Neutrino cross sections at the T2K near detectors

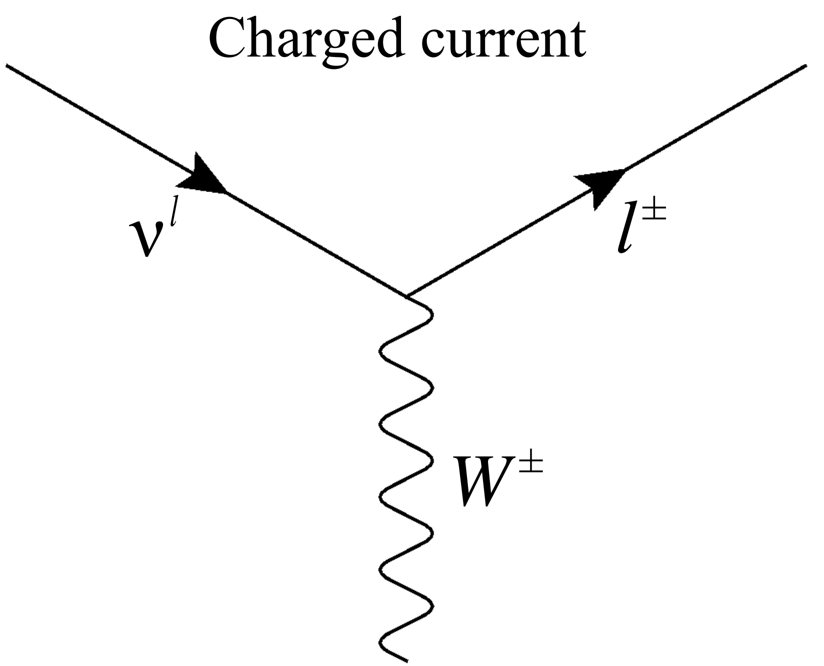
Mark Scott

CAP Congress 2014

16/06/14

How do neutrinos interact?

- Neutrinos – left handed, neutral leptons – interact through the weak nuclear force



- Neutral current – rely on hadronic side of interaction to provide information
- Charged current:
  - Identifying lepton flavour tells us the neutrino flavour
  - Lepton kinematics can give information on neutrino energy

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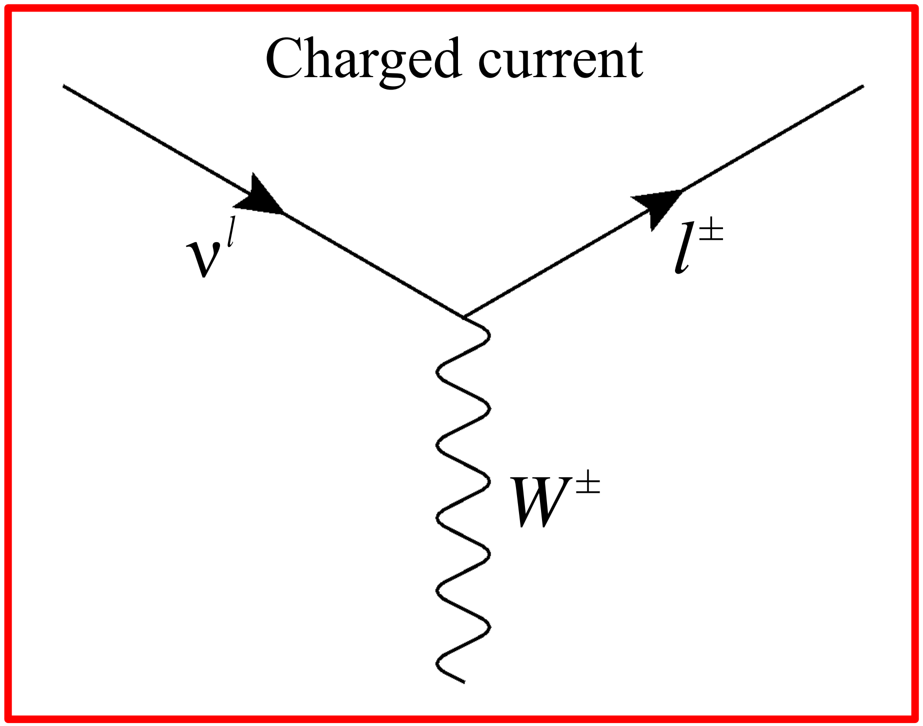

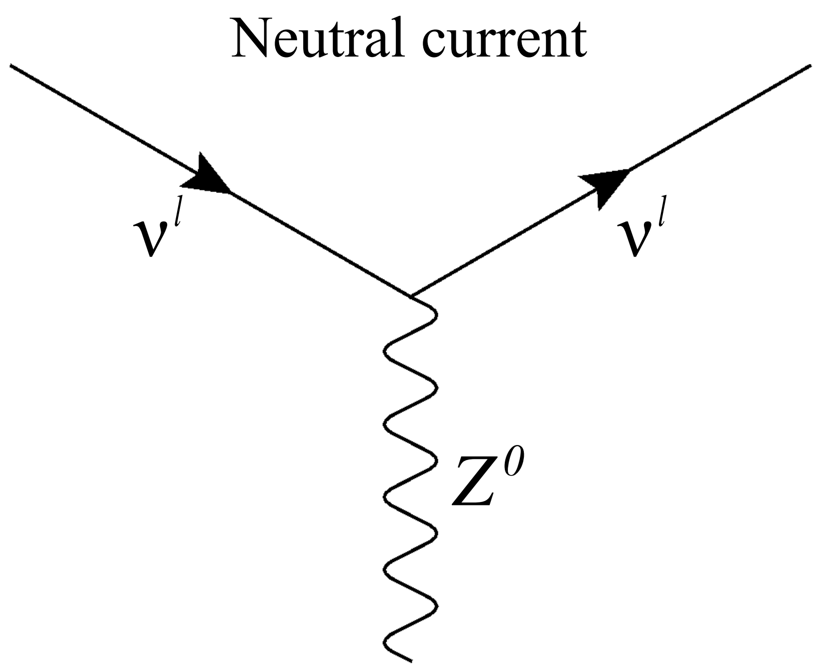

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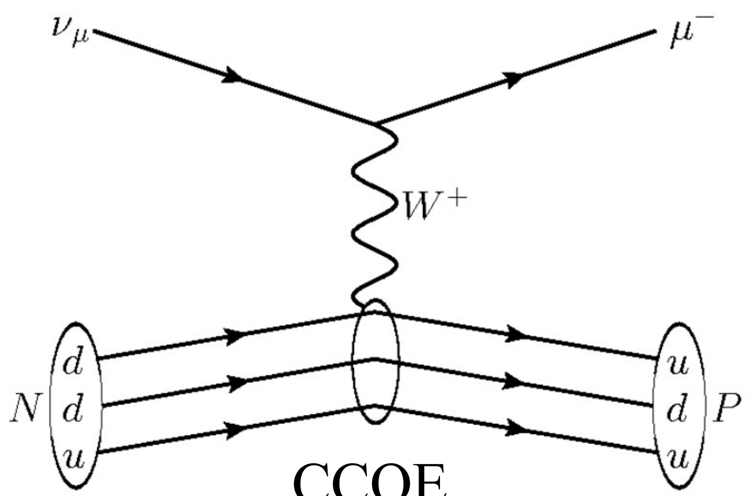
Types of neutrino interaction

Three principal types of neutrino interaction



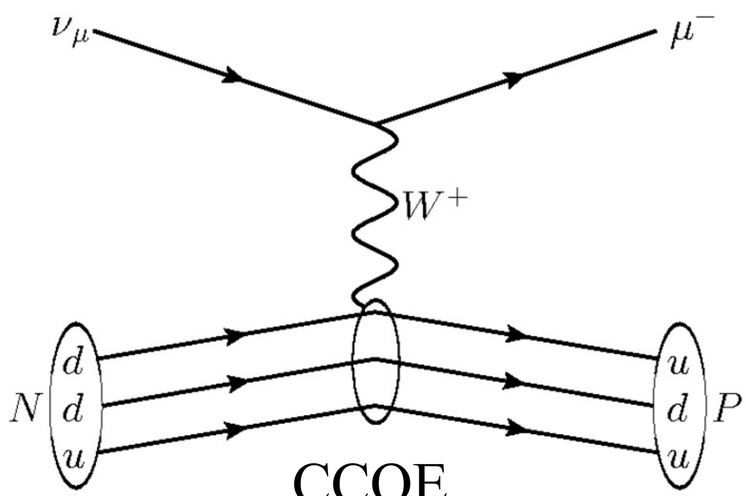
CCQE

Charged Current Quasi Elastic Scattering (CCQE)

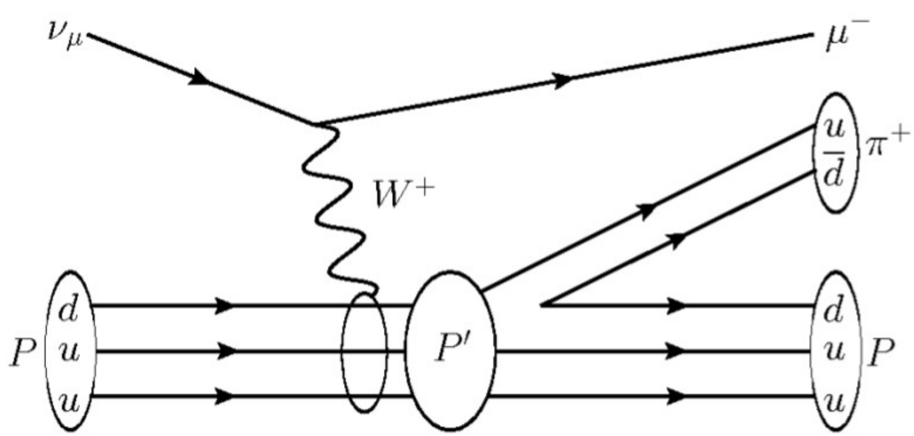
- Principal signal for most neutrino experiments
- Single muon and a proton enter the detector

Types of neutrino interaction

Three principal types of neutrino interaction



CCQE



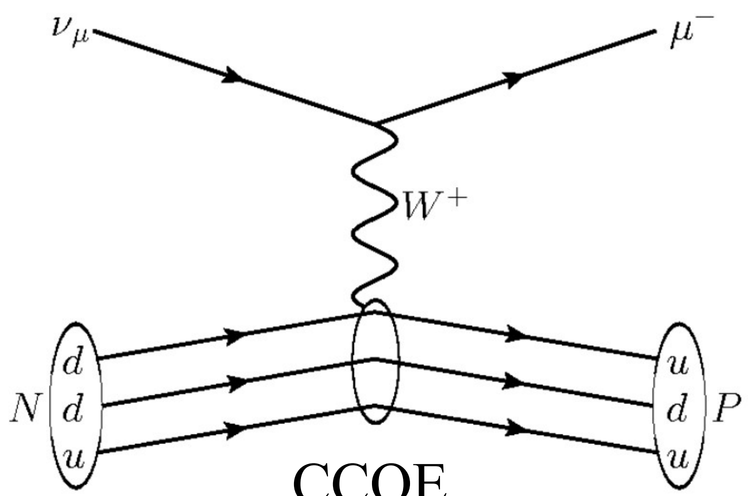
CCRES

Charged Current Resonant production (CCRES)

- Neutrino excites proton, decays by emitting a pion
- Might see a muon, pion and the proton

Types of neutrino interaction

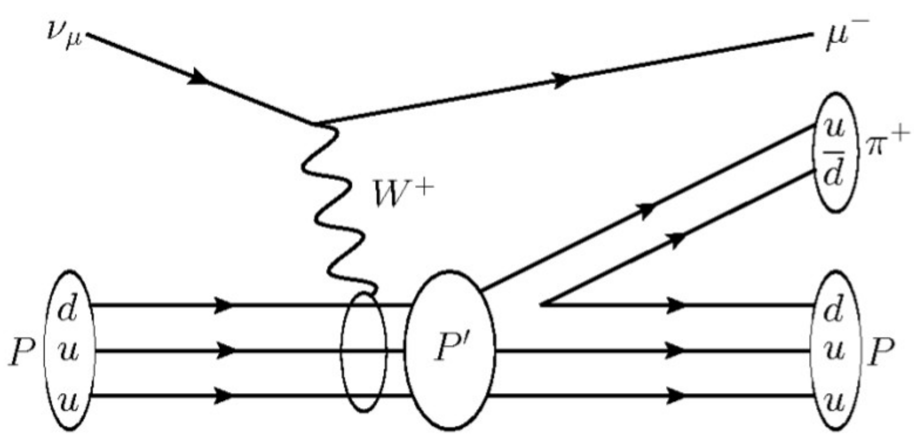
Three principal types of neutrino interaction



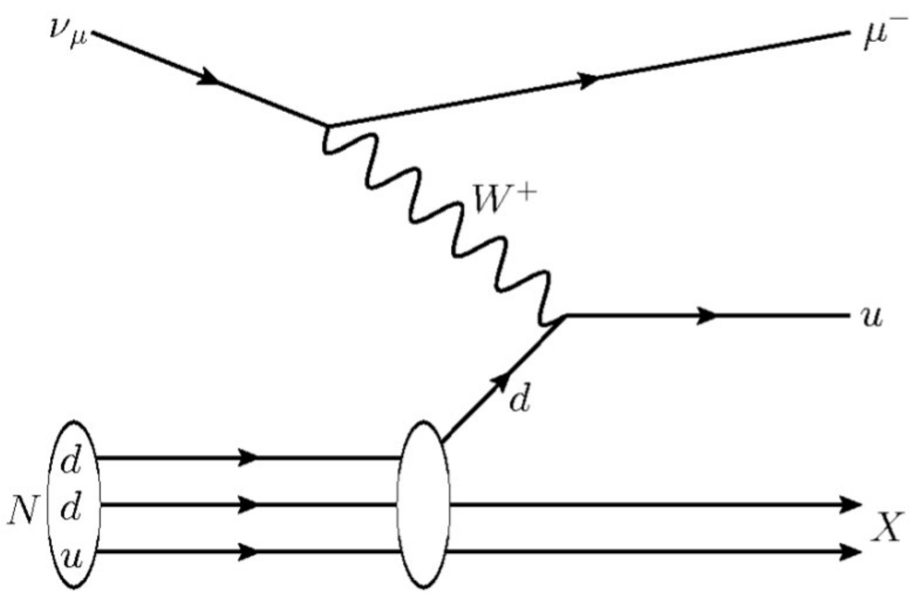
CCQE

Charged Current Deep Inelastic Scattering (CCDIS)

- Neutrino interacts with a quark
- Produces a shower of particles as the nucleus breaks apart



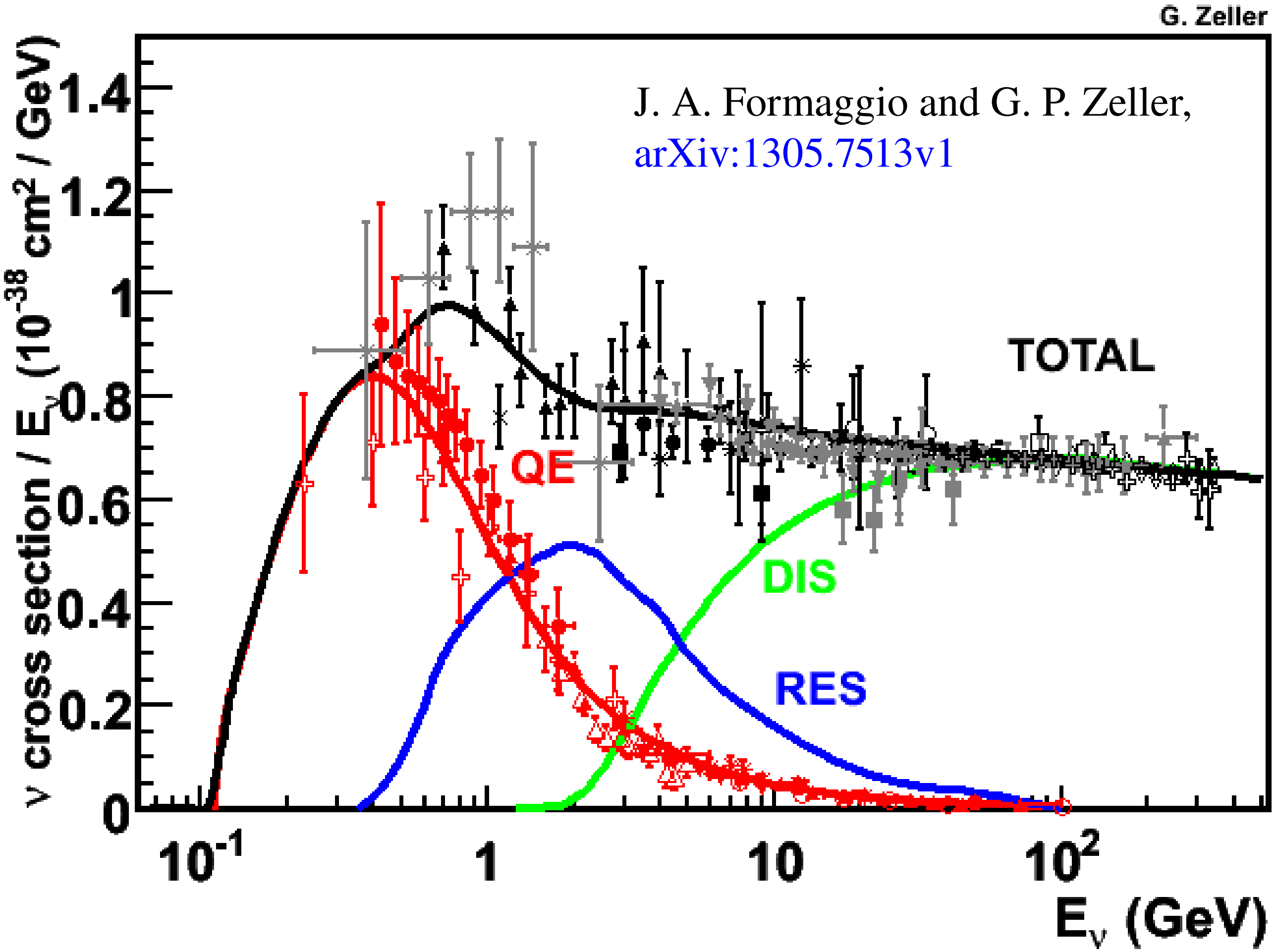
CCRES



CCDIS

Neutrino interactions - CC

- Neutrino charged current (CC) cross section measurements
- Consistent results at high energies (> 10 GeV)
- Disagreement below 1 GeV



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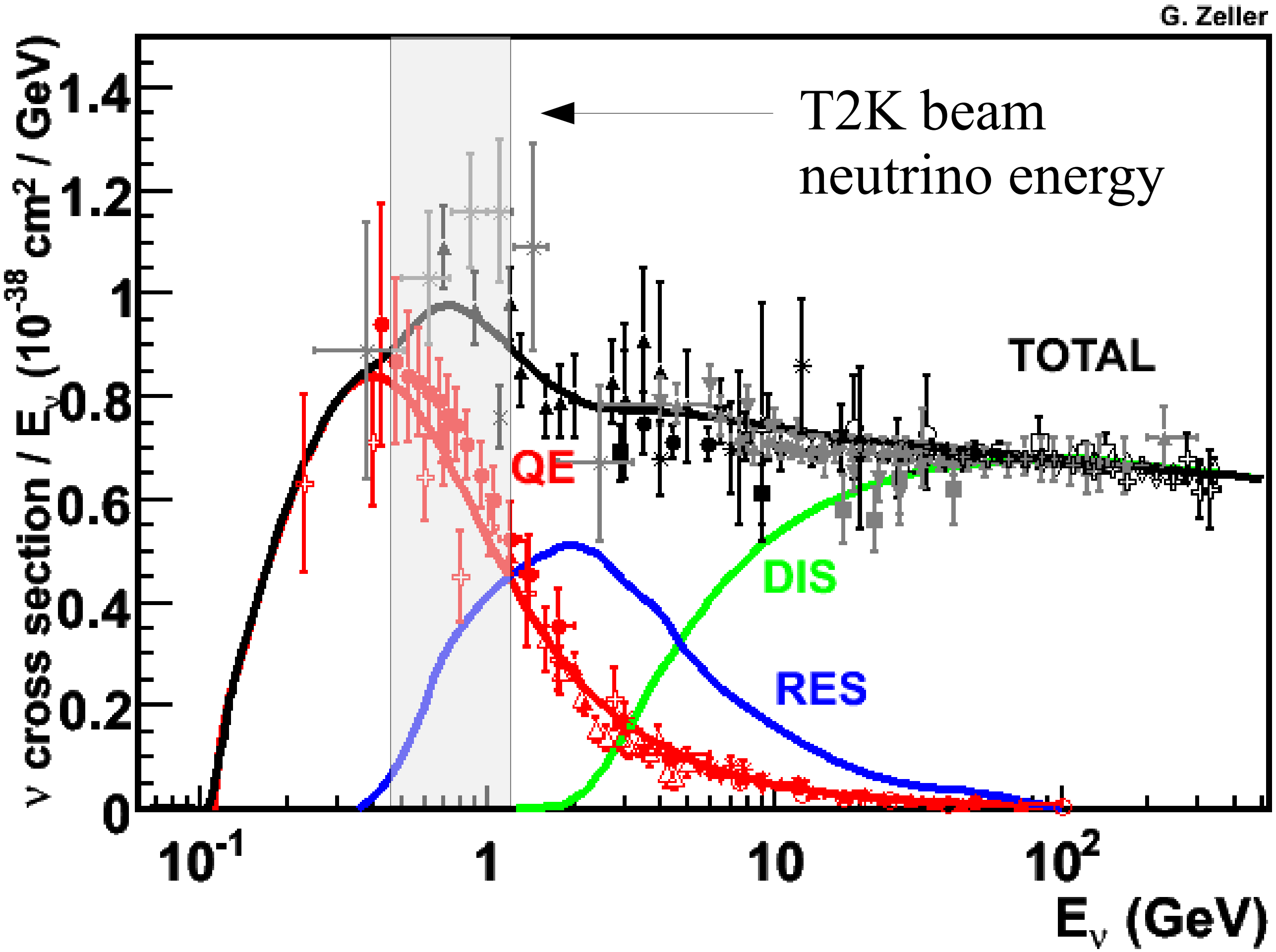
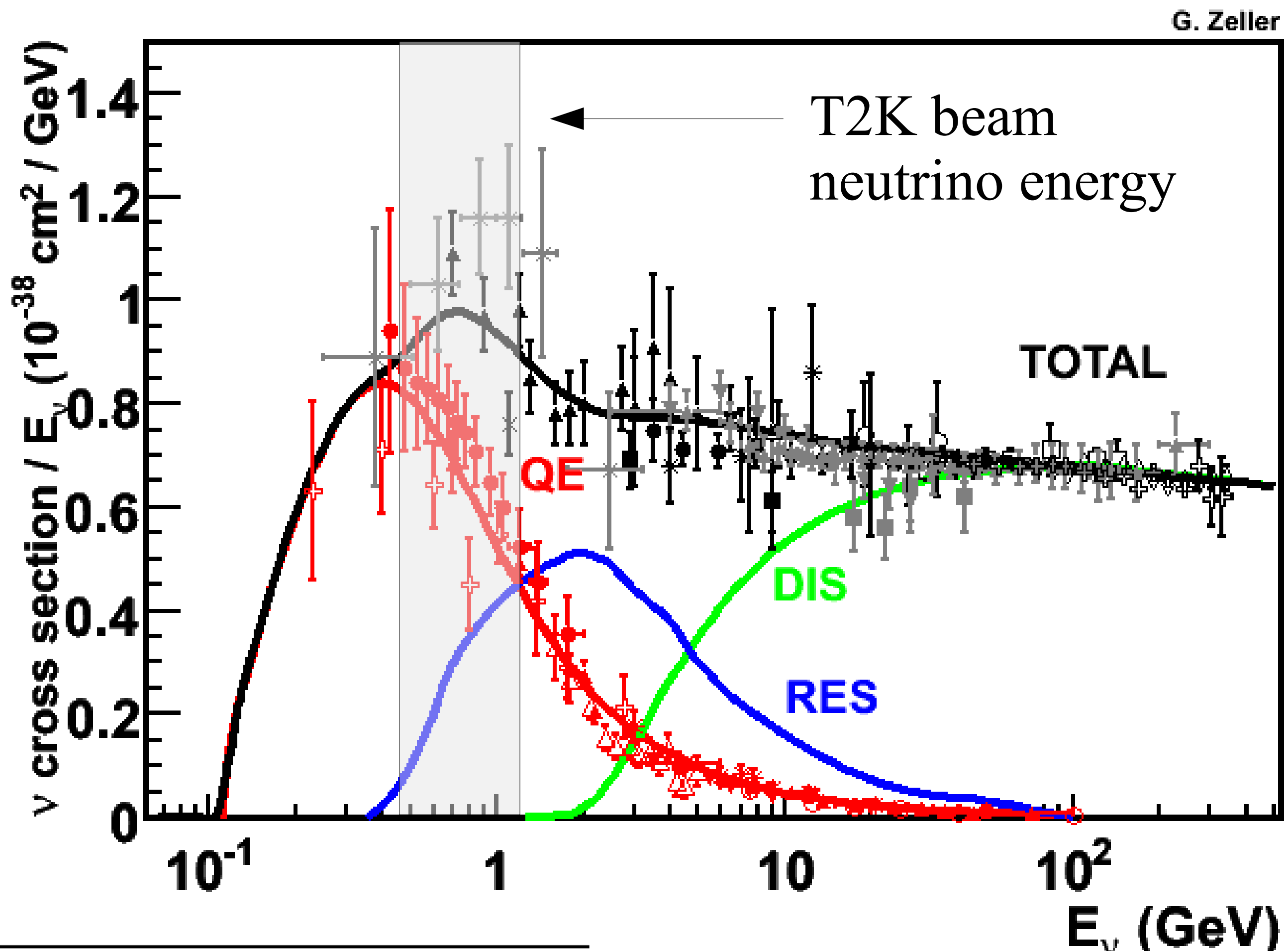


Neutrino interactions - CC

- Neutrino charged current (CC) cross section measurements
- Consistent results at high energies (> 10 GeV)
- Disagreement below 1 GeV
- In oscillation experiments:

N^{obs} = Flux * Cross section



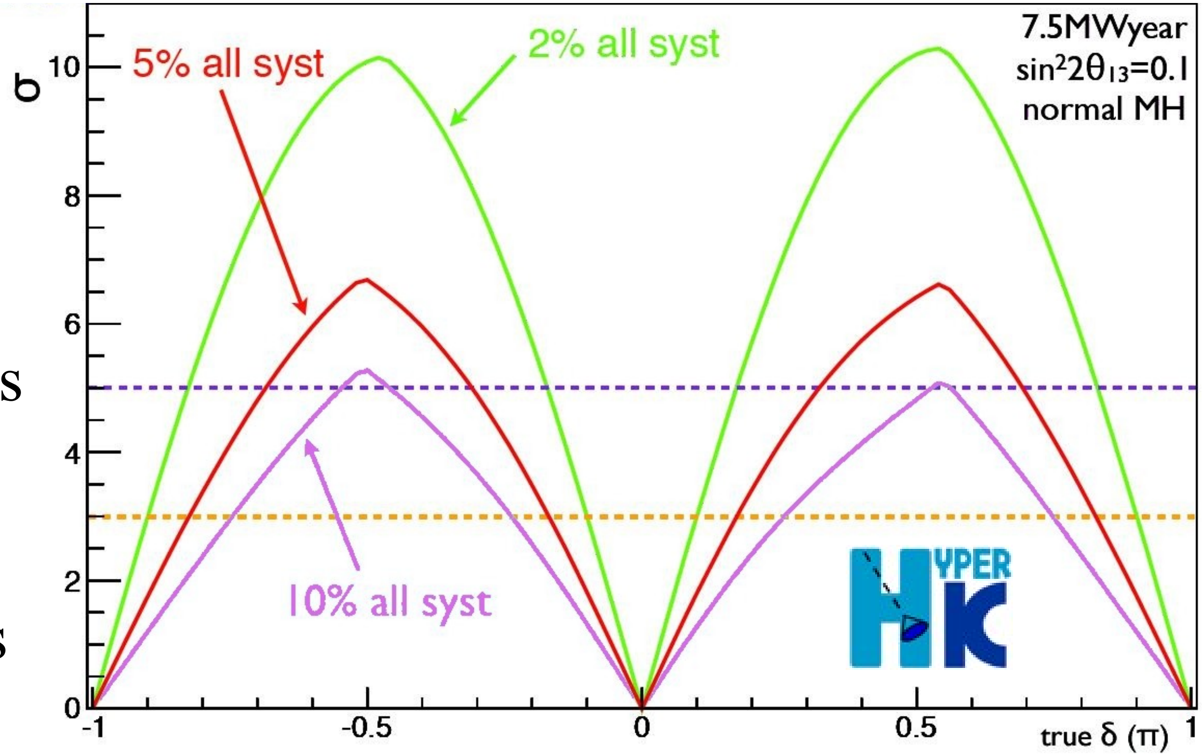
T2K Collaboration, Phys. Rev. Lett. 112, 181801, 2014

Source of uncertainty (number of parameters)	$\delta n^{\mathrm{exp}}_{\mathrm{SK}} / n^{\mathrm{exp}}_{\mathrm{SK}}$
ND280-independent cross section (11)	4.9%
Flux and ND280-common cross section (23)	2.7%
SK detector and FSI+SI systematics (7)	5.6%
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{21}, δ_{CP} (4)	0.2%
Total (45)	8.1%

- Cross section uncertainties are the dominant systematic in muon neutrino disappearance

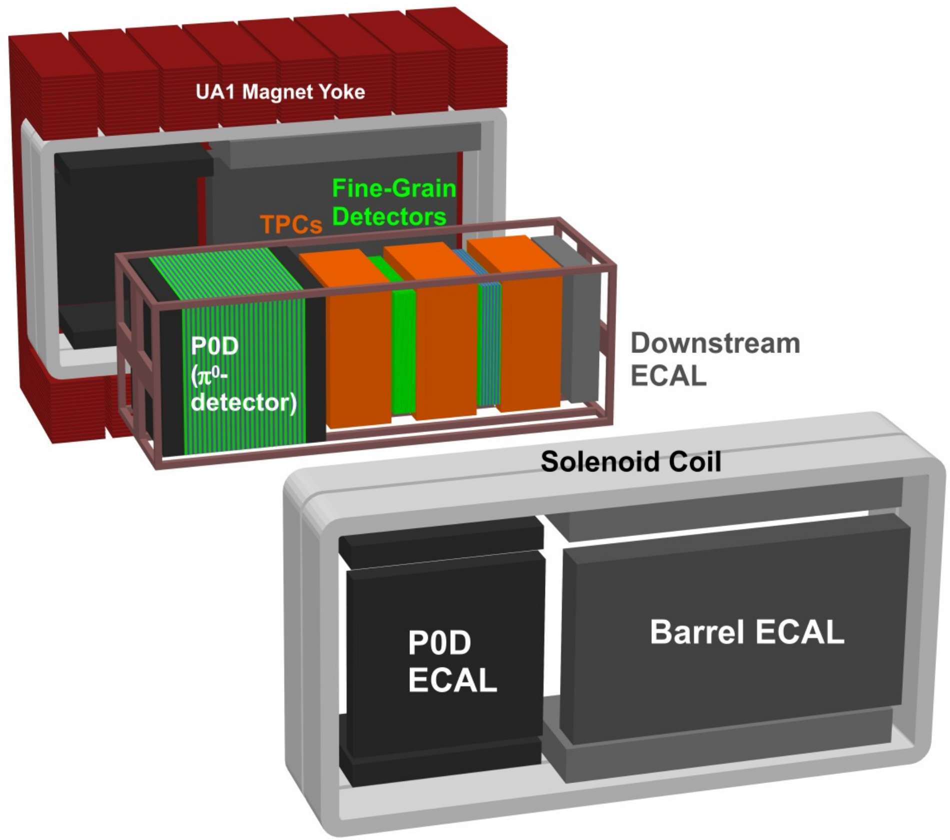
How does this affect oscillation physics?

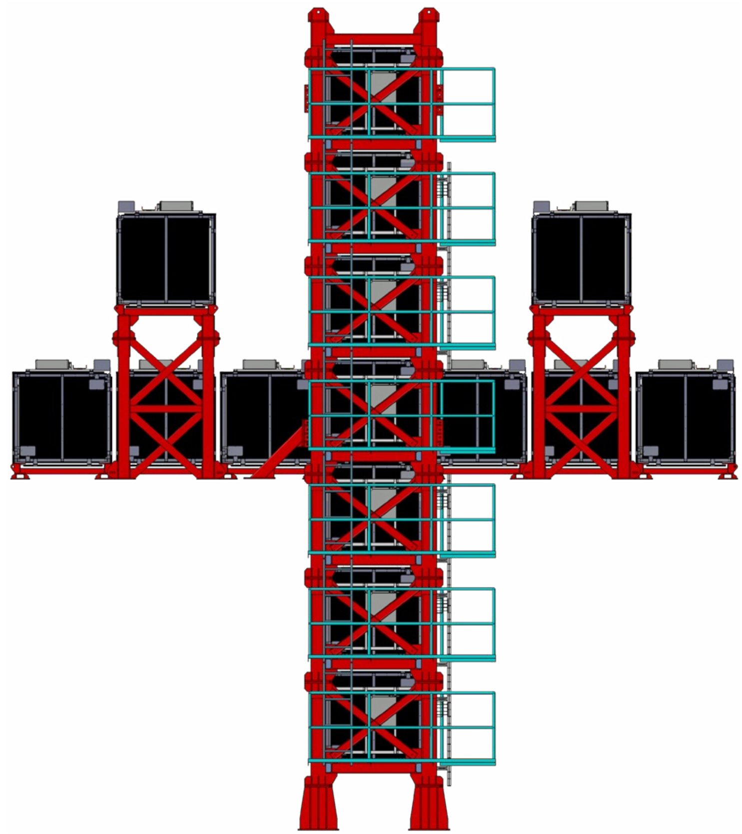
- All next generation oscillation experiments have **total** systematic error budget ~5%
- Hyper-K $\delta_{CP} \neq 0$ sensitivity
- We need more and better cross section measurements:
  - Multiple target nuclei
  - Differential measurements
  - Model independent
  - Electron neutrino cross sections
  - Publish neutrino flux predictions



M. Yokoyama, 1st Open Hyper-K Meeting

Cross section measurements at the T2K near detectors



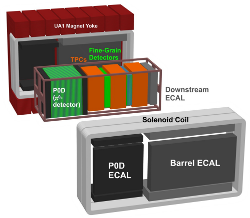


Near Detector at 280m (ND280)

- Fine grained scintillator and water targets
- Magnetic field - charge and momentum measurements
- 2.5º off neutrino beam axis – same as SK

Interactive Neutrino GRID (INGRID)

- 7 x 7 cross
- Iron and plastic scintillator sheets
- On-axis
- Proton module – scintillator only

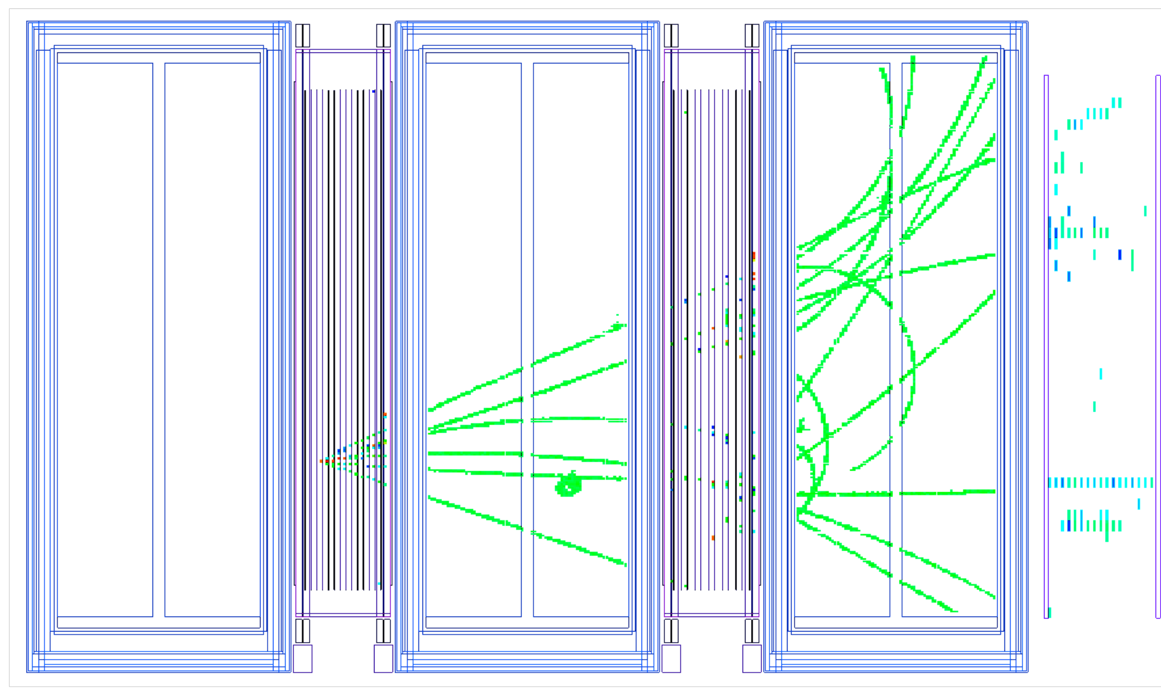


ν_μ CC inclusive cross section

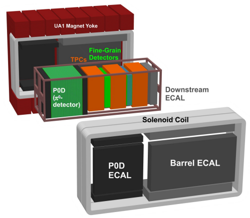
- Charged current inclusive ν_μ cross section published - Phys. Rev. D 87, 092003 (2013)

- Select neutrino interactions in the fine grained targets (FGDs) of the ND280
  - Look for negative, muon-like tracks starting in the target

- Carbon target
- Differential measurement:
  - Muon angle
  - Muon momentum
- Minimal model dependence



ND280 event display showing interaction identified as ν_μ CC DIS

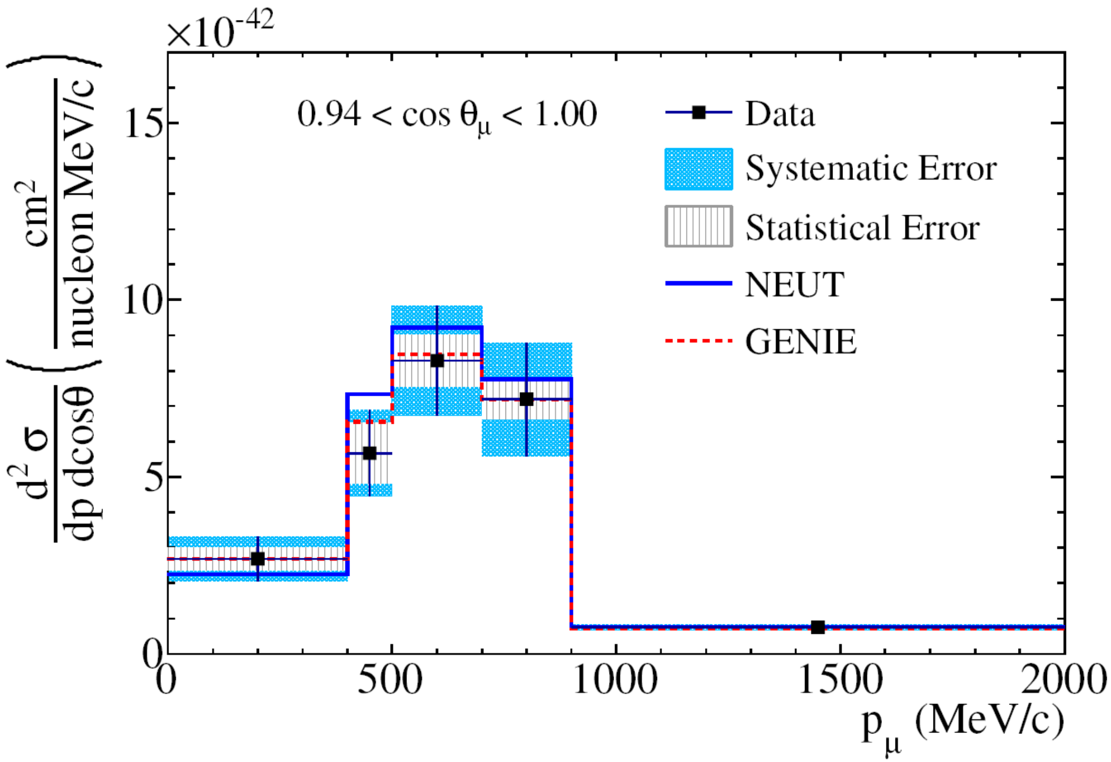


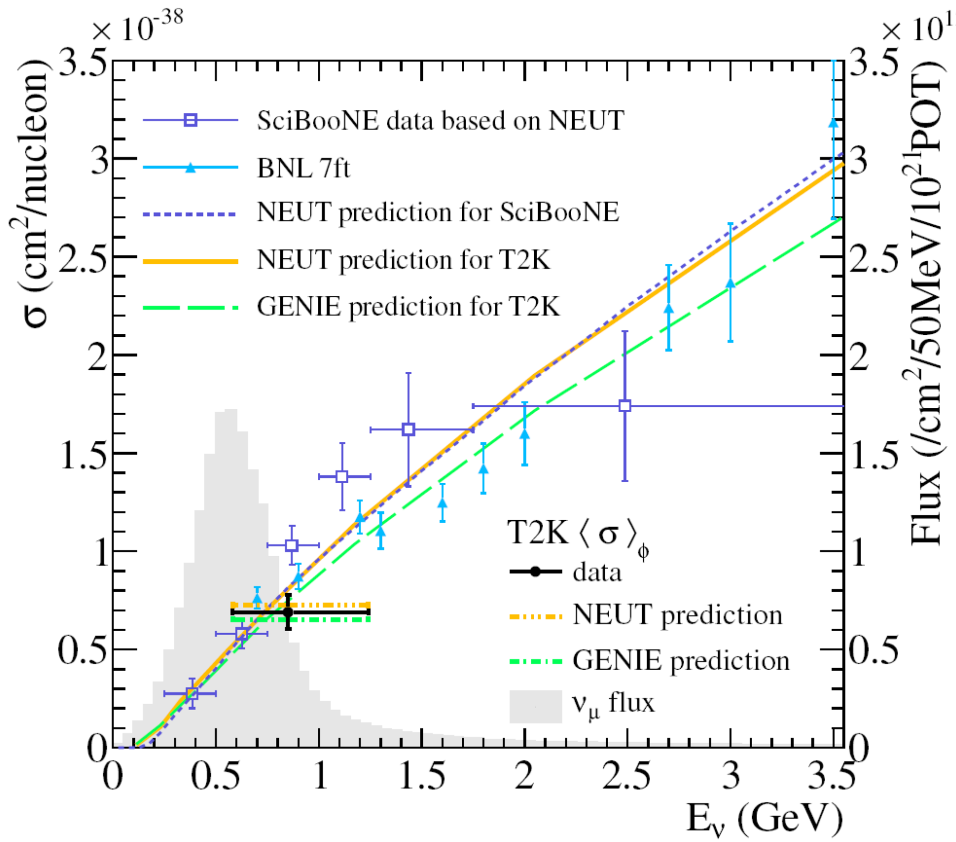
ν_μ CC inclusive cross section

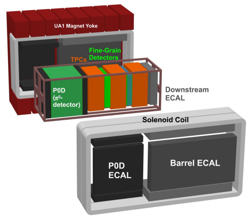
- Data tables published along with T2K flux
  - allows theorists to directly compare their models to experimental data

(http://t2k-experiment.org/results/nd280data-numu-cc-inc-xs-on-c-2013/)

(http://t2k-experiment.org/results/neutrino-beam-flux-2013/)







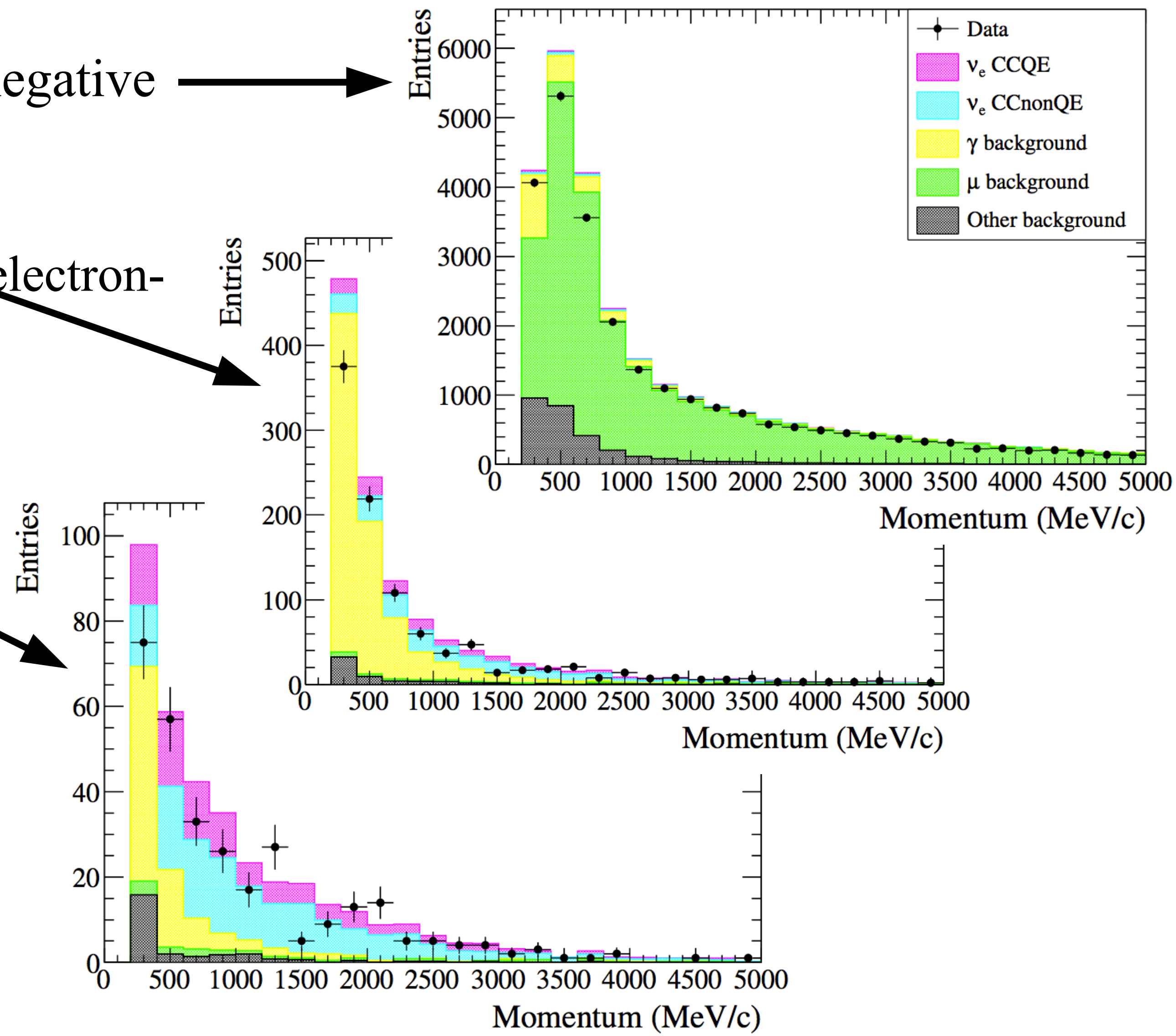
ν_e CC inclusive cross section

- Single differential charged current inclusive electron neutrino cross section
  B. Smith, 9th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, (NuInt 2014)

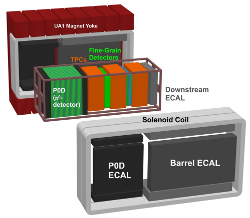
- Select highest momentum negative track in FGD

- Require it is identified as an electron-like track

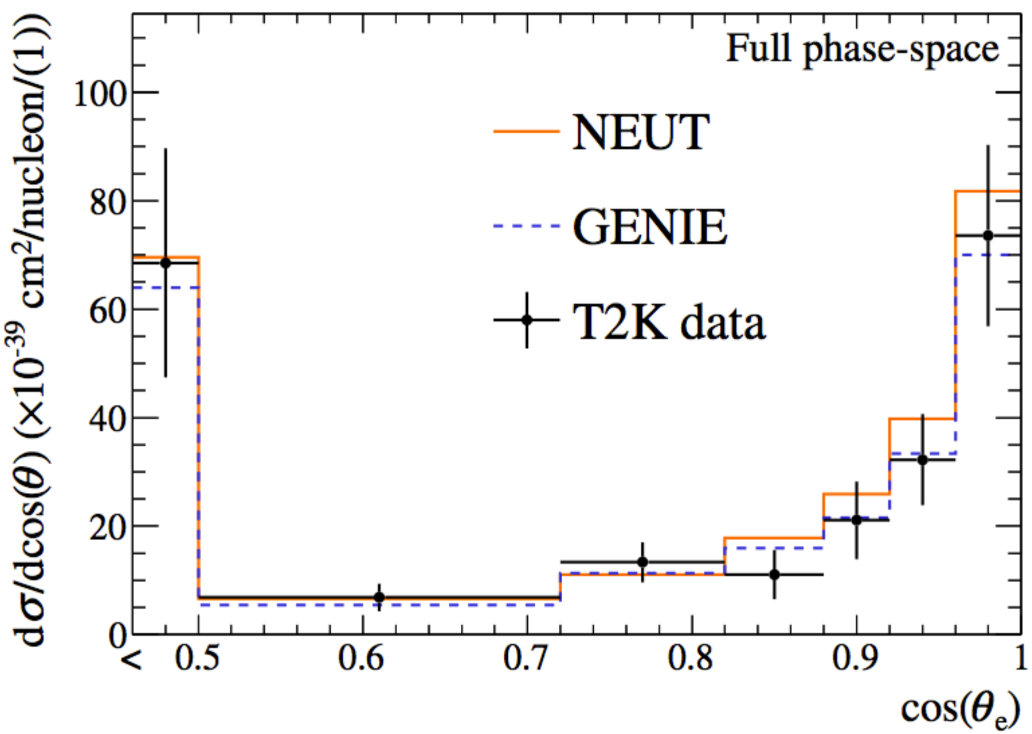
- Reduce background events from $\gamma \rightarrow e^+e^-$ conversions:
  - Veto upstream activity
  - No positron tracks

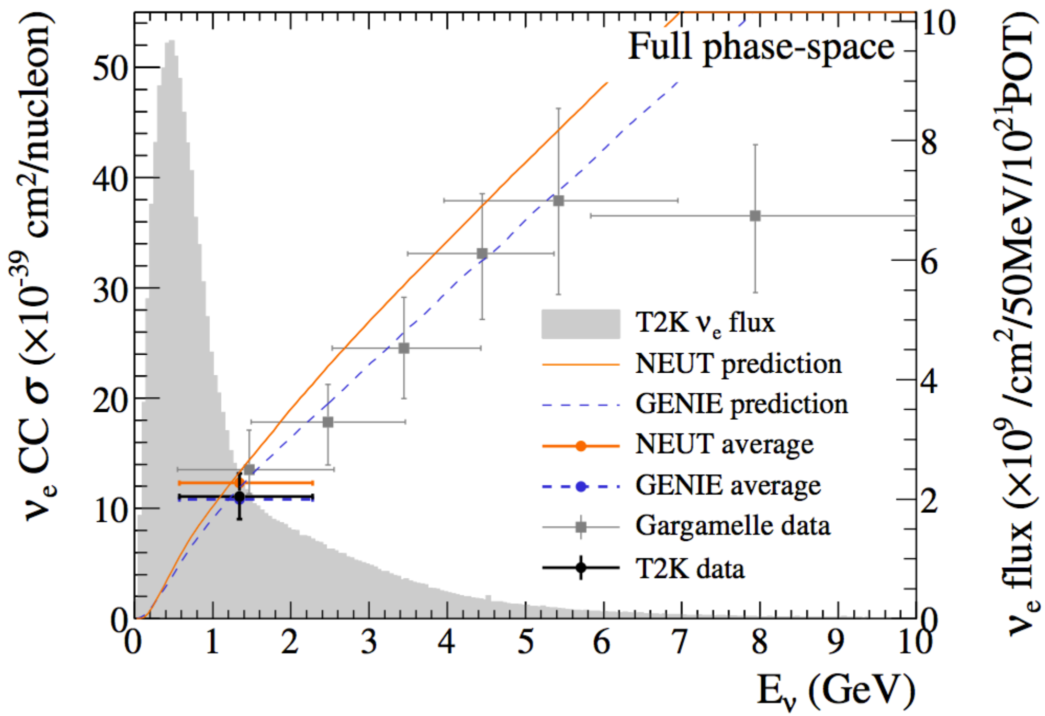


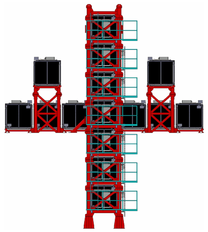
ν_e CC inclusive cross section



- Results show good agreement with the NEUT and GENIE neutrino interaction generators
- Single differential measurements as a function of electron momentum and electron angle to the neutrino beam
- Paper being prepared for publication

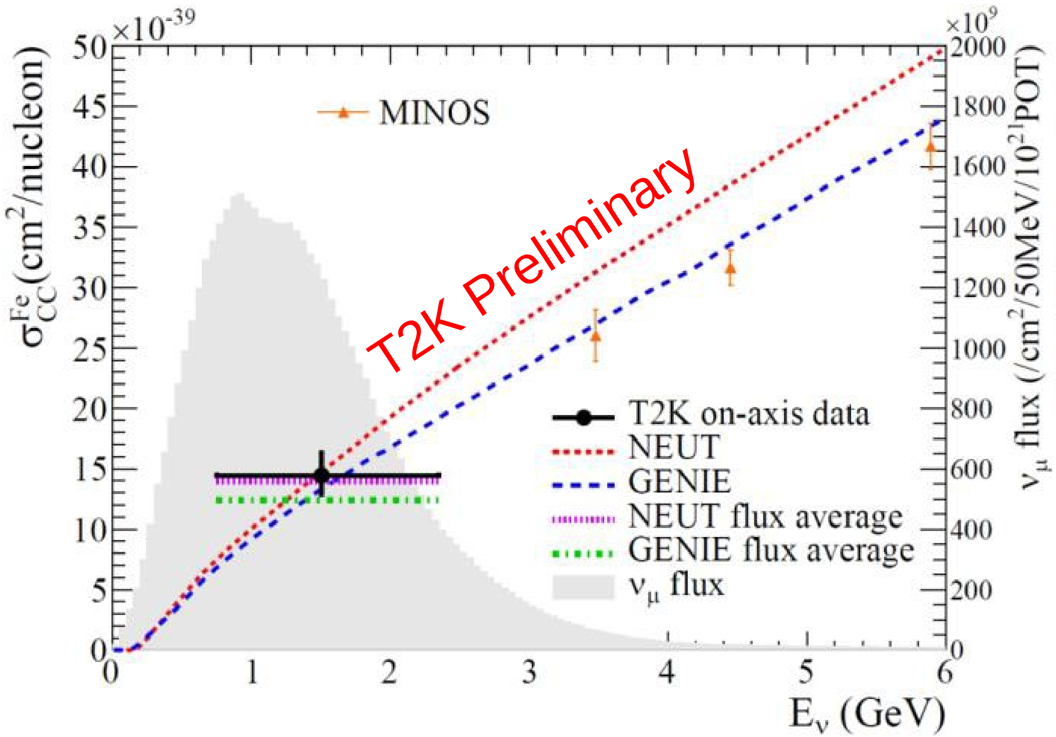


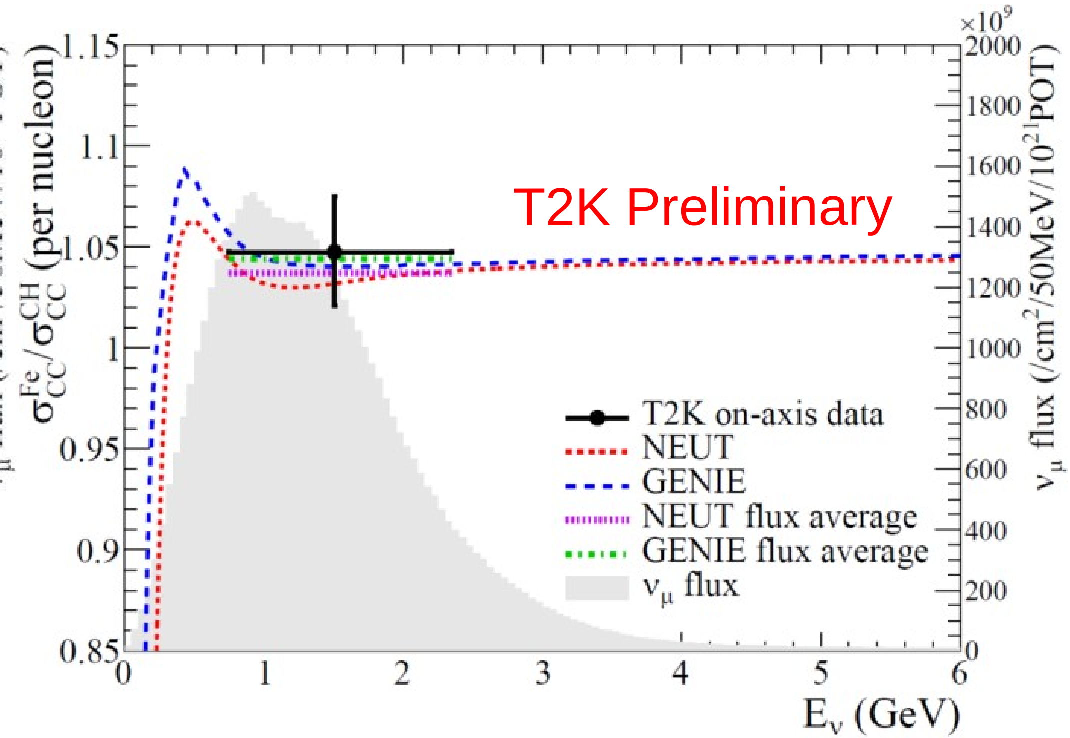


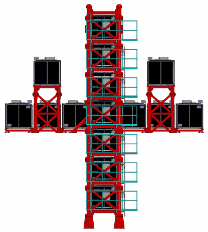


ν_μ CC inclusive cross section on Fe and CH

- Iron makes up 96% of standard INGRID modules
- CH makes up 99% of the Proton Module
- Measure CC inclusive cross section in both modules – T. Kikawa, NuInt 2014
  - First measurement on Fe below 3 GeV
  - Compare same cross section on different target nuclei
- Paper being prepared for publication

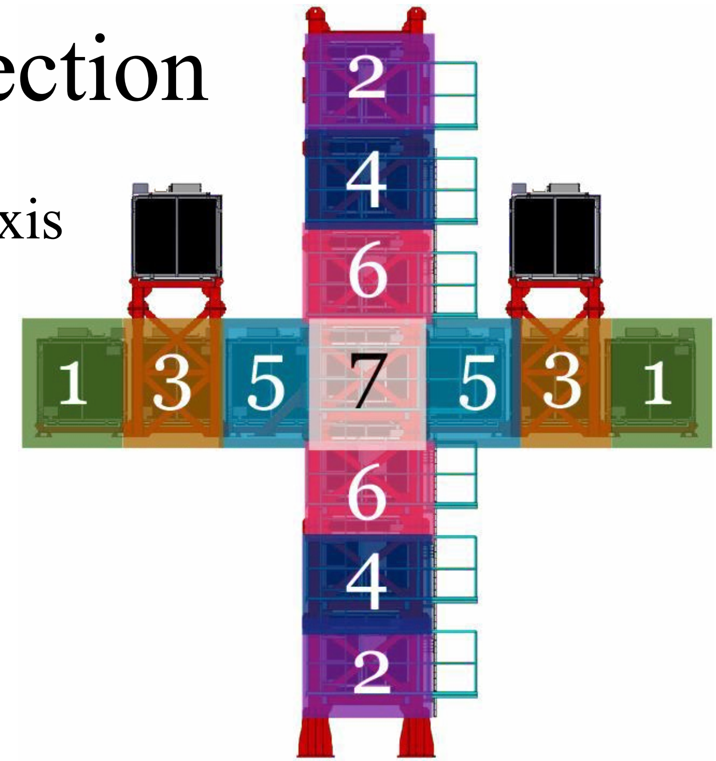


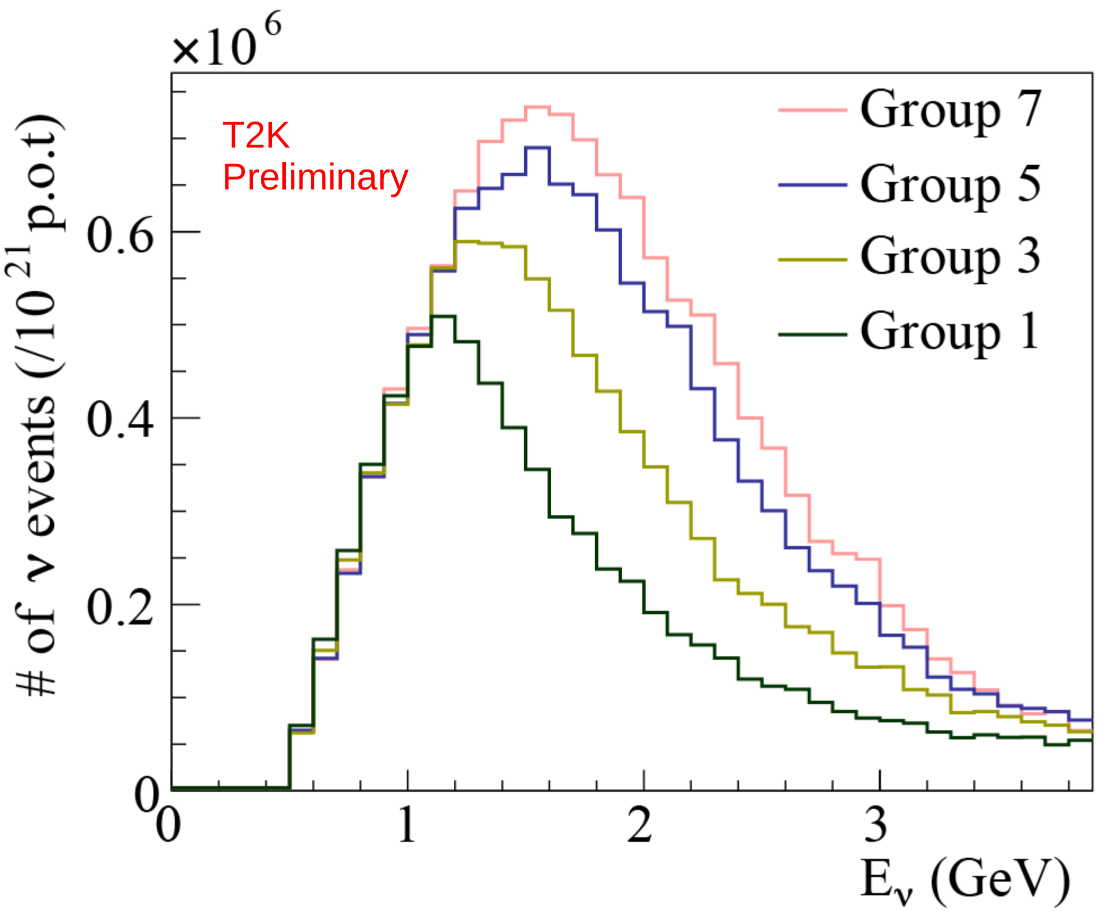




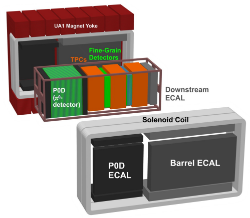
ν_μ CC inclusive energy dependent cross section

- INGRID 'cross' covers ± 0.8° off neutrino beam axis
- Group modules according to off axis position
- Module groups see different neutrino fluxes



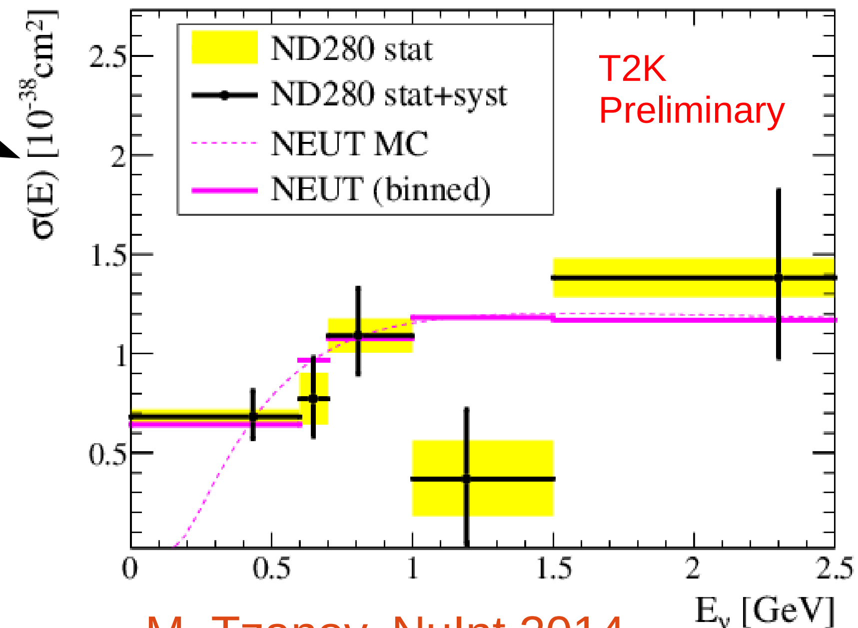


- Fit CC inclusive cross section in each module
- Model independent measurement of CC inclusive cross section as a function neutrino energy
- Result coming soon

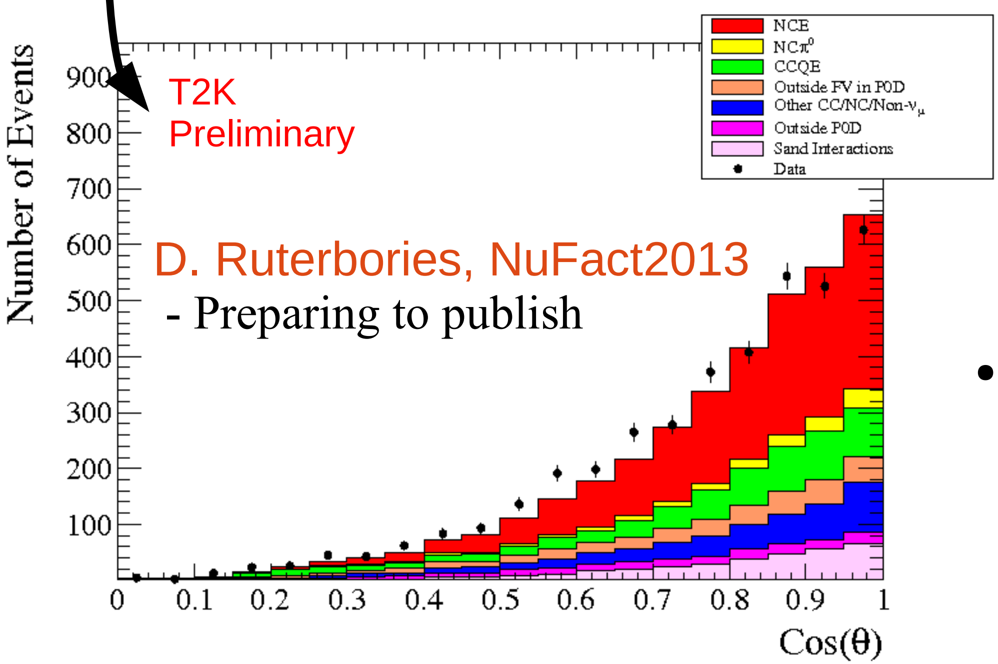


Future ND280 results

- Many more analyses underway or in the process of publication
  - CCQE exclusive measurements
  - NuE/NuMu cross section ratio
  - CC single pion
  - CC coherent pion production
  - CC inclusive on multiple target nuclei
  - NC elastic
  - Multi-nucleon ejection searches
  - Anti-neutrino measurements
  - Pi0 cross sections



M. Tzanov, NuInt 2014
- Preparing to publish



- Expect many exciting results soon!

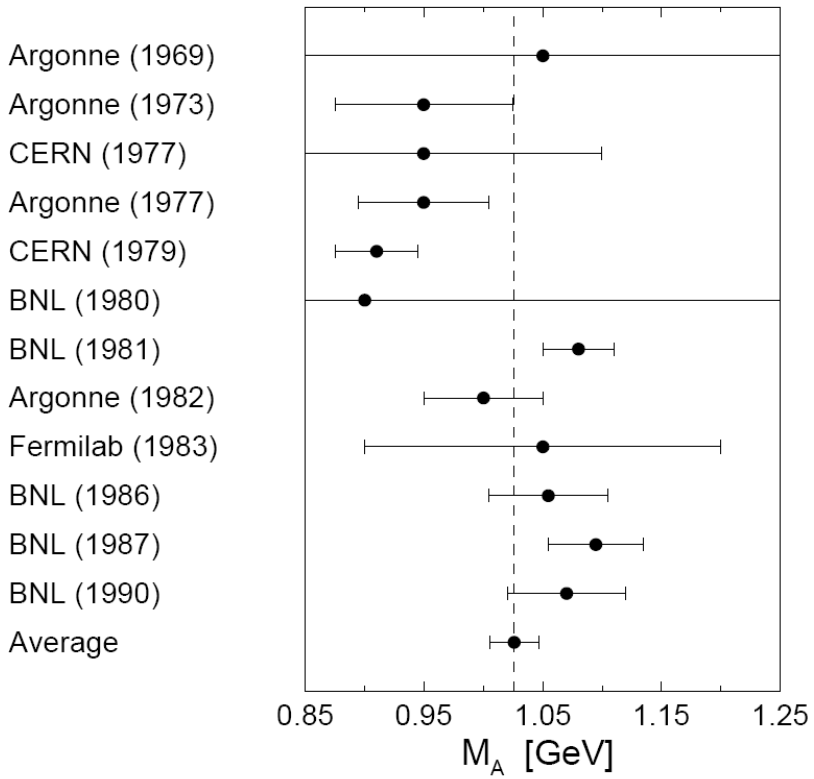
Summary

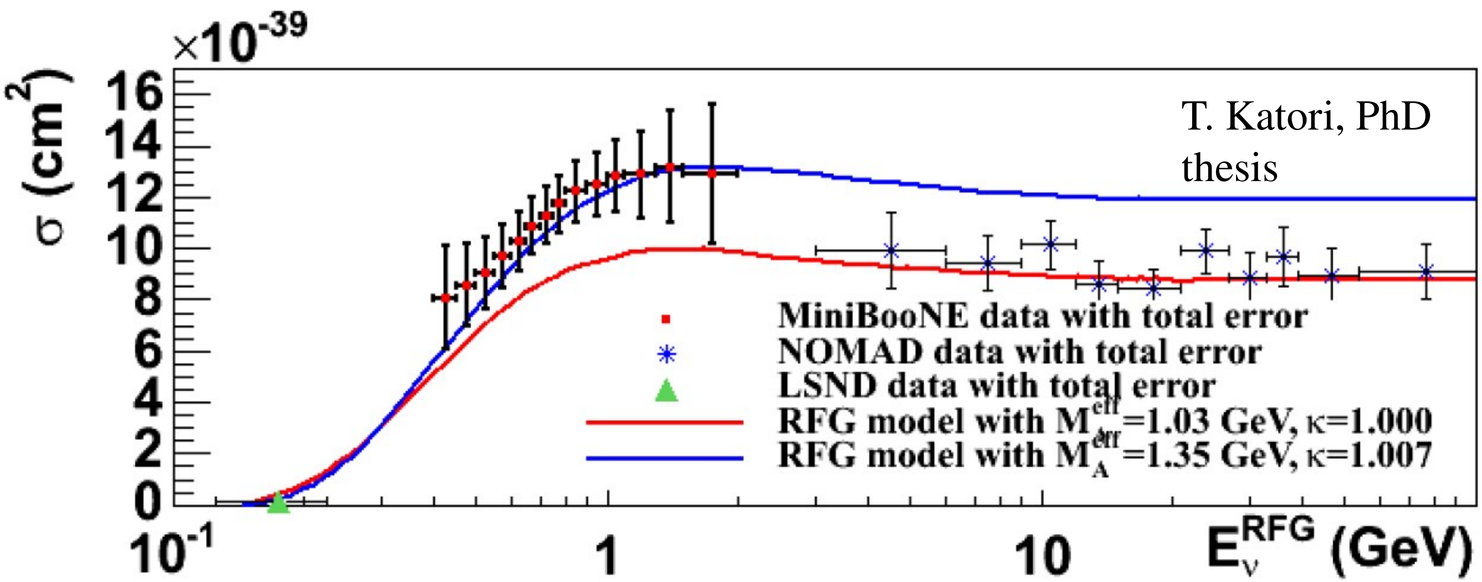
- Neutrino cross sections around 1GeV are complicated:
  - Tension between results leads to large systematic uncertainties
  - We need to understand neutrino cross sections to achieve future long baseline neutrino experiment targets
- To make progress we need more data:
  - Model independent, differential measurements
  - Flux integrated result with the flux prediction made available
- T2K near detectors are providing these measurements:
  - New results nearing publication
  - Many people working on next set of analyses
  - Working to provide the most useful measurements in the most useful way to the community

Backup slide

Neutrino interactions

- Early measurements of M_A^{QE}:
  - Give average value of M_A^{QE} as 1.026 ± 0.021[1]
- K2K, MiniBooNE, SciBooNE, NOMAD, MINOS
  - Nuclear targets
  - High statistics





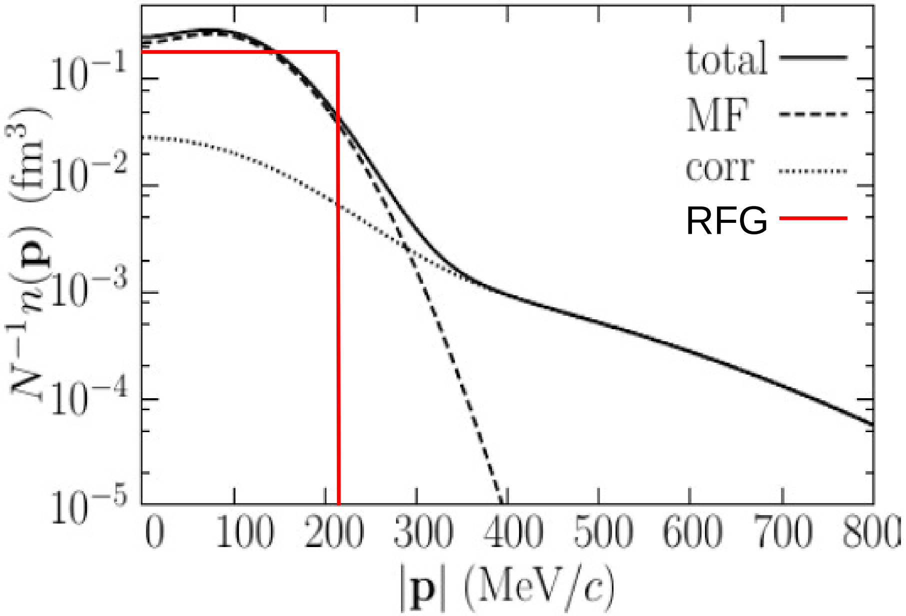
- MiniBooNE fit gives $M_A^{QE} = 1.35$

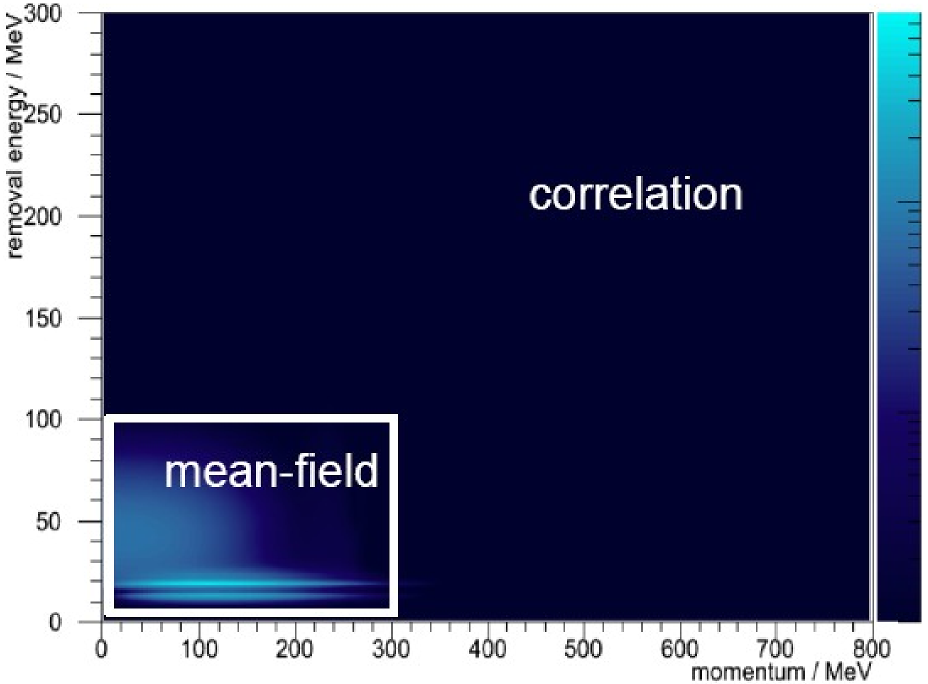
1. Bernard *et al.*, JPhysG28, 2002

Spectral functions

- Describes the momentum distribution of nucleons within the nucleus
- By default NEUT uses a relativistic Fermi gas (RFG) model, want to transition to using the O. Benhar's spectral function model

A. Ankowski and J. Sobczyk, arxiv:nucl-th/0512004v4



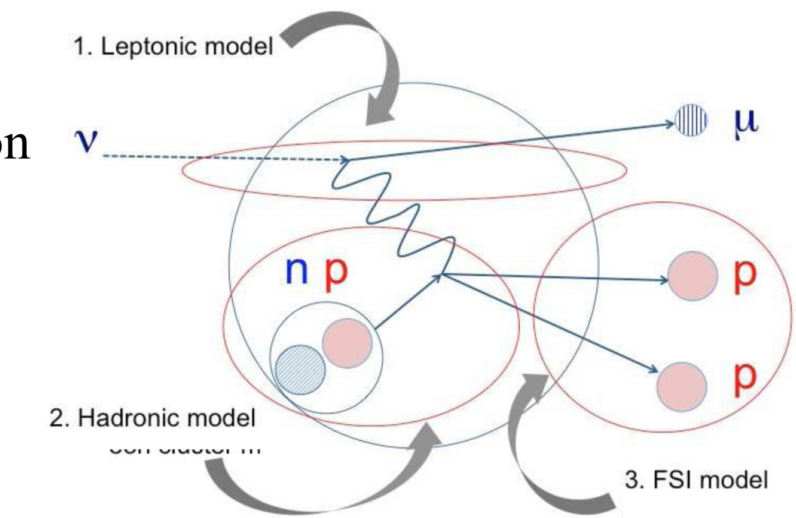


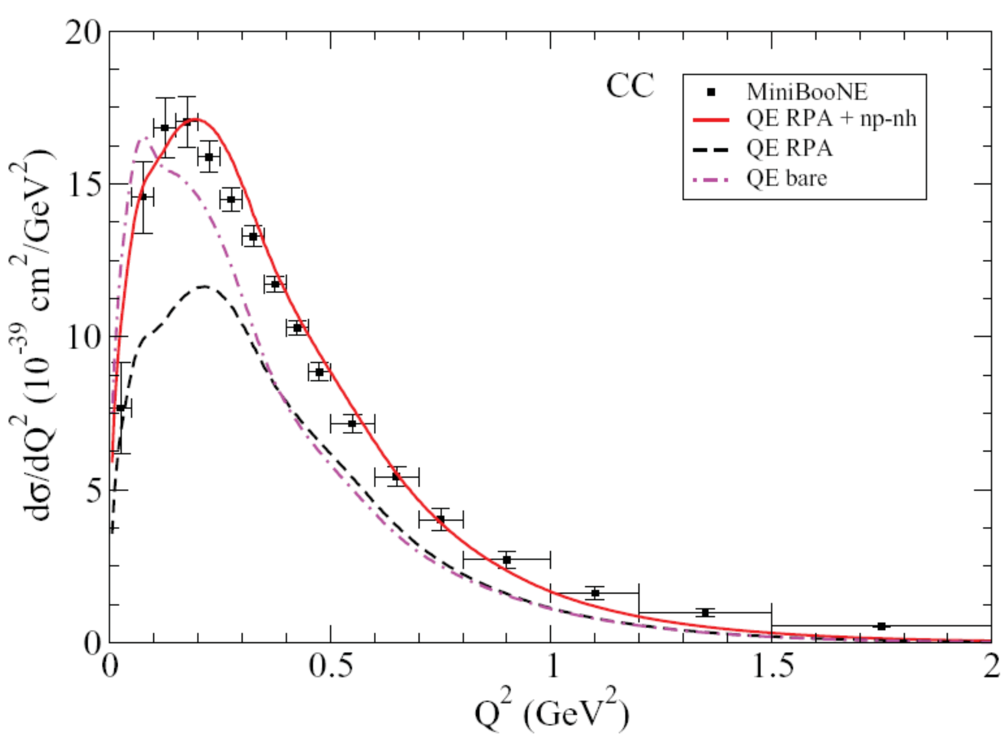
- The spectral function model composed of a mean-field region, includes a correlated term giving a high momentum tail
- Performs better than RFG in electron scattering experiments
- Correlated term leads to two nucleon ejection

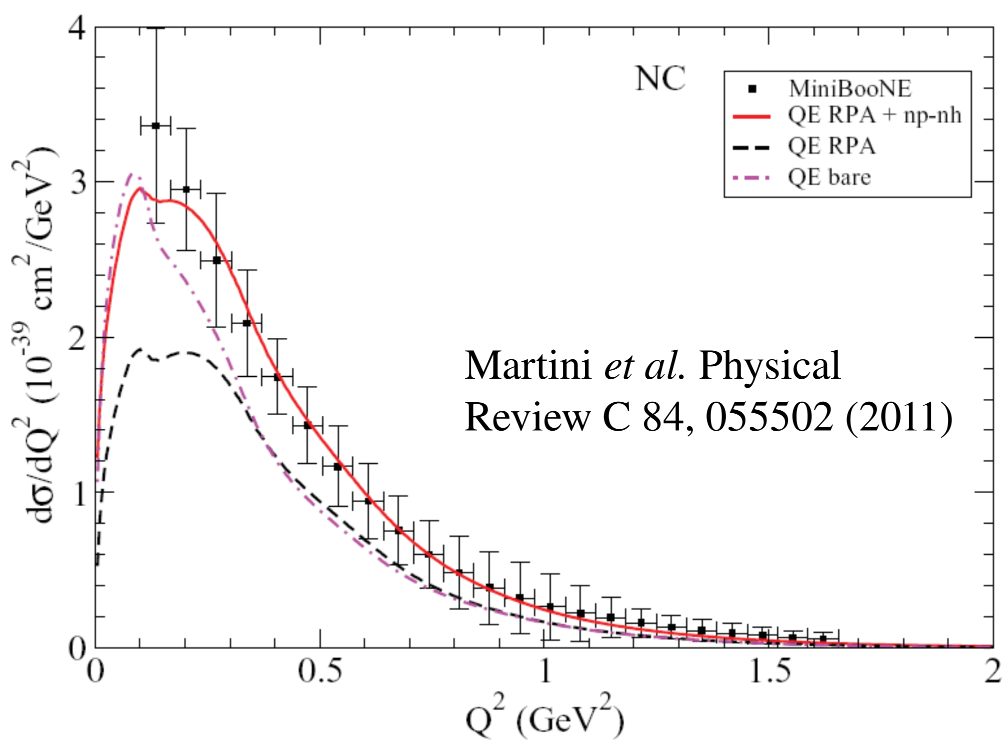
Meson exchange currents

- Many names
  - np-nh, MEC, multi-nucleon ejection
- All refer to (roughly) the same thing
  - Neutrino interacts with more than one nucleon
- An additional processes alongside CCQE
- Evidence for models in electron scattering data
- Can reproduce observed MiniBooNE QE data
- Multiple nucleons can exit the nucleus

T. Katori, arXiv:1304.6014v3





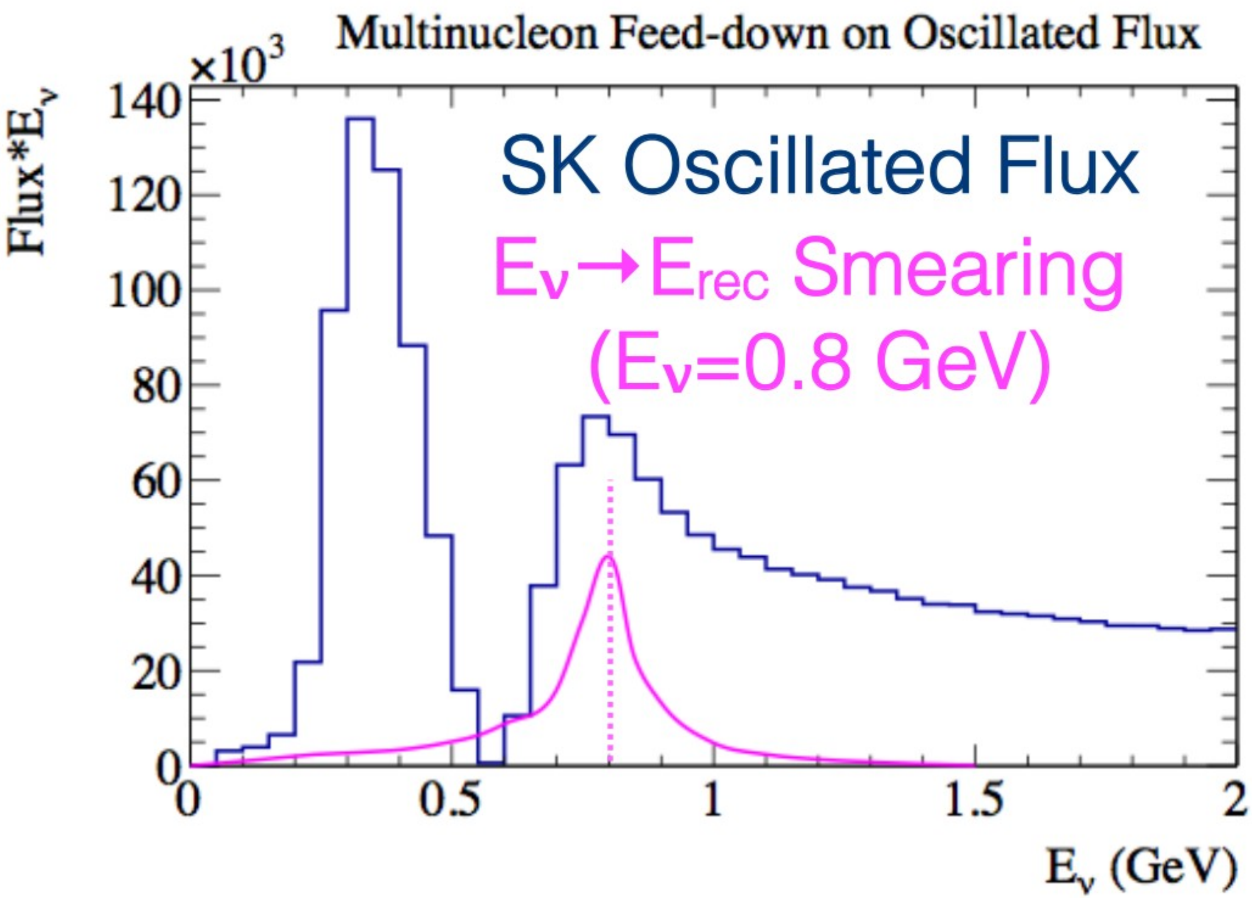


Martini *et al.* Physical Review C 84, 055502 (2011)

Meson exchange currents – cont.

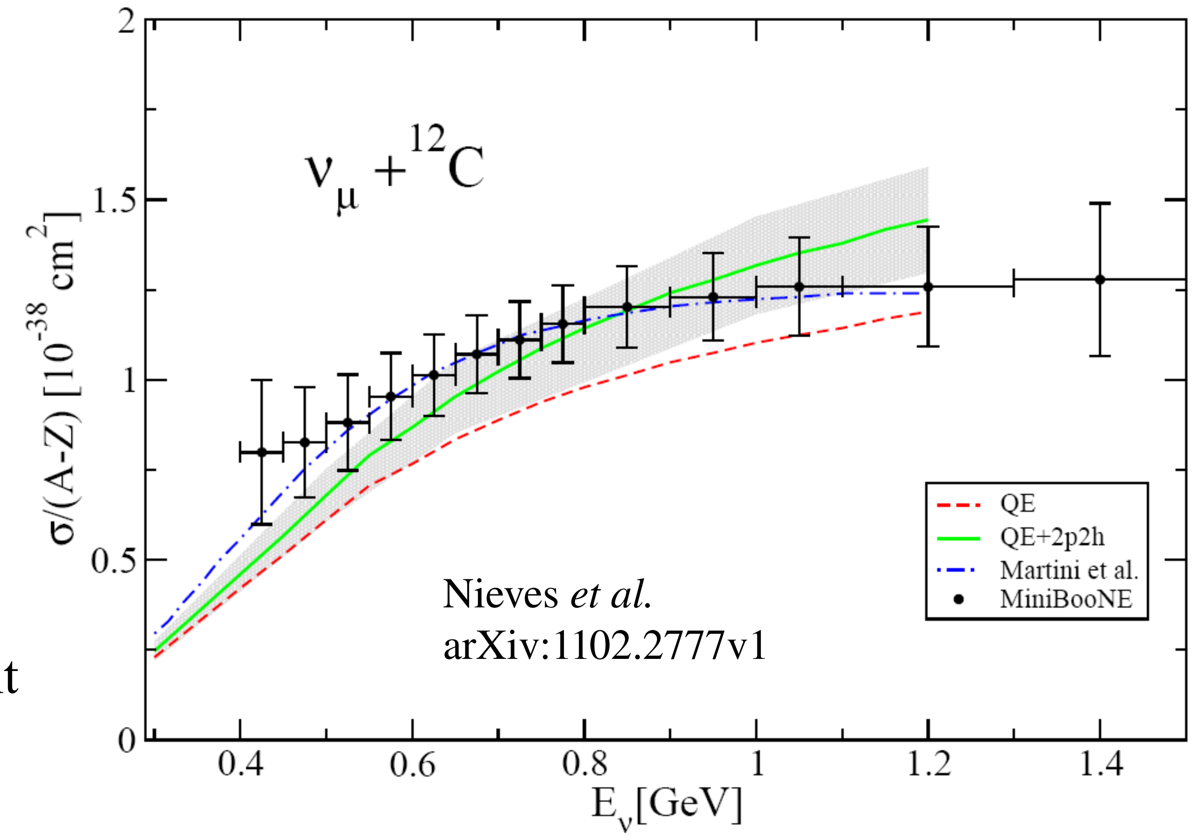
- CCQE events are the primary signal channel in oscillation analyses, and spectral information is important
- MiniBooNE and SK cannot reconstruct ejected nucleons – MEC events ≡ CCQE events in these detectors
- Reconstructing neutrino energy assuming CCQE kinematics leads to biases

- Reconstructed neutrino energy in pink for 800 MeV neutrinos
- Oscillated SK spectrum in blue (true neutrino energy)
- MEC events biased to lower reconstructed energy – fills oscillation dip



Disentangling CCQE

- Lots of different models can explain both electron scattering and neutrino data
- Need more data to distinguish them
- Muon neutrino CCQE cross section on carbon
- MEC model (2p-2h, green)
- np-nh model (blue)
- MiniBooNE data
- Experiments need to provide data for theorists to work with:
  - Model independent
  - Differential measurement
  - Lepton kinematics
  - Publish neutrino flux



Cross sections and oscillations

- In current oscillation analyses we have large errors coming from the neutrino cross section parameters

From ND280

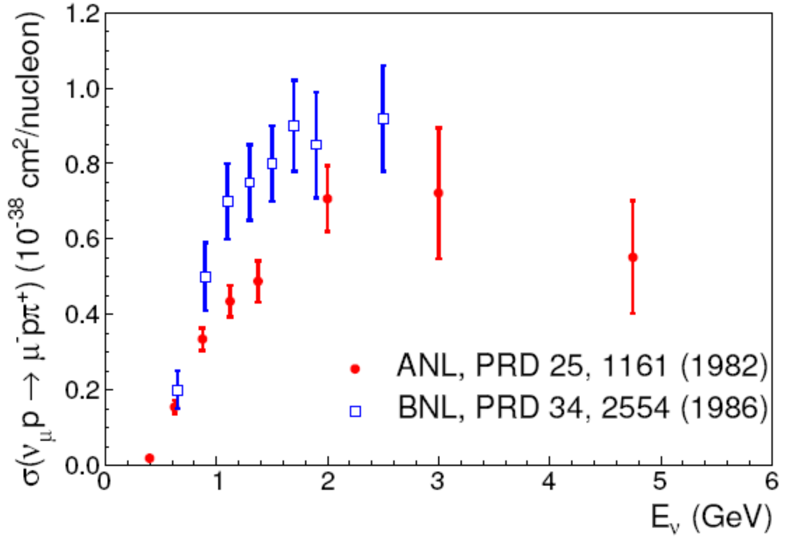
SK only

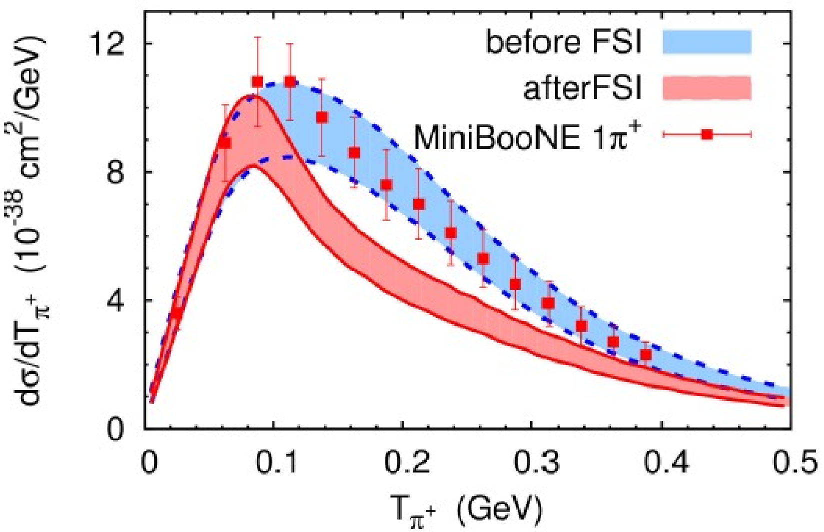
Error source	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	11.6	7.5
M_A^{QE}	21.5	3.2
M_A^{RES}	3.3	0.9
CCQE norm. ($E_\nu < 1.5$ GeV)	9.3	6.3
CC1π norm. ($E_\nu < 2.5$ GeV)	4.2	2.0
NC1π^0 norm.	0.6	0.4
CC other shape	0.1	0.1
Spectral Function	6.0	6.0
p_F	0.1	0.1
CC coh. norm.	0.3	0.2
NC coh. norm.	0.3	0.2
NC other norm.	0.5	0.5
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.9	2.9
W shape	0.2	0.2
pion-less Δ decay	3.7	3.5
SK detector eff.	2.4	2.4
FSI	2.3	2.3
PN	0.8	0.8
SK momentum scale	0.6	0.6
Total	28.1	8.8

units: percentage error on N_{SK}

CC1π measurement

- There are discrepancies in the existing CC1π data:
  - Bubble chamber data disagreement
  - MiniBooNE data prefers no FSI?
- Currently use these datasets to constrain pion cross section uncertainties in oscillation analyses
  - Disagreements lead to larger errors
  - Is it correct to do this? Different targets, fluxes etc.
  - Leads to O(2%) uncertainties in near-far extrapolation
- Now working on pion cross section analyses





Olga Lalakulich, NuInt 2012