Pion production in neutrino-nucleus scattering

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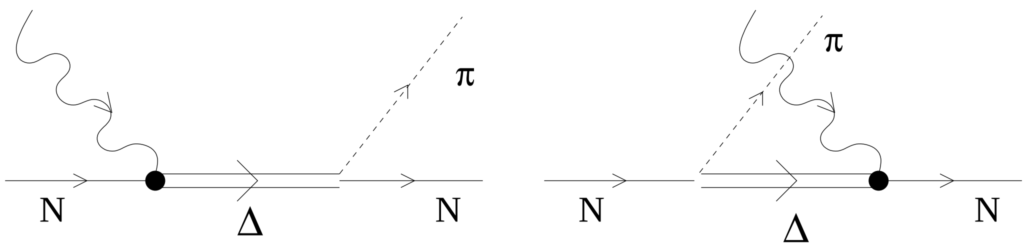
Outline of the talk

- Very brief (mostly pictorial) description of our pion production model at the nucleon level
- Incoherent pion production in nuclei
  - Pion production inside the nucleus
  - Medium modifications
  - Pion FSI
- Coherent pion production in nuclei
- Old results for MiniBooNE (CH_2 target)
- New (preliminary) results for MiniBooNE (CH_2 target)
- New (preliminary) results for MINERνA (CH target)
- New (preliminary) results for T2K (H_2O target)

Delta Pole Term for weak pion production off the nucleon

The dominant contribution for weak pion production at intermediate energies is given by the Δ pole mechanism



In Phys. Rev D 95 (2017) 053007, aiming at improving the description of the $\nu_\mu n \to \mu^- n \pi^+$ channel, we modified the Delta propagator

$$\frac{P_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2} \to \frac{P_{\mu\nu}(p_\Delta) + c\left(P_{\mu\nu}(p_\Delta) - \frac{p_\Delta^2}{M_\Delta^2} P^{\frac{3}{2}}_{\mu\nu}(p_\Delta)\right)}{p_\Delta^2 - M_\Delta^2} = \frac{P_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2} + c\,\delta P_{\mu\nu}(p_\Delta)$$

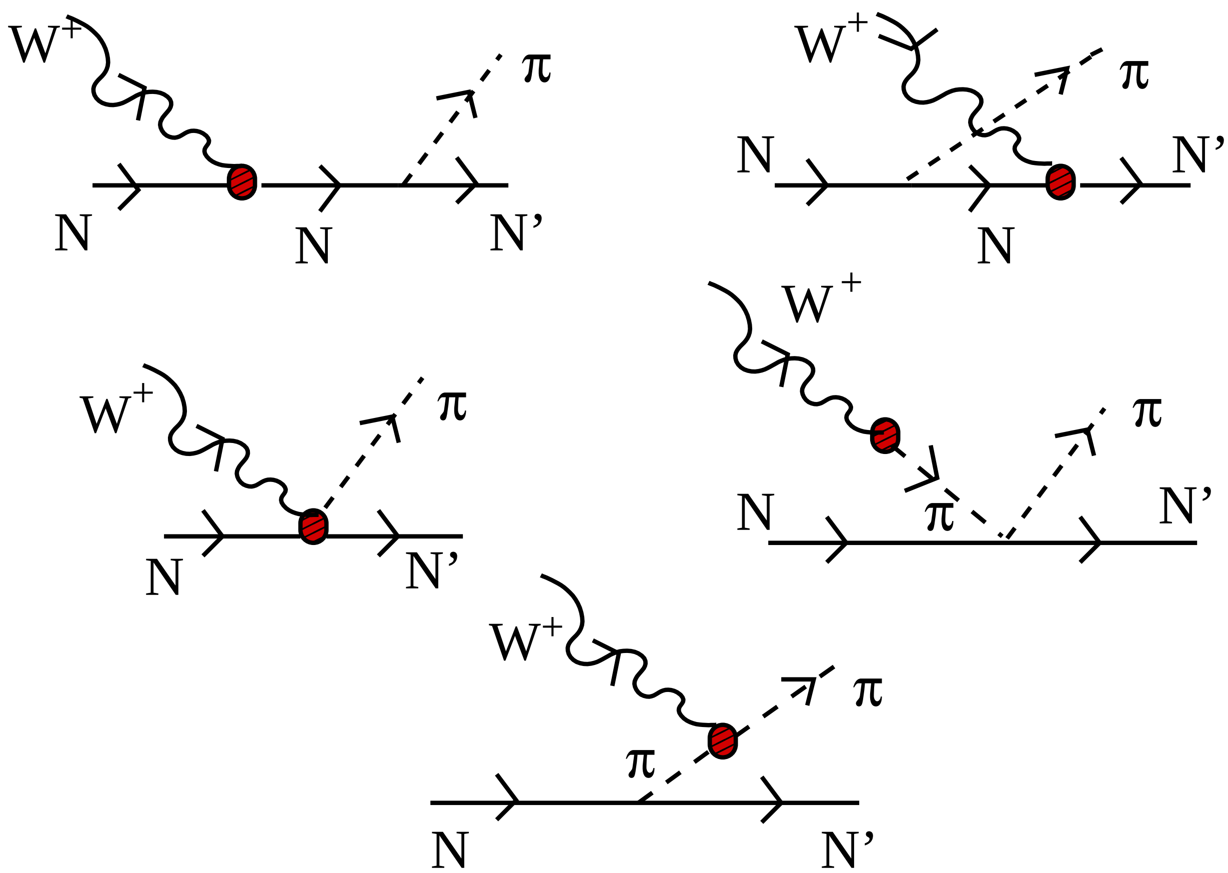
$$\to \frac{P_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta} + c\,\delta P_{\mu\nu}(p_\Delta)$$

The above modification amounts to the introduction of extra contact terms and is very important for the crossed-Delta contribution.

Background Terms

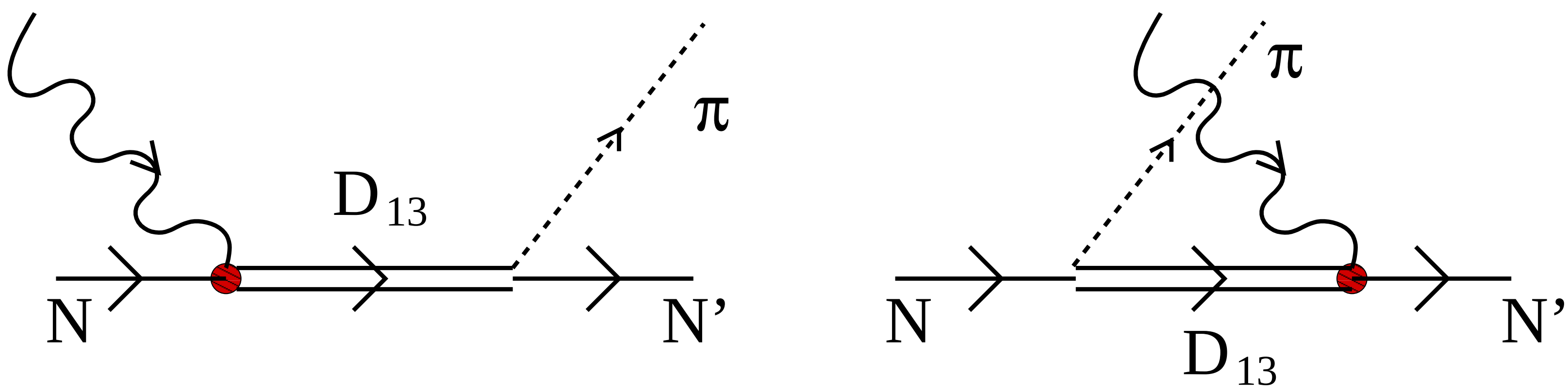
Our model in Phys. Rev. D 76 (2007) 033005 includes background terms required by chiral symmetry. To that purpose we use a SU(2) non-linear σ model Lagrangian.

- No freedom in coupling constants.
- We supplement it with well known form factors in a way that preserves CVC and PCAC.



Other resonances

In order to go to higher neutrino energies (aiming at describing MiniBooNE data on CH_2), in Phys. Rev D87 (2013) 113009, we included in our model the $D_{13}(1520)$ resonance (isospin 1/2, spin 3/2).



Apart from the Δ, it gives the most important contribution [T. Leitner et al., Phys. Rev. C79 034601 (2009)] up to 2 GeV neutrino energy.

Imposing Watson theorem.

Watson theorem is a consequence of unitarity and time reversal invariance and states that in a transition $W(Z)N \to \pi N$ the phase of the amplitude should be the same as the phase of the amplitude for the strong $\pi N \to \pi N$ process.

Since weak pion production is dominated by the Δ, in our work in Phys. Rev. D 93 (2016) 014016 we followed M. Olsson prescription [Nuc. Phys. B78 (1974) 55] and modified our amplitude as

$$T_B + T_{\Delta P} \to T_B + e^{i\delta} T_{\Delta P}$$

so that we got the right $\delta_{P_{33}}$ phase for the $J = 3/2, I = 3/2, L = 1$ channel.

Things are more complicated that described here and, in fact, we have only been able to impose this condition on the dominant vector and axial multipoles for which we use different δ_V and δ_A Olsson phases.

Pion production inside the nucleus I

Our starting point is the differential cross section at the nucleon level. For instance for CC processes and massless neutrinos we have

$$\frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi dE_\pi} = 2\pi \frac{G_F^2}{4\pi^2}\frac{|\vec{k}_\pi|}{|\vec{k}|}\frac{1}{4E_N}\frac{1}{(2\pi)^3}\int d\Omega' dE' |\vec{k}'| \frac{1}{2E_{N'}}\,\delta(E_N + q^0 - E_\pi - E_{N'})\,\mathcal{L}_{\mu\sigma}\mathcal{W}^{\mu\sigma}$$

with

$$q = k - k',\ E_{N'} = \sqrt{M^2 + (\vec{p}_N + \vec{q} - \vec{k}_\pi)^2}$$

$$\mathcal{L}_{\mu\sigma} = k_\mu k'_\sigma + k_\sigma k'_\mu - k\cdot k' g_{\mu\sigma} + i\epsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta$$

$$\mathcal{W}^{\mu\sigma}(p_N, q, k_\pi) = \overline{\sum_{\text{spins}}}\left\langle N'\pi | j^\mu_{CC}(0) | N\right\rangle \left\langle N'\pi | j^\sigma_{CC}(0)|N\right\rangle^*$$

For incoherent production on a nucleus we have to sum over all nucleons in the nucleus.

Pion production inside the nucleus II

We assume the nucleus can be described by its density and we shall use the local density approximation

The cross section at the nucleus level for initial pion production (prior to any FSI) is then

$$\frac{d\sigma}{d\cos\theta_\pi dE_\pi} = \int d^3r \sum_{N=n,p} 2 \int \frac{d^3p_N}{(2\pi)^3}\, \theta(E_F^N(r) - E_N)\, \theta(E_N + q^0 - E_\pi - E_F^{N'}(r)) \times \frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi dE_\pi}$$

To compare with experiment, we have to convolute it with the neutrino flux $\Phi(|\vec{k}|)$

$$\frac{d\sigma}{d\cos\theta_\pi\, dE_\pi} = \int d|\vec{k}|\, \Phi(|\vec{k}|)\, 4\pi \int dr r^2 \sum_{N=n,p} 2 \int \frac{d^3p_N}{(2\pi)^3}\, \theta(E_F^N(r) - E_N)\, \theta(E_N + q^0 - E_\pi - E_F^{N'}(r)) \times \frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi dE_\pi}$$

Pion production inside the nucleus III

From there we obtain

$$\frac{d\sigma}{d|\vec{k}|\,4\pi r^2 dr\, d\cos\theta_\pi\, dE_\pi} = \Phi(|\vec{k}|)\sum_{N=n,p} 2\int \frac{d^3p_N}{(2\pi)^3}\,\theta(E_F^N(r) - E_N)\,\theta(E_N + q^0 - E_\pi - E_F^{N'}(r))$$

$$\times \frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi dE_\pi}$$

Apart from modifications discussed in what follows, the above differential cross section is used in our simulation code to generate, in a given point inside the nucleus, and by neutrinos of a given energy, pions with a certain charge, energy and momentum direction.

Defining $P = q - k_\pi$ (the four momentum transferred to the nucleus) and writing $d^3p_N = d\cos\vartheta_N\, d\phi_N\, |\vec{p}_N| E_N dE_N$, where the angles are referred to a system in which the Z axis is along $\vec{P}$, we can integrate in the ϑ_N variable using the energy delta function present in $\frac{d\sigma(\nu N\to l^- N'\pi)}{d\cos\theta_\pi dE_\pi}$

Pion production inside the nucleus IV

The final result is

$$\frac{d\sigma}{d|\vec{k}|4\pi r^2\, dr\, d\cos\theta_\pi\, dE_\pi} = \Phi(|\vec{k}|)\int d\Omega' dE' |\vec{k}'| \Bigg\{ \sum_{N=n,p} \frac{G_F^2}{512\pi^7}\frac{|\vec{k}_\pi|}{|\vec{P}|\,|\vec{k}|}\theta(E_F^N(r)-\mathcal{E})\,\theta(-P^2)\,\theta(P^0)\,\mathcal{L}_{\mu\sigma}(k,k')$$

$$\int_0^{2\pi} d\phi_N \int_{\mathcal{E}}^{E_F^N(r)} dE_N \mathcal{W}^{\mu\sigma}(p_N,q,k_\pi)\Bigg|_{\cos\vartheta_N=\cos\vartheta_N^0}\Bigg\},$$

where

$$\cos\vartheta_N^0 = \frac{P^2+2E_N P^0}{2|\vec{p}_N||\vec{P}|},\ \mathcal{E}' = \frac{-P^0+|\vec{P}|\sqrt{1-4M^2/P^2}}{2},\ \mathcal{E} = \max\{M, E_F^{N'} - P^0, \mathcal{E}'\}.$$

To speed up the computational time, we approximate the last two integrals by

$$\int_0^{2\pi} d\phi_N \int_{\mathcal{E}}^{E_F^N(r)} dE_N \mathcal{W}^{\mu\sigma}(p_N,q,k_\pi)\Bigg|_{\cos\vartheta_N=\cos\vartheta_N^0} \approx 2\pi(E_F^N(r)-\mathcal{E})\mathcal{W}^{\mu\sigma}(\tilde{p}_N,q,k_\pi)\Bigg|_{\cos\vartheta_N=\cos\vartheta_N^0}$$

where $\tilde{p}_N$ is evaluated at the value $\tilde{E}_N = (E_F^N(r)+\mathcal{E})/2$, (middle of the integration interval), with the corresponding $\cos\tilde{\vartheta}_N^0$ value, and $\tilde{\phi}_N$ is set to zero.

Similar approximations were done, in the works of Carrasco et al. and Gil et al. to study pion photo- and electroproduction in nuclei.

Medium corrections I

Δ properties are strongly modified in the nuclear medium.

Its imaginary part changes due to

- Pauli blocking of the final nucleon which reduces the free width.
- In medium modification of the pionic decay width other than Pauli blocking
- Absorption processes $\Delta N \to NN$ and $\Delta NN \to NNN$.

We thus modify the Δ propagator of the direct Δ contribution approximating

$$\frac{1}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta} \approx \frac{1}{\sqrt{p_\Delta^2} + M_\Delta} \frac{1}{\sqrt{p_\Delta^2} - M_\Delta + i\Gamma_\Delta/2}$$

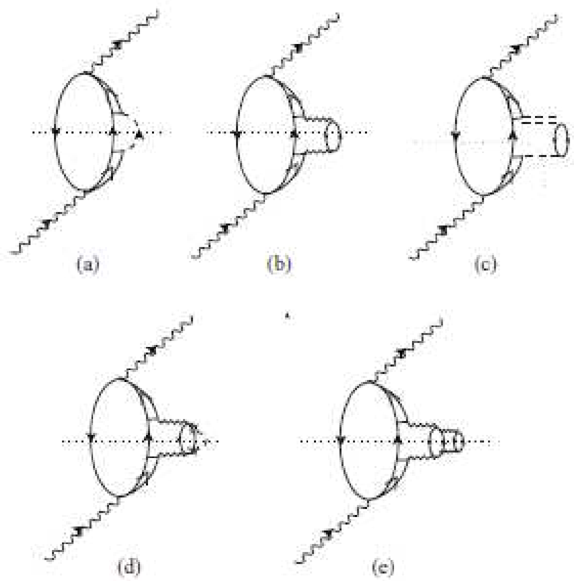
and substituting

$$\frac{\Gamma_\Delta}{2} \to \frac{\Gamma_\Delta^{\mathrm{Pauli}}}{2} - \mathrm{Im}\,\Sigma_\Delta$$

while keeping M_Δ in the particle propagator unchanged.

Medium corrections II

Delta width in a nuclear medium



The double dashed line represents the effective spin-isospin interaction originated by π and ρ exchange in the presence of short range correlations.

The wavy line includes an RPA sum with particle-hole and Delta-hole excitations.

The evaluation of $\mathrm{Im}\,\Sigma_{\Delta}$ was done by E. Oset and L.L. Salcedo [Nuc. Phys. A468 (1987) 631].

Incoherent pion production in nuclei. Medium corrections III

The imaginary part can be parameterized as

$$-\mathrm{Im}\,\Sigma_\Delta = C_Q\left(\frac{\rho}{\rho_0}\right)^\alpha + C_{A2}\left(\frac{\rho}{\rho_0}\right)^\beta + C_{A3}\left(\frac{\rho}{\rho_0}\right)^\gamma$$

with $\rho_0 = 0.17\,\text{fm}^{-3}$.

- The C_Q term corrects the pionic decay in the medium.
- The C_{A2} term corresponds to the process $\Delta N \to NN$
- The C_{A3} term corresponds to the $\Delta NN \to NNN$ process

The C_Q, α, C_{A2}, β and C_{A3}, γ coefficients are parametrized as a function of the kinetic energy of a pion that would excite a Δ of the corresponding invariant mass and are valid in the range $85\,\mathrm{MeV} < T_\pi < 315\,\mathrm{MeV}$.

Below 85 MeV the contributions from C_Q and C_{A3} are rather small and we take them from Nieves et al. [Nuc. Phys. A 554 (1993) 554], where the model was extended to lower energies. The term with C_{A2} shows a very mild energy dependence and we still use the original parameterization even at low energies.

For T_π above 315 MeV, we have kept these self-energy terms constant and equal to their values at the bound. The uncertainties in these pieces are not very relevant there because the $\Delta \to N\pi$ decay becomes very large and dominant.

Incoherent pion production in nuclei. Medium corrections IV

The C_Q term not only modifies the Δ propagator but it also gives rise to a new source of pion production in the nuclear medium that has to be taken into account.

This new contribution has to be added incoherently and we implement it in a approximate way by taking as amplitude square for this process the amplitude square of the ΔP contribution multiplied by

$$\frac{C_Q(\rho/\rho_0)^\alpha}{\Gamma_\Delta^{\rm Free}/2}$$

Its effect increases the total pion production cross section by less that 10%

Final state interaction

Once the pions are produced, we follow their path on its way out of the nucleus.

We use, with slight modifications, the model of L.L. Salcedo et al. [Nuc. Phys. A484 (1988) 557]

- P and S-wave pion absorption.
- P and S-wave quasielastic scattering on a nucleon.
  - Pions change energy and direction.
  - Pions could change charge.
- Pion propagate on straight lines in between collisions.

The P- wave interaction is mediated by the Δ resonance excitation where the different contributions to the imaginary part of its self-energy give rise to pion two- and three-nucleon absorption and quasielastic processes.

The intrinsic probabilities for each of the above mentioned reactions are evaluated microscopically as a function of the density and we use the local density approximation to evaluate them in finite nuclei.

The MonteCarlo program. Generating an event

Let us take as an example the $\nu_\mu N \to \mu^- \pi N'$ process for wich we have three different channels $\nu_\mu p \to \mu^- \pi^+ p$, $\nu_\mu n \to \mu^- \pi^+ n$ and $\nu_\mu n \to \mu^- \pi^0 p$

- For a given event, the neutrino energy is selected according to the $\Phi(|\vec{k}\,|)$ flux distribution function using the acceptance-rejection method.
- Knowing the neutrino energy $|\vec{k}_0|$ we generate the distance from the nucleus center where the interaction takes place using the distribution

$$r^2 \int d\cos\theta_\pi \int dE_\pi \left.\frac{d\sigma(p\pi^+ + n\pi^+ + p\pi^0)}{d|\vec{k}\,|4\pi r^2 dr\, d\cos\theta_\pi\, dE_\pi}\right|_{|\vec{k}\,|=|\vec{k}_0|}$$

  while the polar angles for the position are “evenly” distributed ($\cos\theta \in [-1, 1], \varphi \in [0, 2\pi]$)
- Next we generate the values for $cos\theta_\pi$, E_π (ϕ_π is evenly distributed in $[0, 2\pi]$) using the distribution

$$\left.\frac{d\sigma(p\pi^+ + n\pi^+ + p\pi^0)}{d|\vec{k}\,|4\pi r^2 d\cos\theta_\pi\, dE_\pi}\right|_{|\vec{k}\,|=|\vec{k}_0|, r=r_0}$$

  The pion charge is generated according to the weights

$$\left.\frac{d\sigma(p\pi^+ + n\pi^+)}{d|\vec{k}\,|4\pi r^2 d\cos\theta_\pi\, dE_\pi}\right|_{|\vec{k}\,|=|\vec{k}_0|, r=r_0} , \quad \left.\frac{d\sigma(p\pi^0)}{d|\vec{k}\,|4\pi r^2 d\cos\theta_\pi\, dE_\pi}\right|_{|\vec{k}\,|=|\vec{k}_0|, r=r_0}$$

The MonteCarlo program. Pion progagation

- In between collisions, pions propagate in straigth lines.
- The increment $|\Delta\vec{r}|$ has to be small so that the different collision probabilities (absorption, quasielastic)

$$P_A = p_A|\Delta\vec{r}| \ll 1, \;\; P_Q = p_Q|\Delta\vec{r}| \ll 1$$

  with p_A, p_Q probabilities per unit length.
- We choose the charge q' of the pion after the quasielastic step, by means of a random number, according to the probabilities that a pion of charge q becomes one of charge q' in a collision.
- To evaluate the pion exit angle one first select a random nucleon out of the Fermi sea and studies the collision in the center of mass. There the $\varphi_\pi^{\mathrm{c.m.}}$ distribution is flat whereas $\cos\theta_\pi^{\mathrm{c.m.}}$ follows a distribution $\frac{1}{2}(1+3\cos^2\theta_\pi^{\mathrm{c.m.}})$ for P-wave scattering and a flat one for S-wave scattering, up to a maximum value dictated by Pauli blocking of the final nucleon (in the lab frame).

  Once $\varphi_\pi^{\mathrm{c.m.}}$ and $\cos\theta_\pi^{\mathrm{c.m.}}$ are generated, the pion momentum is boosted to the lab frame.

  The whole process changes the direction and the energy (it decreases) of the pion.

Coherent pion production in nuclei I

[Amaro et al., Phys. Rev D 79 (2009) 013002]

For a CC+ process, the unpolarized differential cross section is given by

$$\frac{d^5\sigma_{\nu_l l}}{d\Omega(\hat{k}')dE'd\Omega(\hat{k}_\pi)} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2} L_{\mu\sigma}\, W^{\mu\sigma}_{\mathrm{CC}\pi+}$$

The hadronic tensor includes all the nuclear effects and it can be approximated by

$$W^{\mu\sigma}_{\mathrm{CC}\pi+} = \frac{|\vec{k}_\pi|}{64\pi^3 M^2}\, \mathcal{A}^\mu_{\pi+}(q,k_\pi)\left(\mathcal{A}^\sigma_{\pi+}(q,k_\pi)\right)^*$$

where the hadronic amplitude at the nucleus level is written as a sum over the amplitudes for each nucleon. Neglecting for the moment non-localities and pion distortion one arrives at

$$\mathcal{A}^\mu_\pi(q,k_\pi) = \int d^3\vec{r}\, e^{\mathrm{i}(\vec{q}-\vec{k}_\pi)\cdot\vec{r}}\left\{\rho_p(\vec{r})\left[\mathcal{J}^\mu_{p\pi}(q,k_\pi)\right] + \rho_n(\vec{r})\left[\mathcal{J}^\mu_{n\pi}(q,k_\pi)\right]\right\}$$

$$\mathcal{J}^\mu_{N\pi}(q,k_\pi) = \frac{1}{2}\sum_r \bar{u}_r(\vec{p}\,')\Gamma^\mu_{i;N\pi} u_r(\vec{p})\frac{M}{\sqrt{p^0 p'^0}}, \quad i = \Delta P,\ C\Delta P,\ NP,\ CNP,\ CT,\ PP,\ PF$$

(We did not include the D_{13} contribution)

Coherent pion production in nuclei II

The momenta are selected as

$$p^\mu = \left(\sqrt{M^2 + \frac{1}{4}\left(\vec{k}_\pi - \vec{q}\right)^2}, \frac{\vec{k}_\pi - \vec{q}}{2} \right), \; p' = p + q - k_\pi \; , \; q^0 = k_\pi^0 \text{ (neglecting nucleus recoil)}$$

The above prescription allows to write

$$\mathcal{J}^\mu_{N\pi}(q, k_\pi) = \sum_i \mathcal{J}^\mu_{i;N\pi}(q, k_\pi), \quad i = \Delta P,\, C\Delta P,\, NP,\, CNP,\, CT,\, PP,\, PF$$

$$\mathcal{J}^\mu_{i;N\pi}(q, k_\pi) = \frac{1}{2}\mathrm{Tr}\left((\not{p} + M)\gamma^0 \Gamma^\mu_{i;N\pi} \right) \frac{M}{p^0} \; ,$$

Coherent pion production in nuclei II

Medium modification and pion distortion

- Δ properties are strongly modified inside the nuclear medium. We consider selfenergy modifications due to quasielastic, two and three nucleon absorption and Pauli blocking.

$$\Gamma_\Delta/2 \to \Gamma_\Delta^{\rm Pauli}/2 - {\rm Im}\Sigma_\Delta$$
$$M_\Delta \to M_\Delta + {\rm Re}\Sigma_\Delta \approx M_\Delta + 40\,{\rm MeV}\,\frac{\rho}{\rho_0}$$

Now $\mathcal{J}^\mu_{N\pi^+}(\vec r; q, k_\pi)$ becomes in effect $\vec r-$dependent so that factorization of the nuclear form factor is no longer possible.

- Pion distortion effects are also very important, specially for $|\vec k_\pi| < 0.5$ GeV

$$e^{-{\rm i}\vec k_\pi\cdot\vec r} \quad \to \quad \widetilde\varphi^*_\pi(\vec r; \vec k_\pi)$$

$$\left[-\vec\nabla^2 + m_\pi^2 + 2E_\pi V_{\rm opt}(\vec r)\right]\widetilde\varphi^*_\pi(\vec r;\vec k_\pi) = E_\pi^2\widetilde\varphi^*_\pi(\vec r;\vec k_\pi)$$

$V_{\rm opt}$ is explained in J. Nieves et al. Nucl. Phys. A554 (1993) 509. It reproduces fairly well the data of pionic atoms and low-energy pion-nucleus scattering.

- Nonlocalities in pion momentum

$$\vec k_\pi e^{-{\rm i}\vec k_\pi\cdot\vec r} \quad \to \quad {\rm i}\vec\nabla\widetilde\varphi^*_\pi(\vec r;\vec k_\pi) \;\; (\text{only first order terms in } {\rm k}_\pi)$$

Coherent pion production in nuclei III

Medium modification and pion distortion

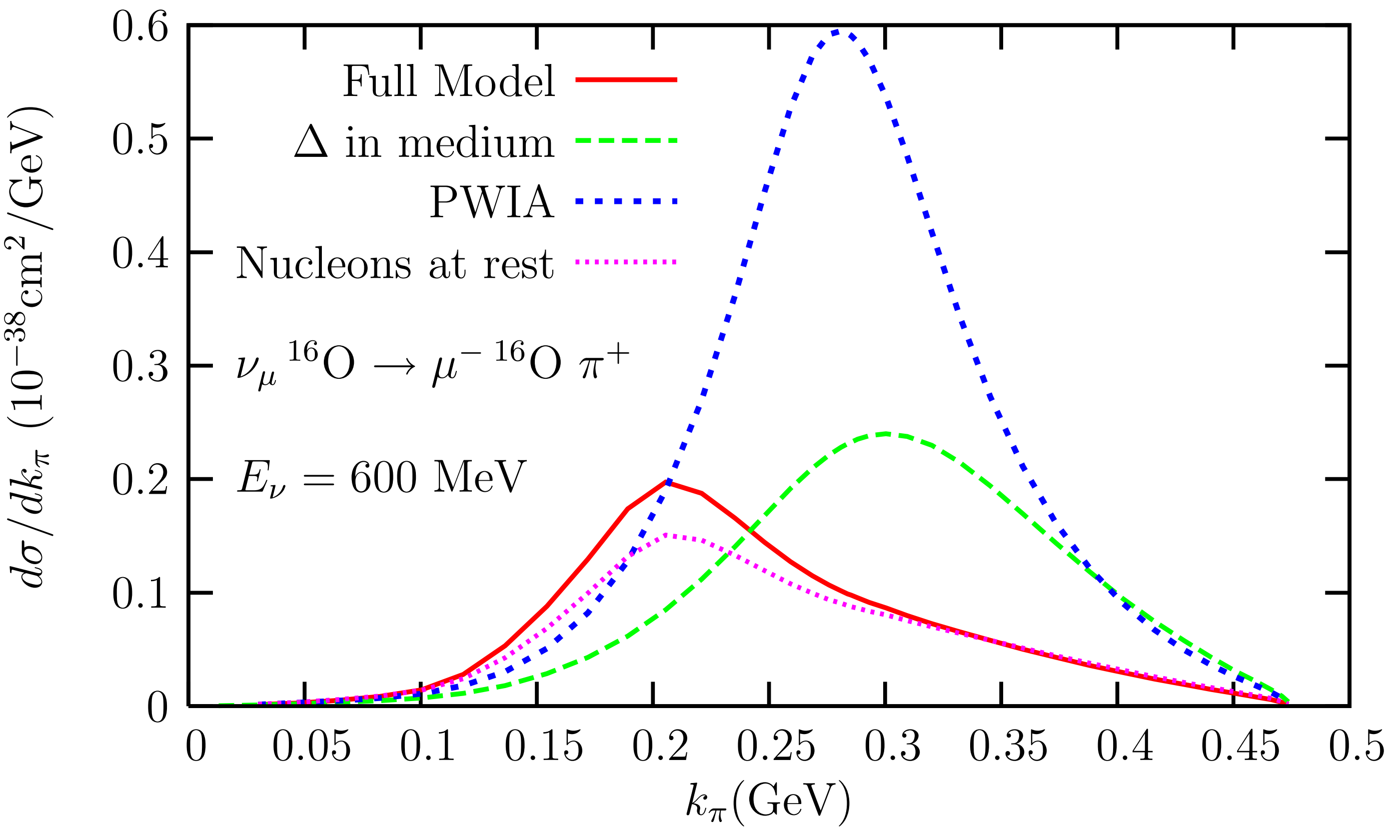


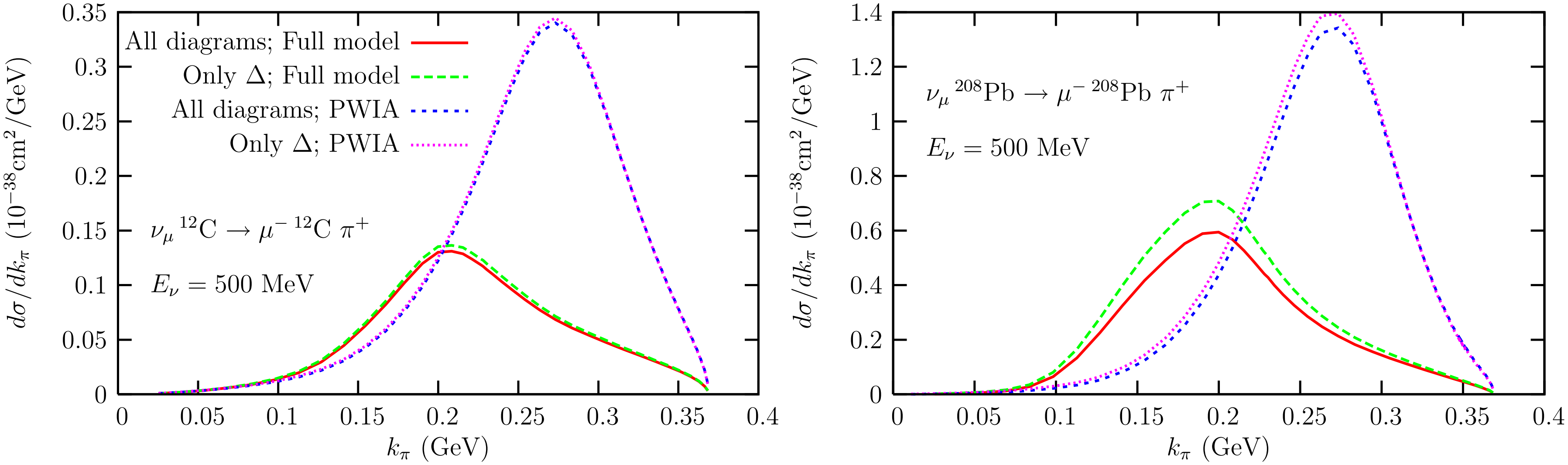
Figure taken from E. Amaro et al.[Phys. Rev. D79 (2009) 013002]

Coherent pion production in nuclei IV

Irrelevance of background terms for coherent production

- CC case
  - $\mathcal{J}^{\mu}_{PF;N\pi^+}(q,k_\pi) = 0$ (Due to the trace)
  - $\mathcal{J}^{\mu}_{CT;p\pi^+}(q,k_\pi) = -\mathcal{J}^{\mu}_{CT;n\pi^+}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei
  - $\mathcal{J}^{\mu}_{PP;p\pi^+}(q,k_\pi) = -\mathcal{J}^{\mu}_{PP;n\pi^+}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei
  - $\mathcal{J}^{\mu}_{NP;p\pi^+}(q,k_\pi) = 0, \mathcal{J}^{\mu}_{CNP;n\pi^+}(q,k_\pi) = 0$
- NC case
  - $\mathcal{J}^{\mu}_{PF;N\pi^0}(q,k_\pi) = 0$
  - $\mathcal{J}^{\mu}_{CT;N\pi^0}(q,k_\pi) = 0$
  - $\mathcal{J}^{\mu}_{PP;N\pi^0}(q,k_\pi) = 0$
  - $\mathcal{J}^{\mu}_{NP;p\pi^0}(q,k_\pi) = -\mathcal{J}^{\mu}_{NP;n\pi^0}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei
  - $\mathcal{J}^{\mu}_{CNP;p\pi^0}(q,k_\pi) = -\mathcal{J}^{\mu}_{CNP;n\pi^0}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei

Coherent pion production in nuclei V
Irrelevance of background terms for coherent production

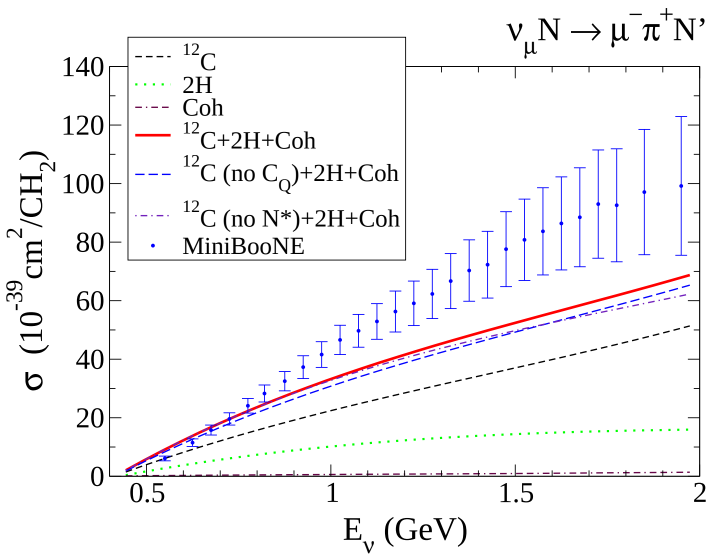


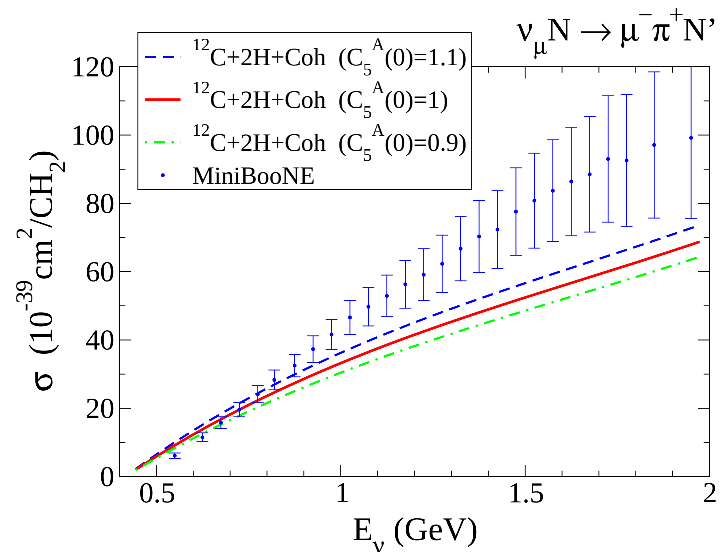
Figures taken from E. Amaro et al.[Phys. Rev. D79 (2009) 013002]

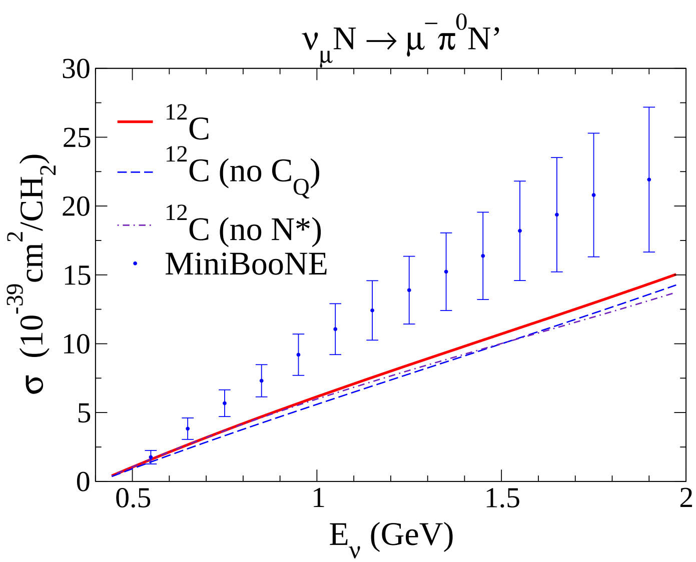
Old results for MiniBooNE (CH_2 target) I

The model is the one in E. Hernández et al. [Phys. Rev. D87 (2013) 113009] which means Watson theorem is not implemented and there is no modification in the Delta propagator (no extra contact term). There, we also used $C_5^A(0) = 1.00 \pm 0.11$ as compared to the present value $C_5^A(0) = 1.18 \pm 0.07$.

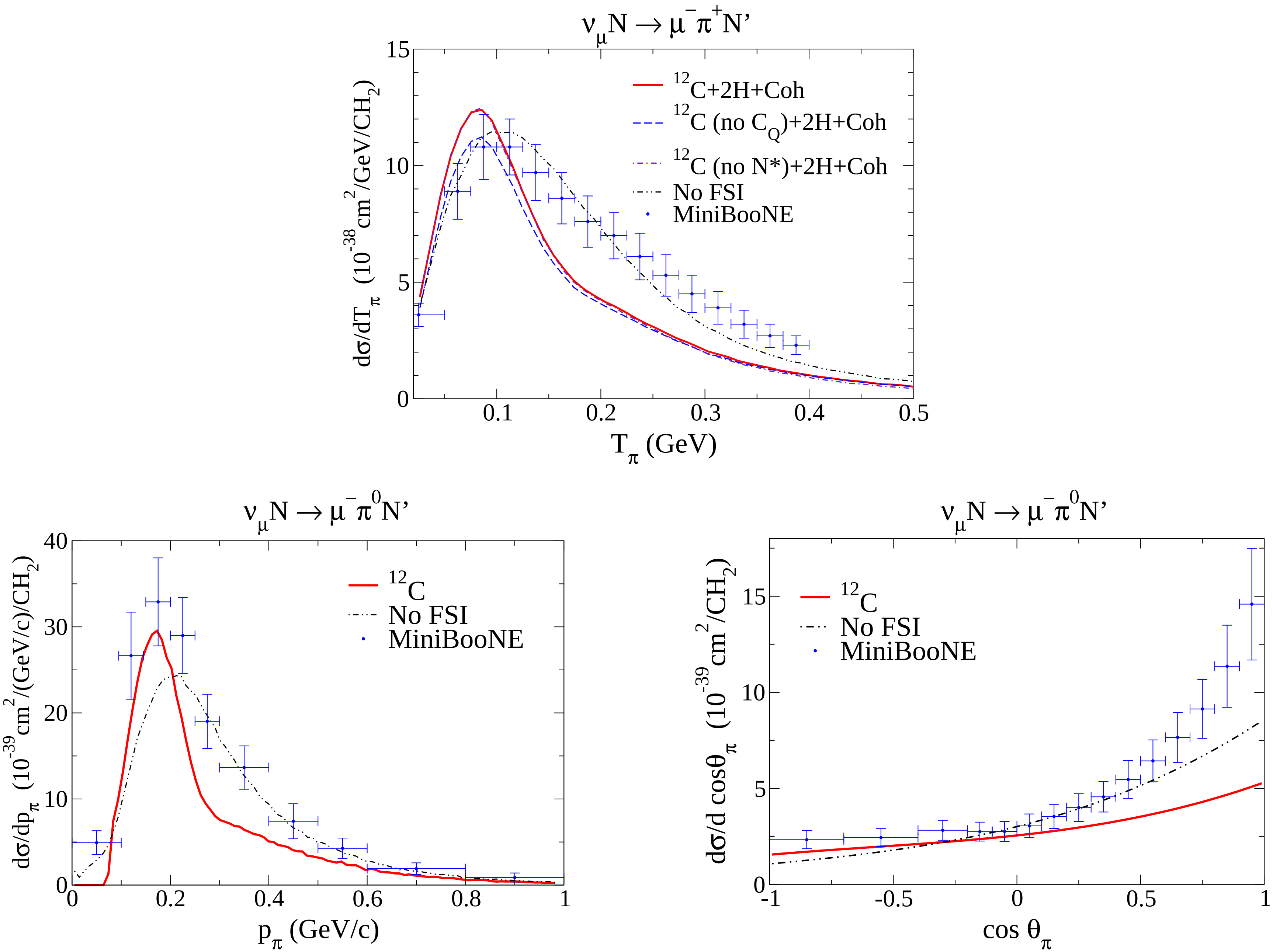
MiniBooNE data taken from A. Aguilar-Arevalo et al. [PRD83 (2011) 052007].



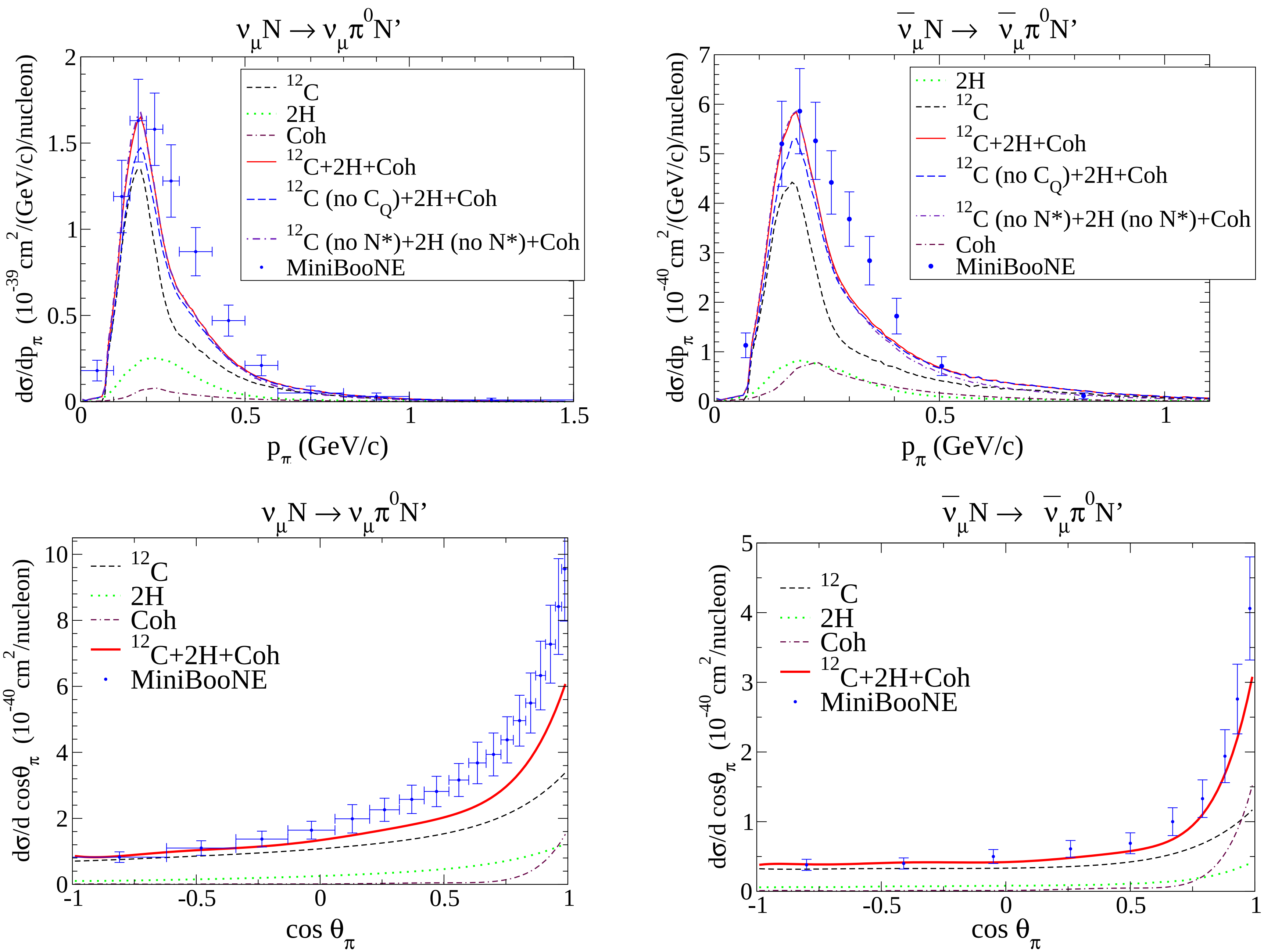




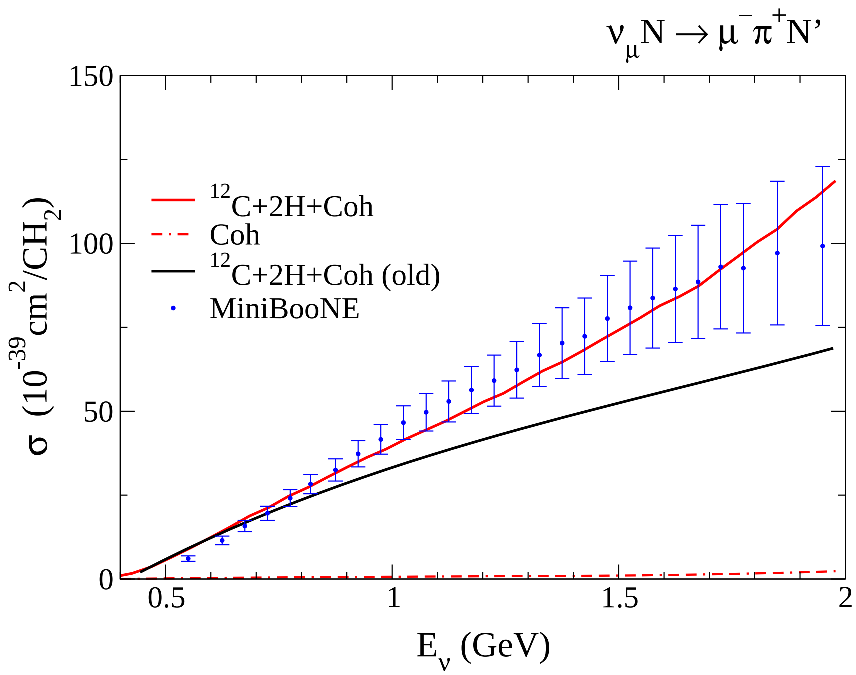
Old results for MiniBooNE (CH_2 target) II

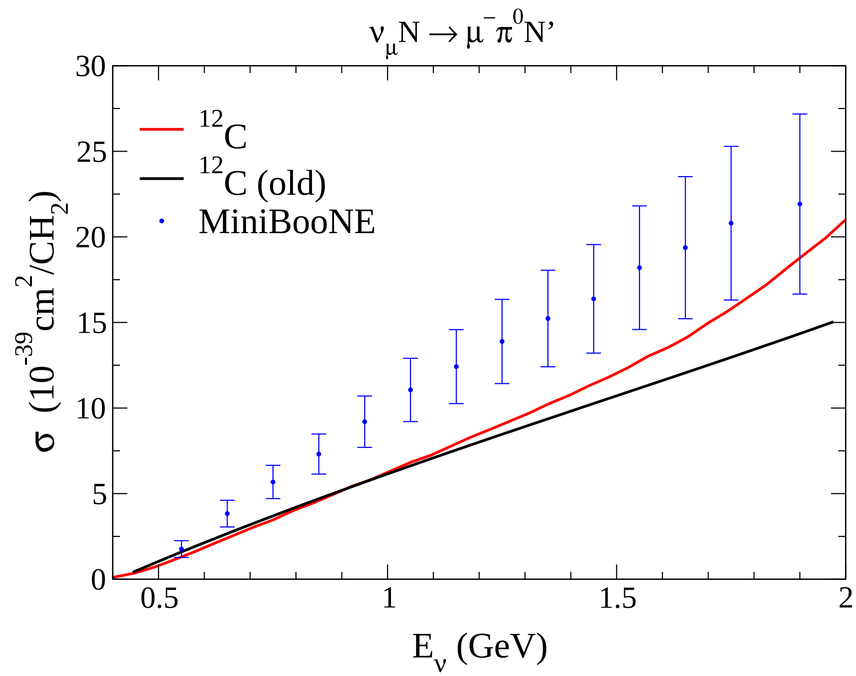


Old results for MiniBooNE (CH_2 target) II



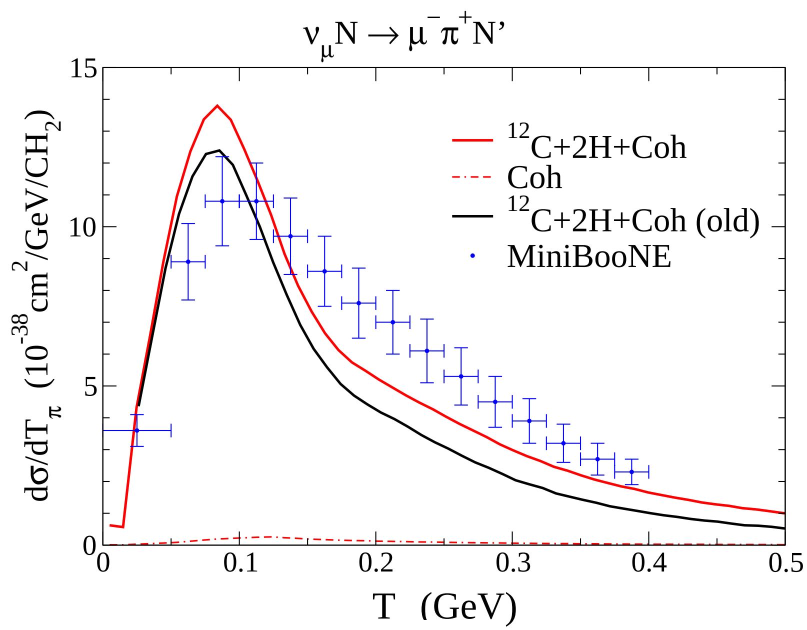
New (preliminary) results for MiniBooNE (CH_2 target) I

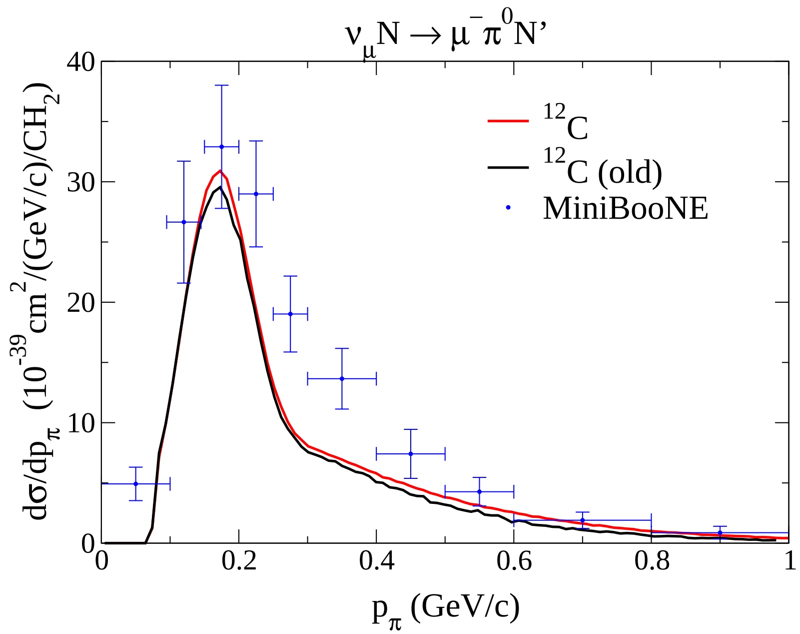


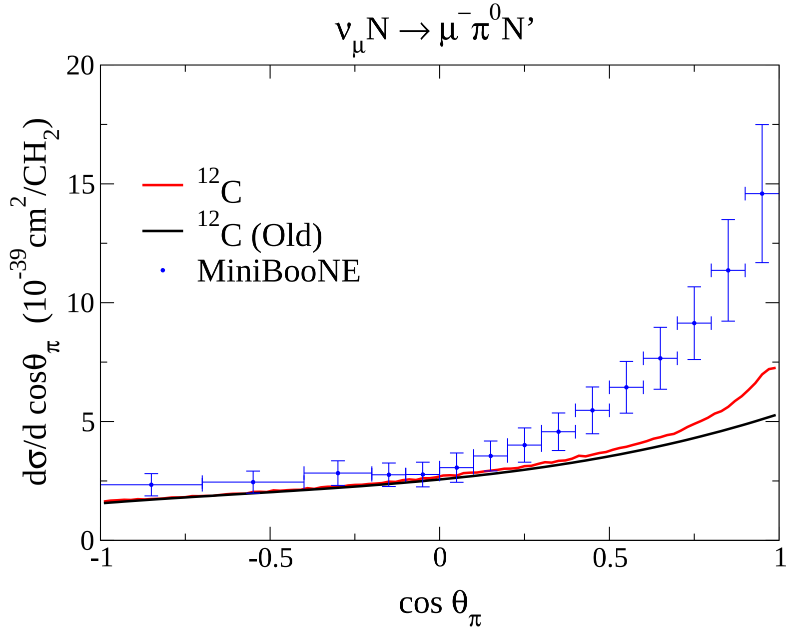


We get a better agreement at higher energies than before.

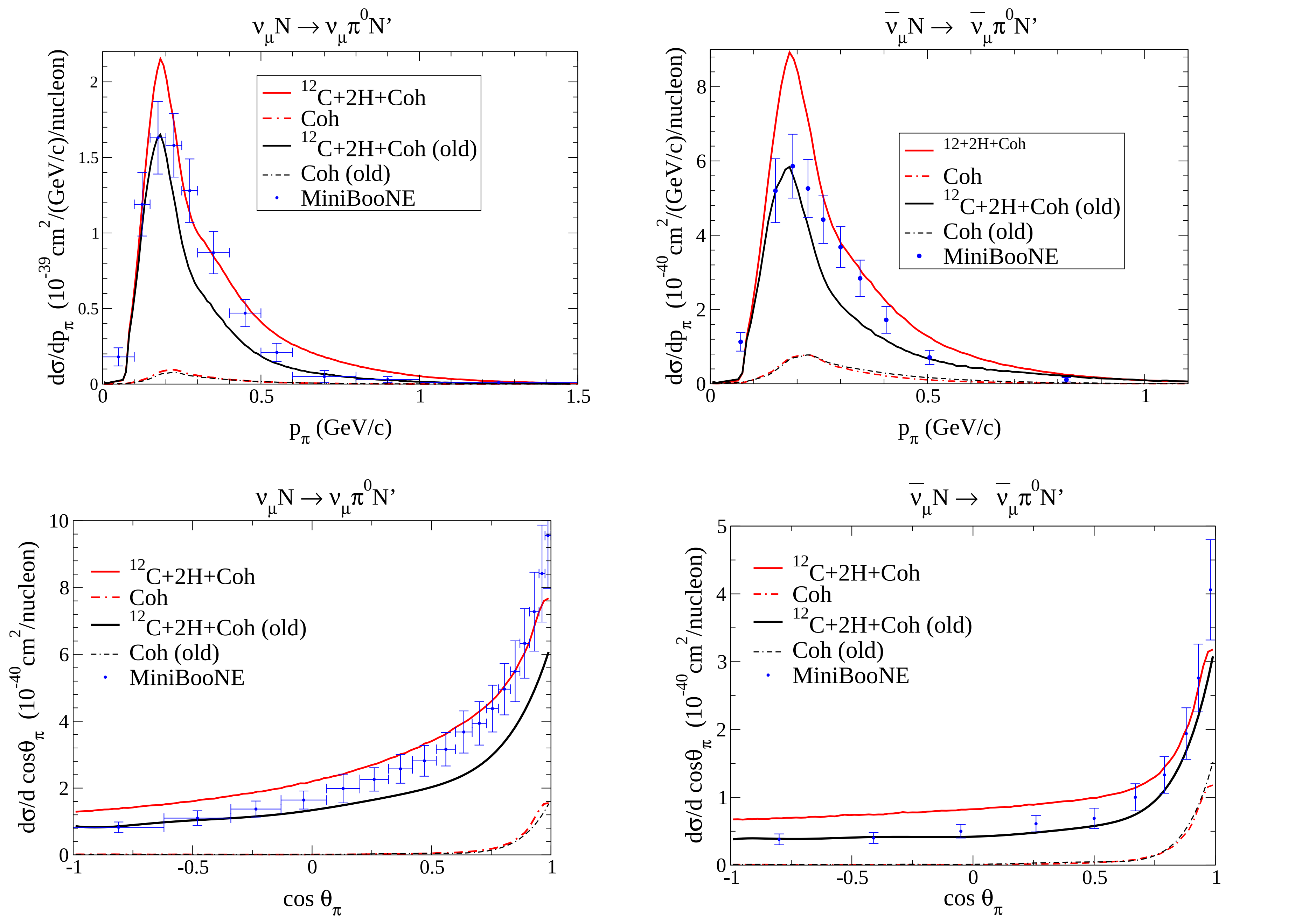
New (preliminary) results for MiniBooNE (CH_2 target) II





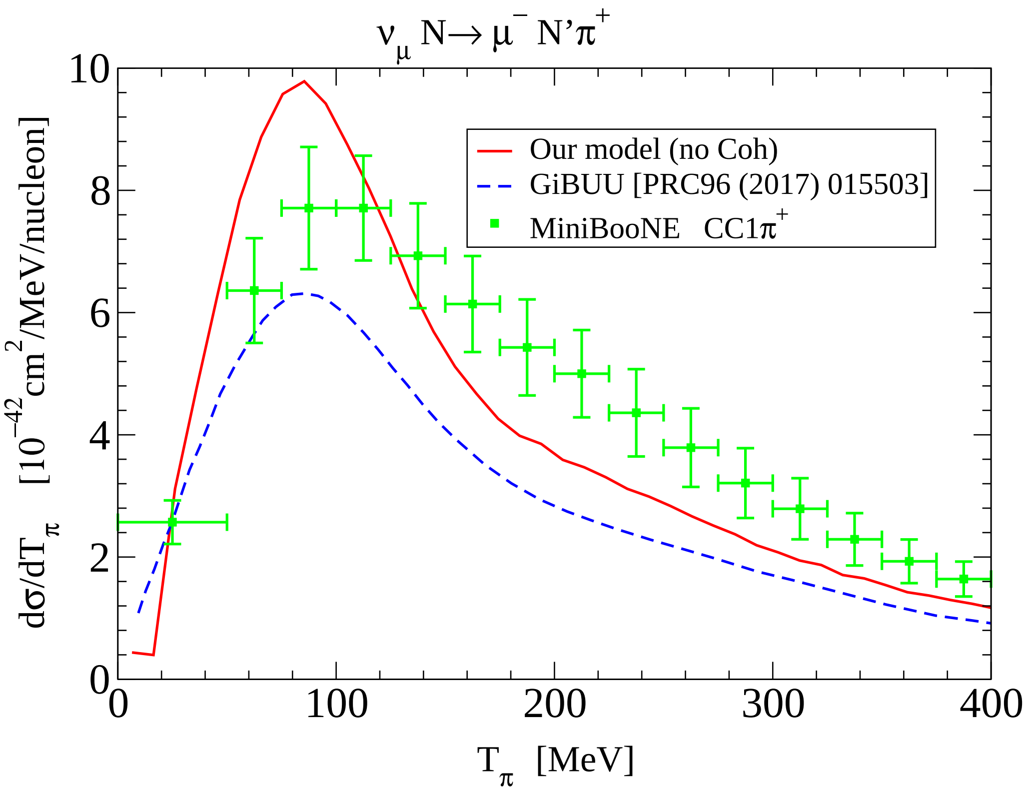


New (preliminary) results for MiniBooNE (CH_2 target) II



New (preliminary) results for MiniBooNE (CH_2 target)III

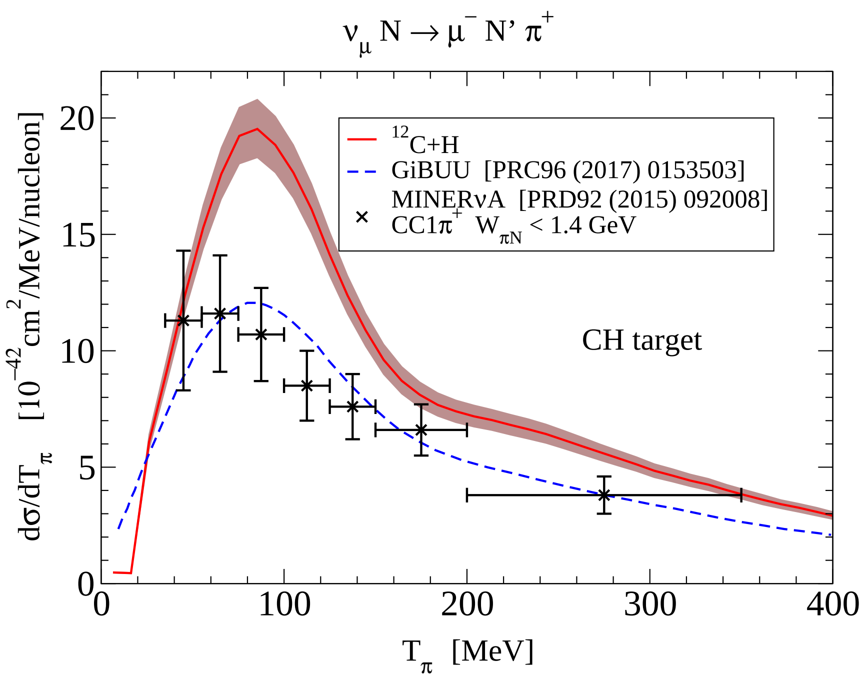
Comparison with GiBUU [PRC96 (2017) 015503]

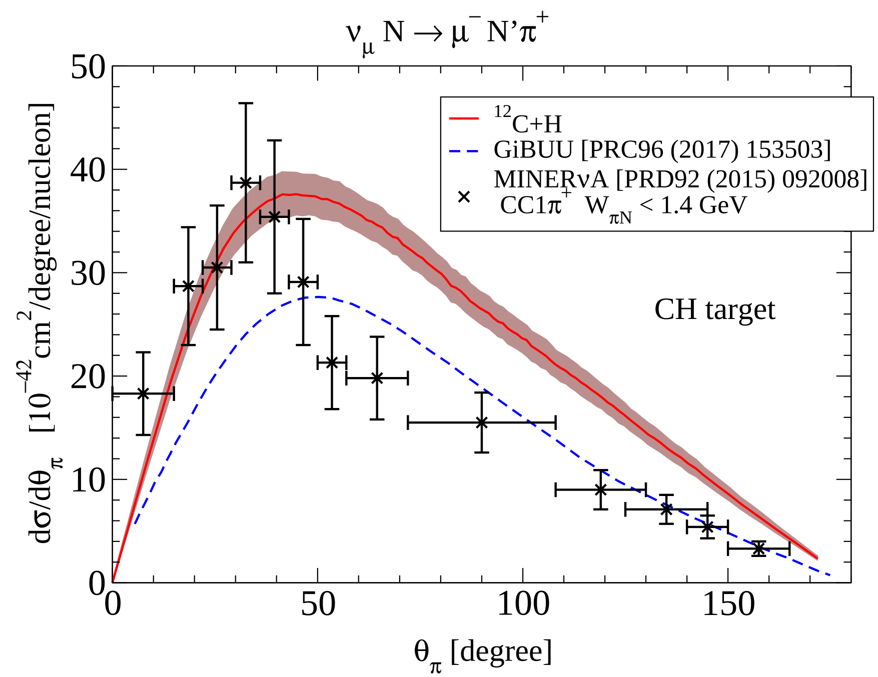


Our results for high energy pions are in better agreement with experiment.

New (preliminary) results for MINERνA (CH target)

We integrate the MINERνA flux up to $E_\nu = 5\,$GeV.



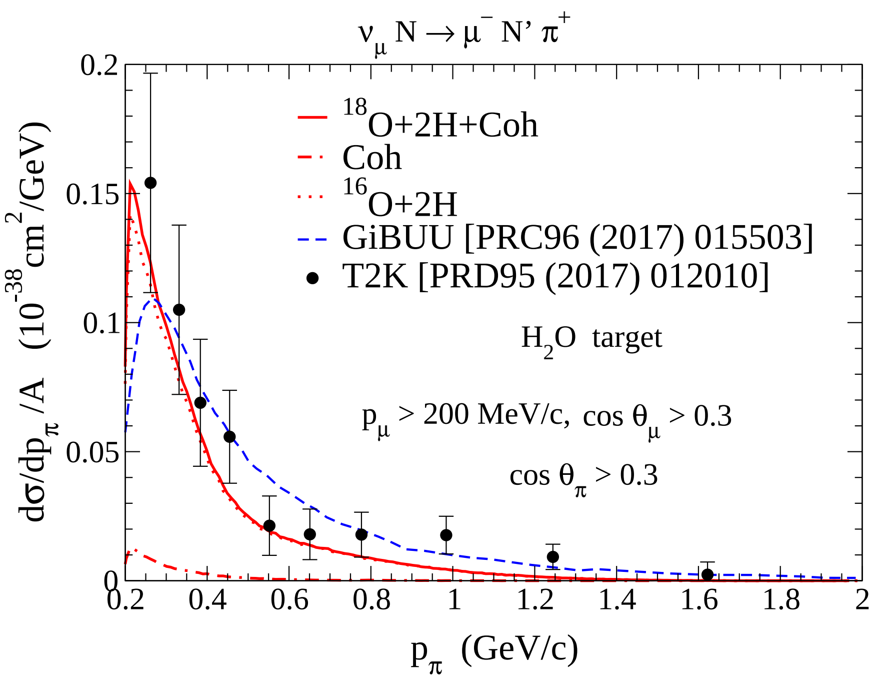


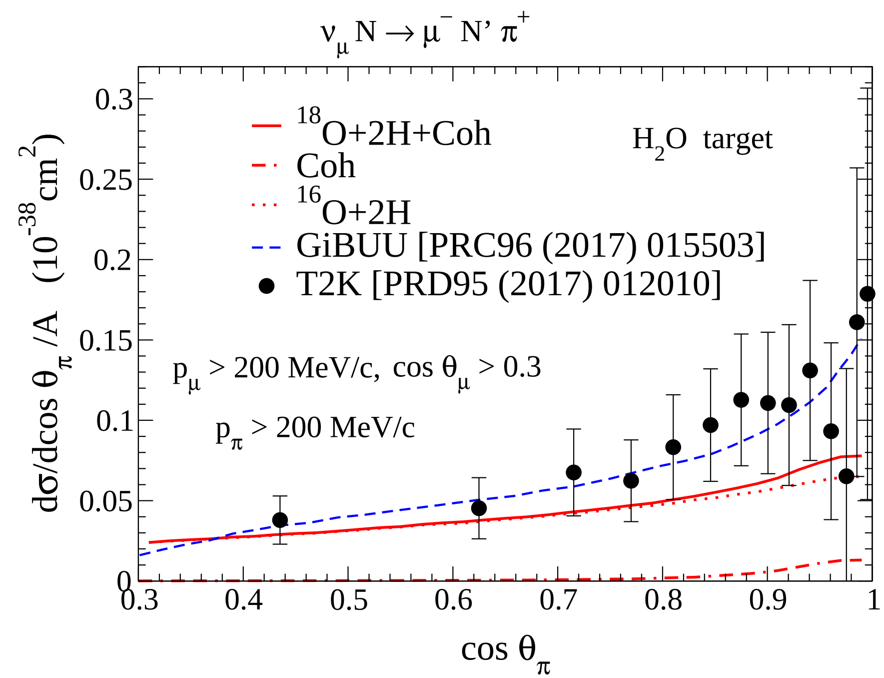
We produce too many pions in the backward direction while GiBUU underestimates the production of forward pions.

GiBUU gives a good reproduction of the $d\sigma/dT_\pi$ differential cross section

New (preliminary) results for T2K (H_2O target)

We integrate the T2K flux up to $E_\nu = 2$ GeV.
We implement the cuts on the muon momentum on production (neglecting FSI for the muon)





$< \sigma >_\phi^{\rm exp.} = 4.25 \pm 0.48 \pm 1.56 \times 10^{-40} {\rm cm}^2$

$< \sigma >_\phi^{\rm GiBUU} \approx 4.0 \times 10^{-40} {\rm cm}^2$ (it does not include coherent)

$< \sigma >_\phi^{\rm ours} \approx 2.9 \times 10^{-40} {\rm cm}^2$

Summary

- For pion production in nuclei we modify our microscopic model at the nucleon level by means of different medium corrections.
  - Δ propagator is modified inside the medium.
  - New net contribution to pion decay due to the in medium modification of the pionic width of the Δ.
- A MonteCarlo program is used to evaluate production and final state interaction (Quasielastic scattering and absorption) of the outgoing pion
- We have also included coherent pion production which is of some relevance for NC channels.

Summary

- Our present reproduction of CC processes has improved for MiniBooNE but we now produce too many backward pions in the case of NC processes.
- For T2K, our results agree with data within errors but our cross sections are smaller, mainly for forward pions.
- In the case of MINERνA (data with $W_{\pi N} < 1.4$ GeV) we also produce too many pions in the backward direction.