Summer Conference Highlights on Pion Production

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FNAL PPD/Neutrino, October 8th 2010

Summer Conference Highlights on Pion Production

- Resonant pion production.
- Coherent pion production.
- Future experiments.
- Summary.

Neutrino Induced Pion Production

Two reactions:

- Resonant
  - CC and NC

$\nu_\mu + A \rightarrow l + \pi + X$

- Coherent
  - CC p+ , NC p0

$\nu_\mu + A \rightarrow l^- + \pi^+ + A$

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

Resonant Pion Production

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

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

Neutrino resonant pion production:

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

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

Resonant Pion Production Model

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.

Review of the Experiments

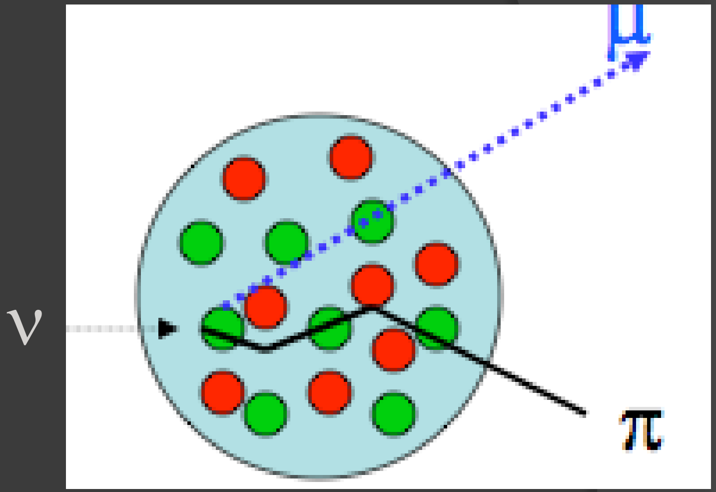
All experiments that have published/presented results on resonant pion production in the last 5 years.

Experiments	$\langle E_\nu \rangle$ GeV	Main goal	Detector	ν target	ν MC	Cross section results
K2K	1.3	θ_{23}, Δm_{23}	Fine Grained, Water Cher	CH, H_2O	NEUT	Pub: $NC\pi^0$, $CC\pi^+$ Prelim: $CC\pi^0$
MiniBooNE	0.7	$\nu_\mu \rightarrow \nu_e$	Oil Cher	CH_2	NUANCE	Pub: $NC\pi^0$ Prelim: $CC\pi^+$, $CC\pi^0$
SciBooNE	0.7	σ_ν	Fine Grained	CH	NEUT, NUANCE	Pub: $NC\pi^0$ Prelim: $CC\pi^0$

- two oscillation experiments + a dedicated cross section experiment,
- nuclear targets,
- resonant single pion production results.

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.



Measuring Cross Sections for Nuclear Targets

Signal definition:

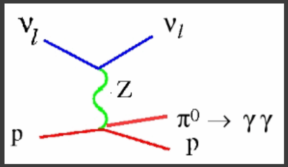
- observable signal - all events experimentally indistinguishable at nuclear level – least model dependent - no FSI correction.
- nucleon level signal – needs correction for FSI - model dependent, large uncertainties due to large FSI model uncertainty.

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.



Resonant ν_μ NC π^0

$$\nu + n(p) \rightarrow \Delta^0 (\Delta^+) + \nu$$
$$\downarrow$$
$$n(p) + \pi^0 \rightarrow n(p) + \gamma + \gamma$$

Neutrino oscillation:

- **very important for ν_e appearance searches**
  - **if one of the γ's is lost or below threshold.**

Neutrino cross section:

- **important for understanding coherent and resonant production.**
- **no data below 2GeV.**

World data consists of several measurements of cross section ratios.

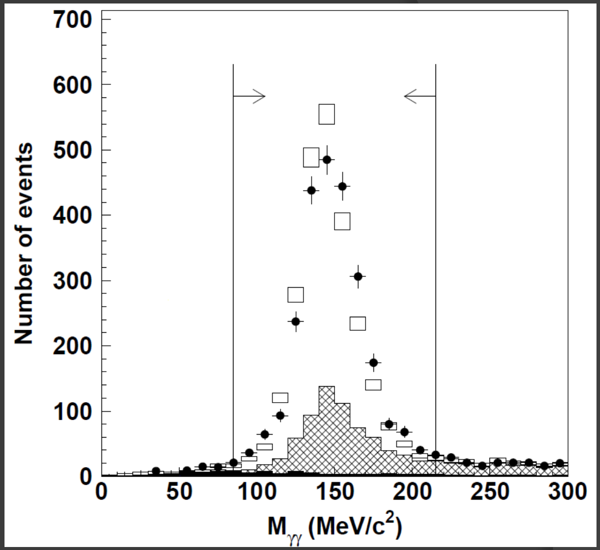
ν_μ NC π^0 Cross Section Ratio

K2K measurement - 1kt water Cherenkov

Reconstruction – 2 γ rings
$\sigma^{NC\pi^0}/\sigma^{CC}$= 0.064±0.001(stat.)±0.007(sys.)
MC prediction is 0.065.

Very good π^0 reconstruction.

K2K Collaboration, Phys.Lett. B619 (2005) 255-262

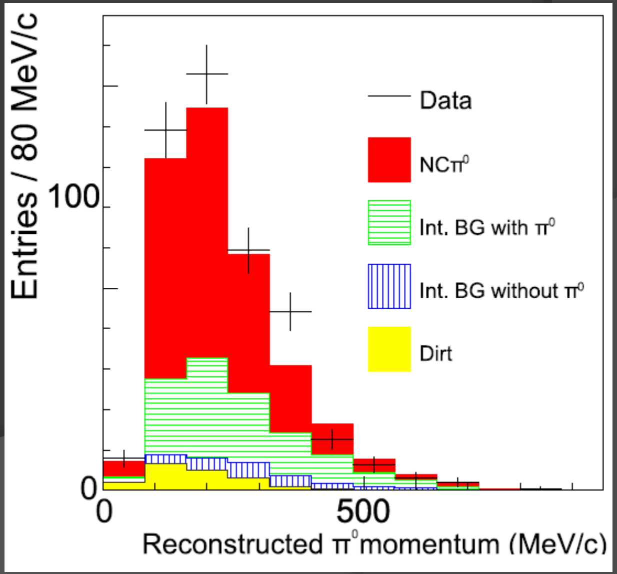


SciBooNE measurement

Reconstruction:
- **2 γ reconstructed with SciBar and EC**

$\sigma^{NC\pi^0}/\sigma^{CC}$= (7.7 ± 0.5(stat.) ± 0.5(sys.)) × 10^{-2}
MC prediction 6.8x10^{-2}

SciBooNE Collaboration, Phys. Rev. D 81, 033004 (2009)

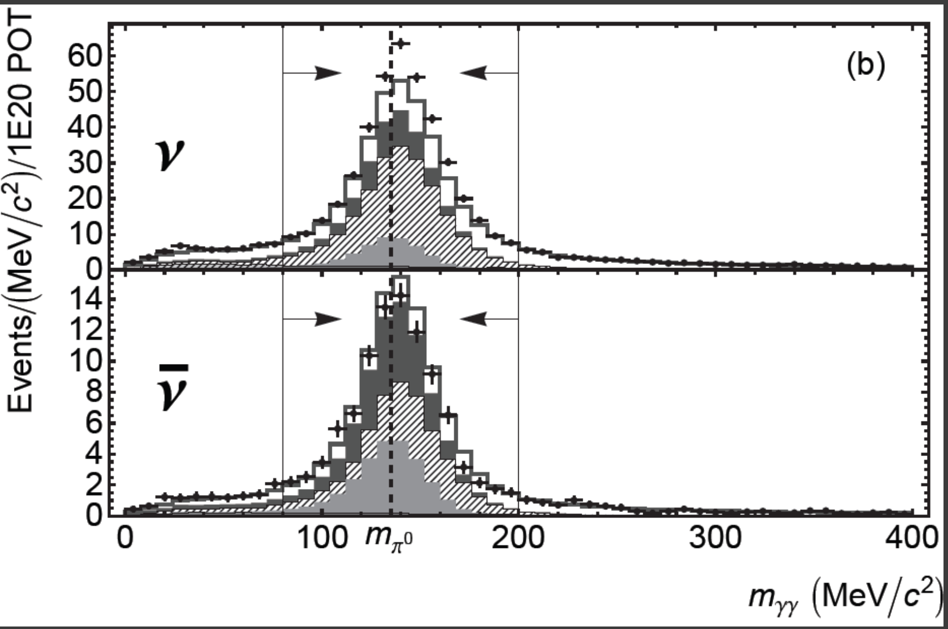


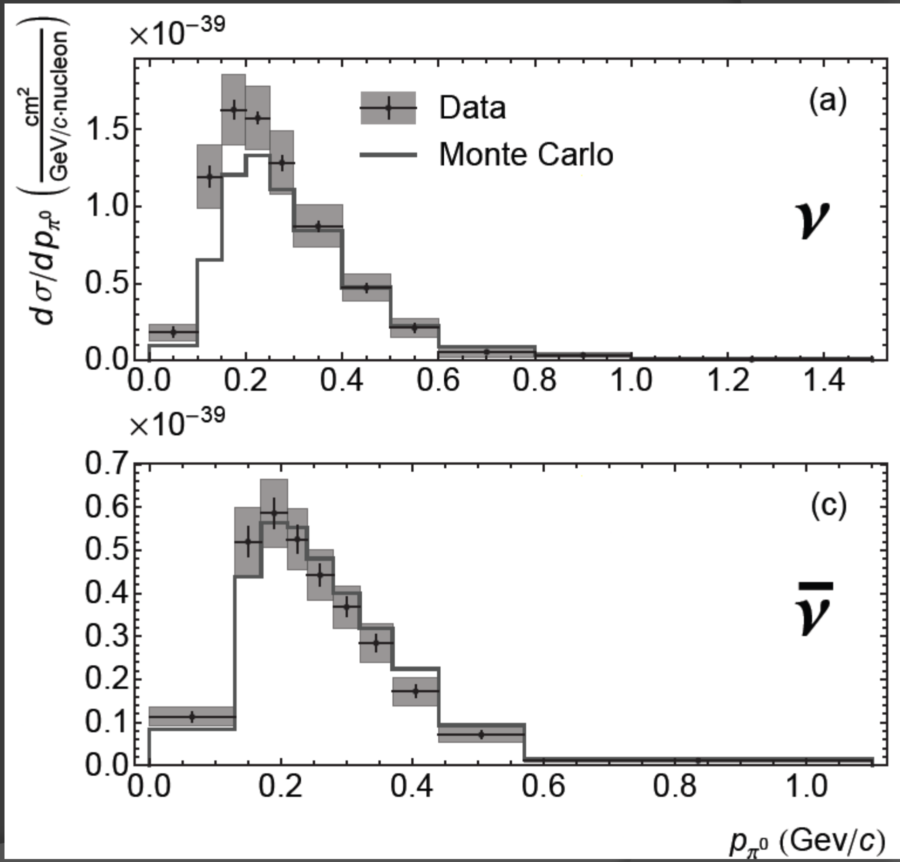
MiniBooNE ν_μ NC π^0 Measurement

Excellent π^0 containment (4π).
Signal definition – observable.

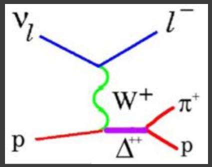
First inclusive differential cross sections for this channel for both ν and $\bar{\nu}$:
$d\sigma/dp_{\pi^0}$, $d\sigma/d\cos\theta_{\pi^0}$

Reconstruction:
- 2γ rings
- fully reconstructed π^0 sample – 21,542 events, 73% purity, 36% efficiency





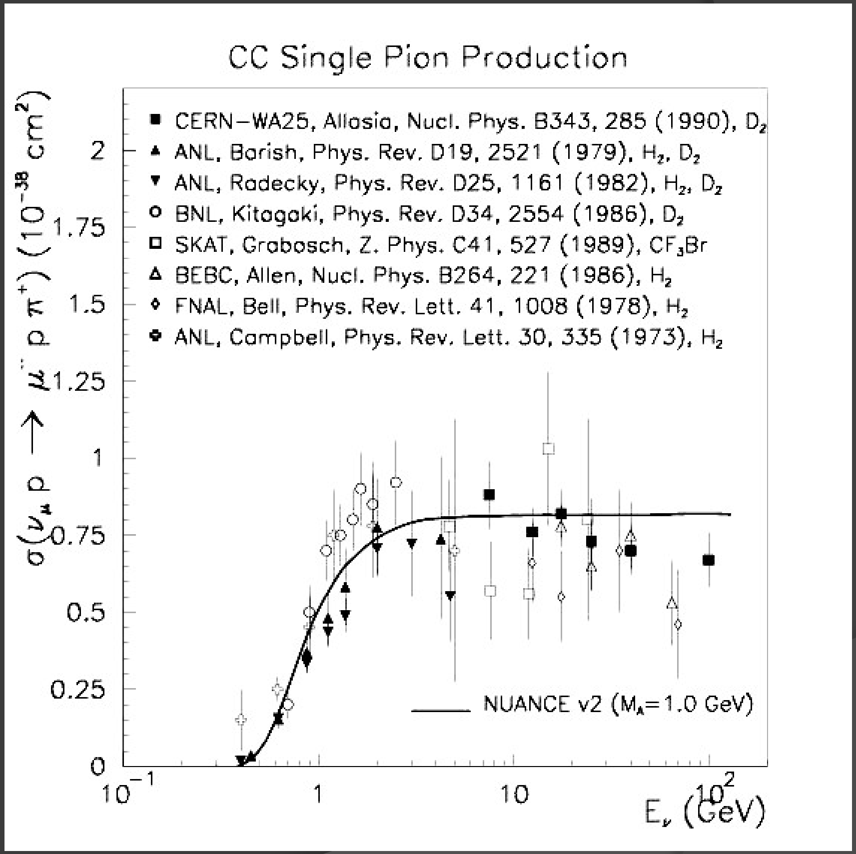
MiniBooNE Collaboration, Phys.Rev.D81:013005,2010



Resonant ν_μ CC π^+

$$\nu + n(p) \rightarrow \Delta^+(\Delta^{++}) + \mu$$
$$\downarrow$$
$$n(p) + \pi^+$$

ν_μ CCπ^+ world data



Important for neutrino oscillation:

- major background for ν_μ disappearance
  - modifies ν_μQE energy spectrum.
- need to know ν_μCCπ+/ν_μCCQE(E_ν) to better than 5%.

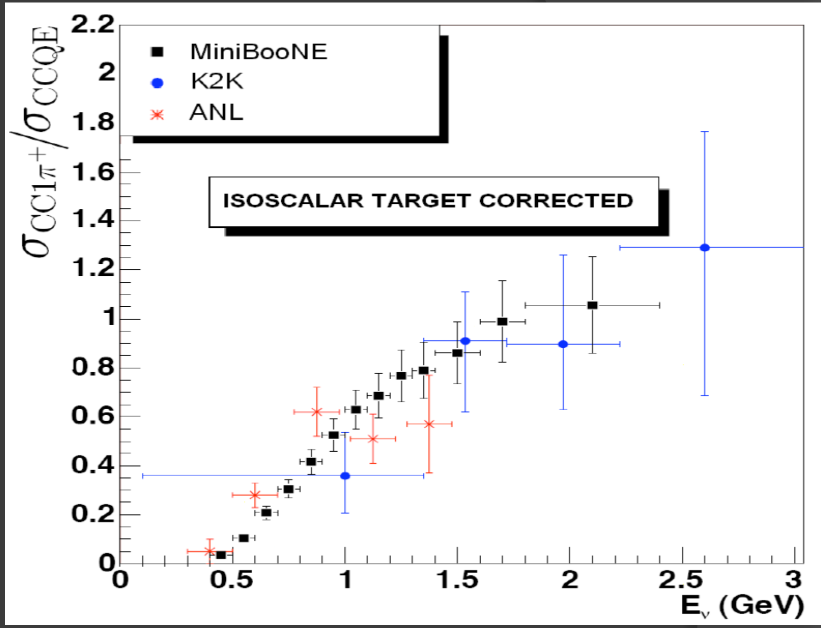
Existing data from bubble chamber experiments:

- D_2, H_2 targets.

ν_μ CC π^+ Cross Section Ratio

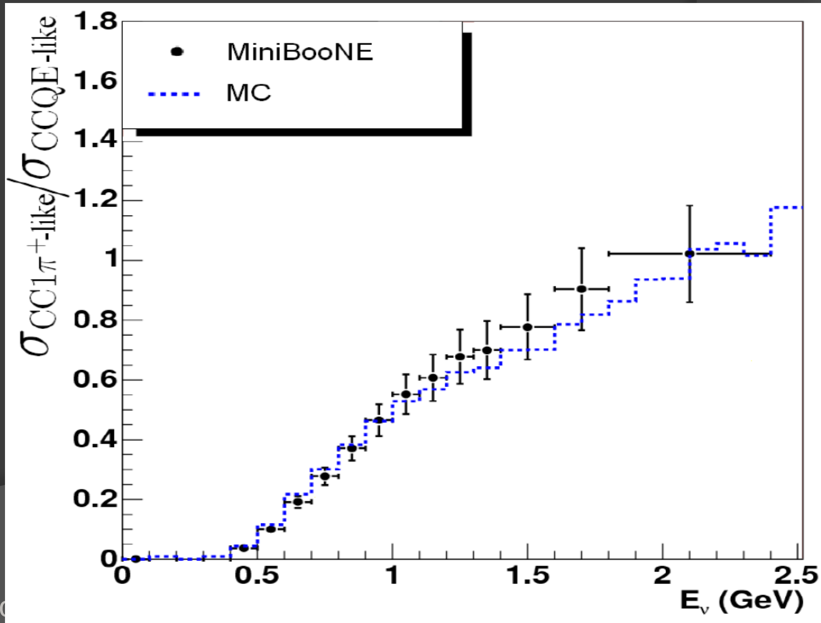
K2K measured the ratio to the ν_μCCQE events.

K2K Collaboration,Phys.Rev.D78:032003,2008



MiniBooNE measured the ratio to the ν_μCCQE events.

MiniBooNE Collaboration,
Phys. Rev. Lett. 103, 081801 (2009)



- Both measurements are consistent with previous measurements.
- Both measurements are consistent with Rein-Sehgal model.

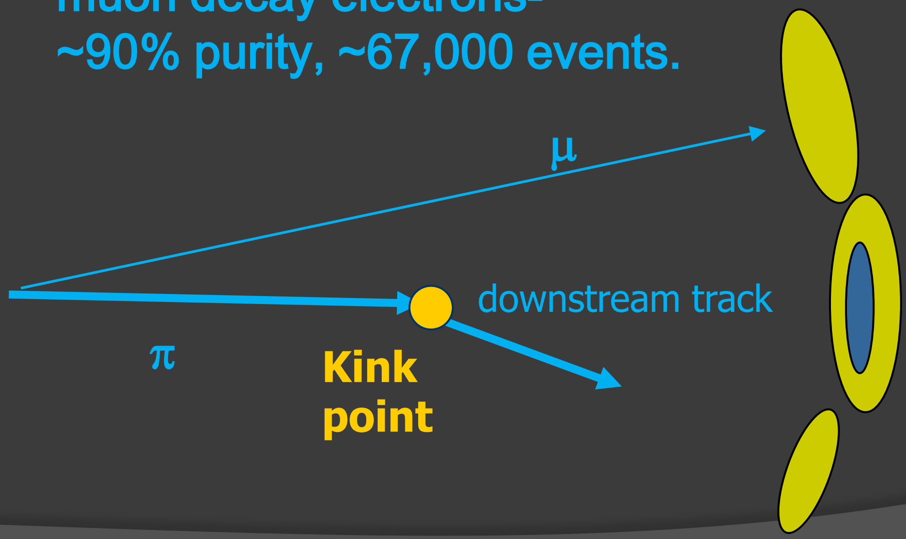
MiniBooNE ν_μ CC π^+ - Fully Reconstructed

Signal definition:

- observable – only $1\pi^+$ and 1μ emerging from the target nucleus with no other mesons.

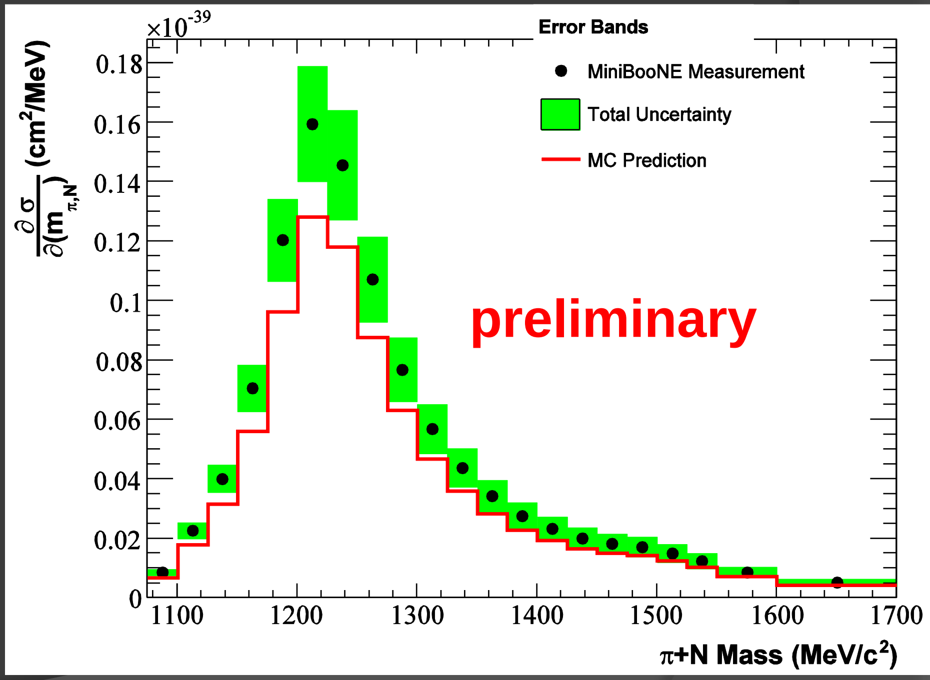
Reconstruction:

- π^+ undergoes hadron interactions results in kinked tracks.
- 3 rings - μ and kinked π^+
- events are tagged by two stopped muon decay electrons- ~90% purity, ~67,000 events.



First full reconstruction of $CC\pi^+$ events in Cherenkov detector.

First Δ peak from neutrino experiment in more than 20 years.



MiniBooNE ν_μ CC π^+ - Fully Reconstructed

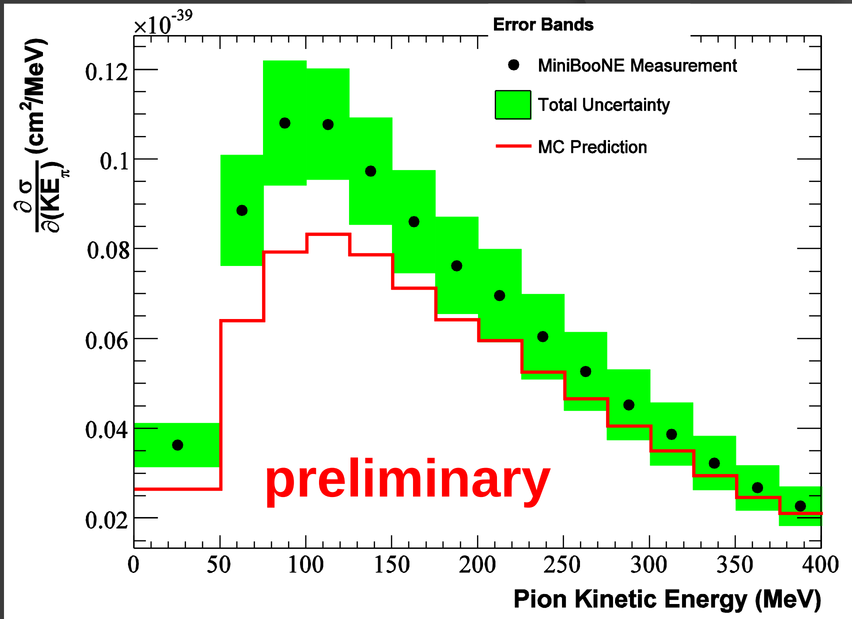
First measurement of inclusive CCπ^+ differential cross sections

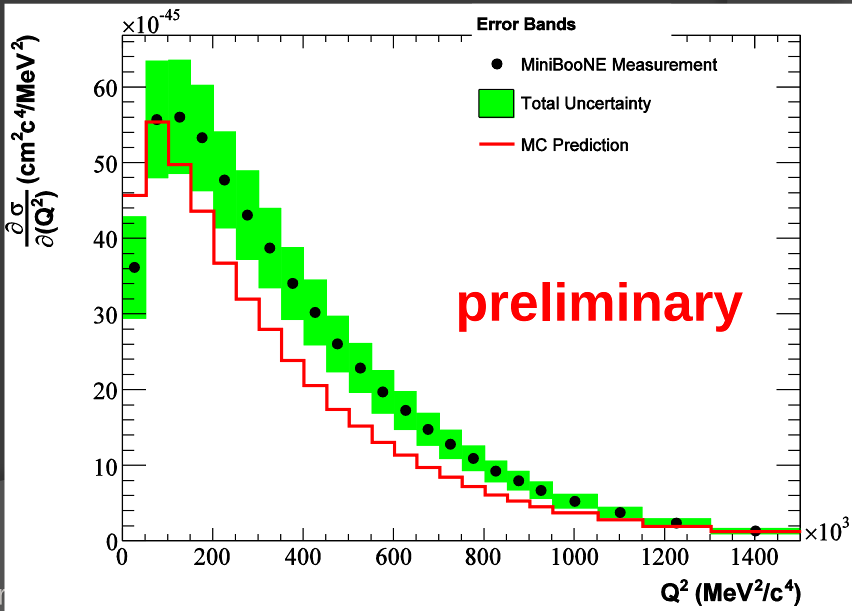
Differential cross sections (flux averaged)
  $d\sigma/d(Q^2)$, $d\sigma/d(E_\mu)$, $d\sigma/d(\cos\theta_{\mu,\nu})$
  $d\sigma/d(E_\pi)$, $d\sigma/d(\cos\theta_{\pi,\nu})$:

Double Differential Cross Sections
- $d^2\sigma/d(E_\mu)d(\cos\theta_{\mu,\nu})$, $d^2\sigma/d(E_\pi)d(\cos\theta_{\pi,\nu})$

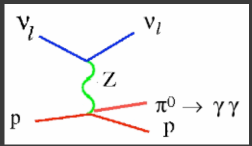
- Data Q^2 shape differs from the model

Paper is in preparation.





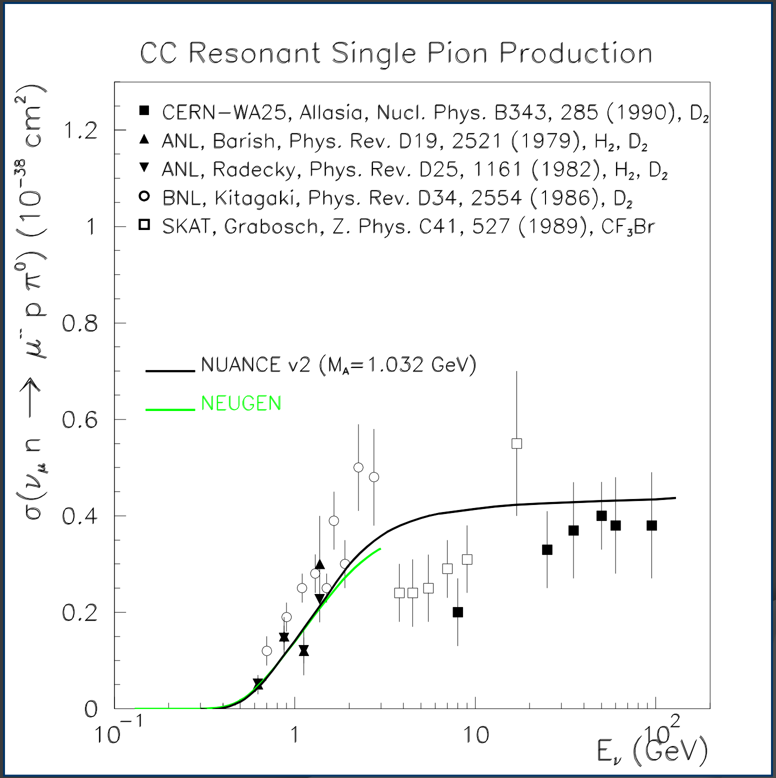
M. Wilking, PhD Thesis, University of Colorado, 2009



ν_μ CC π^0 Cross Section

$$\nu + n \rightarrow \Delta^+ + \mu$$
$$\downarrow$$
$$p + \pi^0 \rightarrow p + \gamma + \gamma$$

ν_μ CCπ^0 world data

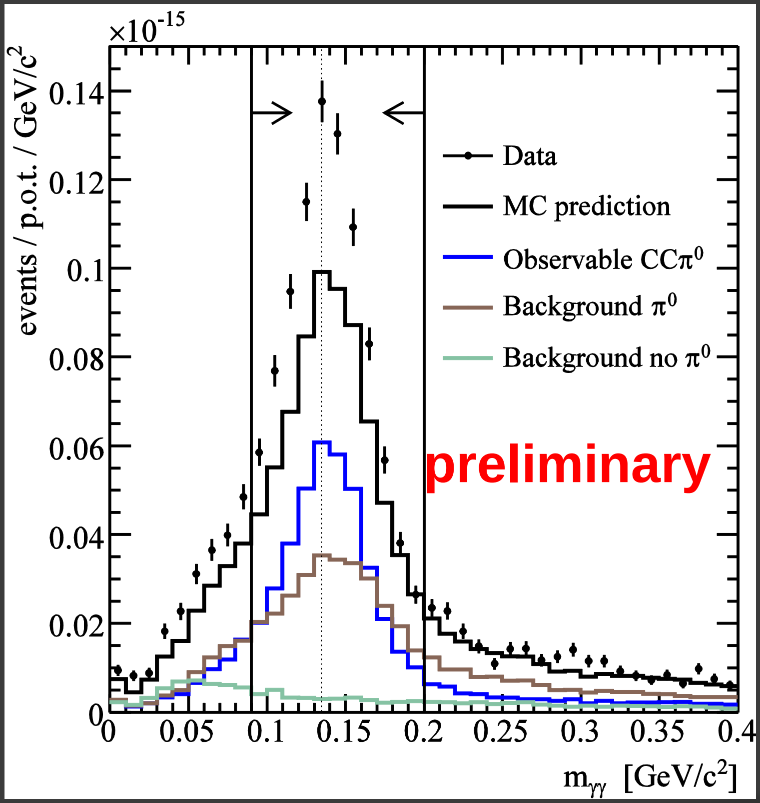


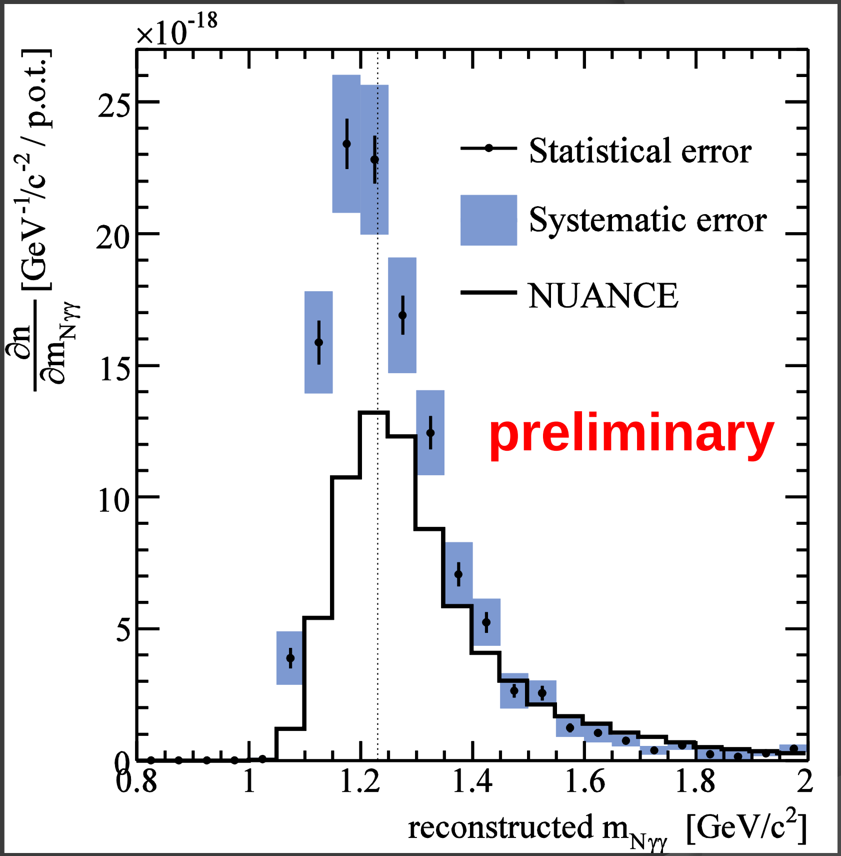
- Not a major concern as an oscillation background, BUT
- Resonant only– valuable for understanding the resonant production without coherent contamination.
- Existing data from bubble chamber experiments on H_2, D_2

MiniBooNE ν_μ CC π^0 Kinematics

Reconstruction:

- 3 rings – $\mu + 2\gamma$ - reconstruct entire event
- $\gamma\gamma$ invariant mass shows clear π^0 mass peak.
- Non-π^0 background doesn't peak at the π^0 mass.





Background subtracted $m_{N\gamma\gamma}$.
First reconstruction of CCπ^0 events in Cherenkov detector.

MiniBooNE ν_μ CC π^0 Cross Section

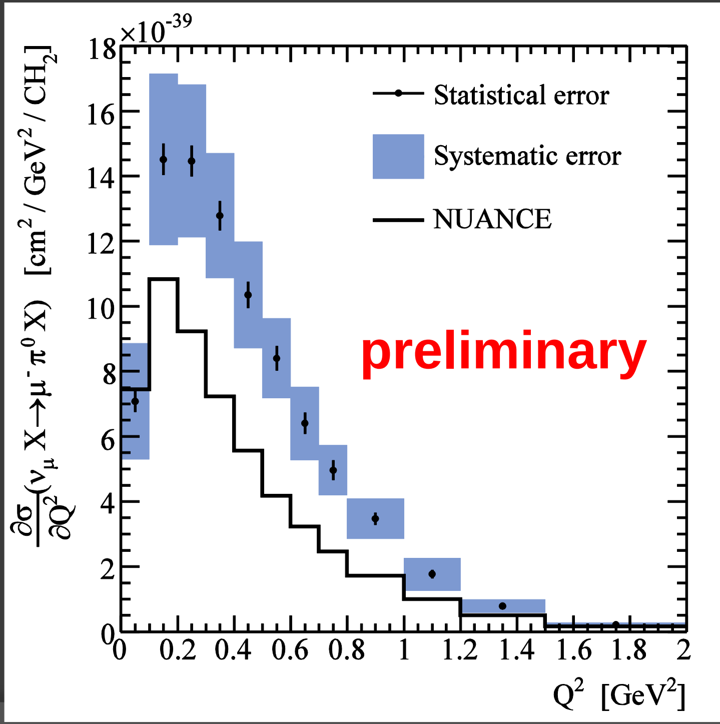
Signal definition: observable - $1\pi^0$ and 1μ emerging from the target nucleus with no other mesons.

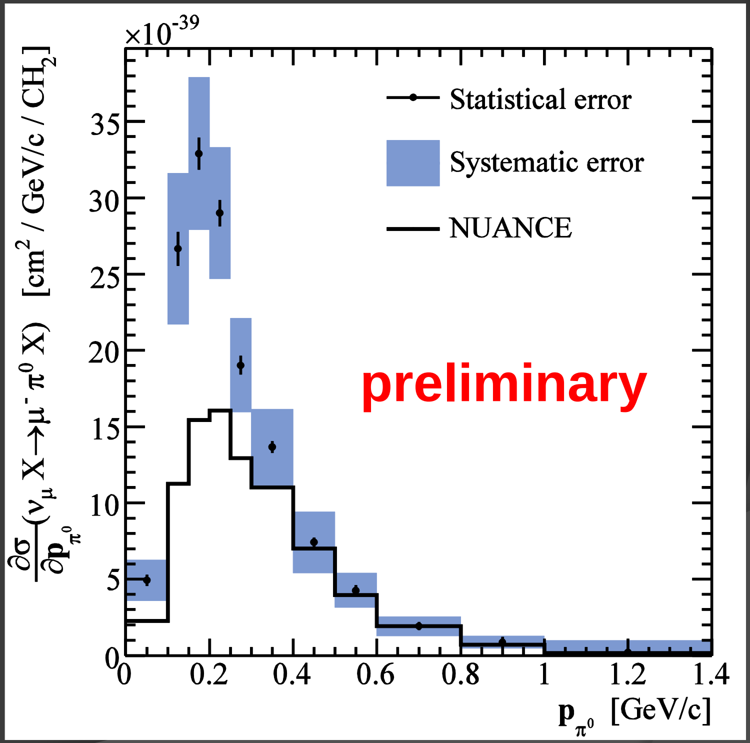
First measurement of inclusive $CC\pi^0$ differential cross sections:

- **$\sigma(E)$, $d\sigma/dQ^2$, $d\sigma/dE_\mu$, $d\sigma/d\cos\theta_\mu$ $d\sigma/dE_{\pi^0}$, $d\sigma/d\cos\theta_{\pi^0}$**

- **Total fractional error is 18%.**
- **Largest systematic error 12% is due to π^+ charge exchange model in the oil (background).**

Paper in preparation.





R. Nelson, PhD Thesis, University of Colorado, 2010

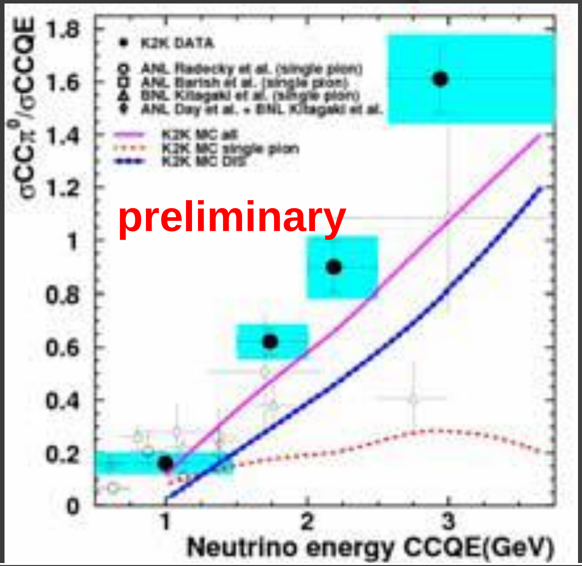
ν_μ CC π^0 Cross Section

K2K ongoing analysis
Signal definition - observable - 1 or more π^0
Reconstruction:
- **using SciBar + muon range detector (MRD)**
- **μ track in SciBar with a matched track in MRD.**
- **2 electron showers in SciBar or EC.**

Total cross section ratio to CCQE.
$\sigma^{CC\pi^0}/\sigma^{CCQE}$ =0.443 ±0.033(stat.) ±0.036(syst.)

Data is higher than MC. *Mariani, NuInt09*

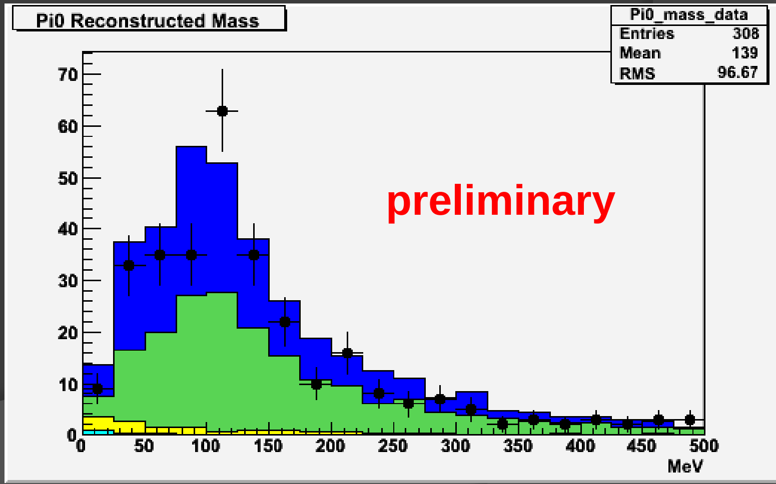
Total cross section ratio to CCQE in 4 energy bins.



SciBooNE ongoing analysis.
Signal definition – observable.
Reconstruction:
- **similar to K2K - using SciBar + MRD**
- **no electron showers in SciBar or EC are required.**

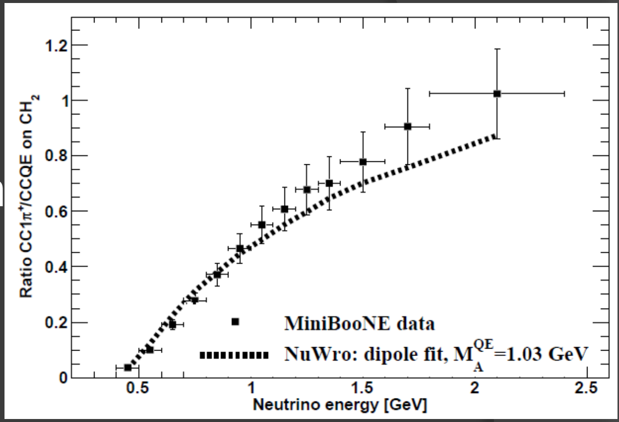
Goal is to calculate absolute cross section.

J. Catala, NuInt09



Resonant Pion Production Summary

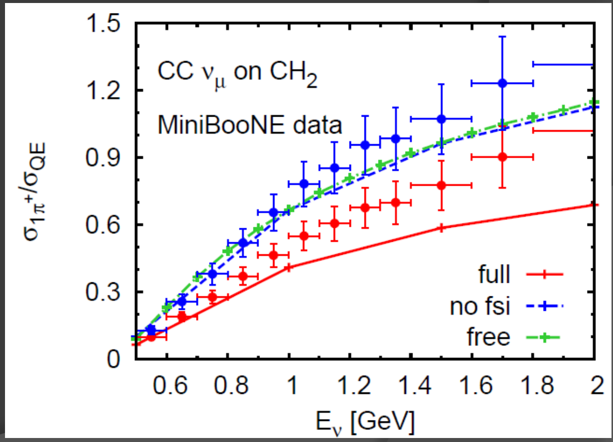
Current models disagree in both shape and normalization



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



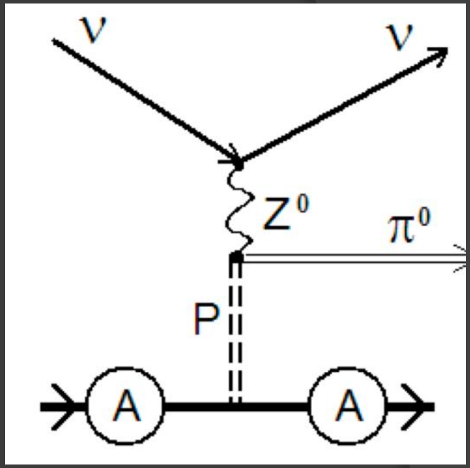
- N-Δ axial formfactor $C^5_A(0)$
  Graczyk et al., PRD 80 (2009)
  Hernandez et al., PRD 81 (2010)

- FSI models:
  GiBUU Leitner et al., PRC 73 (2006)
  Ahmad et al., PRD 74 (2006)

Coherent Pion Production

$\nu_\mu + A \rightarrow l^- + \pi^+ + A$

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



Interacts coherently with the whole nucleus

- No break up.
- Small momentum transfer.
- Very forward pion.
- No other particles in the final state.

Coherent Pion Production Model

Model used by experiments to build MC is
Rein and Sehgal model Nucl. Phys. B223 (1983) 29:

- Process dominated by AXIAL Vector current.
- Isovector current contribution small.
- Use PCAC
- AT $Q^2 = 0$ related to the π-A cross section
- Isospin: σ(CC: π+) = 2 σ(NC: πo)

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

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

As $Q^2 \to 0$ only σ_s survives.

$$\sigma_S = \frac{|q|}{\kappa Q^2} f_\pi^2 \sigma_{\pi N}$$

Review of the Experiments

All experiments that have published/presented results on coherent pion production in the last 5 years.

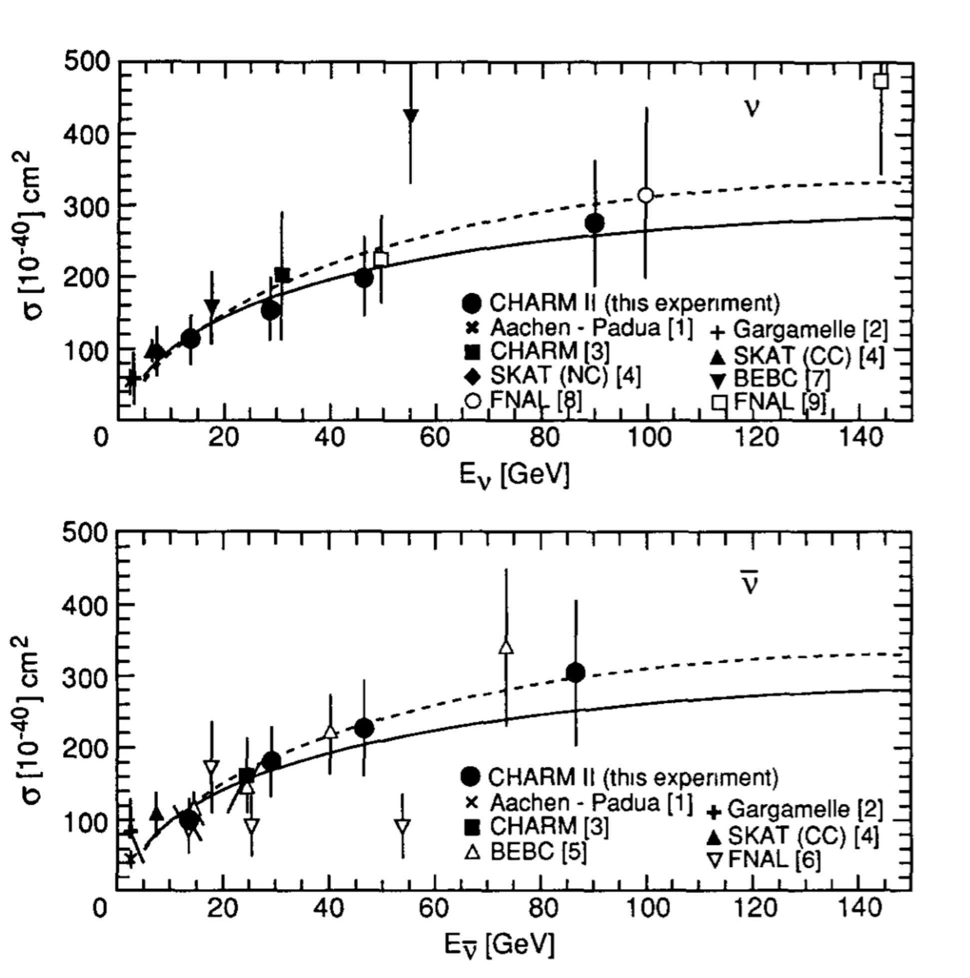
Experiments	$\langle E_\nu \rangle$ GeV	Main goal	Detector	ν target	ν MC	Cross section results
K2K	1.3	θ_{23}, Δm_{23}	Fine Grained, Water Cher	CH, H_2O	NEUT	Pub: $CC\pi^+$
MiniBooNE	0.7	$\nu_\mu \rightarrow \nu_e$	Oil Cher	CH_2	NUANCE	Pub: $NC\pi^0$
SciBooNE	0.7	σ_ν	Fine Grained	CH	NEUT, NUANCE	Pub: $NC\pi^0$, $CC\pi^+$
NOMAD	24.8	$\nu_\mu \rightarrow \nu_\tau$	Drift Chambers	C		Pub: $NC\pi^0$

Coherent CC π^+ Production

Measured well at energies > 2 GeV.

Experimental difficulties:

- Large background: DIS at high energy and resonant pion at low energy.
- Proton from CCQE could be misID as a π^+.
- At low energy usual technique is to assume a model for the resonant production – large uncertainties.



K2K CC π^+ Production

SciBar detector + MRD.

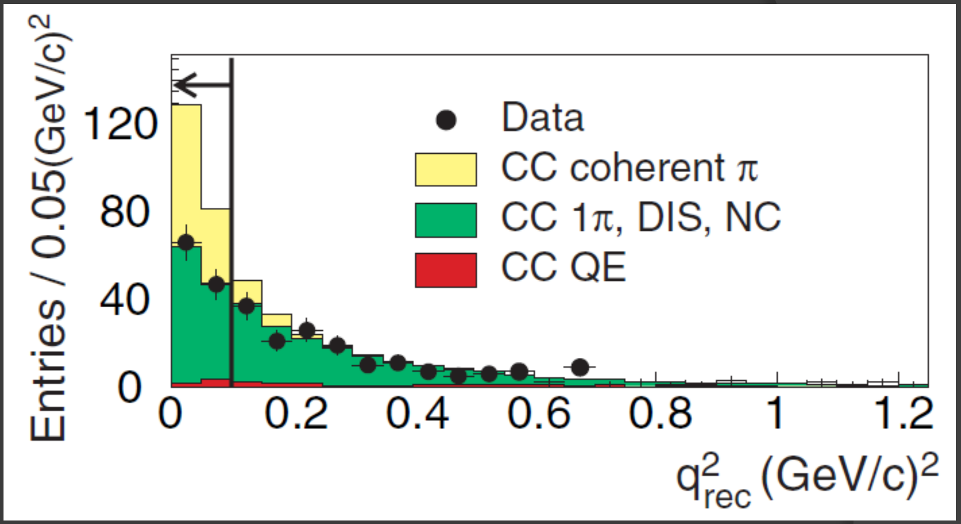
2 track only sample.

One track MRD matched.

Looking at the low Q^2 bins – enhanced coherent fraction.

Data is inconsistent with coherent pion production.

$\langle E_\nu \rangle$ = 1.3 GeV



Phys. Rev. Lett. 95:252301 (2005)

Measured ratio $\sigma(\text{CC coh } \pi^+)/\sigma(\text{CC}) = [0.04 \pm 0.29(\text{stat})\ ^{+0.32}_{-0.35}\ (\text{syst})] \times 10^{-2}$

Limit $\sigma(\text{CC coh } \pi^+)/\sigma(\text{CC}) < 0.006$ at 90% CL.

SciBooNE CC π^+ Production

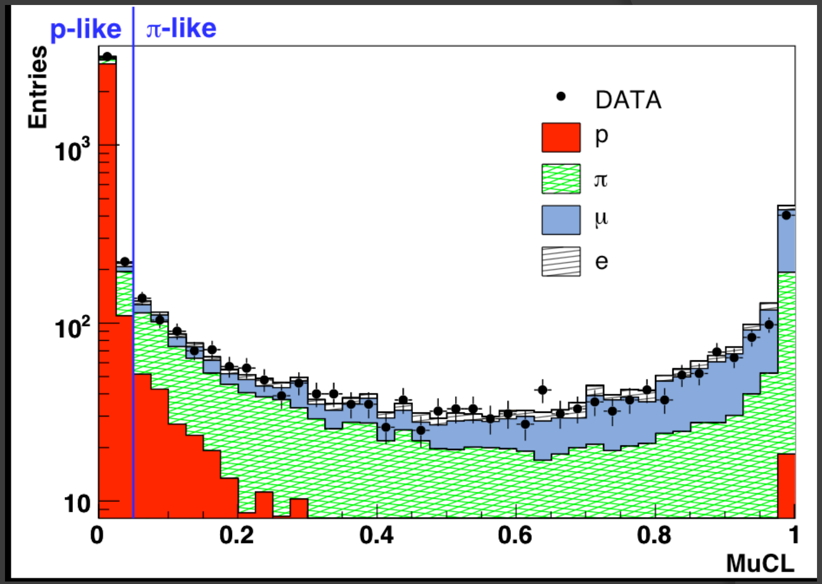
SciBar detector + MRD.

Similar analysis.

2 track only sample.

One track MRD matched.

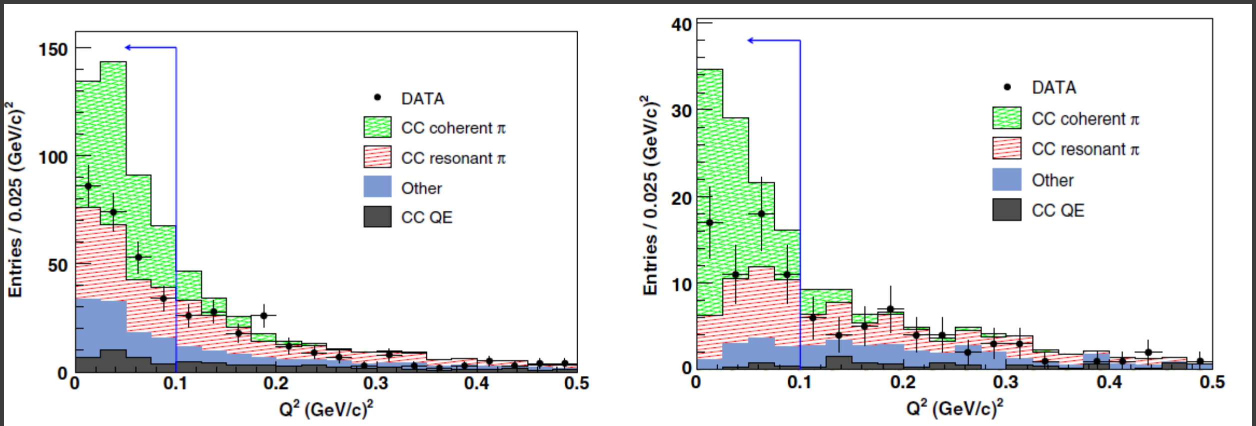
NEUT using Reing-Seghal model for resonant and Coherent production.



Phys. Rev. D78:112004 (2008)

In addition SciBooNE used muon CL to remove the protons.

SciBooNE CC π^+ Production



2 samples with different energy:

MRD stopped

$\langle E_\nu \rangle = 1.1$ GeV

$\sigma(\text{CC coh } \pi^+)/\sigma(\text{CC}) = [0.16 \pm 0.17(\text{stat})\ ^{+0.30}_{-0.27}\ (\text{syst})] \times 10^{-2}$

$\sigma(\text{CC coh } \pi^+)/\sigma(\text{CC}) < 0.0067$ at 90% CL.

MRD traversed

$\langle E_\nu \rangle = 2.2$ GeV

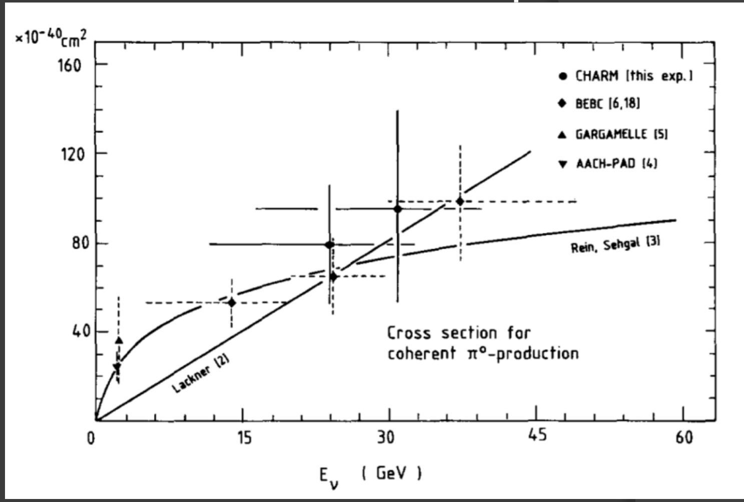
$\sigma(\text{CC coh } \pi^+)/\sigma(\text{CC}) = [0.68 \pm 0.32(\text{stat})\ ^{+0.39}_{-0.25}\ (\text{syst})] \times 10^{-2}$

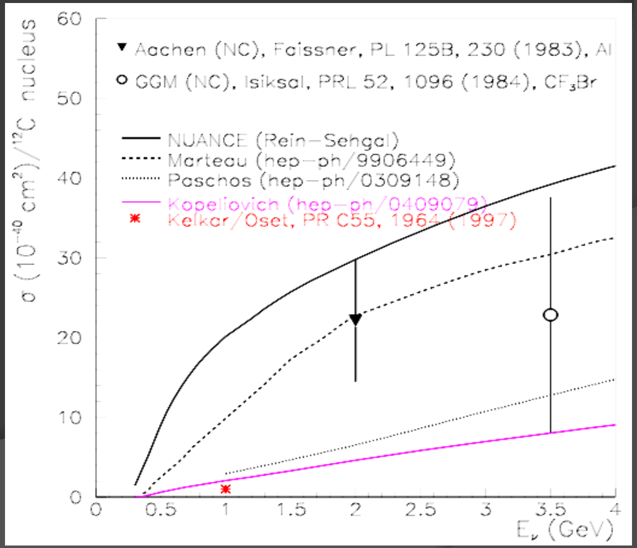
$\sigma(\text{CC coh } \pi^+)/\sigma(\text{CC}) < 0.0136$ at 90% CL.

Coherent NC π^0 Production

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

World data on coherent production





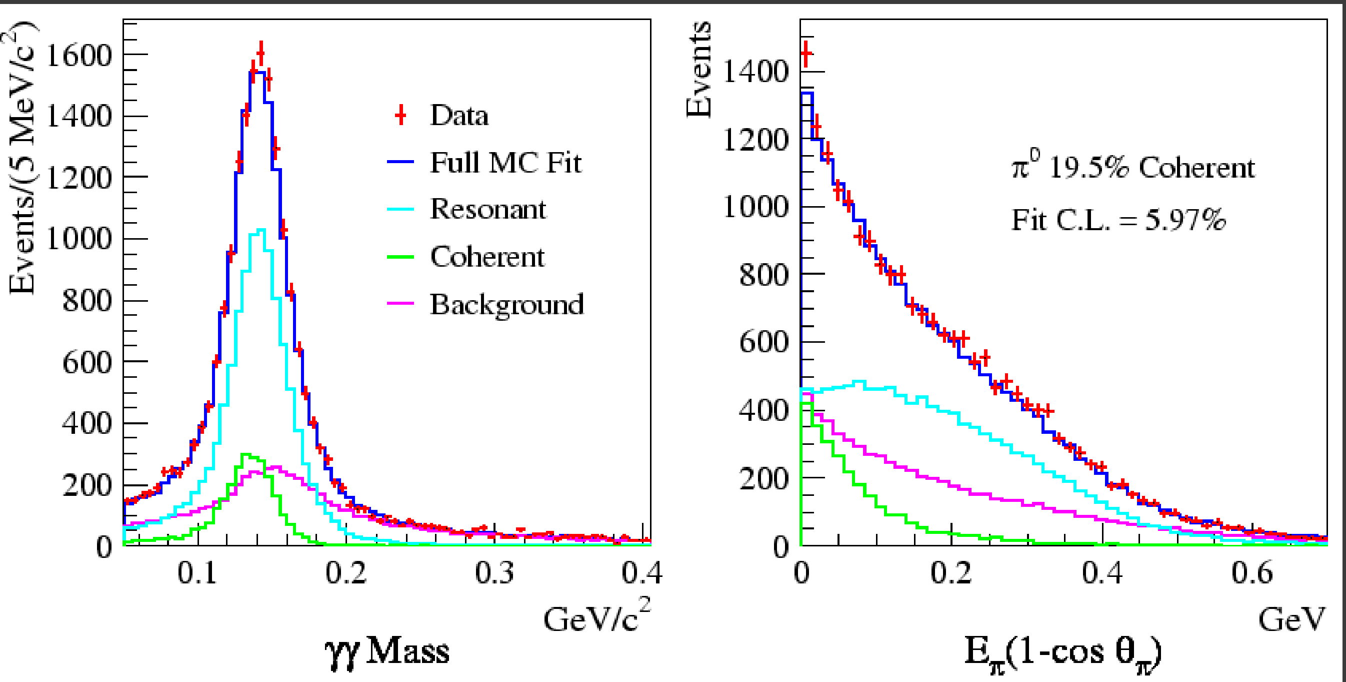
Neutrino oscillation:

- very important for ν_e appearance searches
  - if one of the γ's is lost or below threshold

Neutrino cross section:

- important for understanding coherent and resonant production.
- no data below 2GeV.
- Rein – Sehgal model used for prediction.

MiniBooNE NC π^0 Production



First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with E_ν<2 GeV, Phys Lett B.664, 41 (2008)

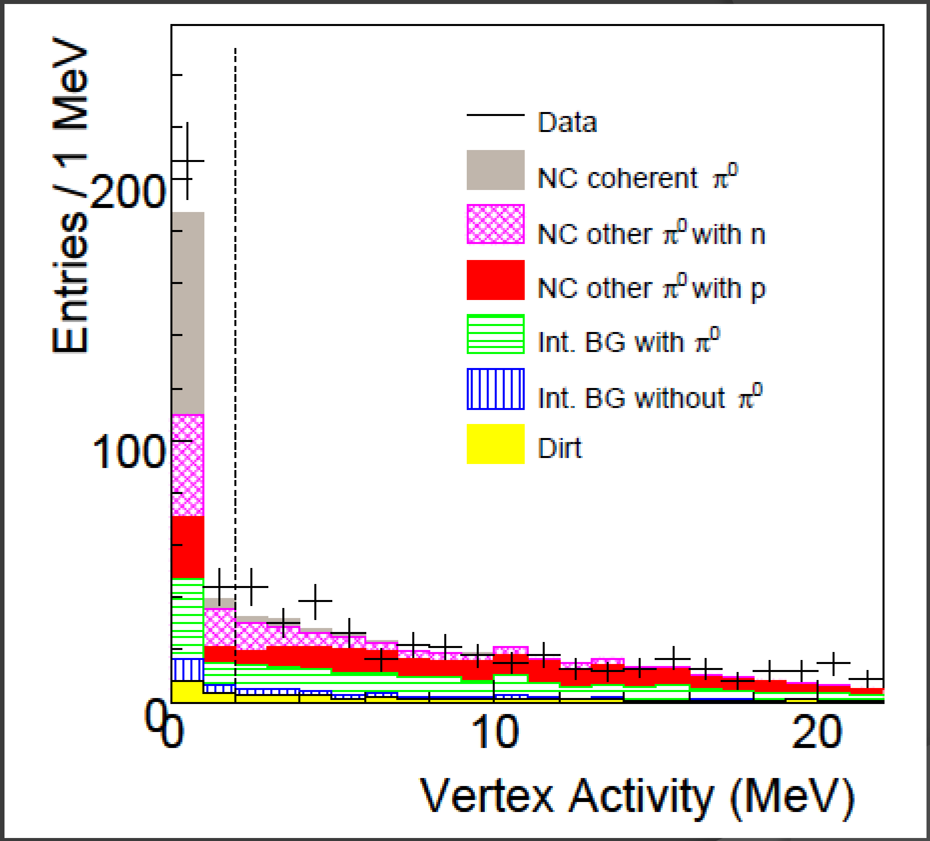
- excellent π^0 containment (4π)
- fully reconstructed π^0 sample – 28,600 events, 97% purity, 40% efficiency
- reweighting of momentum distribution gives very good agreement in other kinematic variables.

- very different angular distributions – coherent is much more forward
- fit for resonant and coherent fractions yields [19.5±1.1(stat)±2.5(syst)]% coherent fraction.

SciBooNE NC π^0 Production

Event selection:

- Most coherent pion events have low vertex activity near the reconstructed vertex.
- In the remaining events the high activity due recoil proton.
- 2 samples: with activity and without activity.



arXiv:1005.0059 hep-ex

SciBooNE NC π^0 Production

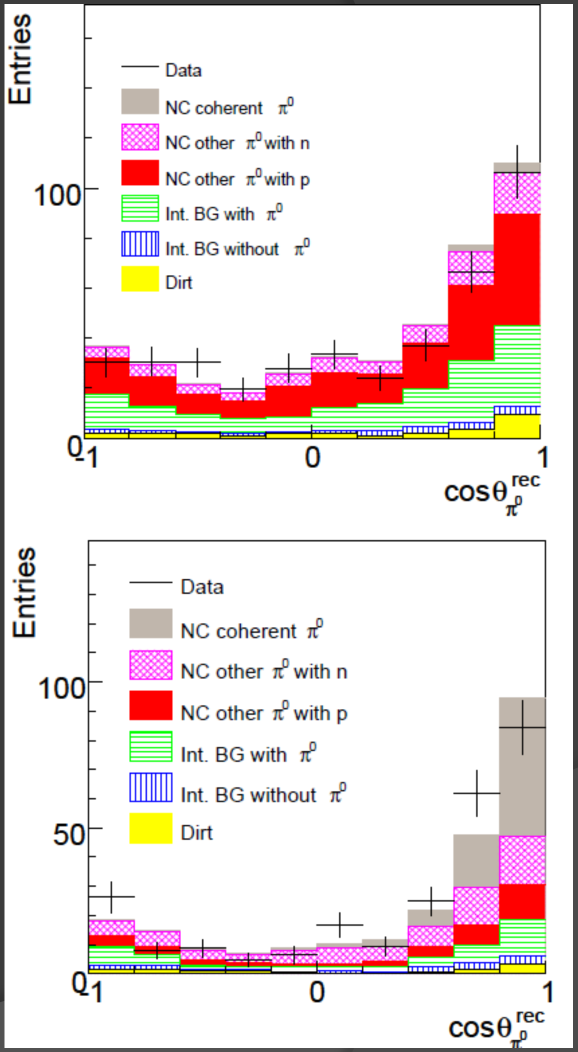
Perform a simultaneous template fit to the $E_{\pi 0}(1-\cos\theta_{\pi 0})$ for both samples using coherent, resonant and background templates.

Fitted coherent fraction:

Rcoh = 0.96±0.20

$\sigma(CCcoh\pi^0)/\sigma(CC) = [0.16 \pm 0.17(stat)\ ^{+0.30}_{-0.27}\ (syst)] \times 10^{-2}$

$\sigma(CCcoh\pi^0)/[\sigma(CCcoh\pi^0)+ \sigma(CCres\pi^0)]= (17.9 \pm 4.1)\%$



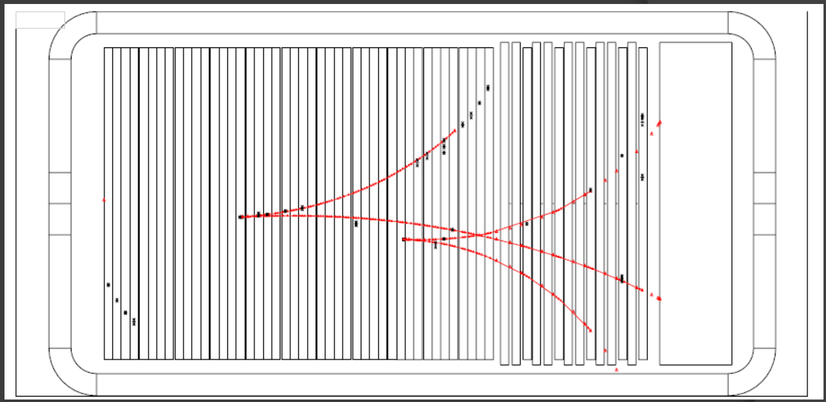
NOMAD NC π^0 Production

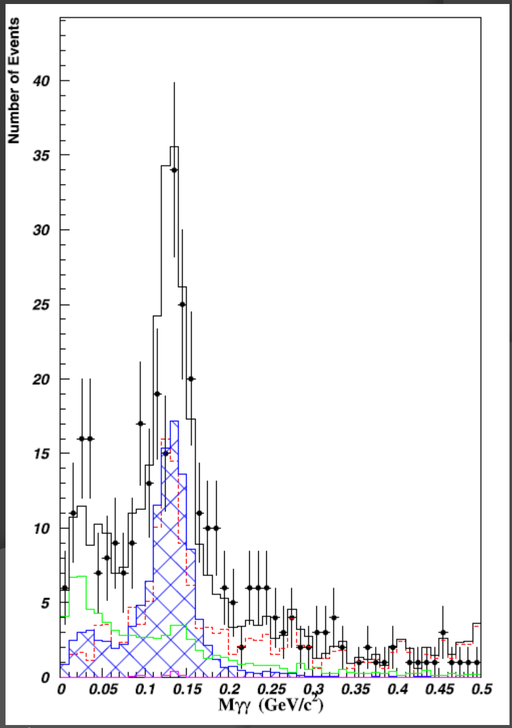
Signal definition: 2 photons converted in the DC target.

Reconstruction: able to reconstruct The 4 momentum of the pions -both e^+ and e^- momenta are analyzed using the magnetic field.

Vertex determined from Distance of closest approach – Z-DCA 13cm resolution.

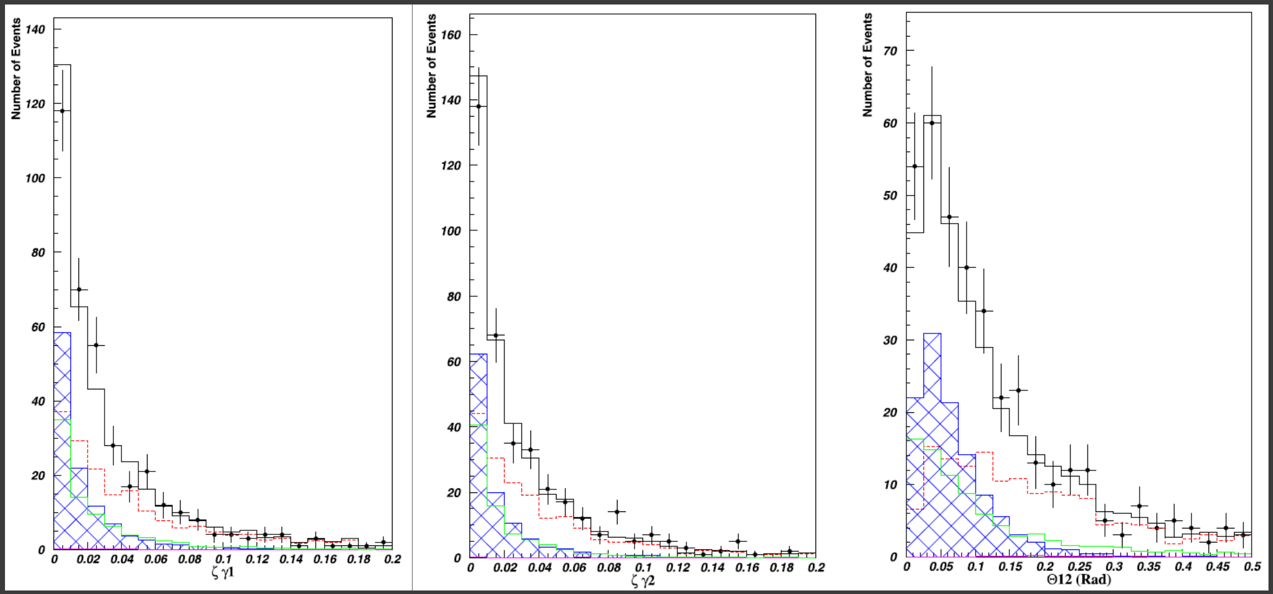
NC DIS events are at $M_{\gamma\gamma} > 0.2$ GeV/c^2





Phys. Lett. B682: 177 (2009)

NOMAD NC π^0 Production



Simultaneous fit to the distributions ζ_1, ζ_2, θ_{12}, where $\zeta_i = E_{\gamma i}(1-\cos\theta_{\gamma i})$ and θ_{12} is the $\gamma\gamma$ angle.

Using NC DIS template (fixed) + upstream bkg + Coh

$\sigma(\mathrm{NCcoh}\pi^0)/\sigma(\mathrm{CC})$= [3.21 ± 0.36(stat) ± 0.29(syst)]x10^{-3}

$\sigma(\mathrm{NCcoh}\pi^0)$= [72.6 ± 8.1(stat) ± 0.29(syst)]x10^{-40} cm^2/nucleus

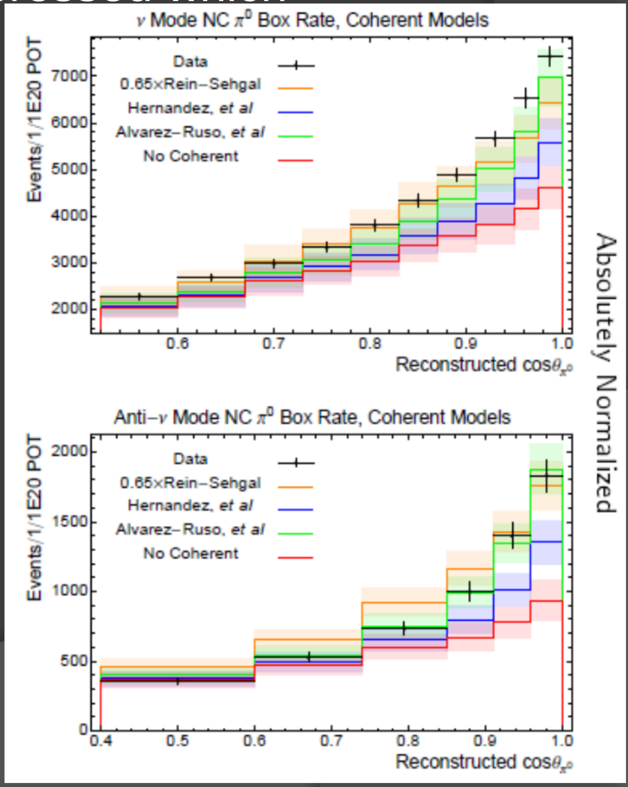
Agrees well with Rein-Sehgal.

Coherent Pion Production Summary

Coherent pion production is measured at E_ν>2GeV
- Rein-Sehgal model agrees with data in this region for both CC and NC

At energies below 2GeV predictions disagree with measurements
- For NC new measurements imply the coherent component is non 0.
- Model dependent measurements.
- For CC data suggests coherent pion production is suppressed which is inconsistent with models.

Theoretical models:
- PCAC
  Hernandez et al., PRD 80 (2009) 013003
  Paschos & Schalla, PRD 80 (2009),
  Berger & Sehgal, PRD 76 (2007),79 (2009)
- Microscopic
  Singh et al., PRL 96 (2006)
  Alvarez-Ruso et al, PRC 76 (2007)
  Amaro et al., PRD 79 (2009)
  Nakamura et al., PRC 81 (2010)



What Is Next?

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:

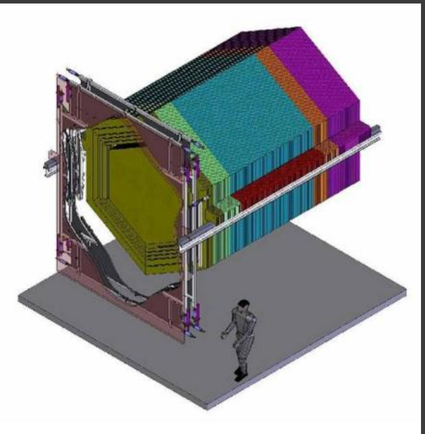
- Models explaining data.
- Refrain from fitting.
- Predictions which can be tested in new detectors.

The Future is Here

T2K and MINERvA are taking data – results soon.

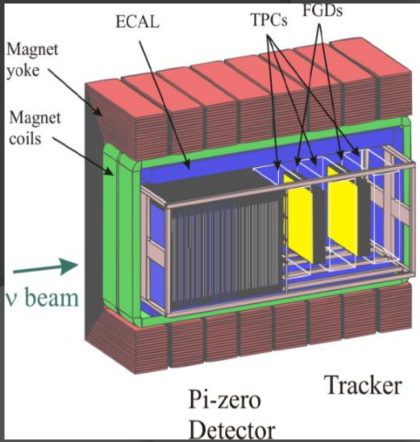
Experiments	$\langle E_\nu \rangle$ GeV	Hadron Prod. Exp.	Main goal	Detector	ν Target	ν MC
T2K ND280	0.7	NA61	θ_{13}, δ^{CP}	Fine-grain	C, H_2O	NEUT, GENIE
MINERvA	1-20	MIPP	σ_ν	Fine-grain	C, Fe, Pb, He, D	GENIE

MINERvA



- 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.

T2K ND280



Conclusions

There has been a major effort to measure the neutrino induced pion 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 and MINERVA have the potential to improve our understanding of the pion production.

- high power neutrino beams – sufficient statistics.
- dedicated hadron production experiments – flux.
- various targets.

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