Resonance Production
in the Medium Energy Region

M. Tzanov
Louisiana State University

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Resonance Production in the Medium Energy Region

- Resonance production.

- Event topologies.

- Challenges.

- Impact on neutrino oscillation experiments.

- Future and Summary.

Resonance production

Resonance production contributes in several ways

- Inclusive cross section $\nu + N \rightarrow l + X$

- Exclusive channels
  - $\nu + N \rightarrow l + N' + \pi$
  - $\nu + N \rightarrow l + N' + \gamma$
  - $\nu + N \rightarrow l + N' + \eta$
  - $\nu + N \rightarrow l + N' + \overline{K}$

Resonance Production Model in Most MC

Model used by experiments to build MC is
Rein-Sehgal, Ann. Phys. 133 (1981) 79:
- Relativistic quark model Feynman-Kislinger-Ravndal
- SU(6) spin flavor symmetry
- Lepton mass is neglected
- Helicity amplitudes for 18 baryon resonances.

$$M = \frac{G \cos \theta_C}{\sqrt{2}} l^\alpha J_\alpha$$

$$\frac{\partial \sigma}{\partial q^2 \partial \nu} = \frac{G^2}{4\pi^2} \left(\frac{-q^2}{Q^2} \right) \kappa (u^2 \sigma_L + v^2 \sigma_R - 2uv\sigma_S)$$

- Hadronic current is parameterized with form factors,
- Helicity amplitudes.

Non-resonant Background

- Different for different exclusive channels

- Interferes with the resonant production

- In Rein-Sehgal model: Rein, Sehgal, Ann. Phys. 133 (1981) 79.

"we have represented the background by a resonance amplitude of P11 character (like the nucleon), with the Breit-Wigner factor replaced by an adjustable constant. The corresponding cross section is added incoherently to the resonant cross section."

Resonance Production Model in Most MC

This model has problems predicting
π elecroproduction data on p
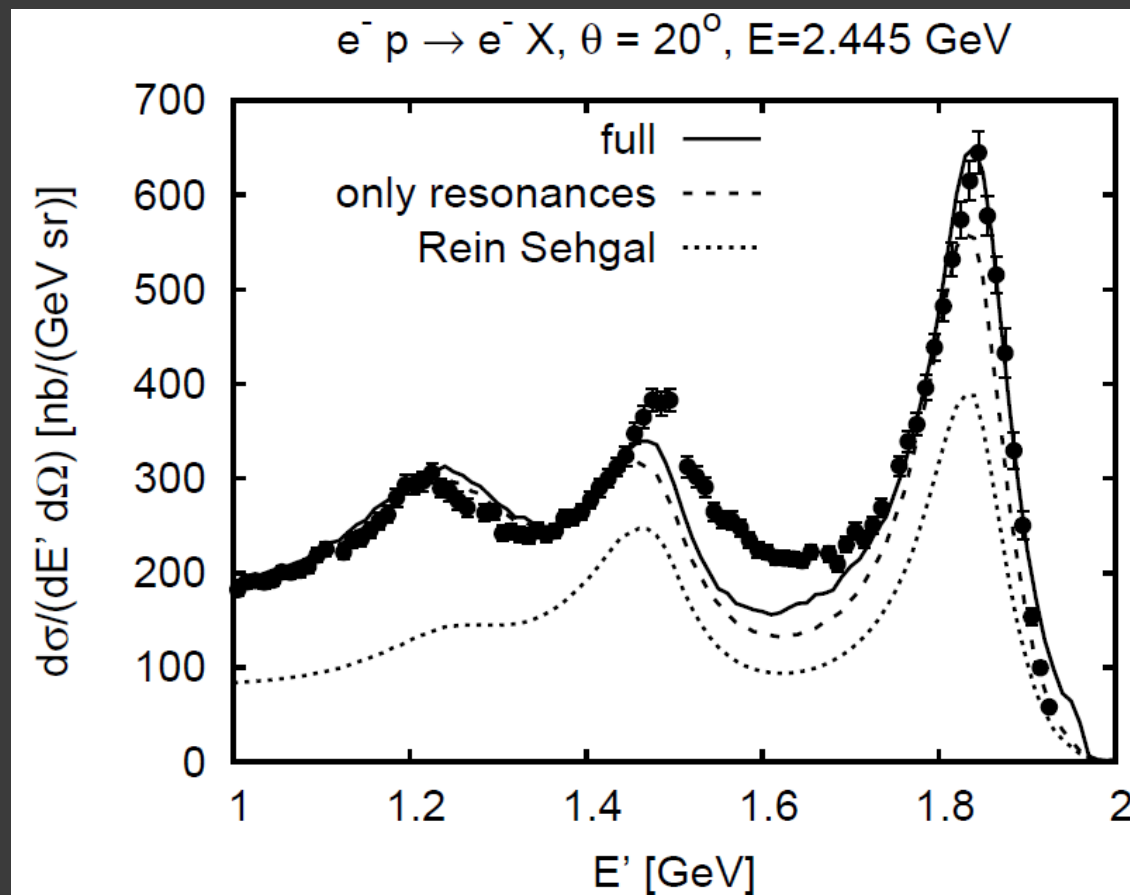
Resonance Production – New Development

Current models disagree in both shape and normalization

New theoretical developments:

- Several theoretical models correct for mass of the lepton
  Kuzmin et al., Mod. Phys. Lett. A19 (2004)
  Berger, Sehgal, PRD 76 (2007)
  Graczyk, Sobczyk, PRD 77 (2008)

- Unitary isobar model MAID used for N-R helicity amplitudes
  Drechsel, Kamalov, Tiator, EPJA 34 (2007) 69

- N-Δ axial formfactor $C^5_A(0)$
  Graczyk et al., PRD 80 (2009)
  Hernandez et al., PRD 81 (2010)
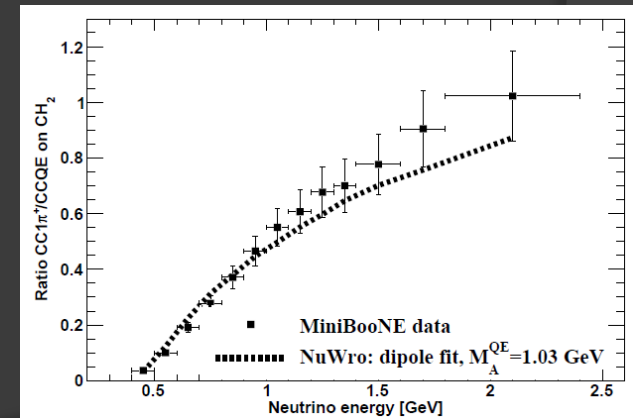
Resonant π Production

- **Problems Even Before FSI**
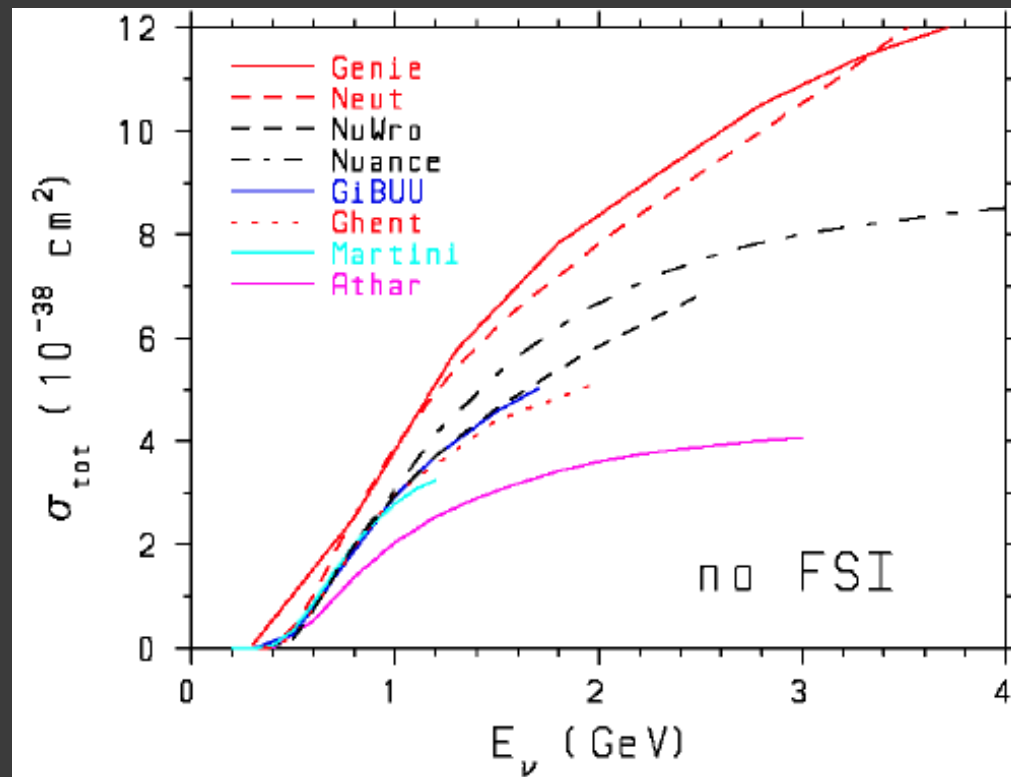
- **ANL and BNL data don't help much.**
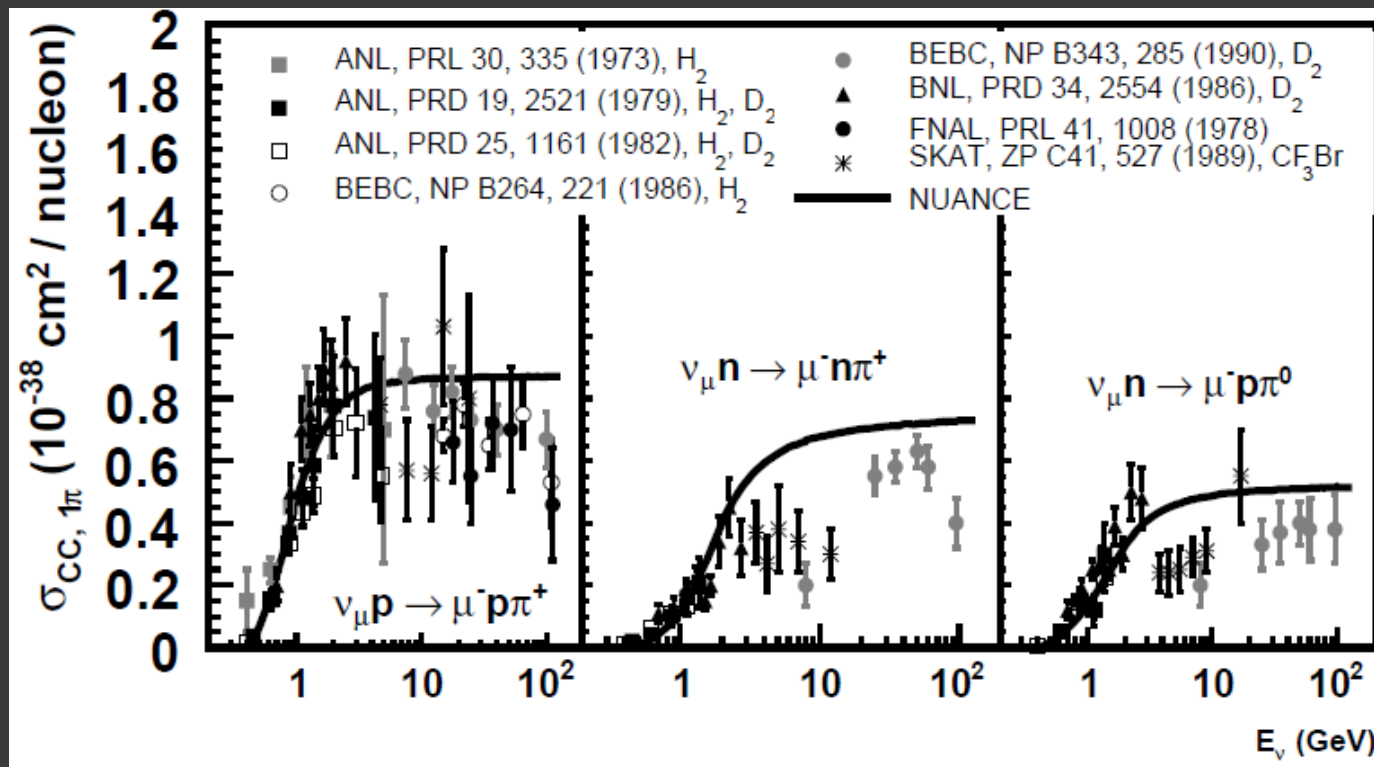
Rodriguez, NuInt12
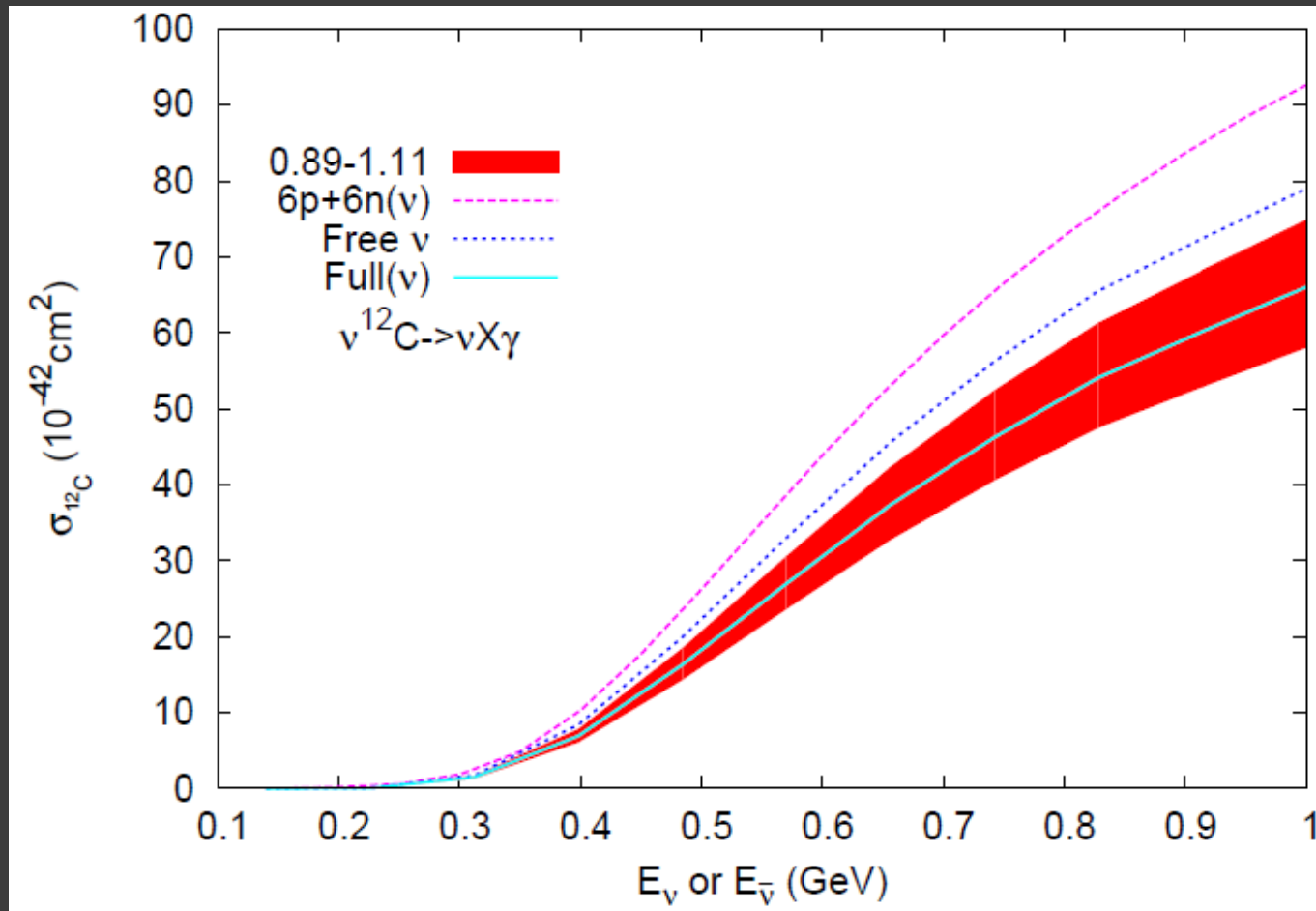
Resonant π Production

- **Problems Even Before FSI**

- **Theoretical models.**
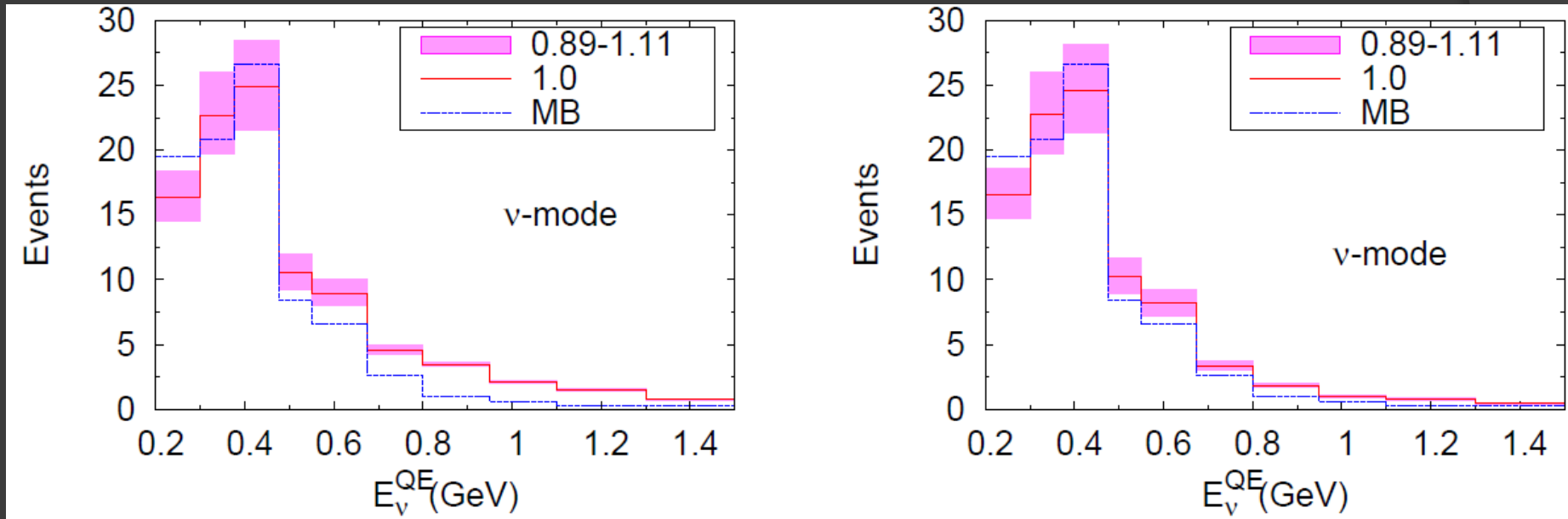

Boyd et al., AIP Conf. Proc. 1189

NC Photo Emission

Cross section on nuclei:

*Alvarez-Ruso, PittPACC2013*

NC Photo Emission

Comparison to the MiniBooNE estimate:
Taking into account the E° dep. efficency

Challenges – Nuclear Targets

- Nuclear target – re-interactions in the nucleus.

- Different primary neutrino interactions become indistinguishable experimentally.

- Final State Interactions (FSI) model is needed to extract nucleon cross section – large uncertainties.
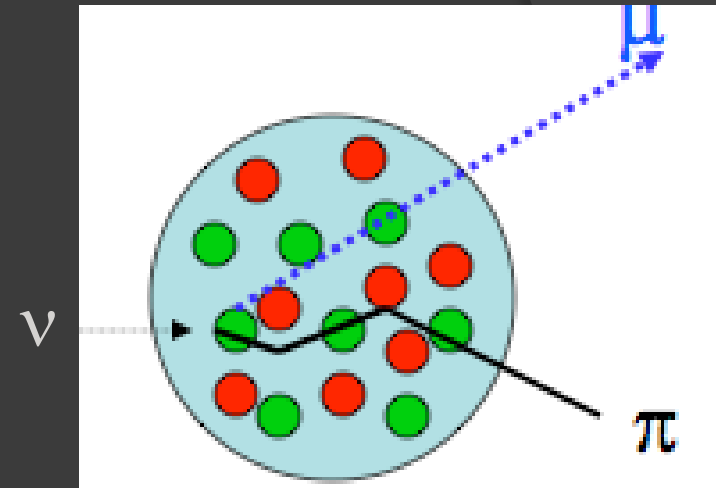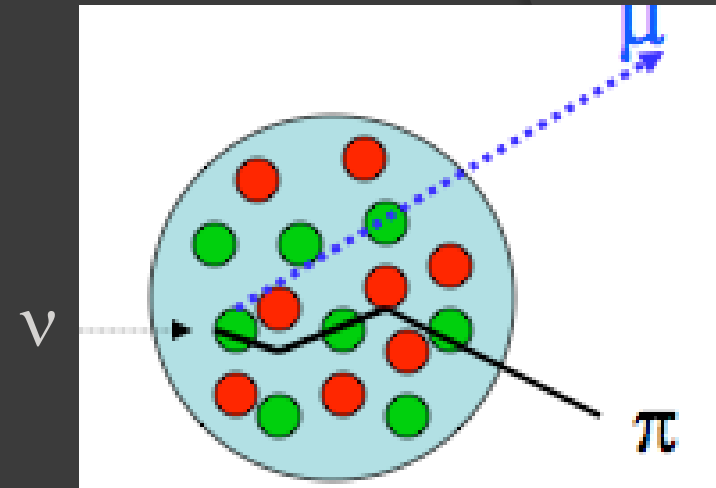
FSI-Models

Transport models:

    GiBUU Leitner et al., PRC 73 (2006)

- 13 resonances
- Resonance propagation
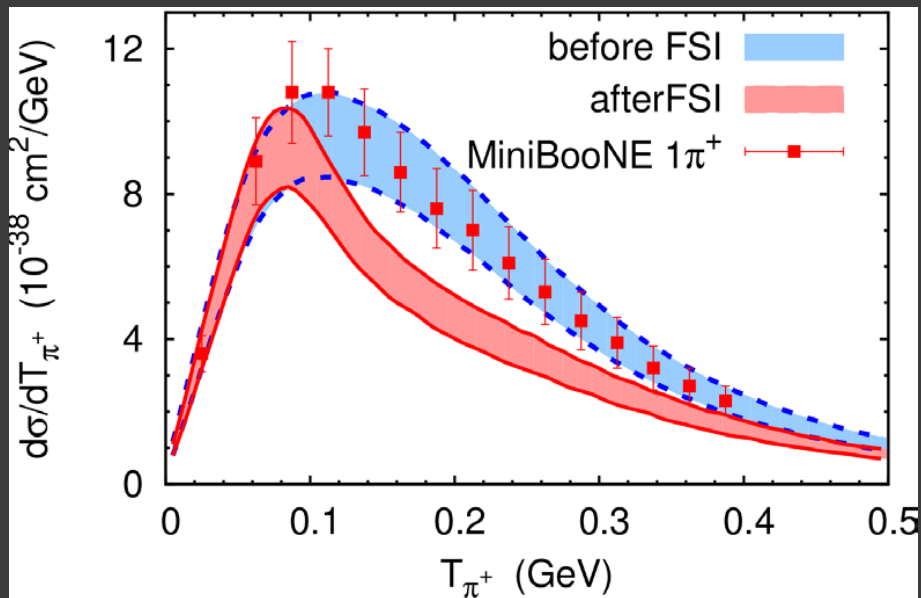- contribution from DIS

Cascade Models:

- Cascade
- 2 resonances
- No resonance propagation
- No DIS
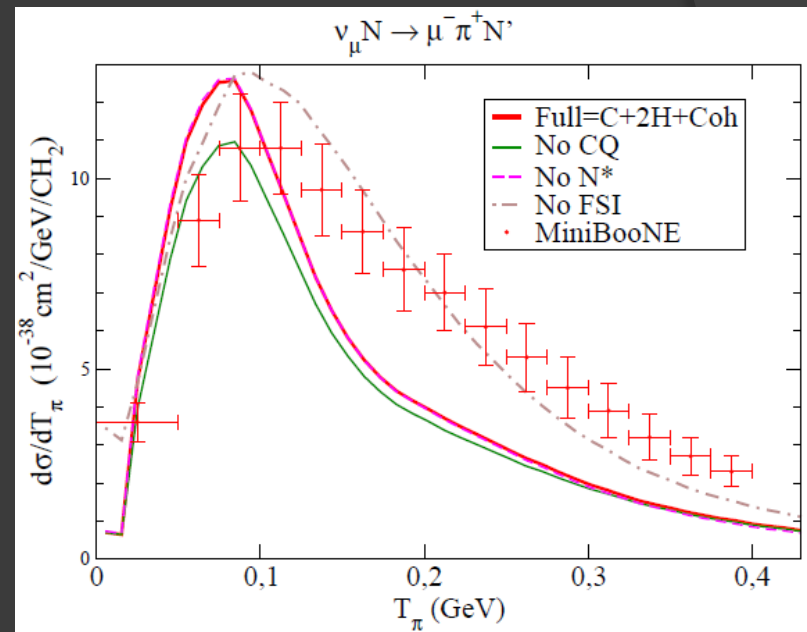
FSI Puzzles

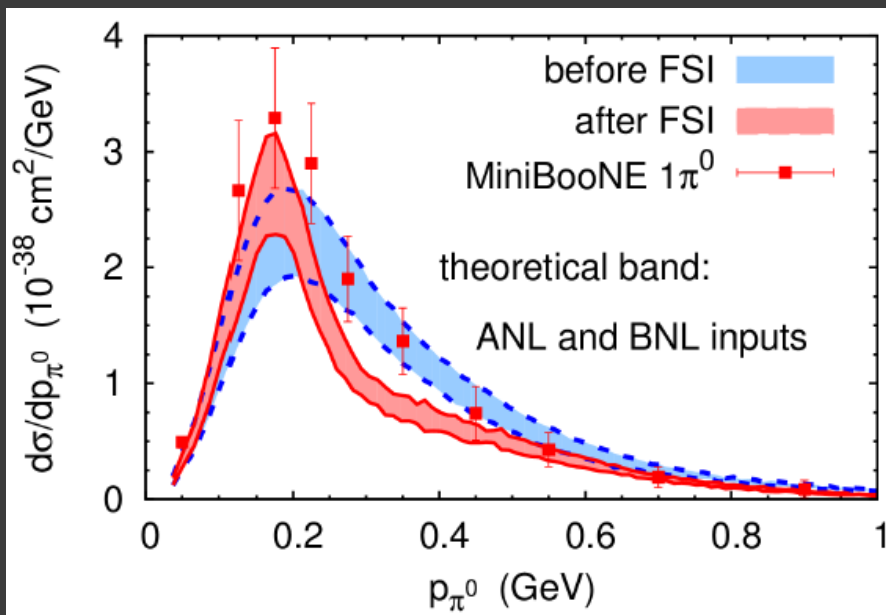Comparison to the MiniBooNE estimate:

Lalakulich, NuInt12

Hernandez, NuInt12

FSI Puzzles

Comparison to the MiniBooNE estimate:

Lalakulich, NuInt12
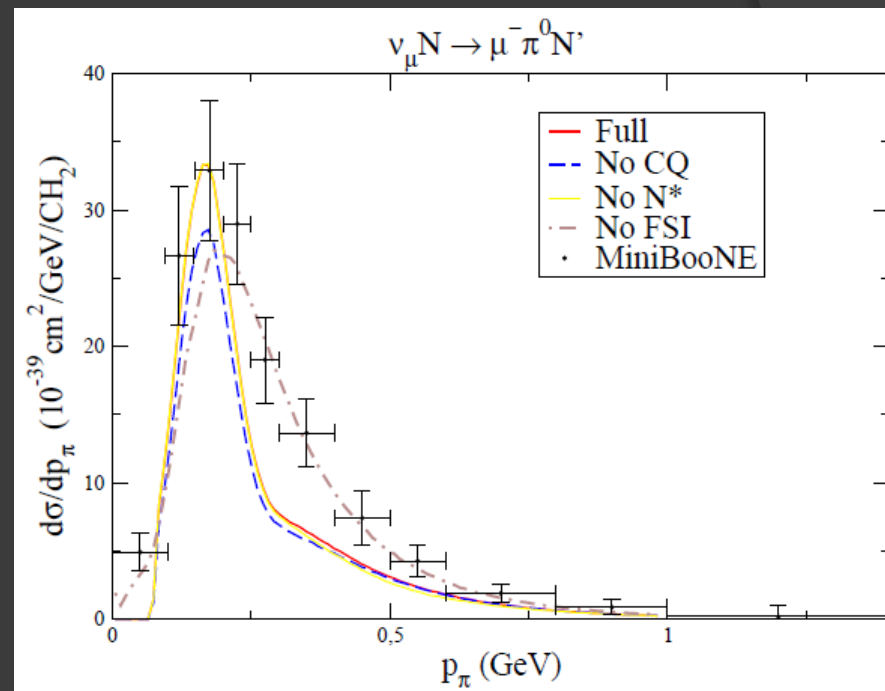
Hernandez, NuInt12

FSI Puzzles

Comparison to the MiniBooNE estimate:

Dytman, NuInt12
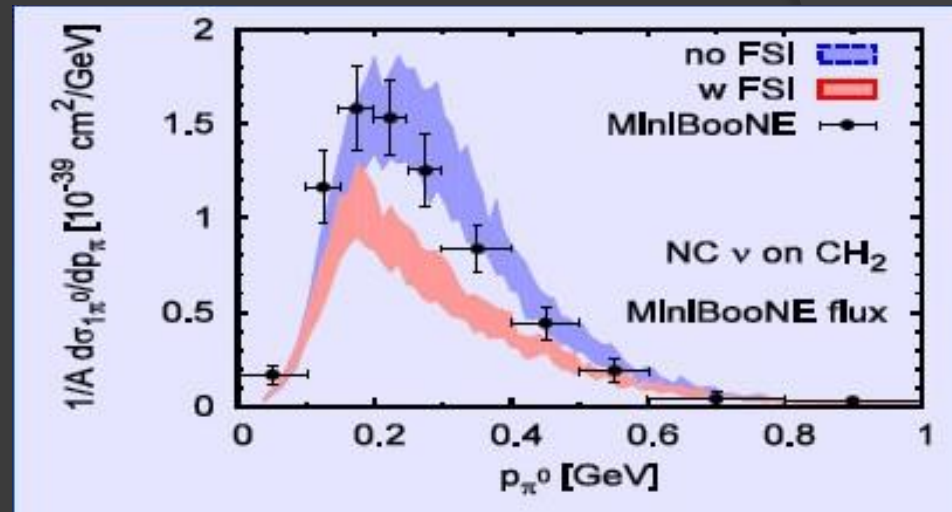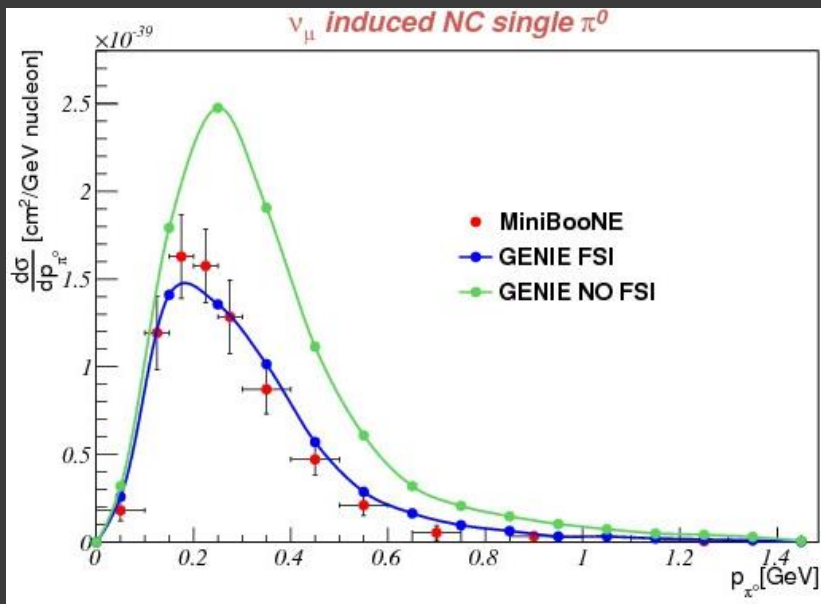
- Both GENIE and GiBUU describe similarly well ANL and BNL data
- It seems the before FSI cross sections are very different.

Even More Unaddressed Issues

We haven't even tried to estimate the multinucleon effects for the resonant channels.

Similar to CCQE multinucleon effects like MEC will modify the resonance cross section.

So far, the hope is that the effect is small.

Why Do We Need Theory?

Oscillation experiments need to predict the neutrino rate precisely for both signal and background, which requires:
• accurate neutrino cross section models describing data.
• good nuclear models.
• accurate prediction of the flux.

From experiments we need:
• more precise least model dependent measurements by dedicated experiments. MiniBooNE started this trend with a full suite of absolute observable differential cross section.

From theorists we need:
•   Models explaining data.
•   Refrain from fitting.
•   Predictions which can be tested in new detectors.

Resonance Production Topologies
In the ~1 GeV Region

A new interest in neutrino interactions in the few-GeV region started with the discovery of neutrino oscillations.

Neutrino charged-current quasi elastic (CCQE) has been the golden mode for neutrino oscillation searches (MiniBooNE, T2K), while the resonance production is a major background and a source of large uncertainty.

Neutrino resonant pion production:

$$\nu + N \rightarrow \Delta + l$$
$$\downarrow$$
$$N' + \text{mesons (usually pions at these energies)}$$

Resonant pion production mainly comes from $\Delta(1232)$ with small contributions from higher resonances and non-resonant background for the energy range of the reviewed experiments.

Resonance Production Topologies
In the ~1 GeV Region

Charged-current pion production modifies the CCQE kinematic distributions through FSI's which is a major problem for shape based oscillation analyses.

NC π^0 production is a major background for ν_e appearance searches as it could mimic the signal.

NC photo production is a background as well.

NC π^+ is also a background for $\nu_\mu \rightarrow \nu_\mu$ disappearance analysis. Currently the uncertainty on this channel is 100%. Yes, it has a small contribution but.......

Precision physics is hard.

Resonance Production Topologies
In the >1 GeV Region

Neutrino charged-current quasi elastic (CCQE) might not be the golden mode for neutrino oscillation searches (MINOS, NOvA, LBNE). However, resonance production will still be a major background and a source of large uncertainty.

Charged-current resonance production will be part of the signal.
We need to know the shape of the kinematic distributions very well.

Neutral current p0 production is still a background for appearance searches.

Neutrino resonant pion production:

$$\nu + N \rightarrow \Delta + l$$
$$\downarrow$$
N' + mesons (usually pions at these energies)

Resonant pion production mainly comes from $\Delta(1232)$. In this region N* resonance becomes important.

Measuring Cross Sections for Nuclear Targets

Signal definition:
- observable signal - all events experimentally indistinguishable at nuclear level – least model dependent - no FSI correction.
- nucleon level signal – needs correction for FSI - model dependent, large uncertainties due to large FSI model uncertainty.

Backgrounds:
- data constrained backgrounds. No models involved.
- better hadron interaction models are needed. Current uncertainty for π^+ charge exchange in carbon is 50% and for π^+ absorption is 35% for ~300MeV pions.

Measured quantity:
- cross section ratio – many systematic effects cancel (especially beam related).
- absolute observable cross sections - requires good understanding of the flux and control of flux uncertainties.

Do We Really Need Theory?

It sure is good to have theory that describes the physics!

But let's daydream a bit:
In an alternate universe of infinite funding……

We can map out the cross sections in all channels over
the whole phase space according to different final states.
After that we can simply parameterize the measured cross
sections and use them as look up tables.

This of course requires calibration of the detector with test
beams. It requires good knowledge of the flux. Preferably
narrow band beams with measured meson production.
The flux requirement might not be so difficult to achieve.
A group of T2K members is developing nuPRISM detector
to allow cross section measurements with narrow neutrino beam
in a broad band beam.

The Future is Here

T2K and MINERvA are taking data – results soon.

| Experiments	$\langle E_\nu \rangle$ GeV	Hadron Prod. Exp.	Main goal	Detector	ν Target	ν MC
T2K ND280	0.7	NA61	θ_{13}, δ^{CP}	Fine-grain	C, H_2O	NEUT, GENIE
MINERvA	1-20	MIPP	σ_ν	Fine-grain	C, Fe, Pb, He, D	GENIE

MINERvA
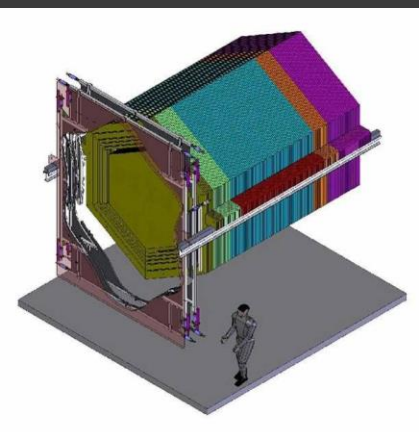
T2K ND280

- Both designed to measure cross sections.

- Overlapping energy range will allow measuring neutrino cross sections from 0.3 – 20 GeV.
  - map out CCQE and resonant 1π turn-on regions.

- Measurement of the A dependence.
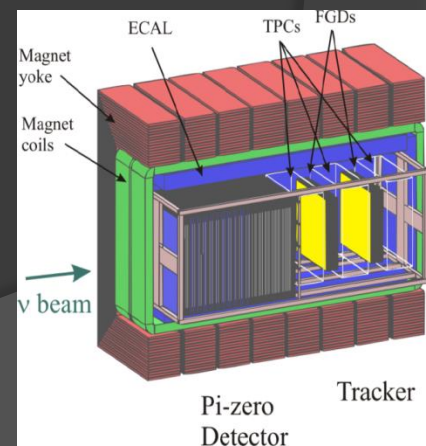
Hopefully Near Future - CAPTAIN
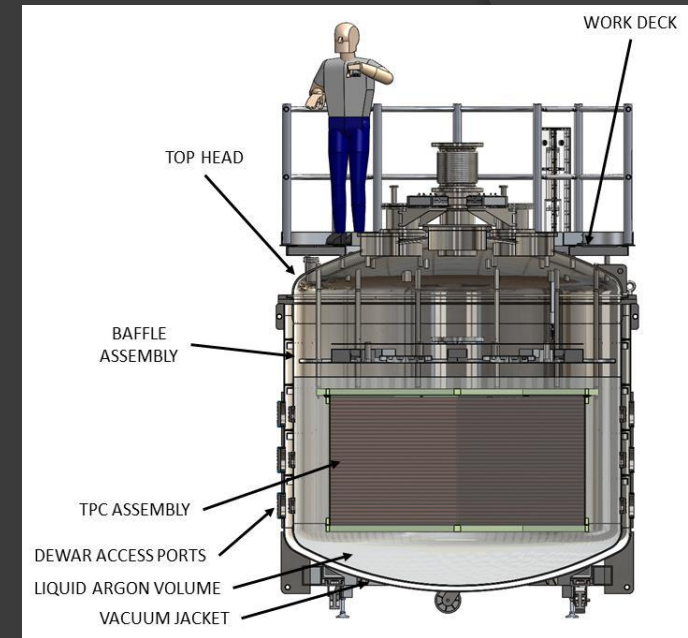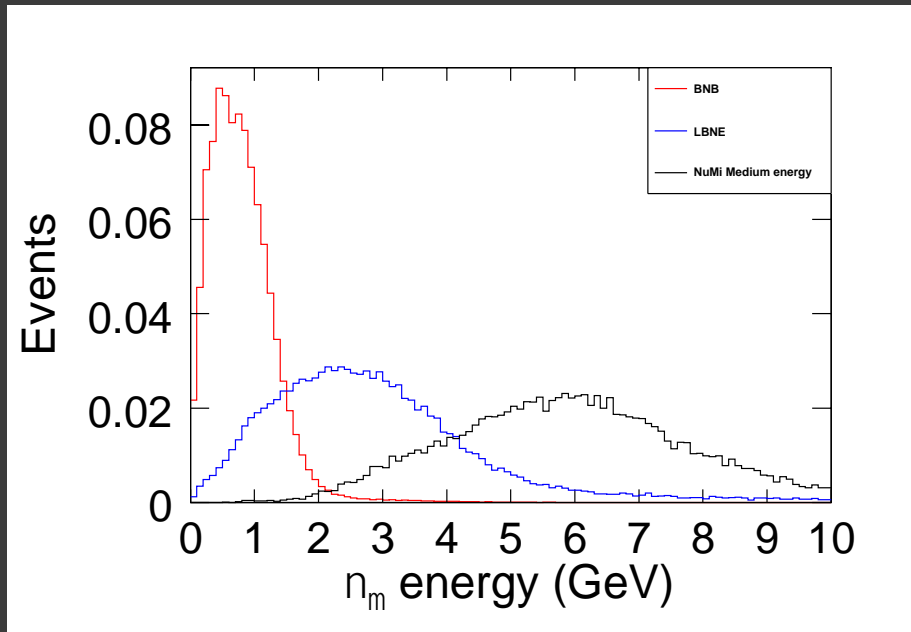
- Expose CAPTAIN to NuMi beam
- Map out cross sections in the whole kinematic phase space
- Complimentary to MicroBooNE

Conclusions

Both theoretical and experimental efforts are needed
to understand neutrino cross sections, which is
crucial for precise measurement of all oscillation parameters.

There has been a major effort to measure the
neutrino induced resonance cross sections:
• new results mainly from oscillation experiments.
• first complete sets of differential cross sections have been
  measured by MiniBooNE.

There has been major effort in theory as well.

T2K, MINERvA, and CAPTAIN have the potential to improve our
understanding of the pion production.
• high power neutrino beams – sufficient statistics.
• dedicated hadron production experiments – flux.
• various targets.