

# NuFact09

IIT Chicago

## Single pion production experiments review

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The scope of this talk is to review the recent results on neutrino induced pion production through resonance production and decay.

Coherent pion production will be covered tomorrow in Hide Tanaka's talk.

# Outline

Brief theoretical introduction  
(for more details see Ulrich Mosel talks)

Experiments providing recent results.

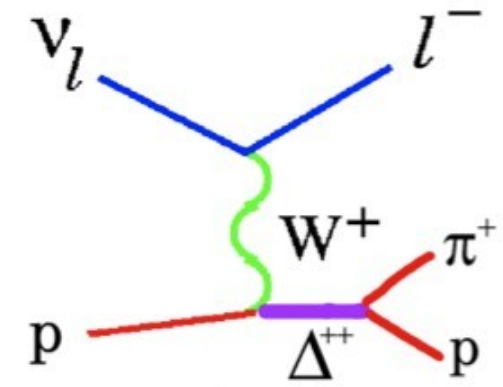
CC resonant  $\pi^+$  and  $\pi^0$   
NC resonant  $\pi^0$

Upcoming experiments

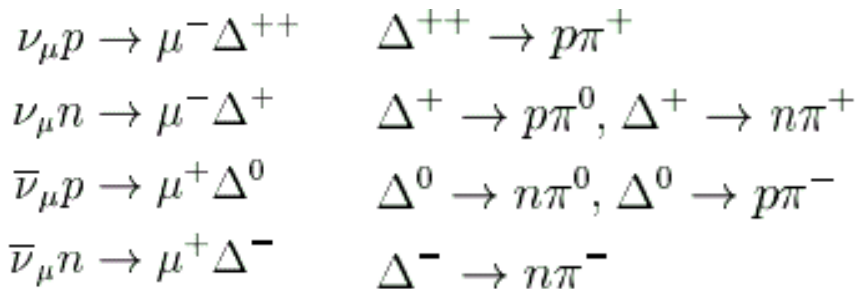
Summary

# Theory

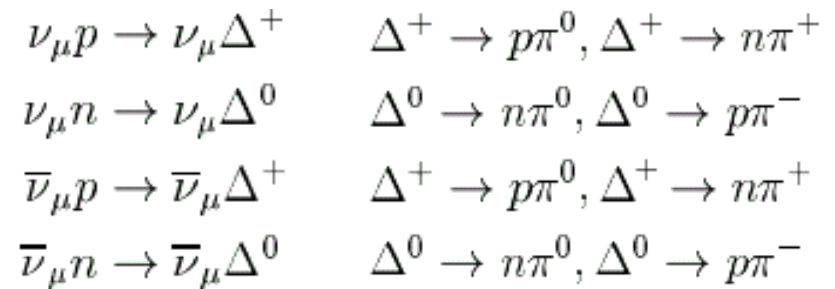
14 Interactions through  $\Delta$  resonance :



CC



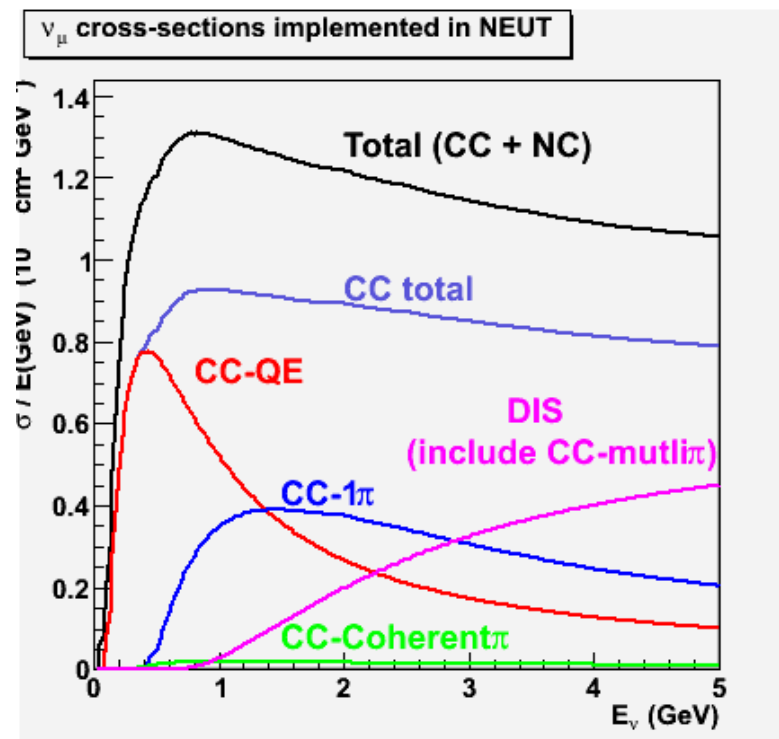
NC



In the scheme I show the resonance  $\Delta(1232)$  which is the main contribution to resonant processes. Several other resonances, together with a non-resonant background, contribute also to pion production at low neutrino energies. In MC codes, all measured resonances in the hadronic invariant mass region  $W < 2$  GeV are typically modeled.

# Historical measurements

Experimental points to be added during the weekend



# Experimental setups

# K2K near detector

1.3 GeV mean energy  $\nu$ -beam produced by 12 GeV protons on Aluminum

## Fine grained detector

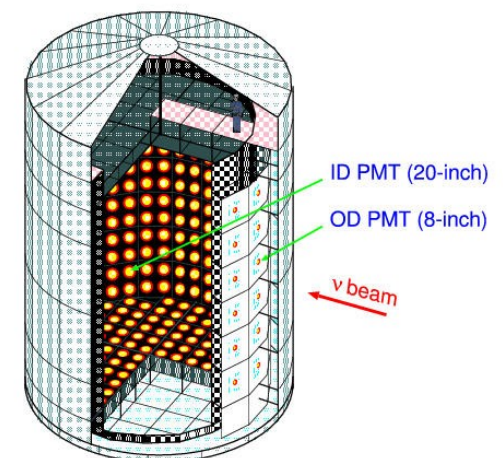
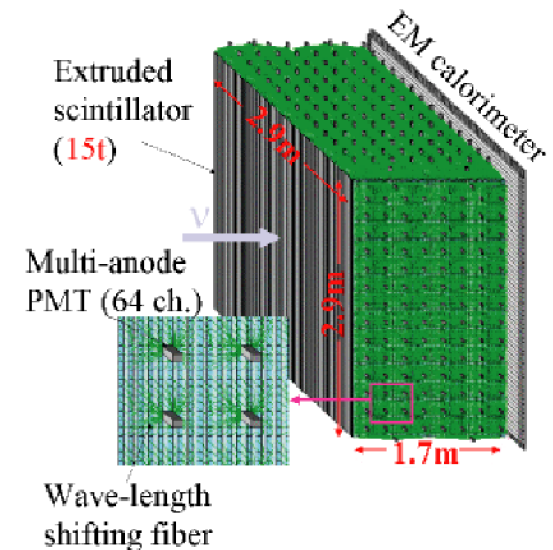
- SciFi (not used in the presented analysis)
- SciBar
  - Fully-active fine-grained scintillator detector.
  - 14592 bars (15 tons)
  - $dE/dx$  particle identification
- EC
  - Scintillator-Lead spaghetti calorimeter.
  - Identifies  $e^-$  and  $\pi^0$
- MRD
  - Used for muon tagging.

## Water cherenkov detector

- 1KT
  - 1,000 ton water Cherenkov detector.
  - 8.6m high, 8.6m diameter cylinder containing 680 50cm PMT's facing inward .
  - 40% photocatode coverage.

NEUT event generator is used in K2K.

Rein and Sehgal model for resonant pion production with an axial mass  $M_A=1.1\text{GeV}/c^2$  is implemented



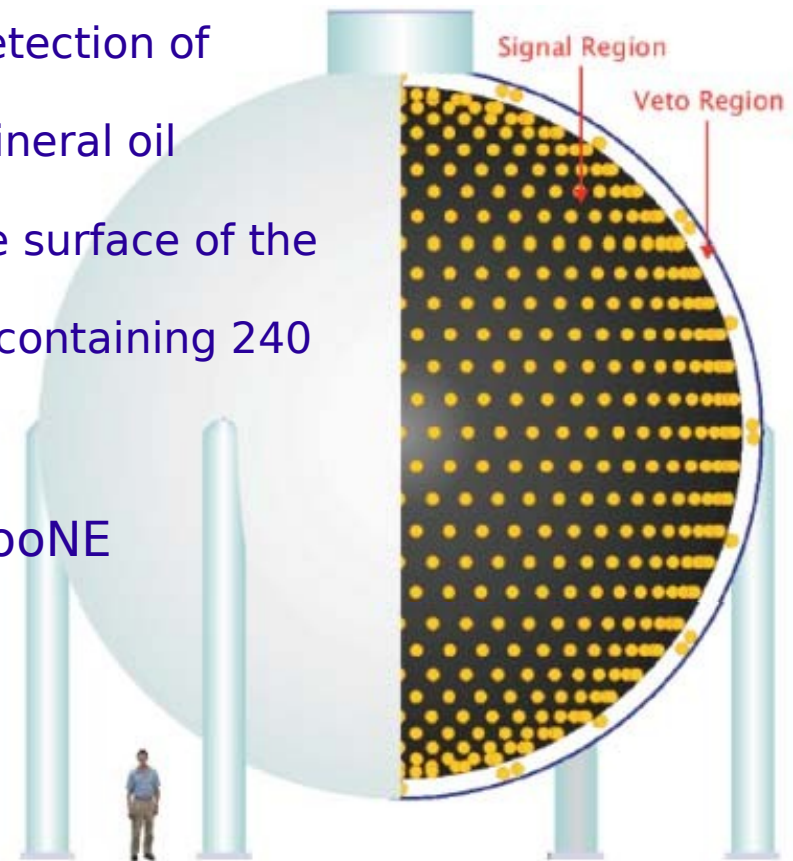
# MiniBooNE

0.8 GeV mean energy neutrino/anti-neutrino beam produced by 8 GeV protons on Beryllium.

- Particle reconstruction is based primarily on detection of Cherenkov radiation
- The tank is filled with 800 tons of ultra-pure mineral oil (modeled as CH<sub>2</sub>)
- 1280 8" photo-tubes are attached to the inside surface of the tank (10% coverage)
- Outside the main tank is a thin spherical shell containing 240 phototubes to veto entering particles

NUANCE event generator is used in MiniBooNE

- Resonant
  - Rein-Sehgal with  $M_A = 1.1$  GeV.
  - Non-isotropic  $\Delta$  decay
- Coherent
  - Rein-Sehgal with  $M_A = 1.03$  GeV
  - NUAGE FSI model

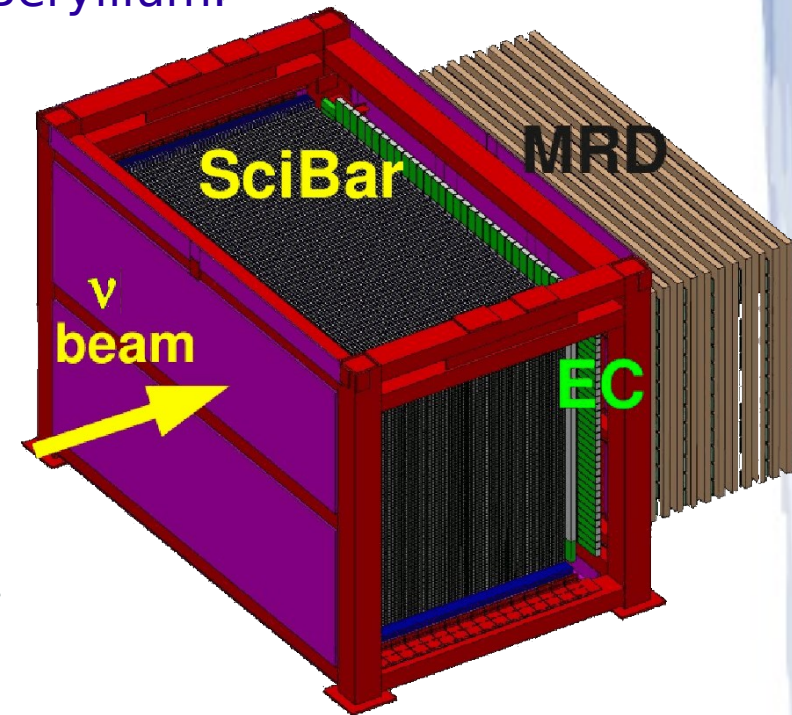


# SciBooNE

Same beam than MiniBooNE: 0.8 GeV mean energy neutrino/anti-neutrino beam produced by 8 GeV protons on Beryllium.

Detector setup:

- SciBar
  - Fully-active fine-grained scintillator detector.
  - 14336 bars (~15 tons)
  - $dE/dx$  particle identification
- EC
  - Scintillator-Lead spaghetti calorimeter.
  - Identifies  $e^-$  and  $\pi^0$
- MRD
  - Used for muon tagging only.



NEUT/NUANCE montecarlo generators implemented. Only NEUT used in the presented analysis.

Rein and Seghal model with  $M_A=1.2$  GeV

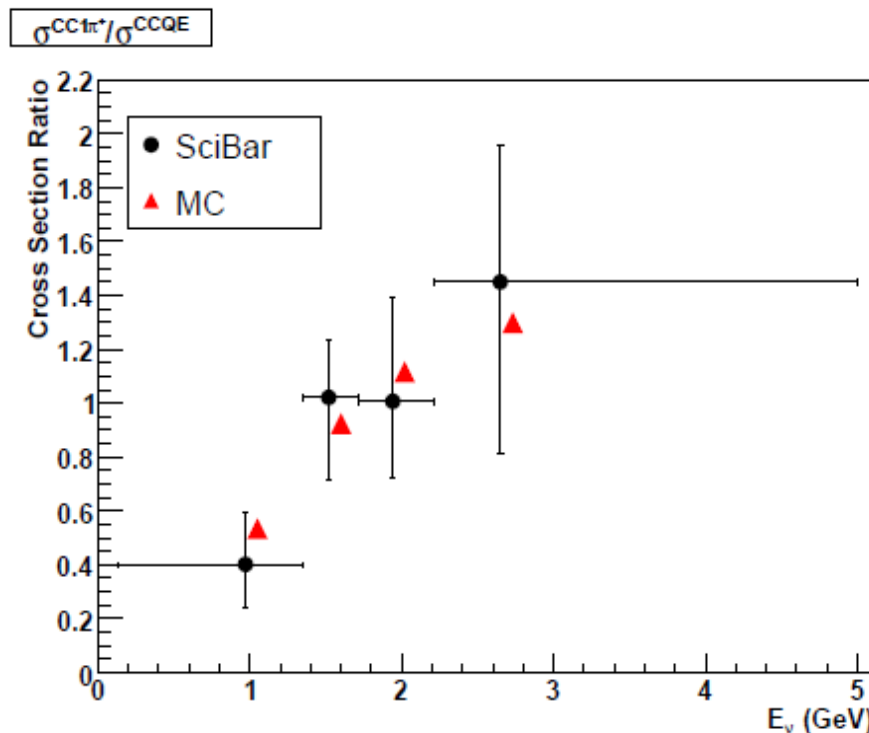
# Charged Current

# CC- $\pi^+$ k2k

CC- $\pi^+$  event definition:

- Neutrino interacting with the nucleon via CC- $\pi^+$ , correcting for FSI.

CC1pi experimental signature based on muon kinematics rather than on full final state topology.



Dominant contribution:  $\text{numu} + p \rightarrow \mu^- + p + \pi^+$ , with small contribution from  $\text{numu} + n \rightarrow \mu^- + n + \pi^+$

CC- $\pi^+$  xsec measured relative to CC-QE one, to reduce impact of neutrino flux systematic uncertainties

Data in good agreement with MC prediction and also ANL data.

$$\nu\text{-induced } \sigma^{CC1\pi^+/CCQE} = 0.734 \pm 0.086 (\text{fit}) \begin{matrix} +0.076 \\ -0.103 \end{matrix} (\text{nucl.}) \begin{matrix} +0.079 \\ -0.073 \end{matrix} (\text{syst.})$$

# CC- $\pi^0$ k2k

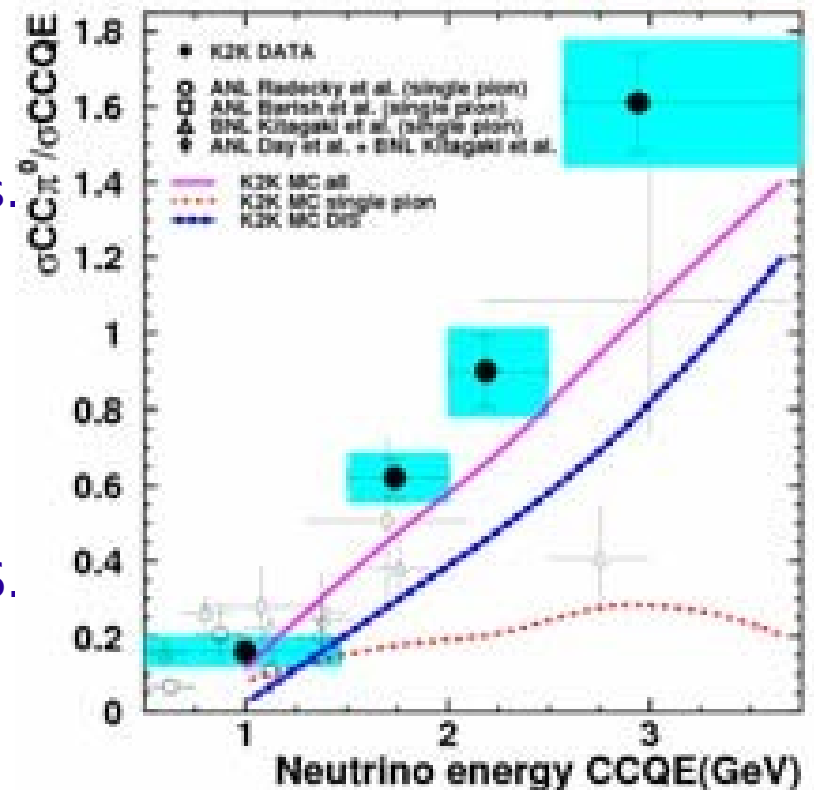
## CC- $\pi^0$

- 1 or more  $\pi^0$ 's from the neutrino interaction vertex
- 1 or more  $\pi^0$ 's from a re-interaction inside the target nucleus;
- 1 or more  $\eta$  (decaying either in  $\pi^0$ 's or photon pairs).

For this inclusive  $\pi^0$  signal definition, about half of CC- $\pi^0$  is due to resonant processes, half to deep inelastic processes.

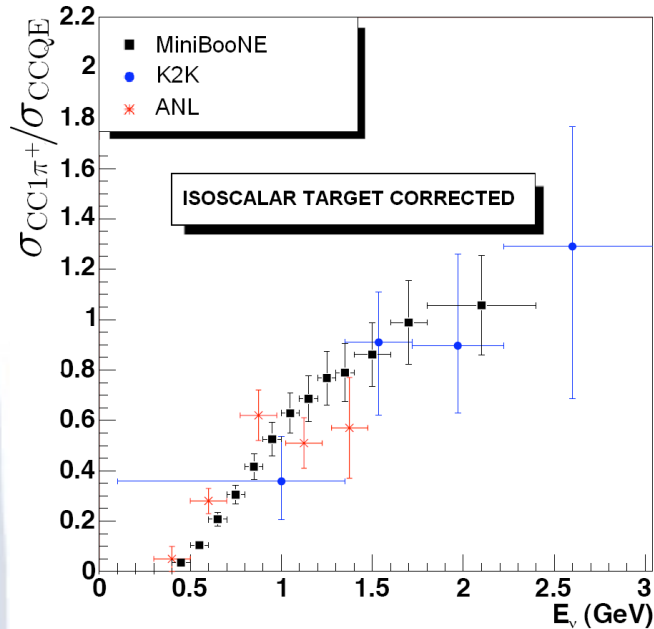
Identify muon with SciBar and MRD and two showers due to photon conversions from  $\pi^0$  decay using SciBar and/or EC

Data shows excess with respect to MC prediction, interpreted as excess in CC-DIS.



$$\nu\text{-induced } \sigma^{CC\pi^0/CCQE} = 0.443 \pm 0.033 (stat.) \pm 0.036 (syst.)$$

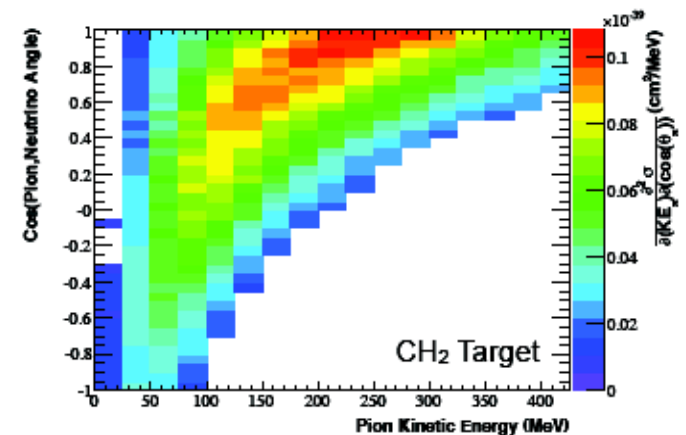
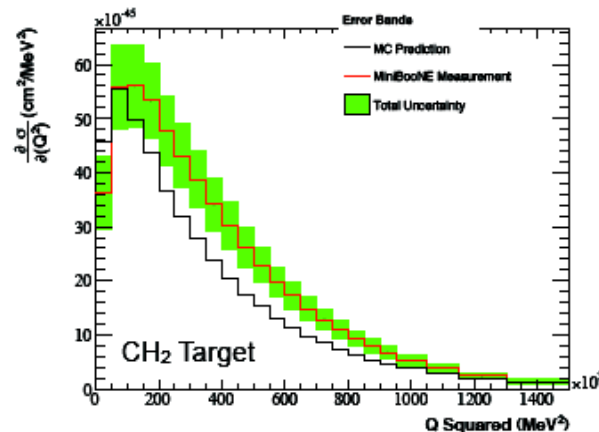
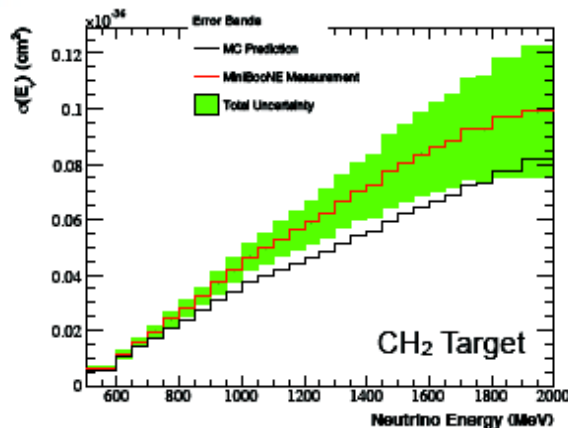
# CC- $\pi^+$ MiniBooNE



- An observed **CC- $\pi^+$**  event is defined to be any interaction that produces the following final state:
- One and only one muon
- one and only one pion
- any number of photons and baryons from the breakup of the nucleus

Improved pion reconstruction. Event kinematics fully specified. No assumptions on  $\Delta$  mass.

Absolute **CC- $\pi^+$**  cross section in energy,  $Q^2$  and pion energy and angle double differential:

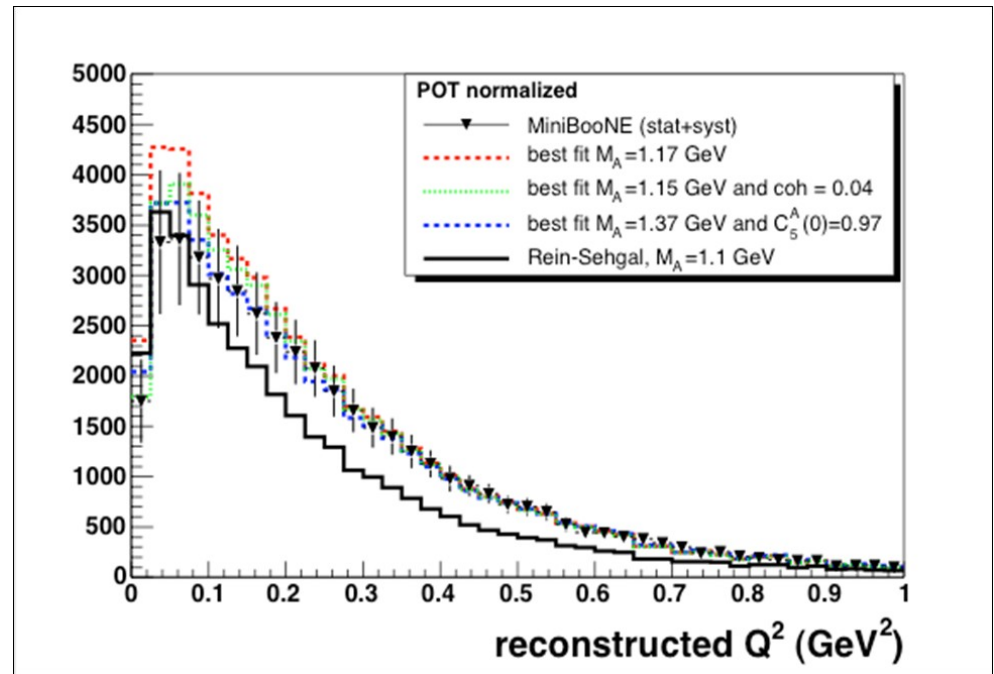


# CC- $\pi^+$ MiniBooNE

MiniBooNE CC-  $1\pi^+$  (resonant plus coherent) data also used to tune MC models.

Performed the fits for three different models:

- $M_A^{1\pi}$  for  $Q^2 > 0.2 \text{ GeV}^2$ 
  - $M_A^{1\pi} = 1.17 \pm 0.13 \text{ GeV}$
- Coherent contribution and  $M_A^{1\pi}$ 
  - $M_A^{1\pi} = 1.15 \text{ GeV}$
  - Coherent  $< 0.04$
- $M_A^{1\pi}$  and  $C_5^A(0)$ 
  - $M_A^{1\pi} = 1.37 \text{ GeV}$
  - $C_5^A(0) = 0.97$



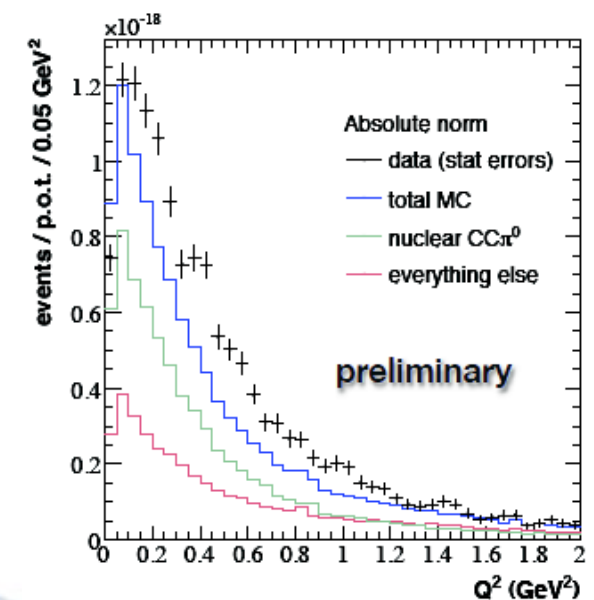
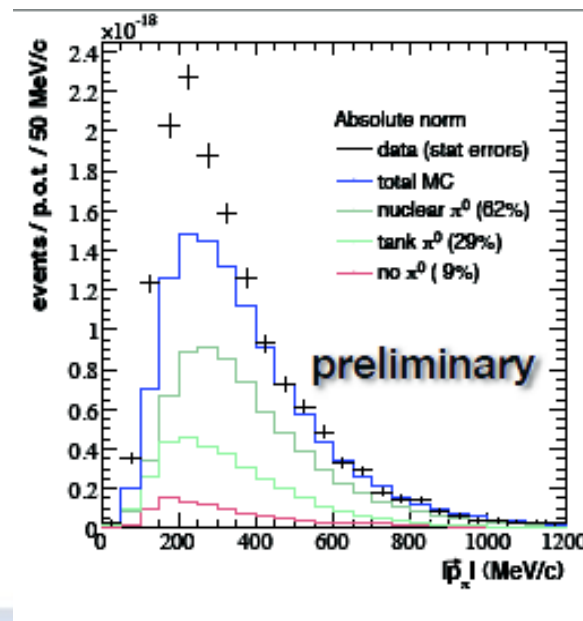
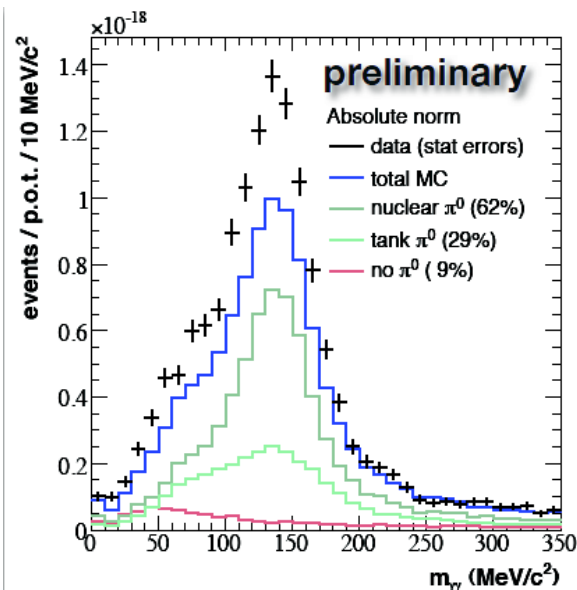
# CC- $\pi^0$ MiniBooNE

An observed **CC- $\pi^0$**  event is defined to be any interaction where a  $\pi^0$  exits the interaction nucleus.

- charge exchanged events are included.

Reconstruct muons and two gammas in the final state with three Cherenkov ring fitter, assuming target nucleon at rest and incoming neutrino direction, full event kinematics can be constructed.

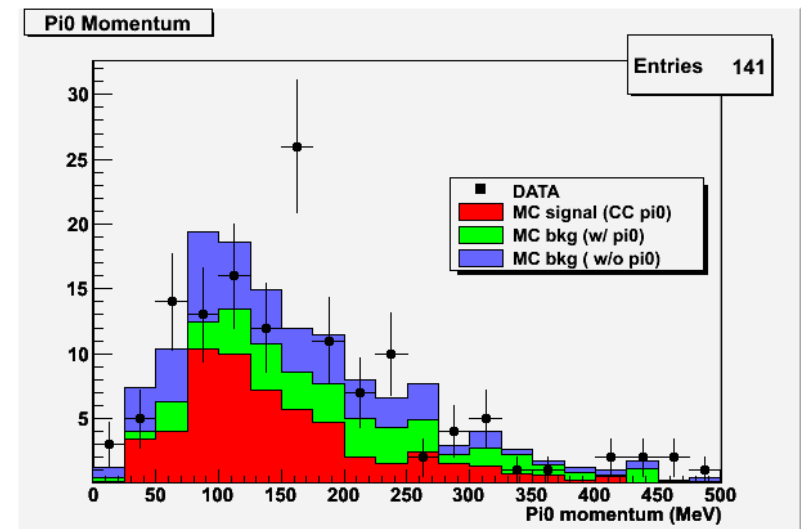
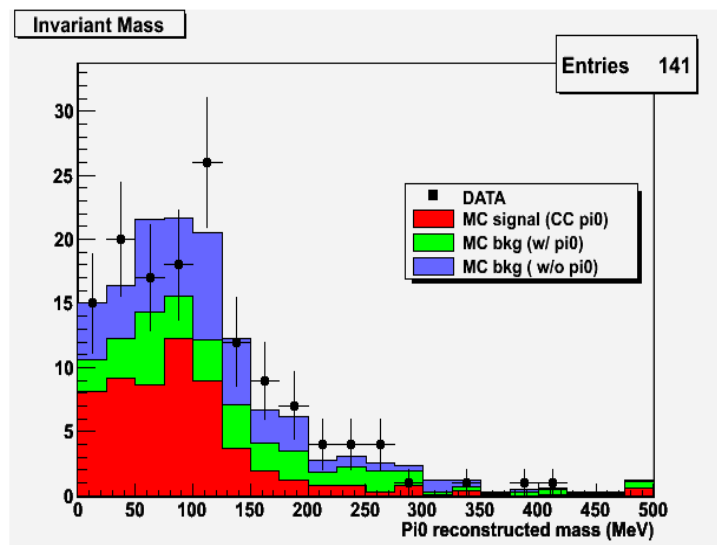
With respect MC, softer  $\pi^0$  momentum distribution and larger rate.



# CC- $\pi^0$ SciBooNE

- CC- $\pi^0$ : One muon and one  $\pi^0$  coming out from the interaction nucleus.

Reconstruct mu with SciBar plus MRD and two gammas contained in SciBar (no EC used)



Analysis improvements since shown plots were produced (work in progress):

- Narrower invariant mass peak.
- Higher efficiency for high momentum  $\pi^0$ 's.

# Neutral Current

# NC- $\pi^0$ k2k

Using the 1KT water detector.

Signal definition:

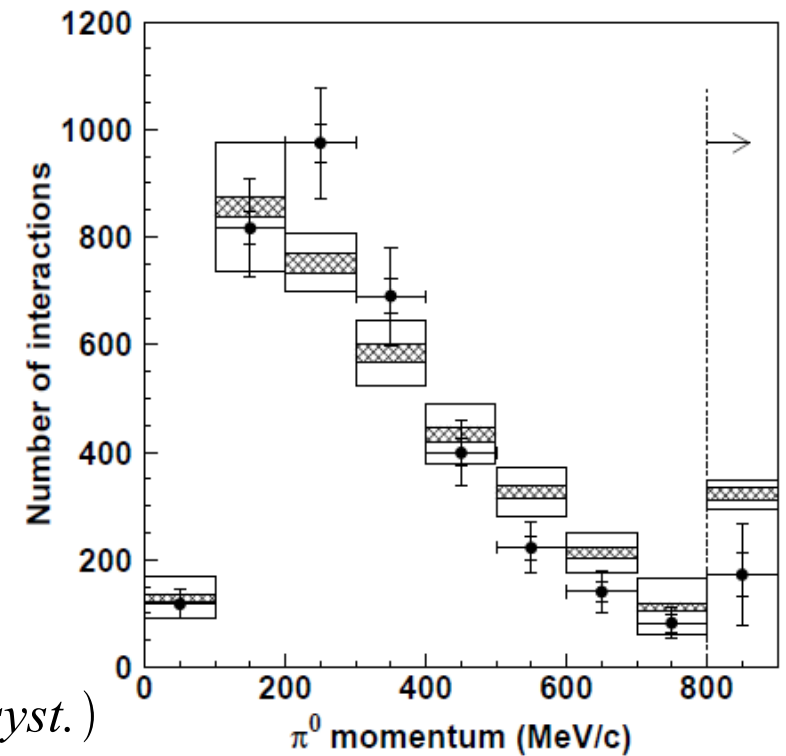
A neutral pion and no other mesons emitted in the final state from the nucleus.

Reconstruct 2 cherenkov rings from e-like, fully contained tracks, with invariant mass close to  $\pi^0$  mass (85-215 MeV).

MC is normalized by the number of total events in the fiducial volume

MC prediction for  $\sigma$  (NC $\pi^0$ /CC-inc) = 0.065

$$\nu\text{-induced } \sigma^{NC\pi^0/CC-inc} = 0.064 \pm 0.001 (stat.) \pm 0.007 (syst.)$$



# NC- $\pi^0$ MiniBooNE

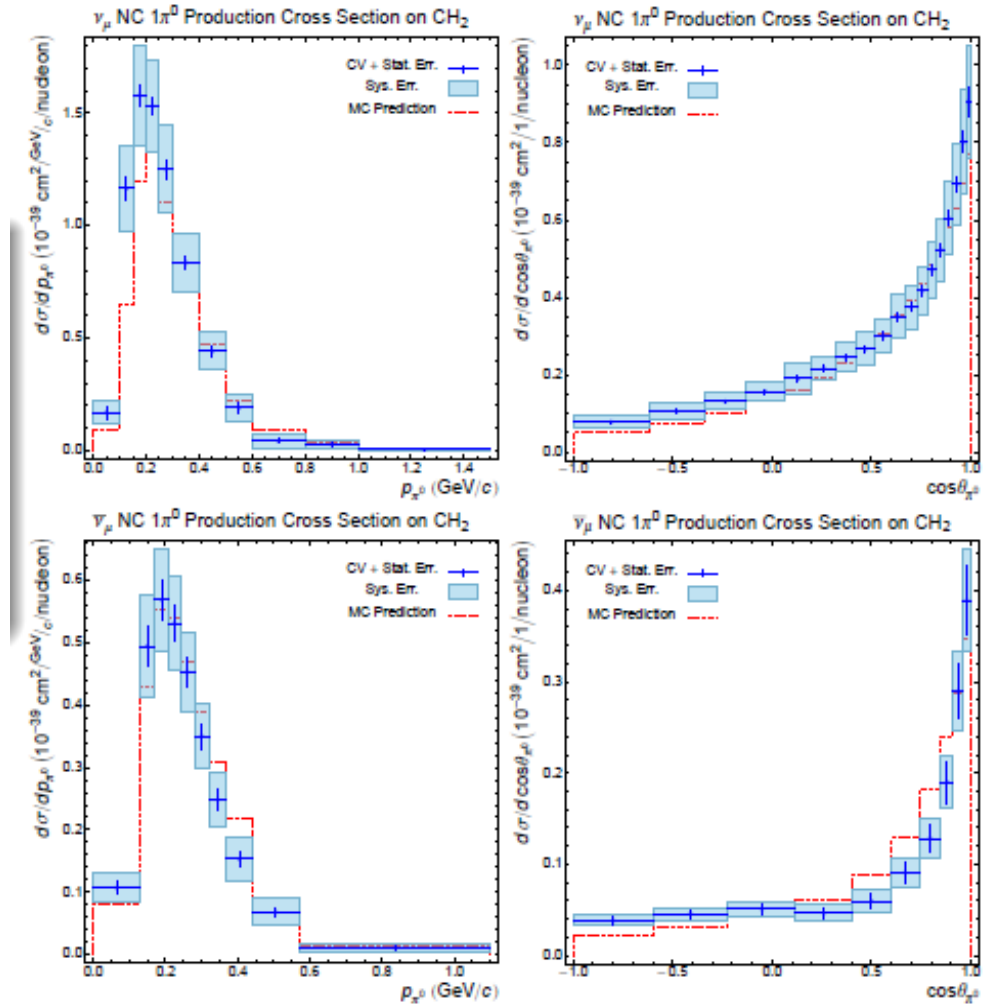
Signal definition:

Neutral Current events with a  $\pi^0$  exiting from the target nucleus and no other mesons.

Event selection similar to K2K 1KT one.

First absolute differential xsec measured for NC- $\pi^0$  production using neutrinos and antineutrinos.

Overall xsec and  $\pi^0$  kinematics in good agreement with absolute MC prediction.



$$\begin{aligned} \nu\text{-induced } \sigma &= (4.54 \pm 0.04_{\text{stat.}} \pm 0.71_{\text{sys}}) \times 10^{-40} \text{ cm}^2 / \text{nucleon} \\ \bar{\nu}\text{-induced } \sigma &= (1.43 \pm 0.03_{\text{stat.}} \pm 0.23_{\text{sys}}) \times 10^{-40} \text{ cm}^2 / \text{nucleon} \end{aligned}$$

# NC- $\pi^0$ SciBooNE

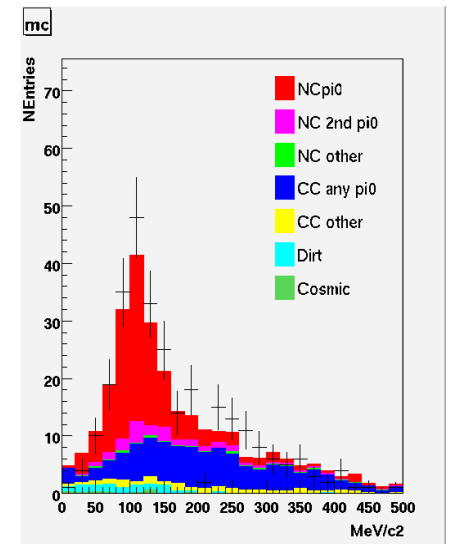
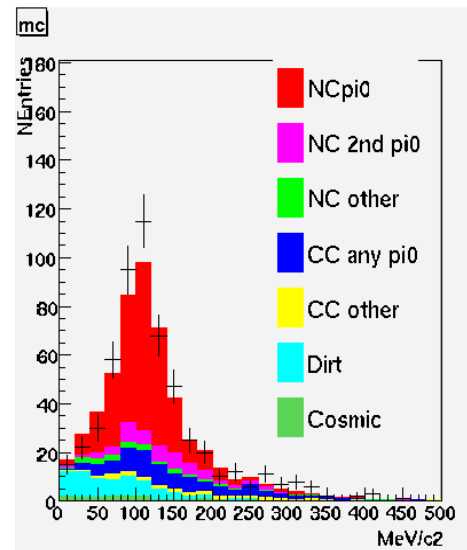
**Signal definition:** At least 1  $\pi^0$  coming out from the target nucleus.

**Two gammas reconstructed with SciBar and EC**

**Two samples:**

- SciBar contained events (systematics included)
- SciBar + EC events (not all systematics included)

Good agreement with MC prediction, normalized to CC-inclusive events.



$$\nu - induced \text{ contained } \sigma^{NC\pi^0/CC-inc} = 0.075 \pm 0.00574_{stat.} \begin{matrix} +0.00756 (sys.) \\ -0.00901 \end{matrix}$$

$$\nu - induced \text{ non-contained } \sigma^{NC\pi^0/CC-inc} = 0.073 \pm 0.00924_{stat.} \begin{matrix} +0.00626 (sys.) \\ -0.00838 \end{matrix}$$

# Upcoming measurements

# Minerva

- Will be able to measure total resonance cross sections with 5% estimated error (using MIPP data).
- $d\sigma/dQ^2$  and  $d\sigma/dW$  differential cross sections will also be calculated. The largest error will likely be from bias in the energy reconstruction.
- Will be able to measure exclusive final states on a variety of nuclei (C, Fe and Pb) allowing to measure final state nuclear effects.

# T2K ND280

# Conclussions

# Backup