Neutral Current $1\pi^0$ Production at MiniBooNE

Sixth International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

Colin Anderson

May 21, 2009

Outline

- The Measurement
- Isolating the NC $1\pi^0$ Sample
- Cross Section Calculation
  - Background Subtraction
  - Unsmearing
  - Efficiency Correction, Flux
- Coherent Production Models
- Resonant Production Measurement

NC π^0 Production

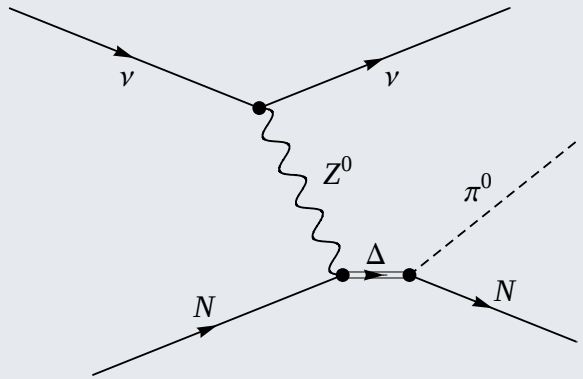
What Was Measured

We measured the cross section for NC interactions resulting in one π^0 exiting the target nucleus and no other mesons

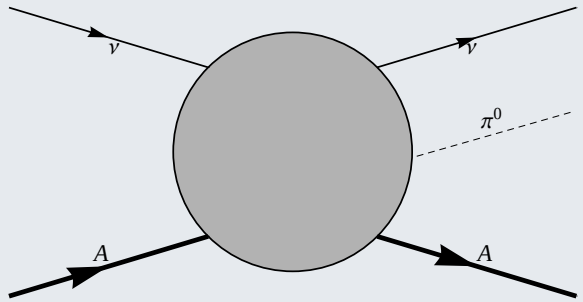
- Includes production from the intial interaction as well as production from final state interactions in the nucleus
- Excludes interactions in which an initially produced π^0 was lost to final state interactions
- $d\cos\theta_{\pi^0}$, dp_{π^0} differential cross sections measured for neutrino and antineutrino induced production

Direct π^0 Production Interactions

- Resonant
  $\nu_\mu \mathrm{N} \rightarrow \nu_\mu + (\Delta \rightarrow \mathrm{N} + \pi^0)$



- Coherent/Diffractive
  $\nu_\mu \mathrm{A} \rightarrow \nu_\mu + A + \pi^0$



NC π^0 Production

What Was Measured

We measured the cross section for NC interactions resulting in one π^0 exiting the target nucleus and no other mesons

- Includes production from the intial interaction as well as production from final state interactions in the nucleus
- Excludes interactions in which an initially produced π^0 was lost to final state interactions
- $d\cos\theta_{\pi^0}$, dp_{π^0} differential cross sections measured for neutrino and antineutrino induced production

Models Used in MC

- Resonant
  - Rein-Sehgal (Annals Physics, **133**, 79 (1981))
  - $M_A = 1.1$ GeV
  - Includes $\Delta(1232)$ and 17 higher mass resonances
  - Non-isotropic Δ decay
- Coherent
  - Rein-Sehgal (Nucl. Phys. **B223**, 29 (1983))
  - $M_A = 1.03$ GeV
  - NUANCE FSI model used in lieu of F_{abs} term
- Diffractive
  - Rein (NP **B278**, 61 (1986))

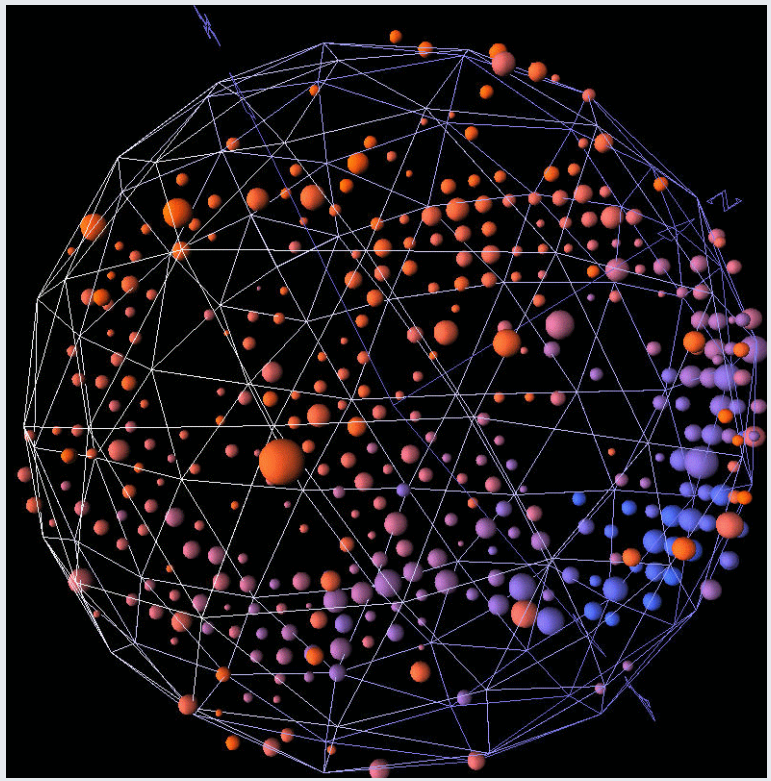
NC π^0 Production

What Was Measured

We measured the cross section for NC interactions resulting in one π^0 exiting the target nucleus and no other mesons

- Includes production from the intial interaction as well as production from final state interactions in the nucleus
- Excludes interactions in which an initially produced π^0 was lost to final state interactions
- $d\cos\theta_{\pi^0}$, dp_{π^0} differential cross sections measured for neutrino and antineutrino induced production

Signature



- π^0 decays to two γs that induce electromagnetic showers via pair-production

Filling the π^0 Box

Cuts

- Preliminary Cuts
  - One subevent
    Eliminates events with decays, which we do not expect from most NC π^0 events
  - Veto hits < 6
  - Tank hits > 200
- Analysis Cuts
  - Fiducial volume cut
  - Choose events with $e - \mu$ fit likelihood difference favoring e-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring π-like hypothesis
  - Choose events with two-track invariant mass similar to π^0 mass

Filling the π^0 Box

Cuts

- Preliminary Cuts
  - One subevent
  - Veto hits < 6
    Eliminates cosmics, uncontained events (which disproportionally eliminates muon containing events)
  - Tank hits > 200
- Analysis Cuts
  - Fiducial volume cut
  - Choose events with $e - \mu$ fit likelihood difference favoring e-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring π-like hypothesis
  - Choose events with two-track invariant mass similar to π^0 mass

Filling the π^0 Box

Cuts

- Preliminary Cuts
  - One subevent
  - Veto hits < 6
  - Tank hits > 200
    Eliminates substantial portion of NC elastic events
- Analysis Cuts
  - Fiducial volume cut
  - Choose events with $e - \mu$ fit likelihood difference favoring e-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring π-like hypothesis
  - Choose events with two-track invariant mass similar to π^0 mass

Filling the π^0 Box

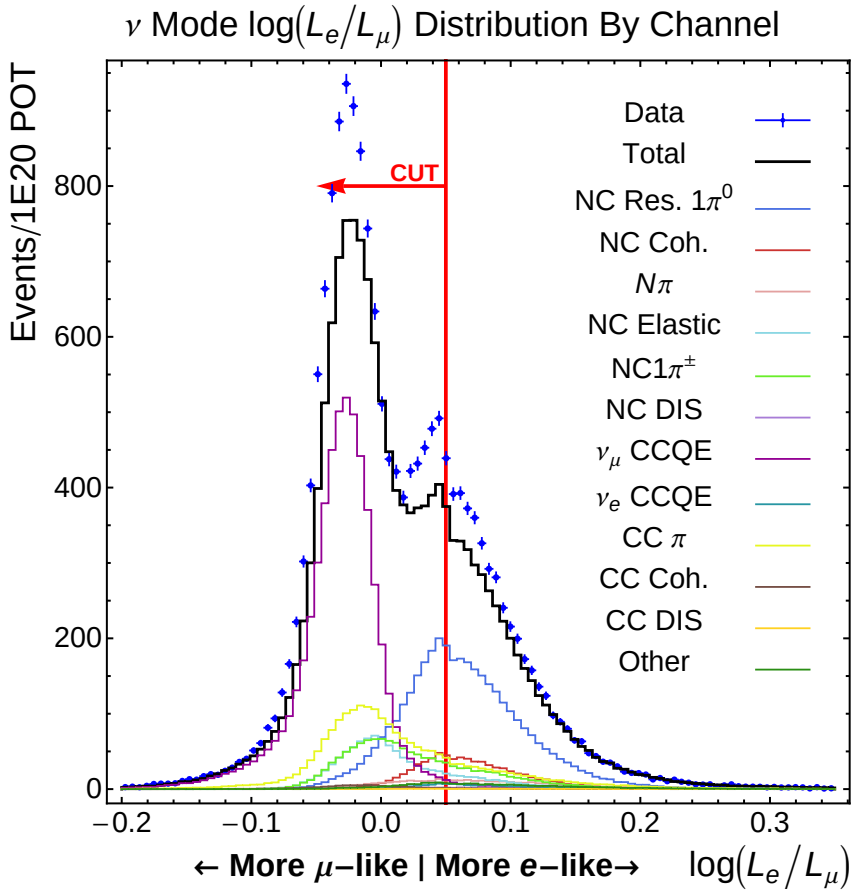
Cuts

- Preliminary Cuts
  - One subevent
  - Veto hits < 6
  - Tank hits > 200
- Analysis Cuts
  - Fiducial volume cut
    Eliminates events subject to poor reconstruction at the edge of the detector
  - Choose events with $e - \mu$ fit likelihood difference favoring e-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring π-like hypothesis
  - Choose events with two-track invariant mass similar to π^0 mass

Filling the π^0 Box

Cuts

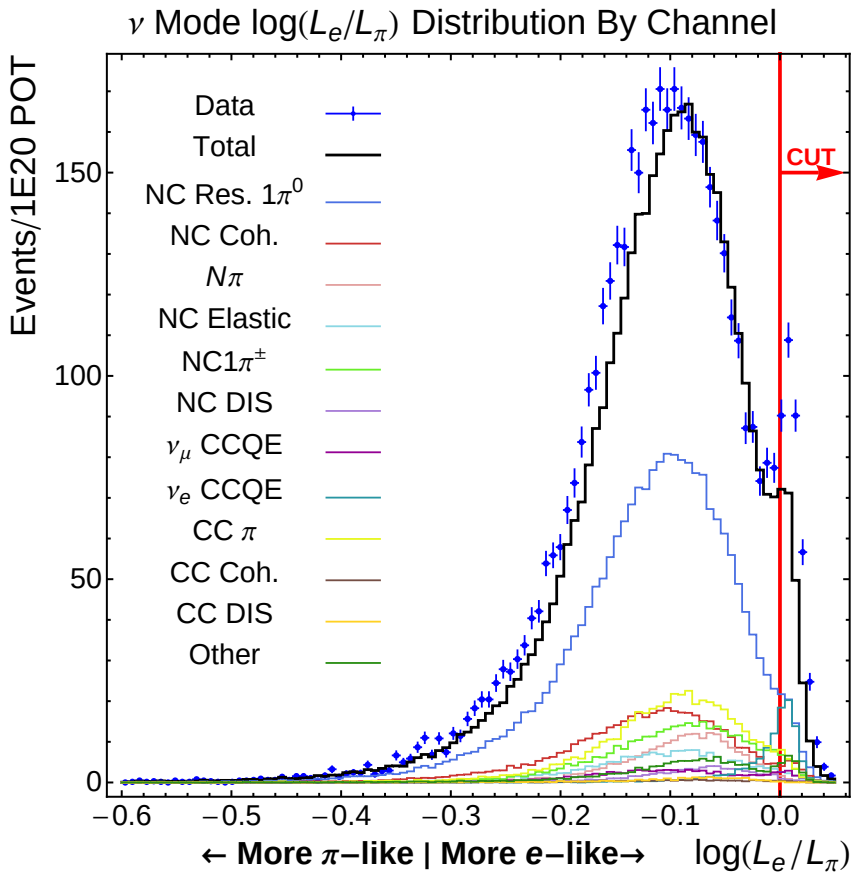
- Preliminary Cuts
  - One subevent
  - Veto hits < 6
  - Tank hits > 200
- Analysis Cuts
  - Vertex within 500 cm
  - Choose events with $e - \mu$ fit likelihood difference favoring e-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring π-like hypothesis
  - Choose events with two-track invariant mass similar to π^0 mass



Filling the π^0 Box

Cuts

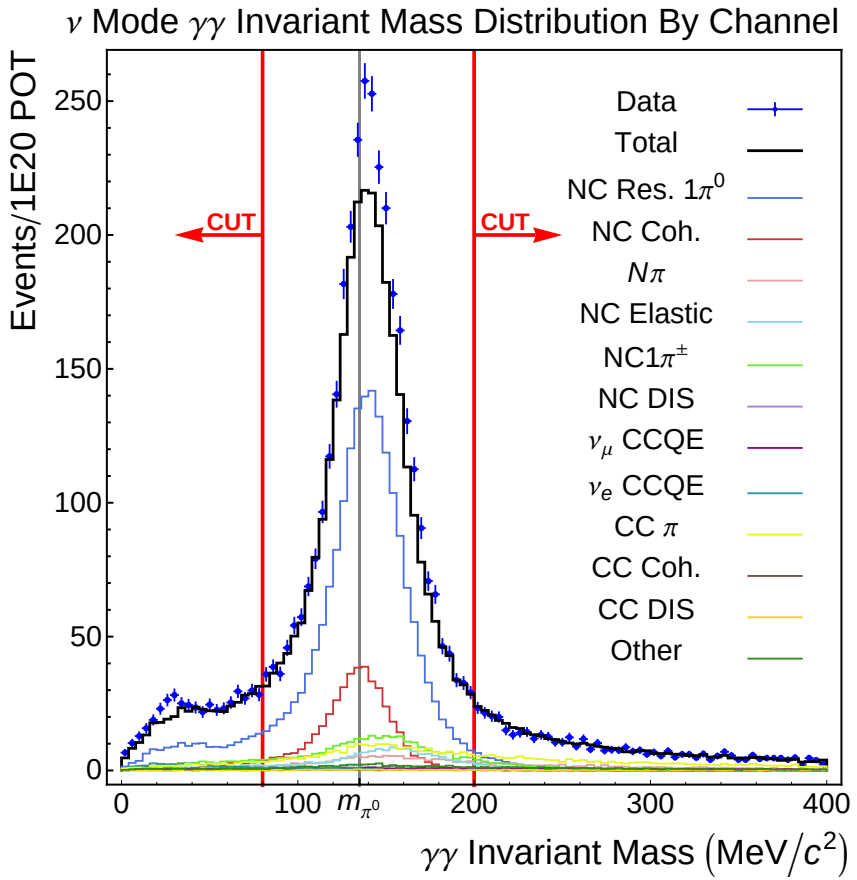
- Preliminary Cuts
  - One subevent
  - Veto hits < 6
  - Tank hits > 200
- Analysis Cuts
  - Vertex within 500 cm
  - Choose events with $e - \mu$ fit likelihood difference favoring e-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring π-like hypothesis
  - Choose events with two-track invariant mass similar to π^0 mass



Filling the π^0 Box

Cuts

- Preliminary Cuts
  - One subevent
  - Veto hits < 6
  - Tank hits > 200
- Analysis Cuts
  - Vertex within 500 cm
  - Choose events with $e - \mu$ fit likelihood difference favoring e-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring π-like hypothesis
  - Choose events with two-track invariant mass similar to π^0 mass



Filling the π^0 Box

In The Box

	Events Passing Cuts	Purity	Efficiency
Neutrino Mode	21542 w/ 6.461E20 POT Data/MC = 1.10	73%	36%
Antineutrino Mode	2305 w/ 3.386E20 POT Data/MC = 0.94	58%	36%

Signal Composition

	ν	$\bar{\nu}$
NC Res.	77% (77%)	58% (59%)
NC Coh.	18% (17%)	39% (38%)
NC $\pi^{\pm}$	2% (3%)	2% (2%)
NC El.	2% (2%)	1% (1%)
$N\pi$,DIS	$< 1\%$ ($< 1\%$)	$< 1\%$ ($< 1\%$)

After Cuts% (Before Cuts%)

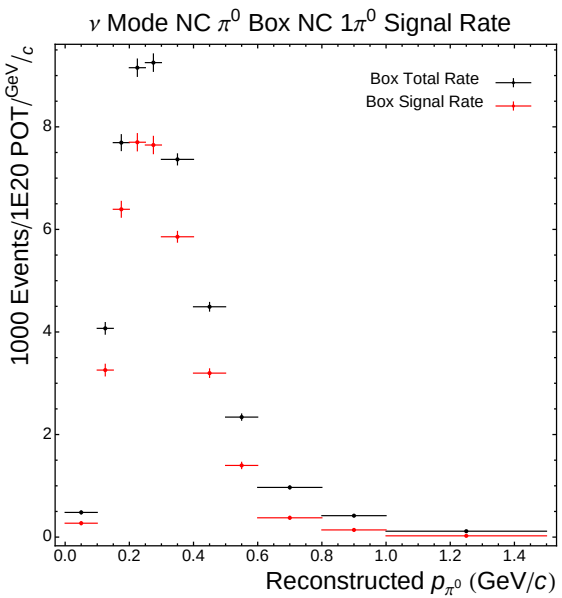
Background Composition

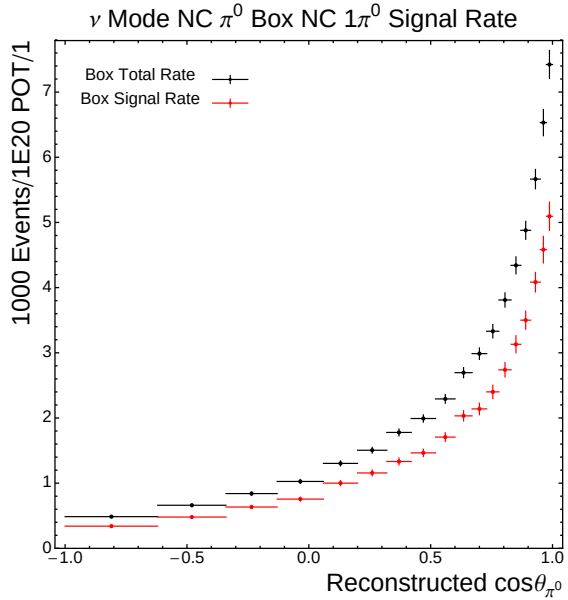
	ν	$\bar{\nu}$
NC $\pi^{\pm}$	23%	13%
NC El.	13%	5%
$N\pi$	12%	7%
CC $\pi^{\pm}$	13%	4%
CC π^0	10%	3%
ν_e Induced	7%	3%
Wrong-sign	5%	57%

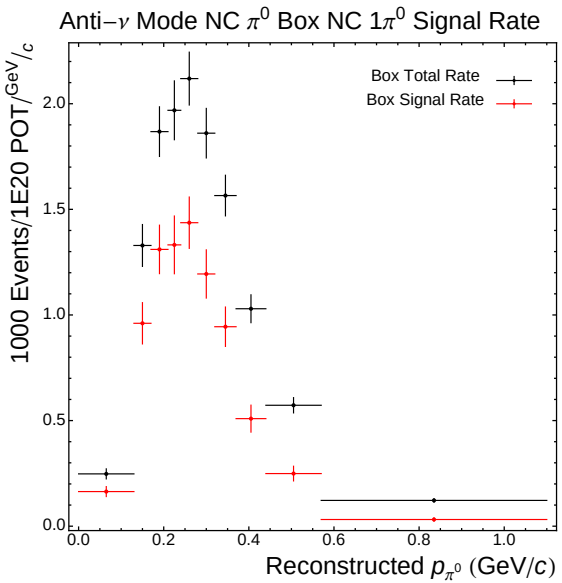
Background Subtraction

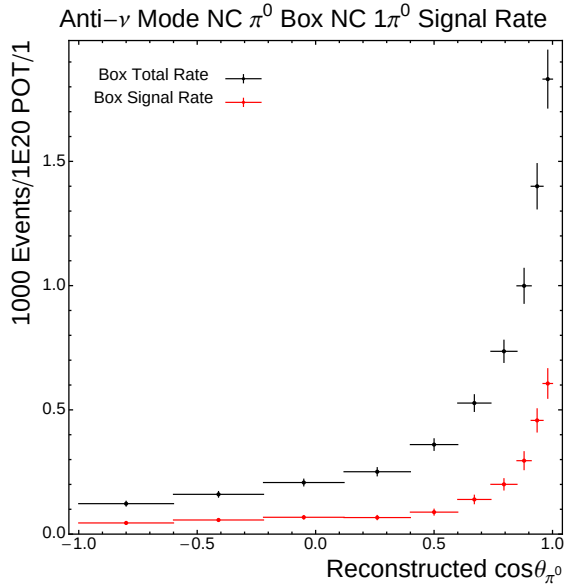
First step is to subtract background contamination from the π^0 box

- MC predicted background is relatively normalized and subtracted



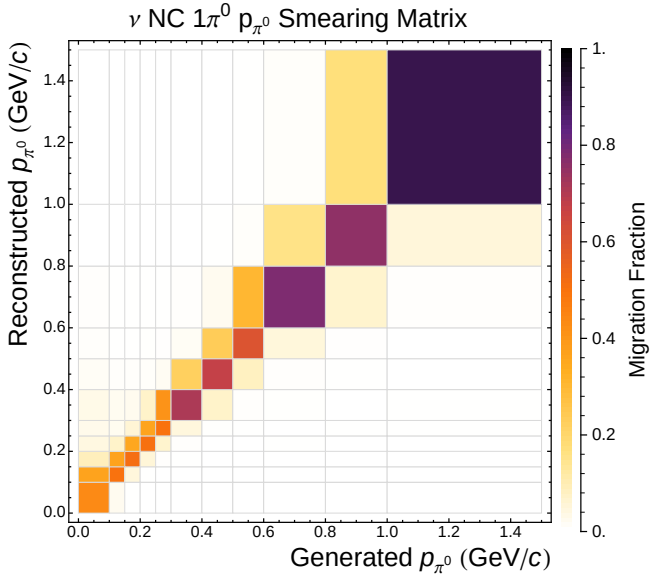


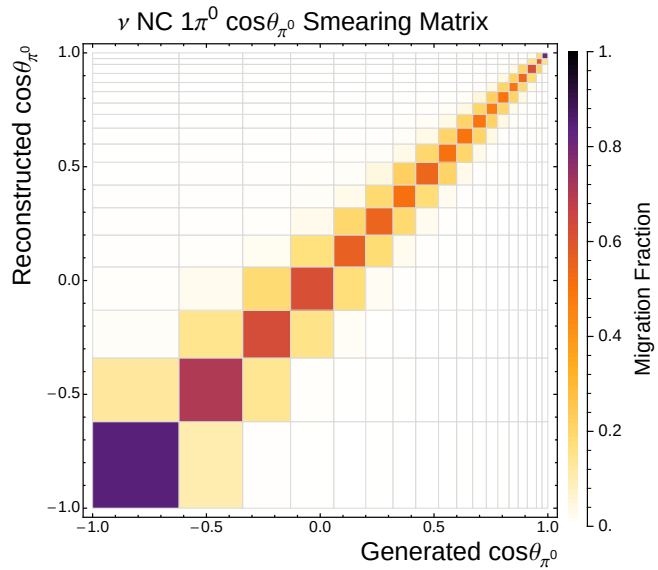


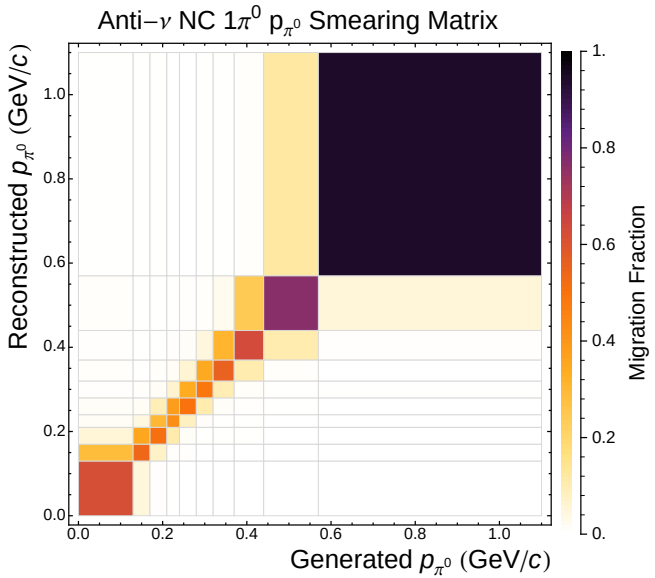


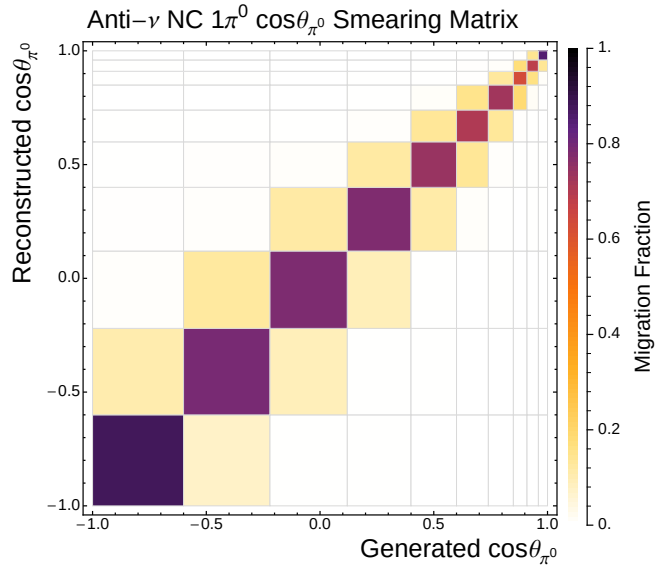
Unsmearing

- Effects in the detector and reconstruction scatter measured values from the true value
- Need to deconvolve these experiment-specific effects to produce externally useful results
- Angle is measured very well
- Momentum has a tendency to be overestimated



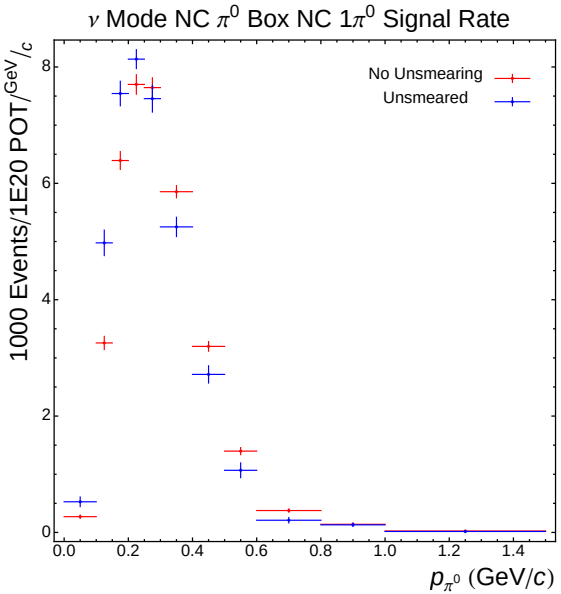


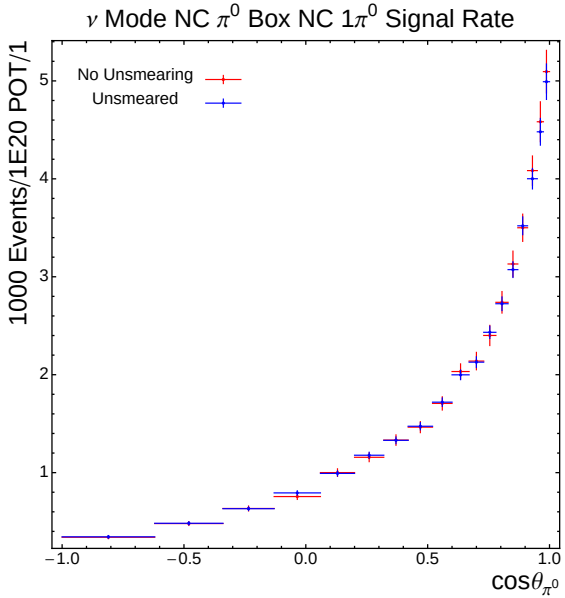


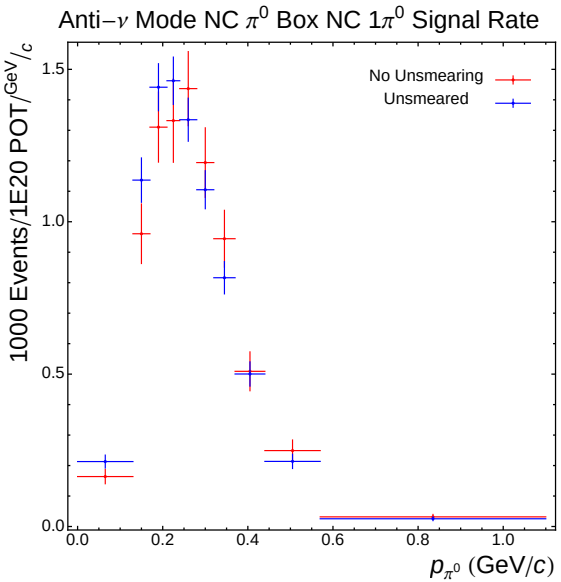


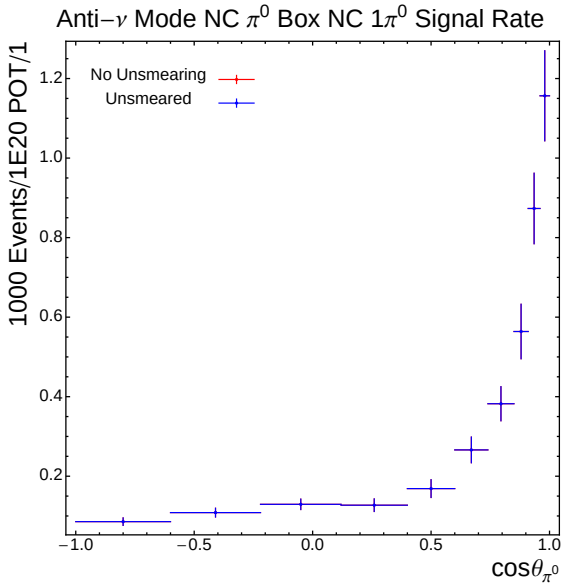
Unsmearing

- Differing characteristics of each measurement, *e.g.* statistics, smearing behavior, distribution shape, call for different smearing techniques
- Choose the least biased (estimated) result after applying various tested techniques[a b] which includes not unsmearing at all







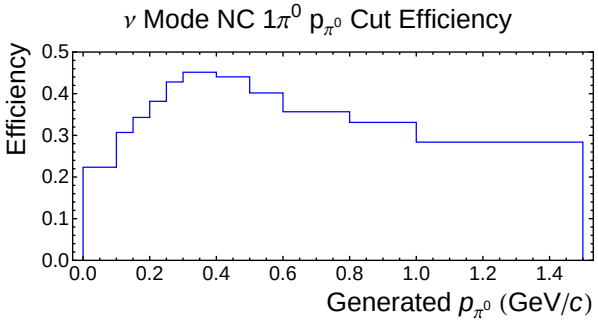


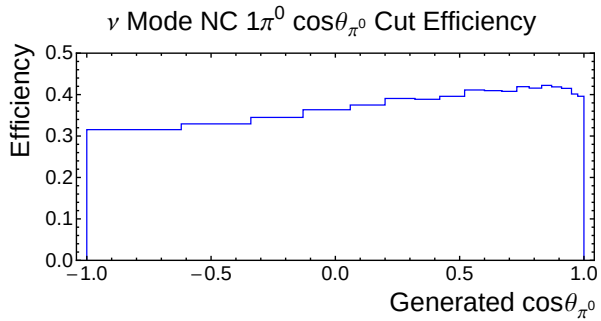
[a] G. D'Agostini, NIM A **362** (1995) 487

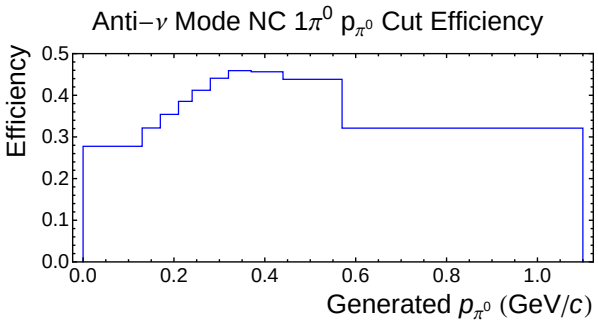
[b] A. Hocker and V. Kartvelishvili, NIM A **372** (1996) 469

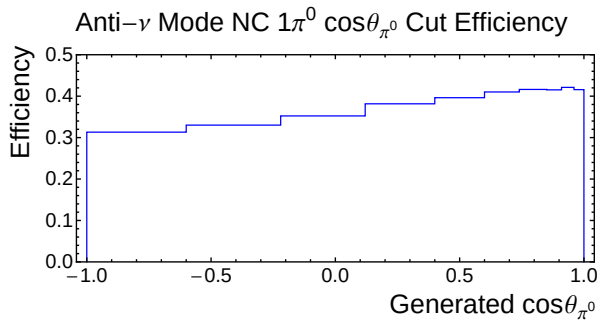
Correcting to the Cross Section

- Correct for events lost to cuts using efficiency







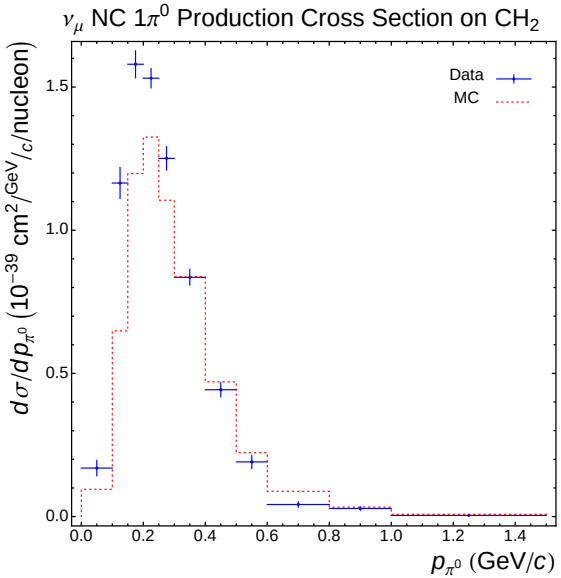


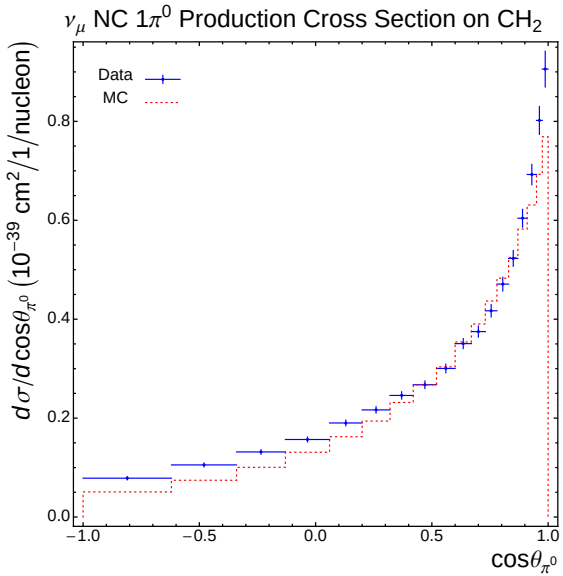
- Divide by number of targets in detector and integrated flux to get cross section
  - 4.88×10^{32} nucleons in fiducial volume
  - $3.36(43) \times 10^{11}$ ν_μ/cm^2 at $\langle E_\nu \rangle = 808$ MeV in neutrino running
  - $9.0(12) \times 10^{10}$ $\bar{\nu}_\mu/\mathrm{cm}^2$ at $\langle E_\nu \rangle = 630$ MeV in antineutrino running

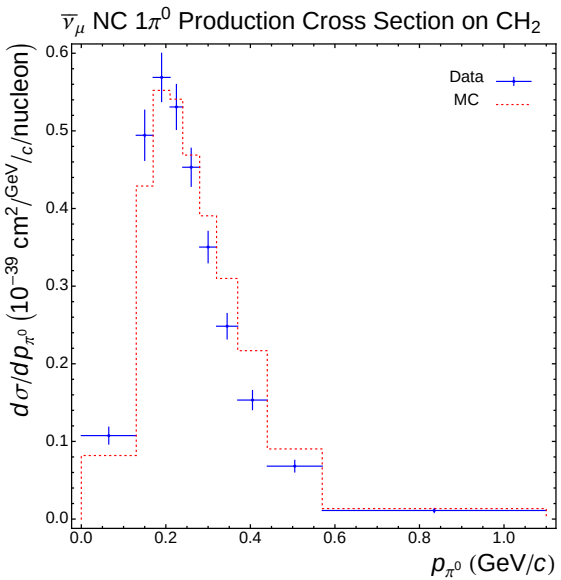
See Phys. Rev. D **79**, 072002 (2009) for flux prediction

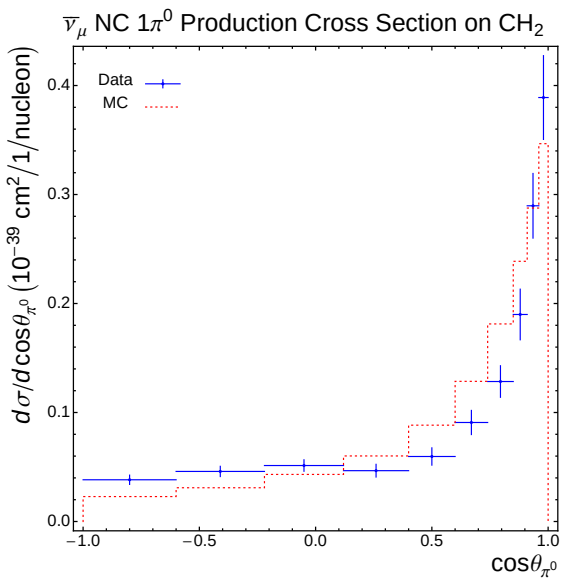
Cross Sections

- These are cross sections for inclusive NC $1\pi^0$ production per nucleon , averaged over MiniBooNE flux, and uncorrected for FSI
- MC prediction generated with NUANCE v3 using Rein-Sehgal for π^0 production with coherent production scaled by 0.65;
  - Measurement is more forward peaked than prediction
  - More production is measured in neutrino mode than predicted and *vise versa* in antineutrino mode









Cross Sections

- Systematic errors are calculated by measuring the covariance matrix of the cross section under random, correlated variations of the underlying parameters of the MC thrown according to their uncertainties

- Systematic errors include uncertainty in the integrated flux, cross section uncertainties on background model, and detector response uncertainties including bias introduced by unsmearing

Normalization Error

	ν_μ	$\bar{\nu}_\mu$
Flux	11.3%	12.9%
X-Sec.	9.3%	9.4%
Detector	4.3%	4.2%
Total	15.3%	16.5%

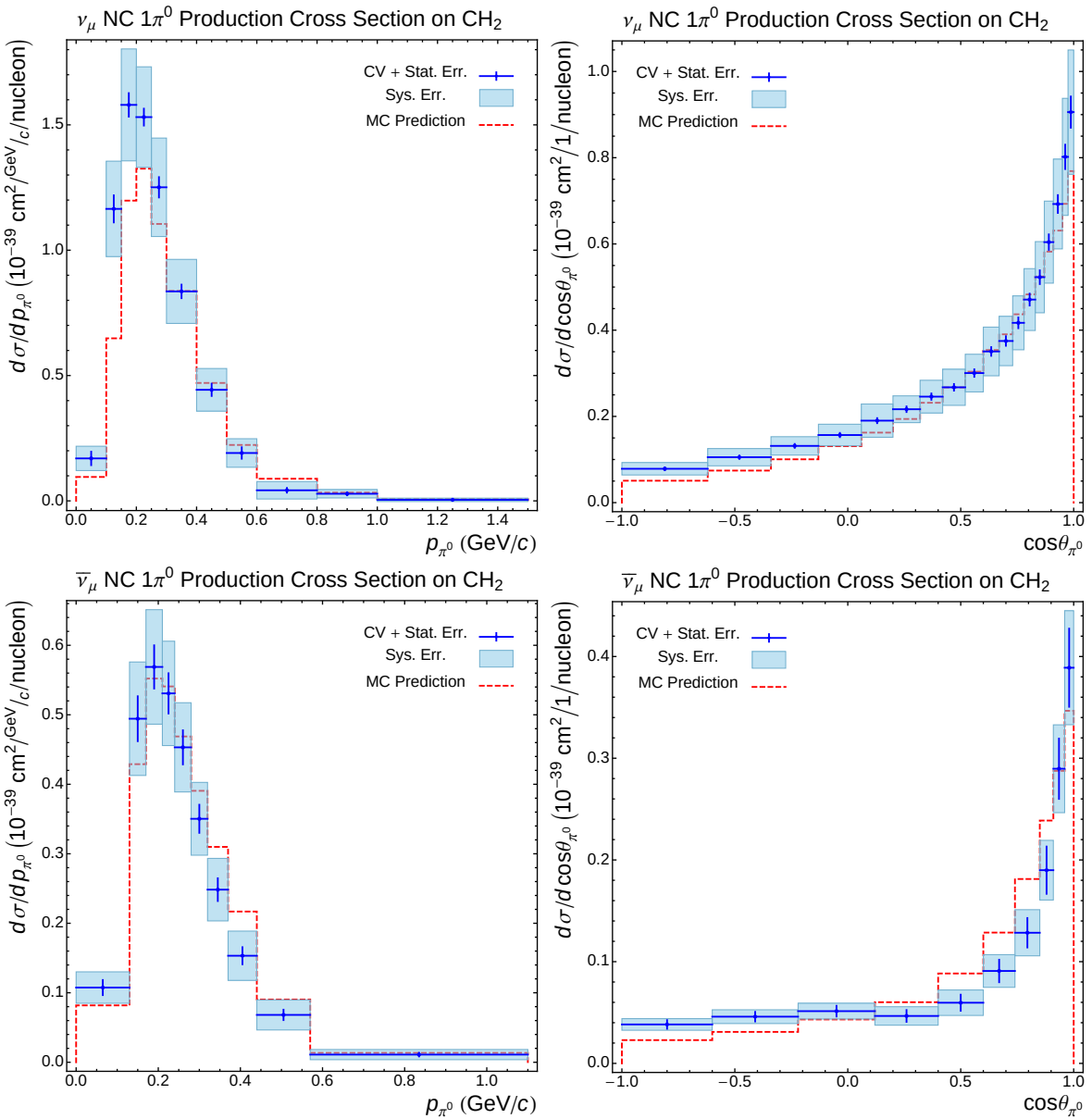
- Measurements largely systematics dominated

Cross Sections

Total NC $1\pi^0$ Production Cross Sections

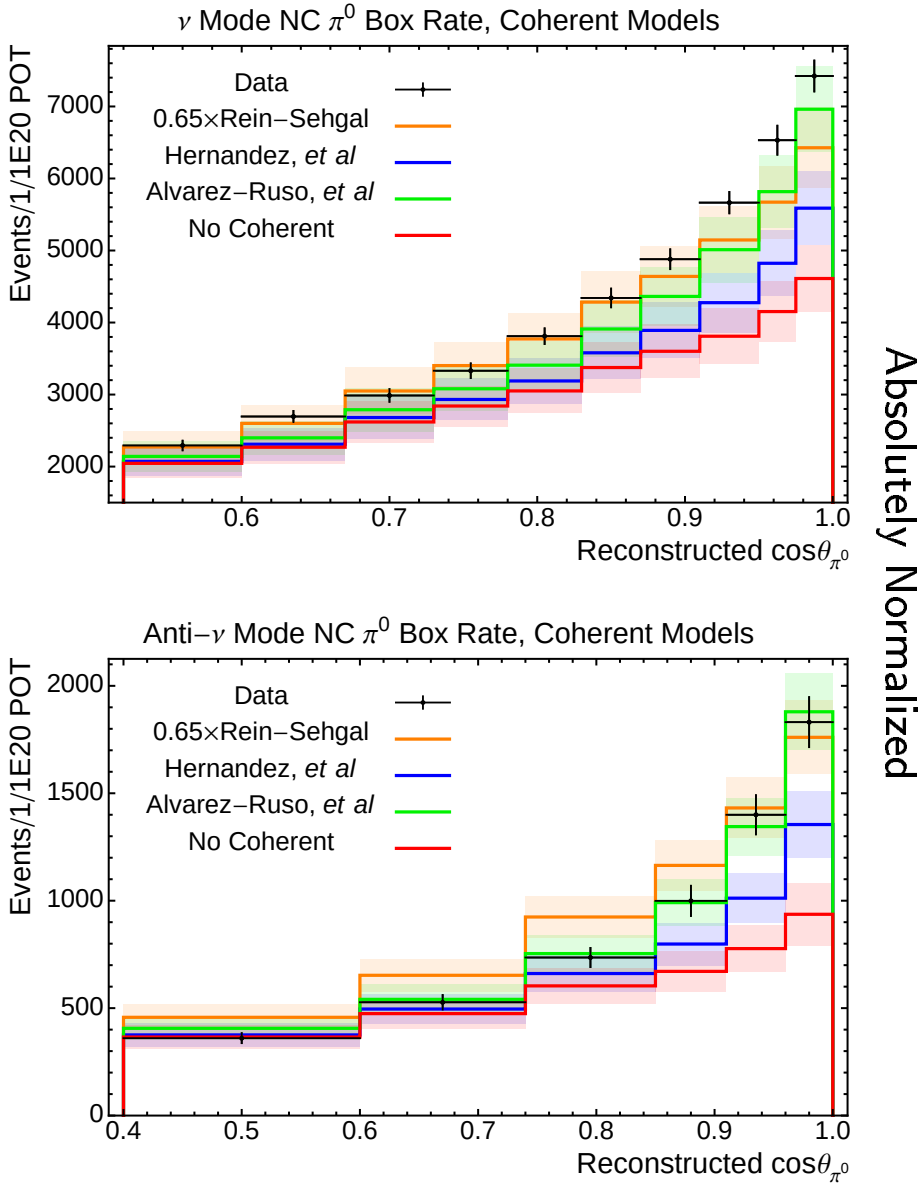
- ν_μ Induced $\sigma = (4.54 \pm 0.04_{stat} \pm 0.71_{sys}) \times 10^{-40}\,\mathrm{cm}^2/\mathrm{nucleon}$
- $\bar{\nu}_\mu$ Induced $\sigma = (1.43 \pm 0.03_{stat} \pm 0.23_{sys}) \times 10^{-40}\,\mathrm{cm}^2/\mathrm{nucleon}$

First absolute differential cross sections measured for NC π^0 production



Coherent Production Models

- Models for NC coherent π^0 production demonstrate wide variabilities in their predictions
- Forward angular distribution (particularly for antineutrino mode) is very sensitive to predictions
- Calculated rate of events passing cuts using MiniBooNE default coherent production and predictions from Hernandez, *et al*[a], and Alvarez-Ruso, *et al*[b]

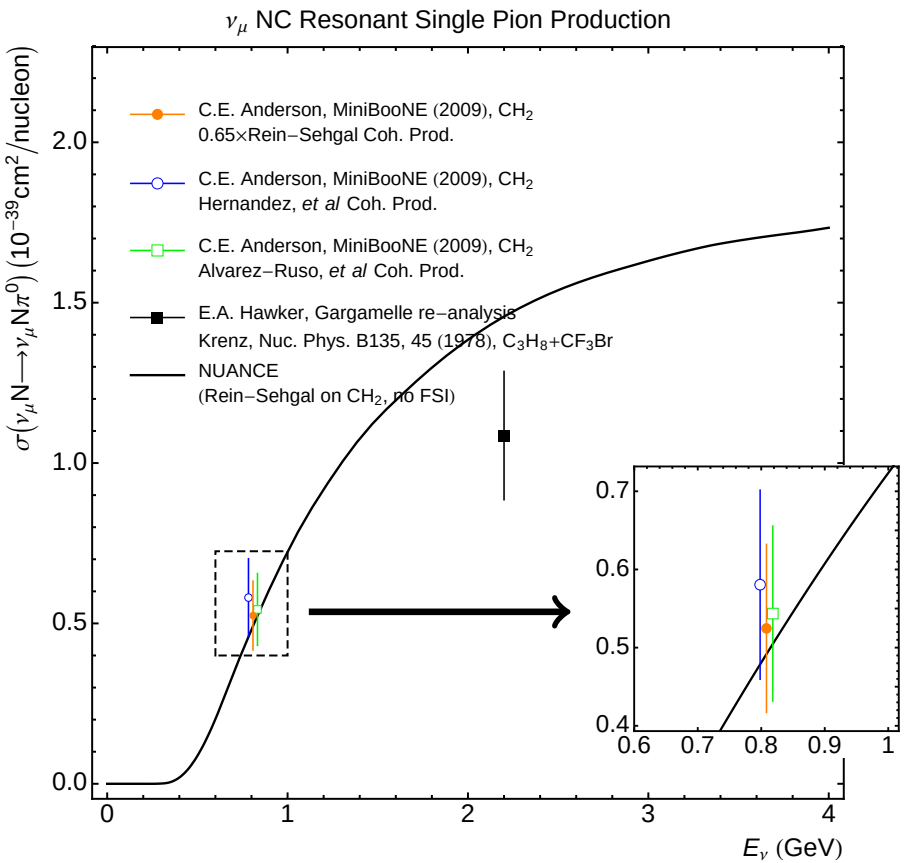


[a] arXiv:0903.5285v1; thanks to Juan Nieves for predictions

[b] Phys. Rev. C **76**, 068501 (2007); thanks to Luis Alvarez-Ruso for predictions

Resonant Production

- Previous absolute measurements of NC π^0 productions measured only resonant production
  - Hawker - Reanalysis of GGM data (Krenz et al., Nucl. Phys. B135, 45 (1978)) producing separate ν_μ cross sections on protons and neutrons
  - Faissner, *et al* (Phys. Lett. B125, 230 (1983)) - $\bar{\nu}_\mu$ and ν_μ cross section on protons only
- We can subtract the additional background and correct for FSI to produce an absolute total resonant cross section for comparison
  - Calculated using each of the coherent production models mentioned previously



Conclusions

- MiniBooNE has collected the largest sample of both neutrino and antineutrino induced NC π^0 events to date ($\sim 20k$ events in neutrino running and $\sim 2k$ events in antineutrino running)
- We have calculated the first differential NC $1\pi^0$ cross sections and the first absolute NC $1\pi^0$ total cross section
  - Measurement is systematics dominated
  - Angular cross sections will be invaluable in testing models of coherent production
  - Measurements will be published in the coming months