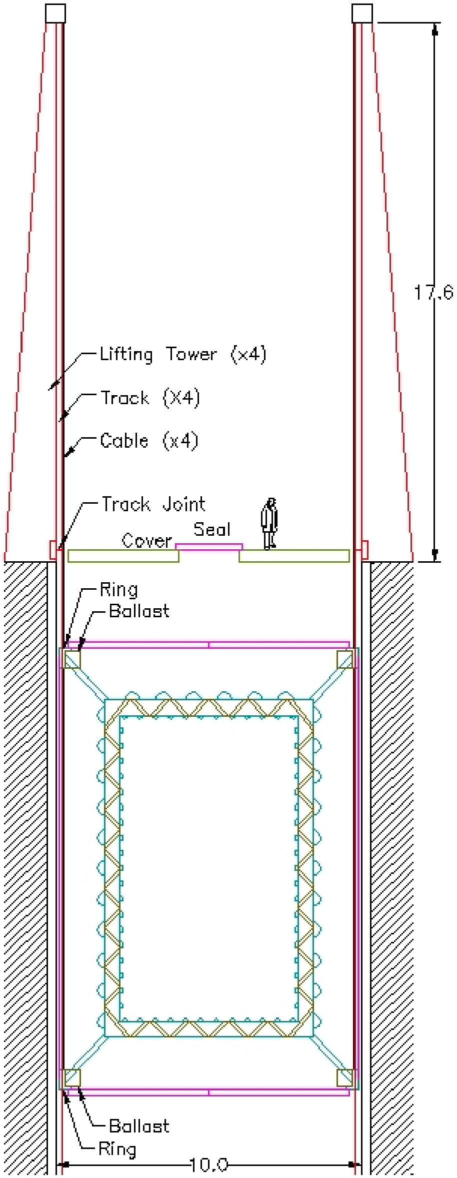


- νPRISM nominal: 19 ID PMTs in hexagonal grid, 7 OD PMTs in hexagonal grid. Vessel diameter is 48cm. Cylinder is 29cm.
- Need to find balance between maximizing projected photocathode area and directionality.
- More detailed calculations and optimization in progress at York.



Conceptual Design

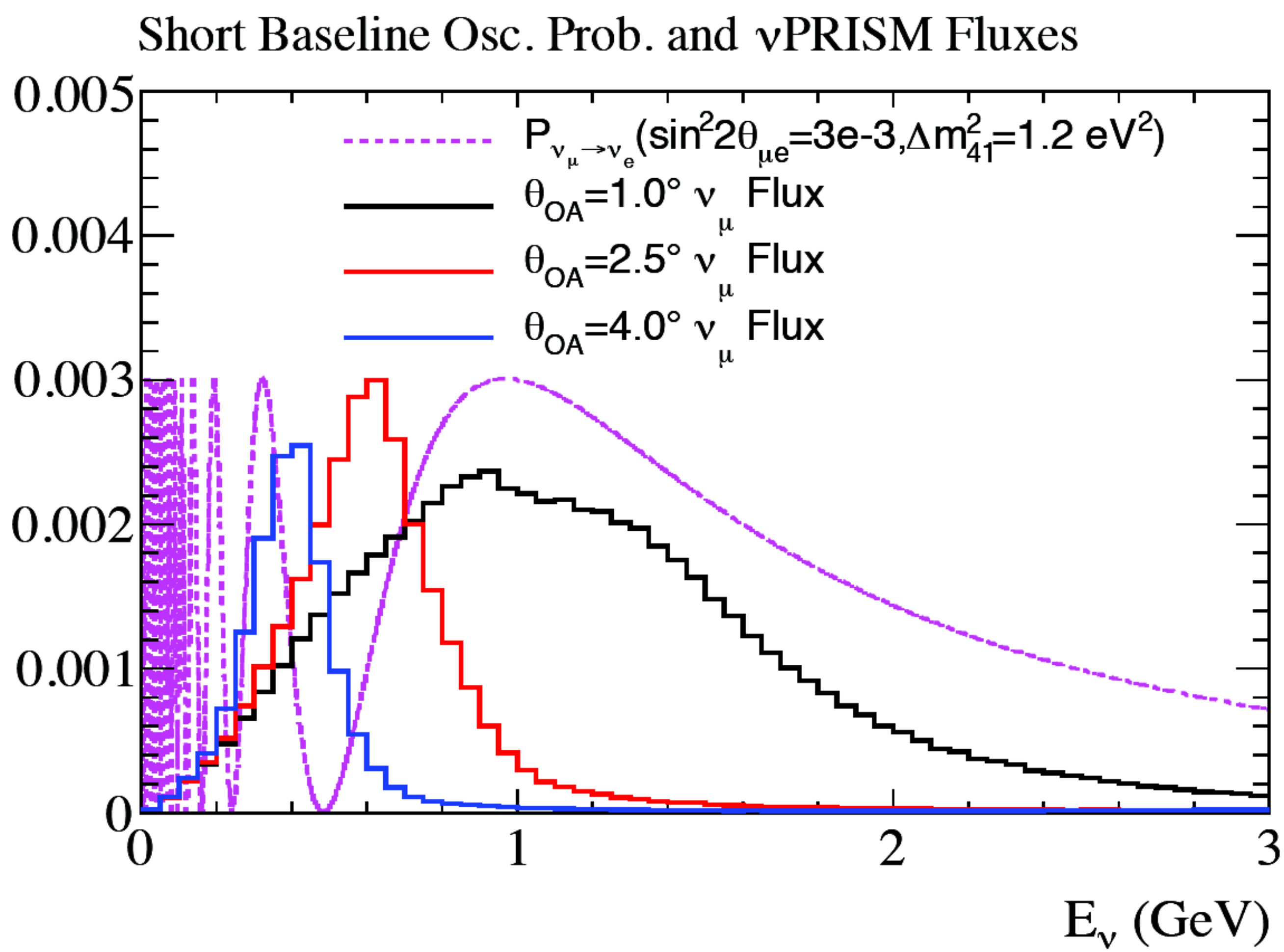


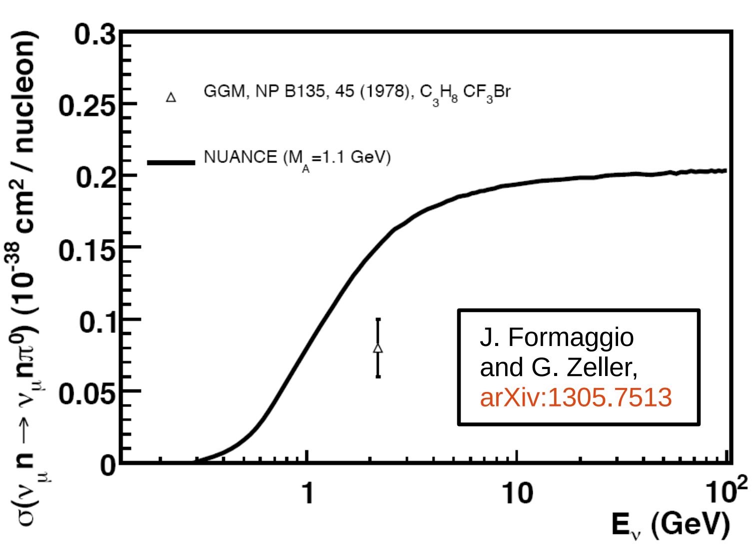


- Winches on each tower raise and lower detector on rails
- Will need full design by engineers

Short baseline oscillations

- NuPRISM – same L/E range as LSND and MiniBooNE sterile results
- Neutrino flux variation across NuPRISM provides unique capabilities
  - Directly probe oscillation curve
  - Constrain backgrounds
    - Energy dependence
    - Direct measurements



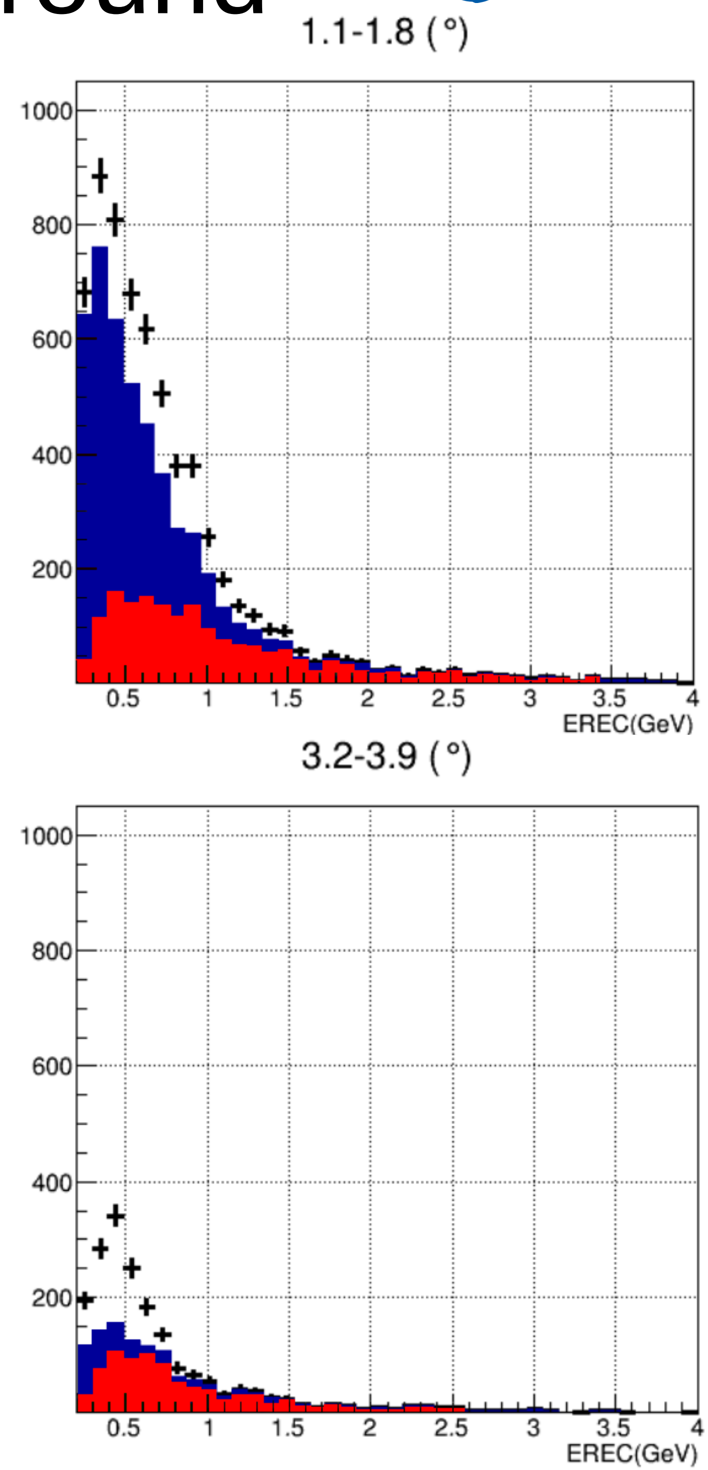


Signal and background

- Search for ν_e appearance using ν_μ events to constrain flux
- Full T2K flux and cross section uncertainties included

Points = Appearance signal
Red = Intrinsic ν_e bkgd
Blue = ν_μ bkgd

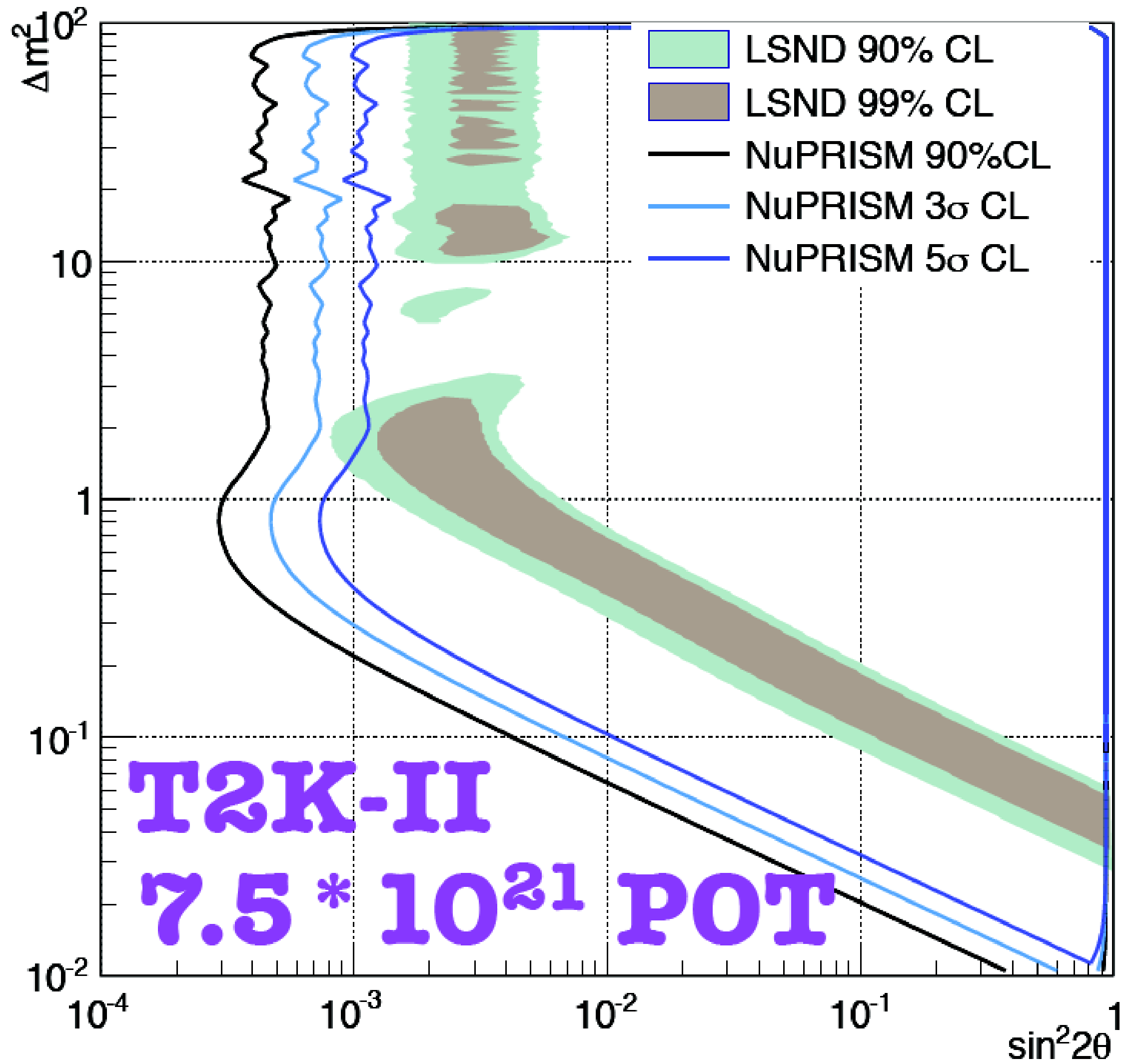
- On-axis (top)
  - High ν_μ contamination
  - Broad signal distribution
- Off-axis (bottom)
  - Very little ν_μ contamination
  - Signal peaked at low reconstructed energy



Sterile sensitivity

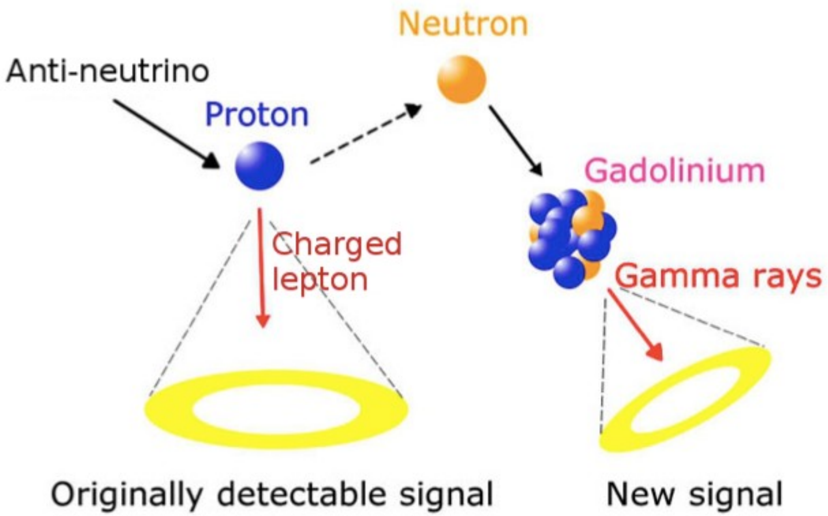
- NuPRISM neutrino fluxes peak at different energies for a given baseline
- Sterile oscillation has different energy dependency than background cross-sections → can separate them

- Excludes (almost) entire LSND allowed region at 5σ
  - Comparable to Fermilab SBN
- Statistics limited!
  - Expect results to improve:
    - Full reconstruction and selection
    - Direct constraint of backgrounds
    - Include T2K near detector



Gadolinium doping

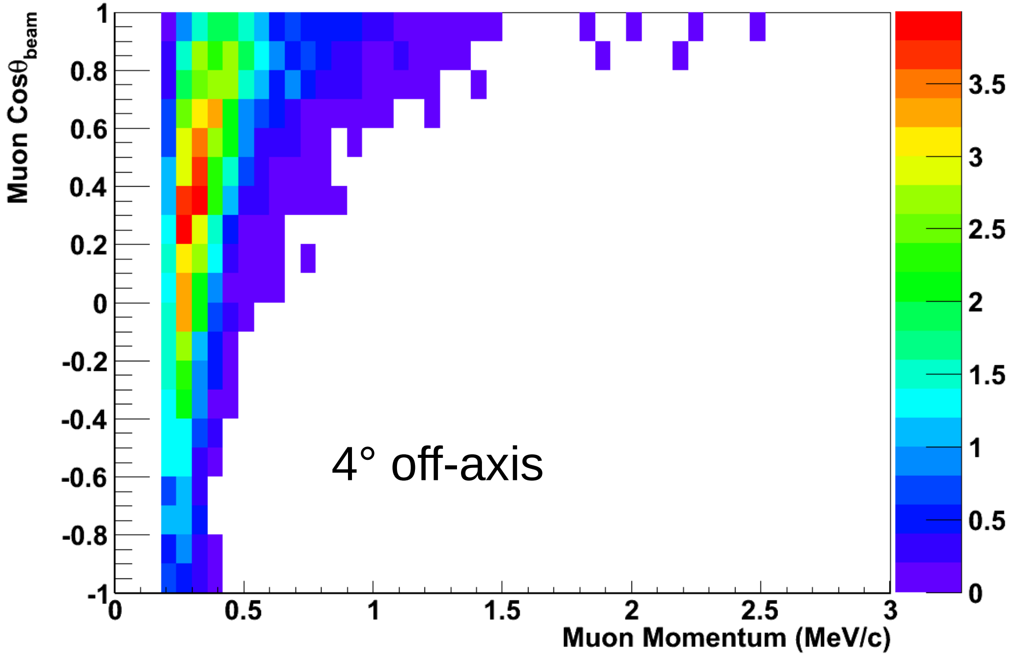
- Neutrons capture on Gd
  - 49,000b capture cross section
  - 8 MeV gamma cascade, 4-5 MeV visible
  - 0.1% doping → 90% neutrons capture on Gd

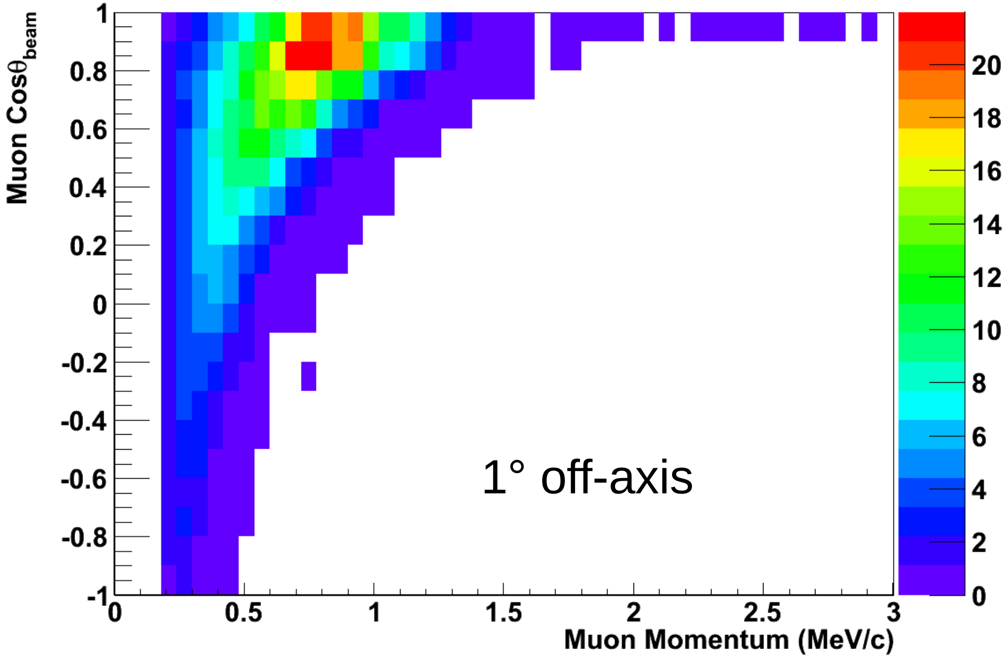


- SK planning to load Gd in future – increase sensitivity to supernovae
  - Statistically separate neutrino interactions from anti-neutrino
  - Tag proton decay backgrounds
- But, neutron emission from neutrino interactions largely unknown
- NuPRISM can measure this:
  - Mono-energetic neutrino source
  - Neutron capture rates as a function of lepton kinematics

Event Selection

- Same event selection as at SK:
  - Single ring
  - Muon-like
  - Fully contained in fiducial volume

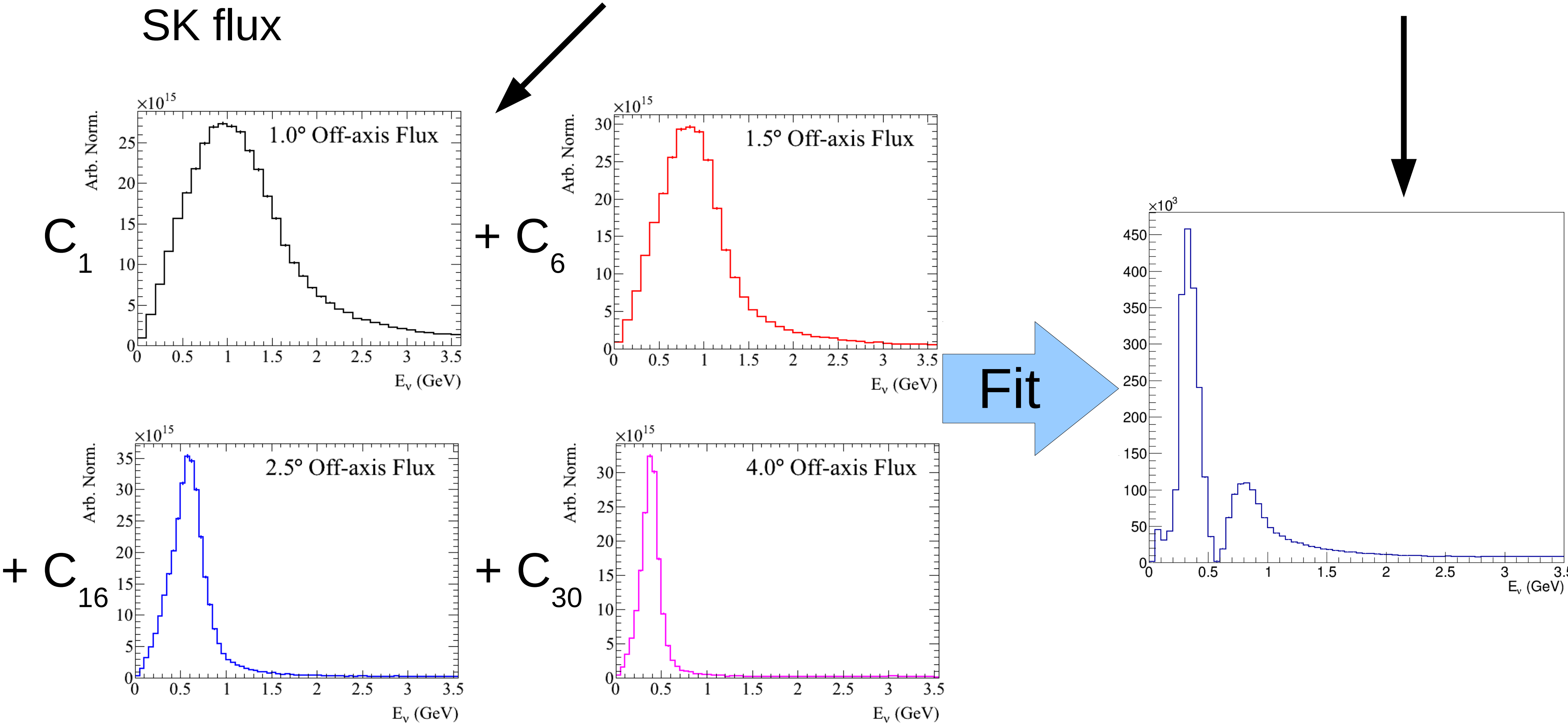




- Record the off-axis angle of the interaction, using the reconstructed vertex position

Building the oscillated flux

- All based on simulated neutrino flux at SK and νPRISM
- Slice νPRISM into 60 slices of 0.05 degree – assign each a weight
- MINUIT χ^2 fit between sum of weighted νPRISM slices and oscillated SK flux



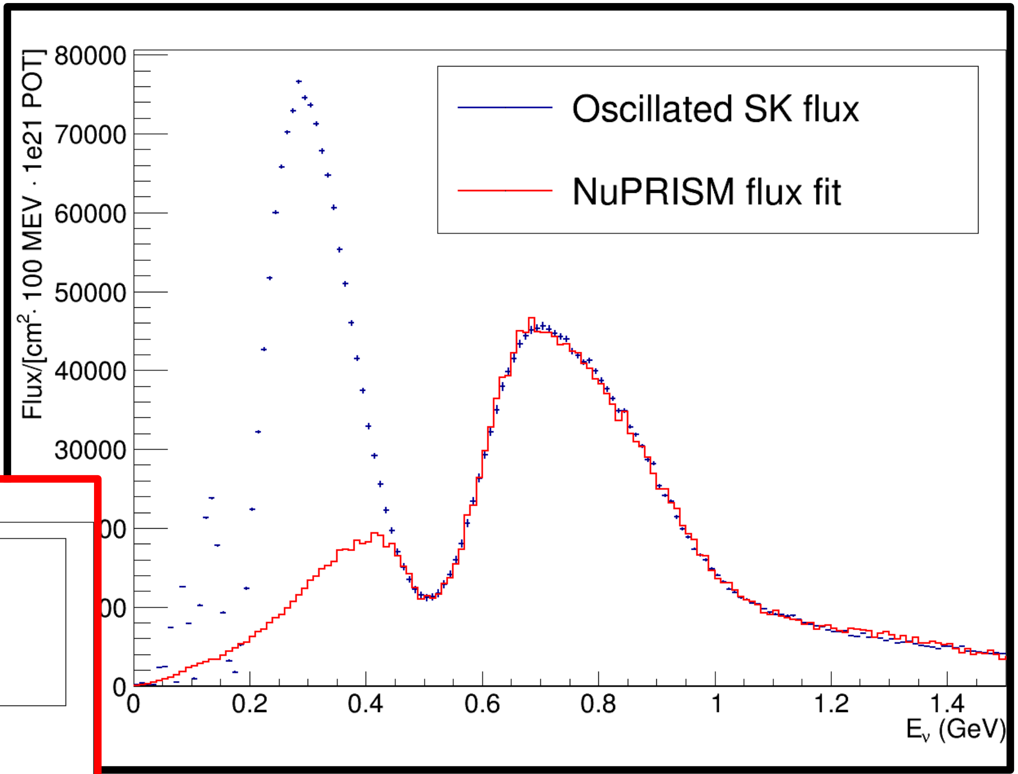
Building the oscillated flux

NuPRISM

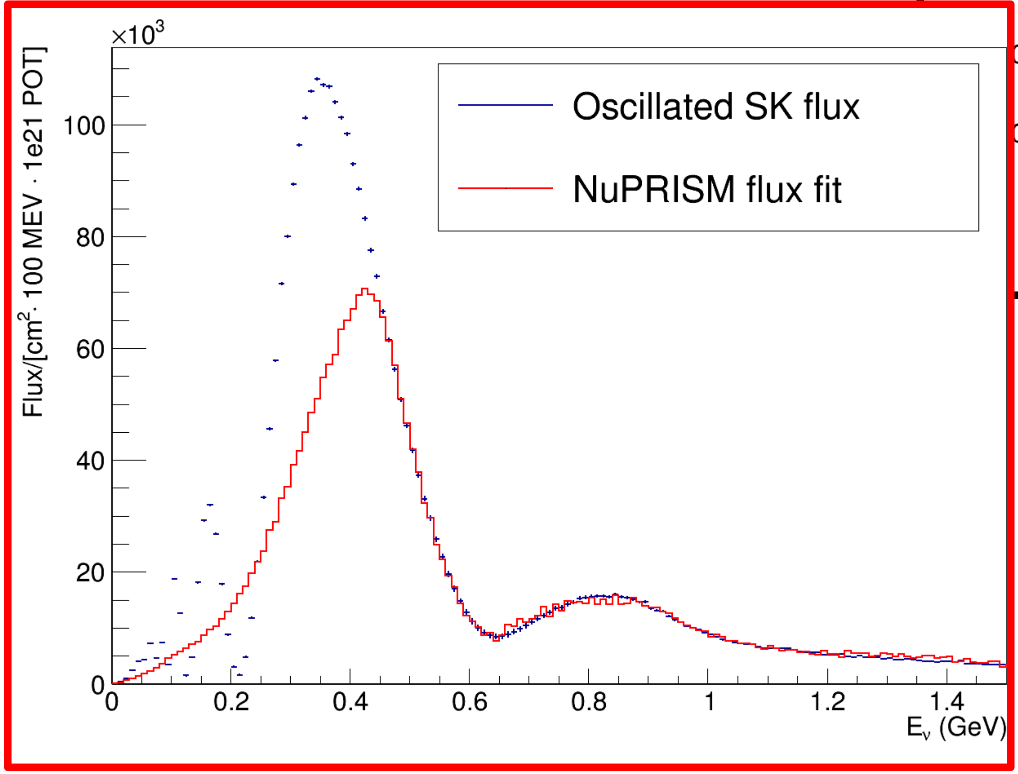
TRIUMF

- Perform fit for all combinations of oscillation parameters used in the oscillation fit

$\sin^2\theta_{23} = 0.40$
$\Delta m^2_{23} = 2.15\text{x}10^{-3}$



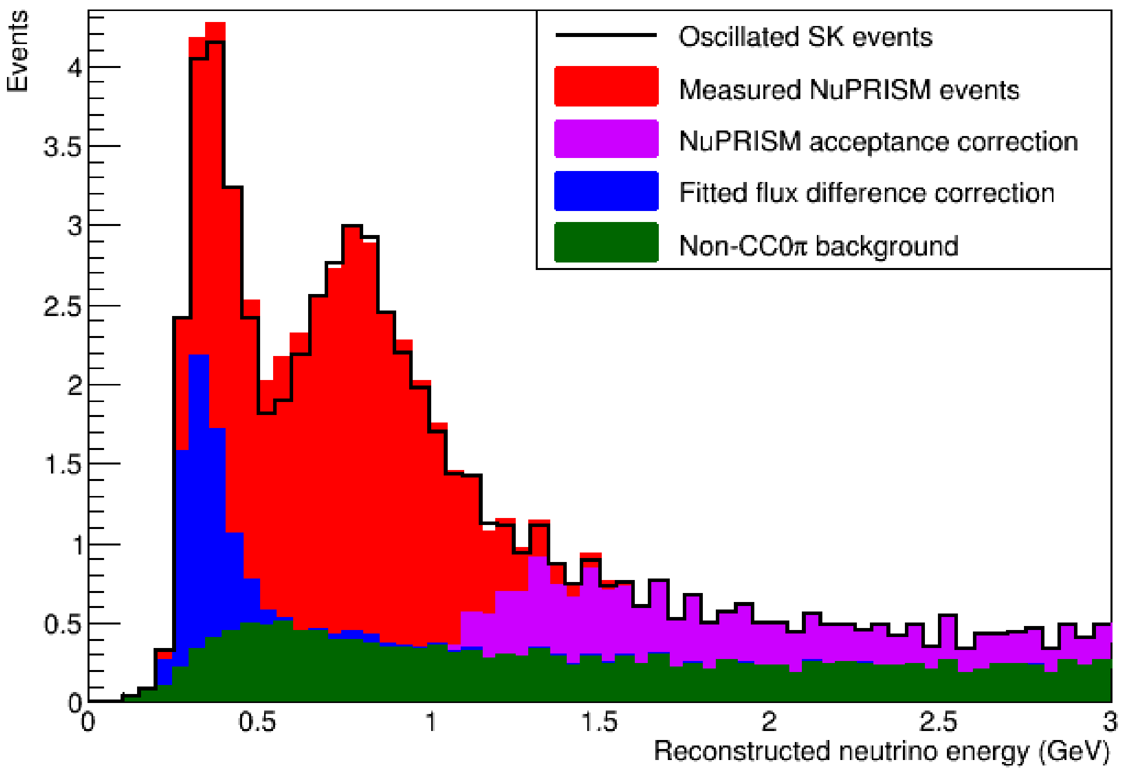
$\sin^2\theta_{23} = 0.60$
$\Delta m^2_{23} = 2.65\text{x}10^{-3}$



- Get a set of 60 C_i coefficients for each pair of oscillation parameters

SK prediction

- Apply these weights to the selected events in each off-axis slice of νPRISM
- Now looking at reconstructed neutrino energy - events smeared into oscillation dip by nuclear effects and energy resolution



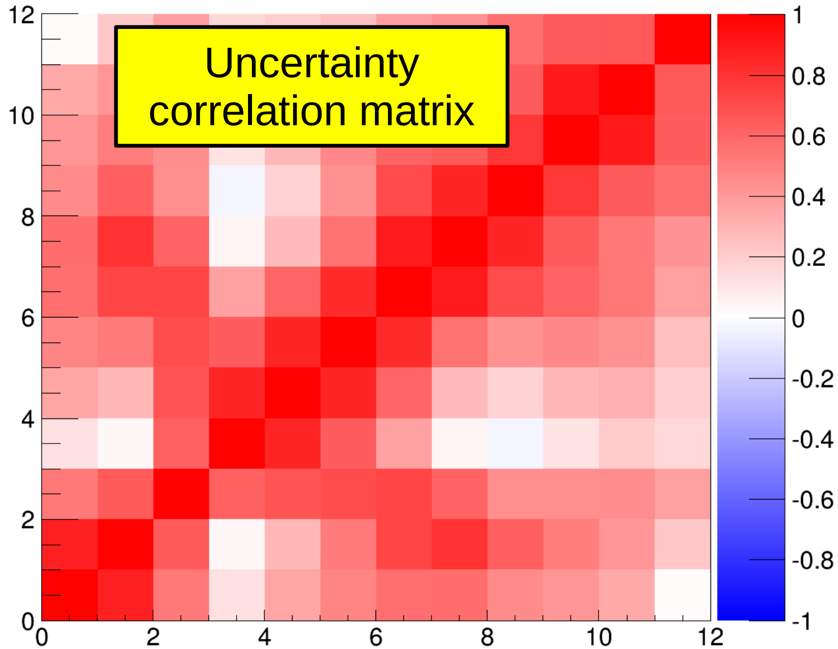
- To νPRISM data:
  - Flux correction
  - Acceptance correction
  - Addition of selected SK background
- Introduce some model dependence

Systematic uncertainties

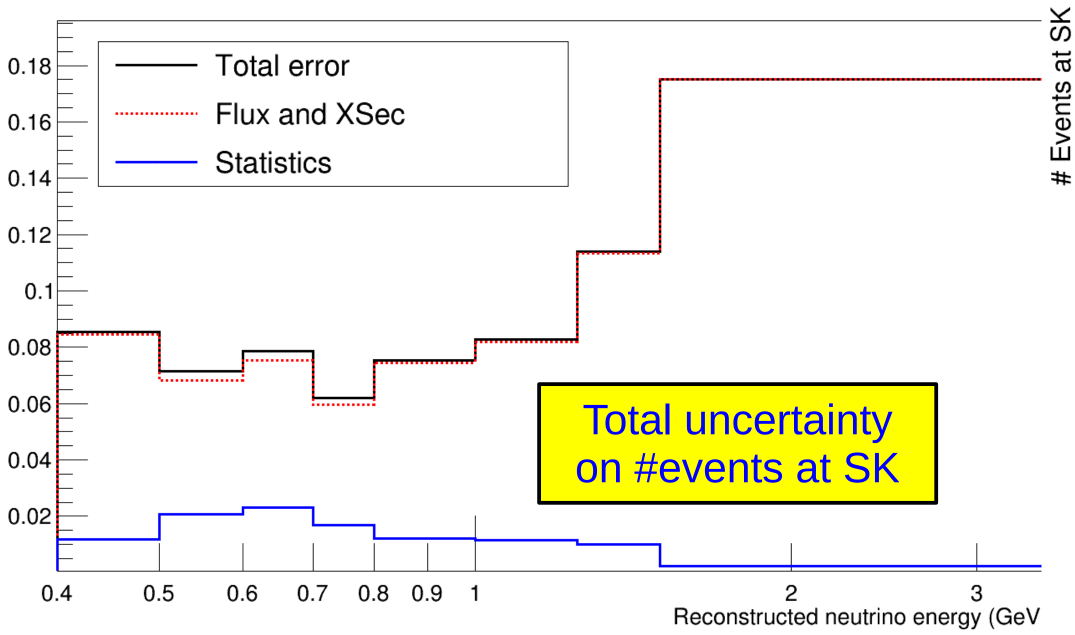
- Every correction made to the νPRISM prediction is calculated from our nominal MC – all are constant corrections
- To calculate systematic uncertainties:
  - Apply a variation to the νPRISM and SK MC
  - Changes number of selected events at both detectors
  - Apply corrections (from the unvaried, nominal MC)
  - Calculate change in the νPRISM prediction
  - Use this to calculate fractional covariance matrix for νPRISM prediction
- This analysis takes flux and cross section uncertainties into account
  - Conservative detector systematics coming soon!

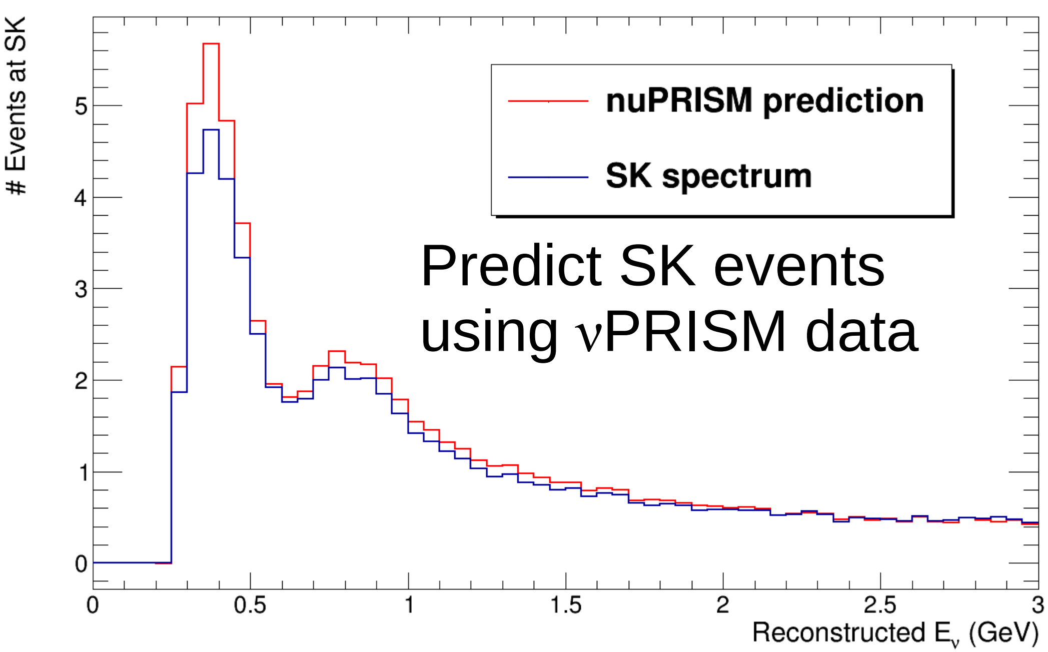
NuPRISM

νPRISM disappearance analysis



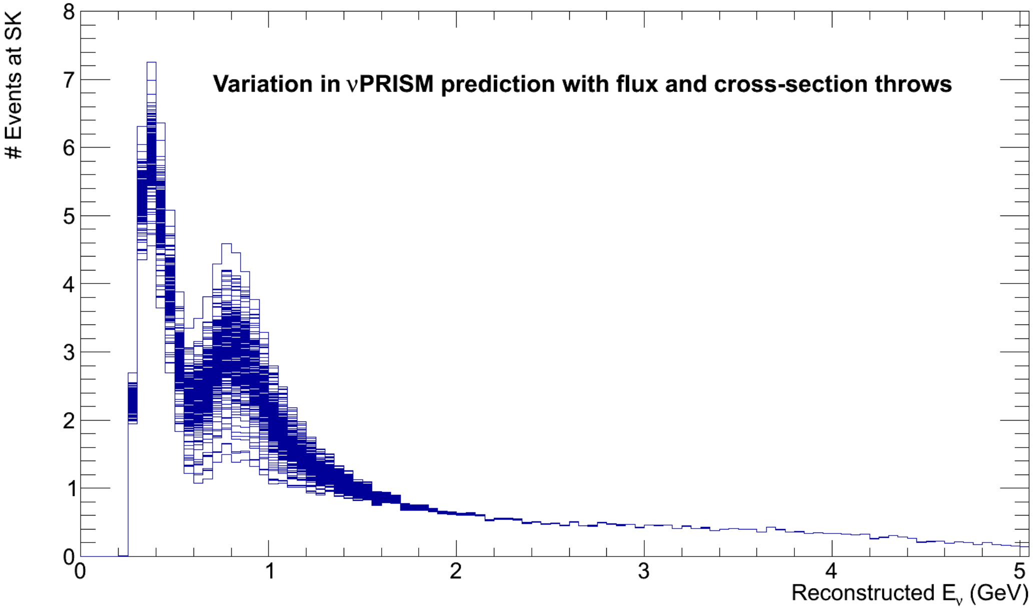
- Full analysis using νPRISM as near detector for T2K
- Take into account:
  - Statistical error from linear combinations
  - Neutrino beam uncertainties – direction, flux etc.
  - Interaction model uncertainties

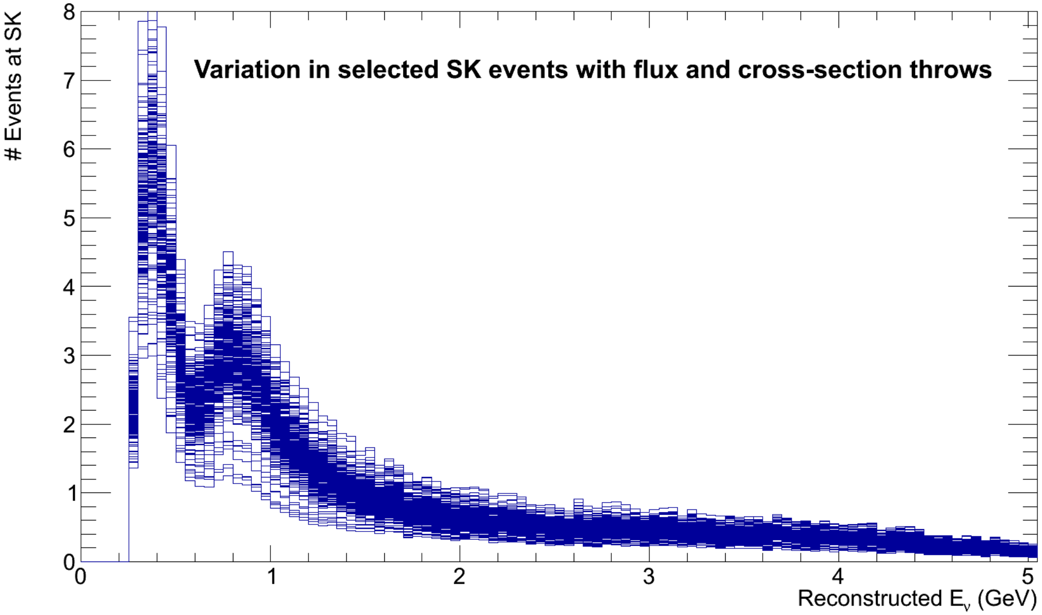




Systematic throws

- Look at fake data throws of both flux and cross section uncertainties



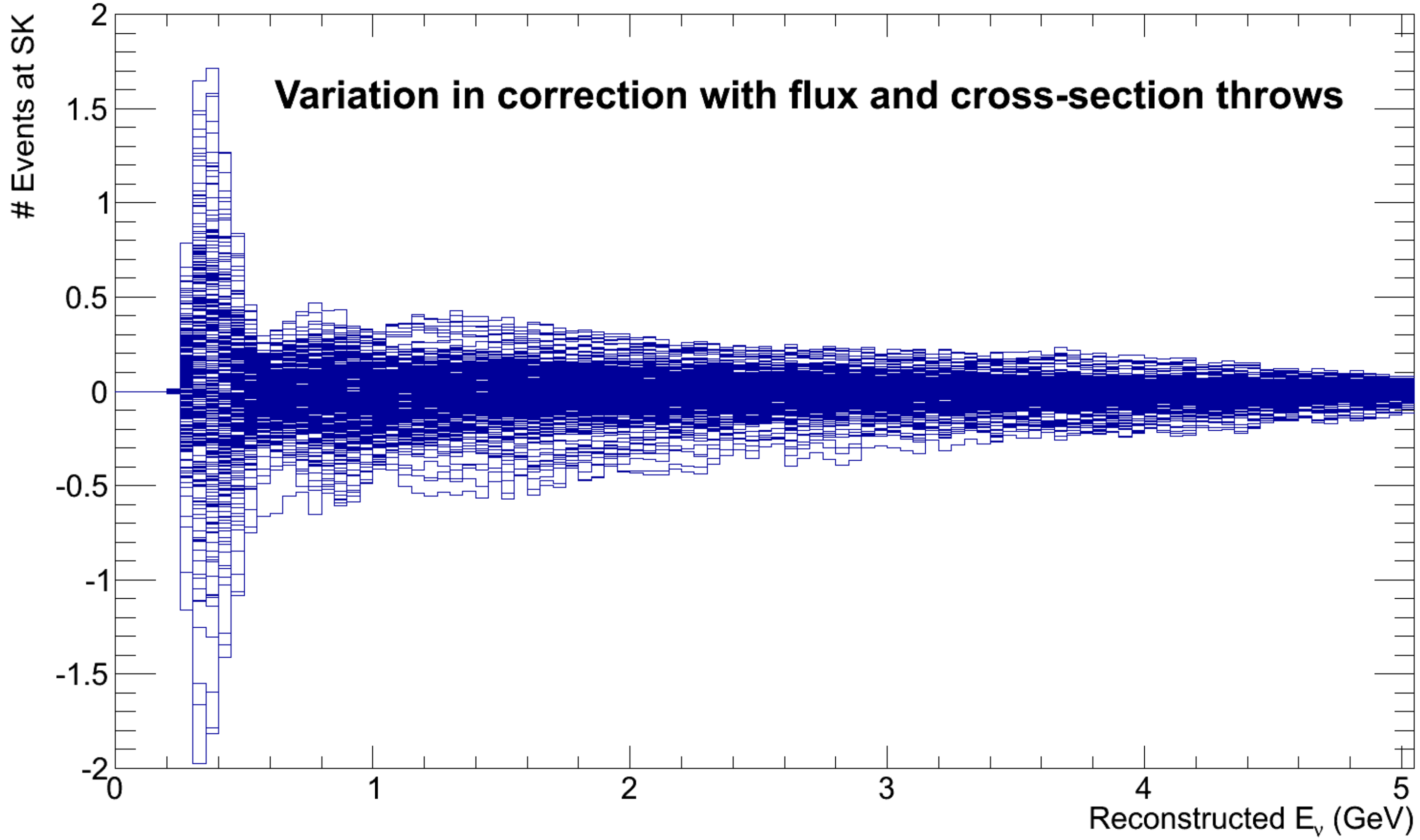


- Plots show all 300 throws of the νPRISM prediction (left) and selected SK events (right)

- νPRISM - very few events at low or high energy, little variation
- In oscillation region variations similar at SK and νPRISM
- Spectra are ~Gaussian distributed about the central value

Systematic throws

- Plot difference between selected SK events and νPRISM prediction for each throw

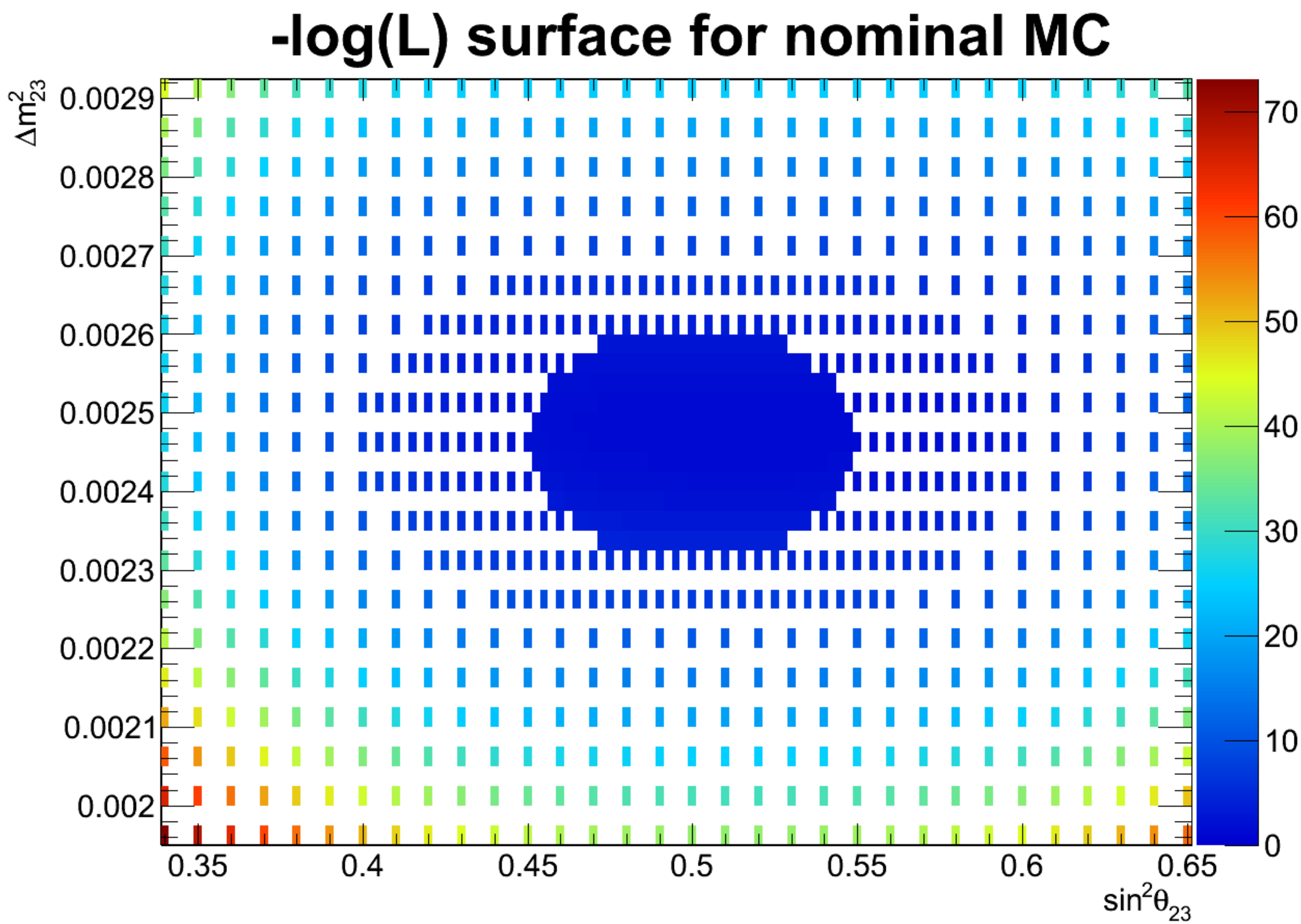


- Most of spectrum shows less than 0.5 event difference between SK and νPRISM prediction
- Systematic uncertainties are cancelling between the two detectors

Oscillation fit

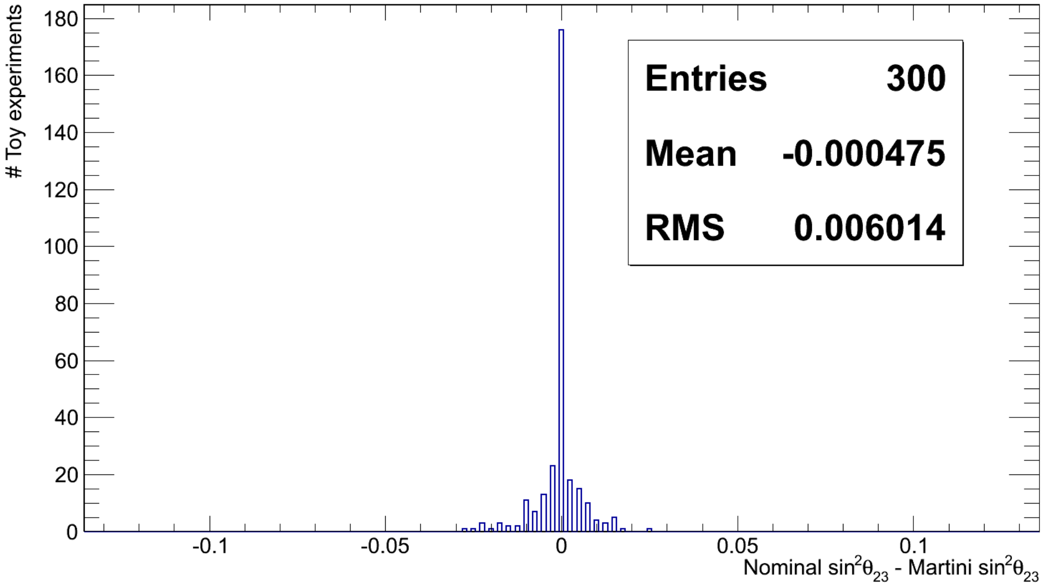
- Calculate covariance matrix and νPRISM prediction for various points in θ_{23} and Δm^2 phase space

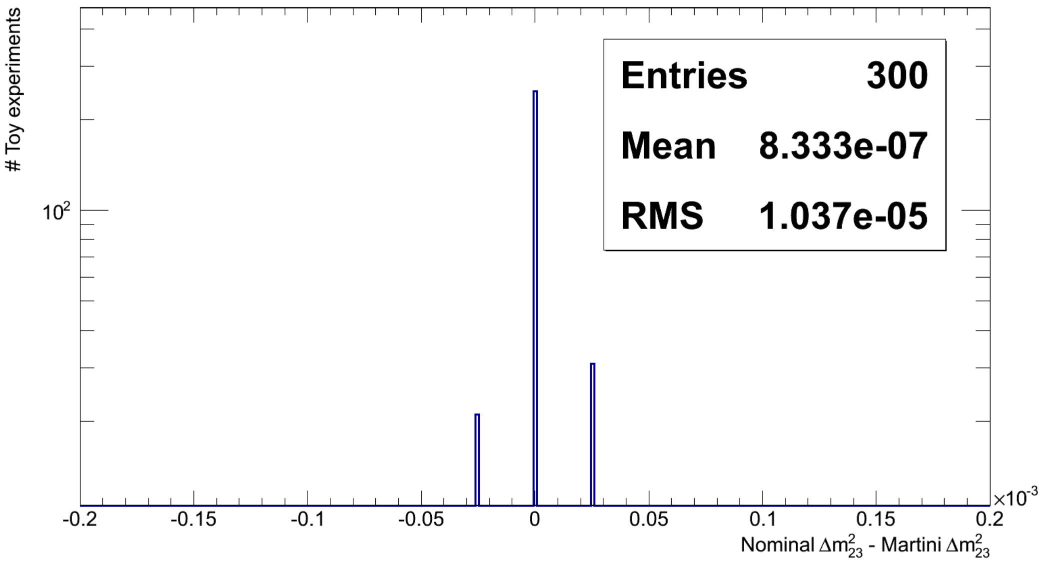
- Use Simple Fitter to calculate likelihood (L)
- Plot - ln(L) for all points in θ_{23} and Δm^2
- Minimum bin gives best fit oscillation parameters



Martini MEC result

- Look at effect of adding MEC events to 300 fake data sets

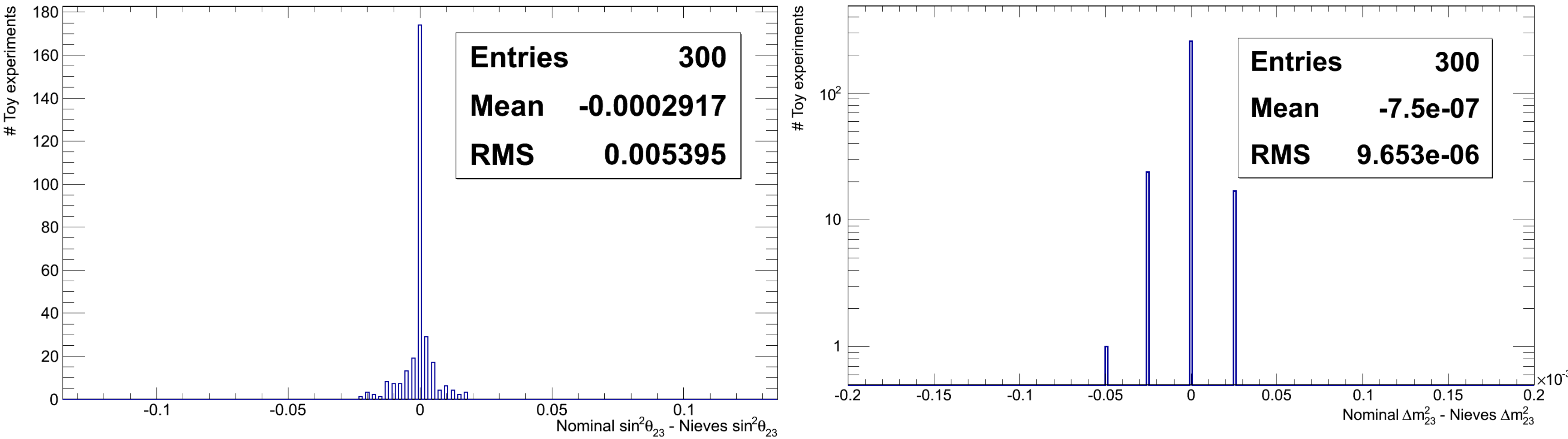




- Much smaller RMS in θ_{23} (left) and Δm^2 (right) than in T2K analysis
- No bias seen in θ_{23} plot
- νPRISM will provide the first data driven constraint on the effect of multi-nucleon events in oscillation measurements

Nieves' result

- Look at the difference in best fit oscillation parameters between the nominal MC and the MC with additional Nieves MEC events

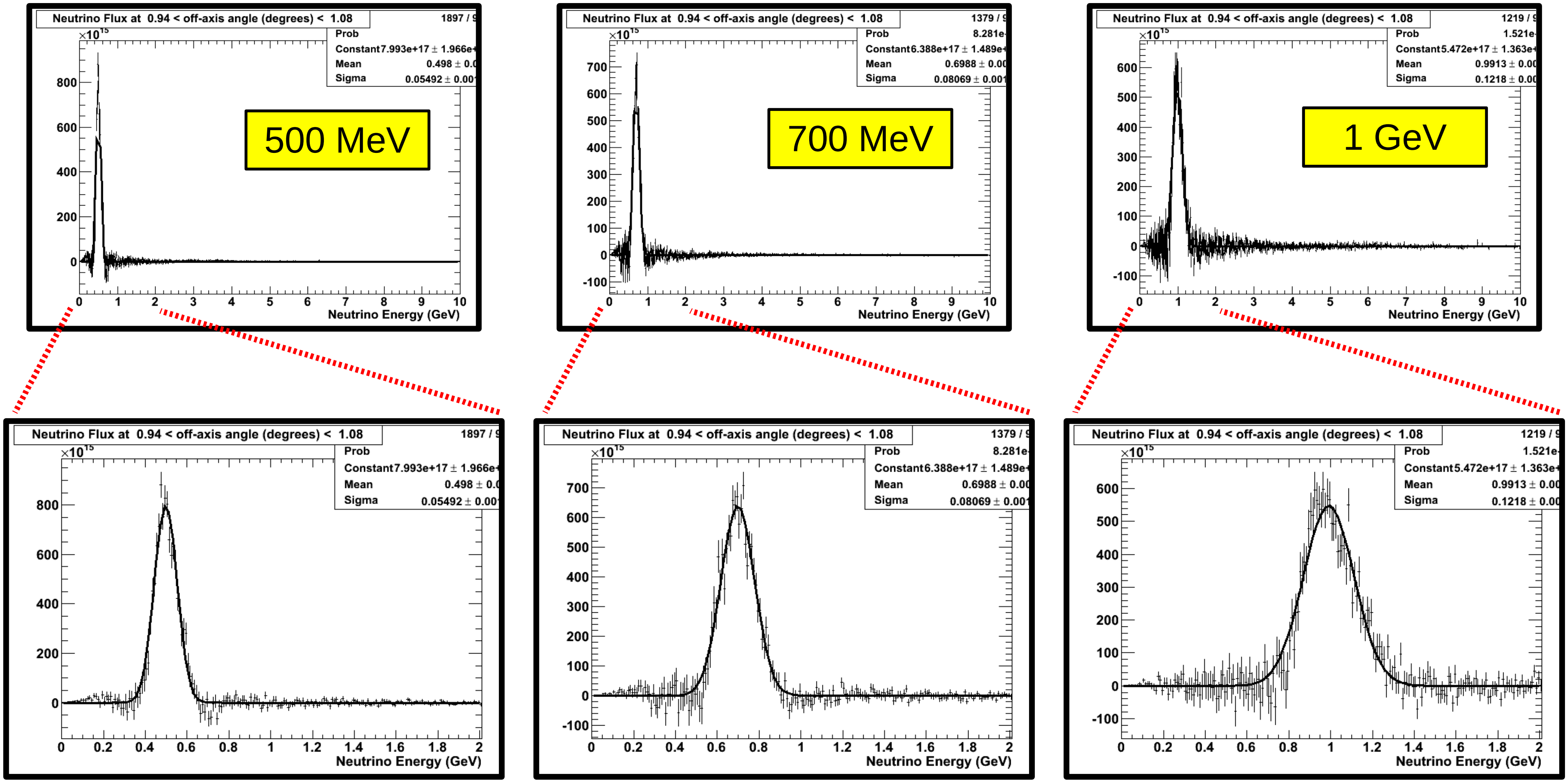


- Much smaller RMS in θ_{23} (left) and Δm^2 (right) than in T2K analysis
- Large spike at 0 difference in both plots

NuPRISM

A neutrino spectrometer

TRIUMF

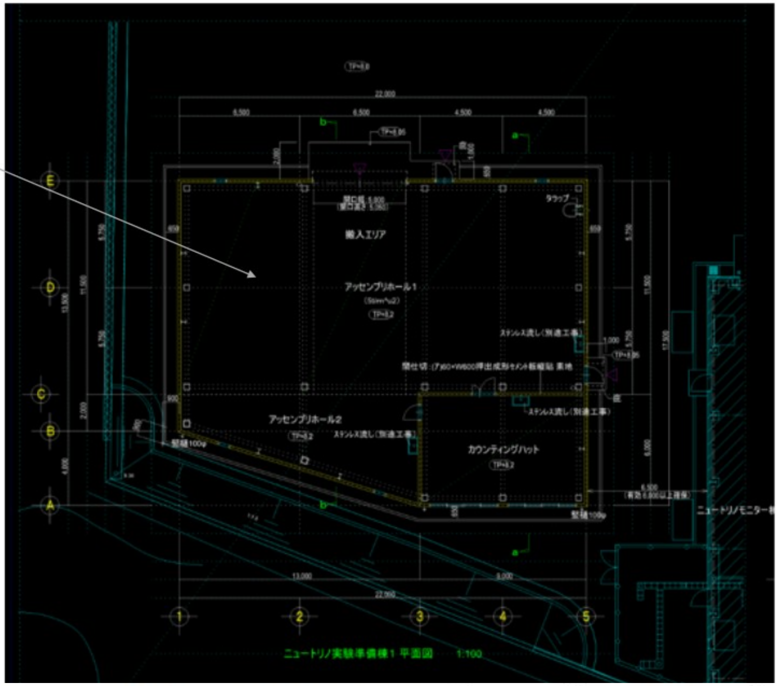


- Gaussian spectra from ~0.4 GeV to ~1 GeV
  - Depends on off-axis span of νPRISM: 6° - 0.25 GeV, 0° - 1.2 GeV
- High energy tail cancelled in all cases

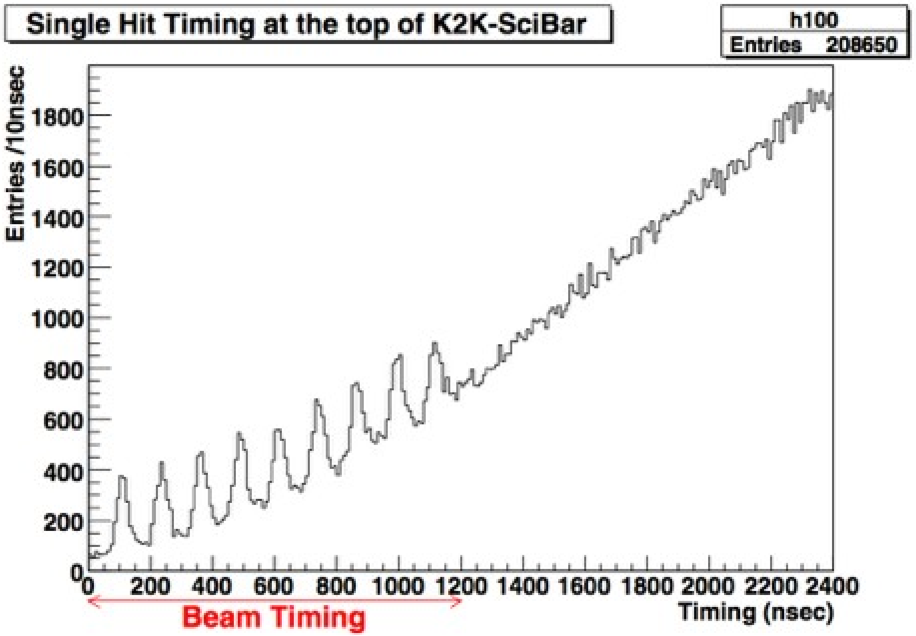
NuPRISM Phase 0

- Some considerations:

13 m x 13 m space



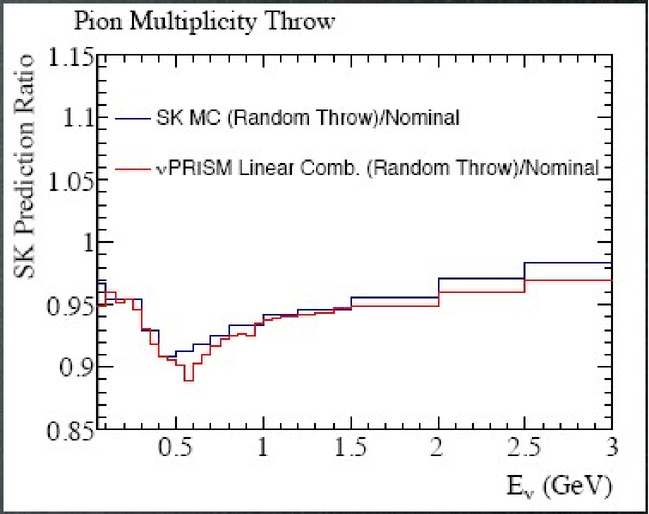
- Is there space?
  - Will use EGADs tank + water system to estimate footprint
  - Maybe requires a new (cheap) building
- Sky-shine neutrons
  - Seen at K2K 1T detector
  - Need to measure for T2K beam

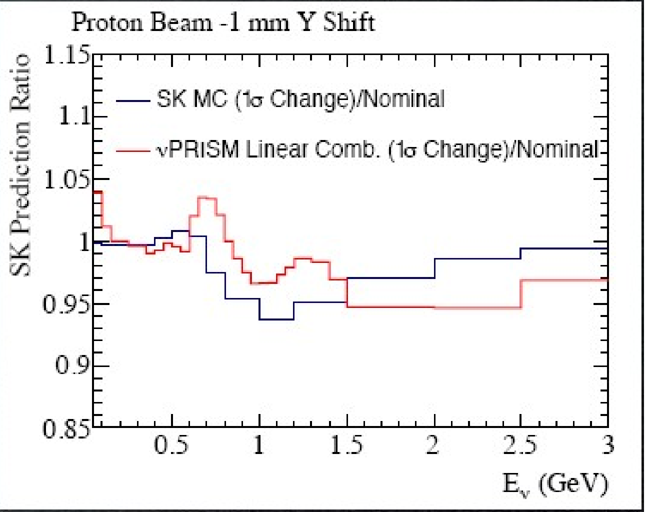


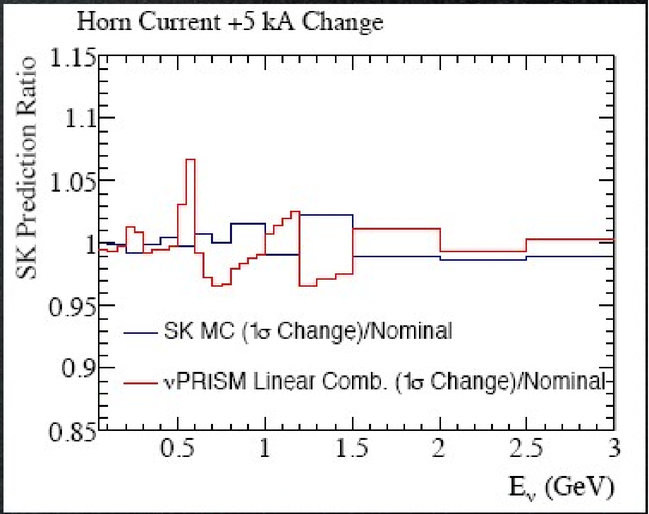
- Low energy neutrinos from beam dump or MLF – search for sterile oscillations
- Long-term tests of HK PMTS
- Can put magnetized muon range detector behind tank
  - Calibrate Gd tagging

Beam Errors

- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Cancelation exist between νPRISM and far detector variations
- **Normalization uncertainties will cancel** in the νPRISM analysis
  - Cancelations persist, even for the νPRISM linear combination
  - Shape errors are most important
- For scale, **10% variation** near the dip means **~1% variation** in $\sin^2 2\theta_{23}$
  - Although this region is dominated by feed down
- Full flux variations are reasonable
  - No constraint used (yet) from existing near detector!
    - Uncertainties set by NA61 and T2K beam data

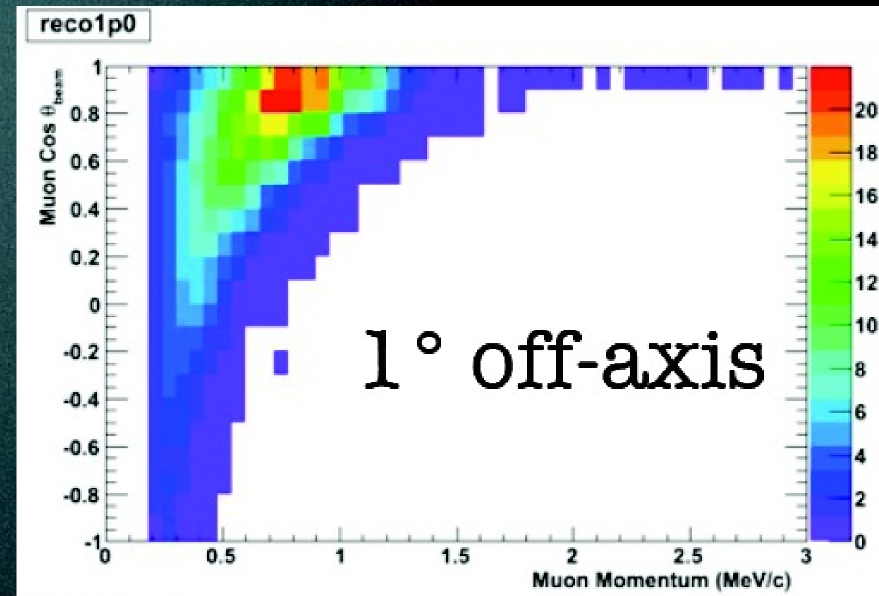




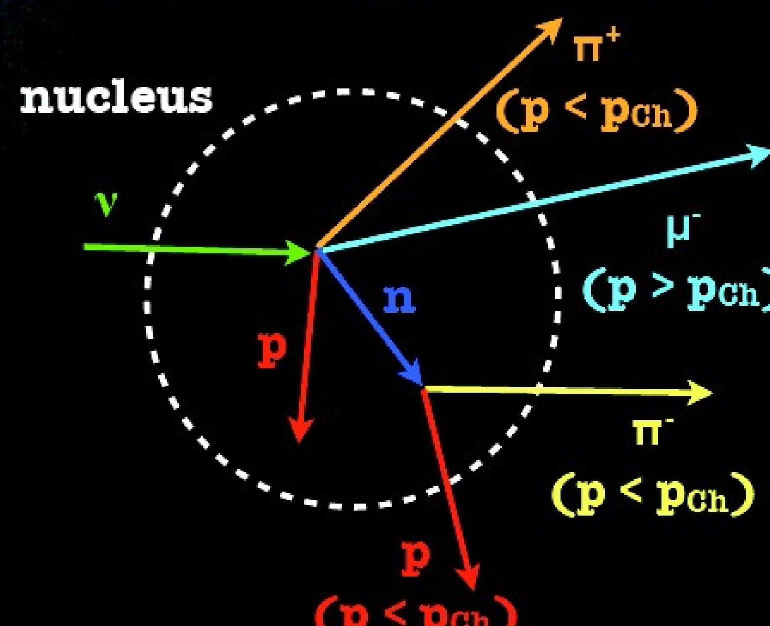


Signal Selection/Definition

- **Same signal selection as used at Super-K**
  - Single, muon-like ring
- Signal events are defined as **all true single-ring, muon-like events**
  - A muon above Cherenkov threshold
  - All other particles below Cherenkov threshold
- νPRISM can measure **single muon response** for a given E_ν spectrum
  - Signal includes CCQE, multi-nucleon, $CC\pi^+$, etc.
  - No need to make individual measurements of each process and extrapolate to T2K flux

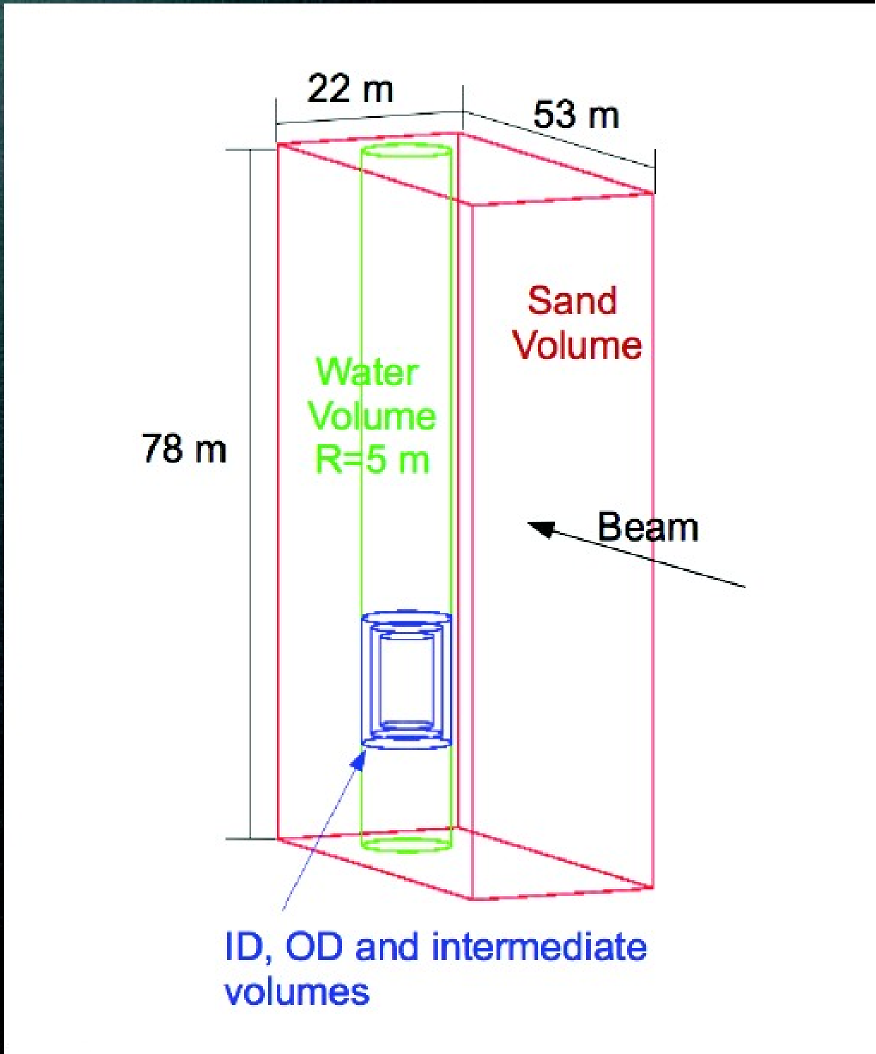


Example Signal Event



Event Pileup at 1 km

- Full GEANT4 simulation of water and surrounding sand
  - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **41% chance of in-bunch OD activity during an ID-contained event**
  - Want to avoid vetoing only on OD light (i.e. using scintillator panels)
- **17% of bunches have ID activity from more than 1 interaction**
  - 10% of these have no OD activity
  - Need careful reconstruction studies
    - (but multi-ring reconstruction at Super-K works very well)



Pileup Rates at 1 km Look Acceptable!