Resonant Pion Production – Recent Measurements

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Resonant Pion Production – Recent Measurements

- Introduction.
- Experiments Review.
- Recent results.
- Future experiments.
- Summary.

Introduction

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:

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

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

Detailed theory - covered by L. Alvarez-Ruso.

Review of the Experiments

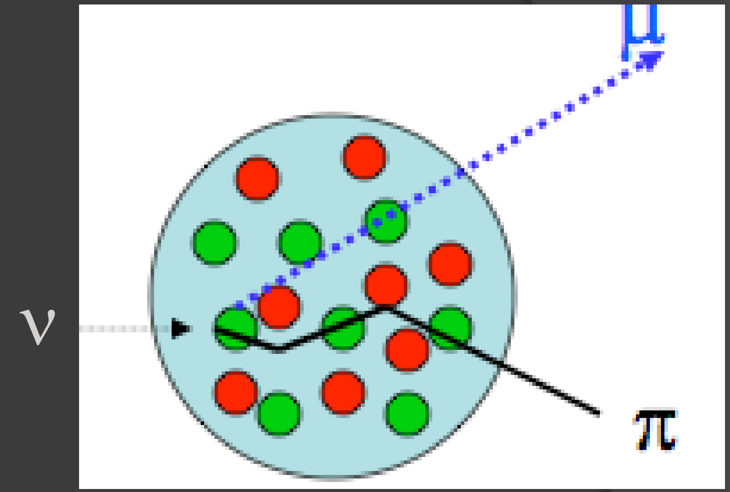
All experiments that have published/presented results on resonant pion production in the last 5 years.

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.



Nuclear model details - covered by O. Benhar.

Measuring Cross Sections for Nuclear Targets

Signal definition:

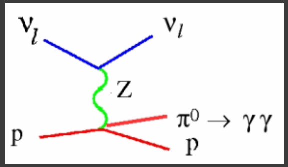
- observable signal - all events experimentally indistinguishable at nuclear level – least model dependent - no FSI correction.
- nucleon level signal – needs correction for FSI - model dependent, large uncertainties due to large FSI model uncertainty.

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. Flux prediction difficulties and *in-situ* flux techniques covered by M. Bishai and S. Kopp.



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.

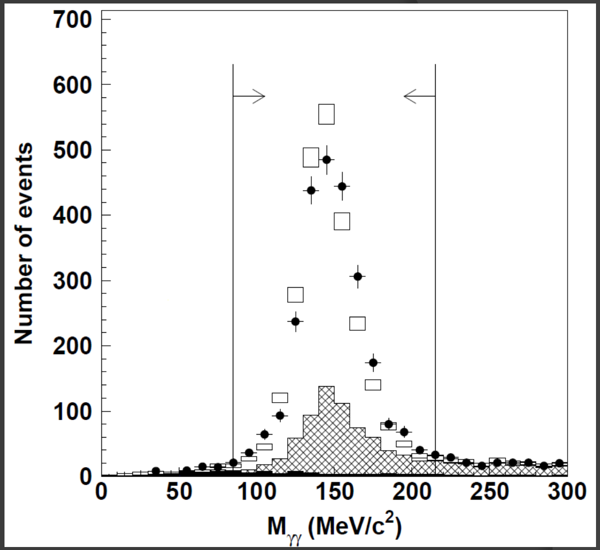
ν_μ NC π^0 Cross Section Ratio

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

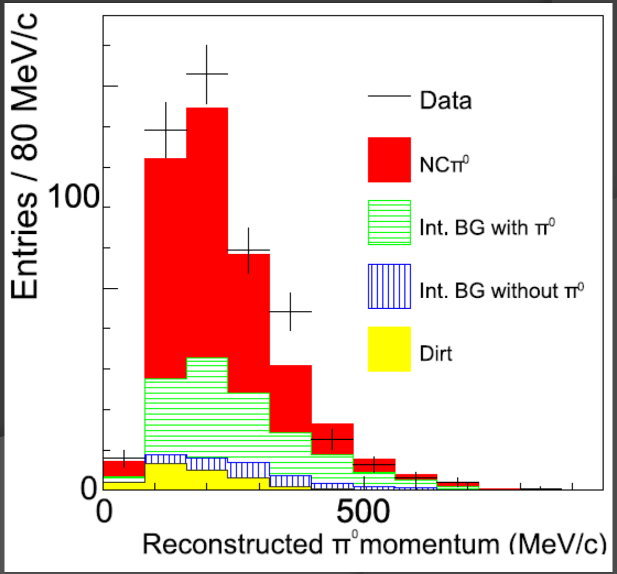


SciBooNE measurement

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)



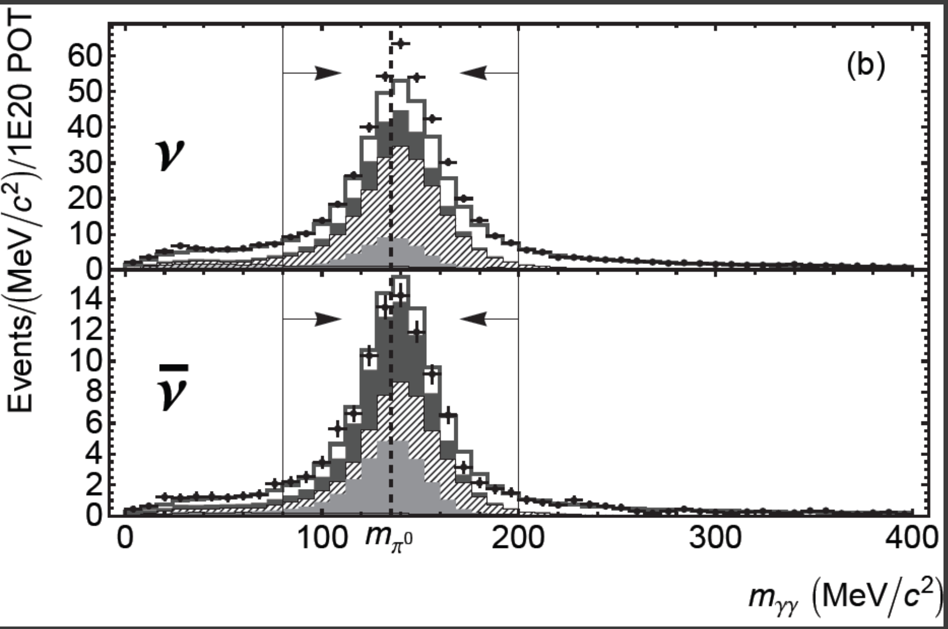
MiniBooNE ν_μ NC π^0 Measurement

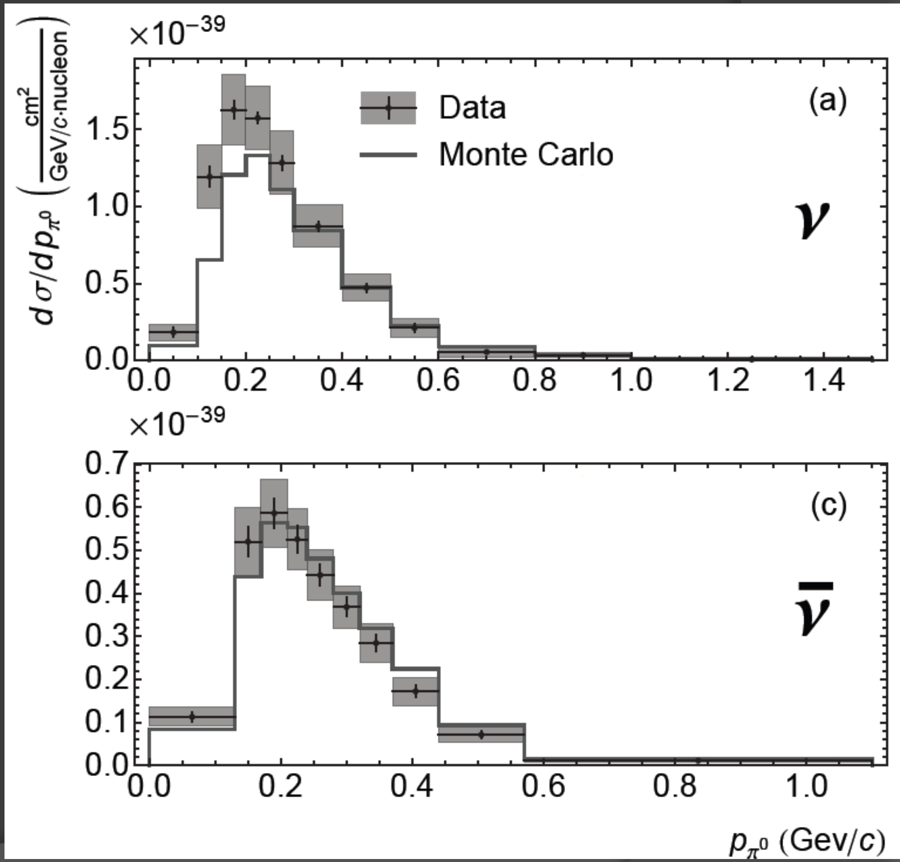
Excellent π^0 containment (4π).
Signal definition – observable.

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

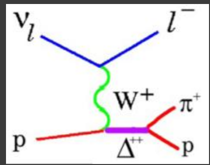
Reconstruction:

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





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



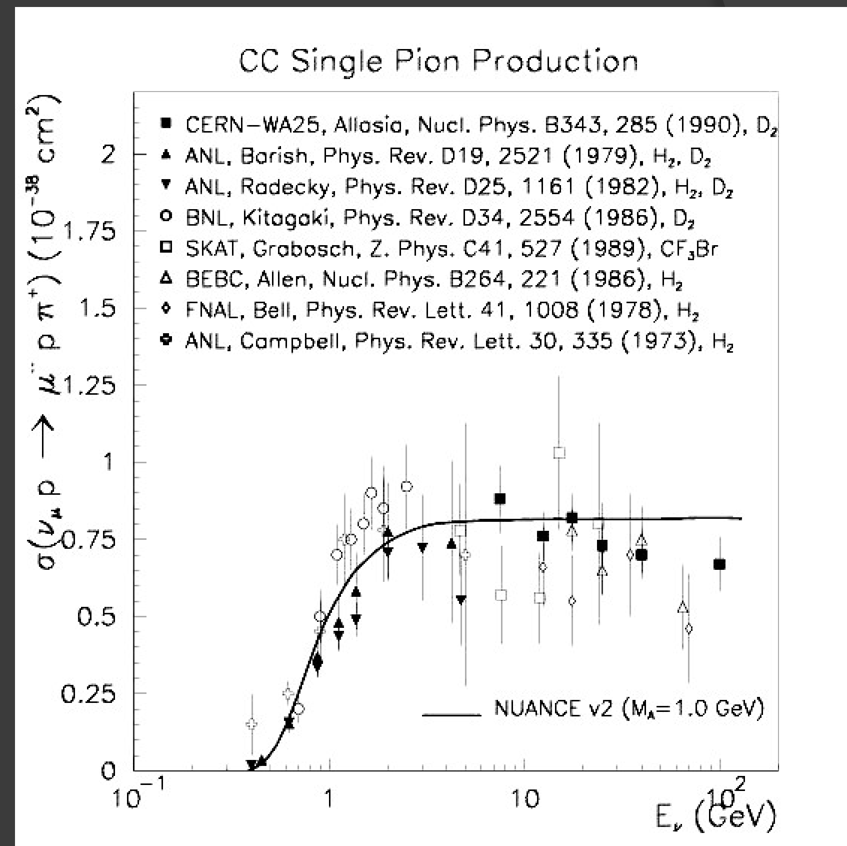
Resonant ν_μ CC π^+

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

$\downarrow$

$n(p) + \pi^+$

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.

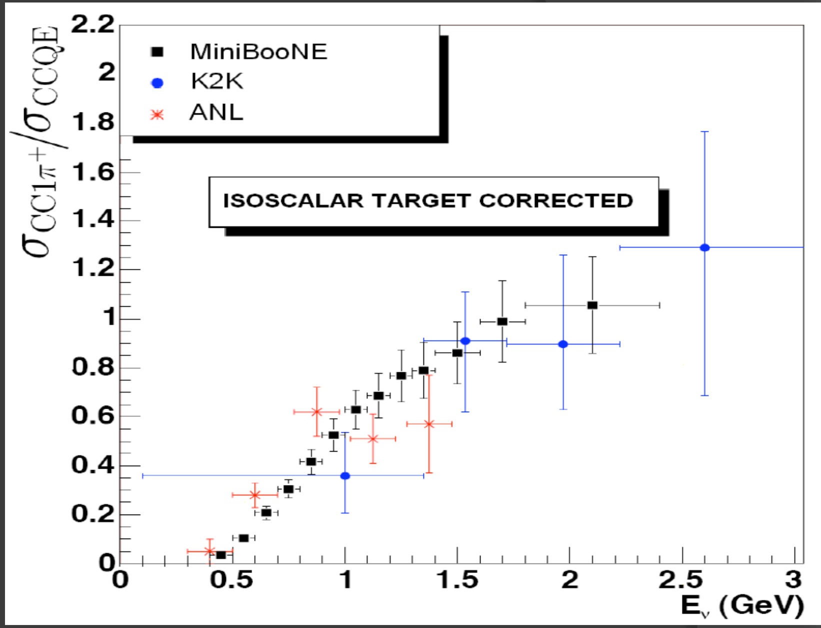
ν_μ CC π^+ Cross Section Ratio

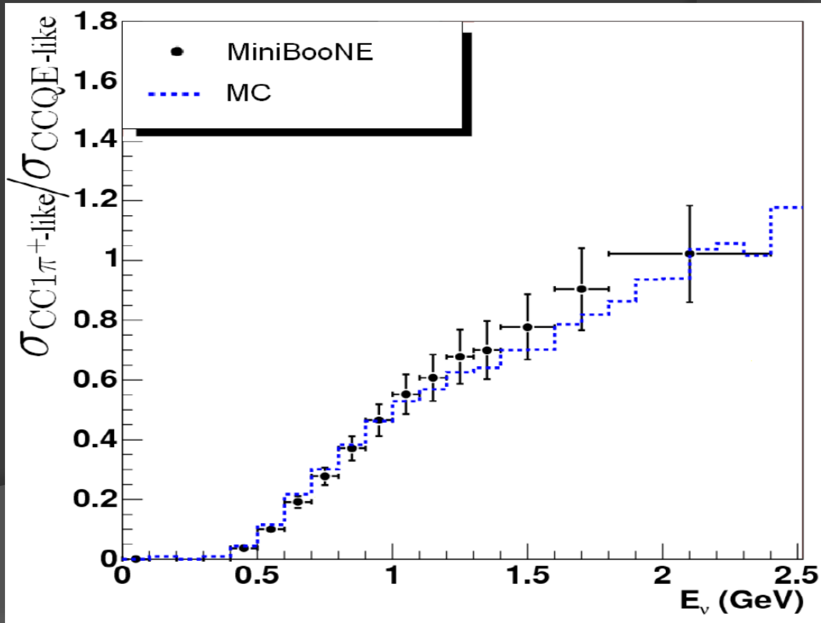
K2K measured the ratio to the ν_μCCQE events.

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.

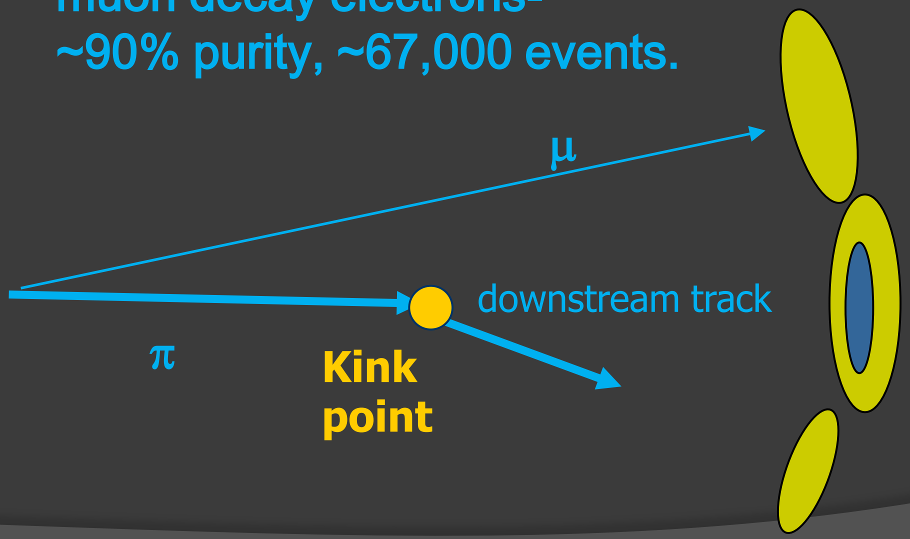
MiniBooNE ν_μ CC π^+ - Fully Reconstructed

Signal definition:

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

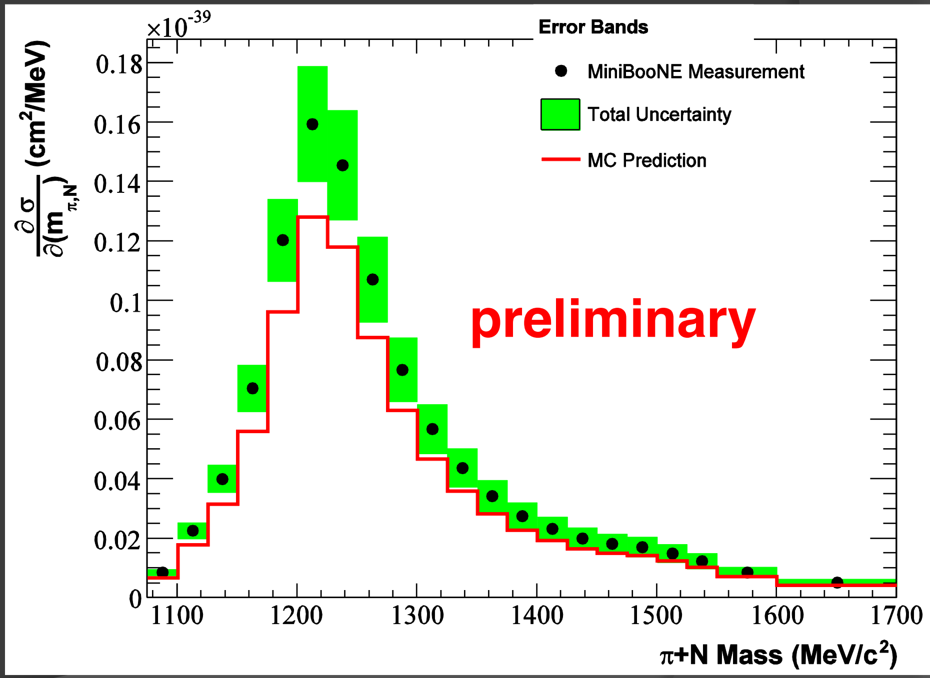
Reconstruction:

- 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

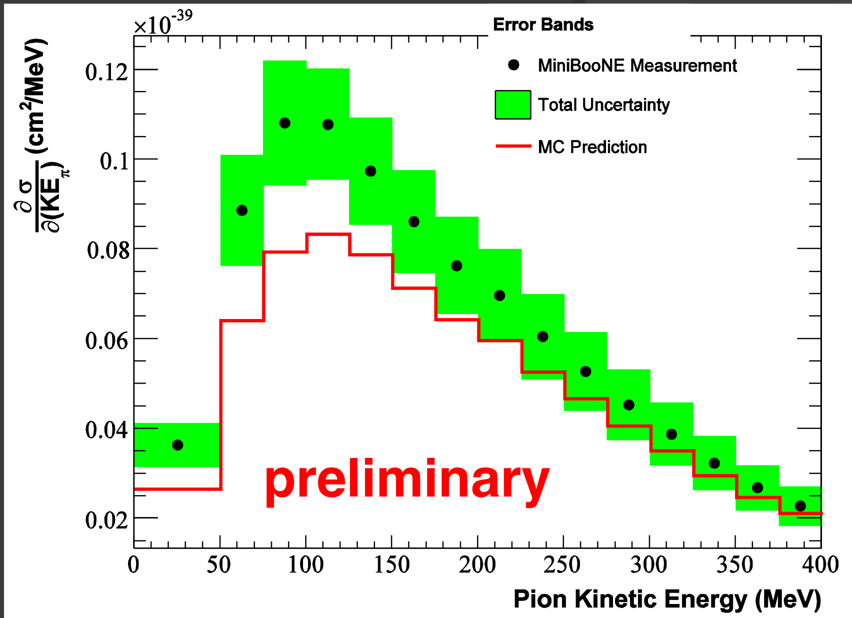
First measurement of inclusive CCπ^+ differential cross sections

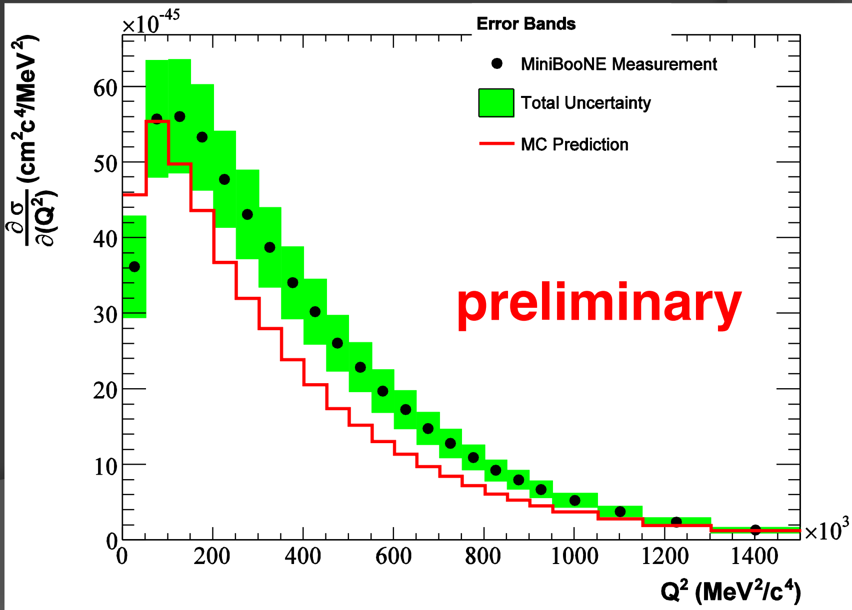
Differential cross sections (flux averaged)
$d\sigma/d(Q^2)$, $d\sigma/d(E_\mu)$, $d\sigma/d(\cos\theta_{\mu,\nu})$
$d\sigma/d(E_\pi)$, $d\sigma/d(\cos\theta_{\pi,\nu})$:

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

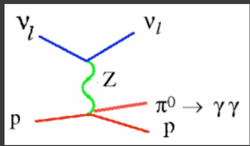
- Data Q^2 shape differs from the model

Paper is in preparation.





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

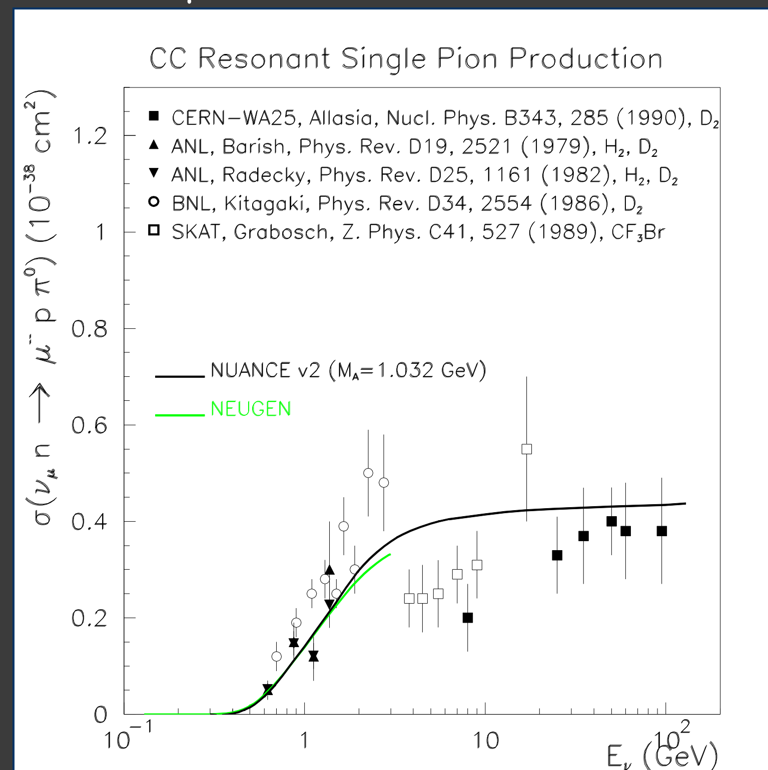


ν_μ CC π^0 Cross Section

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

- 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

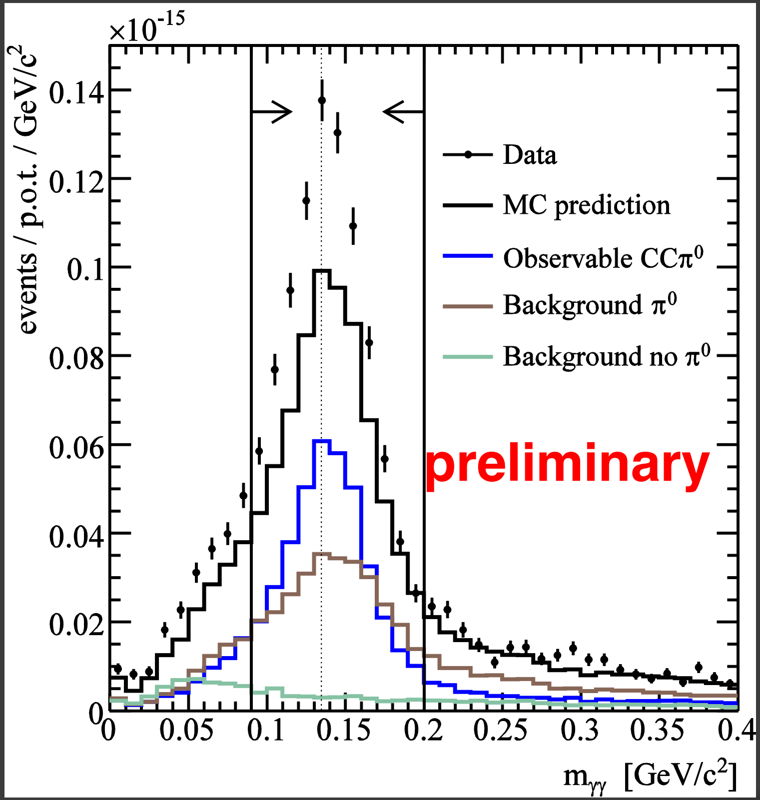
ν_μ CCπ^0 world data

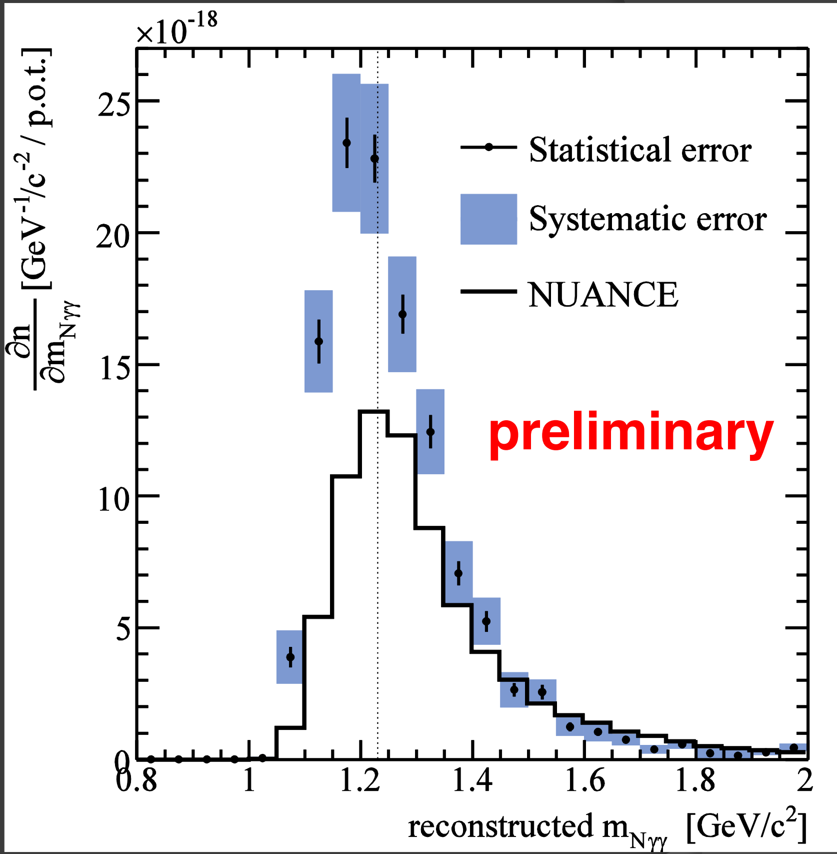


MiniBooNE ν_μ CC π^0 Kinematics

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

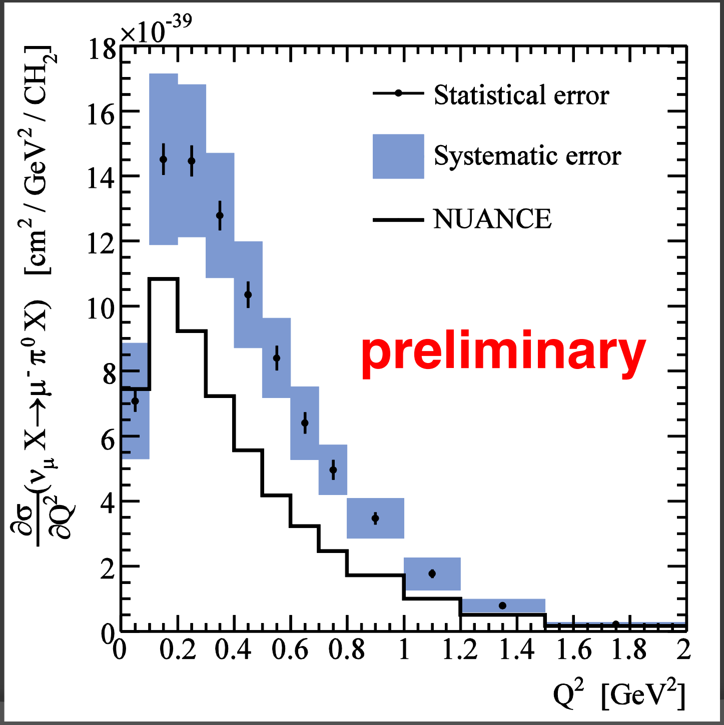
Signal definition: observable - $1\pi^0$ and 1μ emerging from the target nucleus with no other mesons.

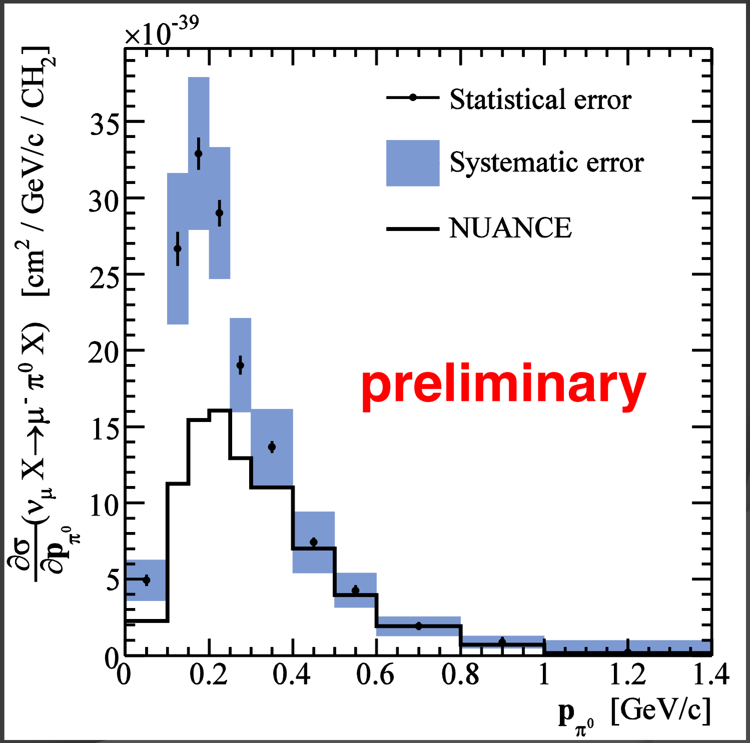
First measurement of inclusive CCπ^0 differential cross sections:

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

- **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:

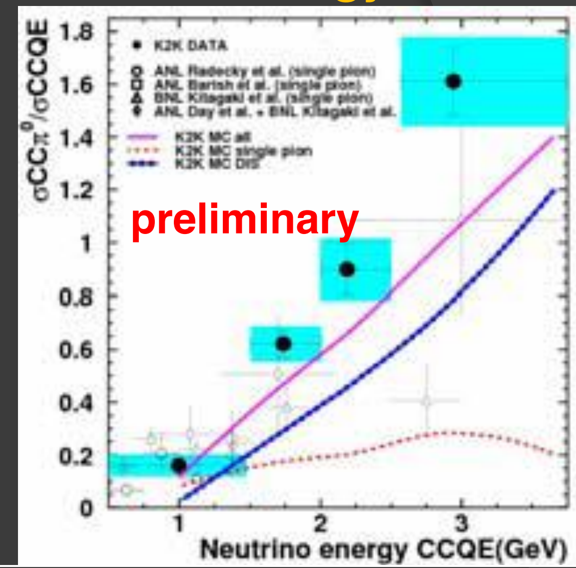
- **using SciBar + muon range detector (MRD)**
- **μ track in SciBar with a matched track in MRD.**
- **2 electron showers in SciBar or EC.**

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.

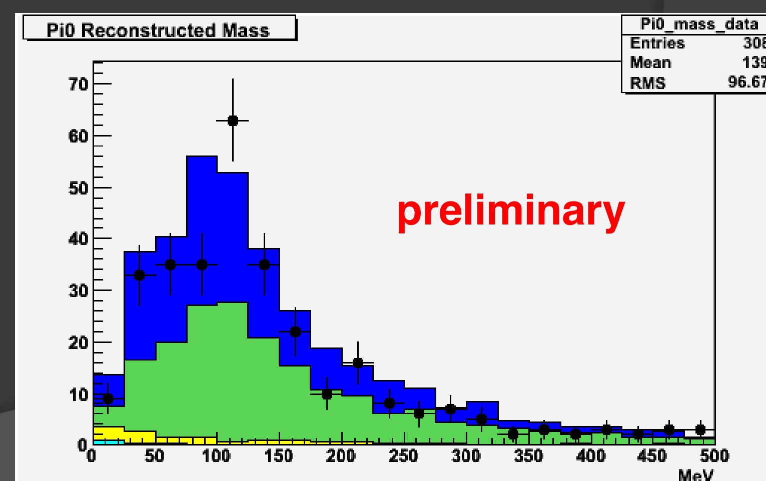
Signal definition – observable.

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



Summary

Current measurements show discrepancies in both shape and normalization with the existing models.

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.

We need:

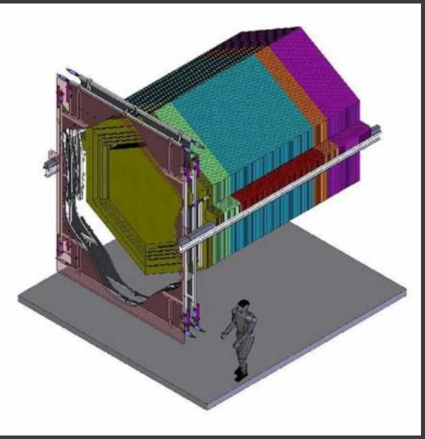
- more precise least model dependent measurements by dedicated experiments. MiniBooNE started this trend with a full suite of absolute observable differential cross section.

The Future is Here

T2K and MINERvA are taking data – results soon.

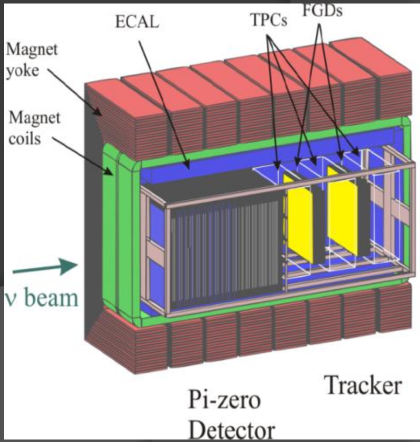
Experiments	$\langle E_\nu \rangle$ GeV	Hadron Prod. Exp.	Main goal	Detector	ν Target	ν MC
T2K ND280	0.7	NA61	θ_{13}, δ^{CP}	Fine-grain	C, H_2O	NEUT, GENIE
MINERvA	1-20	MIPP	σ_ν	Fine-grain	C, Fe, Pb, He, D	GENIE

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 resonant pion cross sections:

- new results mainly from oscillation experiments.
- first complete sets of differential cross sections have been measured by MiniBooNE.

T2K and MINERVA have the potential to improve our understanding of the resonant 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 resonant cross sections, which is crucial for precise measurement of all oscillation parameters.

Thank you!