Constraining systematic errors using the T2K near detector

Kendall Mahn

TRIUMF

For the T2K collaboration

T2K

The Tokai-to-Kamioka (T2K) experiment

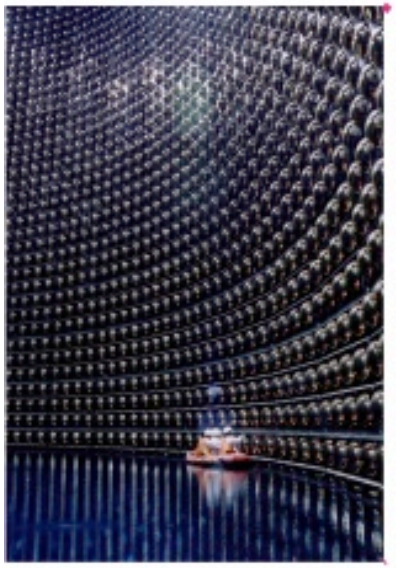
T2K sends a ~1 GeV ν_μ beam across Japan to study neutrino oscillations

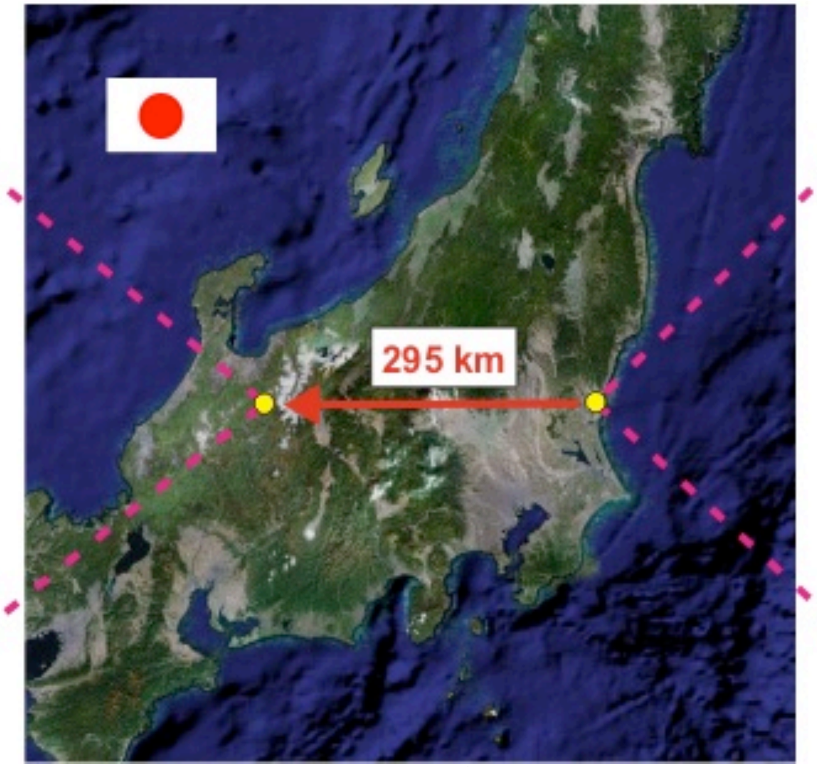
- Measure ν_μ disappearance (Δm^2_{32}, θ_{23})
  - Deficit of ν_μ rate and distortion of ν_μ energy spectrum
- Measure ν_e appearance (θ_{13})
  - Excess of ν_e rate over background
  - Subleading terms depend on mass hierarchy, δ_{CP}

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

- Precision measurements depend upon understanding of systematic errors

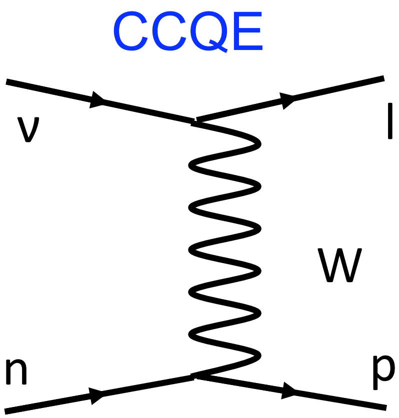
Far detector:
Super-Kamiokande
located near Kamioka

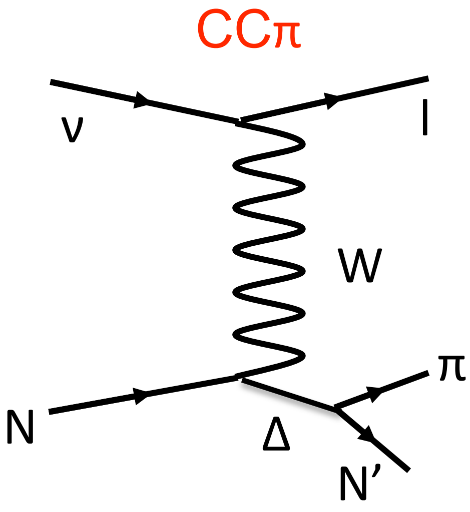


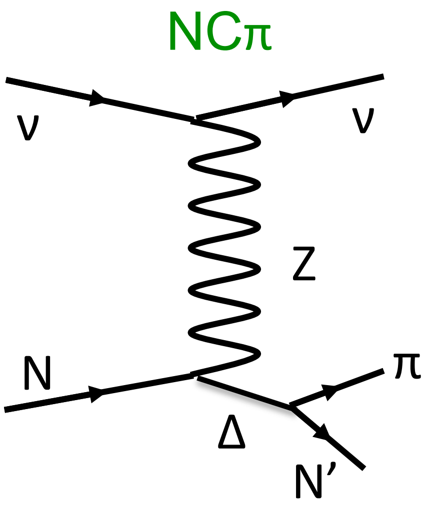


Beam source and near detectors:
J-PARC accelerator complex
located in Tokai-mura

Neutrino interactions at T2K





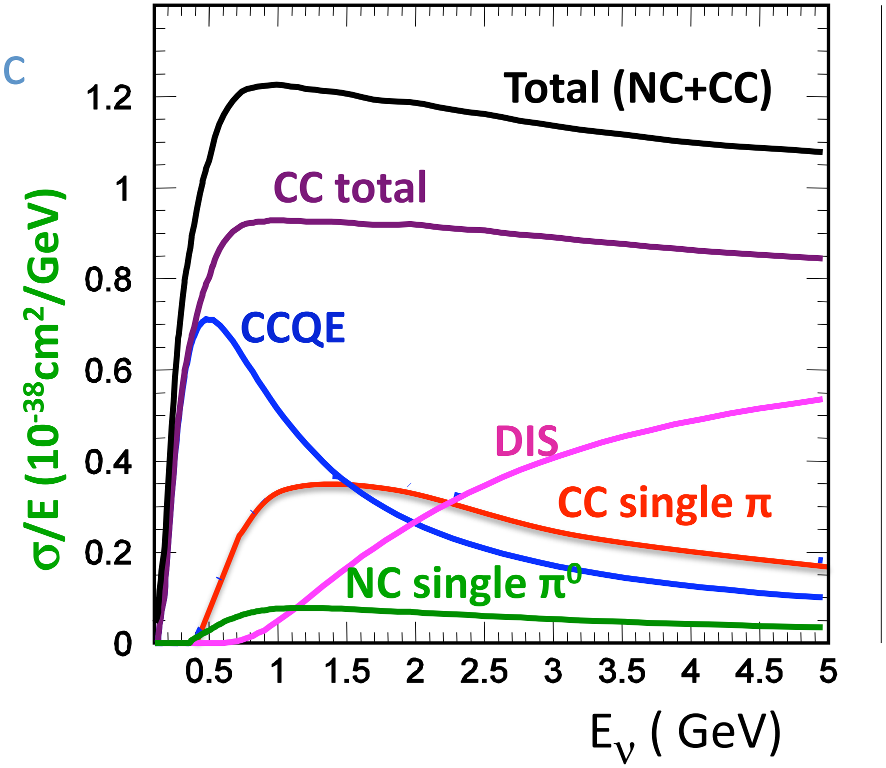


Most interactions are Charged Current Quasi Elastic

- Neutrino flavor determined from flavor of outgoing lepton i.e. e for ν_e, μ for ν_μ
- Llwellyn Smith base model, with Smith-Moniz relativistic Fermi Gas representation of nucleus

Additional interactions important for analysis are CCπ and NCπ (single pion production)

- Rein-Seghal resonance model

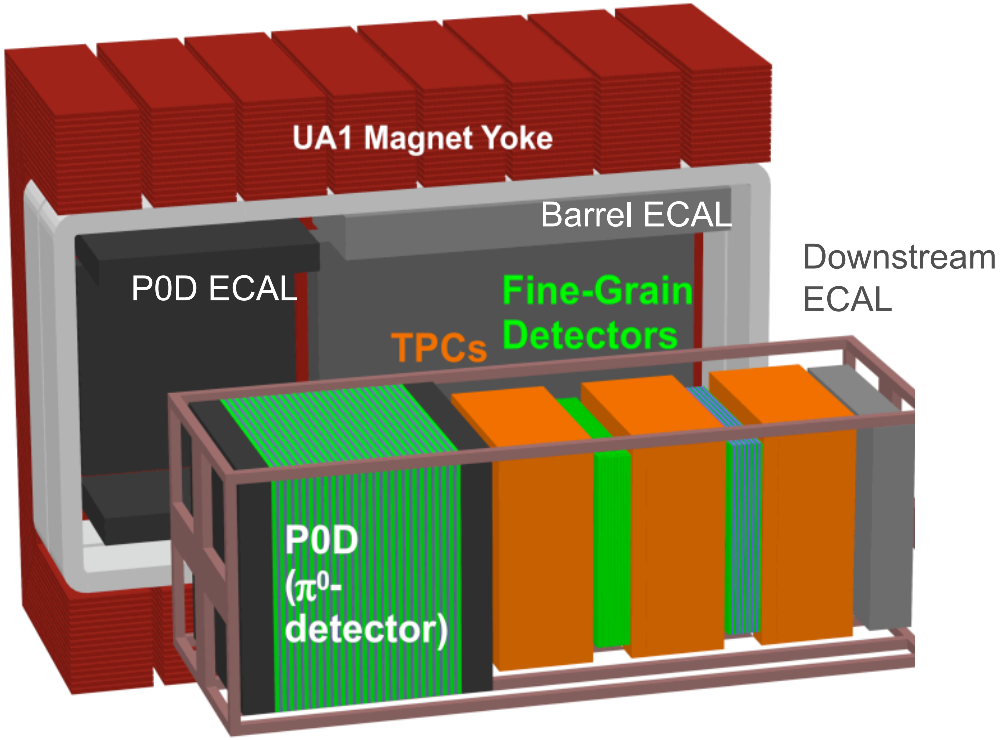


Off-axis near detectors: ND280

Suite of near detectors sit within UA1 (B=0.2T, 850 tons) magnet

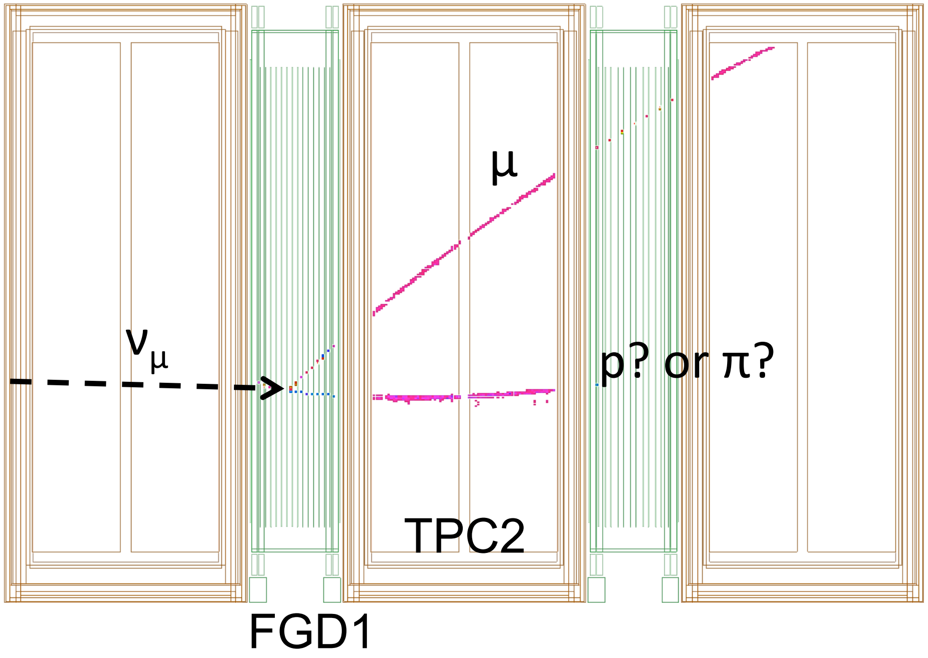
Measure unoscillated CC ν_μ rate in Tracker:

- Neutrinos interact on FGDs (carbon target)
- Measure lepton angle, momentum and flavor with TPCs
- Separate selection into CCQE-like (CCQE) and all other CC (CCnQE)
- CC ν_e rates also measured in P0D, Tracker



NIM A 624, 591 (2010)

ND280 CCnQE ν_μ candidate

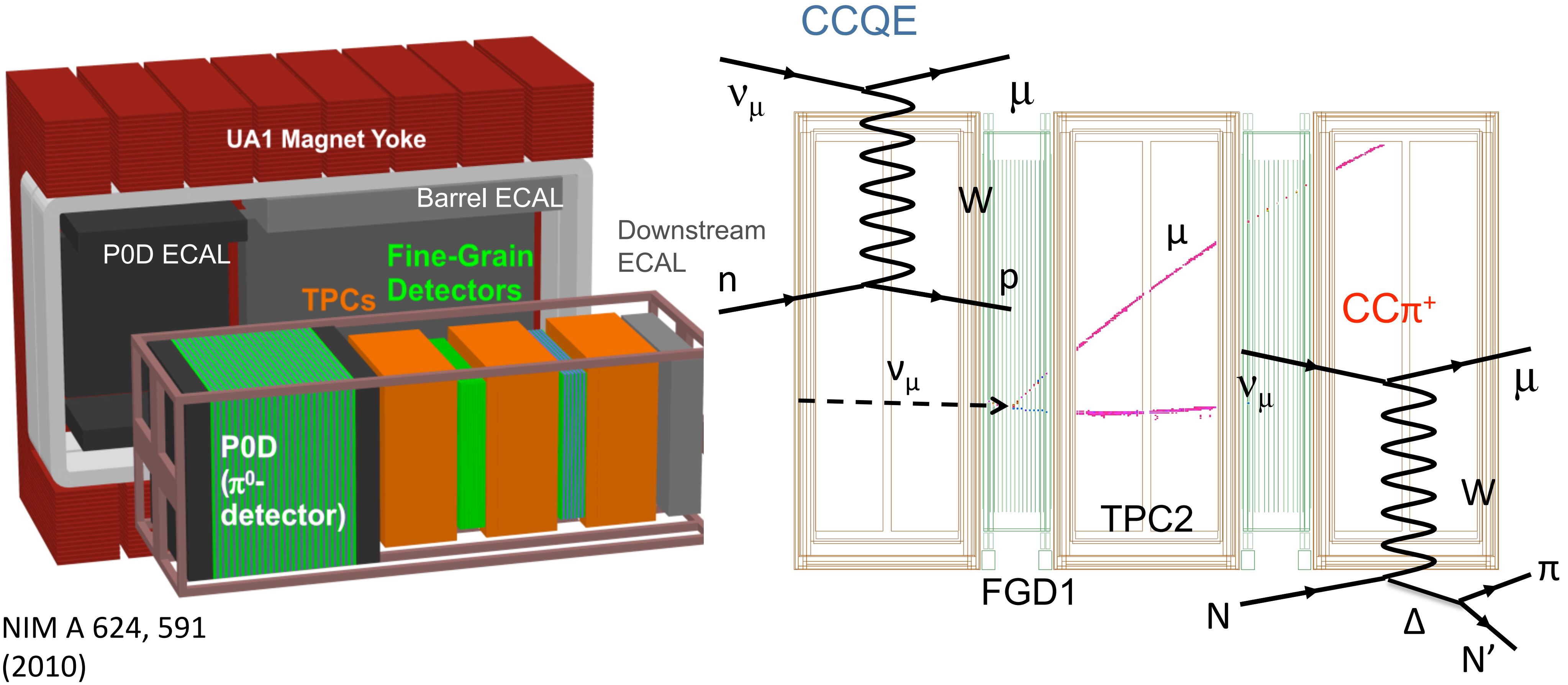


Off-axis near detectors: ND280 (ND)

Suite of near detectors sit within UA1 (B=0.2T, 850 tons) magnet

Measure unoscillated CC ν_μ rate in Tracker:

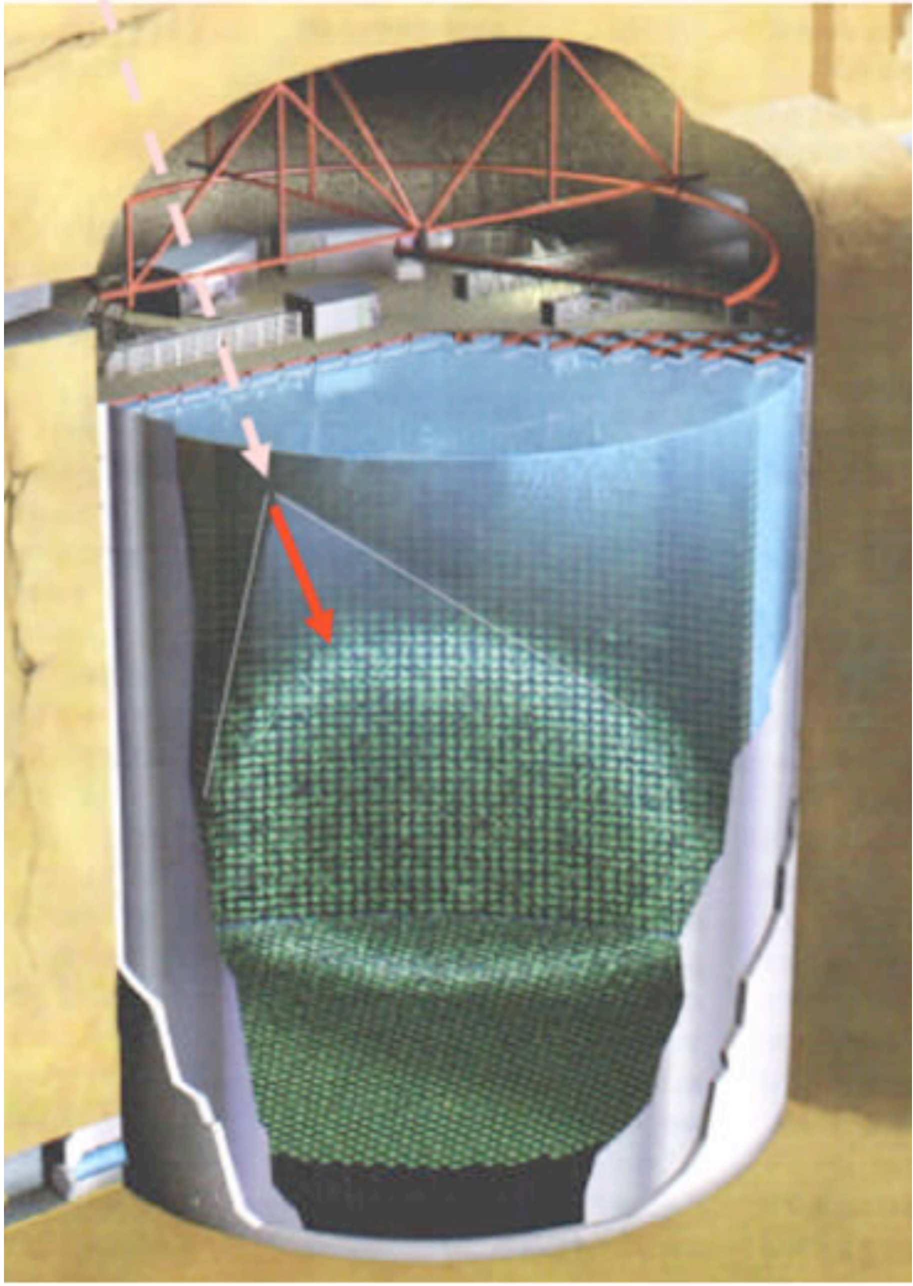
- Neutrinos interact on FGDs (carbon target)
- Measure lepton angle, momentum and flavor with TPCs
- Separate selection into CCQE-like (CCQE) and all other CC (CCnQE)
- CC ν_e rates also measured in P0D, Tracker



NIM A 624, 591 (2010)

Far detector: Super-Kamiokande (SK)

- 22.5kton fiducial mass Cherenkov detector (water target)
- 11,129 inner region PMTs
- 1885 outer veto region PMTs
- Select ν_e events from ring shape and topology



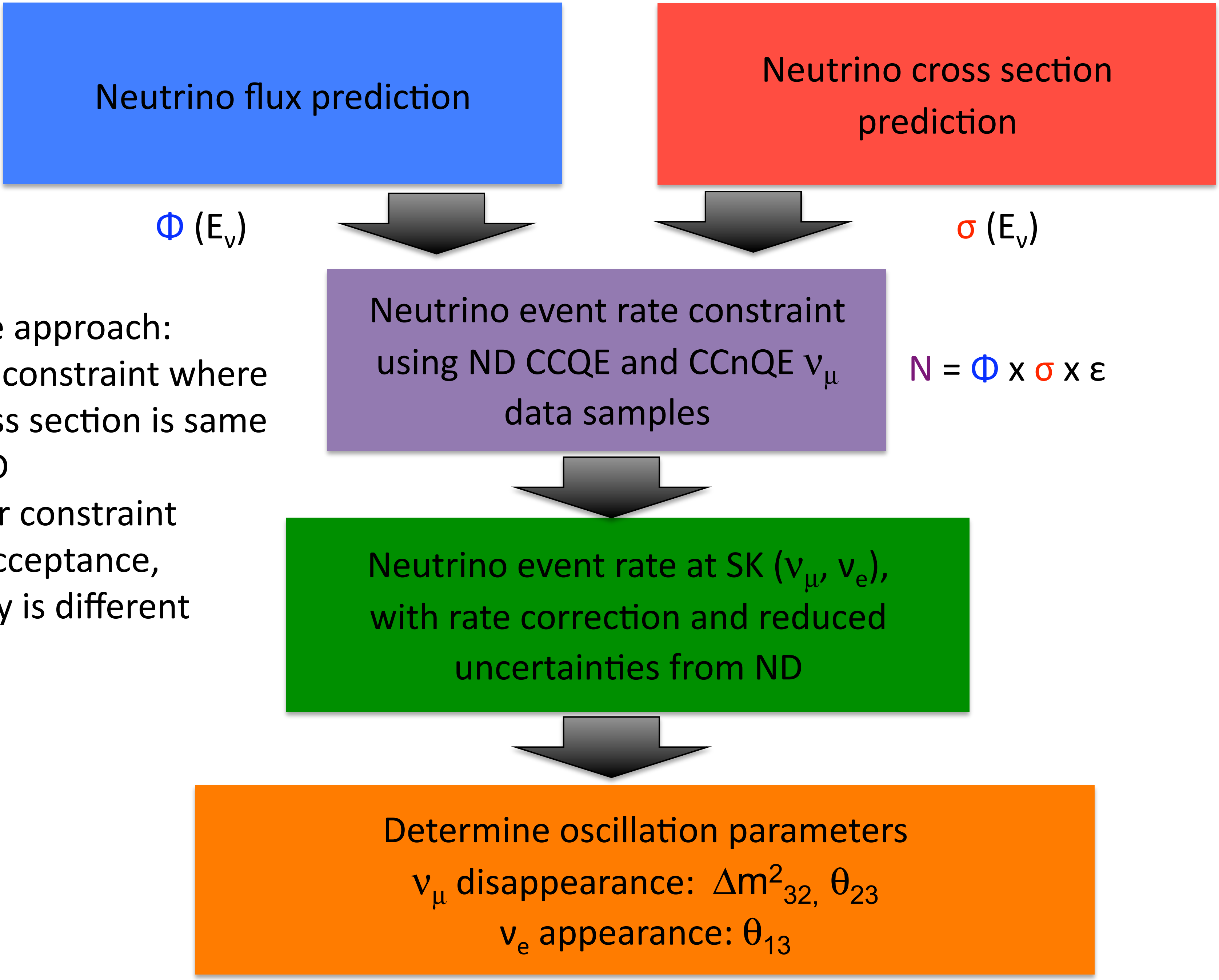
ν_e appearance analysis

Signal: CC ν_e
ν_μ to ν_e oscillation

Background: CC ν_e
Irreducible beam ν_e

Background: NC ν_μ
Mimics CC ν_e

Oscillation analysis strategy



Neutrino flux prediction

Neutrino cross section prediction

$\Phi\ (E_\nu)$

$\sigma\ (E_\nu)$

Neutrino event rate constraint using ND CCQE and CCnQE ν_μ data samples

$N = \Phi \times \sigma \times \varepsilon$

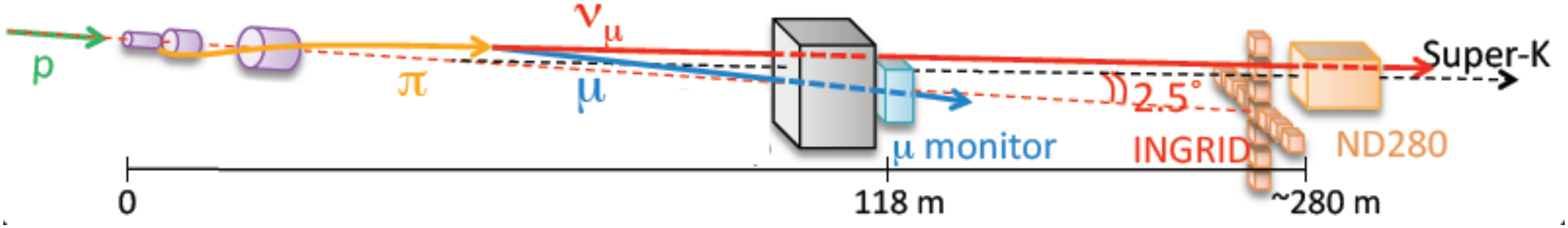
Stepwise approach:

- Strong constraint where flux, cross section is same at SK, ND
- Weaker constraint where acceptance, efficiency is different

Neutrino event rate at SK (ν_μ, ν_e), with rate correction and reduced uncertainties from ND

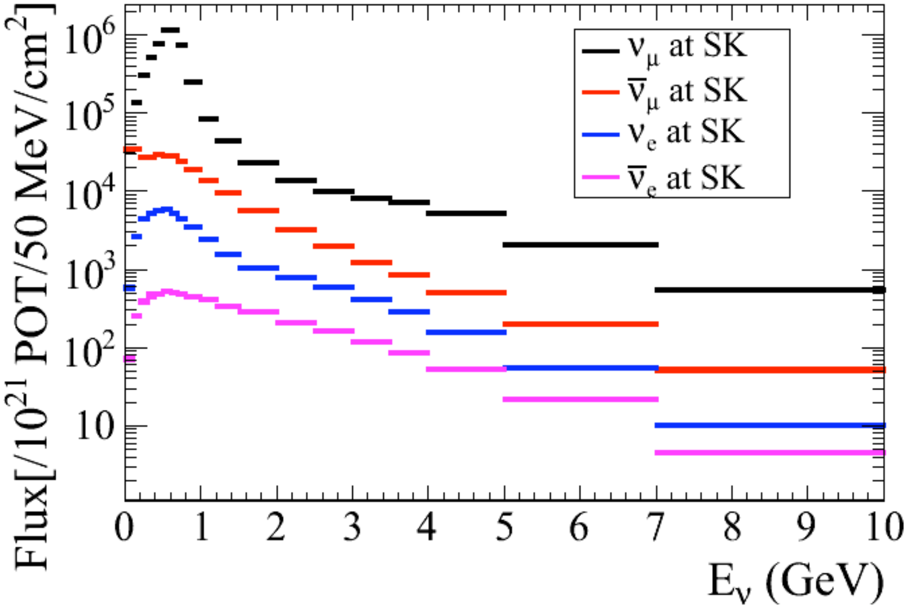
Determine oscillation parameters
ν_μ disappearance: Δm^2_{32}, θ_{23}
ν_e appearance: θ_{13}

Neutrino flux prediction



Off-axis (narrow band) neutrino beam

FLUKA/Geant3 beam simulation



Unoscillated flux at SK:

- ν_μ from π^+, K decay
- ~1% ν_e from μ, K decay

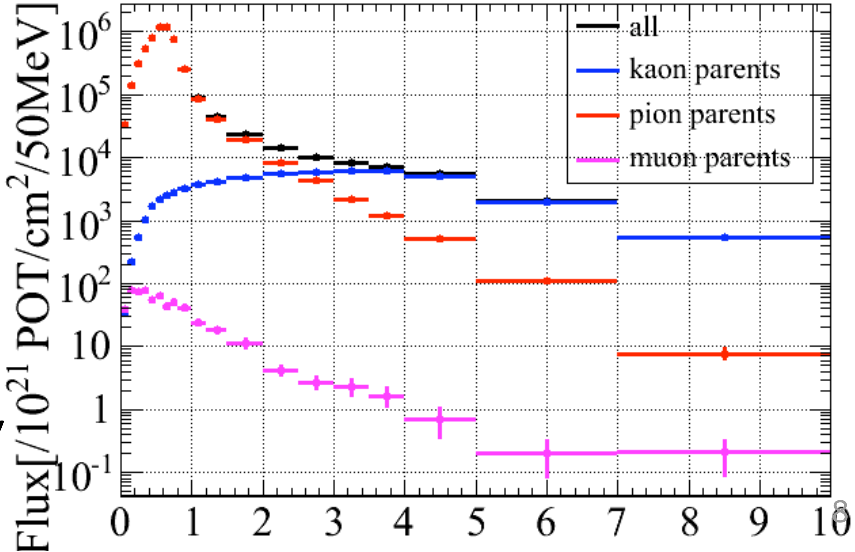
Prediction and uncertainties determined by external or in-situ measurements

- π, K production from NA61 experiment

Phys.Rev.C 84, 034604 (2011)

Phys.Rev.C 85, 035210 (2012)

Details in Wed joint WG1-2-3 session, S. Murphy

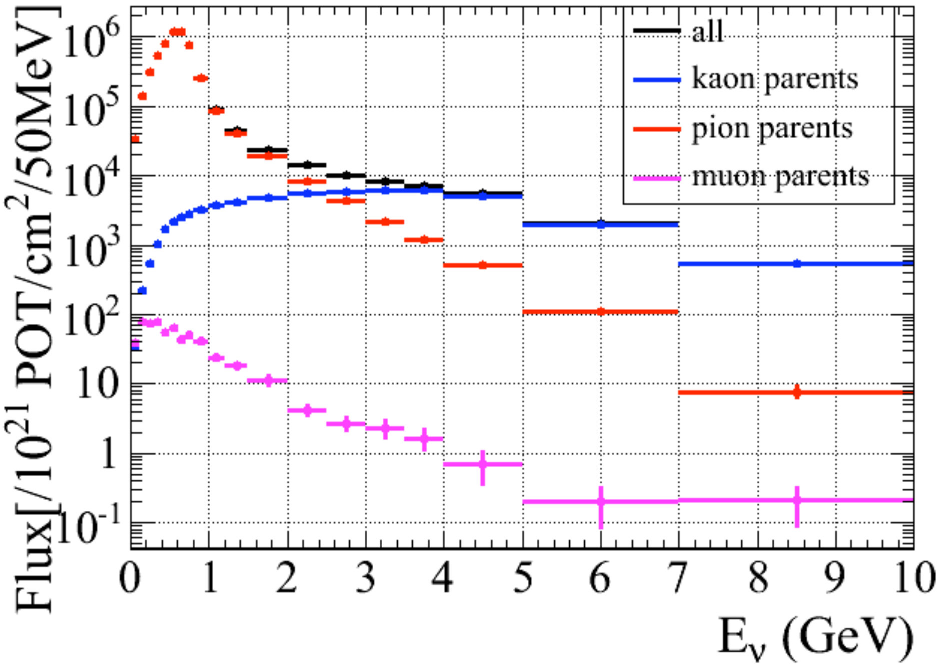


Neutrino flux at ND and SK

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

ND samples represent ν_μ flux

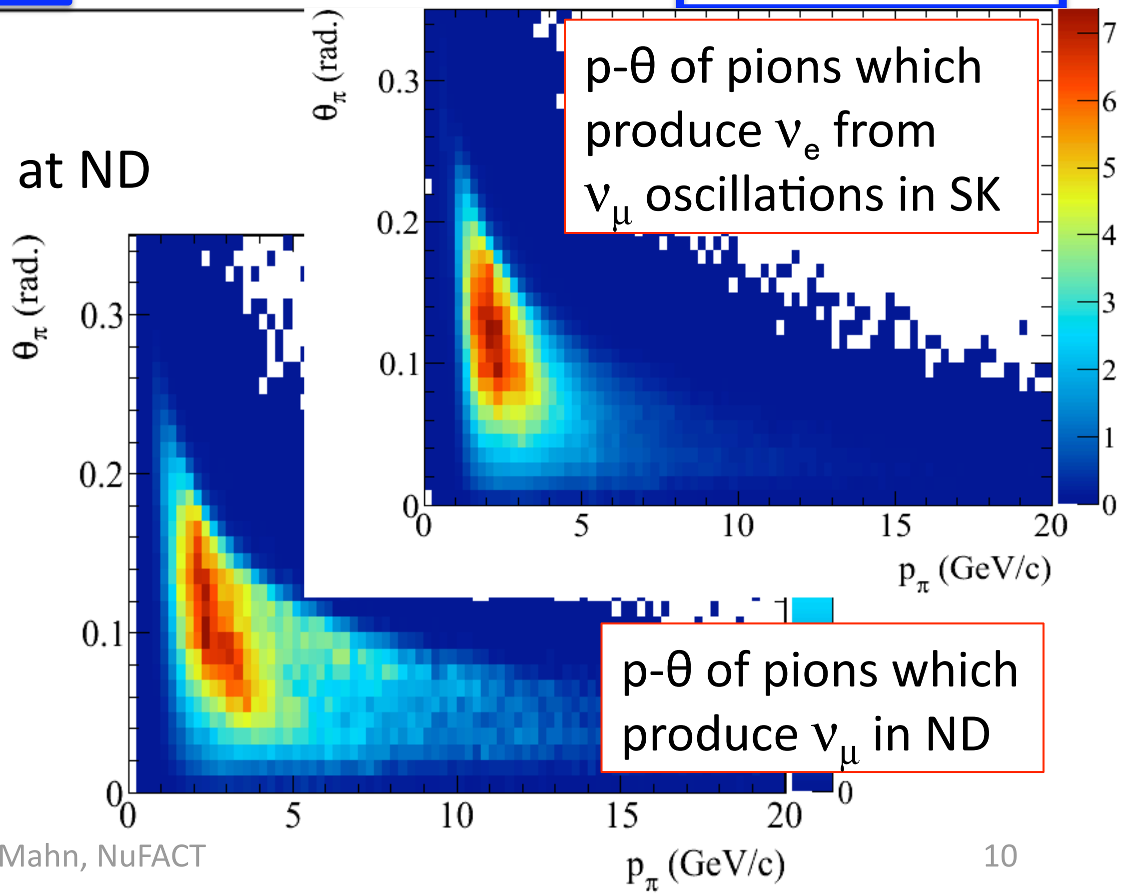
- ν_μ from π decay: CCQE, CCnQE samples
- ν_μ from K decay: CCnQE sample



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.
$\pi^+ \rightarrow \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \rightarrow \nu_e + e^+ + \bar{\nu_\mu}$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \rightarrow \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \rightarrow \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

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



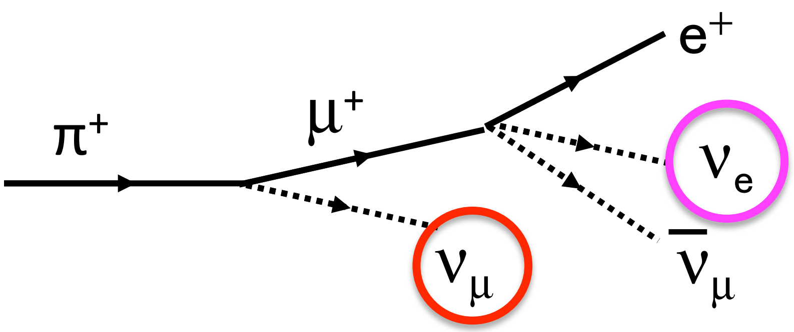
p-θ of pions which produce ν_e from ν_μ oscillations in SK

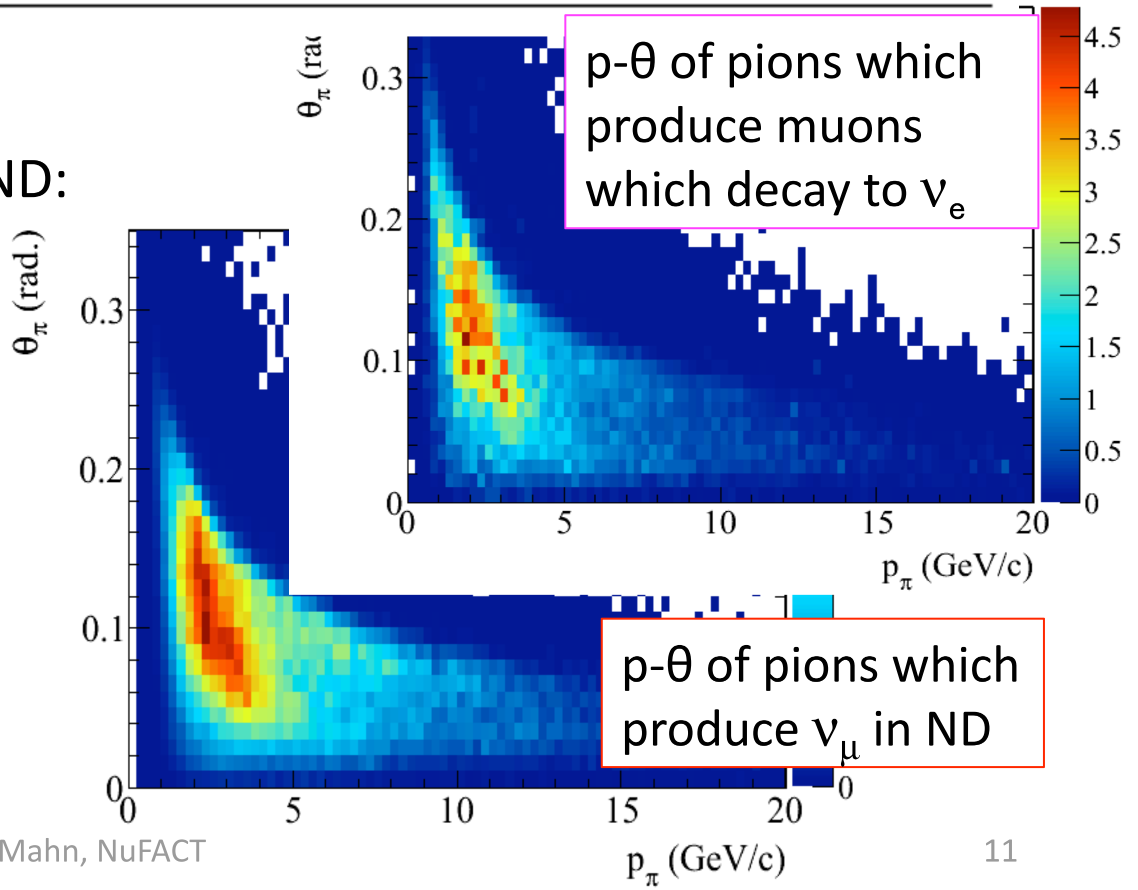
p-θ of pions which produce ν_μ in ND

Neutrino flux at ND and SK

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

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





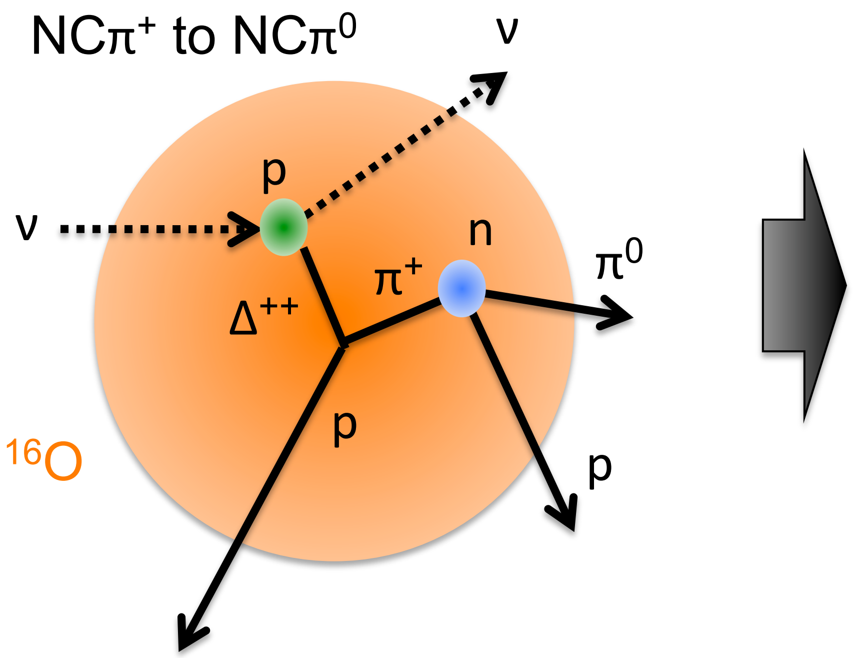
p-θ of pions which produce muons which decay to ν_e

p-θ of pions which produce ν_μ in ND

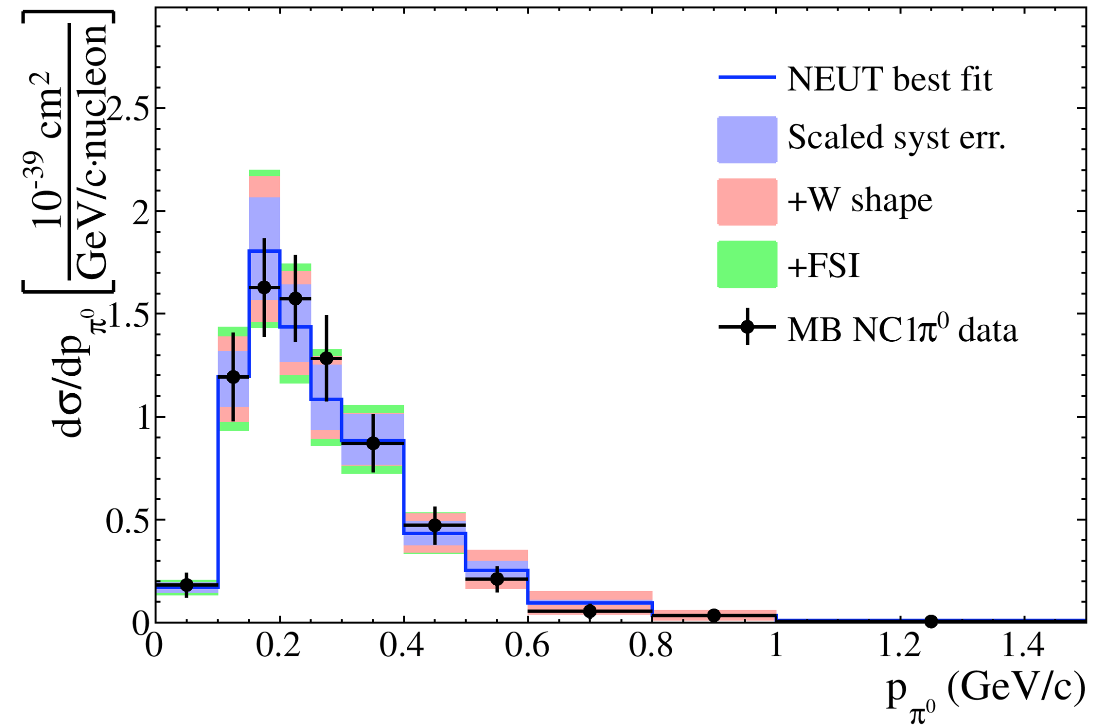
Neutrino interaction uncertainties

Cross section model (NEUT, GENIE) composed of:

- Base model prediction
- Final state interaction model (FSI)



NCπ^+ to NCπ^0

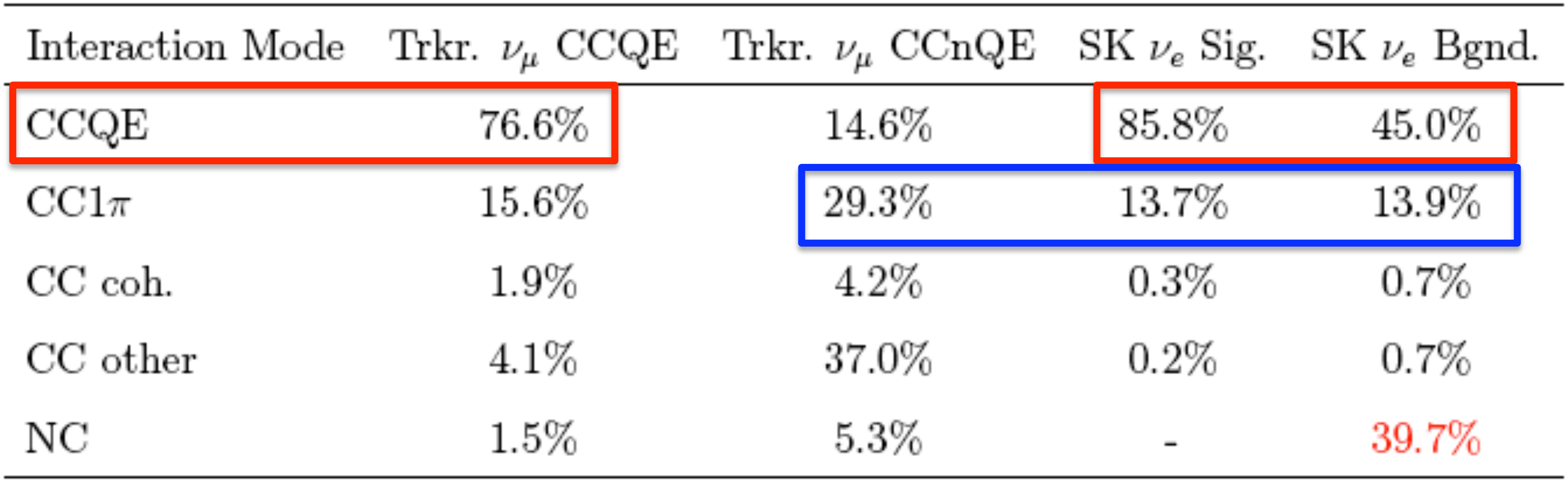


Cross section model uncertainties set from fits to MiniBooNE data (E_ν ~ 1 GeV) for signal and background (CCQE, CC1π and NCπ^0) interactions

- Single pion (CC and NC) interaction datasets fit simultaneously

  (details in Thurs WG2 session by P. Rodrigues)
- SciBooNE, K2K datasets used as cross check

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%

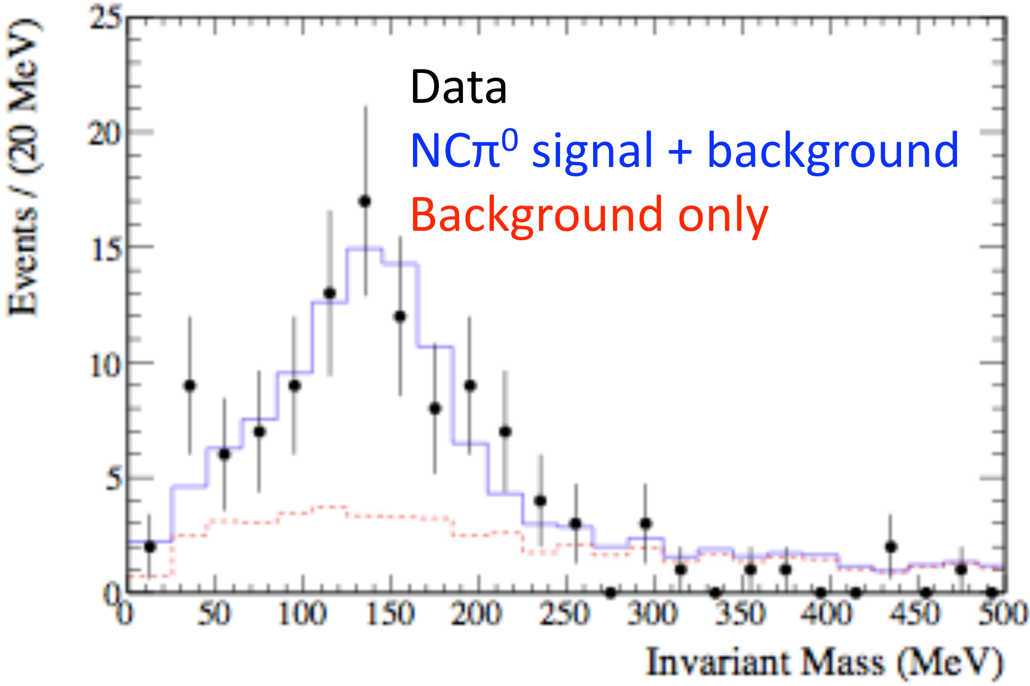
CCQE and CC1π are the largest interaction mode in ND, SK samples

Caveats:

- Acceptance: ND sample is forward going (small angle, low Q^2)
  - External data covers larger Q^2 (MiniBooNE, 4π Cherenkov detector)
- Target: ND selection is C, SK is O
  - C-O model dependent uncertainties included

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
  - No MiniBooNE-based tuning applied here

ND280 constraint fit pieces

Neutrino flux term

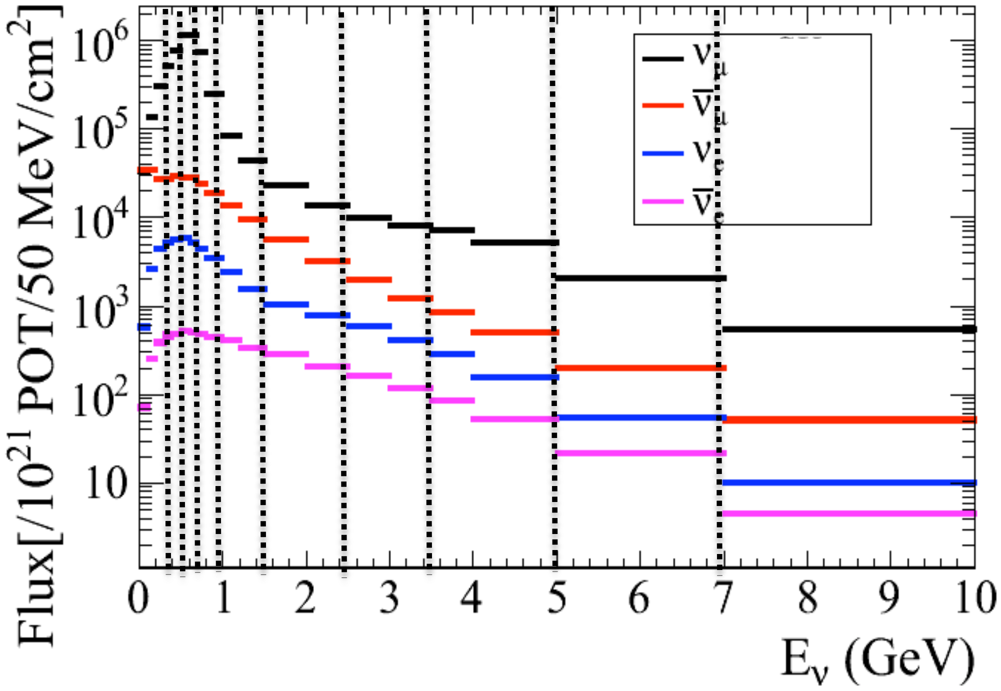
$$\ln L_{flux}(\vec{f}\,)$$

Neutrino cross section term

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

Flux parameterization, f

- Normalization on E_ν bins
- 11 bins for ν_μ flux



Cross section parameterization, x

- Combination of normalization and model parameters
- Used reweighting techniques

MAQE (GeV)	Axial mass (QE)
MARES (GeV)	Axial mass (1π)
QE1 $0<E_\nu<1.5$ GeV	Normalization
QE2 $1.5<E_\nu<3.5$ GeV	Normalization
QE3 $E_\nu>3.5$ GeV	Normalization
CCRES1 $E_\nu<2.5$ GeV	Normalization
CCRES2 $E_\nu>2.5$ GeV	Normalization
NC1π^0	Normalization
pF (MeV/c)	Fermi momentum
Spectral Function	Model comparison
CC other	Normalization

ND280 constraint fit pieces

Neutrino flux term

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

Neutrino cross section term

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

+ +

ND280 constraint

$$\ln L_{ND280}(\vec{f}, \vec{x}, \vec{d}\,)$$

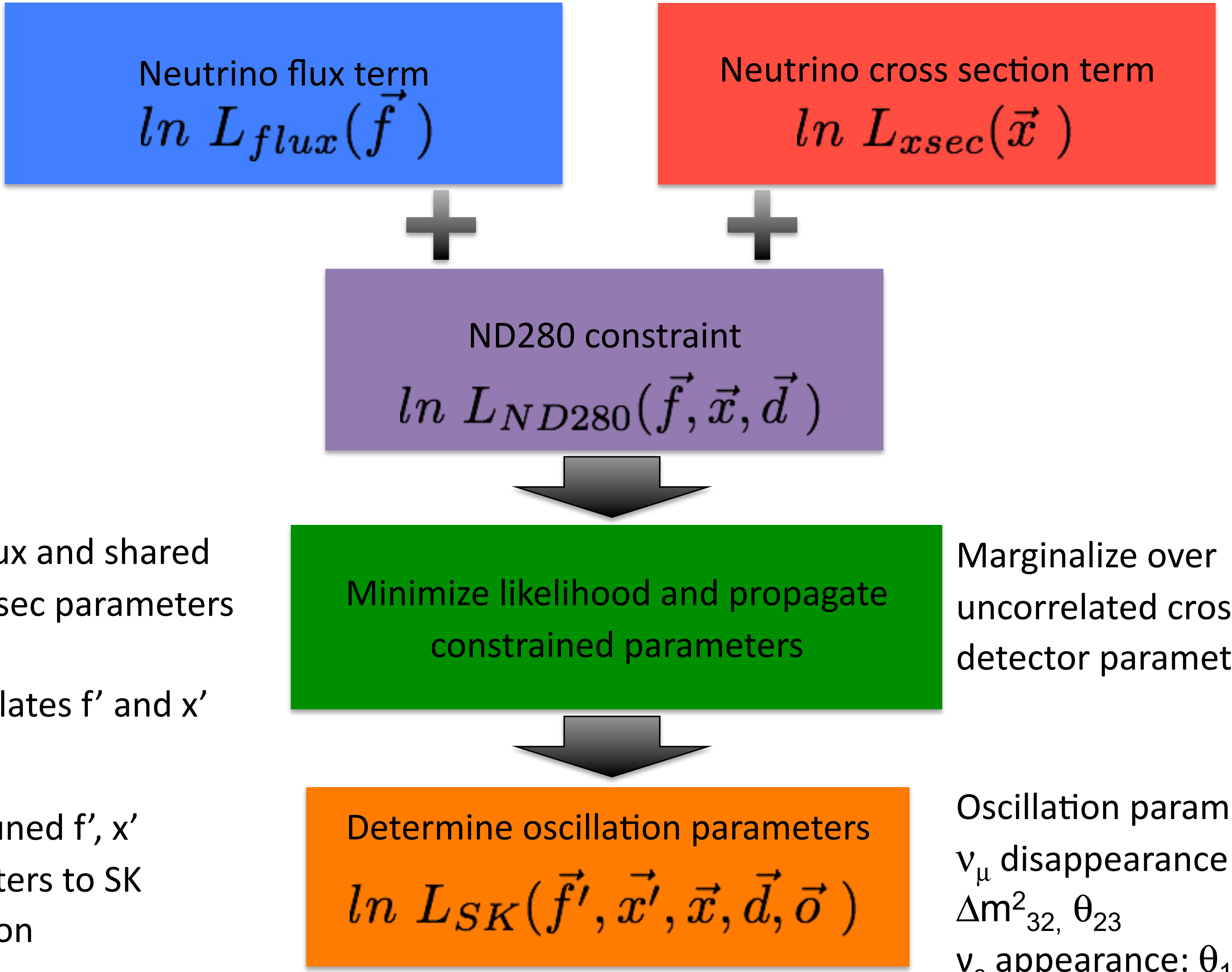
Compare CCQE, CCnQE sample data to prediction assuming a given flux, cross section pars

Binned in p_μ-$\cos(\theta_\mu)$

Detector systematics, d

Normalization on recon momentum, angle bins

ND280 constraint fit pieces



Neutrino flux term

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

Neutrino cross section term

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

ND280 constraint

$$ln\ L_{ND280}(\vec{f}, \vec{x}, \vec{d}\ )$$

Fit for flux and shared
ND/SK xsec parameters
(f’, x’)
Fit correlates f’ and x’

Minimize likelihood and propagate constrained parameters

Marginalize over
uncorrelated cross section,
detector parameters

Apply tuned f’, x’
parameters to SK
prediction

Determine oscillation parameters

$$ln\ L_{SK}(\vec{f'}, \vec{x'}, \vec{x}, \vec{d}, \vec{o}\ )$$

Oscillation parameters, o
ν_μ disappearance:
Δm^2_{32}, θ_{23}
ν_e appearance: θ_{13}

ND280 likelihood

$$
\begin{aligned}
-2lnL = 2 \sum_{i}^{p,\theta\ bins} & N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})] \\
& + \sum_{j}^{E_\nu\ bins} \sum_{k}^{E_\nu\ bins} (1-f_j)(V_f^{-1})_{j,k}(1-f_k) \\
& + \sum_{l}^{xsec\ pars} \sum_{m}^{xsec\ pars} (x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m) \\
& + \sum_{i}^{p,\theta\ bins} \sum_{n}^{p,\theta\ bins} (1-d_i)(V_d^{-1})_{i,n}(1-d_n) \\
& + ln\left(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|}\right)
\end{aligned}
$$

ND280 constraint

$ln\ L_{ND280}(\vec{f},\vec{x},\vec{d}\ )$

+

Neutrino flux term

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

+

Neutrino xsec term

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

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:

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

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

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

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

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

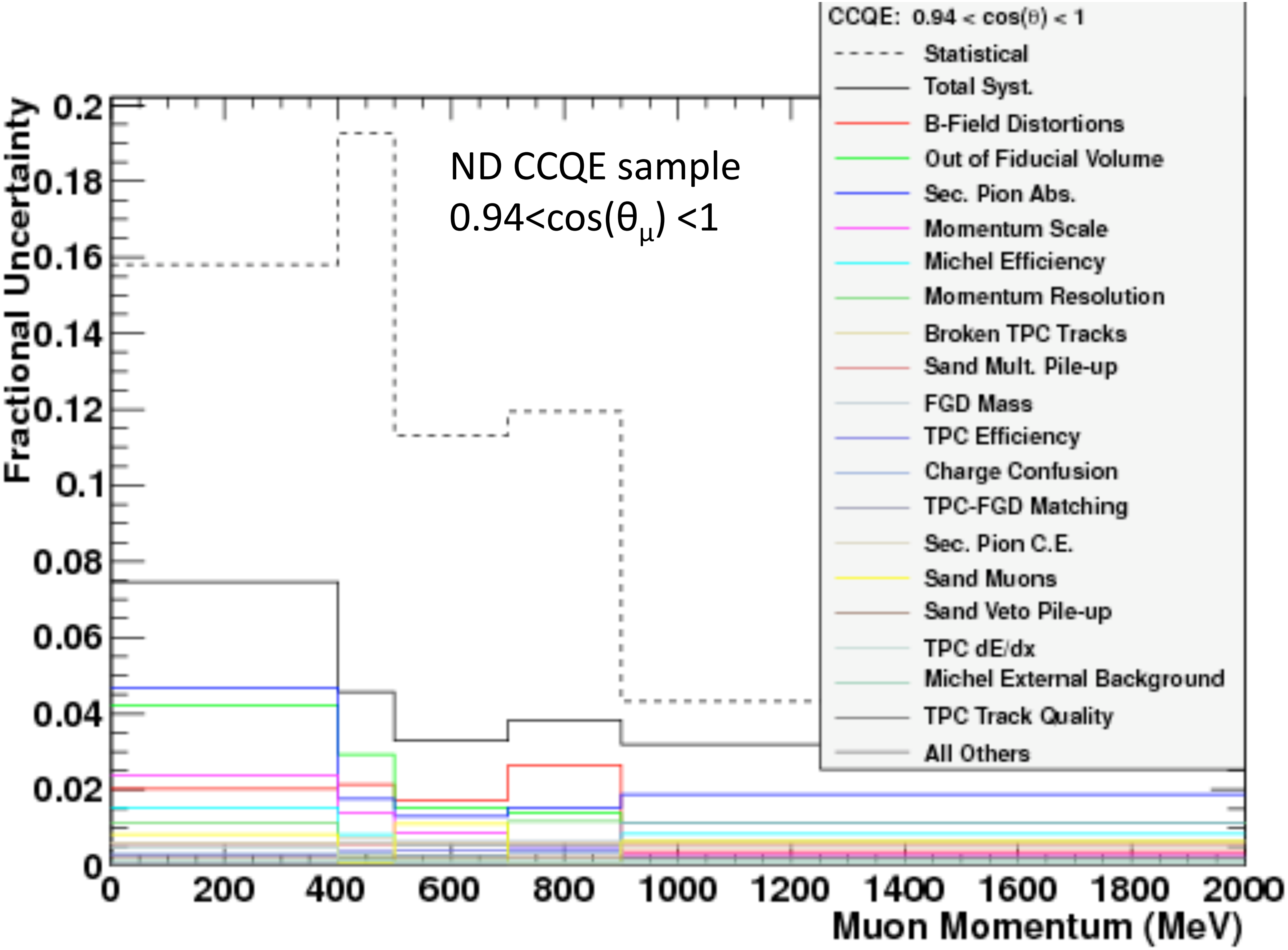
$$+\sum_{i}^{p,\theta\ bins}\sum_{n}^{p,\theta\ bins}(1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

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

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

Detector systematic errors



ND CCQE sample
$0.94<\cos(\theta_\mu)<1$

Fractional systematic uncertainty for vs. momentum

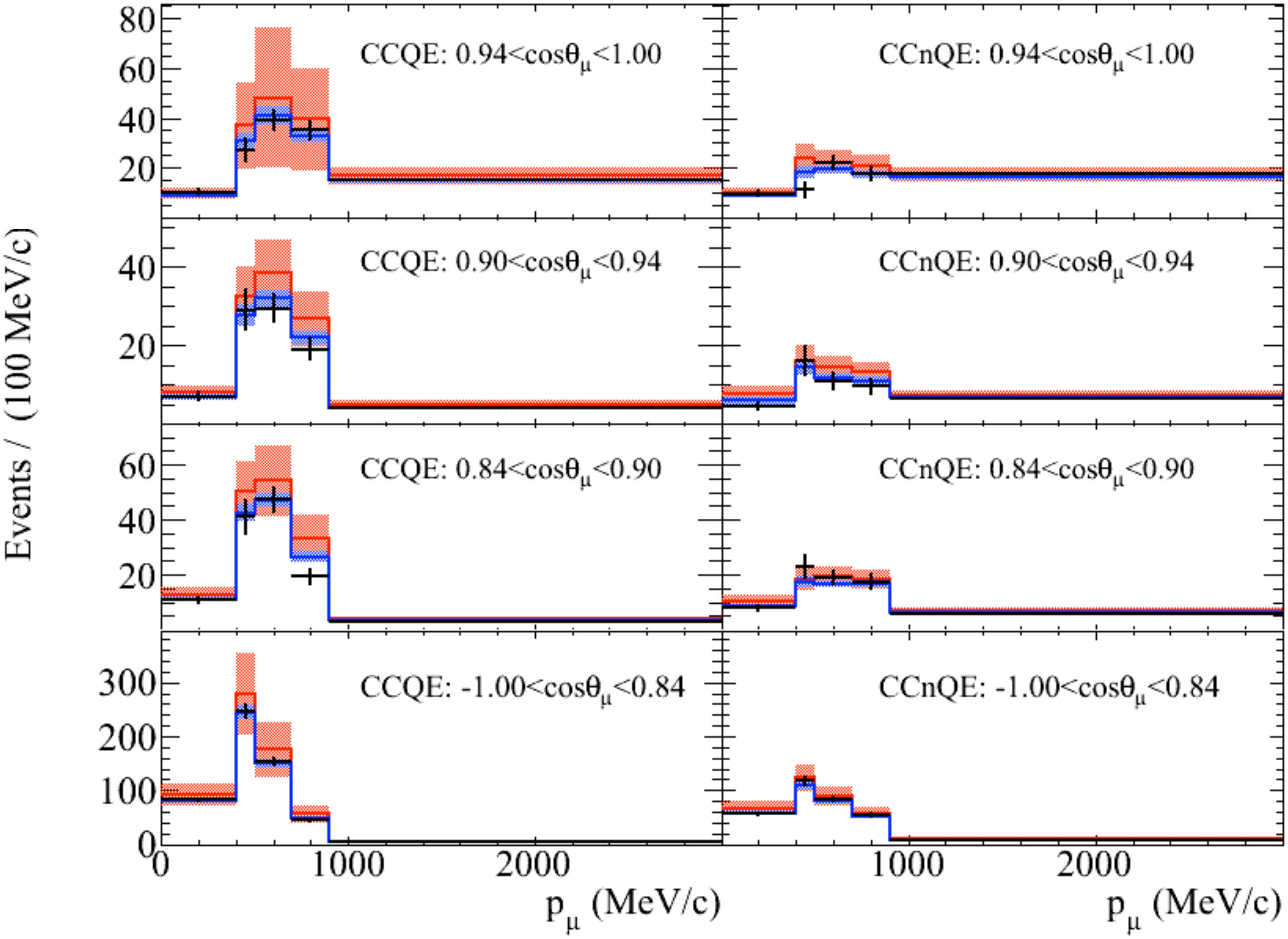
Currently statistics dominated

ND measurement results

Data

without ND information

with ND information

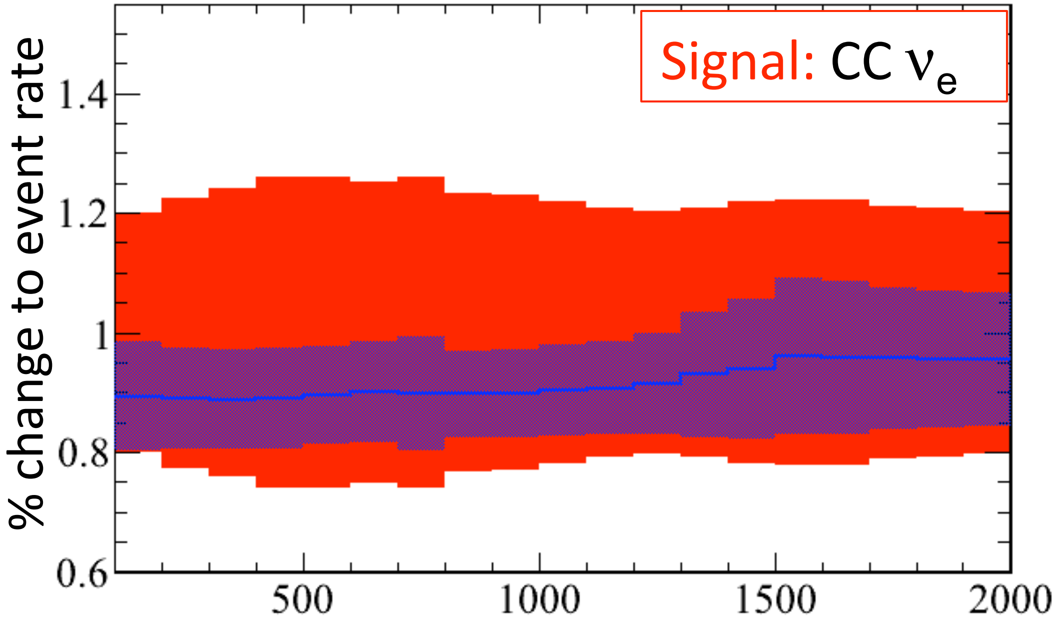


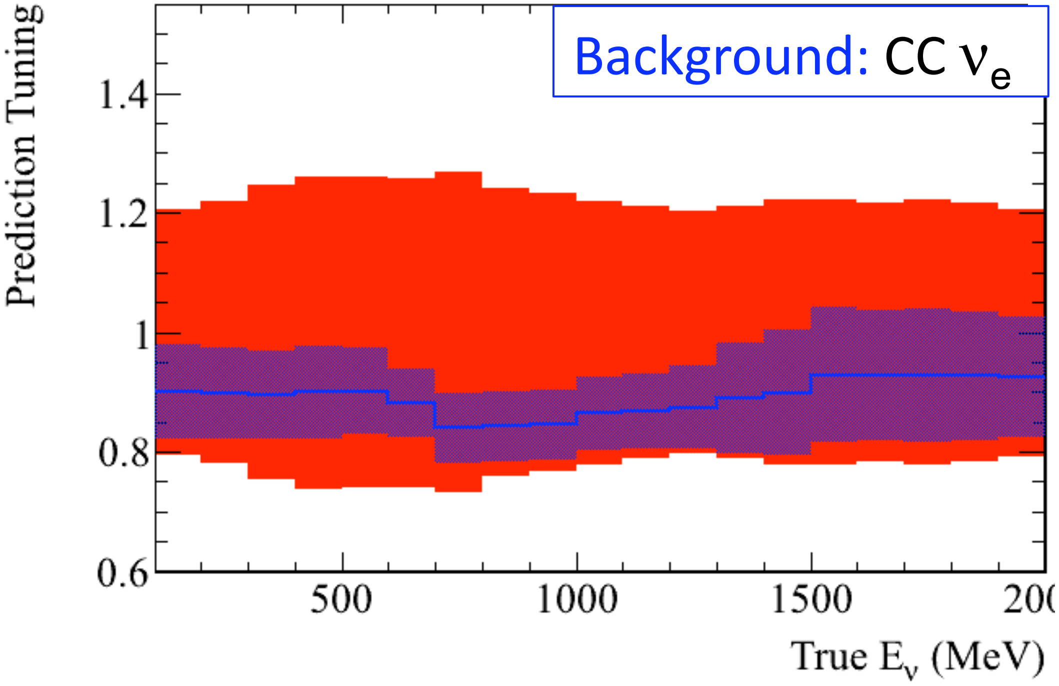
Distribution of ND samples

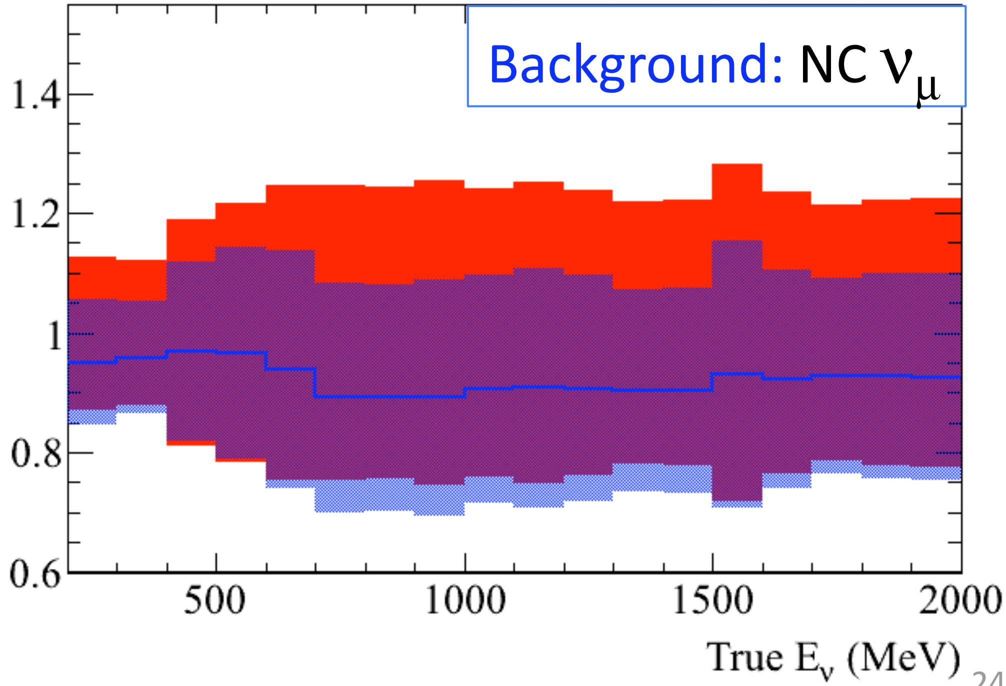
$\Delta\chi^2$ = 29.1 (p-value 0.925 based on pseudo-experiments)

Effect of ND measurement on ν_e signal, background

- Rate of ν_e signal and backgrounds without ND measurement and with ND measurement
- Uncertainty envelope from constrained flux, cross section parameters
- Includes correlation between flux and cross section at ND, SK







Total systematic uncertainty for ν_e appearance

Determine $\sin^2 2\theta_{13}$ from ν_e candidates' rate and kinematic distributions

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

More details in Fri plenary session (C. McGrew)

Signal (ν_μ to ν_e osc)	**# events**
@$\sin^2 2\theta_{13}$=0.1,δcp=0	7.81

Background	**# events**
beam $\nu_e + \overline{\nu}_e$	1.73
$\nu_\mu + \overline{\nu}_\mu$ (mainly NC) background	1.31
osc through θ_{12}	0.18
total:	3.22±0.43(sys)

Uncertainties	**ν_e bkrd**	**ν_e sig+bkrd**
ν flux+xsec (constrained by ND280)	±8.7%	±5.7%
ν xsec (unconstrained by ND280)	±5.9%	±7.5%
Far detector	±7.7%	±3.9%
Total	±13.4%	±10.3%
No ND measurement	**26%**	**22%**

ν_e signal@Δm^2_{32}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0

Event predictions normalized by ND280

Total systematic uncertainty for ν_e appearance

Determine $\sin^2 2\theta_{13}$ from
ν_e candidates' rate and
kinematic distributions

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

More details in Fri plenary session (C. McGrew)

Signal (ν_μ to ν_e osc)	**# events**
@$\sin^2 2\theta_{13}$=0.1,δcp=0	7.81

Background	**# events**
beam $\nu_e + \overline{\nu}_e$	1.73
$\nu_\mu + \overline{\nu}_\mu$ (mainly NC) background	1.31
osc through θ_{12}	0.18
total:	3.22±0.43(sys)

ν_e signal@Δm^2_{32}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0
Event predictions normalized by ND280

Uncertainties	**ν_e bkrd**	**ν_e sig+bkrd**
ν flux+xsec (constrained by ND280)	±8.7%	±5.7%
ν xsec (unconstrained by ND280)	±5.9%	±7.5%
Far detector	±7.7%	±3.9%
Total	±13.4%	±10.3%
2011 (normalization-only) analysis	**23%**	**18%**

Reduction in total uncertainty from:

- Reduced individual uncertainties (e.g. far detector and flux uncertainties)
- Improved use of ND information

Summary

Precision measurements of neutrino mixing parameters requires increased control over systematic uncertainties:

- ν_μ disappearance ($\Delta m^2_{32,}$ θ_{23}) and ν_e appearance (θ_{13})

For the T2K ν_e appearance analysis, the systematic errors are constrained to ~10% on the far detector expected ν_e rate using data from the near detector

- Improvement since 2011 result (~22%)
- ν_μ disappearance results will be updated soon with the improved near detector constraint

Future T2K analyses will extend the current ND measurement to include:

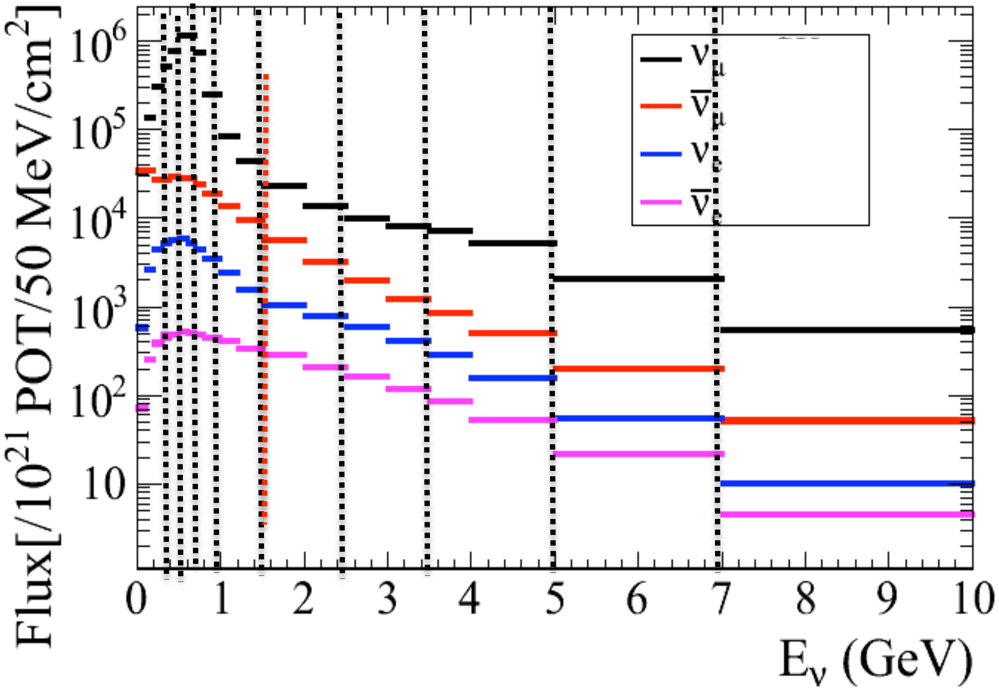
- More control samples (CC1π selection)
- Backward going tracks for increased acceptance
- Carbon and water target comparisons

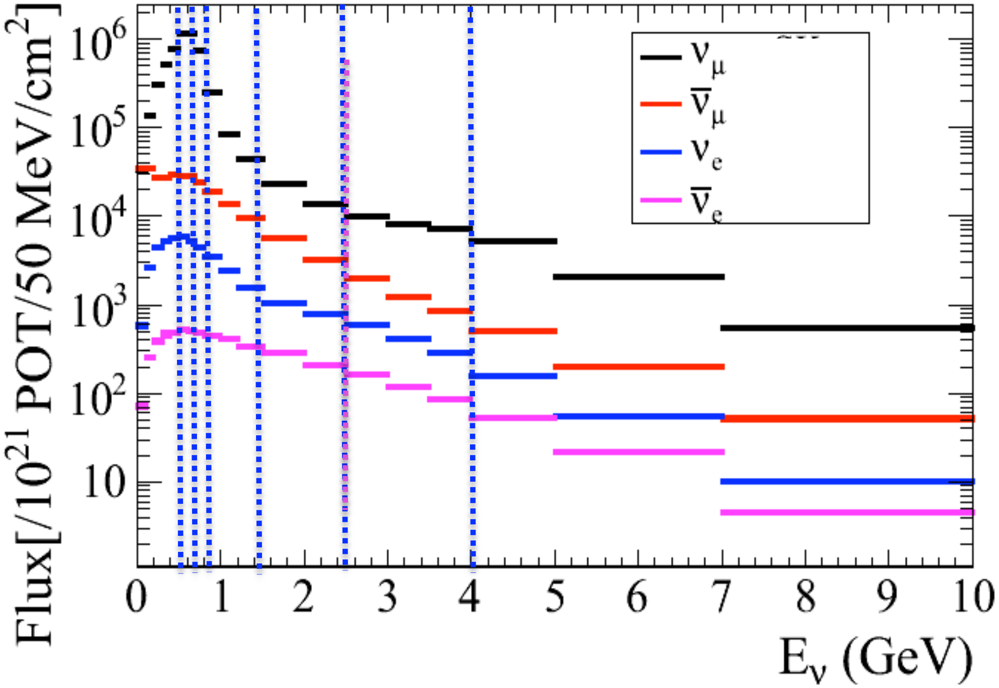
Backup slides

Core of analysis: Flux parameterization

Neutrino flux prediction

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





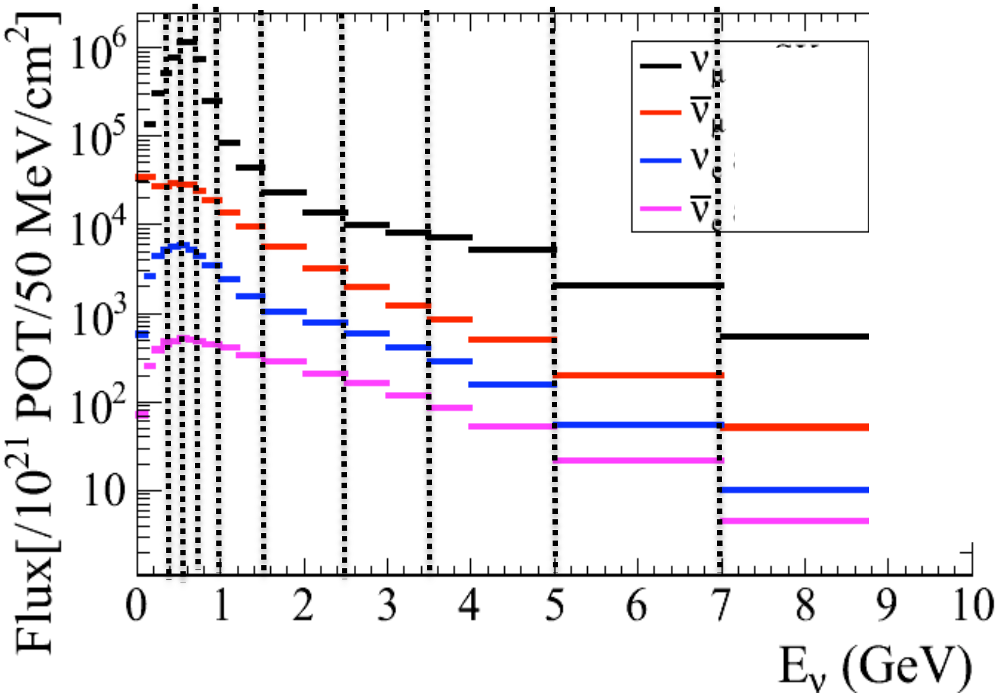
<u>Current binning for T2K flux:</u>

- ν_μ: 0.0-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-1.0, 1.0-1.5,1.5-2.5, 2.5-3.5, 3.5-5.0, 5.0-7.0, 7.0-30.0 GeV *(11 bins each ND and SK samples, index 0-10 and 11-21)*
- $\overline{\nu}_\mu$: 0.0-1.5, 1.5-30.0 GeV *(2 bins, SK sample, index 22-23)*
- ν_e : 0.0-0.5, 0.5-0.7, 0.7-0.8, 0.8-1.5, 1.5-2.5, 2.5-4.0, 4.0-30.0 GeV *(7 bins, index 24-30)*
- $\overline{\nu}_e$: 0.0-2.5, 2.5-30.0 GeV *(2 bins, SK sample, index 31-32)*

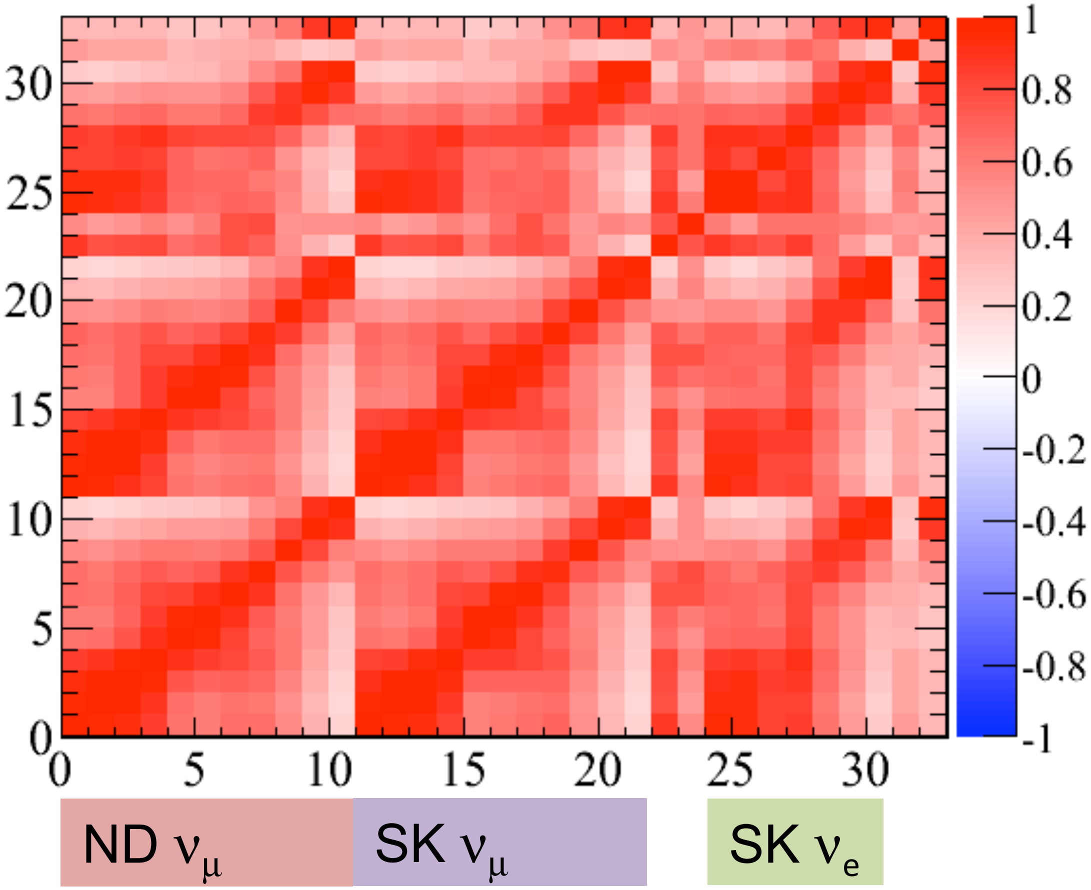
Flux parameterization

Neutrino flux prediction

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



Correlations between flux bins

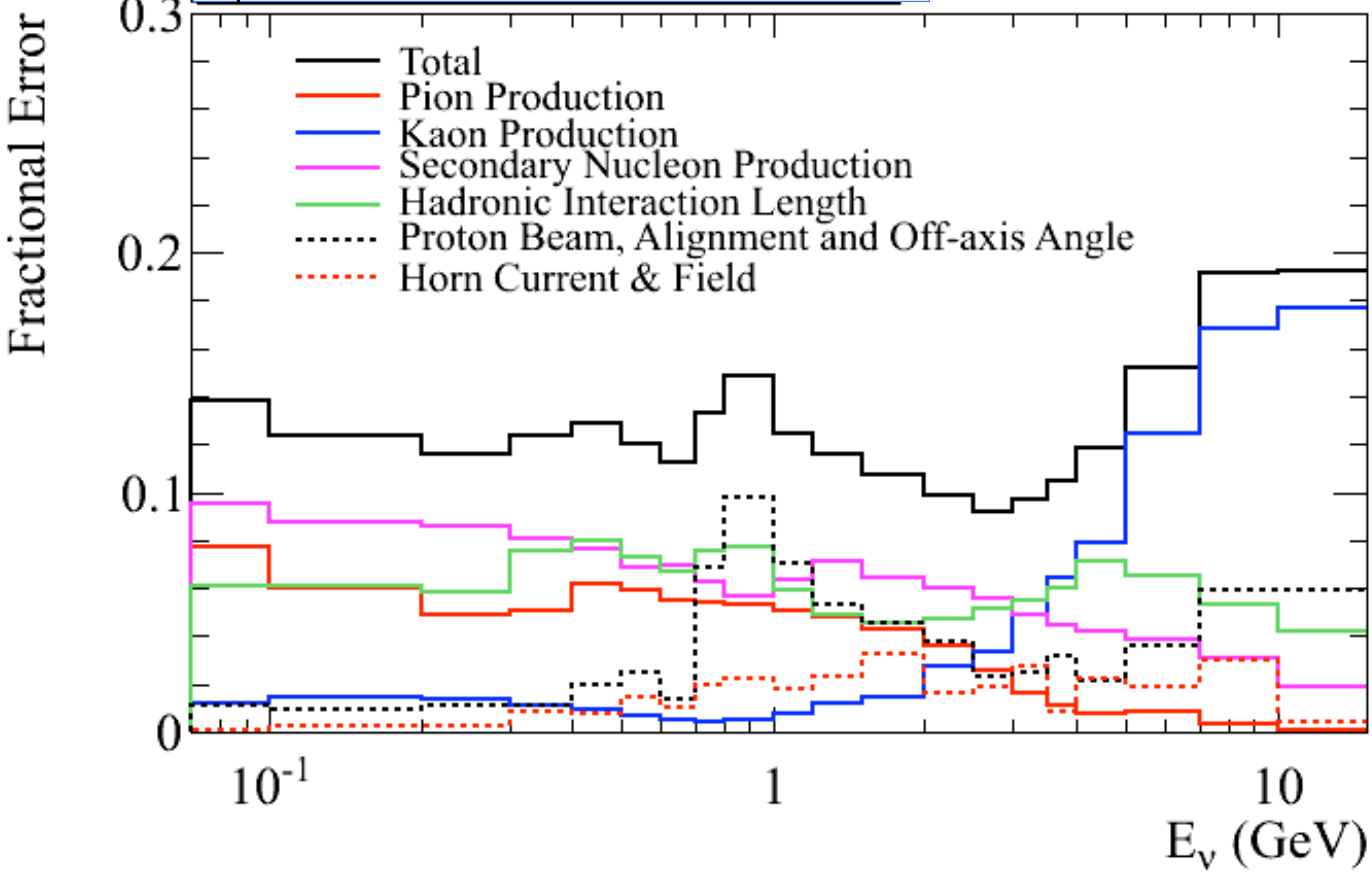


Correlations in flux covariance are shared hadron production uncertainties

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

T2K neutrino flux uncertainties

ν_μ flux fractional 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

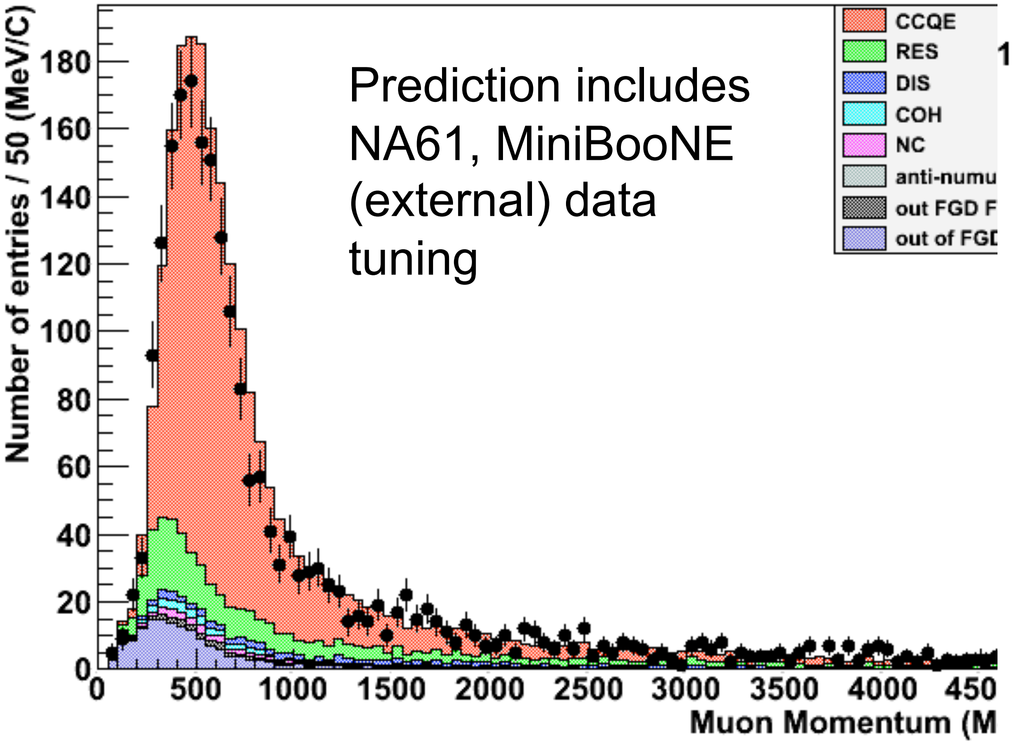
Parameter value, uncertainty is determined from MiniBooNE single pion samples

Parameter value, uncertainty is extrapolated to SK sample

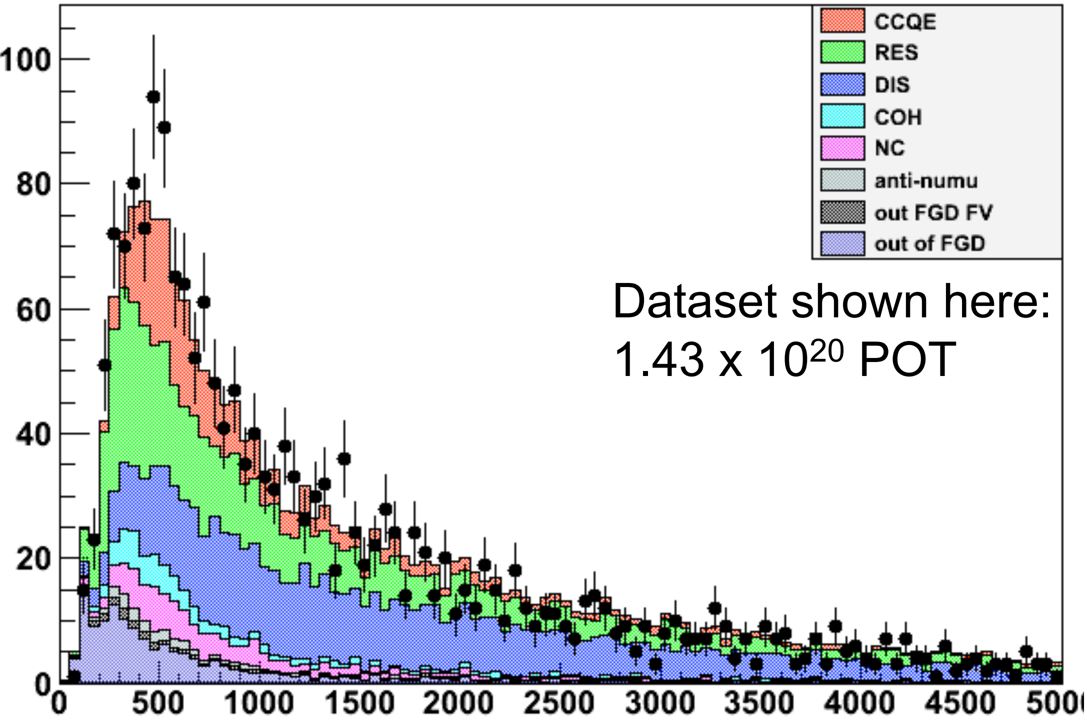
ND CCQE and CCnQE ν_μ samples

CC inclusive ν_μ candidate selection:

1. Require no tracks in TPC1 (veto ν interactions upstream of FGDs)
2. Select events which originate in FGD1 fiducial volume
3. Use the highest momentum, negative TPC2 track
4. Select μ from TPC dE/dx information to determine flavor of neutrino



Prediction includes NA61, MiniBooNE (external) data tuning



Dataset shown here: 1.43×10^{20} POT

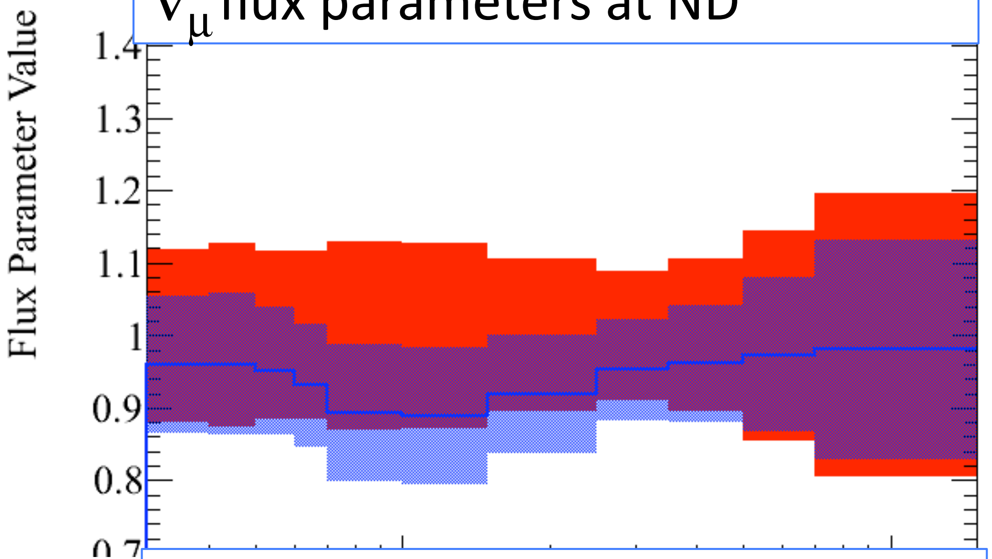
Separate sample into two subsamples, CCQE enhanced and CCnQE enhanced

CCQE enhanced: 1 TPC-FGD matched track, no decay electron in FGD1

CCnQE enhanced: all other CC inclusive

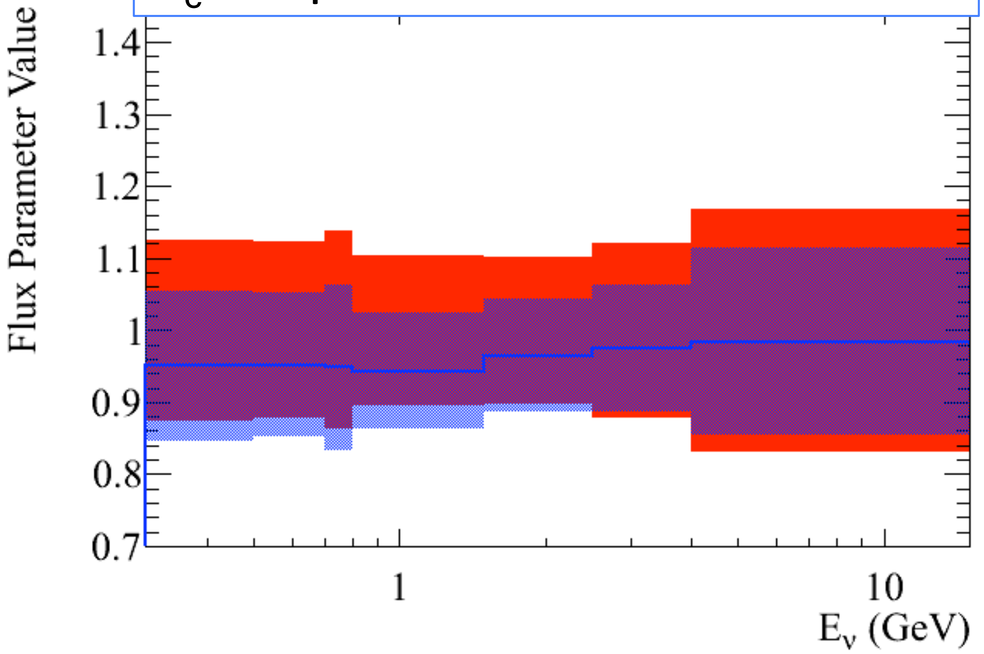
Flux parameters change after ND measurement

ν_μ flux parameters at ND

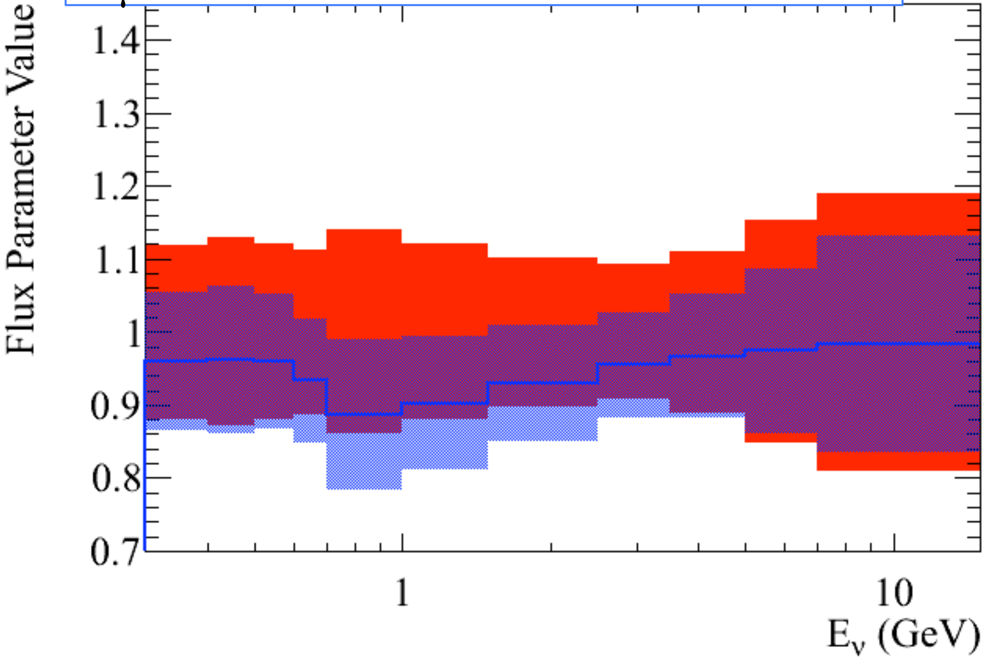


- Flux parameters without ND measurement and with ND measurement

ν_e flux parameters at SK

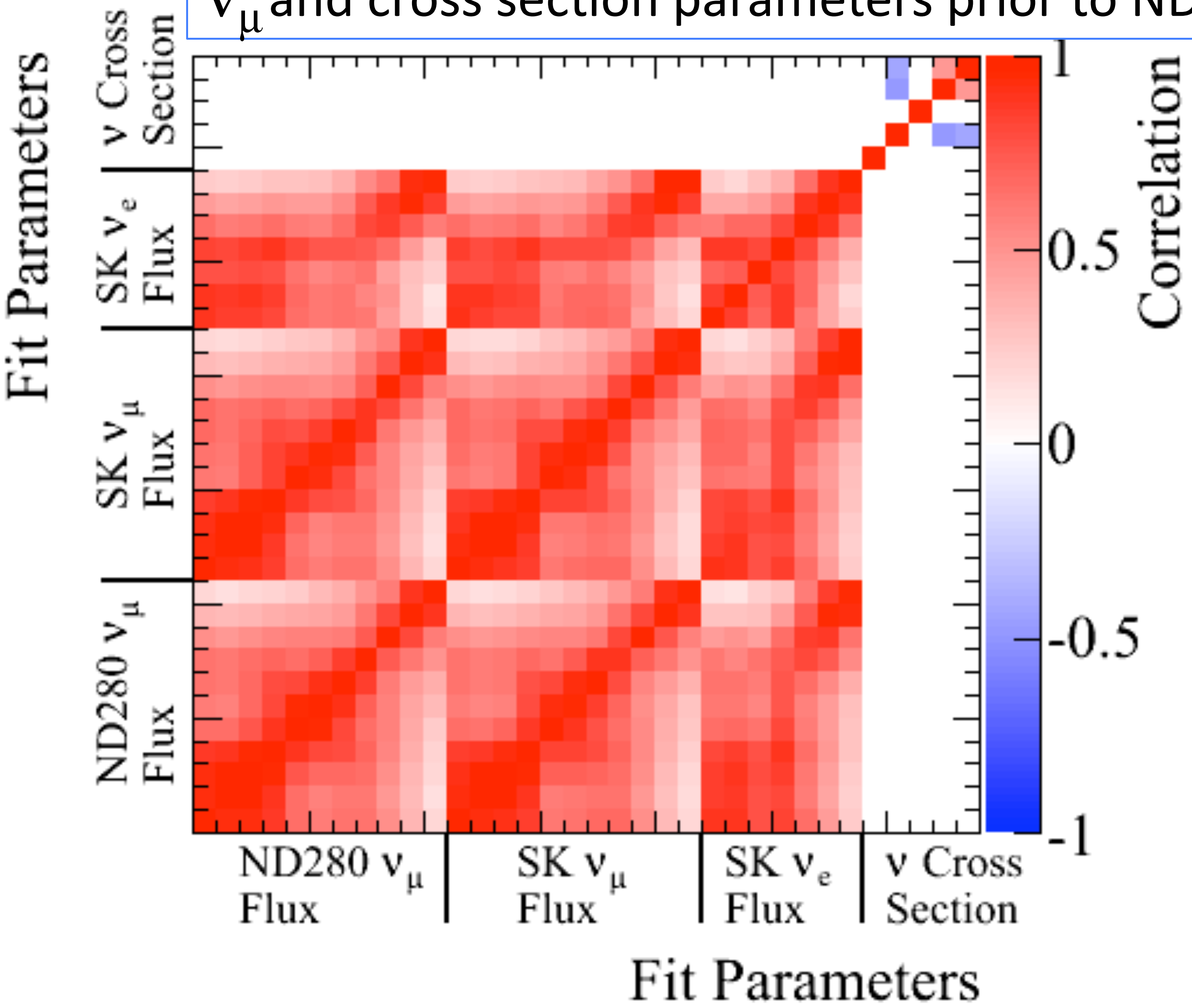


ν_μ flux parameters at SK



Covariance

ν_μ and cross section parameters prior to ND measurement

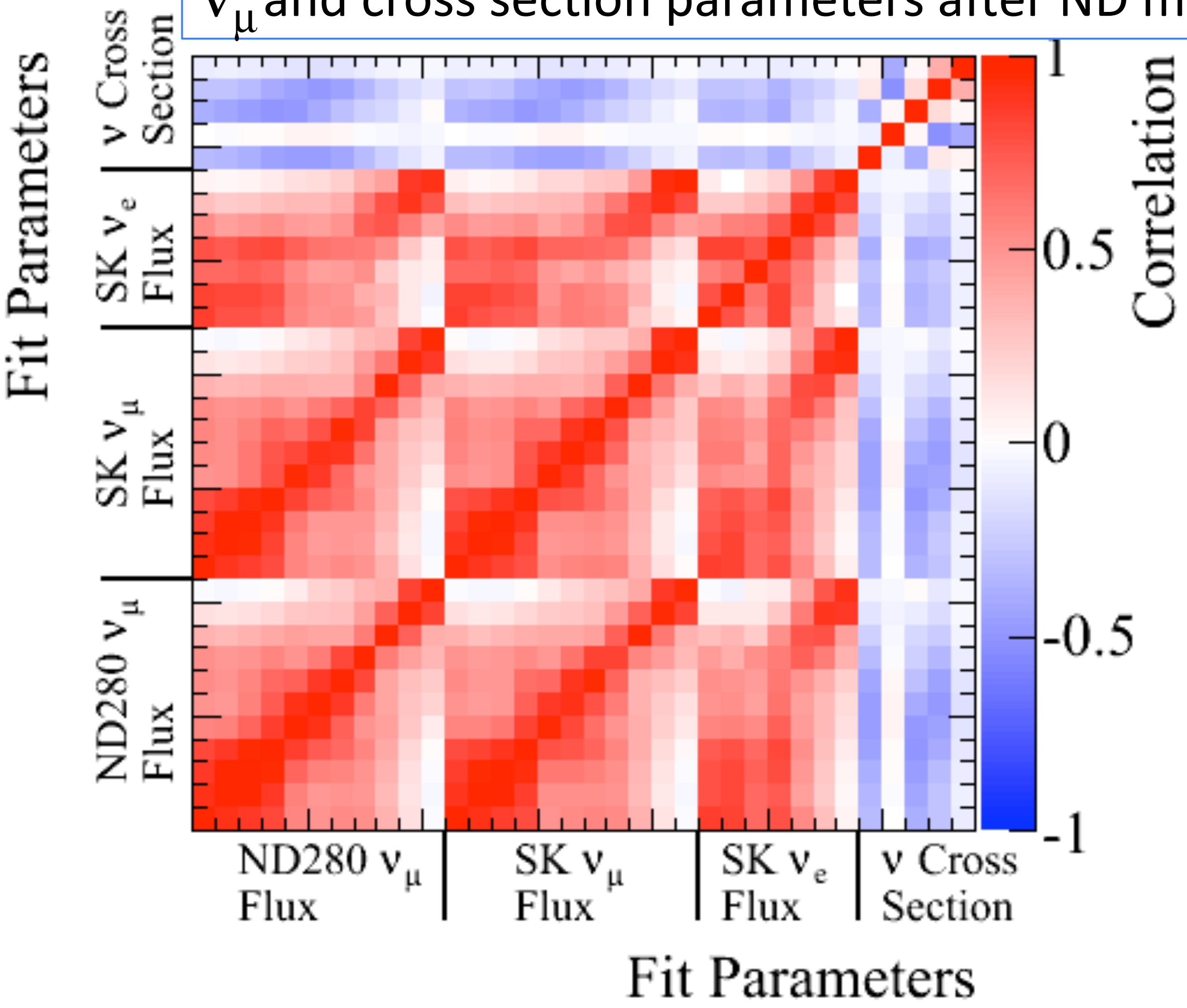


ν_μ, ν_e fluxes are correlated according to external data and how flux at ND, SK is shared

Correlations between ND, SK shared cross section parameters determined from external data fits

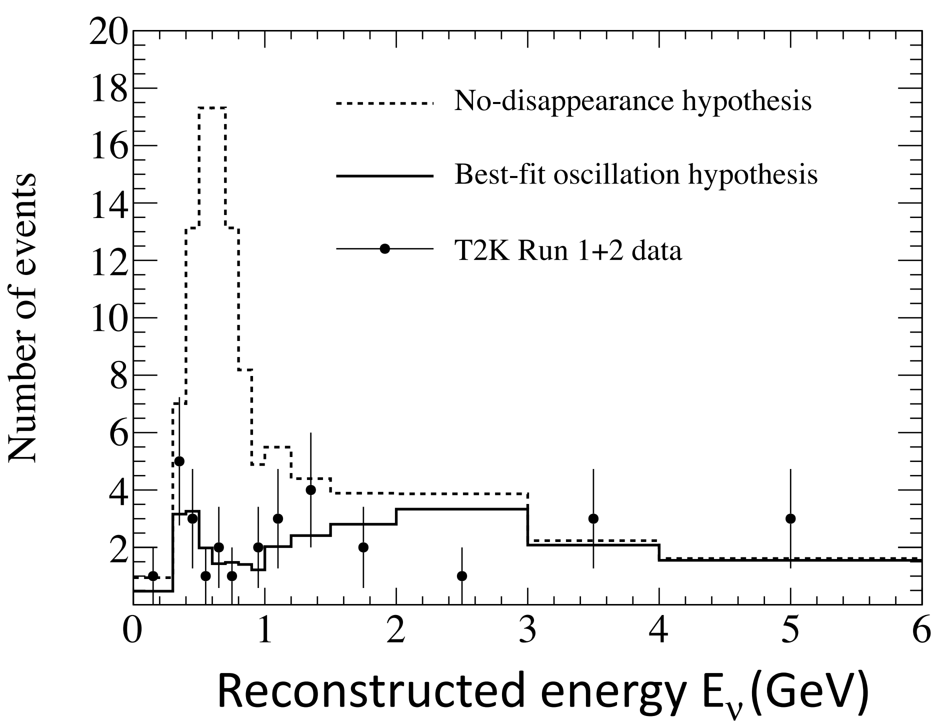
Covariance post-ND measurement

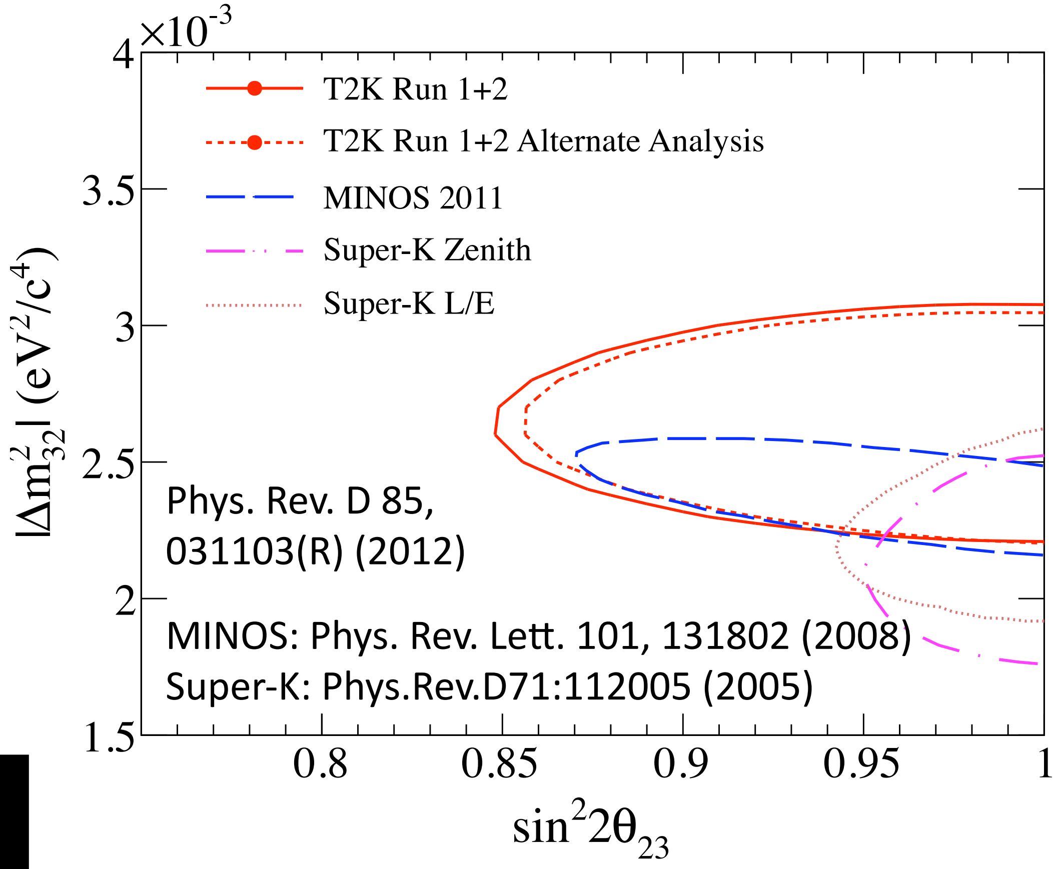
ν_μ and cross section parameters after ND measurement



Flux and shared cross section become correlated

ν_μ disappearance results





Phys. Rev. D 85, 031103(R) (2012)

MINOS: Phys. Rev. Lett. 101, 131802 (2008)
Super-K: Phys.Rev.D71:112005 (2005)

Summary of uncertainties	**ν_μ signal** **$\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2** **$\sin^2 2\theta_{23} = 1.0$**
ν flux	±4.8%
ν interactions	+8.3 -8.1%
Near detector	+6.2 -5.9%
Far detector	±10.3%
Total	+15.4 -15.1%

- Disappearance distorts energy spectrum and rate of ν_μ candidates
- 31 events pass ν_μ selection with $103.6^{+13.8}_{-13.4}$ expected for no oscillation

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

The T2K Collaboration

Canada
TRIUMF
U of Alberta
U of B Columbia
U of Regina
U of Toronto
U of Victoria
U Winnipeg
York U

Switzerland
Bern
ETH Zurich
U of Geneva
Poland
NCBJ
IFJ PAN
T U Warsaw
U of Silesia
Warsaw U
Wroclaw U

Russia
INR

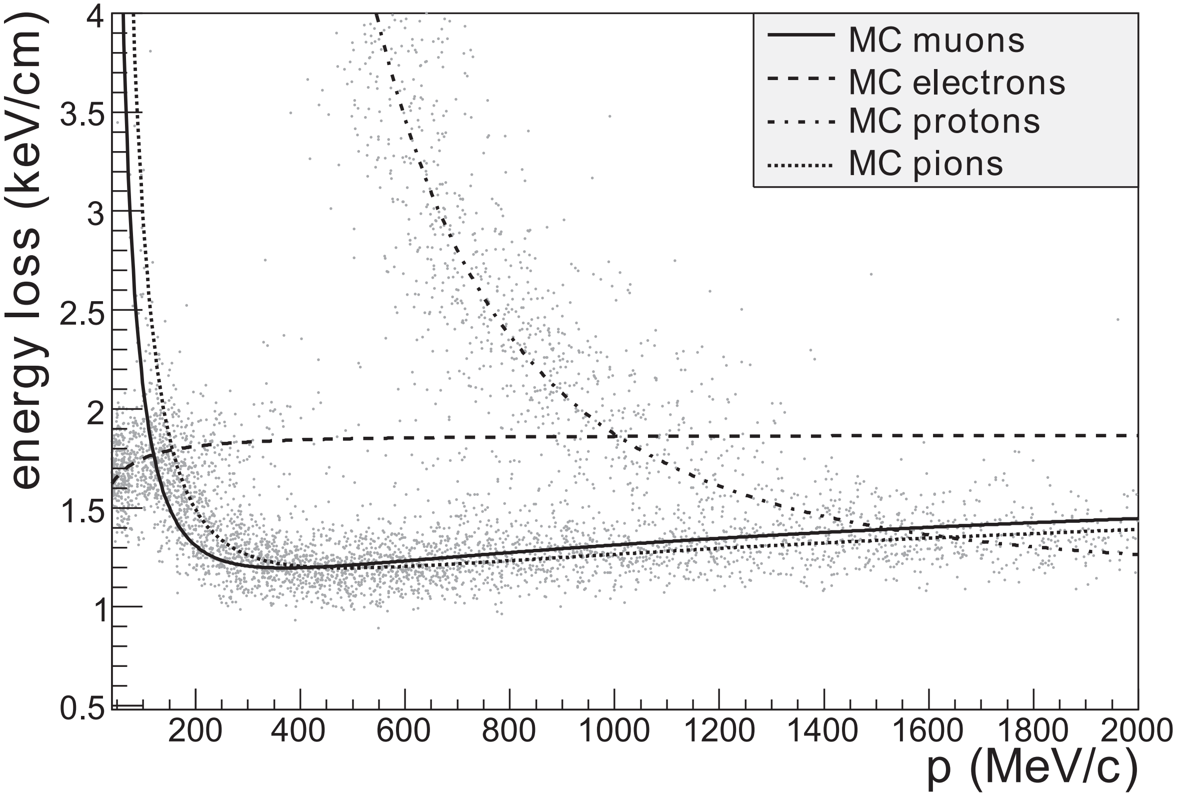
Korea
Chonnam Nat'l U
Dongshin U
Seoul Nat'l U
Italy
INFN Bari
INFN Roma
Napoli U
Padova U

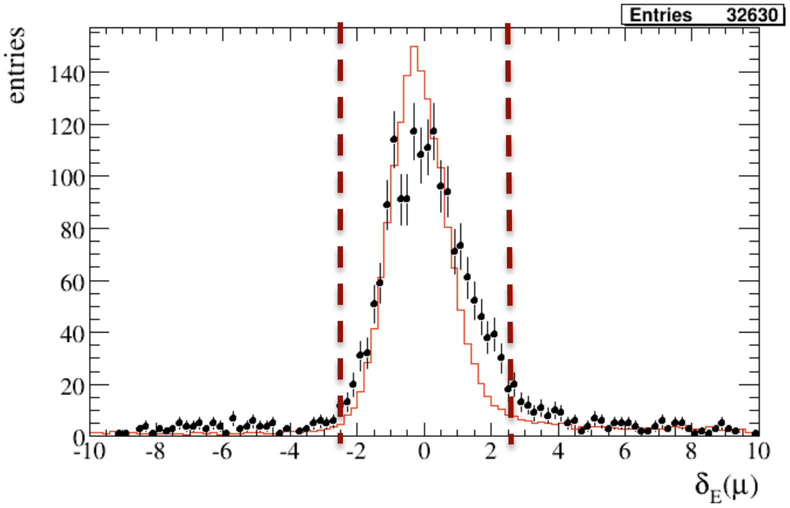
France
CEA Saclay
IPN Lyon
LLR E Poly
LPNHE-Paris
Spain
IFIC, Valencia
IFAE, Barcelona

Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe U
Kyoto U
Miyagi U of Ed
Osaka City U
U of Tokyo

USA
Boston U
Colorado State U
Duke U
Louisiana State U
Stony Brook U
U of California, Irvine
U of Colorado
U of Pittsburgh
U of Rochester
U of Washington
UK
U of Oxford
Imperial C London
Lancaster U
Queen Mary U of L
Sheffield U
STFC/RAL
STFC/Daresbury
U of Liverpool
U of Warwick
Germany
RWTH Aachen U

TPC dE/dx particle ID





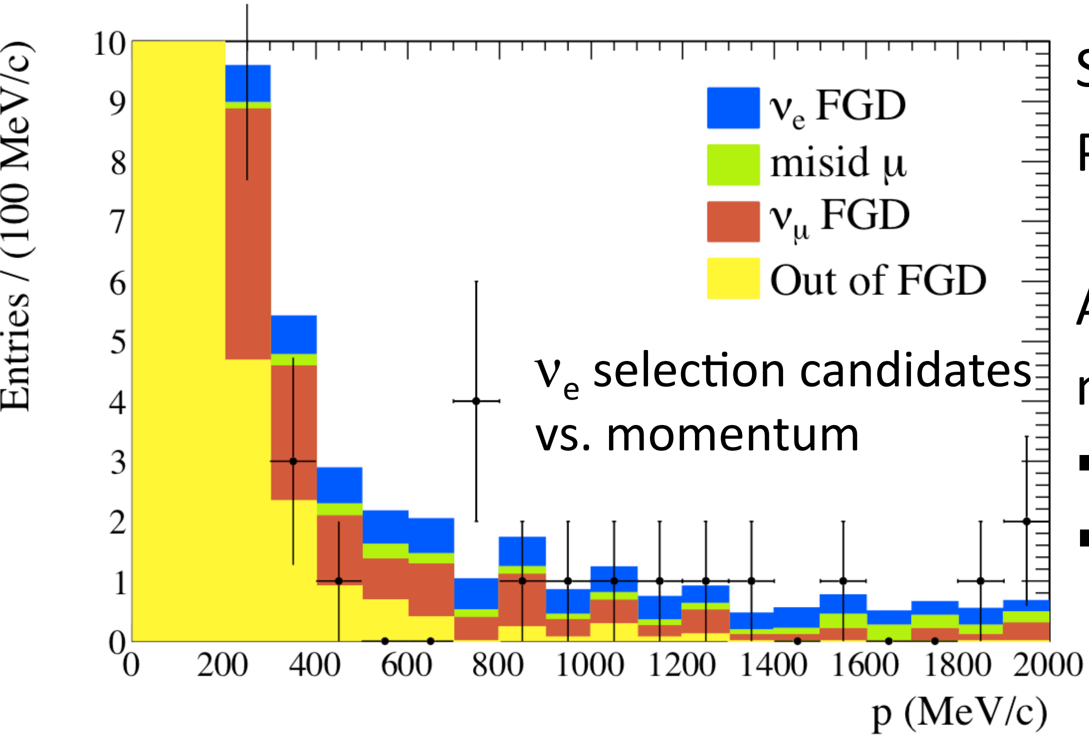
PID “pull” variable

Energy loss of the particle (dE/dx) can be used to separate particle type

dE/dx resolution for MIPs is 8%

Probability for a muon between 0.2 and 1.0 GeV to be identified using dE/dx as an electron is less than 0.2%

ND280 beam ν_e rate cross-check (I)



ν_e selection candidates vs. momentum

Select ν_e candidates at ND280 with TPC PID to check rate of intrinsic beam ν_e

Additional backgrounds to ν_e selection, measured via control samples

- μ misidentified as e
- e from photon conversion (photons emitted in ν_μ interactions in FGD and other subdetectors)

Ratio of observed ν_e / ν_μ events is consistent with untuned prediction

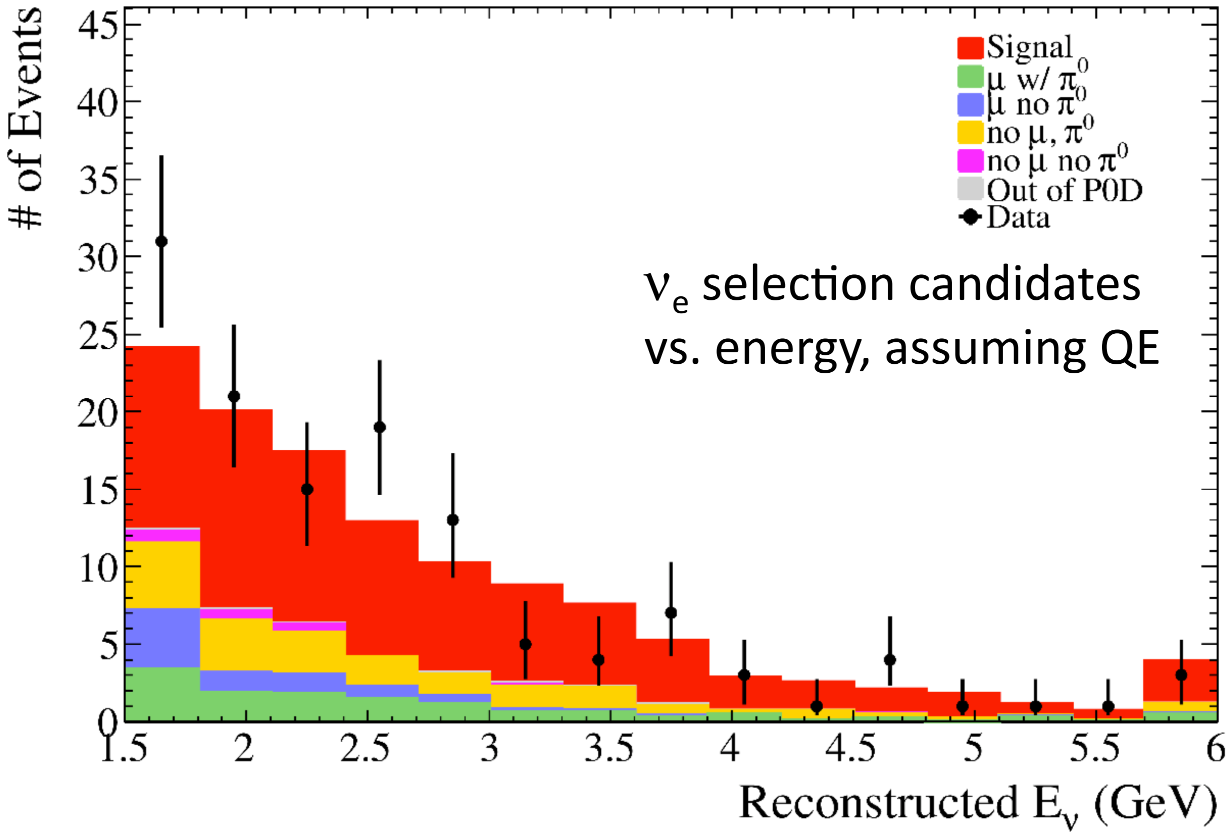
$N(\nu_e)/N(\nu_\mu) = R(e{:}\mu) = 1.0\% \pm 0.7\%$ (statistics) $\pm 0.3\%$ (systematics)

$R(e{:}\mu, \text{data}) / R(e{:}\mu, \text{MC}) = 0.6 \pm 0.4$ (statistics) ± 0.2 (systematics)

Improvements to the analysis:

- Improved rejection of backgrounds with ECals
- More data: 2.88×10^{19} POT shown here

ND280 beam ν_e rate cross-check (II)



ν_e selection candidates vs. energy, assuming QE

Select high energy CC ν_e candidates within the P0D:

- Reconstructed track matched in x,y with vertex in FV consistent with an single EM shower (reject π^0 mutiple photon showers and muons)
- Primary backgrounds are HE π^0 events

Consistent with current untuned MC:

data-bkrd(MC)/sig(MC)= R = 1.19 ± 0.15(statistics) ± 0.26 (systematics)