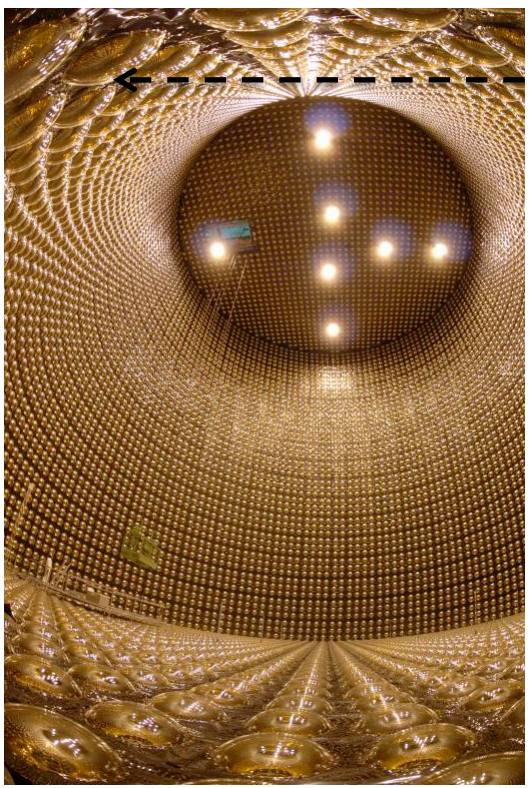
The Tokai-to-Kamioka (T2K) experiment

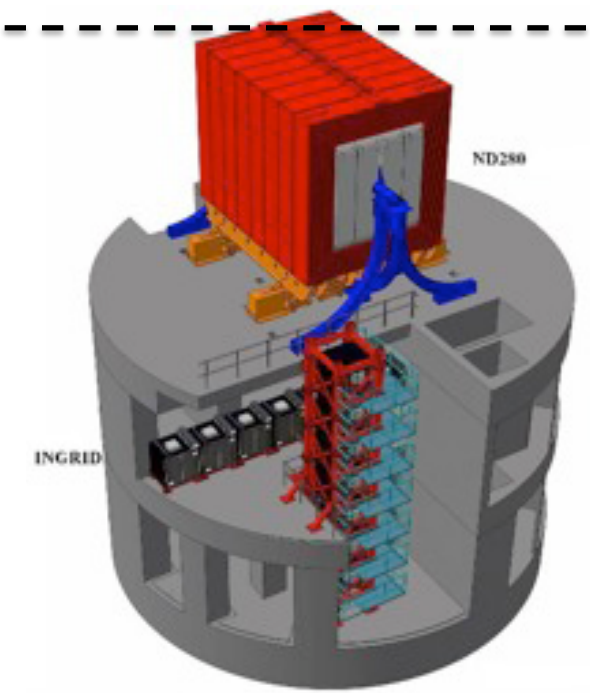
``Long baseline" (L~ 295km) neutrino experiment designed to measure ν_e appearance (θ_{13} and more) and ν_μ disappearance (Δm^2_{32}, θ_{23})

Far detector
Super-Kamiokande

Near detectors
ND280

Neutrino beam
Peak E_ν~0.6 GeV





ν_e appearance analysis

$$N(\nu_e) = \Phi(E_{\nu_\mu})\ \sigma(E_{\nu_e})\ \epsilon\ P(\nu_\mu \rightarrow \nu_e)$$

Fit the observed rate to determine oscillation parameters. Depends on:

Neutrino flux prediction

Neutrino cross section model

Far detector selection, efficiency

ν_e appearance analysis

$$N(\nu_e) = \Phi(E_{\nu_\mu})\ \sigma(E_{\nu_e})\ \epsilon\ P(\nu_\mu \rightarrow \nu_e)$$

Fit the observed rate to determine oscillation parameters. Depends on:

- Neutrino flux prediction
- Neutrino cross section model
- Far detector selection, efficiency

We reduce the error on the rate of ν_e with the near detector:

$$N(\nu_\mu) = \Phi(E_{\nu_\mu})\ \sigma(E_{\nu_\mu})\ \epsilon$$

- Neutrino flux prediction
- Neutrino cross section model
- Near detector selection, efficiency

ν_e appearance analysis

$$N(\nu_e) = \Phi(E_{\nu_\mu})\ \sigma(E_{\nu_e})\ \epsilon\ P(\nu_\mu \rightarrow \nu_e)$$

Important points:

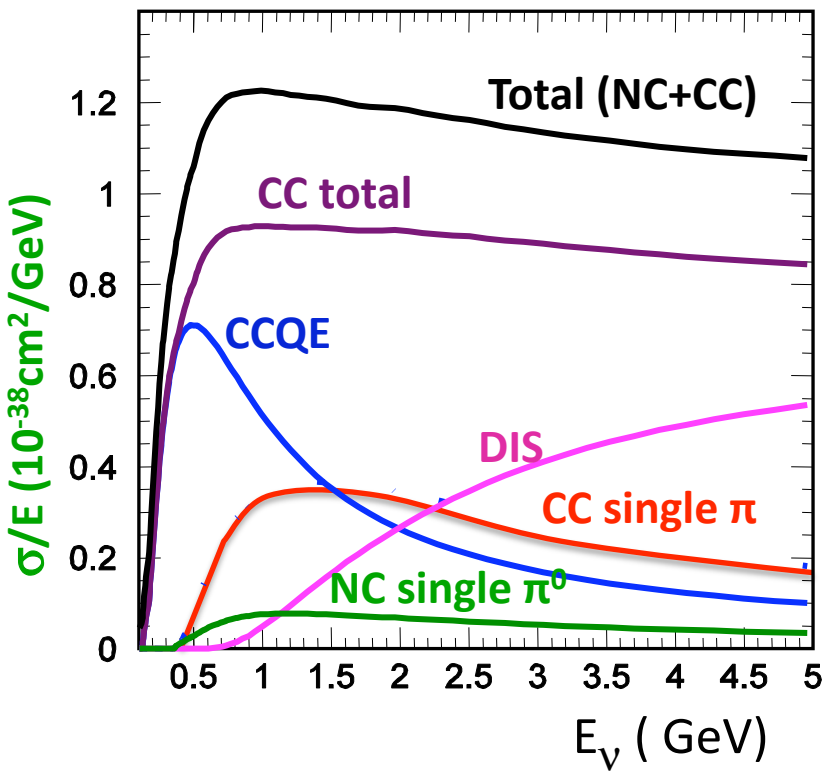
1) Event rate depends on convolution (flux x xsec x osc prob) so even assuming an "identical" flux, the energy dependence of the cross section must be correct

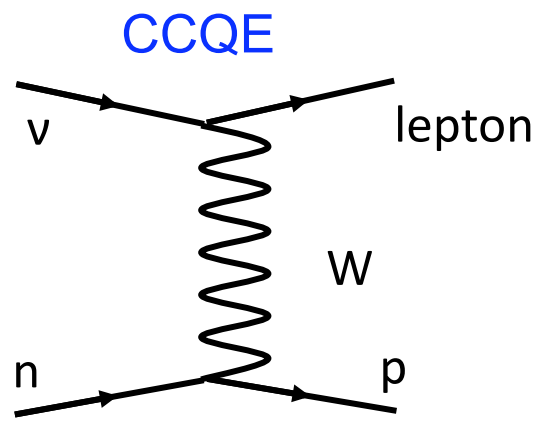
2) Which cross section processes are relevant really depends on the flux spectrum and detection efficiency

3) We assume ν_e and ν_μ cross sections are identical, except for lepton mass

4) Near detector constraint includes kinematic information (not just rate)

Neutrino interactions at T2K





$$\nu_e \rightarrow e$$
$$\nu_\mu \rightarrow \mu$$

At E_ν~0.6 GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

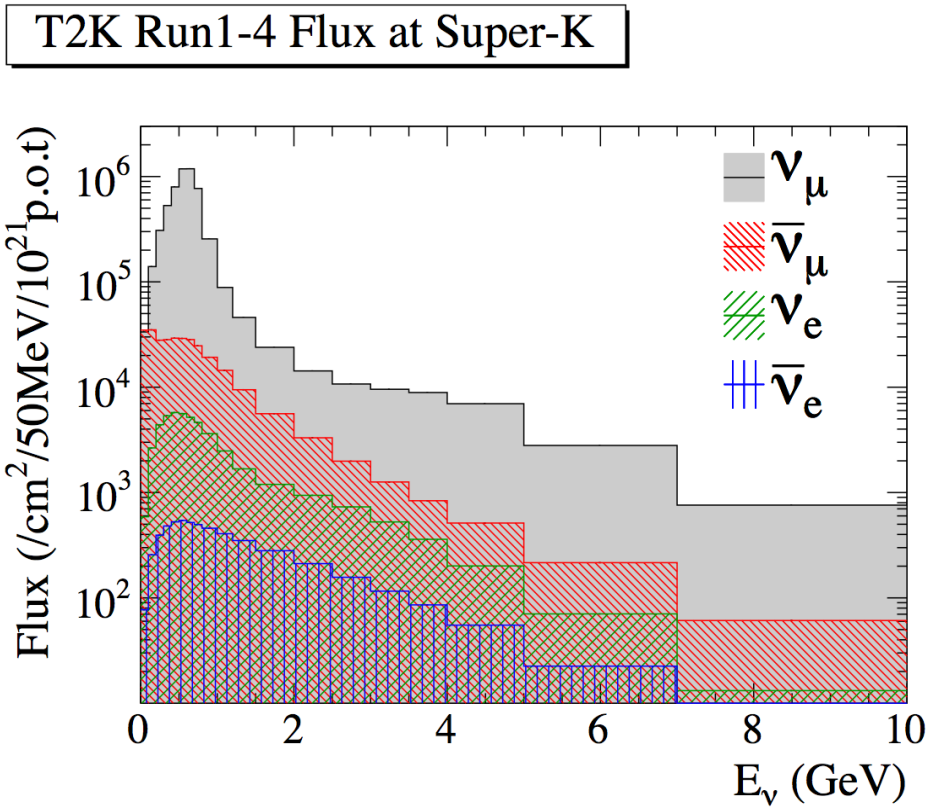
- Neutrino flavor determined from flavor of outgoing lepton
- Infer neutrino properties from the muon (or electron) momentum and angle:

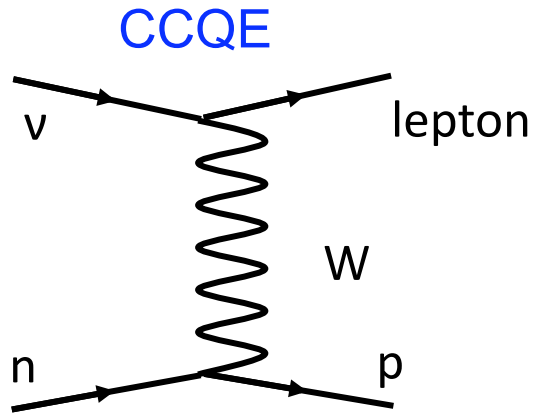
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics assumes the target nucleon is at rest

Nuclear effects, such as Fermi motion of the nucleon, are considered

Consider: unknown incident neutrino energy



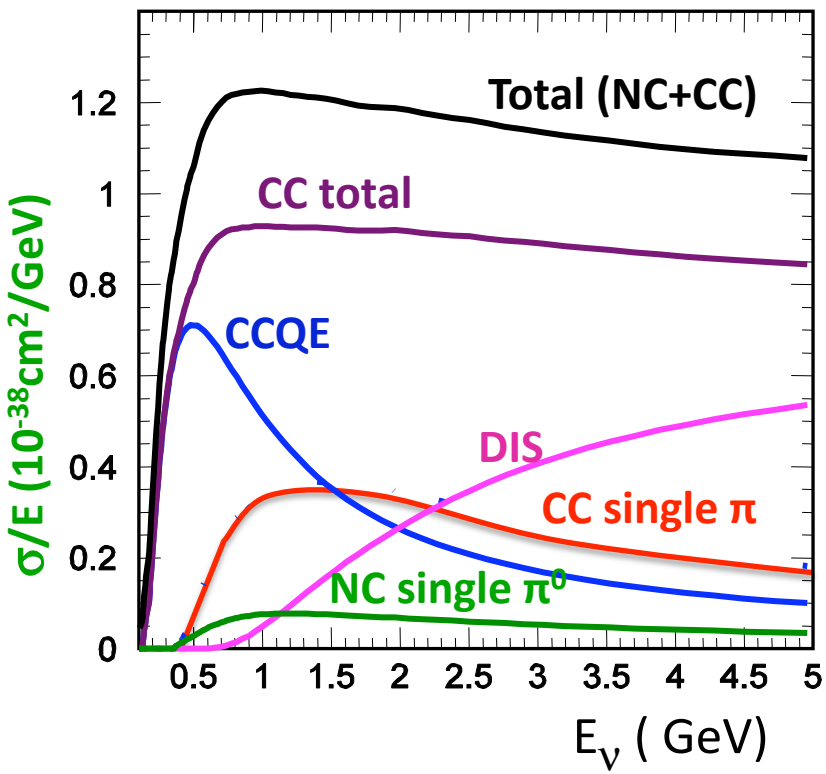


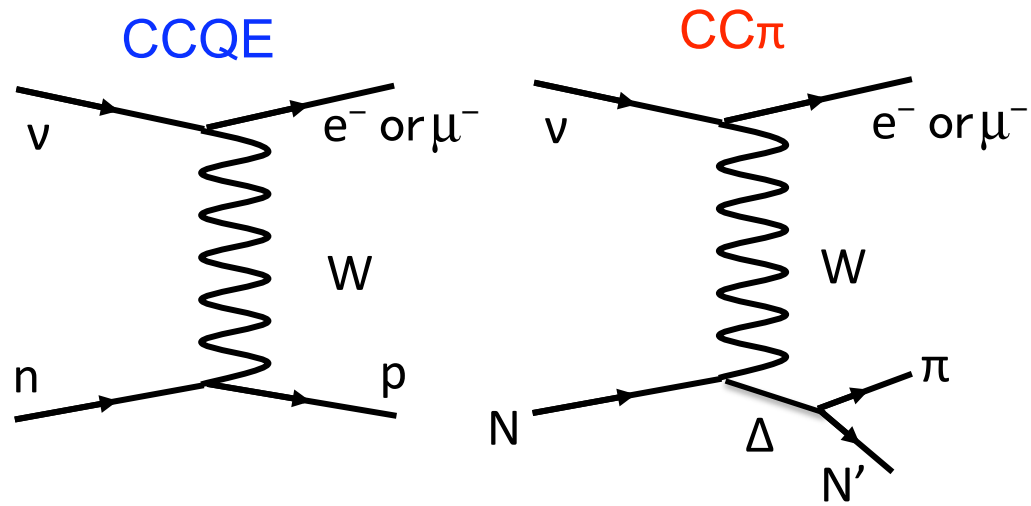
$$\nu_e \rightarrow e$$
$$\nu_\mu \rightarrow \mu$$

T2K's neutrino flux is from $0<E_\nu<30$ GeV

- For each interaction, incident neutrino energy is unknown
  - Uncertainties are typically 10-15% from beam monitors, hadroproduction experiments
- Near detector can constrain event rate in lepton kinematic bins, but relationship to neutrino kinematics is model dependant. *Estimating the correct energy dependence of the cross section is important*

Neutrino interactions at T2K

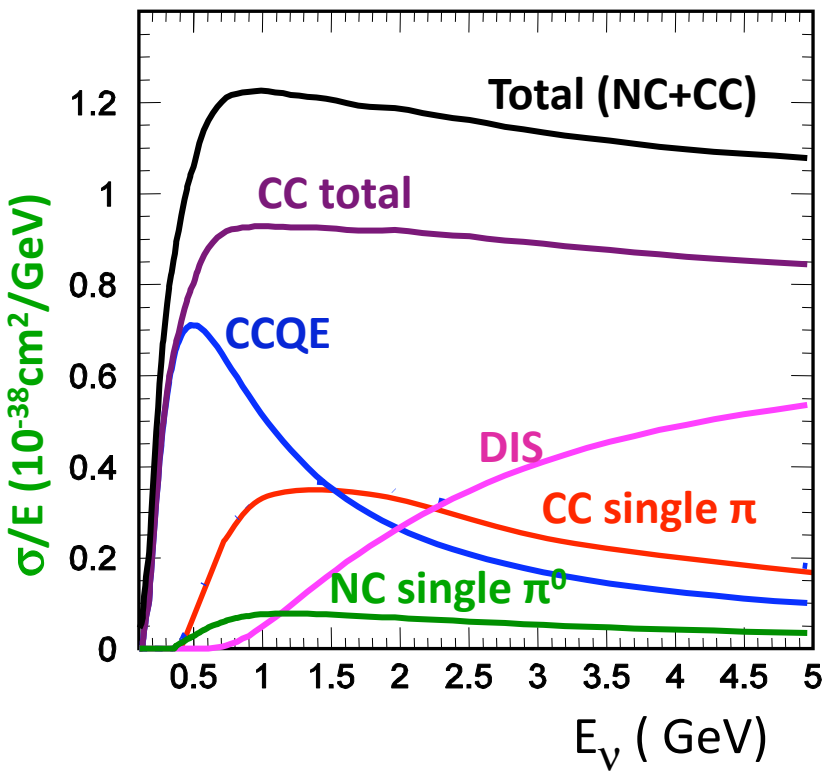


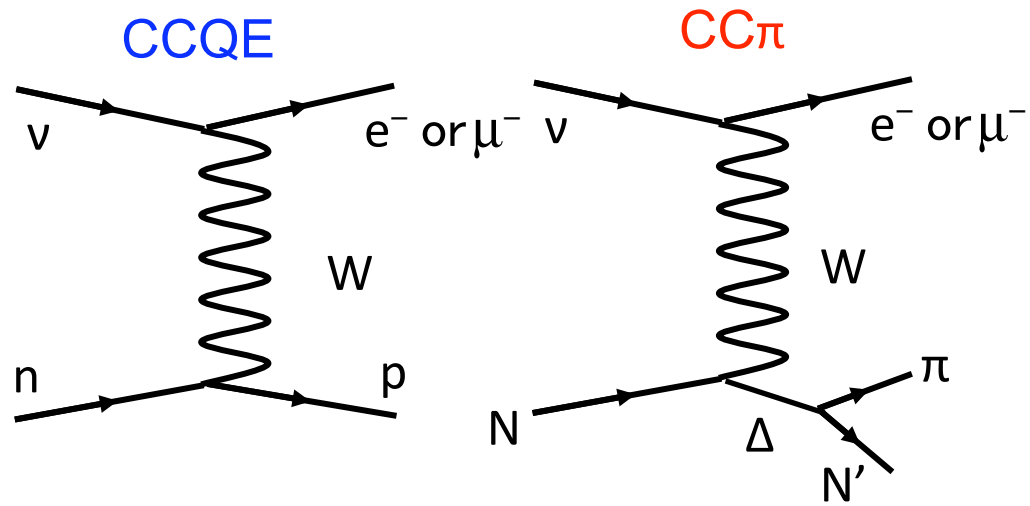


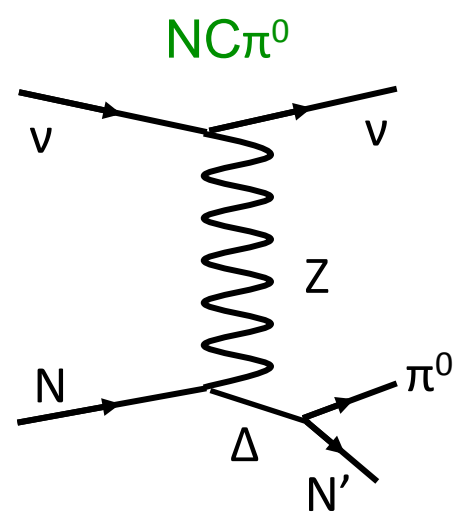
Other interactions important for T2K analysis:

- Charged current single pion production (CCπ)
  - Lepton and pion (charged or neutral) produced
  - Oscillation signal (and background if pion is not identified)
  - Other CC interactions (multipion production -> DIS) also are important

Neutrino interactions at T2K



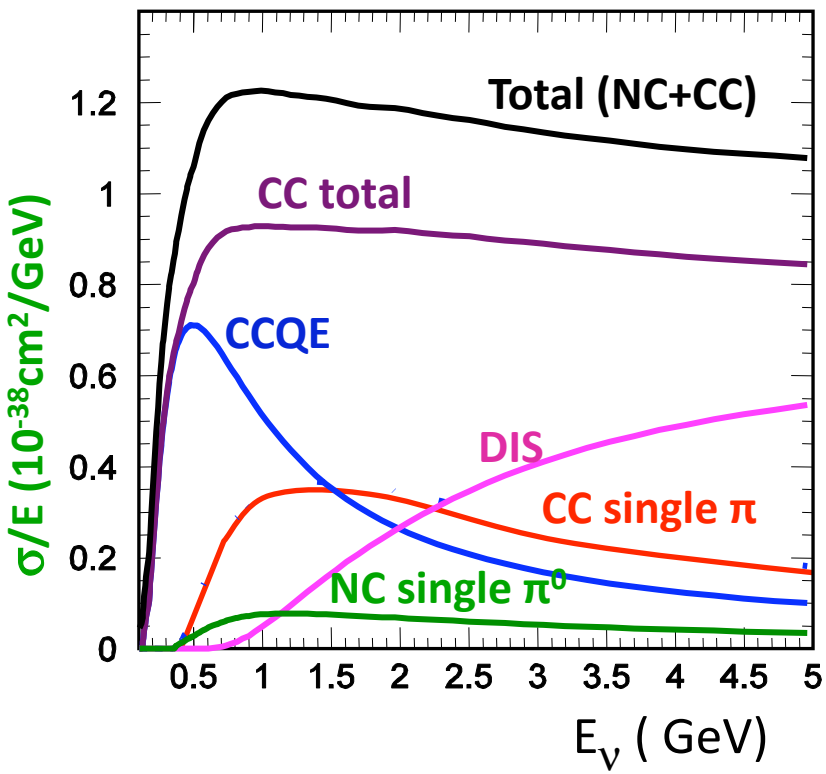


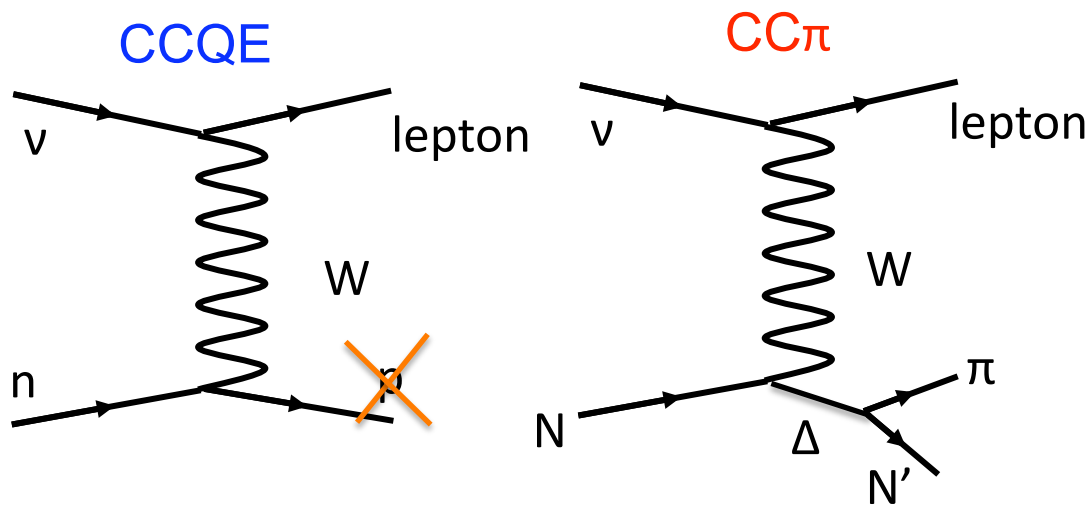


Other interactions important for T2K analysis:

- Neutral current single pion production ($NC\pi^0$)
  - No lepton in final state (happens for all flavors)
  - Only neutral pion (π^0) produced in detector
  - Can mimic ν_e signal in Cherenkov detectors (also to some extent in scintillator, LAr detectors)

Consider: nuclear targets





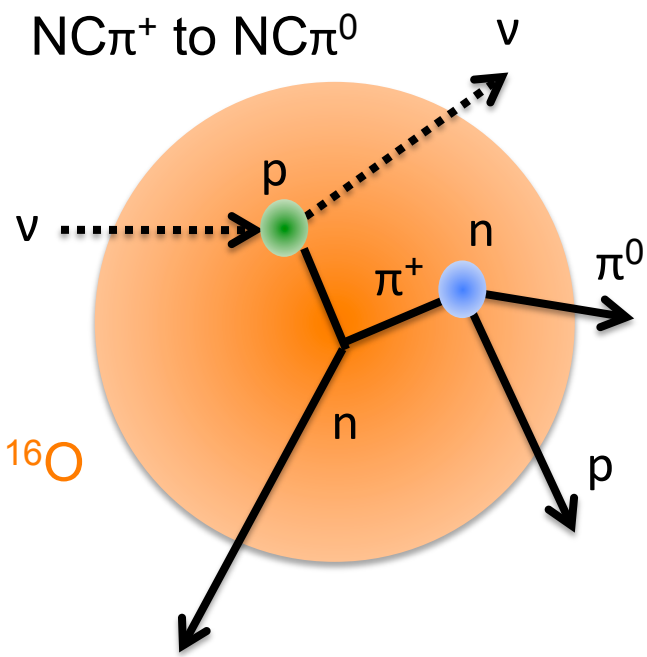
Near detectors can measure exiting particles, like p, π, but... nuclear effects matter

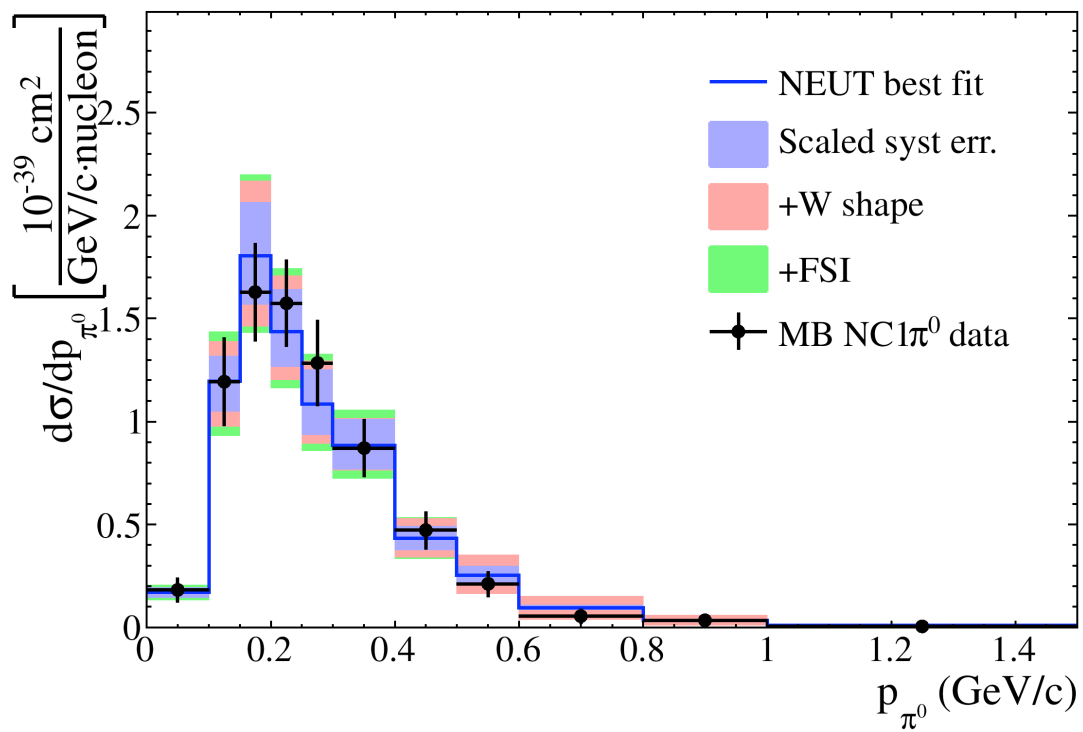
- Exiting nucleons experience "final state interactions", e.g. pion absorption, proton rescattering
- Observe "CC0π" (1muon, no charged pion) after FSI
- Detection threshold for particles other than lepton and response of detectors to all particles affects use of calorimetric/total information

Neutrino interaction uncertainties

Cross section model (NEUT, GENIE) simulate stepwise:

- Initial interaction of neutrino with nucleon
- Final state interaction model (FSI) of outgoing particles





Estimate uncertainties on each process, including single nucleon cross section, nuclear effects, FSI and energy dependence

Infer uncertainties on outgoing particles from neutrino, electron scattering data

1) Neutrino-deuterium data tests single nucleon xsec
2) Multiple fluxes test xsec energy dependence indirectly
3) Different targets tests nuclear effects and FSI

Information from near detectors

- Select CC with 0π, 1π, and "other" in the event
- Fit near detector kinematic distributions to determine constraint on far detector rate (Φ x σ)
- Includes prior information from external measurements (e.g. beam monitors, neutrino cross section measurements)
- Shared flux, similar CC cross section composition of near and far detector selections result in substantial reduction to CC cross section parameters, ν_μ flux uncertainties

Parameter	Prior to ND280 Constraint	After ND280 Constraint (Runs 1-4)	After ND280 Constraint (2012 analysis, Runs 1-3)
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072	1.269 ± 0.194
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063	1.223 ± 0.127
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076	0.951 ± 0.086
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16	1.37 ± 0.20
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25	1.15 ± 0.27

*For E_ν<1.5 GeV **For E_ν<2.5 GeV

Information from Near detector

Single nucleon axial vector form factors appear here, as an effective M_A^{QE} which encodes an experimental dependant variation to the Q^2 distribution due to nuclear effects (effect of RPA is similar)

LQCD help:

1) Is the dipole assumption reasonable? What is the Q^2 dependence of the axial mass for light quarks?
2) What is the axial radius (the slope of F_A at Q^2->0)?
3) What is the strangeness content of the axial form factor? (Δs)

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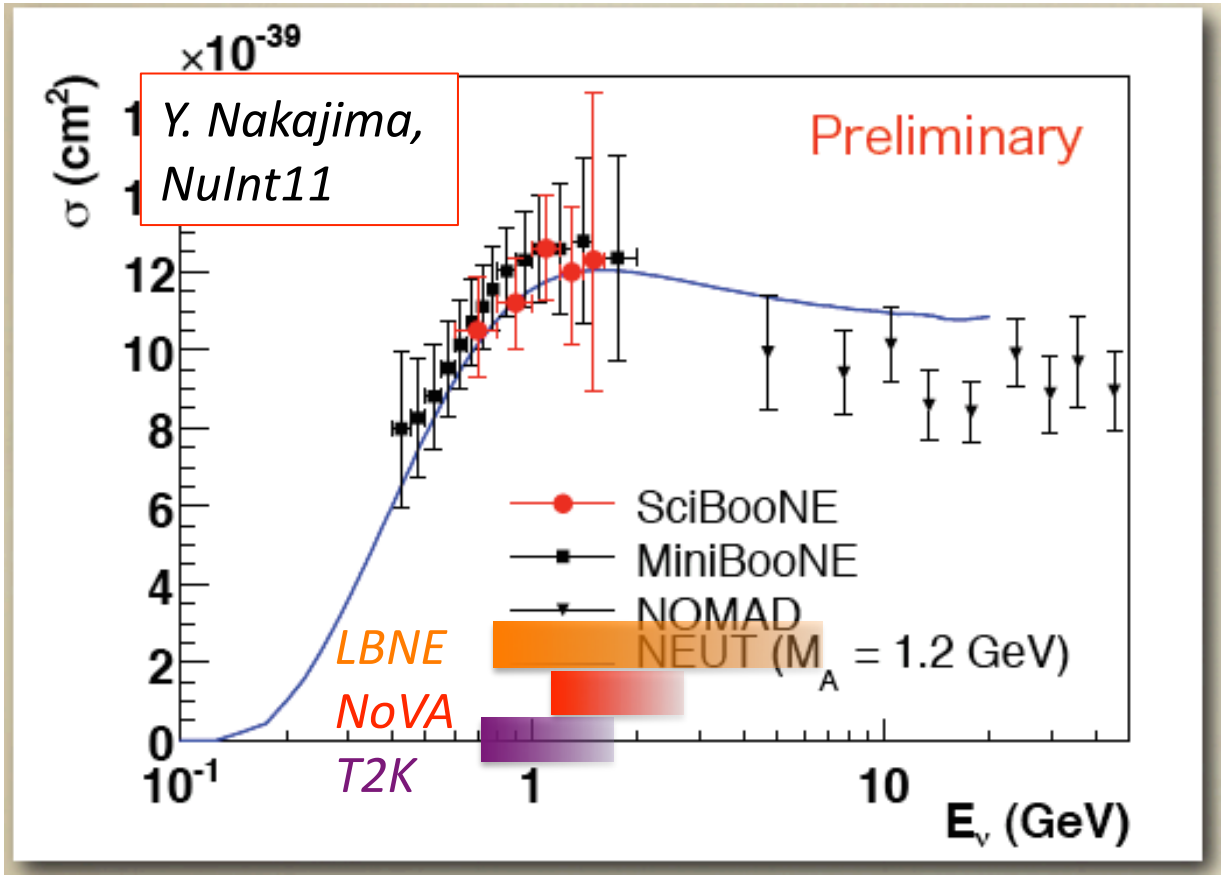
*For E_ν<1.5 GeV **For E_ν<2.5 GeV

Current limitations in T2K analyses

Uncertainties	ν_e sig+bkrd
ν flux+xsec (constrained by ND280)	±3.0%
ν xsec (unconstrained by ND280)	±7.5%
Far detector	±3.5%
Total	±8.8%

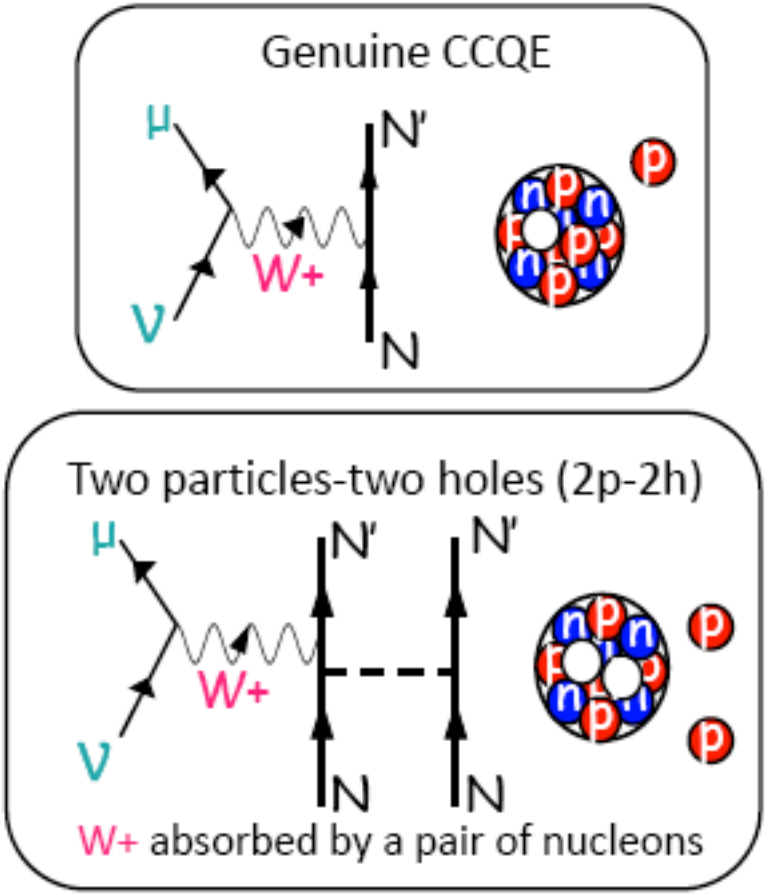


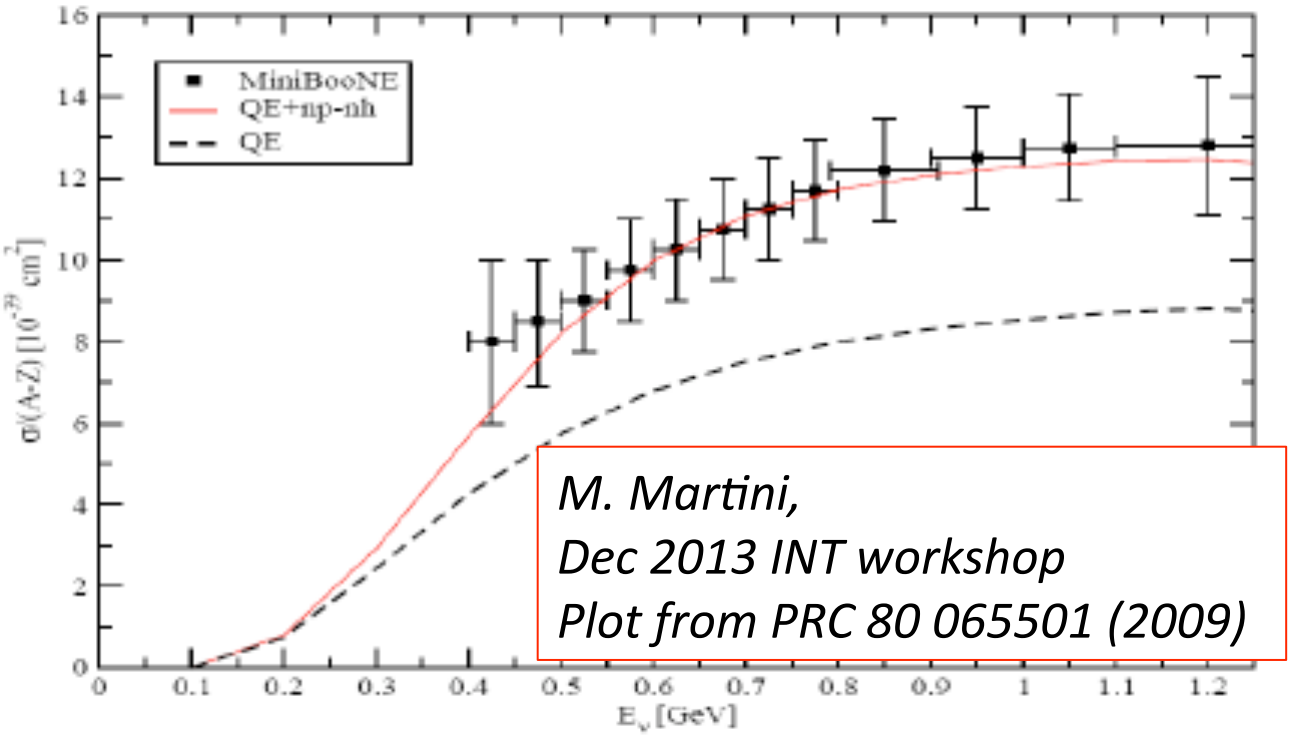
Goal of future LBL (e.g. LBNE) experiments is ~1%(5%) signal (bkrd) uncertainties

The largest systematic uncertainties currently on the T2K ν_e appearance analysis are from uncertainties on the CCQE, CC1π neutrino interaction models

- Disagreements between models and existing neutrino experiment data (e.g. MiniBooNE, SciBooNE)
- Differences between new theoretical models and those currently used by T2K

CCQE and multinucleon interactions



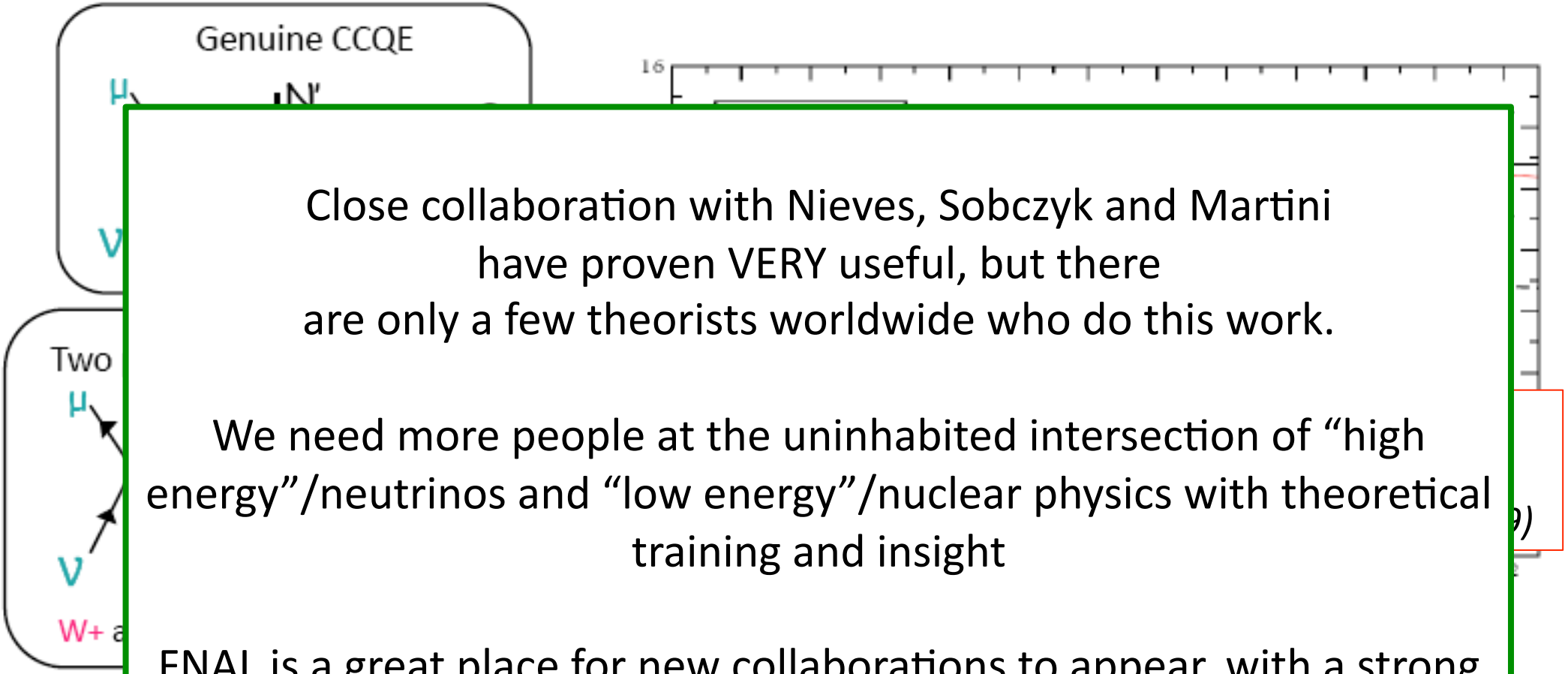


M. Martini,
Dec 2013 INT workshop
Plot from PRC 80 065501 (2009)

"Multinucleon" processes may explain the enhanced CCQE cross section observed by MiniBooNE, SciBooNE experiments

- Effort to include multinucleon models into neutrino generators used by T2K (NEUT)
  - Currently working with Nieves et al model (PRC 70, 055503 (2004)) combined with Sobczyk multinucleon ejection model (PRC 86, 015504 (2012))
  - Further details at recent Dec 2013 INT workshop: http://www.int.washington.edu/talks/WorkShops/int_13_54W/

CCQE and multinucleon interactions



Close collaboration with Nieves, Sobczyk and Martini have proven VERY useful, but there are only a few theorists worldwide who do this work.

We need more people at the uninhabited intersection of "high energy"/neutrinos and "low energy"/nuclear physics with theoretical training and insight

FNAL is a great place for new collaborations to appear, with a strong experimental expertise on neutrino cross sections (SciBooNE, MiniBooNE, MINERvA, and soon to come NoVA, MicroBooNE)

"Mult … by MiniB …

- Effo … T)
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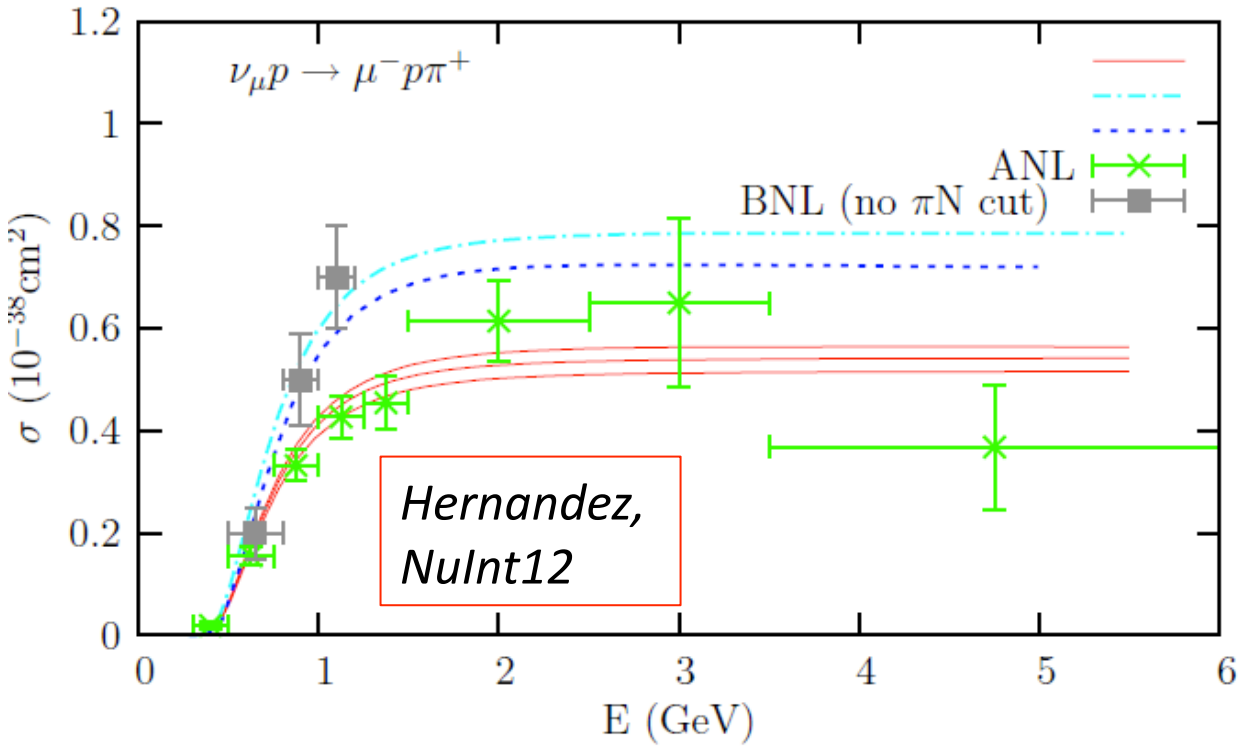
CC1pi and existing experimental data



Use neutrino-deterium data to estimate axial form factor for CC1π

- Difference between ANL/BNL data results in substantial error on C^5_A (leading axial coupling in Q^2 expansion of about ~15%)

LQCD help (some existing work by Alexandrou et al.)

1) What is the value and Q^2 dependence of C^5_A?
2) What about subleading terms? Are they important?
3) What about heavier resonances?

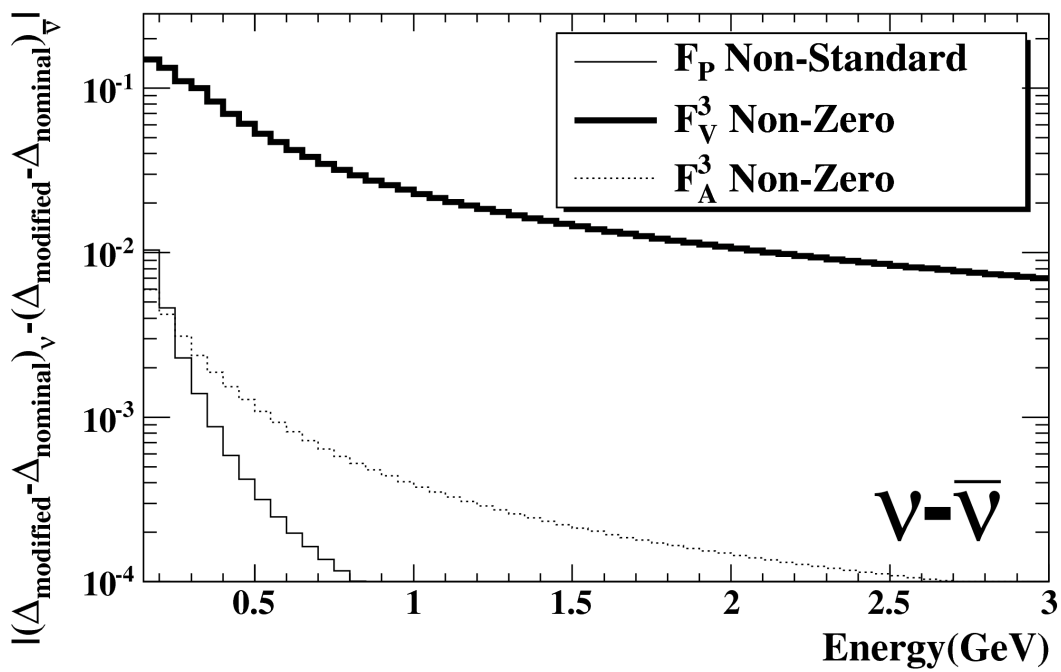
Additional important systematics for LBL

Future δ_{CP} searches depend on CP asymmetry, which relies on knowing:

- The differences between nue and numu cross sections
  - 3% in T2K analysis, difficult to test experimentally
- The differences between neutrinos and antineutrino cross sections

Example from PRD 86, 053003 (2012)

- Vector second class current (F^3_V) is assumed to be 0 because it violates charge sym in the nucleon system
- Impt for muon but not electron neutrinos, as it enters in the cross section proportional to lepton mass
- Has few percent effect, but different for neutrinos vs. antineutrinos



Not sure if clearly a lattice QCD problem, but worth considering

Summary

We always depend on a cross section model

- If there are two cross section models with different energy dependences, but predict same rate at the near detector, then there will be a bias in the oscillation parameters

We observe a interaction which depends on the single nucleon, nuclear potential and FSI; the effects are not easy to isolate directly

- We address this with as much experimental data as we can, however experimental data can conflict
- Theory is important to test fundamental assumptions

Help welcome!

Clear tasks for Lattice QCD include:

- Is the dipole assumption reasonable? What is the q2 dependance of the axial mass for light quarks? What is the axial radius (the slope of Fa at q2->0)?
- What is the strangeness content of the axial form factor? (Delta s)
- What is the value and Q^2 dependence of C^5_A? What about subleading terms and heavier resonances?

Important for current generation (T2K, NoVA, MINERvA) experiments over ~1-5yrs

Possible tasks, for Lattice QCD (though may not pan out):

- Single nucleon level differences in the axial form factor for nue/nuebar/numu/numubar cross sections?

Important for next generation LBL experiments over ~5 yrs

Thank you so much for the invitation today and for considering this work

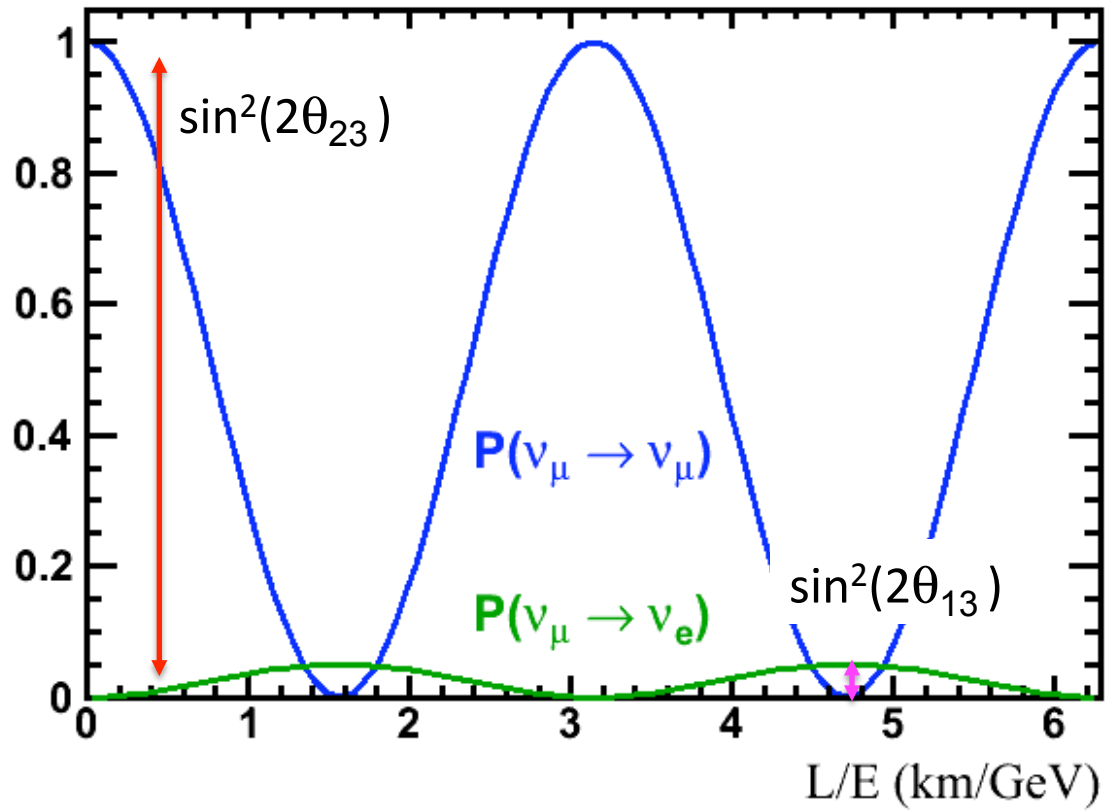
- Theoretical support on T2K has been extremely valuable; I expect FNAL based programs feel similarly. Let us know how we can help get started in more detail.
- The world needs more people worrying about neutrino cross sections

Backup slides

Oscillation experiments

We infer the values of oscillation parameters from:

- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)



$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

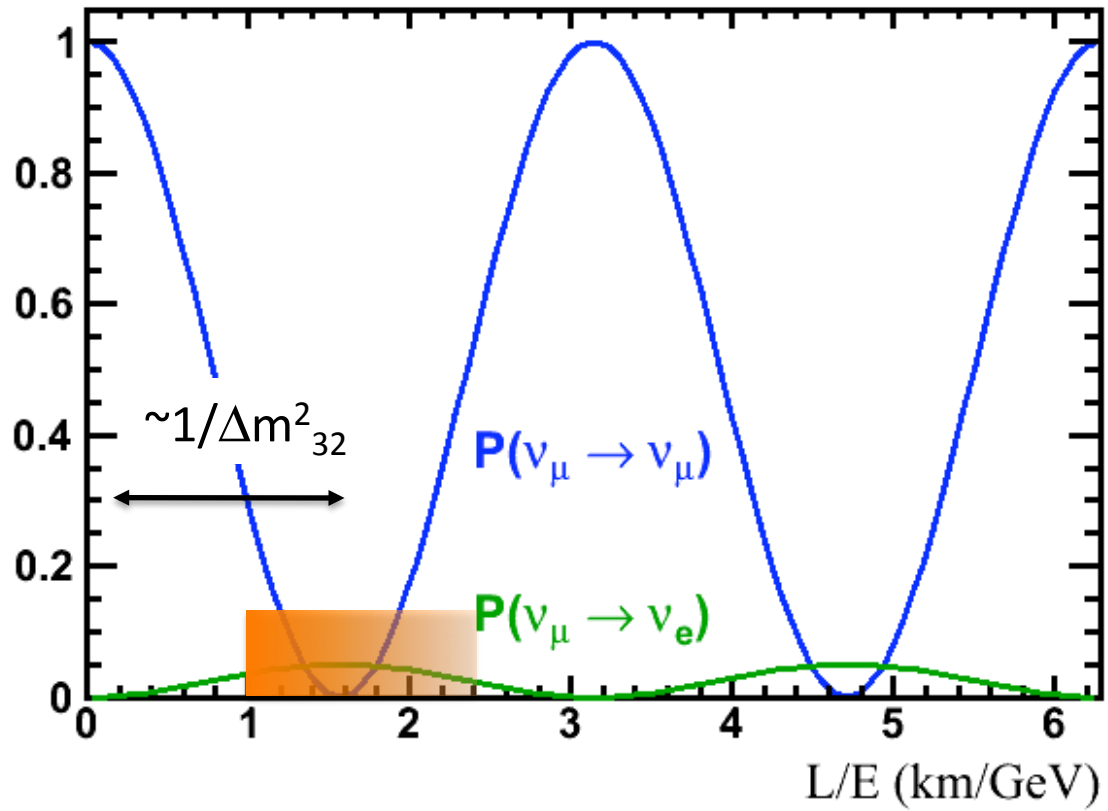
Only leading order terms shown

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right)$$

Oscillation experiments

We infer the values of oscillation parameters from:

- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)
- and the distortion to the neutrino spectrum (Δm^2_{32})



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Oscillation experiments

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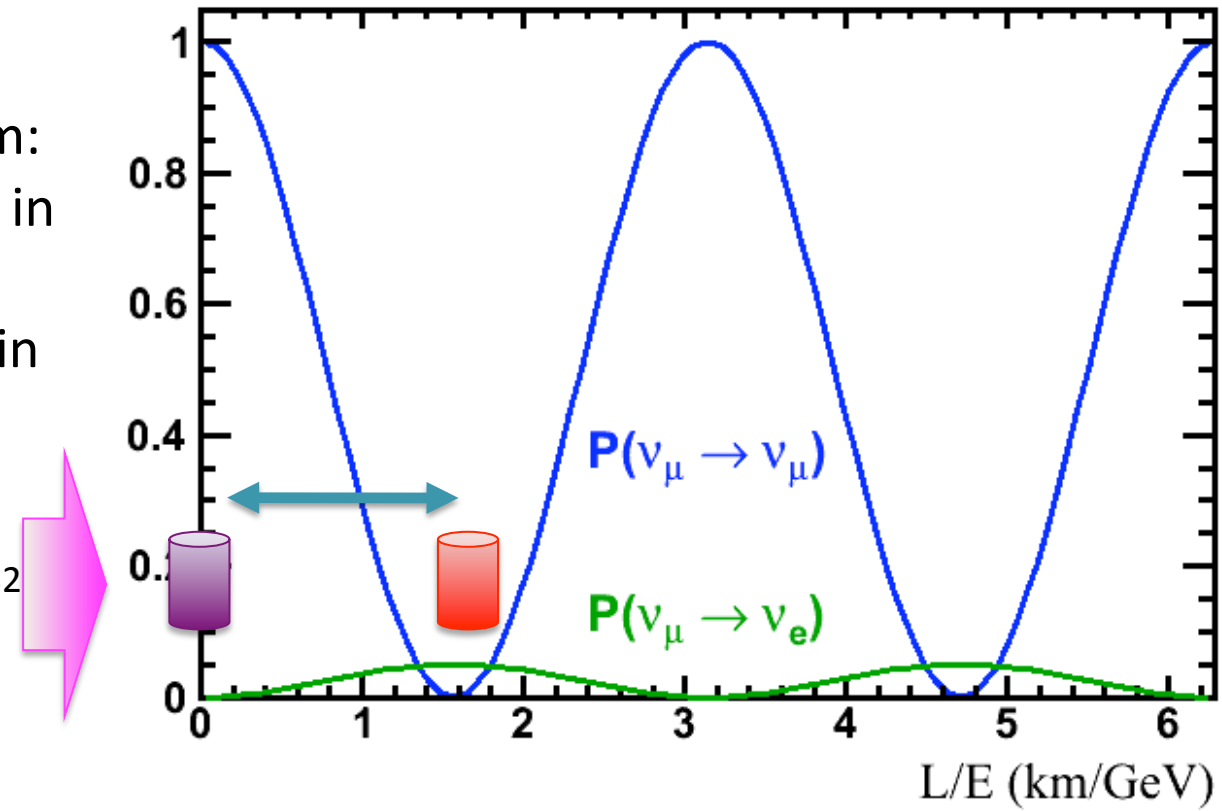


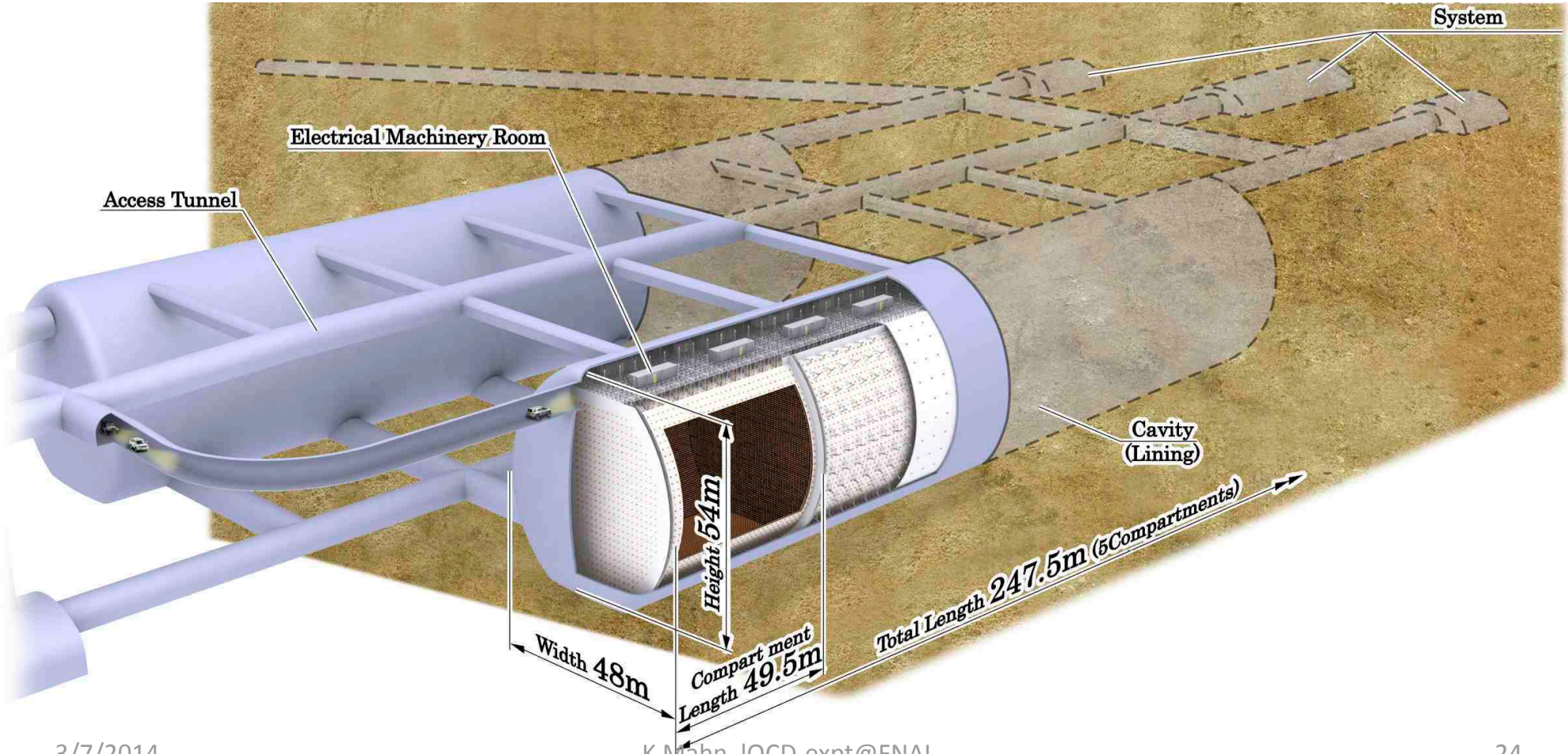
To search for neutrino oscillation, we need:

1) An intense neutrino source of muon neutrinos
2) A sufficient distance for oscillation to occur
3) A measurement of unoscillated ν_μ (and ν_e background) rate at L~0
4) A measurement of ν_μ, ν_e at L~ oscillation maximum

Hyper-Kamiokande

~1Mton detector, approximately 25x Super-Kamiokande

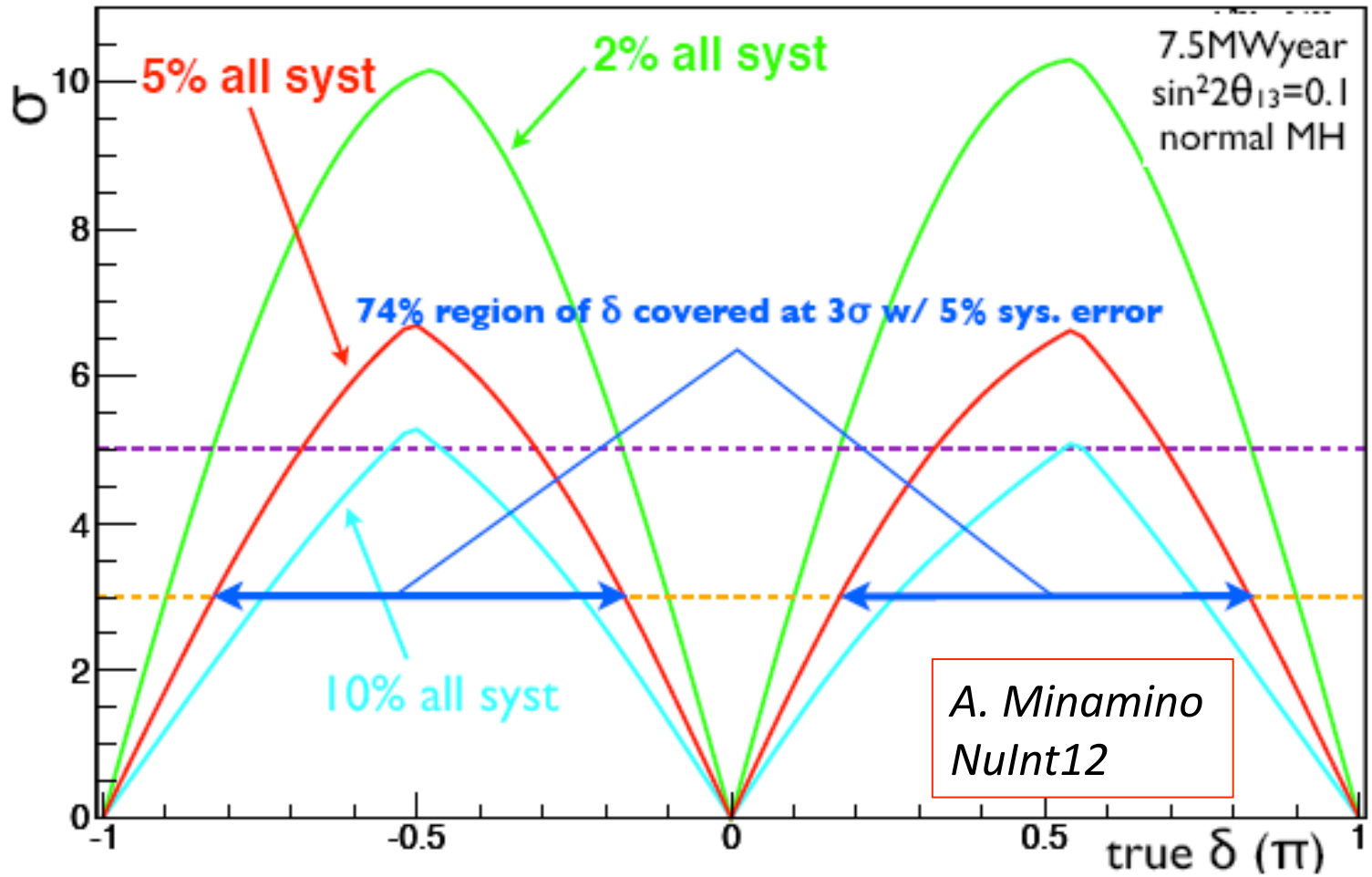
- 99,000 inner PMTs, 25,000 veto region PMTs (10 compartments)
- Same neutrino beamline as T2K, different cavern
- Other physics reach: solar neutrinos, atmospheric neutrinos, astrophysical neutrinos (supernova), geo-neutrinos and proton decay



δ_{CP} discovery sensitivity

HK LOI: hep-ex 1109.3262

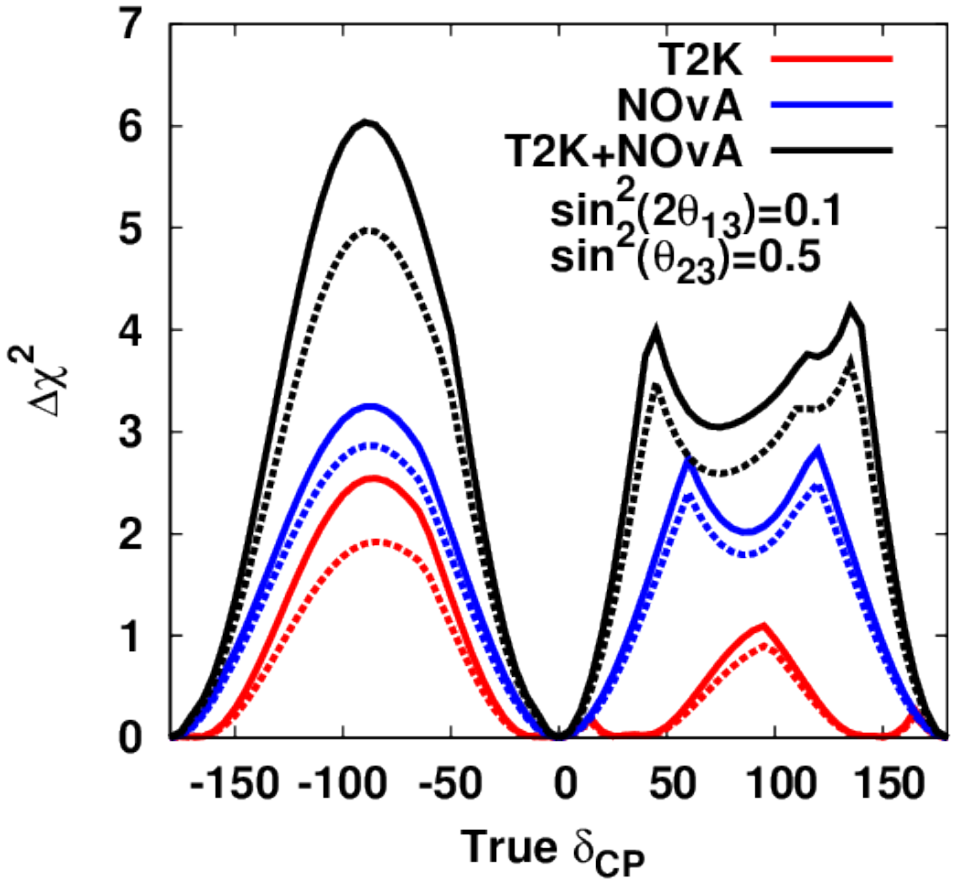
	ν run	ν run
Signal ν_e, ν_e	3560	1959
NC	649	678
CC ν_e ν_e	880	878
Other	81	403

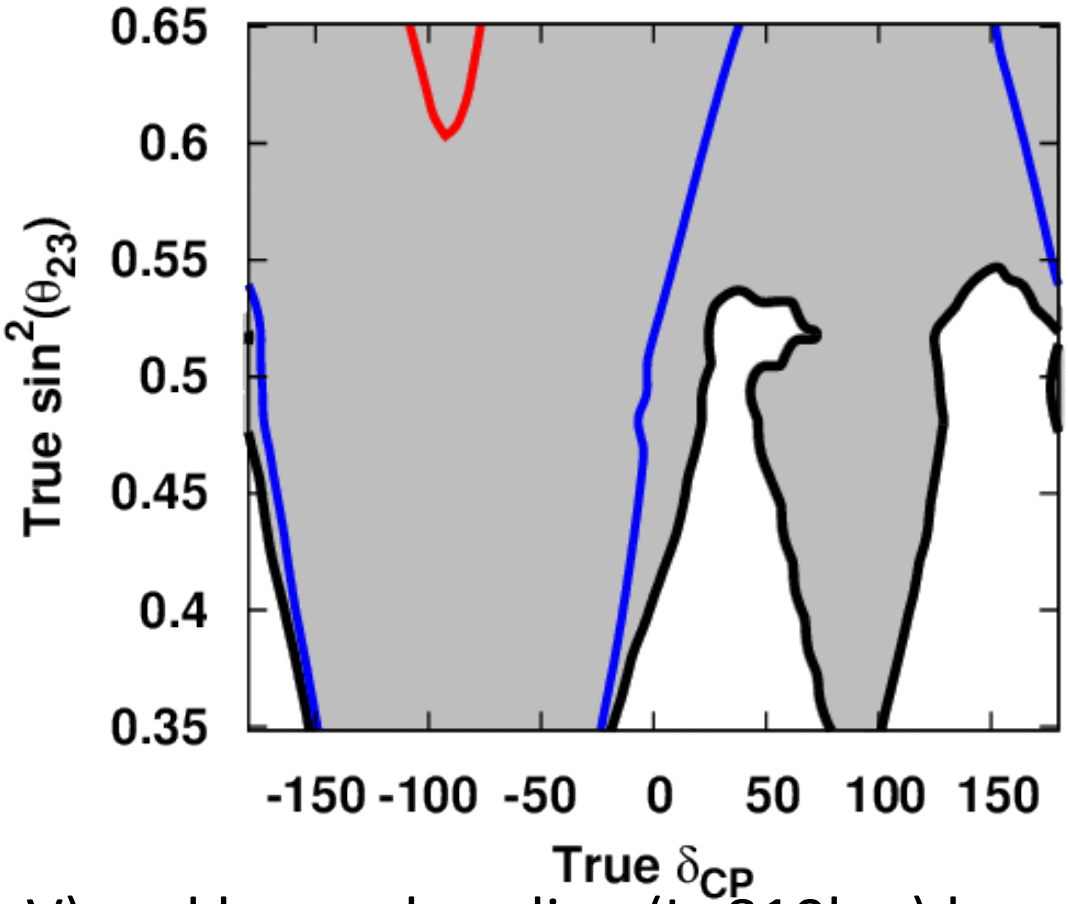


With <5% overall systematic uncertainty, HK could observe evidence of nonzero δ_{CP}

- Statistical uncertainty ~2%
- Improved control of systematic uncertainties corresponds to increased physics impact
- Similar assumptions for LBNE experiment (1% signal, 5% background knowledge)

What will we learn from T2K/NOvA?

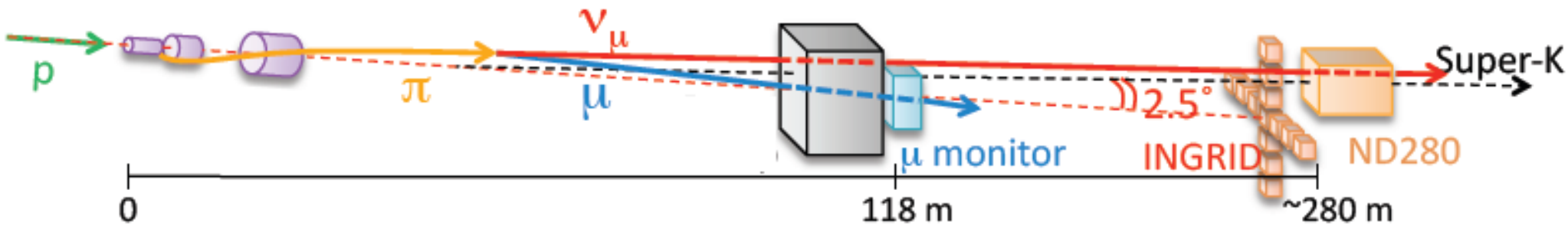




NOvA's higher energy (peak E_ν~2 GeV) and longer baseline (L~810km) has a different dependence on mass hierarchy than T2K through the matter effect

- Left: Increased sensitivity to value of δ_{CP}, with for fixed values of θ_{13}, θ_{23} and with (dashed) and without (solid) systematic uncertainties applied
- Right: Gray regions are where the mass hierarchy can be determined to 90% CL for T2K(red), NOvA (blue), and T2K+NOvA (black)

T2K Neutrino flux prediction



FLUKA/Geant3 beam simulation

Phys. Rev. D 87, 012001 (2013)

- 3 horn focusing system
- 280m from target:
  - INGRID on-axis ND280 off-axis
- ν_μ from π^+, K decay

Prediction and uncertainties determined by external or in-situ measurements of:

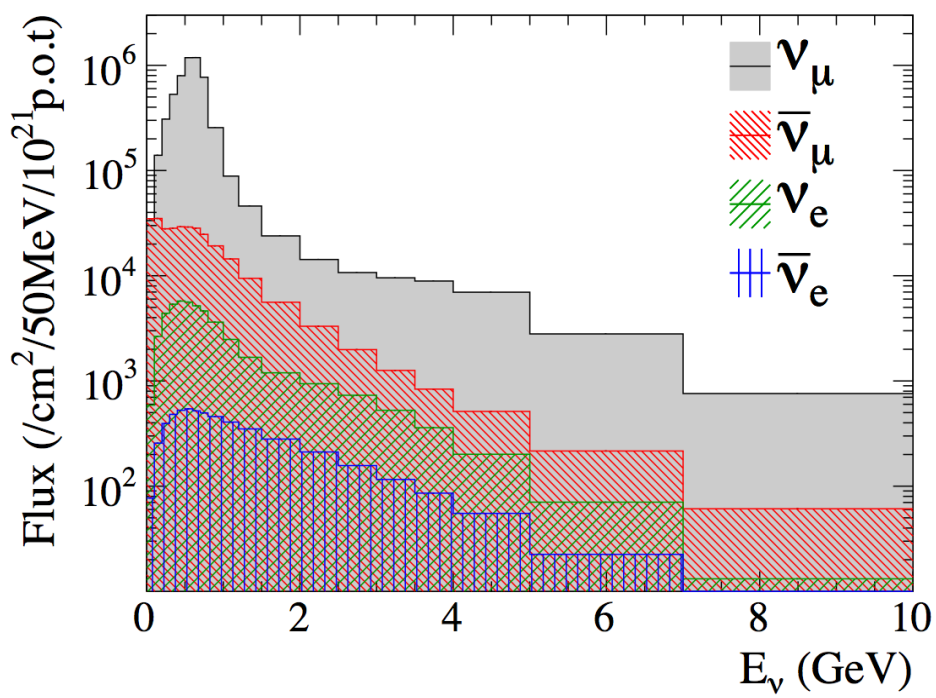
- proton beam (30 GeV)
- π, K production from NA61 experiment

Phys.Rev.C 84, 034604 (2011)

Phys.Rev.C 85, 035210 (2012)

- alignment and off-axis angle

T2K Run1-4 Flux at Super-K

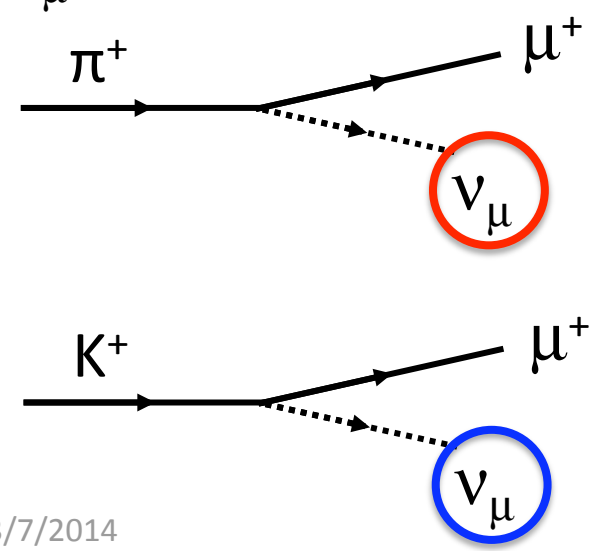


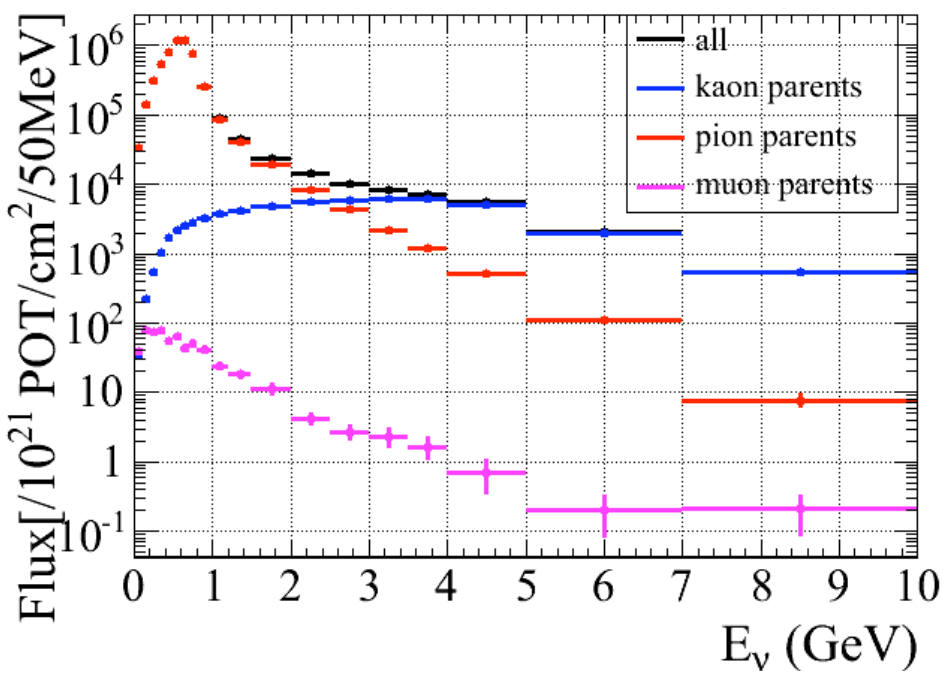
Neutrino flux at ND and SK

Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_e NC Bgnd.
$\pi^+ \to \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \to \nu_e + e^+ + \bar{\nu}_\mu$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \to \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \to \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

ND samples represent ν_μ flux

- ν_μ from π decay: CCQE, CCnQE samples
- ν_μ from K decay: CCnQE sample

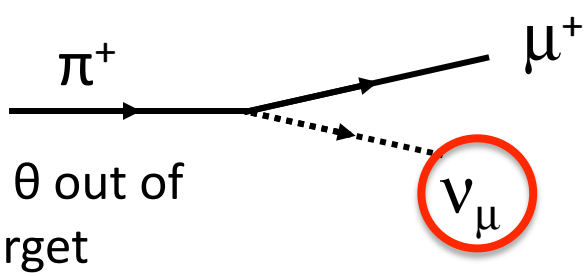




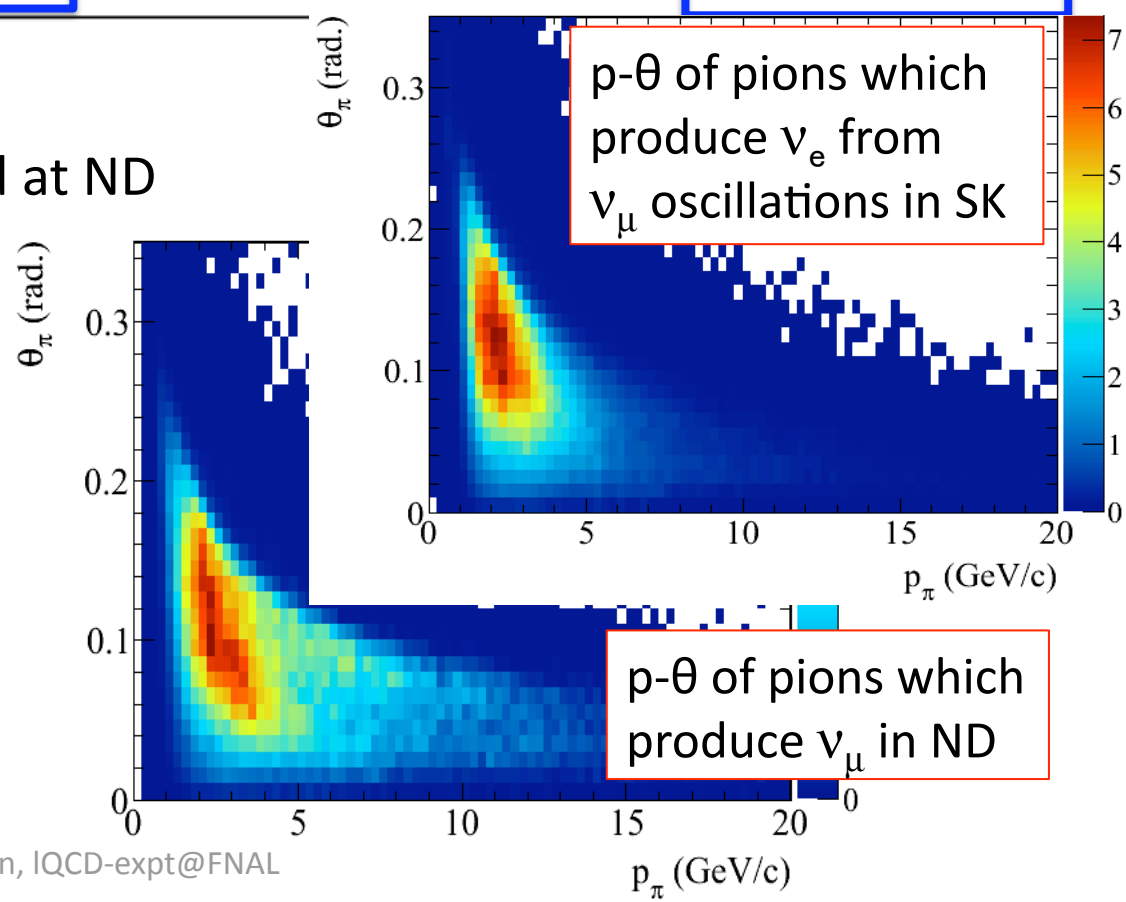
Neutrino flux at ND and SK

Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_e NC Bgnd.
$\pi^+ \to \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \to \nu_e + e^+ + \bar{\nu}_\mu$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \to \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \to \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

SK signal and NC background events come from ν_μ flux directly measured at ND



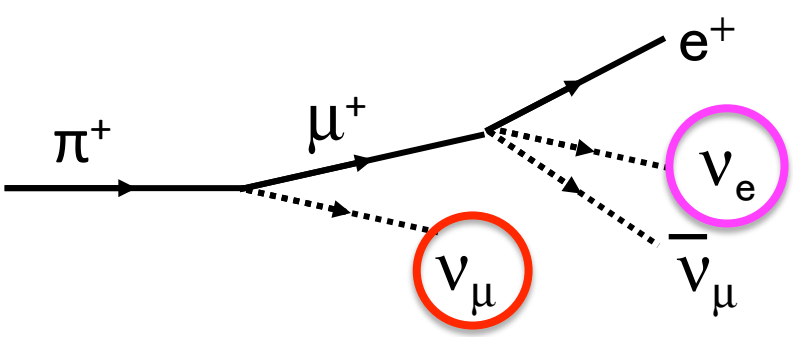
p, θ out of target

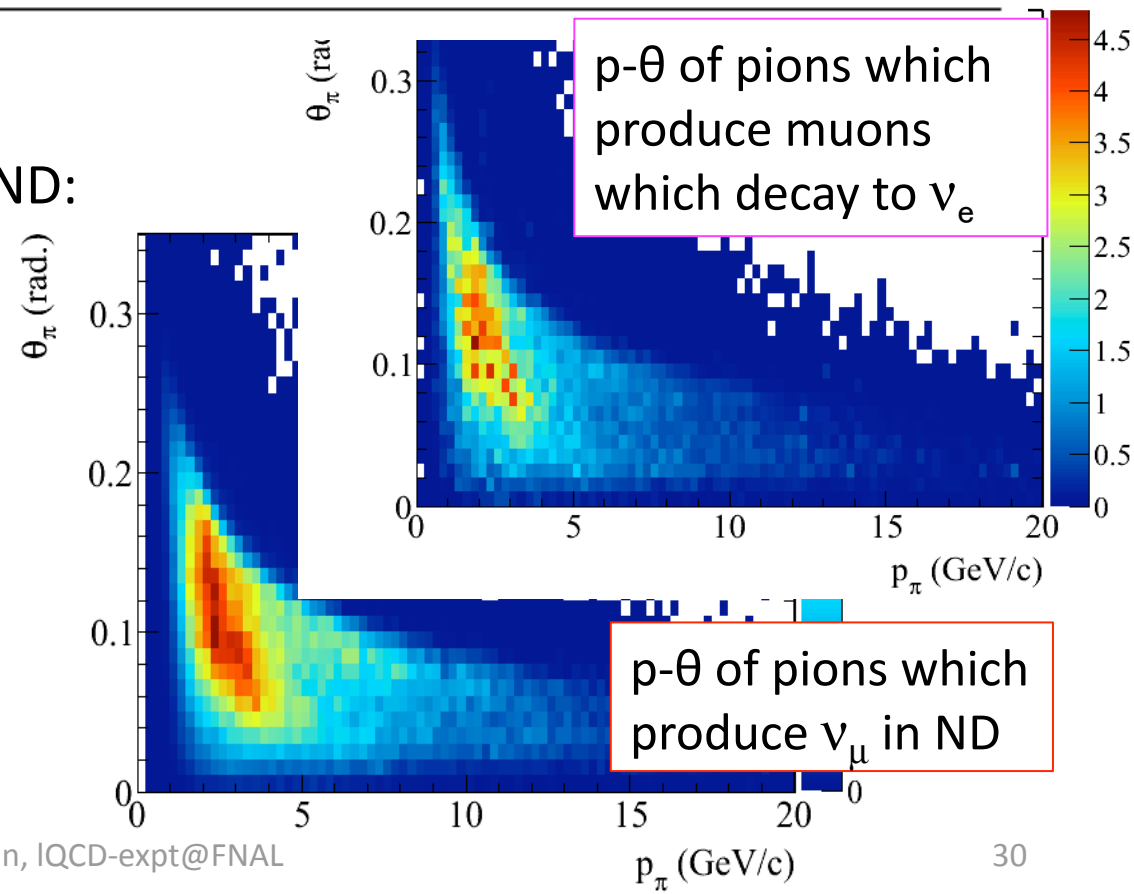


Neutrino flux at ND and SK

Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_e NC Bgnd.
$\pi^+ \to \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \to \nu_e + e^+ + \bar{\nu}_\mu$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \to \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \to \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

CC background from beam ν_e is strongly correlated with ν_μ flux at ND:





Neutrino interactions at ND and SK

Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

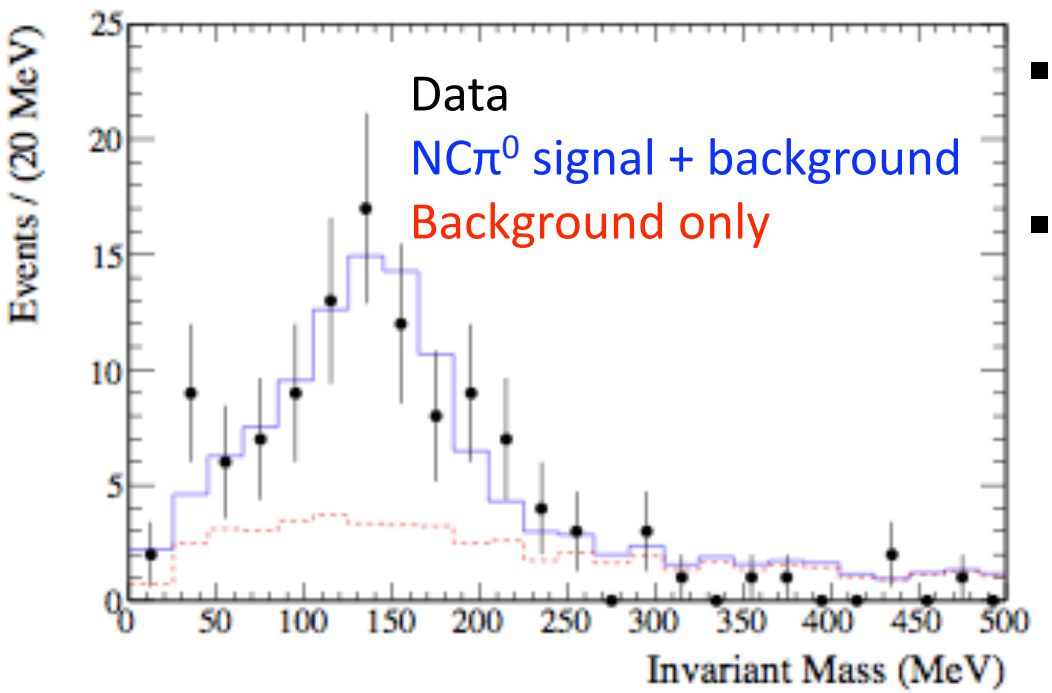
CCQE and CC1π are the largest interaction mode in ND, SK samples

- Separation of CCQE and CCnQE ND samples gives additional power for fit to constrain cross section models
- Need to account for acceptance difference between ND (forward going selection) and SK (4π selection) for identical changes to cross section to correlate the two samples

From experience with SciBooNE/MiniBooNE joint analysis, developed machinery to alter the cross section for each simulated event

Neutrino interactions at ND and SK

Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

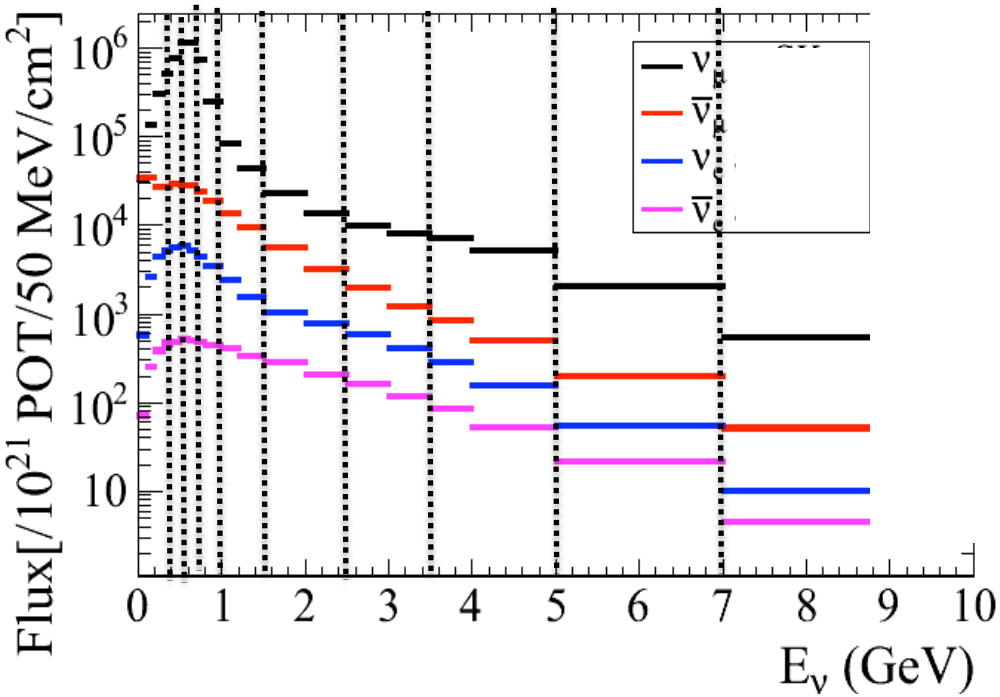


- Indirect constraint on NC ($1\pi^0$) through CC1π in ND measurement
- Additional ND selection of NCπ^0 with P0D detector to cross check rate prediction

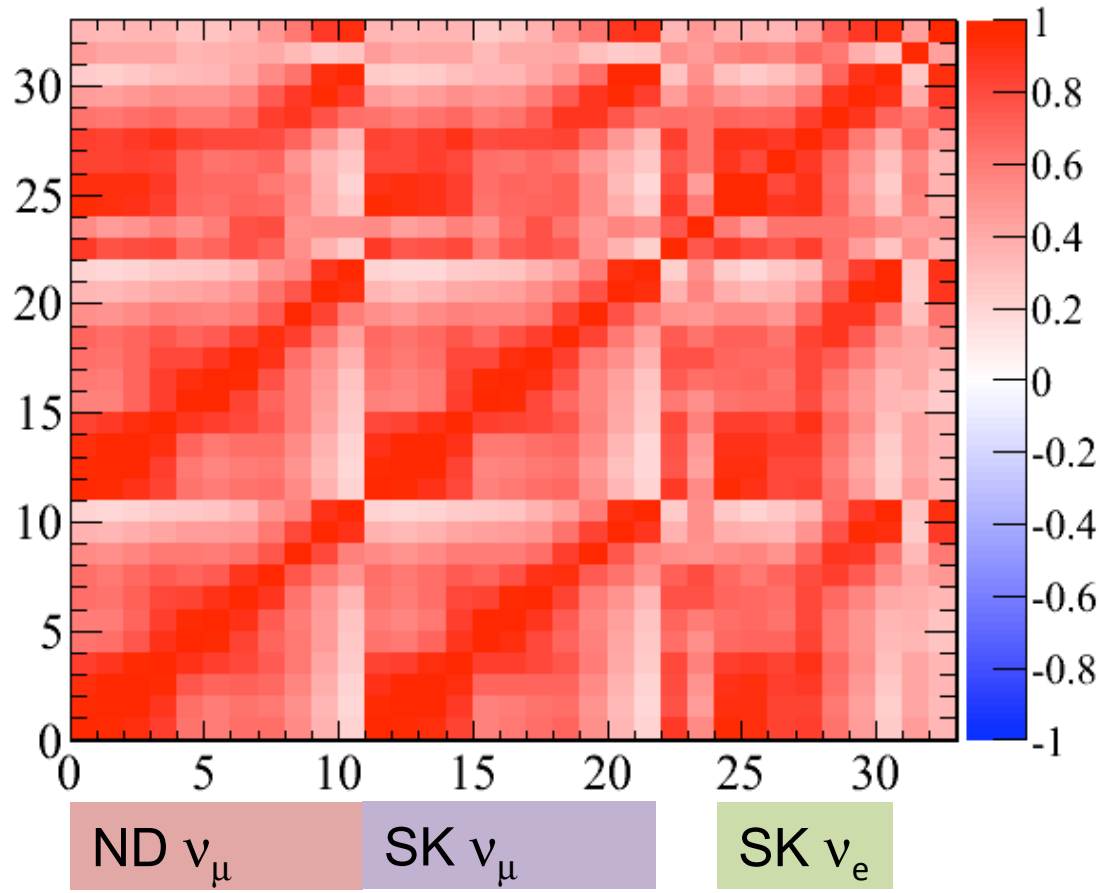
Flux parameterization

Neutrino flux prediction

Flux parameterization: f_i
Normalization on E_ν bin i for SK and ND samples



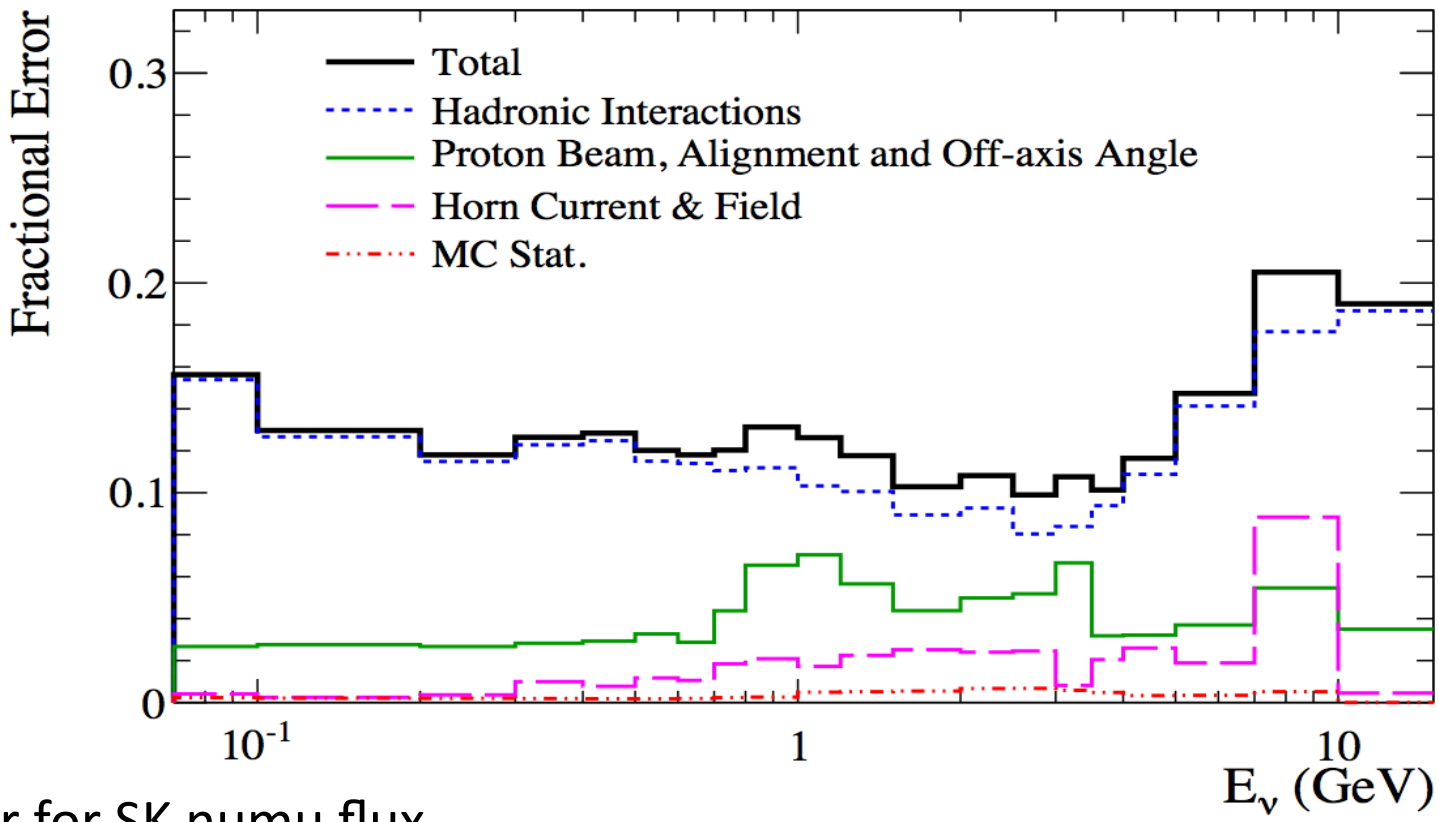
Correlations between flux bins



Correlations in flux covariance are shared hadron production uncertainties

Flux covariance built from measurements of beam or external data (e.g. NA61)

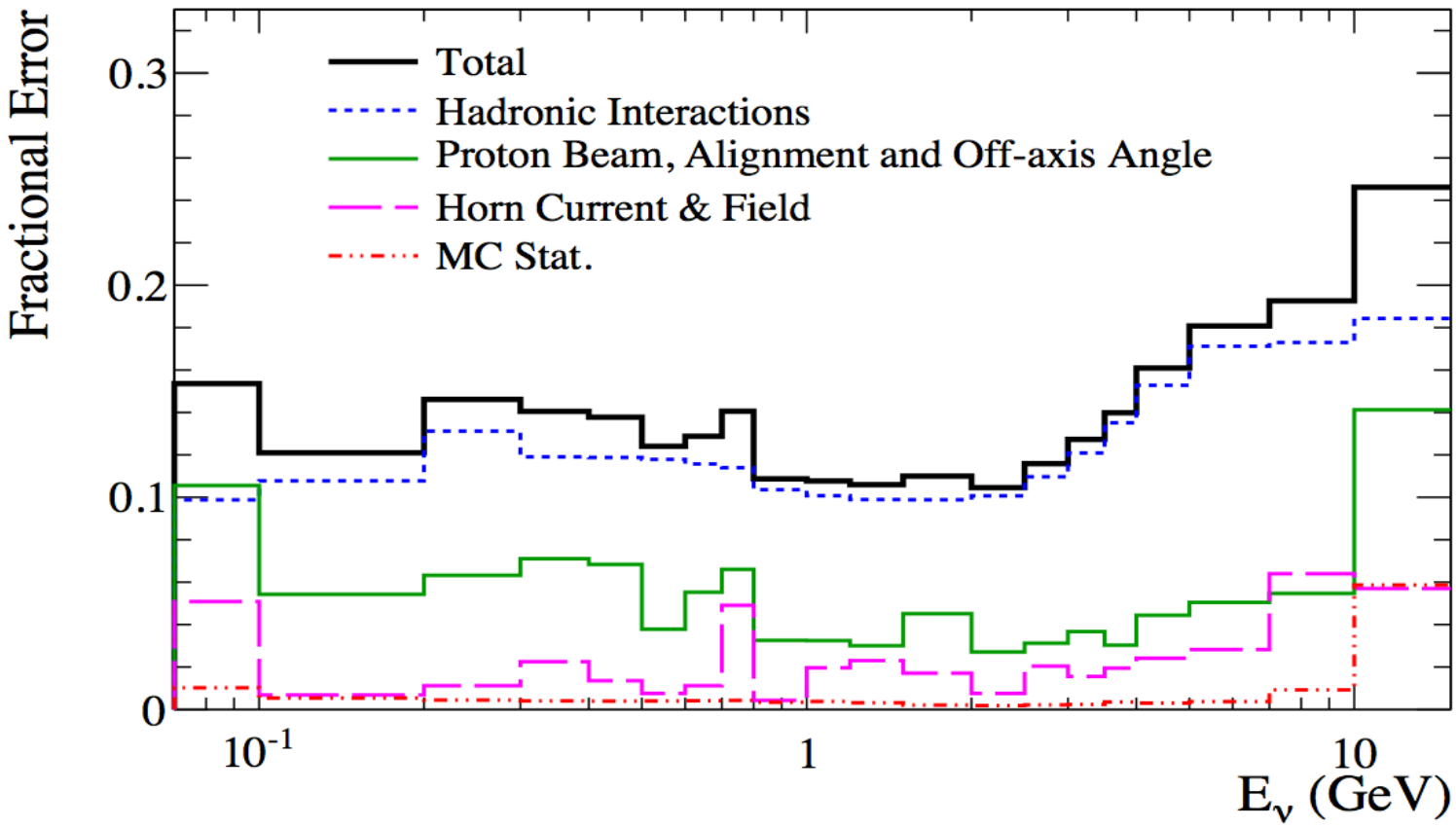
ND280 numu flux uncertainties



Similar for SK numu flux

- Pion production and kaon production were substantially reduced thanks to NA61 data
- Proton beam, alignment and off-axis angle uncertainties are constrained from beam monitors, survey data and INGRID
- Secondary nucleon production (reinteractions of protons, pions within the target which compose ~30% of the flux) will be constrained with new thick target NA61 data

SK nue flux uncertainties



Cross section parameterization

Cross section parameterization: x_k

Model parameters:

- MAQE and MARES (modify Q^2 distribution of QE and resonant 1pi cross sections)
- Fermi momentum (pF) provides low Q2 handle, and is target dependant (C vs. O)
- Spectral function – RFG model-model difference is also target dependant

Normalizations provide overall scaling independent of Q^2 on a particular interaction

Apply cross section to observables at ND, SK using reweighting techniques

M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
M_A^{RES} (GeV)	1.162 ± 0.110	1.137 ± 0.095
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CCQE Norm. 1.5-3.5 GeV	1.00 ± 0.30	0.92 ± 0.23
CCQE Norm. >3.5 GeV	1.00 ± 0.30	1.18 ± 0.25
CC1π Norm. 0-2.5 GeV	1.63 ± 0.43	1.67 ± 0.28
CC1π Norm. >2.5 GeV	1.00 ± 0.40	1.10 ± 0.30
NC1π^0 Norm.	1.19 ± 0.43	1.22 ± 0.40
Fermi Momentum (MeV/c)	217 ± 30	224 ± 24
Spectral Function	0(off) ± 1(on)	0.04 ± 0.21
CC Other Shape (GeV)	0.00 ± 0.40	-0.05 ± 0.35

Parameter value, uncertainty is determined from MiniBooNE single pion samples

Parameter value, uncertainty is extrapolated to SK sample

ND280 likelihood

$$-2lnL = \boxed{2\sum_{i}^{p,\theta\ bins} N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})]}$$

Likelihood function, with Poisson statistics

$$+ \sum_{j}^{E_\nu\ bins} \sum_{k}^{E_\nu\ bins} (1-f_j)(V_f^{-1})_{j,k}(1-f_k)$$

$$+ \sum_{l}^{xsec\ pars} \sum_{m}^{xsec\ pars} (x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m)$$

$$+ \sum_{i}^{p,\theta\ bins} \sum_{n}^{p,\theta\ bins} (1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

$$+ ln(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|})$$

Fit CCQE, CCnQE p_μ-θ_μ distribution (20x2 bins)

Sensitive to to rate (Φ x σ) changes:

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

ND280 likelihood

$$-2lnL = 2 \sum_{i}^{p,\theta\ bins} N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})]$$

$$+ \sum_{j}^{E_\nu\ bins} \sum_{k}^{E_\nu\ bins} (1-f_j)(V_f^{-1})_{j,k}(1-f_k)$$

$ln\ L_{flux}(\vec{f}\ )$

$$+ \sum_{l}^{xsec\ pars} \sum_{m}^{xsec\ pars} (x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m)$$

$ln\ L_{xsec}(\vec{x}\ )$

$$+ \sum_{i}^{p,\theta\ bins} \sum_{n}^{p,\theta\ bins} (1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

$$+ ln(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|})$$

Prior constraint terms for flux, cross section parameters

- V_f and V_x are covariance matricies
- Determined using in-situ and external datasets: beam monitors, NA61, MiniBooNE

ND280 likelihood

$$-2lnL = 2 \sum_{i}^{p,\theta\ bins} N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})]$$

$$+ \sum_{j}^{E_\nu\ bins} \sum_{k}^{E_\nu\ bins} (1-f_j)(V_f^{-1})_{j,k}(1-f_k)$$

$$+ \sum_{l}^{xsec\ pars} \sum_{m}^{xsec\ pars} (x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m)$$

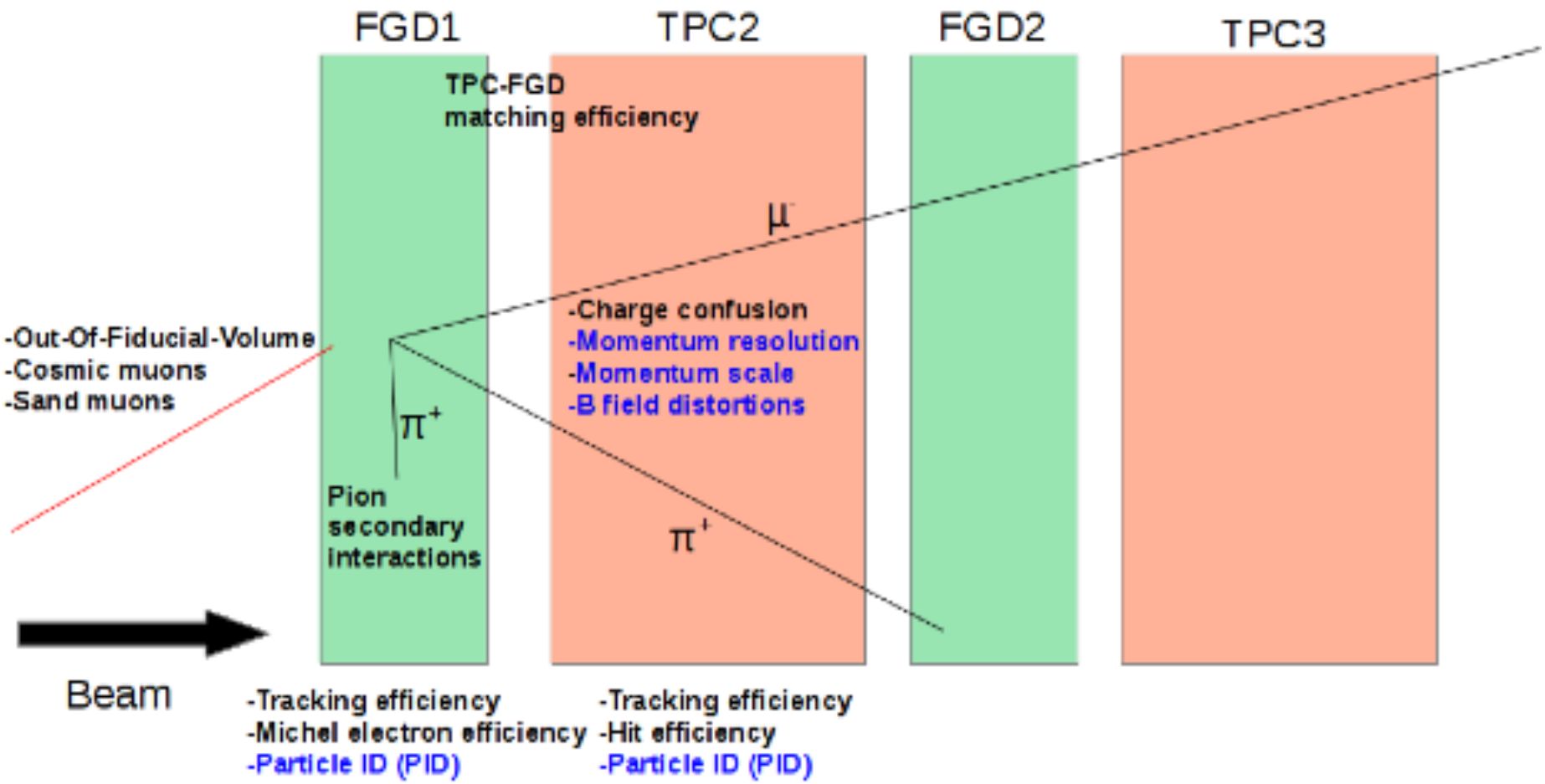
$$+ \sum_{i}^{p,\theta\ bins} \sum_{n}^{p,\theta\ bins} (1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

$$+ ln(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|})$$

Prior constraint likelihood terms for detector systematic errors

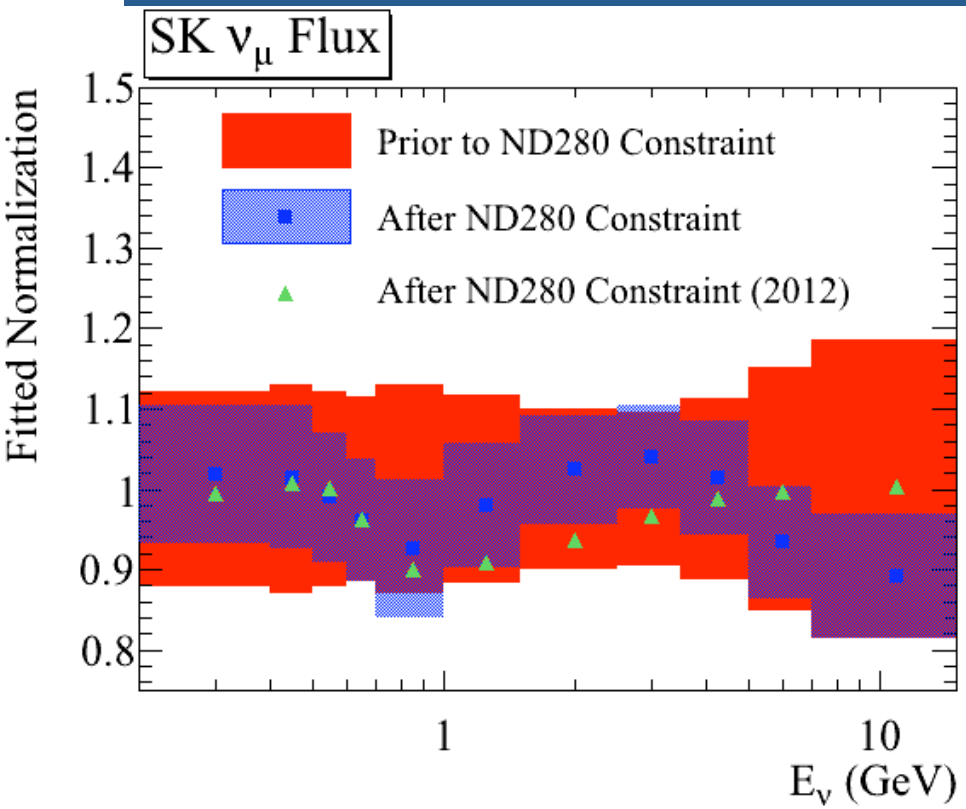
- Also includes uncertainties (e.g. FSI) which could not be otherwise easily parameterized
- Determined from control samples, calibration data, and external pion scattering data

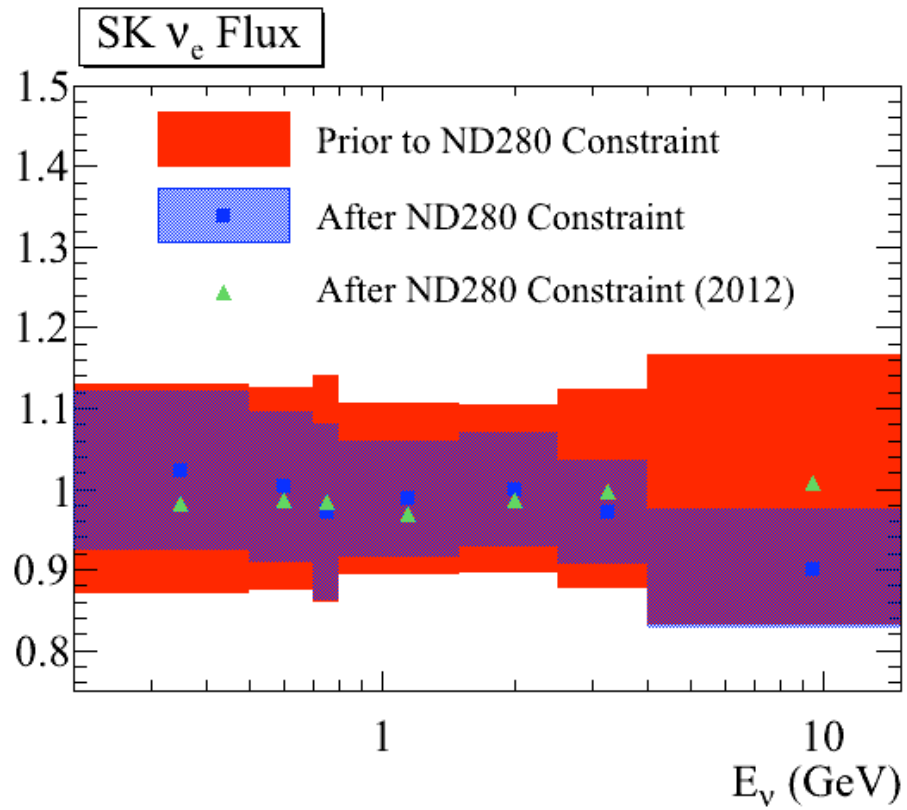
Systematic Errors



- Many sources of systematic error have been evaluated for the ND280 constraint
  - All errors are assigned using data control samples

Effect of constraint on SK fluxes

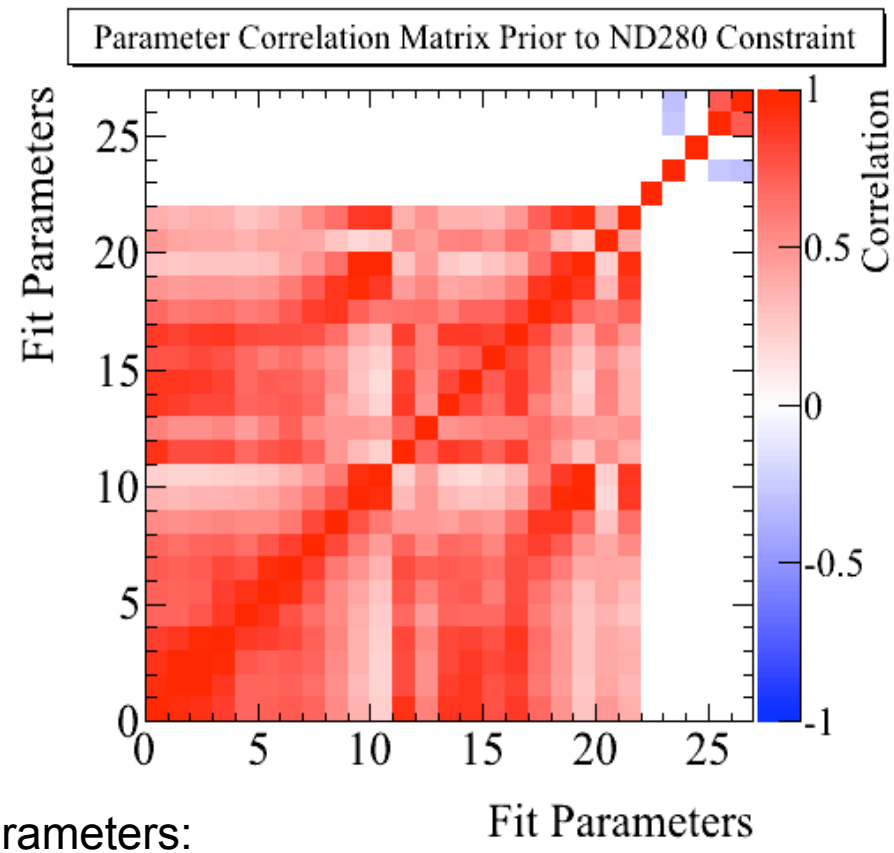


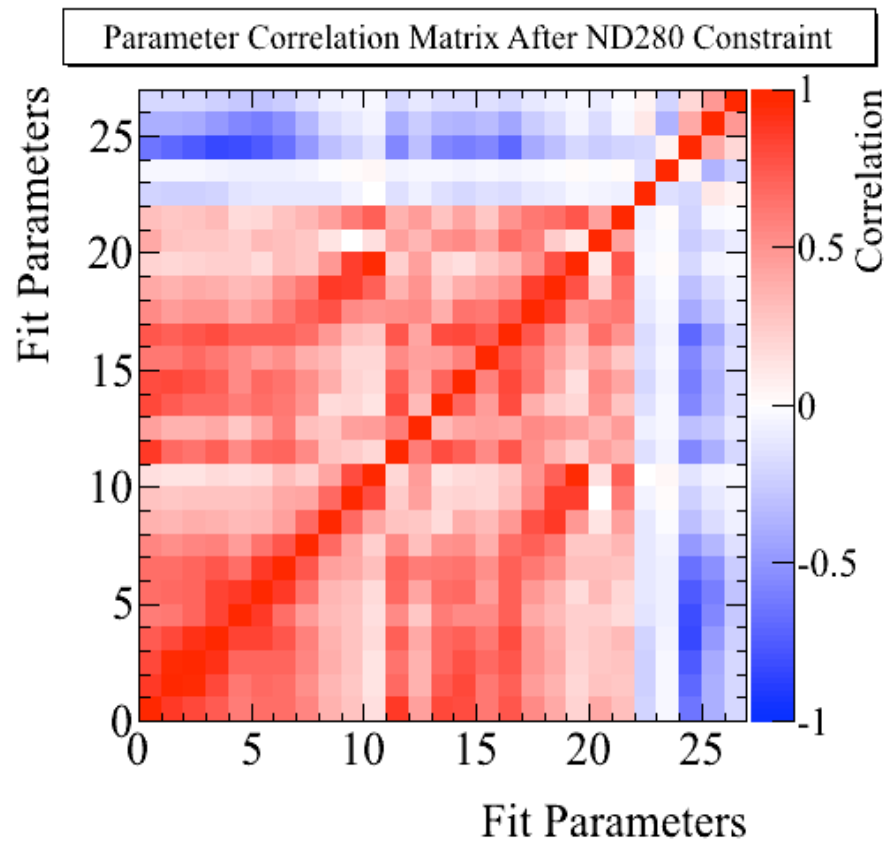


Plots show central values and error bands for normalization parameters before and after the constraint

Central values are change from 2012 results: due to finer bins and new selection

Correlations before and after fit





Parameters:

0-10: SK ν_μ flux

11-12: SK $\bar{\nu}_\mu$ flux

13-19: SK ν_e flux

20-21: SK $\bar{\nu}_e$ flux

22: M_A^{QE}

23: M_A^{RES}

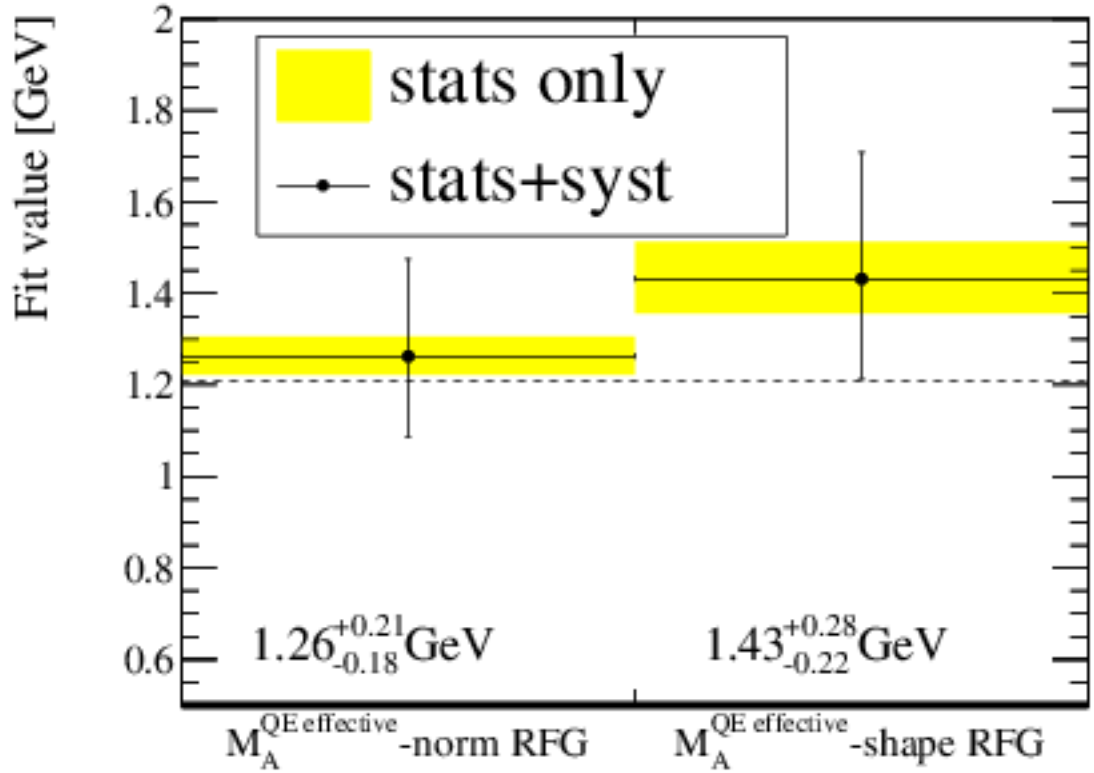
24: CCQE Norm.

25: CC1π Norm.

26: NC1π^0 Norm.

The constraint from the measured event rates causes anti-correlations between flux and cross section nuisance parameters

MAQE fit



The best-fit MAQE when fitting with normalisation (left) and shape only (right). Both fit results are consistent with the nominal value used in NEUT. It is possible to fit different values of depending on which effects are included in the model and which effects the input data samples are sensitive to. One should avoid interpreting this result as a measurement of a fundamental parameter. As the meaning of this effective parameter depends on the details of the QE model, comparison with results from other experiments should be done with care.

$\nu_\mu \to \nu_e$ Oscillation Probability

Precise measurement of $\sin^2 2\theta_{13}$ enhances the T2K sensitivity to δ_{CP} and the θ_{23} octant:

(ν_μ disappearance measures $\sin^2 2\theta_{23}$ and cannot distinguish the octant alone)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \quad \to \text{Leading, matter effect}$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23}(C_{12} C_{23}\cos\delta - S_{12} S_{13} S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \quad \to \text{CP conserving}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23}\sin\delta\sin\Phi_{32}\sin_{31}\sin\Phi_{21} \quad \to \text{CP violating}$$

$$+ 4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13}\cos\delta)\sin^2\Phi_{21} \quad \to \text{Solar}$$

$$- 8C_{13}^2 S_{13}^2 S_{23}^2(1 - 2S_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31} \quad \to \text{Matter effect}$$

($C_{ij} = \cos\theta_{ij}$, $S_{ij} = \sin\theta_{ij}$, $\Phi_{ij} = \Delta m_{ij}^2 L/4E$)

- δ_{CP} completely unknown
- MH completely unknown
- $\theta_{12} = 33.6^\circ \pm 1.0^\circ$
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90% C.L.) – is θ_{23} maximal?
- $\theta_{13} = 9.1^\circ \pm 0.6^\circ$ – from reactor

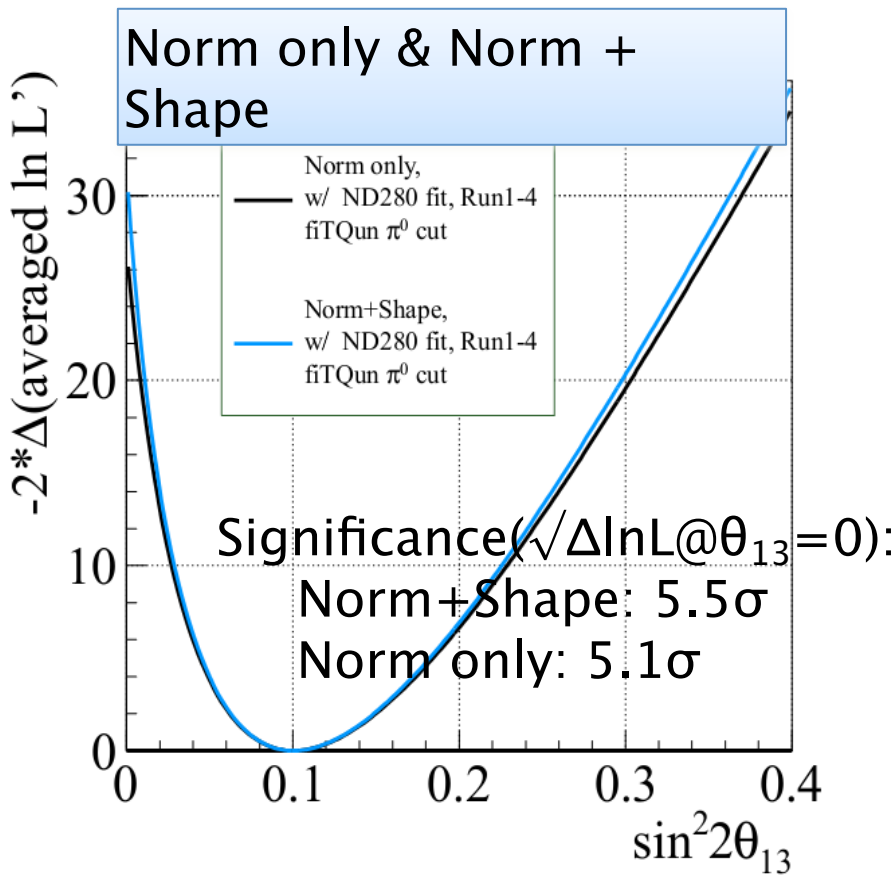
Appearance analysis is limited by CCQE model uncertainties (Spectral function)
This is comparable to the ND280 rate constraint (5%)

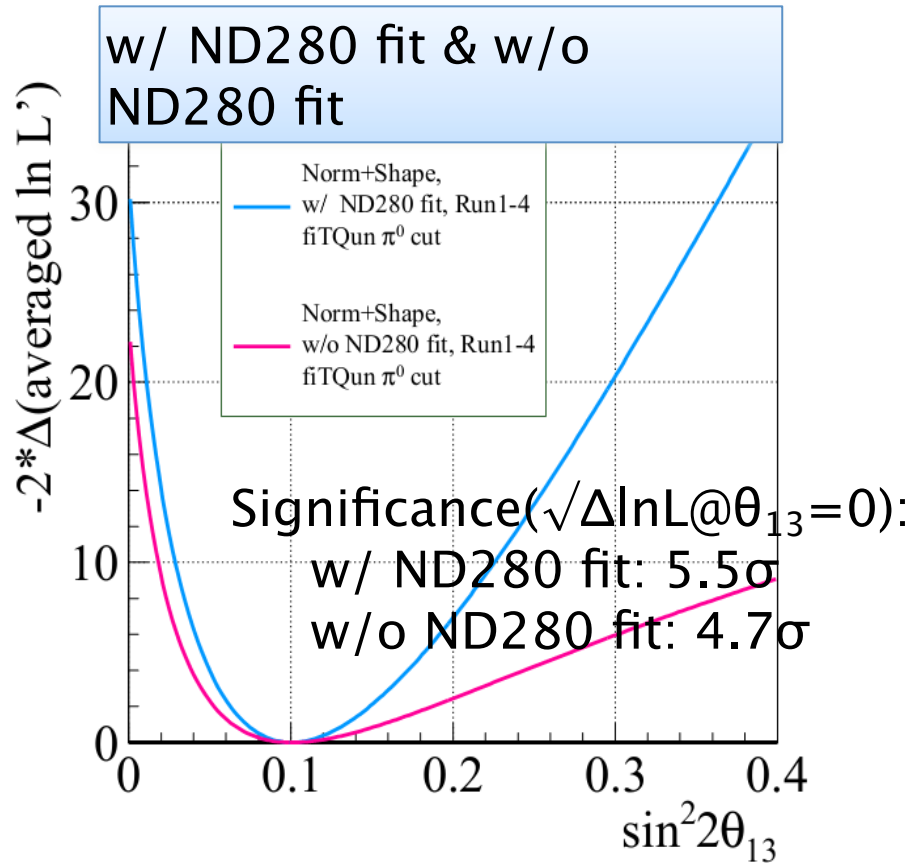
Black: 2013
Blue: 2012

(unit: %)

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	10.6 10.8	7.3 7.5	11.6 11.9	7.5 8.1
M_A^{QE}	15.6 9.5	2.4 4.0	21.5 16.3	3.2 6.7
M_A^{RES}	7.2 4.5	2.1 3.9	3.3 2.0	0.9 1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1 4.9	4.8 3.8	9.3 7.9	6.3 6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9 5.1	2.4 3.5	4.2 5.2	2.0 3.5
NC1π^0 norm.	2.7 7.9	1.9 7.3	0.6 2.3	0.4 2.2
CC other shape	0.3 0.2	0.3 0.2	0.1 0.1	0.1 0.1
Spectral Function	4.7 3.3	4.8 3.3	6.0 5.7	6.0 5.7
p_F	0.1 0.3	0.1 0.3	0.1 0.0	0.1 0.0
CC coh. norm.	0.3 0.2	0.3 0.2	0.3 0.2	0.2 0.2
NC coh. norm.	1.1 2.1	1.1 2.0	0.3 0.6	0.2 0.6
NC other norm.	2.3 2.6	2.2 2.6	0.5 0.8	0.5 0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4 1.8	2.4 1.8	2.9 2.6	2.9 2.6
W shape	1.0 1.9	1.0 1.9	0.2 0.8	0.2 0.8
pion-less Δ decay	3.3 0.5	3.1 0.5	3.7 3.2	3.5 3.2
SK detector eff.	5.7 6.8	5.6 6.8	2.4 3.0	2.4 3.0
FSI	3.0 2.9	3.0 2.9	2.3 2.3	2.3 2.3
PN	3.6	3.5	0.8	0.8
SK momentum scale	1.5 0.0	1.5 0.0	0.6 0.0	0.6 0.0
Total	24.5 21.0	11.1 13.0	28.1 24.2	8.8 9.9

The lnL curves below are generated by averaging 4000 toy experiments





numu disap osc probability (in vacuum)

$$P(\nu_\mu \to \nu_\mu) = 1 - \left(c_{13}^4 \ \sin^2 2\theta_{23} + s_{23}^2 \ \sin^2 2\theta_{13}\right) \sin^2 \Delta_{atm}$$
$$+ \left\{ c_{13}^2 \left(c_{12}^2 - s_{13}^2 \ s_{23}^2\right) \sin^2 2\theta_{23} + s_{12}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} - c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{23} \ \sin 2\theta_{12} \ \cos\delta \right\}$$
$$\times \left\{ \frac{1}{2} \sin 2\Delta_{solar} \ \underline{\sin 2\Delta_{atm}} + \underline{2 \sin^2 \Delta_{solar}} \ \sin^2 \Delta_{atm} \right\}$$
$$- \left\{ \sin^2 2\theta_{12} \left(c_{23}^2 - s_{13}^2 \ s_{23}^2\right)^2 + s_{13}^2 \ \sin^2 2\theta_{23} \left(1 - c_\delta^2 \ \sin^2 2\theta_{12}\right) \right.$$
$$+ 2 s_{13} \ \sin 2\theta_{12} \ \cos 2\theta_{12} \ \sin\theta_{23} \ \cos 2\theta_{23} \ c_\delta$$
$$- \frac{1}{2} c_{13} \ \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \ \cos\delta \ s_{23}^2 \ s_{12}^2$$
$$\left. + \sin^2 2\theta_{23} \ c_{13}^2 \ \left(c_{12}^2 - s_{13}^2 \ s_{12}^2\right) + s_{13}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} \right\} \times \underline{\sin^2 \Delta_{solar}}$$

$$\begin{aligned} s_{ij} &= \sin\theta_{ij} \\ c_{ij} &= \cos\theta_{ij} \\ c_\delta &= \cos\delta \\ \Delta_{atm} &= \frac{\Delta m_{13}^2 \ L}{4 \ E_\nu} \\ \Delta_{solar} &= \frac{\Delta m_{21}^2 \ L}{4 \ E_{/nu}} \end{aligned}$$

T2K: L = 295 km, E_n peaks at ~ 0.6 GeV
-> $\sin^2 D_{solar}$ ~ 0, $\sin 2D_{atm}$ ~ 0

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\underbrace{\cos^4\theta_{13} \cdot \sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{\sin^2 2\theta_{13} \cdot \sin^2\theta_{23}}_{\text{Next-to-leading}}\right) \cdot \sin^2 \frac{\Delta m_{31}^2 \cdot L}{4E}$$

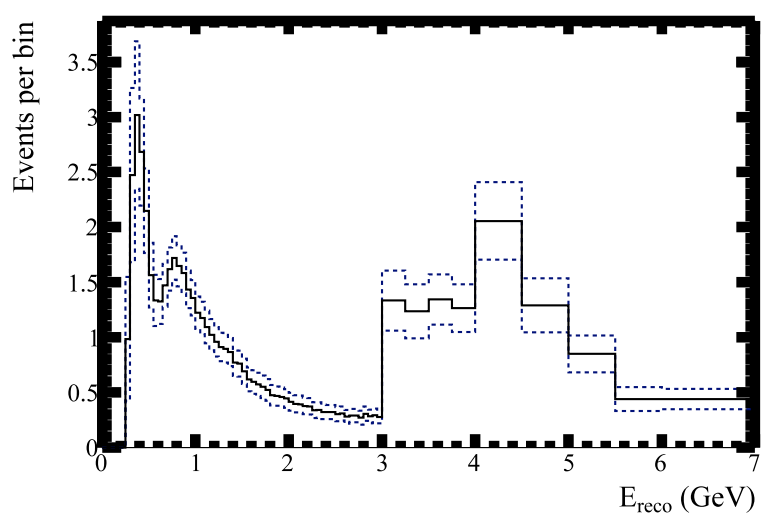
is different between 1st/2nd octants

Source of uncertainty (no. of parameters)	$\delta n_{\rm SK}^{\rm exp} \ / \ n_{\rm SK}^{\rm exp}$
ND280-independent cross section (11)	6.3%
Flux & ND280-common cross section (23)	4.2%
Super-Kamiokande detector systematics (8)	10.1%
Final-state and secondary interactions (6)	3.5%
Total (48)	13.1%

TABLE I. Effect of 1σ systematic parameter variation on the number of 1-ring μ-like events, computed for oscillations with $\sin^2(\theta_{23}) = 0.500$ and $|\Delta m^2_{32}| = 2.40 \times 10^{-3}\,\mathrm{eV}^2/\mathrm{c}^4$.

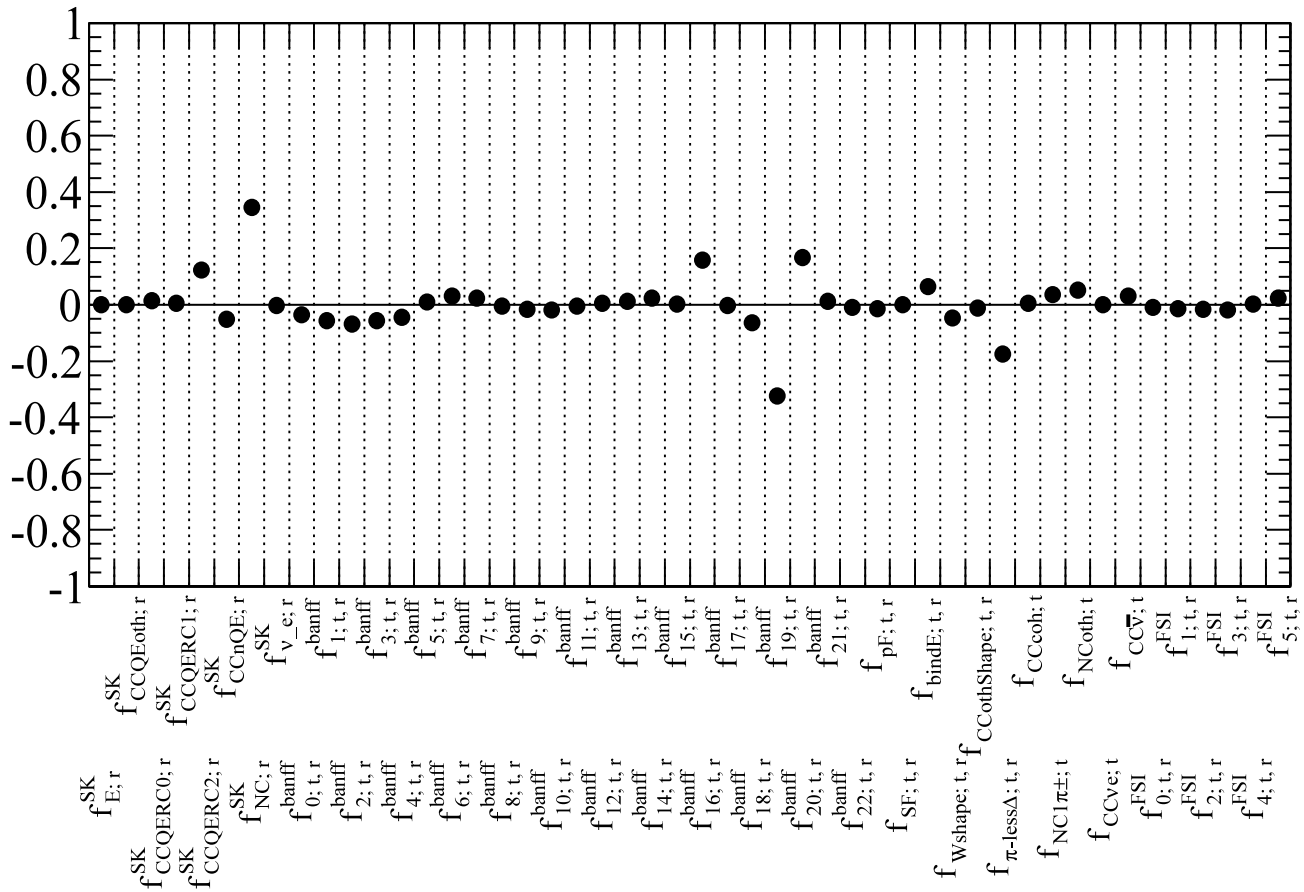
Disappearance analysis is limited by pionless delta decay (6.2%, largest contribution to ND280-independant cross section)

±1s total syst. error envelope



numu disappearance (Run 1-3) pulls

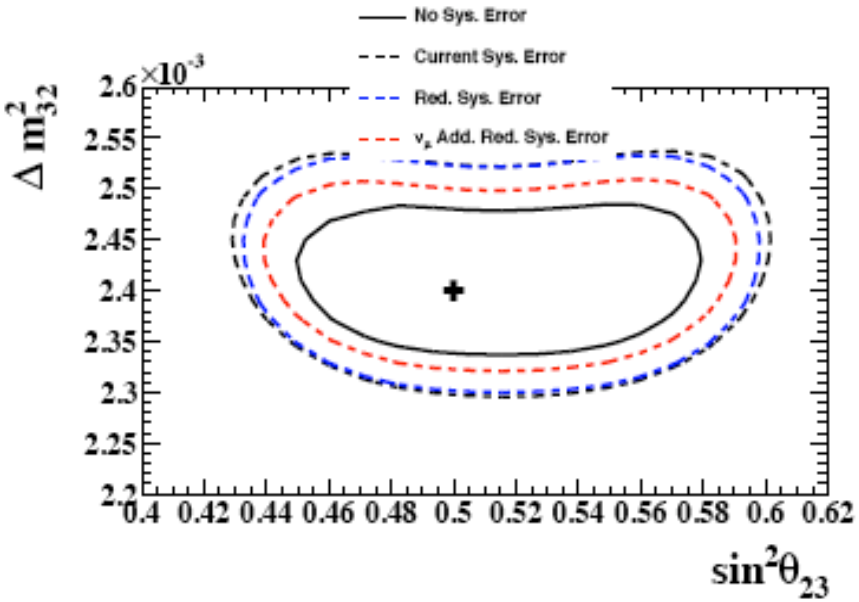
Evaluated at best fit point



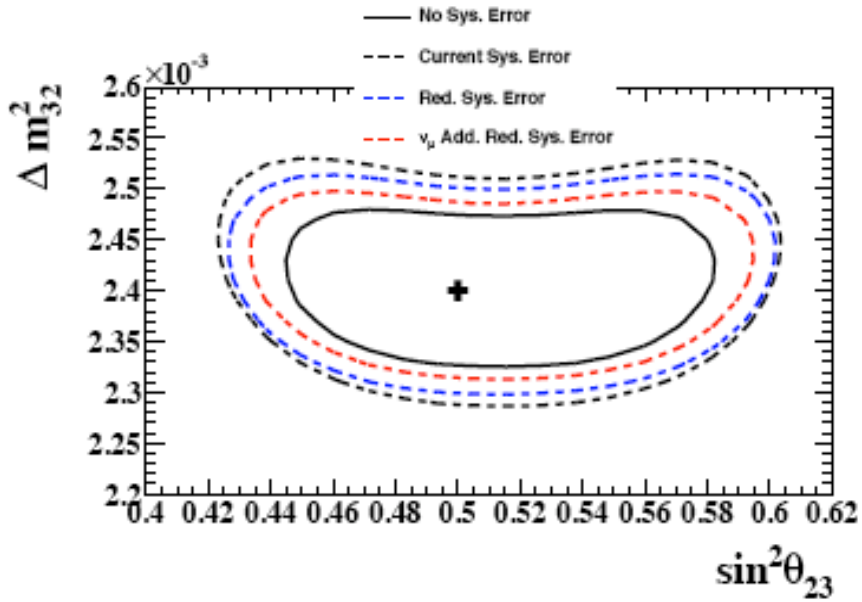
$$\text{pull} = \frac{f_{\text{best fit}} - f_{\text{nominal}}}{\sigma_{\text{best fit}}}$$

T2K Future Sensitivity Study

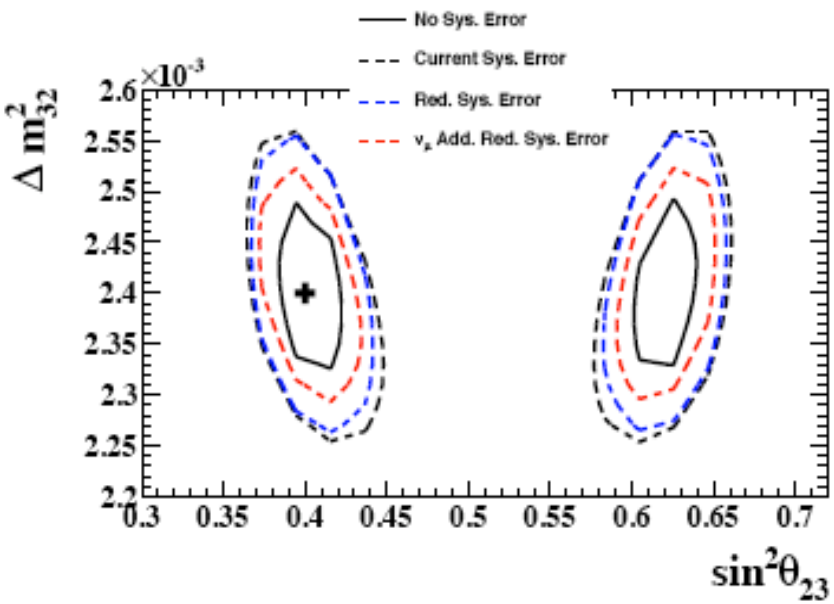
- T2K combined 3 flavor appearance + disappearance fits
  - At full T2K statistics – 7.8×10^{21} POT
  - Simultaneously fit MC SK reconstructed energy spectra for ν_e, ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$
  - Maximum likelihood fit
  - Uncertainties on $\sin^2 2\theta_{13}$, δ_{CP}, $\sin^2 \theta_{23}$, and Δm^2_{32} are considered
  - Nominal assumption: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, normal MH
- Current T2K systematic errors used
  - ~10% for ν_e, ~13% for ν_μ
  - $\bar{\nu}$ errors estimated as equal to ν errors with an additional 10% normalization uncertainty
- With and without a reactor constraint based on the expected ultimate precision of Daya Bay + RENO + Double Chooz on $\sin^2 2\theta_{13}$ $(= 0.1 \pm 0.005)$



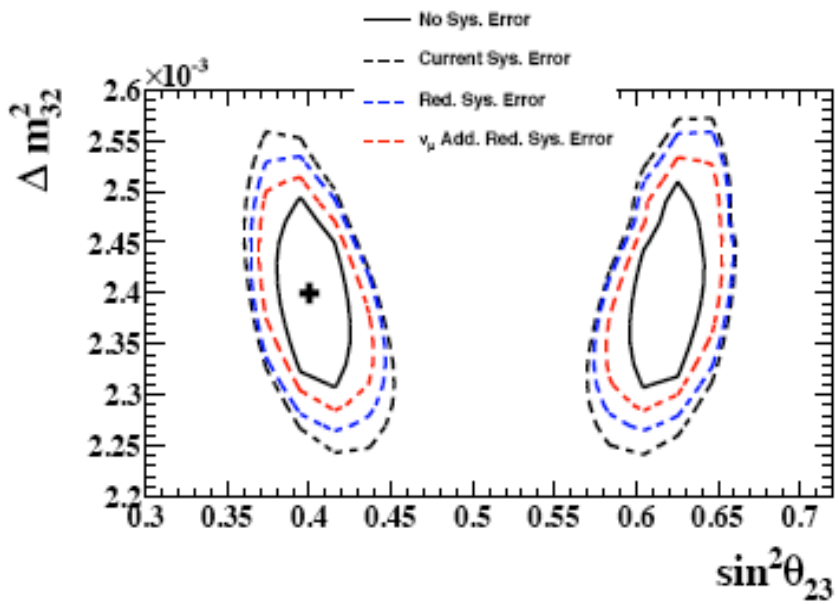
(a) 100% ν-running, $\sin^2\theta_{23} = 0.5$.



(b) 50% ν-, 50% $\bar{\nu}$-running, $\sin^2\theta_{23} = 0.5$.



(c) 100% ν-running, $\sin^2\theta_{23} = 0.4$.



(d) 50% ν-, 50% $\bar{\nu}$-running, $\sin^2\theta_{23} = 0.4$.

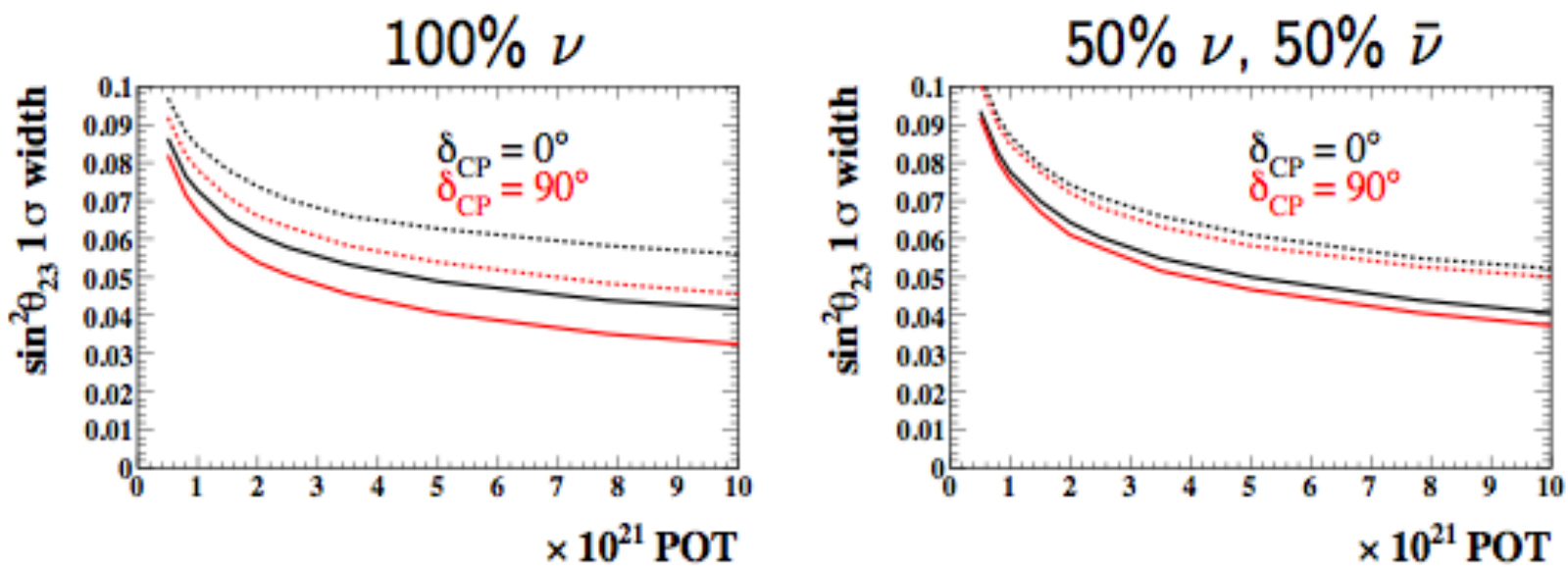
black: no systematic error; dashed: current errors

blue: removed spectral function (and CCnue/numu error)

red: reduce numu disap uncertainties by an additional factor of 2

T2K $\sin^2\theta_{23}$ 1σ Precision vs. POT

Solid: no sys. err., Dashed: with current sys. err.



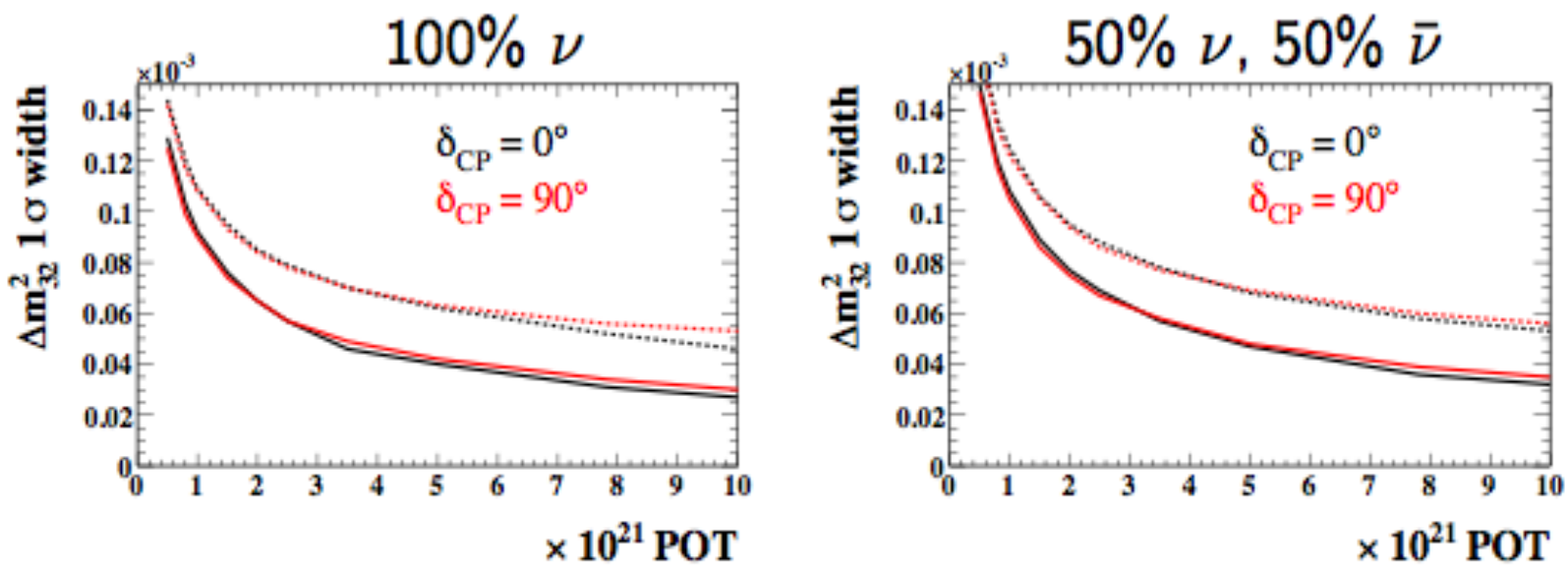
Assuming true:

$\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by the ultimate reactor sensitivity

T2K Δm^2_{32} 1σ Precision vs. POT

Solid: no sys. err., Dashed: with current sys. err.



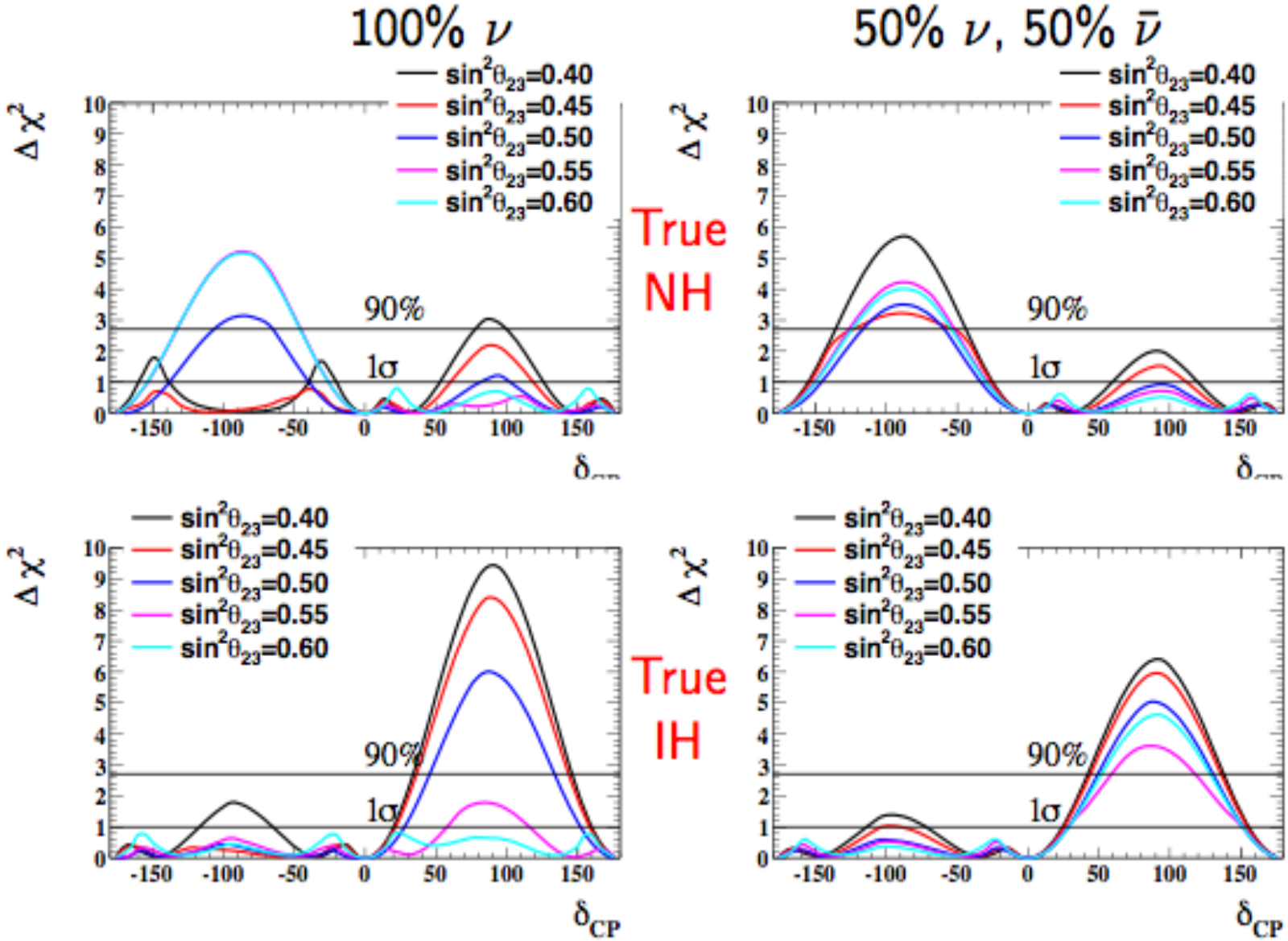
Assuming true:

$\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by the ultimate reactor sensitivity

T2K Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

Without systematic error

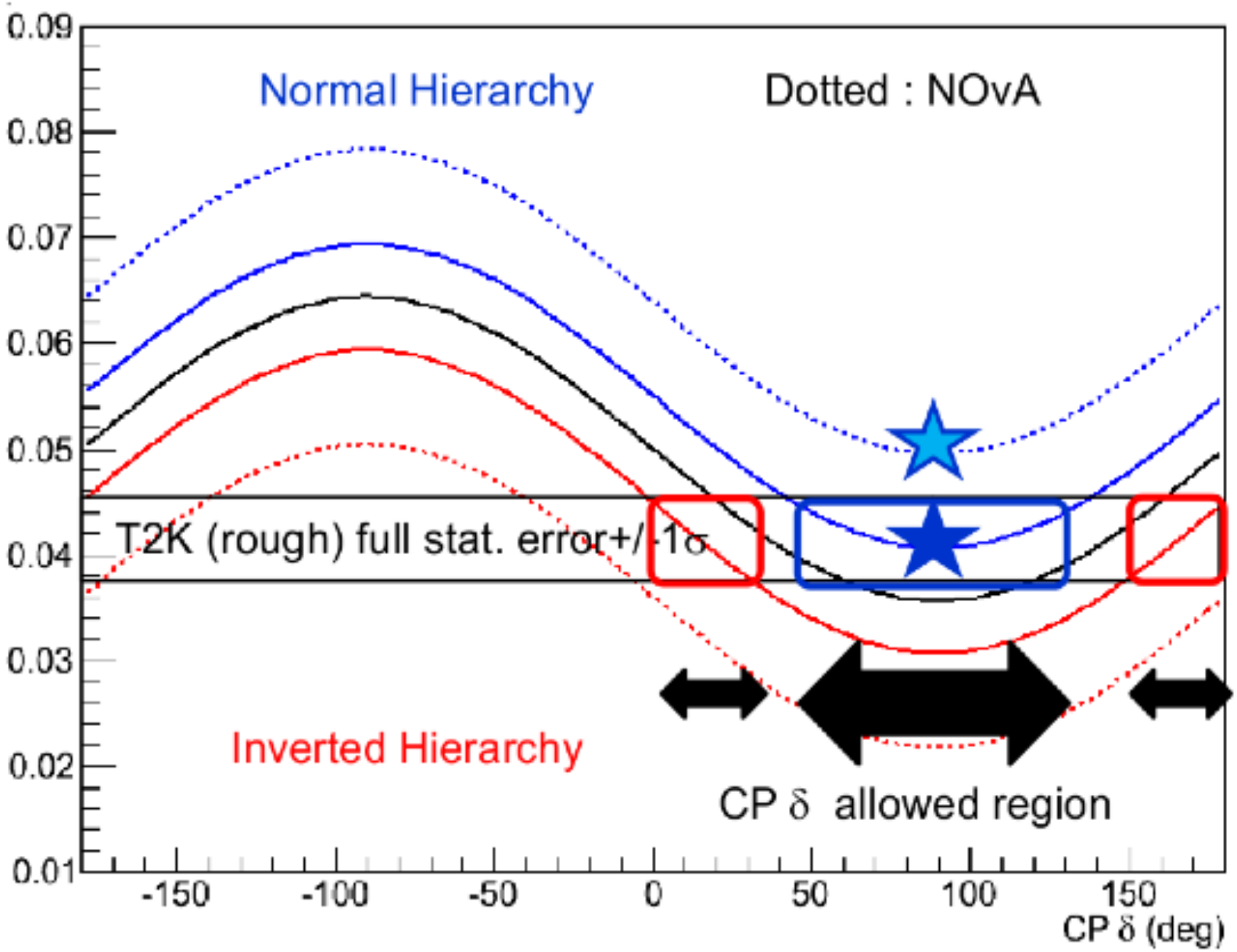


Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by the ultimate reactor sensitivity

Advantage of Combining T2K + NOνA

$P(\nu_\mu \to \nu_e)$ $\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$, with Matter Effect



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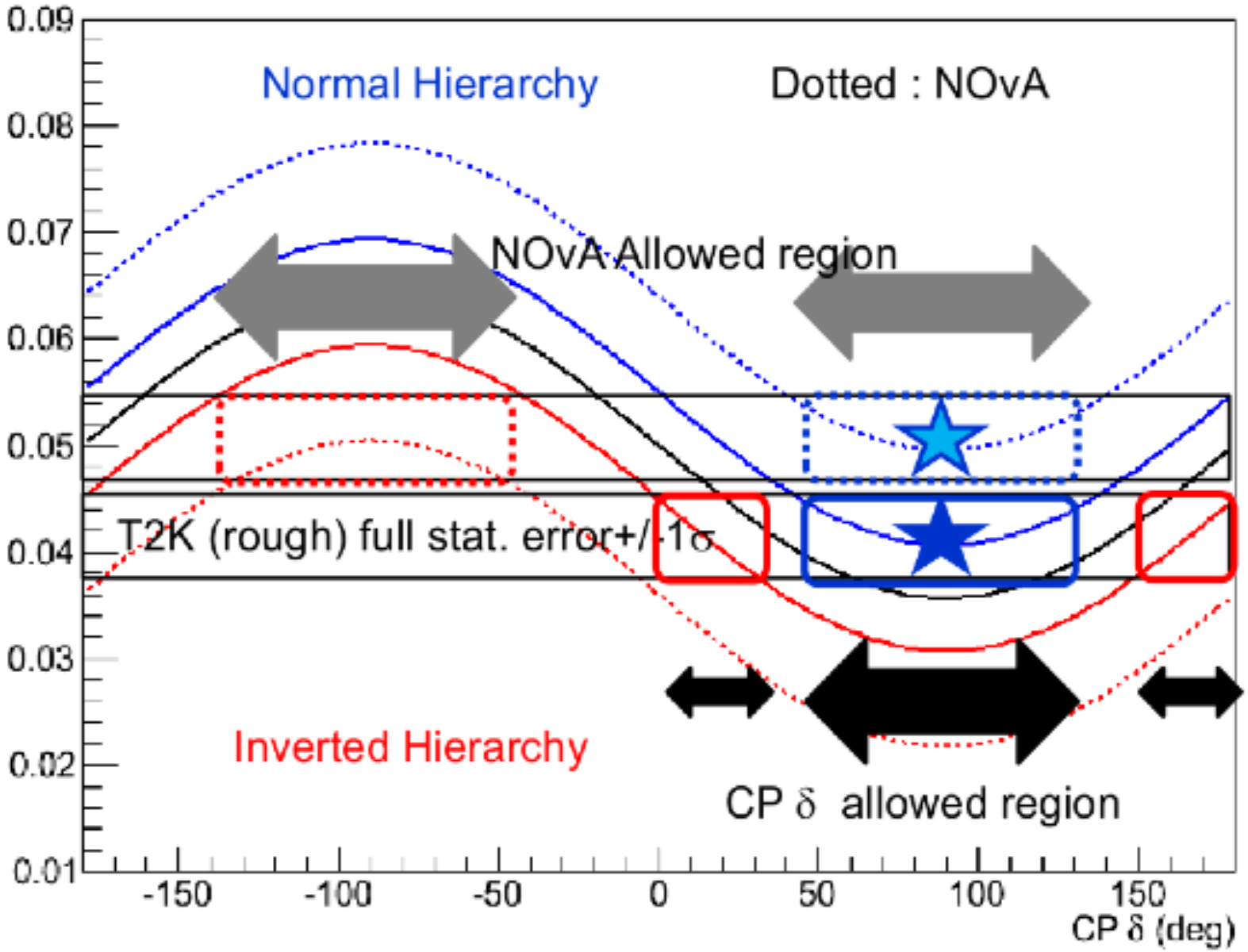

Advantage of Combining T2K + NOνA

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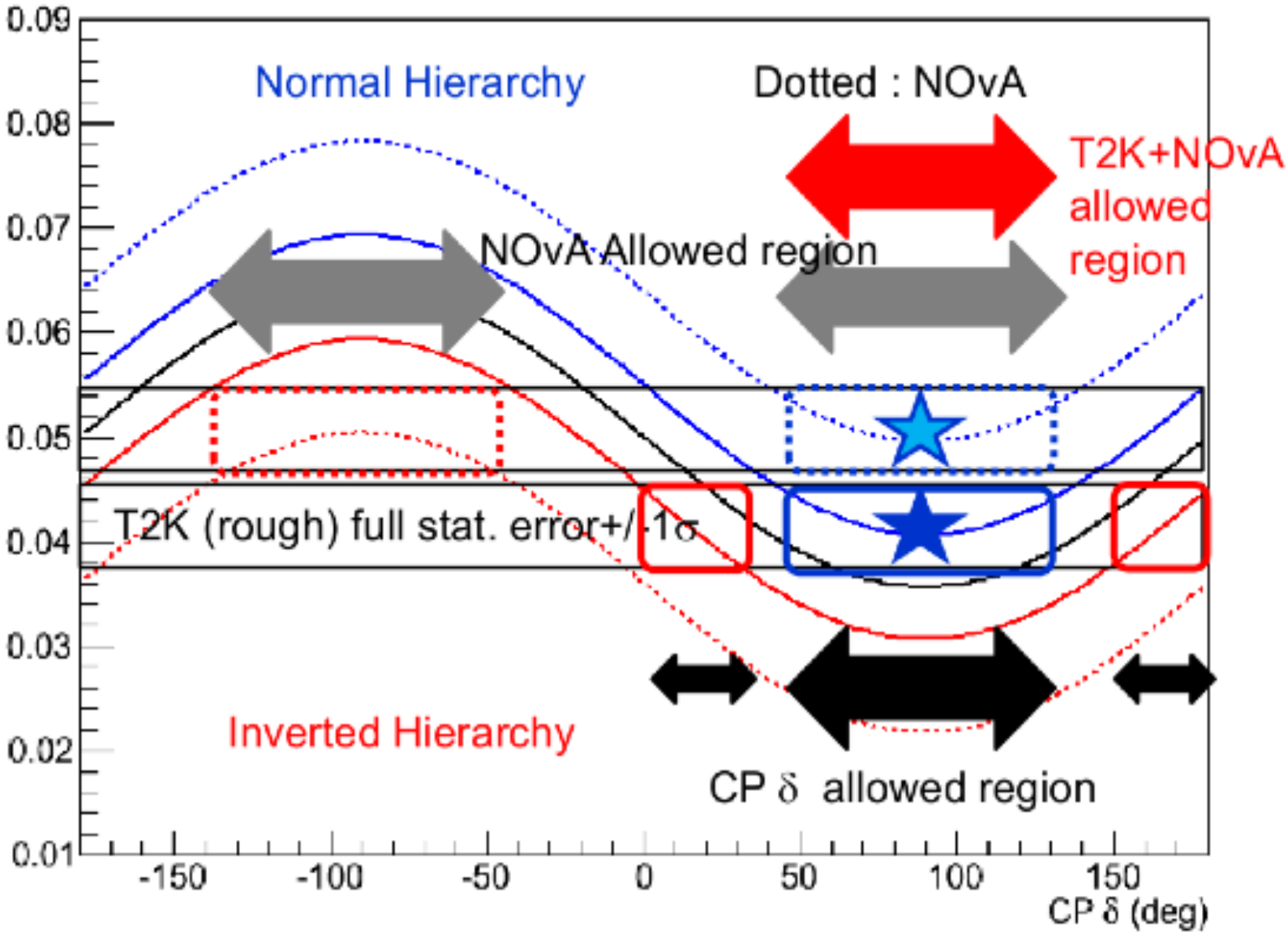

Degeneracies in δ_{CP} Resolved with Combination!

Advantage of Combining T2K + NOνA

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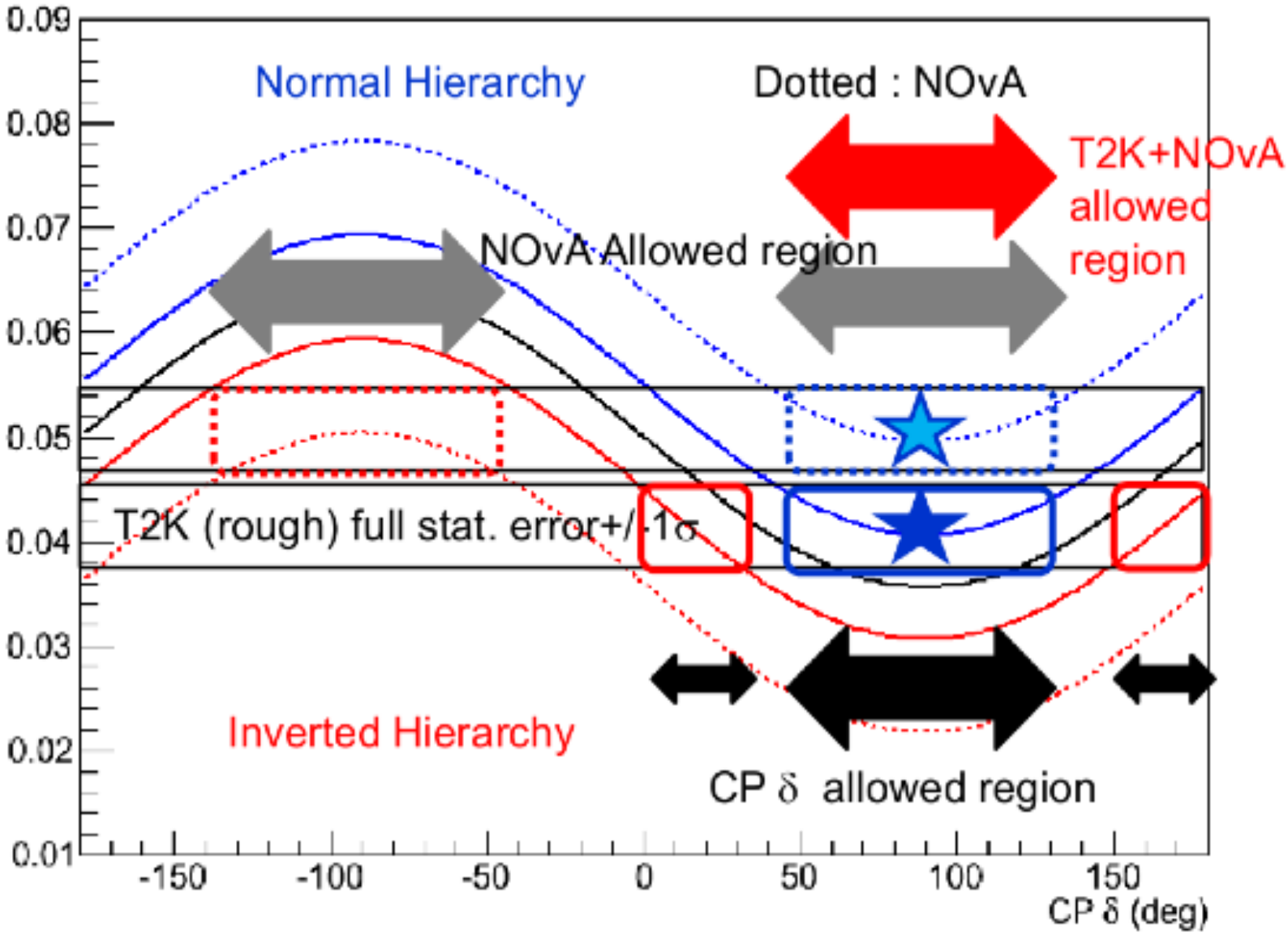

Degeneracies in δ_{CP} Resolved with Combination!