Status of Neutrino Cross Sections

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<u>Outline:</u>

- motivation: why need to know low E ν cross sections
- review current knowledge of low energy ν interactions
  - $\hookrightarrow$ past: bubble chamber experiments
  - $\hookrightarrow$ present: K2K, MiniBooNE
  - $\hookrightarrow$ future: MINERvA, FINeSSE
- what are the gaps that need to be filled in?
  (gaps which ν osc exps will have to confront to achieve max sensitivity)
- what could a proton driver add to this?

Why Measure Low Energy ν Cross Sections?

- because they're interesting
- because we need them as input to our neutrino oscillation experiments $\rightarrow$

Jim Cronin: "if you can measure something 10 times better, you should just do it" (B. Bernstein)

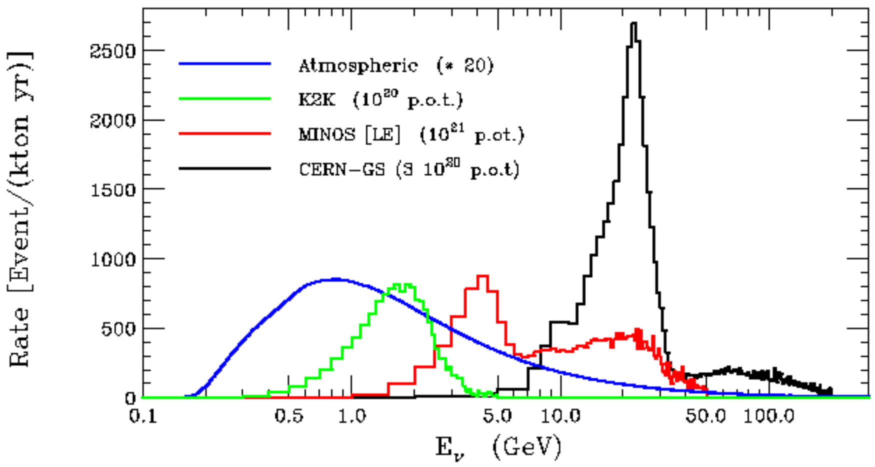
Why Need to Know Low E ν σ's?

understanding ν interactions is a critical piece of ν osc exps

- Atmospheric Neutrinos
  - $\hookrightarrow$ Δm^2_{23}, θ_{23} limited by systematics on flux, σ_ν
  - $\hookrightarrow$ $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$ limited by σ_ν uncertainties
- Proton Decay Searches
  - $\hookrightarrow$ good knowledge of σ_ν required to reliably evaluate expected backgrounds
- Disappearance Experiments ($\nu_\mu \to \nu_\mu$)
  - $\hookrightarrow$ measure shape of survival probability as fcn E
  - $\hookrightarrow$ need to know background σ's for precise E reconstruction & shape can be biased by uncertainties in model (nuclear effects, FSI, etc.)
- Appearance Experiments ($\nu_\mu \to \nu_e$), θ_{13}
  - $\hookrightarrow$ limited by stat & syst unc of background subtraction
  - $\hookrightarrow$ intrinsic ν_e component in the beam
  - $\hookrightarrow$ misidentified NC π^0 production

    (not only understand rate but contrib from diff channels)
    - $\star$ resonant single π^0 production σ's
    - $\star$ coherent π^0 production σ
- future experiments aiming at precise determination of ν oscillation parameters will have even more stringent requirements on control of ν cross sections

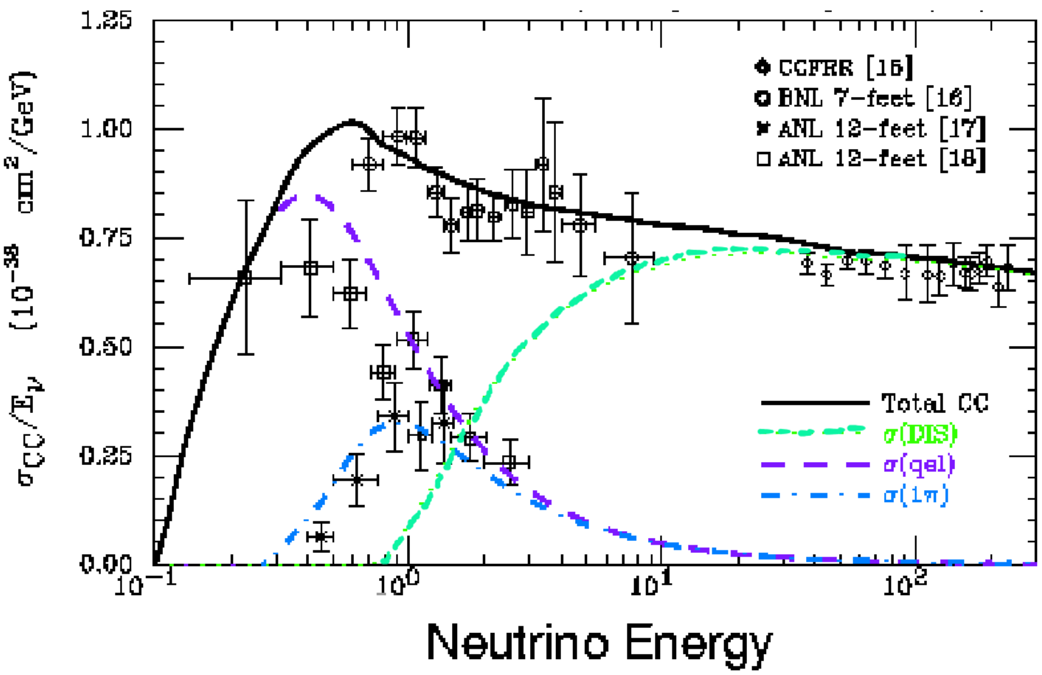
Status of Low E ν Cross Sections



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 $\rightarrow$ 100's GeV)

scattering off entire nucleon $\longrightarrow$



$\longleftarrow$ scattering off constituents in nucleon

Principal reactions:

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

No consensus on best way to combine channels at fixed E_ν

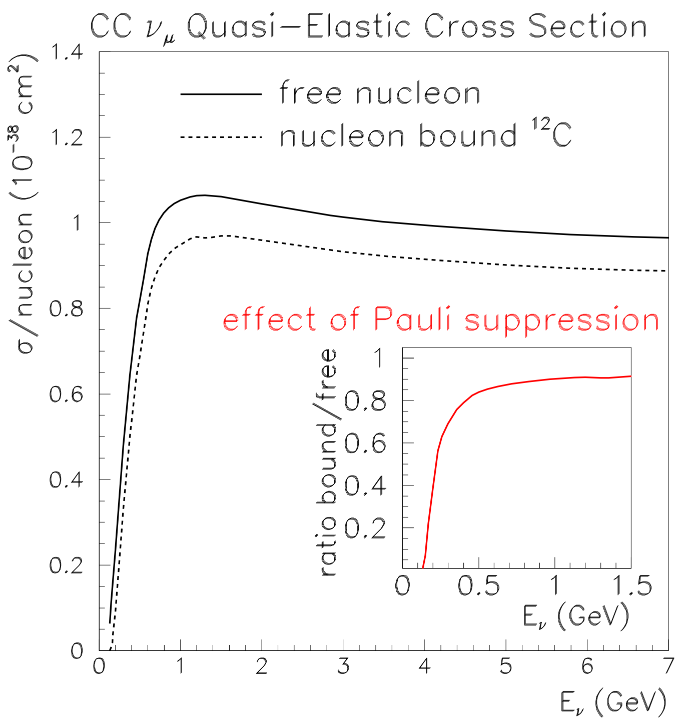
Nuclear Effects

Oscillation experiments measure ν reactions on nuclear targets ($O^{16}, C^{12}, Ar^{40}, Fe^{56}$, ...)

$\Rightarrow$ complicates description of ν reactions ...

- Pauli suppression and fermi motion

- Final state interactions (much larger and have not been disentangled exp'ly)
  - $\hookrightarrow$ nuclear reinteractions
  - $\hookrightarrow$ π absorption
  - $\hookrightarrow$ charge exchange



- nuclear effects impact kinematics/rates of various ν interactions as well as observed final states

- nuclear effects studied extensively in μ, e^- DIS, but have only been glanced at over a limited kinematic range in early low statistics ν exps
  - $\hookrightarrow$ Gargamelle, SKAT (C_3H_8 CF_3Br)
  - $\hookrightarrow$ FNAL (Ne)
  - $\hookrightarrow$ Serpukov (Al spark chamber)
  - $\hookrightarrow$ CHARM, CHARM II (marble, glass)

- high intensity ν beams made possible w/ proton driver could offer possibility for advanced study of nuclear structure (collect large stats on variety of target materials)

Modeling Low E ν Cross Sections

many complex effects must be taken into account through detailed interaction models (Monte Carlos)

- recent neutrino experiments using a variety of Monte Carlos (many have long histories)
  - $\hookrightarrow$ `NUANCE` (IMB, K2K, Super-K, MiniBooNE)
  - $\hookrightarrow$ `NEUT` (Kamiokande, K2K, Super-K)
  - $\hookrightarrow$ `NEUGEN` (Soudan 2, MINOS, MINERvA)
  - $\hookrightarrow$ `NUX,GENEVE` (Icarus, NOMAD)
  - $\hookrightarrow$ `JETTA,RESQUE` (CHORUS, OPERA)
- share common theoretical inputs
- but nontrivial differences
  - $\hookrightarrow$ treatment of nuclear and FSI effects
  - $\hookrightarrow$ joining of resonance and DIS regions
- in general, little ν data to constrain various model choices; what data do we have? $\rightarrow$

Currently Existing Data

Our present low E ν cross section knowledge comes from:

- bubble chamber experiments (70's-80's)
  old data is sketchy

more recently, new data is on the way
(already have order of magnitude more ν data than bubble chambers)

- K2K near detector data
- MiniBooNE data

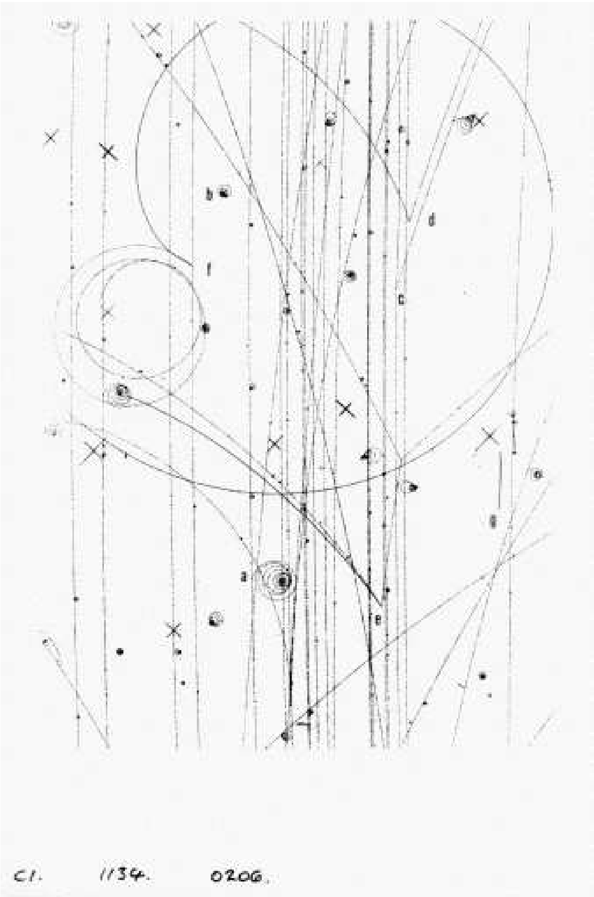
but still lots of room to contribute!

- MINERvA, FINeSSE
- $+$ proton driver?

Early Bubble Chamber Measurements

- low E ($\sim 1 - 10$ GeV) σ_ν measurements come mainly bubble chamber experiments
- early experiments at ANL, BNL, CERN, and FNAL

Gargamelle at CERN



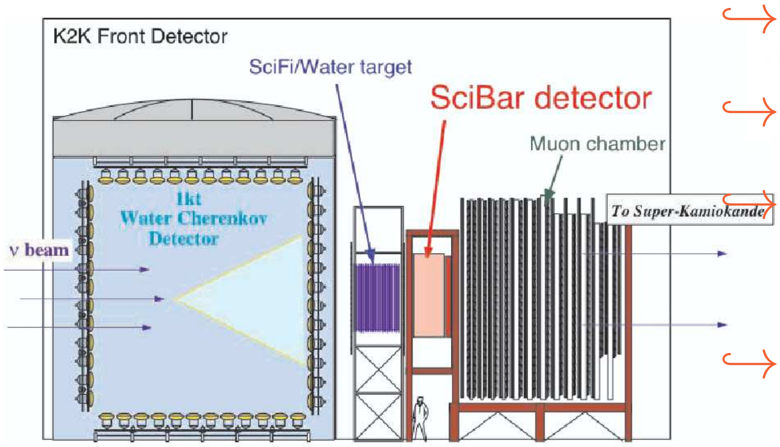
- simplest exclusive states measured
- considerable errors due to:
  - ↪ low statistics
  - ↪ imprecise knowledge of incoming ν flux
- in addition to large errors, results are often conflicting
- even ignored by PDG (σ_ν removed after 1996)

Contrast: in 30–200 GeV range, high statistics DIS data from variety of experiments (NuTeV, CCFR, CHARM, CDHS)

Present Experimental Handles

this situation already being improved ...

- K2K near detector: H_2O Čerenkov, SciFi, MRD



↪ started taking data June '99

↪ $< E_\nu > \sim 1.3$ GeV

↪ $\sim$ **100,000 evts collected** ($\sim 1/2$ of total data sample)

↪ NC π^0 yield in H_2O Č (hep-ex/0408134)

↪ QE, non-QE in all 3 detectors

↪ **high resolution detectors**

- MiniBooNE: CH_2 Čerenkov

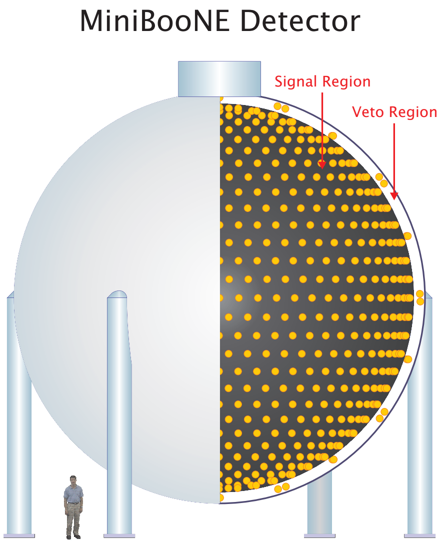
↪ started taking data late Aug '02

↪ $< E_\nu > \sim 0.8$ GeV

↪ $>$ **300,000 evts collected** ($\sim 25\%$ of total data sample)

↪ NC π^0, QE, NC elastic, CC π^+

↪ **higher statistics**



both data sets putting present Monte Carlo models to the test

Evaluating Present Knowledge

- how adequate is our current understanding of low energy neutrino interaction?

- review the status of present measurements of σ_ν at $E_\nu \sim 1$ GeV:

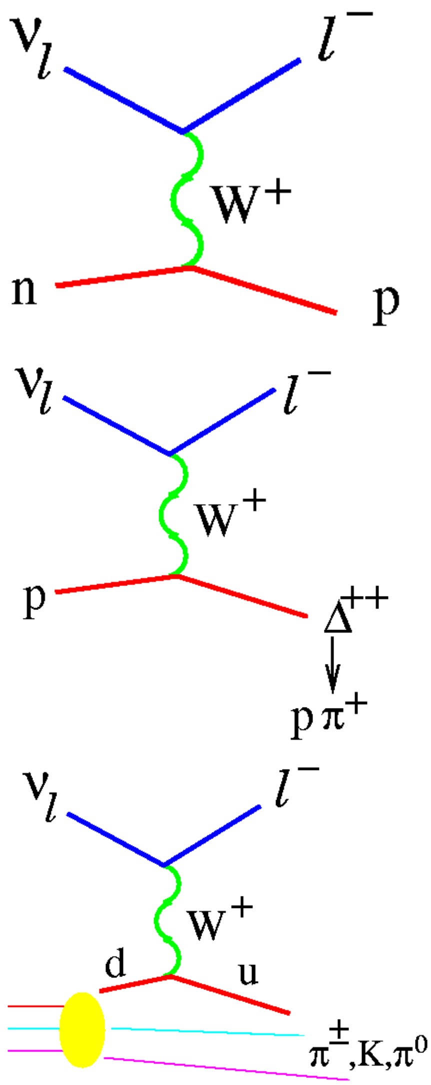
$\hookrightarrow$ Quasi–elastic scattering

$\hookrightarrow$ Resonance production (CC and NC single 1π)
(becomes comparable to QE ~ 2 GeV)

$\hookrightarrow$ Coherent π production

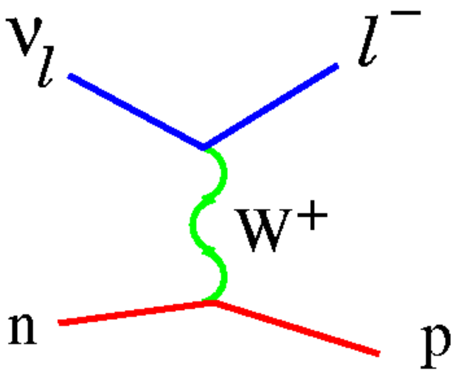
$\hookrightarrow$ Multi π production
(small σ but can feed down)

$\hookrightarrow$ ν production of strange particles



Quasi Elastic Scattering

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



- lowest energies are most relevant to ν oscillation experiments
- at these energies, quasi-elastic (QE) scattering dominates the ν interaction rates
- most well known cross section at low energy (both experimentally and theoretically)

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

$$< N'|J_\mu|N > \; = \; \overline{u}(N')\left[\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu\xi F_V^2(q^2)}{2M} + \gamma_5\gamma_\mu F_A(q^2)\right]u(N)$$

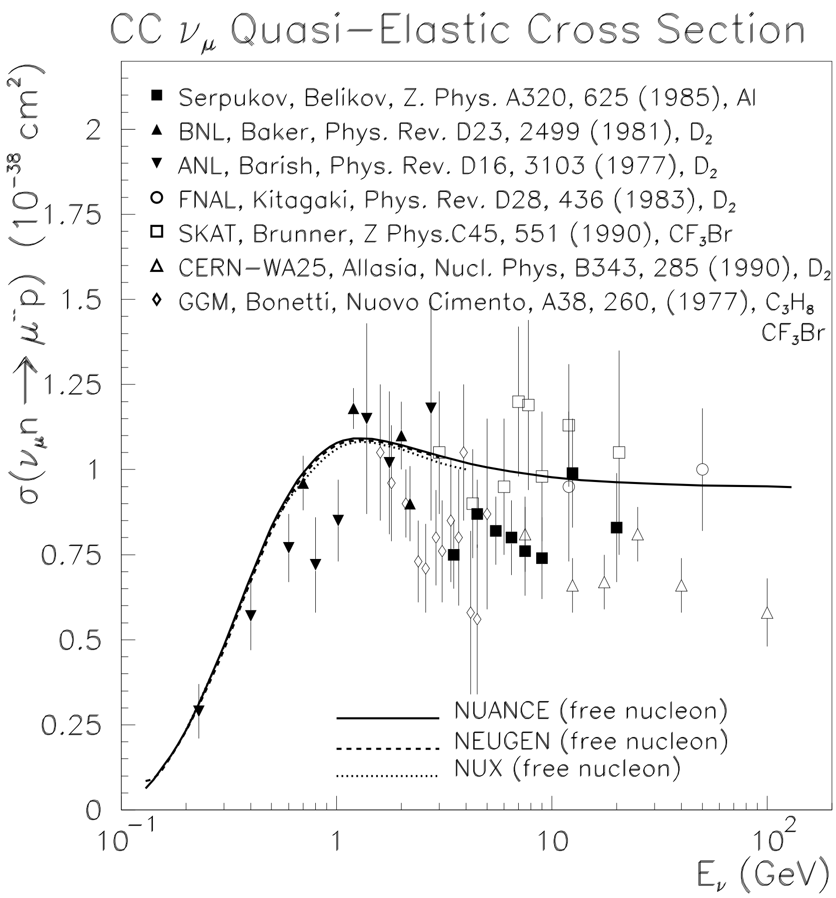
$$F_V(q^2) \sim \frac{1}{(1-q^2/M_V^2)^2} \qquad F_A(q^2) = \frac{F_A(0)}{(1-q^2/M_A^2)^2}$$

- form factors depend on M_V, $F_A(0)$, M_A
- $+$ nuclear effects (most osc exps use Fermi gas models)

Quasi-Elastic Cross Section

existing QE σ measurements were made ~ 20 years ago

- considered the "well-measured" reaction
- dominated by large $15-20\%$ flux uncertainties
  (considerable spread in the QE σ data for any given E_ν)
- less well known in important threshold region and for antineutrinos (more on $\overline{\nu}$ later)



- data below 1 GeV is all on light targets (D_2)
- $\leftarrow$ highest stats: ~ 2500 events

Basis of Existing QE σ Knowledge

$< E_\nu >$	Exp	Mode	Target	Year	# QE events
0.7 GeV	ANL	ν	D_2	1973	166
0.5 GeV	ANL	ν	D_2	1977	600
2 GeV	CERN	ν	C_3H_8	1979	26
2 GeV	GGM	ν	C_3H_8	1979	622
0.5 GeV	ANL	ν	D_2	1981	1737
1.6 GeV	BNL	ν	D_2	1981	1138
5-200 GeV	FNAL	ν	D_2	1983	362
6-7 GeV	SKAT	ν	CF_3Br	1988	464
9 GeV	SKAT	ν	CF_3Br	1990	540
54 GeV	BEBC	ν	D_2	1990	552
1.6 GeV	FNAL	ν	D_2	1990	2538
5-7 GeV	SKAT	ν	CF_3Br	1992	1465
2 GeV	GGM	$\overline{\nu}$	$C_3H_8CF_3Br$	1979	766
1.3 GeV	BNL	$\overline{\nu}$	H_2	1980	13
6 GeV	FNAL	$\overline{\nu}$	NeH_2	1984	405
6-7 GeV	SKAT	$\overline{\nu}$	CF_3Br	1988	52
9 GeV	SKAT	$\overline{\nu}$	CF_3Br	1990	159
5-7 GeV	SKAT	$\overline{\nu}$	CF_3Br	1992	256

- largest existing QE ν ($\overline{\nu}$) data sample is ~ 2500 (~ 800) events $\Rightarrow$ a lot of room for improvement!
- K2K & MiniBooNE have already collected an order of magnitude more ν QE events than previous low E bubble chambers ($>$ all combined!); all ν data, no $\overline{\nu}$

Neutrino Resonance Production

- in addition to elastic and QE interactions, there are excitation of resonances and their subsequent decays:

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

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

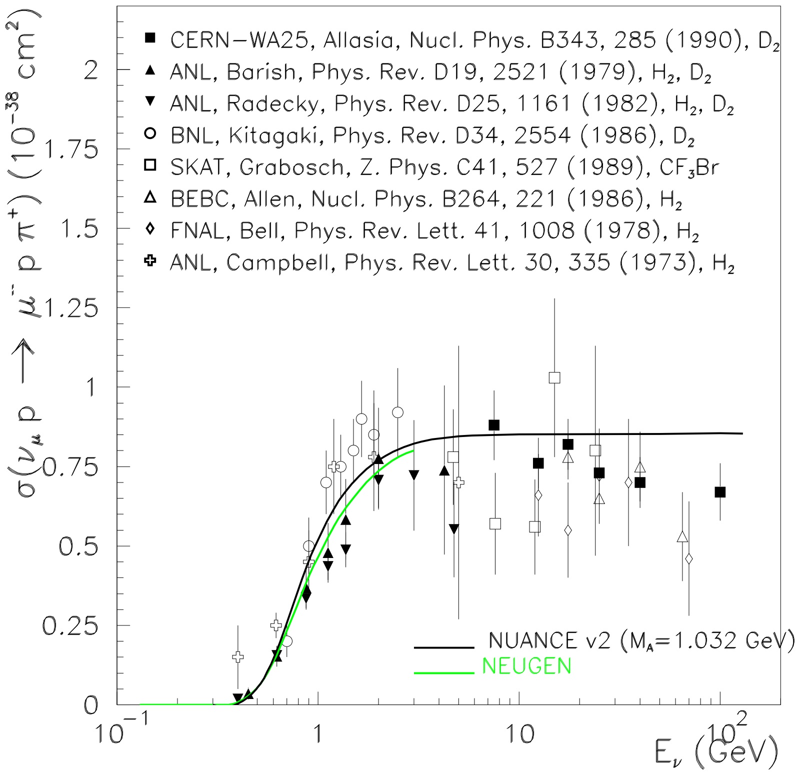
$$\begin{aligned} \nu_\mu p &\to \mu^- p \pi^+ \\ \nu_\mu n &\to \mu^- n \pi^+ \\ \nu_\mu n &\to \mu^- p \pi^0 \end{aligned} \qquad \begin{aligned} \nu_\mu p &\to \nu_\mu n \pi^+ \\ \nu_\mu p &\to \nu_\mu p \pi^0 \\ \nu_\mu n &\to \nu_\mu n \pi^0 \\ \nu_\mu n &\to \nu_\mu p \pi^- \end{aligned}$$

- main contribution is from $\Delta(1232) \to N\pi$

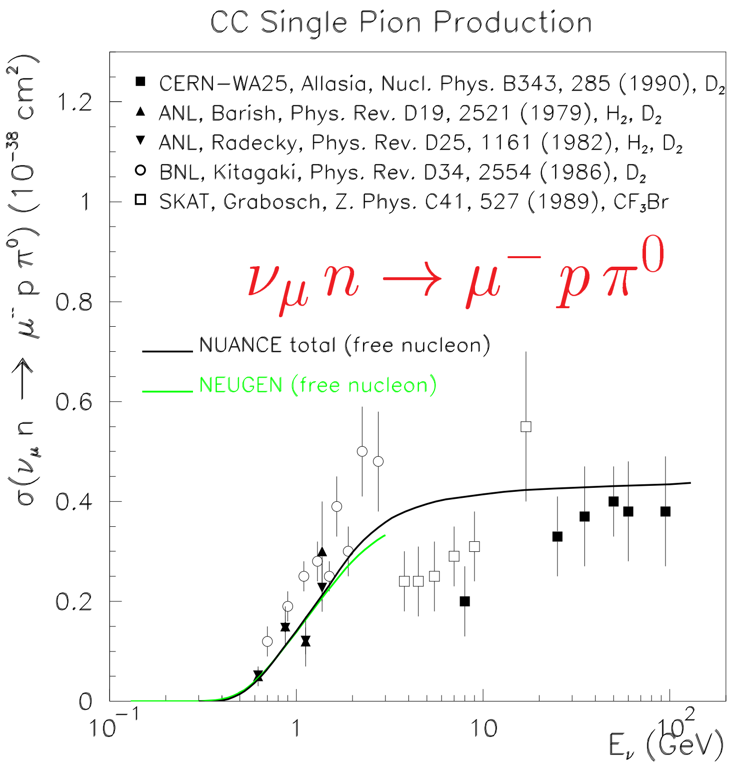
- $\Delta \to N\gamma$ can be an important background for $\nu_\mu \to \nu_e$
- 1π resonant cross sections not as well known (typically known to $20-40\%$ from bubble chamber meas)
- plus, such interactions complicated by final state effects (π absorption, charge exchange)

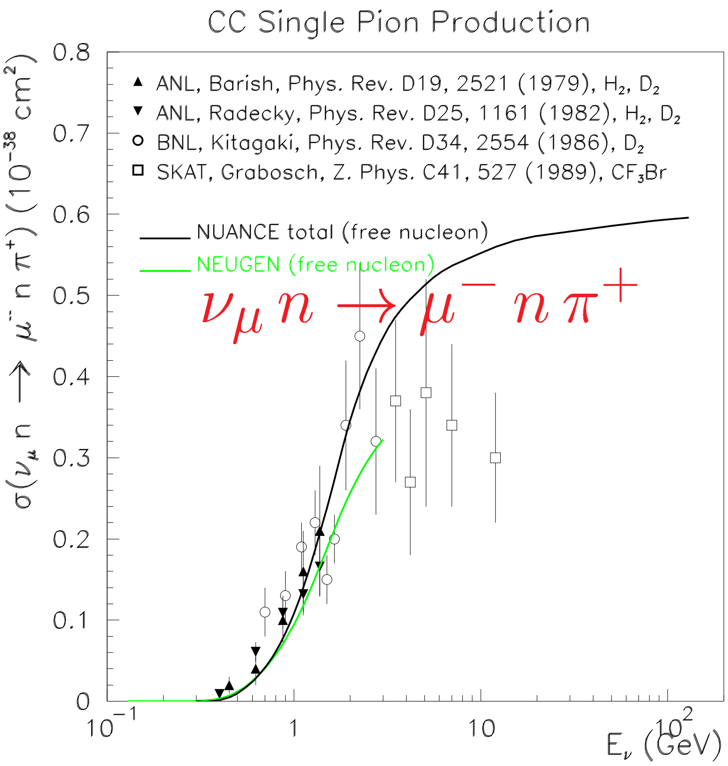
quality and quantity of present data varies ...

CC Single Pion Production



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

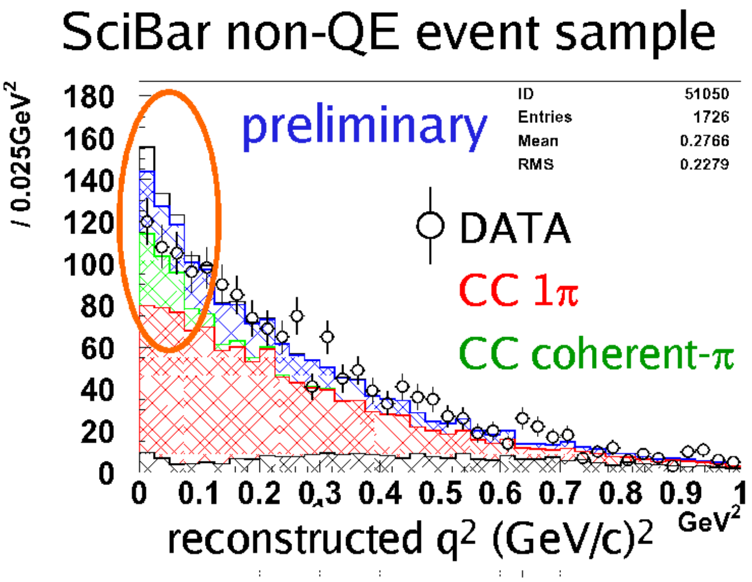




- as in QE case, <u>all</u> data < 2 GeV is off light targets (H_2, D_2)
- some meas differ by much more than their total error bars

New Resonant CC 1π Data

- higher stats CC 1π data becoming available
- important since a background to ν_μ disappearance searches (in the case in which final state π is not observed, e.g. π absorbed)
- also useful for study of $p \to \mu\pi^0$ backgrounds



← R. Gran, DPF04

- K2K non-QE 2-track evts
- hint of low Q^2 (forward μ) deficit?

M. Wascko, DPF04 →

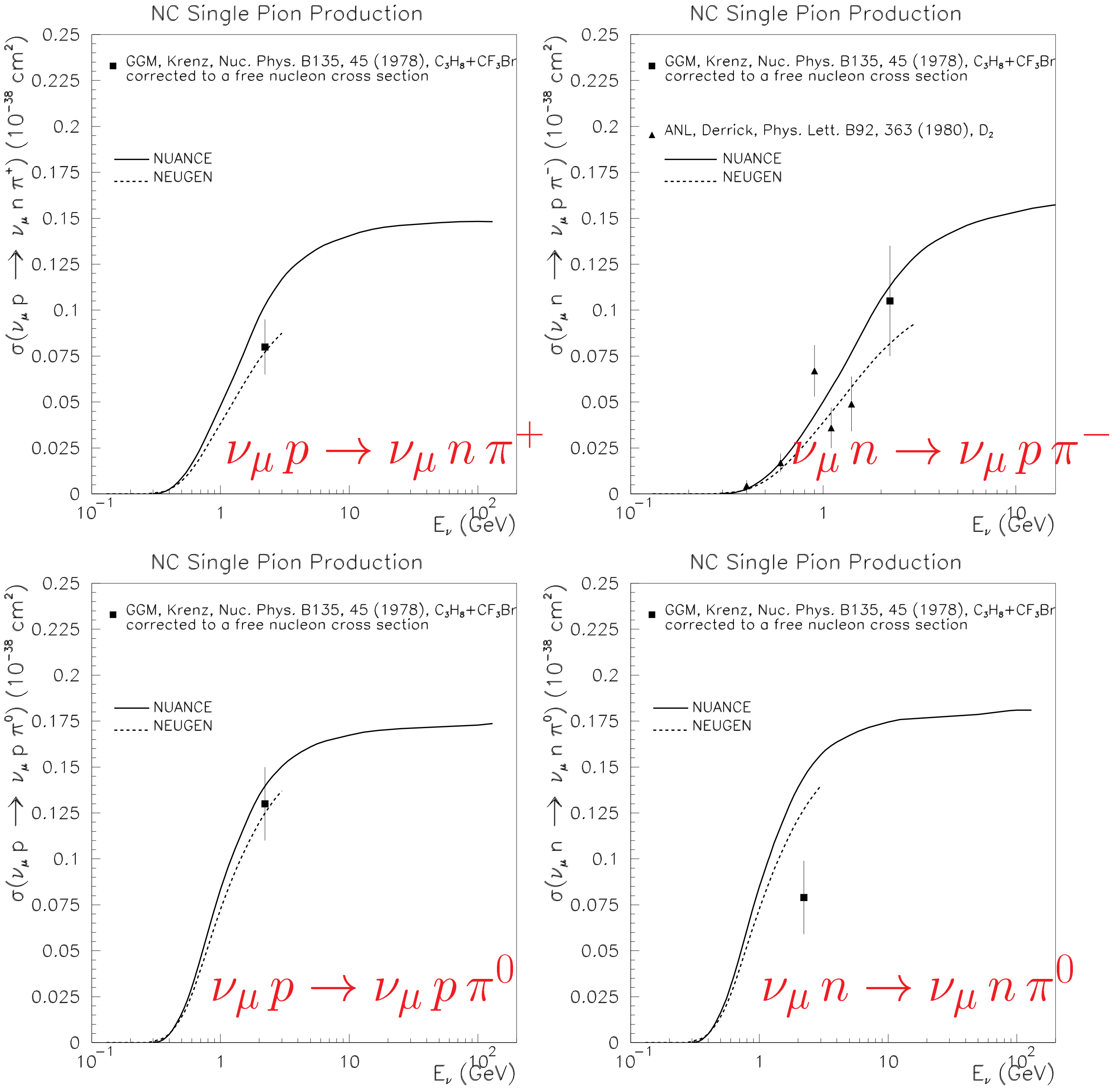
- MiniBooNE CC $1\pi^+$ events
- $\sim 36,000$ CC $1\pi^+$ events (5$\times$ more than bubble chamber exps)

- perhaps learning some interesting things about low E ν ints from present data (or at least how deficient our current models are)?
- caution: there are no systematics on these plots

Resonant NC 1π Absolute σ's

- data constraints on resonant NC 1π are even worse ...
- recent re–analysis of Gargamelle bubble chamber data

(E. Hawker w/ help from J. Morfin, M. Pohl, to be published in Nucl.Phys.B)

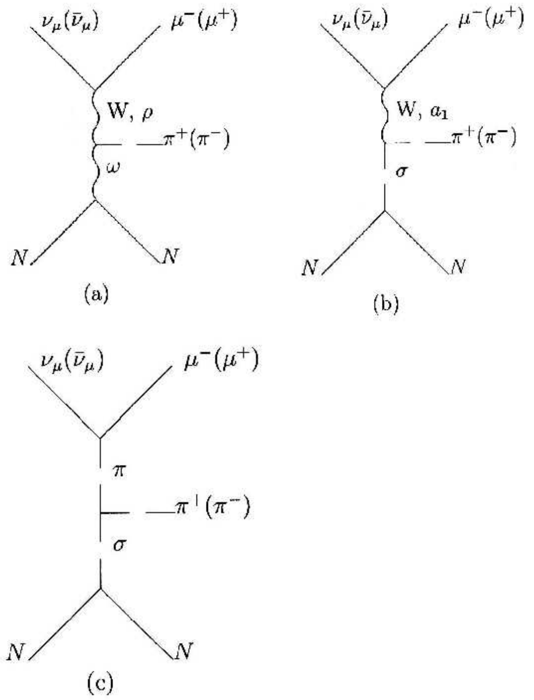


- recall: NC π^0 important background for ν_e appearance

Coherent Pion Production

- in addition to resonant 1π production, can also ...
- scatter from entire nucleus rather than from its individual constituents
- both NC and CC possible:

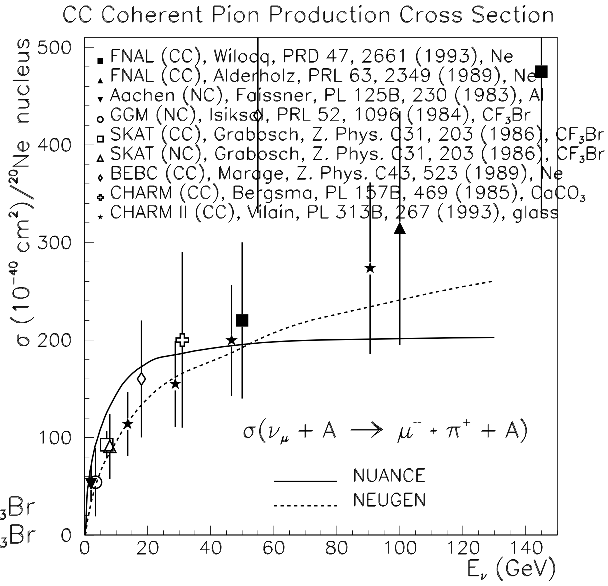
$$\text{NC}: \nu_\mu\, A \;\rightarrow\; \nu_\mu\, A\, \pi^0$$
$$\text{CC}: \nu_\mu\, A \;\rightarrow\; \mu^-\, A\, \pi^+$$

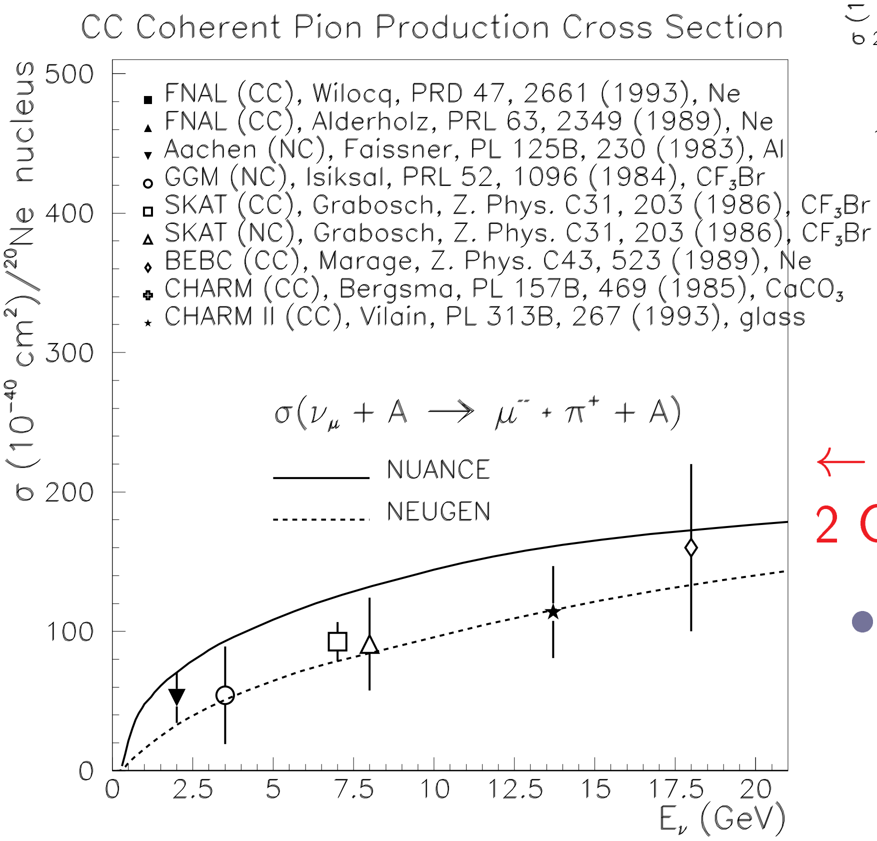


E.A. Paschos & A.V. Kartavtsev, (hep-ph/0309148)

- distinct kinematics
  - ↪ negligible energy transfer to the target (low Q^2)
  - ↪ forward scattered π
- kinematics well known, but overall rate less certain (exps typically assign a 100% uncertainty)
- largely a $\nu-$specific process as coupling is dominated by the axial current

Coherent Pion Production Data



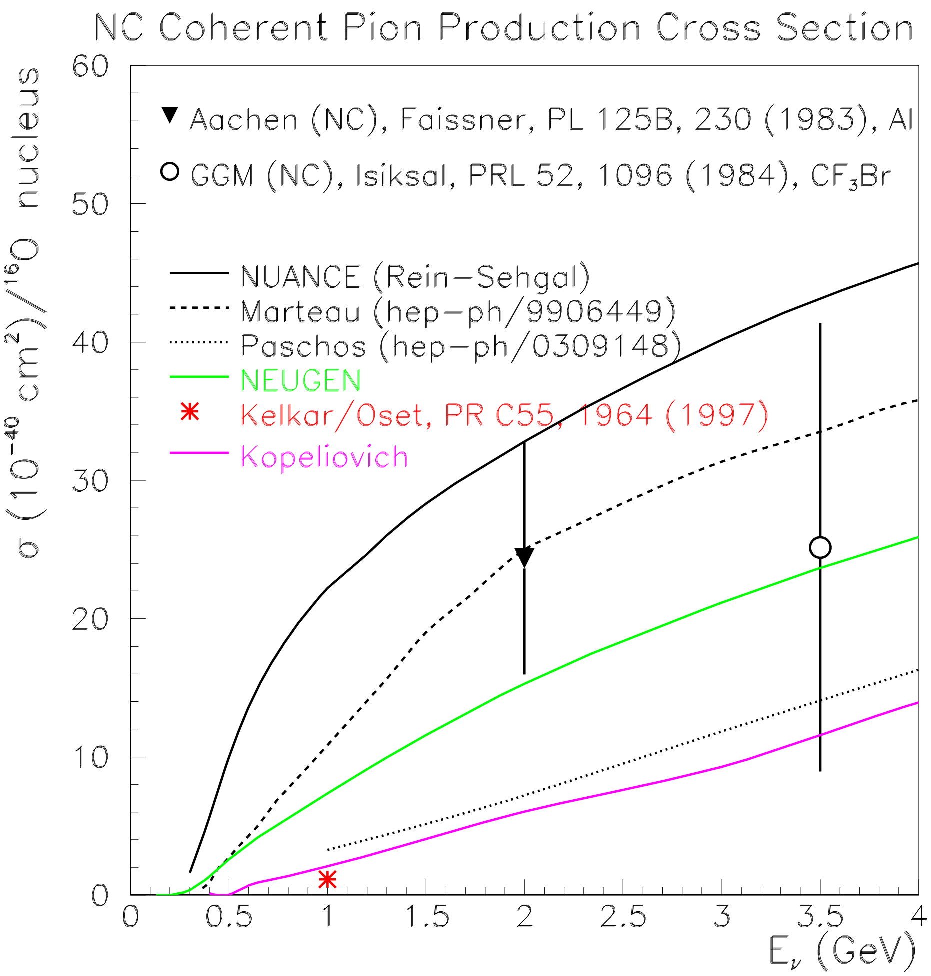


← lowest energy data is at 2 GeV off *Al* target

- both K2K and MiniBooNE can measure < 2 GeV

- NC π^0 production significant background for $\nu_\mu \rightarrow \nu_e$ & impacts limits on osc of standard ν's to sterile states
- coherent production predicted to be up to $\sim 20\%$ of NC $1\pi^0$ rate (80% resonant)
- no e^- scattering analogue exists to constrain this process

Coherent Pion Prod at Low E

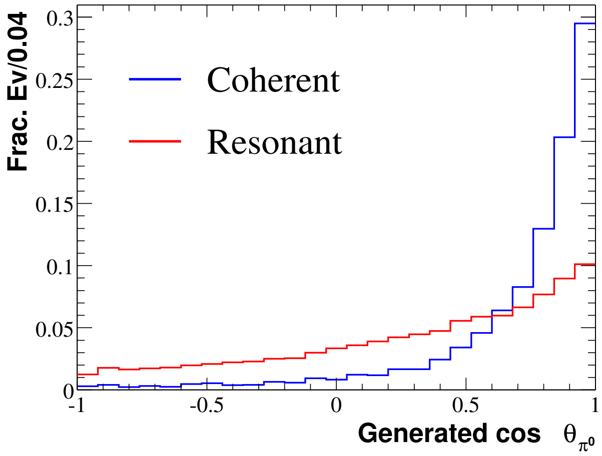


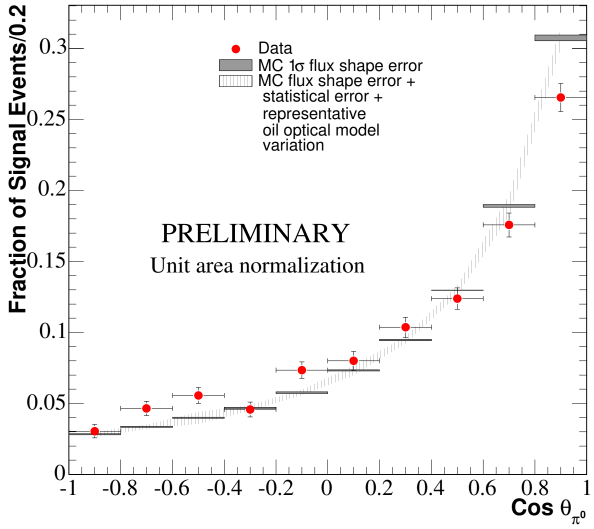
- calculations of coherent π production at low E all assume PCAC but quickly diverge (diff procedures & assumptions)
- $\times 20$ variation in recent models at $E \sim 1$ GeV !!
- existing data has not been precise enough to discriminate between different models
- MiniBooNE and K2K already weighing in here ...

More Recent NC π^0 Data

- for oscillation exps, we care about absolute NC π^0 rate on a nuclear target (sum of resonant + coherent), but:

- measured π^0 angular dist is also sensitive to mode of production $\rightarrow$





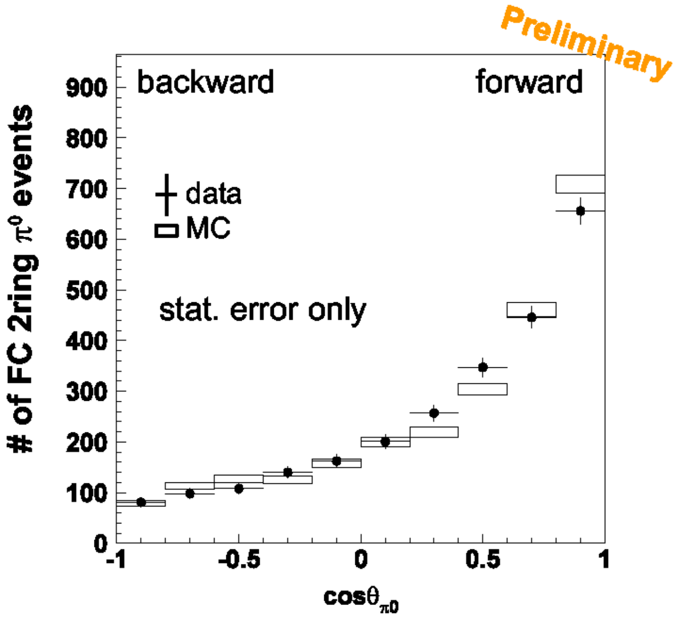
J. Raaf, MiniBooNE
$\sim 7,000\ \pi^0$ events

$\longleftarrow$ present data **appears** to be suggesting a lower level of coherent π^0 prod than (most popular) Rein-Sehgal model predicts

$\downarrow$

similar effect seen at K2K $\rightarrow$
(their MC assumes 1/2 Rein-Sehgal coh)

Nakayama, K2K (NuFact04)
NC π^0 in H_2O Č



Proton Decay Searches

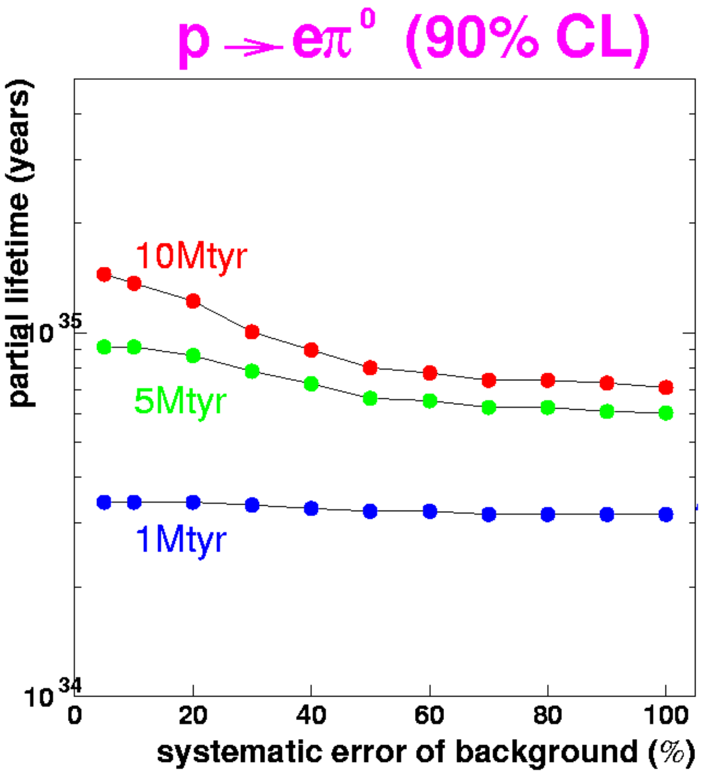
dominant modes (GUTs):

- $p \to e\,\pi^0$ (non-SUSY)
- $p \to \overline{\nu}\,K^+$ (SUSY)

dominant background

$\nu_e\,N \to e\,\pi^0\,N$

$\nu\,p \to \nu\,\Lambda\,K$



S. Mine, Nucl. Phys. **B112**, 154 (2002)

lifetime sensitivity vs. precision of bkgd determin
(assuming current SK analysis)

- not surprisingly, precise background determination is more important for higher exposures
- to achieve a p decay lifetime of 1×10^{35} yr for 10Mt*yr $\Rightarrow$ requires determining ν CC π^0 background to precision of $\leq 30\%$

continued progress either by improving limits to 10^{34} yr lifetimes (or discovery) hinge upon improved knowledge of certain ν ints $\Rightarrow$ important for future mega-ton detectors

Single Kaon Production

- important background for nucleon decay searches

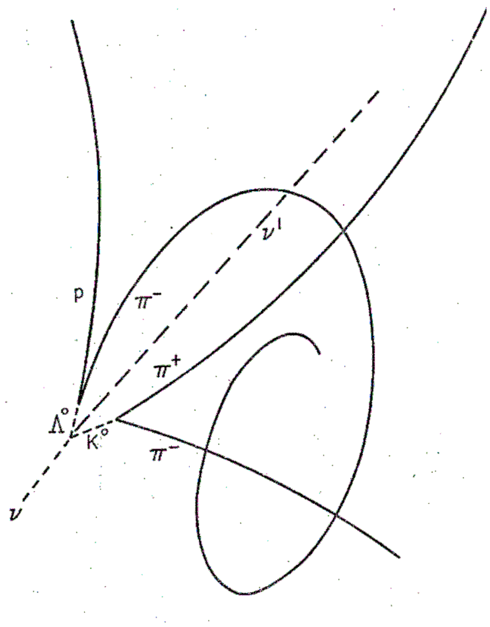
  $p \to K^+ \nu$ (preferred in SUSY GUTs)

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

$$\nu_\mu n \to \mu^- K^+ \Lambda^0$$
$$\nu_\mu p \to \nu_\mu K^+ \Lambda^0$$

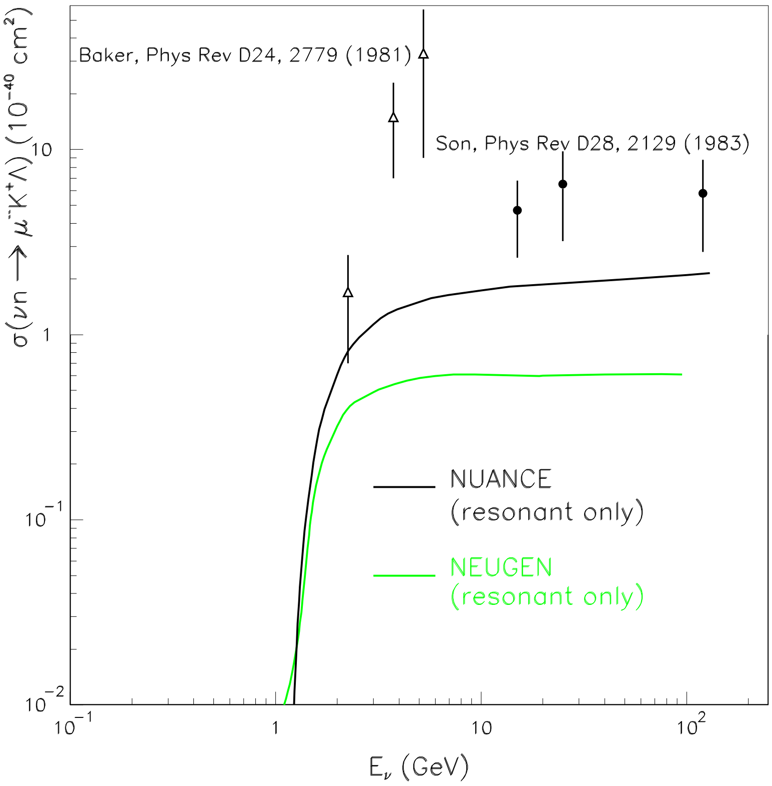
- important to reliably estimate this background

- little experimental data - most from bubble chambers where strange particle decays easily observed:



- few theoretical models:
  - ↪ R. Shrock, Phys. Rev. **D12**, 2049 (1975)
  - ↪ A. A. Amer, Phys. Rev. **D18**, 2290 (1978)
- not very predictive
- phenomenology stalled in 70's due to lack of constraining data

CC Associated Production of $K^+\Lambda$



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

experimental measurements based on handfuls of events

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

- ability to meas strange production rates in ν ints will play imp role in helping p decay exps reach their ultimate sensitivity

- want to study at low E near threshold where data is most scarce (most relevant for proton decay searches)

↪ NOMAD: has studied at higher E (hep-ex/0409037)

↪ MiniBooNE: expects 100's of $K\Lambda$ events

↪ K2K: plans to measure using K2K new SciBar detector

↪ MINERvA: expects $> 10,000$ of $\nu_\mu\, n \rightarrow \mu^-\, K^+\, \Lambda$

Where to Go From Here?

- Booster and NuMI neutrino beams offer further room for improved ν cross section measurements:

  $\hookrightarrow$ convenient (both already exist)

  $\hookrightarrow$ relevant (in an E range that is most relevant for ν osc exps)

  $\hookrightarrow$ high intensity

  $\hookrightarrow$ well-controlled (will be known to better than 10% level)
  (compare to bubble chamber $15-20\%$ flux uncertainties)

  $\hookrightarrow$ complementary ...

  $\star$ **Booster:** $\leftarrow$ 60% QE/EL, 40% RES, $<2\%$ DIS
  $E_{peak}=0.5$ GeV
  $<E_\nu>=0.8$ GeV

  $\star$ **NuMI LE:** $\leftarrow$ 10% QE/EL, 25% RES, 50% DIS
  $E_{peak}=3$ GeV
  $<E_\nu>=10.2$ GeV

  $\star$ **NuMI ME:**
  $E_{peak}=7$ GeV
  $<E_\nu>=8.5$ GeV

- advancement comes in coupling intense ν beams with new fine-grained detectors ...

Future Fine-Grained ν Exps

Next generation neutrino experiments ...

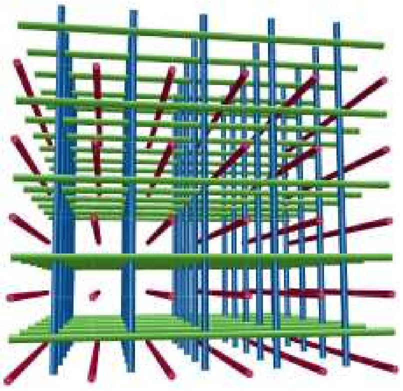
MINERvA (NuMI beamline):

- Main INjector ExpeRiment v-A
- spokespeople: K.McFarland,J.Morfin
- program of hadronic & nuclear phyx

Process	QE	RES	COH	DIS
δσ/σ NOW (CC,NC)	20%	40%	100%	20%
δσ/σ after MINERνA (CC/NC)	5%/na	5%/10%	5%/20%	5%/10%

table from D. Casper

FINeSSE (Booster beamline)



- Fine-grained Intense Neutrino Scattering Scintillator Exp
- spokespeople: B.Fleming,R.Tayloe
- main goal: study form factors with NC elastic scattering (Δs)
- also low E (~ 1 GeV) ν cross sections

cross section measurements in these cases will most likely be dominated by systematics ...

Neutrino Fluxes

Largest limiting systematic will still come from how well we know our incoming neutrino fluxes (Φ_ν):

- previous bubble chamber σ measurements limited by $15-20\%$ flux uncertainties (dominant syst in most cases)
- this will still be true (even with p driver):

$$N_\nu = \Phi_\nu \times \sigma_\nu \times \epsilon$$

- our neutrino flux uncertainties will improve ($< 10\%$) in the near future with guidance from:
  - $\hookrightarrow$ thin target data from BNL E910
    (J. Link talk from NuFact04)
  - $\hookrightarrow$ thin & thick target data from HARP (K2K, MBooNE)
  - $\hookrightarrow$ MIPP E907 (NuMI, MINERvA)

- given that we will have new σ measurements from K2K, MiniBooNE, MINERvA, FINeSSE and the fact that uncertainties in hadron production cross sections will likely remain a limitation to these measurements:
  - $\hookrightarrow$ what does a proton driver buy us?
  - $\hookrightarrow$ high statistics should be matched with dedicated precision hadron production exps

What Might a Proton Driver Add?

Appeal of proton driver, of course, is that you gain much **higher statistics** which allows you to explore add'l possibilities: *(as was also discussed at NuFact04)*

- H_2, D_2 (light) targets, nucleon targets
  $\leftarrow$ minimize nuclear effects, disentangle form factors
- off-axis, narrow band beam studies
  $\leftarrow$ detailed NC studies (as fcn E)
- antineutrino exposure $\longrightarrow$

Antineutrino Cross Sections

$\overline{\nu}$ reactions are generally more difficult to study (there's a reason why there's little existing low energy $\overline{\nu}$ σ data)

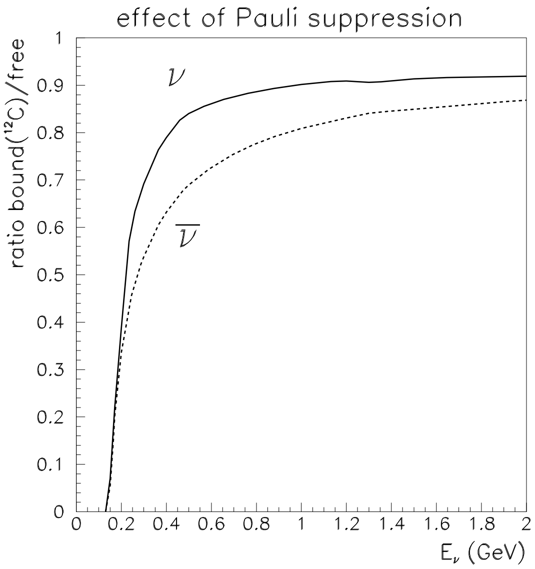
- $\overline{\nu}$ fluxes down by factor ~ 2
- $\overline{\nu}$ cross sections down by factor ~ 2
- $\Rightarrow$ $\overline{\nu}$ event rates down by factor 4
- proton driver could certainly help with such statistics-starved $\overline{\nu}$ measurements

- larger wrong sign component (not really a $\overline{\nu}$ beam, but a "$\overline{\nu}$-enhanced" beam)
  - $\hookrightarrow$ $\overline{\nu}$ backgrounds in ν beam few-%
  - $\hookrightarrow$ whereas ν backgrounds in $\overline{\nu}$ beam 10's of %

- why measure?
  - $\hookrightarrow$ interesting in their own right
  - $\hookrightarrow$ will need for future neutrino oscillation experiments (need to control $\nu/\overline{\nu}$ systs at % level for mass hierarchy and CP studies)

Do Neutrinos Violate CP?

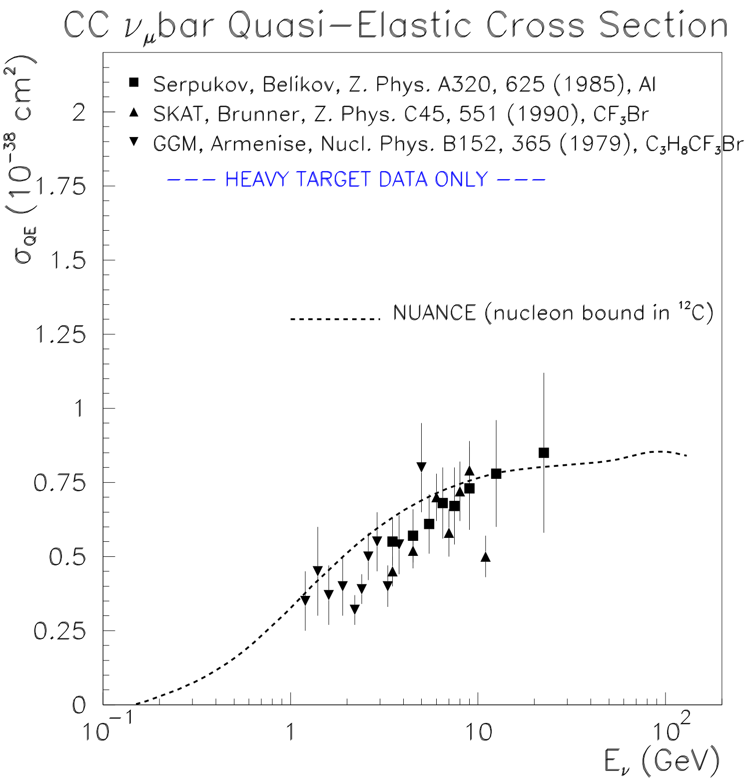
- will measure δ by comparing oscillation probabilities of $\nu_\mu \to \nu_e$ vs. $\overline{\nu}_\mu \to \overline{\nu}_e$
- one needs control of the ratio $\sigma(\overline{\nu}/\nu)$ to a better precision than the size of the expected asymmetry



- can't just infer $\sigma^{\overline{\nu}}$ from σ^{ν}
- ν, $\overline{\nu}$ nuclear effects not exactly identical (important if have nuclear target)
- $\overline{\nu}$'s have softer Q^2 distribution means larger Pauli suppression (suppression depends strongly on Q^2)

$\hookrightarrow$ $20 - 30\%$ larger for $\overline{\nu}$'s

- currently no $\overline{\nu}$ data below 1 GeV (on light or heavy targets)
- relying completely on theoretical models and their extrapolation to low E
- imperative to verify low E $\overline{\nu}$ QE σ w/ exp'l data



$\overline{\nu}$: Neutrino Scattering Physics

In $\overline{\nu}$ case, the composition of events changes:

- pick up additional free scattering component (can now elastically scatter off H_2); Φ_ν, form factor meas

$$\begin{array}{rcccl} & \nu_\mu\, n & \rightarrow & \mu^-\, p & \quad \text{(CCQE)} \\ \text{vs.} & \overline{\nu}_\mu\, p & \rightarrow & \mu^+\, n & \end{array}$$

- because of the diff isospin content of the final states, resonances produced in ν, $\overline{\nu}$ ints are very different

$$\begin{array}{lcll} \nu_\mu\, p & \rightarrow & \mu^-\, p\, \pi^+ & \quad \text{dominated by } \Delta^{++}(1232) \\ \overline{\nu}_\mu\, p & \rightarrow & \mu^+\, p\, \pi^- & \quad \Delta^0(1232) \end{array}$$

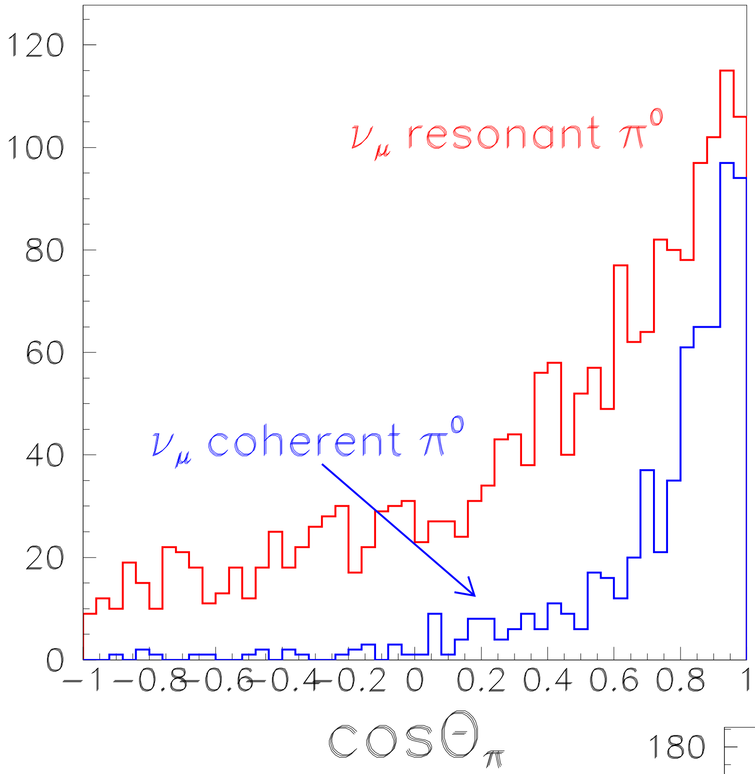
$\Rightarrow$ get different W dists for ν vs. $\overline{\nu}$

- dominant resonant interactions go from being CC $1\pi^+$ (ν) $\rightarrow$ CC $1\pi^-$ $(\overline{\nu})$

- resonant π fraction $\downarrow$ while coherent π contribution remains the same $(\sigma^{\overline{\nu}}_{coh} = \sigma^{\nu}_{coh})$

  $\hookrightarrow$ effectively end up amplifying coherent scattering contribution ...

Antineutrino NC π^0 Events

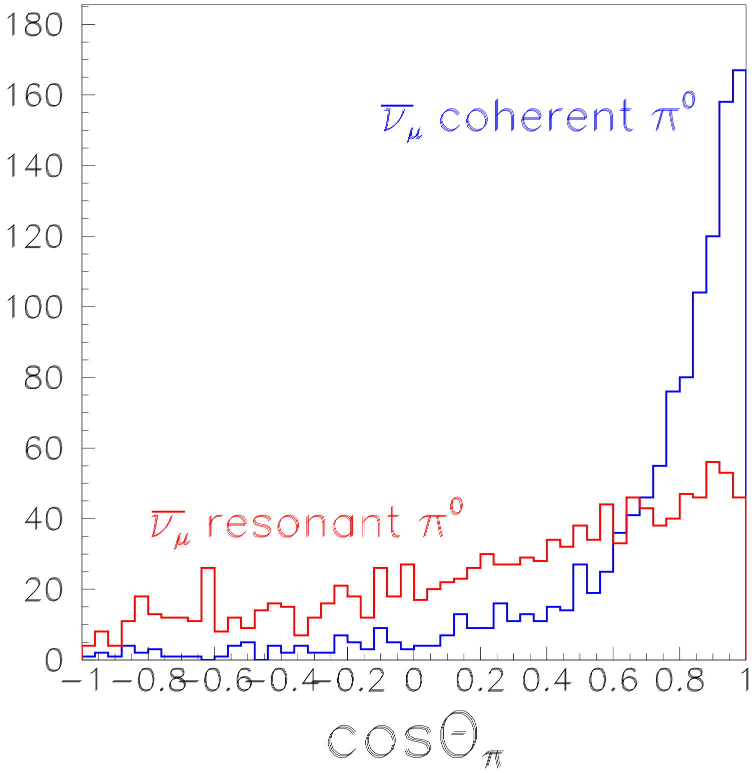


$$\nu_\mu\, N \rightarrow \nu_\mu\, N\, \pi^0$$

- in ν case, coherent π prod is $\sim$ 20% of NC π^0 evts

$$\overline{\nu}_\mu\, N \rightarrow \overline{\nu}_\mu\, N\, \pi^0$$

- in $\overline{\nu}$ case, coherent π prod still very forward peaked
- but is now $>$ 40% of the NC π^0 evts



$\overline{\nu}$ running: provides an effective means of enhancing coherent π contribution (so if there were very little coherent π production at low E, you would definitely see it in $\overline{\nu}$ data)

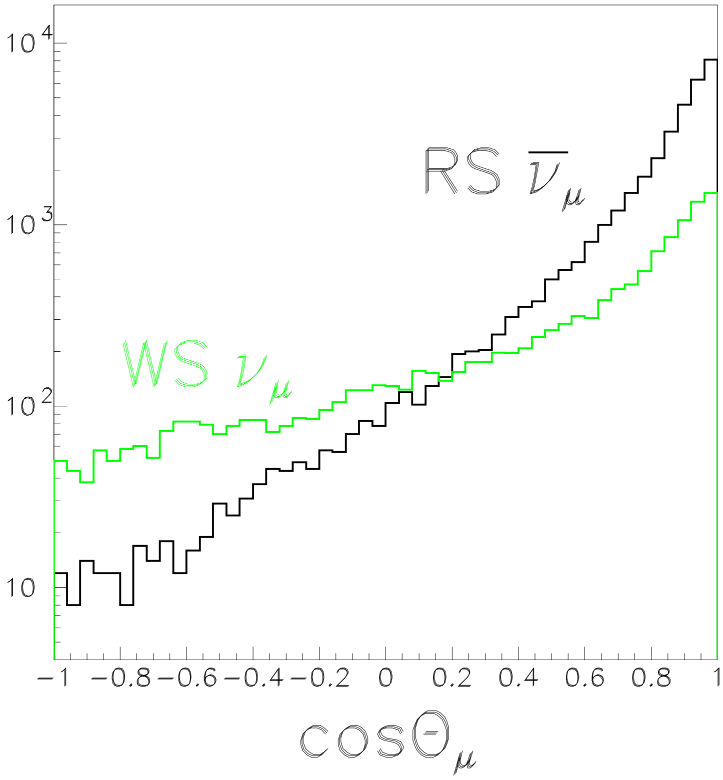
$\overline{\nu}$ Data: Wrong-Sign Constraints

Of course, there is still the problem that up to $\sim 30\%$ of this data can be "wrong-sign" neutrino background events

- standard technique: use B field to sign select ν vs. $\overline{\nu}$ (works for CC case in differentiating μ^- from μ^+)

- might be able to use some other tricks to constrain/measure WS ν content in $\overline{\nu}$ data (don't want to rely completely on MC)

  ↪ "poor man's sign selection"



- make use of different angular distributions

- $\overline{\nu}$ QE's are suppressed in backward hemisphere relative to ν QE's

- look at large angle QE interactions as means of "measuring" WS contam

- also true that in the $\overline{\nu}$ data, CC $1\pi^+$ events can only come from ν interactions (another handle on WS)

Conclusions

- compelling indications of neutrino oscillations have increased interest and need for low E ν measurements
- continued progress on measuring these input σ's will become even more critical as planned experiments aim to determine oscillation parameters with high precision

- results from K2K, MiniBooNE already expanding our knowledge well beyond bubble chamber data
- existing ν beams at Fermilab provide unprecedented new opportunities in high rate ν physics at low E

  $\hookrightarrow$ should make full use of both beams (Booster, NuMI)

  $\hookrightarrow$ includes ν and $\overline{\nu}$ running

  $\hookrightarrow$ requires modest investment in new near-source fine-grained detectors (MINERvA, FINeSSE)

- and should fully explore entire phase space of opportunities in ν scattering physics w/ combined addition of extremely high rate environment made possible with proton driver

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

Neutrino Roadmap