Neutrino oscillation experiments and electron scattering

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TRIUMF

Neutrino oscillation experiments

T2K experiment

"Long baseline" L~ 295km

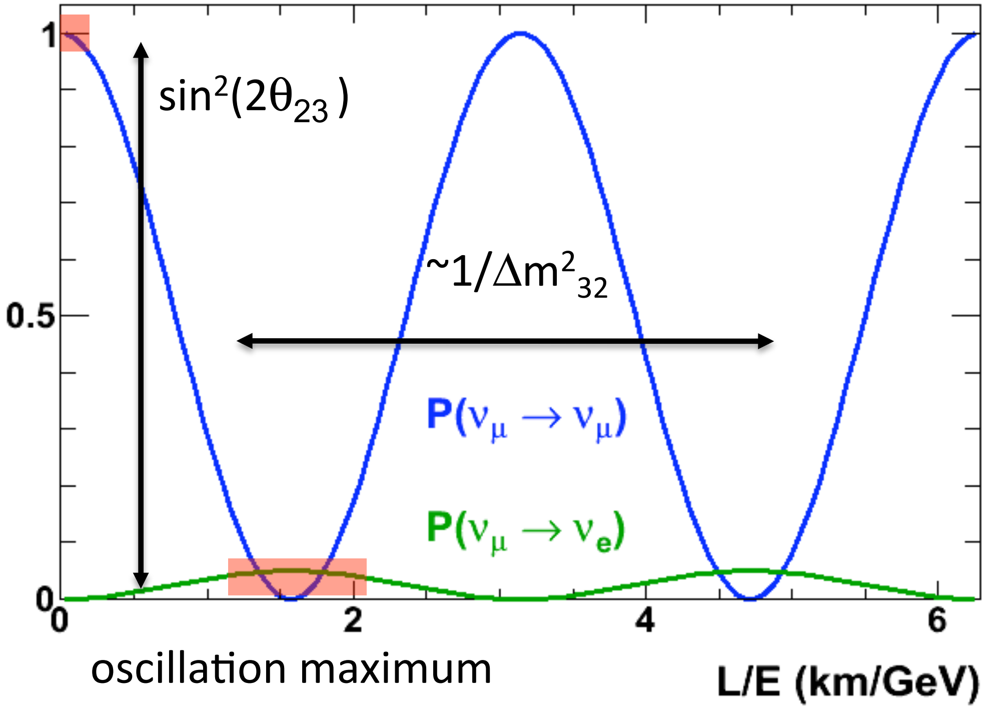
Peak neutrino beam energy ~0.6 GeV

Measure: ν_e appearance (θ_{13})

and ν_μ disappearance (Δm^2_{32}, θ_{23})

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

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



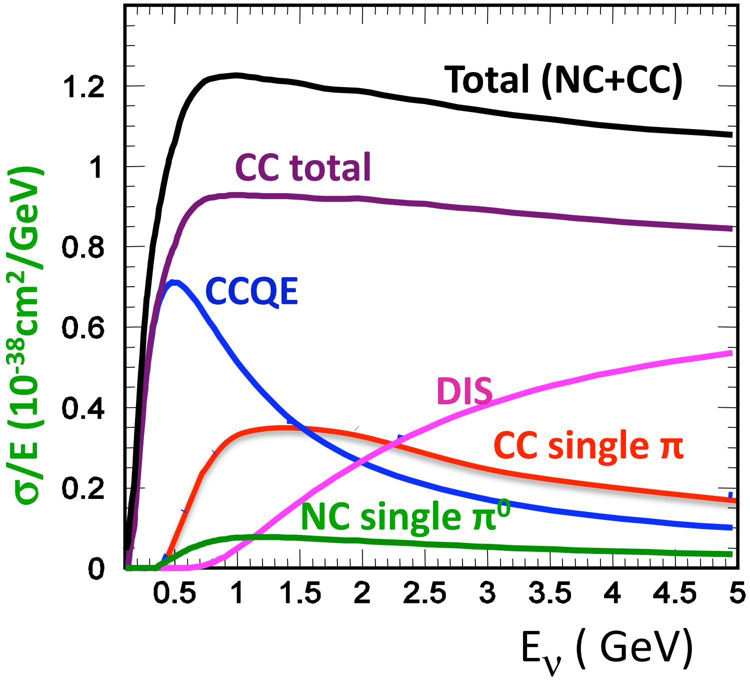
oscillation maximum

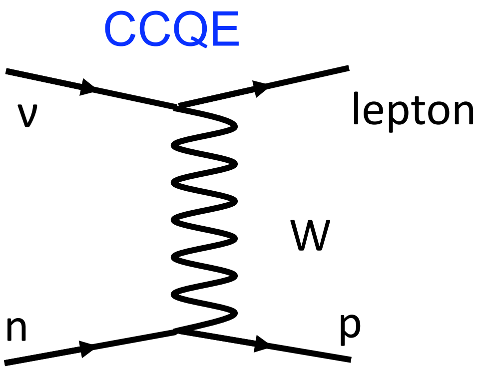
Infer oscillation parameters from rate change and distortion of Eν spectrum

- Measure ν_μ rate* at L=0
- Measure ν_μ , ν_e rate at L~oscillation maximum

*In practice also measure any ν_e background rates at L=0

Simple view of neutrino interactions at T2K





$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$

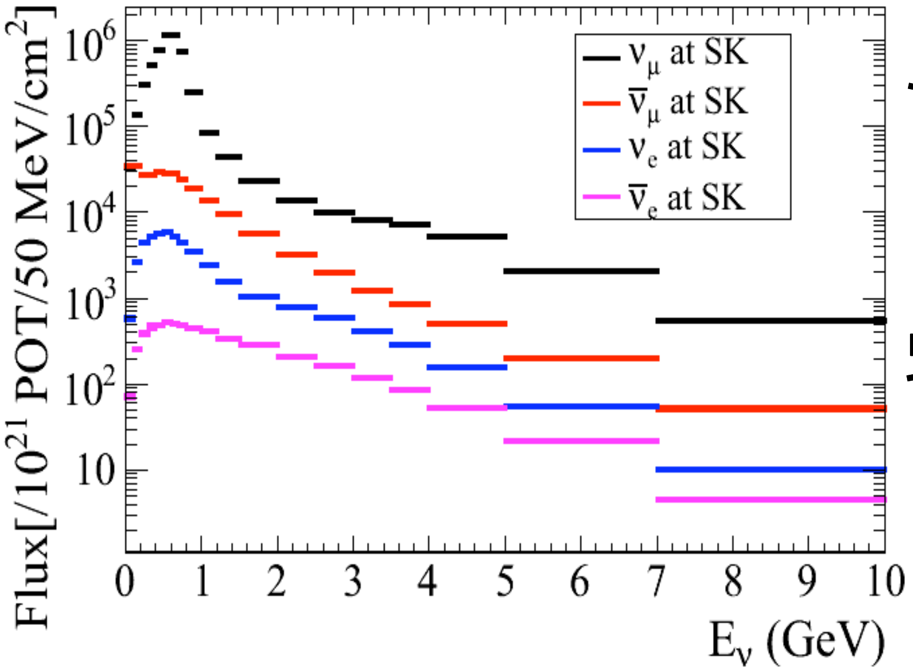
At E_ν~0.6 GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

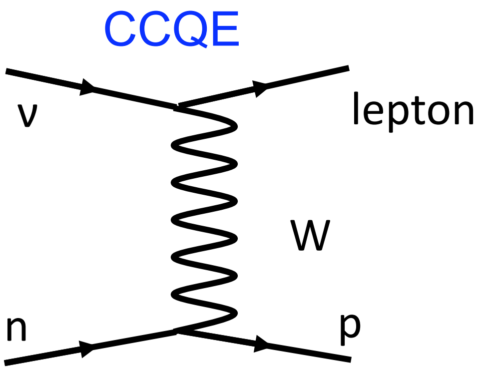
- Neutrino flavor determined from flavor of outgoing lepton
- Infer neutrino properties from the muon (or electron) momentum and angle:

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

2 body kinematics
Assumes the target nucleon is at rest

Complication #1: unknown incident neutrino energy





$$\nu_e \longrightarrow e$$

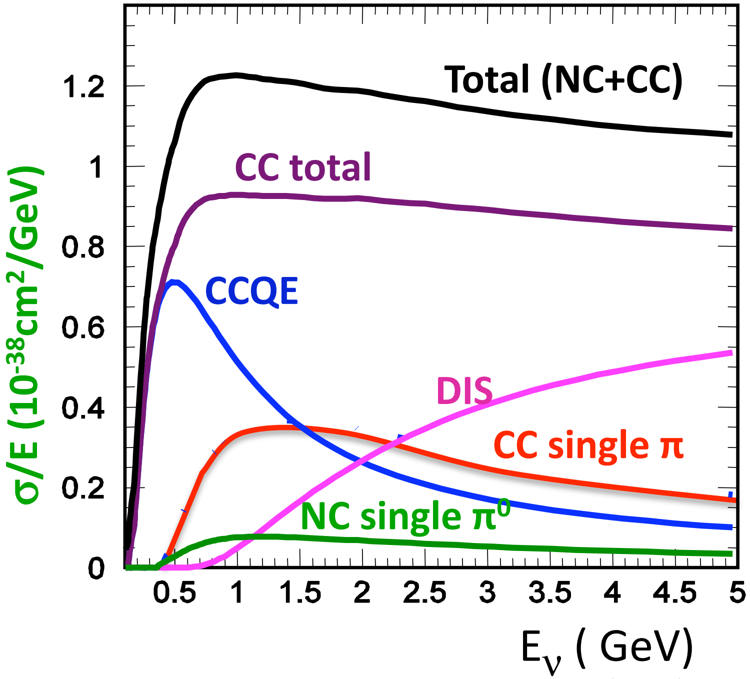
$$\nu_\mu \longrightarrow \mu$$

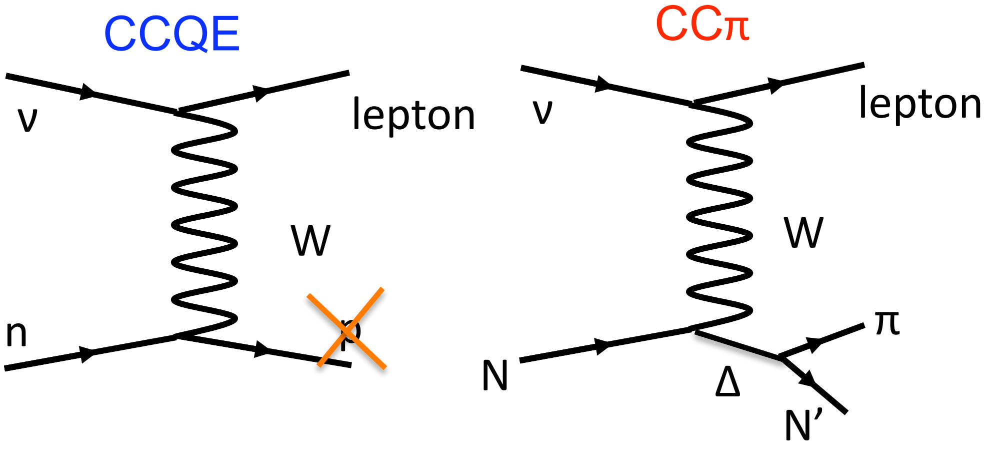
T2K's neutrino flux is from $0<E_\nu<30$ GeV

For each interaction, incident neutrino energy is unknown

- Near detector can constrain event rate in lepton kinematic bins, but relationship to neutrino kinematics is model dependant

Complication #2: nuclear targets





Neutrino detectors need to be large and massive (σ_{CC} ~10^{-38} cm^2 ~10^{-11} mb)

- Water Cherenkov: proton is below Cherenkov threshold, only lepton information
- Near detectors can measure exiting particles, like p, π, but...
- Nuclear target
  - Exiting nucleons experience "final state interactions", e.g. pion absorption leads to observable "CCQE-like" interaction, also proton rescattering
  - Representation of nucleus also affects lepton kinematics
  - neutrino-deuterium data has low statistics, sometimes in disagreement

Neutrino interaction models

Two "event generators" used: NEUT and GENIE

Generators often factorize the interactions

- CCQE (QE) is simulated separately from Δ resonance (CC1π)
- FSI is applied to all particles after the interaction has occurred

CCQE:

- Llewelyn-Smith formalism for neutrino-nucleon interaction
  - single, quasi-free nucleon interaction
- Relativistic Fermi Gas (RFG) model: bound nucleon targets treated as independent particles subject to binding energy and Fermi momentum
  - Pauli blocking may be added as an empirical parameter

CC1π:

- Rein-Seghal model for single pion production

Work ongoing to improve what is currently implemented

How electron scattering data helps

Two “event generators” used: NEUT and GENIE

Generators often factorize the interactions

- CCQE (QE) is simulated separately from Δ resonance (CC1π)
- FSI is applied to all particles after the interaction has occurred

CCQE:

- Llewelyn-Smith formalism for neutrino-nucleon interaction
  - Electron scattering is used to infer vector piece of cross section (CVC)
- Relativistic Fermi Gas (RFG) model: bound nucleon targets treated as independent particles subject to binding energy and Fermi momentum
  - Pauli blocking may be added as an empirical parameter

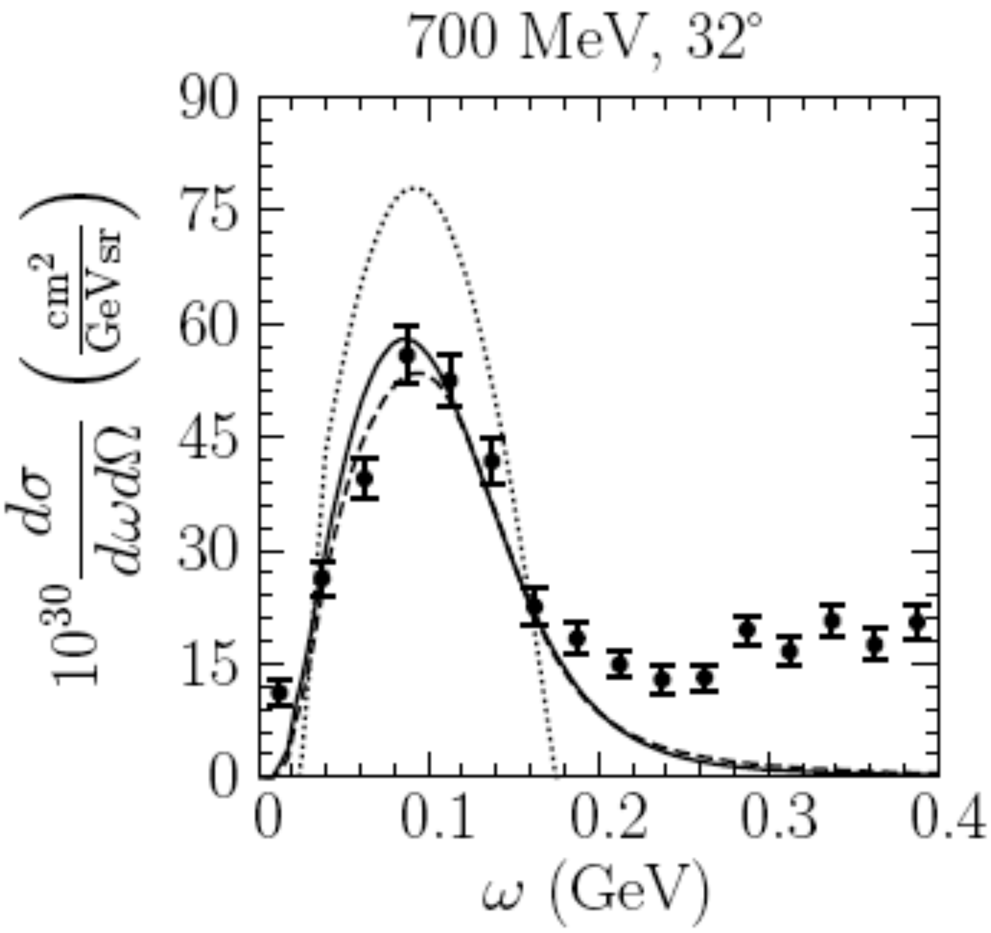
CC1π:

- Rein-Seghal model for single pion production

How electron scattering data helps

Electrons can be used on a variety of targets

- Determine nuclear potential (RFG, dotted) to alternate spectral functions (Benhar et al, dashed) and Ankowski et al (solid) from electron scattering on carbon



A.M. Ankowski, J. Sobczyk, Phys. Rev. C 77 044311 (2008)

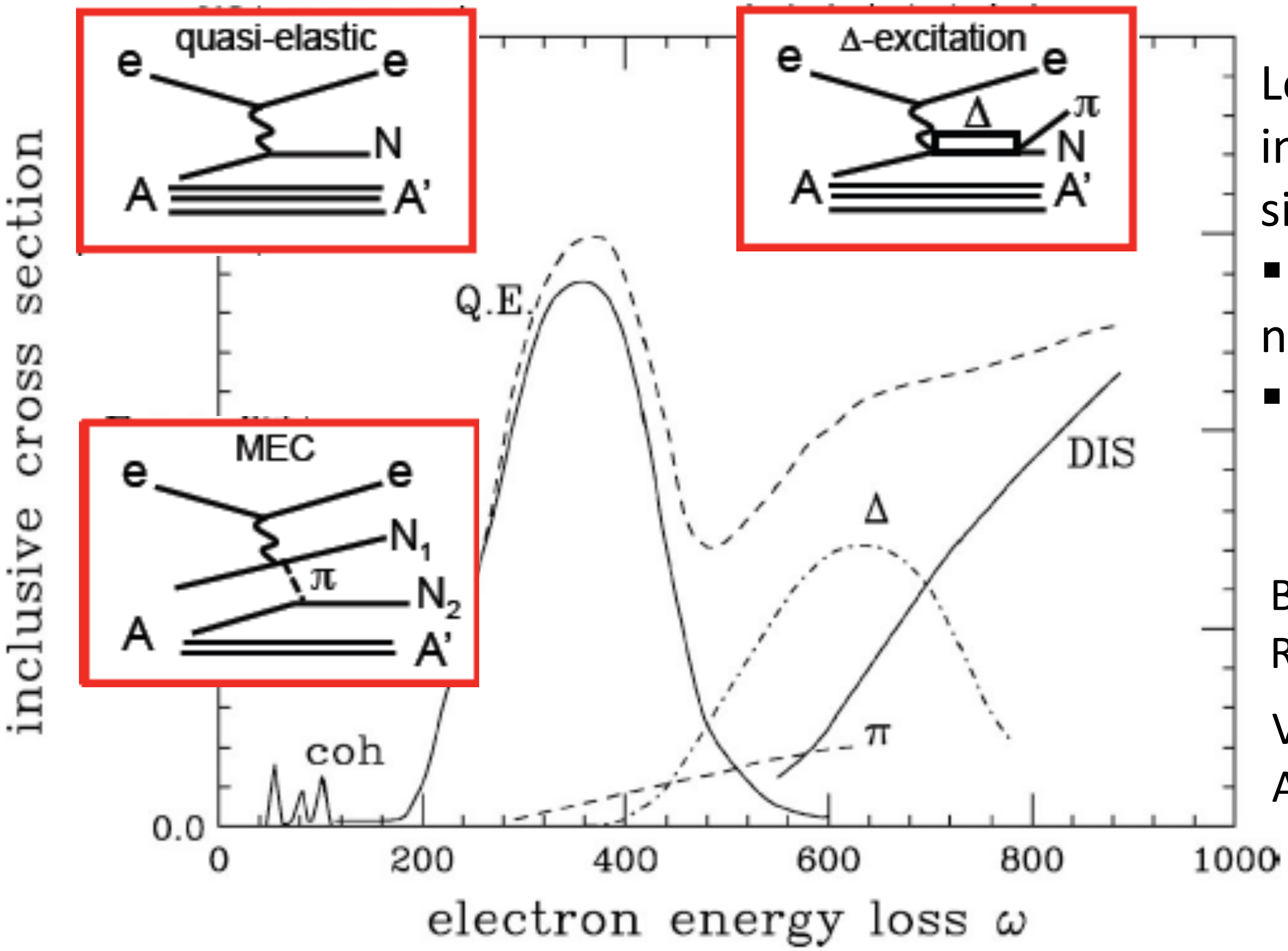
O. Benhar, N. Farina, H. Nakamura, M. Sakuda, and R. Seki, Phys. Rev. D 72, 053005 (2005).

Work ongoing to implement this into neutrino generators

How electron scattering data helps

Electrons are at a known energy

- Inclusive data can be used probe what processes contribute to the cross section
- Contribution to "dip" (w~500 MeV) region from meson exchange currents? (MEC)



Lepton interacts can interact on more than a single nucleon

- Two body current multi-nucleon knock-out
- "n-p, n-h"

Benhar, Day, Sick Rev.Mod.Phys80(2008)189

Van Orden and Donnelly Annals.Phys.131(1981)451

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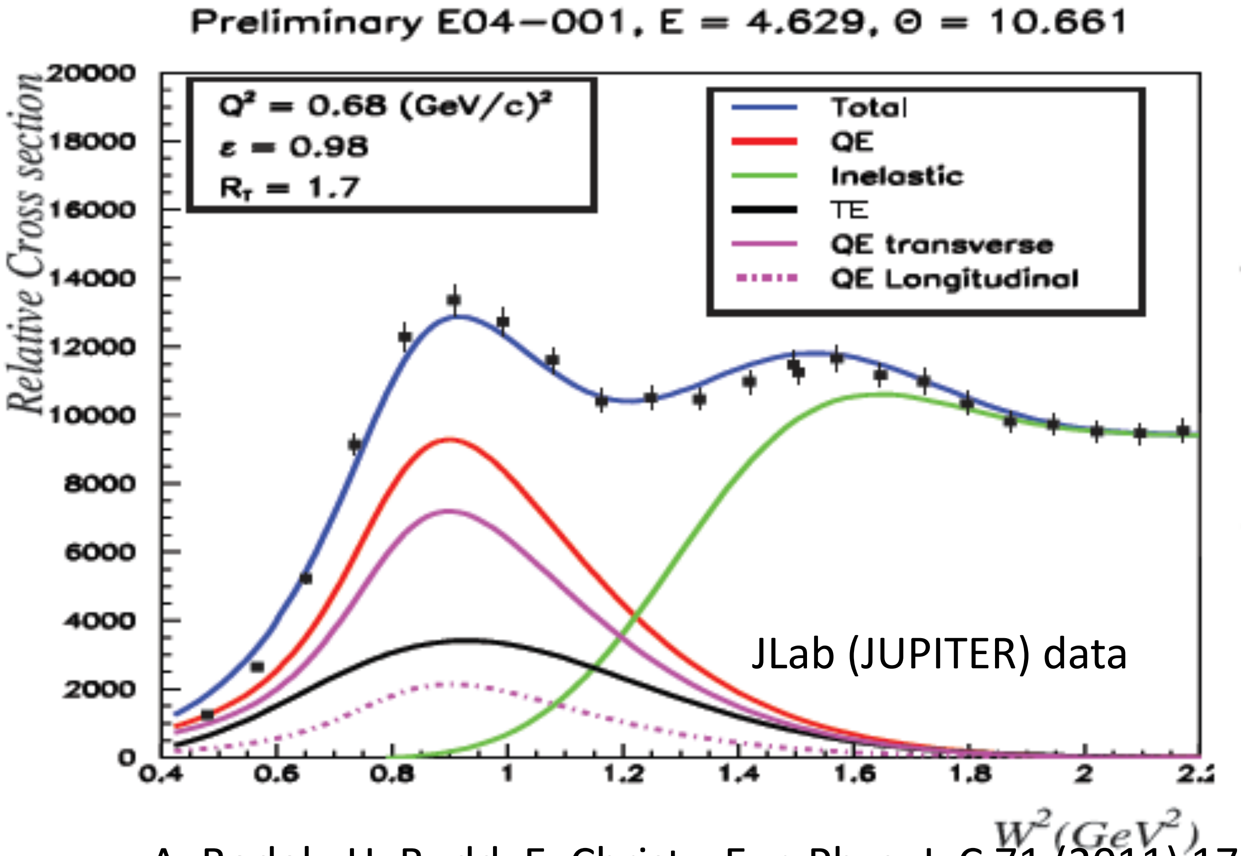

JLab (JUPITER) data

Neutrino experimentalists consider empirical models, like:

- Transverse component of QE cross section is enhanced (“TEM” model) due to MEC
- Parameterization based on electron scattering results

A. Bodek, H. Budd, E. Christy, Eur. Phys. J. C 71 (2011) 1726

J. Carlson, J. Jourdan, R. Schiavilla, I. Sick, Phys.Rev. C65, 024002 (2002)

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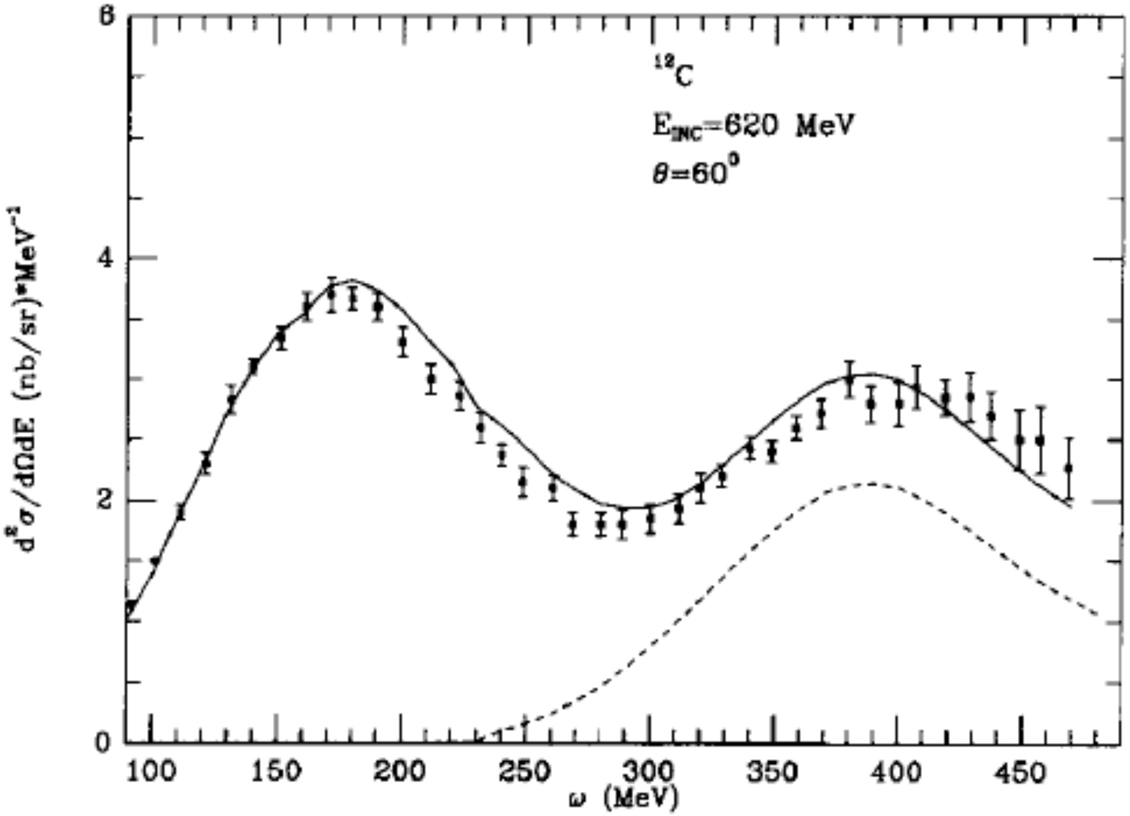


Neutrino experimentalists also consider “microscopic” models, like:

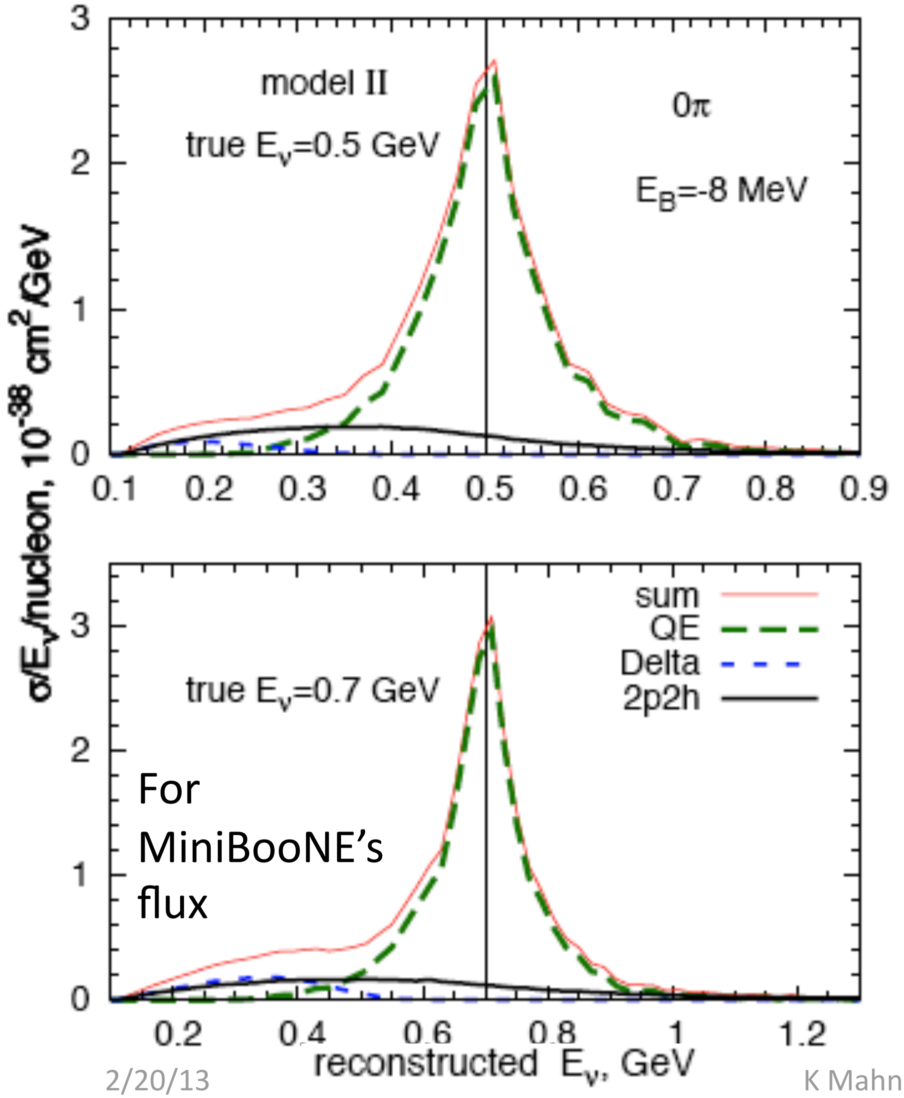
- Describes QE and Δ region and also reproduces neutrino data
- Predicts lepton kinematics, but nucleon multiplicity and kinematics are modeled separately

Gil, Nieves, Oset, Nucl.Phys.A 627 (1997)

Nieves et al, Phys. Rev. C83 (2011) 045501

Why do multinucleon processes matter?

O. Lalakulich, K. Gallmeister, U. Mosel
Phys. Rev. C86, 014614 (2012)



For MiniBooNE's flux

MEC introduces a bias between reconstructed variables and true E_ν

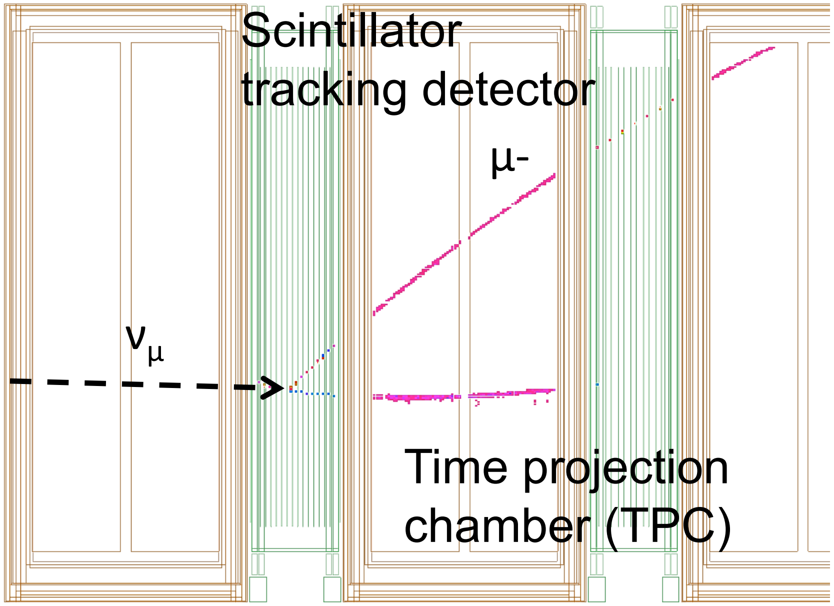
- Partially covered by current uncertainties on CC1π identified as CCQE-like
- Preliminary implementation of Nieves' model show a small bias in oscillation parameters determined from ν_μ disappearance, likely no effect on ν_e appearance yet

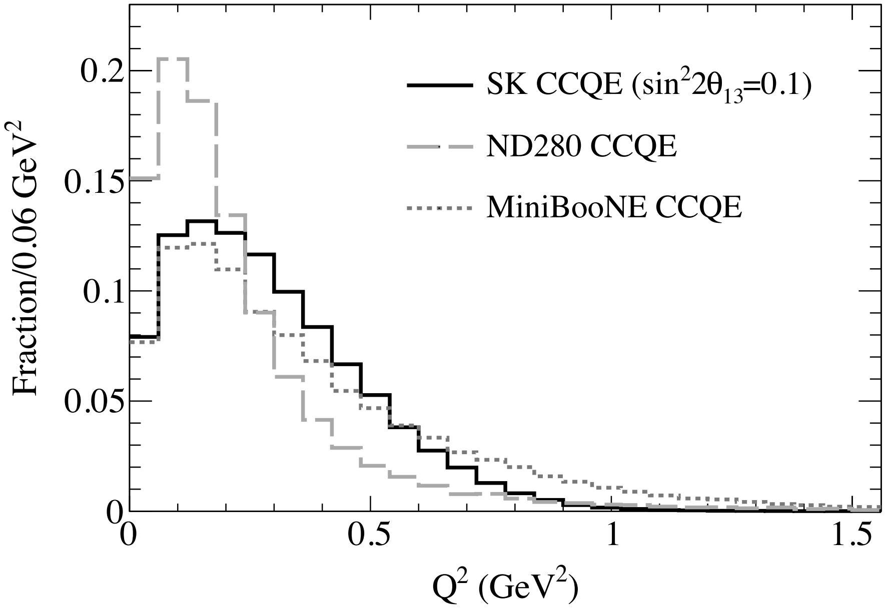
Characterizing the size of the MEC contribution is important for precision oscillation experiments... and so is understanding CC1π

What else can electron data help with?

T2K near detectors measure neutrino interactions on a range of targets

- Materials: carbon, water, brass, lead
- Proton momentum from ~0.4-1.2 GeV/c, also investigating charge at vertex
- Pion momentum from ~0.2-3 GeV/c
- Predominantly forward (or backward) acceptance





<u>Constrain final state interaction models by comparing e data on diff't targets:</u>

What is the multiplicity of protons, neutrons out of QE (and MEC?) interactions?

What is the kinematics of protons, pion out of Δ resonance interactions?

Summary

Electron scattering data has already had a large impact on neutrino oscillation experiments

- Known beam energy, isolation of nuclear effects has informed neutrino event generators
    - Improved nuclear model
    - Determination of vector form factors

Still more to be gleaned from electron scattering data

- Precision neutrino oscillation experiments need help isolating the effect of final state interactions on the exiting particles from the interaction
    - Further characterizes MEC interactions, validates QE, Δ models
    - Complementary to measurements made at the near detector

To discuss with DM collaboration

What kind of data is available?

- What beam energies? Any comparable to T2K?
- What target data?
    - Expect: D, C, Pb, Sn, Fe, Al, though for what energies?
- What final state information is available?
    - Expect: p/pi/K/e PID, 8-144deg for charged particles
    - Are there any CLAS limitations on multiplicity?

A few T2K collaborators have had fruitful collaborations within CLA

- Challenge (as usual) is often manpower

Is it possible (or sensible) to implement neutrino event generators' eA as an event generator in the CLAS simulation?

- GENIE has this functionality now; also has a basic CLAS setup
- Cross sections are the most broadly useful, but also useful to have detector-specific information from generator to guide or focus effort

To discuss with DM collaboration

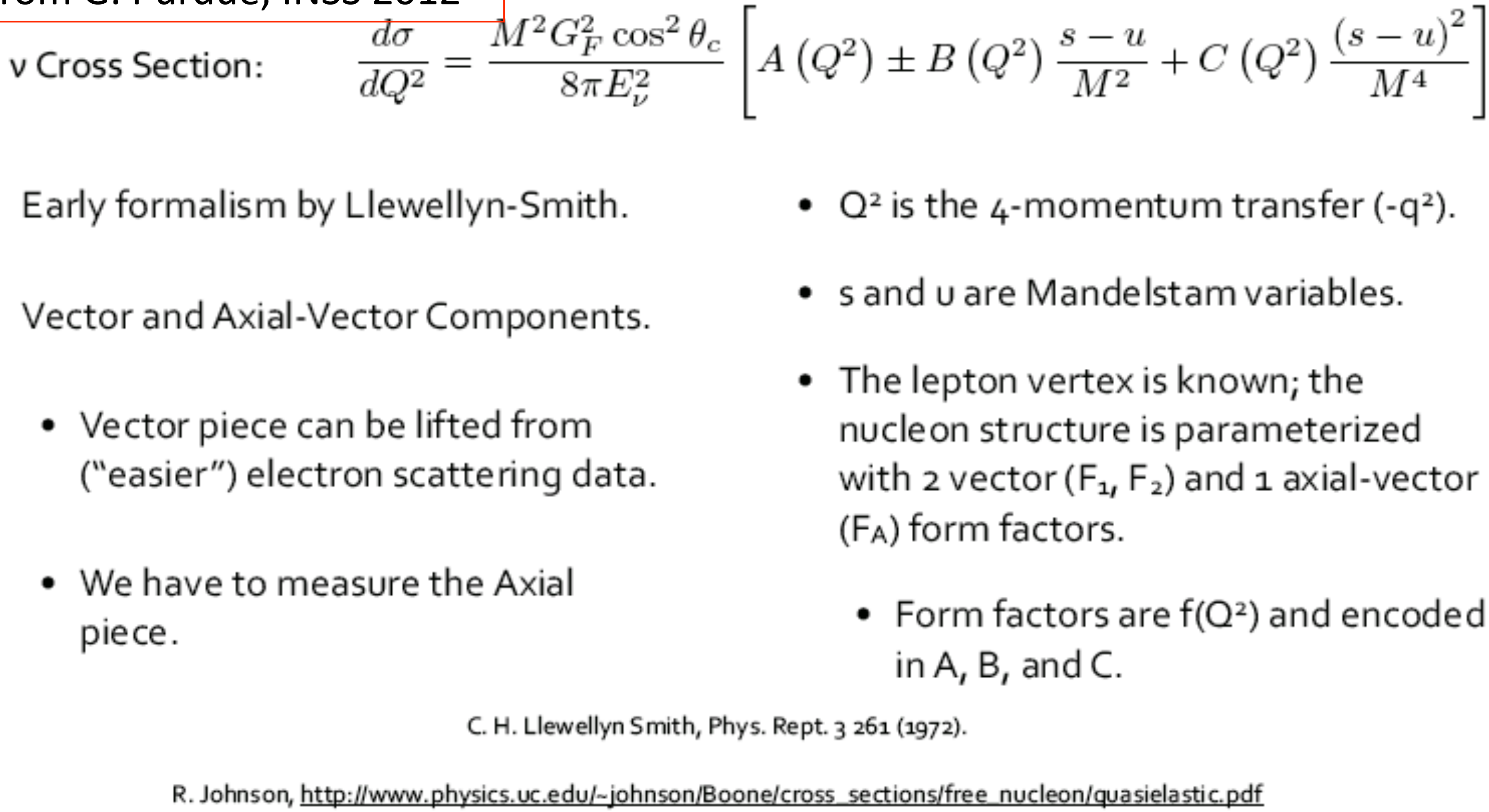
Logistics...

- Will there be a standardized format for data releases?
    - How do we present data in many kinematic variables/dimensions?
- What tools/resources will be available to interested parties?
    - Will there be a analysis core at JLab we should participate in?
    - Understanding complicated acceptance, radiative corrections, and details of simulation will be important to produce meaningful results
    - Are there details on how the CLAS simulation is set up?
        - How is the elastic scattering region is implemented? Nuclear target elastic part may be very different from neutrino generators, and may affect how MEC studies are interpreted.
- What will be the approval process for using this data with CLAS collaboration?

Backup

CCQE cross section

From G. Purdue, INSS 2012



ν Cross Section:

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A\left(Q^2\right) \pm B\left(Q^2\right)\frac{s-u}{M^2} + C\left(Q^2\right)\frac{(s-u)^2}{M^4}\right]$$

- Early formalism by Llewellyn-Smith.
- Vector and Axial-Vector Components.
  - Vector piece can be lifted from ("easier") electron scattering data.
  - We have to measure the Axial piece.

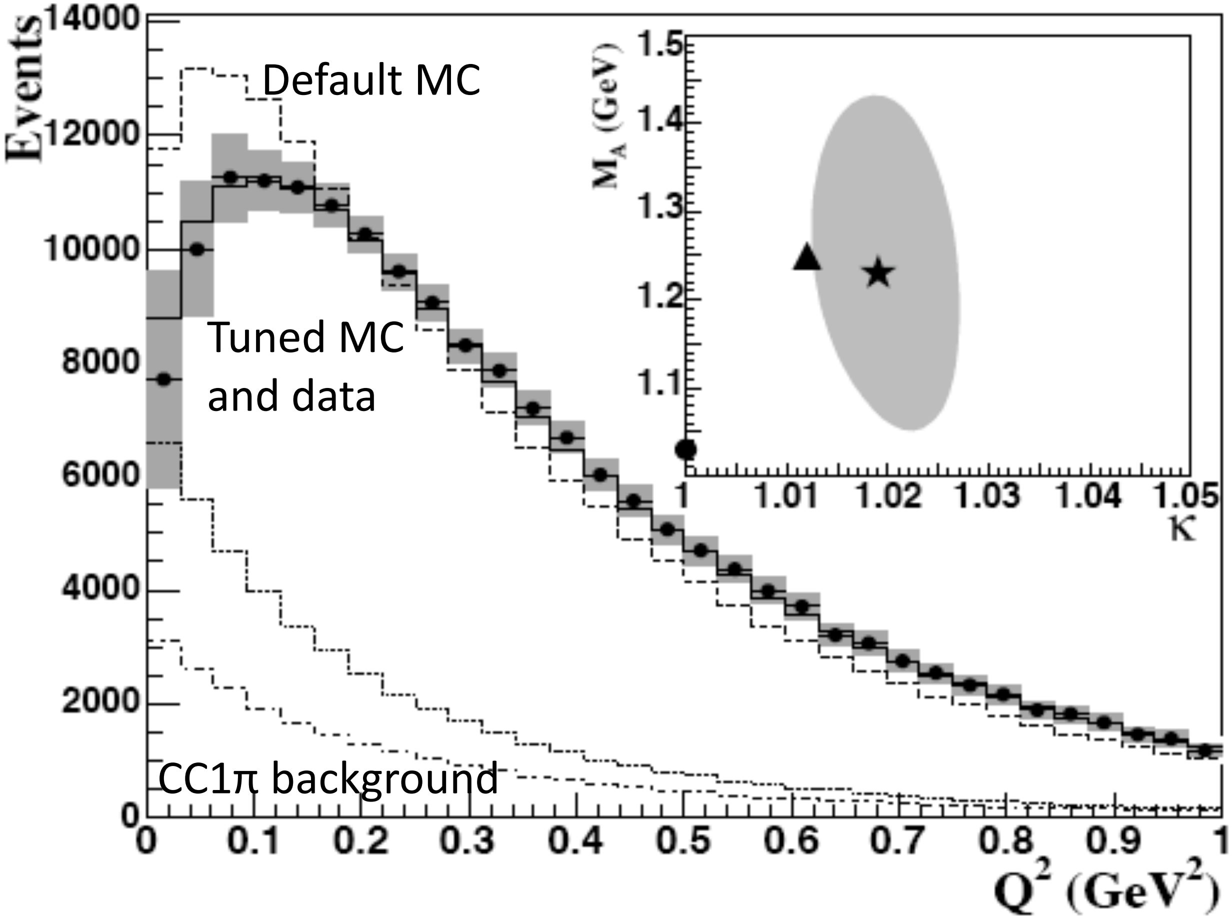
- Q^2 is the 4-momentum transfer ($-q^2$).
- s and u are Mandelstam variables.
- The lepton vertex is known; the nucleon structure is parameterized with 2 vector (F_1, F_2) and 1 axial-vector (F_A) form factors.
  - Form factors are f(Q^2) and encoded in A, B, and C.

C. H. Llewellyn Smith, Phys. Rept. 3 261 (1972).

R. Johnson, http://www.physics.uc.edu/~johnson/Boone/cross_sections/free_nucleon/quasielastic.pdf

- Axial piece is parameterized as a dipole form factor with 1 free parameter, M_A
- M_A affects normalization and shape of Q^2 distribution
- Shape fits are sometimes done to minimize dependence on flux model

Measurements of CCQE cross section



MiniBooNE

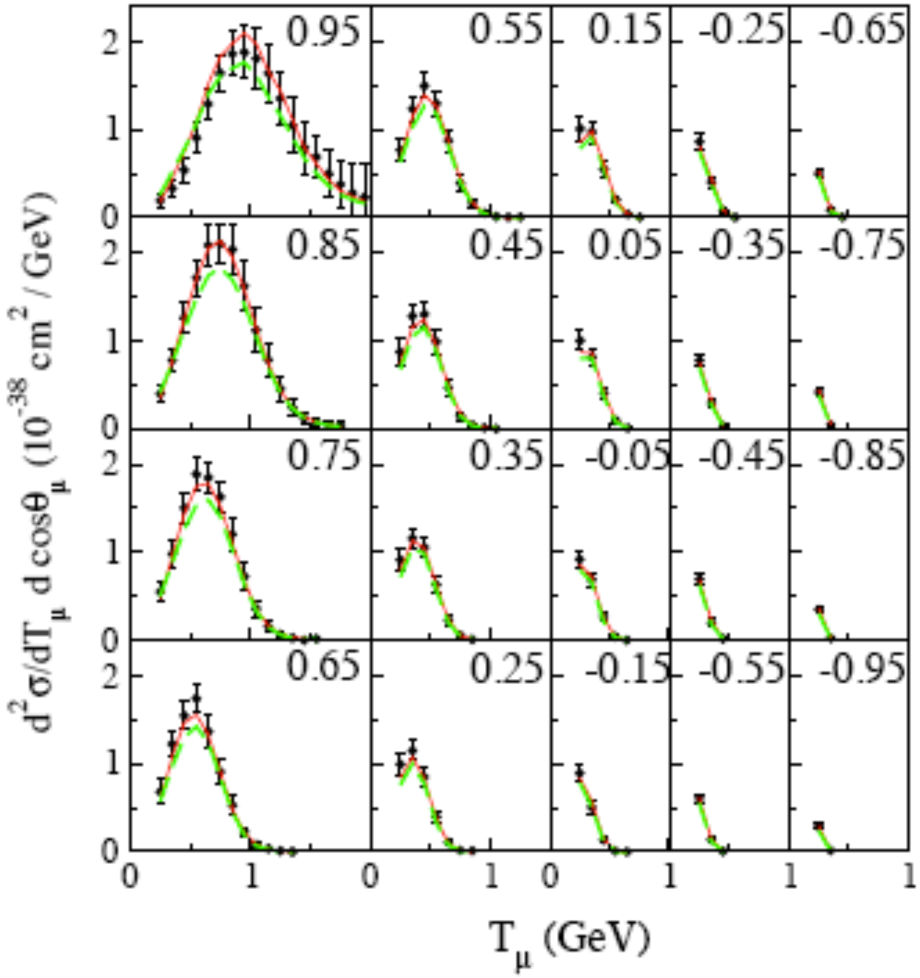
- Spherical Cherenkov detector
- Wide band beam Eν~0.8 GeV
- Select muon using decay electron
- Reject CC1π by rejecting 2nd decay electron

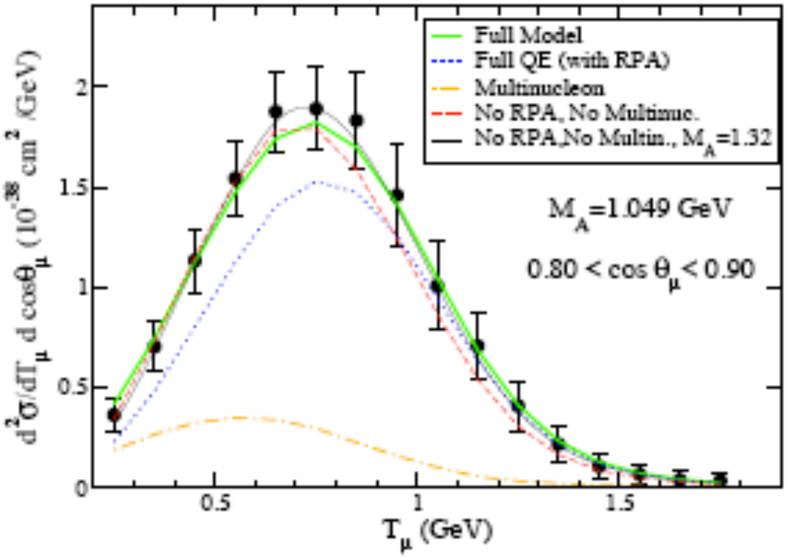
MiniBooNE experiment at ~1 GeV reports a higher value of M_A, due to excess of events at high Q^2 *arXiv:1002.2680, Phys. Rev. D81, 092005 (2010)*

- Persists after dedicated correction to CC1π background (dot dashed)
- Higher values of “M_A(effective)” is also reported by other experiments on non deuterium target material and represents the differential CCQE cross section well

Current neutrino-nucleon cross sections

Nieves – NuInt 2012 conference. Full model + MEC does as well as a higher M_A(effective) https://indico.fnal.gov/conferenceDisplay.py?confId=5361

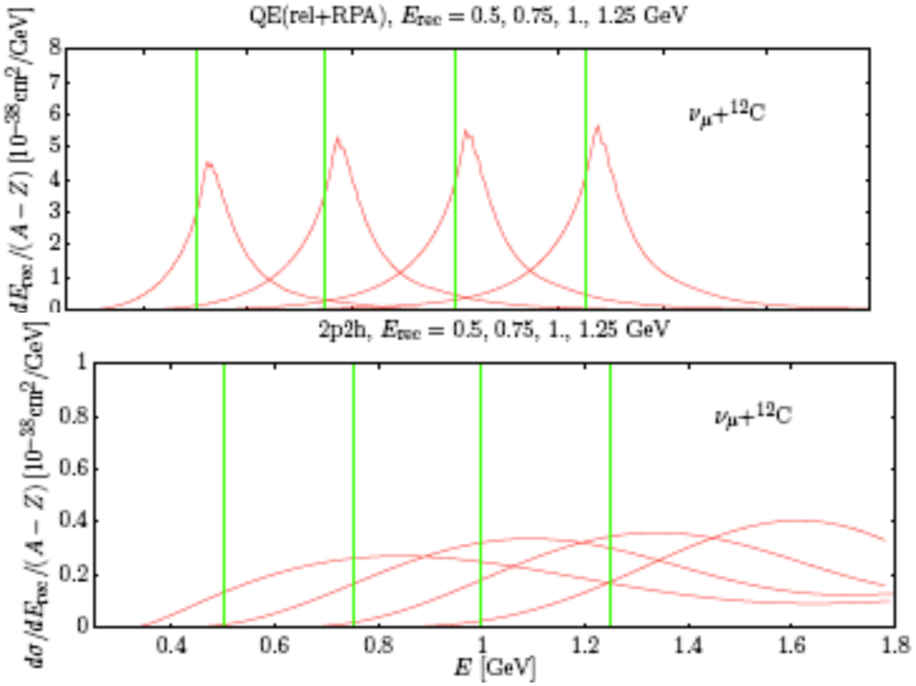




Model	Scale	M_A (GeV)	$\frac{\chi^2}{\#bins}$
LFG	0.96±0.03	1.32±0.03	35/137
Full	0.92±0.03	1.08±0.03	50/137
Full $\lvert q\rvert > 0.4^\dagger$ GeV	0.83±0.04	1.01±0.03	30/123

† : As suggested by Sobczyk et al. PRC 82, 045502

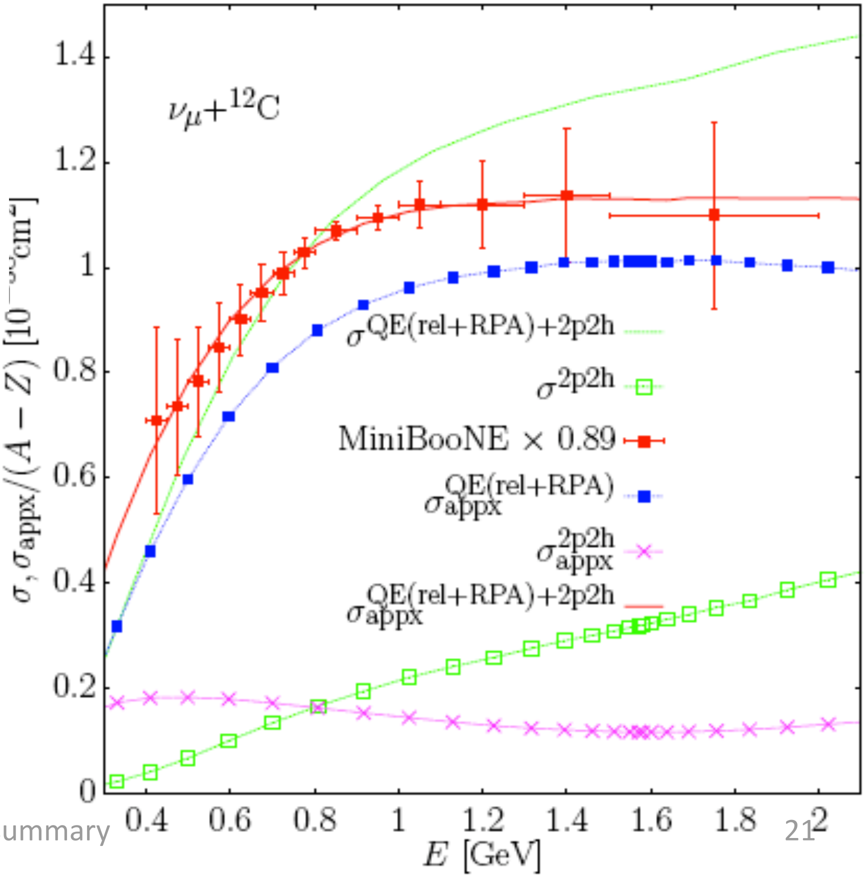
J. Nieves Friday morning, NuInt2012 conference



MEC interactions have a broader spread in neutrino energy (true relative to simple reconstructed quantity)

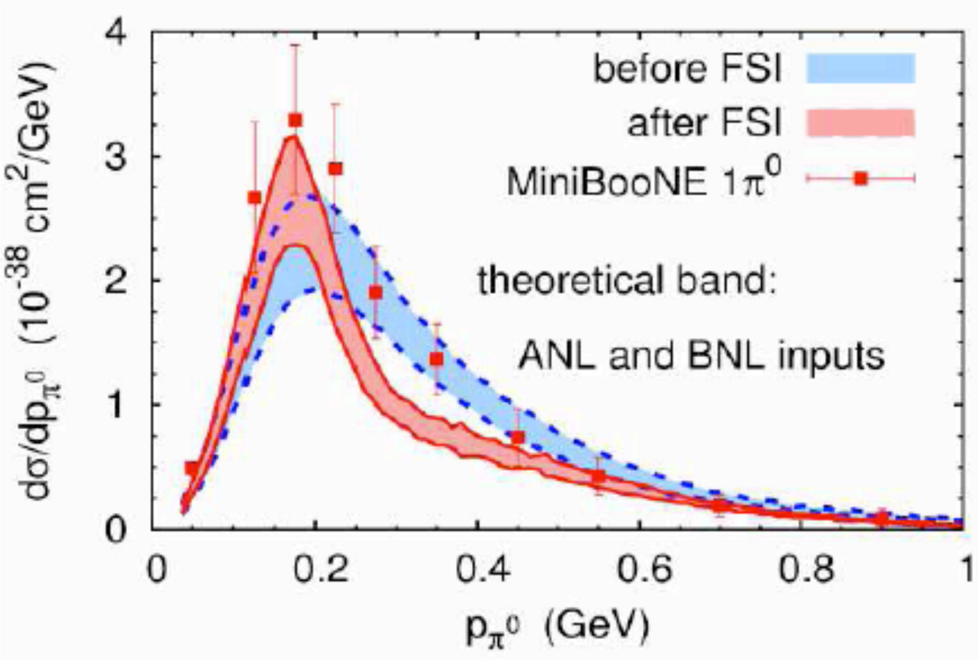
Redo neutrino energy reco-> true unfolding using MiniBooNE differential data with and without MEC components

Agreement within MiniBooNE 10% flux errors, much improved shape dependence

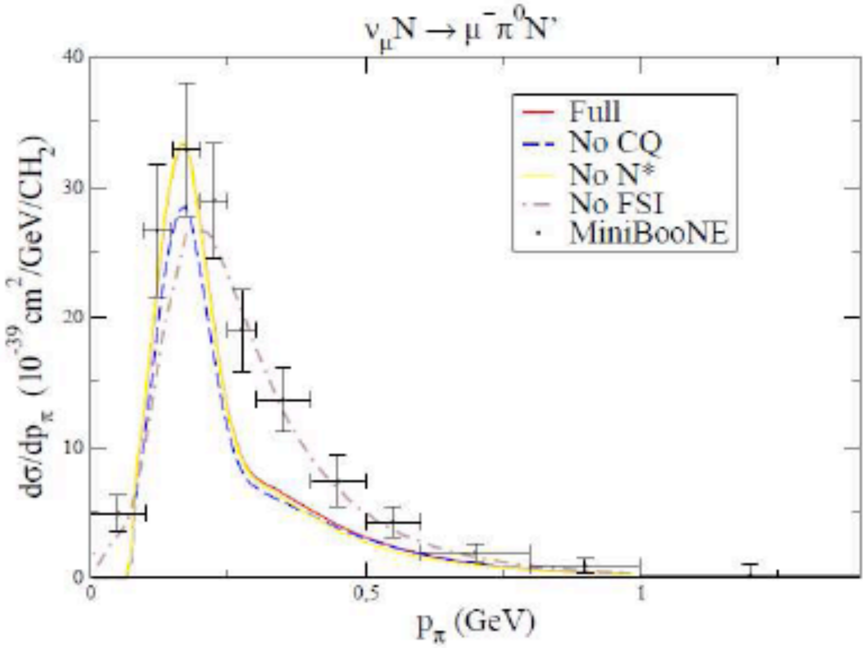


L. Alvarez-Ruso, Saturday morning, NuInt2012 conference

- State of the art calculations describe better the data without FSI



Lalakulich@NuInt12

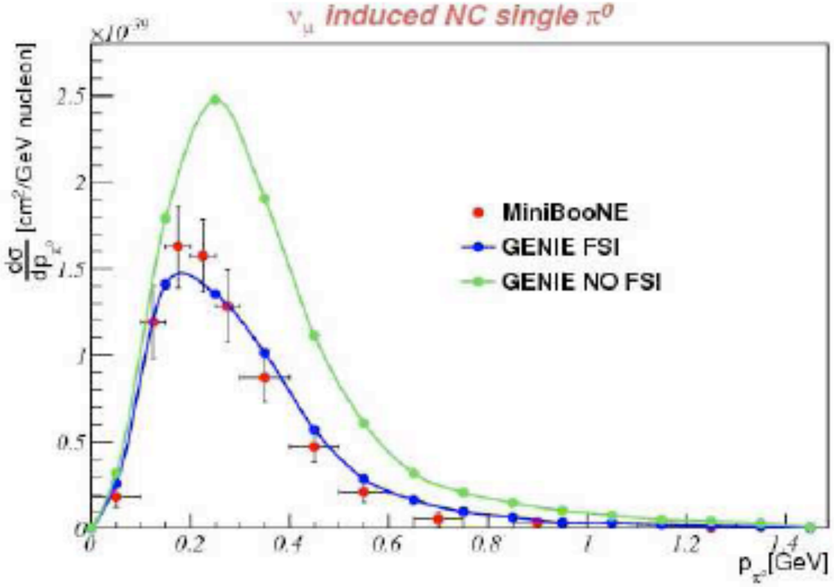


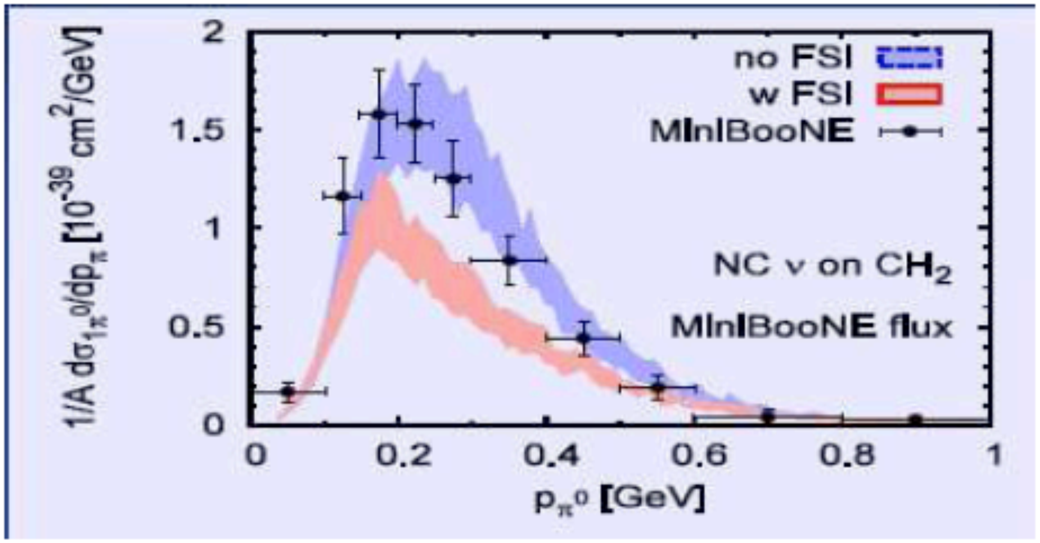
Hernandez@NuInt12

- Possible problems in:
  - π production model on the nucleon
  - medium modifications of amplitudes
  - FSI

L. Alvarez-Ruso, Saturday morning, NuInt2012 conference

- GENIE vs GiBUU NCπ^o

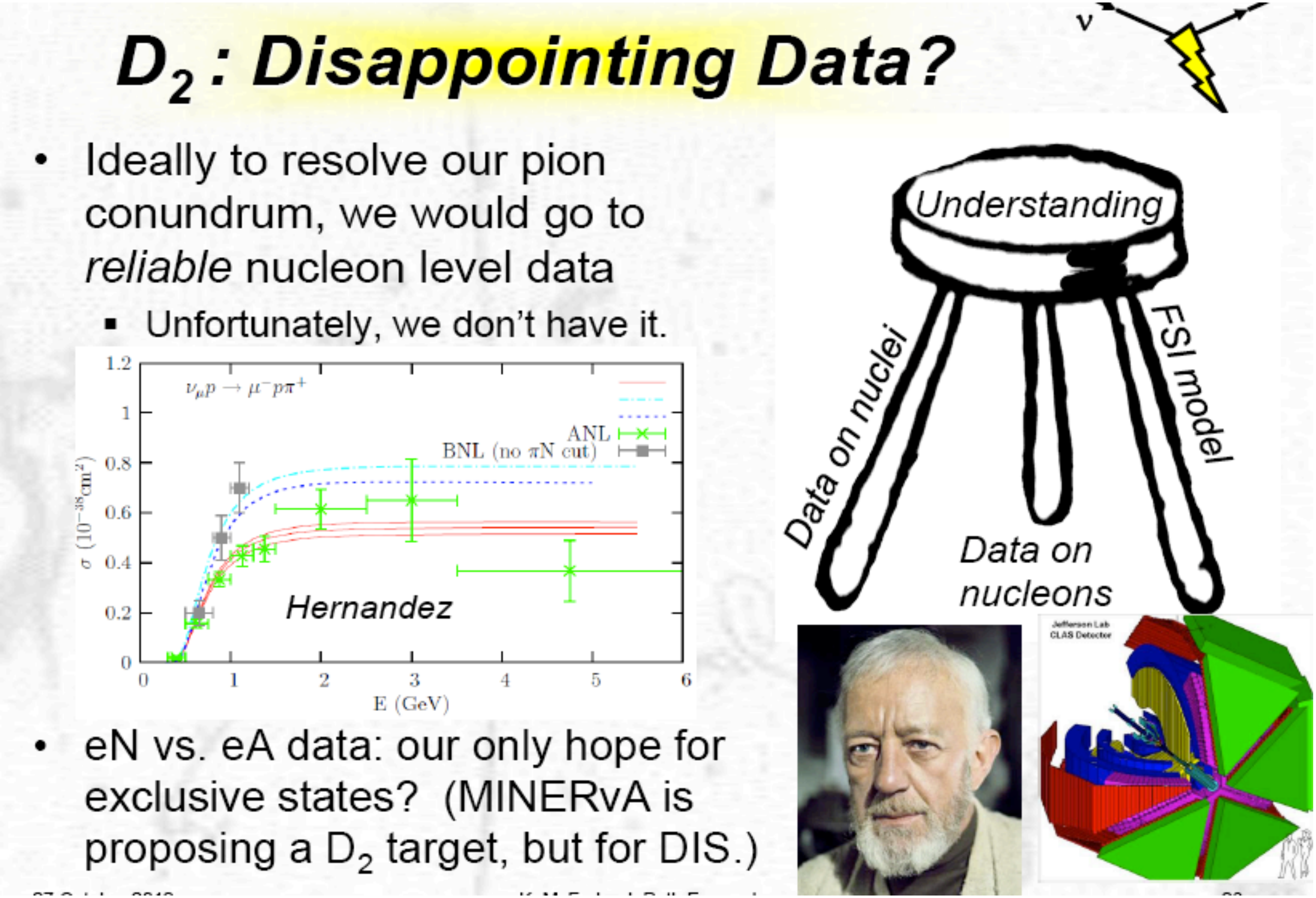




Dytman@NuInt12

- Largest discrepancies seem to be in the cross sections before FSI
- At the nucleon level, both compatible with ANL/BNL data!

K. McFarland, Saturday morning, NuInt2012 conference



D_2 : Disappointing Data?

- Ideally to resolve our pion conundrum, we would go to *reliable* nucleon level data
    - Unfortunately, we don't have it.
- eN vs. eA data: our only hope for exclusive states? (MINERvA is proposing a D_2 target, but for DIS.)