Towards Reduced Neutrino Flux & Interaction Uncertainties for a J-PARC to Hyper-K Experiment

Mark Hartz

mhartz@physics.utoronto.ca

(York University/University of Toronto)

Reminder of Hyper-K LOI Uncertainties

The Hyper-K LOI used the following χ^2 for sensitivities studies:

$$\chi^2 = \sum_{\nu,\overline{\nu}} \sum_i \left[N^i - \left\{ 1 \pm \frac{1}{2} f_{\nu/\overline{\nu}} \right\} \cdot \left((1 + f_{\text{sig}}) \cdot n^i_{\text{sig}} + (1 + f_{\nu_\mu}) \cdot n^i_{\nu_\mu} + (1 + f_{\nu_e}) \cdot n^i_{\nu_e} \right) \right]^2 / N^i$$
$$+ \frac{{f_{\text{sig}}}^2}{{\sigma_{\text{sig}}}^2} + \frac{{f_{\nu_\mu}}^2}{{\sigma_{\nu_\mu}}^2} + \frac{{f_{\nu_e}}^2}{{\sigma_{\nu_e}}^2} + \frac{{f_{\overline{\nu}/\nu}}^2}{{\sigma_{\nu/\overline{\nu}}}^2},$$

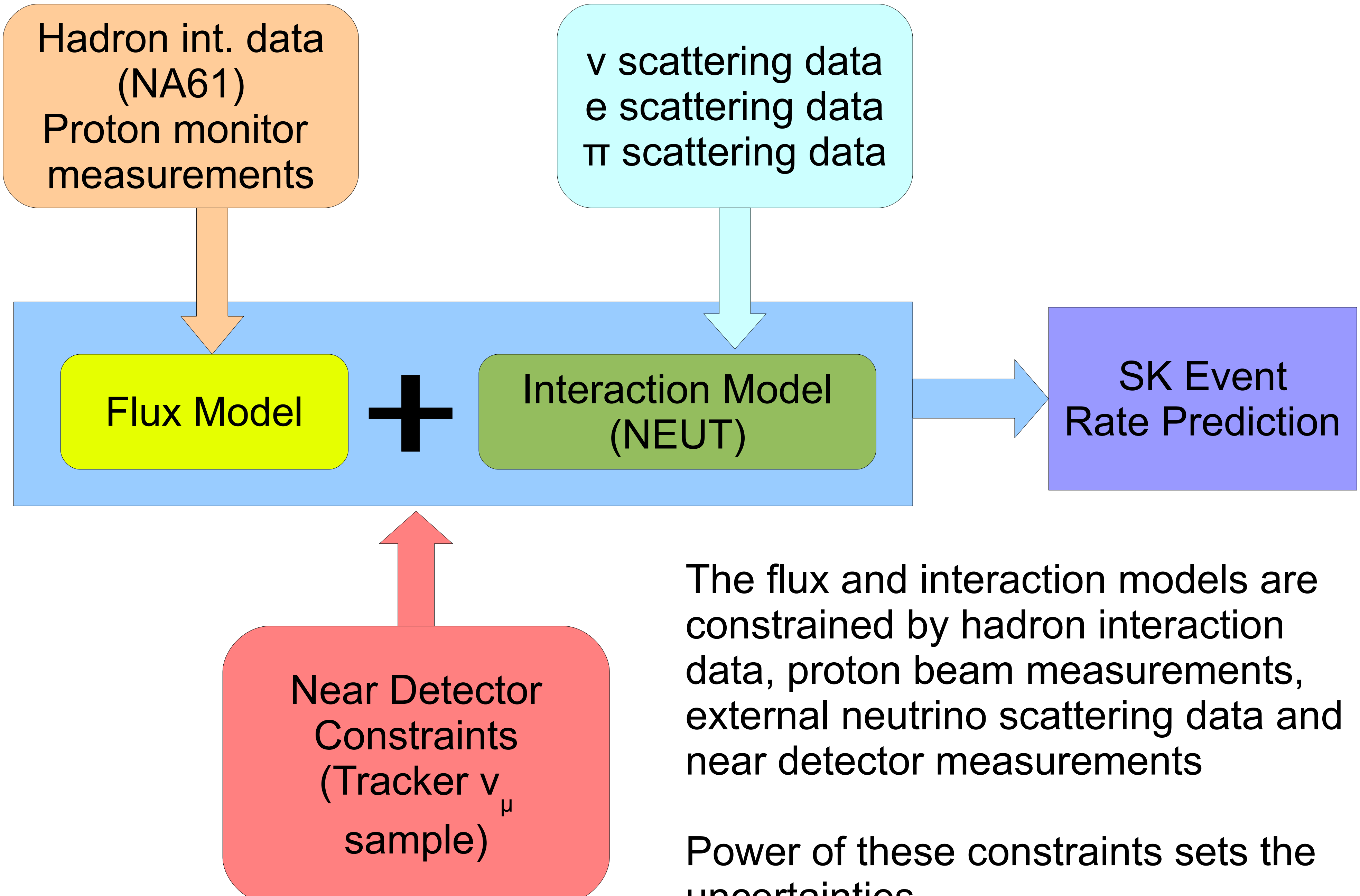
5% normalization errors for the signal and background sources

5% normalization error with anti-correlated effect on the neutrino and antineutrino samples

No shape (E_v or E_{rec}) uncertainties applied

Based on T2K's experience so far, can we achieve something close to that level of uncertainty?

The T2K Event Rate Prediction



The flux and interaction models are constrained by hadron interaction data, proton beam measurements, external neutrino scattering data and near detector measurements

Power of these constraints sets the uncertainties

T2K Extrapolation Method

Use maximum likelihood method to apply the near detector constraint

Normalization in bins of Enu

Model parameters, normalizations

Oscillation parameters

$$L_{tot} = \boxed{L_{flux}(\vec{f})\, L_{xsec}(\vec{x})\, L_{near}(\vec{f}, \vec{x})}\, L_{sk}(\vec{f}, \vec{x}, \vec{o})$$

In practice fit separately and then propagate to SK fit

Advantages of this method (compared to Far/Near ratio):

Includes off-diagonal correlations in the flux (as function of energy or between ν_{μ} and ν_{e})

Allows simple inclusion of additional near or far detector data sets

Uncertainties from T2K 2012 Analysis

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	10.8	7.9	11.8	8.5
M_A^{QE}	10.6	4.5	18.7	7.9
M_A^{RES}	4.7	4.3	2.3	2.0
CCQE norm. ($E_\nu < 1.5$ GeV)	4.6	3.7	7.8	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	5.3	3.7	5.5	3.9
NC1π^0 norm.	8.1	7.7	2.4	2.3
CC other shape	0.2	0.2	0.1	0.1
Spectral Function	3.1	3.1	5.4	5.4
p_F	0.3	0.3	0.1	0.1
CC coh. norm.	0.2	0.2	0.2	0.2
NC coh. norm.	2.1	2.1	0.6	0.6
NC other norm.	2.6	2.6	0.8	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	1.8	1.8	2.6	2.6
W shape	2.0	2.0	0.9	0.9
pion-less Δ decay	0.5	0.5	3.5	3.5
CC1π, NC1π^0 energy shape	2.5	2.5	2.2	2.2
SK detector eff.	7.1	7.1	3.1	3.1
FSI	3.1	3.1	2.4	2.4
SK momentum scale	0.0	0.0	0.0	0.0
Total	21.5	13.4	25.9	10.3

Constrained by the fit to ND280 data

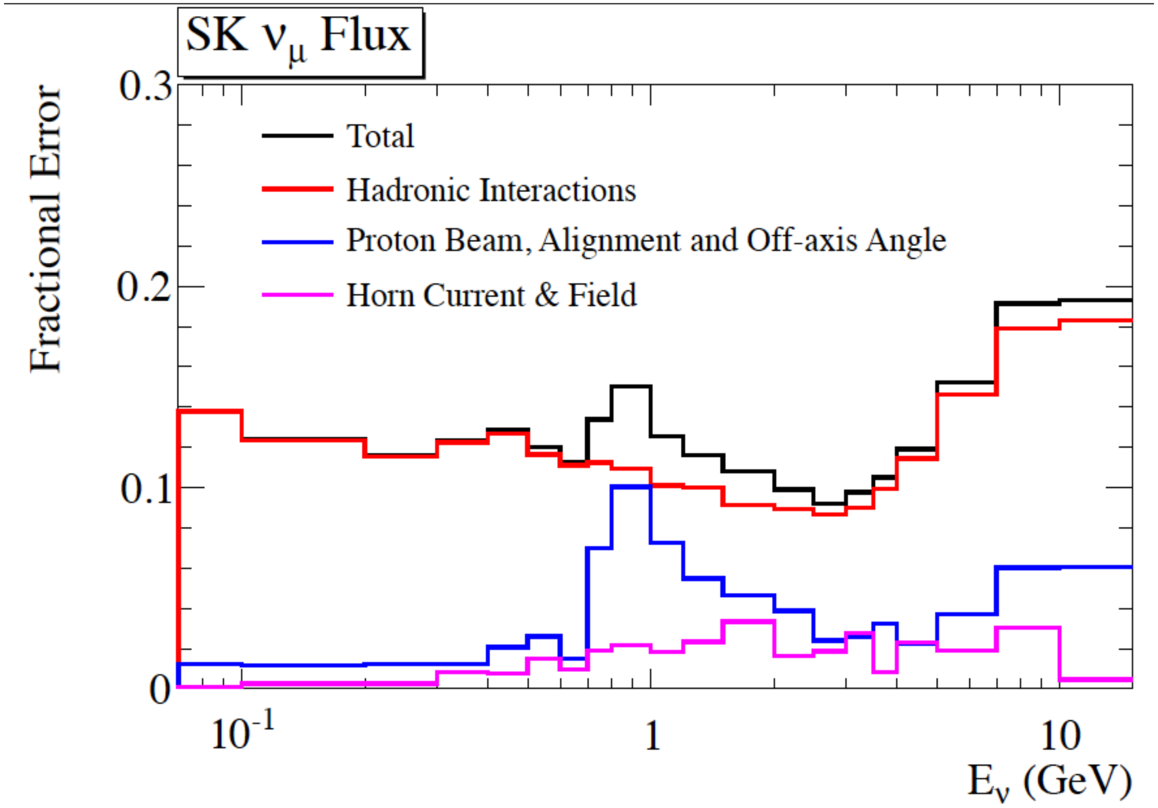
Depends on nuclear target. No constraint from ND280 (C vs. O)

Only using ν_μ sample at ND280

Uncertainties are at x2 or more of the 5% used in the Hyper-K LOI

The Flux Model

- The flux uncertainties fall into 3 general categories:
  1) Hadron interaction uncertainties (production of pions, kaons and muons that decay to neutrinos)
  2) Off-axis angle uncertainties (proton beam positioning at the target, horn and target alignment
  3) Horn current/filed uncertainties (absolute current error or current asymmetries)



NA61 Hadron Data

Currently NA61 thin target data is used to model most π+/π- interactions and some K+ interactions (Phys. Rev. C 84, 034604, Phys. Rev. C 85, 035210)

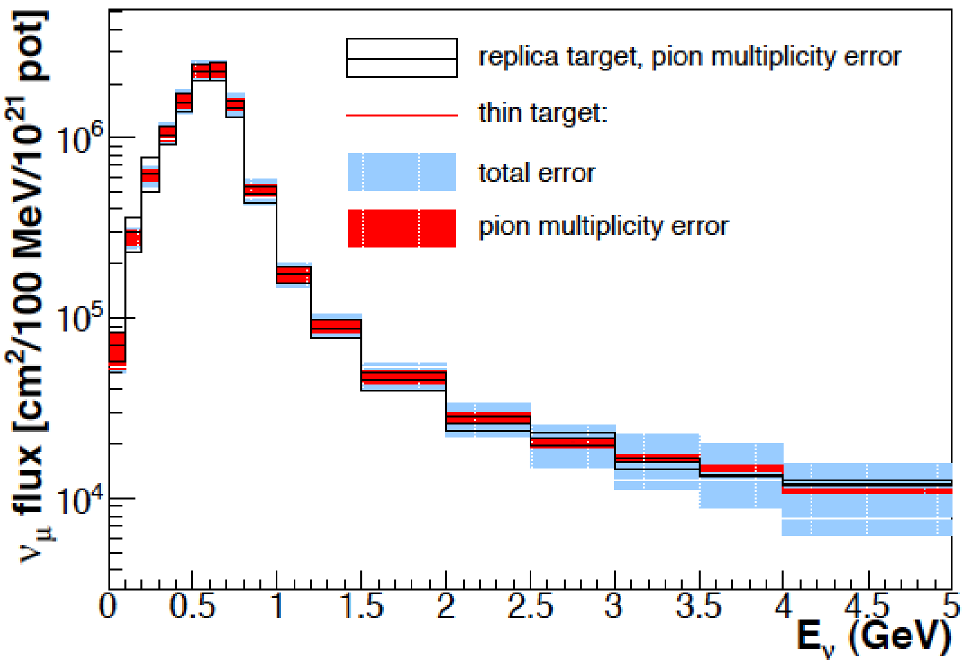
For pions, systematic errors dominate → ~6% error on the flux

NA61 has taken T2K replica target data also

Eventually will have systematics dominated π+/π-, K+/K-, p, K^0 yields measured from the replica target

Pilot (low stats) replica target pion analysis already done:

Replica target based tuning of pion yields gives consistent results with current thin target tuning of the T2K flux



Submitted to NIMA
arXiv:1207.2114

Expected Hadron Interaction Uncertainties

NA61 goal is to reduce replica target systematic errors to 5%

Should expect 3-5% uncertainty on the particle yields from the target

Correlated π+/π- production uncertainties

What about interactions outside of the target?

	Number of Inelastic Hadronic Interactions in Chain Producing the Neutrino		
	1 Interaction	≥2 Interactions	≥1 Out of Target Interaction
SK ν_μ flux	63.2%	36.8%	12.4%
SK anti-ν_μ flux	41.5%	58.5%	45.1%
SK ν_e flux	61.7%	38.3%	12.7%

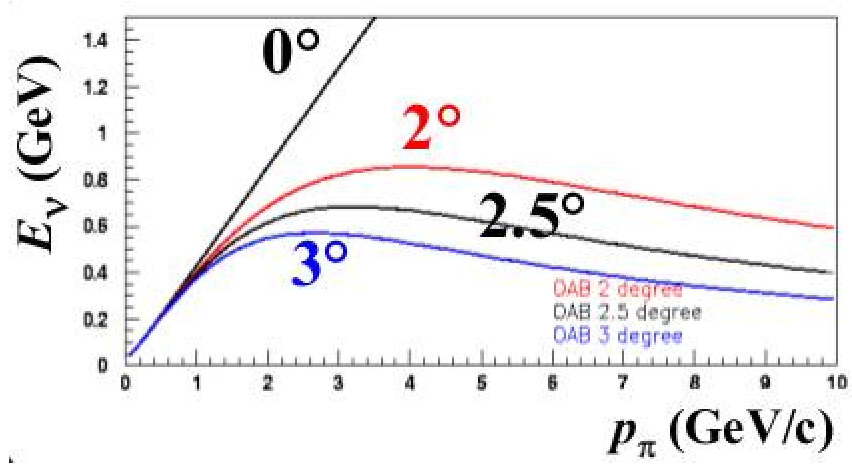
Interactions in Al, Fe, He, etc.

For out of target tuning, use NA61 thin target data and scale to other materials → ~10% scaling errors

Biggest effect may be in ν_μ flux when running in anti-neutrino mode – needs more study

Hadron Interaction Errors (Shape Unc.)

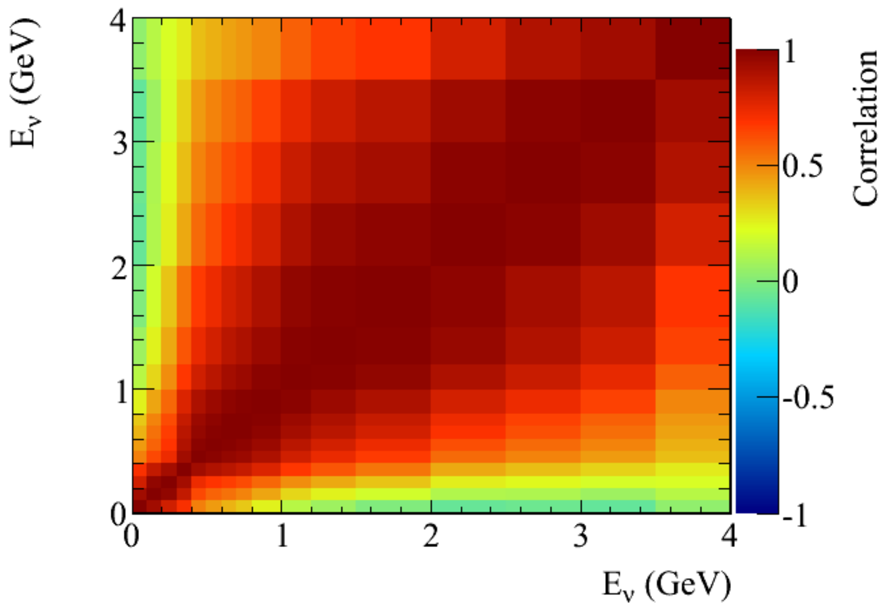
Nice advantage of off-axis angle setup is that each E_ν bins is integral over large momentum range



Even with momentum dependent errors (particle ID) in the measured pion production, the correlations across energy bins are large

Correlations of the pion production uncertainty in the SK ν_μ flux

Don't expect a significant “shape” uncertainty from hadron interaction errors



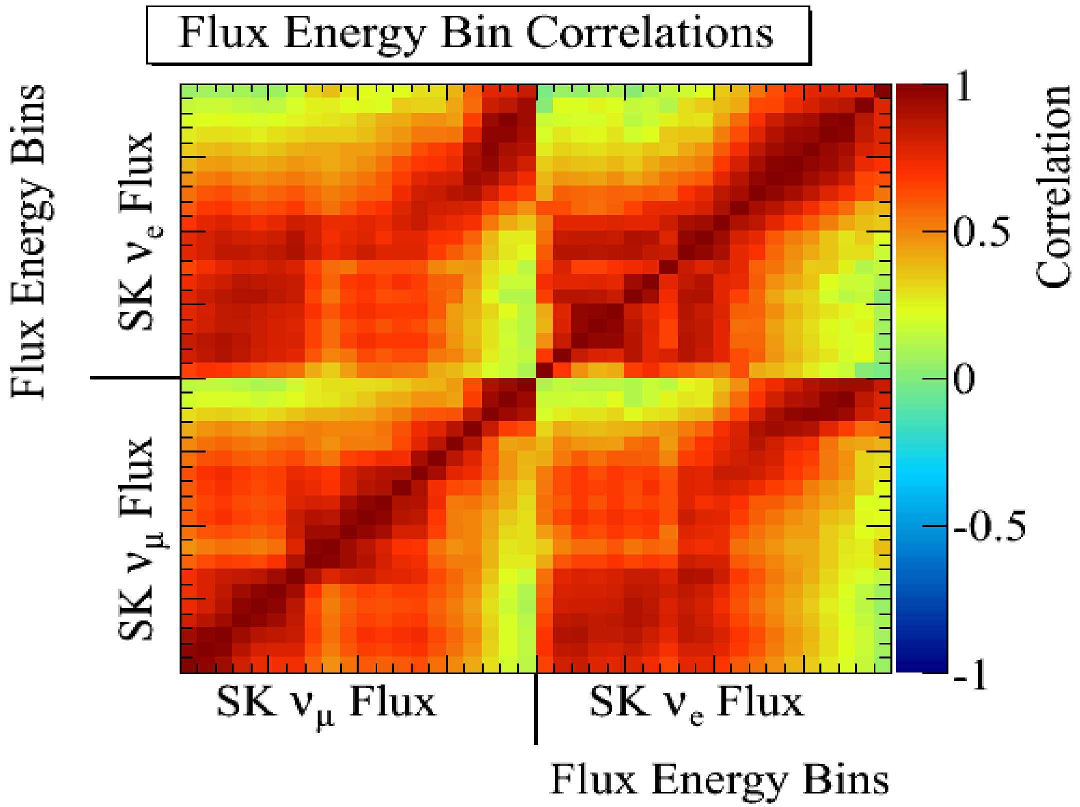
ν_e Flux Uncertainties

The low energy ν_μ and ν_e flux originate from the same pions

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Flux uncertainties have large correlations



Can constrain the ν_e background by measuring ν_μ interactions

Need to make sure the difference in the ν_e and ν_μ cross sections are understood (see next talk by K. McFarland)

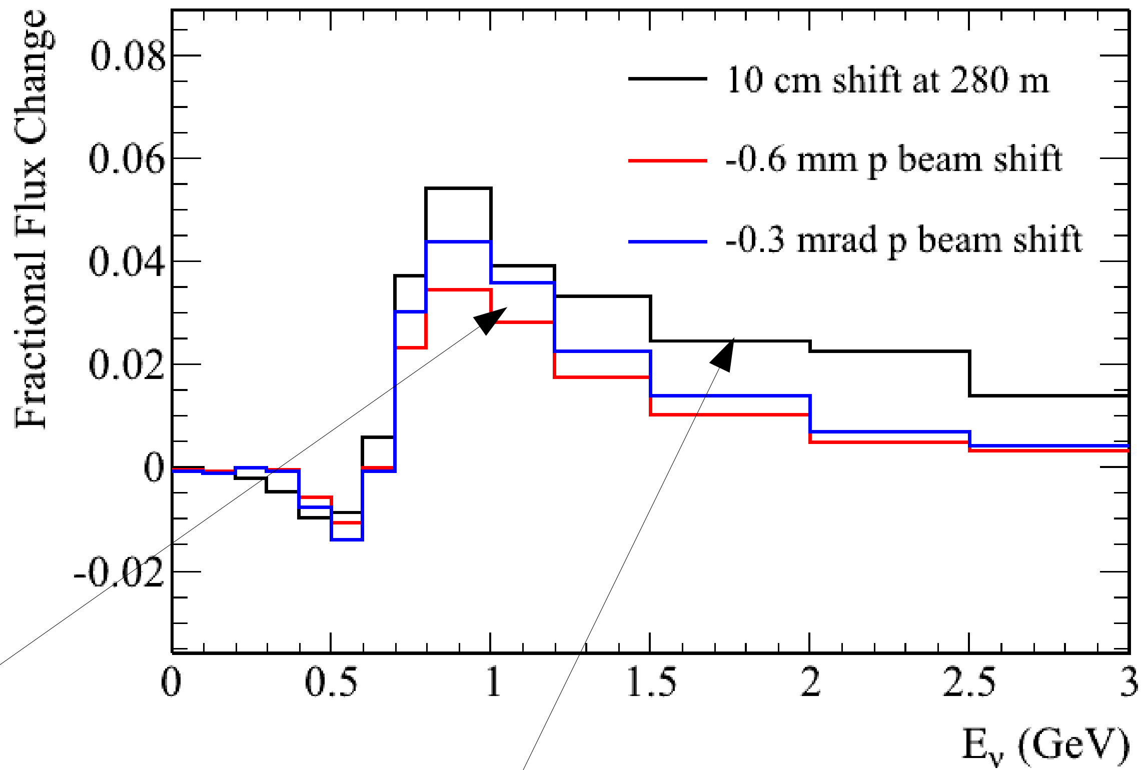
Off-axis Uncertainties

Introduces a shape uncertainty corresponding to a shift in the peak energy

~10 MeV shift for errors shown here

Correlated effect for neutrino and anti-neutrino running

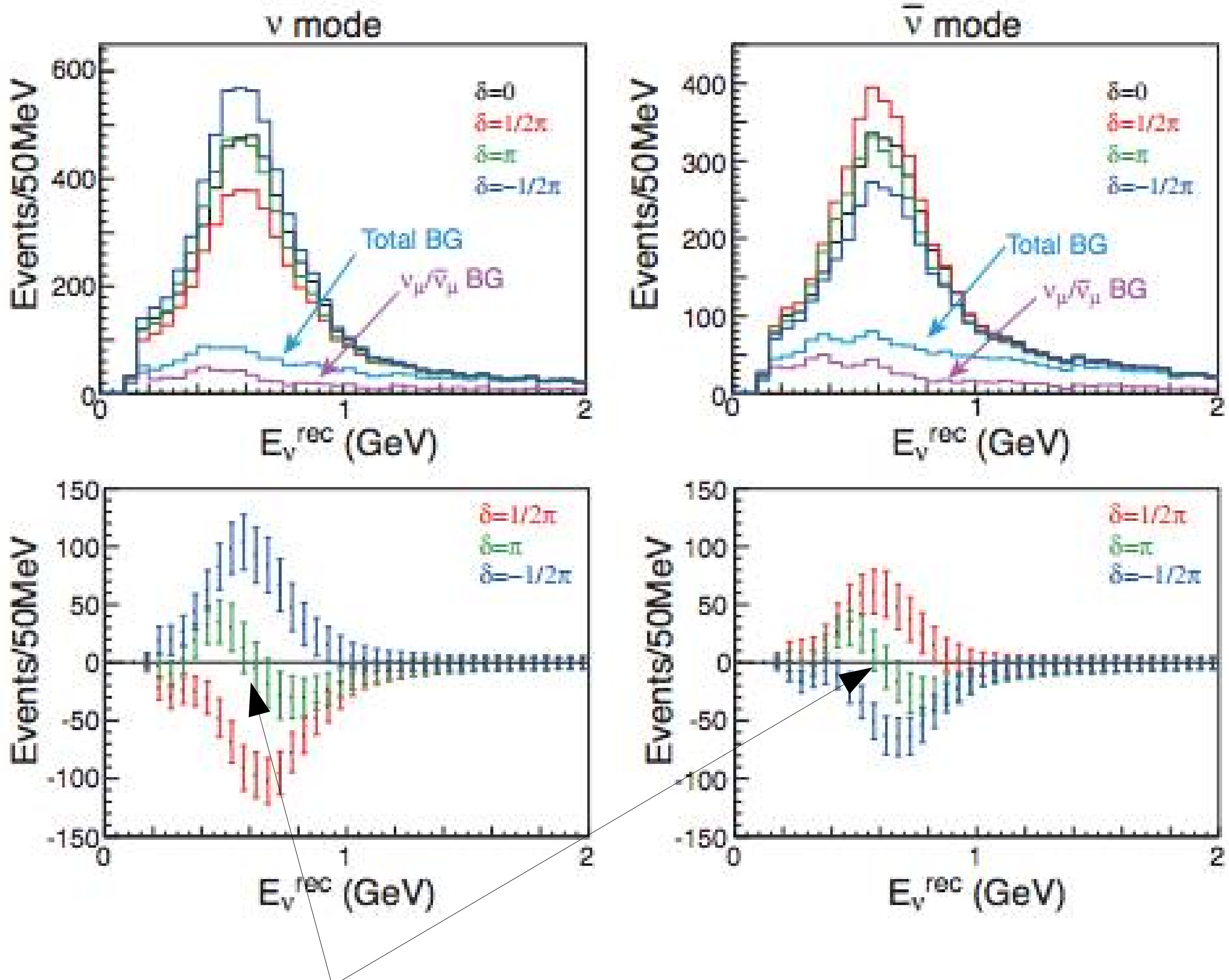
Uncertainty from proton beam monitor measurements are dominant source



INGRID can currently constrain direction to ~10 cm

Can also look for peak shift at ND280
- Current TPC momentum scale error is ~10 MeV/c at 600 MeV/c

Effect of Off-axis Angle Uncertainty



From Hyper-K LOI

Energy dependent off-axis angle type error may increase degeneracy between solutions near δ=0 and δ=π

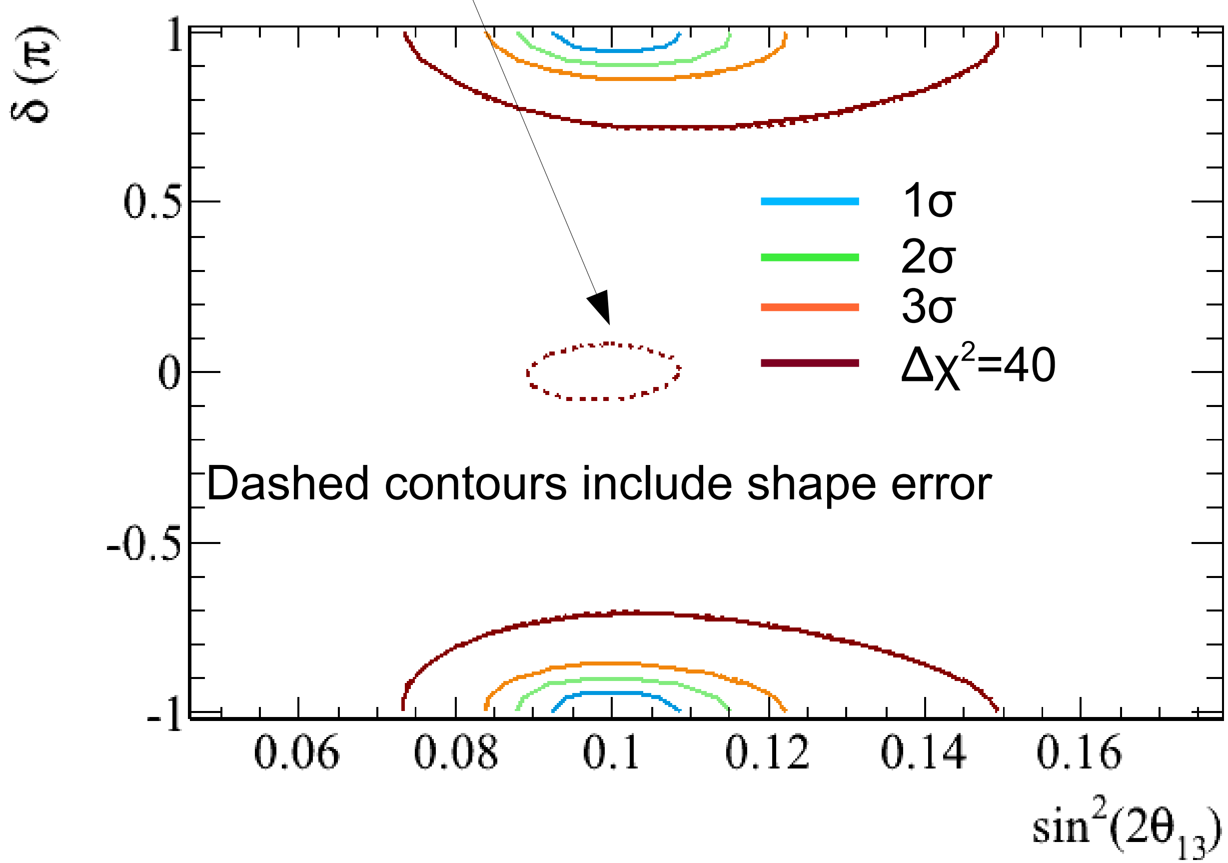
Off-axis Study

Study using Hyper-K LOI MC

Add off-axis angle type shape error to the χ^2 (based on current p beam errors)

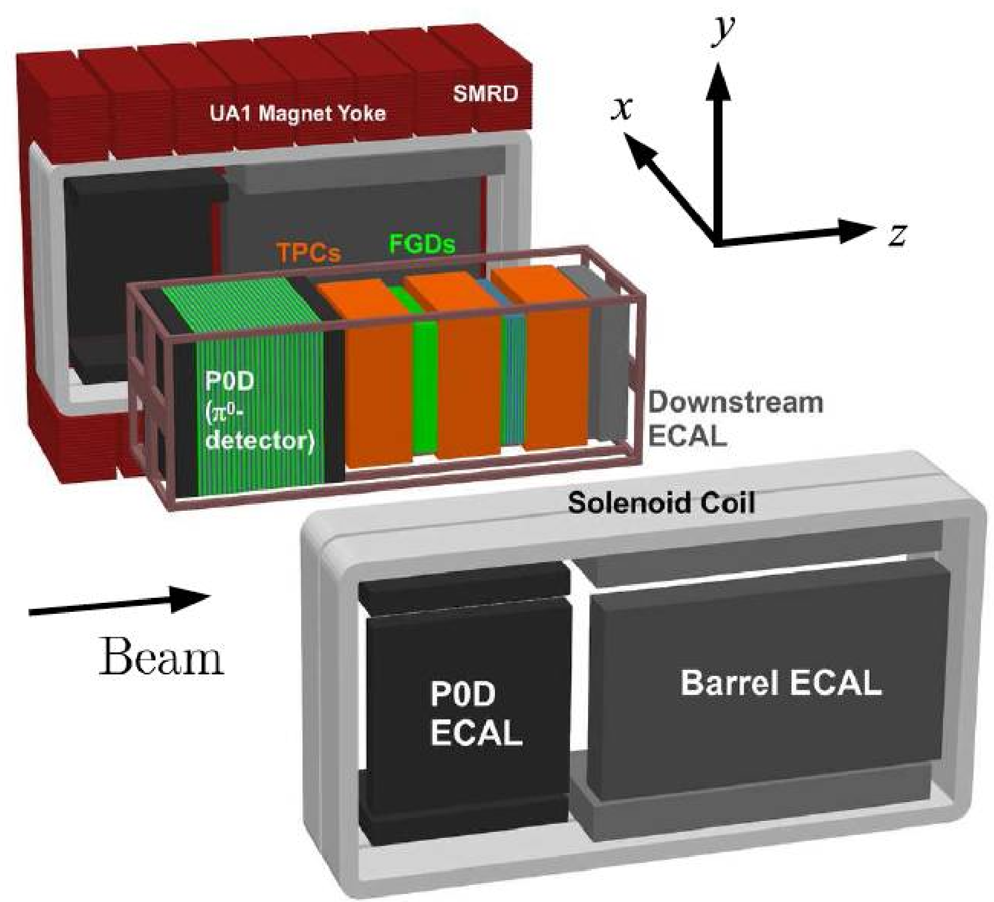
Look at allowed regions for fit to sample with $\sin^2(2\theta_{13})=0.1$, $\delta=\pi$

Second minimum is lowered – should study in combination with other shape error sources and check sensitivities



ND280 (Near) Off-axis Detector

- 0.2 T UA1 magnet
  - Can measure the momentum of charged particles



Used in current osc. analysis

- Fine Grained Detectors (FGD) – neutrino target mass and tracking
- Time Projection Chambers (TPC) – momentum and dE/dx measurements

Important for ν_e and NCπ^0 measurements

- Electromagnetic calorimeters
- P0D – water and scintillator layers, water can be removed for subtraction analysis

ND280 Tracker ν_μ Sample

Select events with a μ candidate

Interaction in FGD1, tracked in TPC2

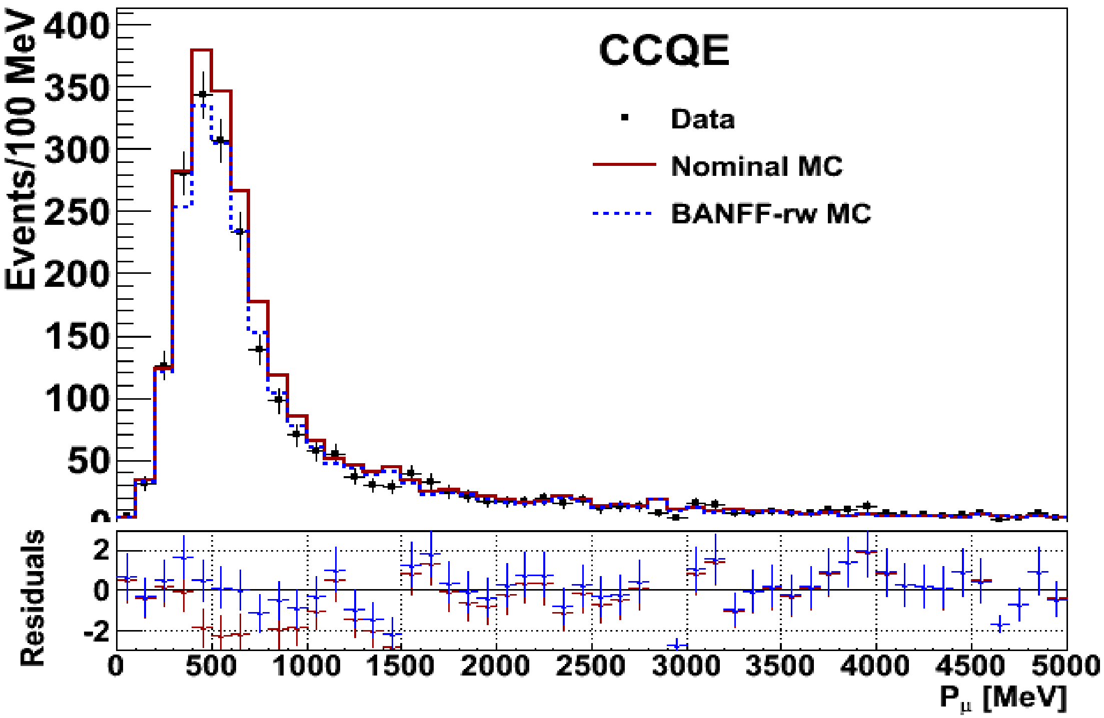
Split into CCQE like and CCnonQE like samples

~2400 CCQE-like events for ~50 kWx10^7 sec exposure (plenty of stats)

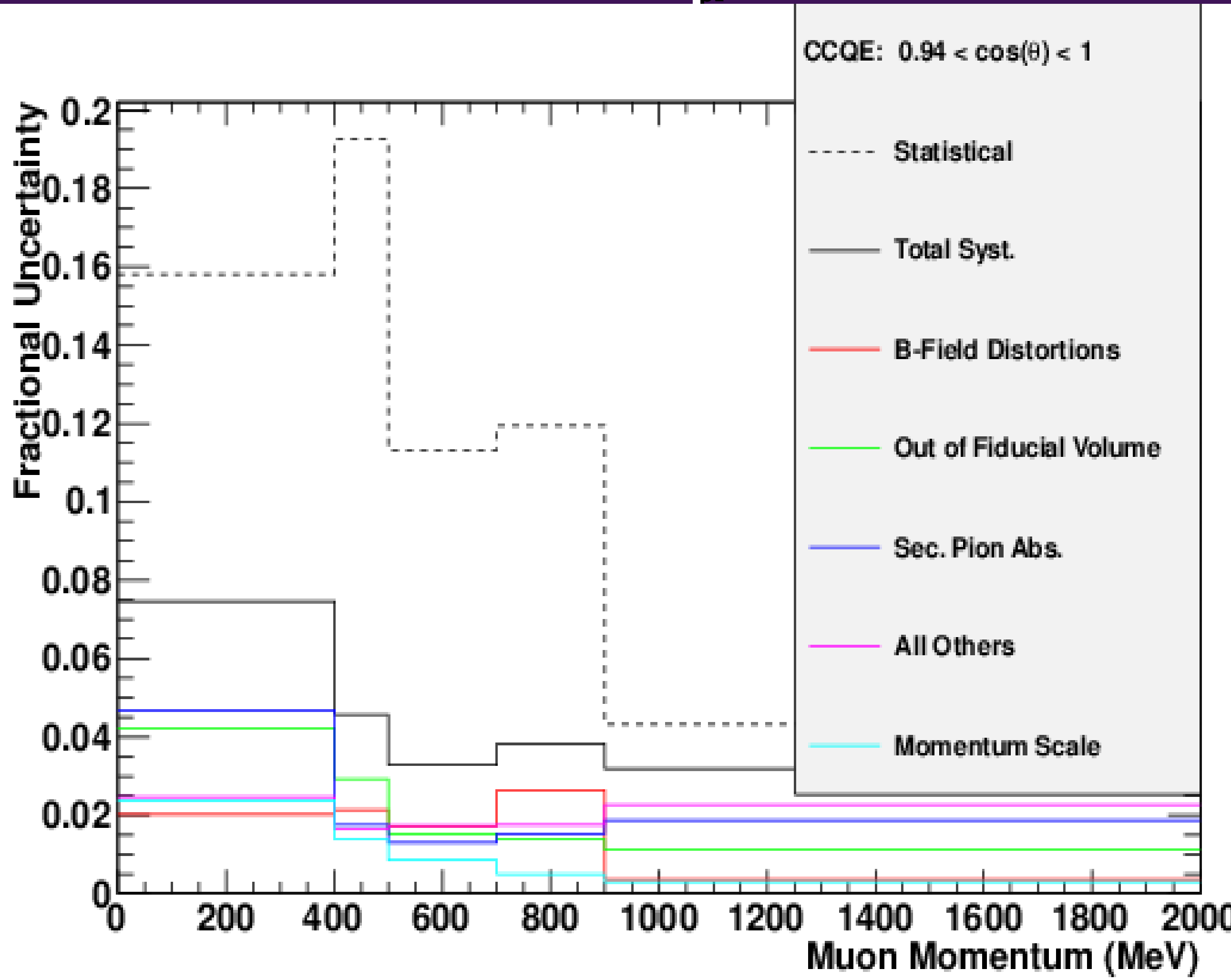
- CCQE purity of 72%

Charge mis-id less <2% for tracks with p<2.6 GeV/c

Fits to this sample constrain the flux and cross section models for the current T2K oscillation analyses



ND280 Tracker ν_μ Uncertainties



Dominant error sources are: out of FGD backgrounds, B field uncertainties, pion absorption uncertainties

Better than 5% on the normalization is already achieved

Momentum or energy dependent errors will evolve with time

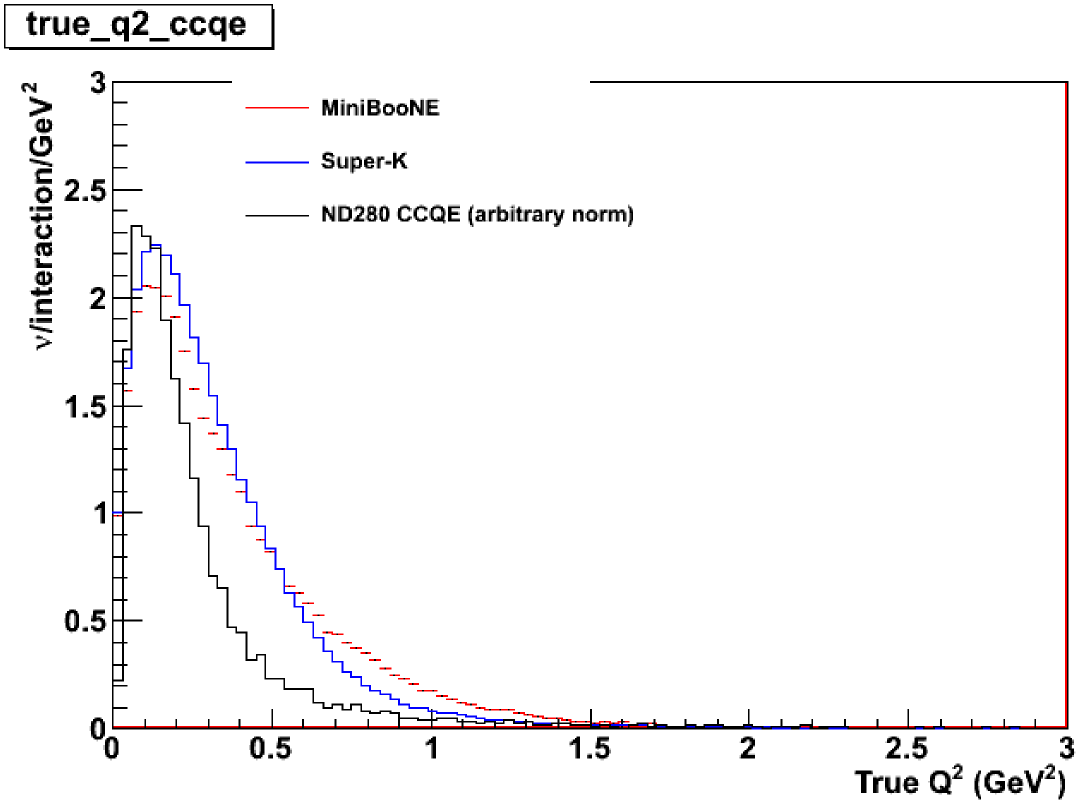
ND280/SK Differences

Target material (see slide 5) – FGD1 interactions are on C. FGD2 contains water layers

- Need near detector measurements on O to get <5% on nuclear target related cross section uncertainties

Backwards tracks – so far only forward going tracks are used (limits high Q^2 component at ND280)

Analyses with backward tracks will come on line as relative detector timing is understood



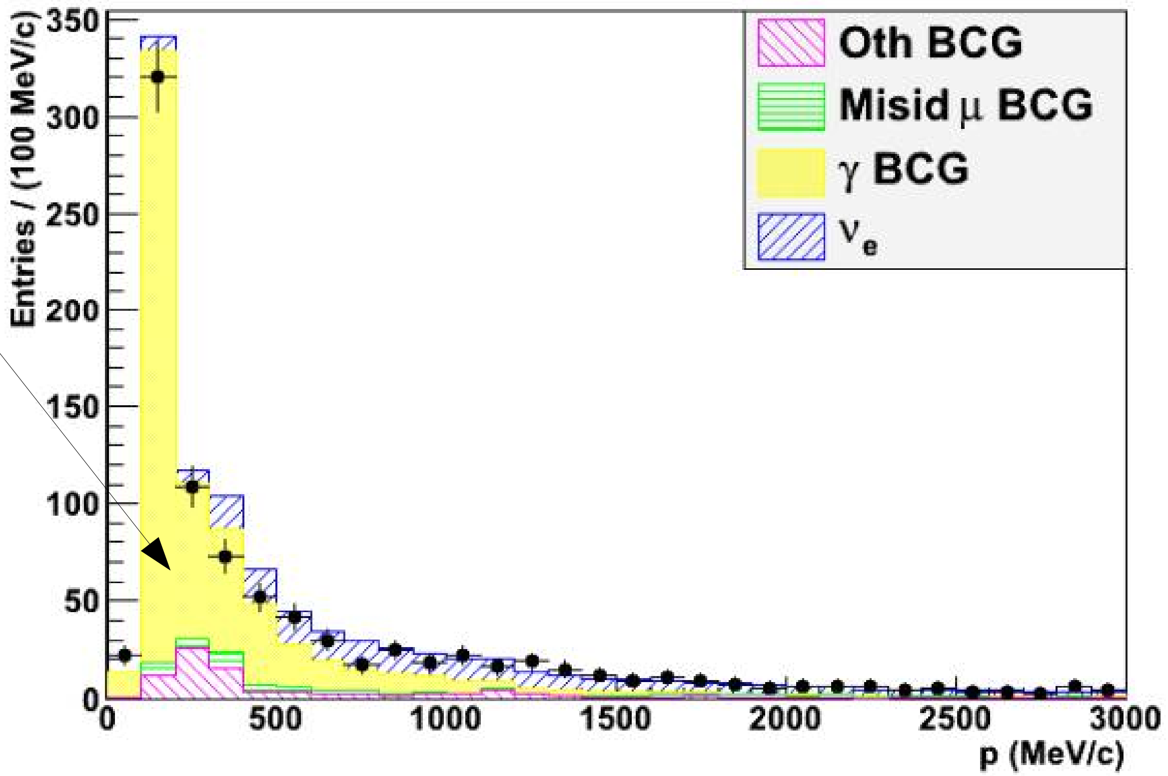
Other ND280 Samples

Measuring the ν_e background directly at ND280 with tracker events

Current analysis has a large background at low e momentum from photons

Can this be significantly reduced?

Better constraint than measurements of ν_μ interactions?



NCπ^0 measurements are ongoing at ND280 in P0D and tracker

- Same issues with target material and angular acceptance
- Could NC backgrounds be constrained by far detector measurements? (same coverage, target material)

Conclusions

T2K has taken significant steps to achieving the levels of systematic uncertainty that will be necessary for a CP violation measurement

Flux uncertainties should be at 5% level or better with NA61 replica target data

- Need careful study of neutrinos in anti-neutrino running
- And energy dependent off-axis angle type errors

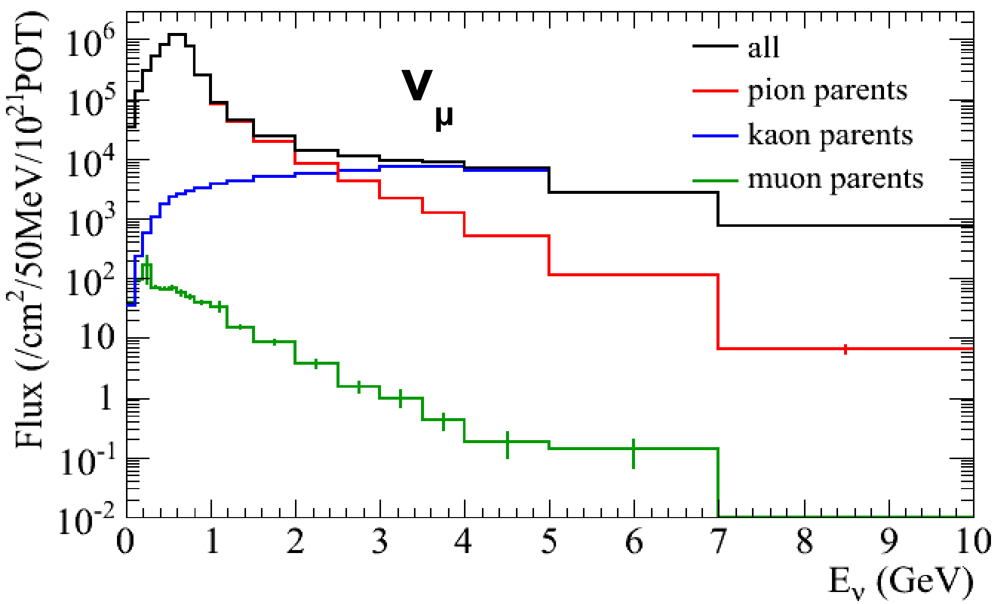
Near detector samples already have large statistics and allow for reduction of total errors to the 10% level

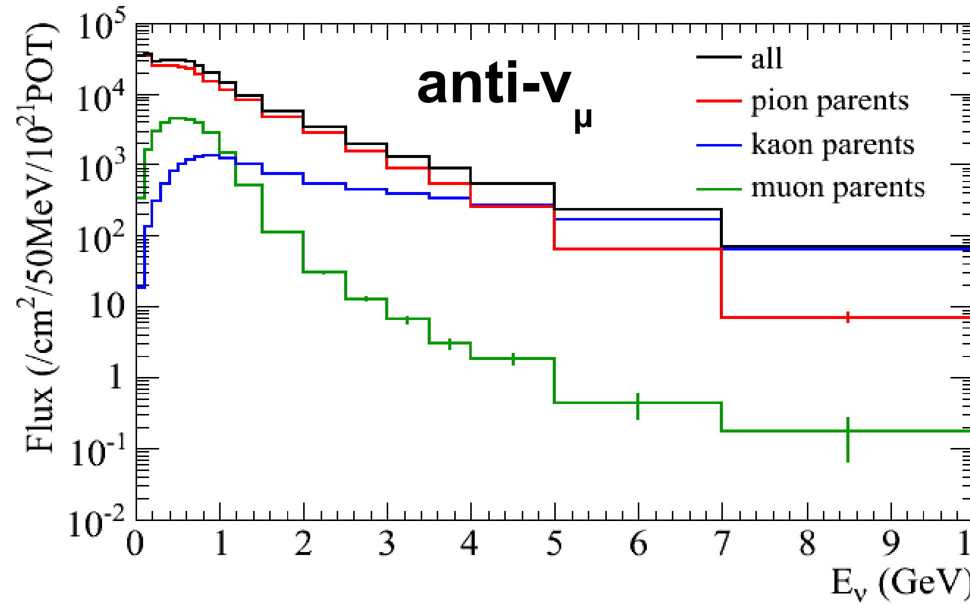
- Need to understand energy dependent constraints
- Measurements on O are important
- Need to improve angular coverage
- Ongoing work for ν_e and $NC\pi^0$ measurements important for background

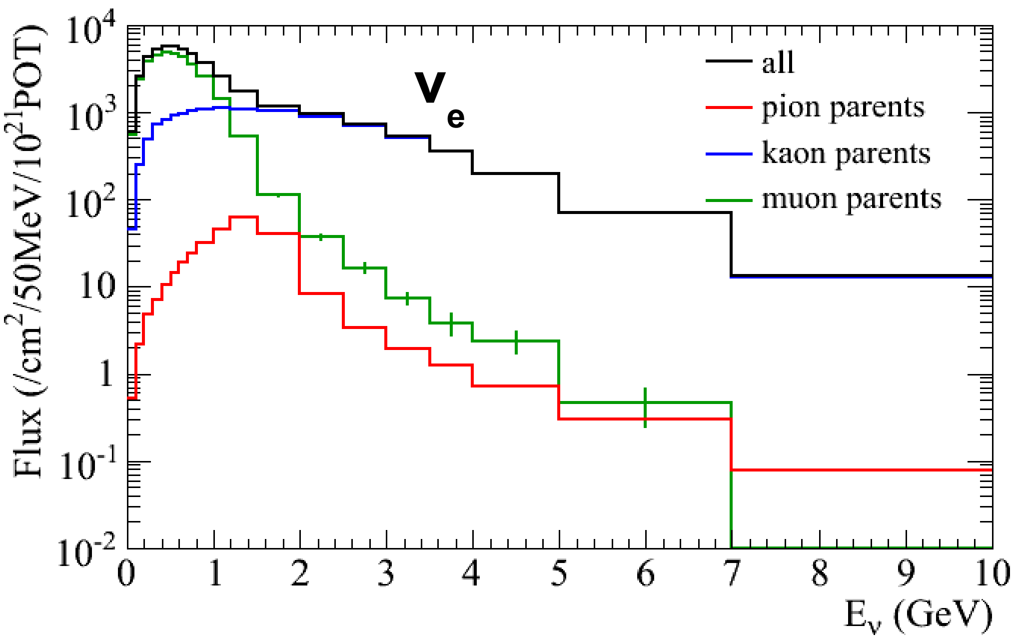
See next talk for details on cross section modeling uncertainties

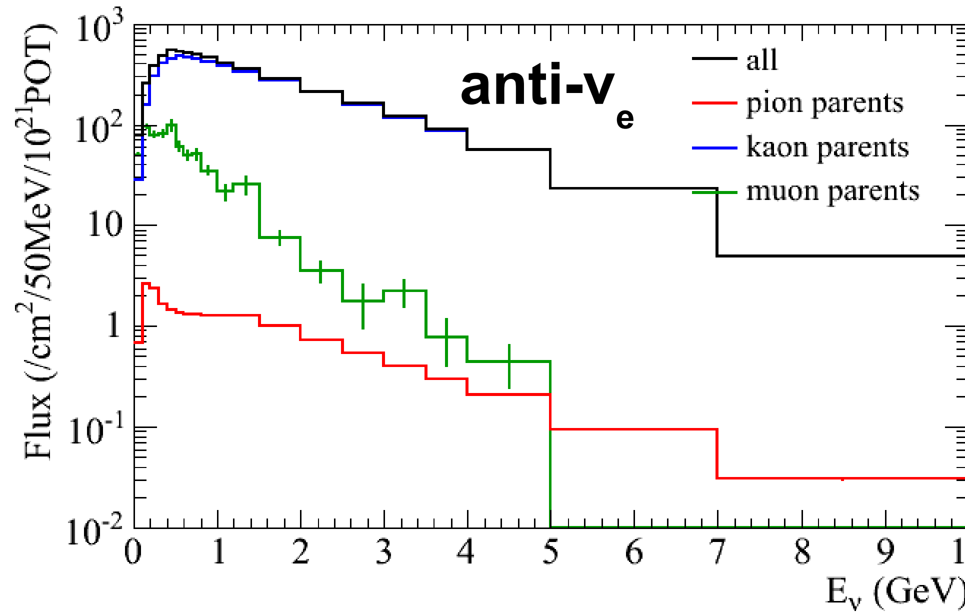
Extra Slides

T2K Flux (Neutrino Mode at SK)

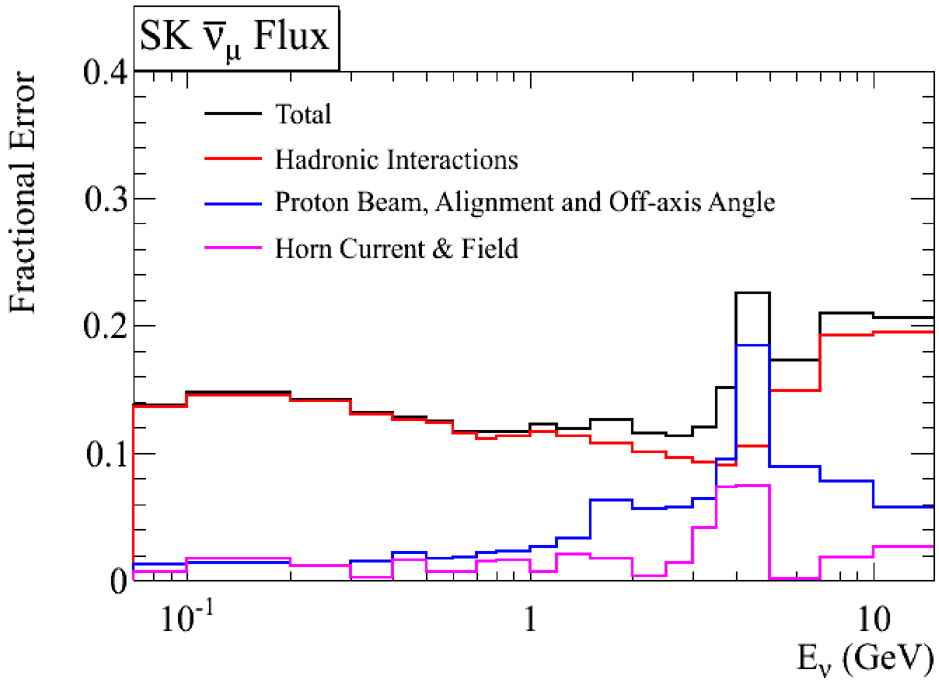


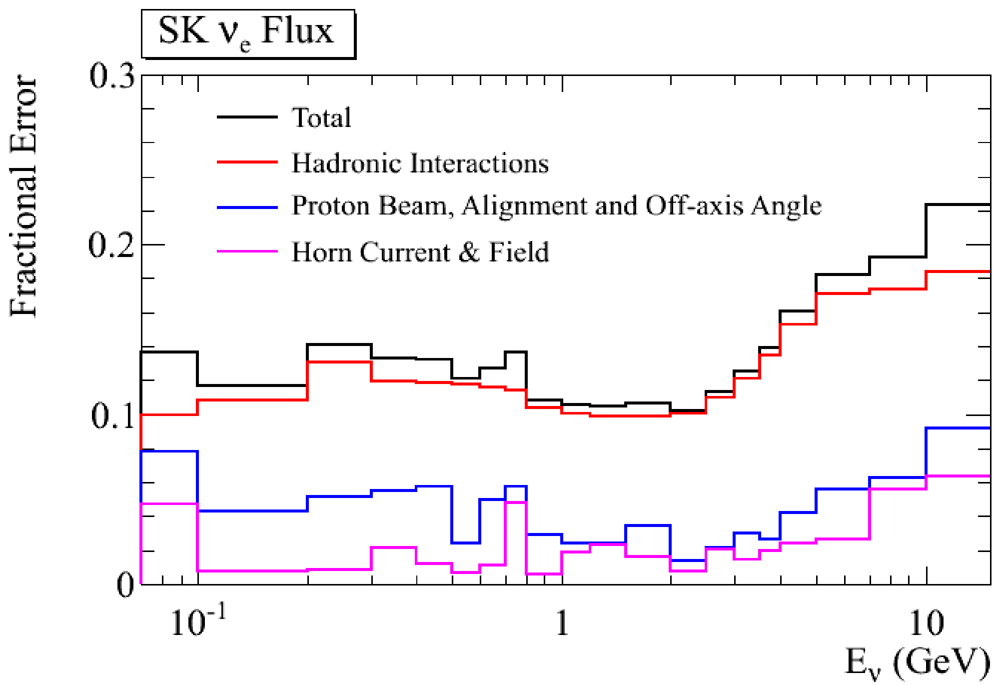


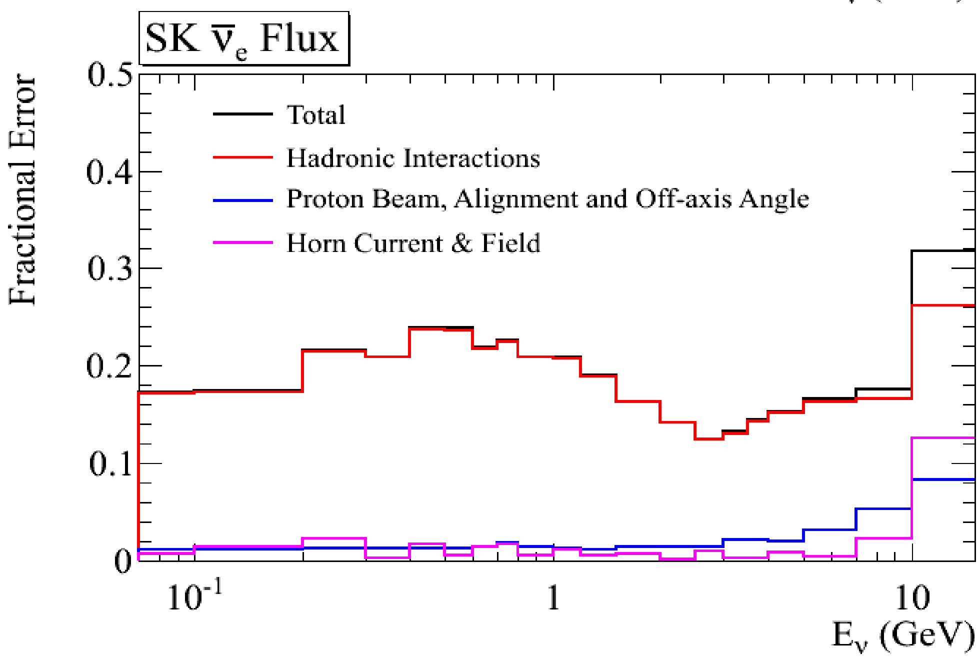




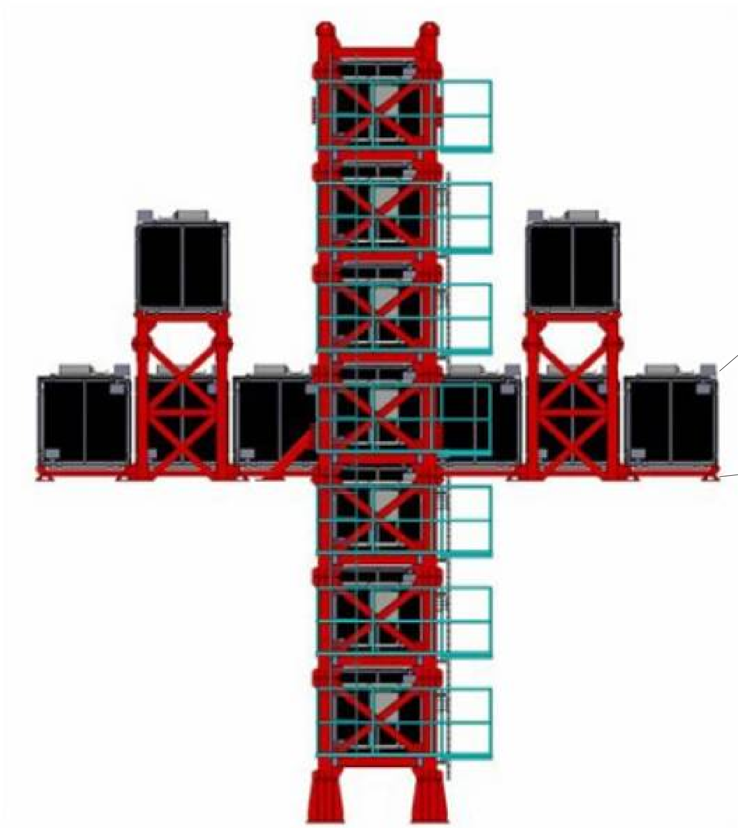
Flux Errors

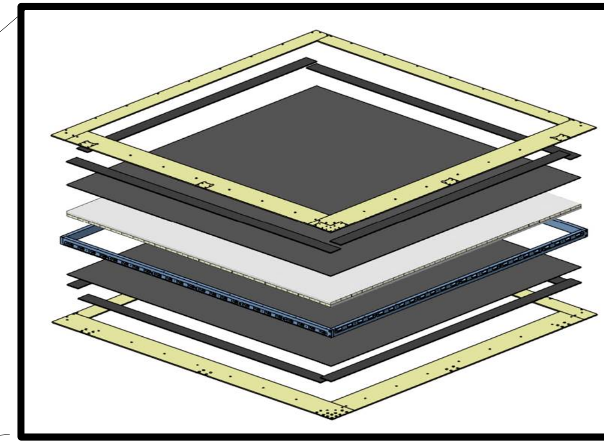

SK $\bar{\nu}_\mu$ Flux
Fractional Error
0.4
0.3
0.2
0.1
0
Total
Hadronic Interactions
Proton Beam, Alignment and Off-axis Angle
Horn Current & Field
10^{-1}
1
10
E_ν (GeV)

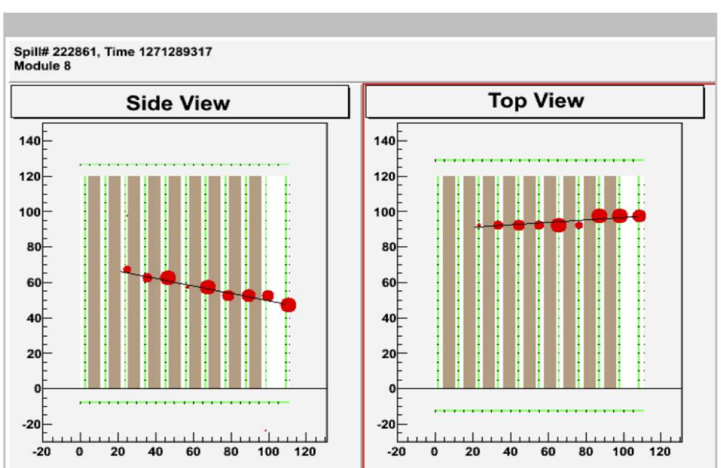

SK ν_e Flux
Fractional Error
0.3
0.2
0.1
0
Total
Hadronic Interactions
Proton Beam, Alignment and Off-axis Angle
Horn Current & Field
10^{-1}
1
10
E_ν (GeV)


SK $\bar{\nu}_e$ Flux
Fractional Error
0.5
0.4
0.3
0.2
0.1
0
Total
Hadronic Interactions
Proton Beam, Alignment and Off-axis Angle
Horn Current & Field
10^{-1}
1
10
E_ν (GeV)

INGRID On-axis Detector

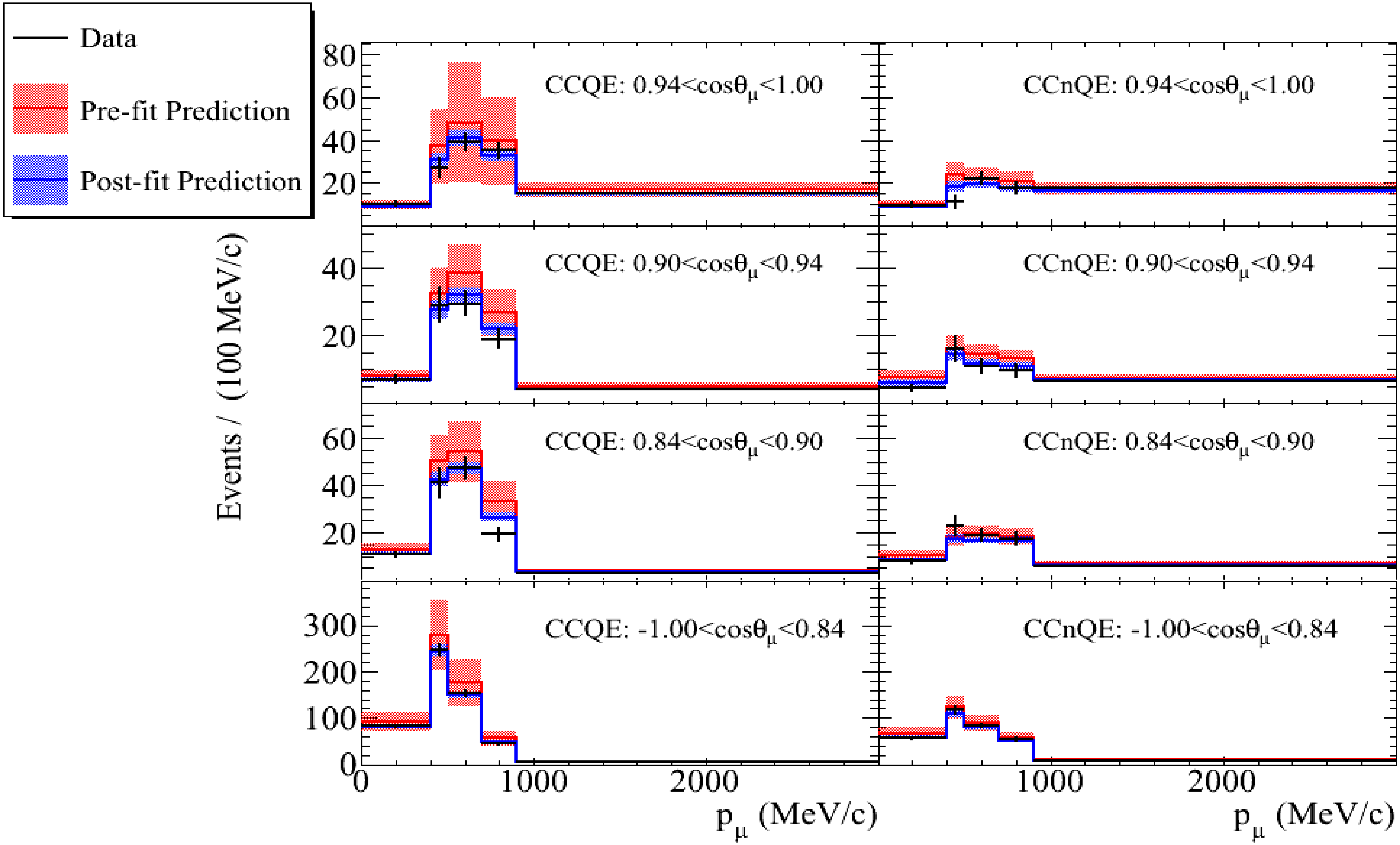






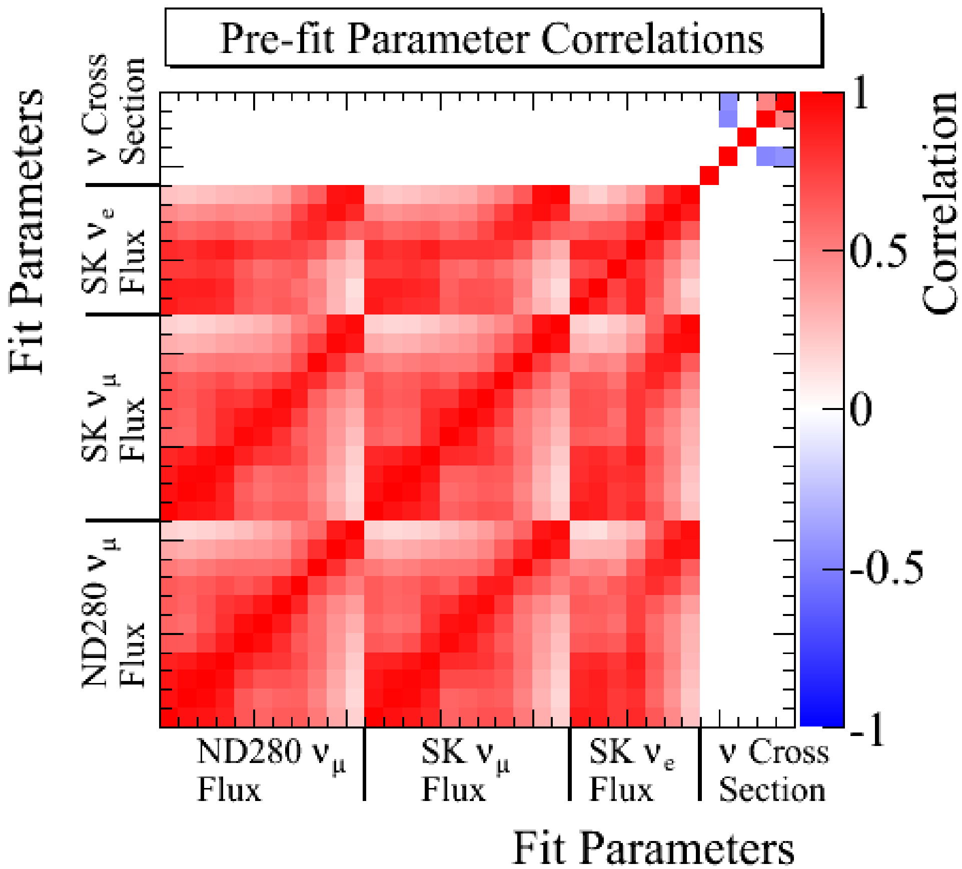
- On-axis neutrino detector at 280 m from target
- 16 modules (14 in cross configuration)
- Modules consist of iron and scintillator layers
- Measures neutrino beam profile and rate

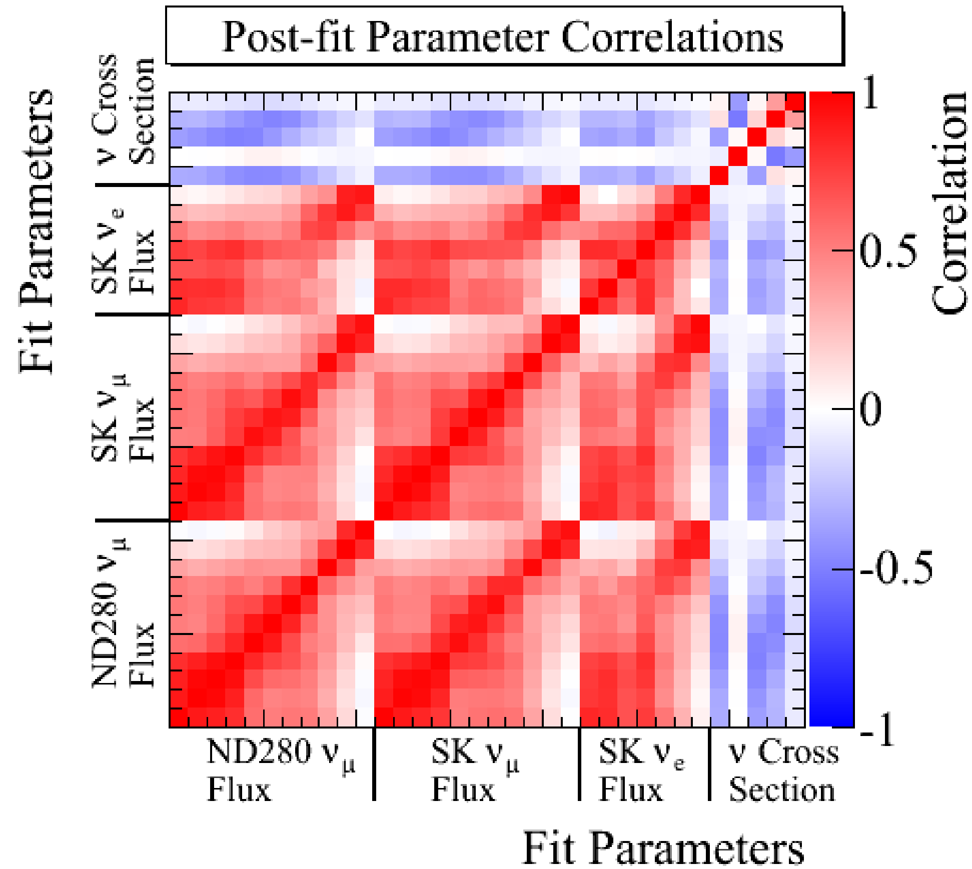
ND280 Fit



Data
Pre-fit Prediction
Post-fit Prediction
CCQE: 0.94<cosθμ<1.00
CCnQE: 0.94<cosθμ<1.00
CCQE: 0.90<cosθμ<0.94
CCnQE: 0.90<cosθμ<0.94
CCQE: 0.84<cosθμ<0.90
CCnQE: 0.84<cosθμ<0.90
CCQE: -1.00<cosθμ<0.84
CCnQE: -1.00<cosθμ<0.84
Events / (100 MeV/c)
pμ (MeV/c)
pμ (MeV/c)

ND280 Fit Constraint (Correlations)





ND280 Fit, Interaction Constraints

	Prior Value and Uncertainty	Fitted Value and Uncertainty
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

(Blue) Prior value and uncertainty from fit to MiniBooNE single pion samples

(Yellow) Fitted value and uncertainty are propagated to the SK ν_e appearance fit

ND280 Fit Flux Constraint