Coherent Pion Production (Recent experimental results)

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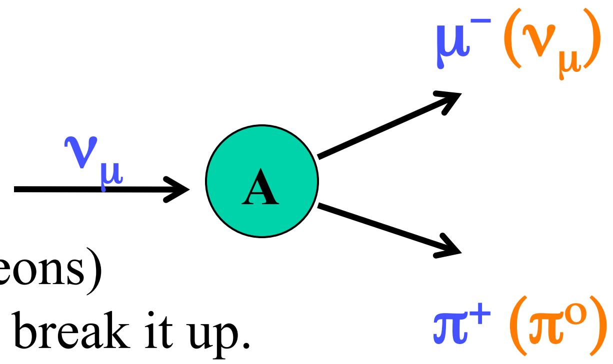
The Experiments

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

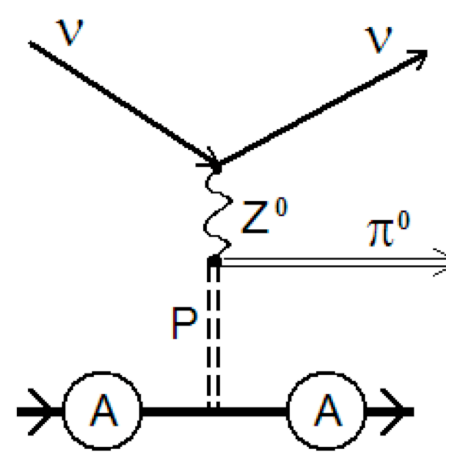
Coherent Pion Production

- Coherent production
  - CC: $\nu_\mu + A \rightarrow \mu^- + A + \pi^+$
  - NC: $\nu_\mu + A \rightarrow \nu_\mu + A + \pi^o$



- 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

NC



- 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: $\sigma(CC: \pi^+) = 2\ \sigma(NC: \pi^o)$

Rein and Sehgal 1983 NC Cross section

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

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

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

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

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 (~ 1GeV):** Resonance production (especially Δ):
  - $\Delta \rightarrow \pi\, p \quad \rightarrow$ Missing proton.
  - For CC: QEL and misidentification proton $\rightarrow \pi^+$.

- **Higher energy:** DIS.

- Interactions **OUTSIDE** the detector (Especially for π^o).

Other difficulty

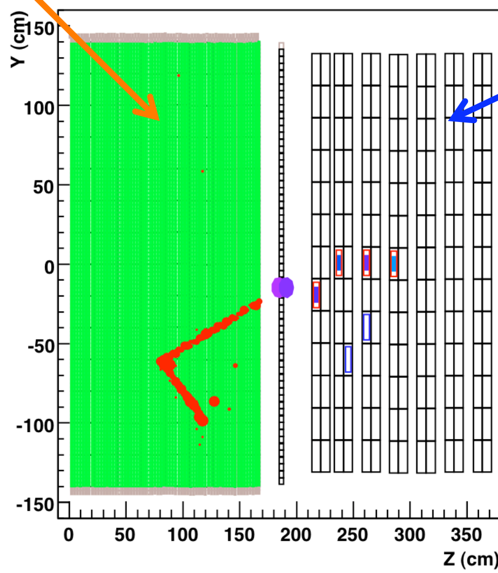
- Reinteractions of final state hadrons, on the “way out” of the nucleus:

  $\rightarrow$ 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. **$<E_\nu> = 1.1$ GeV**
  - μ traverses the MRD and exits. **$<E_\nu> = 2.2$ GeV**

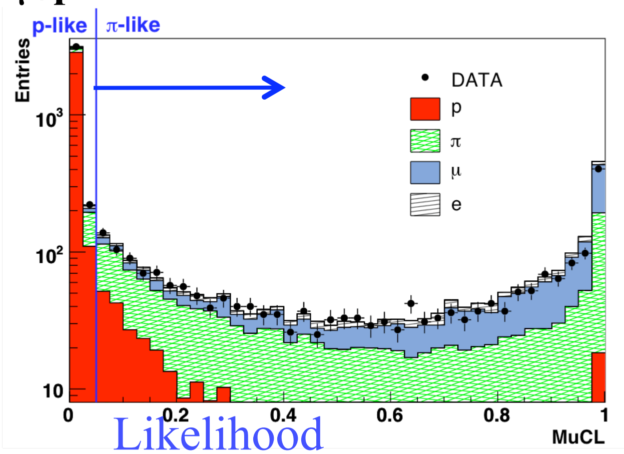
- K2K: M. Hasegawa et al Phys. Rev. Lett. **95**:252301 (2005)
- SciBooNE: K. Hiraide et al Phys. Rev. **D78**:112004 (2008).

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

CC Coherent: 2-track sample

QEL background: Proton fakes a pion

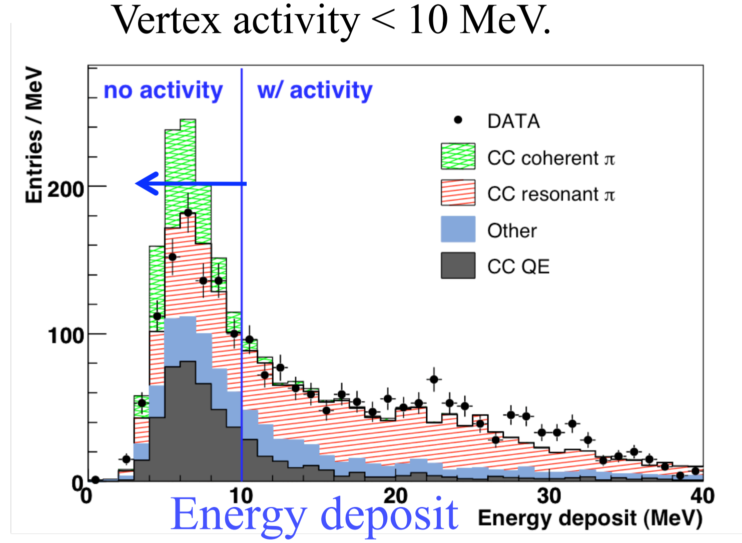
μ/p/π ID based on dE/dx Likelihood



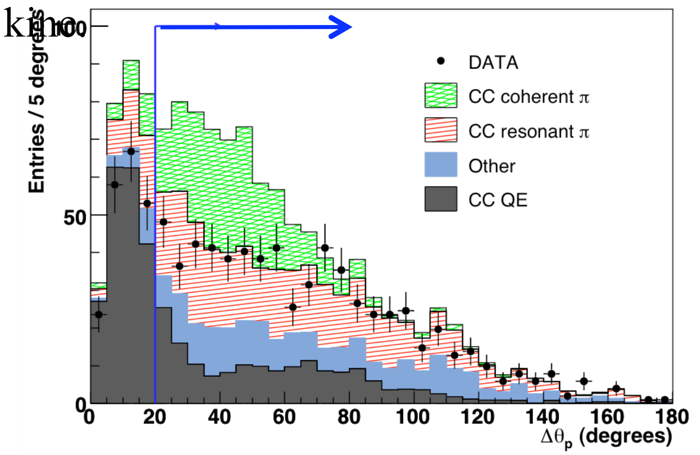
Δ Background: Proton not reconstructed

Only Keep events with

Vertex activity < 10 MeV.

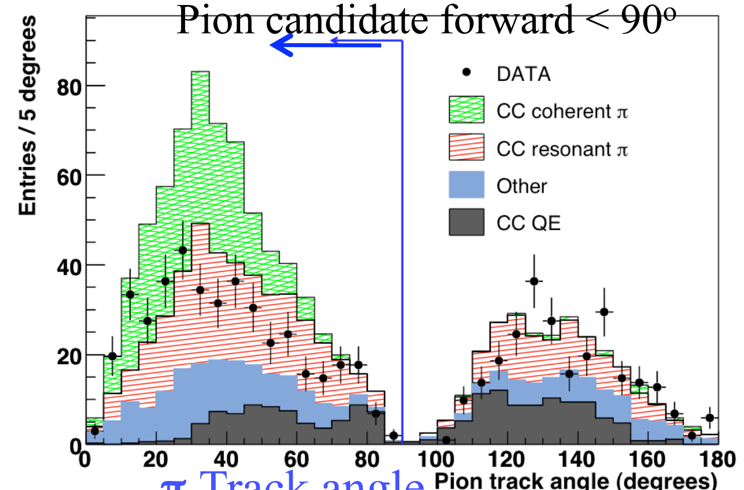


QEL:Angle of non-μ track inconsistent with proton direction calculated based on μ and QEL kine

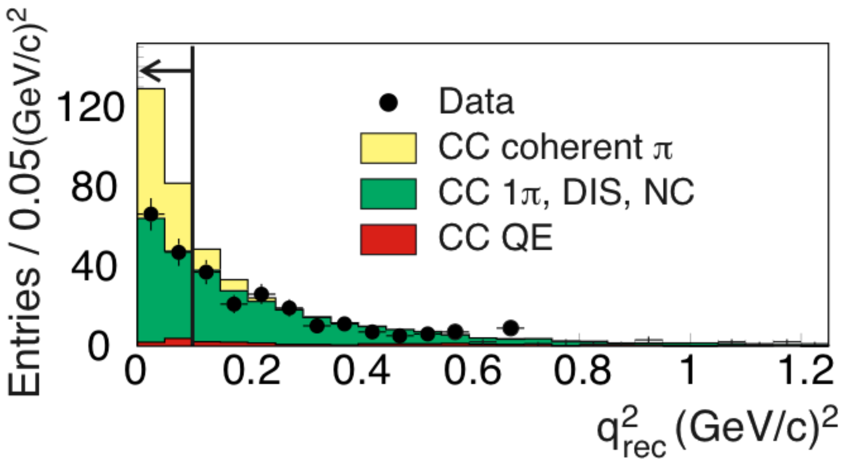


$\Delta\theta_p$

Pion candidate forward < 90°



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



K2K: $<E_\nu> = 1.3$ GeV

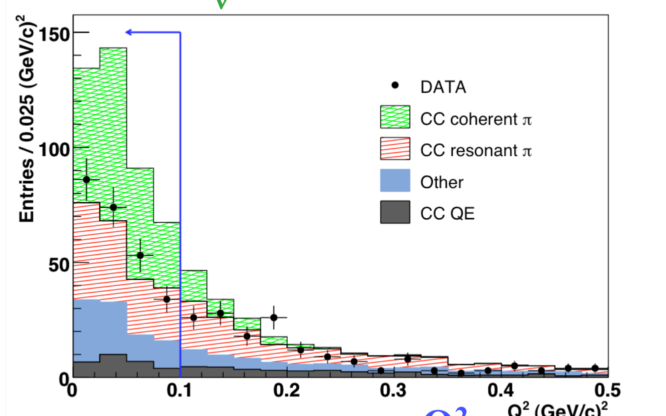
σ(CC coh.π)/ σ (ν_μ CC)

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

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

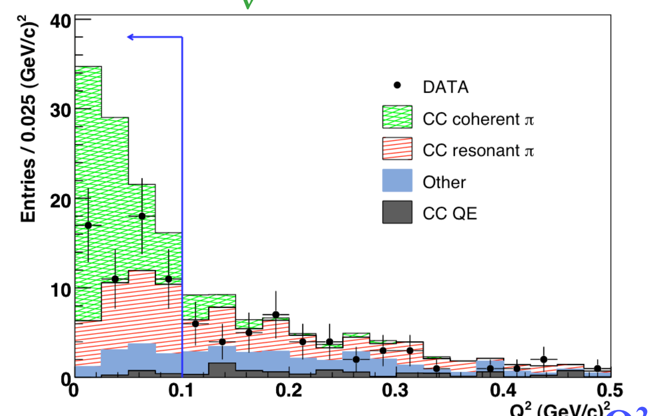
SciBooNE:

$<E_\nu> = 1.1$ GeV



Q^2

$<E_\nu> = 2.2$ GeV



Q^2

σ (CC coh.π)/ σ (ν_μ CC)

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

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

NO Evidence For CC coh π+

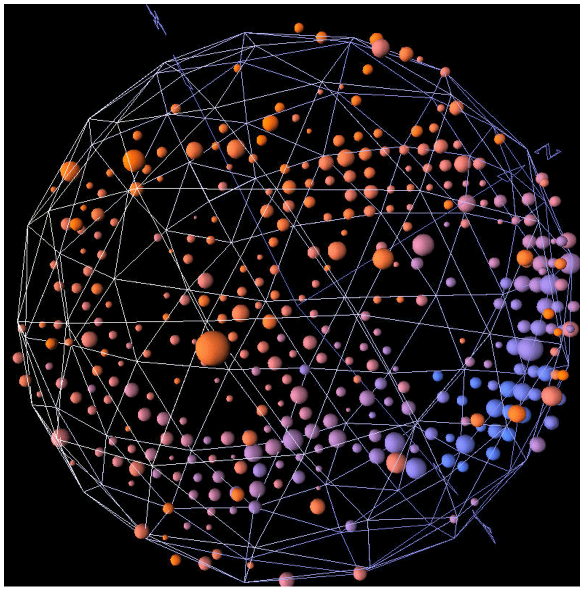
σ (CC coh.π)/ σ (ν_μ CC)

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

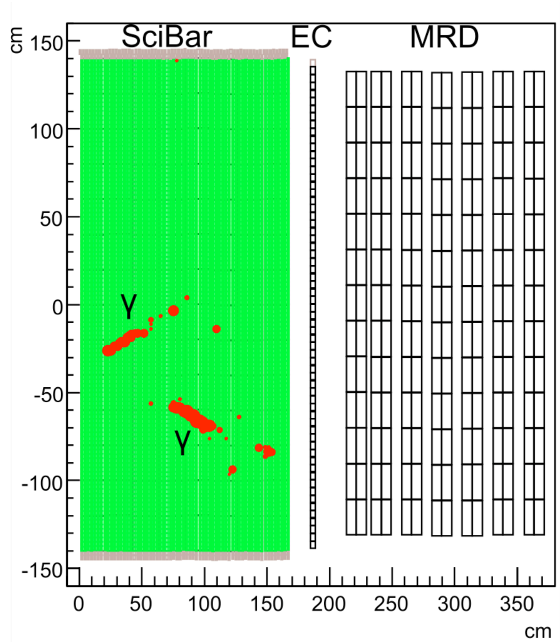
$< 1.36 \times 10^{-2}$ at 90% CL.

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

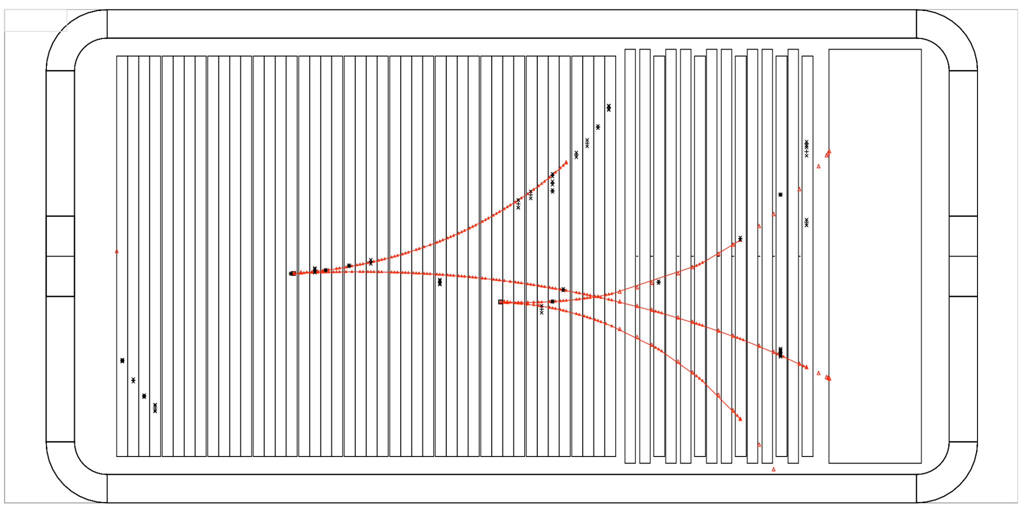
- Three experiments: MiniBooNE, SciBooNE and NOMAD.



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

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

- **No μ** based on absence of delayed decay electron.
- **μ/e/π^o** separation based on Likelihoods (sharpness and numbers of Cerenkov rings)

Use 2 variables

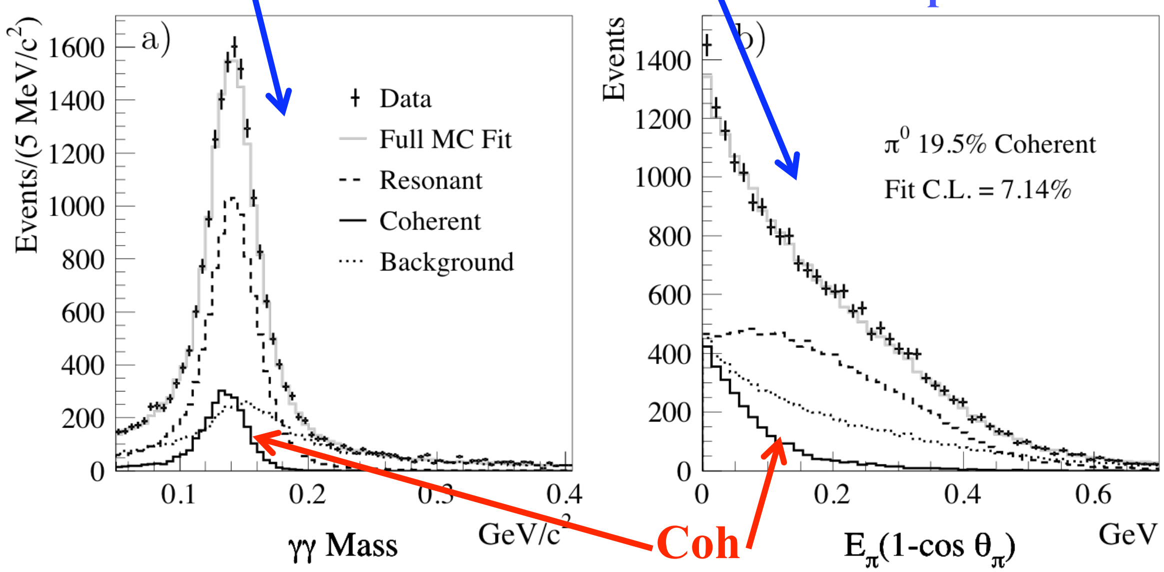
$m_{\gamma\gamma}$ vs $E_\pi (1-\cos\theta_\pi)$

Measure of "Forwardness" ~ independent of Energy

- Fit 2D data distribution

To TEMPLATES of

- Coherent +
- Incoherent +
- All other backgrounds



F_{coh} = coh / (coh + incoh) = [19.5 ± 1.1 (stat) ± 2.5 (syst)]%   RS-based NUANCE: **30%**

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

SciBooNE Results

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

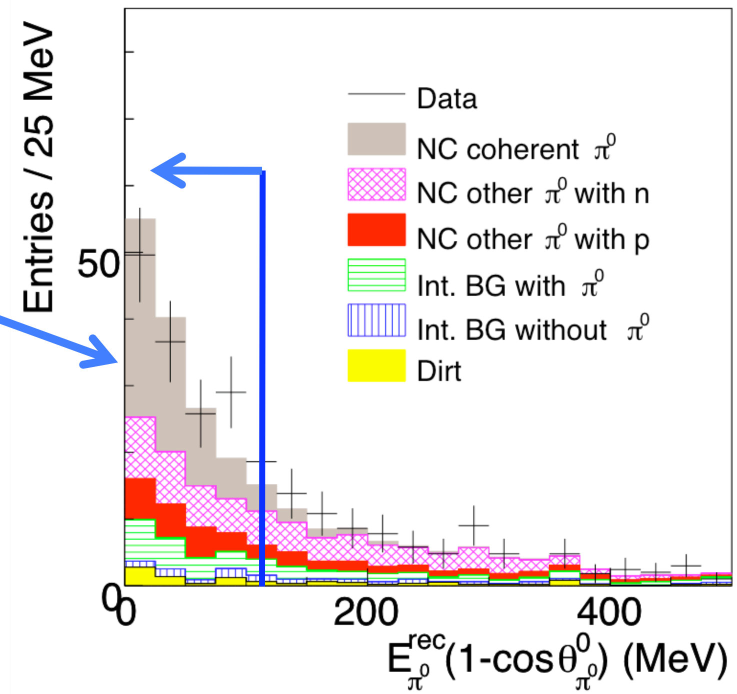
$<E_\nu> = 0.8$ GeV

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

◆No proton, defined as:
Energy deposition near vertex **< 2 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 ± 0.20] x Rein - Sehgal estimate in NEUT Simulation

σ (CC coh.π)/ σ (ν_μ CC) = [1.16 ± 0.24] x 10^{-2}

Rein & Sehgal = [1.21] x 10^{-2}

Definite signal in good agreement with RS.

NC Coherent: NOMAD

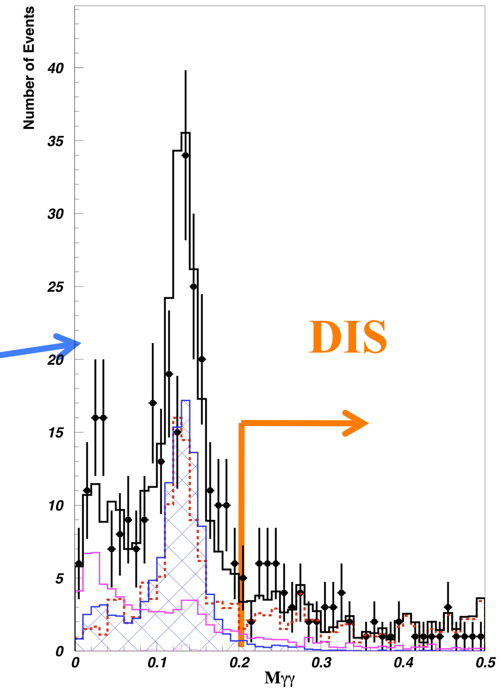
- C.T.Kullenberg et al, Phys. Lett. **B682**: 177 (2009)

◆Two converted γ's and no other particle. "Forwardness"

γγ opening angle

Define 4 variables

→ $\zeta_{\gamma 1} = E_{\gamma 1}(1\text{-}\cos\theta_{\gamma 1})$, $\zeta_{\gamma 2} = E_{\gamma 2}(1-\cos\theta_{\gamma 2})$, Θ12, **mγγ**.

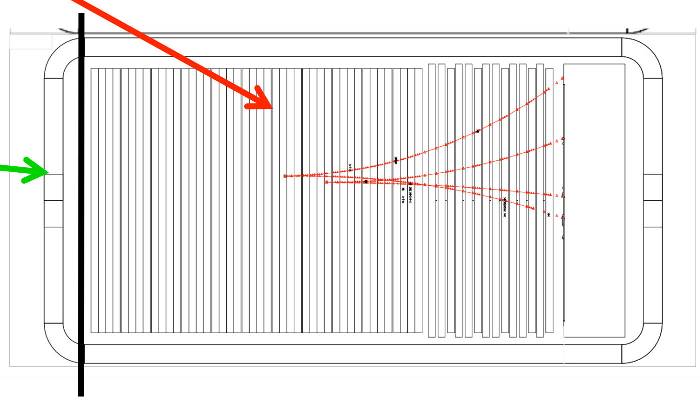


Background determined from data

◆Main non-coherent background is
NC DIS (NOT resonances at $<E_\nu> \sim 25$ GeV).

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

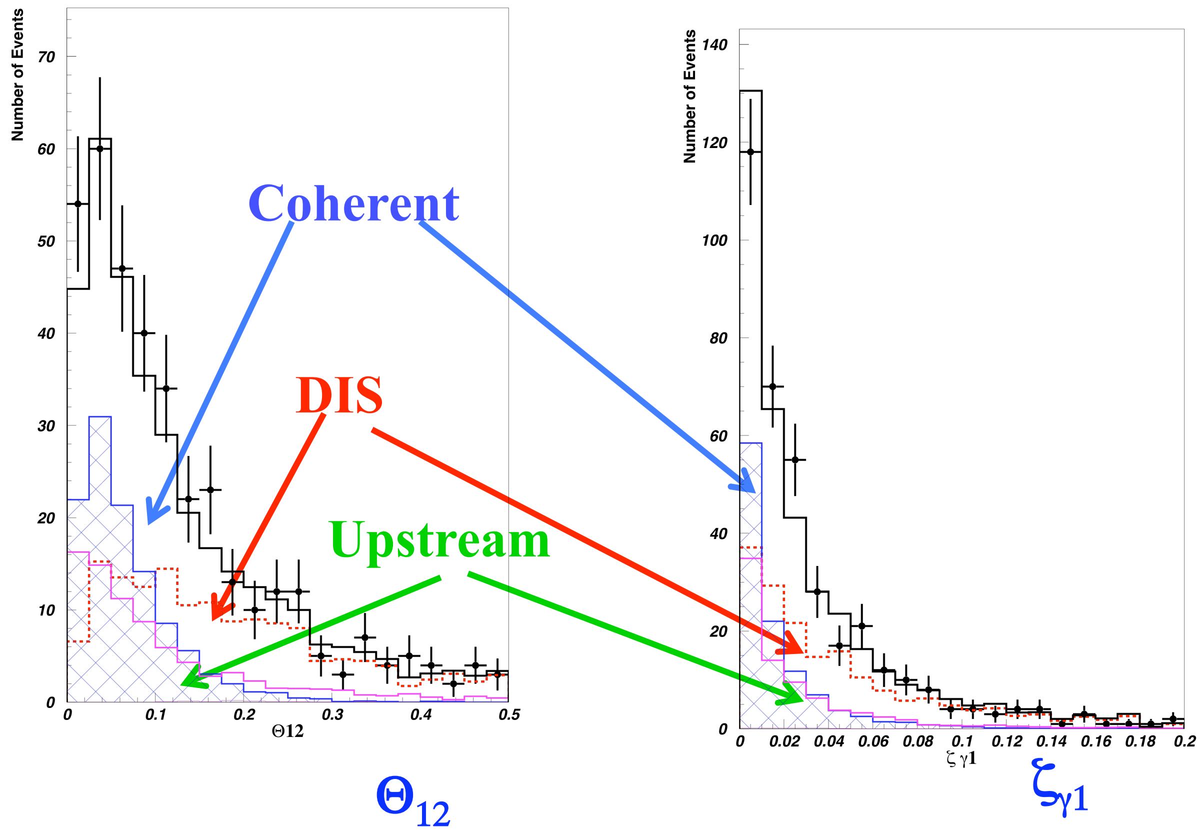
◆Distance of closest approach of 2 photons → ν interaction vertex
Retain those **INSIDE** fiducial volume



◆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 → Known Background.

NOMAD Results



$<E_\nu> = 25$ GeV

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

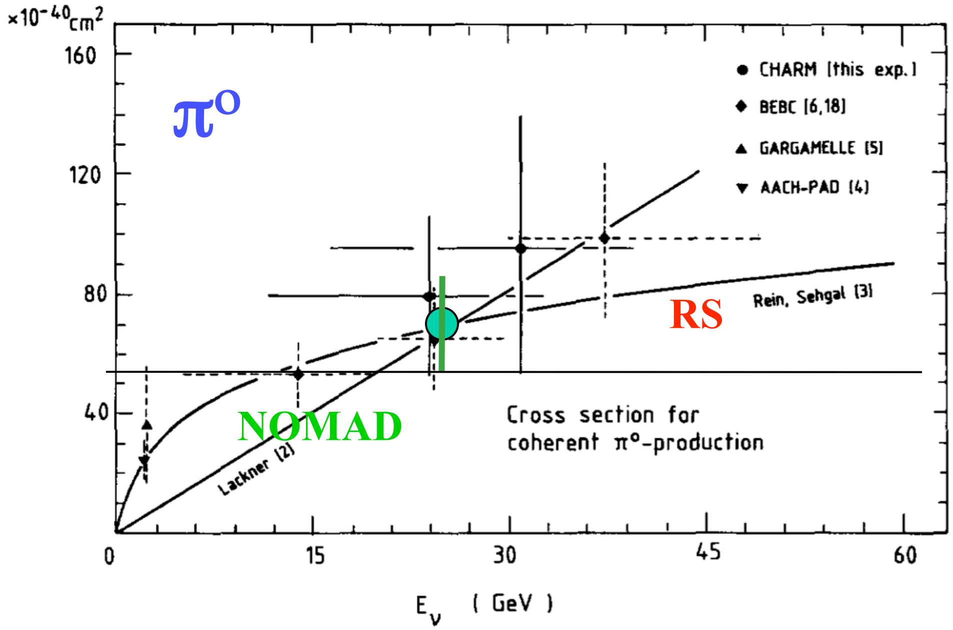
$$\alpha = 0.985 \pm 0.113 \text{ (stat)}$$

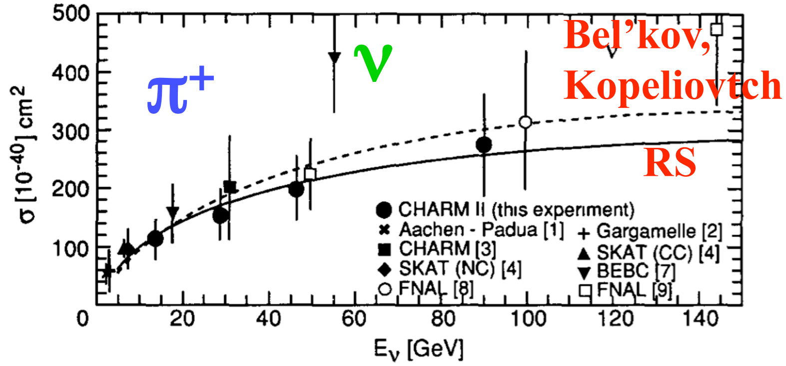
σ (NC coh.π)/ σ (ν_μ CC)=[3.21±0.36(stat)±0.29(syst)] x 10^{-3} Rein & Sehgal = 3.5 x 10^{-3}

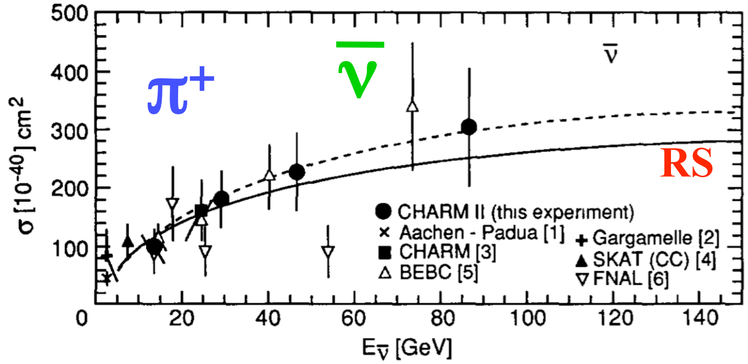
σ (NC coh.π) = [72.6 ± 8.1(stat) ± 6.9(syst)] x 10^{-40} cm^2/nucleus

RS = 78 x 10^{-40} cm^2/nucleus **Definite signal in good agreement with RS .**

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

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

Extension II :

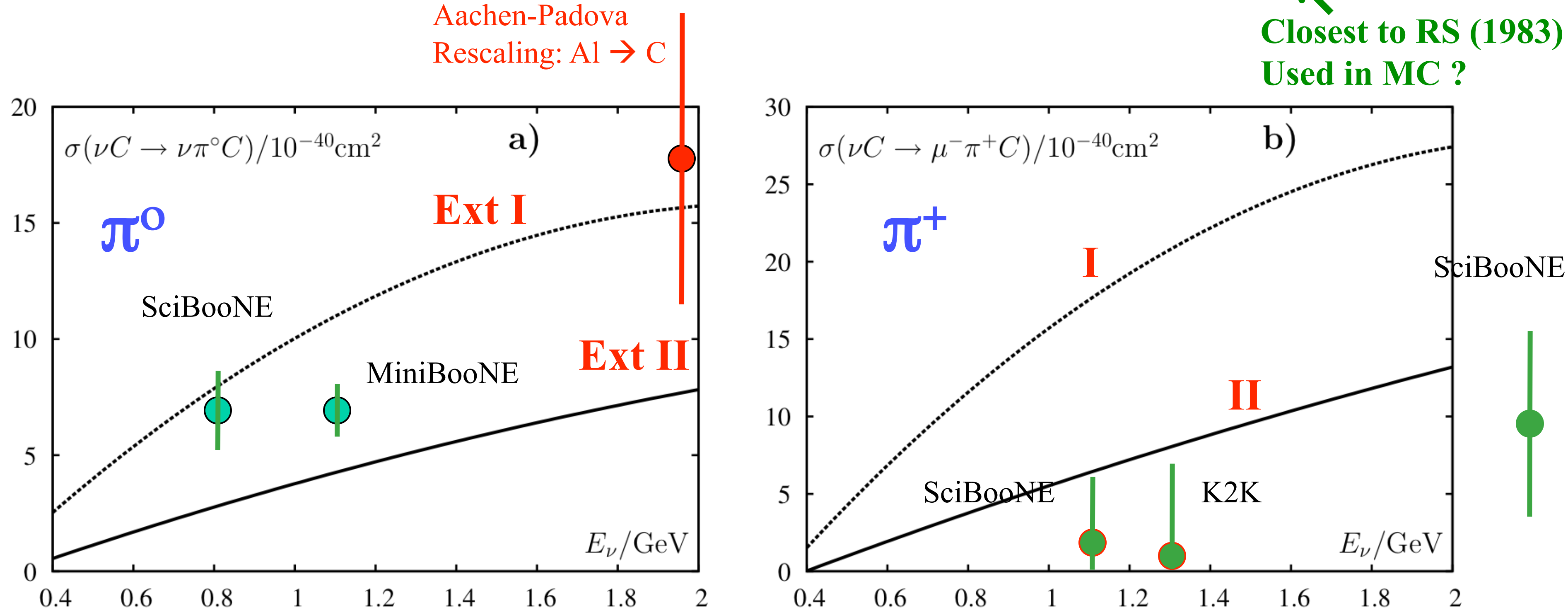
- To avoid modelling nuclear processes, use total and differential

  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 $\sigma|_{Exp} = \mathrm{Coh}|_{Exp \cdot Obs} / \mathrm{Coh(RS)}|_{Exp.MC} \times \mathbf{Coh(RS)}|_{\mathbf{Model(Ext\ I)}}$

Closest to RS (1983)
Used in MC ?

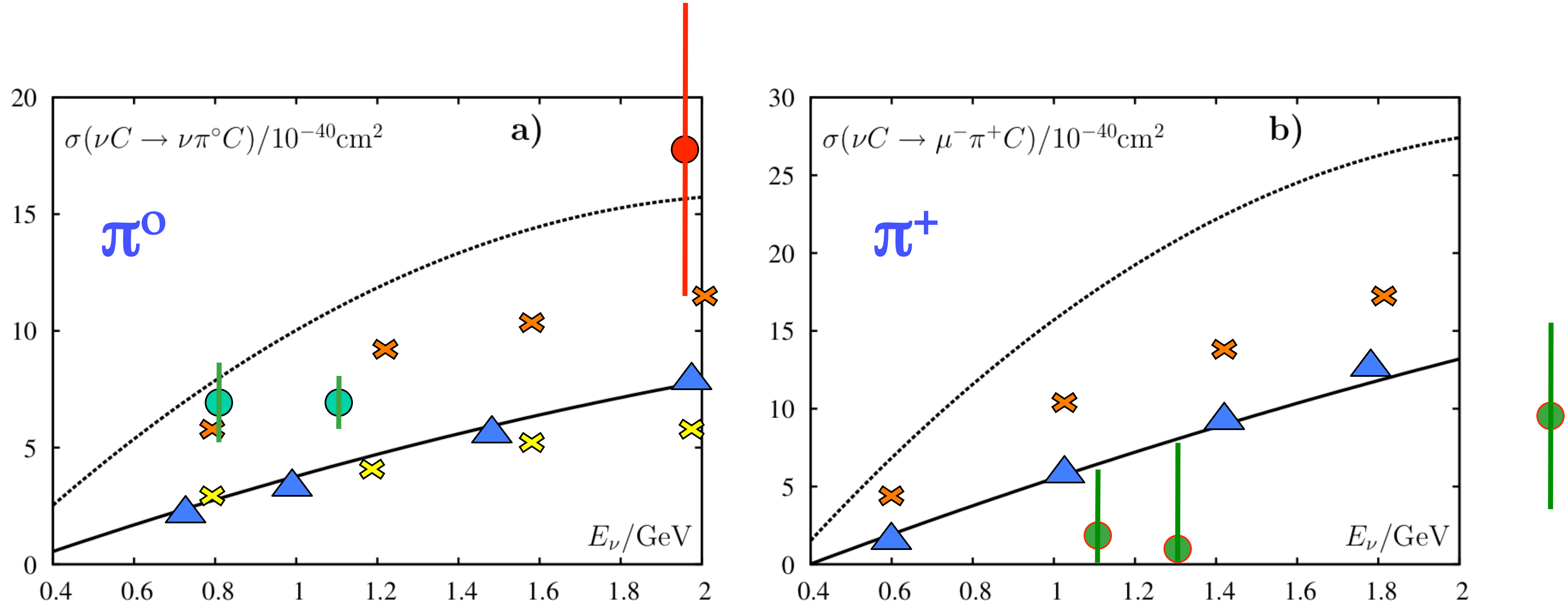


Good agreement with Ext. I

Data lower than both Ext. I and II

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

Other models



L. Alvarez-Ruso et al π^+: Phys. Rev. **C75**, 055501 (2007) and π^o :Phys. Rev. **C76**, 068501 (2007)
Model: Δ production. Modified in nuclear medium. Final pion distortion.
Different colour symbols refer to different sets of form factors used in calculation.

S.K. Singh et al Phys. Rev. Lett. **96** 241801 (2006)

What needs to be done systematically:

- Understand the implementation, in the various Monte Carlo's of:
  - The Rein-Sehgal model
  - Nuclear re-interactions
  - Fermi momentum

- Implement newer models in the Monte Carlo's: Important at low energy mostly.
- Study the stability of measured cross-sections vs different models in simulations

Example: MiniBooNE/SciBooNE or NUANCE/NEUT ???

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

(Table supplied by MiniBooNE, SciBooNE physicists)

MicroBooNE

- **Coherent π^0:**
  - Excellent photon identification.
  - Good angular and energy resolution allows the use of "forwardness" and pizero mass

- **Coherent π^+:**
  - Range and dE/dx should allow p/π^+ discrimination.
  - Muon range should allow momentum measurement. Multiple scattering?

- For both π^0 and π^+ excellent vertex activity capability should clean up samples.

Conclusions

- **At high energy (> 2 GeV),**

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

- **At lower energies (< 2Gev),**

◆ Coherent π^+ (CC) **HAS NOT** been observed by K2K and SciBooNE.

◆ Their upper limits are consistent with several models.

◆ Coherent π^o **HAS** been observed by SciBooNE and MiniBooNE.
Their measured rate tend to favour models with a high π^o 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^o :Phys. Rev. **C76**, 068501 (2007)
Model: Δ production. Modified in nuclear medium.
Final pion distortion.

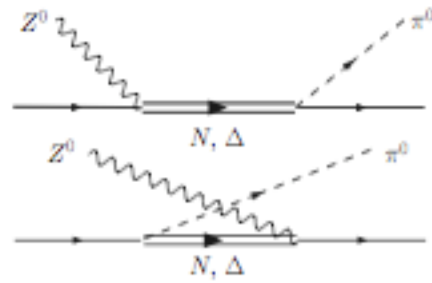


FIG. 1: Mechanisms contributing to coherent π^0 production in isospin symmetric matter.

- Form factors:

- **Set 1:** $C^A_3 = 0$, $C^A_4 = - C^A_5/4$, $C^A_5(0) = 1.2$, $M_{A\Delta} = 1.28$ GeV

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

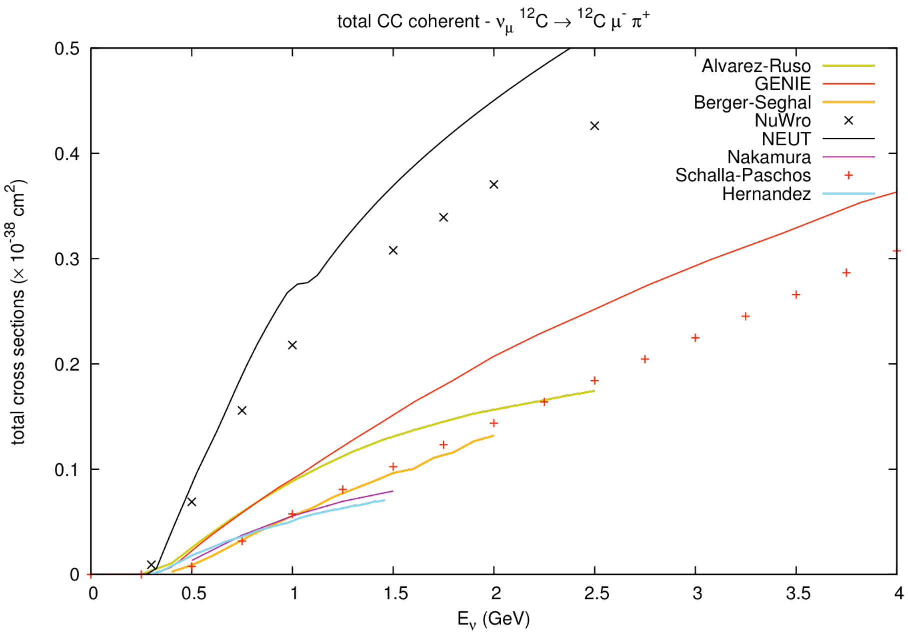
- **Set 2:** $C^A_5(0) = 0.867$, $M_{A\Delta} = 0.985$ GeV

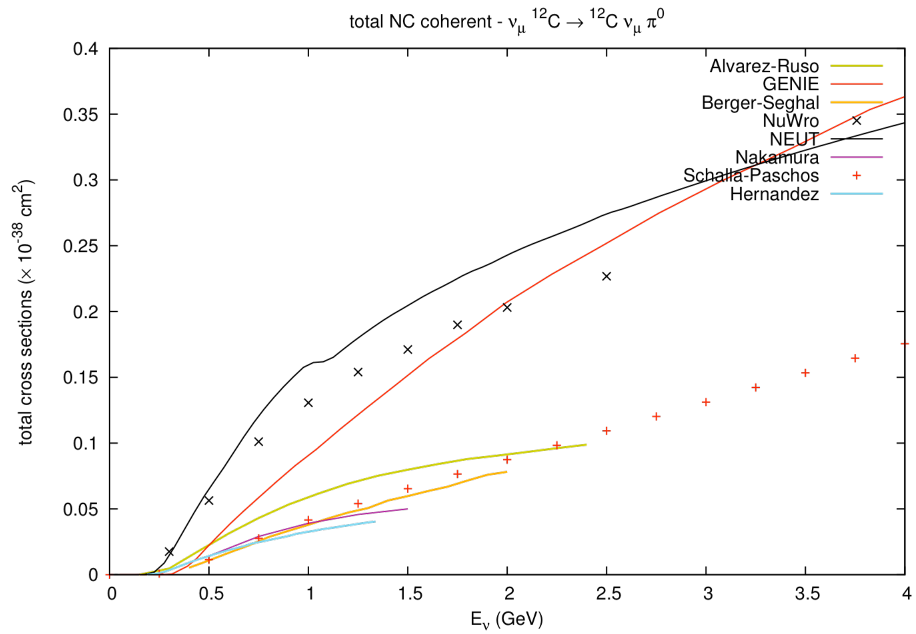
$$C_5^A = C_5^A(0)\left(1 - \frac{q^2}{3M_{A\Delta}^2}\right)^{-1}\left(1 - \frac{q^2}{M_{A\Delta}^2}\right)^{-2}.$$

Vector from new analysis of electron scattering data.

Summary: Data vs Models.

Models from E. Hernandez NuInt09





Cross section

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