Fitting External Data Sets and Extracting Model Parameters With Neutrino Interaction Monte Carlo

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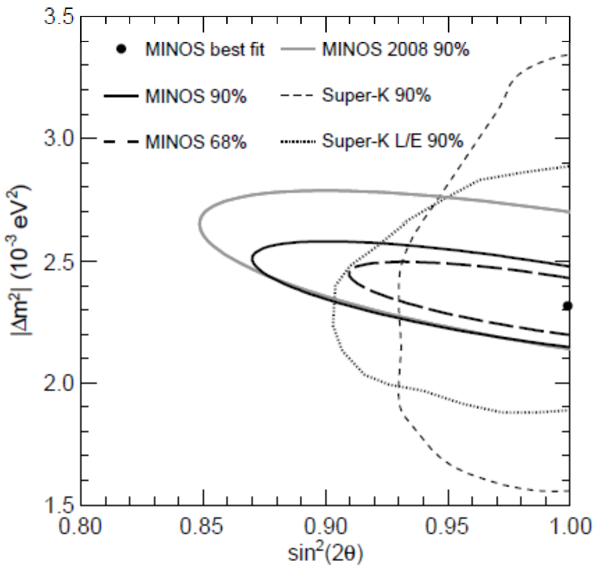
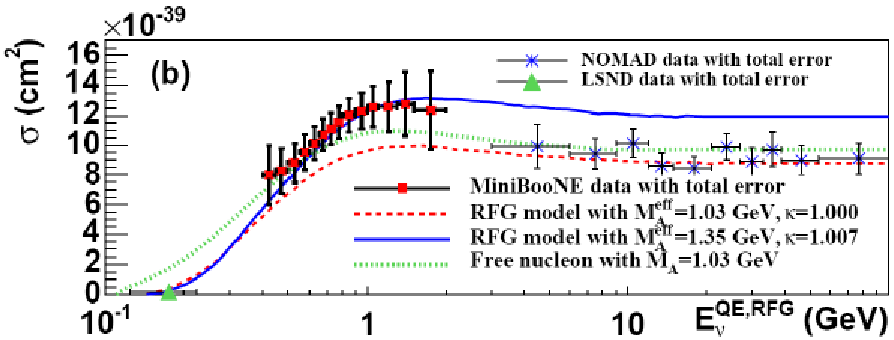
Iop HEPP/APP Meeting

2-4 April 2012

Motivation

- Entering precision era of oscillation parameters
  - Daya Bay has θ_{13} to 18%
  - PDG has $|\Delta m_{23}^2|$ to 5.3%
    - MINOS a little smaller
- In order to gain precision on the oscillation parameters, need to reduce systematic errors
  - Difficult to constrain in early phases of the experiment
- Also, recent cross section measurements are showing differences from in parameters from previous experiments





Problem/(Road to a) Solution

- Early stages of an experiment don't have the statistics to limit systematic errors from the cross section model
- Rather than estimate errors based on varying model parameters, try to find external measurements and extract errors using the experiment's Monte Carlo generator

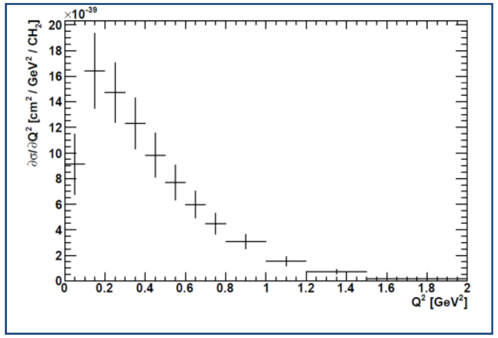
Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}$%	$^{+5.6}_{-5.2}$%
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$^{+22.8}_{-22.7}$%	$^{+17.6}_{-17.5}$%

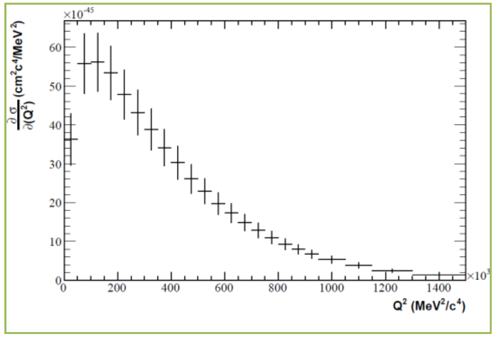
Source of systematic uncertainty	$\delta(\Delta m^2)$ (10^{-3} eV^2)	$\delta(\sin^2(2\theta))$
(a) Hadronic energy	0.051	$<$ 0.001
(b) μ energy (range 2%, curv. 3%)	0.047	0.001
(c) Relative normalization (1.6%)	0.042	$<$ 0.001
(d) NC contamination (20%)	0.005	0.009
(e) Relative hadronic energy (2.2%)	0.006	0.004
(f) σ_ν(E$_\nu$ $<$ 10 GeV)	0.020	0.007
(g) Beam flux	0.011	0.001
(h) Neutrino-antineutrino separation	0.002	0.002
(i) Partially reconstructed events	0.004	0.003
Total systematic uncertainty	0.085	0.013
Expected statistical uncertainty	0.124	0.060

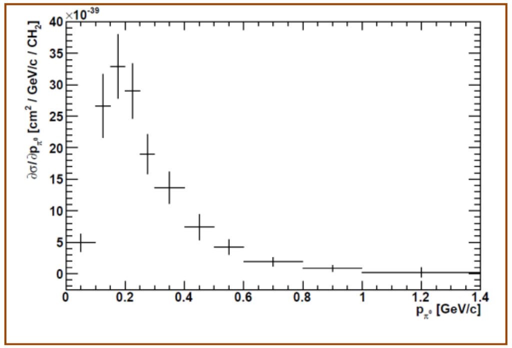
T2K ν_e (top) & MINOS ν_μ (bottom) systematic errors

MiniBooNE Released Data Sets

- CH_2 target, ν_μ beam at FNAL
  - Can measure inclusive samples (i.e. particles in final state)
- Recent experimental results
  - Using $CC1\pi^0$, $CC1\pi^+$, $NC1\pi^0$ inclusive released results (also have, for example, CCQE)
  - Released neutrino flux
- MB $CC1\pi^0$ event selection
  - Muon, only meson is 1 π^0
  - Covariance matrix given
- MB $CC1\pi^+$ event selection
  - Muon, only meson is 1 π^+
  - Only diagonal errors
- MB $NC1\pi^0$ event selection
  - NC, only meson is 1 π^0
  - Covariance matrix given
- Spectra given are for unfolded data/MC
  - Corrects detector effects, etc.

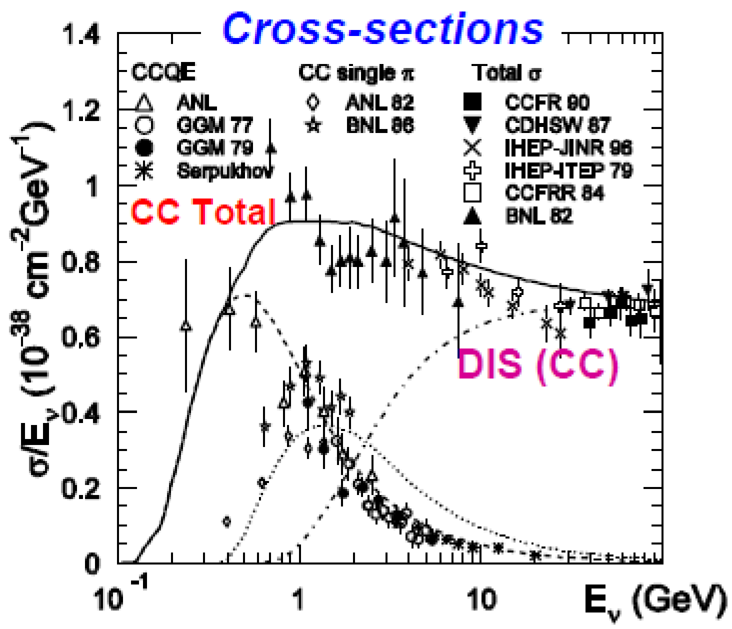




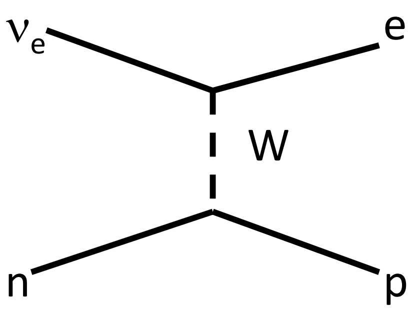


NEUT (MC Generator)

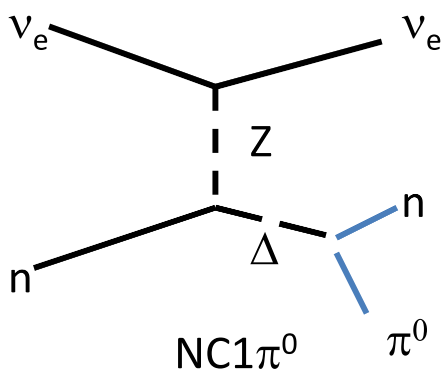
ν interaction MC
Valid from range ~100 MeV-~TeV
Used in Super-Kamiokande, K2K, SciBooNE, & T2K



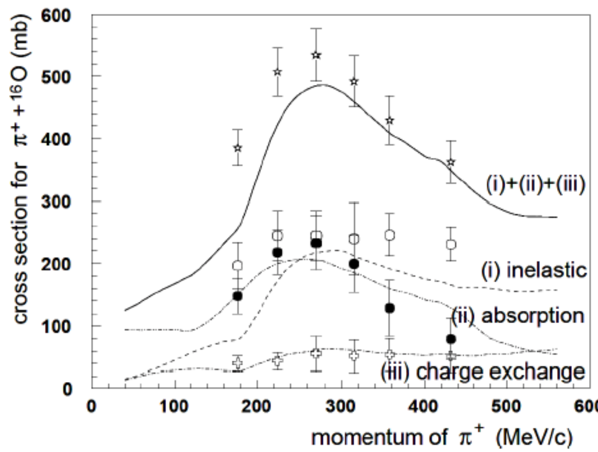
CCQE & NCEL: Smith-Moniz (relativistic Fermi Gas)
 axial form factor (dipole), M_A^{QE} = 1.21 GeV/c^2
Resonant/coherent interactions: Rein-Sehgal
 axial form factor (dipole), M_A^{RES} = 1.21 GeV/c^2
DIS/multi-π: GRV98 LO PDF w/ Bodek-Yang correction
Nuclear model: cascade (step-wise) model



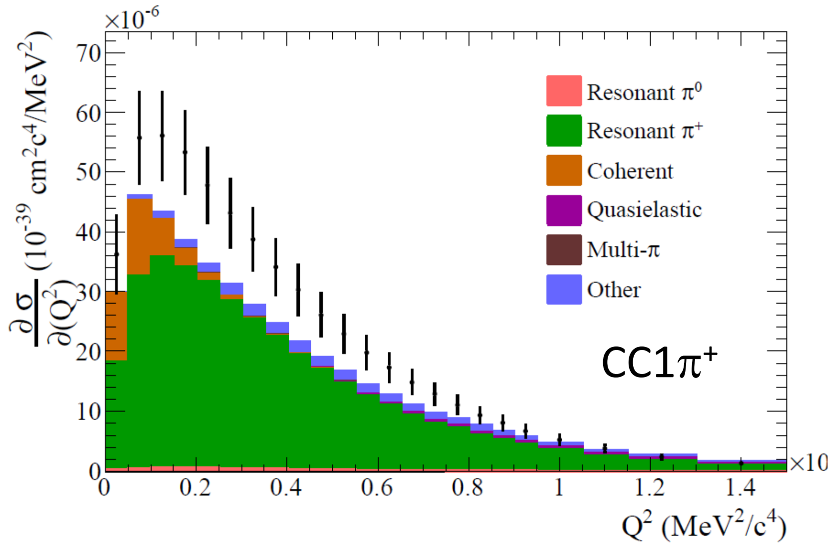
CCQE

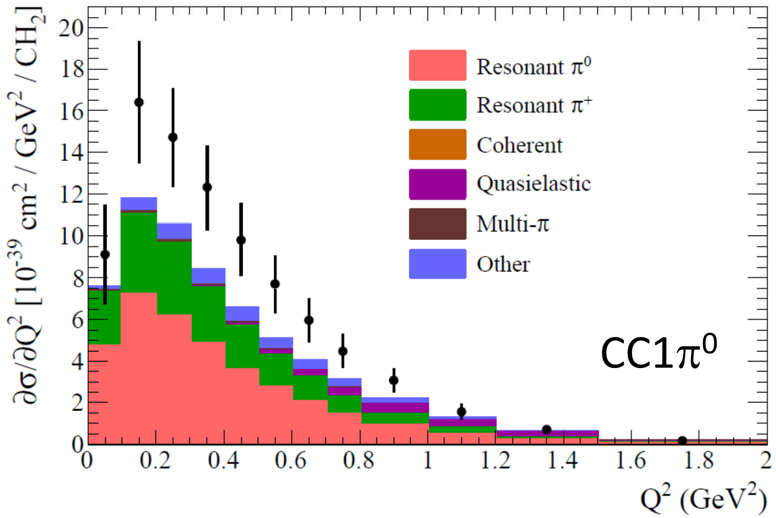


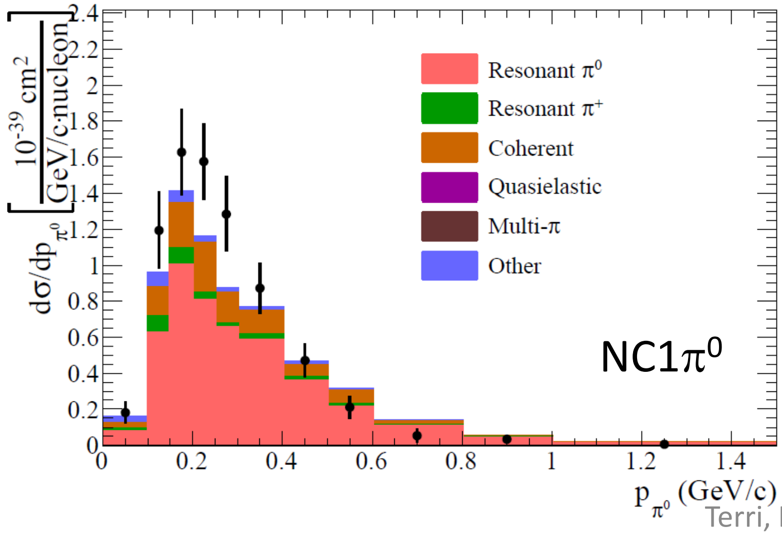
NC1π^0



NEUT Default & MiniBooNE Data







For CC sample, fit Q^2 distributions
NC1π^0, fit pion momentum

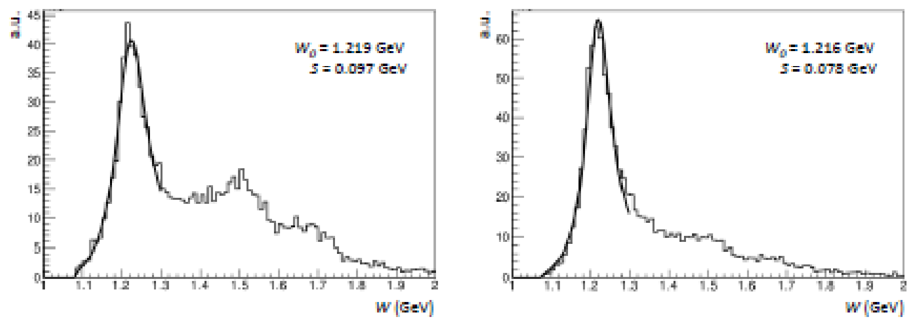
Contributions from other interactions due to intranuclear effects

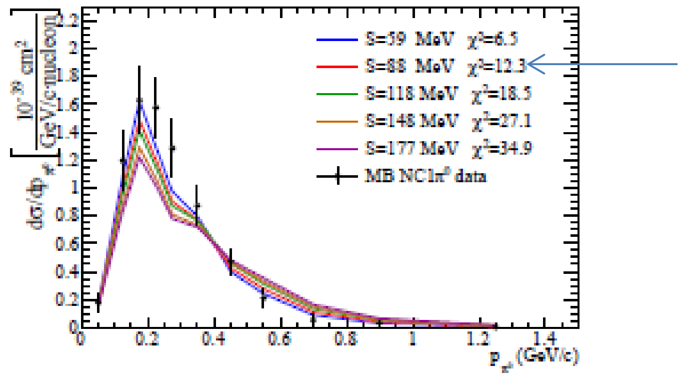
Overall normalization mainly due to NEUT's π-less resonance decay (20% of resonances)

Fit Parameters

- Resonant interaction axial mass
  - Parameter in R&S model
  - Affects both shape & normalization
- Normalization terms for various interactions
  - CC1π, NC1π^0, CCcohπ, NCcohπ, NC other
  - E.g. compensate for normalization hit from π-less Δ decay
- W (invariant hadronic mass) shape
  - Ad hoc parameter, nominally for Δ width in-medium being smaller than for free Δ
  - Most likely hides other issues from the initial interaction & FSI effects
- CC multiπ shape error
  - Ad hoc to take into account xsec error is ~10% at 4 GeV and goes like $1/E_\nu$
- CCQE terms held constant from other fit of MB CCQE data

$$r(W;S) = \alpha \cdot \frac{S}{(W - W_0)^2 + S^2/4} \cdot P(W; m_\pi, m_N)$$





χ^2 Definition

Sum of χ^2 of the distributions:

$$\chi^2 = \chi^2_{\mathrm{CC}1\pi^0} + \chi^2_{\mathrm{CC}1\pi^+} + \chi^2_{\mathrm{NC}1\pi^0} + \chi^2_{\mathrm{pen}}$$

$$\chi^2_{\mathrm{CC}1\pi^0} = \sum_i \sum_j (D_i - M_i) C^{-1}_{ij} (D_j - M_j)$$

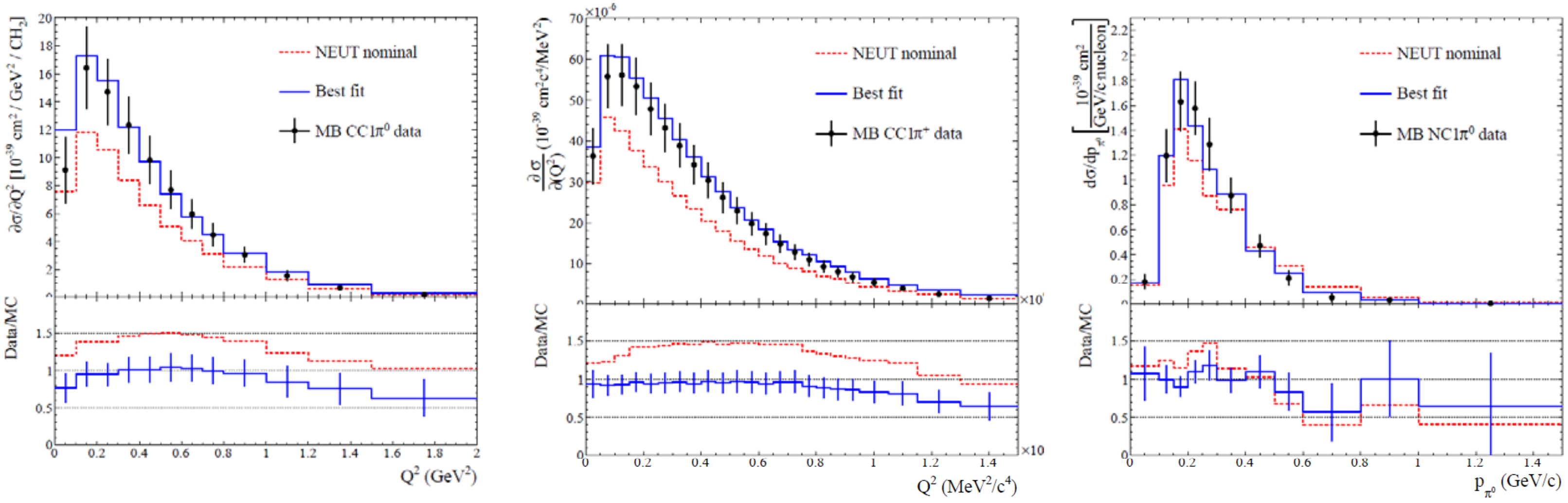
$$\chi^2_{\mathrm{NC}1\pi^0} = \sum_i \frac{(D_i - M_i)^2}{\sigma_i^2}$$

$$\chi^2_{\mathrm{pen}}(\mathbf{s}) = \sum_k \frac{(s_k - s_k^{\mathrm{nom}})^2}{\sigma_k^2}$$

CC1π^+, no correlation between bins provided; assume dominant correlation is from neutrino flux at 11% for off-diagonal elements and MB provided errors on diagonal

NC1π^0 has high energy tail component not in CC samples, and using p_π spectrum, so leave off possible correlations for now

Results/Comparison



Parameter	Nominal	Fit Output	Error
M_A^{RES}/GeV/c^2	1.21	1.16	0.05
CC1π Norm.	1.00	1.63	0.16
NC1π^0 Norm.	1.00	1.19	0.14
W shape	87.7 MeV	42.4 MeV	0.46 MeV
CC multiπ	0.4	0.389	
NC cohπ	1	0.96	0.73
CC cohπ	1	0.66	0.70

What To Do With The Results

- For the experiment:
  - Look to see if this fits the current needs and use fitted parameters as defaults in the analysis
    - Float them in case your own data has a preference for a particular parameter value
  - When there's enough statistics, use own data to tune model
    - Cross check with these samples
- For the fitting & MC experts
  - Look for improvements in the way to fit
    - More recent tuning of a particular interaction mode?
    - New model that better represents interaction?
    - Is there a way to get more information about the experimental data you're currently fitting? (e.g. get the correlations between samples)
    - Can you use the other distributions of the same data sets to get a feel for other error sources?
  - Incorporate other samples from other experiments to constrain cross sections as well
    - E.g. SciBooNE has released NC1π^0 inclusive and CC inclusive samples