Multinucleon-neutrino interactions and the T2K experiment

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IOP 2013 HEPP & APP Group Meeting

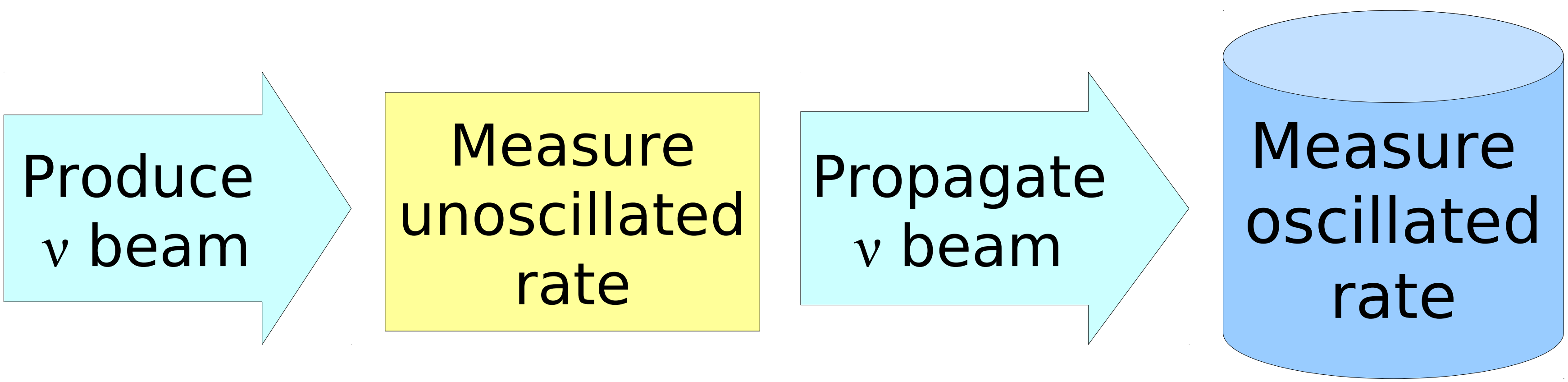
9th April 2013

T2K 101

T2K is an experiment to measure the parameters governing neutrino oscillations

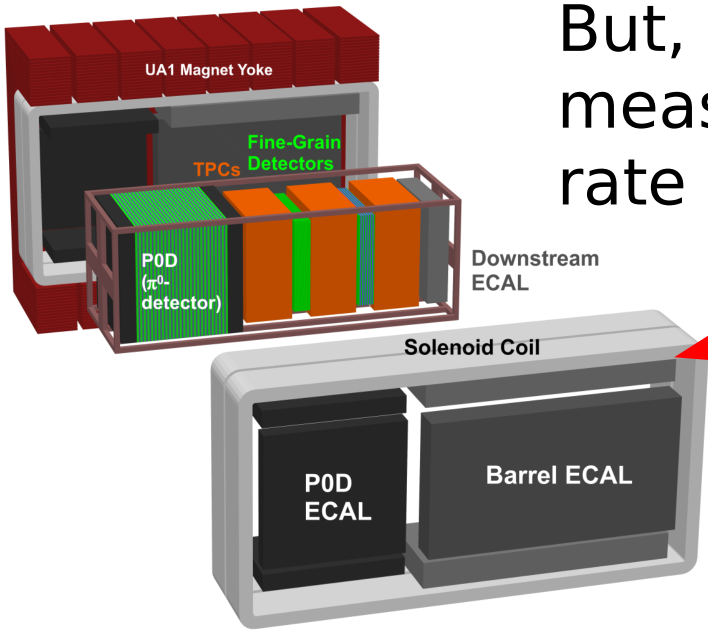
Important: 'beyond the standard model', possible source of CP violation → leptogenesis

How? Produce neutrino beam, look how it changes at a distance



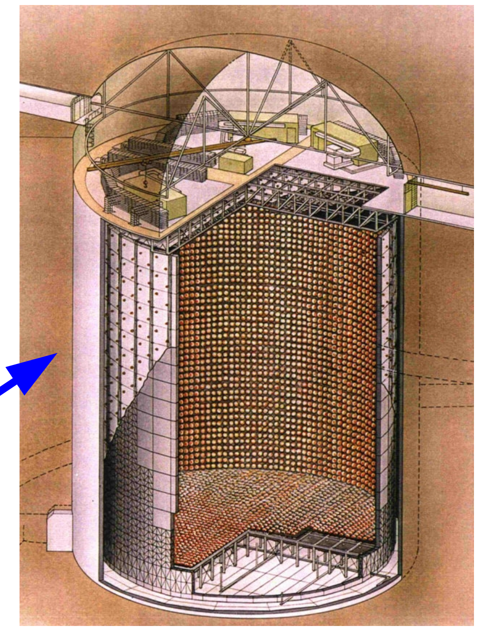
Detector differences

Oscillation parameters are measured by looking at flux differences



But, we can only measure an interaction rate at each detector

Near detector ≠ far detector so can't just look at ratio:



rate = flux × cross-section → Need cross-sections to get flux

How do you get a cross-section prediction?

Cross-section predictions come from **interaction models**

Interaction model: the theoretical ingredients

- Which interaction modes?
- What form-factors?
- Nucleon momentum?

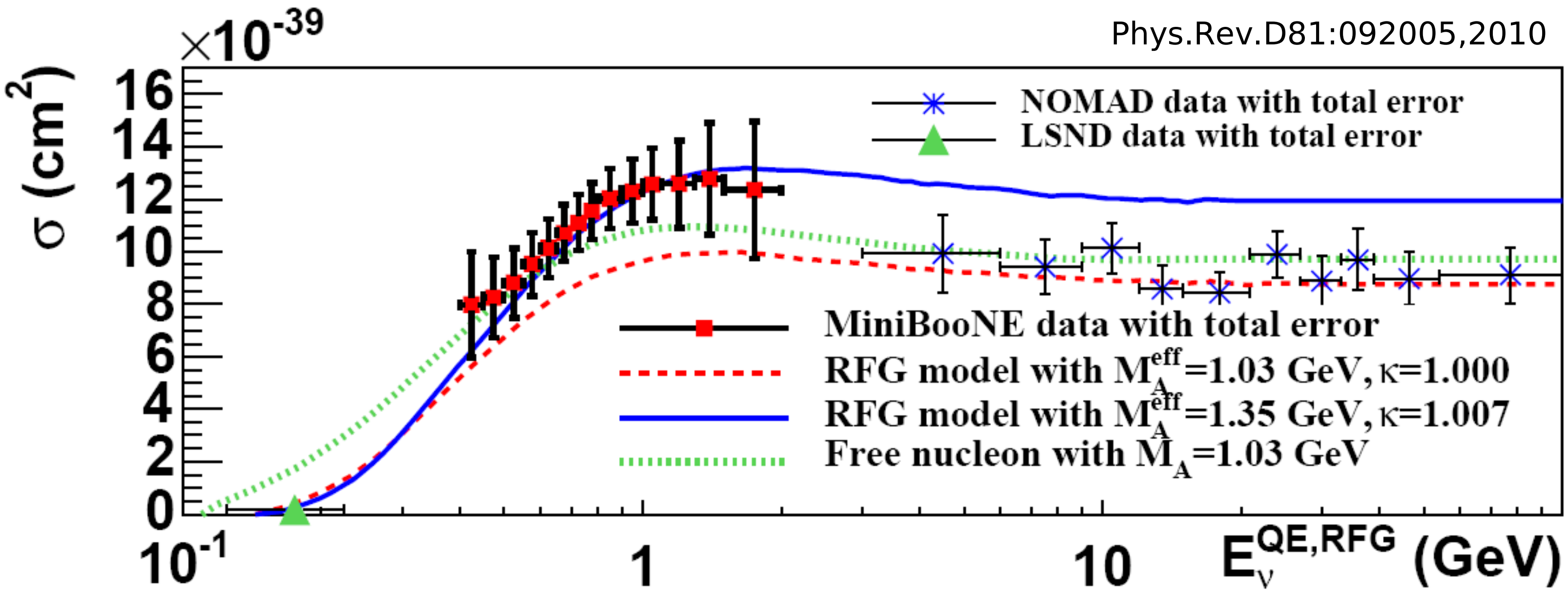
Phenomenologists

Cross-section prediction

What could go wrong?

Problem: neutrino interaction models cannot consistently describe current data

Phys.Rev.D81:092005,2010

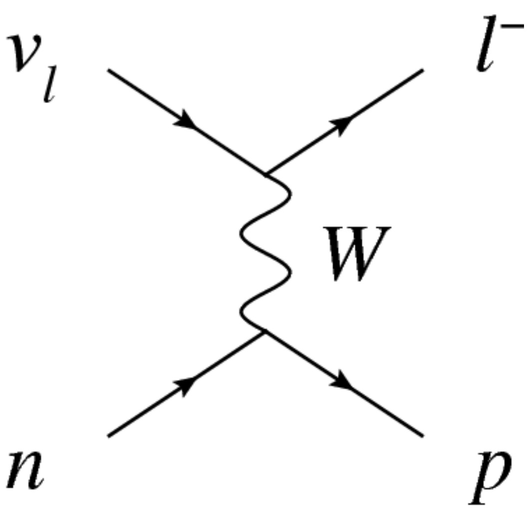


Consequence: must assign large errors to cross-section parameters → large error on final measurement

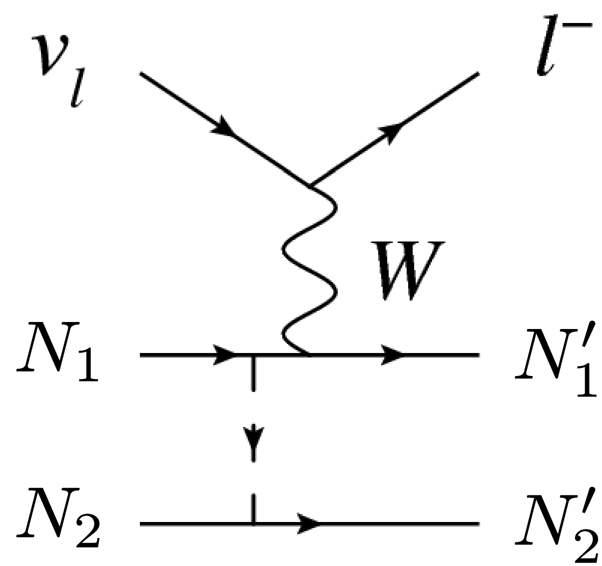
Calculations on free nucleons

To resolve tensions, need better models for neutrino-nucleus interactions

Currently, modelling of neutrino interactions: quasi-free nucleons



But in nucleus, can also have **multi-nucleon interactions**



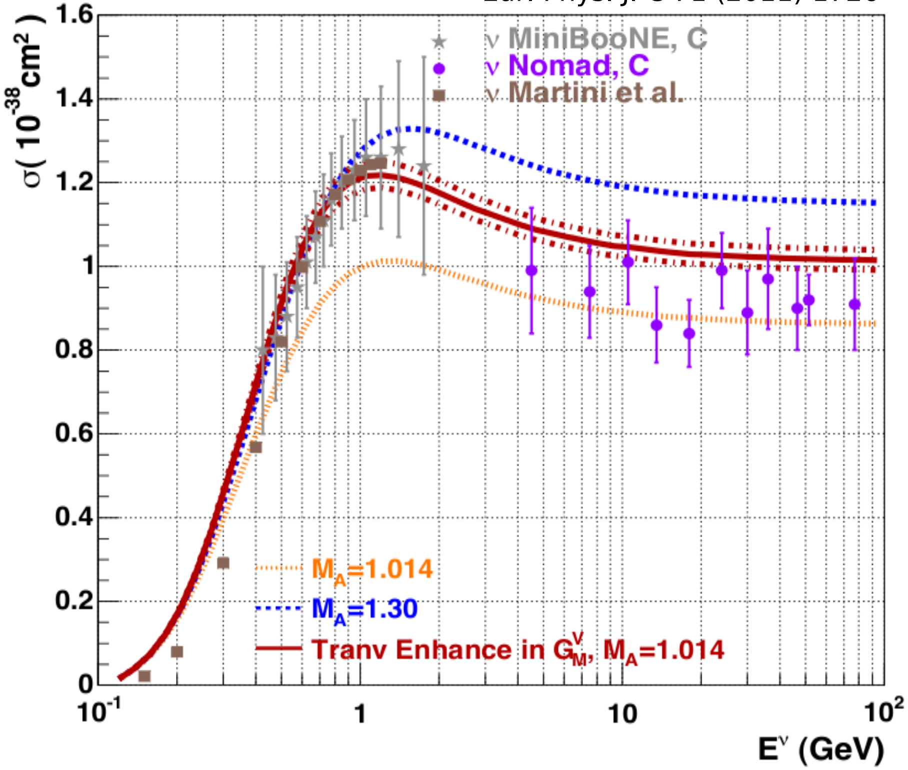
Multinucleon interactions

Evidence to suggest multinucleon interactions could relieve tensions between datasets

Plot: same data, models as before, with multi-nucleon model prediction (red line)

Some indication that multinucleon interactions can consistently describe multiple datasets

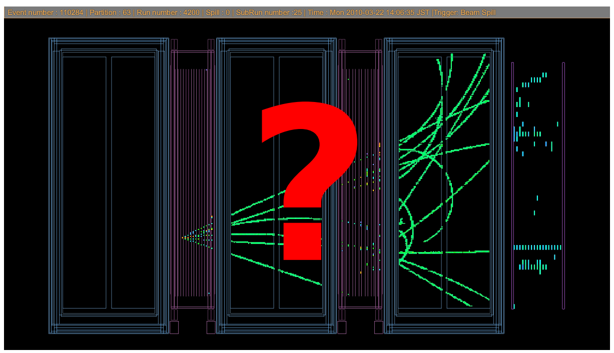
Eur. Phys. J. C 71 (2011) 1726



Simulating multinucleon interactions

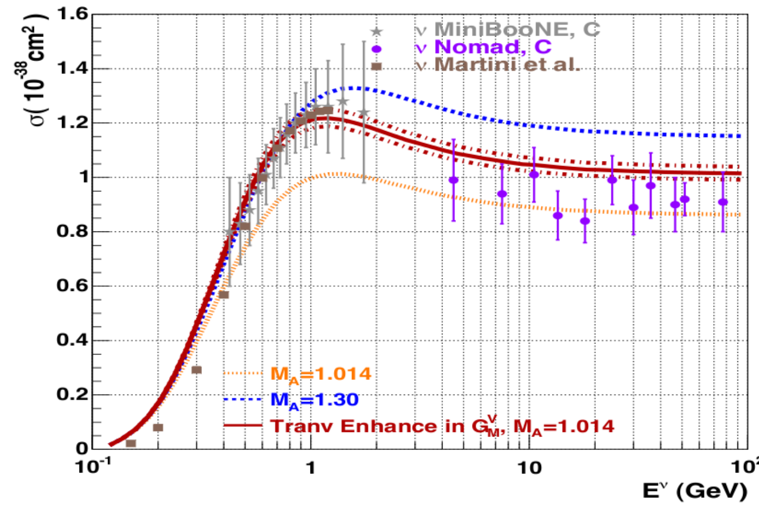
My work: **implement multinucleon model into T2K generator**. Why is this important?

Simulate in detector



1) Contamination of selected samples
2) Bias on fitted osc. parameters
3) Energy misreconstruction

External data fits

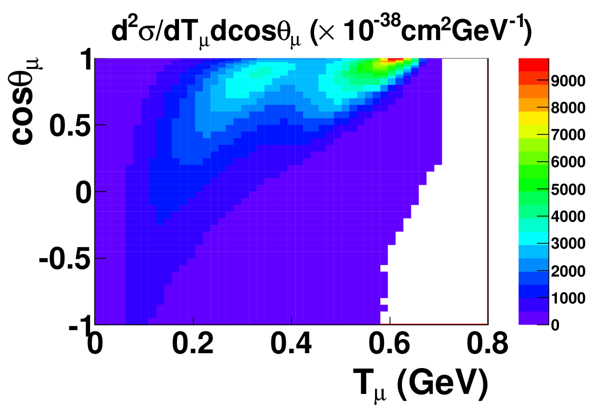


1) Consistent fit between datasets
2) Reduce cross-section uncertainty

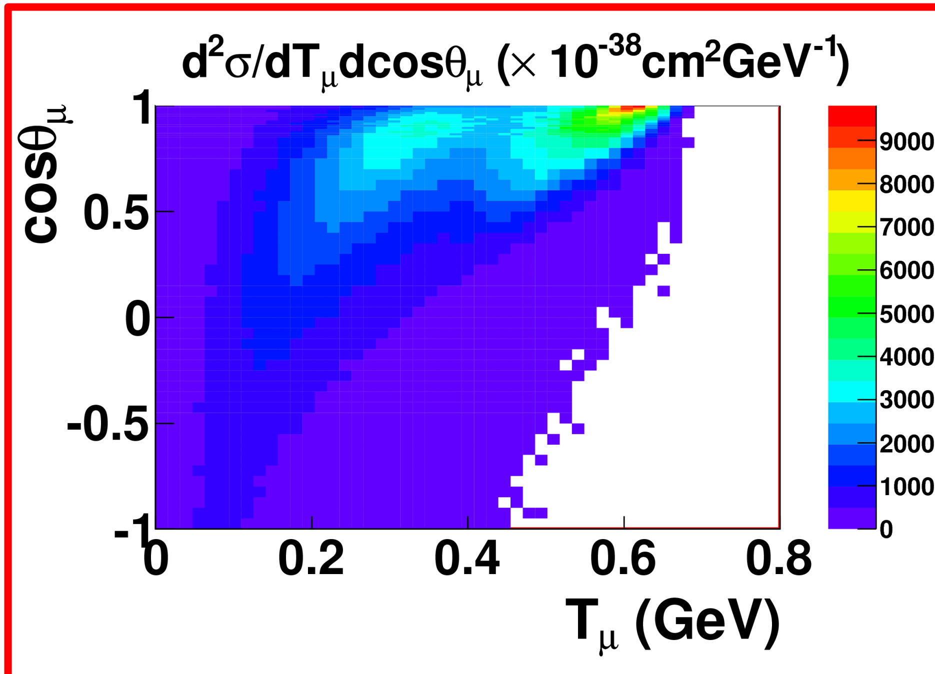
Better model → reduce oscillation parameter uncertainty

Generator predictions

So far, good progress towards getting model into T2K generator (NEUT)



Theory prediction
(Juan Nieves' multinucleon interaction model at E_ν = 800MeV)



NEUT output

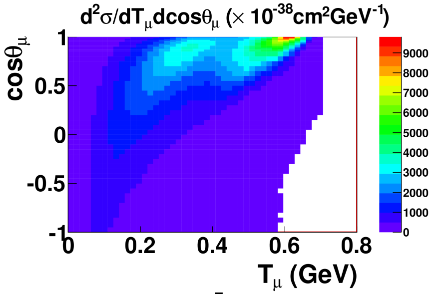
Able to predict lepton kinematics of multinucleon interactions

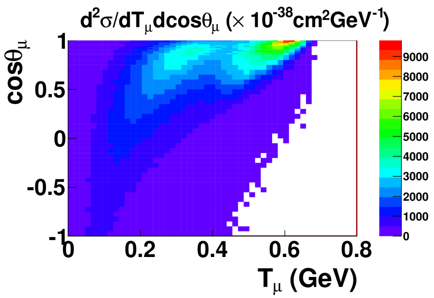
Validation studies

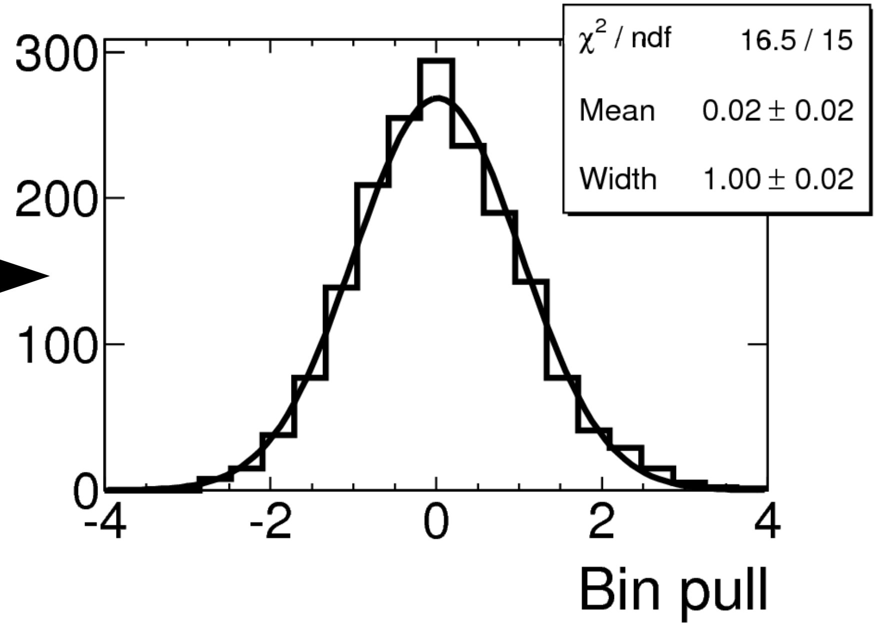
Quantify statistical agreement: look at pull distribution

$$\mathrm{Pull} = \frac{N^{\mathrm{NEUT}} - N^{\mathrm{theory}}}{\sigma^{\mathrm{NEUT}}}$$

Defined in each histogram bin
Error from MC statistics





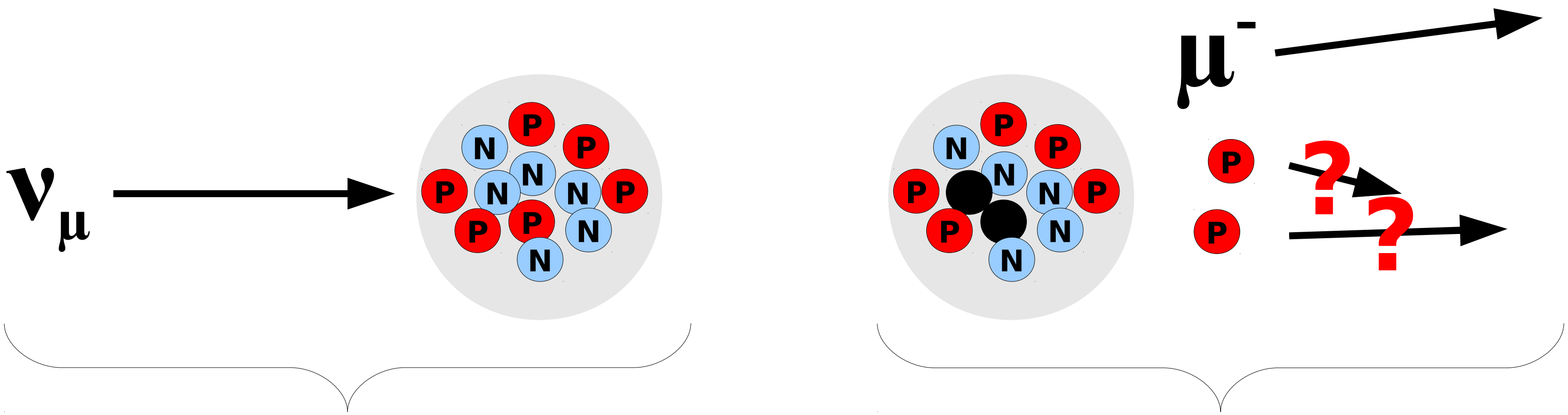


For each energy, calculate pull between prediction and MC for each bin.

All energies tested have shown statistical consistency between NEUT output and Nieves prediction.

Towards hadronic simulation

Model used in NEUT predicts outgoing lepton momentum and angle not outgoing hadron momenta



Initial state

Final state

For simulation in generator, need model for all particles.

Next steps: develop full hadron simulation based on examples from other generators

Summary

T2K measures parameters governing neutrino oscillations by measuring how neutrino beam changes as it propigates.

More consistent models allow us to reduce cross-section uncertainties on T2K measurements: multinucleon-neutrino interactions

Work commenced to put multinucleon-neutrino interactions in T2K generators

So far: leptonic simulation. To do: hadronic simulation

Hope to reduce uncertainty on T2K measurements → produce tight constraints on oscillation parameters → continue to expand knowledge of neutrino physics

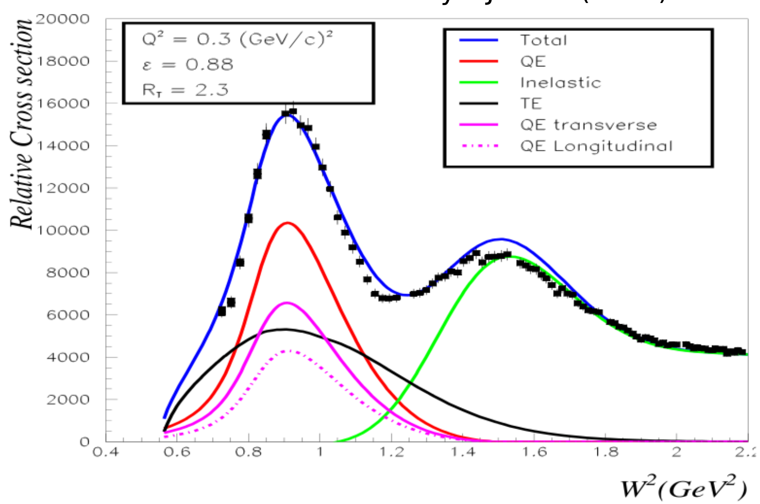
Supplementary slides

Indications of npnh in electron scattering

Further indication that the basic model (CCQE + resonances) is incomplete – look at electron scattering data

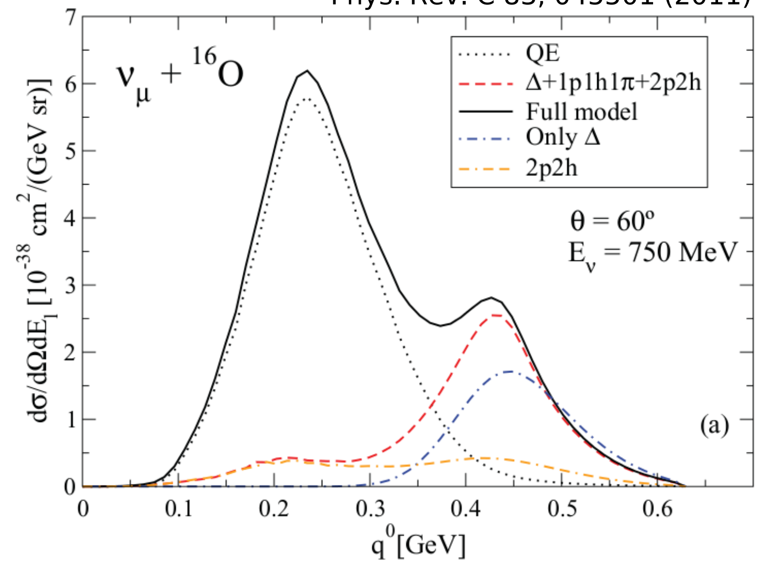
e-N can tell us about ν-N – shared parameters in e and ν cross-sections AND electrons much easier to measure

Eur. Phys. J. C 71 (2011) 1726



Plot of W^2 (W=mass of hadronic system) showing regions populated by CCQE (red) and resonant (green). 'Dip region' between CCQE and resonant peaks is much higher in data.

Phys. Rev. C 83, 045501 (2011)



Plot of q0 (energy transfer to hadronic system) showing region populated by CCQE (black dotted), resonant (blue) and 2p2h (orange). 2p2h populates the dip region

npnh models tend to populate a region in W with a large data-model disagreement (not unambiguous evidence for npnh, but indication that this model could plug the gap)

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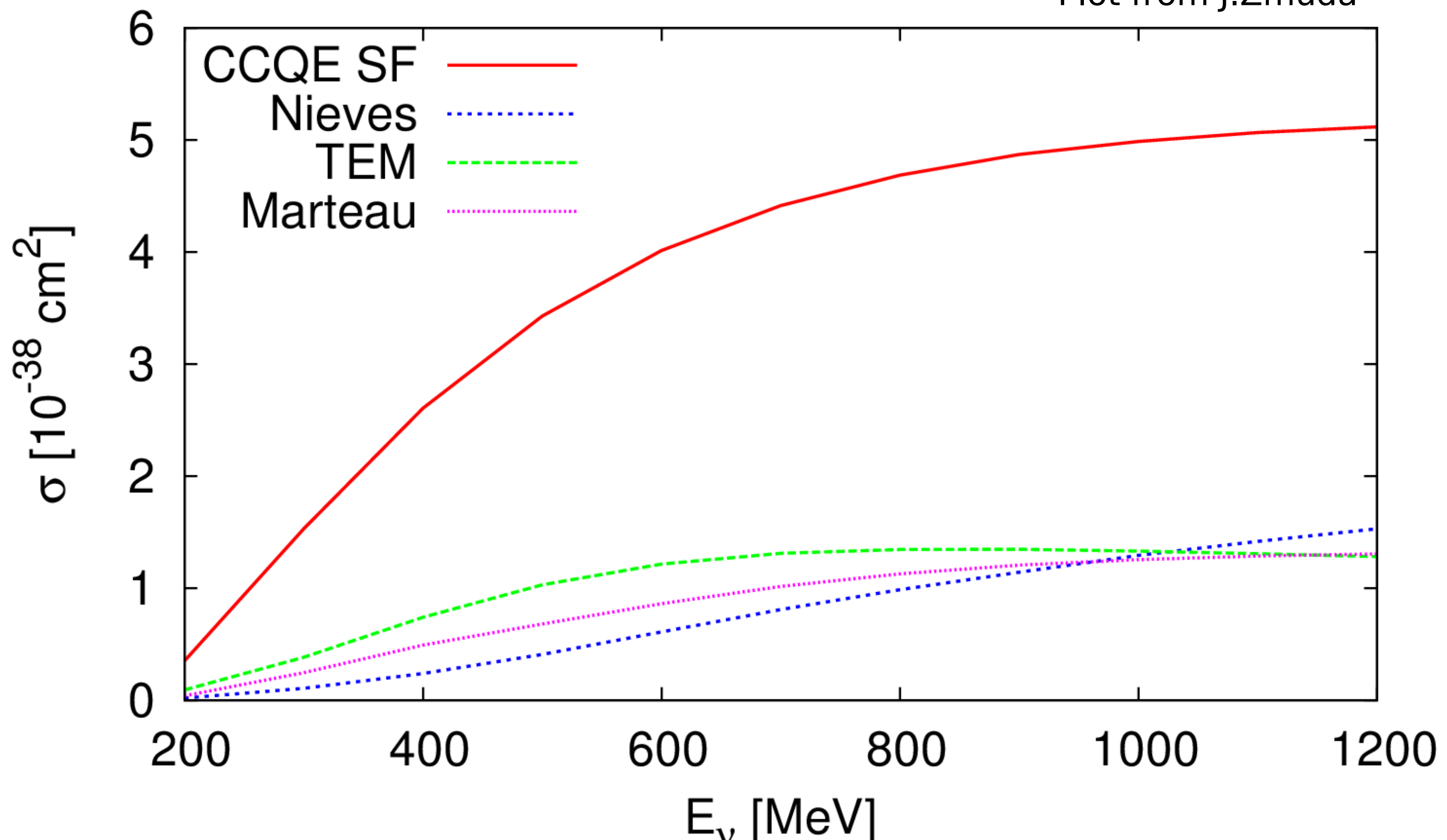
Multi-nucleon cross-sections

This plot shows the cross-sections for several multi-nucleon cross-section calculations compared to the CCQE cross-section

Plot from J.Zmuda



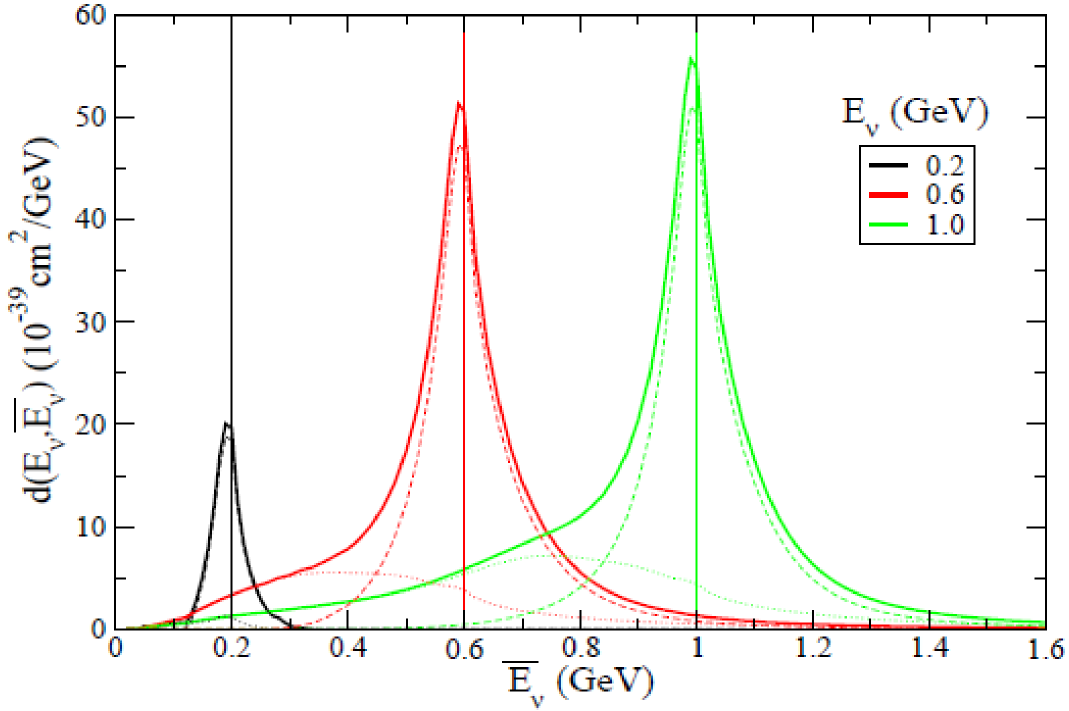
Energy mis-reconstruction

Plot shows reconstructed energy for three neutrino energies in Marteau's MEC model

CCQE contribution centred on true value.

MEC contribution generally $E_{rec} < E_{true}$

Plot from: Martini et. al. arXiv:1211.1523



Where 2p-2h enter in V-A cross-section?

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial k'} = \frac{G_F^2\,\cos^2\theta_c\,(\boldsymbol{k}')^2}{2\,\pi^2}\,\cos^2\frac{\theta}{2}\,\Big[G_E^2\,(\frac{q_\mu^2}{\boldsymbol{q}^2})^2\,R_\tau^{NN}$$ isovector nuclear response

$$+\;G_A^2\,\frac{(M_\Delta - M_N)^2}{2\,\boldsymbol{q}^2}\,R_{\sigma\tau(L)}$$ isospin spin-longitudinal

$$+\;\left(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2}+G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2}+2\tan^2\frac{\theta}{2}\right)R_{\sigma\tau(T)}$$ isospin spin-transverse

$$+\;2\,G_A\,G_M\,\frac{k+k'}{M_N}\,\tan^2\frac{\theta}{2}\,R_{\sigma\tau(T)}\Big]$$ interference V-A

The 2p-2h term affects the magnetic and axial responses
(terms in G_M, G_A)
(spin-isospin, στ excitation operator)

Slide from M.Martini showing how 2p2h terms enter ν-N cross-section

Antineutrino *vs* Neutrino-nucleus cross-section

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial k'} = \frac{G_F^2\,\cos^2\theta_c\,(\boldsymbol{k}')^2}{2\,\pi^2}\cos^2\frac{\theta}{2}\left[G_E^2\,(\frac{q_\mu^2}{\boldsymbol{q}^2})^2\,\boxed{R_\tau^{NN}}\right.$$ isovector nuclear response

$$+\;G_A^2\,\frac{(M_\Delta - M_N)^2}{2\,\boldsymbol{q}^2}\,\boxed{R_{\sigma\tau(L)}}$$ isospin spin-longitudinal

$$+\;\left(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2}+G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2}+2\tan^2\frac{\theta}{2}\right)\boxed{R_{\sigma\tau(T)}}$$ isospin spin-transverse

$$\begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases}\;\boxed{\pm}\;2\,G_A\,G_M\,\frac{k+k'}{M_N}\tan^2\frac{\theta}{2}\left.\boxed{R_{\sigma\tau(T)}}\right]$$ interference V-A

The 2p-2h term affects the magnetic and axial responses (terms in G_A ,G_M)

The isovector response R_τ (term in G_E) is not affected

Slide from M.Martini showing how 2p2h terms enter $\bar{\nu}$-N cross-section

NuWro's multinucleon ejection model

1) In lab frame, pick neutrino energy and lepton kinematics. Q^2 defined by these
2) For initial state nucleons, loop over possible momenta until viable combination found (i.e. so that total energy will allow for two real nucleons to exist outside nuclear potential)
3) Boost into CoM frame of nucleon momenta + q
4) Divide available momentum between nucleons, eject in random direction
5) Boost back into lab frame

Purely based on energy/momentum conservation and phase-space arguments

Relative importance of axial mass uncertainty

Uncertainty	Fractional change (no oscillation)	Fractional change (typical oscillation)
Super-K detector	5.57%	10.08%
Correlated near/far (before ND280 data fit)	24.14%	21.84%
Correlated near/far (after ND280 data fit)	4.38%	4.15%
Uncorrelated cross-section	3.64%	6.26%
FSI+SI	1.87%	3.48
Total (after ND280 data fit)	8.18%	13.04%

Contributions to uncertainty on number of expected rings at T2K far detector. Shown here: all uncertainties, combined into broad groups, as well as total uncertainty.

Uncertainties shown for no oscillation, and for typical oscillation parameters

Uncertainty	Fractional change			
	No oscillation		Typical oscillation	
	before	after	before	after
M_a^{QE} (shape)	21.40%	8.35%	15.99%	6.66%
M_a^{RES}	2.80 %	1.86%	6.65%	4.31%
CCQE norm. $0 < E_\nu < 1.5$GeV	7.86%	6.46%	4.23%	3.52%
CC1π norm. $0 < E_\nu < 2.5$GeV	3.76%	2.14%	4.90%	2.84%
ν_μ flux norm. $0.7 < E_\nu < 1.0$GeV	3.69%	2.71%	2.38%	1.79%

Sample of significant contributions to correlated near/far uncertainty. Uncertainties shown for no oscillation and for typical oscillation parameters, as well as before and after fit to ND280 data.

Note: correlations are present between parameters (not shown here), so uncertainty smaller than quadratic sum