Weak pion production in neutrino-nucleus scattering

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I. A little History

- We have calculated the total cross section for weak pion-production on nucleons. In addition to the Δ(1232MeV), we included the N*(1440MeV), N*(1535), and N*(1520) contributions, which improves the description. Also, results for antineutrinos are properly described.

- We also developed a model to describe quasi elastic (QE) ν and $\bar{\nu}$ (~ GeV) by nuclei within a nuclear matter quantum hadrodynamics relativistic approach. We introduced the effect of ground-state correlations (GSC) through a momentum distribution calculated perturbatively, and also final-state interactions (FSI) using a perturbed nucleon and Δ propagators dressed by a self-energy with nucleon-nucleon and Δ-nucleon correlations.

- The model takes into account of 2p2h and 3p3h excitations in addition to the CCQE 1p1h ones. Results are promising, and the model worked quit well. It is clear that now to analyze weak pion production (CC π) on the detector nucleus, many additional effects appear regards the production on nucleons.

- Pions could be produced by FSI suffered by the emitted primary nucleon or by the decay of primary excited resonances. We will adopt the same formalism that in the QE case adding the contributions in the nucleon and Δ self energies, that lead to a pion-nucleon pair in the final state.

II. FORMALISM

We start with the cross section for the $\nu(\bar{\nu})A \to \mu(\mu^+)X'A'$ process in the LAB system, where $k_A = (M_A, \mathbf{0})$, $k_{\nu\equiv\nu,\bar{\nu}} = (E_\nu, E_\nu\hat{\mathbf{k}})$ and since we are going to analyze lepton or pion observables we use

$$p_{l\equiv\mu\mu^+(\pi)} \;=\; (E_{l(\pi)} = \sqrt{\mathrm{p}^2_{l(\pi)} + m^2_{l(\pi)}}, \mathrm{p}_{l(\pi)} sin\theta_{l(\pi)} cos\phi_{l(\pi)}, \mathrm{p}_{l(\pi)} sin\theta_{l(\pi)} sin\phi_{l(\pi)}, \mathrm{p}_{l(\pi)} cos\theta_{l(\pi)})$$

$$\frac{d\sigma_{\nu A}}{dT_{l(\pi)} dcos\theta_{l(\pi)}} \;=\; \frac{\Omega_A}{2E_\nu} \sum_{m_\nu} 2Im\left[\mathcal{M}(k_\nu m_{s_\nu} T_{l(\pi)}\theta_{l(\pi)} \to k_\nu m_{s_\nu} T_{l(\pi)}\theta_{l(\pi)})\right] \tag{1}$$

$$2Im\left[\mathcal{M}(k_\nu T_{l(\pi)}\theta_{l(\pi)} \to k_\nu T_{l(\pi)}\theta_{l(\pi)})\right] \;=\; \sum_{m_s' s\, m_t' s} \left(\int \frac{d\Phi_{l(\pi)}}{(2\pi)^3} \mathcal{N}_{l(\pi)} \prod_{i=1}^{n} \int \frac{d^3 p_i}{(2\pi)^3} \mathcal{N}_{p_i} \frac{d^3 k_i}{(2\pi)^3} \mathcal{N}_{k_i} \right) |\mathcal{M}(k_\nu k_1 k_2 ... \to p_{l(\pi)} p_1 p_2 ...)|^2$$

$$\times \;\; (2\pi)^4 \delta^4 (p_{l(\pi)} + p_1 + p_2 ... - k_\nu - k_1 - k_2 - ...), \tag{2}$$

$$\xi \equiv p_{l(\pi)}, p_i, k_i, \;\; \xi = (E(\boldsymbol{\xi}), \boldsymbol{\xi}), \;\; \mathcal{N} \;=\; \frac{m^2}{\sqrt{\boldsymbol{\xi}^2 + m^2}}, \frac{1}{2\sqrt{\boldsymbol{\xi}^2 + m^2}}, \;\; \boldsymbol{\xi} \equiv \mathbf{p}_{l(\pi)}, \mathbf{k}_i, \mathbf{p}_i, \;\; m \equiv m_{l(\pi)}, m_N, m_\pi \tag{3}$$

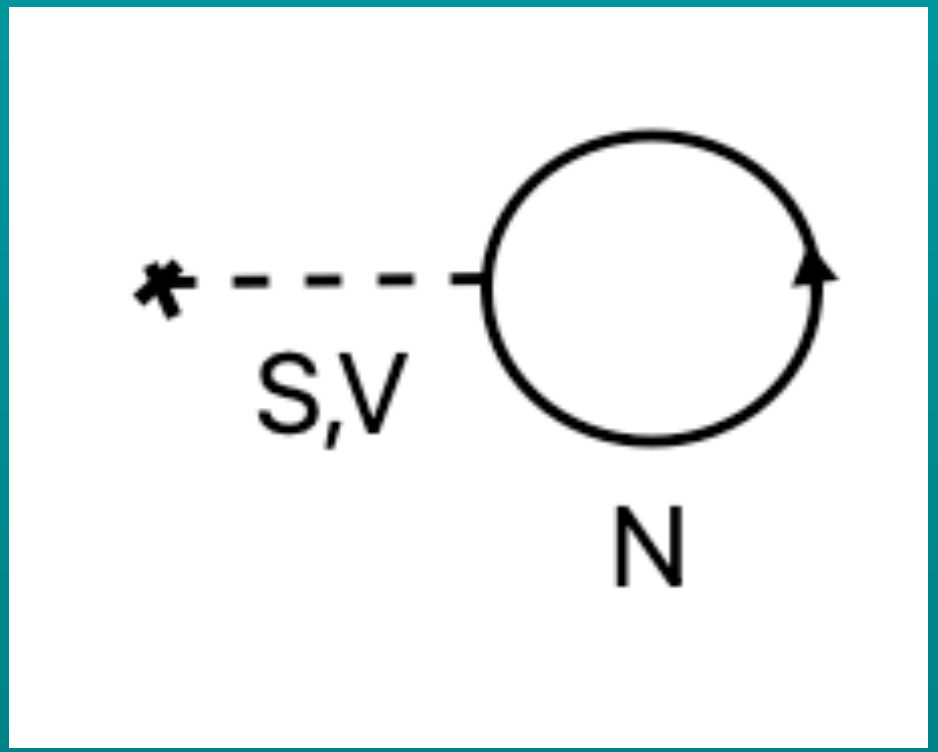
We will proceed choosing a determined 1p1h, 2p2h, 1p1h+π ,2p2h+π, etc. intermediate states and evaluating its contribution to $\mathcal{M}(k_\nu T_{l(\pi)}\theta_{l(\pi)} \to k_\nu T_{l(\pi)}\theta_{l(\pi)})$ through the Feynman rules in quantum hadrodynamics(QHDI) with neutral vector(v)

$$S_N(p) \;=\; \frac{\tilde{\not{p}} + \tilde{m}_N}{\tilde{p}^2 - \tilde{m}^2_N + isgn(Re[\tilde{\not{p}}^0])sgn(p^0 - E_F)\epsilon}, \tag{7}$$

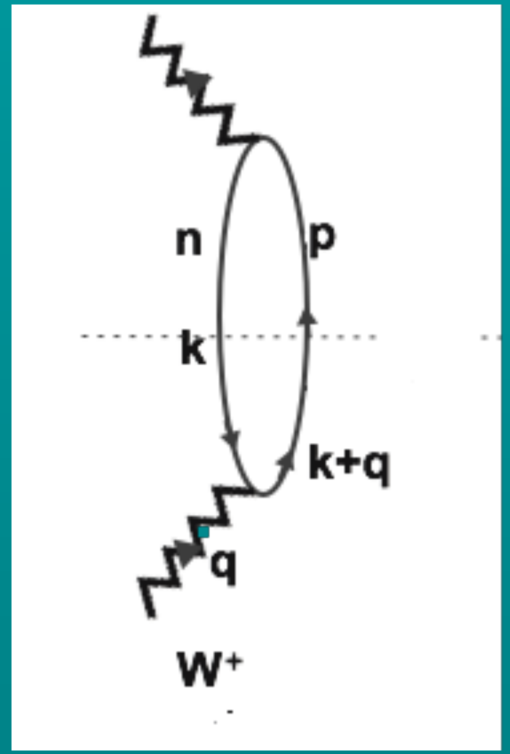
$$\tilde{p}^\mu \;=\; (p^0 + \Sigma^0(p), \mathbf{p}(1 + \Sigma^v(p))), \;\; \tilde{m}_N(p) = m_N + \Sigma^s(p), \tilde{E}(p) = \sqrt{\tilde{\mathbf{p}}^2 + \tilde{m}^2_N}$$

A. Binding and QE→ npnh, N→Nπ contributions

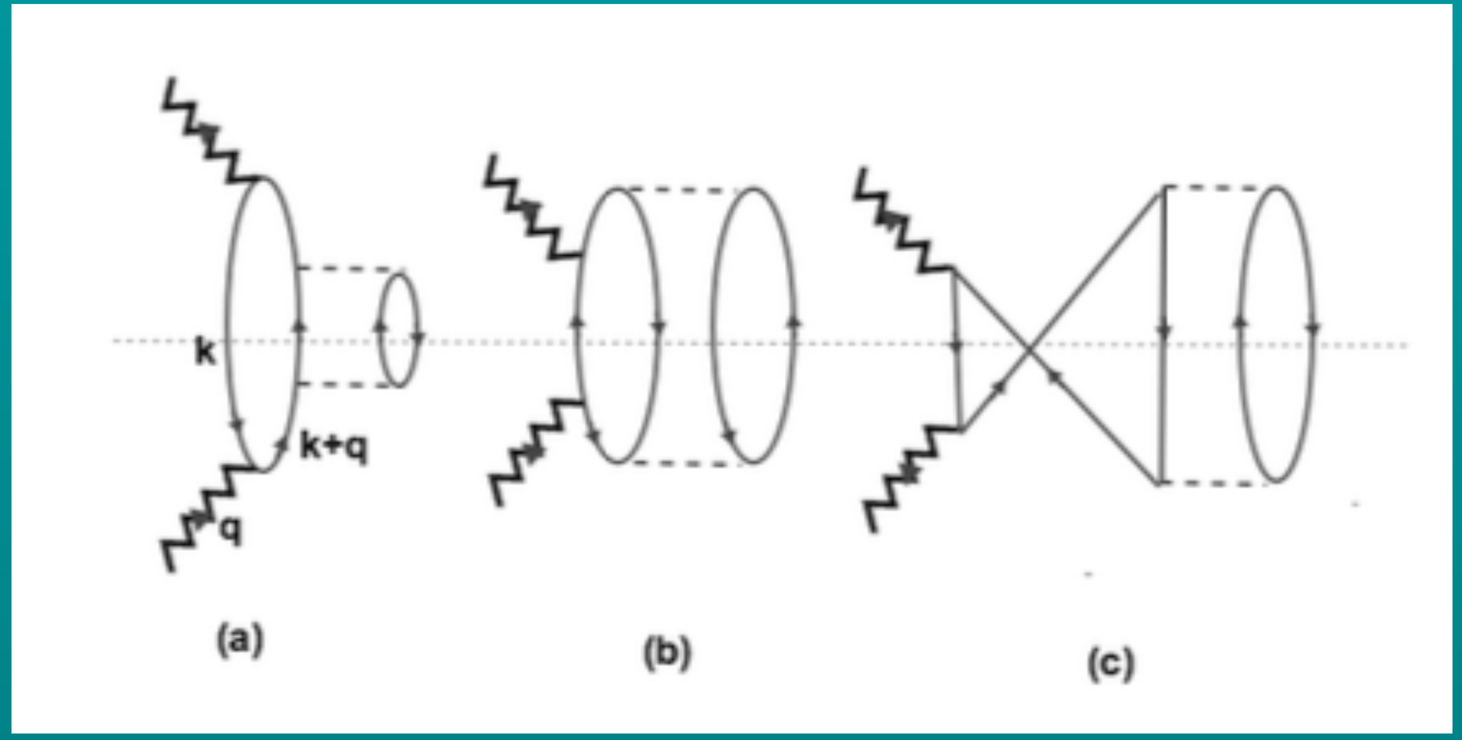
RHA



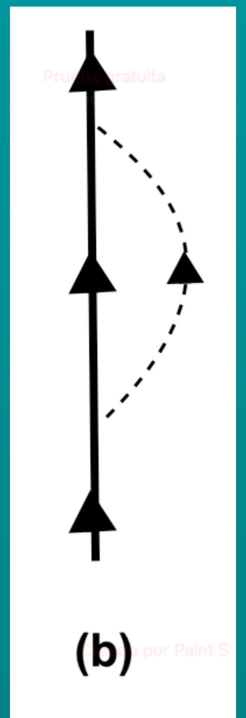
1p1h



2p2h+3p3h



$N\pi$



QE

π-production

$$\Gamma_N = \Gamma_N^{1p1h}(\to 0) + \Gamma_N^{2p2h} + \Gamma_N^{3p3h} + \Gamma_N^{\pi} - \Delta\Gamma_N^{\pi Pauli}$$

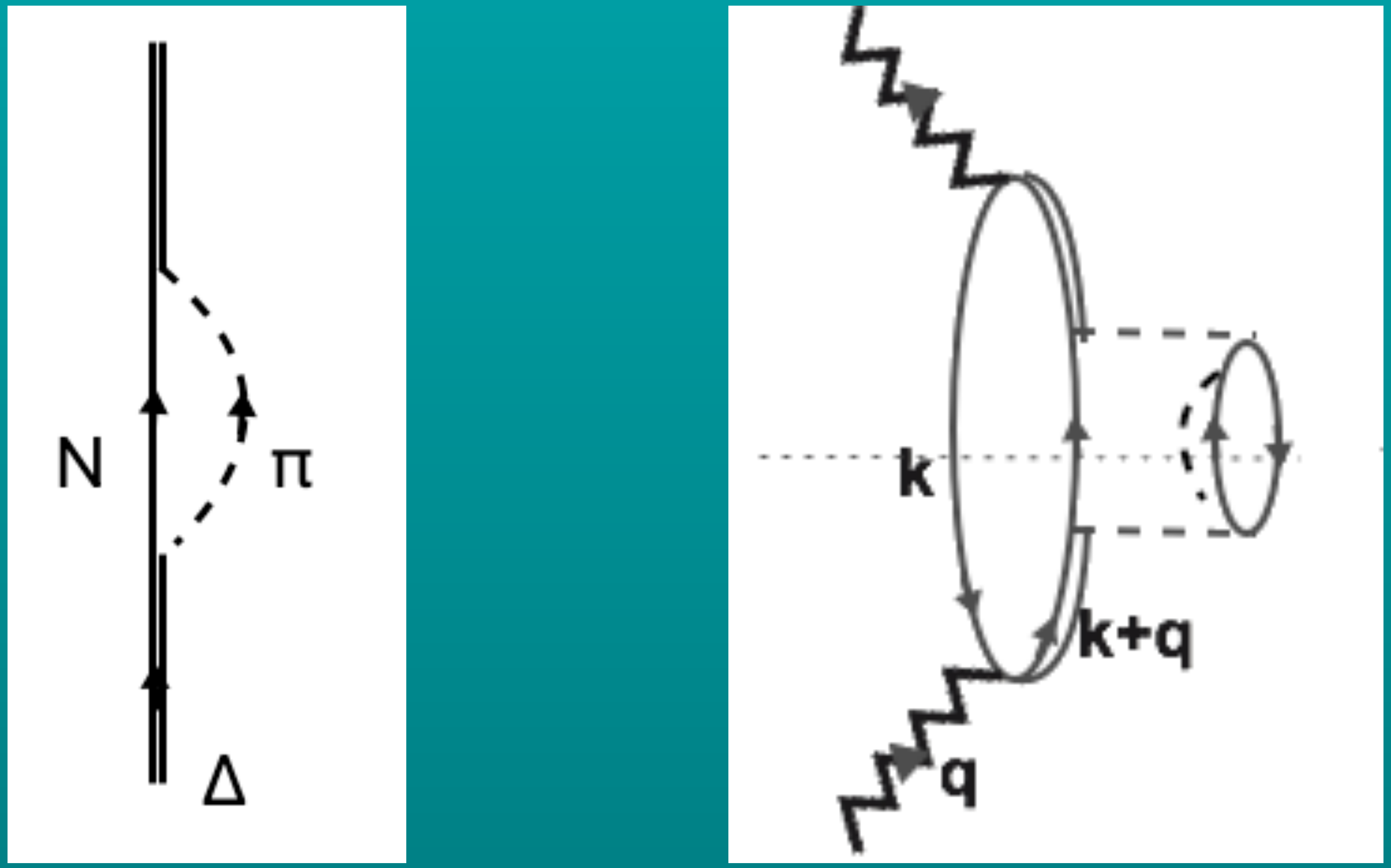
Using Lehmann spectral representation for the propagator we get

$$
\begin{aligned}
2Im\sum_{m_\nu}\mathcal{M}_{1p1h} &= \frac{16}{(2\pi)^5}\left(\frac{G_F}{\sqrt{2}}\right)^2 cos^2\theta_c\tilde{m}_N\tilde{m}_{N_f}\int dk^3\int dE_l dcos\theta_l\int d\phi_l \mathrm{p}_l\theta(E_l-E_\nu)L_{\mu\nu} \\
&\times\sum_{m's}\bar{u}(k+q,m')(-i)\sqrt{2}\hat{J}^\mu_H(q)u(k,m)[\bar{u}(k+q,m')(-i)\sqrt{2}\hat{J}^\nu_H(q)u(k,m)]^* \\
&\times\int_{E_{min}}^{E_F}\frac{\tilde{m}_{N_f}\Gamma_N(\omega+q_0)(1-n(\mathbf{k}+\mathbf{q}))}{\pi((\omega+q_0)^2-\tilde{E}(\mathbf{k}+\mathbf{q})^2)^2+(\tilde{m}_{N_f}\Gamma_N(\omega+q_0))^2}\frac{\tilde{m}_N\Gamma_N(\omega)n(\mathbf{k})}{\pi((\omega)^2-\tilde{E}(\mathbf{k}))^2+(\tilde{m}_N\Gamma_N(\omega))^2}d\omega,
\end{aligned}
$$

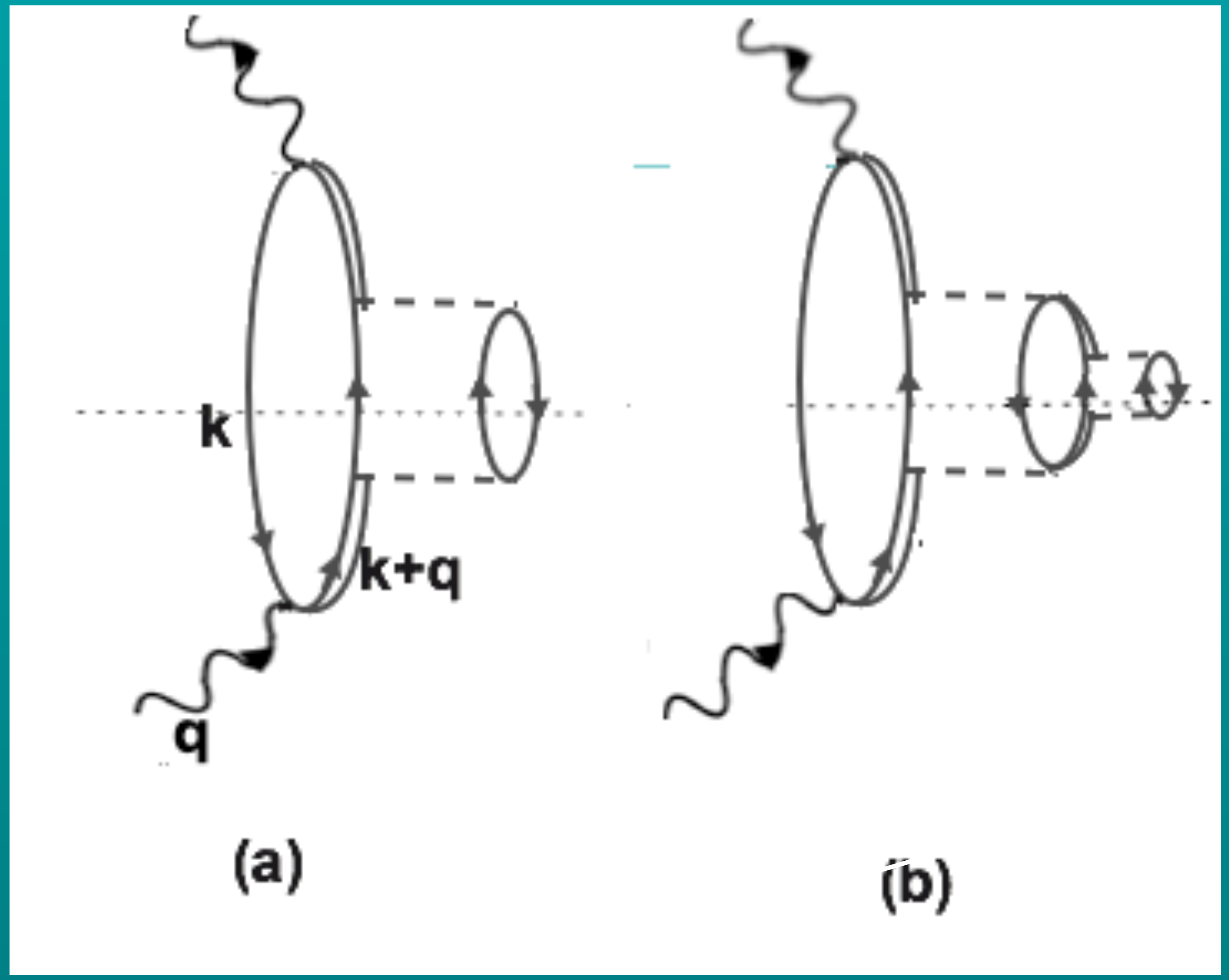
$$
\begin{aligned}
\Gamma^\pi_N-\Delta\Gamma^{\pi Pauli}_N &= I_{isos}\frac{g^2_{\pi NN}}{4\pi m_N^2}\frac{\lambda^{1/2}(m_N^2,m_\pi^2,s)}{8s}(\sqrt{s}+m_N)^2\left[E_N-m_N\right] \\
&\times\left[\left\{\begin{array}{c}\mu_0>1,1\\ -1<\mu_0<1\\ \mu_0<-1,0\end{array}\right., \frac{1+\mu_0}{2}-\frac{1}{2}\frac{\lambda^{1/2}(m_N^2,m_\pi^2,s)(\sqrt{s}-m_N)}{(\sqrt{s}+m_N)((\sqrt{s}-m_N)^2-m_\pi^2)}\frac{\sqrt{p^0-\sqrt{s}}}{\sqrt{p^0+\sqrt{s}}}\left\{\begin{array}{c}0,\mu_0>1\\ \frac{1-\mu_0^2}{2},-1<\mu_0<1\\ 0,\mu_0<-1\end{array}\right.\right] \\
\mu^0 &\equiv \frac{E'_N(s)p^0-\sqrt{s}E_F}{\mathrm{p}'_N(\mathrm{s})\mathrm{p}}, \quad \lambda(x,y,z) = x^2+y^2+z^2-2xy-2xz-2yz
\end{aligned}
$$

- $\Gamma_N^{2p2h+3p3h}(s)$ are taken from another calculations in nuclear matter

B. $\Delta \rightarrow N\,\pi$, 2p2h, 3p3h, 2p2h + π



π-production



QE

$$\Gamma_\Delta = \Gamma_\Delta^{free} - \Delta\Gamma_\Delta^{Pauli} + \Gamma_\Delta^{2p2h+\pi} + \Gamma_\Delta^{2p2h+3p3h}$$

Using Lehmann again

- $$2Im\sum_{m_\nu,I}\mathcal{M}_{\Delta h} = \frac{8}{(2\pi)^5}\left(\frac{G_F}{\sqrt{2}}\right)^2 cos\theta_C^2\int dk^3\sum_I(\sqrt{2})^2C_I^2\int m_l dcos\theta_l dE_l \mathrm{p}_l d\Phi_l\tilde{m}_N\frac{L^{\beta\alpha}}{m_l}\int_{\omega_{min}}^{E_F}d\omega$$
$$\times\sum_{m_s}\left[\bar{u}(\mathbf{k},m_{s_1})\gamma_0\widehat{J}_{\Delta\beta\mu}(q)^\dagger\gamma_0P^{\mu\nu}(k+q)\widehat{J}_{\Delta\nu\alpha}(q)u(\mathbf{k},m_s)\right]$$
$$\times\frac{(-i)}{\pi}Im\left[\frac{1}{(k+q)^2-m_\Delta^2+i\Gamma_\Delta m_\Delta}\right]\frac{\tilde{m_N}\Gamma_N(\omega)n(\mathbf{k})}{\pi\left[((\omega)^2-\tilde{E}(\mathbf{k}))^2+(\tilde{m}_N\Gamma_N(\omega))^2\right]} \quad (12)$$

- $$\Gamma_\Delta^{free}-\Delta\Gamma_\Delta^{Pauli} = \frac{1}{4\pi}\frac{f_{\pi N\Delta}^2}{m_\pi^2}\frac{(\sqrt{s}+m_N)^2-m_\pi^2}{48s^{5/2}}\lambda^{3/2}(m_N^2,m_\pi^2,s)\theta(s-(m_\pi+m_N)^2)$$
$$\times\left[\begin{cases}\mu_0>1,1\\ -1<\mu_0<1\,,\dfrac{1+\mu_0}{2}\\ \mu_0<-1,0\end{cases}-\begin{cases}0,\mu_0>1\\ \frac{1-\mu_0^2}{4},-1<\mu_0<1\\ 0,\mu_0<-1\end{cases}\frac{\sqrt{p_\Delta^0-\sqrt{s}}}{\sqrt{p_\Delta^0+\sqrt{s}}}\frac{\lambda^{1/2}(m_N^2,m_\pi^2,s)}{(\sqrt{s}+m_N)^2-m_\pi^2}\right]$$
$$\mu^0 \equiv \frac{E_N'(s)p_\Delta^0-\sqrt{s}E_F}{\mathrm{p}_N'(\mathrm{s})\mathrm{p}_\Delta},\quad E_N'(s),p_N'(s)\text{in the }\Delta\text{ rest frame.}$$

- $\tilde{m}_\Delta \equiv m_\Delta-(1-\frac{\tilde{m}_N'}{m_N})m_N$

- $\Gamma_\Delta^{2p2h+3p3h+2p2h\pi}(s)$ are taken from another calculations in nuclear matter

π observables

When pion observables want to be analyzed we can get the form

$$\Gamma_\Delta(p_\Delta^2) = \int \frac{d^3p_\pi}{(2\pi)^2 E_\pi}\delta(E_l - E_l^0)\theta(p_\Delta(E_l^0)^2 - (m_\pi + m_N)^2)$$
$$\times \frac{g^2}{48\,(p_\Delta^2)^{3/2}} \frac{\lambda(m_N^2, m_\pi^2, p_\Delta^2)\left[\left(\sqrt{p_\Delta{}^2} + m_N\right)^2 - m_\pi^2\right]}{2\,|(E_\nu + E_1 - E_\pi) - \hat{\boldsymbol{p}}_l.(\boldsymbol{p}_\nu + \boldsymbol{p}_1 - \boldsymbol{p}_\pi)|}$$
$$\times \left[1 - \theta(k_F - (p_\Delta^0 - E_\pi))\left(1 + \frac{\theta(E_F - \mathrm{E}_N)2\sqrt{p_\Delta{}^2}}{\left(\sqrt{p_\Delta{}^2} + m_N\right)^2 - m_\pi^2} p_\pi cos\theta_\pi \frac{\sqrt{p_\Delta^0 - \sqrt{s}}}{\sqrt{p_\Delta^0 + \sqrt{s}}}\right)\right]$$
$$E_l^0 \approx \frac{(E_\nu + E_1 - E_\pi)^2 - (\boldsymbol{p}_\nu + \boldsymbol{p}_1 - \boldsymbol{p}_\pi)^2 - m_N^2 + m_l^2}{2\left[(E_\nu + E_1 - E_\pi) - \hat{\boldsymbol{p}}_l.(\boldsymbol{p}_\nu + \boldsymbol{p}_1) - \hat{\boldsymbol{p}}_l.\boldsymbol{p}_\pi)\right]}, p_\Delta = p_\Delta(E_l^0),$$

and here also the exchange $\int dp_\pi^3 \longleftrightarrow \int dp_l^3$ is done to get an approximate expression for pion observables.

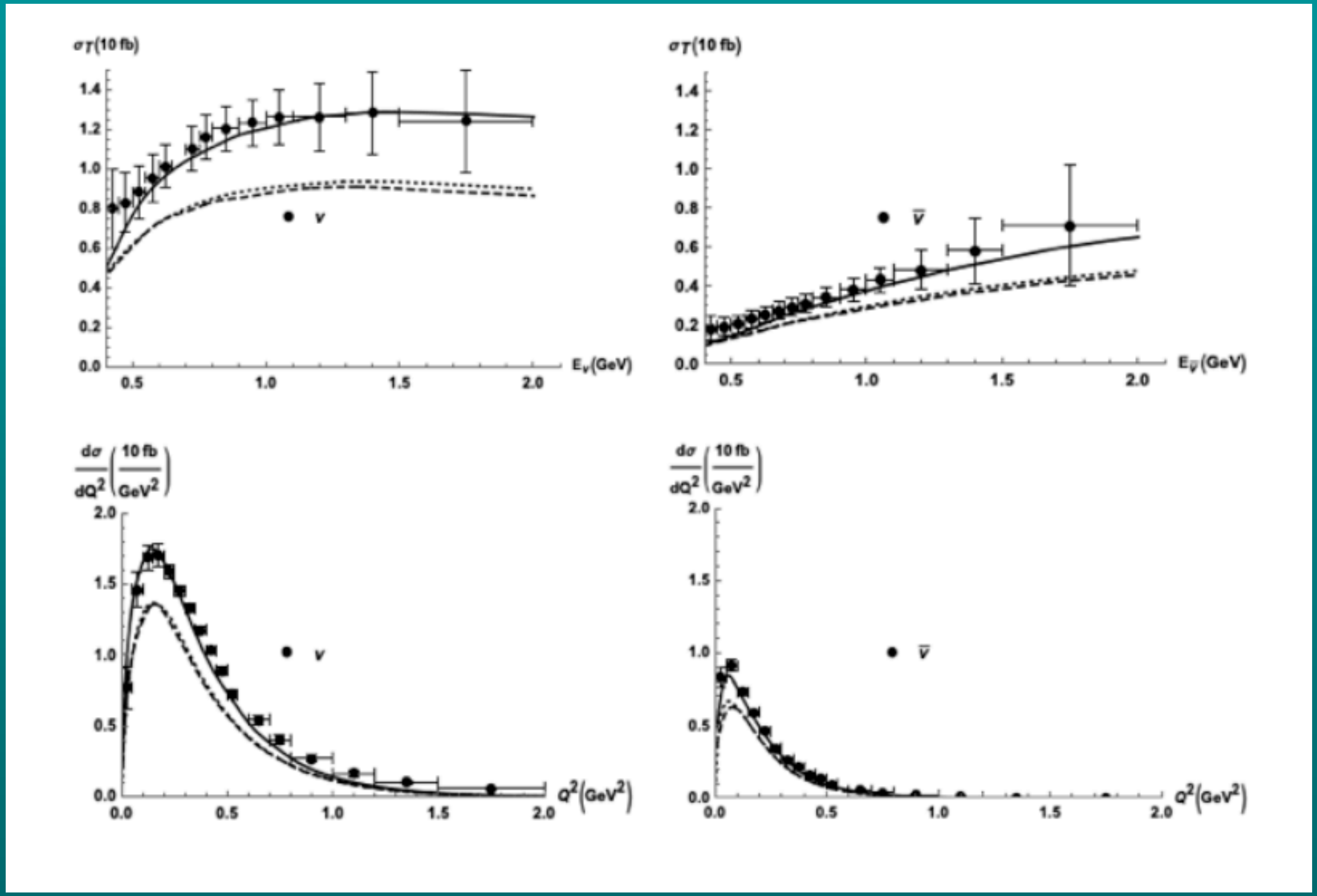
$$\Gamma_N^\pi - \Delta\Gamma_N^{\pi Pauli} = \frac{g_{\pi NN}^2}{m_N^2}\int \frac{\mathrm{p}_\pi dE_\pi d\Omega_\pi}{(2\pi)^2}\frac{1}{16}\frac{\delta(E_l - E_l^0)(\sqrt{s} + m_N)^2\,[E_N(s) - m_N]}{|(E_\nu + E_1 - E_\pi) - \hat{\boldsymbol{p}}_l.(\boldsymbol{p}_\nu + \boldsymbol{p}_1 - \boldsymbol{p}_\pi)|}$$
$$\times \left[1 - \theta(cos\theta_\pi - max\,\{-1, \mu_0\})\left(1 + \frac{\sqrt{s} - m_N}{\sqrt{s} + m_N}\frac{\sqrt{p^0 - \sqrt{s}}}{\sqrt{p^0 + \sqrt{s}}}\frac{\mathrm{k}cos\theta}{[E_N(s) - m_N]}\right)\right]$$

III. RESULTS

▶ folded dif- σ

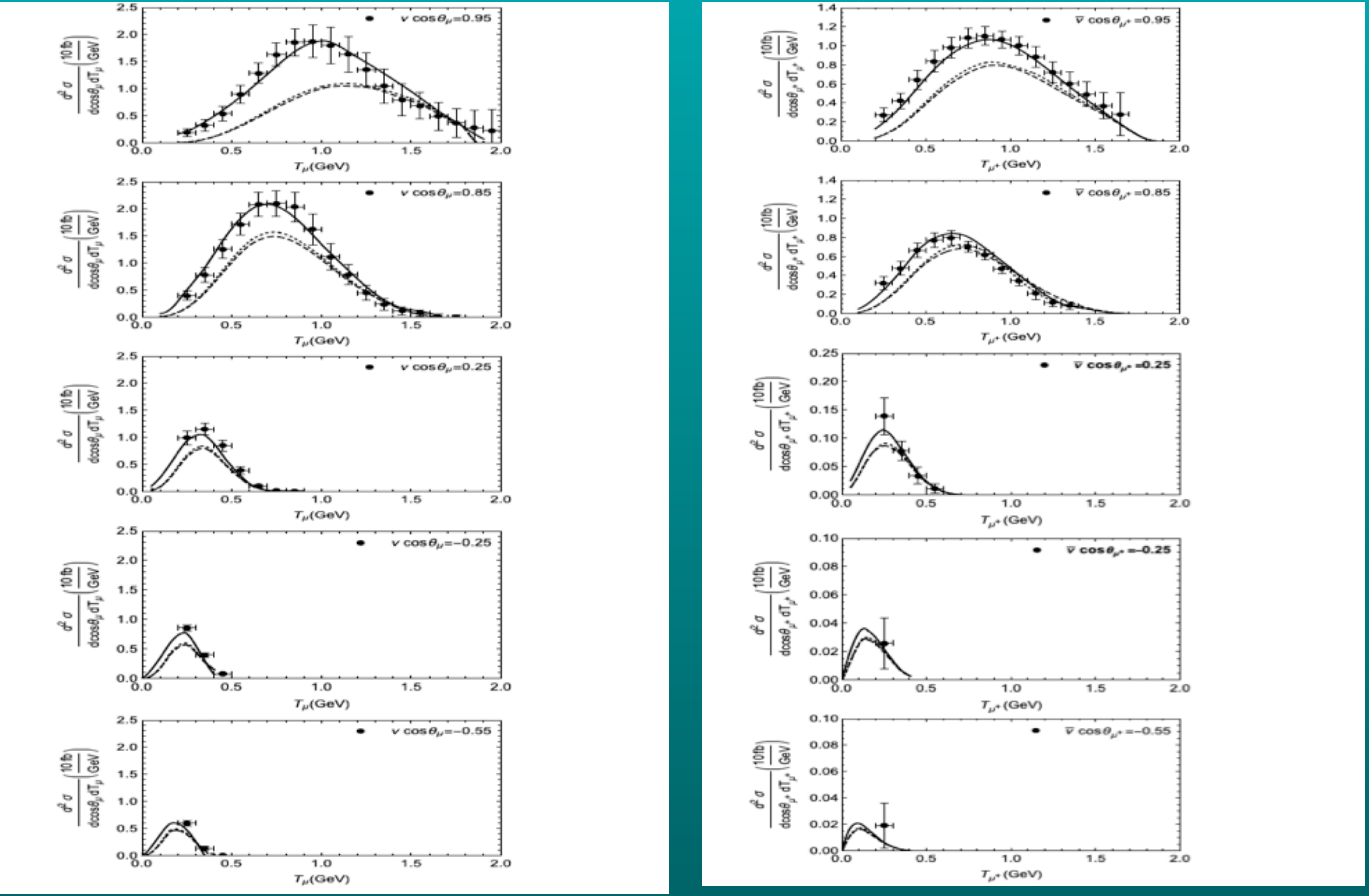
$$\left\langle \frac{d\sigma^2_{\nu A}}{dT_{l(\pi)} dcos\theta_{l(\pi)}}, \frac{d\sigma}{dQ^2} \right\rangle = \frac{1}{\int \Phi(E_\nu) dE_\nu} \times \int dE_\nu \left(\frac{d\sigma^2_{\nu A}}{dT_{l(\pi)} dcos\theta_{l(\pi)}} |_{E_\nu(T_{l(\pi)}, cos\theta_{l(\pi)})}, \frac{d\sigma}{dQ^2} |_{E_\nu(T_{l(\pi)}, Q^2)} \right) \Phi(E_\nu)$$

▶QE on A



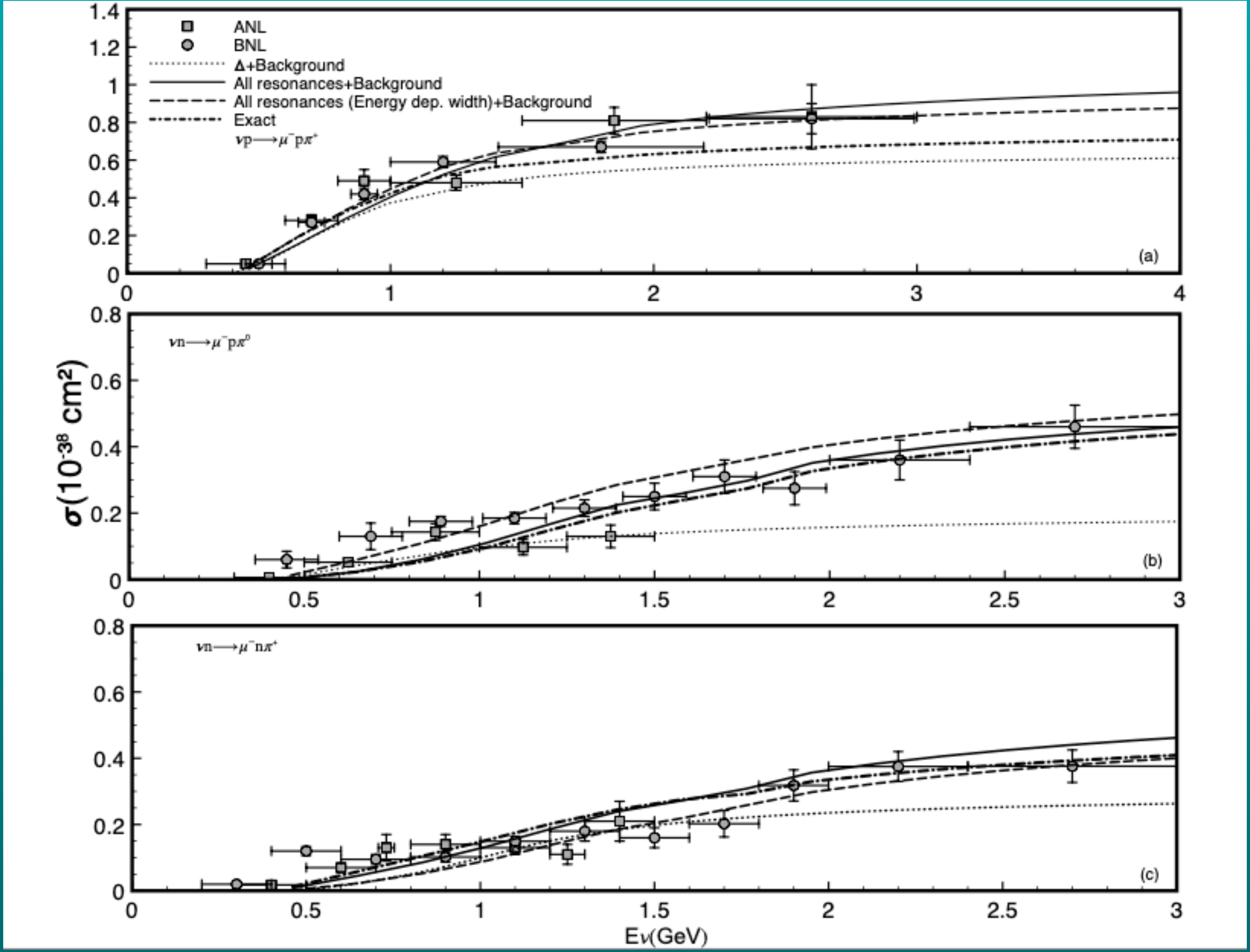
Total unfolded and folded dσ/dQ^2 cross sections. With dotted lines QE 1p1h response within the RHA is indicated. Dashed lines indicate QE 1p1h + 2p2h(coming from FSI and GSC). Finally full lines also include the Δh excitations that decay into 2p2h and 3p3h final states. Data from MiniBooNE (PRD81).

▶QE on A



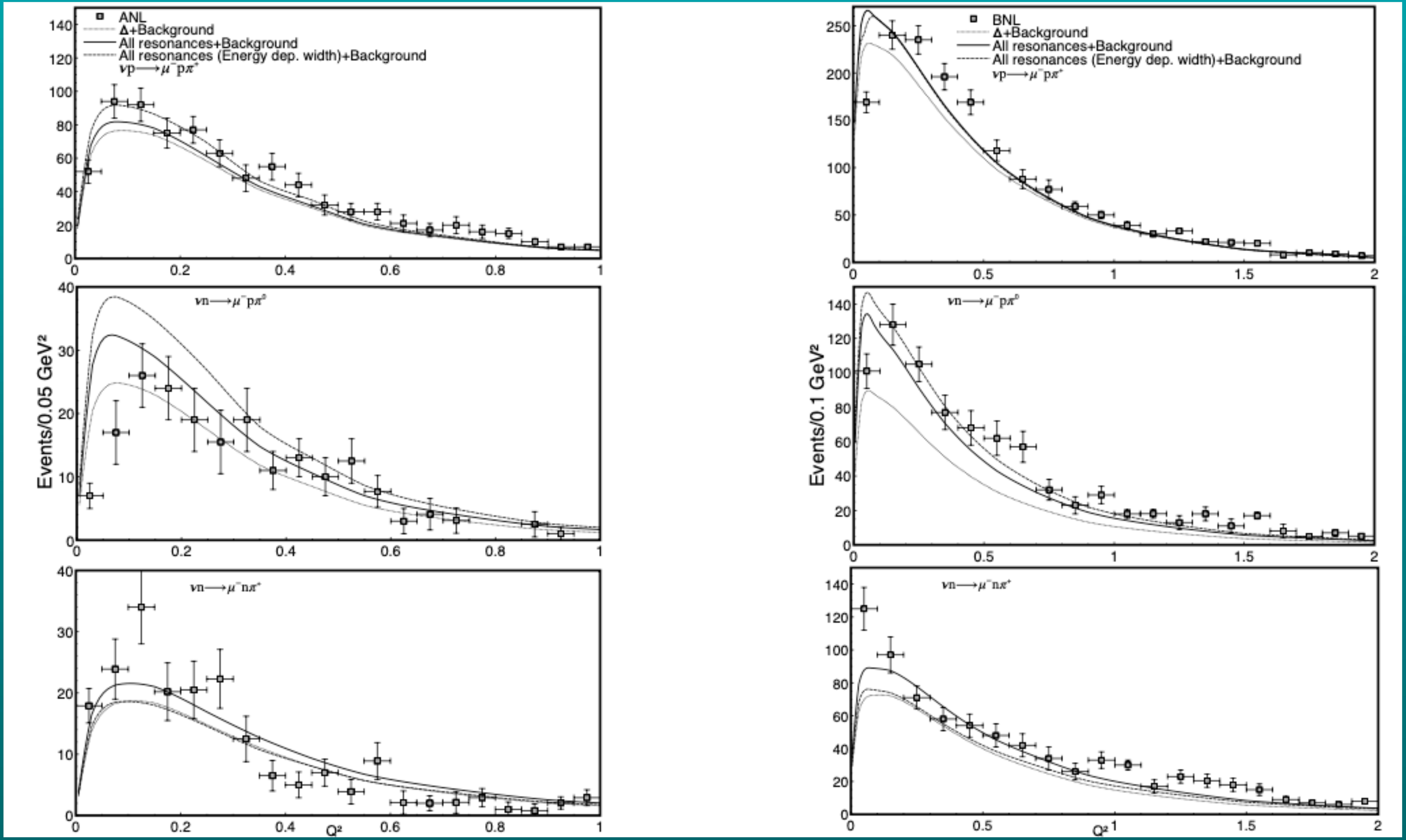
Left (Right) panel double differential cross section for $\nu(\bar{\nu})$ scattering at certain cosθμ(cosθμ+) selected bins.

▶π prod. on N



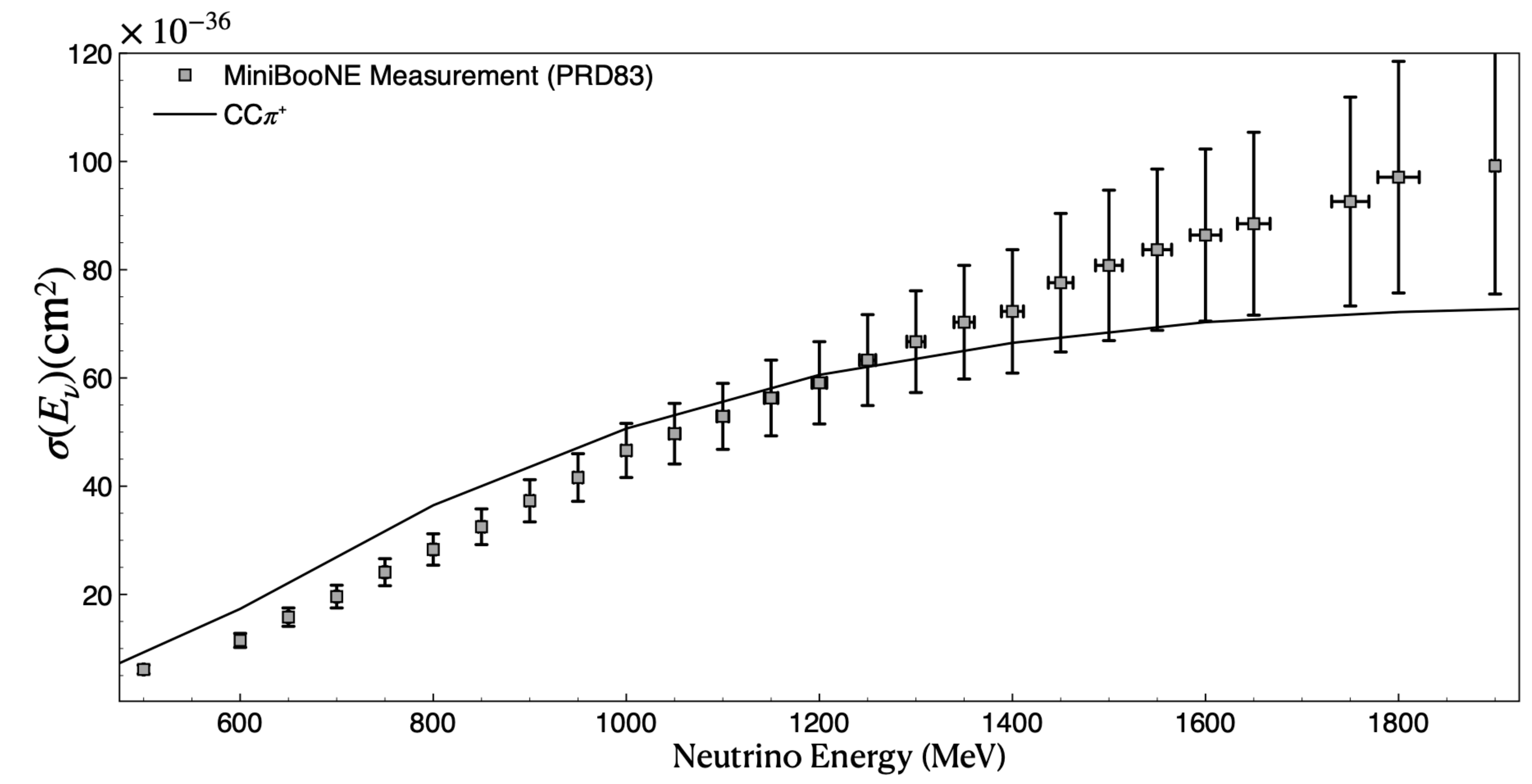
Total νN cross section as function of the neutrino energy for different channels. Results with only the Δ and second region's resonances, plus background. We adopt the reanalyzed ANL and BNL data (EPJC16).

▶ π prod. on N

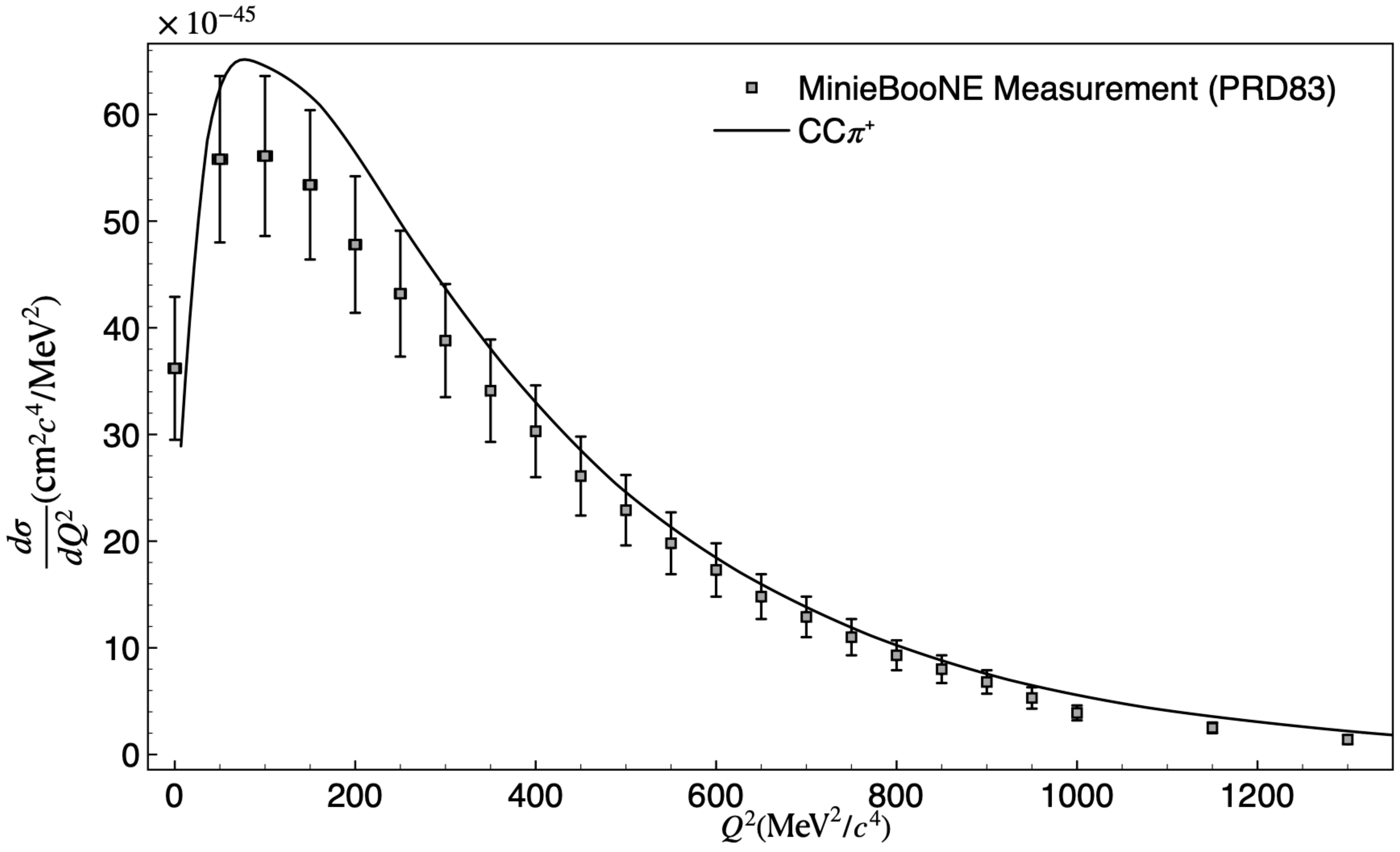


Q^2 Differential cross section. Lines convention are the same that in previous one.

▶π prod. on A

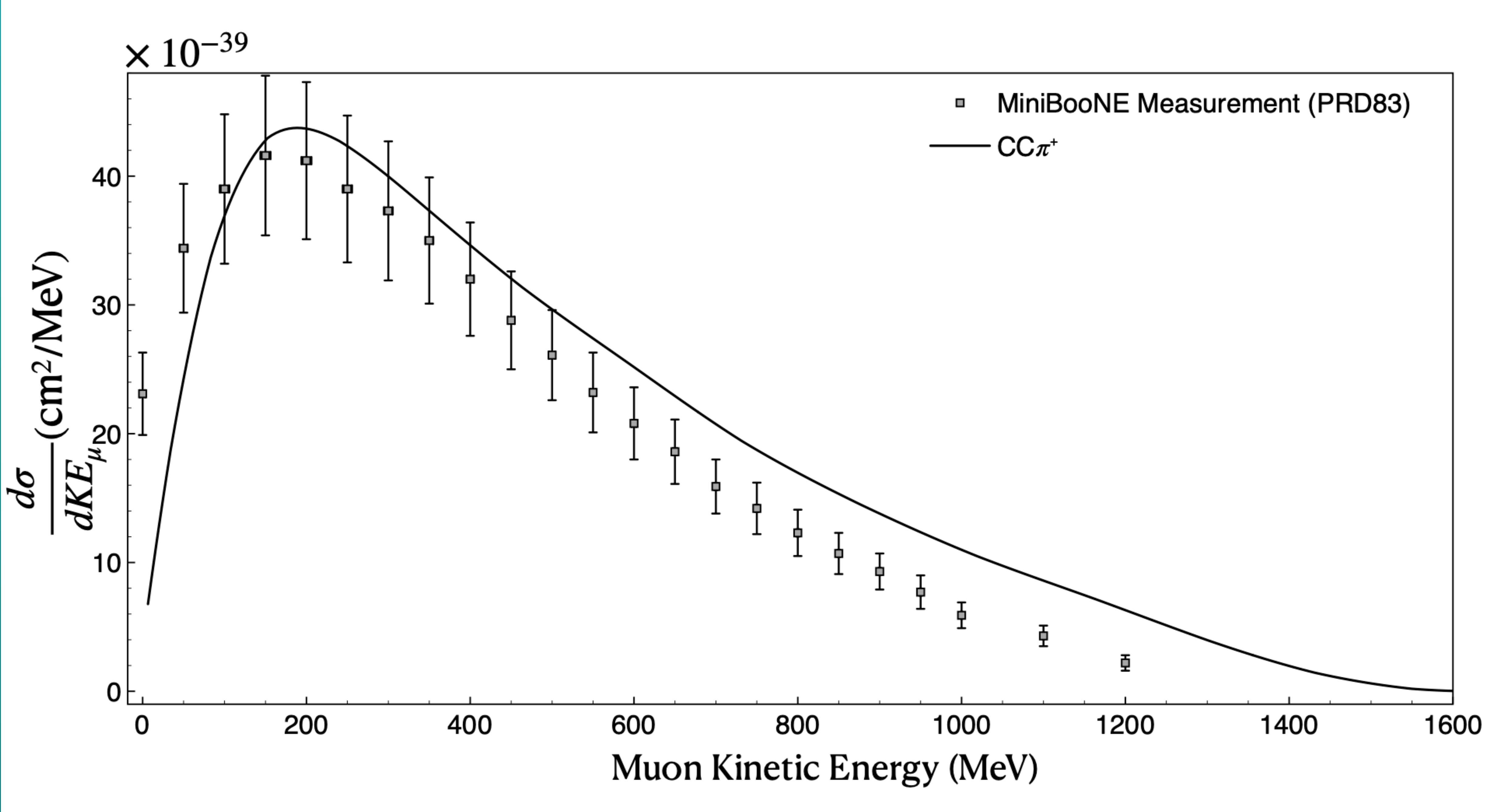


total unfolded cross section

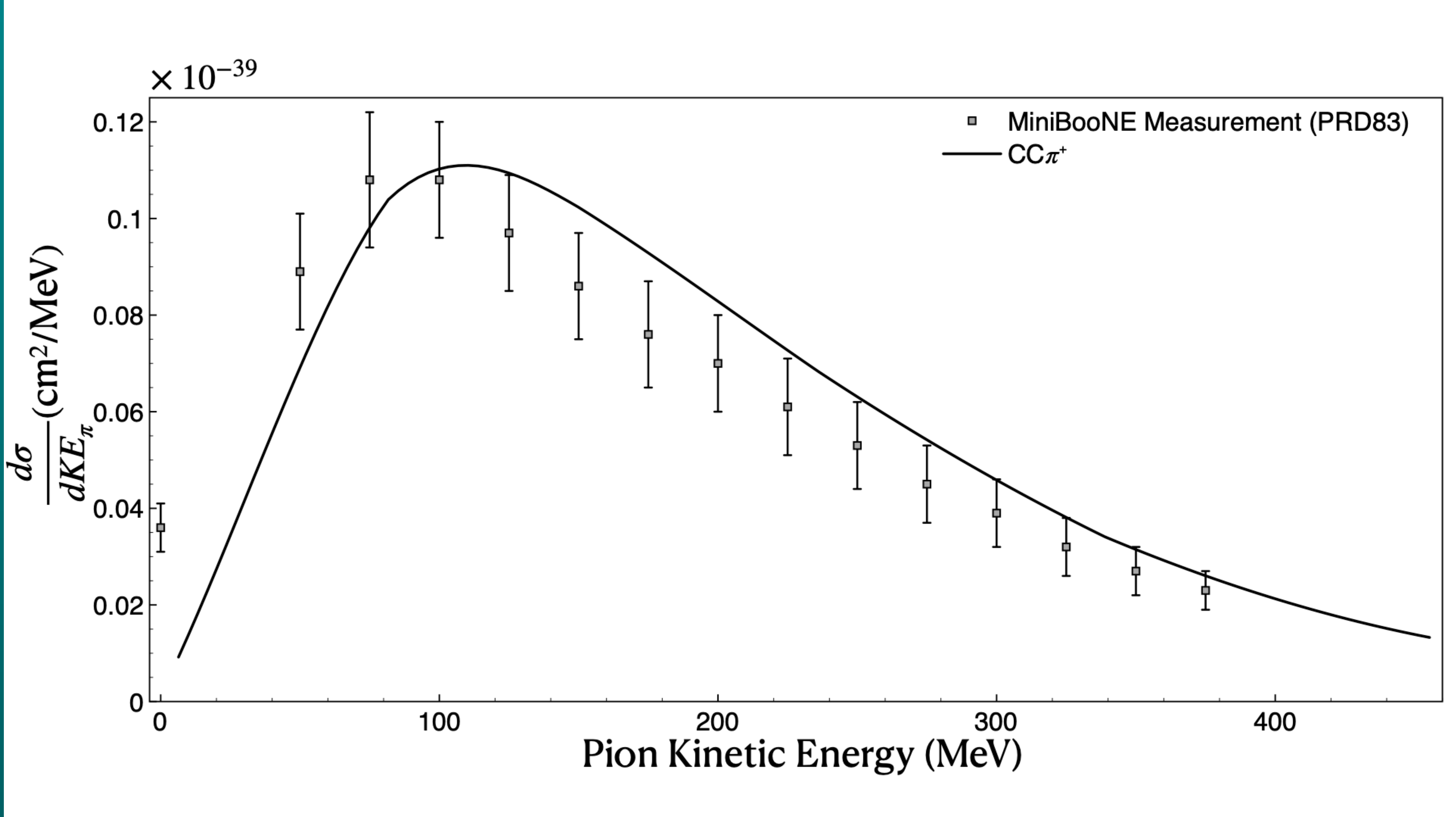


Q^2differential folded cross section

▶ π prod. on A

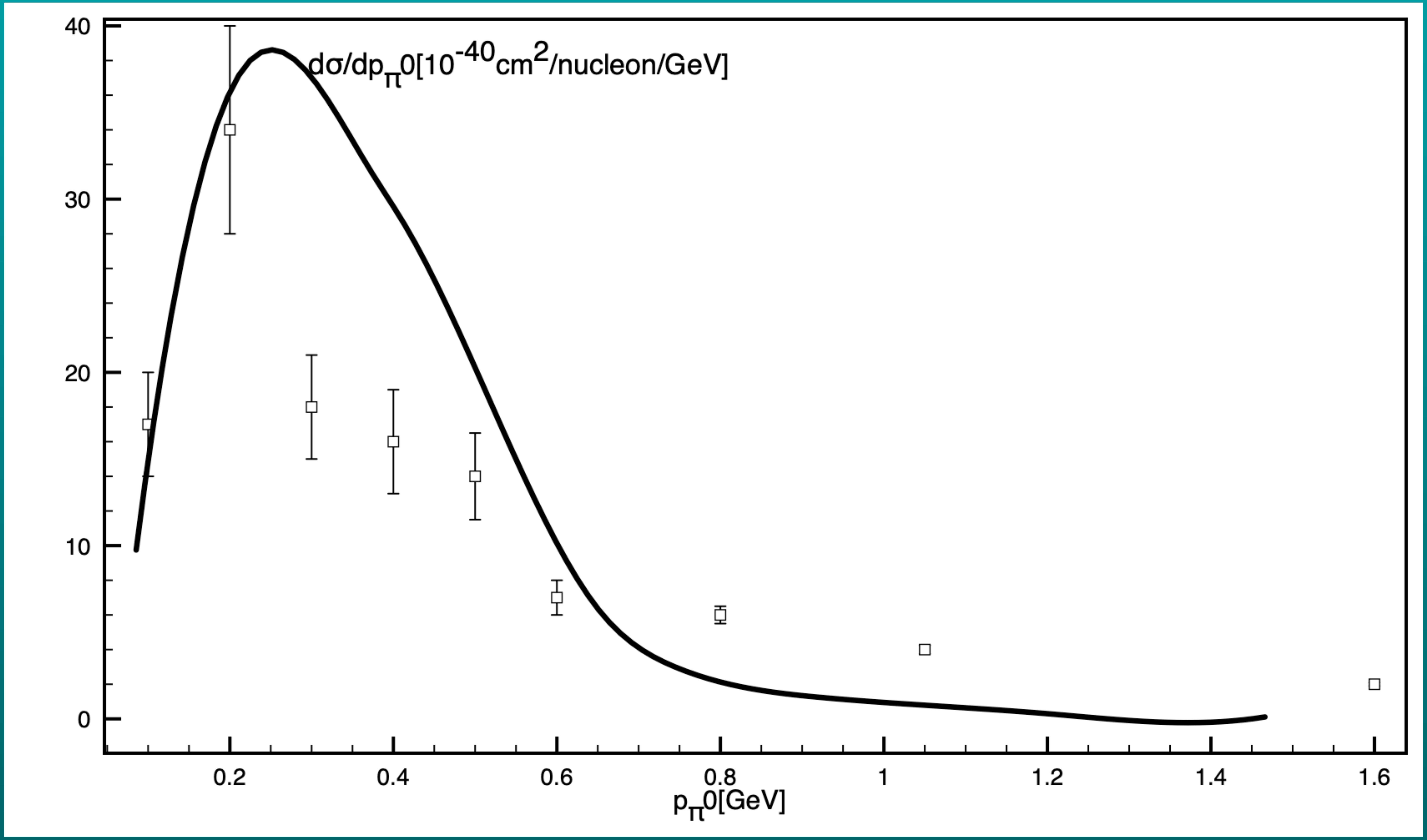


folded muon kinetic energy differential cross section



folded pion kinetic energy differential cross section

- Noνa $\bar{\nu}p \to \mu^+\pi^0 n$



IV. Conclusions

Extended our model for the QE cross section in nuclei to $CC\pi^{+,0}$ in MiniBooNE (encloses QE and $CC\pi^{+}$) and Noνa (preliminary on $CC\pi^{0}$) experiments. Results are preliminary since new isues should be considered for $CC\pi$ case:

• Since we adopt the 2p2h, 2p2h+π , and 3p3h contribution from another model and are strongly energy dependent, we need abandon the CMS(Γ_{Δ}=cte.) approach and replace by the CMW(Γ_{Δ}(s)) for the Δ resonance.

• From pion production results on a free nucleon and from our new results on the total A-cross section, the inclusion of more energetic resonances seems essential.

• Our model in the present form avoids the interference between resonances and background contributions.

• The approximation we use to calculate pion observables should be analyzed more deeply, to conclude if it is acceptable.

• In spite of these difficulties we reproduce roughly well the trends of the data, without making any fitting of parameters.

Thanks !!!