Durham University

IP3

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IPPP/NuSTEC topical meeting on neutrino-nucleus scattering

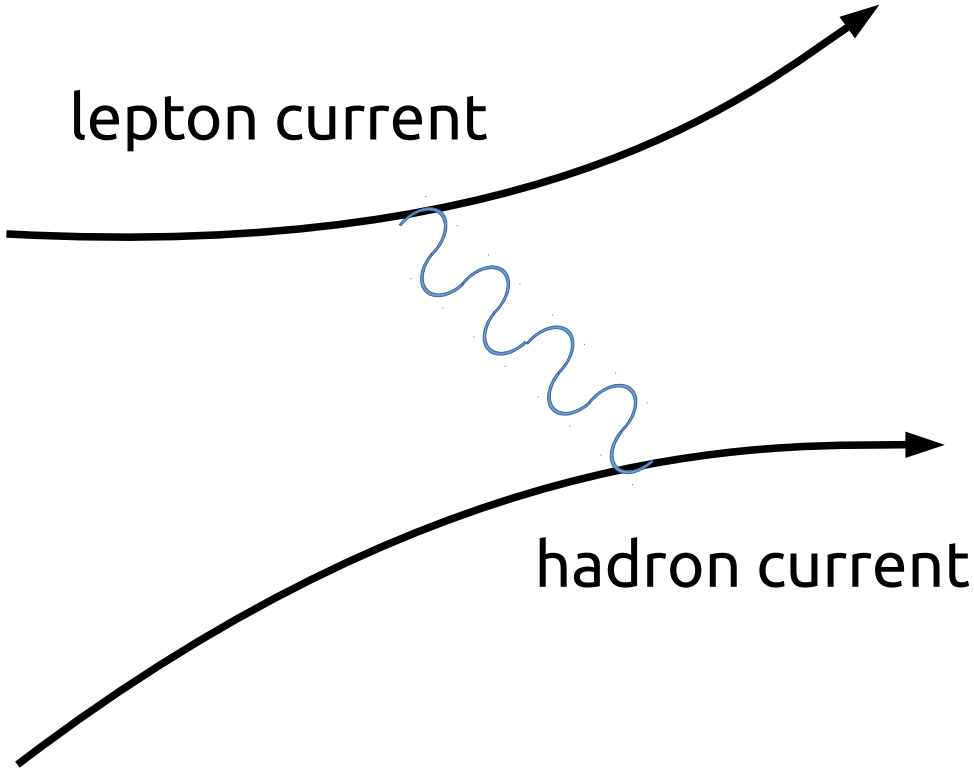
Steve Boyd, 18/3/2017

Neutrino Cross-sections

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$ Leptonic tensor (relatively) easy

$W_{\mu\nu}$ Hadronic tensor is where all the fun is



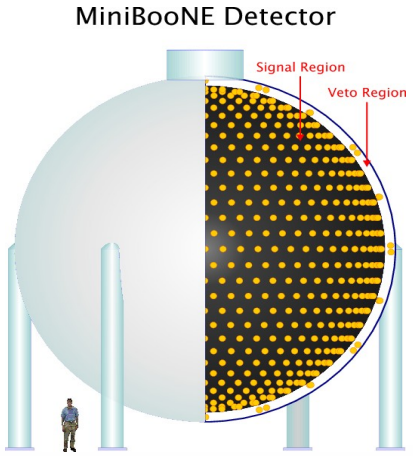
ν MC Codes

- ν MC event generators are important in every experiment to estimate detector acceptances and explore the impact of systematic uncertainties.

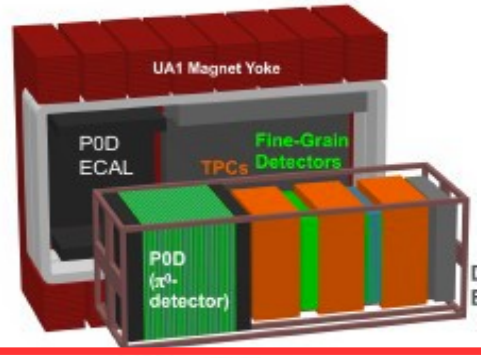
- Four main generators used for experiment and for comparison to data these days

GENIE : general purpose generator used in MINERvA, T2K and NOvA (Costas Andreoupolos et al)
NEUT : Designed for Super-K, then K2K and now used for T2K (Yoshinari Hayato et al)
NuWro : Generator designed in Wroclaw as a testbed for theoretical ideas (Jan Sobczyk et al.)
GiBUU : General purpose generator using transport theory to model ν+A events (U. Mosel et al.)

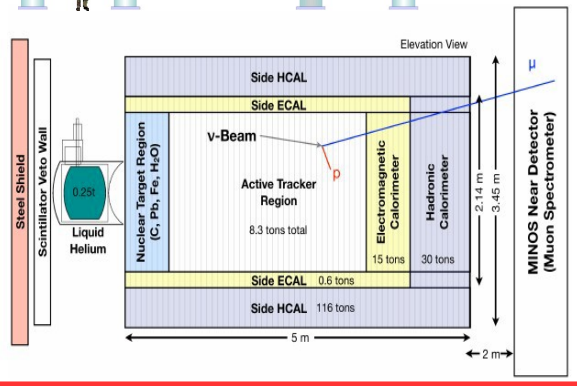
ν Experiments



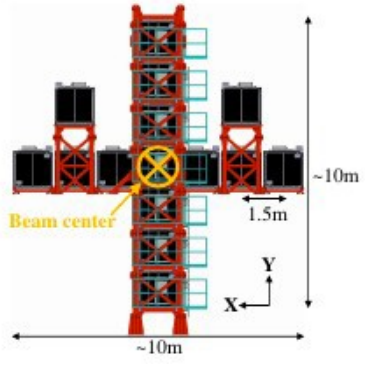
miniBooNE
E_ν ~ 1 GeV
CH target



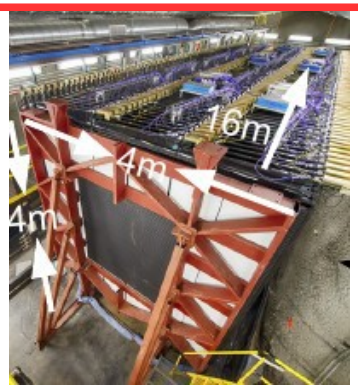
T2K ND280
E_ν ~ 1 GeV
CH/O



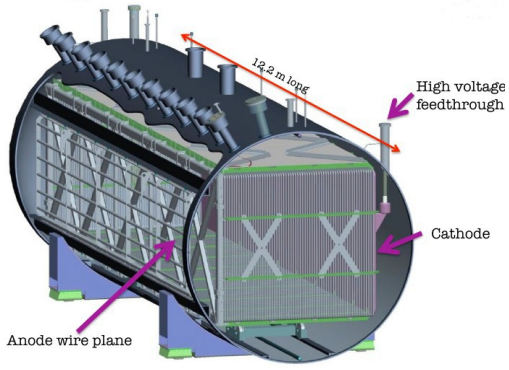
MINERvA
E_ν ~ 3 GeV
C, Fe, Pb, He



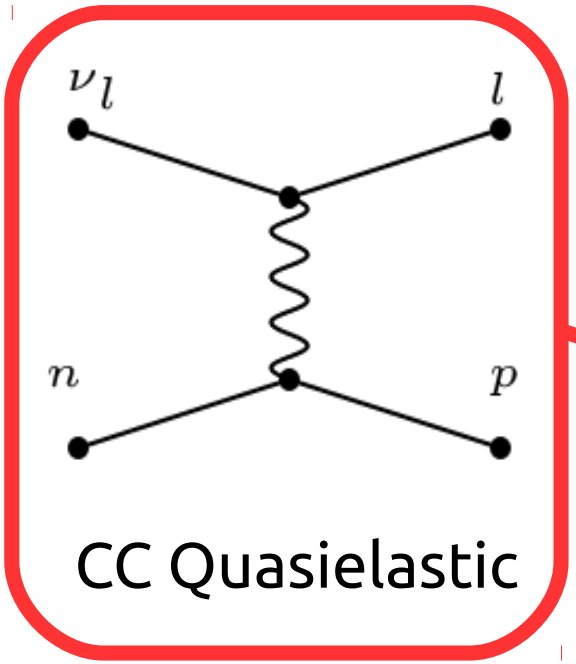
T2K INGRID
E_ν ~ 1 GeV
CH/Iron



NOvA
E_ν ~ 3 GeV
CH

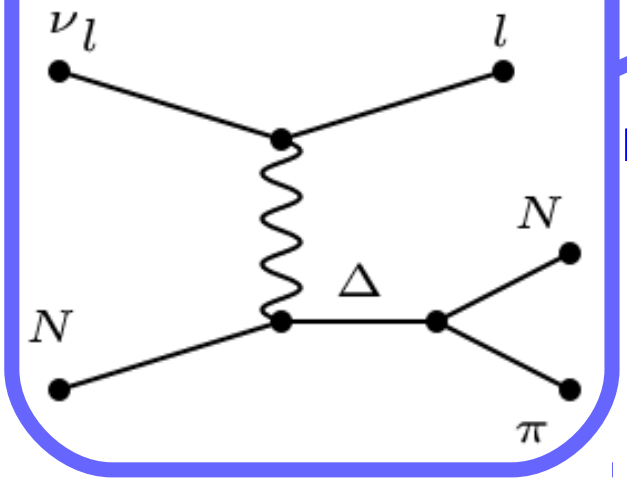


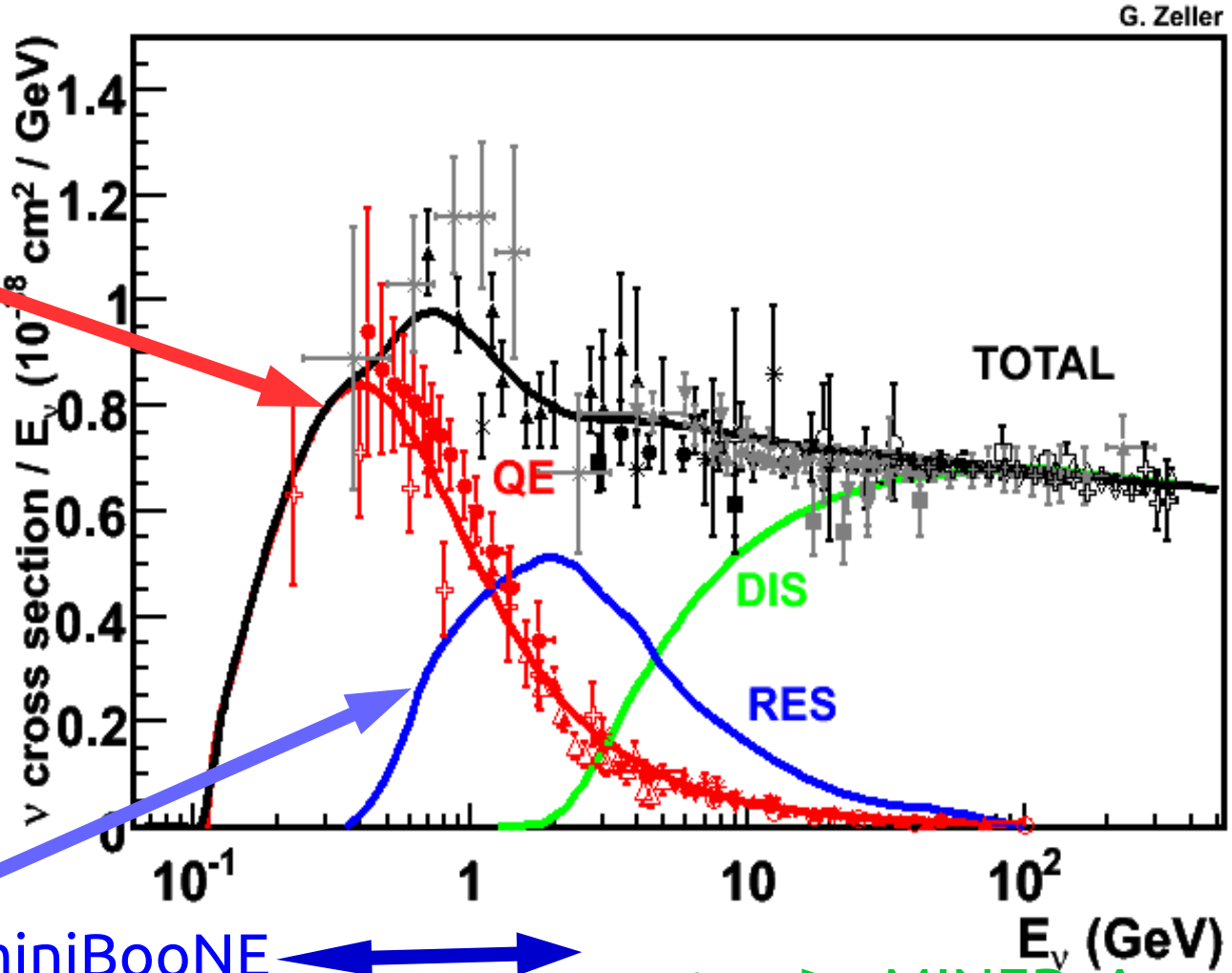
microBooNE,
Argoneut
E_ν ~ 1 GeV
Ar



CC Quasielastic

CC Resonance





miniBooNE

T2K/HyperK

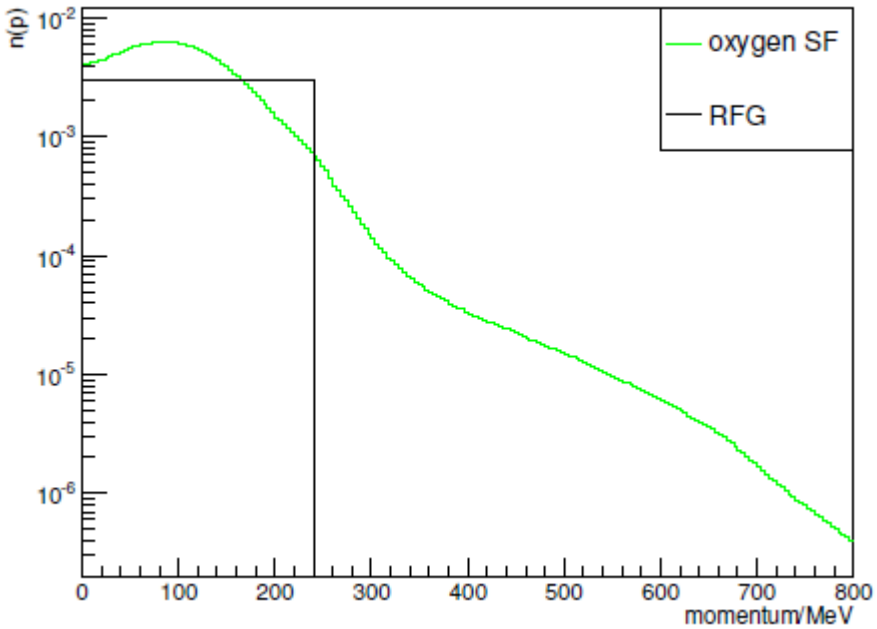
MINERvA

DUNE

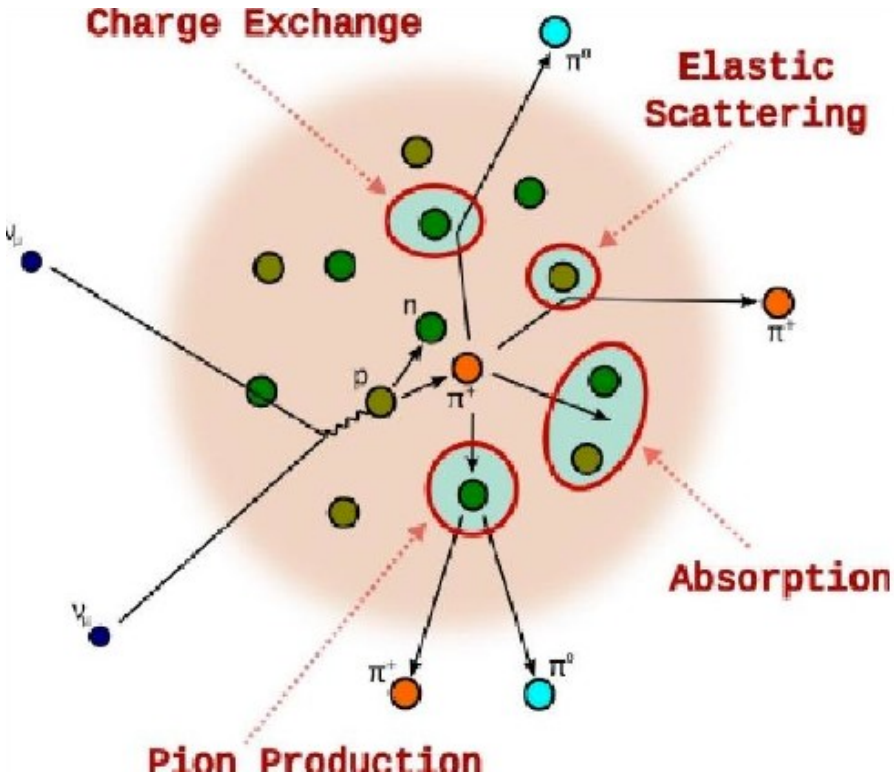
Initial and final states

Adding complication, the bare cross section model must be convolved with initial and final state models.

- Relativistic Fermi Gas (RFG)
- Spectral functions



A. Furmanski, “Charged current Quasi-elastic-like neutrino interactions at the T2K experiment”



FSI cascade model used in most ν MC generators

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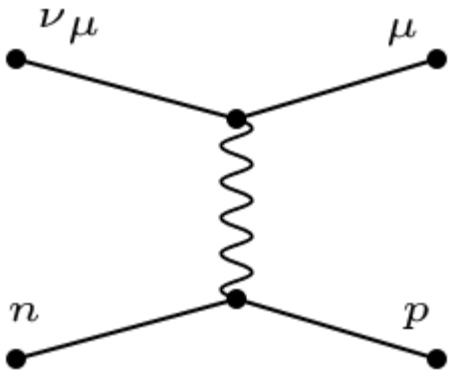
Quasielastic Questions

CCQE – pre-2005

The most abundant process at neutrino energies around 1 GeV



$$E_\nu^{rec} = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

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

Llewellyn-Smith (+ RFG for initial state)

A,B,C contain form factors parametrised using vector/axial masses

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

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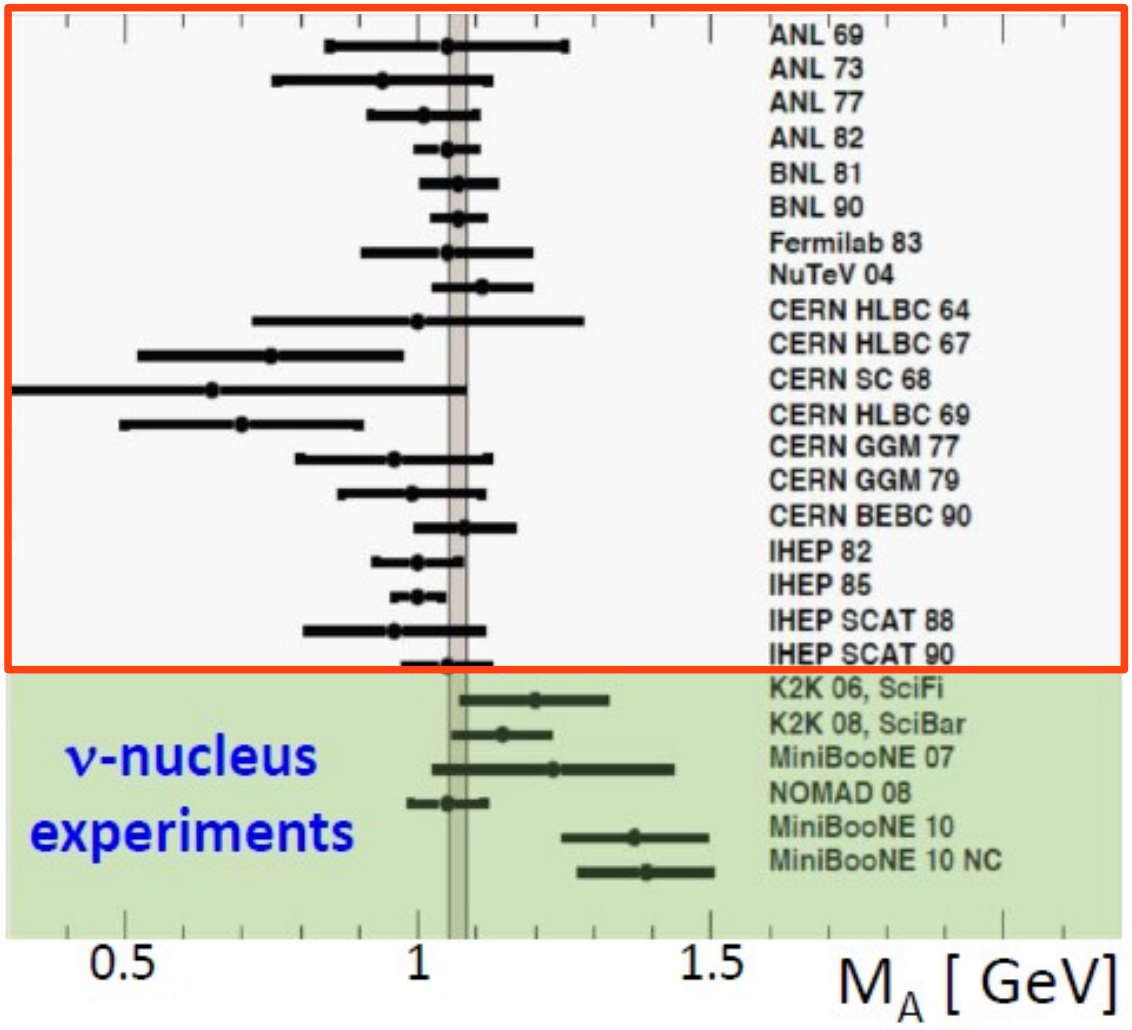
M_A



Measurements of the axial mass came from light target experiments and π-electroproduction suggested that

$$m_A \approx 1.0\, GeV/c^2$$

CCQE problem becomes apparent

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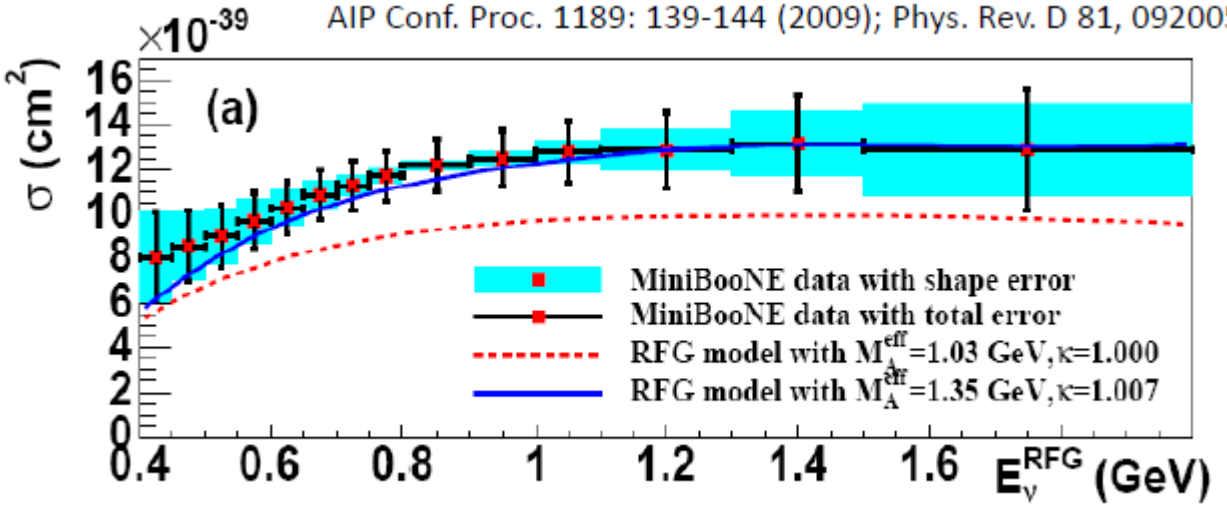
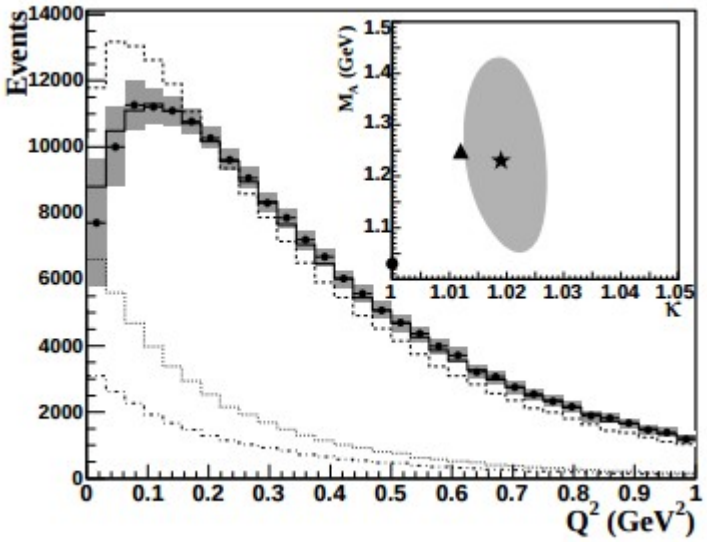
miniBooNE used a heavy (Carbon) target around 1 GeV

AIP Conf. Proc. 1189: 139-144 (2009); Phys. Rev. D 81, 092005 (2010)



Phys.Rev.Lett. 100 (2008) 032301



Effect apparent in reconstructed Q2 distribution.

Fit to CCQE model with an RFG nuclear model yielded

$$m_A \approx 1.3\,GeV/c^2$$

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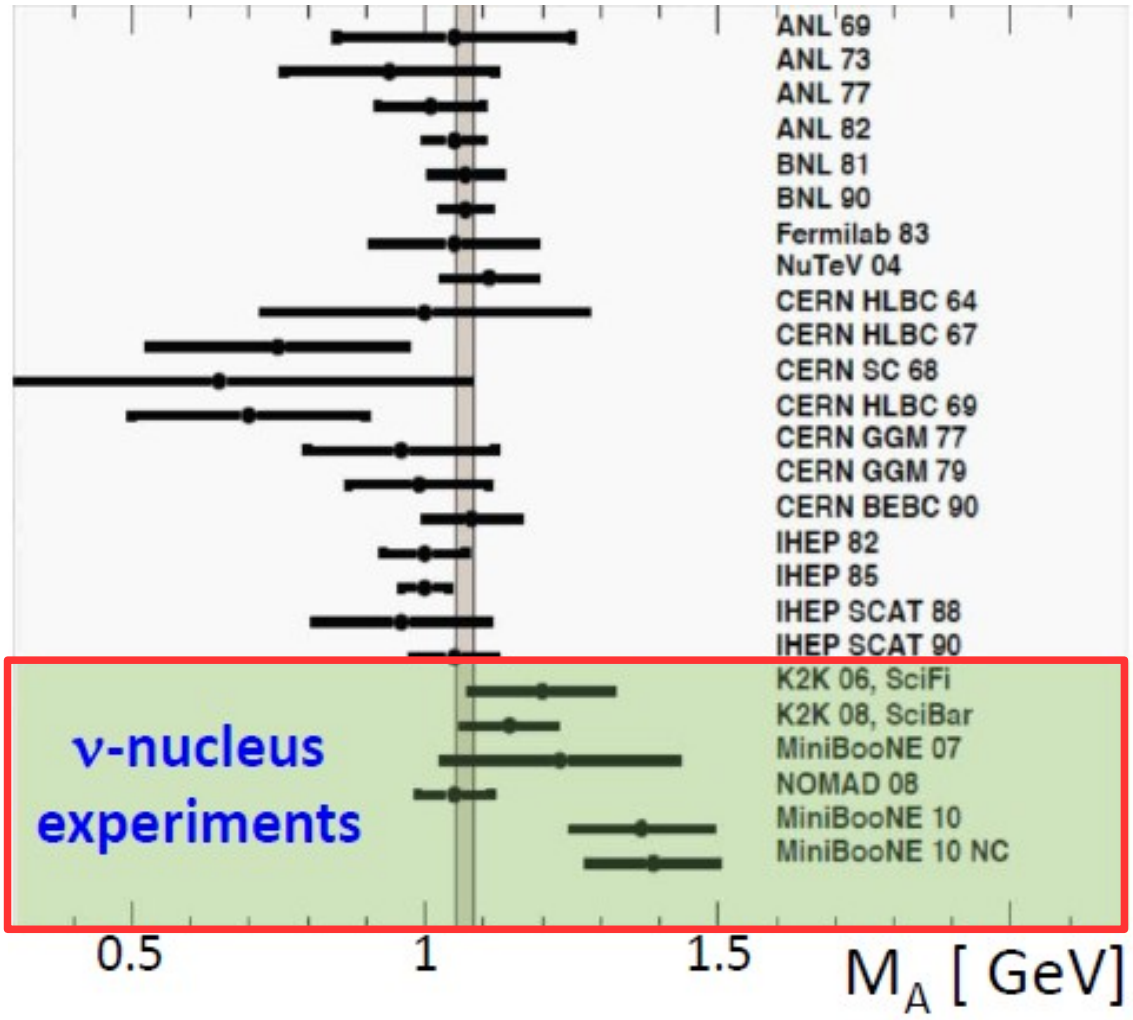
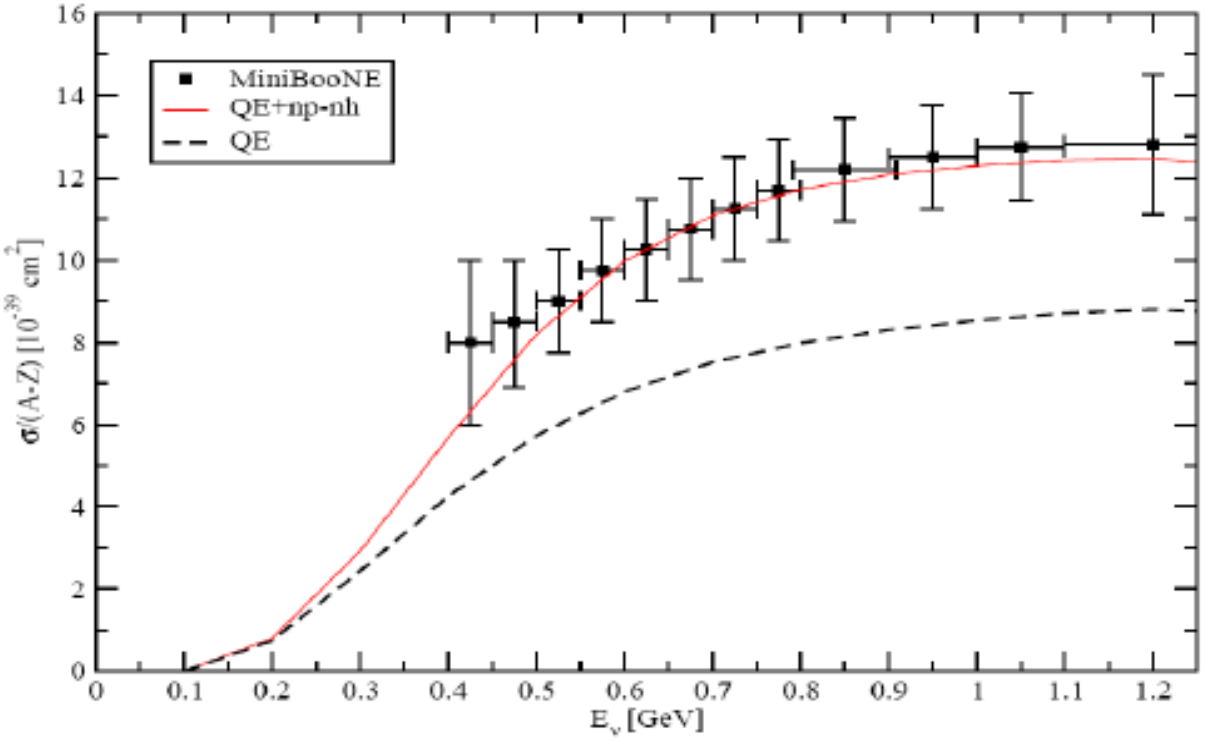
M_A

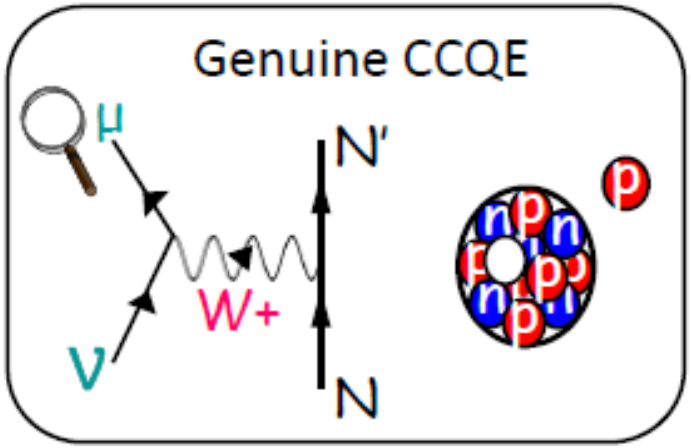


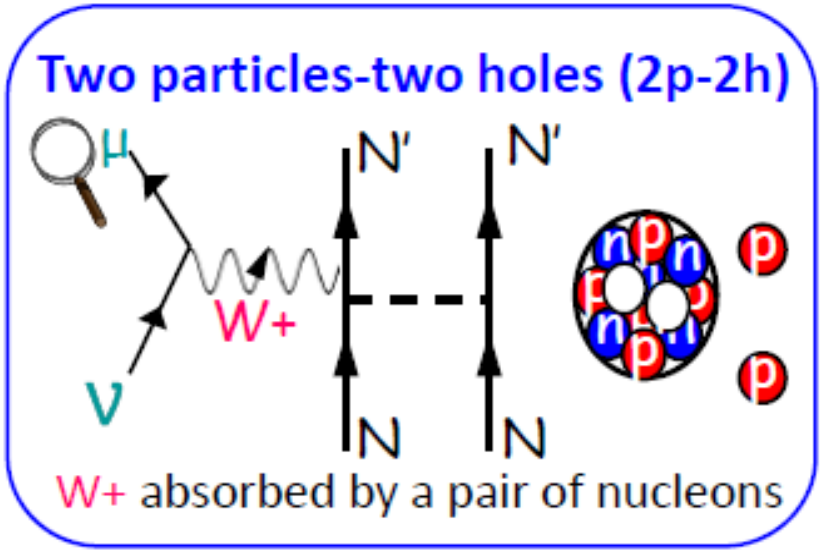
(Part of?) The solution

A significant part of the cross section is now thought to come from multi-nucleon effects



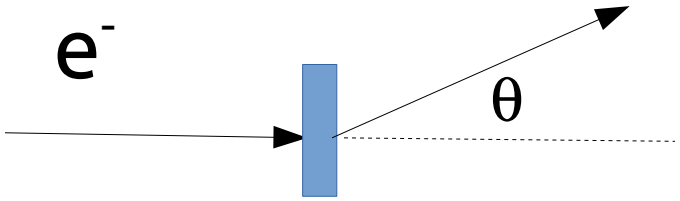
CCQE-like = Genuine CCQE + np-nh

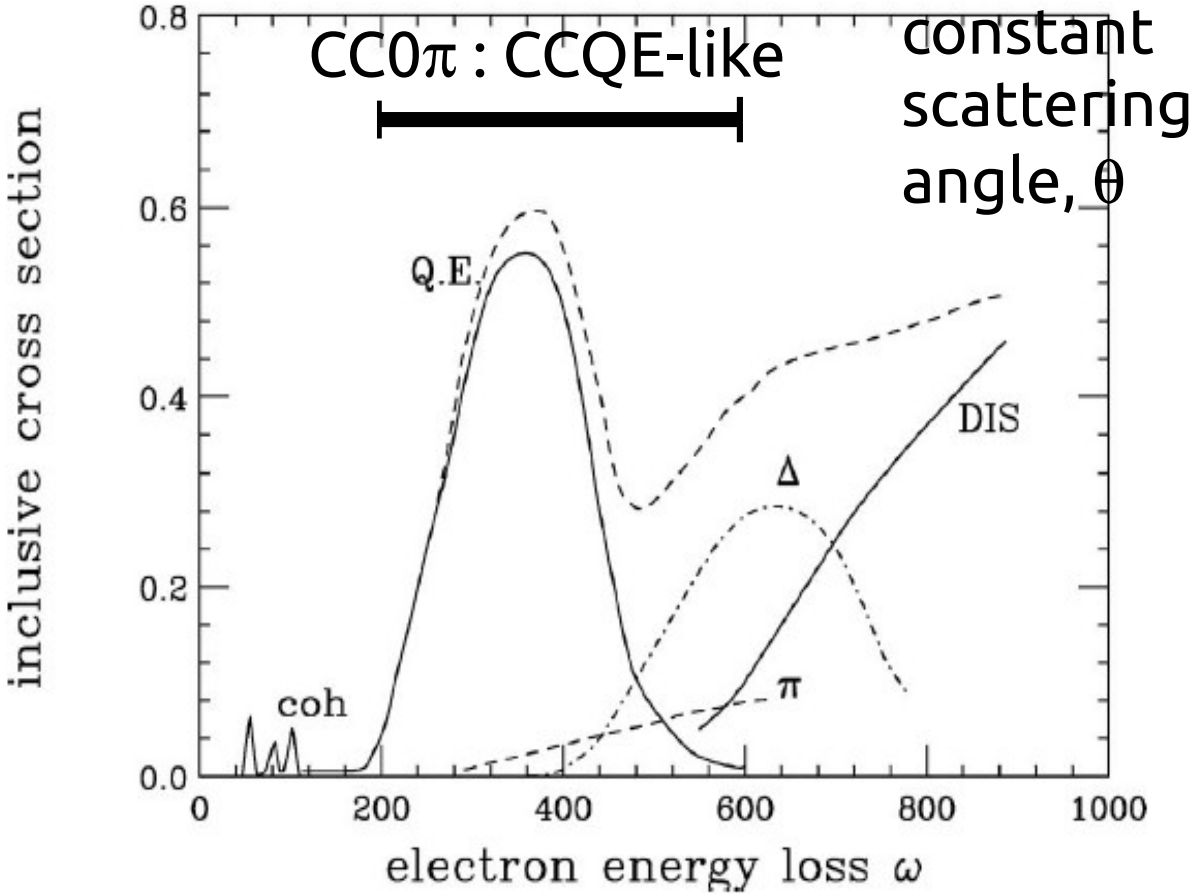




M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 80 065501 (2009)

Caution : what is the signal?

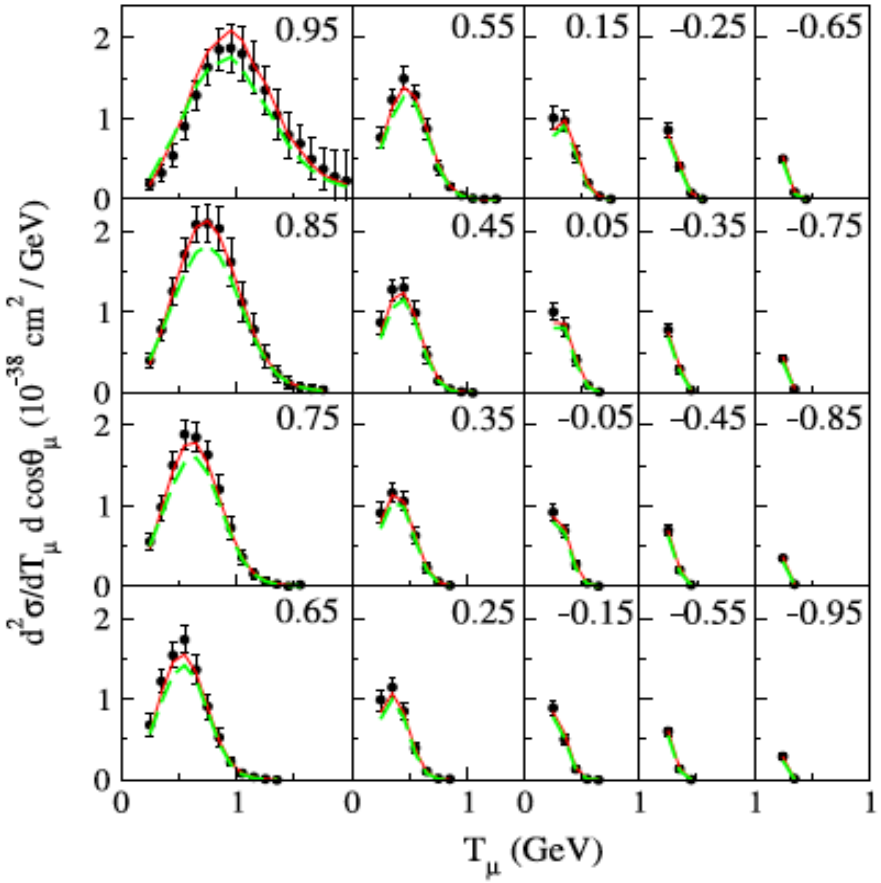




- Incoming neutrinos are not monochromatic
- Signal tends to be muon + no pion, which includes part of the delta peak, the non-resonant background and np-nh effects
- Different experiments can have different signal definitions. Is the invisible pion contribution included as a signal or removed as a background? Is it CCQE or CCQE-like?

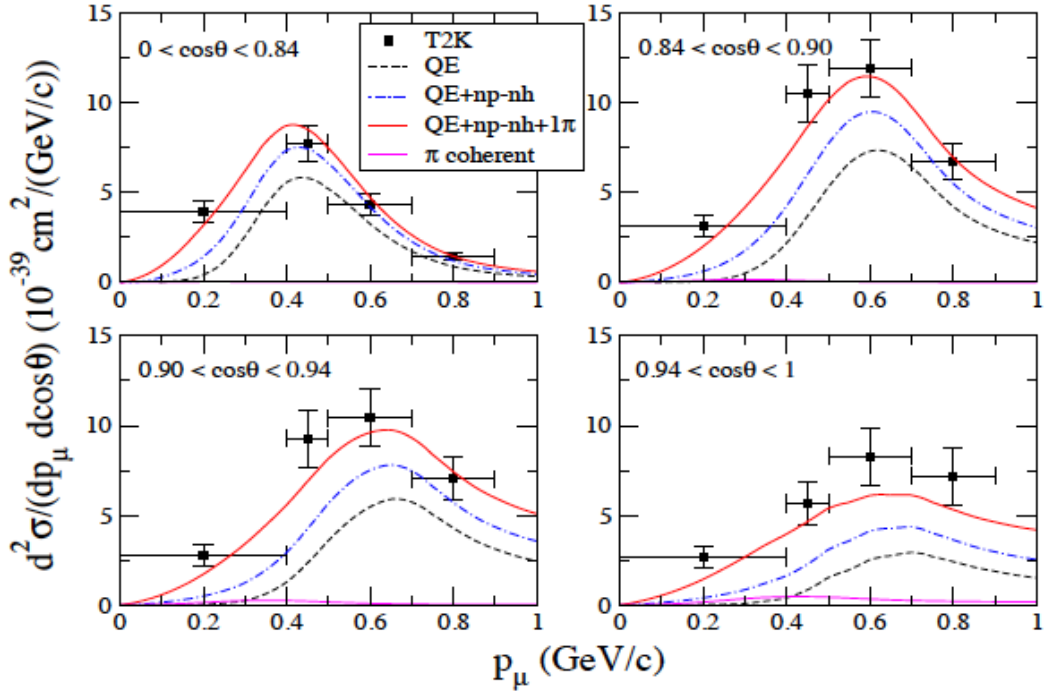
Including many-body effects

J. Nieves et al. Phys. Lett B707 (2012) 72-75



Nieves (Valencia) model applied to miniBooNE data (CCQE)

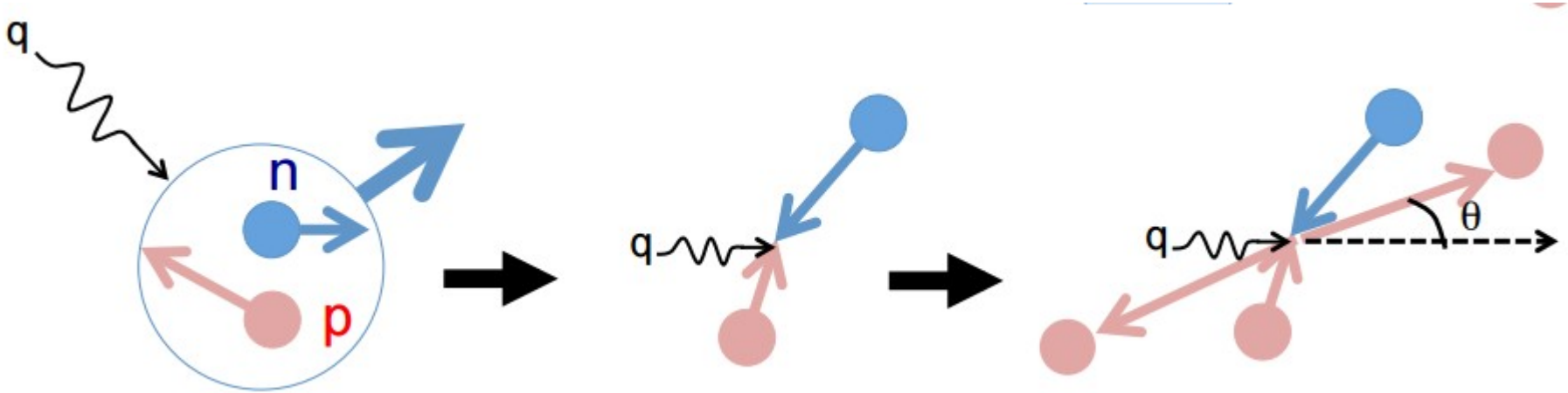
Martini and Ericson, Phys. Rev. C 90 (2014)



Martini model applied to T2K CC inclusive data

Final state np-nh kinematics

- Neutrino event generators must return the 4-vectors of the final state particles.
- QE-like data include 1p1h and 2p2h final states. What are the observed kinematics of the multi-nucleon events?
- Nucleon cluster model in generators due to Sobczyk (NuWro) and Andreopoulos and Dytman (GENIE)
- Experimental tests may be possible with liquid or gas argon TPCs and are being explored by T2K and MINERvA



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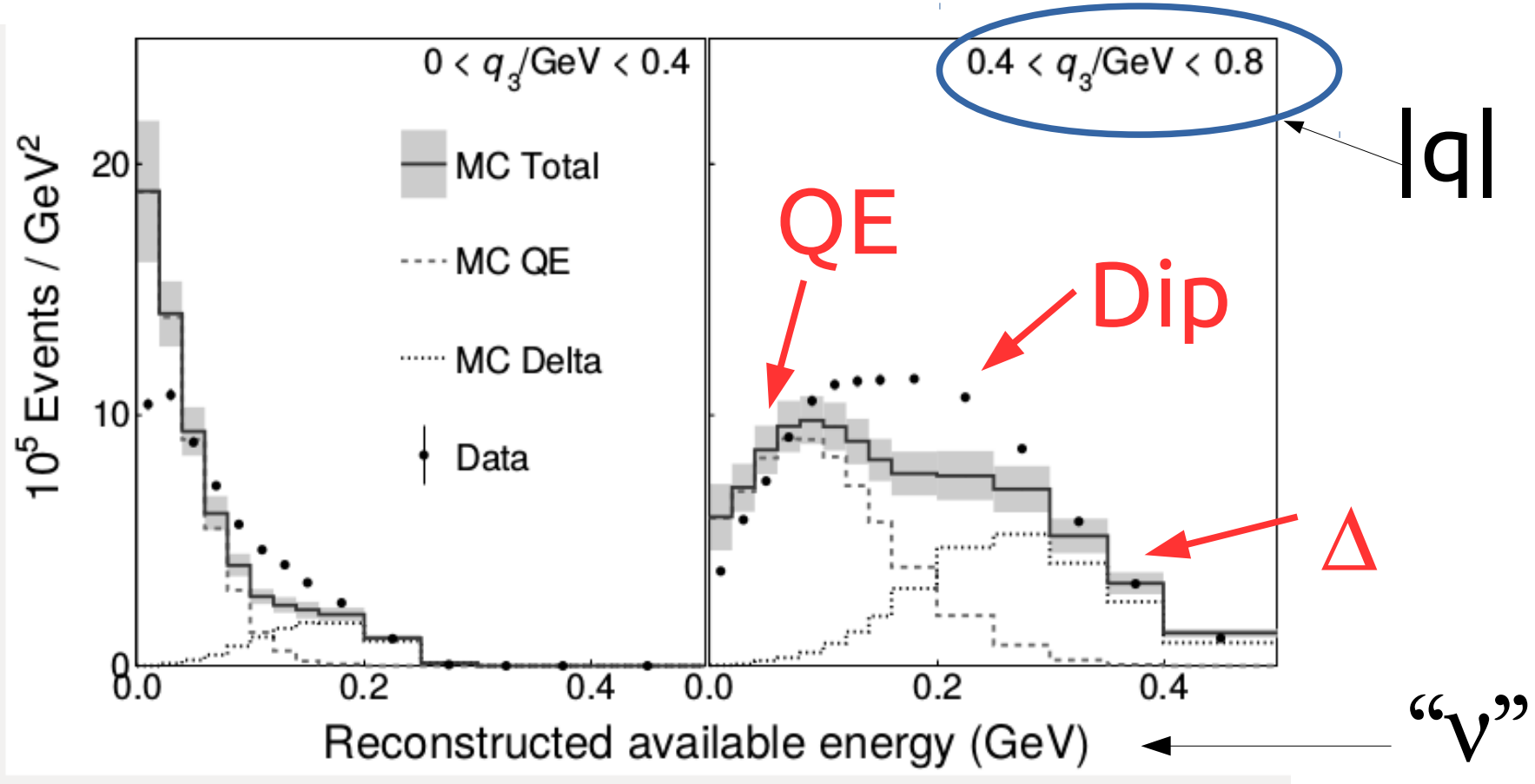
No panacea



MINERvA sample of CC inclusive events with GENIE model including Valencia 2p2h and RPA

P.A.Rodrigues et al., Phys. Lett. 116 (2016), 071802

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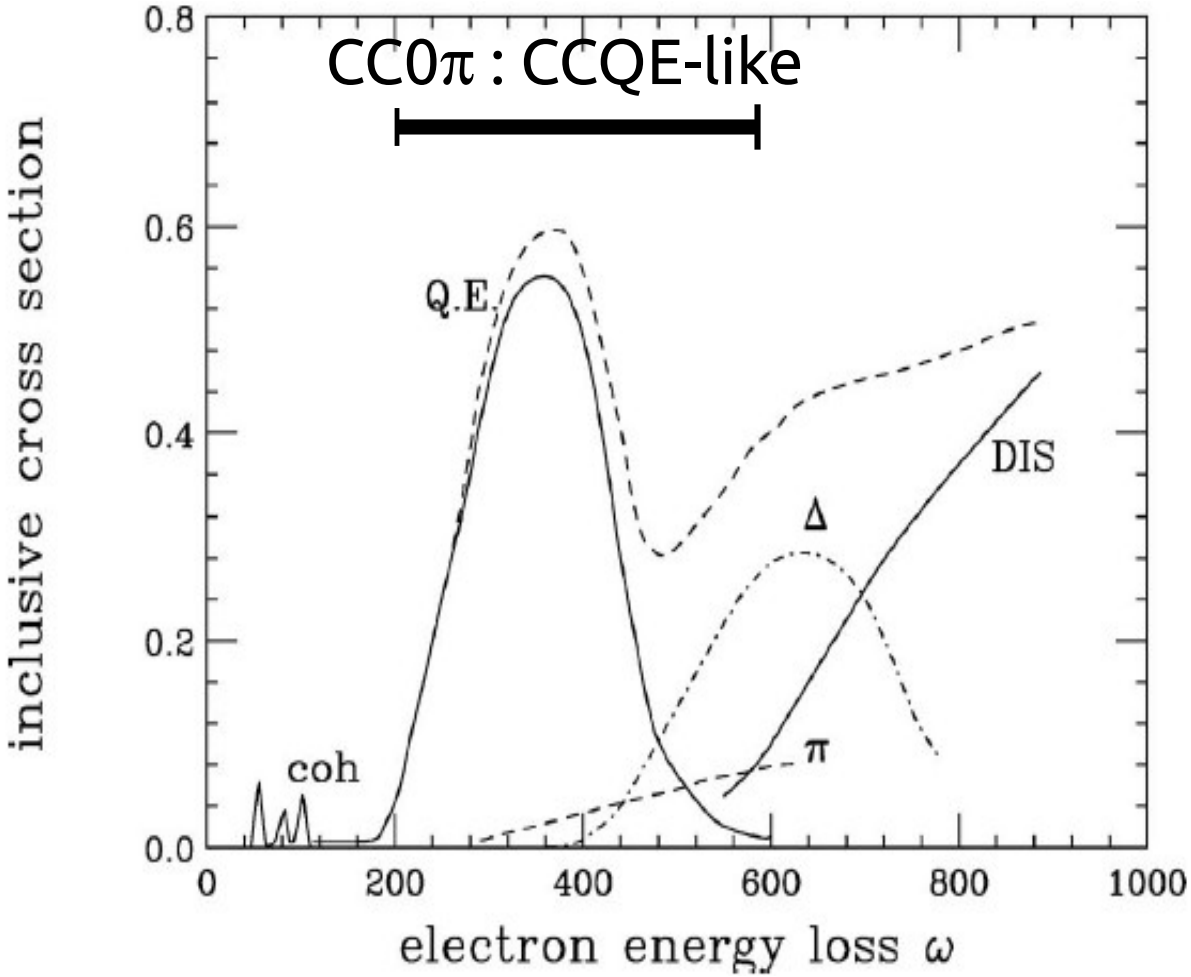
Pion Puzzles

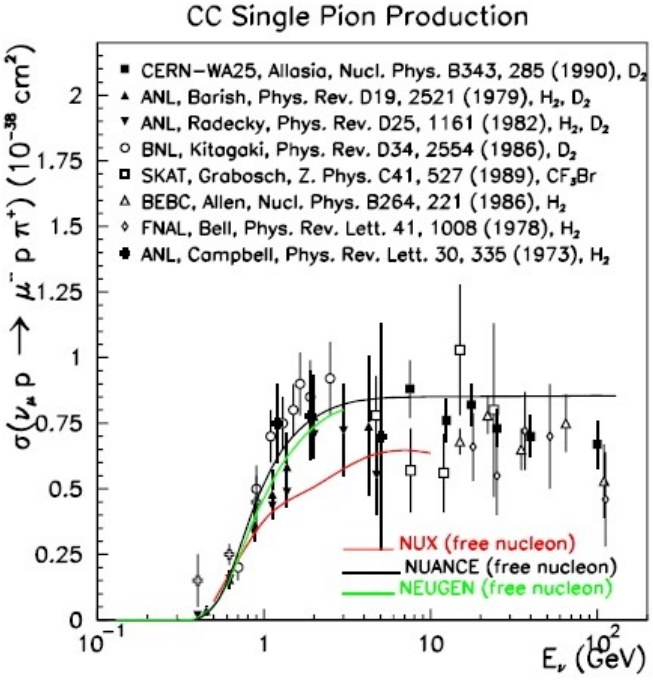
Importance of π production

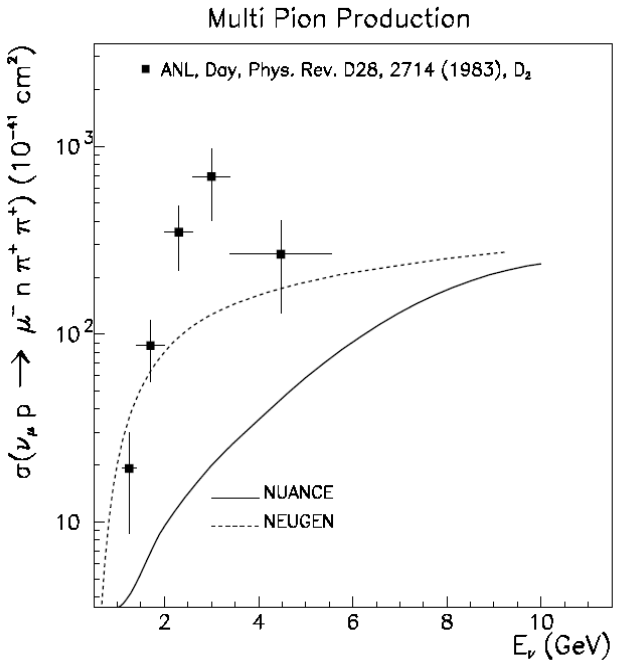


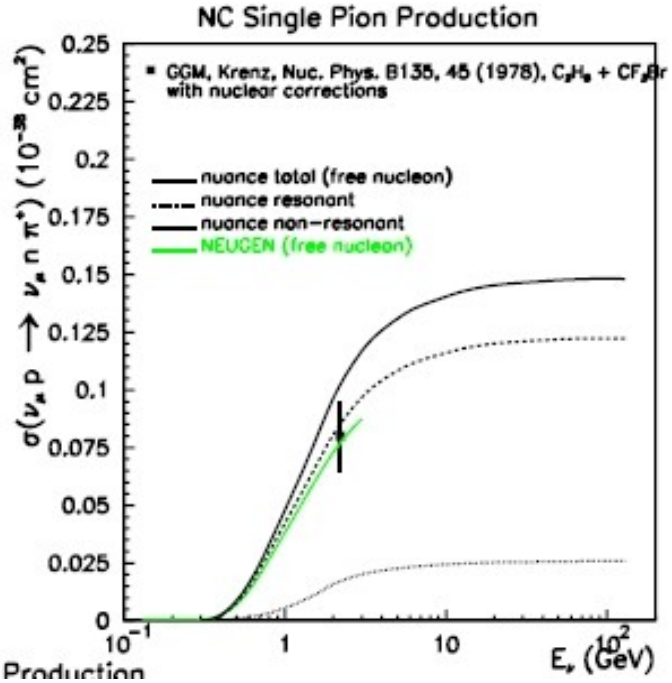
- CCQE-like includes Delta (and non-resonant BG) in which the π is not observed
  - Part of your signal or a background to be subtracted?
- Either because of experimental design or
- because π is affected by FSI and is not observable

π data – pre 2005

Formaggio and Zeller, Rev. Mod. Phys. 84, 1307 (2012)







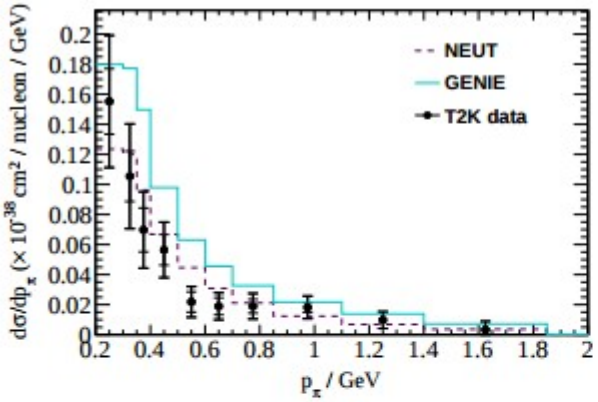
$\nu_\mu p \rightarrow \mu^- p \pi^+$ $\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+$ $\nu_\mu p \rightarrow \nu_\mu n \pi^+$

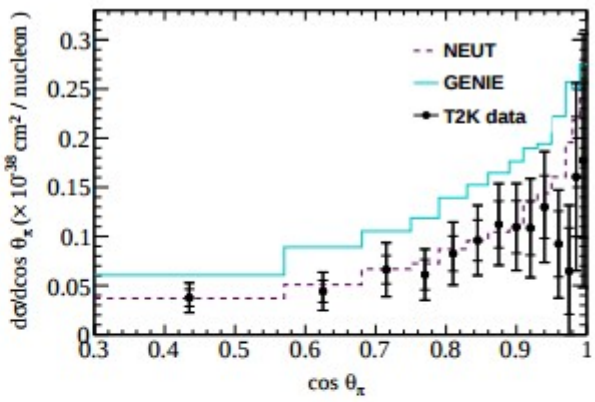
Theoretical model most commonly used is the Rein-Sehgal model.

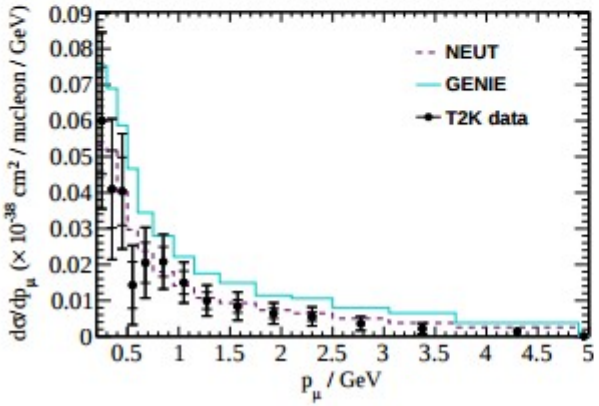
External errors are around 20-30 %

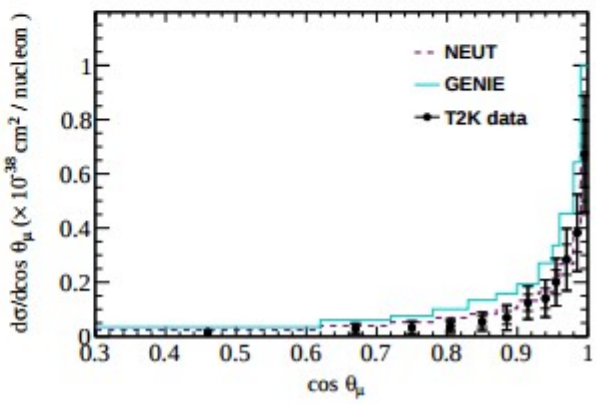
Current data

miniBooNE, MINERvA and T2K are generating detailed doubly differential flux-integrated cross sections.



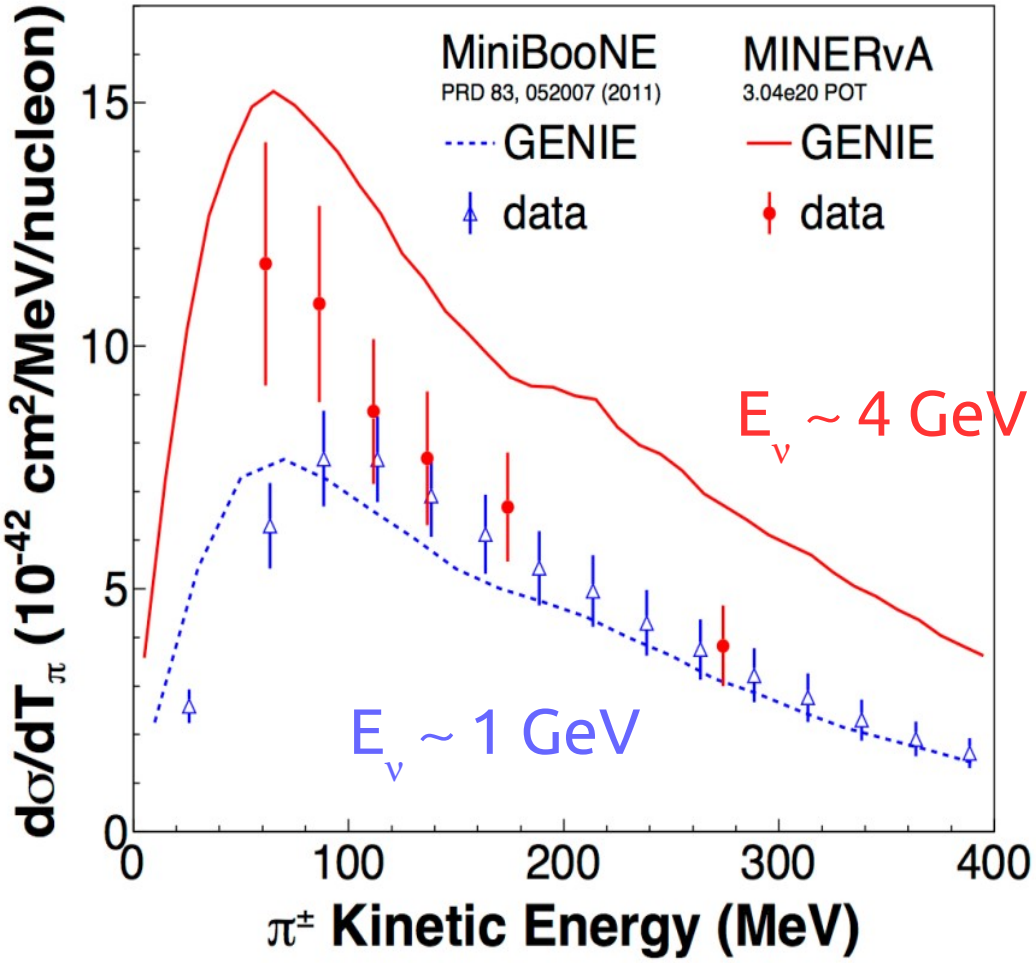






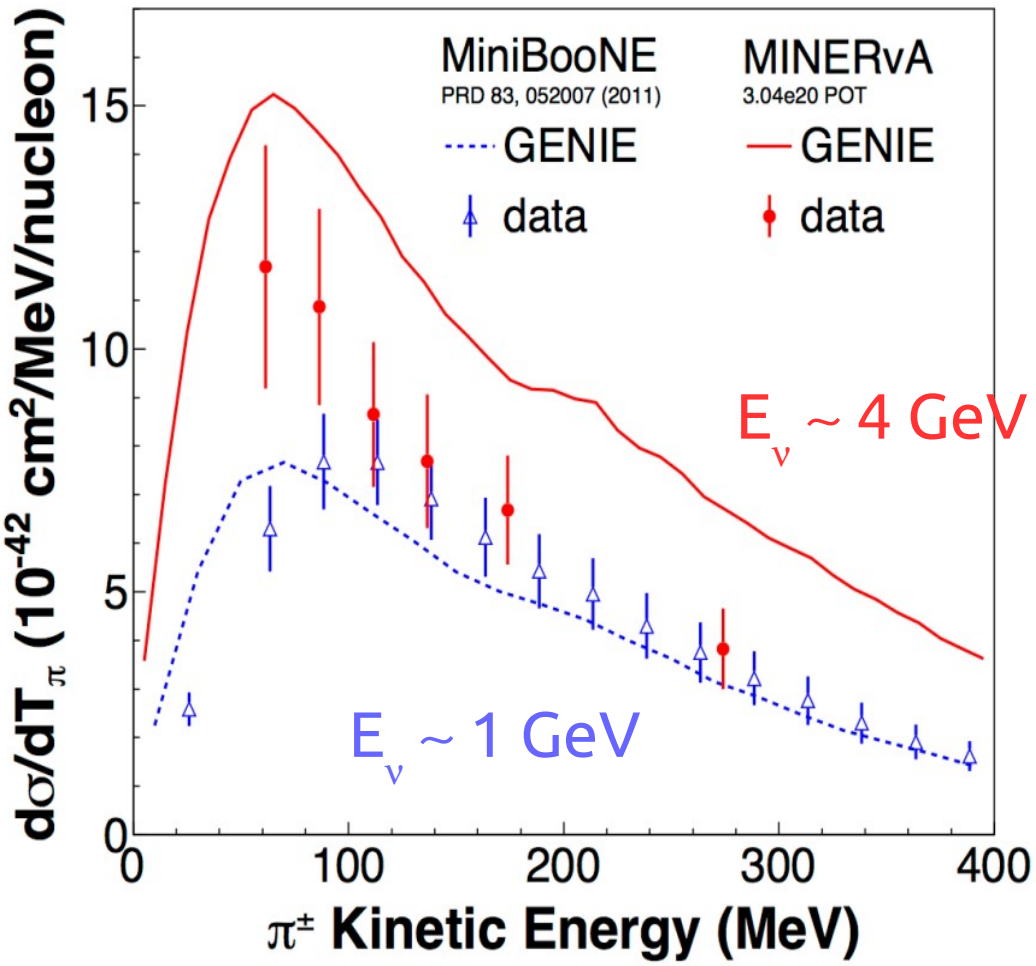
CC1π^+ differential flux integrated cross sections on a water target

Pion production problems



- Flux integrated cross section (can't compare red and blue)
- Data from miniBooNE, MINERvA and model disagree
- GENIE describes MINERvA data shape well (but not normalisation)
- GENIE described miniBooNE data normalisation well(ish) but not shape

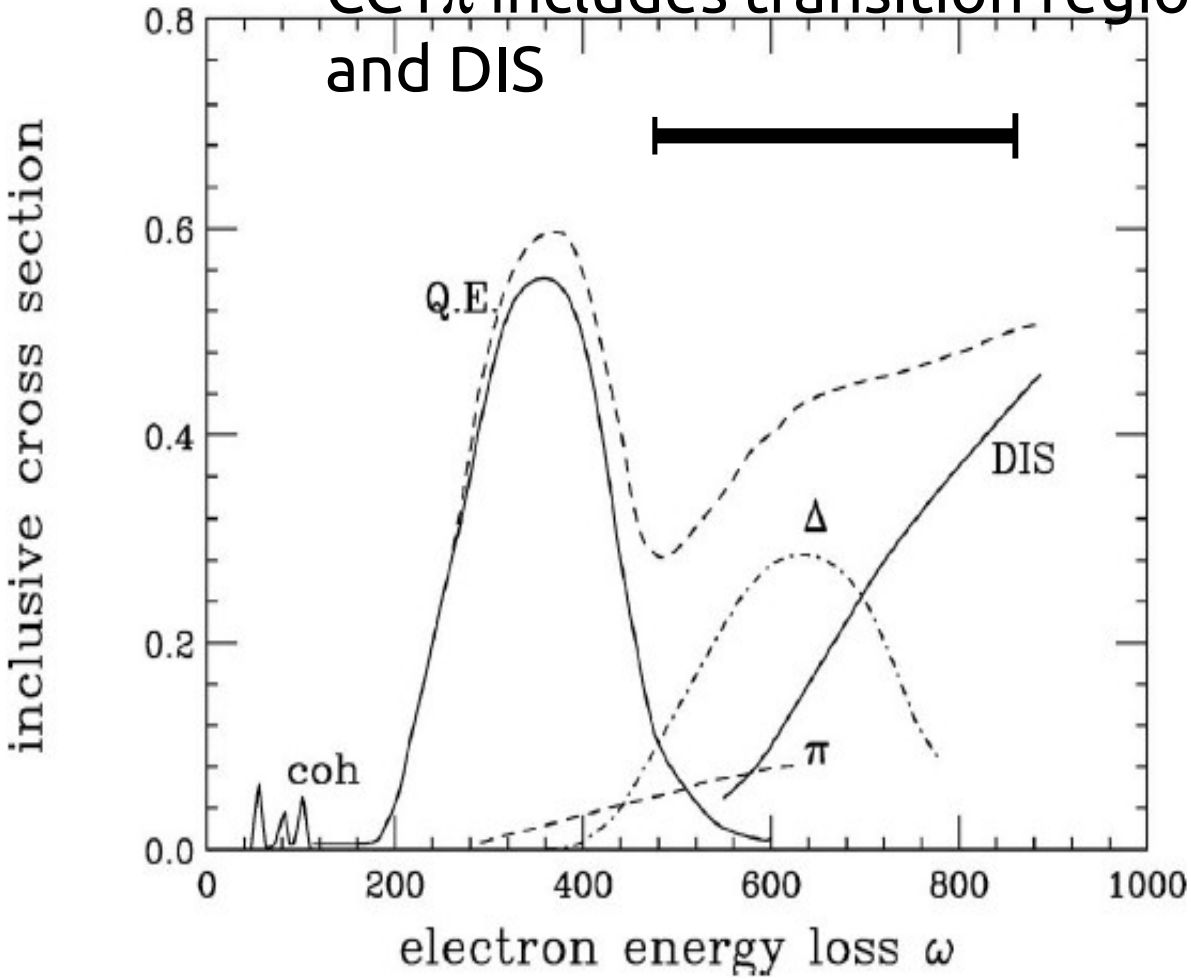
Pion production problems (?)



- Caution : getting these distributions right mean that you need to get
- Flux description right
- pion production right
- FSI right
- Need lots of data from different experiments and different models to disentangle effects
- More work needed.....

Inclusion of SIS/DIS

CC1π includes transition region (SIS) and DIS



See Teppei's talk...

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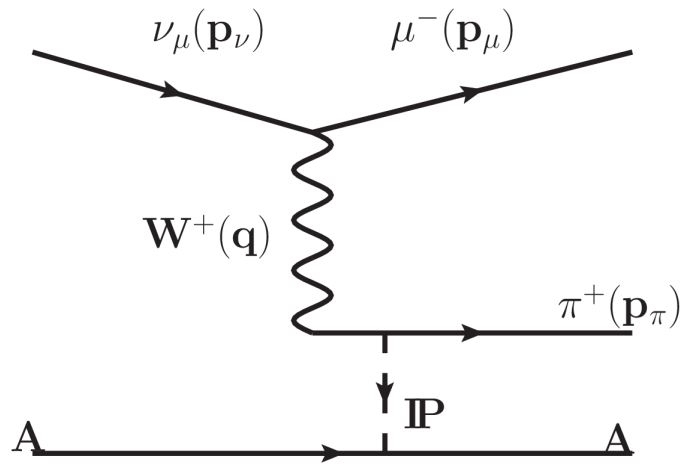
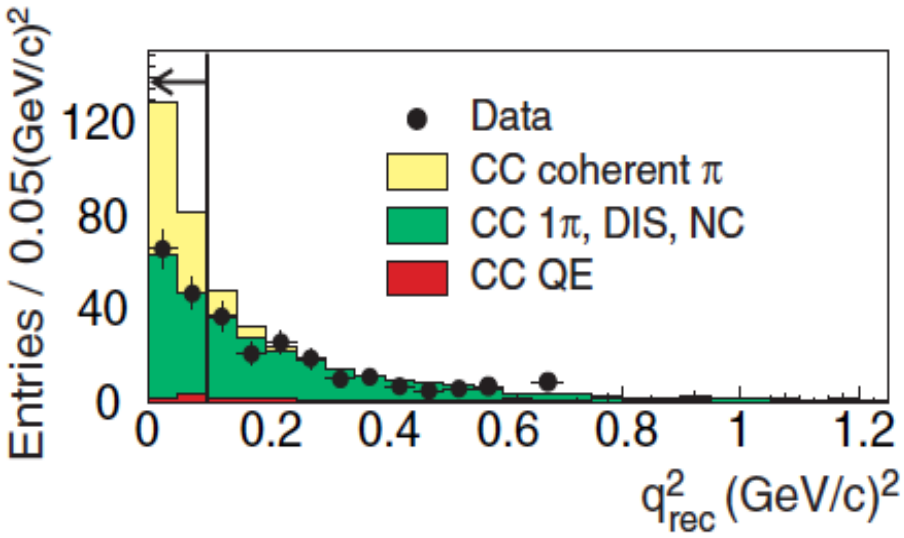
Coherent Conundrums

Coherent pion production – pre 2005

- Rare process
- Forward-going pion production from axial current.
- Described by Rein-Sehgal model building on Adler's theorem for E_ν > 2 GeV
- Not clear what model for E_ν < 2 GeV





Previous experiments observed NC channel but CC measurement consistent with zero

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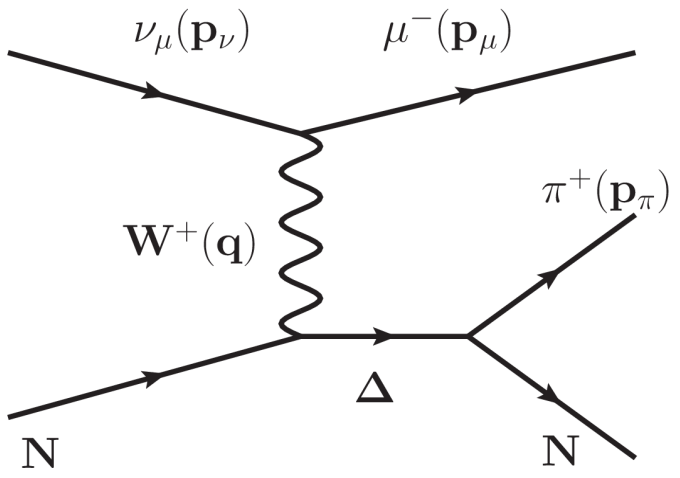
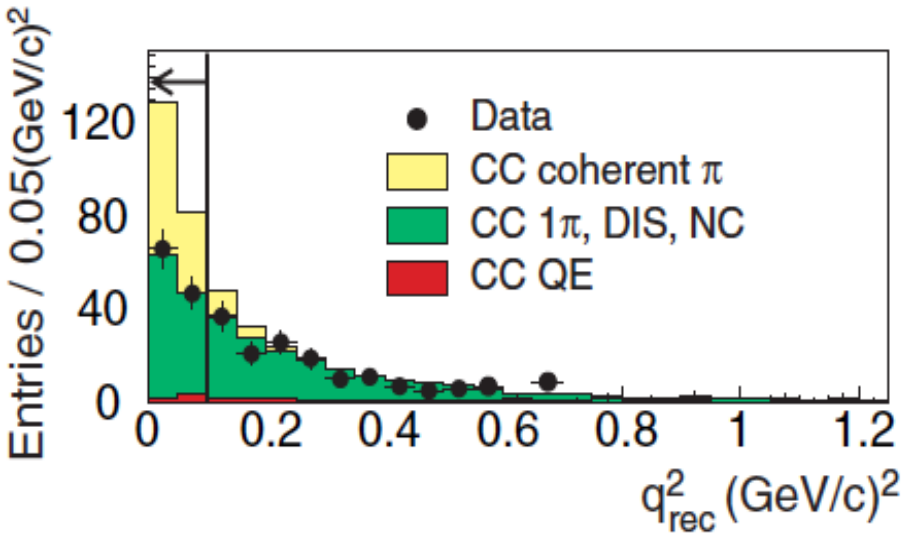


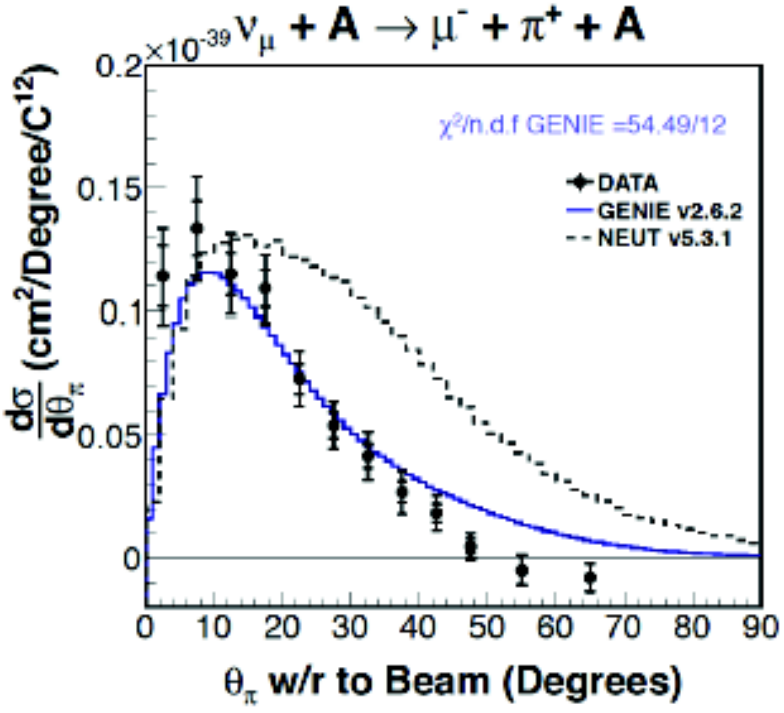


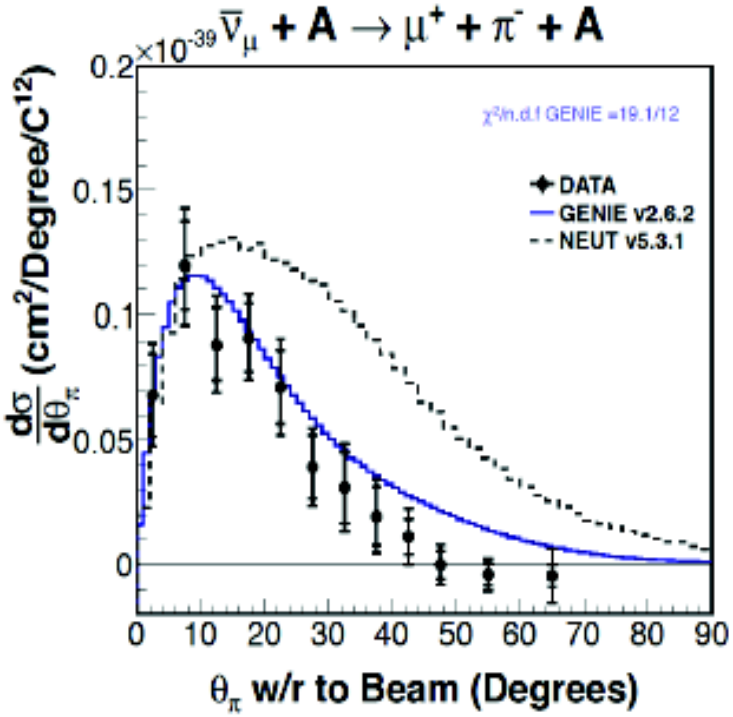
Previous experiments observed NC channel but CC measurement consistent with zero

Coherent pion production

Argoneut, T2K and MINERvA have now measured nonzero CC Coherent pion production in different neutrino energy regions.

Pion kinematics not reproduced by the models (E_ν > 1.5 GeV)

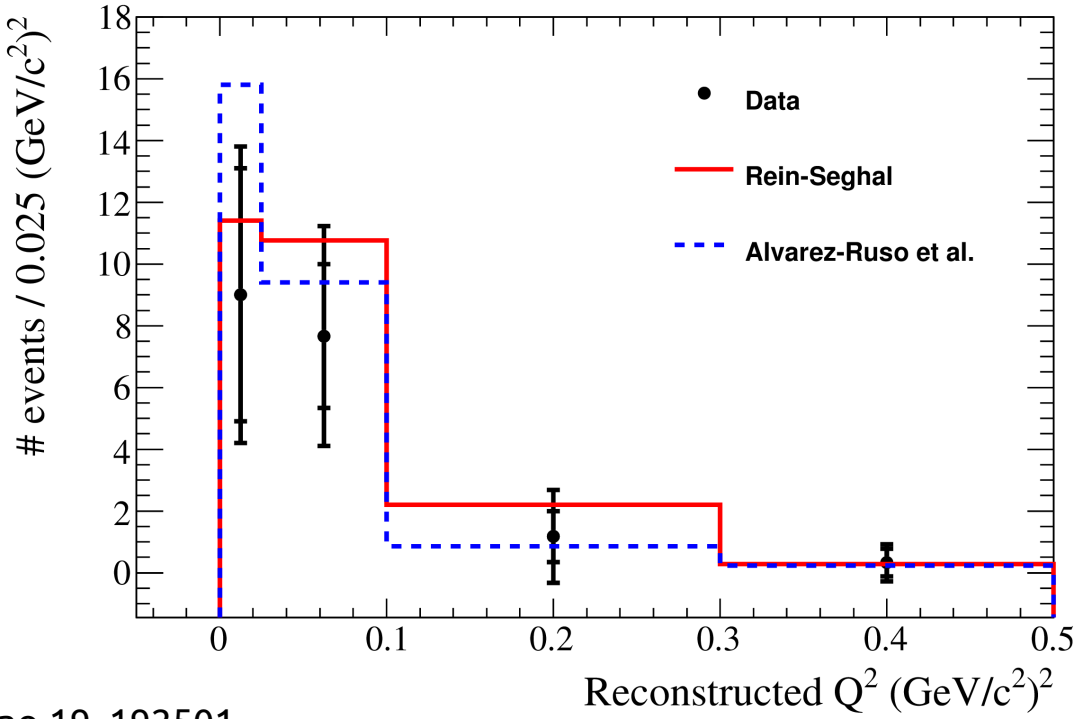




Coherent pion production

Argoneut, T2K and MINERvA have now measured nonzero CC Coherent pion production in different neutrino energy regions.

Data is too sparse at low energies to discriminate between/within models (E_ν < 1.5 GeV).



Phys.Rev.Lett. 117 (2016) no.19, 192501

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Summary

- We have become less complacent : ν-A physics is *complicated*
- Although the basic components of the models are probably (?) understood, there are lots of complex details that we need to work on.
- Need generators that connect to e-nucleus scattering & other relevant data, predict detailed final state kinematics and include relevant initial state and final state effects (*not asking for very much, am I?*)
- Need more ideas, more codes, more experimental data, more imaginative analysis etc etc
- IMHO, the progress the field has made in recent years comes from climbing out of our silos and initiating closer collaboration with the electron community, the nuclear theorists and experimentalists and anyone else who can shed light on this area.

See arXiv:1611.07770 (Katori and Martini) for a nice up-to-date summary of neutrino cross section theory and experiment

An abundance of np-nh models

Microscopic models :

Martini, Ericson, Chanfray and Marteau
Nieves, Simo, Vicente Vacas, Sanchez, Gran
Amaro, Barbaro, Caballero, Donnelly, Udias, WIlliamson,
Simo, Albertus (Superscaling approach)

Phenomenological approaches :

Lalakulish, Gallmeister and Mosel (GiBUU)
Bodek, Budd, Christy (TEM)

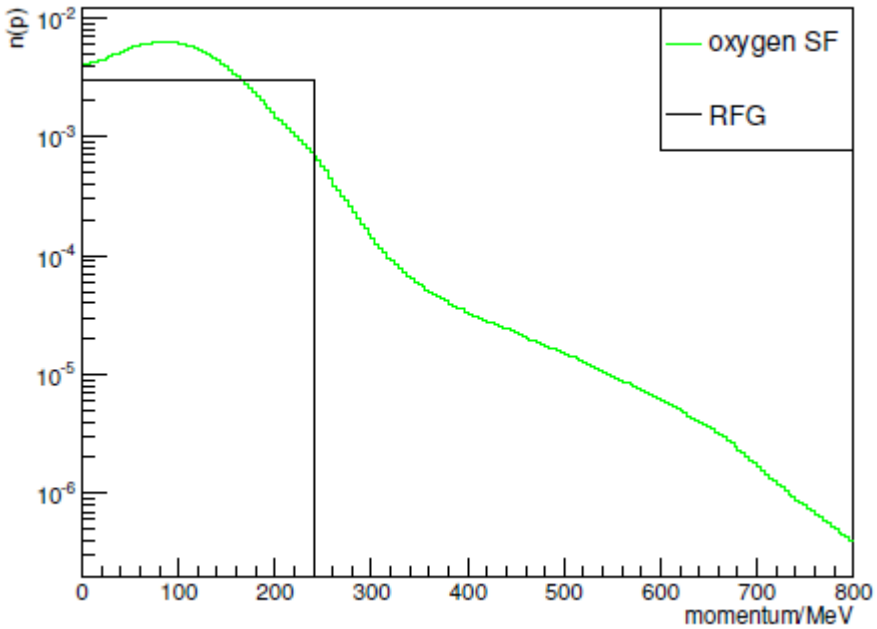
Ab initio approach

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, and R. Schiavilla

Initial and final states

Adding complication, the bare cross section model must be convolved with initial and final state models.

- Relativistic Fermi gas or
- Spectral functions



A. Furmanski, “Charged current Quasi-elastic-like neutrino interactions at the T2K experiment”

- Use of SF within a combined framework including 2p2h and a Final State model can described electron scattering data reasonably well

  Rocco et al., Phys. Rev. Lett. 116, 192501 (2016)

- Neutrino data does not discriminate as well right now.

Final State Effects (FSI)

- Outgoing particles from bare interaction must pass through the nuclear potential
- Most current ν event generators use cascade models in the impulse approximation to simulate final state effects
- FSI (in ν MC) typically has no connection with the final state lepton, or initial hadronic state