Neutrino-Induced Coherent Pion Production

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Introduction

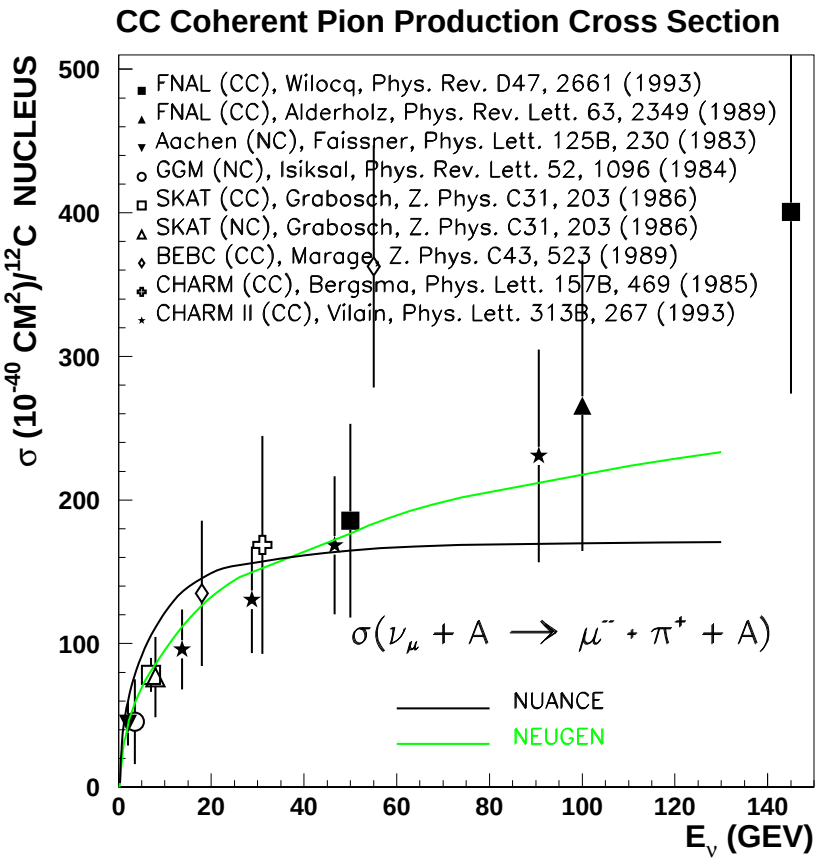
- ν–induced coherent π production reactions:
  - Charged Current $\nu_l \, A \rightarrow l^- \, \pi^+ \, A$
  - Neutral Current $\nu_l \, A \rightarrow \nu_l \;\; \pi^0 \, A$

- Important for oscillation experiments: systematic uncertainties
  - Example: $\nu_l \, A \rightarrow \nu_l \;\; \pi^0 \, X \leftarrow$ 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)

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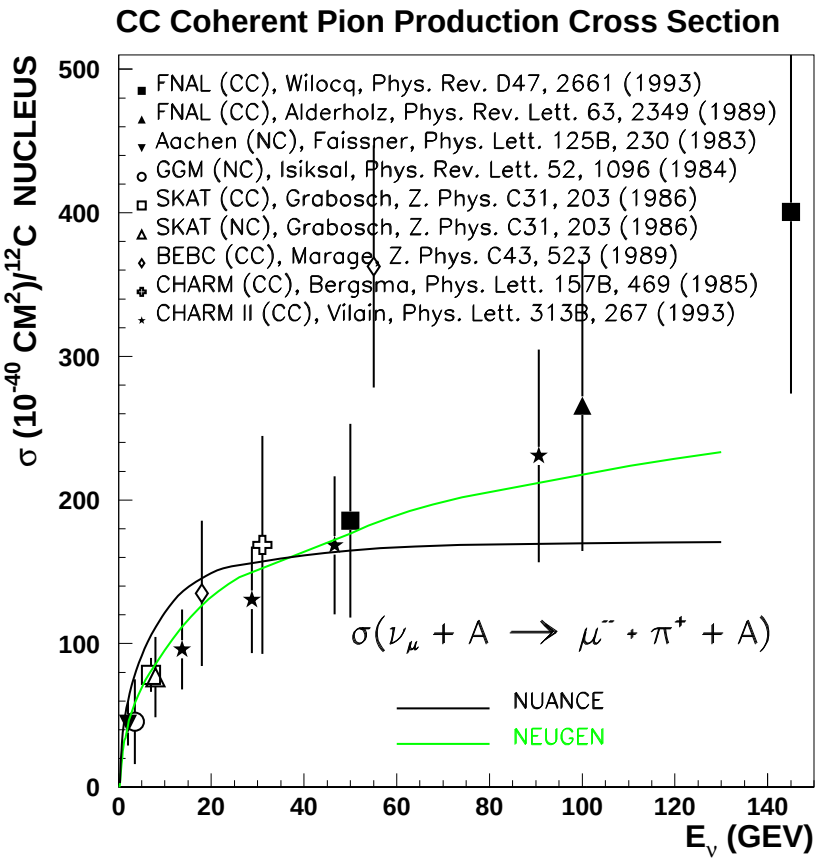

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- Measured at high energies E_ν > 2 GeV (FNAL, GGM, SKAT, BEBC, …)
- These data are well described by models based on PCAC

  Rhein & Sehgal, NPB 223 (83)

  However, at low energies …

Introduction

- K2K (< E_ν >=1.3 GeV) finds a significant deficit of μ^- at forward angles

⬍

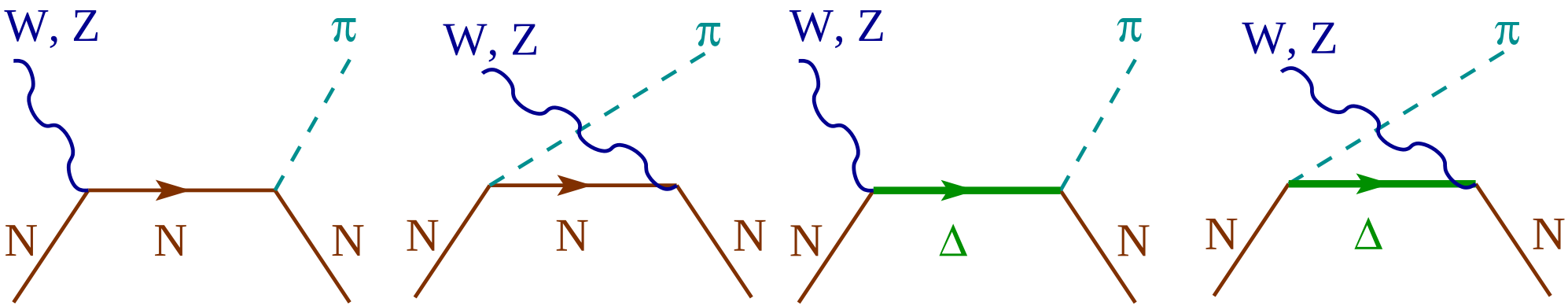
- Upper bound for CC Coh. π^+ production below theoretical expectations

- MiniBooNE (< E_ν >=0.75 GeV) NC π^0 data set is under analysis

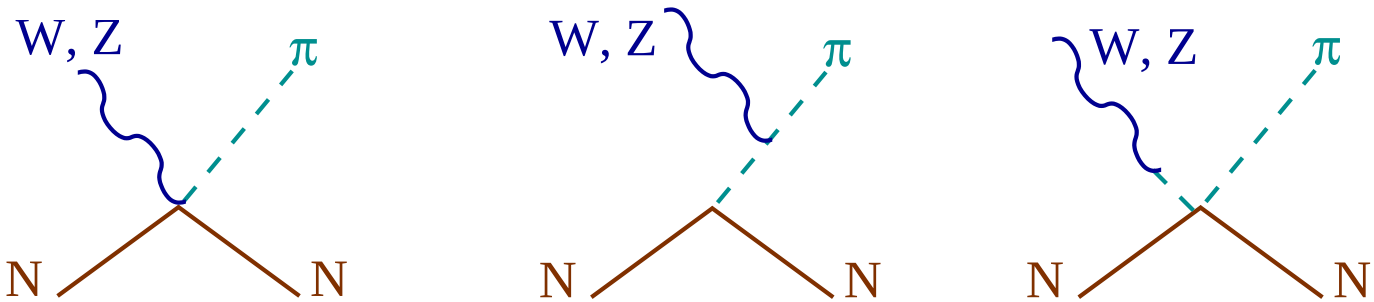
- Our goal: theoretical study of CC and NC Coherent π production at intermediate energies (E_ν ~ 1 GeV) improving the calculations of : Kelkar et al, PRC 55 (97), Singh et al, PRL 96 (06)
  - Complete relativistic elementary amplitude
  - Hadronic degrees of freedom: π, N, $\Delta(1232)$
  - Renormalization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

The model

- Elementary mechanisms (Hernandez, Nieves & Valverde, hep-ph/071149):



- Other contributions



cancel for isospin symmetric nuclei

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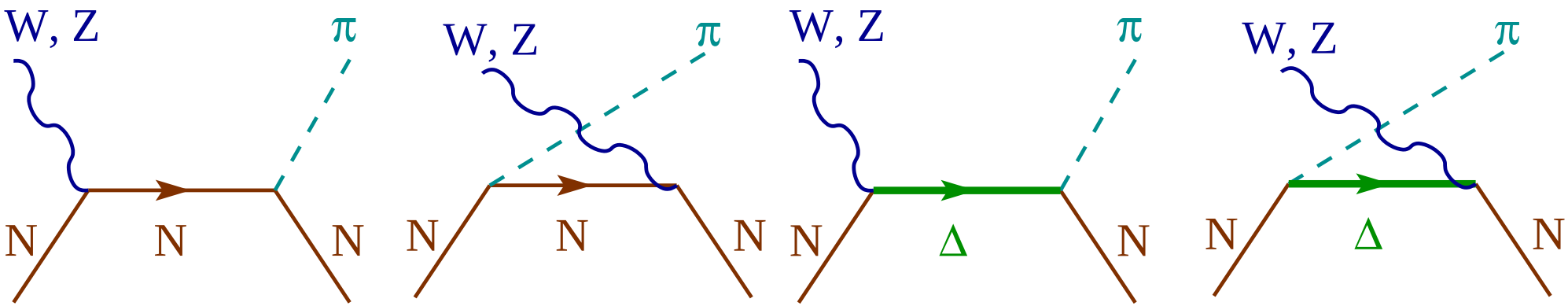

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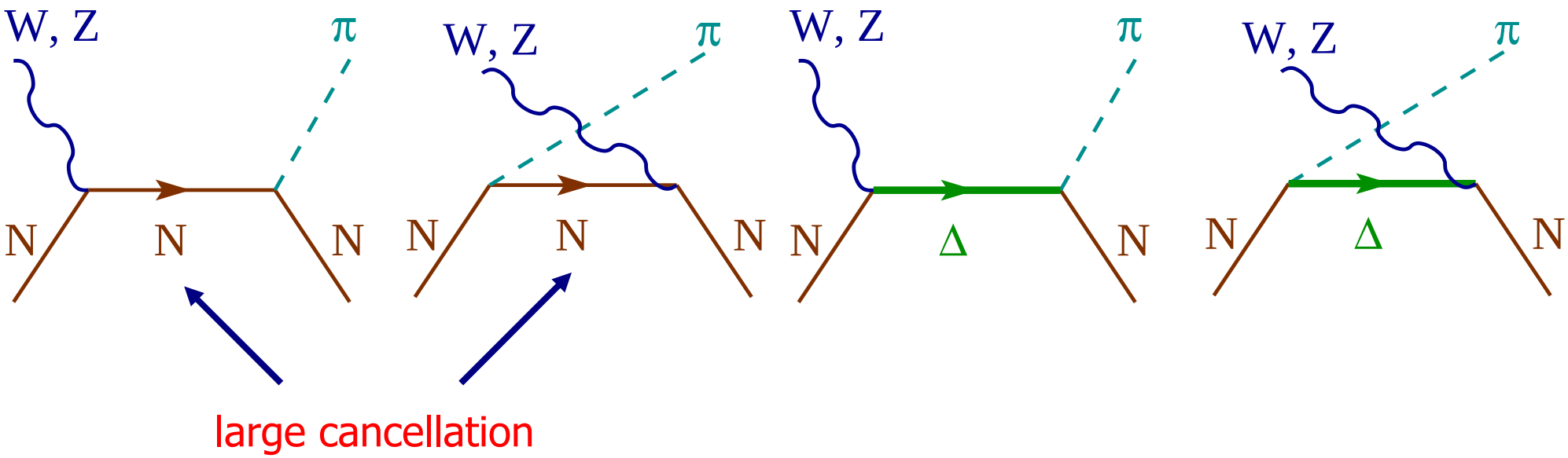

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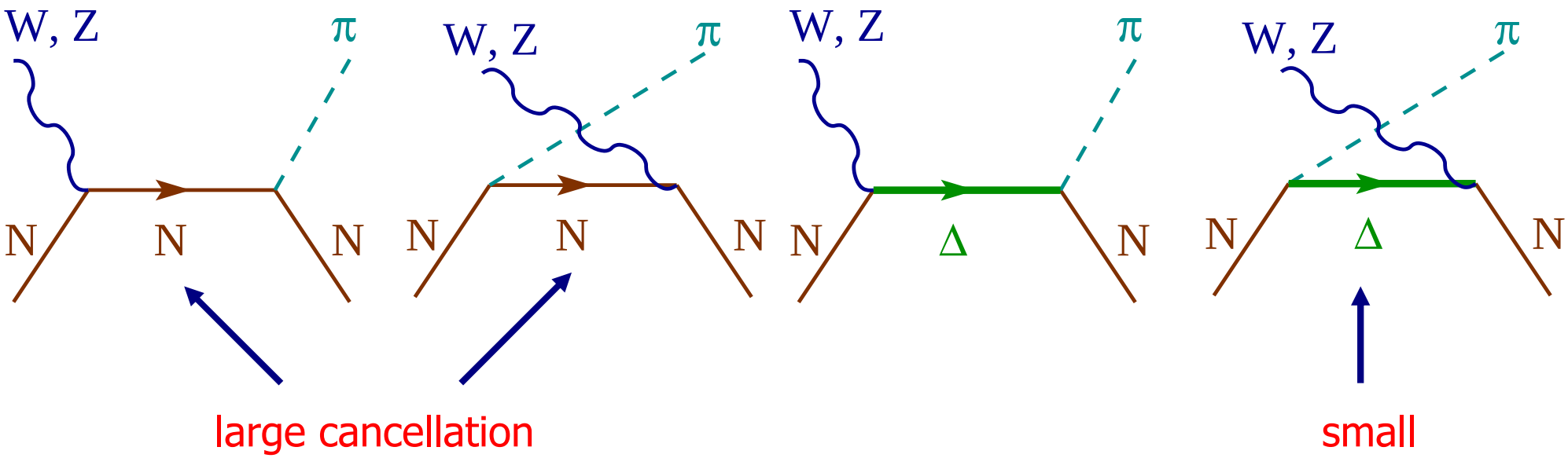

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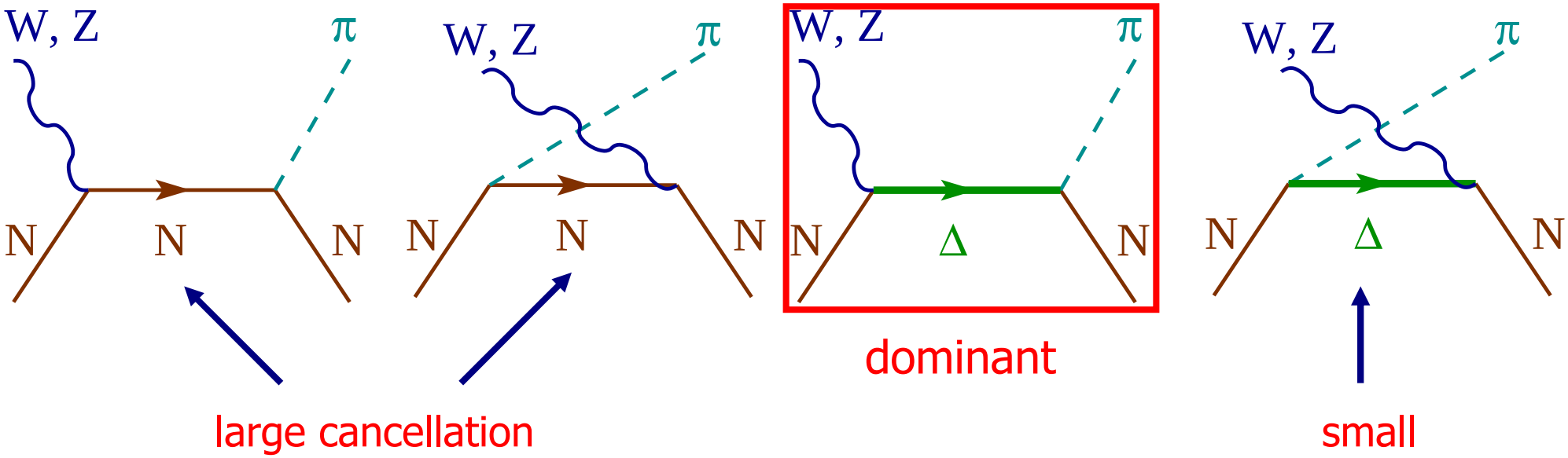


Formalism

- 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 $\Longleftrightarrow$ 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: $C_{3,4,5}^V \leftarrow$ e N scattering $\quad C_6^V = 0 \leftarrow$ CVC

$$C_6^A = C_5^A \frac{M^2}{m_\pi^2 - q^2} \qquad C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2 \leftarrow \text{PCAC}$$

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

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 π 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:

- Δ N $\rightarrow$ N N
- Δ N $\rightarrow$ N N π
- Δ N N $\rightarrow$ N N N

Formalism

- Pion distortion:

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

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

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

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

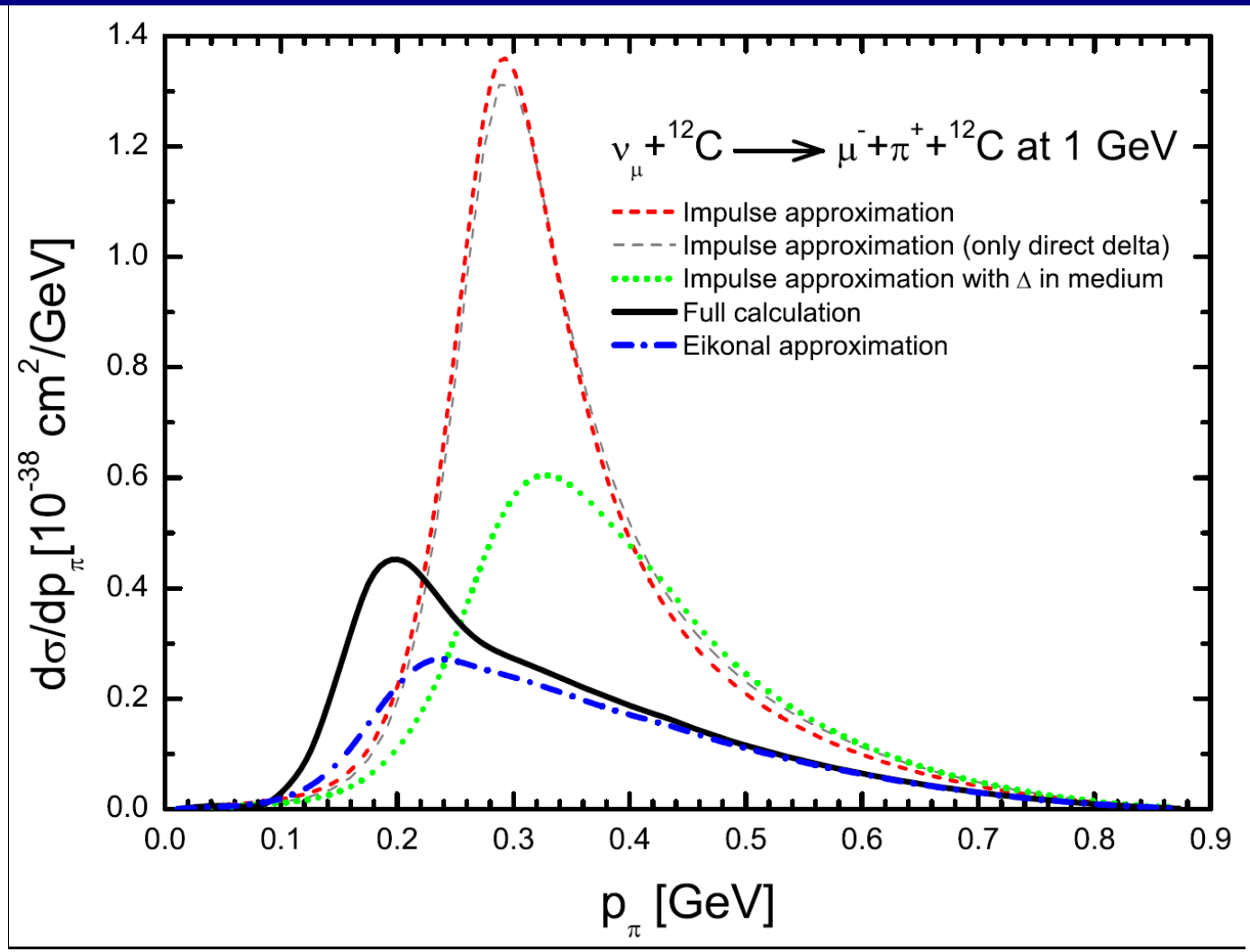
$$2\omega_\pi\,\hat{V}_{opt}(\vec{r}) = 4\pi\frac{M^2}{s}\left[\vec{\nabla}\cdot\frac{\mathcal{P}(r)}{1+4\pi g'\mathcal{P}(r)}\vec{\nabla} - \frac{1}{2}\frac{\omega}{M}\Delta\frac{\mathcal{P}(r)}{1+4\pi g'\mathcal{P}(r)}\right]$$

g′=0.63 ← Landau-Migdal parameter

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

Direct Crossed
Δ–hole excitations

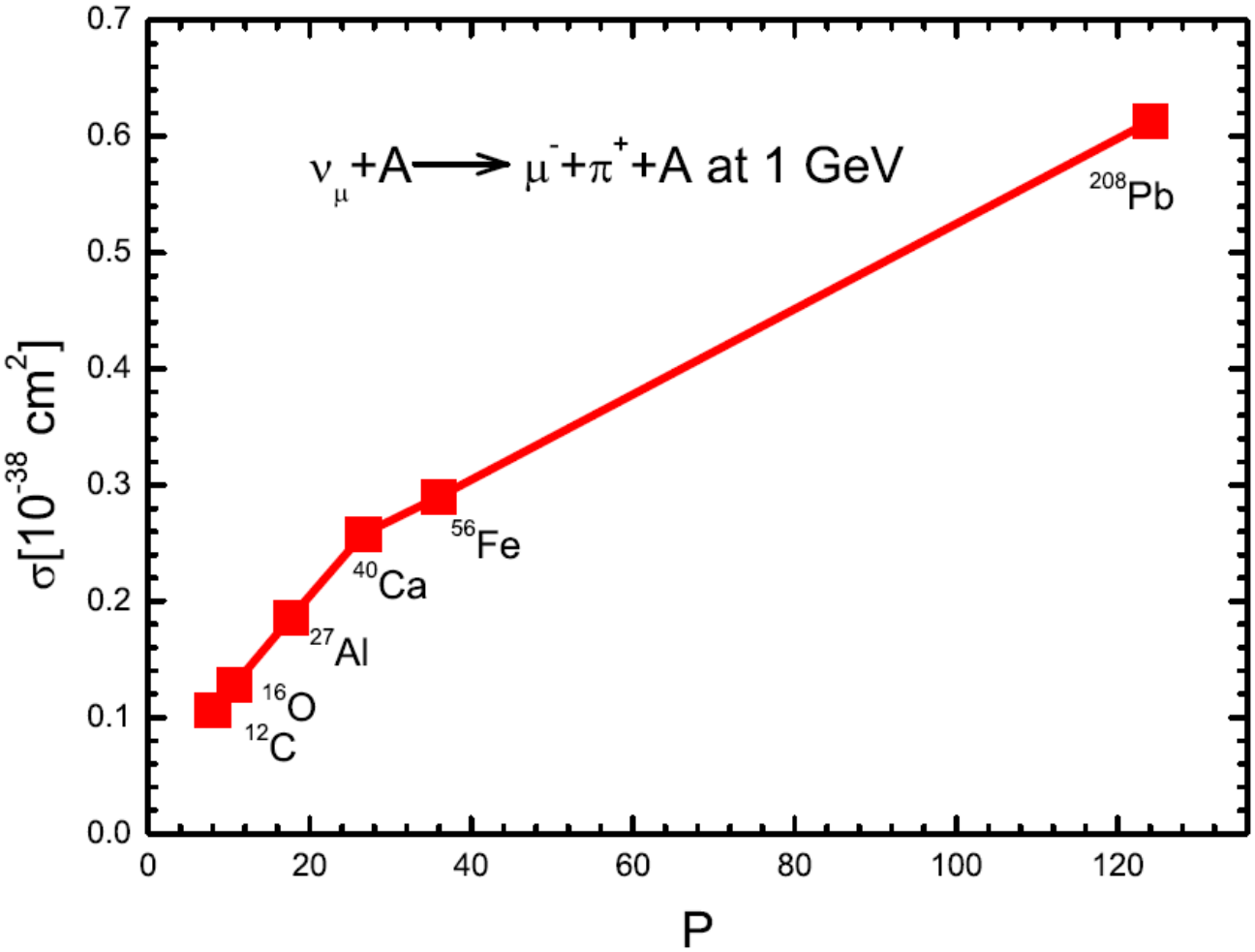
Results



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

Results

- Dependence on the effective number of participants P=Z+N/3



$\sigma \not\sim P^2 \Longleftrightarrow$

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

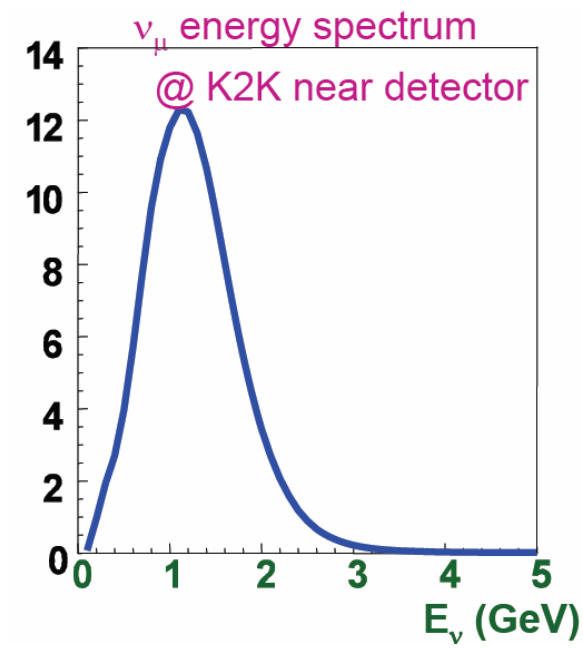
Results

- CC Coherent π production at K2K:
- No evidence for coherent π production:

$$< \sigma_{coh} >_{p_\mu > 450\,\mathrm{MeV/c}} < 7.7 \times 10^{-40}\ \mathrm{cm}^2$$

- Our result:

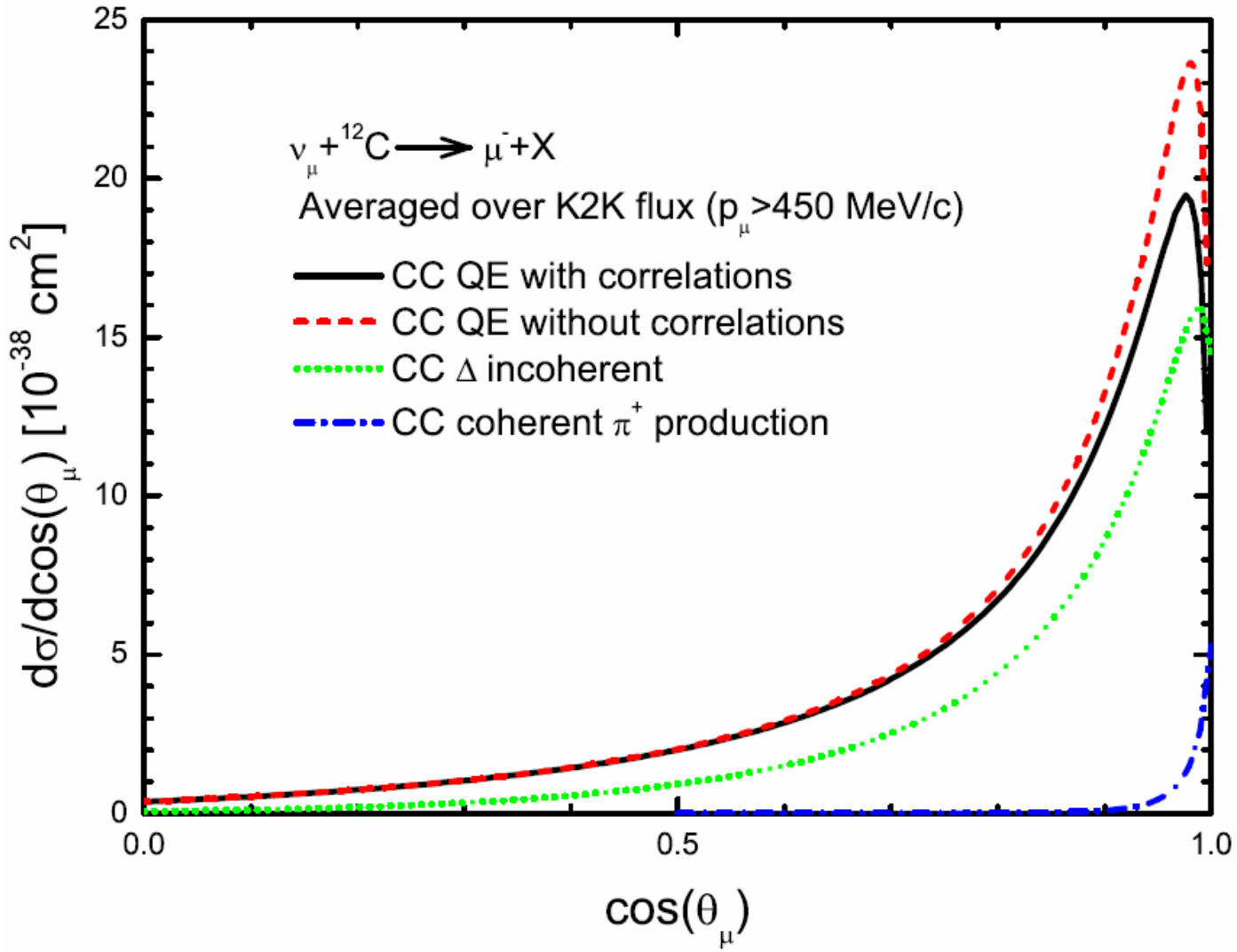
$$< \sigma_{coh} >_{p_\mu > 450\,\mathrm{MeV/c}} = 11 \times 10^{-40}\ \mathrm{cm}^2$$



- Reasons for the discrepancy:
  - 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

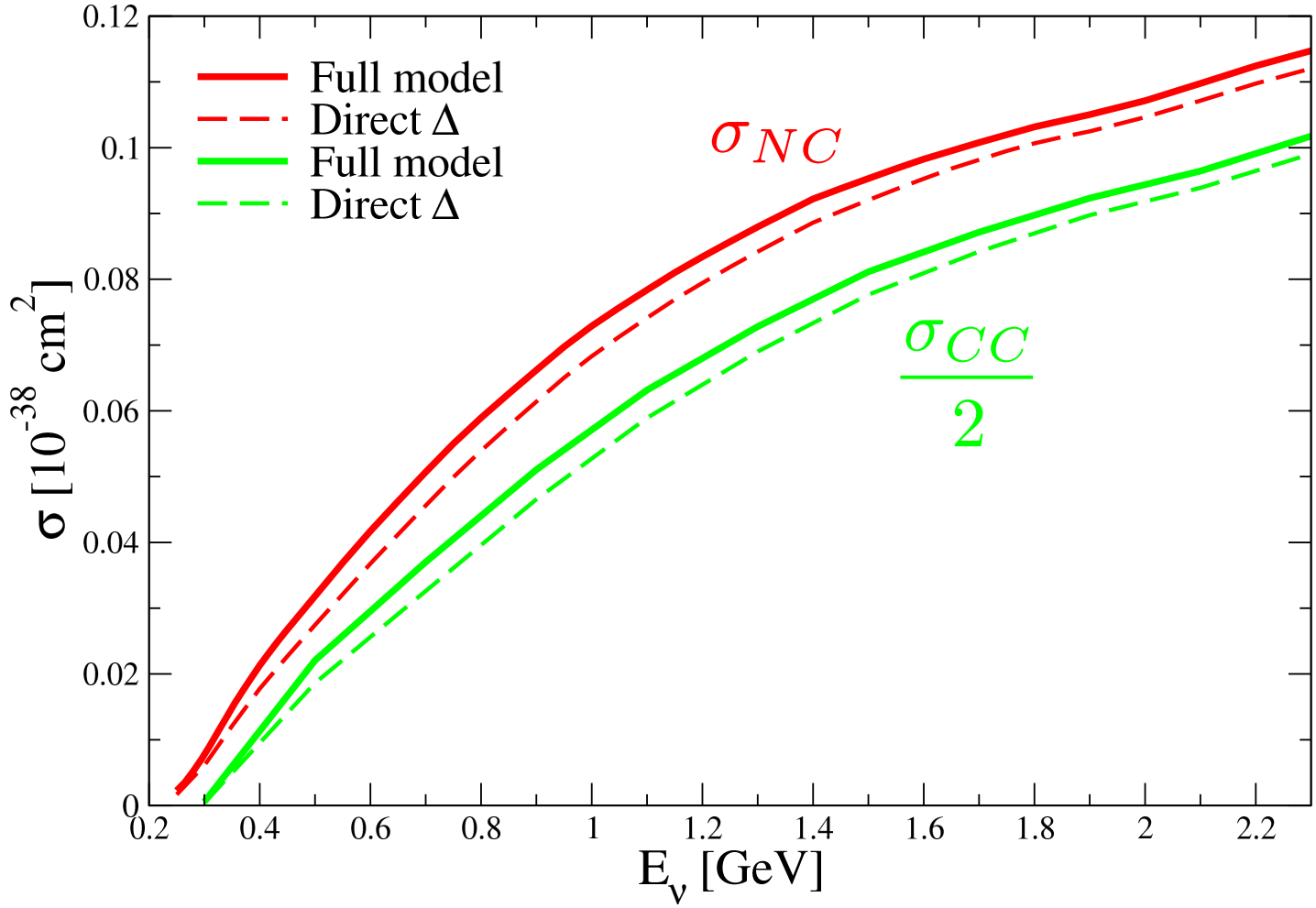
Coherent vs Incoherent Pion Production at K2K



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

Results

- NC Coherent Pion Production: $\nu_l \, A \rightarrow \nu_l \;\; \pi^0 \, A$



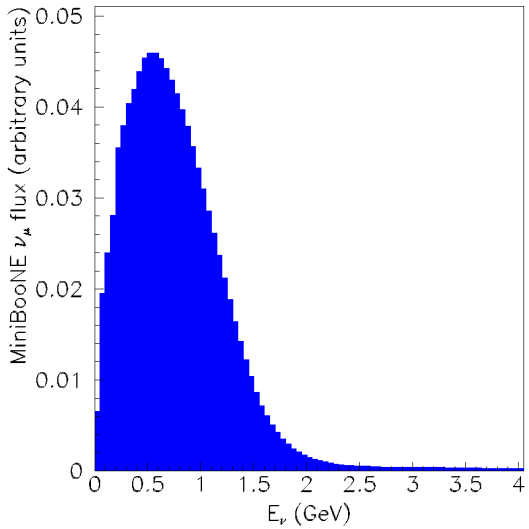
$$\sigma_{NC} \neq \frac{\sigma_{CC}}{2} \Longleftrightarrow$$

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

Results

- Average over the MiniBooNE flux:

$$< \sigma_{coh} >= 8.2 \times 10^{-40}\ \mathrm{cm}^2$$

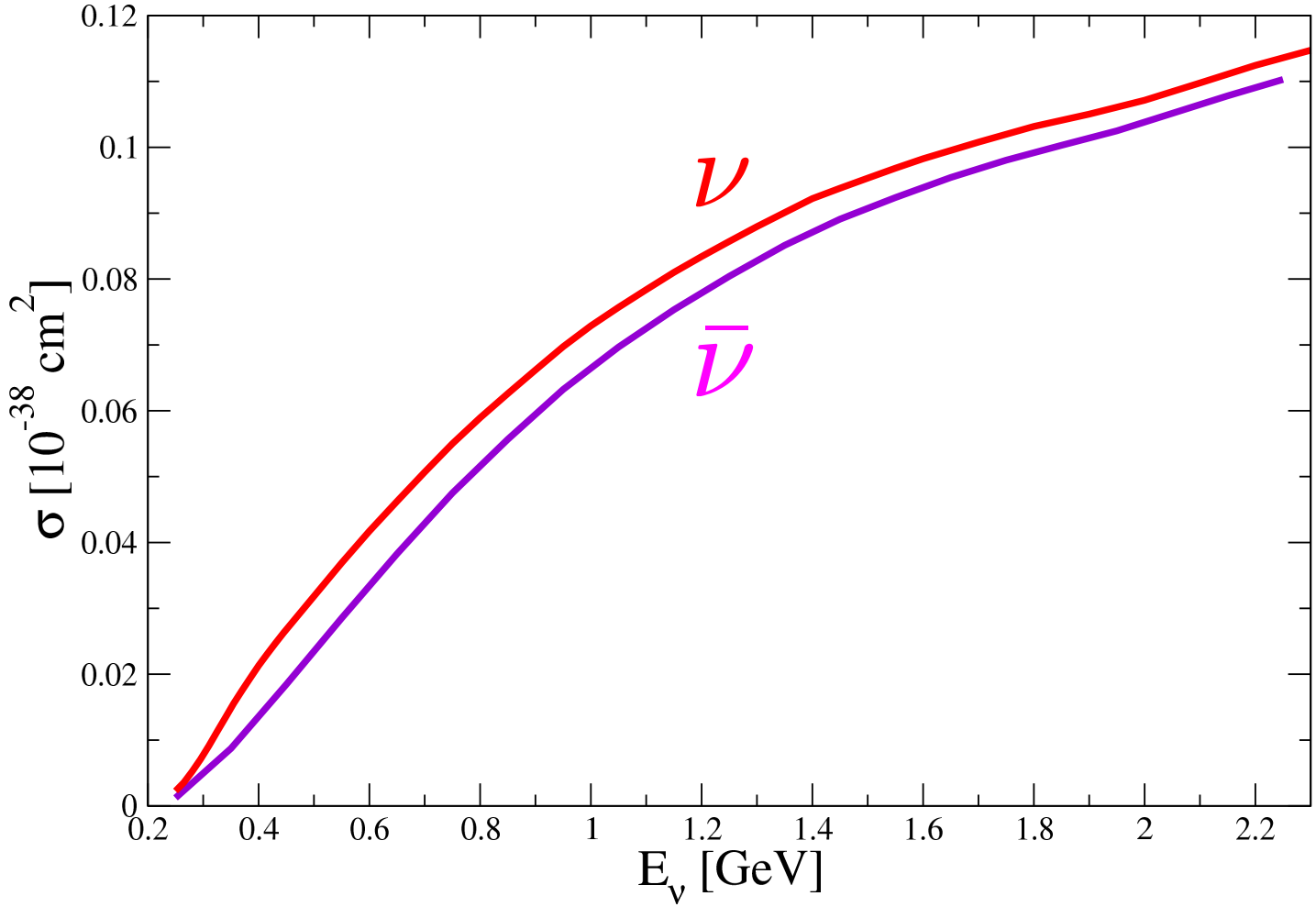


- Preliminary experimental result (J. Raaf, Thesis) :

$$< \sigma_{coh} >= (7.7 \pm 1.6(stat) \pm 3.6(syst)) \times 10^{-40}\ \mathrm{cm}^2$$

Results

- NC Coherent Pion Production:



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

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 $\Longleftrightarrow$ KG equation with a realistic optical potential
- Nuclear effects significantly reduce the coherent cross section
- The experimental separation between coherent and incoherent processes is model dependent and should be handled with care
- Good agreement with preliminary NC MiniBooNE results