Present Understanding of Low Energy Neutrino Cross Sections

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Outline

- Why is it important to know low energy σ_ν's?
- How well have we modeled low energy σ_ν?
  - $\hookrightarrow$ brief overview of neutrino event generators
- How well have we measured low energy σ_ν?
  - $\hookrightarrow$ past ν measurements
  - $\hookrightarrow$ knowledge from bubble chamber experiments
  - $\hookrightarrow$ stick mainly to free nucleon cross sections
- Prospects for the future

Motivation

- Last 5 years have given us compelling indications that neutrinos oscillate
- Evidence for ν mass has sparked intense interest in neutrino experiments ...

- CHOOZ
- ICARUS
- KamLAND
- K2K
- MINOS
- OPERA
- Palo Verde
- BUGEY
- CHORUS
- Karmen
- LSND
- MiniBooNE
- NOMAD
- IMB
- Kamiokande
- MACRO
- Soudan 2
- Super Kamiokande
- BOREXINO
- Homestake
- GALLEX
- GNO
- SAGE
- SNO

Where Do Cross Sections Matter?

Why do we need to know low energy ν cross sections?

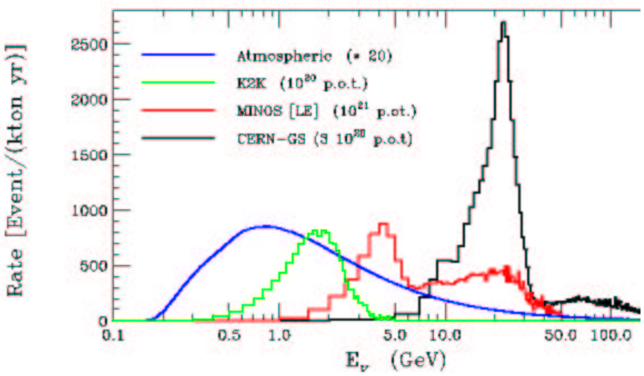
- Atmospheric Neutrinos
  - $\hookrightarrow$ Δm^2_{23}, θ_{23} limited by systematics on flux, σ_ν
  - $\hookrightarrow$ $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$ limited by σ_ν uncertainties

- Proton Decay Searches
  - $\hookrightarrow$ good knowledge of σ_ν required to reliably evaluate expected backgrounds

- Appearance Experiments ($\nu_\mu \rightarrow \nu_e$), θ_{13}
  - $\hookrightarrow$ limited by stat and syst uncertainty of background subtraction
  - $\hookrightarrow$ ν_e component in the beam
  - $\hookrightarrow$ misidentified NC π^0 production
    (important to not only understand rate
    but contributions from different channels)
    - $\star$ resonant single π^0 production
    - $\star$ coherent π^0 production
    - $\star$ feed down from inelastic channels
      (where nuclear absorption of add'l hadrons plays a role)

Systematics are already beginning to dominate these measurements

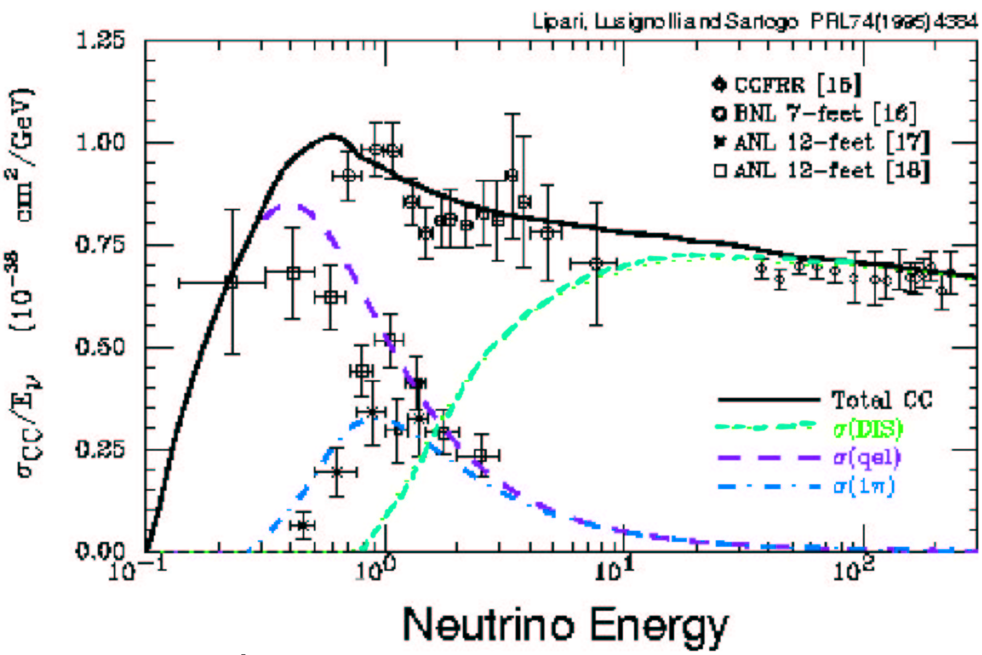
Status of Low E_ν Cross Sections



Knowledge of ν differential and total cross sections in low energy region is limited:

One of biggest challenges is getting the physics right over a large range of energies (100's MeV $\longrightarrow$ 100's GeV)

scattering off entire nucleon $\longrightarrow$



$\longleftarrow$ scattering off constituents in nucleon

No consensus on best way to combine channels at fixed E_ν

- DIS limited to $W > W_0$ to avoid double counting
- modeling DIS at low E (U.K. Yang WG2 6/9)

Principal reactions:

- quasi–elastic scattering
- resonance production
- deep inelastic scattering

Modeling Low E ν Cross Sections

- Recent neutrino experiments using a variety of Monte Carlos (many have long histories)

  $\hookrightarrow$ NUANCE* (IMB, K2K, SuperK, MiniBooNE)

  $\hookrightarrow$ NEUT (Kamiokande, K2K, Super K)

  $\hookrightarrow$ NEUGEN* (Soudan 2, MINOS)

  $\hookrightarrow$ NUX, GENEVE (Icarus, NOMAD)

  $\hookrightarrow$ JETTA, RESQUE (CHORUS, OPERA)

- Generally these Monte Carlos are "proprietary" (many are not well documented publicly) $\longrightarrow$ exceptions*

Big thanks to Dave Casper & Hugh Gallagher for their help

- Share common theoretical inputs

  $\hookrightarrow$ Llewellyn Smith for free nucleon QE cross section

  $\hookrightarrow$ Rein–Sehgal resonance cross sections

  $\hookrightarrow$ standard DIS formula for high W, Q^2

- But nontrivial differences

  $\hookrightarrow$ implementation of Fermi gas model for QE

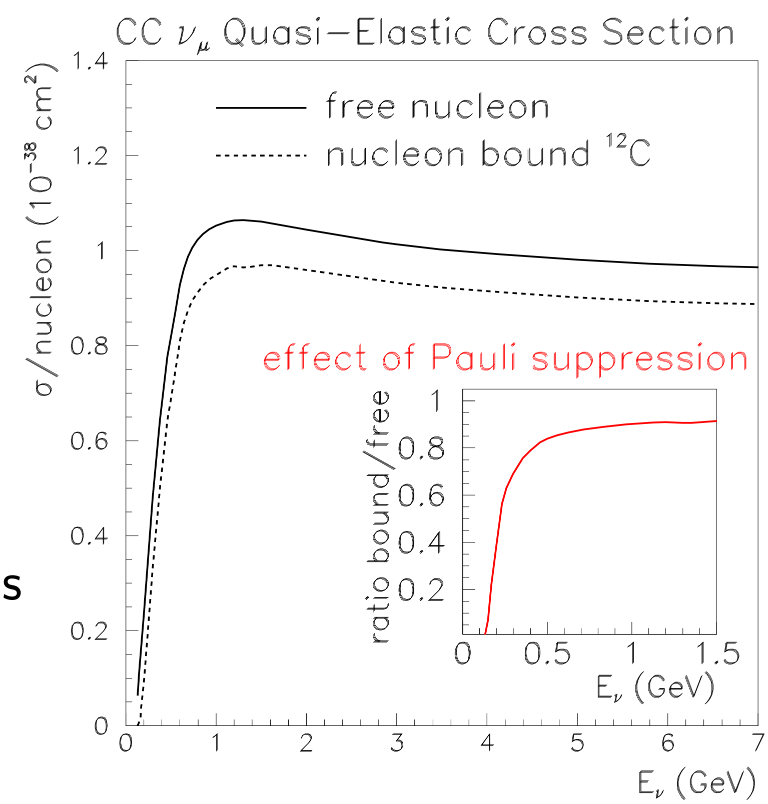
  $\hookrightarrow$ joining of resonance and DIS regions

  $\hookrightarrow$ treatment of nuclear effects (final state interactions of π, K, n, p)

Nuclear Effects

Oscillation experiments measure ν reactions on nuclear targets ($O^{16}, C^{12}, Ar^{40}, Fe^{56}, Pb^{207}$) $\Rightarrow$ vastly complicates description of ν reactions ...

- Pauli suppression
  (relatively straight forward)
- Fermi motion of target nucleons
- Final state interactions
  (much larger and have not been disentangled exp'ly)
  - $\hookrightarrow$ nuclear reinteractions
  - $\hookrightarrow$ π absorption
  - $\hookrightarrow$ charge exchange

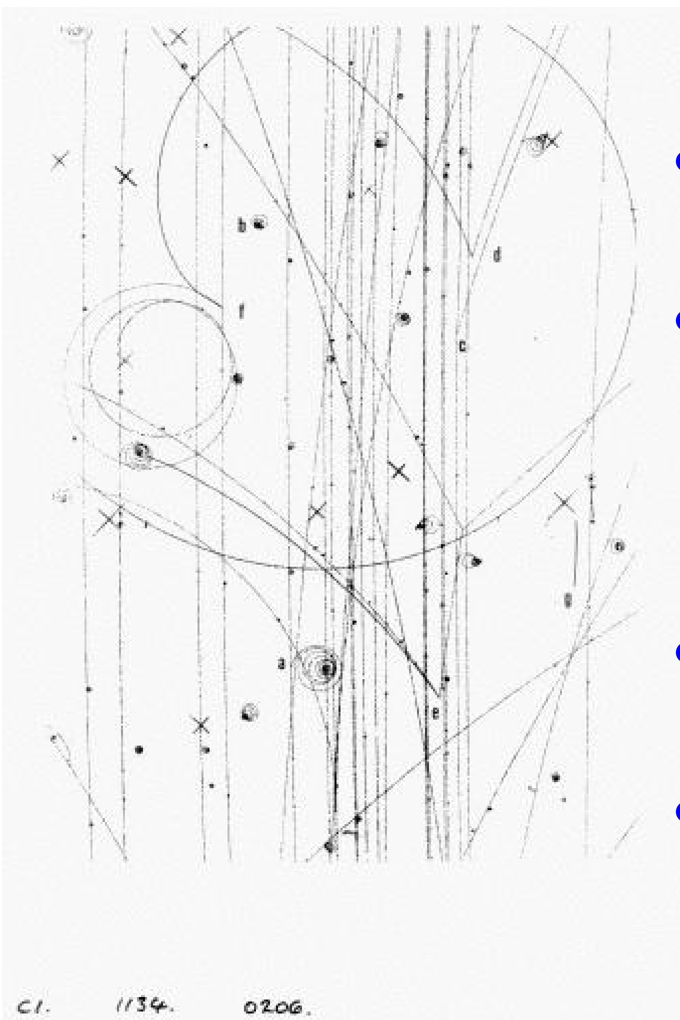


- Impacts kinematics/rates and observed final states
- Nuclear effects studied extensively in DIS using μ, e^- beams, but have only been glanced at in low statistics ν experiments:
  - $\hookrightarrow$ Gargamelle, SKAT ($C_3H_8\ CF_3Br$)
  - $\hookrightarrow$ FNAL (Ne)
  - $\hookrightarrow$ Serpukov (Al spark chamber)
  - $\hookrightarrow$ CHARM, CHARM II (marble, glass)
- but they typically publish free nucleon σ

Early σ_ν Measurements

Gargamelle at CERN

- Low E ($\sim 1-10$ GeV) σ_ν meas come from early experiments at ANL, BNL, CERN, and FNAL
- bubble chamber experiments



- simplest exclusive states measured
- considerable errors due to:
  - $\hookrightarrow$ low statistics
  - $\hookrightarrow$ imprecise knowledge of incoming ν flux
- in addition to large errors, results are often conflicting
- even ignored by PDG (σ_ν removed after 1996)

Contrast: in 30–200 GeV range, high statistics data from variety of experiments (NuTeV, CCFR, CHARM, CDHS) (B. Bernstein talk on NuTeV σ WG2 6/9)

Past σ_ν Measurements

- How well have we measured low energy ν σ's?
  Rely on past measurements for this knowledge

- Along the way, point out how good our current theoretical understanding is

- Review the status of past measurements of σ_ν at $E_\nu \sim 1$ GeV:

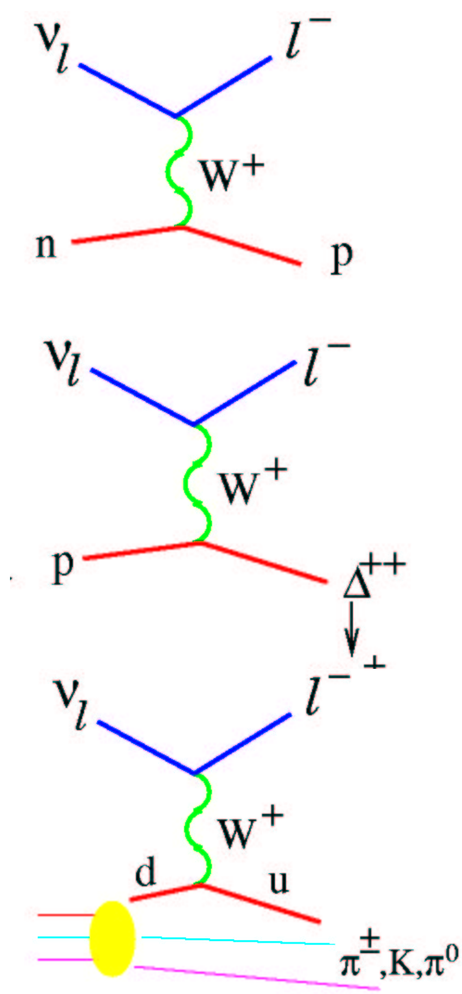
  $\hookrightarrow$ Quasi–elastic scattering

  $\hookrightarrow$ Resonance production (CC and NC single π)

  $\hookrightarrow$ Coherent π production

  $\hookrightarrow$ Multi π production
  (small σ but can feed down)

  $\hookrightarrow$ ν production of strange



Quasi Elastic Scattering

$$\nu_\mu \, n \rightarrow \mu^- \, p$$

- Most well known cross section at low energies
- These processes have been studied with low energy (100 MeV – 10 GeV) bubble chambers experiments; most on light targets:

Experiment	Target Type	Reference
ANL	bubble chamber, D_2	Barish, PRD 16, 3103 (1977)
GGM	bubble chamber, propane–freon	Pohl, Nuovo Cimento 26, 332 (1979)
BNL	bubble chamber, D_2	Baker, PRD 23, 2499 (1981)
FNAL	bubble chamber, D_2	Kitagaki, PRD 28, 436 (1983)
Serpukhov	spark chamber, Al	Belikov, Z. Phys. A320, 625 (1985)
BEBC	bubble chamber, D_2	Allasia, Nucl. Phys. B343, 285 (1990)
SKAT	bubble chamber, CF_3Br	Ammosov, Sov.J.P.Nuc. 23, 283 (1992)

- Theoretical calculations for free nucleons all based on C.H. Llewellyn Smith, Phys. Rep. **3C**, 261 (1972)

$$< N'|J_\mu|N > \; = \; \overline{u}(N') \left[\gamma_\mu F_V'(q^2) + \frac{i\sigma_{\mu\nu} q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5 \gamma_\mu F_A(q^2) \right] u(N)$$

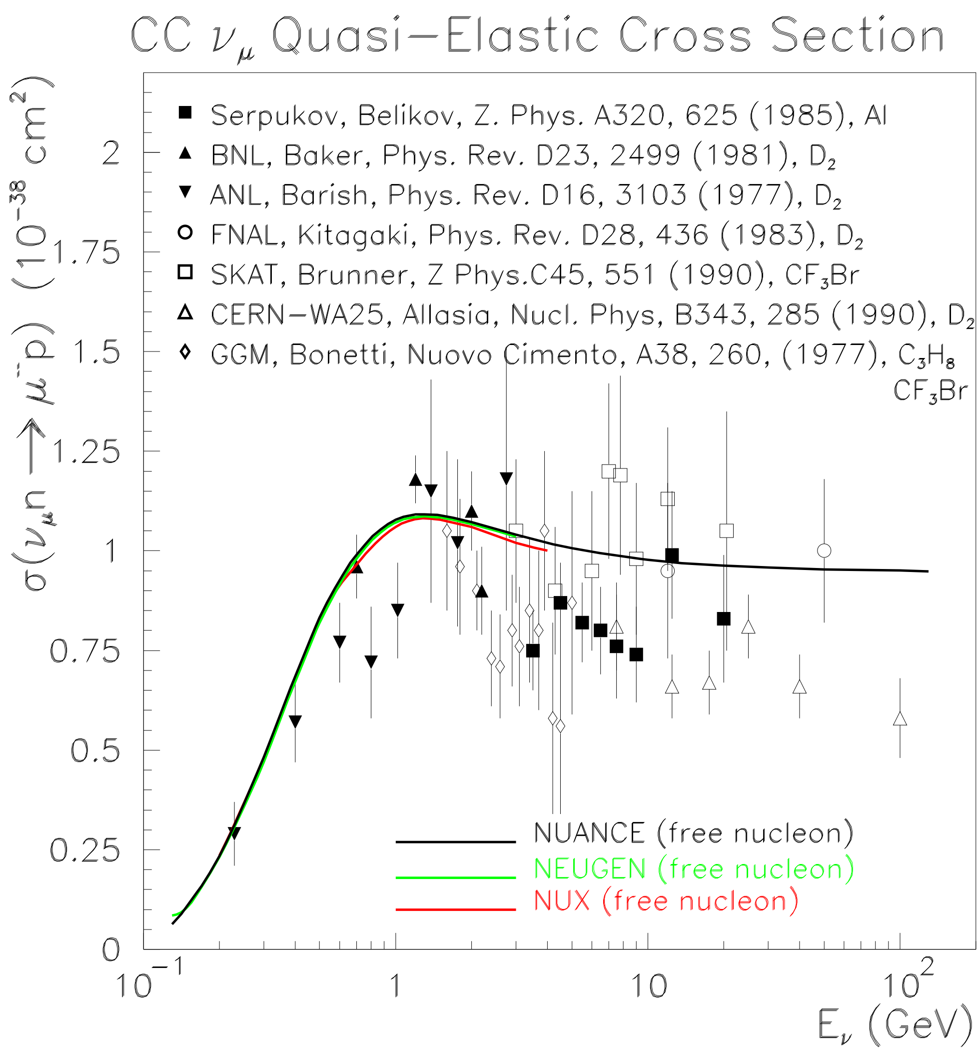
$$F_V(q^2) \; \sim \; \frac{1}{(1 - q^2/M_V^2)^2} \qquad F_A(q^2) = \frac{F_A(0)}{(1 - q^2/M_A^2)^2}$$

- Form factors depend on M_V, $F_A(0)$, M_A

Quasi-Elastic Cross Section

Existing QE σ measurements were made ~ 20 years ago and have limited precision:

- largest contrib to exp'l error $15-20\%$ flux uncertainties

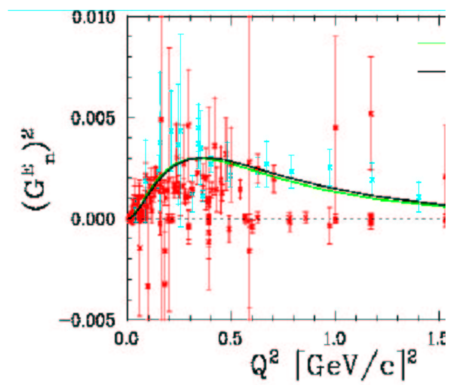


- No big surprise here - Monte Carlo predictions agree (w/ consistent pars)
- apart from nuclear effects, theoretical uncertainty dominated by $M_A = 1.026 \pm 0.021$ GeV (world average)
- considerable spread in the QE σ data for any given E_ν

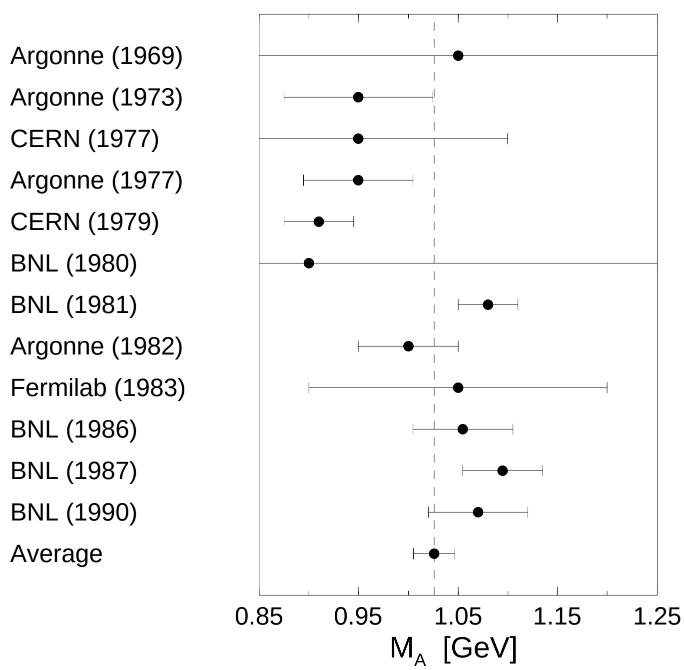
Quasi-Elastic Cross Section

Room for improvement ...

- Recent work by Bodek, Budd, and Arrington
  talk by C. Walter next
- input updated form factors $G_E^{n,p}(Q^2)$, $G_M^{n,p}(Q^2)$ from e^- scattering data
- largest effect $G_E^n(Q^2) \neq 0$



- with latest values, re–analyze ν QE data for M_A



ν data not yet updated

from Bernard *et al.* hep-ph/0107088

Neutrino Resonance Production

- In addition, there are excitation of resonances and their subsequent decays:

$$\nu N \rightarrow l \;\; N^*$$
$$N^* \rightarrow \pi N'$$

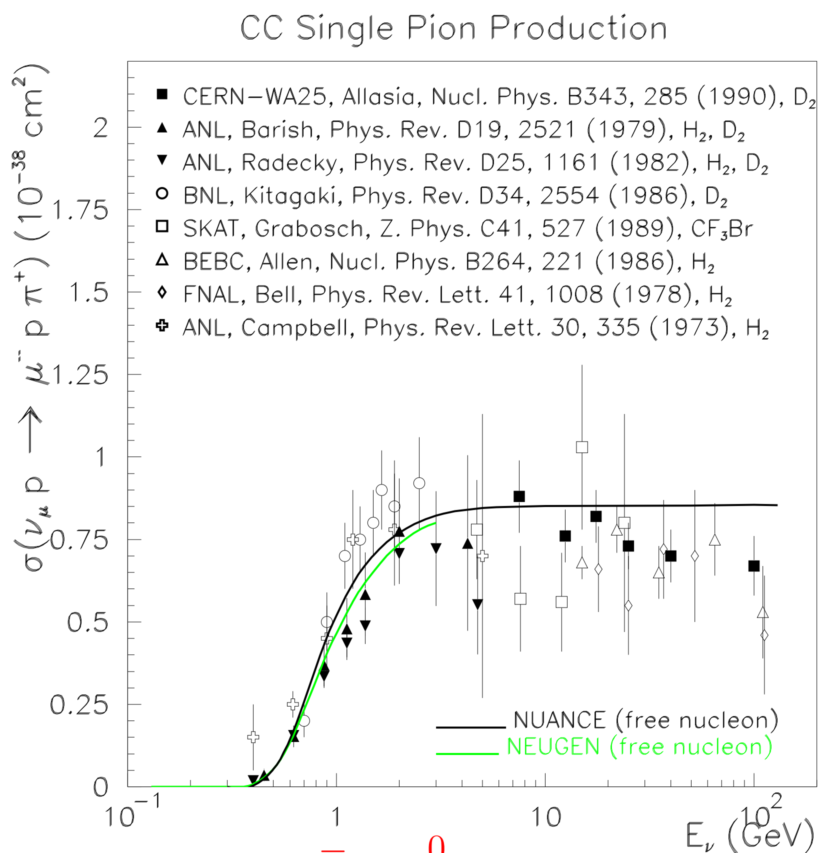
- 7 possible channels (3 CC, 4 NC):

$$\begin{aligned} \nu_\mu p &\rightarrow \mu^- p \pi^+ \\ \nu_\mu n &\rightarrow \mu^- n \pi^+ \\ \nu_\mu n &\rightarrow \mu^- p \pi^0 \end{aligned} \qquad \begin{aligned} \nu_\mu p &\rightarrow \nu_\mu n \pi^+ \\ \nu_\mu p &\rightarrow \nu_\mu p \pi^0 \\ \nu_\mu n &\rightarrow \nu_\mu n \pi^0 \\ \nu_\mu n &\rightarrow \nu_\mu p \pi^- \end{aligned}$$

- Main contribution is from $\Delta(1232)$ (but others can contribute)
- ν Monte Carlos covering this kinematic region have been using early theoretical predictions by Rein–Sehgal
  Rein and Sehgal, Annals Phys 133, 79 (1981)
- Feynman, Kislinger, Ravndal model of baryon resonances (to account for higher mass resonant states)
  Feynman, Kislinger, Ravndal, Phys. Rev. **D3**, 2706 (1971)
- Contributions from 16–18 baryonic resonances (N^*, Δ)
- Recent calcs on nuclear effects (π absorption, CE)
  Paschos, Nucl. Phys. **B588**, 263 (2000)

Quality and quantity of data varies ...

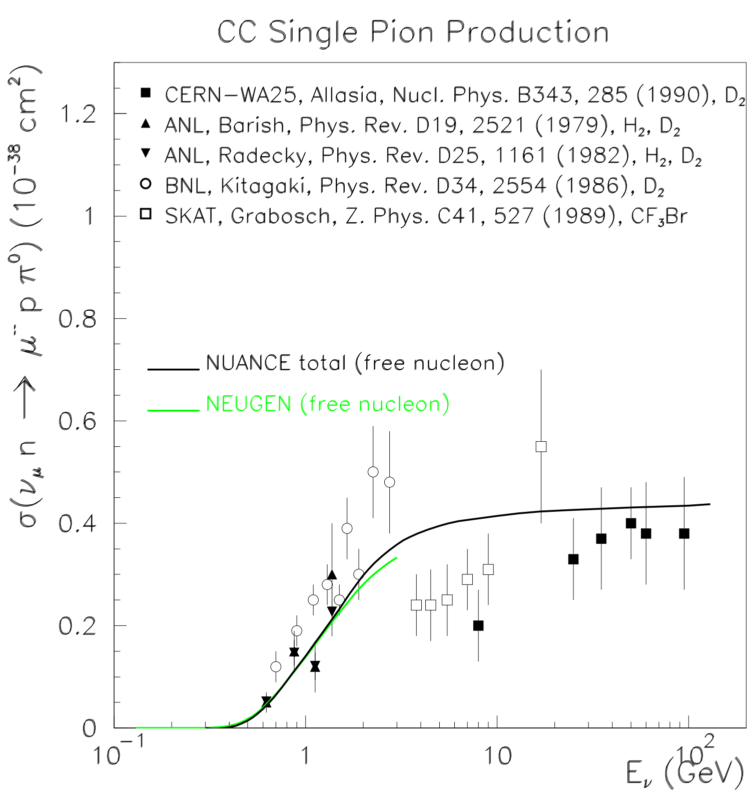
CC Single Pion Production

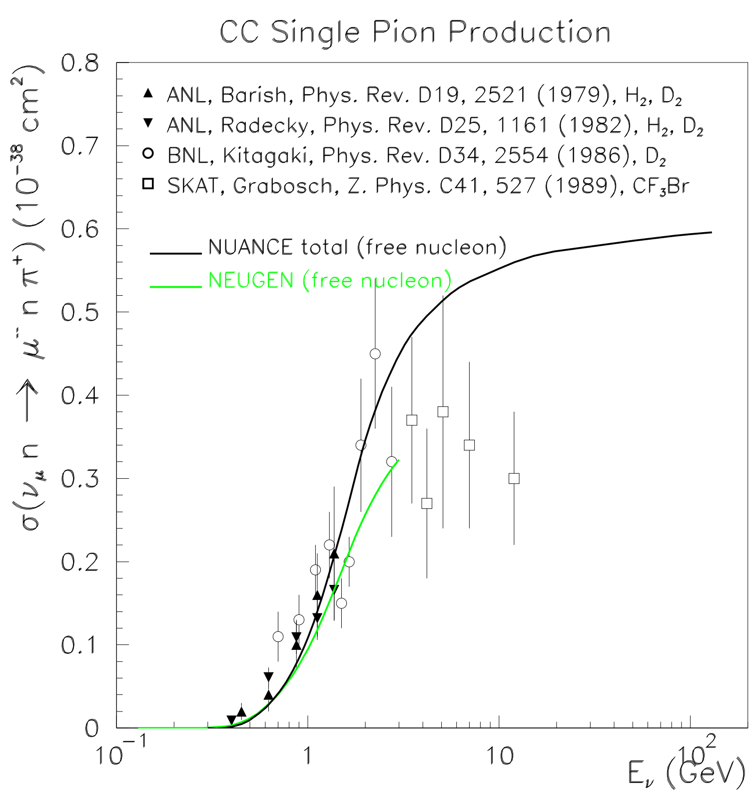


$\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$

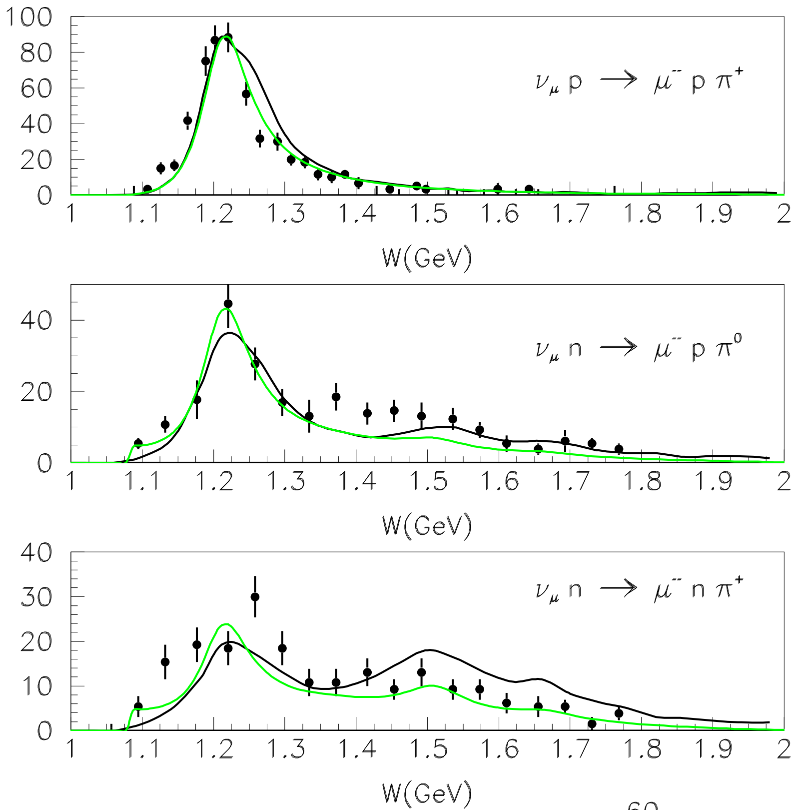
$\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$

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

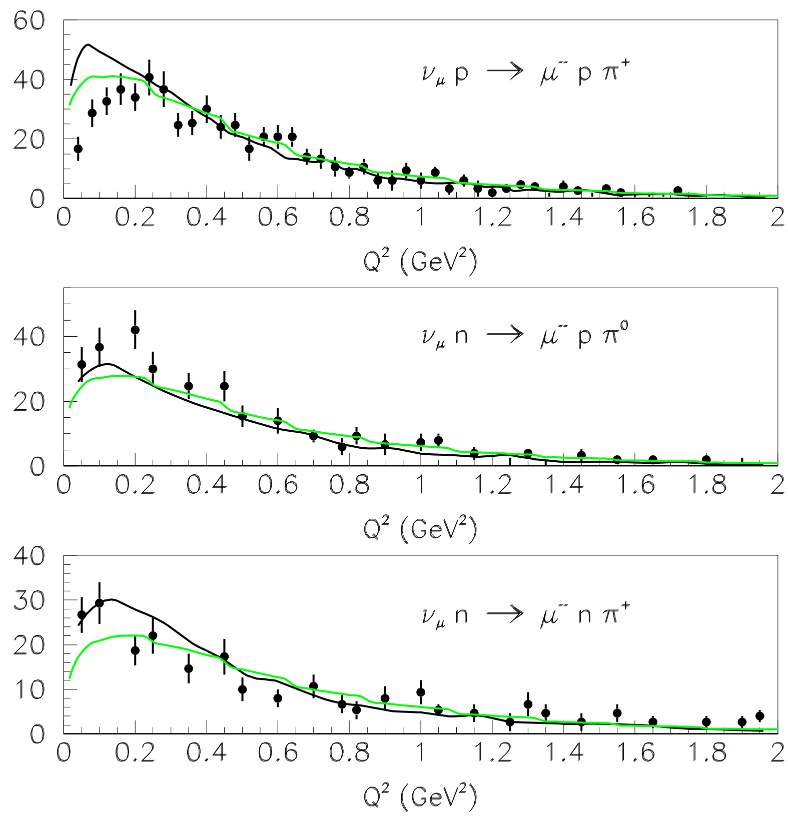




Resonance Production



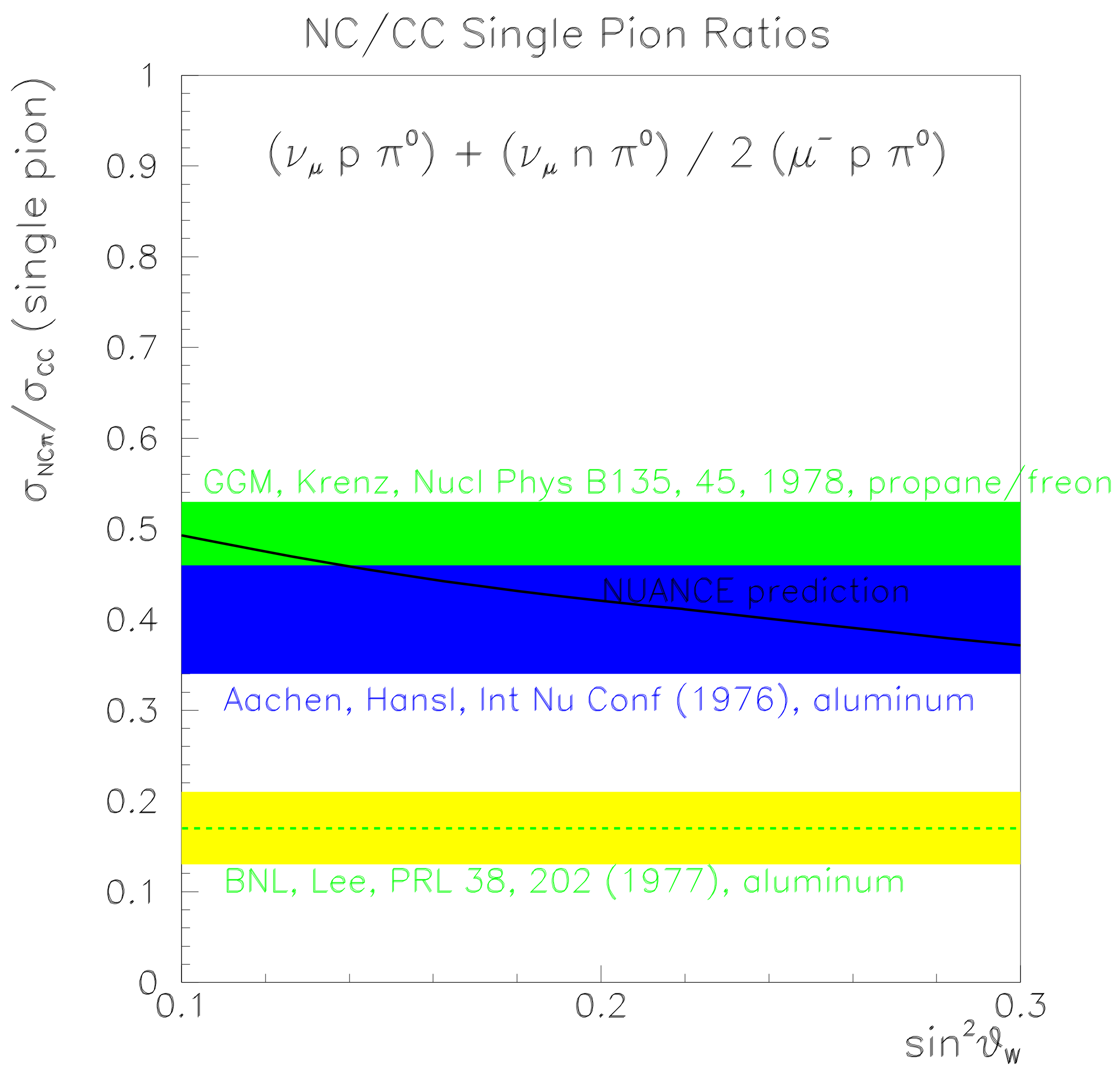
Just showed some rate comparisons, have also performed kinematic comparisons to BNL CC 1π (D_2) data:



NUANCE
vs. **NEUGEN**
(agreement is generally reasonable)

NC Single Pion Production

- NC amplitudes obtained by simply rescaling form factors by terms depending on $\sin^2\theta_W$
- Most of available data on NC single π production exists in the form of NC/CC cross section ratios
- NC single π data more sketchy than CC case

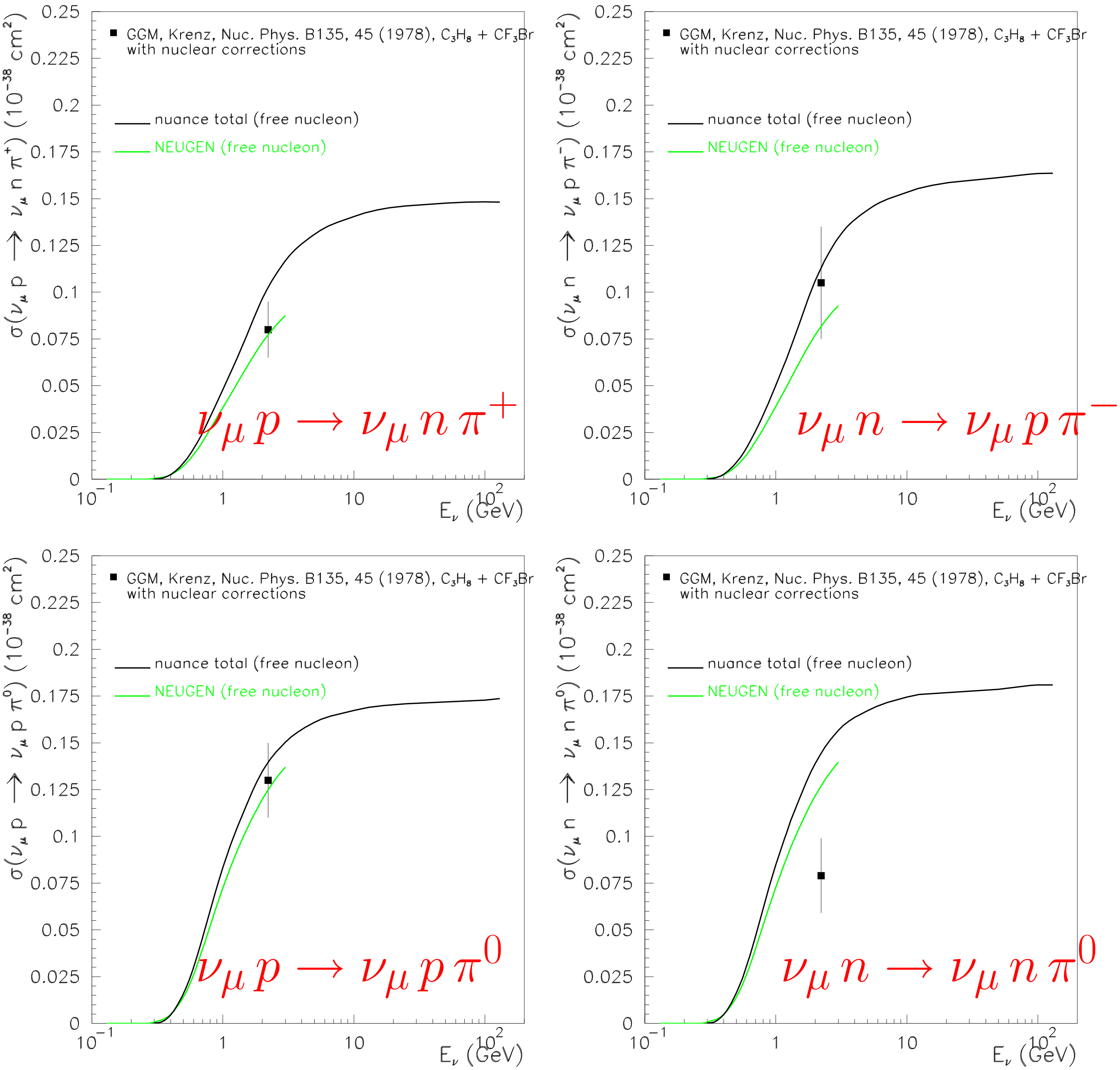


In some cases, measurements can differ by factors 2–3 (experiments needed to understand neutron backgrounds)

Absolute NC 1π Cross Sections

- re–analysis of Gargamelle 1970's bubble chamber data
- using published Φ, σ at $< E_\nu >= 2.2$ GeV

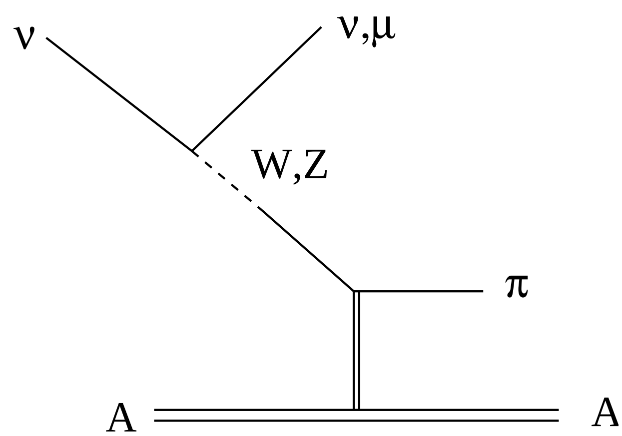
(E. Hawker with help from Morfin, Pohl - shown at NuInt02)



New data from K2K, MiniBooNE can certainly help!

Coherent Pion Production

- Scatter from entire nucleus rather than from its individual constituents



- Both NC and CC processes possible:

  $\nu_\mu\, A \rightarrow \nu_\mu\, A\, \pi^0$
  $\nu_\mu\, A \rightarrow \mu^-\, A\, \pi^+$

- Distinct kinematics

  $\hookrightarrow$ negligible energy transfer to the target (low Q^2)

  $\hookrightarrow$ forward scattered π

- Kinematics well known, but overall rate less certain (exps typically assign a 100% uncertainty)

- Theoretical model based on Adler's PCAC theorem $\sigma(\nu A) \propto \sigma(\pi A)$ as $Q^2 \rightarrow 0$

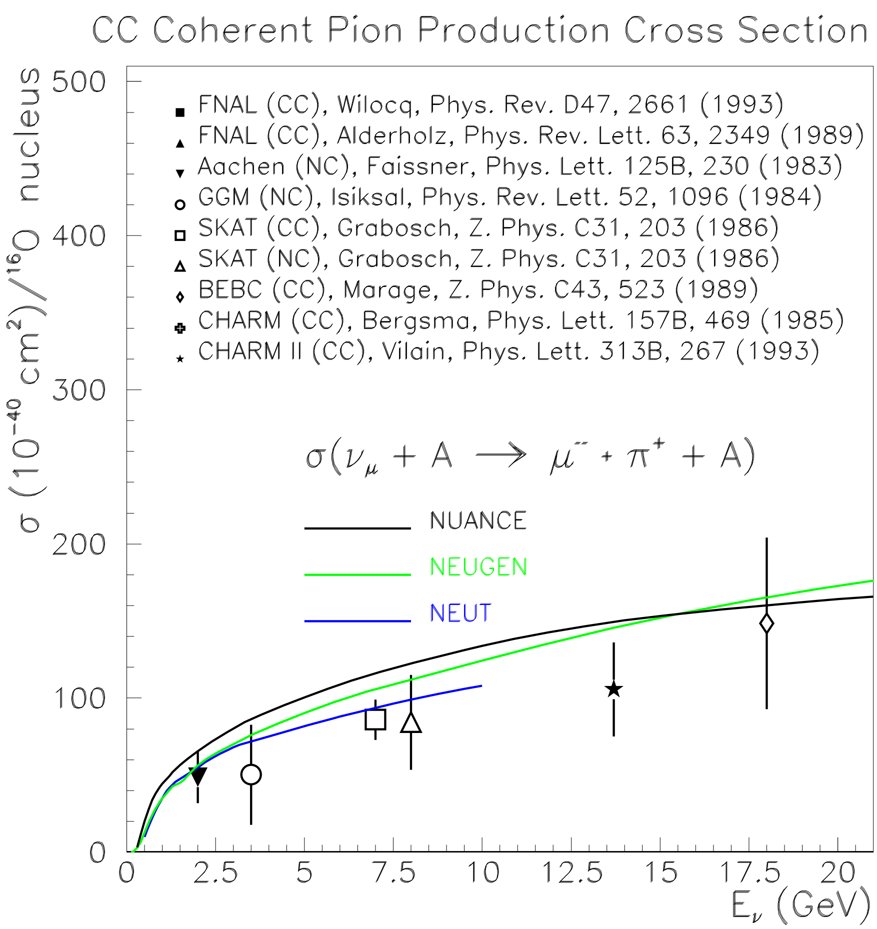
$$\frac{d^3\sigma}{dQ^2 d\nu dt}(\nu A, Q^2 = 0) = \frac{G_F^2}{2\pi^2 \nu} \cdot \frac{E_\mu}{E_\nu} \cdot f_\pi^2 \cdot \frac{d\sigma}{dt}(\pi A)$$

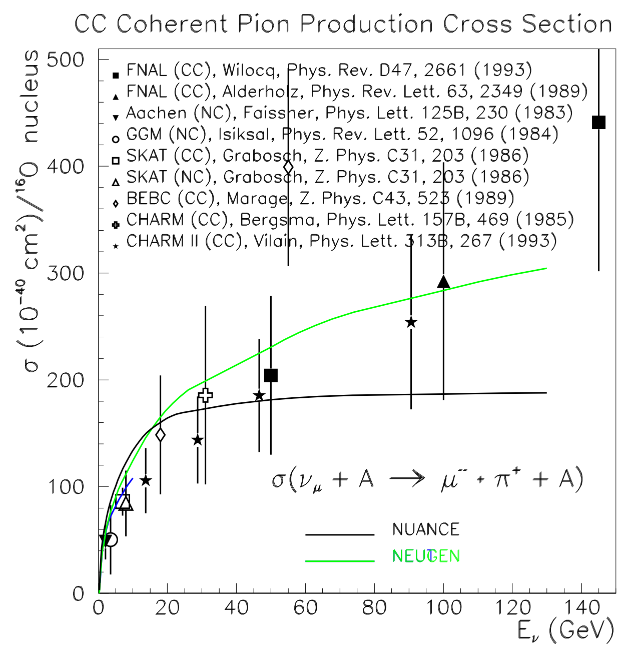
- Extrapolation to $Q^2 \neq 0$ through propagator term: Rein-Sehgal, Nucl. Phys. B223, 29 (1983)

$$\frac{d^3\sigma}{dQ^2 d\nu dt} \cdot \left(\frac{M_A^2}{M_A^2 + Q^2}\right)^2, \; M_A \sim 1 - 1.35\,\mathrm{GeV}$$

Coherent Pion Production

- Shown are NC, CC data off variety of nuclear targets (to allow comparison between exps, assume $A^{\frac{1}{3}}$ scaling)





- Lowest energy data is at 2 GeV off Al target
- Possible to measure at K2K 1kton and at MiniBooNE? $< E_\nu > \sim 1$ GeV

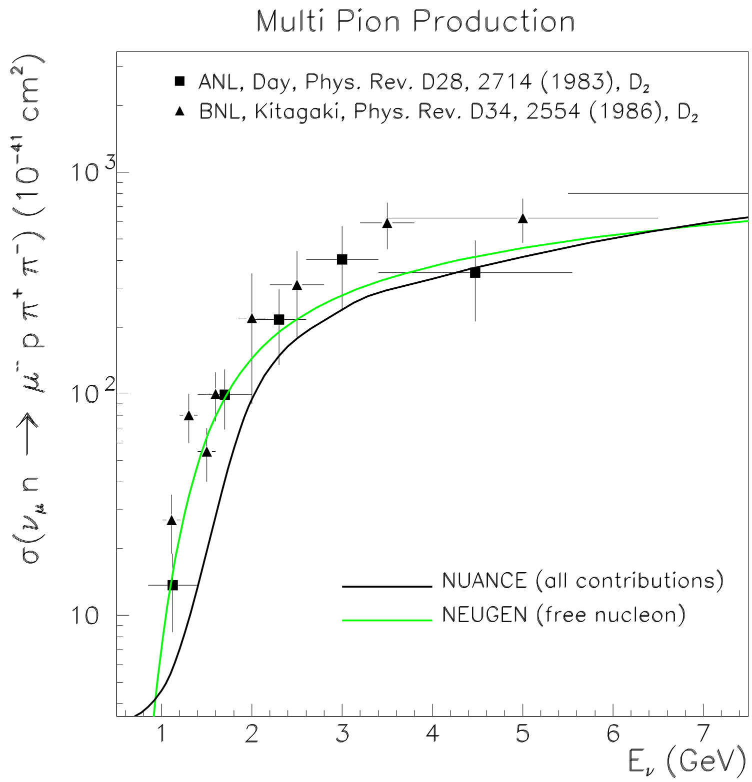
  $\hookrightarrow$ important since $\sim 20\%$ of single π^0 rate

  $\hookrightarrow$ impacts limits on osc of standard ν's to sterile states

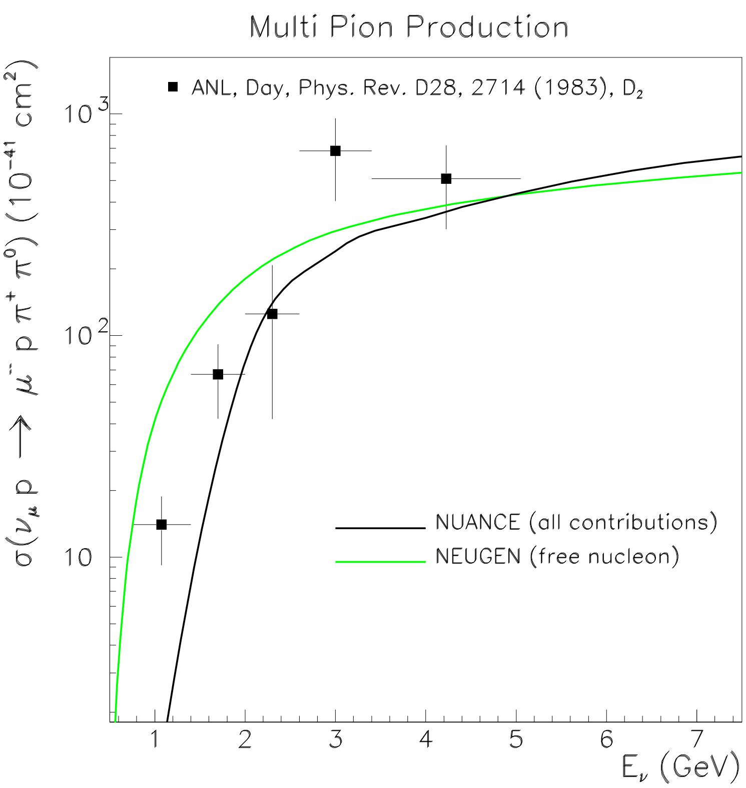
Multi Pion Production

Large 40%-ish uncertainties on dipion production data at $E_\nu \sim 1$ GeV:

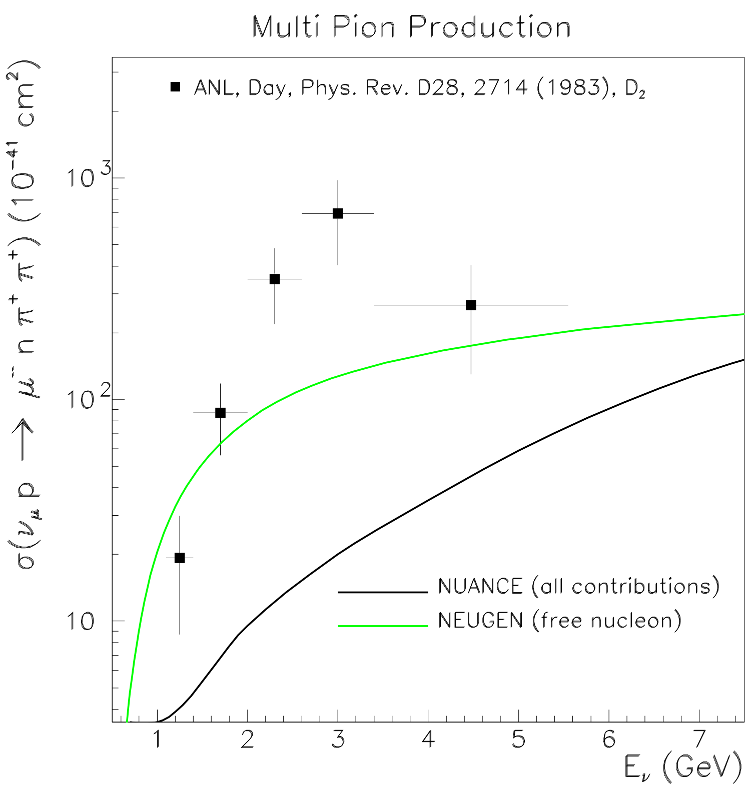
$$\nu_\mu n \rightarrow \mu^- p \pi^+ \pi^-$$



$$\nu_\mu p \rightarrow \mu^- p \pi^+ \pi^0$$



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



Single Kaon Production

- Atmospheric ν's pose an important background for nucleon decay searches

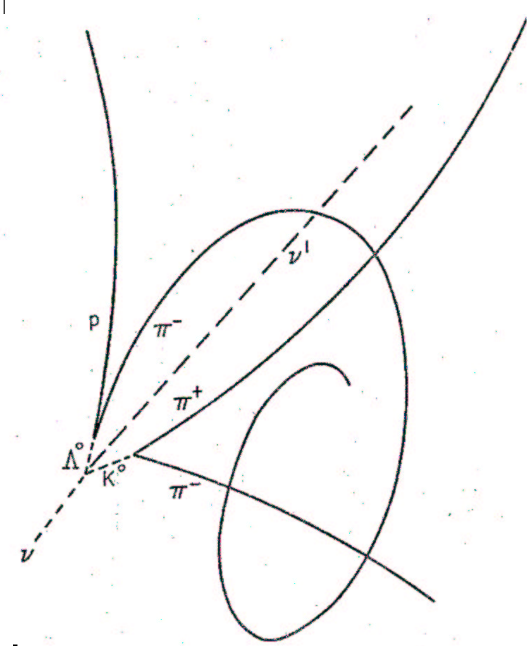
$$p \rightarrow K^+ \nu \quad \text{(preferred in SUSY GUTs)}$$

- Finite probability that a ν int can mimic a proton decay event, since > 800 MeV ν production of strange:

CC	NC
$\nu_\mu n \rightarrow \mu^- K^+ \Lambda^0$	$\nu_\mu p \rightarrow \nu_\mu K^+ \Lambda^0$
	$\nu_\mu n \rightarrow \nu_\mu K^0 \Lambda^0$
$\nu_\mu p \rightarrow \mu^- K^+ p$	
$\nu_\mu n \rightarrow \mu^- K^0 p$	
$\nu_\mu n \rightarrow \mu^- K^+ n$	
$\nu_\mu p \rightarrow \mu^- K^+ \Sigma^+$	$\nu_\mu p \rightarrow \nu_\mu K^+ \Sigma^0$
$\nu_\mu n \rightarrow \mu^- K^+ \Sigma^0$	$\nu_\mu p \rightarrow \nu_\mu K^0 \Sigma^+$
$\nu_\mu n \rightarrow \mu^- K^0 \Sigma^+$	$\nu_\mu n \rightarrow \nu_\mu K^0 \Sigma^0$
	$\nu_\mu n \rightarrow \nu_\mu K^+ \Sigma^-$

$\Rightarrow$ important to reliably estimate this background

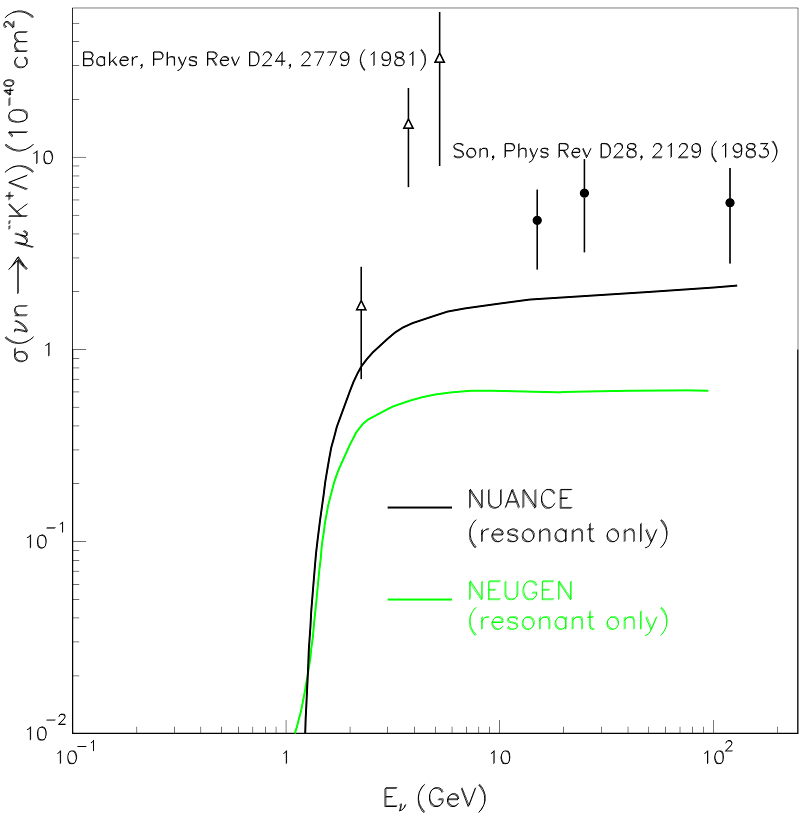
- Little experimental data - most from bubble chambers where strange particle decays easily observed
- Few theoretical models: (not very predictive)
  - $\hookrightarrow$ R. Shrock, Phys. Rev. **D12**, 2049 (1975)
  - $\hookrightarrow$ A. A. Amer, Phys. Rev. **D18**, 2290 (1978)



$\nu_\mu n \rightarrow \mu^- K^+ \Lambda^0$ dominant channel at low energies (and hence the limiting background)

CC Associated Production of $K^+\Lambda$

$$\nu_\mu\, n \to \mu^-\, K^+\, \Lambda$$



Experimental measurements based on handfuls of events

- BNL 7ft, D_2, 8 evts
- FNAL 15ft, D_2, 21 evts

Data on these reactions is scarce particularly at E's near threshold which are relevant for proton decay searches

- Models use same framework as single π (Rein–Sehgal) (add additional resonance decays other than $N\pi$)
- Ability to measure strange production rates in ν ints will play important role in helping p decay exps reach their ultimate sensitivity

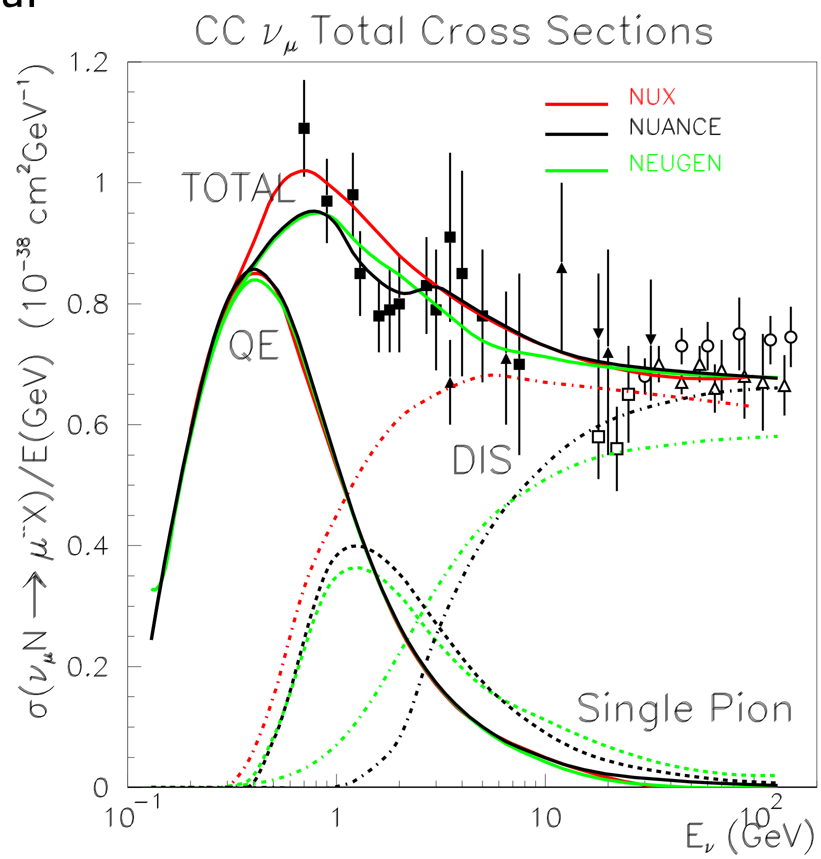
$\hookrightarrow$ Measure at MiniBooNE (expect 100's of events)

$\hookrightarrow$ Plans to measure using K2K new near detector (SciBar)

Total CC ν Cross Sections

Monte Carlos models can differ in how sum various σ contributions to form total

- quasi–elastic scattering
- CC single pion
- NC single pion
- coherent pion
- dipion channels
- associated strangeness production
- total cross sections →



Model comparisons have turned up interesting differences

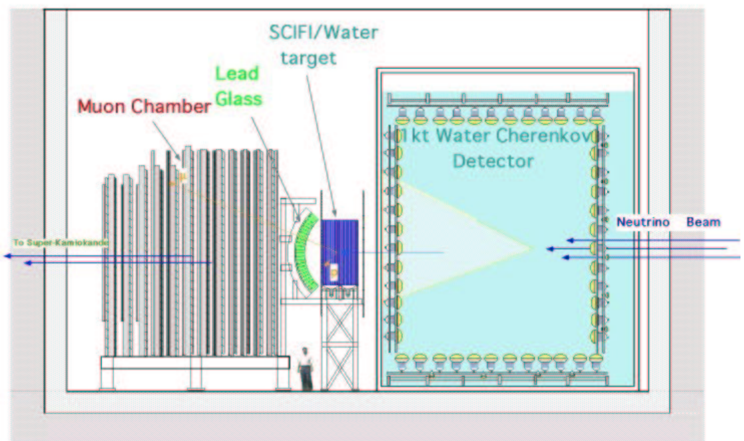
ν Cross Section Score Card

Cross Section	Present Knowledge	ν Data	Theor. Models
DIS	Excellent ★★★★	many exps	parton model
Quasi–Elastic	Good ★★★	bc	form factors
Resonant 1π	Fair ★★	bc	Rein–Sehgal
Coherent π	Poor (low E) ★1/2	bc, counter	several
Combining σ's	Poor ★	little	several +
Nuclear Targets	Poor ★1/2	very limited	variety

Present Experimental Handles

Will this situation be improved in the near future?

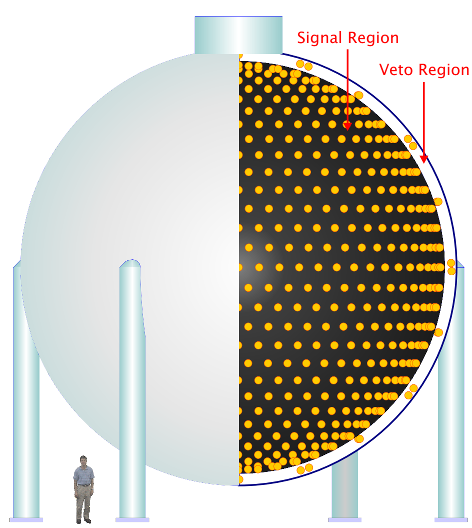
- K2K near detector: H_2O Čerenkov, SciFi, MRD
  - ↪ started taking data June '99
  - ↪ $< E_\nu >\sim 1.3$ GeV, 12 GeV p from KEK



  - ↪ NC π^0 yield in H_2O Č
  - ↪ non–QE/QE ratio in FGD
  - ↪ new SciBar
  - ↪ M. Shiozawa plenary 6/5

- MiniBooNE: CH_2 Čerenkov
  - ↪ started taking data late Aug '02
  - ↪ $< E_\nu >\sim 1$ GeV, 8 GeV p from FNAL Booster
  - ↪ 100,000 ν events collected ($\sim 10\%$ of total data sample)
  - ↪ first physics results this Fall (NC π^0, QE, NC elastic)
  - ↪ B. Louis and C. Moore talks

MiniBooNE Detector

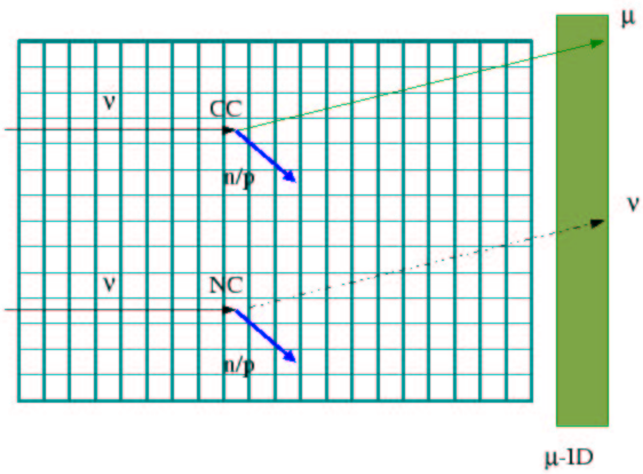


Both data sets putting present Monte Carlo models to the test

Future Experimental Handles

Future proposals for fully active, highly segmented ν detectors

- FINeSE - FNAL Booster beamline



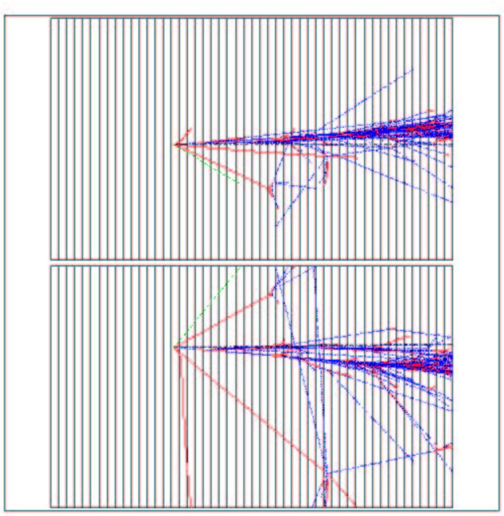
↪ same ν source as MiniBooNE $< E_\nu > \sim 1$ GeV

↪ Δs, precise measurements of NC, CC σ_ν (10–100k samples)

↪ EOI submitted to FNAL PAC Nov 2002 (B. Fleming, R. Tayloe)

↪ (R. Tayloe talk in WG2 6/9)

- MINerVA - FNAL NuMI beamline



↪ precision σ measurements (high stats, $\sim 3\%$ flux syst)

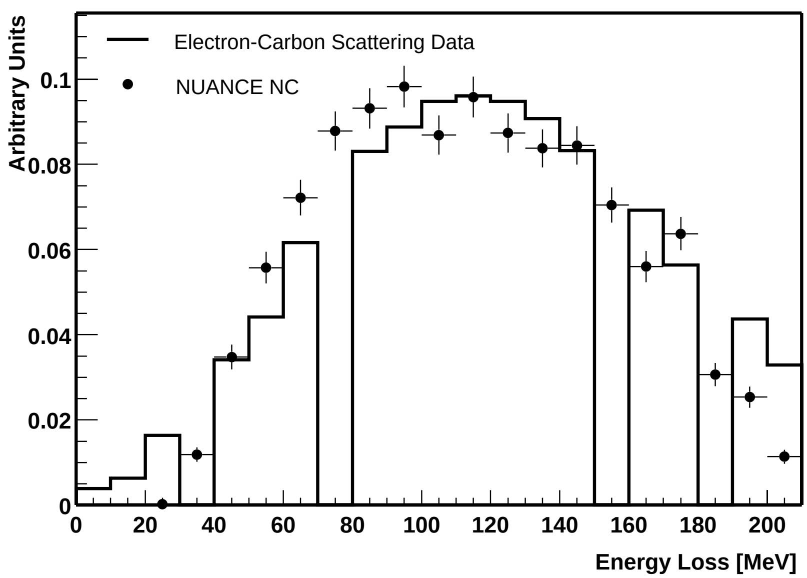
↪ selection of nuclear targets $\Rightarrow$ study of nuclear effects w/ ν's

↪ EOI submitted to FNAL PAC Nov 2002 (K. McFarland, J. Morfin)

See K. McFarland's talk later in this session ...

Testing ν Cross Section Models

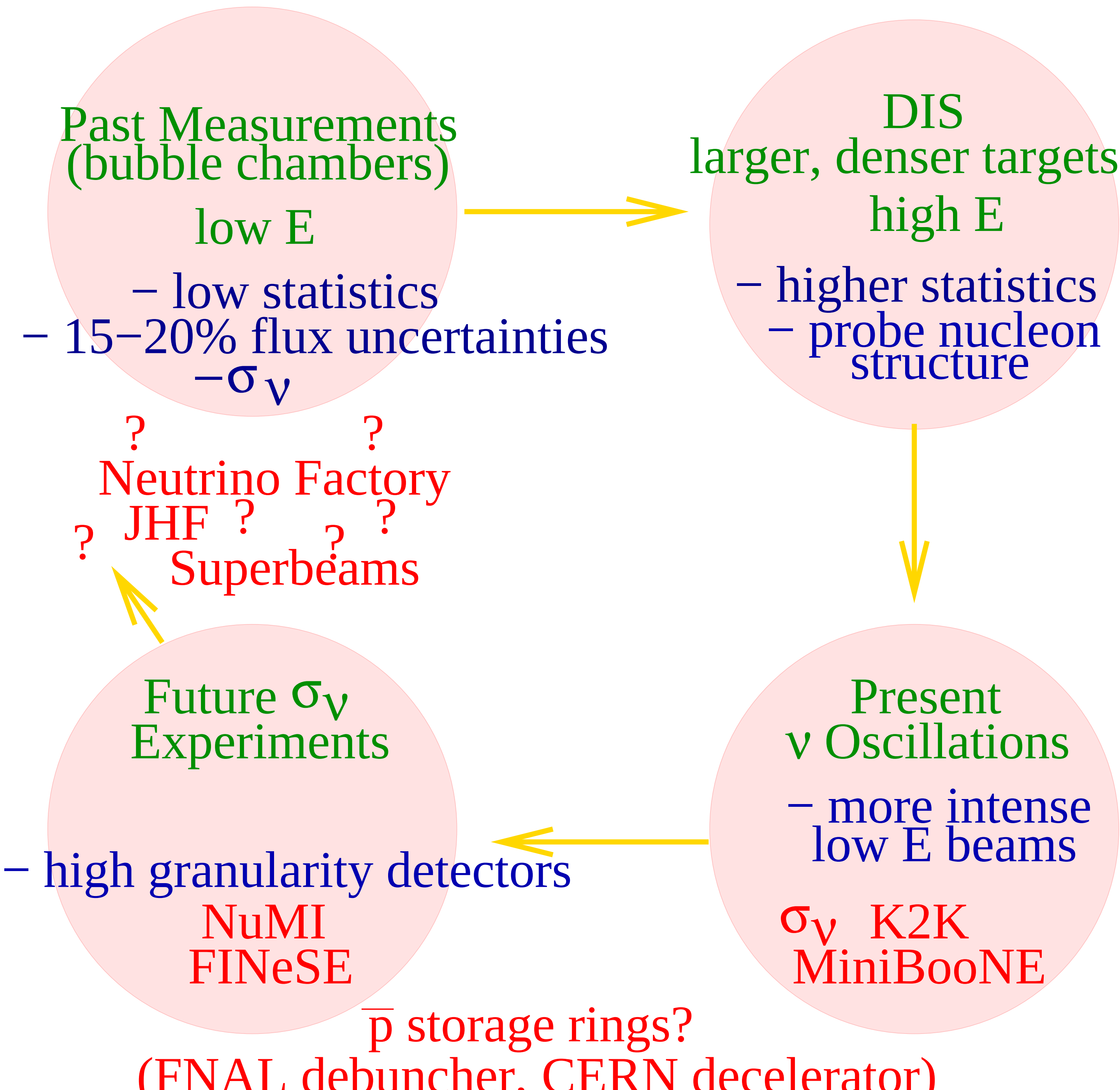
- compare against previous ν measurements ...
  re–analyze old ν data
  - $\hookrightarrow$ NC 1π absolute σ's
  - $\hookrightarrow$ new M_A fits to QE, 1π
- ν–nucleus models can be tested against (more precise)
  e^- scattering data
  - $\hookrightarrow$ can gain valuable information from (e, e') scattering
  - $\hookrightarrow$ high statistics e^- data exists on a variety of relevant targets (C^{12}, O^{16}, etc.)
  - $\hookrightarrow$ can gain insight into meeting of QE, RES regions
  - $\hookrightarrow$ checks Fermi gas model parameters (E_B, p_F)



O'Connell, PRL **53**, 1627 (1984), 730 MeV e^- on ^{12}C, 37.1°

See talk by Chris Walter next ...

Where We've Been and Where We We're Headed



Stay Up to Date on Low E Neutrino Interaction Progress

- NuInt workshops!

  $\hookrightarrow$ brings together nuclear and particle physicists to discuss issues related to our understanding of low E neutrino cross sections

  $\hookrightarrow$ best way to stay in tune

NuInt02 - U. California Irvine (Dec 2002)
Second International Workshop on Neutrino–Nucleus Interactions in the Few–GeV Region

Conclusions

- Interest in low E ν processes has increased following compelling indications of neutrino oscillations
- Several new experiments are now being planned or under construction aimed at determining oscillation parameters with high precision

  $\hookrightarrow$ will be even more sensitive to sources of systematic uncertainties

  $\hookrightarrow$ among them: σ_ν, nuclear effects, FSI
- Although we have been using accelerator based ν beams for over 30 years there is still a surprisingly large amount we don't know about ν interactions at low energy

  $\hookrightarrow$ lack of high statistics low energy ν data

  - $\star$ results often conflicting
  - $\star$ little ν data on nuclear targets
  - $\star$ still valuable, but situation could be improved
- Lack of understanding may haunt next generation exps
- Look forward to improved σ_ν measurements (K2K, MiniBooNE,...,FINeSE, MINerVA,..., ν Factory)

... to help ν oscillation experiments reach their maximum discovery potential ...