

Coherent Pion Production (Recent experimental results)

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The Experiments

Experiment	Lab	Target	Energy (GeV)	Reactions
K2K	KEK	Plastic scint. CH	1.3	CC
MiniBooNE	Fermilab	Mineral Oil CH ₂	1.1	NC
SciBooNE	Fermilab	Plastic scint. CH	1.1, 2.2, 0.8	CC , NC
NOMAD	CERN	Drift Chambers ~C(A=12.8)	24.8	NC

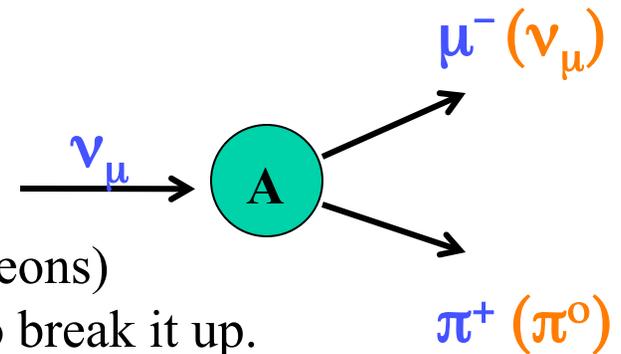
Many thanks to the experimenters for supplying me with their data and for very useful discussions

Coherent Pion Production

◆ Coherent production

- CC: $\nu_\mu + A \rightarrow \mu^- + A + \pi^+$

- NC: $\nu_\mu + A \rightarrow \nu_\mu + A + \pi^0$



◆ Interaction with **whole** nucleus (NOT individual nucleons)

◆ Momentum transfer to Nucleus must be **small** NOT to break it up.

◆ Consequences (and identification criteria):

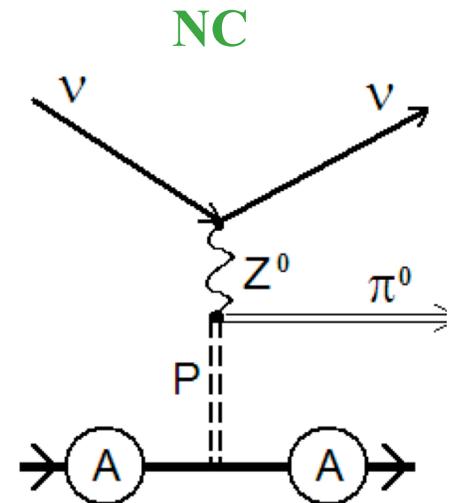
- No other particle emerges
- Pion (and lepton) emitted very forward

◆ Most experiments use the Rein and Sehgal model

◆ Nucl. Phys. **B223** (1983) 29.

◆ to describe coherent production in their Simulation.

- Process dominated by **AXIAL** Vector current.
- Isovector current contribution small.
- Use PCAC
- AT $Q^2 = 0$ related to the π -A cross section
- Isospin: $\sigma(\text{CC: } \pi^+) = 2 \sigma(\text{NC: } \pi^0)$



Rein and Sehgal 1983 NC Cross section

$$\frac{d\sigma}{dQ^2 dy dt} = \frac{G_F^2 f_\pi^2}{4\pi^2} \frac{1-y}{y} \frac{d\sigma(\pi N \rightarrow \pi N)}{dt} \quad \text{with } y = (E-E')/E$$

$$d\sigma(\pi N \rightarrow \pi N)/dt = A^2 \left(\frac{d\sigma_{el}/dt|_{t=0} \right) e^{-bt} F_{abs}$$

Absorption
in nuclear matter
 $e^{-C\sigma(inel)}$

$$\frac{d\sigma_{el}/dt|_{t=0} = (1/16\pi) \left[\frac{\sigma_{tot}(\pi^+ p) + \sigma_{tot}(\pi^- p)}{2} \right]^2$$

Total and Inelastic
Cross-sections
on Nucleons
Taken from Tables

- ◆ Inclusion of **non-zero** lepton mass (for CC):
Reduced phase space, and minimum $q^2 \neq 0$
(Important at low neutrino energy)
Rein and Sehgal Phys. Lett. B657 (2007) 207.

- ◆ Extension to **$Q^2 \neq 0$** Axial Vector Form Factor $G_A = M_A^2 / (Q^2 + M_A^2)$

Backgrounds

- ◆ **Low energy ($\sim 1\text{GeV}$):** Resonance production (especially Δ):
 - $\Delta \rightarrow \pi p \rightarrow$ Missing proton.
 - For CC: QEL and misidentification proton $\rightarrow \pi^+$.
- ◆ **Higher energy:** DIS.
- ◆ Interactions **OUTSIDE** the detector (Especially for π^0).

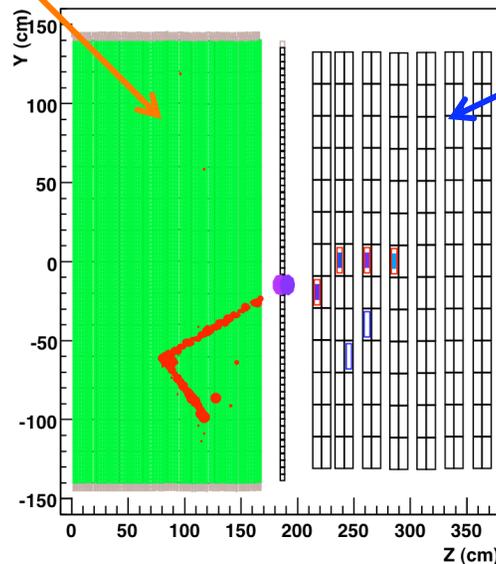
Other difficulty

- ◆ Reinteractions of final state hadrons, on the “way out” of the nucleus:
 - Can produce or destroy a pion.

CC Coherent π^+ : $\nu_\mu + A \rightarrow \mu^- + A + \pi^+$

- ◆ Two experiments: K2K (Near detector) and SciBooNE.
- ◆ Both use the SAME Tracking detector (SciBar) followed by a Muon Range detector

64 planes of Hor. Scint. strips
Interleaved
with 64 planes of Vert. strips



Iron plates Interleaved with
Active detector

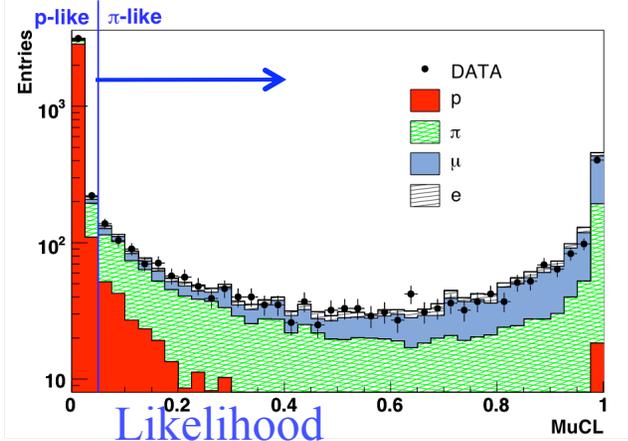
- ◆ CC coh. π^+ events: 2 track events one of which penetrates into the MRD (μ).
- ◆ SciBooNE divides their data into 2 samples:
 - ◆ μ stops in MRD. $\langle E_\nu \rangle = 1.1 \text{ GeV}$
 - ◆ μ traverses the MRD and exits. $\langle E_\nu \rangle = 2.2 \text{ GeV}$
- K2K: M. Hasegawa et al Phys. Rev. Lett. **95**:252301 (2005)
- SciBooNE: K. Hiraide et al Phys. Rev. **D78**:112004 (2008).

- ◆ ν_μ CC for normalization: events with a penetrating track.

CC Coherent: 2-track sample

QEL background: Proton fakes a pion

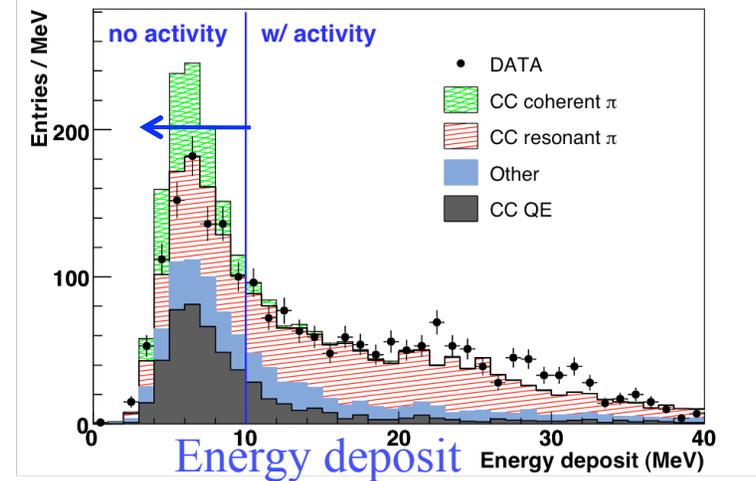
$\mu/p/\pi$ ID based on dE/dx Likelihood



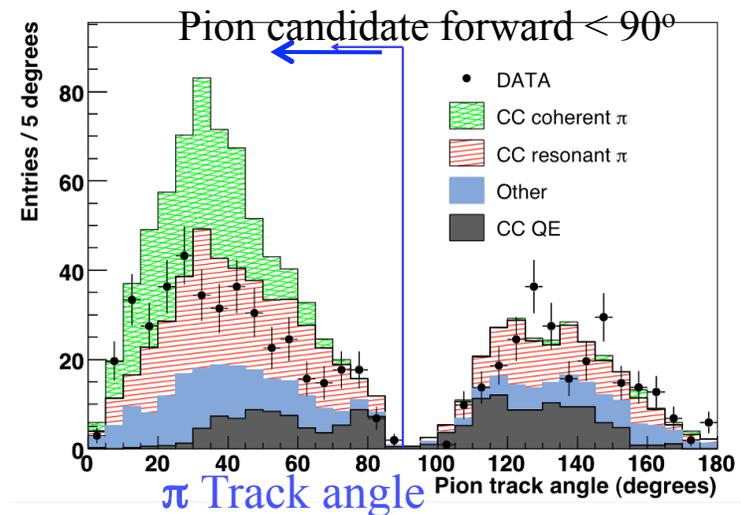
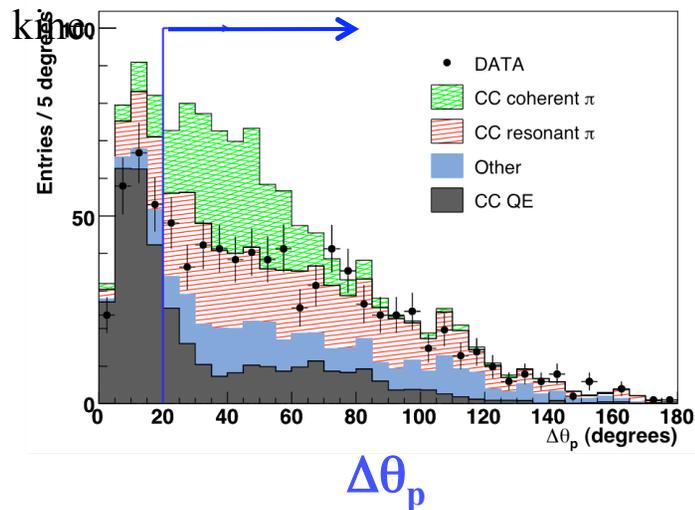
Δ Background: Proton not reconstructed

Only Keep events with

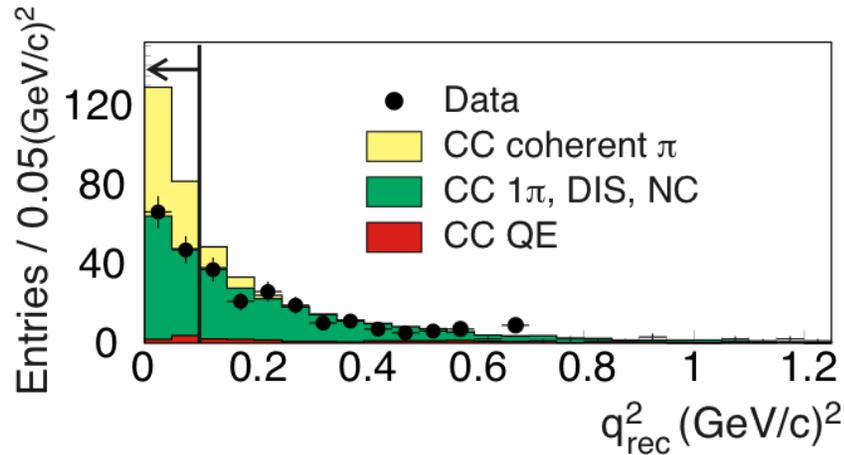
Vertex activity < 10 MeV.



QEL: Angle of non- μ track inconsistent with proton direction calculated based on μ and QEL



CC Coherent: $Q^2 < 0.1 \text{ (GeV/c)}^2$: No evidence.



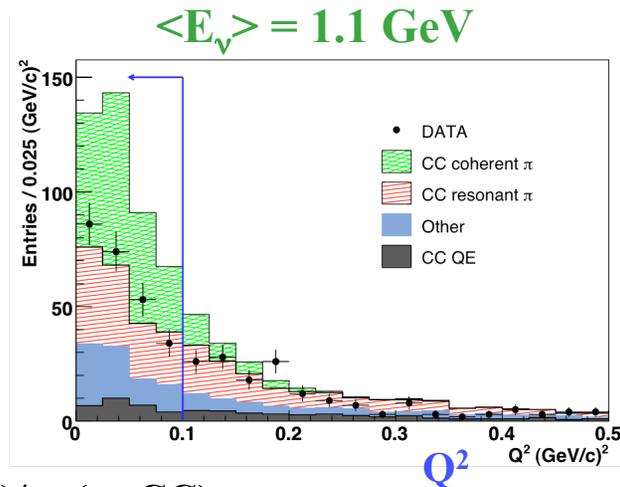
K2K: $\langle E_\nu \rangle = 1.3 \text{ GeV}$

$\sigma(\text{CC coh.}\pi) / \sigma(\nu_\mu \text{ CC})$

$$= [0.04 \pm 0.29 \text{ (stat)} \begin{matrix} +0.32 \\ -0.35 \end{matrix} \text{ (syst)}] \times 10^{-2}$$

$< 0.60 \times 10^{-2}$ at 90% CL.

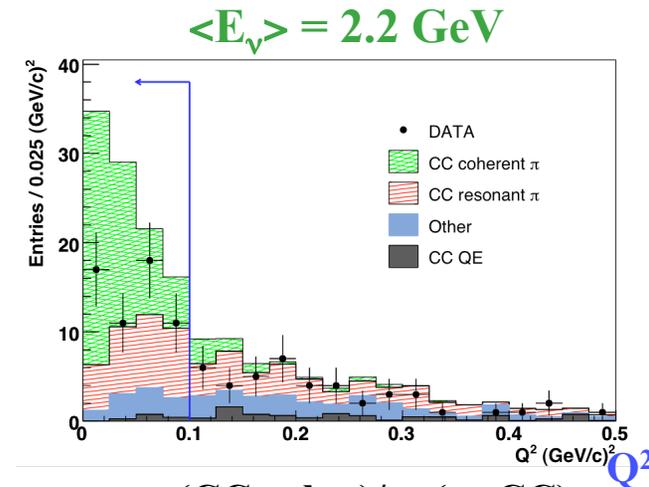
SciBooNE:



$\sigma(\text{CC coh.}\pi) / \sigma(\nu_\mu \text{ CC})$

$$= [0.16 \pm 0.32 \text{ (stat)} \begin{matrix} +0.30 \\ -0.27 \end{matrix} \text{ (syst)}] \times 10^{-2}$$

$< 0.67 \times 10^{-2}$ at 90% CL.



$\sigma(\text{CC coh.}\pi) / \sigma(\nu_\mu \text{ CC})$

$$= [0.68 \pm 0.32 \text{ (stat)} \begin{matrix} +0.39 \\ -0.25 \end{matrix} \text{ (syst)}] \times 10^{-2}$$

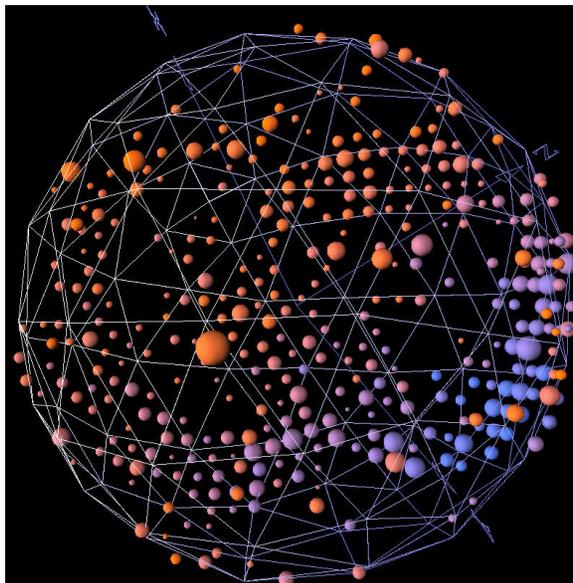
$< 1.36 \times 10^{-2}$ at 90% CL.

**NO
Evidence
For CC
coh π^+**

NC Coherent π^0 : $\nu_\mu + A \rightarrow \nu_\mu + A + \pi^0$

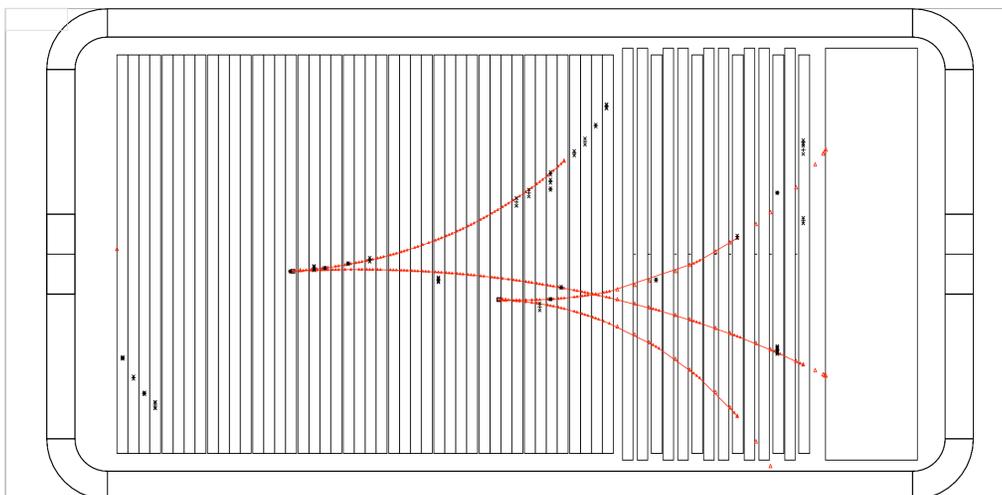
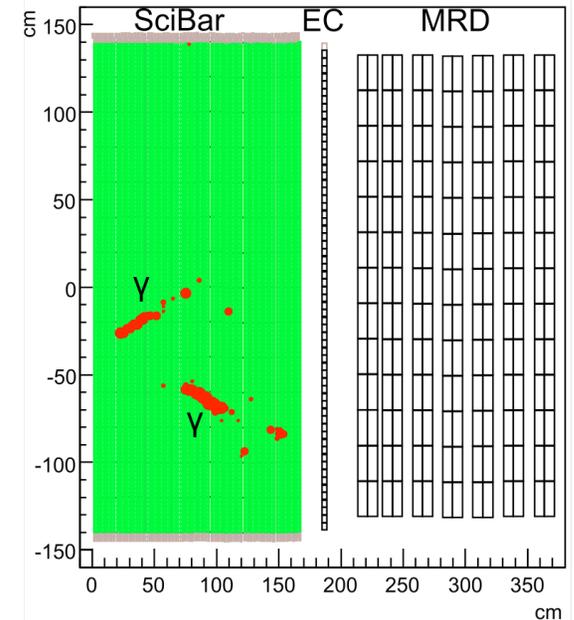
$\gamma\gamma$

◆ Three experiments: MiniBooNE, SciBooNE and NOMAD.



MiniBooNE: 800 tons.
Mineral oil. 1280 pmt's.
Cerenkov rings .
 $\mu/(e,\gamma)/\pi^0$ separation.

SciBooNE: 15 tons SciBar
Same detector as for CC.
Two separated “tracks”
intersecting within SciBar.



NOMAD: 2.7 tons
Drift Chambers target ~ Carbon
2 Photons converting in DC.
Magnetic field opens up e^+e^- .

NC Coherent: MiniBooNE

■ A.A. Aguilar-Arevalo et al, Phys. Lett. **B664**: 41 (2008)

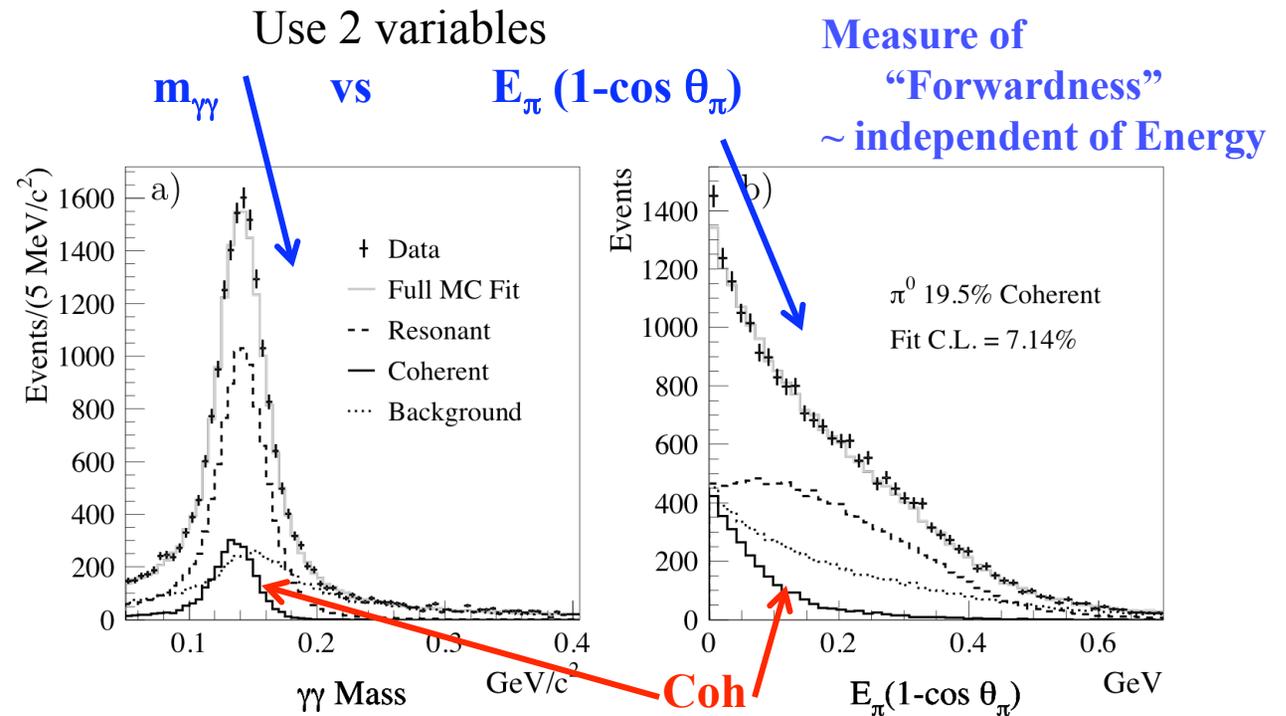
$\langle E_\nu \rangle = 1.1 \text{ GeV}$

- ◆ No μ based on absence of delayed decay electron.
- ◆ $\mu/e/\pi^0$ separation based on Likelihoods (sharpness and numbers of Cerenkov rings)

➤ Fit 2D data distribution

To TEMPLATES of

- ◆ Coherent +
- ◆ Incoherent +
- ◆ All other backgrounds



$$F_{\text{coh}} = \text{coh} / (\text{coh} + \text{incoh}) = [19.5 \pm 1.1 (\text{stat}) \pm 2.5 (\text{syst})]\% \quad \text{RS-based NUANCE: } \mathbf{30\%}$$

Definite signal. ~ 2/3 of RS NUANCE Simulation prediction.

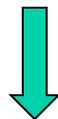
SciBooNE Results

■ Y. Kurimoto et al, arXiv:1005.0059 hep-ex

◆ Small four-momentum transfer to the nucleus:
 $E_\pi (1 - \cos \theta_\pi) < 100 \text{ MeV}$

$\langle E_\nu \rangle = 0.8 \text{ GeV}$

- ◆ No proton, defined as:
 Energy deposition near vertex $< 2 \text{ MeV}$
- ◆ Fit data distributions $E_\pi (1 - \cos \theta_\pi)$,
WITH and **WITHOUT** vertex activity,
 to coherent + incoherent + background (all other)
 Monte Carlo TEMPLATES.



Coh (π^0) Needed

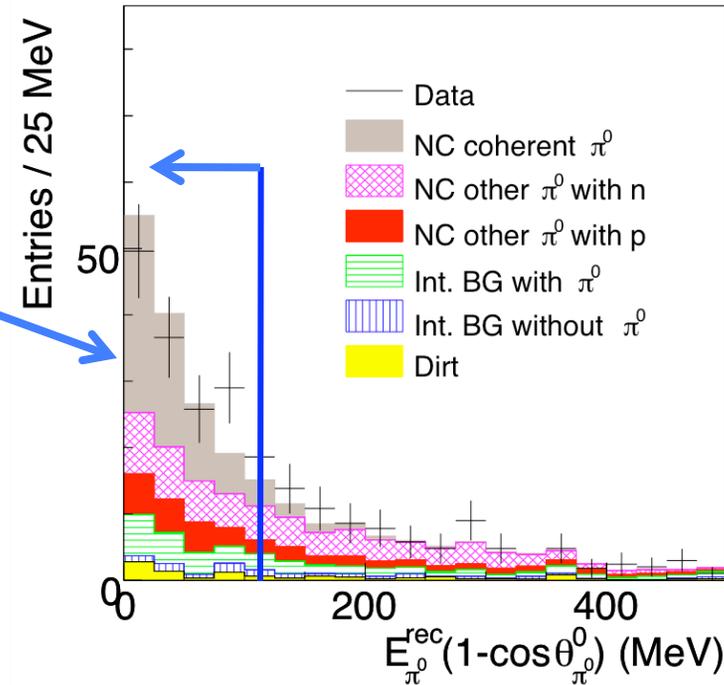
Fit results:

◆ the coherent fraction is $[0.96 \pm 0.20] \times \text{Rein - Sehgal estimate in NEUT Simulation}$

$\sigma (\text{CC coh.}\pi) / \sigma (\nu_\mu \text{ CC}) = [1.16 \pm 0.24] \times 10^{-2}$

Rein & Sehgal = $[1.21] \times 10^{-2}$

**Definite signal in
 good agreement
 with RS.**



NC Coherent: NOMAD

■ C.T.Kullenberg et al, Phys. Lett. **B682**: 177 (2009)

◆ Two converted γ 's and no other particle.

“Forwardness”

$\gamma\gamma$ opening angle

Define 4 variables

$$\rightarrow \zeta_{\gamma_1} = E_{\gamma_1}(1 - \cos\theta_{\gamma_1}), \zeta_{\gamma_2} = E_{\gamma_2}(1 - \cos\theta_{\gamma_2}), \Theta_{12}, m_{\gamma\gamma}.$$

Background determined from data

◆ Main non-coherent background is

NC DIS (NOT resonances at $\langle E_\nu \rangle \sim 25$ GeV).

◆ Determined from data looking at $m_{\gamma\gamma} > 0.2$ GeV/c² and $\zeta_{\gamma_{1,2}} > 0.05$

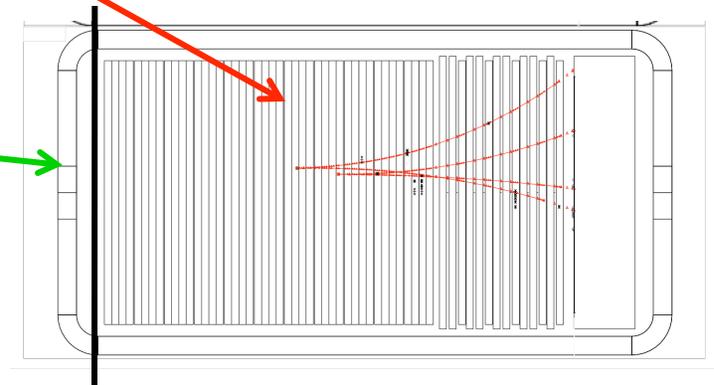
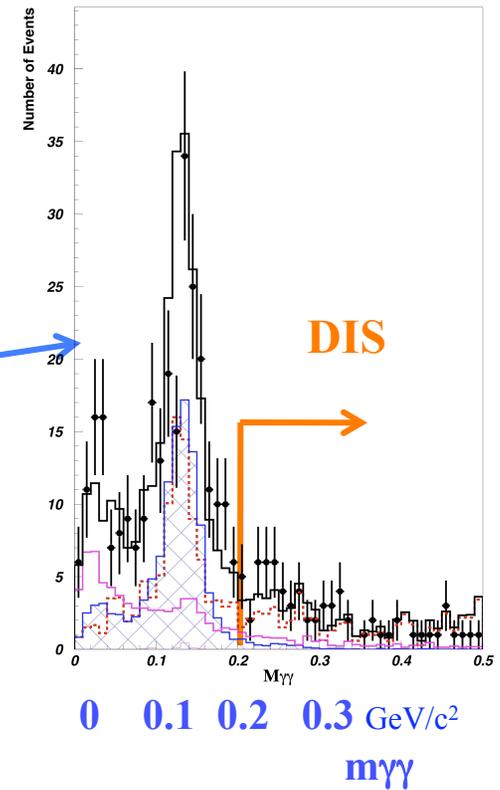
◆ Distance of closest approach of 2 photons $\rightarrow \nu$ interaction vertex

◆ Retain those **INSIDE** fiducial volume

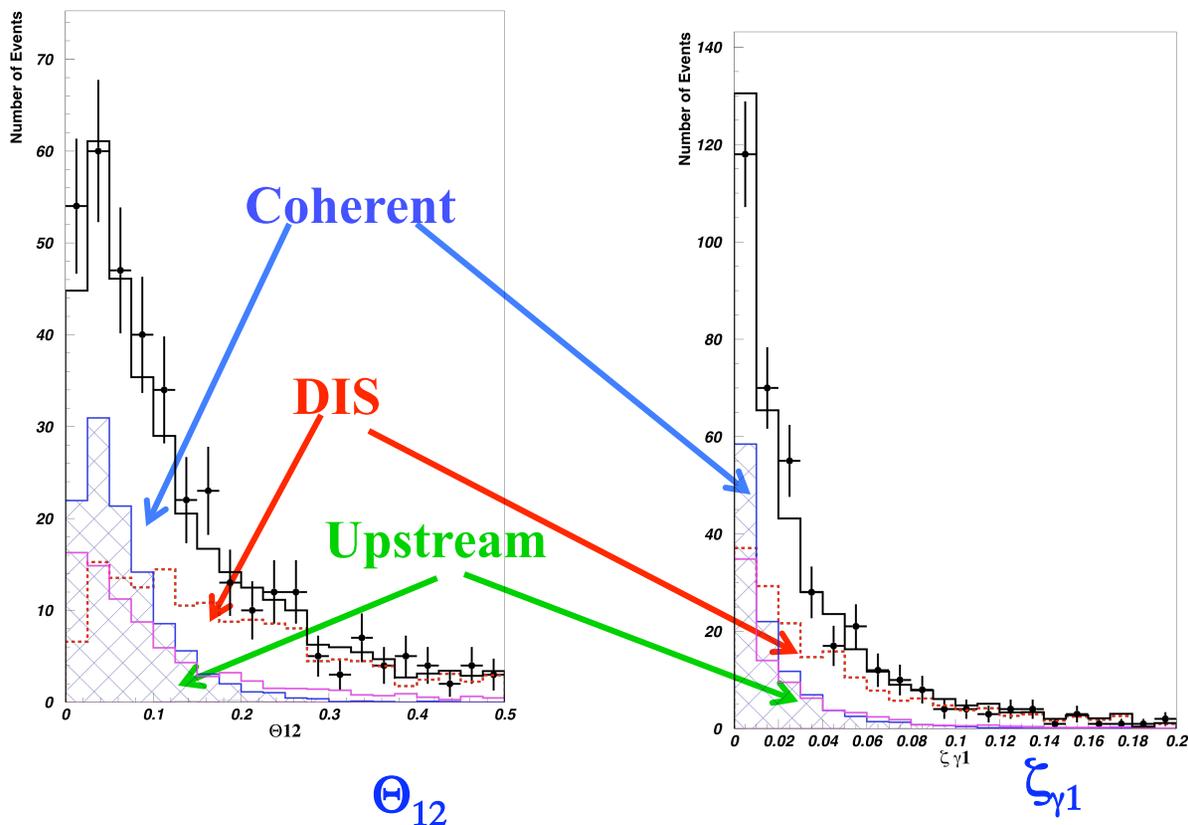
◆ How many **of these** are from ν int. **UPSTREAM** of fid. Vol. giving 2γ 's vertexing **INSIDE** fiducial volume?

◆ Calculated from:

Another 2γ sample from events with additional charged tracks vertexing UPSTREAM \rightarrow Known Background.



NOMAD Results



➤ Fit data distributions 2D $\zeta_{\gamma 1}$ vs $\zeta_{\gamma 2}$ and 1D Θ_{12} to fixed DIS + UPSTREAM back. + α x RS.

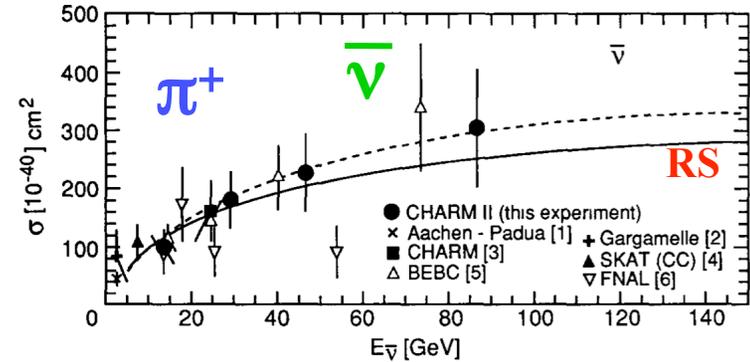
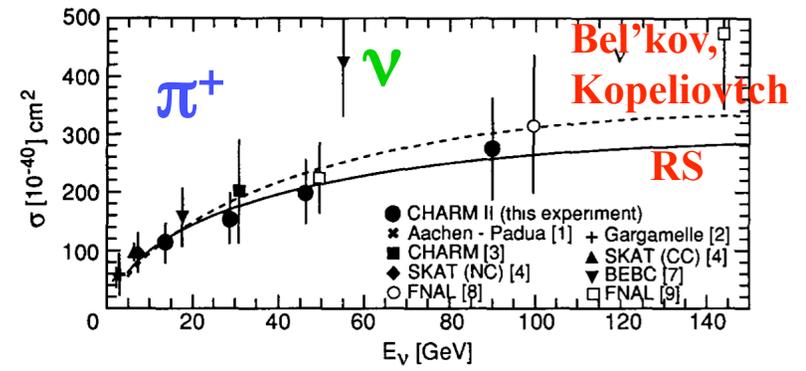
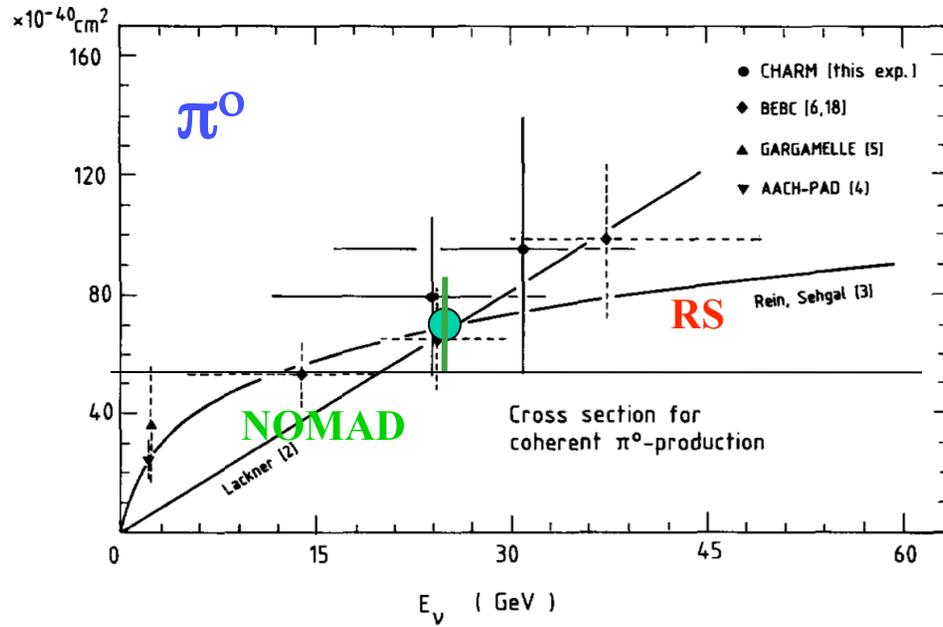
$$\alpha = 0.985 \pm 0.113 \text{ (stat)}$$

$$\sigma (\text{NC coh.}\pi) / \sigma (\nu_{\mu} \text{ CC}) = [3.21 \pm 0.36(\text{stat}) \pm 0.29(\text{syst})] \times 10^{-3} \quad \text{Rein \& Sehgal} = 3.5 \times 10^{-3}$$

$$\sigma (\text{NC coh.}\pi) = [72.6 \pm 8.1(\text{stat}) \pm 6.9(\text{syst})] \times 10^{-40} \text{ cm}^2/\text{nucleus}$$

$$\text{RS} = 78 \times 10^{-40} \text{ cm}^2/\text{nucleus} \quad \text{Definite signal in good agreement with RS.} \quad 13$$

Summary at High Energy



At High energy Rein and Sehgal Model describes older data and NOMAD well

Extensions to Rein and Sehgal model.

Berger and Sehgal, hep-ph arXiv:0812.2653 , Phys. Rev. D79 053003 (2009)

Extension I :

- ◆ Recompute: $d\sigma(\pi N \rightarrow \pi N)/dt = A^2 (d\sigma_{el}/dt|_{t=0}) e^{-bt} F_{abs}$

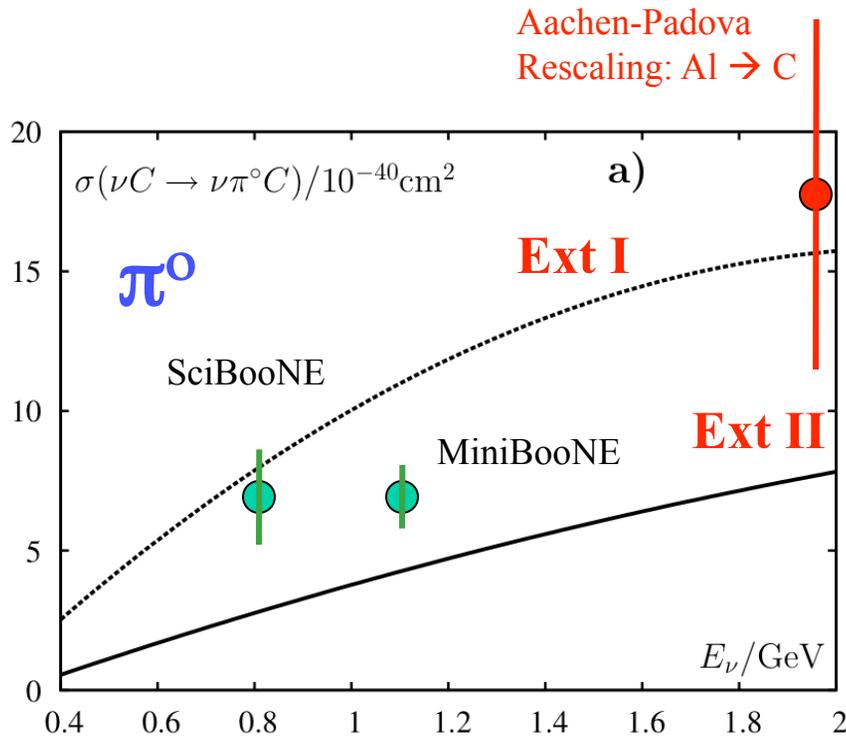
Using latest published **π -Nucleon** cross sections.

Extension II :

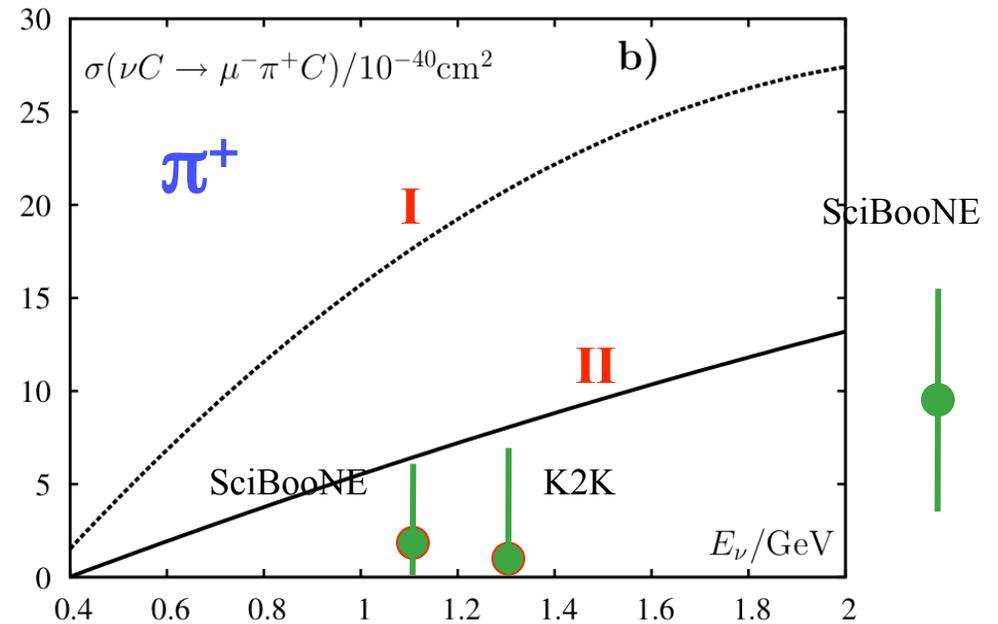
- ◆ To avoid modelling nuclear processes, use total and differential measured **π -Carbon** elastic cross sections.
- ◆ At lower energies yields smaller cross sections than in original RS.

Summary: Data vs Berger and Sehgal.

My estimate of $\sigma|_{\text{Exp}} = \text{Coh}|_{\text{Exp} \cdot \text{Obs}} / \text{Coh}(\text{RS})|_{\text{Exp.MC}} \times \text{Coh}(\text{RS})|_{\text{Model(Ext I)}}$



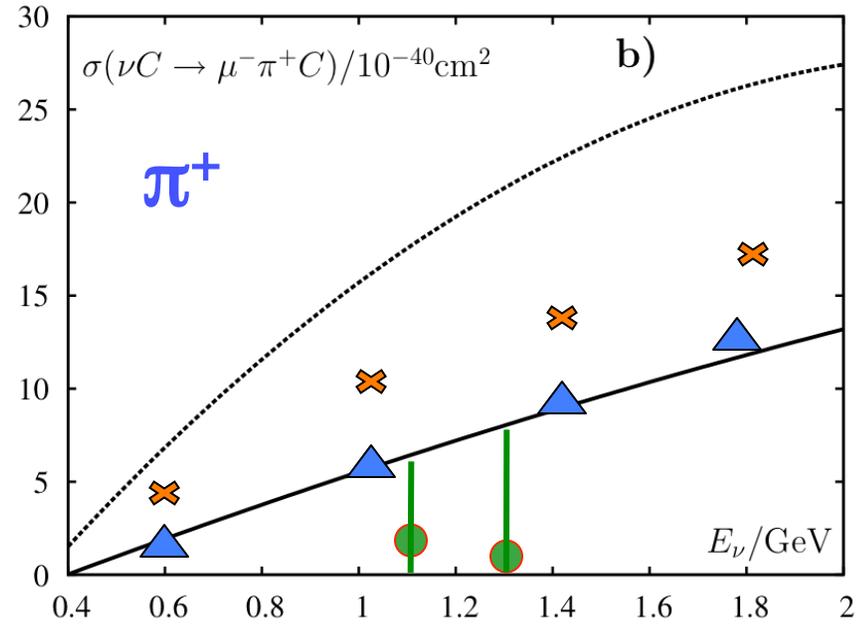
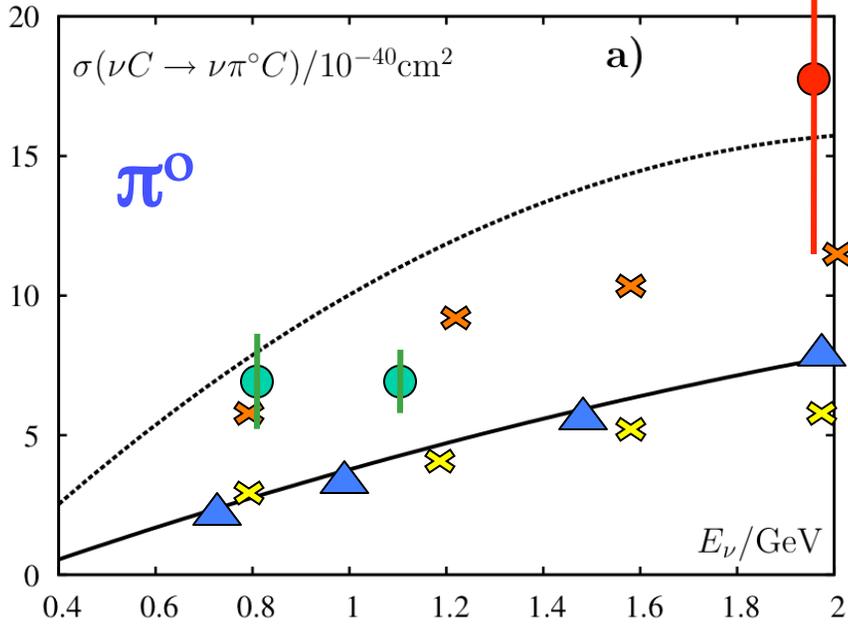
Good agreement with Ext. I



Data lower than both Ext. I and II

SciBooNE ($E_\nu \sim 1 \text{ GeV}$): $\frac{\sigma(\text{CCcoh } \pi^+)}{\sigma(\text{CCcoh } \pi^0)} = 0.14^{+0.30}_{-0.28}$ BS(1 GeV) ~ 1.5

Other models



- }
}
}
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}
- × L. Alvarez-Ruso et al π^+ : Phys. Rev. **C75**, 055501 (2007) and π^0 : Phys. Rev. **C76**, 068501 (2007)
- × Model: Δ production. Modified in nuclear medium. Final pion distortion.
- ▲ S.K. Singh et al Phys. Rev. Lett. **96** 241801 (2006)

Conclusions

➤ At high energy ($> 2 \text{ GeV}$),

- ◆ the Rein - Sehgal model **AGREES WELL** with the data, for both π^0 (new NOMAD data) and π^+ coherent production.

➤ At lower energies ($< 2 \text{ GeV}$),

- ◆ Coherent π^+ (CC) **HAS NOT** been observed by K2K and SciBooNE.
- ◆ Their upper limits are consistent with several models.
- ◆ Coherent π^0 **HAS** been observed by SciBooNE and MiniBooNE. Their measured rate tend to favour models with a high π^0 yield.
- ◆ The ratio of CC/NC coherent pion is **BELOW** expectations, even after taking into account the lepton mass.
- ◆ **WARNING!** Efficiency calculations and conclusions may be affected by different simulation codes used by different experiments.
- ◆ We are looking forward to new data from Minerva and MicroBooNE.

Back Up

Slides

Alvarez-Ruso

L. Alvarez-Ruso et al π^+ : Phys. Rev. **C75**, 055501 (2007)

and π^0 : Phys. Rev. **C76**, 068501 (2007)

Model: Δ production. Modified in nuclear medium.

Final pion distortion.

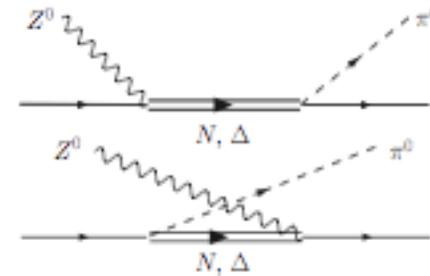


FIG. 1: Mechanisms contributing to coherent π^0 production in isospin symmetric matter.

- Form factors:
- **Set 1:** $C_3^A = 0$, $C_4^A = -C_5^A/4$, $C_5^A(0) = 1.2$, $M_{A\Delta} = 1.28$ GeV

$$C_5^A = C_5^A(0) \left(1 + \frac{1.21 q^2}{2 \text{ GeV}^2 - q^2}\right) \left(1 - \frac{q^2}{M_{A\Delta}^2}\right)^{-2}.$$

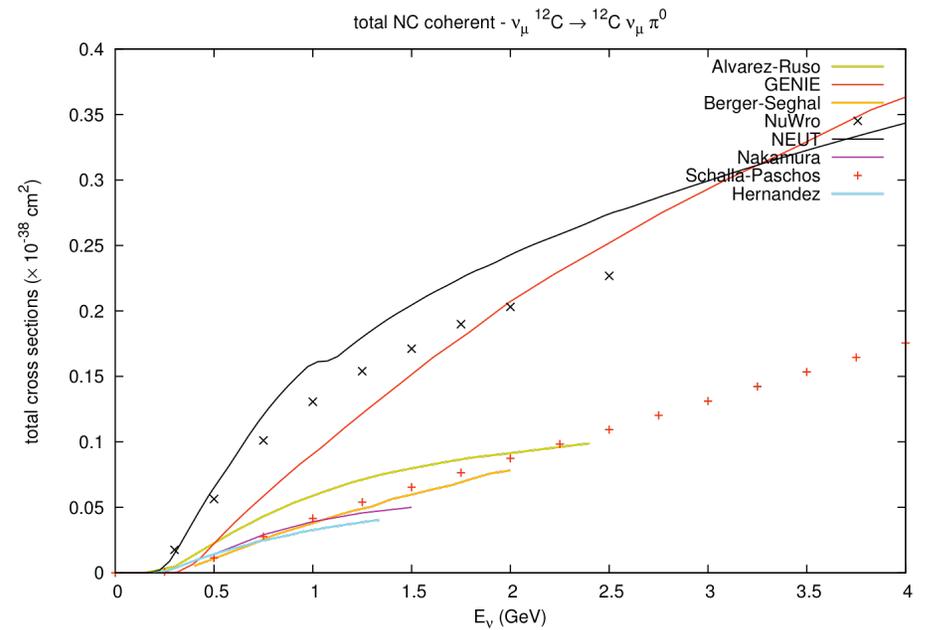
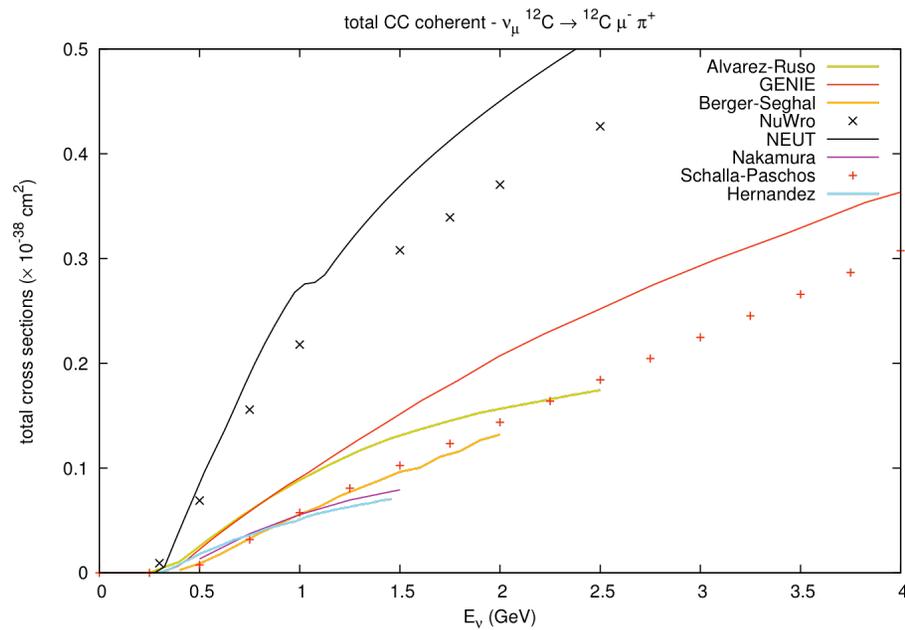
- **Set 2:** $C_5^A(0) = 0.867$, $M_{A\Delta} = 0.985$ GeV

$$C_5^A = C_5^A(0) \left(1 - \frac{q^2}{3M_{A\Delta}^2}\right)^{-1} \left(1 - \frac{q^2}{M_{A\Delta}^2}\right)^{-2}.$$

Vector from new analysis of electron scattering data.

Summary: Data vs Models.

Models from E. Hernandez NuInt09



Cross section

$$\frac{d\sigma^{\text{CC}}}{dQ^2 dy dt} = \frac{G_F^2 \cos^2 \theta_C f_\pi^2}{2\pi^2} \frac{E_{uv}}{|q|} \left[\left(G_A - \frac{1}{2} \frac{Q_{\text{min}}^2}{Q^2 + m_\pi^2} \right)^2 + \frac{y(Q^2 - Q_{\text{min}}^2)}{4} \frac{Q_{\text{min}}^2}{(Q^2 + m_\pi^2)^2} \right] \frac{d\sigma(\pi^+ N \rightarrow \pi^+ N)}{dt}$$

MiniBooNE/SciBooNE

or NUANCE/NEUT???

	MiniBooNE	SciBooNE
Coh/(Coh+Inc)	$(19.5 \pm 2.7)\%$	$(17.9 \pm 4.1)\%$
Rein&Sehal MC Pred.	30%	22%
Monte Carlo	NUANCE	NEUT
Energy	1.1 GeV	0.8 GeV