Neutrino-Induced Coherent Pion Production

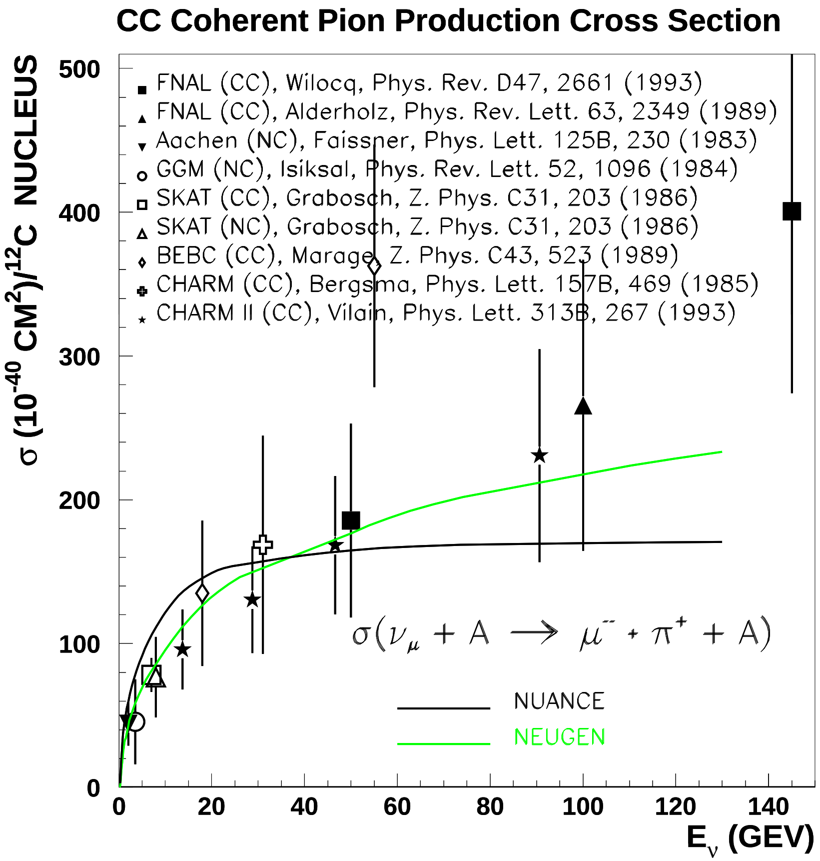
L. Alvarez-Ruso[1], L. Geng[1], S. Hirenzaki[2], M. J. Vicente Vacas[1]

1. Universidad de Valencia
2. Nara Women's University

Introduction

- ν–induced coherent π production reactions:
  - Charged Current $\nu_l \, A \to l^- \, \pi^+ \, A$
  - Neutral Current $\nu_l \, A \to \nu_l \;\; \pi^0 \, A$
- Important for oscillation experiments: systematic uncertainties
  - Example: $\nu_l \, A \to \nu_l \;\; \pi^0 \, X$ $\leftarrow$ background for ν_e appearance
- Also interesting for hadronic and nuclear physics:
  - N, N-R axial form factors
  - Nuclear correlations
  - π in the nuclear medium
- Measured at high energies E_ν > 2 GeV (FNAL, GGM, SKAT, BEBC, …)

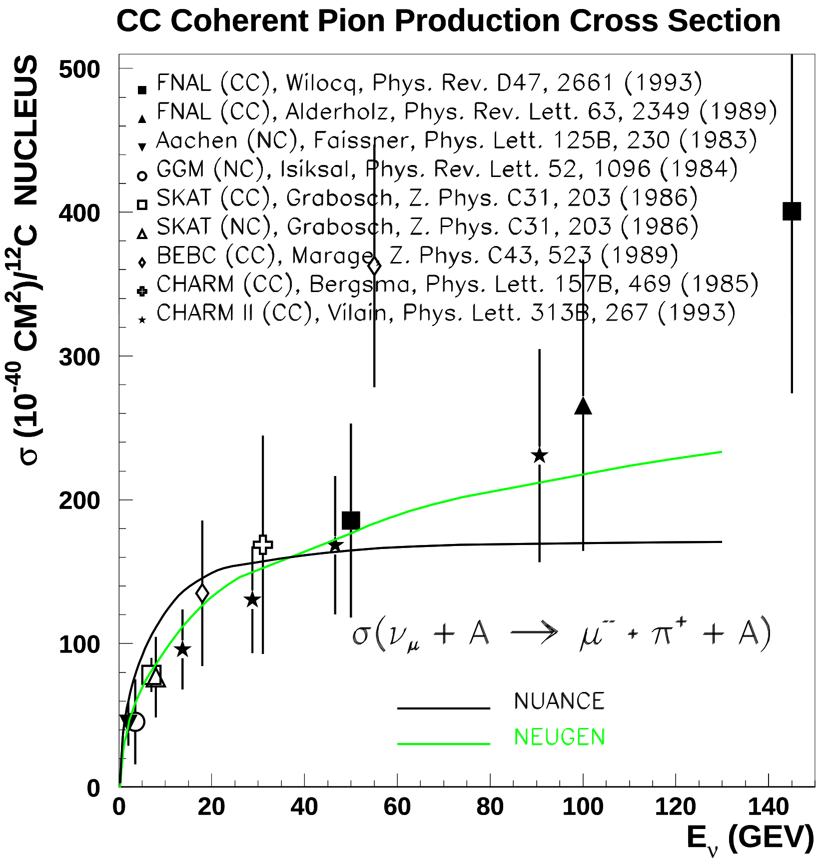
Introduction



- G. Zeller, hep-ex/0312061 (NUINT 02)
- Data scaled to ^{12}C assuming $A^{1/3}$ dependence
- σ(CC)=2 σ(NC)

- Measured at high energies E_ν > 2 GeV (FNAL, GGM, SKAT, BEBC, …)

Introduction



- G. Zeller, hep-ex/0312061 (NUINT 02)
- Data scaled to ^{12}C assuming $A^{1/3}$ dependence
- σ(CC)=2 σ(NC)

- Measured at high energies E_ν > 2 GeV (FNAL, GGM, SKAT, BEBC, ...)
- These data are well described by models based on PCAC

  Rein & Sehgal, NPB 223 (83), Paschos, Kartavtsev, Gounaris, PRD 74(06)

  However, at lower energies ...

Introduction

- K2K ($< E_\nu >$=1.3 GeV) finds a significant deficit of μ^- at forward angles

⇕

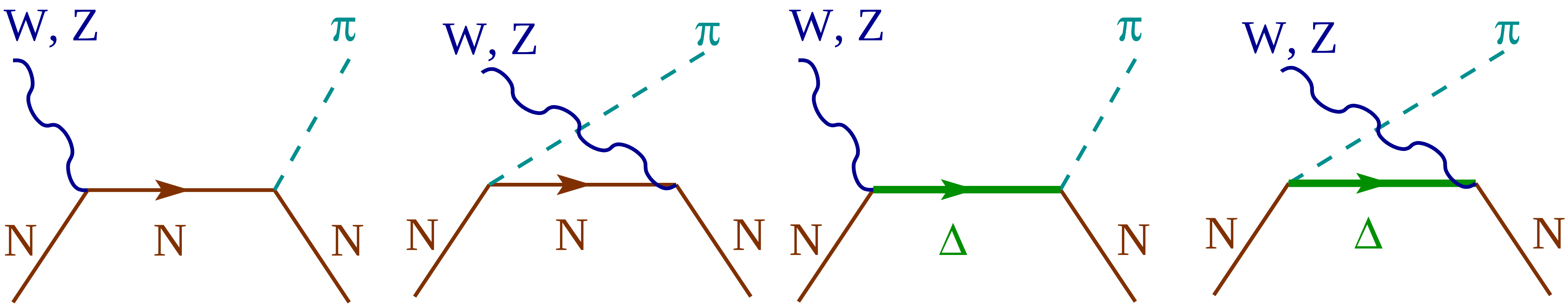
- Upper bound for CC Coh. π^+ production below theoretical expectations

- MiniBooNE ($< E_\nu >$=0.75 GeV) NC π^0 data under analysis.
  First results: J. Link @ NUINT07, arXiv:0709.3213

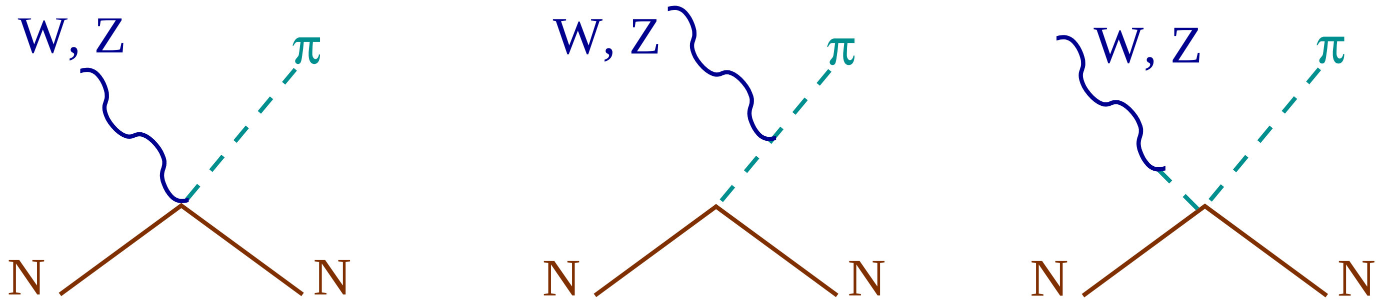
- Our goal: theoretical study of CC and NC Coherent π production at intermediate energies (E_ν ~ 1 GeV) improving the calculations of : Kelkar et al, PRC 55 (97), Singh et al, PRL 96 (06)
  - Complete relativistic elementary amplitude
  - Hadronic degrees of freedom: π, N, Δ(1232)
  - Renormalization of the Δ properties in the nuclear medium
  - Realistic treatment of π distortion

The model

- Elementary mechanisms: Hernandez, Nieves & Valverde, PRD 76 (07)



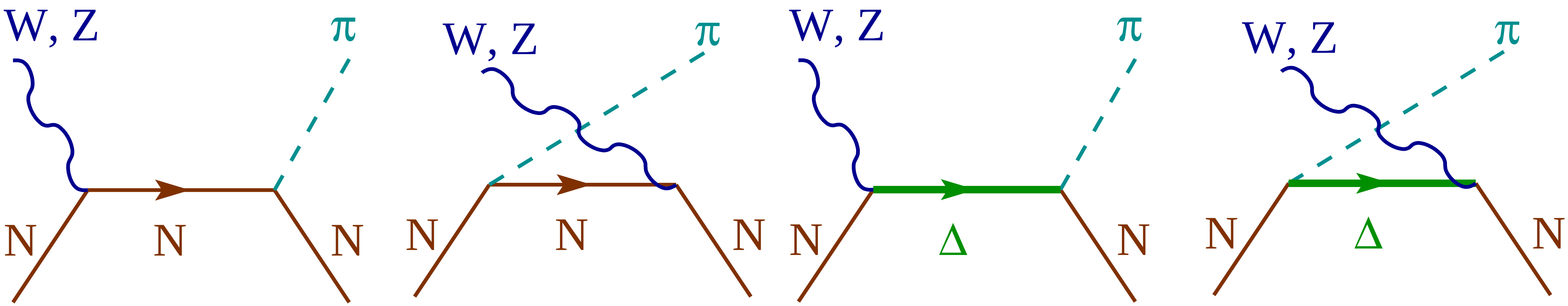
- Other contributions



cancel for isospin symmetric nuclei

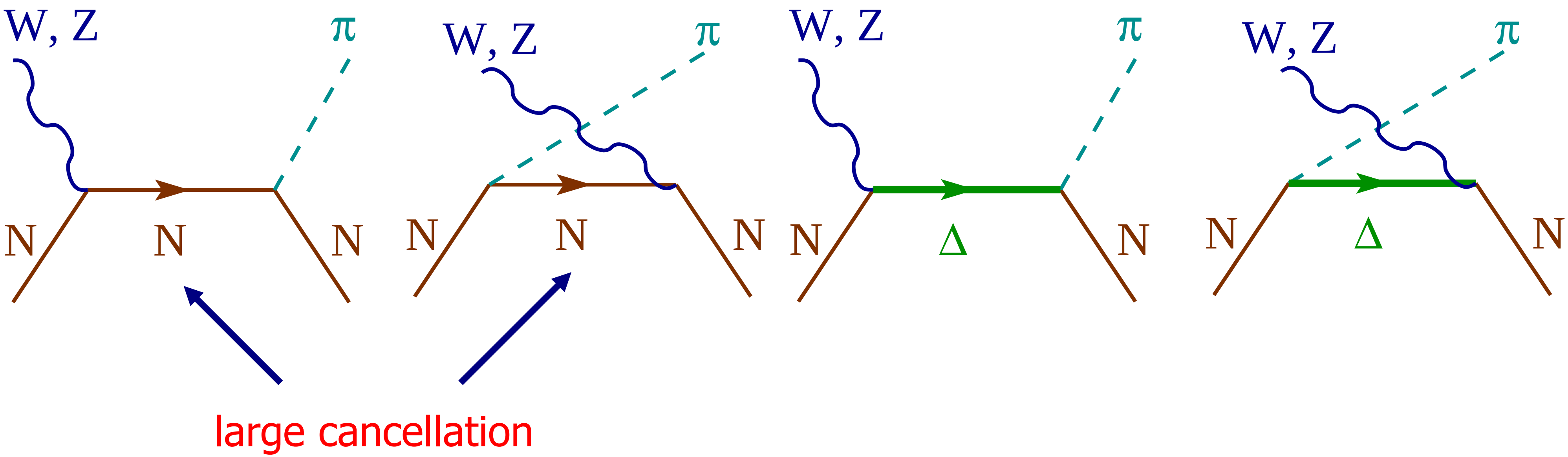
The model

- Elementary mechanisms: Hernandez, Nieves & Valverde, PRD 76 (07)



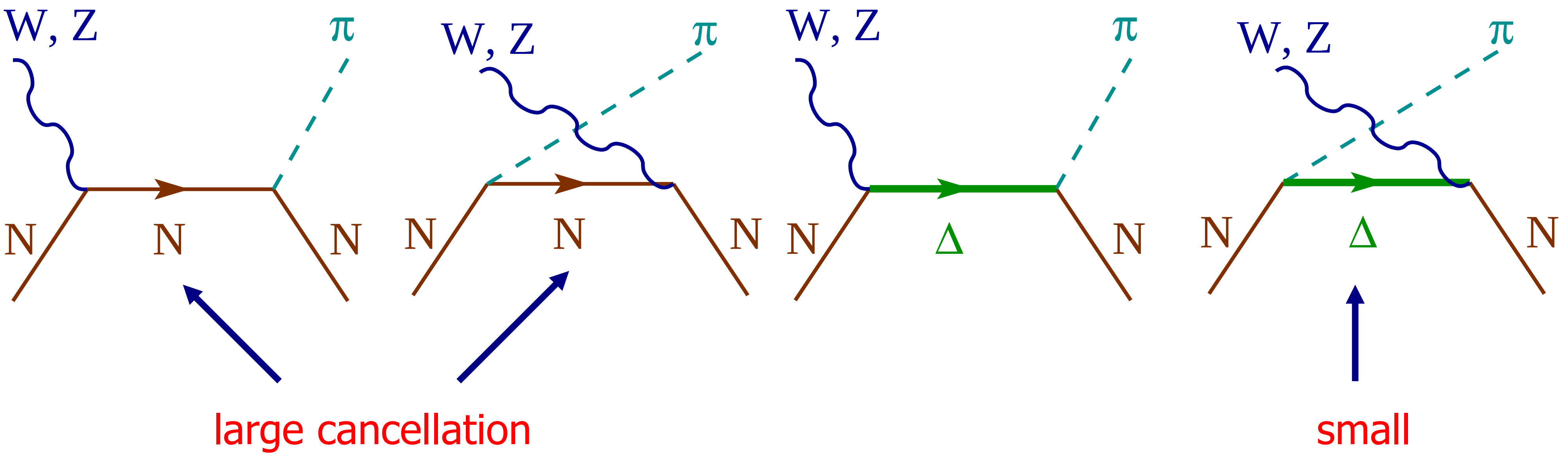
The model

- Elementary mechanisms: Hernandez, Nieves & Valverde, PRD 76 (07)



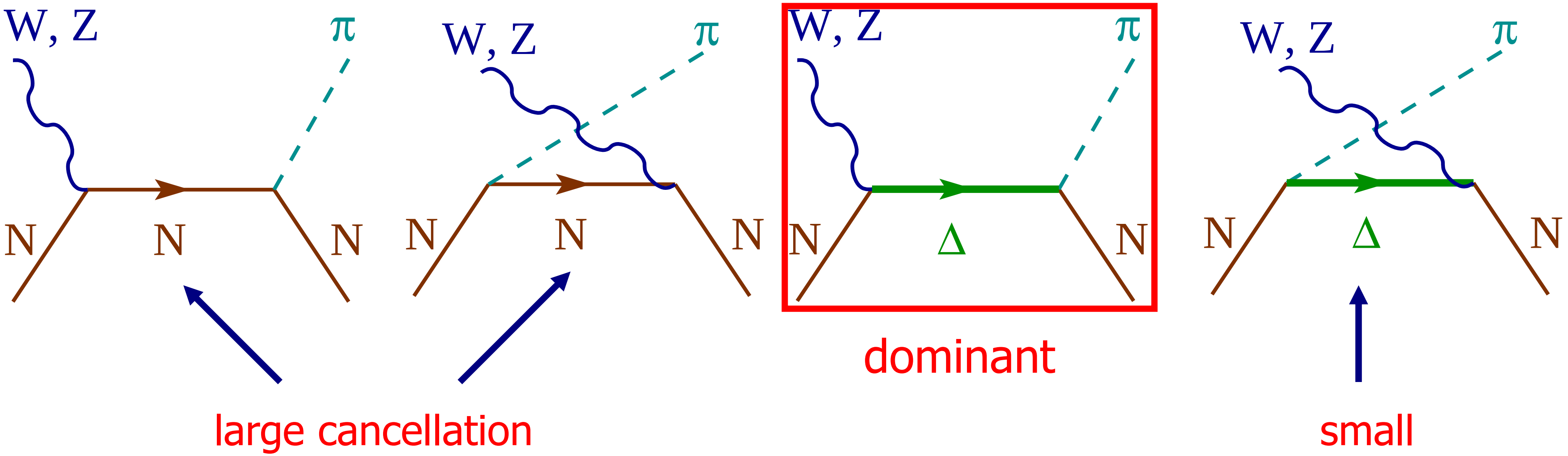
The model

- Elementary mechanisms: Hernandez, Nieves & Valverde, PRD 76 (07)



The model

- Elementary mechanisms: Hernandez, Nieves & Valverde, PRD 76 (07)



Formalism

- The amplitude for CC π^+ production: $\mathcal{M}_c = \frac{G}{\sqrt{2}} \cos\theta_c \, l_\mu J^\mu$
- $J^\mu \leftarrow$ Nuclear current ⟺ sum over all nucleons
- For the dominant direct Δ mechanism:

$$J^\mu{}_{IA} = -\frac{\sqrt{3}}{2} i \int d\vec{r}\, e^{i(\vec{q}-\vec{p}_\pi)\cdot\vec{r}} \left[\rho_p(r) + \frac{\rho_n(r)}{3}\right] \frac{f^*}{m_\pi} D_\Delta \, p_\pi^\alpha \, \mathrm{Tr}\left\{\bar{u}\Lambda_{\alpha\beta}\mathcal{A}^{\beta\mu}u\right\}$$

$D_\Delta \leftarrow$ propagator $\qquad \Lambda_{\alpha\beta} \leftarrow$ spin 3/2 projection operator

$$\mathcal{A}^{\beta\mu} = \left(\frac{C_3^V}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu}q\cdot p - q^\beta p^\mu) + g^{\beta\mu}C_6^V\right)\gamma_5$$

$$+ \frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}q^\beta q^\mu$$

- Form factors: $C^V_{3,4,5} \leftarrow$ e N scattering $\quad C_6^V = 0 \leftarrow$ CVC

$C_6^A = C_5^A \frac{M^2}{m_\pi^2 - q^2} \leftarrow$ PCAC

$C_4^A = -\frac{1}{4}C_5^A \quad C_3^A = 0 \leftarrow$ Adler model

Formalism

- There are different parametrizations of C_5^A in the literature:
  - set I $C_5^A = C_5^A(0)\left(1+\frac{1.21\,q^2}{2\ \mathrm{GeV}^2 - q^2}\right)\left(1-\frac{q^2}{M_{A\Delta}^2}\right)^{-2}$

$$C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2 \leftarrow$$ off-diagonal GT relation

$$M_{A\Delta} = 1.28\ \mathrm{GeV} \leftarrow$$ extracted from BNL data
Kitagaki et al. PRD42 (90)

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

$$C_5^A(0) = 0.867 \pm 0.075$$
$$M_{A\Delta} = 0.985 \pm 0.082\ \mathrm{GeV}$$

$\leftarrow$ extracted from ANL data with $W_{N\pi} < 1.4$ GeV
Hernandez,Nieves,Valverde PRD 76 (07)

- Coherent π production is very sensitive on $C_5^A(0)$

Formalism

- For $\nu_l \, p \to l^- \, \Delta$ at q^2=0 (m_ℓ = 0)

$$\frac{d\sigma}{dq^2}(q^2 = 0) \propto \left[C_5^A(0)\right]^2$$

- Axial coupling $C_5^A(0)$ values in the literature,

  adapted from Barquilla-Cano, Buchmann, Hernandez PRC 75 (07)

Quark models	0.97, 0.83, 1.17, 1.06, 0.87, 1.5, 0.93
Empirical approaches	1.15 ± 0.23, 1.39 ± 0.14, 1.1 ± 0.2, 1.22 ± 0.06, 0.867 ± 0.075
Current Algebra	0.98

Formalism

- Delta in the medium:

$$D_\Delta \Rightarrow \tilde{D}_\Delta(r) = \frac{1}{(W + M_\Delta)(W - M_\Delta - \mathrm{Re}\Sigma_\Delta(\rho) + i\tilde{\Gamma}_\Delta/2 - i\mathrm{Im}\Sigma_\Delta(\rho))}$$

$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \rightarrow N\,\pi$ modified by Pauli blocking

$$\mathrm{Re}\Sigma_\Delta(\rho) \approx 40\mathrm{MeV}\frac{\rho}{\rho_0}$$

$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:

- $\Delta\, N \rightarrow N\, N$
- $\Delta\, N \rightarrow N\, N\, \pi$
- $\Delta\, N\, N \rightarrow N\, N\, N$

Formalism

- Pion distortion:

$$e^{-i\vec{p}_\pi\cdot\vec{r}} \rightarrow \phi^*_{out}(\vec{p}_\pi,\vec{r}) \qquad \vec{p}_\pi e^{-i\vec{p}_\pi\cdot\vec{r}} \rightarrow i\vec{\nabla}\phi^*_{out}(\vec{p}_\pi,\vec{r})$$

$\phi^*_{out}(\vec{p}_\pi,\vec{r}) \leftarrow$ solution of the Klein-Gordon equation

$$\left(-\vec{\nabla}^2 - \vec{p}_\pi^{\,2} + 2\omega_\pi \hat{V}_{\rm opt}\right)\phi^*_{out} = 0$$

$\hat{V}_{\rm opt}(r) \leftarrow$ optical potential in the Δ-hole model:
Nieves, Oset & Garcia Recio NPA 554 (93)

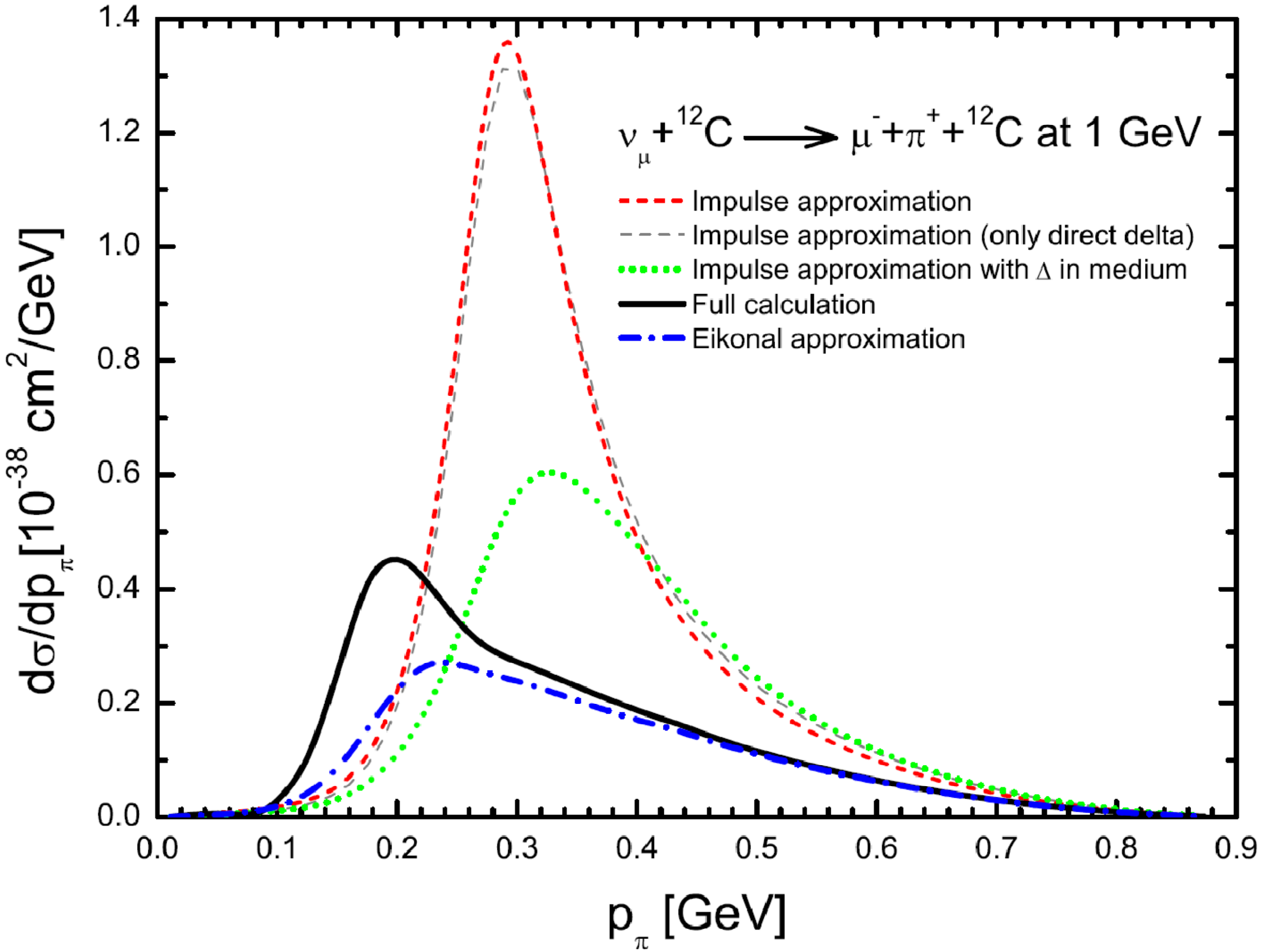
$$2\omega_\pi \hat{V}_{opt}(\vec{r}) = 4\pi\frac{M^2}{s}\left[\vec{\nabla}\cdot\frac{\mathcal{P}(r)}{1+4\pi g'\mathcal{P}(r)}\vec{\nabla} - \frac{1}{2}\frac{\omega}{M}\Delta\frac{\mathcal{P}(r)}{1+4\pi g'\mathcal{P}(r)}\right]$$

g′=0.63 $\leftarrow$ Landau-Migdal parameter

$$\mathcal{P} = -\frac{1}{6\pi}\left(\frac{f^*}{m_\pi}\right)^2\left\{\frac{\rho_p+\rho_n/3}{\sqrt{s}-M_\Delta-\mathrm{Re}\Sigma_\Delta+i\tilde{\Gamma}_\Delta/2-i\,\mathrm{Im}\Sigma_\Delta} + \frac{\rho_n+\rho_p/3}{-\sqrt{s}-M_\Delta+2M-\mathrm{Re}\Sigma_\Delta}\right\}$$

Direct Crossed
Δ–hole excitations

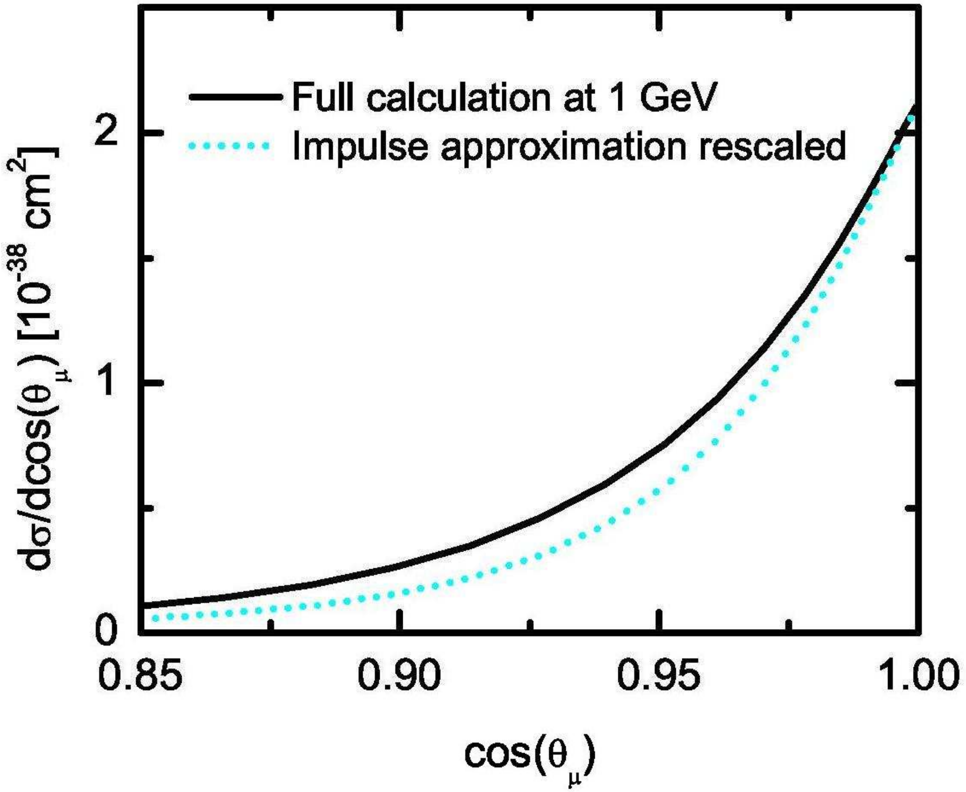
Results

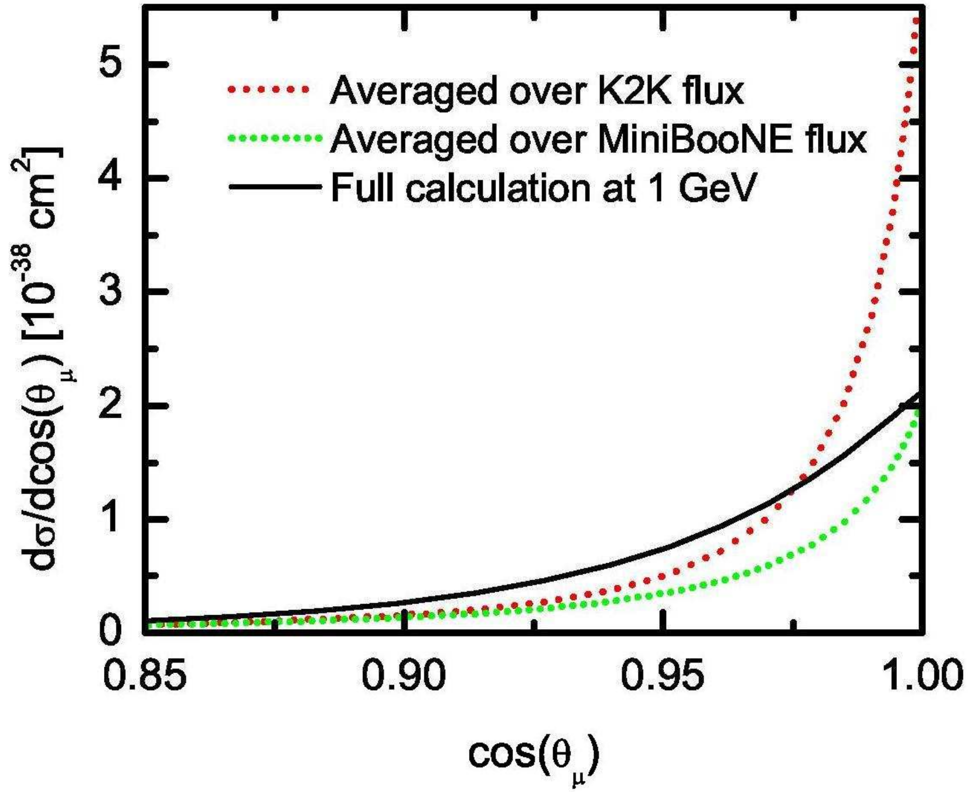


- Medium effects reduce considerably de cross section
- Pion distortion shifts down the peak
- Eikonal fails for p_π<400 MeV

Results

$$\nu_\mu \, {}^{12}C \to \mu^- \, \pi^+ \, {}^{12}C$$

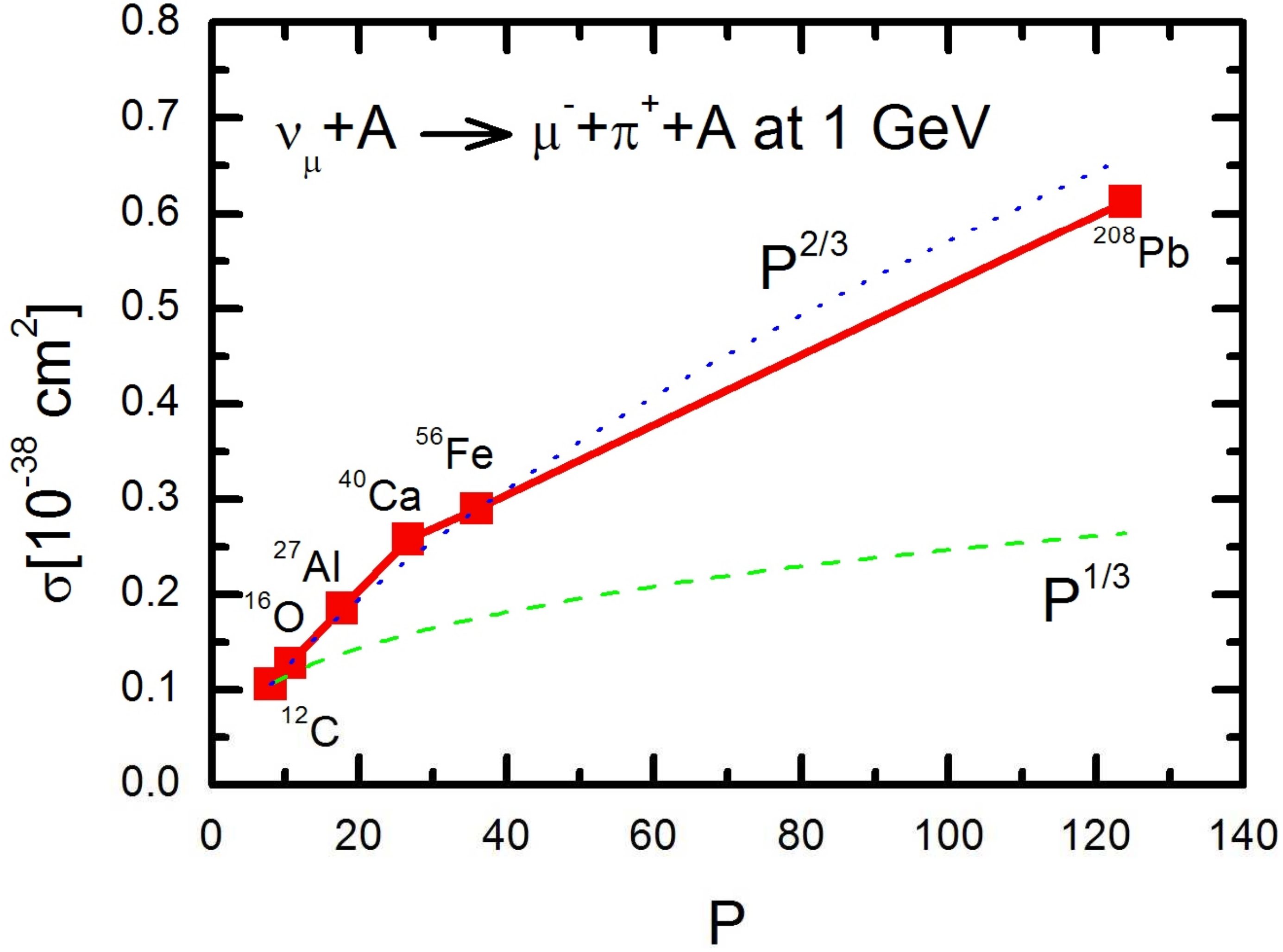




- Muon angular distribution relatively unaffected by the medium
- Presence of higher energy $\nu \Rightarrow$ narrower angular distributions

Results

- Dependence on the effective number of participants P=Z+N/3 (for CC)

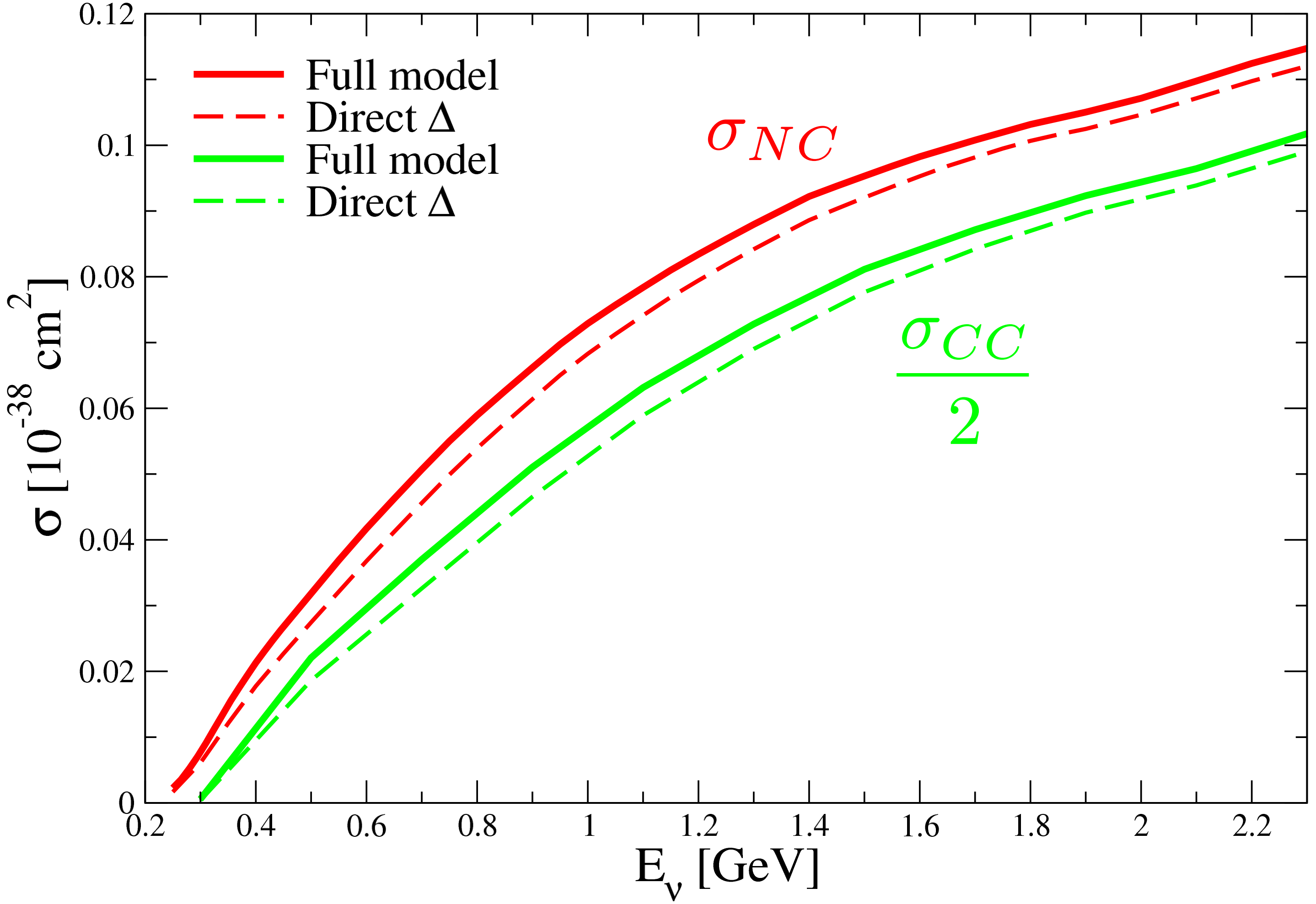


$\sigma \sim \mathrm{P}^{2/3}$ ⟷

- strong pion absorption forces de reaction to be peripheral
- effect of the nuclear form factor on heavier nuclei

Results

- NC Coherent Pion Production: $\nu_\mu \; ^{12}C \rightarrow \nu_\mu \; \pi^0 \; ^{12}C$

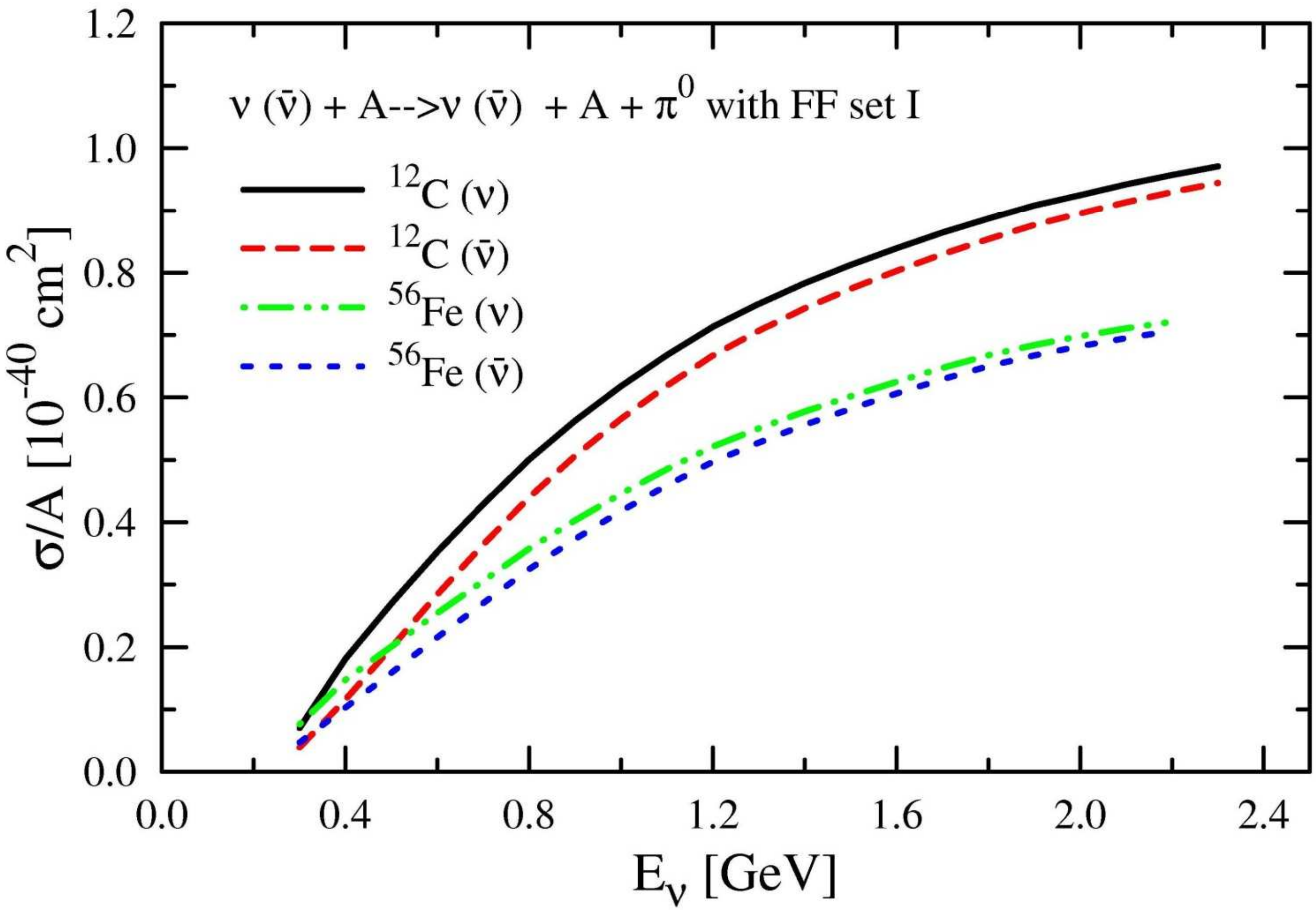


$$\sigma_{NC} \neq \frac{\sigma_{CC}}{2} \Longleftrightarrow$$

- Phase Space: $m_\mu \neq 0$
- Interference terms: $q^2 \neq 0$ contributions

Results

- NC Coherent Pion Production: ν vs. $\bar{\nu}$



- $\sigma(\nu) \neq \sigma(\bar{\nu})$ ⟺ $q^2 \neq 0$ contributions (interference terms)
- The difference is slightly larger for lighter nuclei

Results

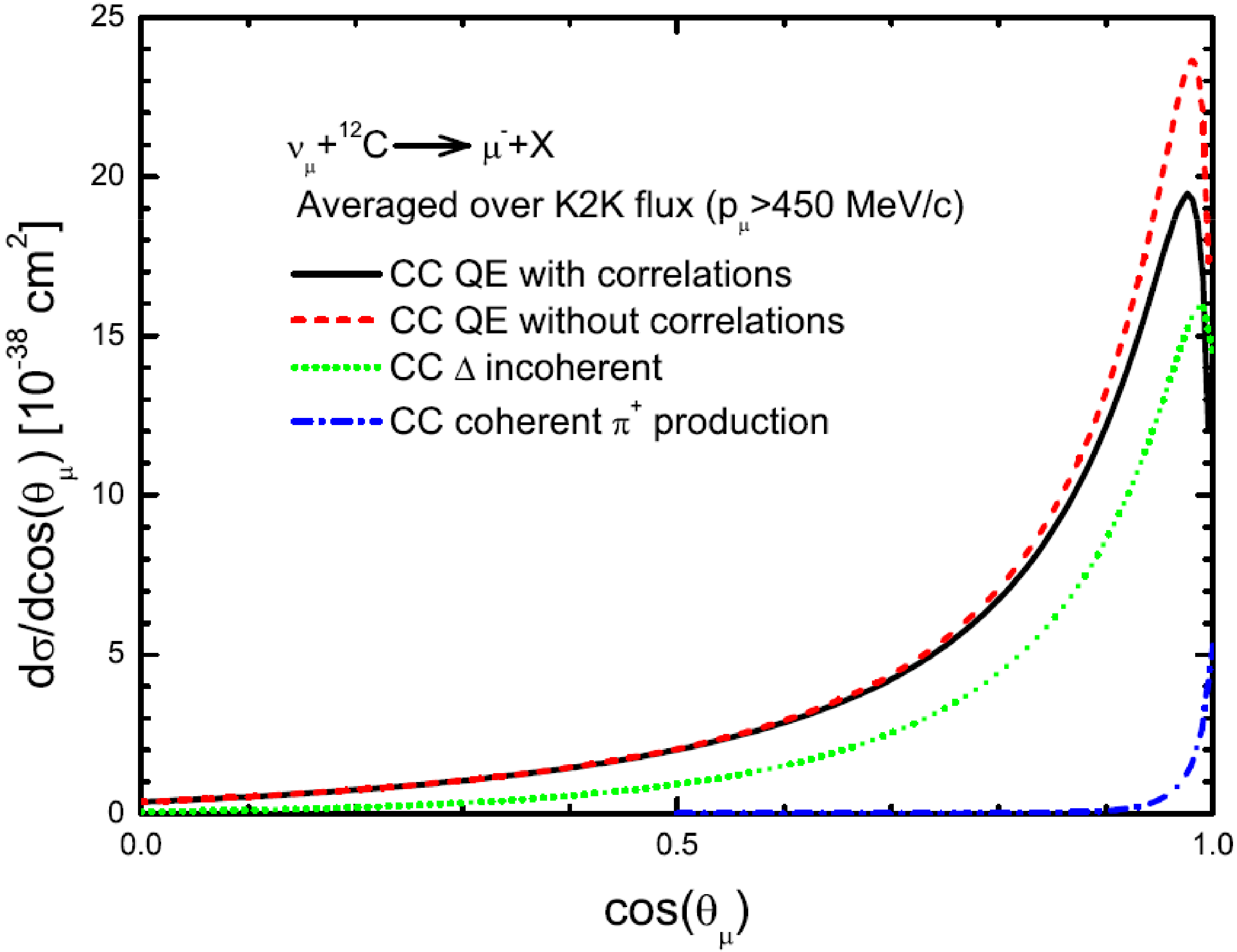
- Predictions and Comparison to experiment: [units of 10^{-40} cm^2]

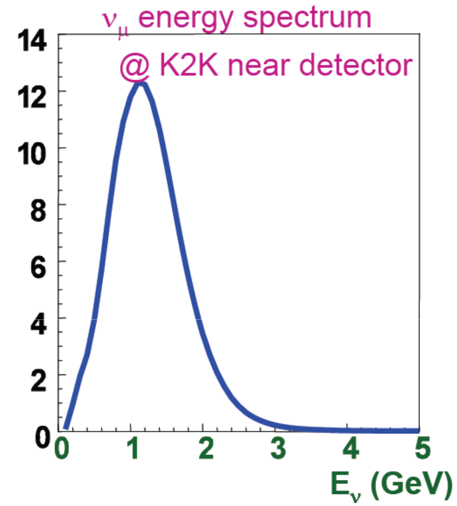
Reaction	Experiment	$\sigma_{\rm I}$	$\sigma_{\rm II}$	σ Experimental
NC $\nu + {}^{27}$Al	Aachen-Padova	19.9	10.1	29 ± 10
NC $\bar{\nu} + {}^{27}$Al	Aachen-Padova	19.7	9.8	25 ± 7
CC $\nu + {}^{12}$C	K2K	10.8	5.7	< 7.7
NC $\nu + {}^{12}$C	MiniBooNE	5.0	2.6	-
NC $\bar{\nu} + {}^{12}$C	MiniBooNE	4.6	2.2	-

- Differences between sets I & II ⟺ $\sigma(\mathrm{I})/\sigma(\mathrm{II}) \sim \left[C^A_{5(\mathrm{I})}(0)/C^A_{5(\mathrm{II})}(0)\right]^2 \approx 1.9$
- Reasons for the discrepancies:
  - Axial N-Δ not sufficiently constrained (more data needed)
  - More complete theoretical description of the elementary amplitude (heavier resonances) required
  - Optical potential at lower and higher energies can be improved
  - Difficulties in the experimental separation of coherent and incoherent processes:

Results

Coherent vs. Incoherent Processes at K2K

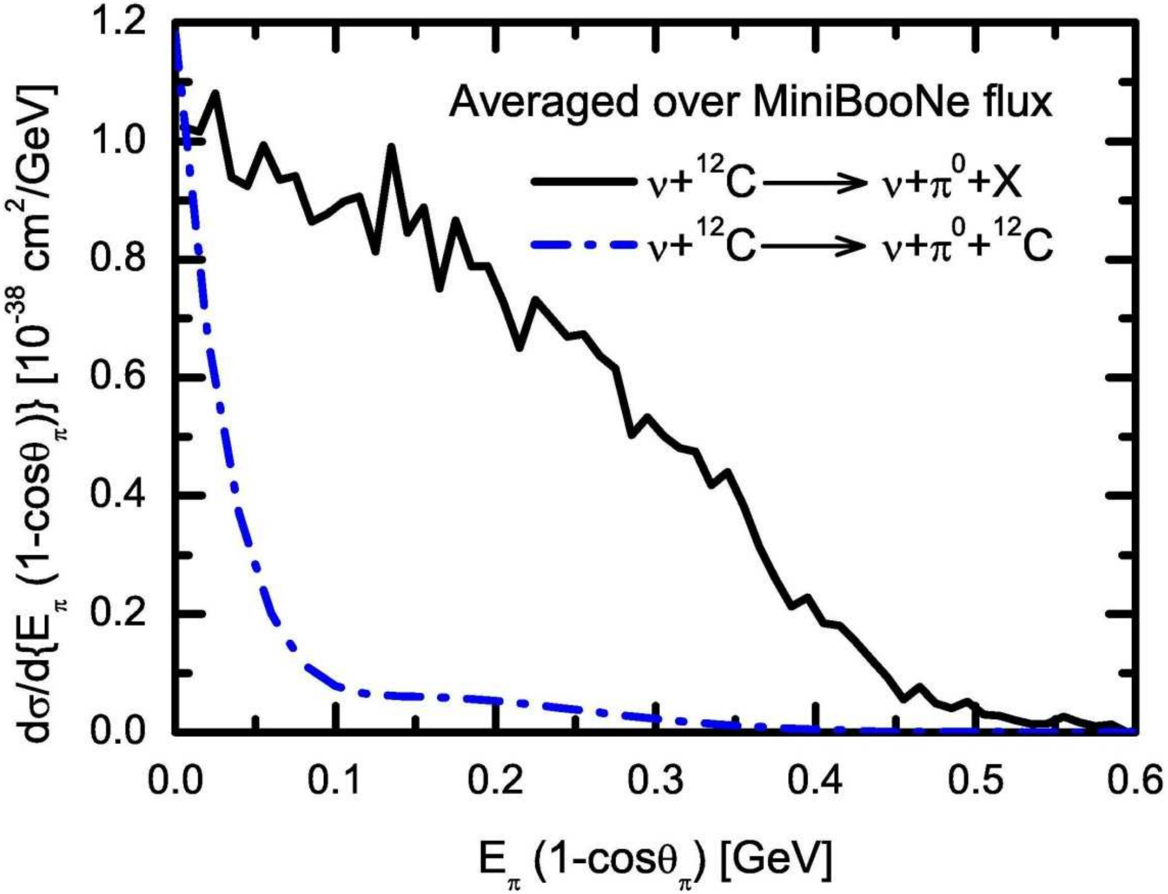


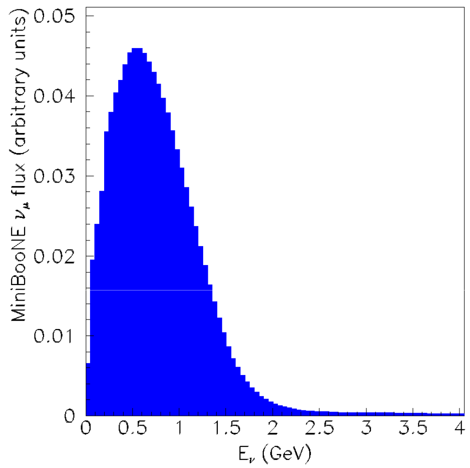


The coherent cross section might be considerably smaller than the Impulse Approximation prediction but still bigger than the K2K upper limit

Results

- Coherent & Incoherent NC π^0 Production @ MiniBooNE





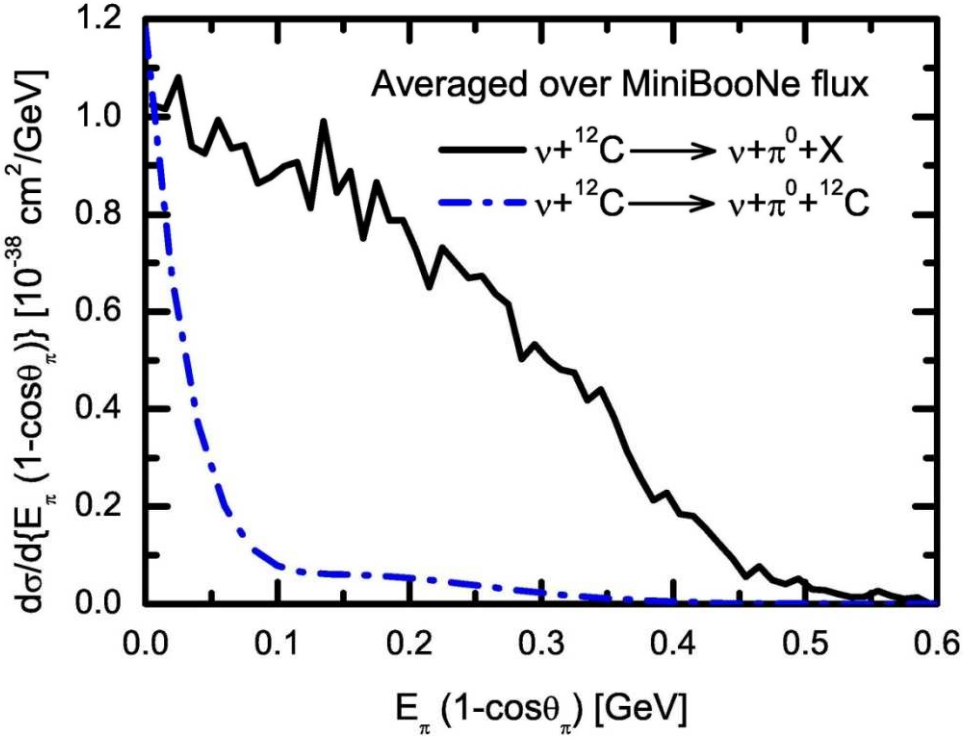
Coherent fraction

$$\frac{\sigma(\text{coh.})}{\sigma(\text{coh.})+\sigma(\text{incoh.})} = 0.14$$

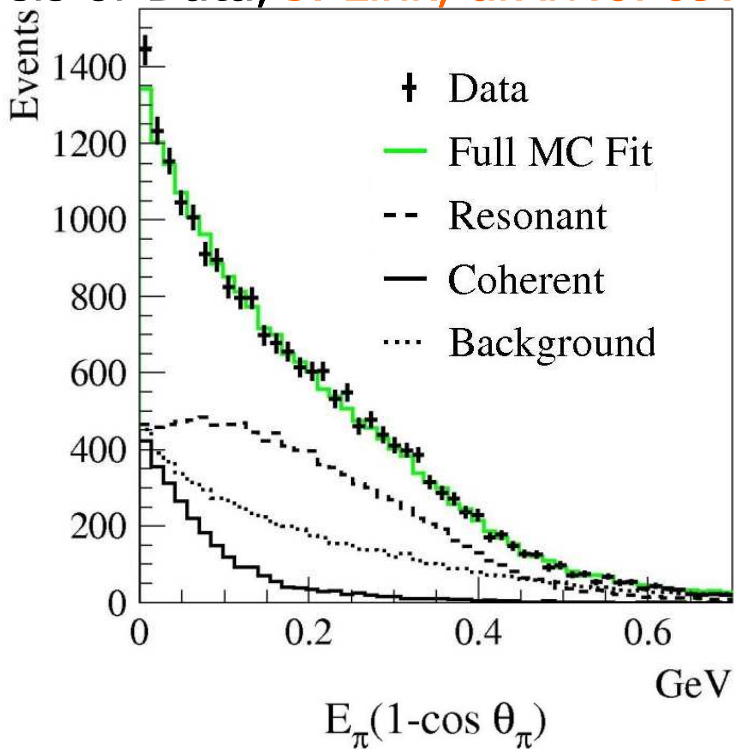
- Incoherent reaction studied with the GiBUU transport model
  T. Leitner, L. Alvarez-Ruso & U. Mosel, PRC 74 (06)

Results

- Coherent & Incoherent NC π^0 Production @ MiniBooNE



Analysis of Data, J. Link, arXiv:0709.3213



Coherent fraction $\dfrac{\sigma(\text{coh.})}{\sigma(\text{coh.}) + \sigma(\text{incoh.})} = 0.14$

19 $\pm$1.1(stat) $\pm$ 2.5 (sys) %

- Exp. Analysis based on the R&S model:
  - Raw MC predicts a coherent fraction of 30 %
  - The coherent axial mass has to be reduced by 3 to get agreement with data

Conclusions

- Theoretical study of CC & NC coherent pion production:
  - Complete relativistic elementary amplitude in terms of π, N, $\Delta(1232)$
  - Nuclear form factor in the Impulse Approximation
  - Renormalization of the Δ properties in the nuclear medium
  - π distortion ⟺ KG equation with a realistic optical potential
- Nuclear effects significantly reduce the coherent cross section
- Results depend strongly on $C_5^A(0)$
- $\sigma \sim P^{2/3}$ with P=(Z+N/3) for CC and P=A for NC
- We predict a 14 % coherent fraction @ MiniBooNE (on ^{12}C)
- The experimental separation between coherent and incoherent processes is model dependent and should be handled with care