Neutrino oscillation experiments and electron scattering

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Neutrino oscillation experiments

Leading order terms shown

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

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

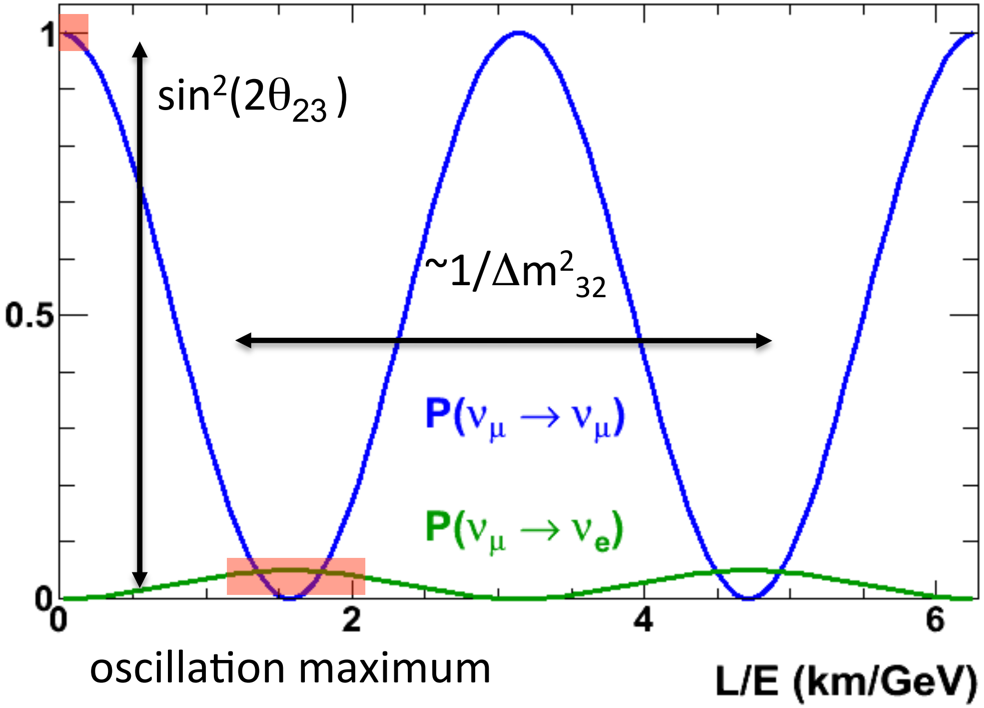
T2K experiment

"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})



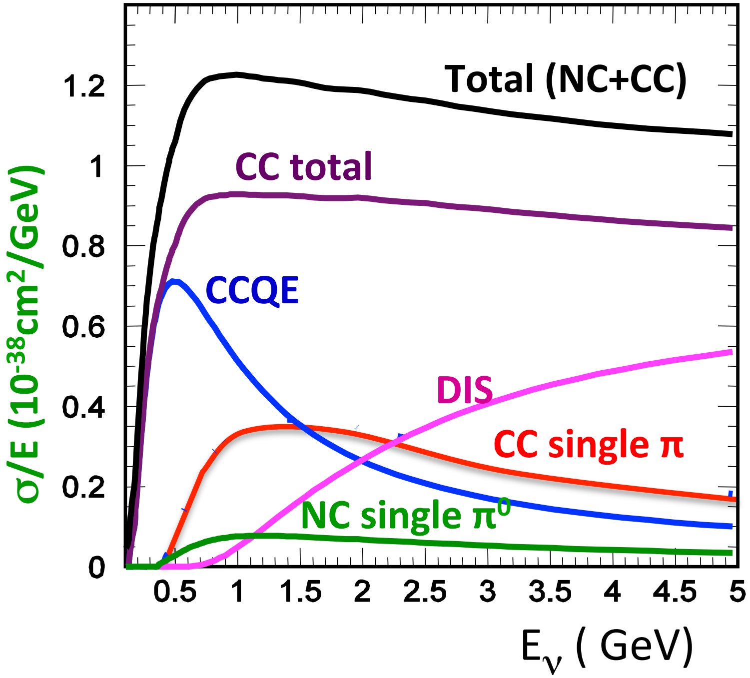
oscillation maximum

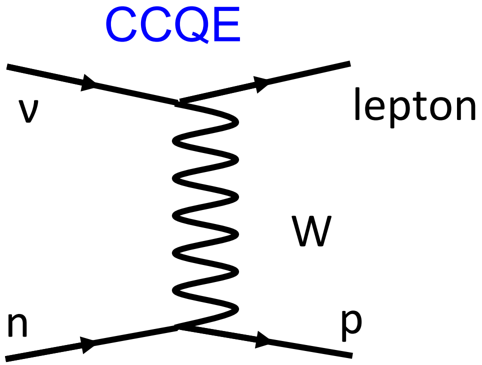
Infer oscillation parameters from rate change and distortion of Eν spectrum

- 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





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

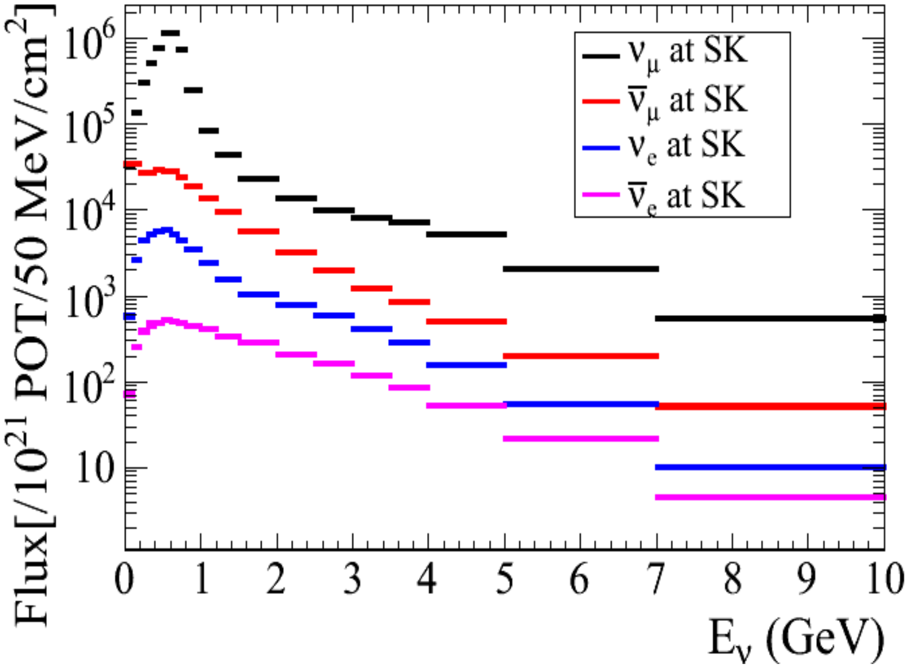
At E_ν~0.6 GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

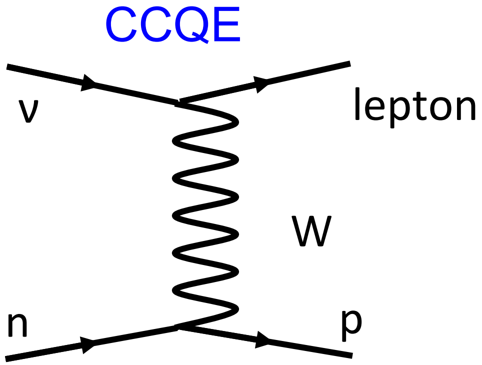
- Neutrino flavor determined from flavor of outgoing lepton
- Infer neutrino properties from the muon (or electron) momentum and angle:

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

2 body kinematics
Assumes the target nucleon is at rest

Complication #1: unknown incident neutrino energy





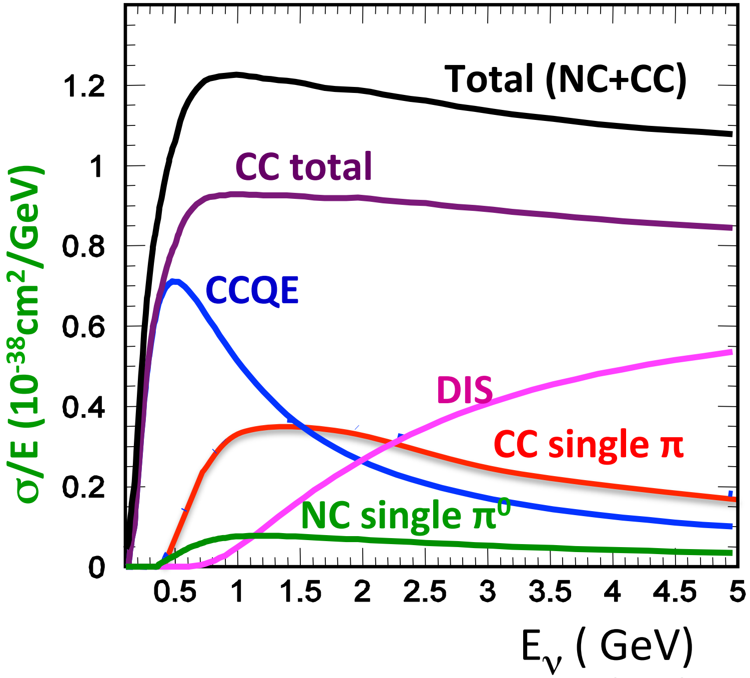
$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$

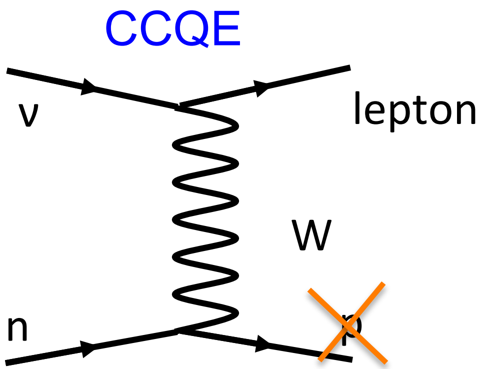
T2K’s neutrino flux is from $0<E_\nu<30$ GeV

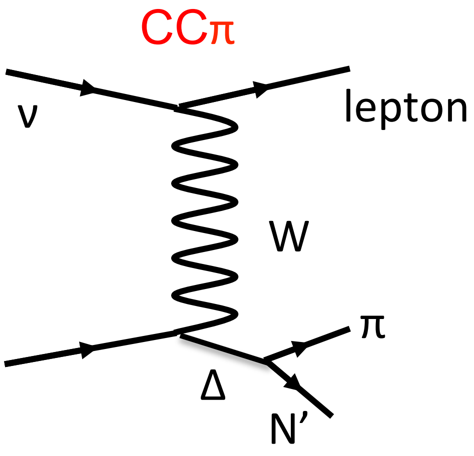
For each interaction, incident neutrino energy is unknown

- 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)

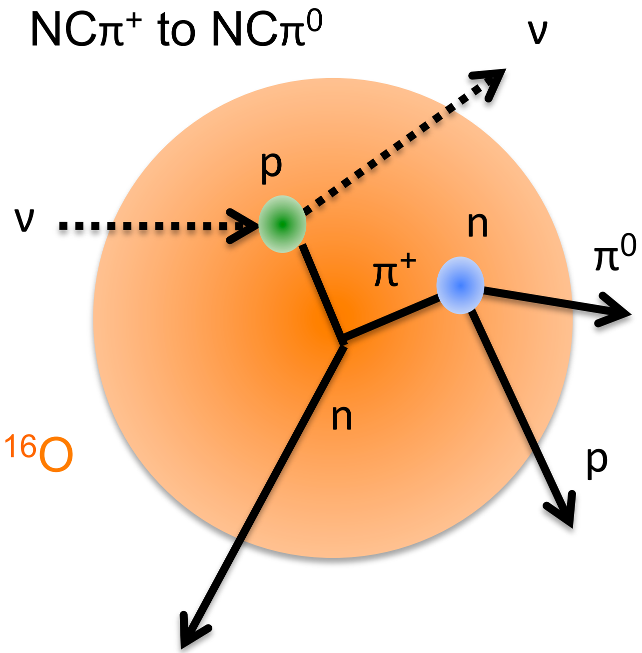
- Water Cherenkov: proton is below Cherenkov threshold, only lepton information
- Near detectors can measure exiting particles, like p, π, but...
- Nuclear target
  - Exiting nucleons experience "final state interactions", e.g. pion absorption leads to observable "CCQE-like" interaction, also proton 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)
  - Electron scattering data used to infer the vector part of the cross section and inform `modern’ models of nucleus
- Final State Interactions (reinteractions of particles after production) is applied separately for pions, nucleons



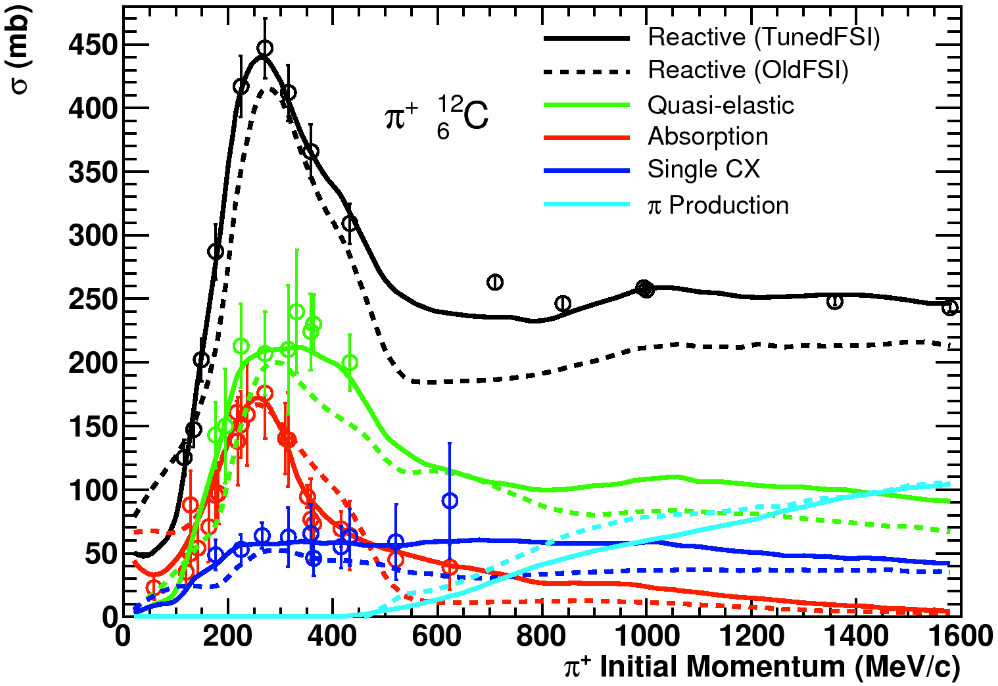
Example of pion interactions in a NC interaction

Proton multiplicity, reinteractions are also important as they may be used to infer the hadronic state

T2K FSI model

NEUT pion FSI model is a cascade model tuned on ``free-range'' π+N data

- ~3% error in disappearance analysis at far detector; future experiments want ~2% or better uncertainties
- No check currently of whether or not our models are representative of Δ -> π in medium
  - Indirect checks perhaps possible through photo-production?



Data from Data Mining collaboration

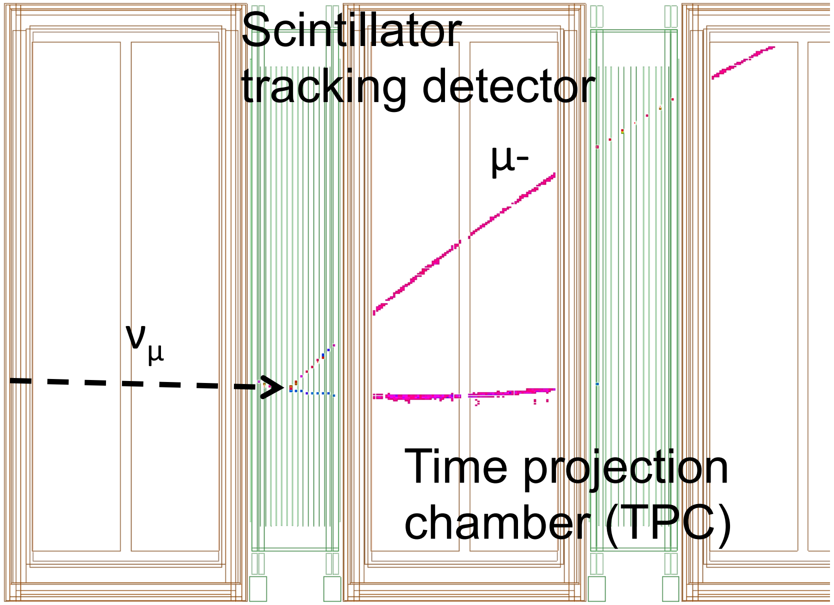
Is a unique probe of in-medium effects directly

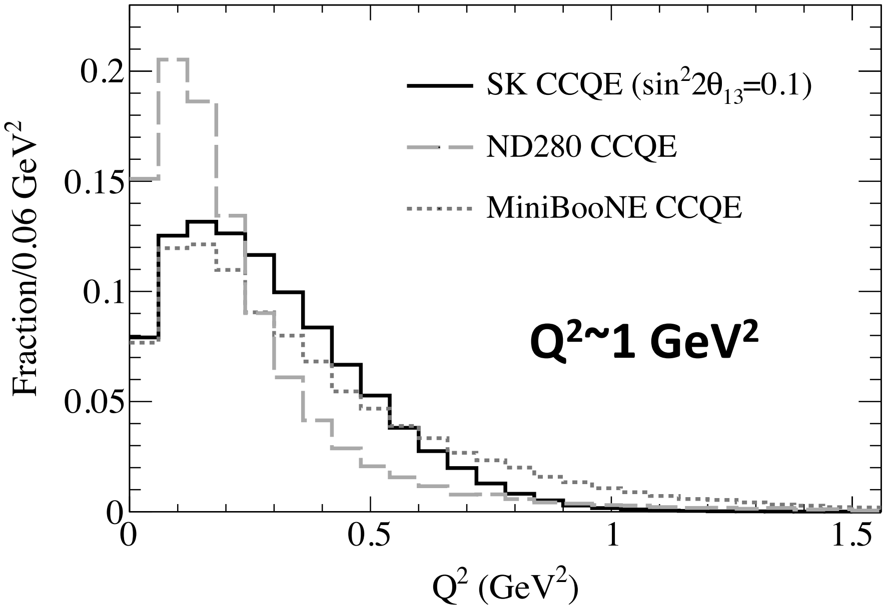
GENIE has an eA mode which can be used for comparisons

T2K specifications

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
- Pion momentum from ~0.2-3 GeV/c; lower momentum inferred from decay e
- Predominantly forward (or backward) acceptance





Q^2~1 GeV^2

Constrain final state interaction models by comparing e data on diff't targets:

What is the multiplicity of protons, neutrons out of QE interactions?

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

To discuss with Data Mining collaboration

What kind of data is available for Q^2~1 GeV^2?

- What beam energies? Any comparable to T2K?
- What target data?
    - Expect: D, C, Pb? (even three data points is helpful)
    - What final state information is available?
    - Expect: p/pi/K/e PID, 8-144deg for charged particles
    - Are there any CLAS limitations on multiplicity?
    - neutron capability is?

Summary

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

- Known beam energy, isolation of nuclear effects has led to efforts to improved nuclear model in neutrino interaction software; models use vector form factors derived from electron data

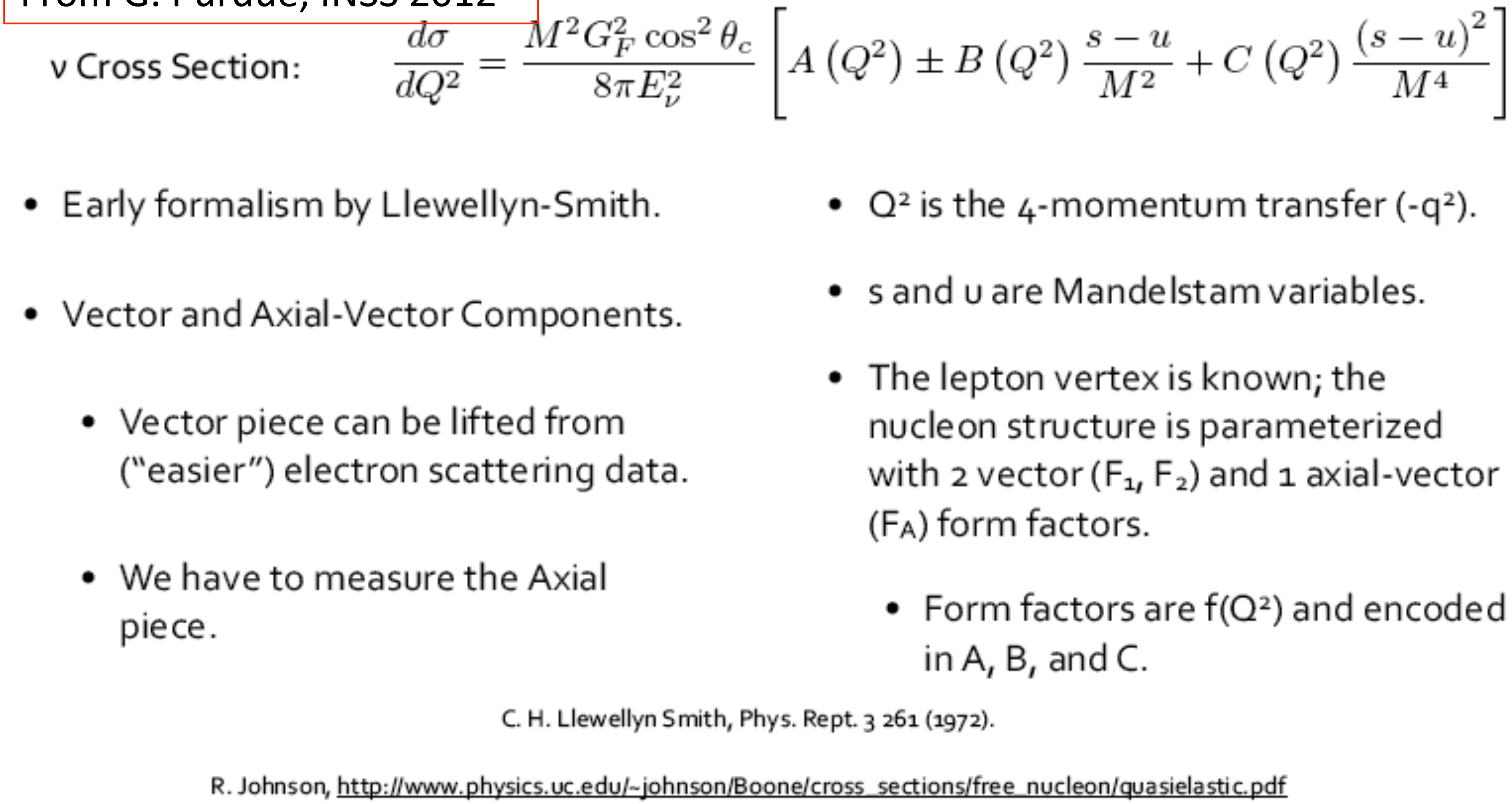
Still more to be gleaned from electron scattering data

- Precision neutrino oscillation experiments need help isolating the effect of final state interactions on the exiting particles from the interaction
  - Unique measurement (how else do we produce a pion WITHIN a nucleus and track it out?)

Backup

CCQE cross section

From G. Purdue, INSS 2012



ν Cross Section:

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

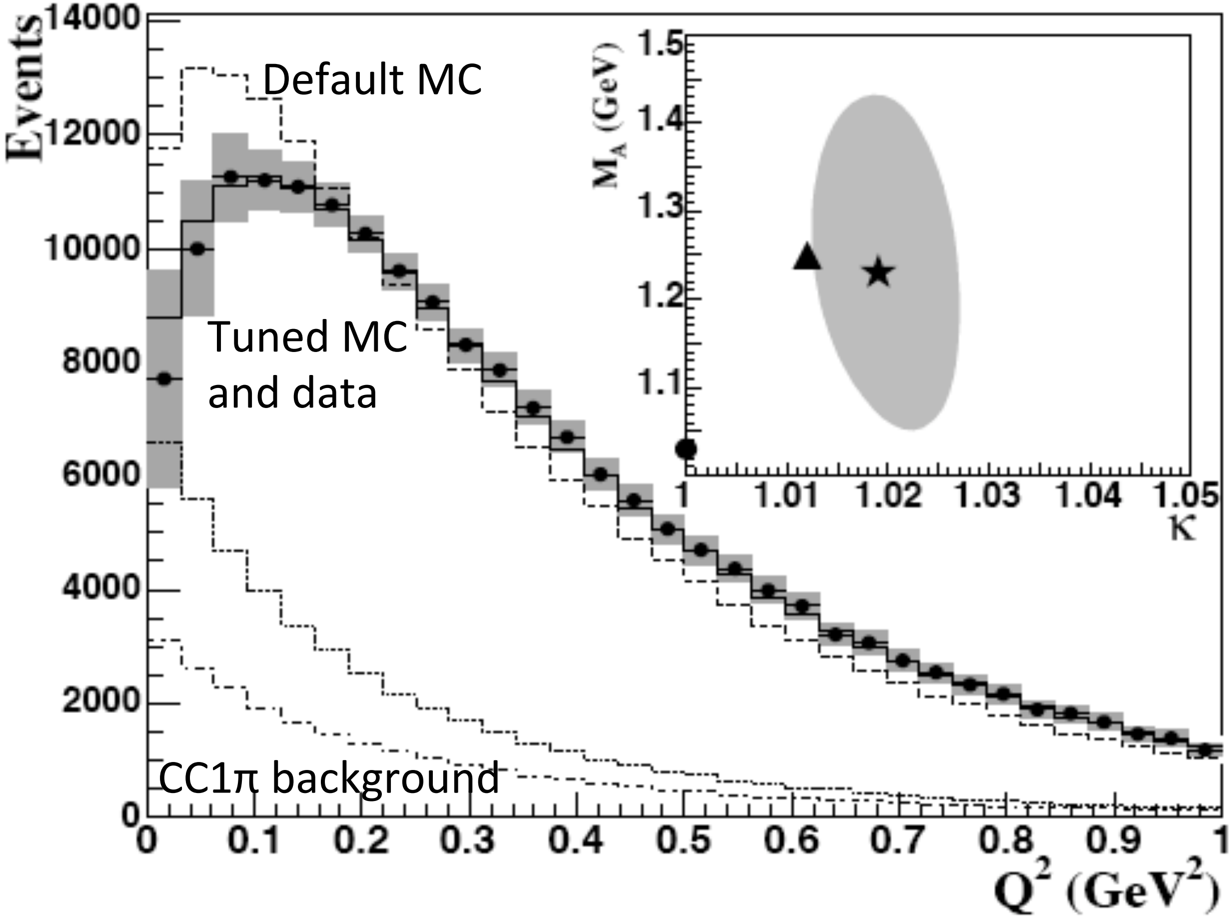
- Early formalism by Llewellyn-Smith.
- Vector and Axial-Vector Components.
  - Vector piece can be lifted from ("easier") electron scattering data.
  - We have to measure the Axial piece.
- Q^2 is the 4-momentum transfer ($-q^2$).
- s and u are Mandelstam variables.
- The lepton vertex is known; the 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

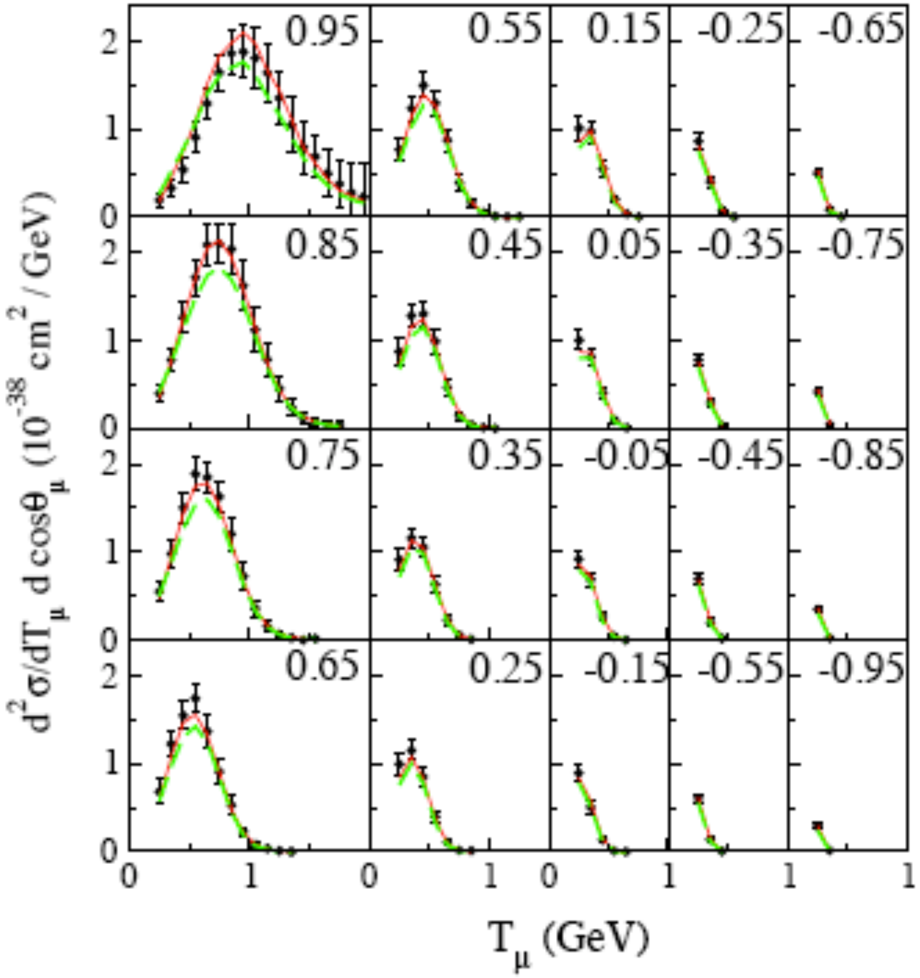
- Spherical Cherenkov detector
- Wide band beam Ev~0.8 GeV
- Select muon using decay electron
- Reject CC1π by rejecting 2nd decay electron

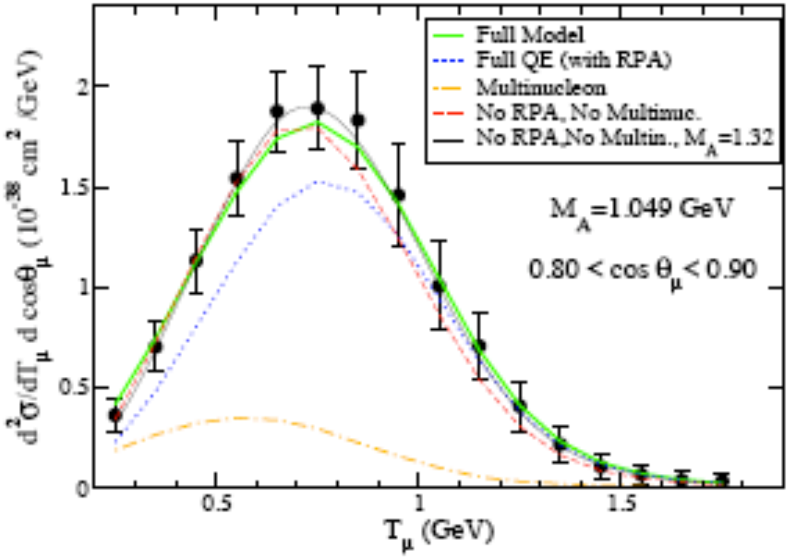
MiniBooNE experiment at ~1 GeV reports a higher value of M_A, due to excess of events at high Q^2 *arXiv:1002.2680, Phys. Rev. D81, 092005 (2010)*

- 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

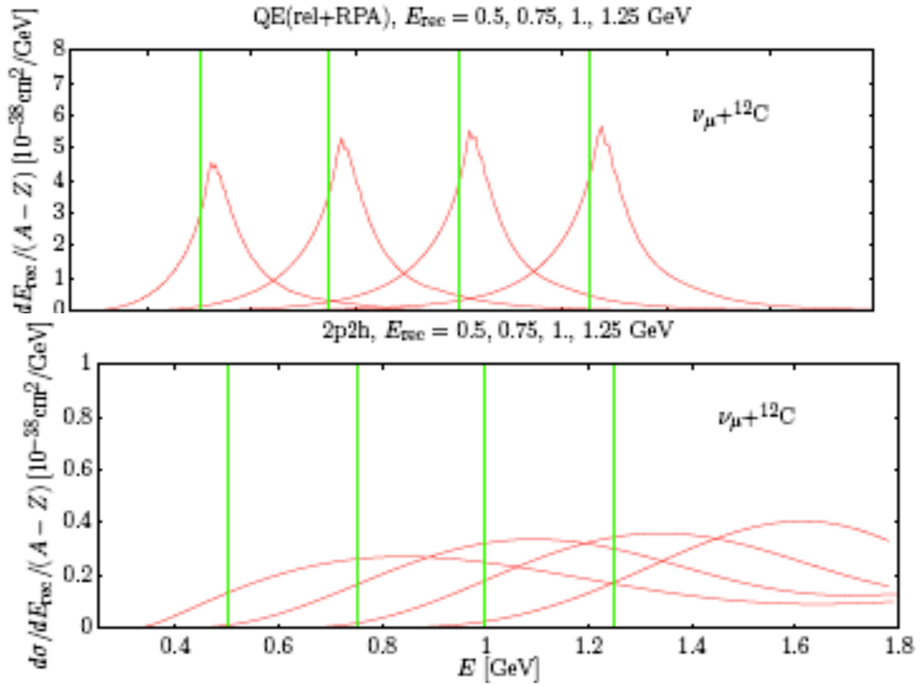




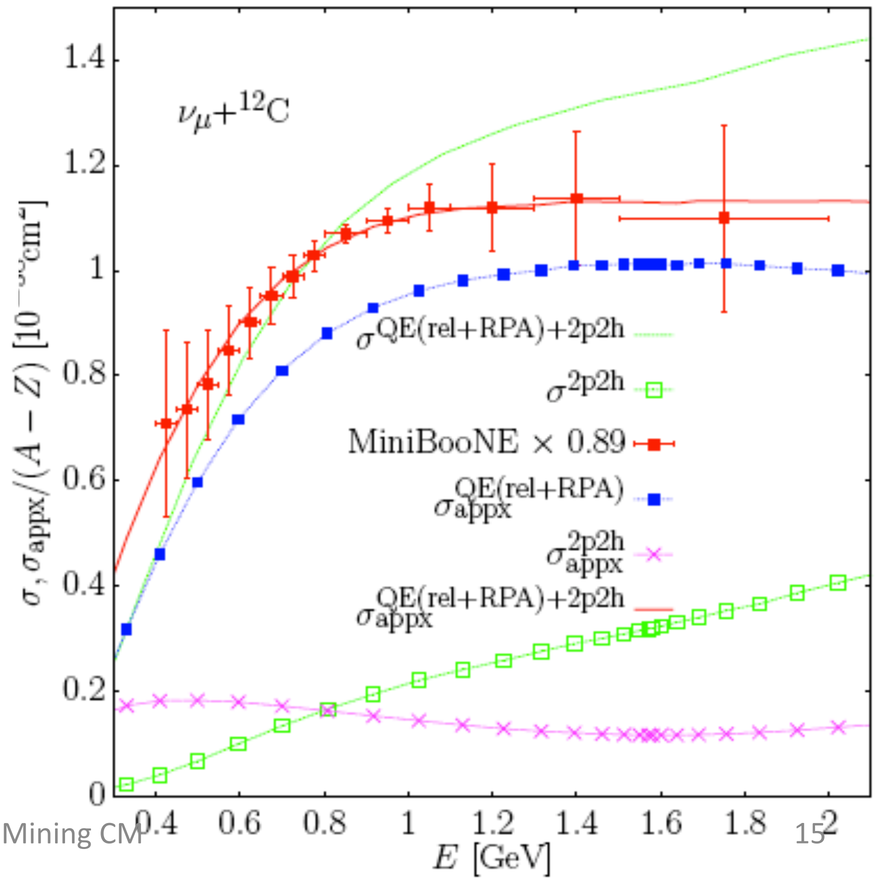
Model	Scale	M_A (GeV)	$\frac{\chi^2}{\#\text{bins}}$
LFG	0.96±0.03	1.32±0.03	35/137
Full	0.92±0.03	1.08±0.03	50/137
Full $\lvert q\rvert > 0.4^{\dagger}$ GeV	0.83±0.04	1.01±0.03	30/123

† : 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)

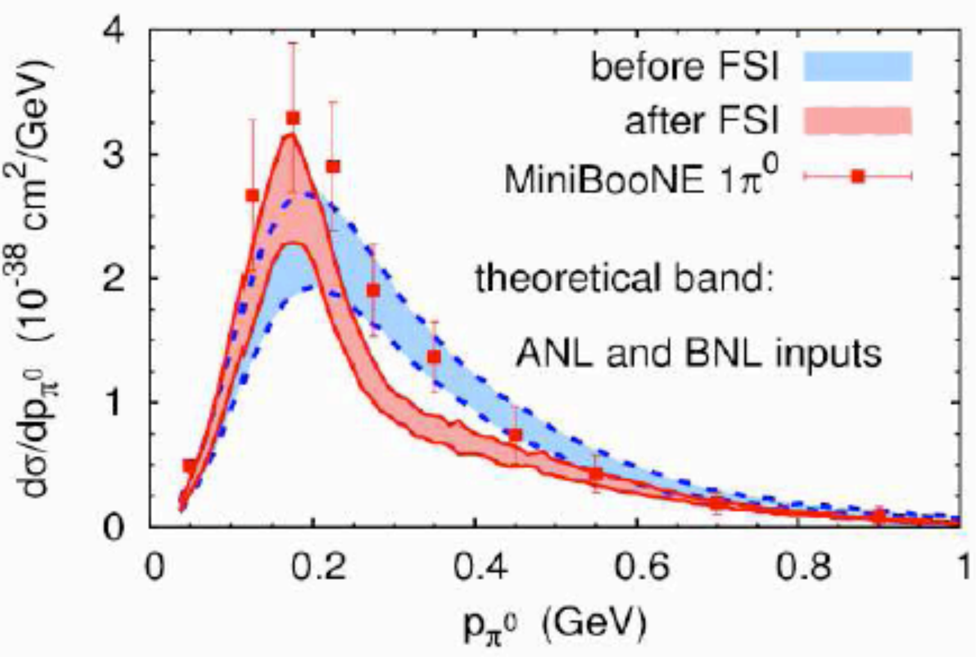


Redo neutrino energy reco-> true unfolding using MiniBooNE differential data with and without MEC components

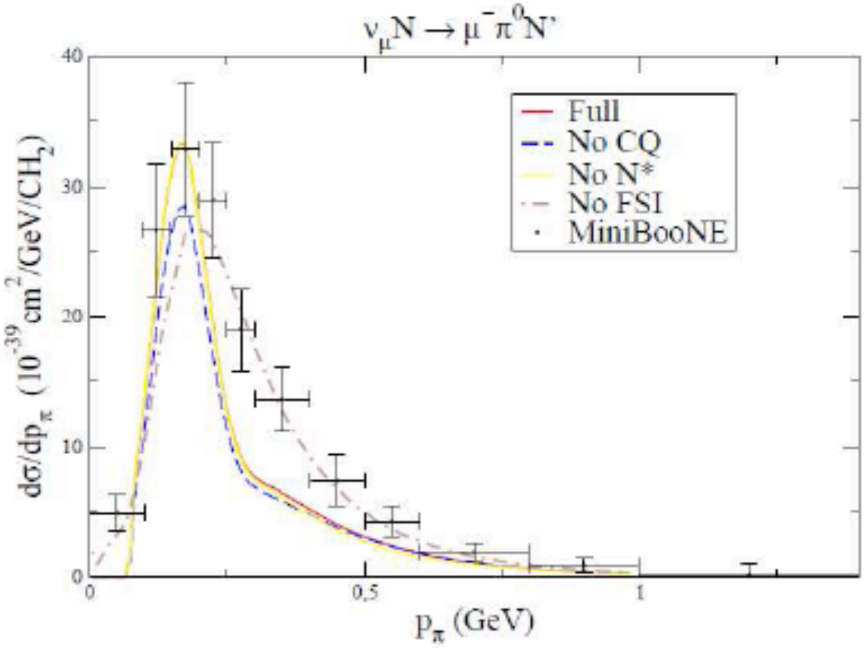
Agreement within MiniBooNE 10% flux errors, much improved shape dependence

L. Alvarez-Ruso, Saturday morning, NuInt2012 conference

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



Lalakulich@NuInt12

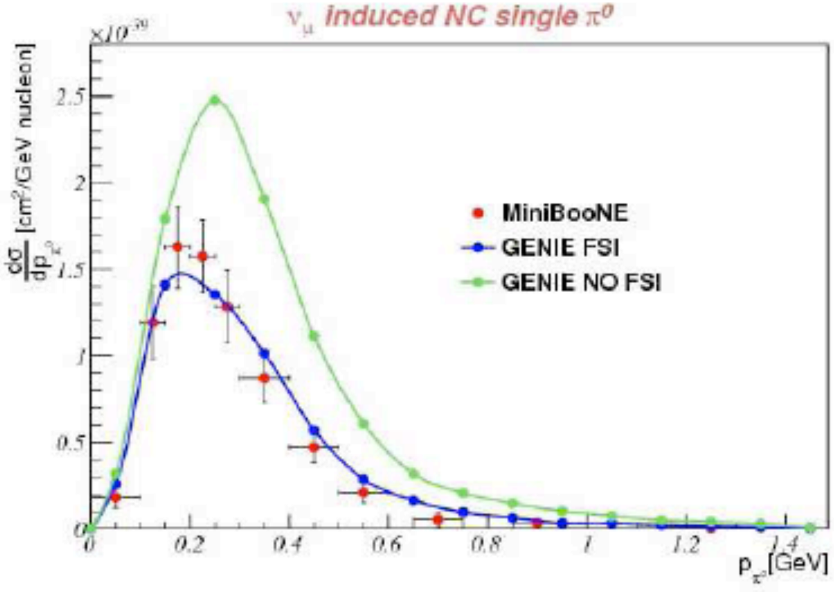


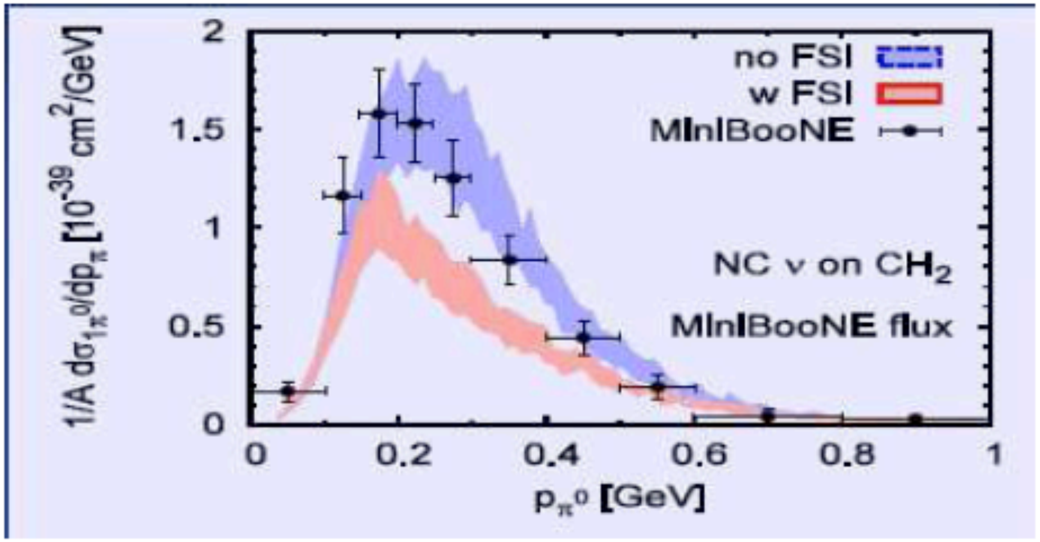
Hernandez@NuInt12

- 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

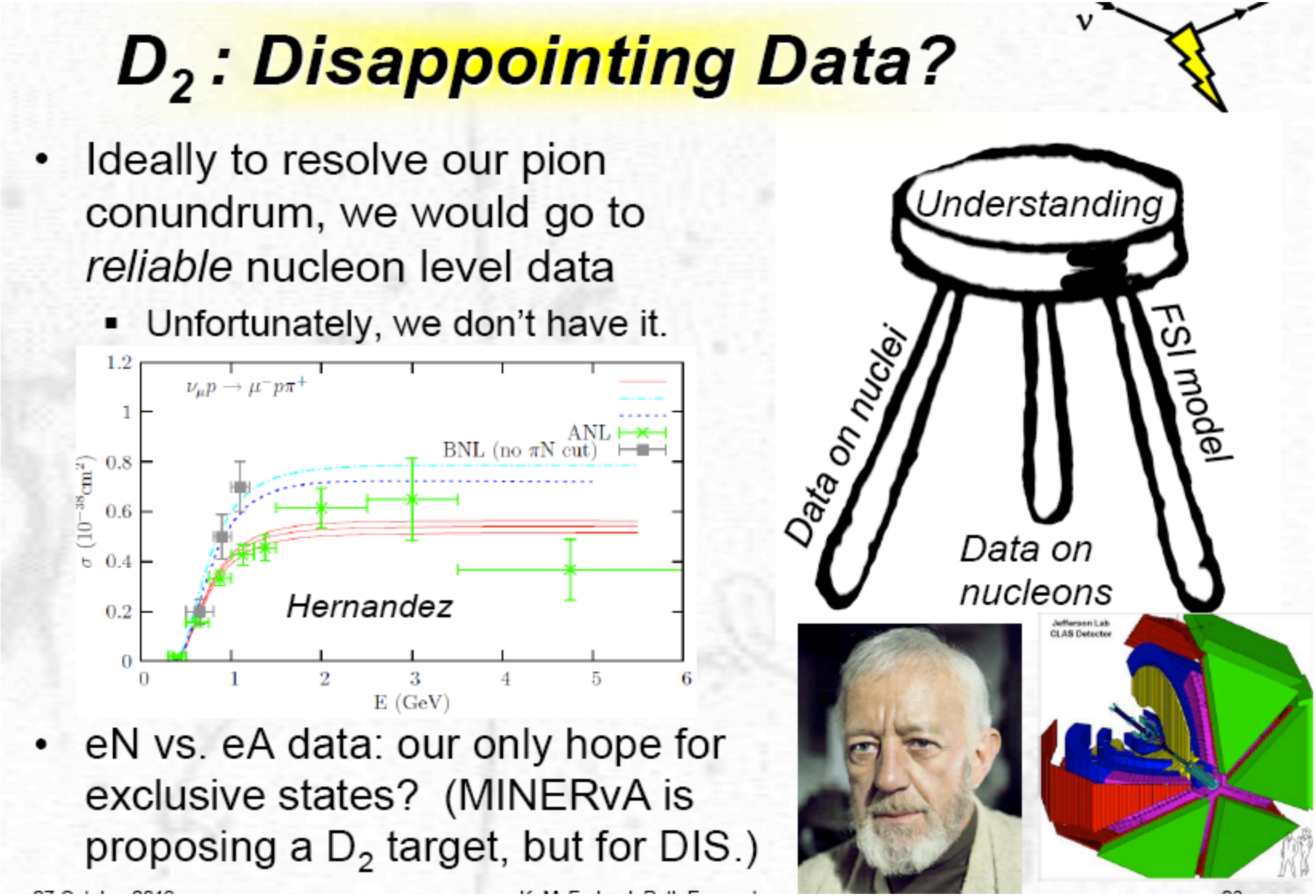




Dytman@NuInt12

- 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.)