CC and NC Pion Production

A. Mariano
Departamento de Física, Facultad de Ciencias Exactas,
Universidad Nacional de La Plata, Argentina.
Instituto de Física La Plata, CONICET, Argentina.

14TH INTERNATIONAL WORKSHOP ON NEUTRINO FACTORIES, SUPER BEAMS AND BETA BEAMS

NuFact 2012

Motivation

Motivation

- Neutrino oscillation experiments search a distortion in the neutrino flux at a detector positioned far away (L) from the source.

Motivation

- Neutrino oscillation experiments search a distortion in the neutrino flux at a detector positioned far away (L) from the source.

- By comparing near and far neutrino energy spectra, one gains information about the oscillation probability

$$P(\nu_i \to \nu_j) = sin^2 2\theta_{ij} sin^2 \frac{\Delta m^2_{i,j} L}{2E_\nu},$$

and then about the θ_{ij} mixing angles and $\Delta m^2_{i,j}$ mass squared differences.

Motivation

- Neutrino oscillation experiments search a distortion in the neutrino flux at a detector positioned far away (L) from the source.

- By comparing near and far neutrino energy spectra, one gains information about the oscillation probability

$$P(\nu_i \to \nu_j) = sin^2 2\theta_{ij} sin^2 \frac{\Delta m^2_{i,j} L}{2E_\nu},$$

and then about the θ_{ij} mixing angles and $\Delta m^2_{i,j}$ mass squared differences.

- New high quality data are becoming from MiniBoone, MINOS, NOMAD, Minerνa and SciBoone full dedicated to measure cross sections.

Problems

CCQE reaction $\nu_l n \rightarrow l^- p$ in the nucleus target is used as signal event or/and to reconstruct the neutrino energy.

Problems

CCQE reaction $\nu_l n \to l^- p$ in the nucleus target is used as signal event or/and to reconstruct the neutrino energy.

Neutrino energy, is not directly measurable but reconstructed from reactions products through two-body kinematics (exact only for free nucleons),and competition of another processes could lead misidentification of the arriving neutrinos.

Problems

CCQE reaction $\nu_l n \rightarrow l^- p$ in the nucleus target is used as signal event or/and to reconstruct the neutrino energy.

Neutrino energy, is not directly measurable but reconstructed from reactions products through two-body kinematics (exact only for free nucleons),and competition of another processes could lead misidentification of the arriving neutrinos.

- Nuclear effects: Smearing of the reconstructed energy by the momentum distribution of the target bound nucleons (GSC+Bounding). FSI of the emerging nucleon generate energy lost,change of direction,charge transfer or multiple nucleon knock out(np-nh). All these affecting QE events determination.

- MEC processes lead to additional contributions to one-body current generated.

- Disappearance searching experiments $\nu_\mu \to \nu_x$ uses $\nu_\mu n \to \mu^- p$ CCQE reaction to detect an arriving neutrino and reconstruct its energy. E_ν determination could be wrong for a fraction of CC1π^+ background events (20%) $\nu_\mu p \to \mu^- p \pi^+$, that can mimic a CCQE one if the pion is absorbed in the target and/or not detected.

- MEC processes lead to additional contributions to one-body current generated.
- Disappearance searching experiments $\nu_\mu \to \nu_x$ uses $\nu_\mu n \to \mu^- p$ CCQE reaction to detect an arriving neutrino and reconstruct its energy. E_ν determination could be wrong for a fraction of CC1π^+ background events (20%) $\nu_\mu p \to \mu^- p \pi^+$, that can mimic a CCQE one if the pion is absorbed in the target and/or not detected.
- In $\nu_\mu \to \nu_e$ appearance experiment, one detects ν_e in an (almost) ν_μ beam. Signal event $\nu_e n \to e^- p$ is dominated by a NC1π^0 $\nu_\mu N \to \nu_\mu N \pi^0$ background, and the detector can not distinguish between e^- and π^0 if one of both photons from the $\pi^0 \to \gamma\gamma$ decay escapes.

1π process

A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings.

1π process

A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings.

We must to analyze:

1π process

A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings.

We must to analyze:

- Elementary amplitude.

1π process

A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings.

We must to analyze:

- Elementary amplitude.
- Bounding+GSC effects.

1π process

A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings.

We must to analyze:

- Elementary amplitude.
- Bounding+GSC effects.
- FSI on the N and π.

Elementary amplitude

For the $\nu N \to l N' \pi$ process

Elementary amplitude

For the $\nu N \rightarrow l N' \pi$ process

$$\sigma(E\nu^{CM}) = \frac{F^{CC/NC}}{(2\pi)^4 E_\nu^{CM}\sqrt{s}} \int_{E_l-}^{E_l^+} dE_l^{CM} \int_{E_\pi^-}^{E_\pi^+} dE_\pi^{CM} \int_{-1}^{+1} dcos\theta \int_0^{2\pi} d\eta \frac{1}{16} \sum_{spin} |\mathcal{M}|^2 , \quad (1)$$

where where $E_\nu^{CM} = \frac{m_N E_\nu^{Lab}}{\sqrt{2E_\nu^{Lab} m_N + m_N^2}}$ and

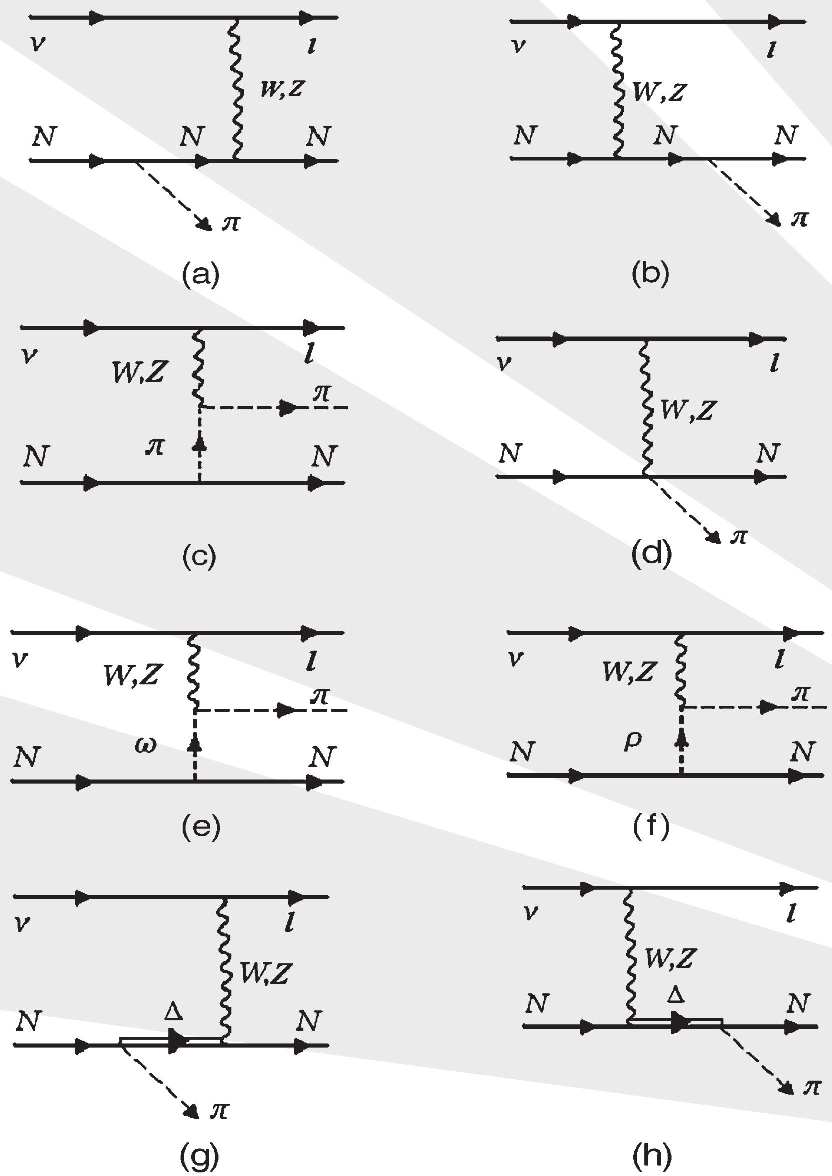
Elementary amplitude

For the $\nu N \rightarrow lN'\pi$ process

$$\sigma(E\nu^{CM}) = \frac{F^{CC/NC}}{(2\pi)^4 E_\nu^{CM}\sqrt{s}} \int_{E_l-}^{E_l^+} dE_l^{CM} \int_{E_\pi^-}^{E_\pi^+} dE_\pi^{CM} \int_{-1}^{+1} dcos\theta$$
$$\int_0^{2\pi} d\eta \frac{1}{16} \sum_{spin} |\mathcal{M}|^2 \,, \tag{1}$$

where where $E_\nu^{CM} = \frac{m_N E_\nu^{Lab}}{\sqrt{2E_\nu^{Lab} m_N + m_N^2}}$ and

$$\mathcal{M} = \mathcal{M}_B + \sum_R \mathcal{M}_R, \quad R \equiv \Delta, N^*. \tag{2}$$


ν
l
W,Z
N
N
N
π
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
ω
ρ
Δ

Requirements on the hadronic amplitud

$$
\begin{aligned}
\mathcal{M}_i &= -\frac{G_F}{\sqrt{2}}\bar{u}(p'_l)(-i)\gamma_\lambda(1-\gamma_5)u(p_\nu)\bar{u}(p')(\mathcal{O}^\lambda_{Vi}-\mathcal{O}^\lambda_{Ai})u(p), \\
i &= B, R
\end{aligned} \quad (3)
$$

Requirements on the hadronic amplitud

$$\begin{aligned} \mathcal{M}_i &= -\frac{G_F}{\sqrt{2}}\bar{u}(p_l')(-i)\gamma_\lambda(1-\gamma_5)u(p_\nu)\bar{u}(p')(\mathcal{O}^\lambda_{Vi}-\mathcal{O}^\lambda_{Ai})u(p), \\ i &= B, R \end{aligned} \tag{3}$$

- It should be Unitary. With real backgrounds this is violated. It is possible a unitarization by introduction of experimental phase shifts and rescattering of the final πN pair, but effect not so important as in photoproduction.

Requirements on the hadronic amplitud

$$\begin{aligned} \mathcal{M}_i &= -\frac{G_F}{\sqrt{2}}\bar{u}(p_l')(-i)\gamma_\lambda(1-\gamma_5)u(p_\nu)\bar{u}(p')(\mathcal{O}^\lambda_{Vi}-\mathcal{O}^\lambda_{Ai})u(p), \\ i &= B, R \end{aligned} \quad (3)$$

- It should be Unitary. With real backgrounds this is violated. It is possible a unitarization by introduction of experimental phase shifts and rescattering of the final πN pair, but effect not so important as in photoproduction.

- Vector amplitude should fulfill electromagnetic gauge invariance(GI) $\rightarrow \bar{u}\mathcal{O}^\lambda_{Vi}q_\lambda u = 0$,

Requirements on the hadronic amplitud

$$\mathcal{M}_i = -\frac{G_F}{\sqrt{2}}\bar{u}(p'_l)(-i)\gamma_\lambda(1-\gamma_5)u(p_\nu)\bar{u}(p')(\mathcal{O}^\lambda_{Vi} - \mathcal{O}^\lambda_{Ai})u(p), \quad i = B, R \qquad (3)$$

- It should be Unitary. With real backgrounds this is violated. It is possible a unitarization by introduction of experimental phase shifts and rescattering of the final πN pair, but effect not so important as in photoproduction.

- Vector amplitude should fulfill electromagnetic gauge invariance(GI) $\rightarrow \bar{u}\mathcal{O}^\lambda_{Vi} q_\lambda u = 0$,
  - In $\mathcal{M}_{V(NP,NC,\pi F,\pi C)}$ same vector FF,
  - $\mathcal{M}_\rho$ is axial and $\mathcal{M}_\omega$ is self-GI,
  - $\mathcal{M}_{VR}$ are built self-GI, but for other reactions involving R must be GI still with finite width effects.

- $\mathcal{M}_R(S=3/2)$ should be invariant on contact transformations (CT)

$$\psi'^{\mu} = R(A)^{\mu\nu}\psi_\nu \equiv (g^{\mu\nu} - 1/2(1+3A)\gamma^\mu\gamma^\nu)\psi_\nu. \quad (4)$$

- $\mathcal{M}_R(S=3/2)$ should be invariant on contact transformations (CT)

$$\psi'^{\mu} = R(A)^{\mu\nu}\psi_\nu \equiv (g^{\mu\nu} - 1/2(1+3A)\gamma^\mu\gamma^\nu)\psi_\nu. \qquad (4)$$

Not a symmetry but a field redefinition of $\psi_\mu \equiv \psi \otimes W_\mu$, ψ Dirac (S=1/2), W_μ a 4-vector (S=0,1 rest or helicity frame)

- $\mathcal{M}_R(S=3/2)$ should be invariant on contact transformations (CT)

$$\psi'^{\mu} = R(A)^{\mu\nu}\psi_\nu \equiv (g^{\mu\nu} - 1/2(1+3A)\gamma^\mu\gamma^\nu)\psi_\nu. \qquad (4)$$

Not a symmetry but a field redefinition of $\psi_\mu \equiv \psi \otimes W_\mu$, ψ Dirac (S=1/2), W_μ a 4-vector (S=0,1 rest or helicity frame)

CT only affects $\psi_{1/2\mu}$ components and let $\mathcal{L}_{free}(\psi^\mu)$ invariant $\Rightarrow$ a whole family $\mathcal{L}_{free}(A)$.

- $\mathcal{M}_R(S=3/2)$ should be invariant on contact transformations (CT)

$$\psi'^{\mu} = R(A)^{\mu\nu}\psi_\nu \equiv (g^{\mu\nu} - 1/2(1+3A)\gamma^\mu\gamma^\nu)\psi_\nu. \qquad (4)$$

Not a symmetry but a field redefinition of $\psi_\mu \equiv \psi \otimes W_\mu$, ψ Dirac (S=1/2), W_μ a 4-vector (S=0,1 rest or helicity frame)

CT only affects $\psi_{1/2\mu}$ components and let $\mathcal{L}_{free}(\psi^\mu)$ invariant $\Rightarrow$ a whole family $\mathcal{L}_{free}(A)$.

$\mathcal{L}_{N(W,\pi)R}(A)$ such that total amplitudes independent on A.

Feynman Rules

$$
\begin{aligned}
G_{\alpha\beta}(p,A) \; = \; & \frac{\not{p}+m}{p^2-m^2}\left\{-g_{\alpha\beta}+\frac{1}{3}\gamma_\alpha\gamma_\beta+\frac{2}{3m^2}p_\alpha p_\beta-\frac{1}{3m}(p_\alpha\gamma_\beta-p_\beta\gamma_\alpha)\right. \\
& \left. -\frac{b(\not{p}-m)}{3m^2}\left[\gamma_\alpha p_\beta-(b-1)\gamma_\beta p_\alpha+(\frac{b}{2}\not{p}+(b-1)m)\gamma_\alpha\gamma_\beta\right]\right\}.
\end{aligned}
$$

where $b=(A+1)/(2A+1)$.

Feynman Rules

$$G_{\alpha\beta}(p,A) = \frac{\not{p}+m}{p^2-m^2}\Big\{-g_{\alpha\beta}+\frac{1}{3}\gamma_\alpha\gamma_\beta+\frac{2}{3m^2}p_\alpha p_\beta-\frac{1}{3m}(p_\alpha\gamma_\beta-p_\beta\gamma_\alpha)$$
$$-\frac{b(\not{p}-m)}{3m^2}\Big[\gamma_\alpha p_\beta-(b-1)\gamma_\beta p_\alpha+(\frac{b}{2}\not{p}+(b-1)m)\gamma_\alpha\gamma_\beta\Big]\Big\}.$$

where $b=(A+1)/(2A+1)$.

$$G\left(p,\underset{-1}{-\frac{1}{3}}\right)_{\mu\nu} = -\left[\frac{\not{p}+m}{p^2-m^2}\hat{P}^{3/2}_{\mu\nu}+\frac{2}{{}_{3}m^2}(\not{p}+m)(\hat{P}^{1/2}_{\underset{22}{11}})_{\mu\nu}+\frac{\sqrt{3}}{{}_{3}m}(\hat{P}^{1/2}_{12}+\hat{P}^{1/2}_{21})_{\mu\nu}\right]$$

Feynman Rules

$$G_{\alpha\beta}(p,A) = \frac{\not p + m}{p^2-m^2}\left\{-g_{\alpha\beta}+\frac{1}{3}\gamma_\alpha\gamma_\beta+\frac{2}{3m^2}p_\alpha p_\beta-\frac{1}{3m}(p_\alpha\gamma_\beta-p_\beta\gamma_\alpha)\right.$$
$$\left.-\frac{b(\not p - m)}{3m^2}\left[\gamma_\alpha p_\beta-(b-1)\gamma_\beta p_\alpha+(\frac{b}{2}\not p+(b-1)m)\gamma_\alpha\gamma_\beta\right]\right\}$$

where $b=(A+1)/(2A+1)$.

$$G\left(p,\underset{-1}{-\frac{1}{3}}\right)_{\mu\nu} = -\left[\frac{\not p+m}{p^2-m^2}\hat{P}^{3/2}_{\mu\nu}+\frac{2}{{}_{3}m^2}(\not p+m)(\hat{P}^{1/2}_{\underset{22}{11}})_{\mu\nu}+\frac{\sqrt{3}}{{}_{3}m}(\hat{P}^{1/2}_{12}+\hat{P}^{1/2}_{21})_{\mu\nu}\right]$$

conventional (C) and spin 3/2-gauge (G) πN couplings

A=-1/3 , $V^{\sigma}_{\pi N\Delta_C} = -\frac{f_{\pi N\Delta}}{m_\pi}p^\sigma_\pi$

A=-1, $V^{\sigma}_{\pi N\Delta_G} = \mathrm{i}\frac{f_{\pi N\Delta}}{m_\pi m}\gamma_5\gamma_\beta p_\alpha p_{\pi\,\mu}\epsilon^{\alpha\mu\beta\sigma}$

Feynman Rules

$$
\begin{aligned}
G_{\alpha\beta}(p,A) \;=\; & \frac{\not p + m}{p^2-m^2}\left\{-g_{\alpha\beta}+\frac{1}{3}\gamma_\alpha\gamma_\beta+\frac{2}{3m^2}p_\alpha p_\beta-\frac{1}{3m}(p_\alpha\gamma_\beta-p_\beta\gamma_\alpha)\right.\\
& \left.-\frac{b(\not p - m)}{3m^2}\left[\gamma_\alpha p_\beta-(b-1)\gamma_\beta p_\alpha+(\frac{b}{2}\not p+(b-1)m)\gamma_\alpha\gamma_\beta\right]\right\}
\end{aligned}
$$

where $b=(A+1)/(2A+1)$.

$$
G\left(p,-\frac{1}{3}\right)_{\mu\nu} \;=\; -\left[\frac{\not p + m}{p^2-m^2}\hat P^{3/2}_{\mu\nu}+\frac{2}{3m^2}(\not p + m)(\hat P^{1/2}_{11})_{\mu\nu}+\frac{\sqrt{3}}{3m}(\hat P^{1/2}_{12}+\hat P^{1/2}_{21})_{\mu\nu}\right]
$$

-1

conventional (C) and spin 3/2-gauge (G) πN couplings

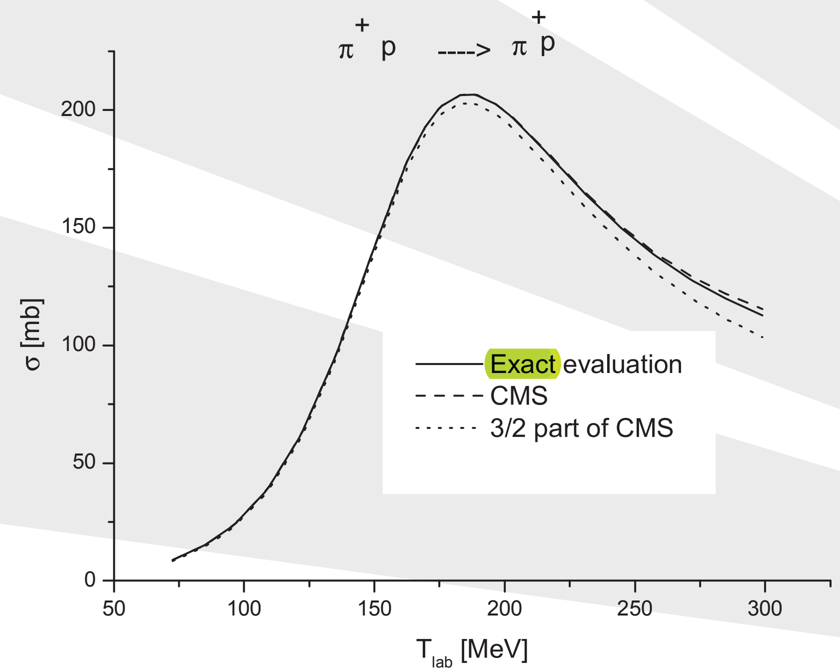
A=-1/3 , $\quad V^{\sigma}_{\pi N\Delta_C} = -\frac{f_{\pi N\Delta}}{m_\pi}p^{\sigma}_{\pi}$

A=-1, $\quad V^{\sigma}_{\pi N\Delta_G} = \mathrm{i}\frac{f_{\pi N\Delta}}{m_\pi m}\gamma_5\gamma_\beta p_\alpha p_{\pi\,\mu}\epsilon^{\alpha\mu\beta\sigma}$

- Unstableness of R included in the $G_{\mu\nu}(p)$ through $\Sigma_{\mu\nu}(p)$(one loop-corrections), which accounts an energy dependent width and vertex corrections to get GI.

- Unstableness of R included in the $G_{\mu\nu}(p)$ through $\Sigma_{\mu\nu}(p)$(one loop-corrections), which accounts an energy dependent width and vertex corrections to get GI.

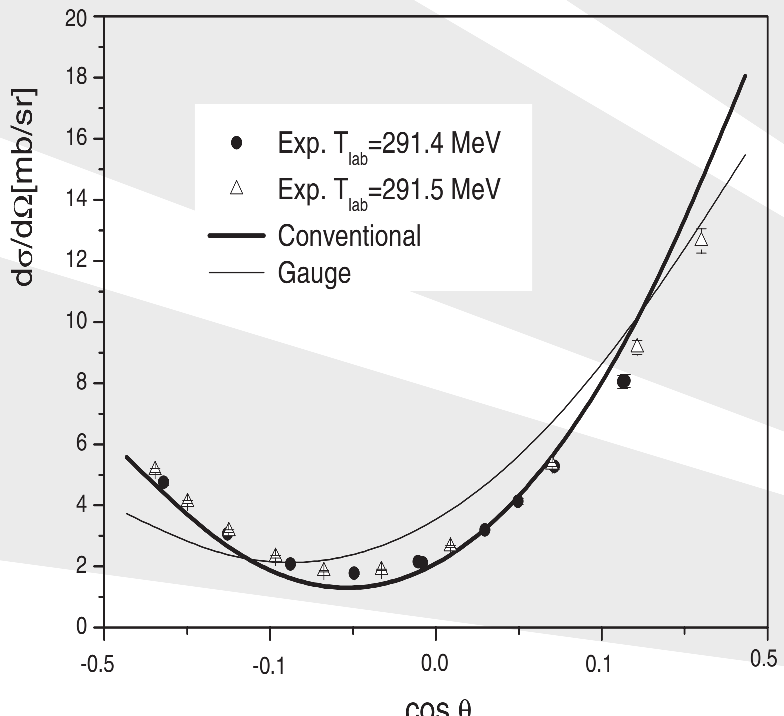
  We make $G^{dressed} \approx G(m_\Delta \to m_\Delta - i\Gamma_\Delta/2)$, referred as complex mass scheme (CB, AM, GLC JPG(2012) in press).



- Electromagnetic and spin-3/2 GI should coexist. But, making the minimal substitution $p_\mu \to p_\mu + iQk_\mu$ spin-3/2 GI is lost in $V_{\pi N R_G}$.

- Electromagnetic and spin-3/2 GI should coexist. But, making the minimal substitution $p_\mu \to p_\mu + iQk_\mu$ spin-3/2 GI is lost in $V_{\pi N R_G}$.

- C couplings work better than G as can be seen in $\pi^+ p$ elastic scattering, (AM, CB, DB JPG 39(2012)035005).



Fixing amplitude parameters(Δ)

- For the non-resonant background, we take $g^2_{\pi NN}/4\pi = 14$, $g^2_{\rho NN}/4\pi = 2.9$, $\kappa_\rho = 3.7$, $g_{\omega NN} = 3 g_{\rho NN}$ and $\kappa_\omega = -0.12$ (vector dominance model), $g_\sigma/4\pi = 1.5$, $m_\sigma = 650 MeV$, and masses from PDG.

Fixing amplitude parameters(Δ)

- For the non-resonant background, we take $g^2_{\pi NN}/4\pi = 14$, $g^2_{\rho NN}/4\pi = 2.9$, $\kappa_\rho = 3.7$, $g_{\omega NN} = 3g_{\rho NN}$ and $\kappa_\omega = -0.12$ (vector dominance model), $g_\sigma/4\pi = 1.5$, $m_\sigma = 650MeV$, and masses from PDG.

- Fitting to the elastic $\pi^+ p \to \pi^+ p$ cross section data, leads to $\mathrm{f}^2_{\Delta\mathrm{N}\pi}/4\pi = 0.317 \pm 0.003$, $m_\Delta = 1211.7 \pm 0.4MeV$ and $\Gamma_\Delta = 92.2 \pm 0.4MeV$ (GLC, AM NPA697,(2001)440).

Fixing amplitude parameters(Δ)

- For the non-resonant background, we take $g^2_{\pi NN}/4\pi = 14$, $g^2_{\rho NN}/4\pi = 2.9$, $\kappa_\rho = 3.7$, $g_{\omega NN} = 3g_{\rho NN}$ and $\kappa_\omega = -0.12$ (vector dominance model), $g_\sigma/4\pi = 1.5$, $m_\sigma = 650 MeV$, and masses from PDG.

- Fitting to the elastic $\pi^+ p \to \pi^+ p$ cross section data, leads to $\mathrm{f}^2_{\Delta \mathrm{N}\pi}/4\pi = 0.317 \pm 0.003$, $m_\Delta = 1211.7 \pm 0.4 MeV$ and $\Gamma_\Delta = 92.2 \pm 0.4 MeV$ (GLC, AM NPA697,(2001)440).

- From data on of $\pi^+ p \to \pi^+ p\gamma$ Bremmsstrahlung (GLC, AM PDG(2002)) $\mu_\Delta = 2(1+\kappa_\Delta)\frac{e}{2m_\Delta} = (6.14 \pm 0.51)\frac{e}{2m_p}$.

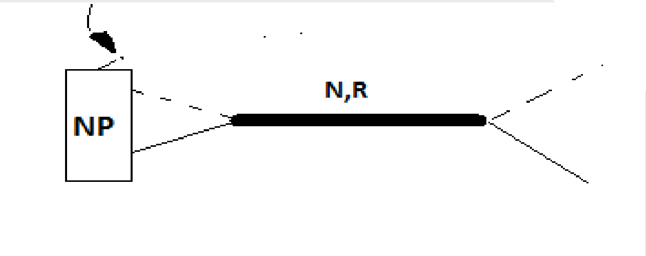
Fixing amplitude parameters(Δ)

- For the non-resonant background, we take $g^2_{\pi NN}/4\pi = 14$, $g^2_{\rho NN}/4\pi = 2.9$, $\kappa_\rho = 3.7$, $g_{\omega NN} = 3g_{\rho NN}$ and $\kappa_\omega = -0.12$ (vector dominance model), $g_\sigma/4\pi = 1.5$, $m_\sigma = 650 MeV$, and masses from PDG.

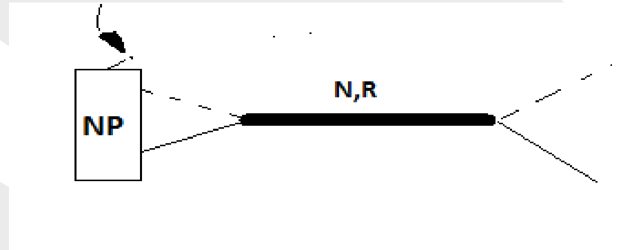
- Fitting to the elastic $\pi^+ p \to \pi^+ p$ cross section data, leads to $\mathrm{f}^2_{\Delta \mathrm{N}\pi}/4\pi = 0.317 \pm 0.003$, $m_\Delta = 1211.7 \pm 0.4 MeV$ and $\Gamma_\Delta = 92.2 \pm 0.4 MeV$ (GLC, AM NPA697,(2001)440).

- From data on of $\pi^+ p \to \pi^+ p\gamma$ Bremmsstrahlung (GLC, AM PDG(2002)) $\mu_\Delta = 2(1+\kappa_\Delta)\frac{e}{2m_\Delta} = (6.14 \pm 0.51)\frac{e}{2m_p}$.

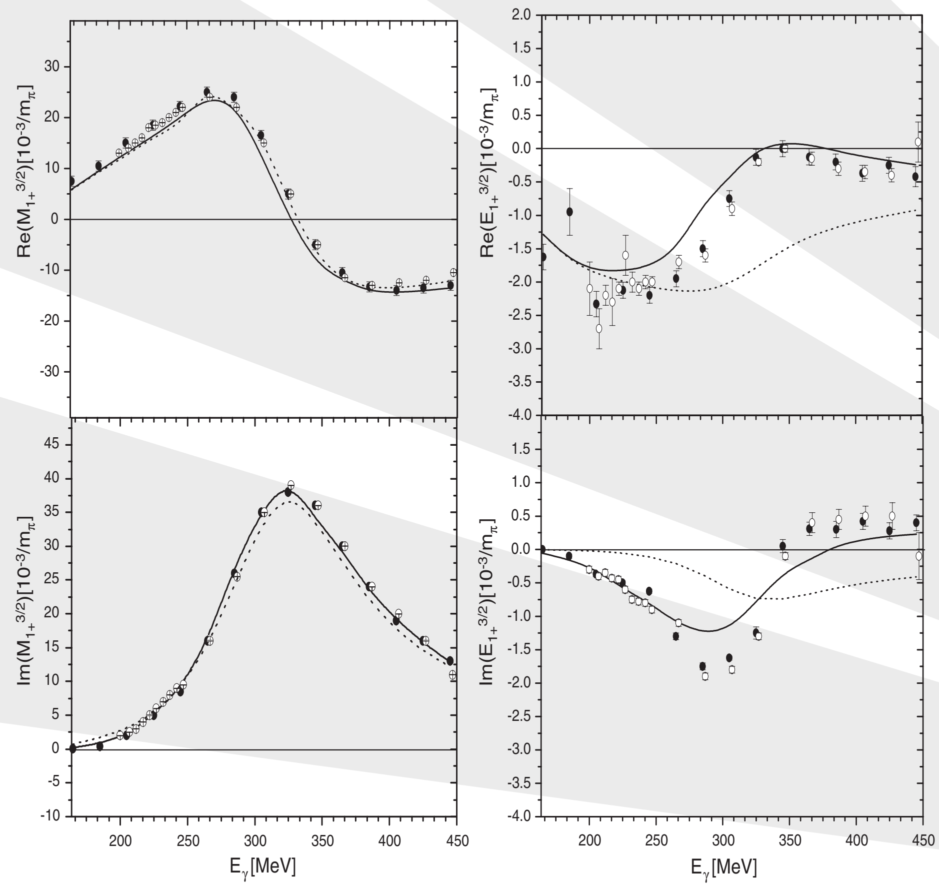
- Fitting $M^{3/2}_{1+}$, $E^{3/2}_{1+}$,from the $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ get dressed values $G_M = 2.97 \pm 0.08$ and $G_E = 0.055 \pm 0.010$ (pion cloud effects), and bare $G^0_M = 1.69 \pm 0.02$ and $G^0_E = 0.028 \pm 0.008$ ones (AM PLB647, (2007)253; JPG34,(2997) 1627).



NP
N,R

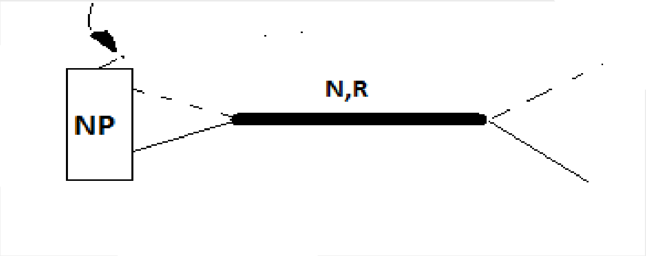


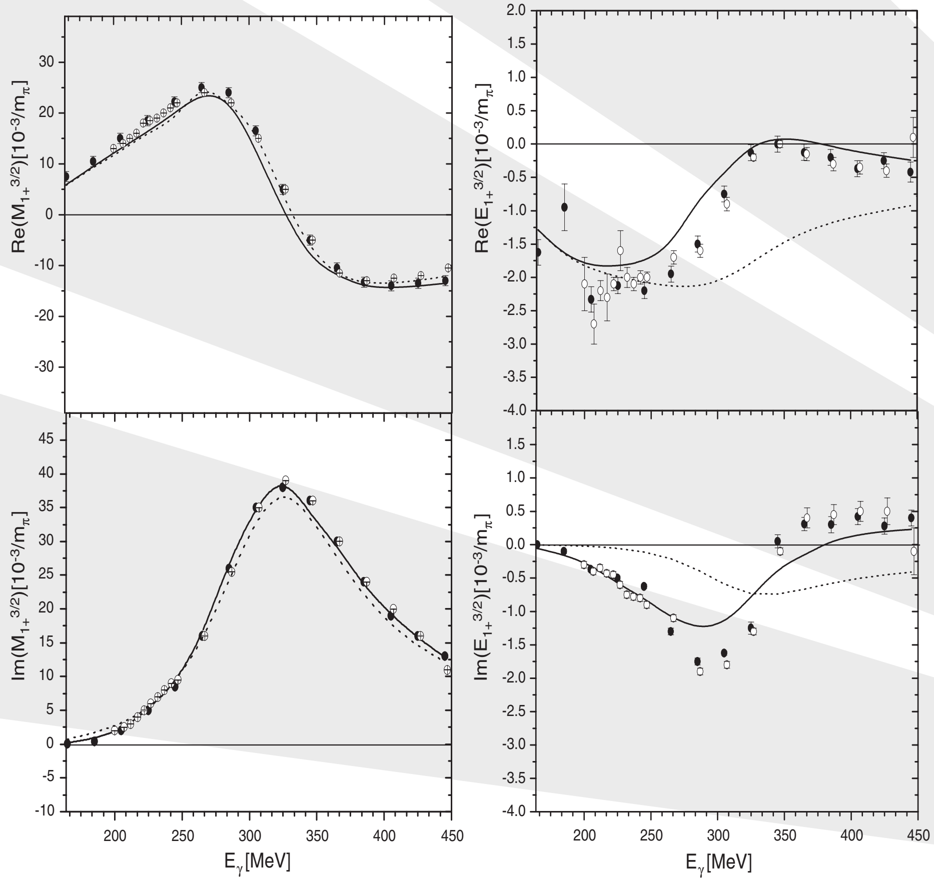
NP
N,R

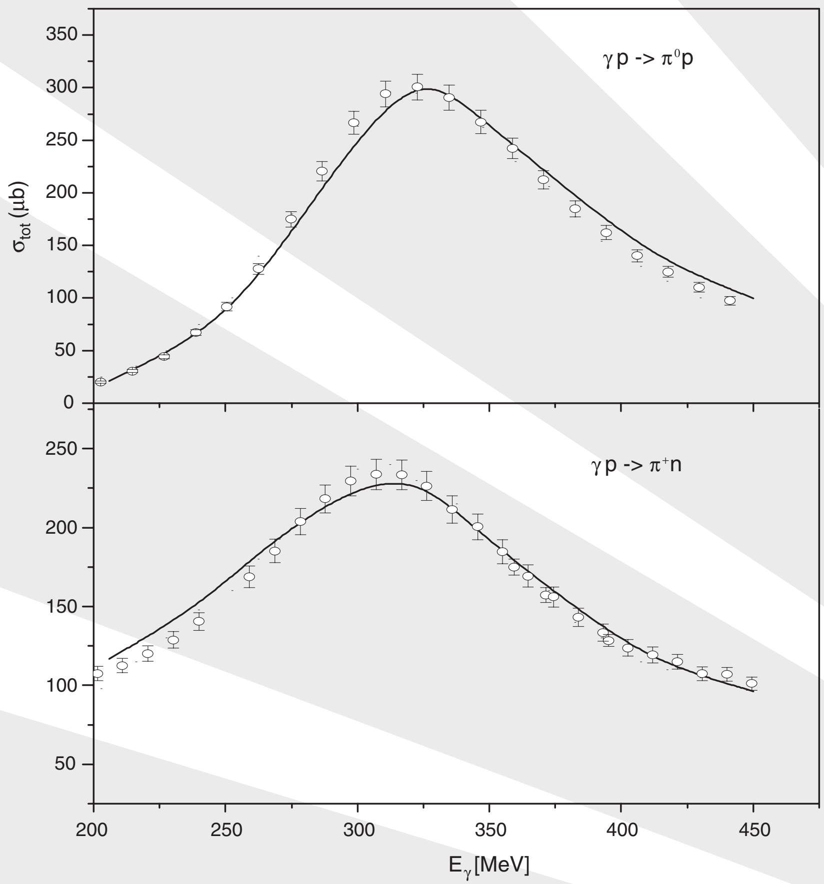


Re(M1+ 3/2)[10-3/mπ]
Im(M1+ 3/2)[10-3/mπ]
Re(E1+ 3/2)[10-3/mπ]
Im(E1+ 3/2)[10-3/mπ]
Eγ[MeV]
Eγ[MeV]

- Motivation
- Problems
-
- 1π process
- Elementary amplitude
-
- Requirements on the hadronic amplitud
-
-
-
-
- Fixing amplitude parameters(Δ)
-
-
-
-
-
- Binding + GSC
-
-
- FSI
- Results for CC and NC
-







γp -> π⁰p
γp -> π⁺n
σtot (μb)
Eγ [MeV]
0
50
100
150
200
250
300
350
50
100
150
200
250
200
250
300
350
400
450

- Weak sector the V coupling constants are fixed by CVC for B and R amplitudes. For the A ones we exploit the PCAC and the Goldberger-Treiman relations in B ($g_V = 1$, $g_{\omega\pi V} = g_{\omega\pi\gamma} = 0.3247e$, $g_A = 1.26$ and $f_{\rho\pi A} = \frac{m_\rho^2}{93MeV g_{\rho NN}}$), and for the FF we adopt a dipole model.

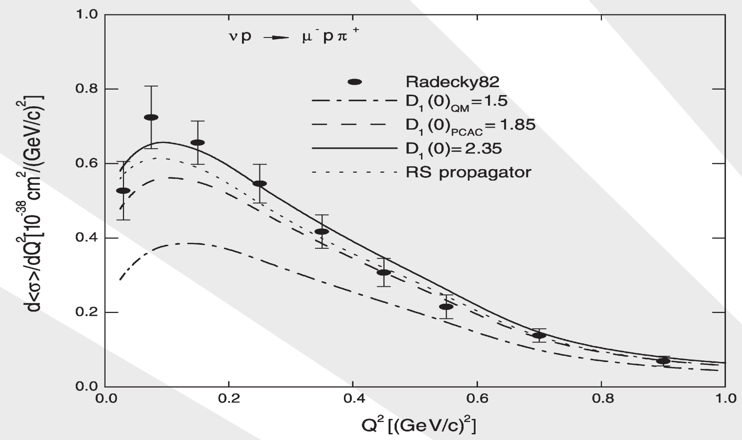
- Weak sector the V coupling constants are fixed by CVC for B and R amplitudes. For the A ones we exploit the PCAC and the Goldberger-Treiman relations in B ($g_V = 1$, $g_{\omega\pi V} = g_{\omega\pi\gamma} = 0.3247e$, $g_A = 1.26$ and $f_{\rho\pi A} = \frac{m_\rho^2}{93MeV g_{\rho NN}}$), and for the FF we adopt a dipole model.

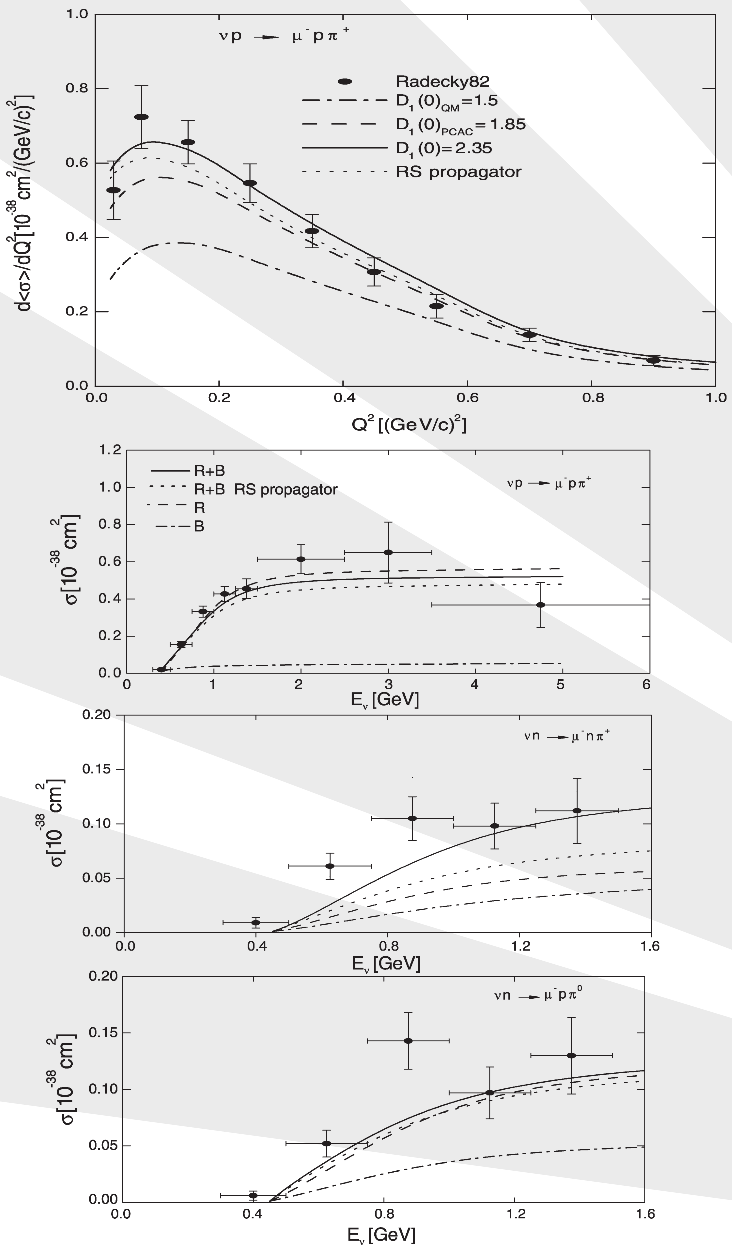
  For the $WN \to \Delta$ C_5^A coupling we make a fit to the differential cross section $\frac{d<\sigma>}{dQ^2}$ for the $\nu p \to \mu^- p\pi^+$ (ANL), getting $C_5^A(0) = 1.35$.

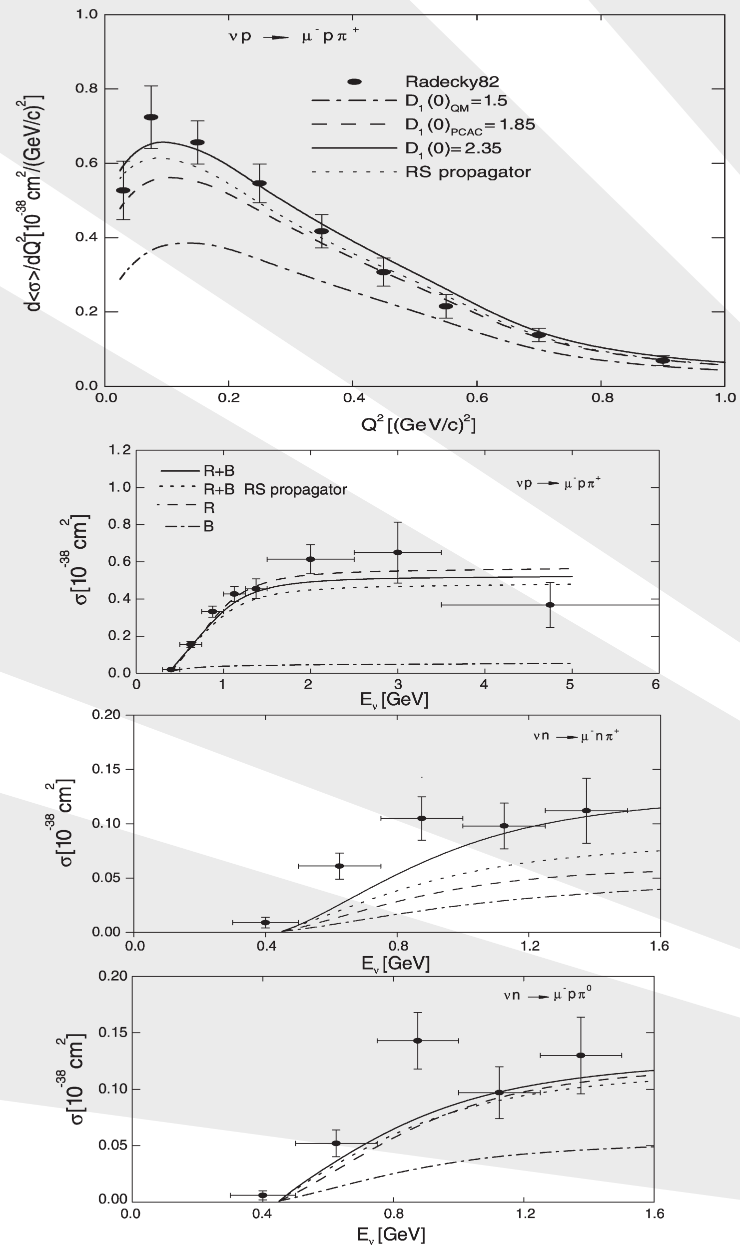
- Weak sector the V coupling constants are fixed by CVC for B and R amplitudes. For the A ones we exploit the PCAC and the Goldberger-Treiman relations in B ($g_V = 1$, $g_{\omega\pi V} = g_{\omega\pi\gamma} = 0.3247e$, $g_A = 1.26$ and $f_{\rho\pi A} = \frac{m_\rho^2}{93MeV g_{\rho NN}}$), and for the FF we adopt a dipole model.

  For the $WN \to \Delta$ C_5^A coupling we make a fit to the differential cross section $\frac{d<\sigma>}{dQ^2}$ for the $\nu p \to \mu^- p \pi^+$ (ANL), getting $C_5^A(0) = 1.35$.

  PCAC values lies $\sim 21\%$ below, while QM value (1) is $\sim 37\%$ smaller (also for Sato and Lee), but it is interesting that $G_M^0(0)$(QM) is also a $\sim 40\%$ below the value of $G_M(0)$ in the vector sector.


$\nu p \to \mu^- p \pi^+$
Radecky82
$D_1(0)_{QM}$=1.5
$D_1(0)_{PCAC}$=1.85
$D_1(0)$=2.35
RS propagator
$d\langle\sigma\rangle/dQ^2[10^{-38}cm^2/(GeV/c)^2]$
Q^2 [(GeV/c)^2]
0.0
0.2
0.4
0.6
0.8
1.0


$\nu p \to \mu^- p \pi^+$
Radecky82
$D_1(0)_{QM}$=1.5
$D_1(0)_{PCAC}$=1.85
$D_1(0)$=2.35
RS propagator
$d\langle\sigma\rangle/dQ^2[10^{-38}cm^2/(GeV/c)^2]$
Q^2 [(GeV/c)^2]
R+B
R+B RS propagator
R
B
$\nu p \to \mu^- p \pi^+$
$\sigma[10^{-38} cm^2]$
E_ν [GeV]
$\nu n \to \mu^- n \pi^+$
$\sigma[10^{-38} cm^2]$
E_ν [GeV]
$\nu n \to \mu^- p \pi^0$
$\sigma[10^{-38} cm^2]$
E_ν [GeV]



νp → μ⁻pπ⁺
Radecky82
D₁(0)QM=1.5
D₁(0)PCAC=1.85
D₁(0)=2.35
RS propagator
d<σ>/dQ²[10⁻³⁸cm²/(GeV/c)²]
Q²[(GeV/c)²]
R+B
R+B RS propagator
R
B
σ[10⁻³⁸cm²]
Eν [GeV]
νn → μ⁻nπ⁺
νn → μ⁻pπ⁰

❖ Motivation

❖ Problems

❖

❖ 1π process

❖ Elementary amplitude

❖

❖ Requirements on the hadronic amplitud

❖

❖

❖

❖

❖ Fixing amplitude parameters(Δ)

❖

❖

❖

❖

❖

❖ Binding + GSC

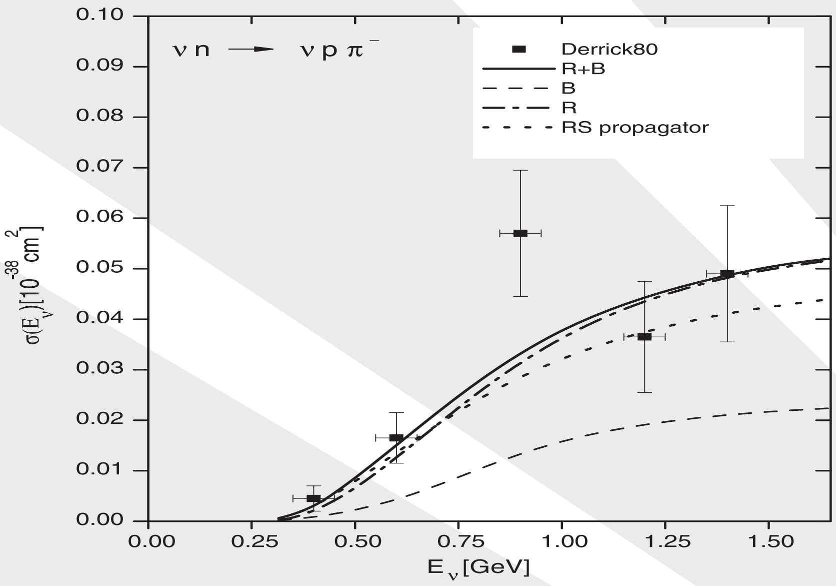
❖

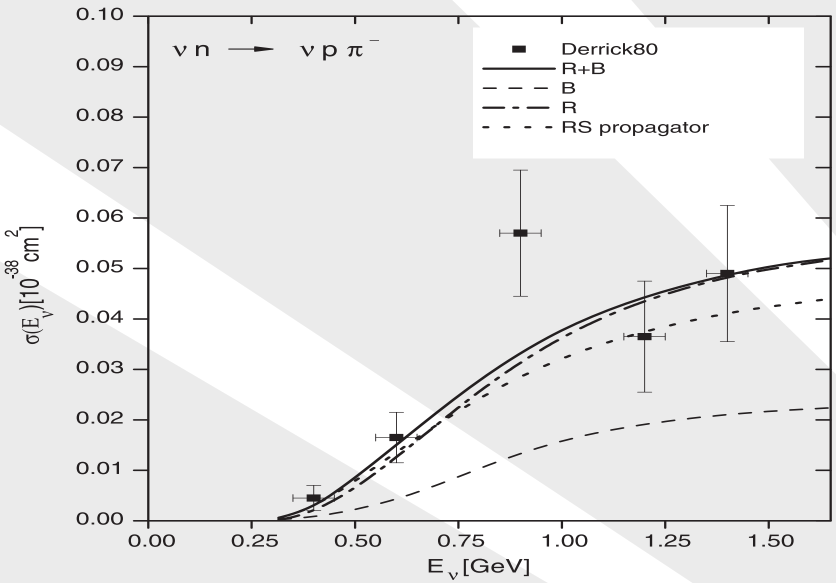
❖

❖ FSI

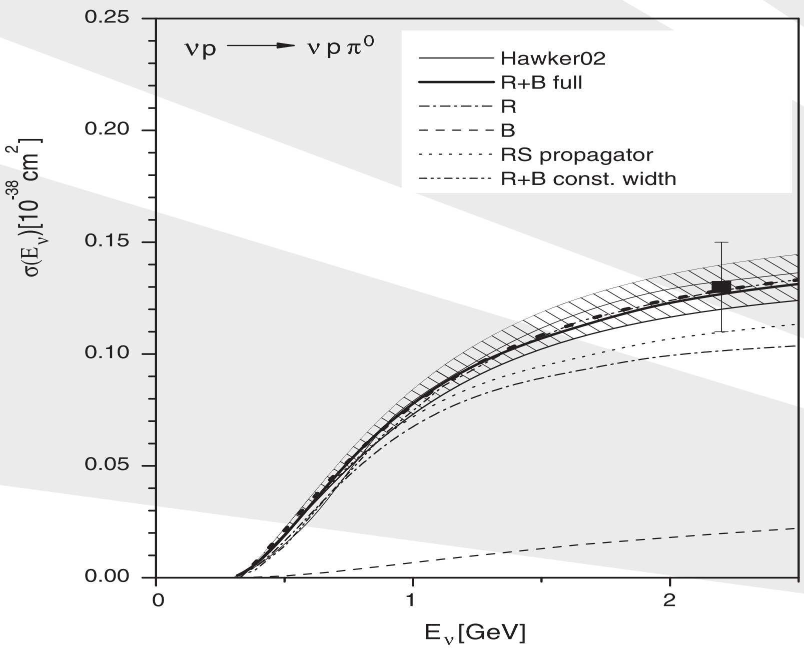
❖ Results for CC and NC

❖





ν n → ν p π⁻
Derrick80
R+B
B
R
RS propagator
σ(E_ν)[10^-38 cm^2]
E_ν [GeV]



νp → ν p π⁰
Hawker02
R+B full
R
B
RS propagator
R+B const. width
σ(E_ν)[10^-38 cm^2]
E_ν [GeV]

Binding + GSC

Impulse approximation

$$d\sigma_{\nu,A} = 2d^3k \left(1 - \frac{|\mathbf{k}|cos\theta_{\nu,\mathbf{k}}}{E(\boldsymbol{k}_\nu)}\right) n_A(\boldsymbol{k}) \sum_m d\sigma(\nu, N_B)^{CM}$$

Binding + GSC

Impulse approximation

$$d\sigma_{\nu,A} = 2d^3k\left(1-\frac{|\mathbf{k}|cos\theta_{\nu,\mathbf{k}}}{E(\boldsymbol{k}_\nu)}\right)n_A(\boldsymbol{k})\sum_m d\sigma(\nu,N_B)^{CM}$$

- Binding within the RHA of QHD I (σ, ω mesons), for N and Δ (universal coupling)

$$\psi_N(x) = \int dp^3 \sum_{m_s m_t}\sqrt{\frac{m_N^*}{(2\pi)^3 E^*(\mathbf{p})}}\left[u(\mathbf{p}m_s m_t)a_{\mathbf{p}m_s m_t}e^{ip\cdot x} + b^\dagger_{\mathbf{p}m_s m_t}v(\mathbf{p}m_s m_t)e^{-ip\cdot x}\right]$$

Binding + GSC

Impulse approximation

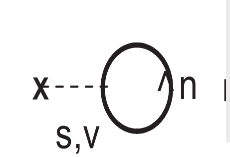
$$d\sigma_{\nu,A} \quad = \quad 2d^3k\left(1-\frac{|\mathbf{k}|cos\theta_{\nu,\mathbf{k}}}{E(\boldsymbol{k}_\nu)}\right)n_A(\boldsymbol{k})\sum_m d\sigma(\nu,N_B)^{CM}$$

- Binding within the RHA of QHD I (σ, ω mesons), for N and Δ (universal coupling)

$$\psi_N(x) \quad = \quad \int dp^3\sum_{m_sm_t}\sqrt{\frac{m_N^*}{(2\pi)^3E^*(\mathbf{p})}}\left[u(\mathbf{p}m_sm_t)a_{\mathbf{p}m_sm_t}e^{ip\cdot x}+b^\dagger_{\mathbf{p}m_sm_t}v(\mathbf{p}m_sm_t)e^{-ip\cdot x}\right]$$

$$p_0 = C_V^2\frac{\rho_B}{m_N^2}+E^*(\mathbf{p})\equiv\Sigma_0^V(C_V)+E^*(\mathbf{p}),$$

$$E^*(\mathbf{p})=\sqrt{\mathbf{p}^2+m_N^{*2}},\ m_N^*\equiv m_N+\Sigma^S(C_S,m_N^*)$$



- GSC (2p2h+4p4h) in ground state, through perturbation theory in nuclear matter

$$n_A(\mathbf{k}) = \langle\tilde{0}|a^{\dagger}_{\mathbf{k}m}a_{\mathbf{k}m}|\tilde{0}\rangle, \quad \int d^3k \;\; n_A(\mathbf{k}) = \frac{A}{4} \tag{5}$$

$$|\tilde{0}\rangle = \mathcal{N}\left[|0\rangle + \frac{1}{(2!)^2}\sum_{p's,h's} c_{p_1p_2h_1h_2}|p_1p_2h_1h_2\rangle \right.$$

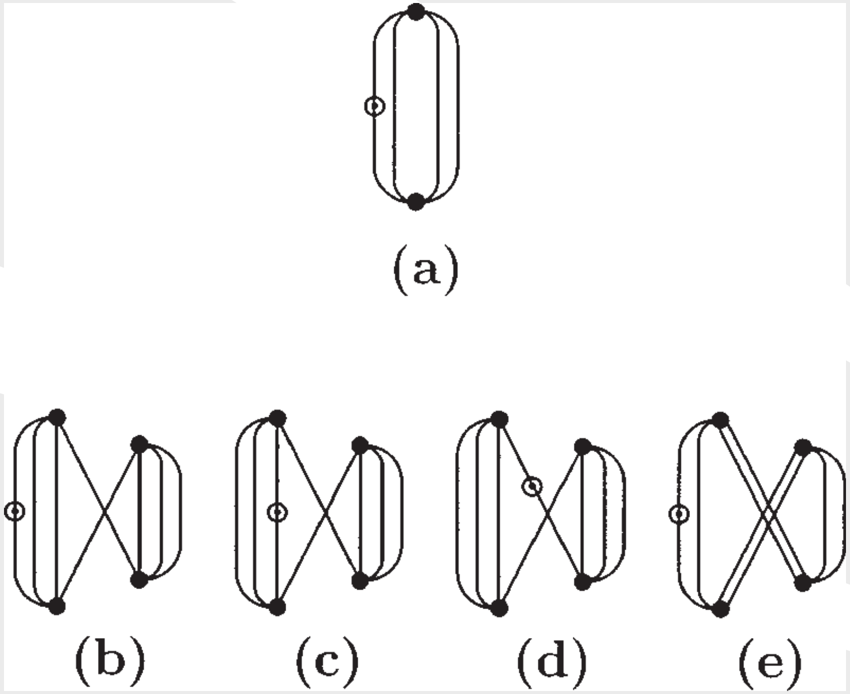
$$\left. + \quad \frac{1}{(4!)^2}\sum_{p's,h's} c_{p_1p_2p_3p_4h_1h_2h_3h_4}|p_1p_2p_3p_4h_1h_2h_3h_4\rangle\right],$$

where

$$c_{p_1p_2h_1h_2} = -\frac{\langle p_1p_2h_1h_2|\hat{V}|0\rangle}{E_{p_1p_2h_1h_2}}, c_{p_1p_2p_3p_4h_1h_2h_3h_4} =$$

$$\frac{\langle 0|\hat{V}|p_1p_2h_1h_2\rangle\langle p_1p_2h_1h_2|\hat{V}|p_1p_2p_3p_4h_1h_2h_3h_4\rangle}{E_{p_1p_2h_1h_2}E_{p_1p_2p_3p_4h_1h_2h_3h_4}},$$

$$n^{m_t}(\mathbf{p}) = \frac{3N^{m_t}}{4\pi p_F^3}\left[\theta(1-p) + \delta n^{(2)}(p) + \delta n^{(4C)}(p)\right],$$



FSI

FSI on nucleons is taken (Toy model !) through the used effective fields within the RHA also for final N. While for pions we use the Eikonal approach in its simplest version, that is $\phi_\pi \rightarrow \phi^*_\pi$, where

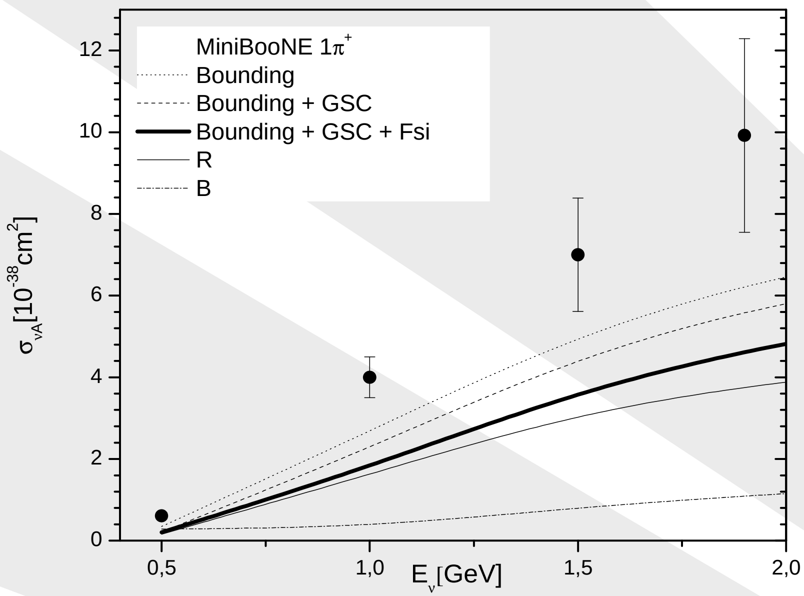
$$\phi^*_\pi(\mathbf{r}) \sim e^{-i\mathbf{p}_\pi\cdot\mathbf{r}} e^{-i/v_\pi \int_{z_\pi}^{\infty} V_{opt}(\mathbf{b},\mathbf{z}')\mathbf{dz}'}, \mathbf{r} = (\mathbf{b}, \mathbf{z}'), \qquad (6)$$

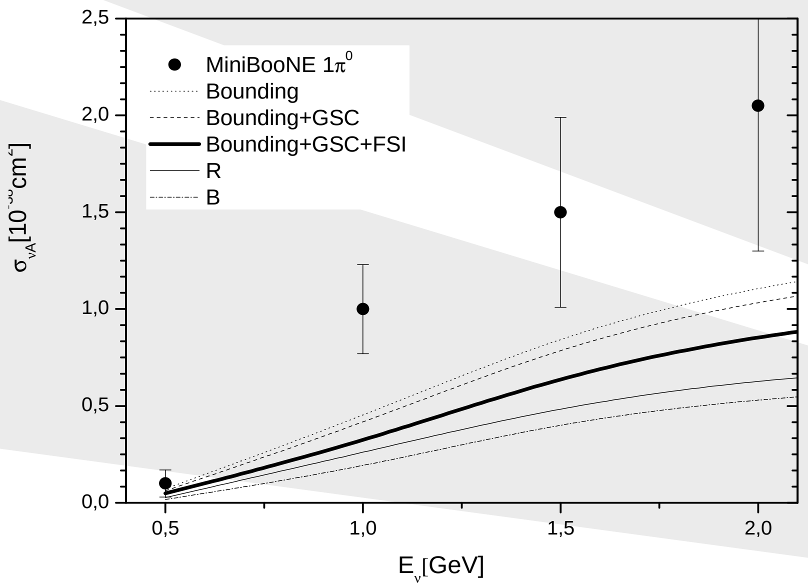
Assuming a mean distance of trip for π in nucleus, constant nucleon density and the Δ-h model for the π-optical potential we get

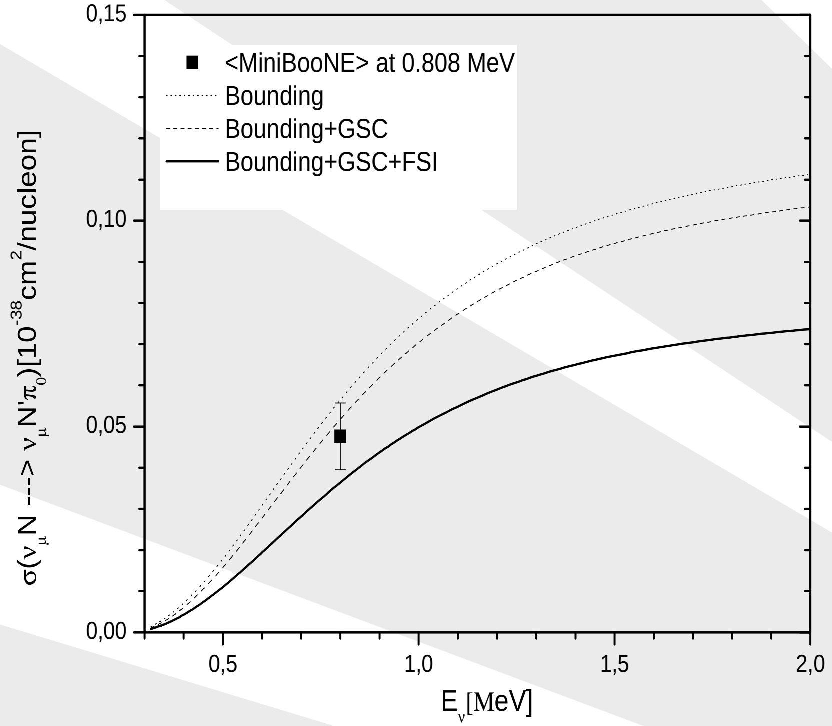
$$\begin{aligned}
\phi^*_\pi(\mathbf{r}) &\sim e^{-i\mathbf{p}_\pi\cdot\mathbf{r}} e^{-i\lambda(s)|\mathbf{p}_\pi| < d >}, \\
\lambda(s) &= \frac{2}{9}\left(\frac{f_{\pi N\Delta}}{m_\pi}\right)^2 \frac{m_N^2 \rho_0 T}{s(\sqrt{s} - m^*_\Delta + 1/2\Gamma^*_\Delta)}, \\
< d > &= \sqrt{R^2 - 2/3 < r >^2}, \quad R = r_0 A^{1/3}, < r >= c A^{1/3}.
\end{aligned}$$

Results for CC and NC

- ❖ Motivation
- ❖ Problems
- ❖
- ❖ 1π process
- ❖ Elementary amplitude
- ❖
- ❖ Requirements on the hadronic amplitud
- ❖
- ❖
- ❖
- ❖
- ❖ Fixing amplitude parameters(Δ)
- ❖
- ❖
- ❖
- ❖
- ❖
- ❖ Binding + GSC
- ❖
- ❖
- ❖ FSI
- ❖ Results for CC and NC
- ❖






<MiniBooNE> at 0.808 MeV
Bounding
Bounding+GSC
Bounding+GSC+FSI
0,15
0,10
0,05
0,00
0,5
1,0
1,5
2,0
E_ν[MeV]
$\sigma(\nu_\mu N \text{--->} \nu_\mu N'\pi_0)[10^{-38} cm^2/nucleon]$

Conclusions

- Claculations are $\sim 50\%$ below MoniBonne for CC 1π (comparable to GiBUU Jul 2011) and $\sim 30\%$ for NC π^0 production.

Conclusions

- Claculations are $\sim 50\%$ below MoniBonne for CC 1π (comparable to GiBUU Jul 2011) and $\sim 30\%$ for NC π^0 production.

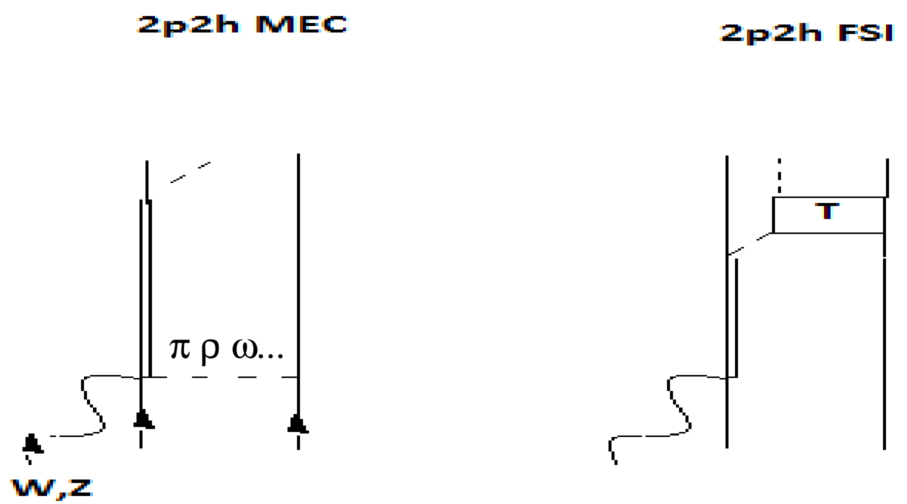
- From $\nu n \to \mu^- N\pi$, with $N = n, p$ and $\pi = \pi^+, \pi^0$, πN invariance mass distribution and the ANL - BNL big errors we see the contribution of higher resonances could be important $\to$ we need to add them consistently to the elemental amplitude.

Conclusions

- Claculations are $\sim 50\%$ below MoniBonne for CC 1π (comparable to GiBUU Jul 2011) and $\sim 30\%$ for NC π^0 production.
- From $\nu n \to \mu^- N\pi$, with $N = n, p$ and $\pi = \pi^+, \pi^0$, πN invariance mass distribution and the ANL - BNL big errors we see the contribution of higher resonances could be important $\to$ we need to add them consistently to the elemental amplitude.
- The FSI inclusion in very primitive and perhaps an overvaluation of them is present $\to$ should be improved, but

- Note that at for example $E_\nu = 1.5GeV$ for MiniBooNE and ANL or BNL (without cuts) data :
$\sigma^{exp}_{ACC1\pi^+}/A\sigma^{exp}_{NCC1\pi^+} \sim 95\%$
$\sigma^{exp}_{ACC1\pi^0}/A\sigma^{exp}_{NCC1\pi^0} \sim 83\%$
$\sigma^{exp}_{ANC1\pi^0}/A\sigma^{exp}_{NNC1\pi^0} \sim 92\%$,
what seems indicate nuclear effects should be of much minor importance, if the IA is assumed or that another mechanisms should be considered

- Note that at for example $E_\nu = 1.5GeV$ for MiniBooNE and ANL or BNL (without cuts) data :
$\sigma^{exp}_{ACC1\pi^+}/A\sigma^{exp}_{NCC1\pi^+} \sim 95\%$
$\sigma^{exp}_{ACC1\pi^0}/A\sigma^{exp}_{NCC1\pi^0} \sim 83\%$
$\sigma^{exp}_{ANC1\pi^0}/A\sigma^{exp}_{NNC1\pi^0} \sim 92\%$,
what seems indicate nuclear effects should be of much minor importance, if the IA is assumed or that another mechanisms should be considered



- Note that at for example $E_\nu = 1.5 GeV$ for MiniBooNE and ANL or BNL (without cuts) data :
$\sigma^{exp}_{ACC1\pi^+}/A\sigma^{exp}_{NCC1\pi^+} \sim 95\%$
$\sigma^{exp}_{ACC1\pi^0}/A\sigma^{exp}_{NCC1\pi^0} \sim 83\%$
$\sigma^{exp}_{ANC1\pi^0}/A\sigma^{exp}_{NNC1\pi^0} \sim 92\%$,
what seems indicate nuclear effects should be of much minor importance, if the IA is assumed or that another mechanisms should be considered