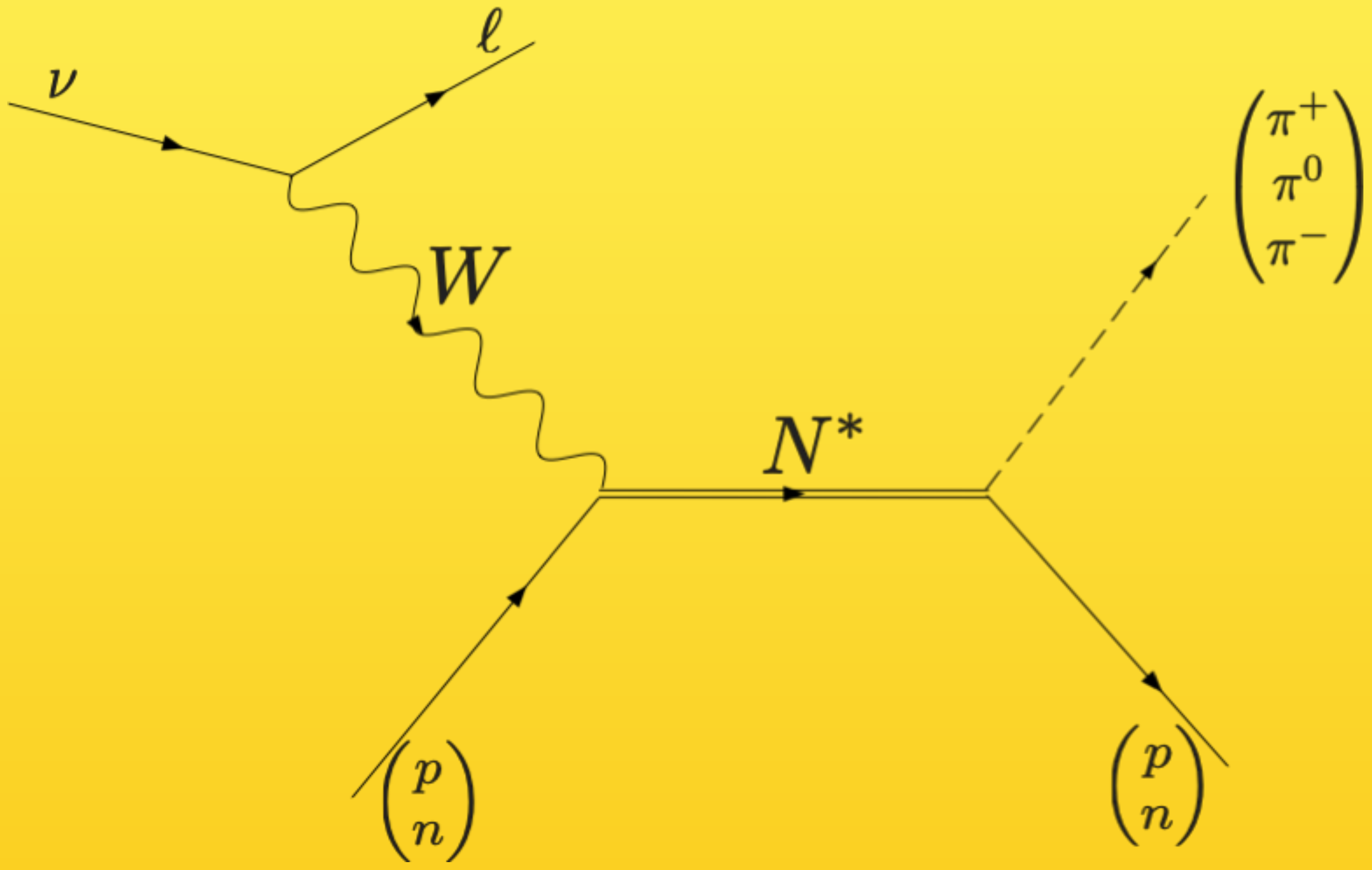
Neutrino-induced single pion production and the reanalyzed bubble chamber data



Alejandro Mariano

David F. Tamayo Agudelo

IFLP CONICET UNLP

UNIVERSIDAD DE ANTIOQUIA 1803

NUINT 2024

Content

Summary

We report the calculation of cross sections for pion production by the scattering of (anti)neutrinos into nucleons incorporating the second resonance region up to 1.6 GeV, in addition to the $\Delta(1232)$ resonance. Background non resonant contributions are also considered and added coherently. We see that:

- The resonances of the second region included are: $N^*(1440)(P_{11})$, $N^*(1520)(D_{13})$ y $N^*(1535)(S_{11})$. It is shown that they are necessary for the description the cross section up to $E_\upsilon \lesssim 2 GeV$, and how to handle the behavior and interference amplitude contributions when we grow in energy.
- We work within a framework of chiral effective Lagrangians and discuss approaches that present certain types of inconsistencies or alternative treatments of 3/2 resonances.
- We compared with the recent reanalyzed data matching ANL and BNL results and with the antineutrinos CERN PS data, for the sake of consistence.

Motivation

From the experimental point of view

- It is known that neutrinos are massive particles that can oscillate (change flavor), it is essential to know precisely the cross sections in the interaction of the neutrino with free, or bounded nucleons in the nucleus detector.
- Quasi-elastic interaction (QE) is the main signal in oscillation experiments or those looking for CP violation

CC

$$\nu_\ell + N \to \ell^- + N'$$
$$\nu_\ell + N \to \nu'_\ell + N'$$

NC

$$\bar{\nu}_\ell + N \to \ell^+ + N'$$
$$\bar{\nu}_\ell + N \to \bar{\nu}'_\ell + N'$$

- More than one nucleon could ejected by (final state interactions) FSI in the detector.

•Inelastic scattering produces additional pions

1π CC

$$\nu_\ell + N \to \ell^- + N'\pi$$

$$\bar{\nu}_\ell + N \to \ell^+ + N'\pi$$

1π NC

$$\nu_\ell + N \to \nu'_\ell + N'\pi$$

$$\bar{\nu}_\ell + N \to \bar{\nu}'_\ell + N'\pi\,.$$

Can generate false QE events when pions are not detected or are absorbed before emerging, or are an important tool to determine resonances axial weak constants, not obtained from electromagnetic interactions.

- At energies of the order of GeV, the dominant pion production mechanism is through the production and subsequent decay of hadronic resonances.

- The axial form factor (FF) for pion production on free nucleons depends on the old ANL (Argonne National Laboratory) and BNL (Brookhaven National Laboratory) bubble chamber data. These data sets differed in normalization by 30% to 40% for the main channel, creating uncertainties in the parameters predictions.

- A method was more recently presented to eliminate such uncertainties by taking ratios between rates from CC1π and CCQE events, in which normalization is cancelled $\rightarrow$ Eur. Phys. J. C 76, 474 (2016)

From the formal point of view

- Several works combine the simplest forms of the free and interaction Lagrangians for spin 3/2 resonances without respecting the contact invariance against transformations that change the spurious 1/2 component

- In addition to the contribution of resonances, we have a background that comes from crossed resonant terms and non-resonants ones involving nucleons Born and exchange of mesons.

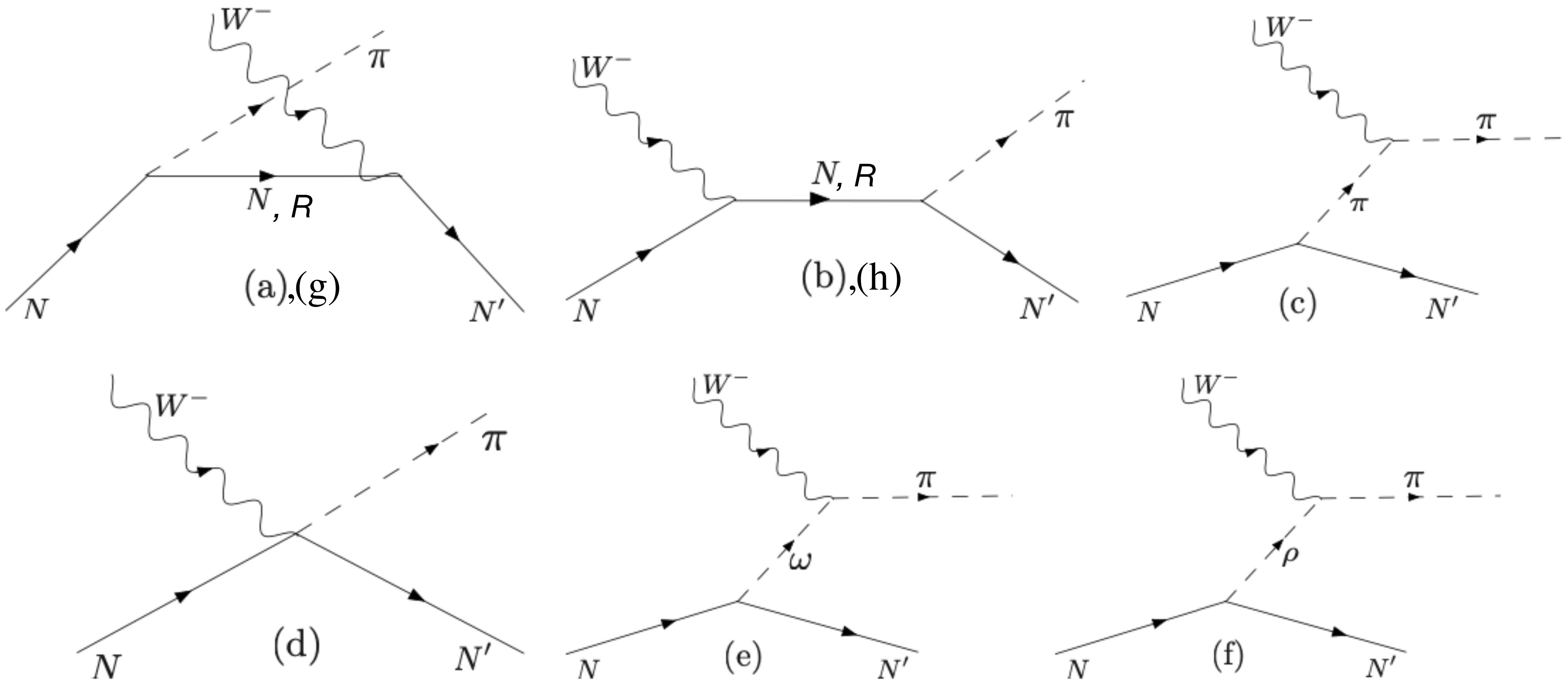
- Many works do not properly consider the interference between both (background + resonant) amplitudes.

- Other separate the production and decay mechanism of a resonance, but resonances are non-perturbative phenomena with poles in the amplitude of the matrix S and their propagation cannot be omitted.

Neutrino-Nucleon Scattering

- The total amplitude is constructed from the resonance plus the background terms, both interfering coherently

$$R = \Delta(1232), N^*(1440), N^*(1520), N^*(1535)$$



Resonance Properties

$\Delta(1232)\ 3/2^+$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Re(pole position) = 1209 to 1211 (≈ 1210) MeV
−2Im(pole position) = 98 to 102 (≈ 100) MeV
Breit-Wigner mass (mixed charges) = 1230 to 1234 (≈ 1232) MeV
Breit-Wigner full width (mixed charges) = 114 to 120 (≈ 117) MeV

Δ(1232) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	99.4 %	229
$N\gamma$	0.55–0.65 %	259
$N\gamma$, helicity=1/2	0.11–0.13 %	259
$N\gamma$, helicity=3/2	0.44–0.52 %	259

$N(1440)\ 1/2^+$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Re(pole position) = 1360 to 1385 (≈ 1370) MeV
−2Im(pole position) = 160 to 195 (≈ 180) MeV
Breit-Wigner mass = 1410 to 1450 (≈ 1430) MeV
Breit-Wigner full width = 250 to 450 (≈ 350) MeV

N(1440) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	55–75 %	391
$N\eta$	<1 %	†
$N\pi\pi$	25–50 %	338
$\Delta(1232)\pi$	20–30 %	135
$\Delta(1232)\pi$, P-wave	13–27 %	135
$N\sigma$	11–23 %	–
$p\gamma$, helicity=1/2	0.035–0.048 %	407
$n\gamma$, helicity=1/2	0.02–0.04 %	406

$N(1520)\ 3/2^-$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 were last included in our 1982 edition, Physics Letters **111B** 1 (1982). Some further obsolete results published before 1984 were last included in our 2006 edition, Journal of Physics (generic for all A,B,E,G) **G33** 1 (2006).

N(1520) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	55–65 %
Γ_2	$N\eta$	$(2.3\pm0.4)\times10^{-3}$
Γ_3	$N\pi\pi$	20–30 %
Γ_4	$\Delta\pi$	15–25 %
Γ_5	$\Delta(1232)\pi$, S-wave	10–20 %
Γ_6	$\Delta(1232)\pi$, D-wave	10–15 %
Γ_7	$N\rho$	15–25 %
Γ_8	$N\rho$, S=3/2, S-wave	(9.0±1.0) %
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<8 %
Γ_{10}	$p\gamma$	0.31–0.52 %
Γ_{11}	$p\gamma$, helicity=1/2	0.01–0.02 %
Γ_{12}	$p\gamma$, helicity=3/2	0.30–0.50 %
Γ_{13}	$n\gamma$	0.30–0.53 %
Γ_{14}	$n\gamma$, helicity=1/2	0.04–0.10 %
Γ_{15}	$n\gamma$, helicity=3/2	0.25–0.45 %

$N(1535)\ 1/2^-$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 were last included in our 1982 edition, Physics Letters **111B** 1 (1982). Some further obsolete results published before 1984 were last included in our 2006 edition, Journal of Physics (generic for all A,B,E,G) **G33** 1 (2006).

N(1535) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–55 %
Γ_2	$N\eta$	(42 ±10) %
Γ_3	$N\pi\pi$	1–10 %
Γ_4	$\Delta\pi$	<1 %
Γ_5	$\Delta(1232)\pi$, D-wave	0–4 %
Γ_6	$N\rho$	<4 %
Γ_7	$N\rho$, S=1/2, S-wave	(2.0± 1.0) %
Γ_8	$N\rho$, S=3/2, D-wave	(0.0± 1.0) %
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	(2 ± 1) %
Γ_{10}	$N(1440)\pi$	(8 ± 3) %
Γ_{11}	$p\gamma$	0.15–0.30 %
Γ_{12}	$p\gamma$, helicity=1/2	0.15–0.30 %
Γ_{13}	$n\gamma$	0.01–0.25 %
Γ_{14}	$n\gamma$, helicity=1/2	0.01–0.25 %

Effective Lagrangians

- The CC interaction is given by the weak Lagrangian

$$\mathscr{L}_{CC} = -\frac{g}{2\sqrt{2}}\left(J^{\mu}_{lCC} W_{\mu} + J^{\mu}_{hCC}\sqrt{2}(\tau \circ \mathbf{T}^{\dagger}) \cdot \mathbf{W}^{*} + \text{h.c} \right)$$

$$J^{\mu}_{lCC} = \sum_{l} \bar{\psi}_l \gamma^{\mu} (1-\gamma^5)\, \psi_{\nu_l}$$

$$J^{\mu}_{hCC} = \sum_{l} \bar{\psi}_h (V^{\mu} - A^{\mu})\, \psi_h$$

- To built the background contribution to hadronic current we

$$\mathcal{L}_{WNN}(x) = -\frac{g}{2\sqrt{2}}\bar{\psi}(x)\left[\gamma_{\mu}F_1^V(Q^2) - \frac{F_2^V(Q^2)}{2m_N}\sigma_{\mu\nu}\partial^{\nu} - F^A(Q^2)\gamma_{\mu}\gamma_5\right]\sqrt{2}\mathbf{W}^{\mu}(x)\cdot\frac{\boldsymbol{\tau}}{2}\psi(x) + \text{H.c.},$$

$$\mathcal{L}_{W\pi\pi}(x) = -\frac{g}{2\sqrt{2}}F_1^V(Q^2)\sqrt{2}[\boldsymbol{\phi}(x)\times\partial_{\mu}\boldsymbol{\phi}(x)]\cdot\mathbf{W}^{\mu}(x),$$

$$\mathcal{L}_{W\pi NN}(x) = -\frac{g}{2\sqrt{2}}\frac{f_{\pi NN}}{m_{\pi}}F_1^V(Q^2)\bar{\psi}(x)\gamma_5\gamma_{\mu}\sqrt{2}(\boldsymbol{\tau}\times\boldsymbol{\phi}(x))\cdot\mathbf{W}^{\mu}\psi(x),$$

$$\mathcal{L}_{W\pi\rho}(x) = \frac{g}{2\sqrt{2}}f_{\rho\pi A}F^A(Q^2)\sqrt{2}(\boldsymbol{\phi}(x)\times\boldsymbol{\rho}_{\mu}(x))\cdot\mathbf{W}(x)^{\mu}$$

$$\mathcal{L}_{W\pi\omega}(x) = -\frac{g}{2\sqrt{2}}\frac{g_{\omega\pi V}}{m_{\omega}}F_1^V(Q^2)\epsilon_{\mu\alpha\lambda\nu}(\partial^{\lambda}\boldsymbol{\phi}(x))\cdot(\partial^{\mu}\mathbf{W}^{\alpha}(x))\omega^{\nu}(x).$$

• while strong Lagrangian read

$$\mathcal{L}_{\pi NN}(x) = -\frac{g_{\pi NN}}{2m_N}\bar{\psi}(x)\gamma_5\gamma_\mu \boldsymbol{\tau}\cdot(\partial^\mu \boldsymbol{\phi}(x))\psi(x),$$

$$\mathcal{L}_{VNN}(x) = -\frac{g_V}{2}\bar{\psi}(x)\left[\gamma_\mu \left\{ \begin{array}{c} \boldsymbol{\rho}^\mu(x)\cdot\boldsymbol{\tau} \\ \omega^\mu(x) \end{array} \right\} - \frac{\kappa_V}{2m_N}\sigma_{\mu\nu}\left(\partial^\nu \left\{ \begin{array}{c} \boldsymbol{\rho}^\mu(x)\cdot\boldsymbol{\tau} \\ \omega^\mu(x) \end{array} \right\}\right)\right]\psi(x),$$

•and finally the propagators

$$\begin{aligned} S(p) &= \frac{\not{p}+m_N}{p^2-m^2}, \text{ nucleon} \\ \Delta(p) &= \frac{1}{p^2-m_\pi^2}, \text{ pion} \\ D_{\mu\nu}(p) &= \frac{-g_{\mu\nu}+\frac{p_\mu p_\nu}{m_V^2}}{p^2-m_V^2}, \text{ vector-meson} \end{aligned}$$

•For $R(s=1/2)$ we get from $\mathcal{L}_{\pi NN}$, $\mathcal{L}_{WNN}$ and $S(p)$ adding γ_5 (parity), and decay width in propagators trough $m \rightarrow m\text{-}i\Gamma_R/2$

• $R(s=3/2)$ are more complex since

$$\psi_\mu \sim A_\mu \otimes \psi$$

$$G(p,A)_{\mu\nu} = R^{-1}(A)_{\mu\alpha} G^{\alpha\beta}(p) R^{-1}(A)_{\beta\nu} \quad R^\rho_\sigma(a) = \delta^\rho_\sigma + a\gamma_\sigma\gamma^\rho \quad a = \left(\frac{1+3A}{2}\right)$$

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

• $\mathcal{L}_{free}$ invariant under contact transformation since change only 1/2 component

$$\psi'^\rho = R(a)^\rho_\sigma \psi^\sigma \qquad \psi^\nu_{3/2}\gamma_\nu = 0$$

• Then, any interaction should looks, to get A-independence (not respected in some works)

$$\mathcal{L}_{int}(A,Z) = g\bar{\Psi}_\mu R(\frac{1}{2}(2Z + (1+4Z)A))_{\mu\nu} F^\nu(\psi, \phi, W, \dots) + h.c.,$$

$$R(A)_{\alpha\mu} R^{-1}(1/2(1-6Z/(1+4Z))^\mu_\beta$$

• Free parameters Z are set such that in the interaction Lagrange multiplier field Ψ_0 does not acquire dynamics ($\partial\ \Psi_0$ absent).

• Once eliminated the dependence on A and fixed Z,Z' we have for the strong and weak interactions for $R = \Delta$

$$\mathcal{L}_{I_1} \equiv \mathcal{L}_{\Delta\pi N}(x) = \frac{f_{\Delta\pi N}}{m_\pi}\bar{\psi}\partial\boldsymbol{\Phi}(x)^{\mu*}\cdot\boldsymbol{T}\Psi_\mu(x) + \frac{f_{\Delta\pi N}}{m_\pi}\bar{\Psi}_\mu(x)\bar{\psi}\partial\boldsymbol{\Phi}^\mu(x)\cdot\boldsymbol{T}^\dagger\psi(x)$$

$$\hat{\mathcal{L}}_{WN\Delta}(x) = \bar{\Psi}^\mu(x)(\hat{W}_\mu^V + \hat{W}_\mu^A)(\mathbf{T}^\dagger\cdot\mathbf{W}^*)\psi(x) + \text{h.c}$$

within the Sachs($G_{M,E}$) parametrization in the vector sector

$$\hat{W}^V_{\mu\nu}(p_\Delta,q,p) = \sqrt{2}[(G_M(Q^2) - G_E(Q^2))K^M_{\nu\mu} + G_E(Q^2)K^E_{\nu\mu} + G_C(Q^2)K^C_{\nu\mu}]\Delta^*\boldsymbol{W}^*\cdot\boldsymbol{T}^\dagger\psi$$

$$\hat{W}^A_{\nu\mu}(p_\Delta,q,p) = -i\left[-D_1(Q^2)g_{\nu\mu} + \frac{D_2(Q^2)}{m_N^2}(p+p_\Delta)^\alpha(g_{\nu\mu}q_\alpha - q_\nu g_{\alpha\nu}) - \frac{D_3(Q^2)}{m_N^2}p_\nu q_\mu + i\frac{D_4(Q^2)}{m_N^2}\varepsilon_{\mu\nu\alpha\beta}(p+p_\Delta)^\alpha q^\beta\gamma_5\right]\Delta^*\boldsymbol{W}^*\boldsymbol{T}^\dagger\psi,$$

•If $R = N^*(1520)$ $\psi_\nu \to \gamma_5 \psi_\nu$ for the parity change and usually many works adopt *Normal Parity*$(C_{i=3,4,5,6})$ parametrization

$$\Gamma^V_{\nu\mu}(p_{D_{13}}, q) = \left[-\frac{C_3^V(Q^2)}{m_N} H_{3\nu\mu} - \frac{C_4^V(Q^2)}{m_N^2} H_{4\nu\mu} - \frac{C_5^V(Q^2)}{m_N^2} H_{5\nu\mu} + \frac{C_6^V(Q^2)}{m_N^2} H_{6\nu\mu} \right]$$

For consistency and since both parametrization are not equivalent nor have same behavior, we make the connection of $Q^2=0$ *FF*

$$C_3^V(Q^2) = \frac{m_{D_{13}}}{m_N} R_M \left[G_M(0) - G_E(0) \right] F^V(Q^2)$$

$$C_4^V(Q^2) = -R_M \left[G_M(0) - \frac{3m_{D_{13}}}{m_{D_{13}} - m_N} G_E(0) \right] F^V(Q^2)$$

$$C_5^V(Q^2) = 0$$

$$C_6^V(Q^2) = -R_M \frac{2m_{D_{13}}}{m_{D_{13}} - m_N} G_E(0) F^V(Q^2),$$

$$R_M = \frac{3}{2} \frac{m_N}{m_{D_{13}} + m_N}$$

Before those who knows these formal topics jump in their chairs demanding!!!

• We are well aware of the use of the ``spin 3/2´´gauge invariante 2nd order $\pi N\Delta$ interaction obtained making $\Psi_\mu \to \Psi_\mu - g_2(\partial_\mu\phi)\psi$ in $\mathcal{L}_{free}(m_\Delta = 0)$

$$\mathcal{L}_{I_2} = -g_2\, \bar{\Psi}\partial_\mu \boldsymbol{\phi}^\dagger \cdot \mathbf{T}\epsilon^{\mu\nu\rho\beta}\gamma_\beta\gamma_5\partial_\rho\Psi_\nu + h.c.$$

which decouples de spin 1/2 in the propagator, is Z independent, but with problems as I_1 (appearance of negative indefinite norm states when field quantization is achieved). Also 2nd order contribution of the Sachs parametrization also comes from $\gamma_\nu\Psi_\mu \to \gamma_\nu\Psi_\mu + i\gamma_5\partial_\nu W^\gamma_\mu$

• When $\Psi_\mu \to \Psi_\mu - g_2(\partial_\mu\phi)\psi$ is done we get $\mathcal{L}_{\text{free}} + \mathcal{L}_{I_1} \to \mathcal{L}_{\text{free}} + \mathcal{L}_{I_2}(g_2 = -\frac{g_1}{m}) + \mathcal{L}_C(\frac{g_1^2}{m^2})$ and I_1 is shifted (or put under the rug), and absorbed within a contact term in the background.

• Another point of view is, as $\gamma_\mu G^{\mu\nu}$ and $G^{\mu\nu}\gamma_\nu$ do not contain pole-contributions, the Z,Z´ dependent terms are again shifted to contact background πN ones, with couplings constants to be fitted. This is referred as looking LEC's of CHPT.

• We will analyze the observables:

$$\sigma(E_\nu^{\rm CM}) = \frac{m_\nu m_N^2}{(2\pi)^4 E_\nu^{\rm CM}\sqrt{s}} \int_{E_\mu^-}^{E_\mu^+} dE_\mu^{\rm CM} \int_{E_\mu^-}^{E_\mu^+} dE_\pi^{\rm CM} \int_{-1}^{+} d\cos\theta \int_0^{2\pi} d\eta \frac{1}{16} \sum_{\rm spin} |\mathscr{M}|^2$$

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

$$\frac{d\langle\sigma\rangle}{dQ^2} = \frac{\int_{E_\nu^{min}}^{E_\nu^{max}} \frac{d\sigma(E_\nu)}{dQ^2}\phi(E_\nu)dE_\nu}{\int_{E_\nu^{min}}^{E_\nu^{max}} \phi(E_\nu)dE_\nu}$$

$$\frac{d\sigma}{dQ^2} = \frac{m_\mu m_N^2}{2(2\pi)^4 (E_\nu^{\rm CM})^2\sqrt{s}} \int_{E_\mu^-}^{E_\mu^+} \frac{dE_\mu^{\rm CM}}{\sqrt{(E_\mu^{\rm CM}) - m_\mu^2}} \int_{E_\pi^-}^{E_\pi^+} dE_\pi^{\rm CM} \int_0^{2\pi} d\eta \frac{1}{16} \sum_{\rm spin} |\mathscr{M}|^2$$

Width and Gauge invariance

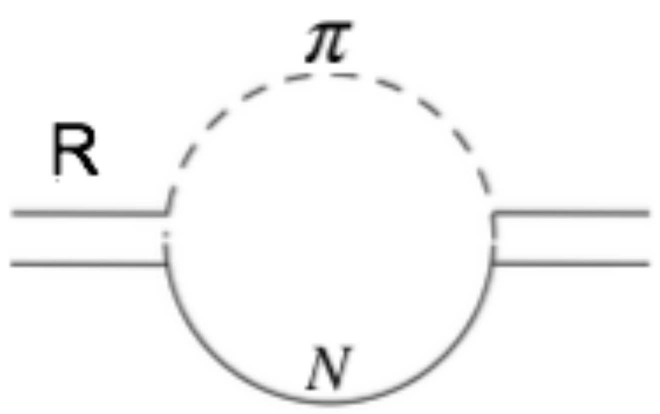
How to give width without violating electromagnetic Gauge Invariance?

- For all R (If $R(1/2)$ $G_{\mu\nu}(p) \rightarrow S(p)$) y $\Gamma_{\alpha\nu\rho} \rightarrow \Gamma_{\alpha}$) Ward's identity must be satisfied

$$i(p-p')_{\alpha}G_{\mu\nu}(p')\Gamma_{\alpha\nu\rho}G^{\rho\sigma}(p) = G^{\sigma}_{\mu}(p) - G^{\sigma}_{\mu}(p')$$

- The propagators are obtained solving $(iG^{-1})^{\mu\nu}(p) = (iG_0^{-1})^{\mu\nu}(p) - \Sigma^{\mu\nu}(p)$ (S. Dyson)

Where the main contribution is $\sum =$



• G_R structure is changed (Exact propagator), only if $s^{1/2} \in (m_R - \Gamma_R,\ m_R + \Gamma_R)$

$$G_R, S_R = G_R^0\,, S_R^0\,(m^0 \rightarrow m - i\Gamma(s)/2)$$

$$\Gamma_R(s) \times B_r = \frac{3\left(\frac{f_{\pi NR}}{m_\pi}\right)^2}{4\pi}\left(\frac{(\sqrt{s}-\pi m_N)^2 - m_\pi^2}{48 s^{5/2}}\right)\lambda^{\frac{3}{2}}(s, m_N^2, m_\pi^2)$$

$$\Gamma_R(s) \times B_r = \frac{3}{4\pi}\left(\frac{f_{\pi NR}}{m_\pi}\right)^2 (m_R + \pi m_N)^2 \left(\frac{(\sqrt{s}-\pi m_N)^2 - m_\pi^2}{4 s^{3/2}}\right)\lambda^{\frac{1}{2}}(s, m_N^2, m_\pi^2)$$

• If we adopt energy dependent width $\Gamma(s)$ or we make $m^0 \rightarrow m - i\Gamma_{exp}/2$ only in e $1/(p^2 - m_R^2)$ Ward identity is violated at order Γ/m_R (at less you introduce vertex corrections)

• Assuming $\Gamma \approx \Gamma_{CMS} = constant$ (fitted) in the full propagator it is possible factorize $(1 + i\Gamma_{CMS}/m_R)$ when we make $m^0 \rightarrow m - i\Gamma_{CMS}/2$, keeping the Ward identity.

Form factors

¿How to take into account the structure of the hadrons involved?

- Amplitudes come from effective Lagrangians where hadrons are treated as elementary particles.

- Strong interaction vertices do not consider particles with structure but points. Description would be appropriate for a certain energy range, but will certainly losesw its validity for higher energies, requiring FF that account particle sizes.

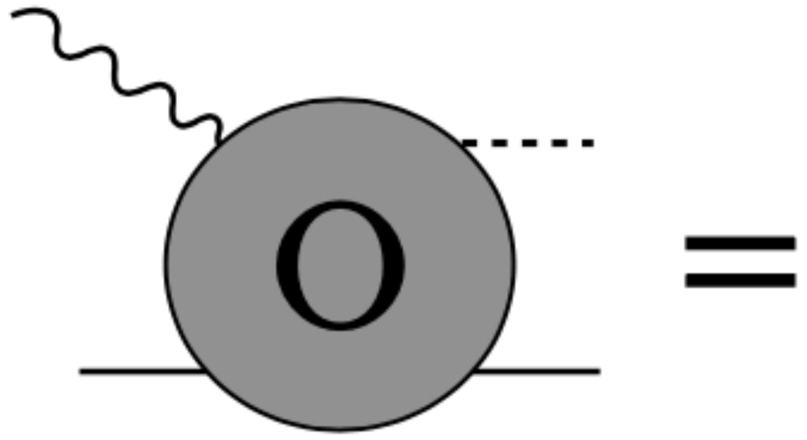
- Such FF could simulate the inclusion of more energetic resonances not explicitly included in the model.

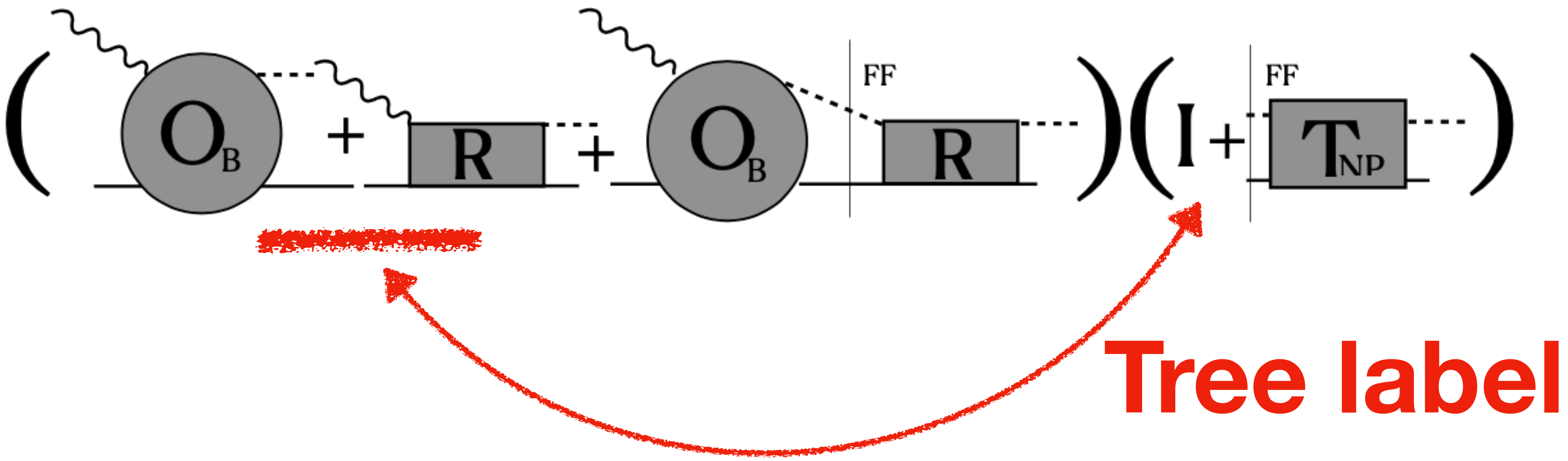
- Weak vertices already have FF.

- The hadronic amplitude looks like

$$\mathscr{M}_h^\lambda \equiv \bar{u}\phi^* O^\lambda u$$

where schematically





- S_R, G_R are dressed by the πN loop (Γ_R)
- T_{NP} introduces rescattering

- The intermediate momenta integrals are normally divergent, to regularize them, FF must be included in $O_{B,R}$

- The *non-pole* (T_{NP}) iterates to all orders the πN potential that encloses Born, Meson exchange and Crossed(u) resonance terms.

- FF introduce deviations from point couplings due to the quark structure in the nucleons and resonances, play the same role as the electromagnetic FF, which reflect the extension of hadrons, and must be calculated from the underlying theory or from the quarks.

- Different individual FF at each vertex of a graph would require vertex corrections to satisfy electromagnetic gauge invariance in radiative processes.

- Guided by previous calculations in πN scattering, pion photoproduction, and the description of the NC1π data obtained by the CERN Gargamelle experiment without applying cuts in the neutrino energies, where $(O_B^\lambda + O_R^\lambda)$ is multiplied by a global regularizing FF at the vertices $RN\pi$ y $NN'\pi$

$$F(k, W_{\pi N}) = \frac{(\Lambda_{\text{eff}})^2}{(\Lambda_{\text{eff}})^2 + k(W_{\pi N})^2}, \Lambda_{\text{eff}} = \Lambda \frac{\Lambda}{W_{\pi N} - W_{\pi N}^{th}}.$$

- This monopolar FF that takes into account the hadronic structure, with a decreasing effective cut with $W_{\pi N} - W_{\pi N}^{th}$, making that certain term of the amplitude πN "disappears" or contributes less when $W_{\pi N}$ grows because other resonances, not considered, could be excited.

Results

Channels to describe

$$\nu p \to \mu^- p \pi^+ \,,$$
$$\nu n \to \mu^- n \pi^+ \,,$$
$$\nu n \to \mu^- n \pi^0$$

$$\bar{\nu} n \to \mu^+ n \pi^-,$$
$$\bar{\nu} n \to \mu^+ N \pi^+$$

We will discuss formal aspects and compare the results of our model for $\sigma(E_\nu)$ and $d\sigma/dQ^2$ and with the reanalyzed experimental data from ANL, BNL.

A previous comment regards other calculations

- In the free RS Lagrangian of RS, $\dot{\Psi}_0$ does not appear, so the equation of motion for Ψ_0 it is a restriction, and has no dynamics. It is then necessary that the interactions do not change this, and it is true for $Z = 1/2$ and A=-1(simplest form of G) in

$$\mathcal{L}_{\text{int}}(A,Z) = g_{\text{int}}\bar{\Psi}^{\mu}R\left(\frac{1}{2}(2Z+(1+4Z)A)\right)_{\mu\nu}F^{\nu}(\psi,\phi,W,\ldots)+\text{H.c.}$$

- Some authors adopting A=-1 try to get the simplest vertices and we read it in two ways: i)doing $Z+\dfrac{1}{2}(1+4Z)A = 0$→Z=-1/2.This value keeps Ψ_0 dynamics. ii)Z=1/2 is adopted $Z+\dfrac{1}{2}(1+4Z)A = 0$→A=-1/3 inconsistent with A=-1 → amplitude with A dependence.

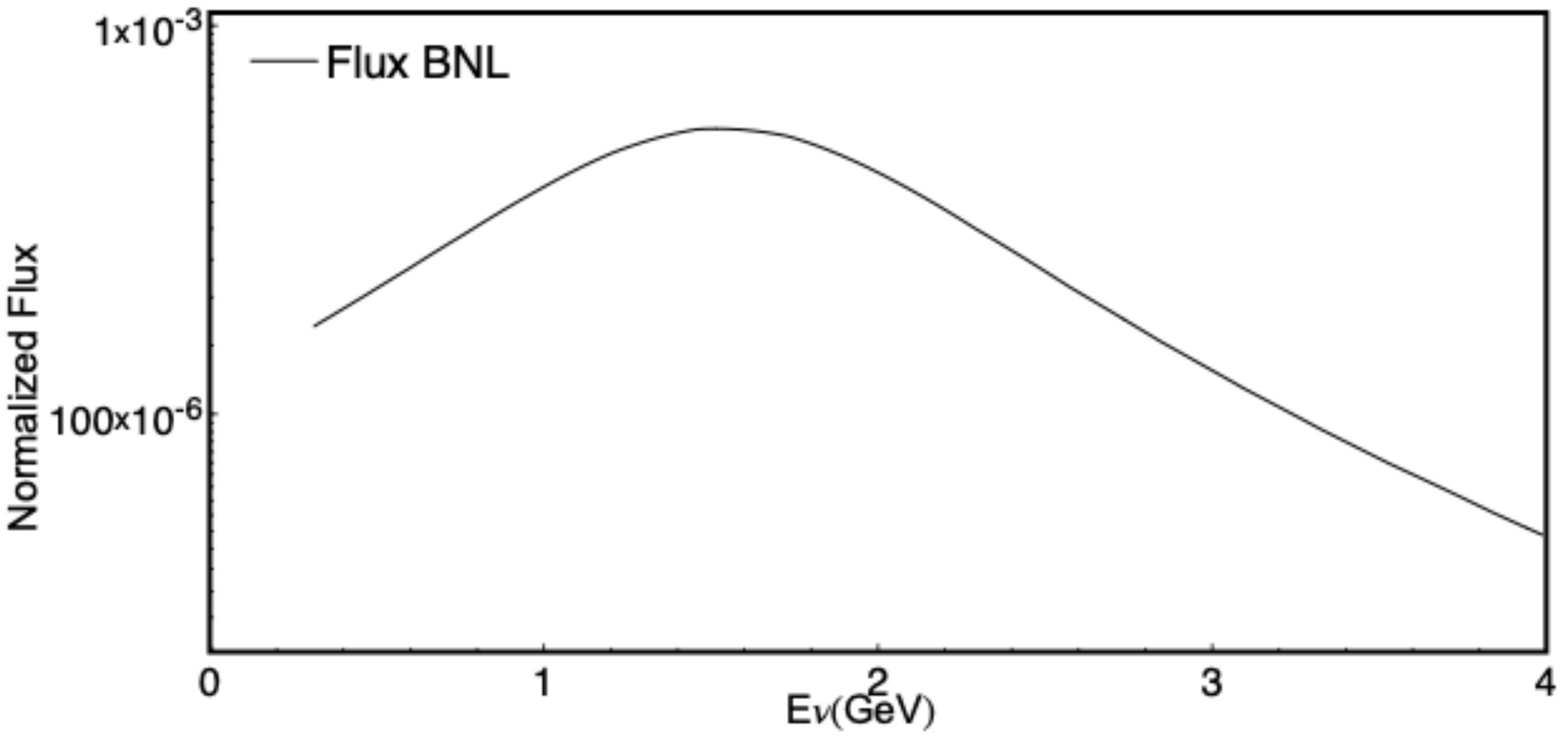
- Results presented without regarding these formal (annoying) issues are only qualified by their proximity to the experimental data.

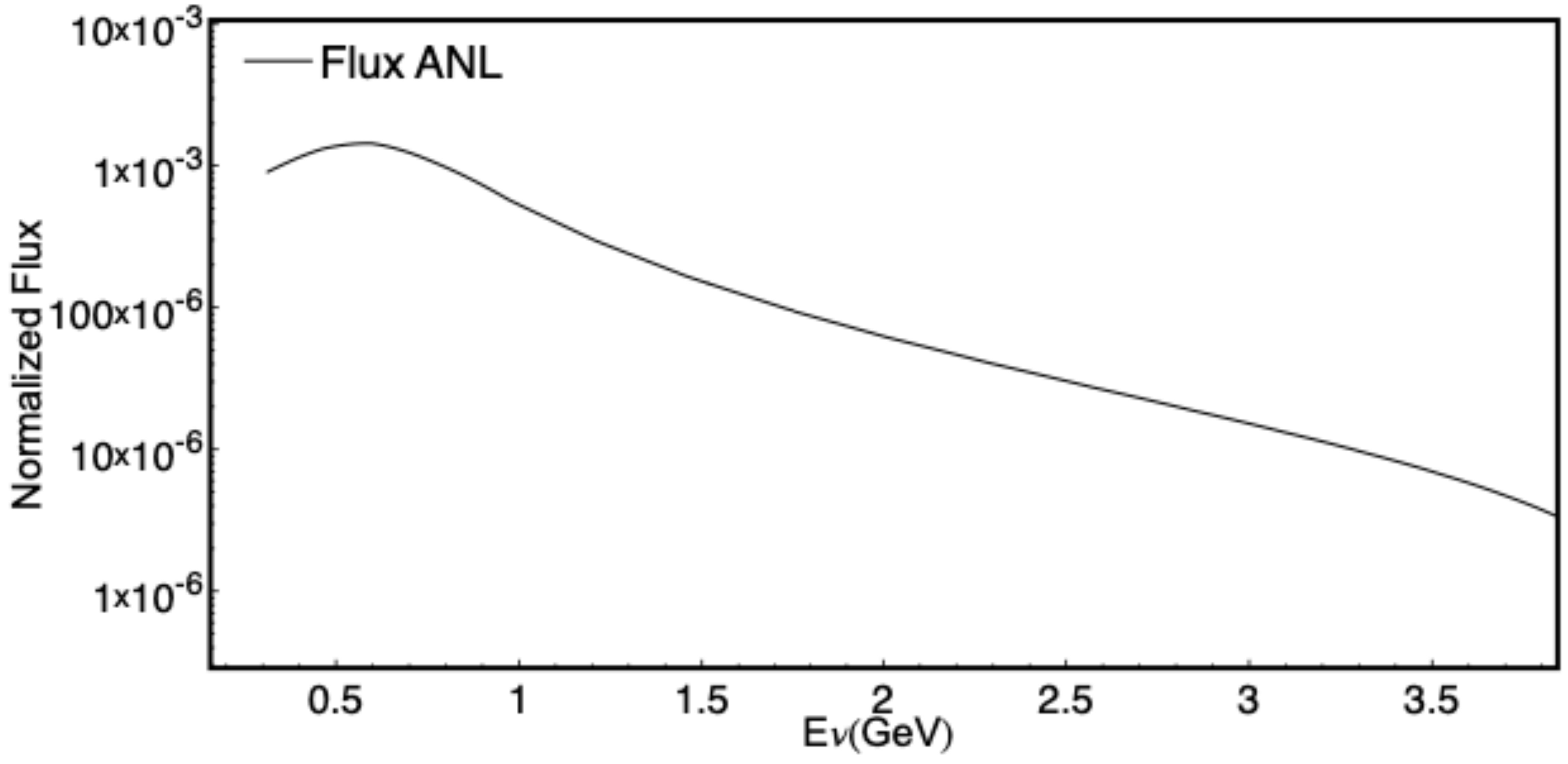
- To avoid model dependencies by introducing FF at each interaction vertex (violates gauge invariance without vertex corrections), we will introduce a global FF on the amplitude. Since we consider resonances up to $M_{\pi N} \sim 1.6\,\mathrm{GeV}$, taking into account the width of the most energetic one $N^*(1535)$, we will turn on this FF above its invariant mass. We will adopt $\Lambda = 600$ MeV as done previously in NC1π

$$F(k) = \frac{\Lambda^4}{\Lambda^4 + k^2(M_{\pi N} - M_{\pi N}^{th})^2 \theta(M_{\pi N} - 1.6\ \mathrm{GeV})}$$

- This FF is expected to effectively correct the behavior of the distribution $d\sigma/dM_{\pi N}$ at higher values of $M_{\pi N}$, as successfully done in pion photoproduction where was a regularization to include final state interactions.

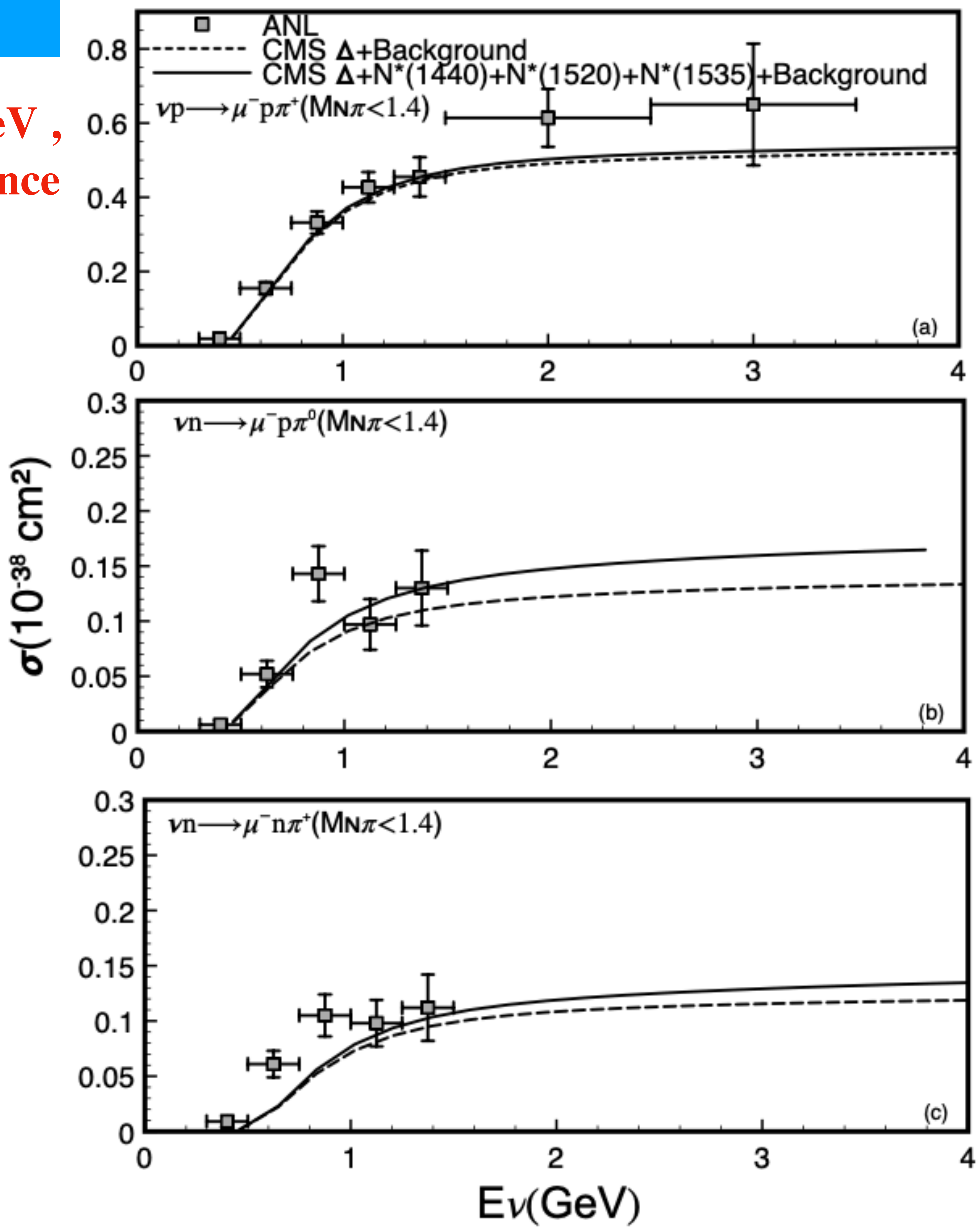
Neutrino fluxes $\phi(E_\nu)$





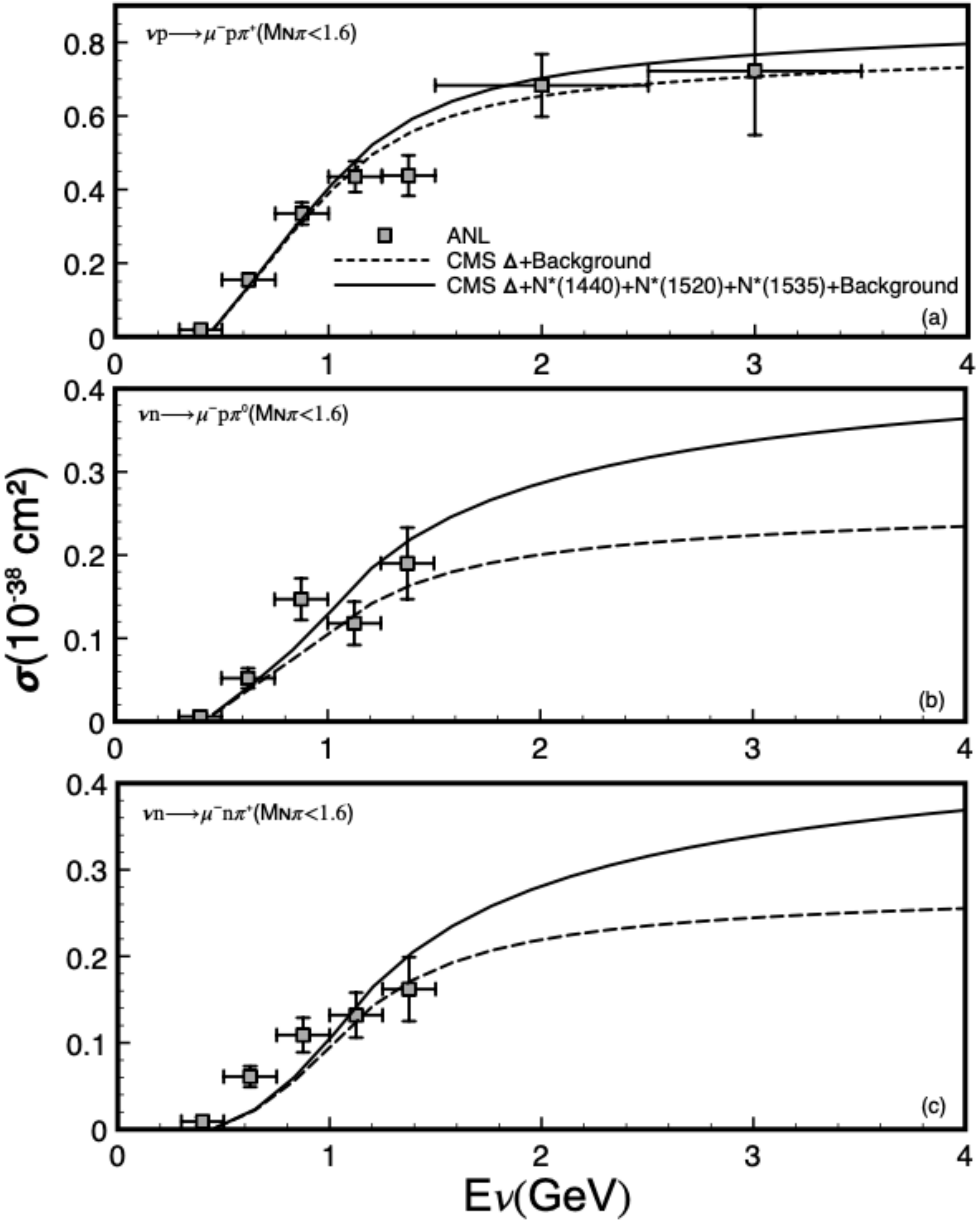
Total cross sections

Results with $M_{\pi N} < 1.4$ GeV , Δ and Δ plus 2nd resonance region (old ANL data)



- We use CMS approach previously implemented to get, strong and weak parameters for the Δ, with $M_{\pi N} < 1.4$ GeV.
- The effect of adding 2nd resonance region depends on the channel, for $E_\nu = 3.0, 1.5, 1.5$ GeV we get a 4%, 17% and 10% of contribution respectively.

Idem with $M_{\pi N} < 1.6$



- As expected, contribution of 2nd region resonances is more important and necessary to improve the agreement with the data.

- Although in first channel the difference is small, the improvement is clear for the last two ones where background-resonance interference is most important.

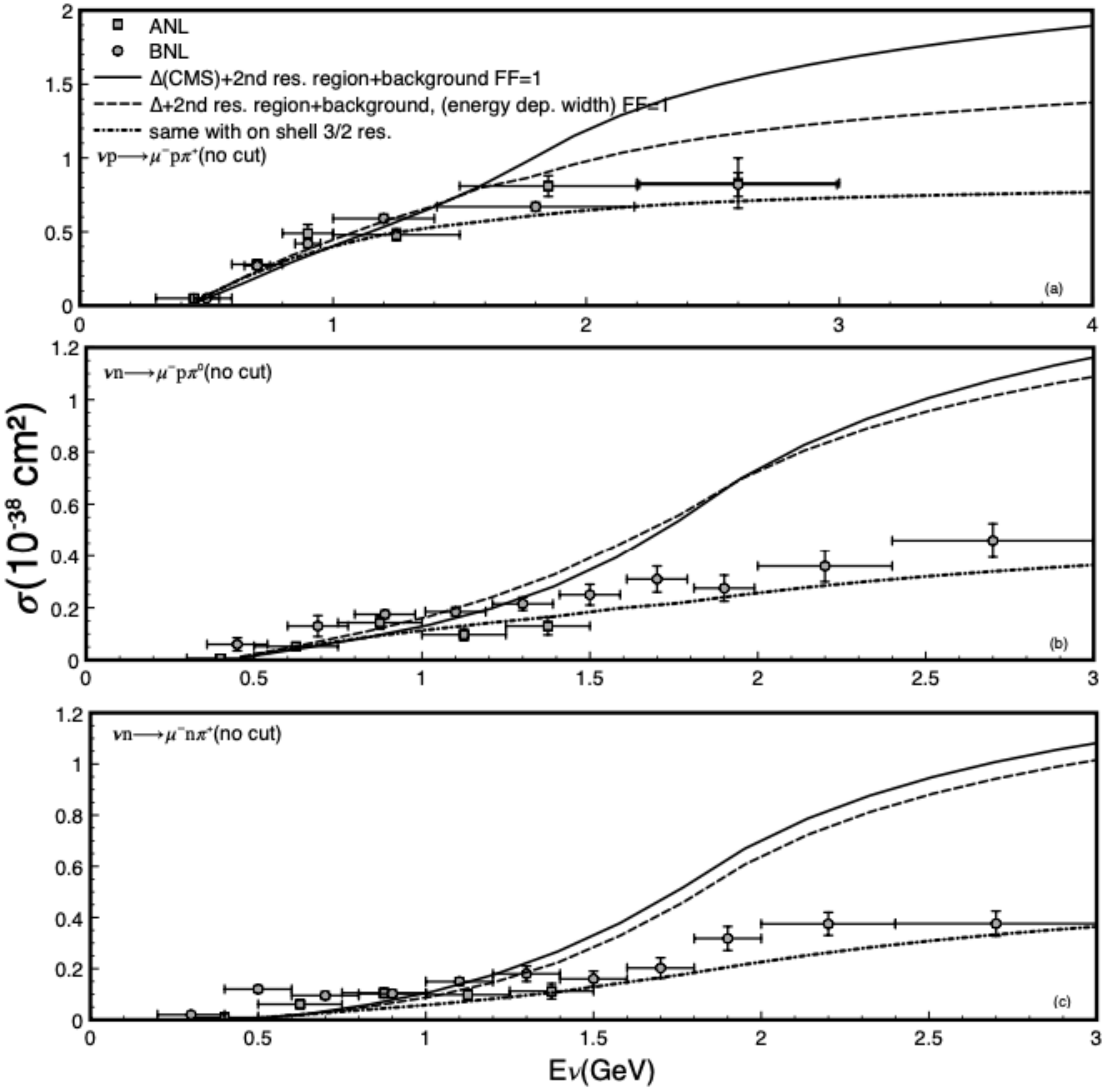
A pause to take a breath and summarize

- Until this moment we stayed within the CMS approach, the simplest to treat consistently all resonances, and backgrounds are added coherently. However, the data also includes uncut ($M_{\pi N} < 2.0$ GeV) results → We need to extend the model to higher energies.

- Before moving on calculations without cutting, we will first analyze the behavior of the total cross section without adding any FF.

- We increase the cut both, within the CMS or introducing energy dependency on the widths, which violates gauge invariance without vertex corrections.

Results with $M_{\pi N} < 2.0$ GeV



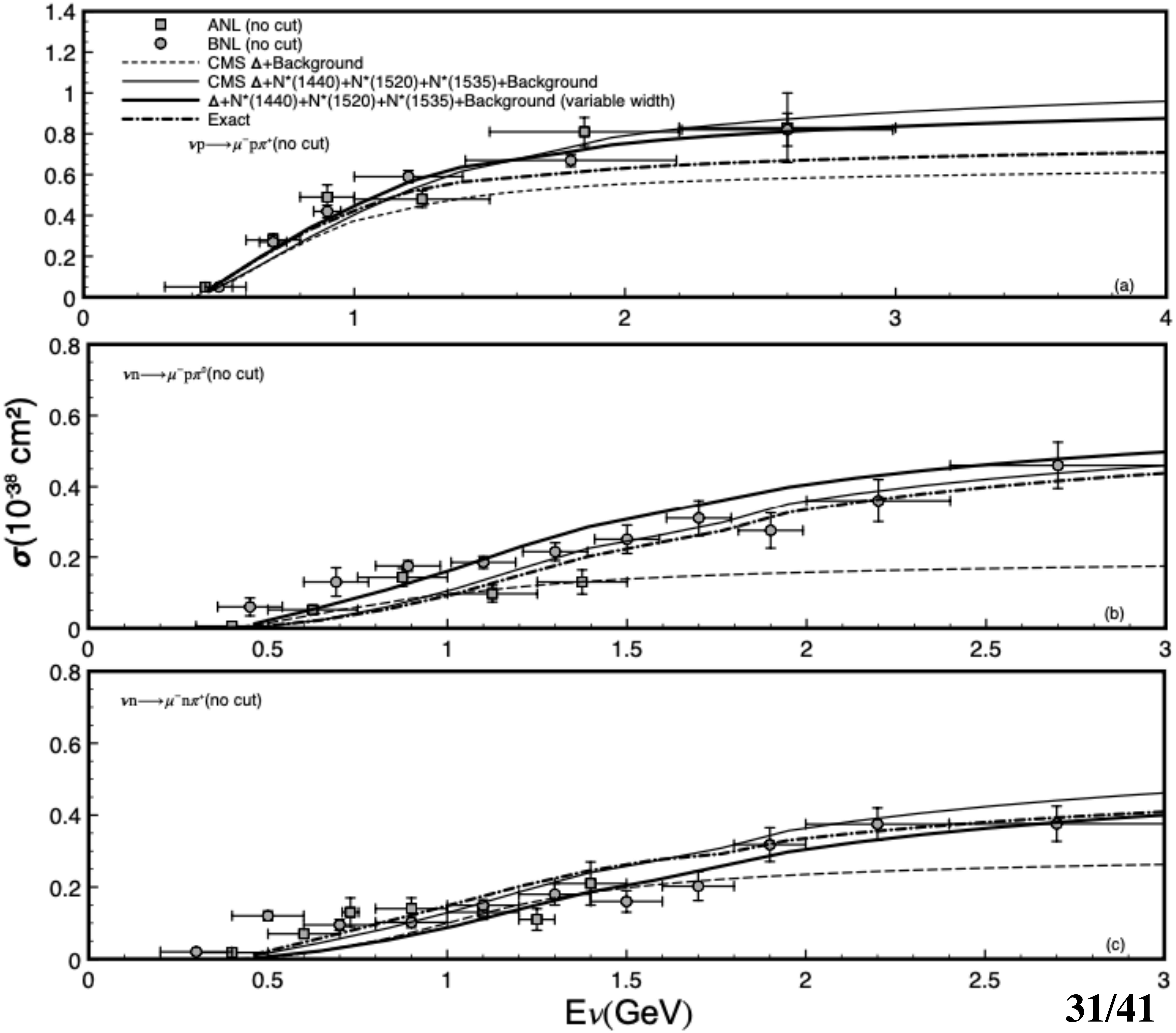
- The R-cross terms grow and should be affected by rescattering.
- Using different A values for 3/2 propagators and vertexes, results are undervalued.
- Due to what was discussed before, we include a global FF:
  $O_R + O_B \rightarrow (O_R + O_B) \times \mathrm{FF}$

$$F(k) = \frac{\Lambda^4}{\Lambda^4 + k^2 (M_{\pi N} - M_{\pi N}^{th})^2 \theta(M_{\pi N} - 1.6\ \mathrm{GeV})}$$

Comparison with reanalyzed ANL and BNL

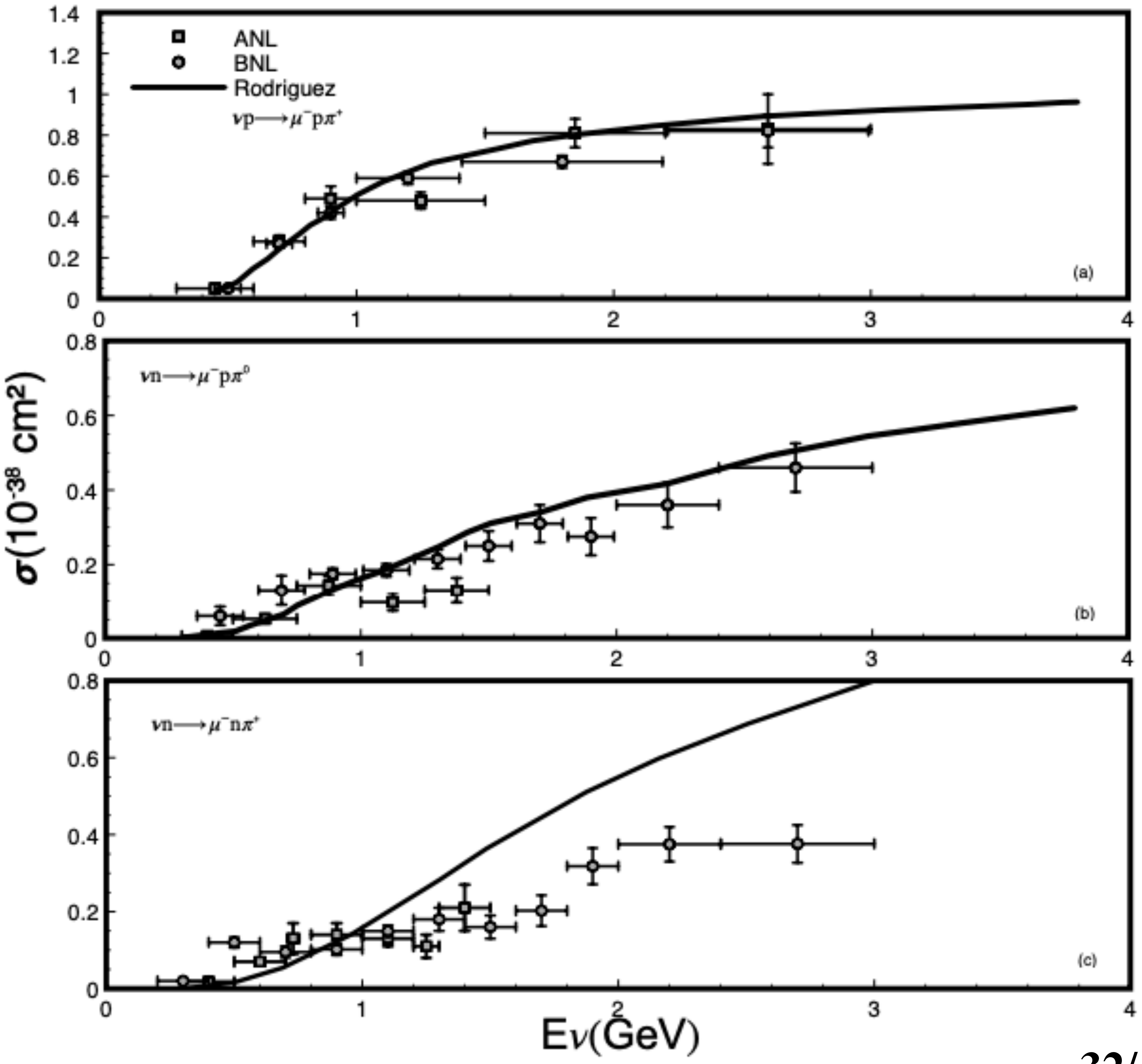
- The increase in the cross section due additional resonances is persistent and the best working approach is CMS as before . We will use χ^2/dof in spite we are not fitting anything.

- We have also shown results with variable widths, which are not consistent without vertex corrections, since there are works with this approach. Also we show results with the exact propagator, which has a more complex structure and one should consistently include the rescattering in the total amplitude.

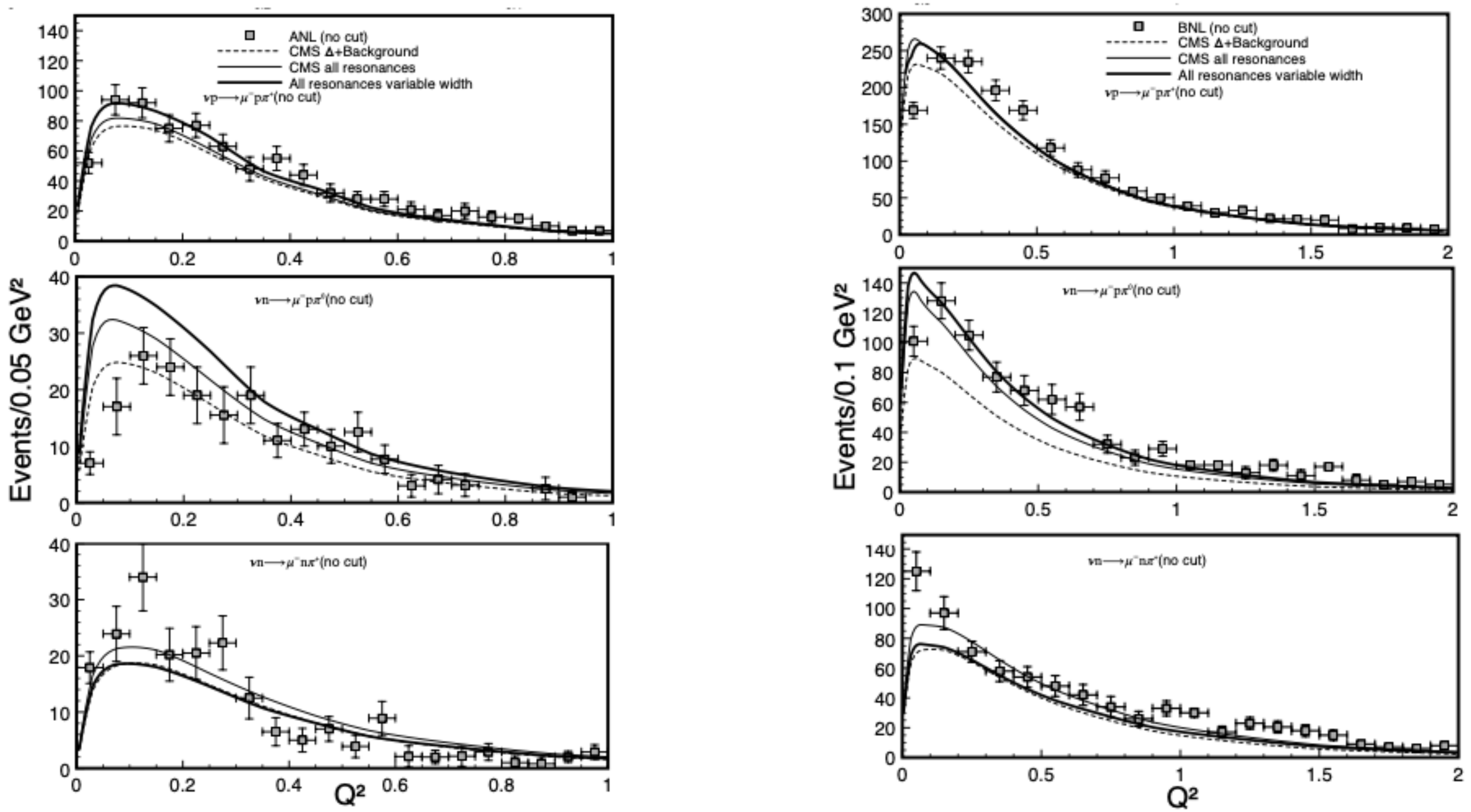


- For comparison, we show the result by GENIE, where seems to be problems in describing well all the channels for the same reanalyzed data sets.

- We can verify that for the total cross sections in the three channels we obtain for χ^2/dof in ANL 0.4(1.13), 1.1(0.34), 1.0(2.6) and BNL 0.6(1.9), 0.7(0.8), 0.8(5.2) results within the CMS (GENIE) models.



Flux averaged differential cross sections



- We show the CMS approximation calculations, and omit the exact one since we should readjust the parameters of the Δ , while for the energy-dependent width, it should not be crucial since we maintain the same structure of the CMS propagator but only replacing the width in the singular terms.

- The results within the CMS are acceptable in all three channels, considering we are not making any adjustments.

- The use of the energy-dependent width increases the theoretical results of the first and second channels and decreases those of the third, this leads to a worse agreement with data depending on the experiment considered ANL or BNL.

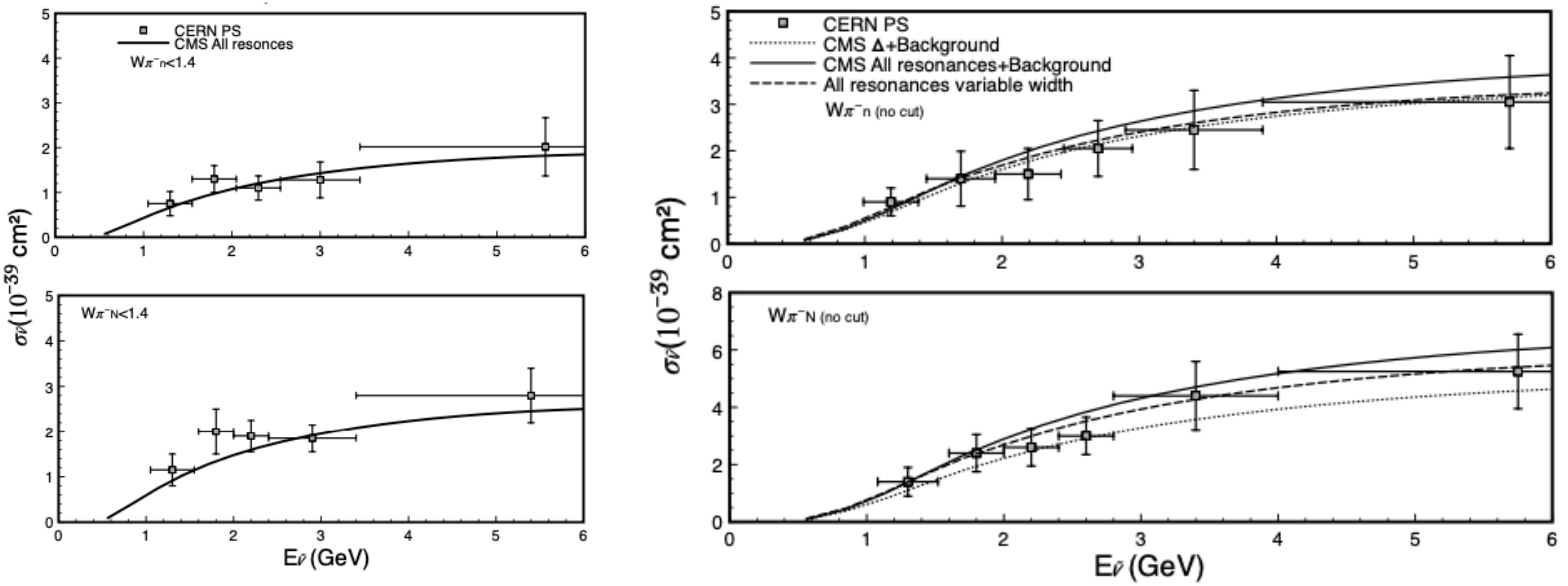
- If we compare with the GENIE results, as before, we obtain a better overall reproduction of the data.

Antineutrinos

- The interactions of neutrinos with hadrons are not the same as those of antineutrinos. We have a sign of difference in the contraction of the lepton currents that makes a different coupling with the hadronic ones. In the experiment we have the detector of a mixture of heavy freon CF_3Br that was exposed to the CERN PS antineutrino beam (with a peak at $E_{\bar{\nu}} \sim 1.5$ GeV GeV). It is reported that we have $0.44\,\%$ neutrons and $0.55\,\%$ protons, and since our calculations were for free nucleons we weighted the results with these percentages depending on the channel.

- First, we only show results within the CMS approach with all resonances.

- Second, we show results without cuts and with the global FF.



- For the $W_{\pi N} \equiv M_{\pi N} = 1.4$ GeV cut, we can see that the data is reproduced but just below the center of the error bars. In the second figure we show the CMS with only Δ the and the $\Delta +$ other resonancias, where we see an appreciable difference. By adding the energy-dependent width, we obtain an improvement, but at the expense of a violation of electromagnetic gauge invariance as it is known.

Conclusions

- Throughout this work we have addressed the description of the weak production of pions, within consistent effective models from the point of view of the treatment of spin 3/2 resonances. Additionally, we have discussed how to include resonances in the second region and how to treat the hadron structure as energy grows. We also include indirectly, the effect of more energetic resonances not considered in the model. We have described total(differential) neutrino and antineutrino scattering cross sections.

- We used the complex mass scheme (CMS) that corresponds to the replacement $m_R \rightarrow m_R - i\frac{\Gamma_R^{\text{CMS}}}{2}$ (with m_R, Γ_R constants) in the full unperturbed propagator, which allows us to comply with the Ward identities that relate propagators and vertices for the radiation of a resonance, and maintain gauge invariance. Finally, use the exact structure of the propagator for the 3/2 resonances, however, in this case a readjustment of the parameters must be made, since the background should also be treated exactly .

- It is important to note that for the first time the Sachs parameterization was used for the D_{13} resonance, where the values of $G_E(Q^2 = 0), G_M(Q^2 = 0), C_A^5(Q^2 = 0)$ were obtained by comparison with those usually adopted values for the Parity Conserving parameterization.

- For results without cuttings a global FF was necessary, adopting the same used successfully in pion photoproduction and NC1π production, taking into account the hadronic structure of the final pair and redispersion (in a troglodyte way) into more energetic resonances.

- Also, results for the average flow cross section $< d\sigma/dQ^2 >$ and the total cross section for antineutrinos were made.

- It should be noted that we have not made adjustments to "any" parameters, as they were taken from previous works, in order to be consistent.

- Regarding the quality of our results, seems that consistency leads to better results than other equivalent but inconsistent models of Literature.

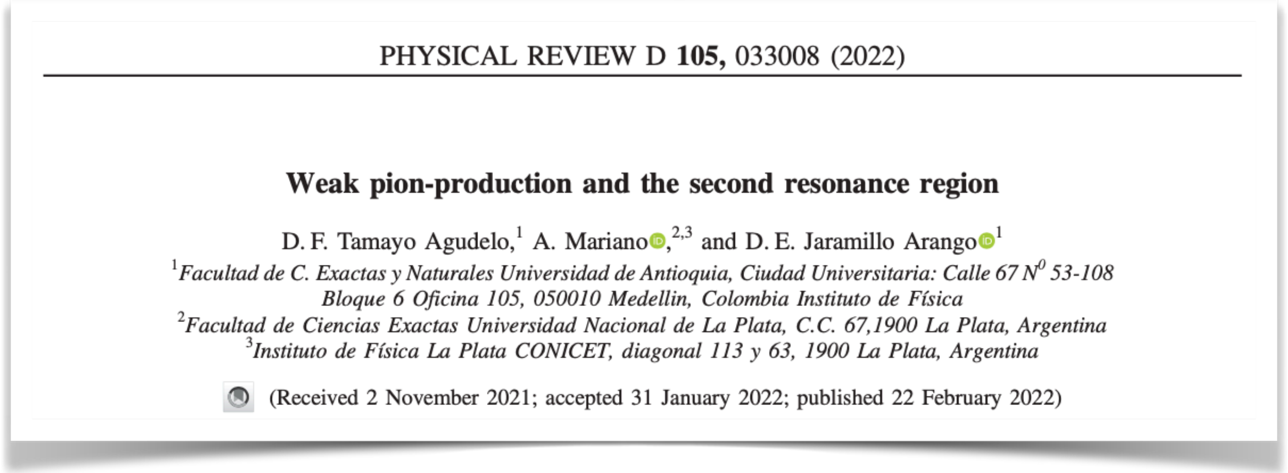
- In GENIE, pion production is separated into resonant and non-resonant terms, and the interference terms between them, as well as the interferences between resonances, are neglected. As consequence is not possible to describe togheter all the channels. The data for channels $\nu n \to \mu^- n\pi^+, \nu n \to \mu^- n\pi^0$ are very similar, but there are large differences between GENIE's nominal predictions for them.

Shortcomings of the model and perspective

- Recall that the axial $C_A^5(0)$ was set to $M_{\pi N} < 1.4$ GeV data with only the Δ resonance included. Perhaps a new adjustment would be necessary that included the other resonances. When $M_{\pi N}$ is expanded, new resonances can be added gradually and the corresponding axial parameters would be adjusted as was done for Δ.

- Rescattering and unitarity must be introduced by a formalism of T-matrix an partial waves expansion, that is not a trivial task.

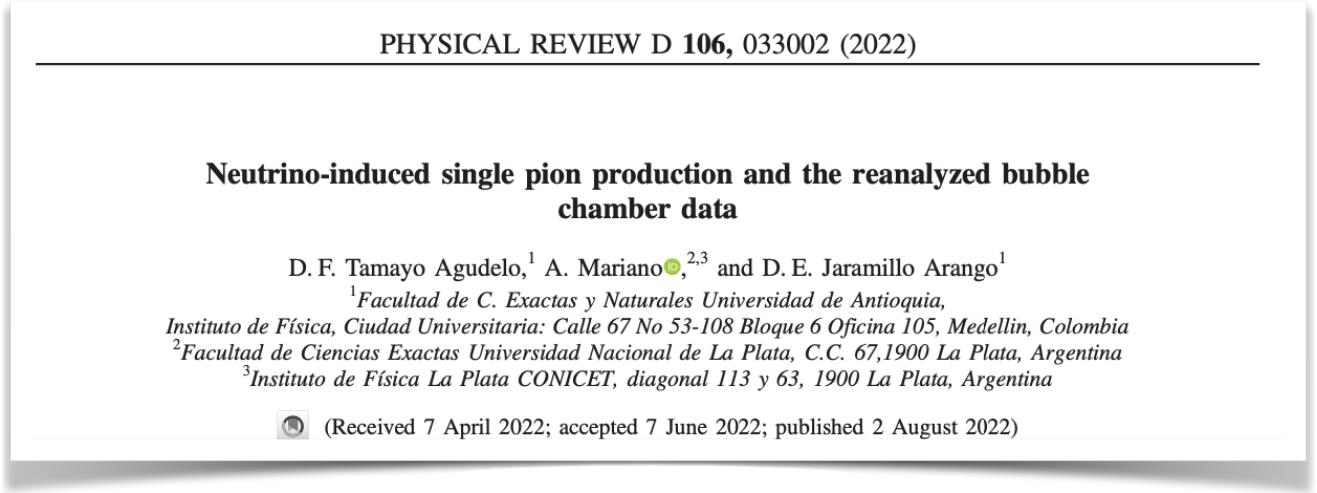
- More details in


PHYSICAL REVIEW D **105,** 033008 (2022)

Weak pion-production and the second resonance region

D. F. Tamayo Agudelo,[1] A. Mariano,[2,3] and D. E. Jaramillo Arango[1]
[1]*Facultad de C. Exactas y Naturales Universidad de Antioquia, Ciudad Universitaria: Calle 67 N⁰ 53-108 Bloque 6 Oficina 105, 050010 Medellin, Colombia Instituto de Física*
[2]*Facultad de Ciencias Exactas Universidad Nacional de La Plata, C.C. 67,1900 La Plata, Argentina*
[3]*Instituto de Física La Plata CONICET, diagonal 113 y 63, 1900 La Plata, Argentina*

(Received 2 November 2021; accepted 31 January 2022; published 22 February 2022)


PHYSICAL REVIEW D **106,** 033002 (2022)

Neutrino-induced single pion production and the reanalyzed bubble chamber data

D. F. Tamayo Agudelo,[1] A. Mariano,[2,3] and D. E. Jaramillo Arango[1]
[1]*Facultad de C. Exactas y Naturales Universidad de Antioquia, Instituto de Física, Ciudad Universitaria: Calle 67 No 53-108 Bloque 6 Oficina 105, Medellin, Colombia*
[2]*Facultad de Ciencias Exactas Universidad Nacional de La Plata, C.C. 67,1900 La Plata, Argentina*
[3]*Instituto de Física La Plata CONICET, diagonal 113 y 63, 1900 La Plata, Argentina*

(Received 7 April 2022; accepted 7 June 2022; published 2 August 2022)

That's all

Thanks to organizers for making possible my participation