NuFact10

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GiBUU and Neutrino-Nucleus scattering

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NEUTRINO-NUCLEUS INTERACTIONS IN A COUPLED-CHANNEL HADRONIC TRANSPORT MODEL

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Dissertation

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2009

Gi what?

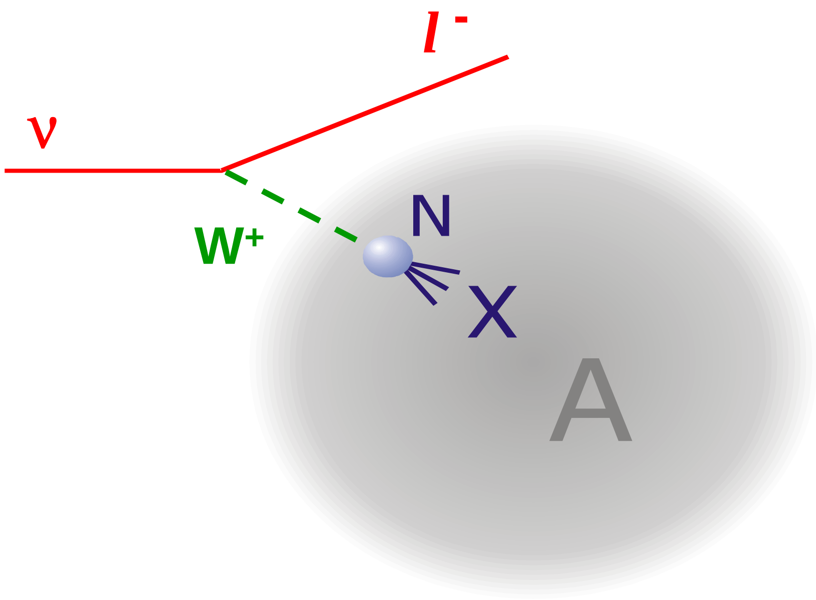
Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

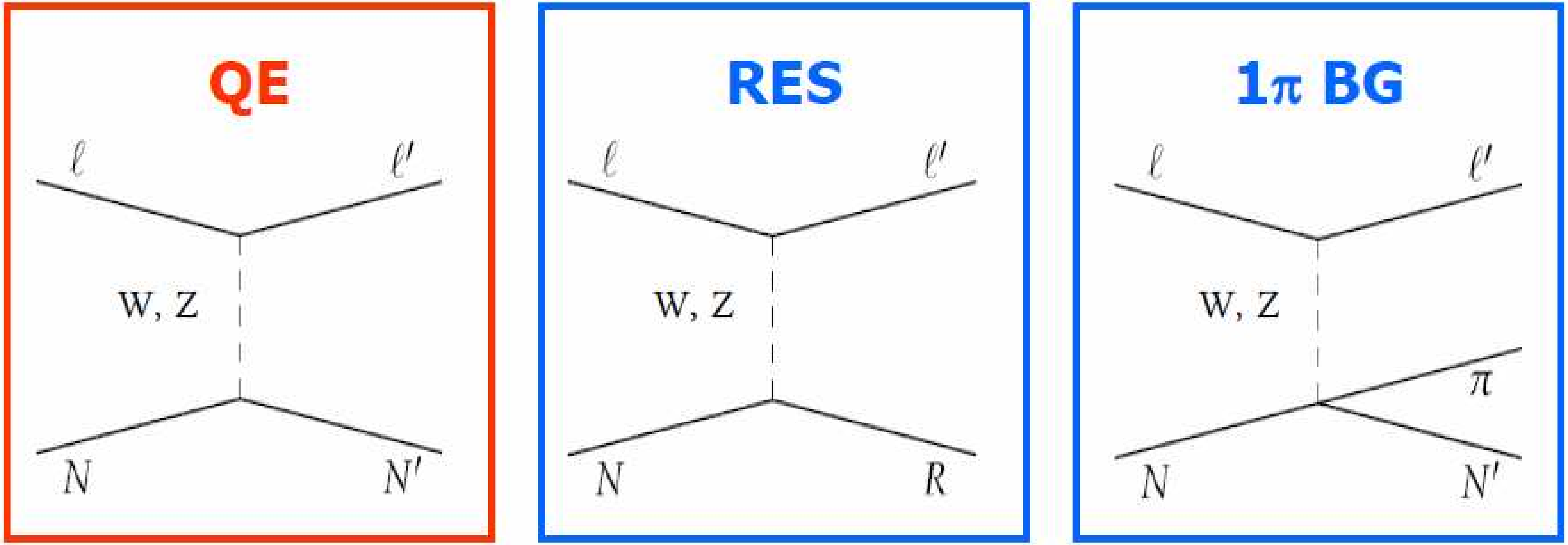
- GiBUU: semiclassical transport model in coupled channels
  - Heavy ion collisions
  - pA, πA reactions
  - γA, eA scattering
  - νA reactions
    - inclusive and exclusive
    - no new parameters
- Information & code: http://gibuu.physik.uni-giessen.de/

Ingredients



1. Primary interaction: ν_l N $\rightarrow$ l^- (ν_l) X
2. Medium modifications
3. Propagation of the final state (FSI)

Elementary νN interactions



1. Primary interaction: ν_l N $\rightarrow$ l^- (ν_l) X
   - on a single nucleon (Impulse Approximation)

Elementary νN interactions

- $l(k) + N(p) \to l'(k') + X(p')$
  - Cross section:

$$\frac{d\sigma_X}{d\omega\ d\Omega_{k'}} = \frac{|\vec{k}'|}{32\pi^2} \frac{\mathcal{A}(p'^2)}{\left[(k\cdot p)^2 - m_l^2 M_N^2\right]^{1/2}} |\bar{\mathcal{M}}_X|^2$$

  - X=R: $\mathcal{A}(p'^2) = \frac{\sqrt{p'^2}}{\pi} \frac{\Gamma(p')}{(p'^2 - M_R^2)^2 + p'^2\Gamma^2(p')}$
  - X=N: $\mathcal{A}(p'^2) = \delta(p'^2 - M_N^2)$
  - Matrix element: $|\bar{\mathcal{M}}_X|^2 = C^2 L_{\alpha\beta} H^{\alpha\beta}$

$$C_{EM} = \frac{4\pi\alpha}{q^2},\ C_{CC} = \frac{G_F \cos\theta_C}{\sqrt{2}},\ C_{NC} = \frac{G_F}{\sqrt{2}}$$

Elementary νN interactions

- $l(k) + N(p) \rightarrow l'(k') + X(p')$
  - Hadronic tensor: $H^{\alpha\beta} \Rightarrow J^{\alpha}_{X}$
    - depends on the specific process
    - parametrized in terms of form factors
  - X = nucleon
  - X = resonance with $M_R < 2$ GeV
    - Spin 1/2: $P_{11}(1440)$, $S_{11}(1535)$, $S_{31}(1620)$, $S_{11}(1650)$, $P_{31}(1910)$

$$J^{\mu}_{1/2} = \left[\frac{(Q^2\gamma^\mu + \not{q}\, q^\mu)}{2M_N^2} F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_\alpha F_2^V + \gamma^\mu\gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P \right] \left\{ \begin{array}{c} 1 \\ \gamma_5 \end{array} \right\}$$

- Spin 3/2: $P_{33}(1232)$, $D_{13}(1520)$, $D_{33}(1700)$, $P_{13}(1720)$

$$J^{\alpha\mu}_{3/2} = \left[\frac{C_3^V}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M_N^2}(g^{\alpha\mu} q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu} q\cdot p - q^\alpha p^\mu) \right.$$

$$\left. + \left(\frac{C_3^A}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M_N^2}(g^{\alpha\mu} q\cdot p' - q^\alpha p'^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^\alpha q^\mu \right)\gamma_5 \right] \left\{ \begin{array}{c} \gamma_5 \\ 1 \end{array} \right\}$$

- Spin > 3/2: $D_{15}(1675)$, $F_{15}(1680)$, $F_{35}(1905)$, $F_{37}(1950)$
  - Treated as spin 3/2
  - negligible contributions to c.s.

Elementary νN interactions

- $l(k) + N(p) \to l'(k') + X(p')$
  - N-R vector form factors:
  - MAID Drechsel, Kamalov, Tiator, EPJA 34 (2007) 69

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = -1/2 \right\rangle \zeta$$

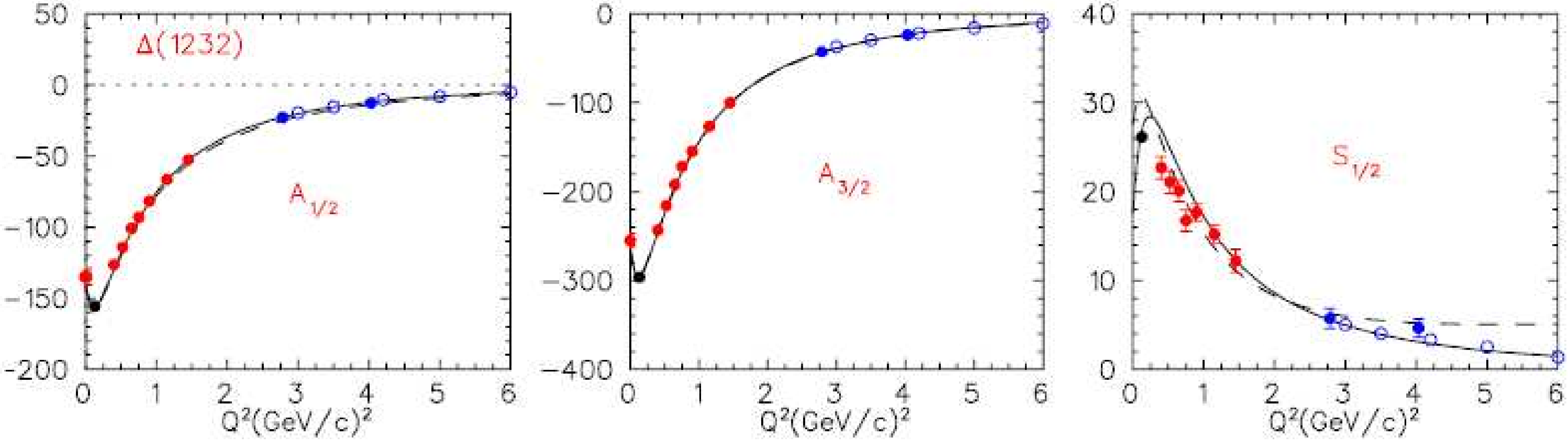
$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \frac{|\mathbf{q}|}{\sqrt{Q^2}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^0 J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

  - Helicity amplitudes $\Rightarrow$ Vector form factors

Elementary νN interactions

- $l(k) + N(p) \to l'(k') + X(p')$
  - N-R vector form factors:
  - MAID Drechsel, Kamalov, Tiator, EPJA 34 (2007) 69
    - Example: N-Δ(1232)



  - Helicity amplitudes $\Rightarrow$ Vector form factors

Elementary νN interactions

- $l(k) + N(p) \rightarrow l'(k') + X(p')$
  - N-R axial form factors:
    - PCAC
    - π-pole dominance of the pseudoscalar form factor
    - Spin 1/2:

$$F_P(Q^2) = \frac{(M_R \pm M_N)M_N}{Q^2 + m_\pi^2} F_A(Q^2)$$

$$F_A(0) = -C_I \sqrt{2} f_\pi \frac{f}{m_\pi}$$

$$\begin{aligned} C_I &= \sqrt{2}\,,\ I = 1/2 \\ C_I &= -\sqrt{1/3}\,,\ I = 3/2 \end{aligned}$$

$f/m_\pi \leftarrow$ RNπ coupling

$$F_A(Q^2) = \frac{F_A(0)}{\left(1 + \frac{Q^2}{M_{AR}^2}\right)}$$

$$M_{AR} = 1 \text{ GeV}$$

Elementary νN interactions

- $l(k) + N(p) \to l'(k') + X(p')$
  - N-R axial form factors:
    - PCAC
    - π-pole dominance of the pseudoscalar form factor
    - Spin 3/2:

$$C_6^A(Q^2) = \frac{M_N^2}{Q^2 + m_\pi^2} C_5^A(Q^2)$$

$$C_5^A(0) = -C_I \sqrt{2} f_\pi \frac{f}{m_\pi}$$

$$C_I = \sqrt{2}\,, \; I = 1/2$$

$$C_I = -\sqrt{1/3}\,, \; I = 3/2$$

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$$M_{AR} = 1 \text{ GeV}$$

Except for the $\Delta(1232)$
Fit to ANL

- Adler: $C_4^A = -\frac{1}{4} C_5^A \qquad C_3^A = 0$

Elementary νN interactions

- $l(k) + N(p) \rightarrow l'(k') + X$
  - N-R axial form factors:
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    - Spin 3/2:

$$C_6^A(Q^2) = \frac{M_N^2}{Q^2 + m_\pi^2} C_5^A($$

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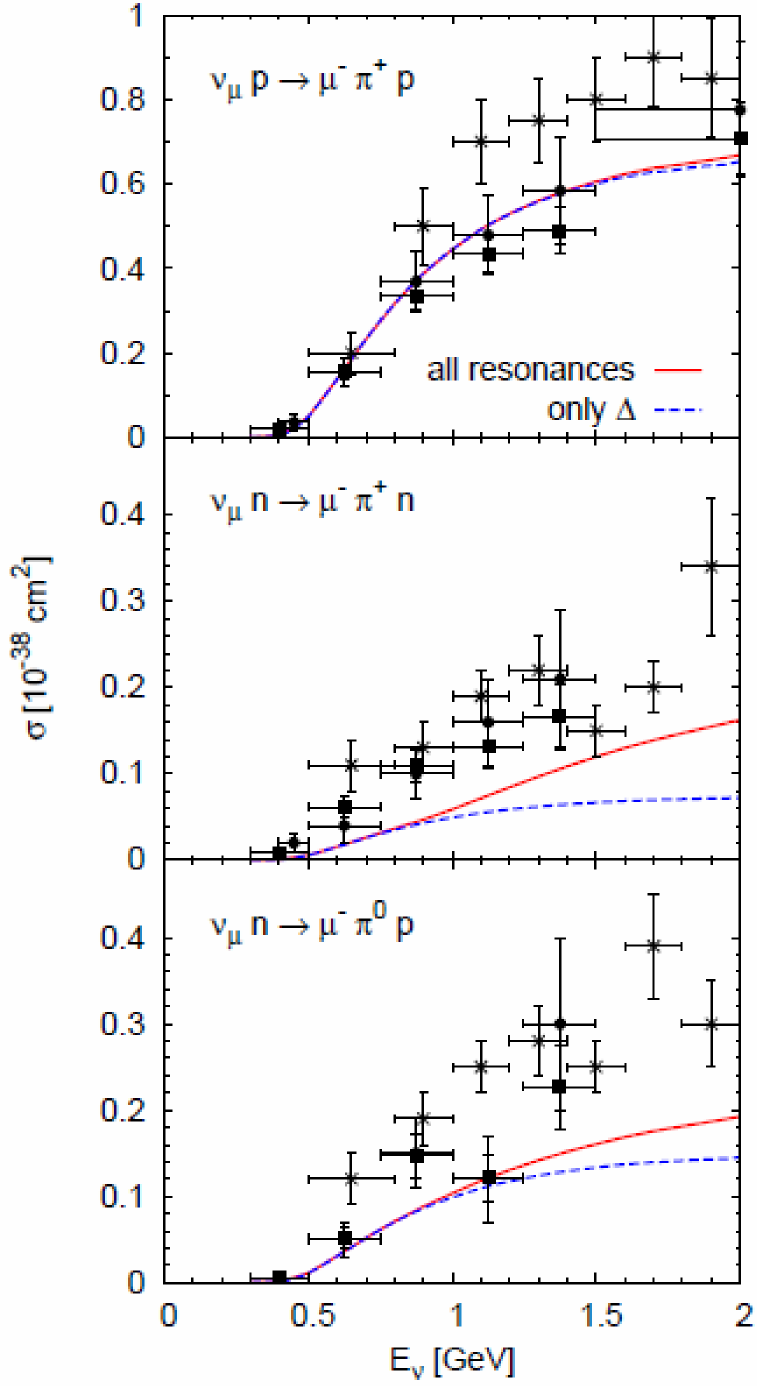


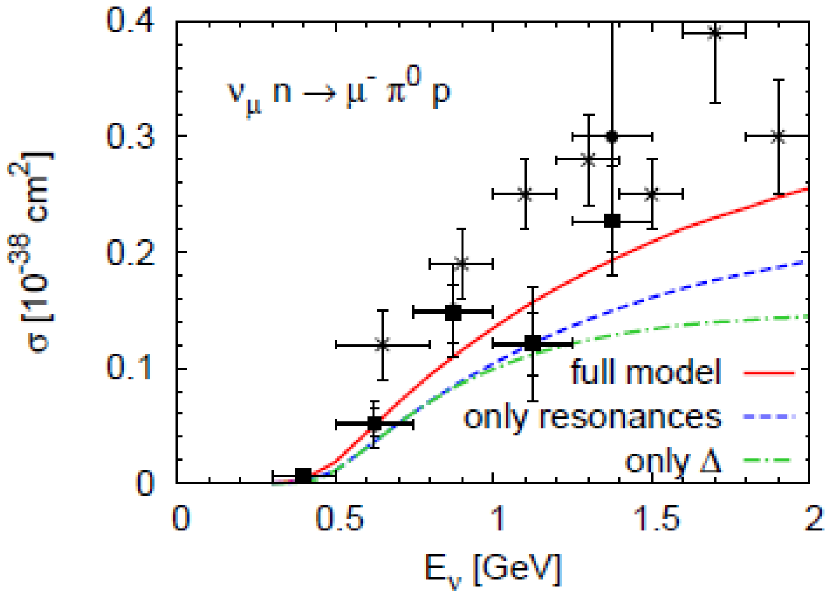
he Δ(1232)

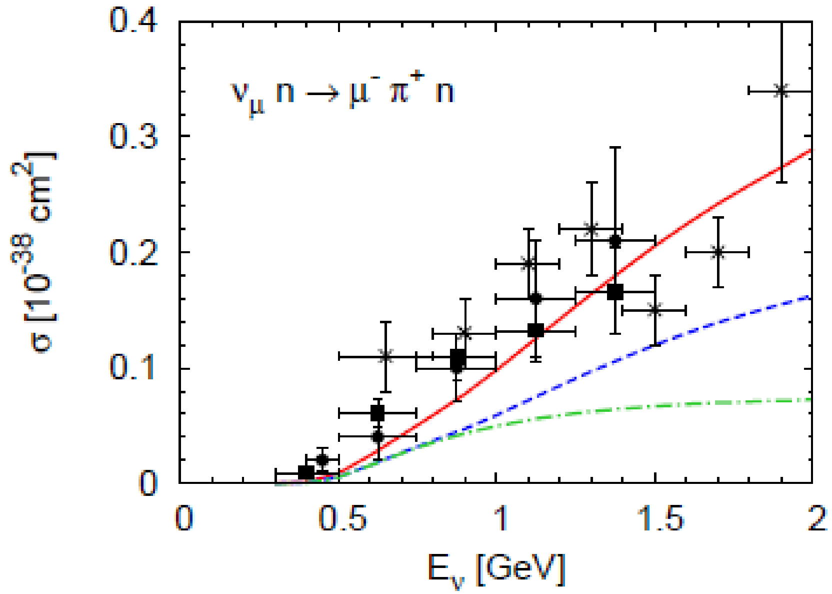
Elementary νN interactions

- $l(k) + N(p) \to l'(k') + X(p')$
  - Non-resonant π background:

$$d\sigma_{BG} = (1 + b^{\pi N}) d\sigma_{BG}^{V}$$

    - Vector part: obtained from e N $\to$ e′ N′ π amplitudes (MAID) subtracting resonance contribution
    - Axial part:
      - same structure as in the vector part assumed
      - constant $b^{\pi N}$ fitted to ANL data





ν N in the nuclear medium

- Local Relativistic Fermi Gas

$$p_F(r) = [\tfrac{3}{2}\pi^2\rho(r)]^{1/3}$$

  - Fermi Motion of initial nucleons:

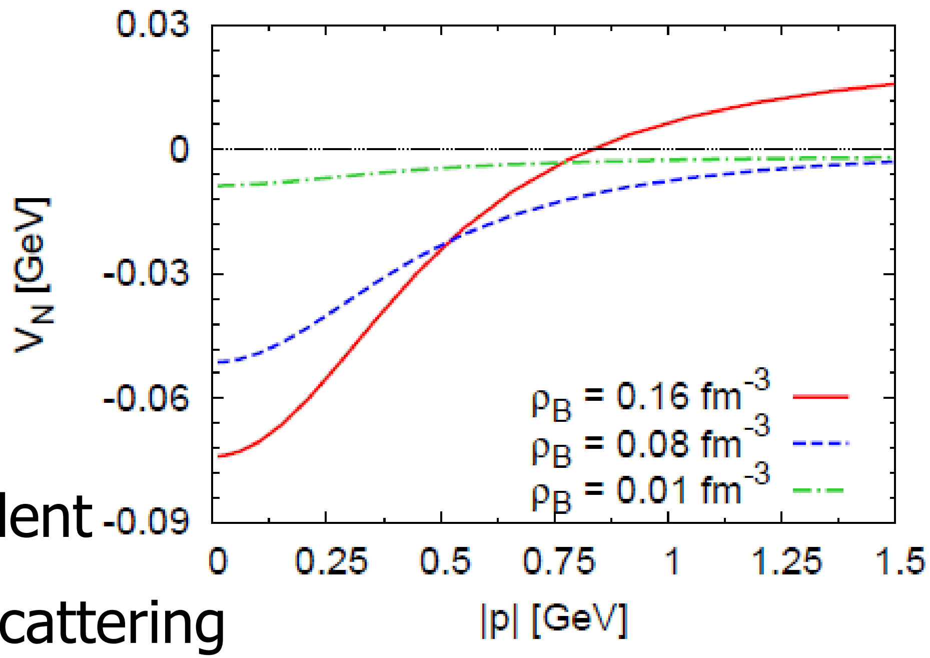
$$f(\vec{r},\vec{p}) = \Theta(p_F(r) - |\vec{p}|)$$

  - Pauli blocking of final nucleons:

$$P_{\rm Pauli} = 1 - \Theta(p_F(r) - |\vec{p}|)$$

  - Mean field potential
    - Density and momentum dependent
    - Parameters fixed in p-Nucleus scattering
    - Nucleons acquire effective masses

$$M_{\rm eff} = M + U(\vec{r},\vec{p})$$



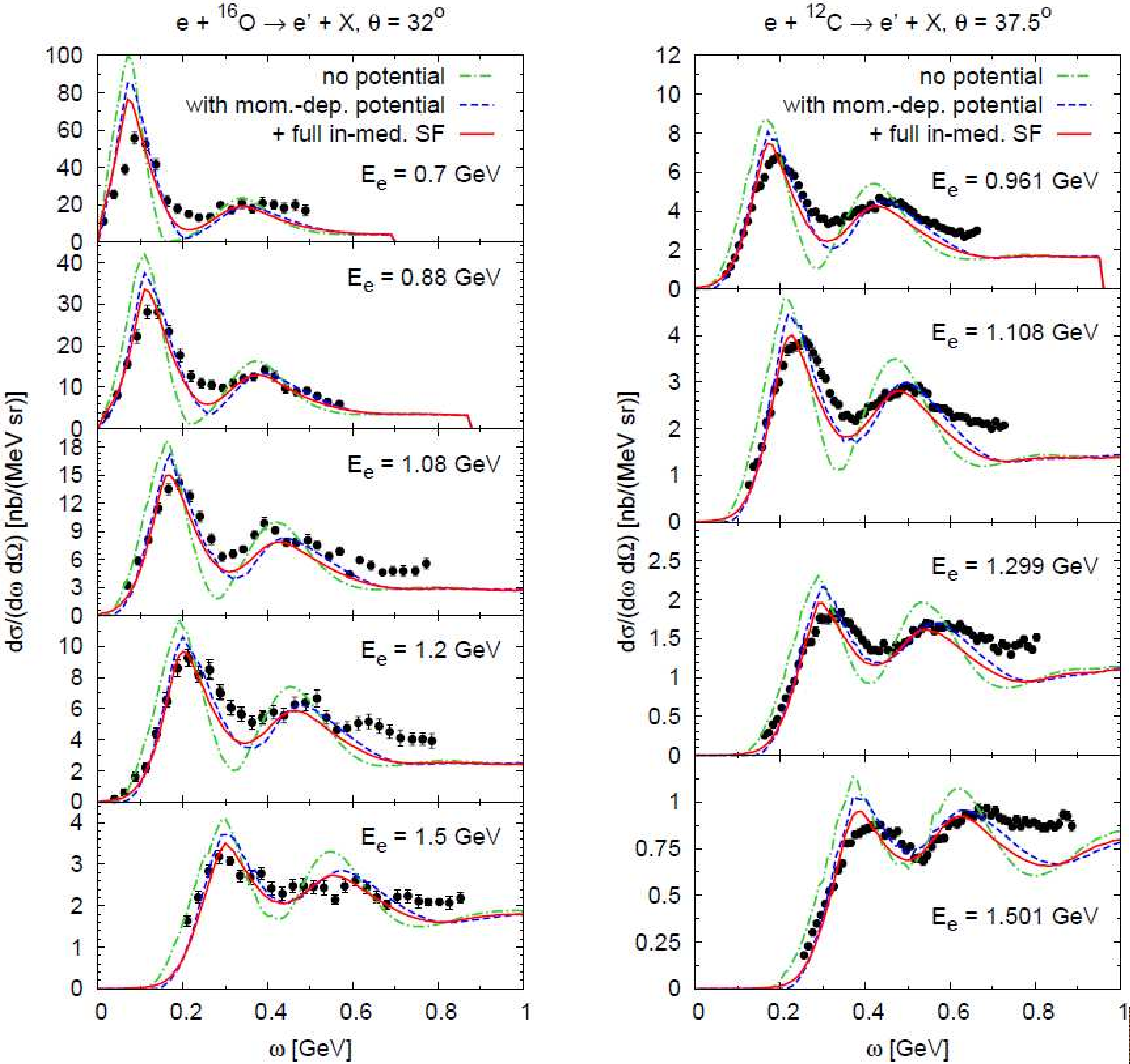
ν N in the nuclear medium

- Spectral functions
  - $$S(p) = -\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$ Σ ← selfenergy
  - Hole spectral function:
    - The correlated part of S_h is neglected

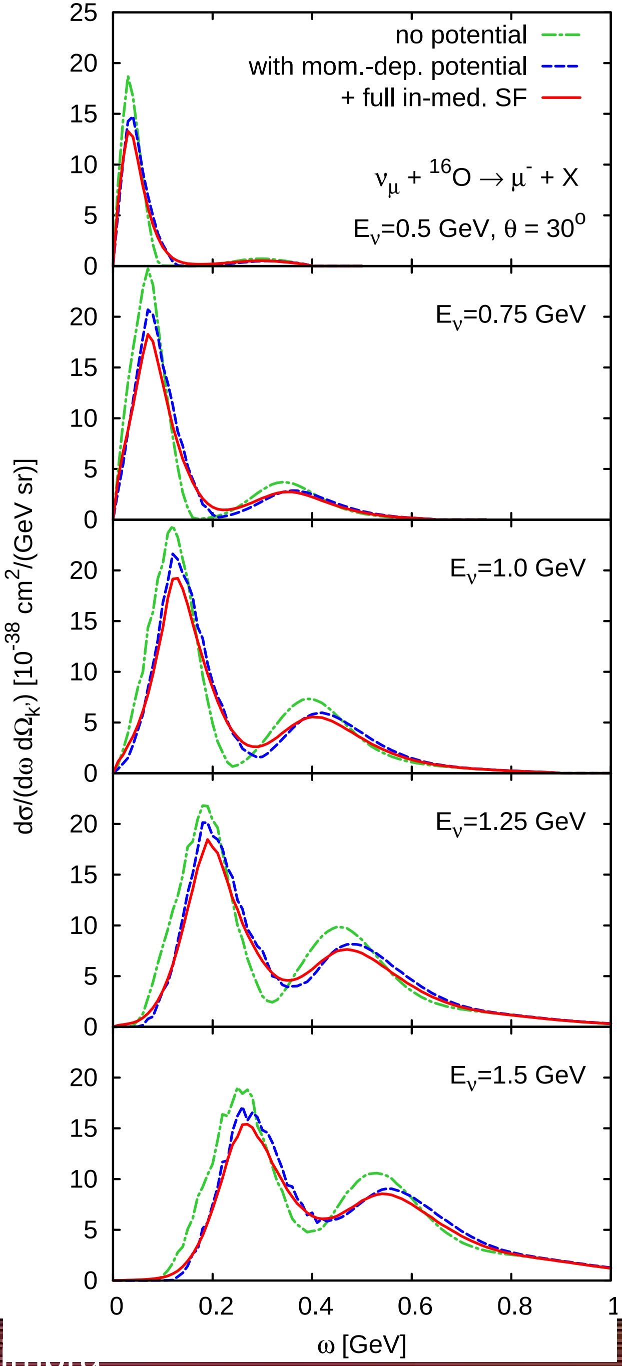
      $$\mathrm{Im}\Sigma \approx 0 \quad S_h(p) \to \delta(p^2 - M_{\mathrm{eff}}^2)$$
  - Particle spectral function:
    - $\mathrm{Im}\Sigma = -\sqrt{(p^2)}\Gamma_{\mathrm{coll}}(p,r)\,,\ \Gamma_{\mathrm{coll}} = \langle \sigma_{XN} v_{\mathrm{rel}} \rangle$ ← collisional broadening
    - $\mathrm{Re}\Sigma$ is obtained from $\mathrm{Im}\Sigma$ with a dispersion relation fixing the pole position:

      $$p_0^{(pole)} = \sqrt{\vec{p}^2 + M_{\mathrm{eff}}^2}$$

Inclusive (e,e') cross section



Inclusive (ν,μ^-) cross section



FSI: transport model

- The time evolution of phase space density $f_i(\vec{r},\vec{p},t)$ (i=N, Δ, π, ρ, ...) is determined by the Boltzmann-Uehling-Uhlenbeck (BUU) equation.

$$\frac{df_i}{dt} = \left(\partial_t + (\nabla_{\vec{p}} H)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H)\nabla_{\vec{p}}\right) f_i(\vec{r},\vec{p},t) = I_{coll}\left[f_i, f_N, f_\pi, f_\Delta, \ldots\right]$$

  - Hamiltonian: $H = \sqrt{(m_i + U)^2 + \vec{p}^{\,2}}$
  - Equations coupled mainly through the collision integral
    - Accounts for changes in $f_i(\vec{r},\vec{p},t)$
    - Elastic & inelastic processes
    - Decay of unstable particles
    - Pauli blocking
  - Most important processes:

$$NN \leftrightarrow NN \qquad N\Delta \leftrightarrow N\Delta$$

$$NN\pi \leftrightarrow NN \qquad \pi N \leftrightarrow \Delta$$

$$NN \leftrightarrow N\Delta \qquad \pi N \leftrightarrow \pi N$$

$$NN \leftrightarrow \Delta\Delta \qquad \pi N \leftrightarrow \pi\pi N$$

FSI: transport model

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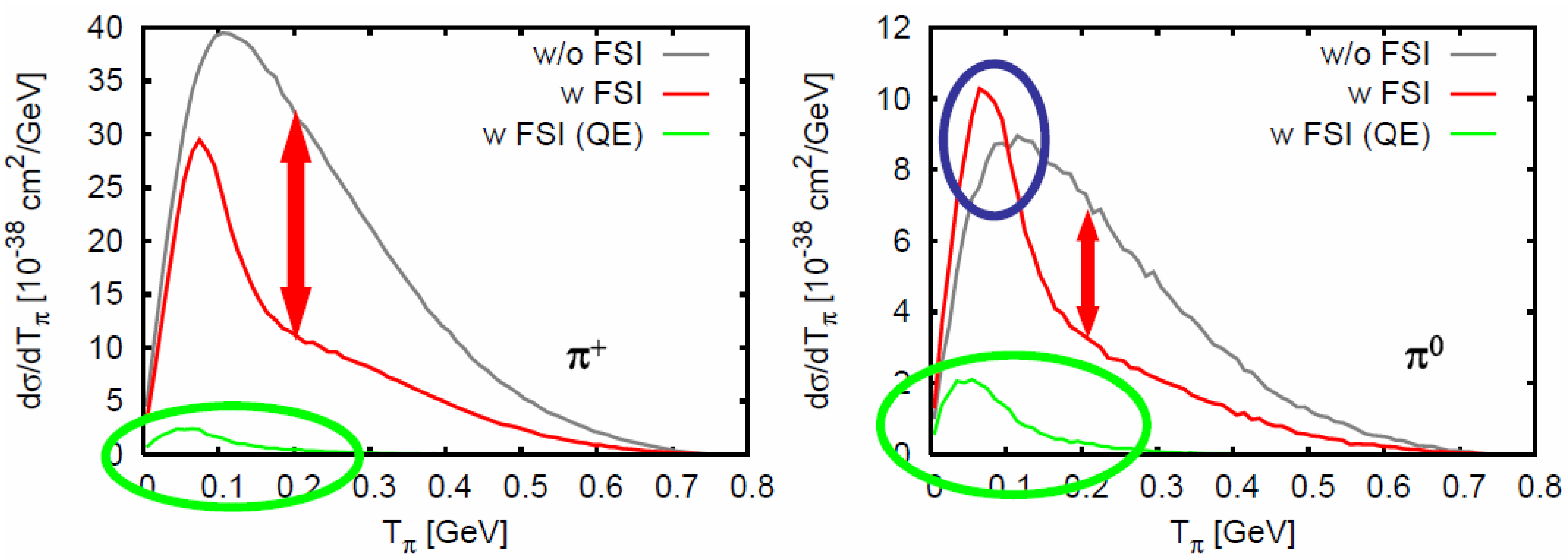
FSI ⟶

- **absorption**
- **charge exchange**
- **redistribution of energy**
- **production of new particles**

1π production

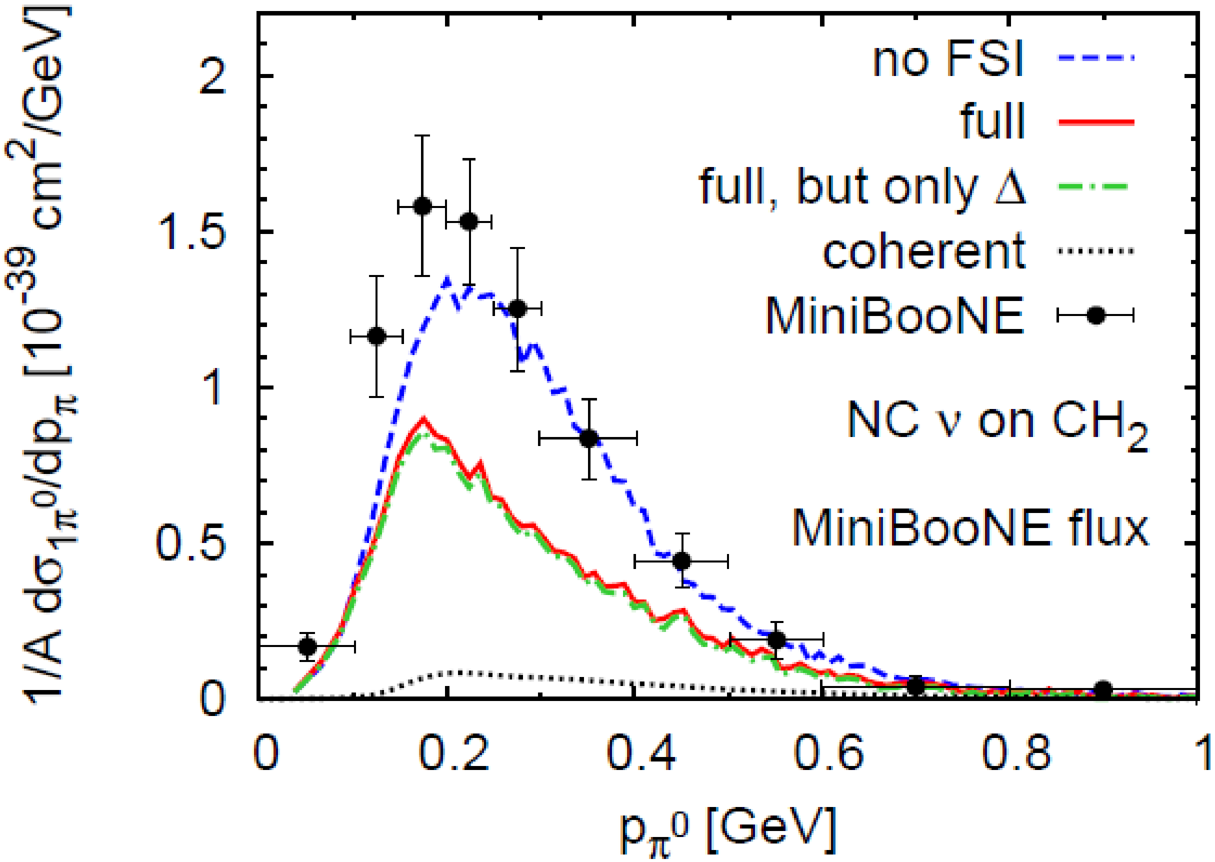
- Effects of FSI on pion kinetic energy spectra
  - strong absorption in Δ region
  - side-feeding from dominant π^+ into π^o channel
  - secondary pions through FSI of initial QE protons



$$\nu_\mu + {}^{56}Fe \to \mu^- \, \pi \, X \quad E_\nu = 1 \text{ GeV}$$

1π production

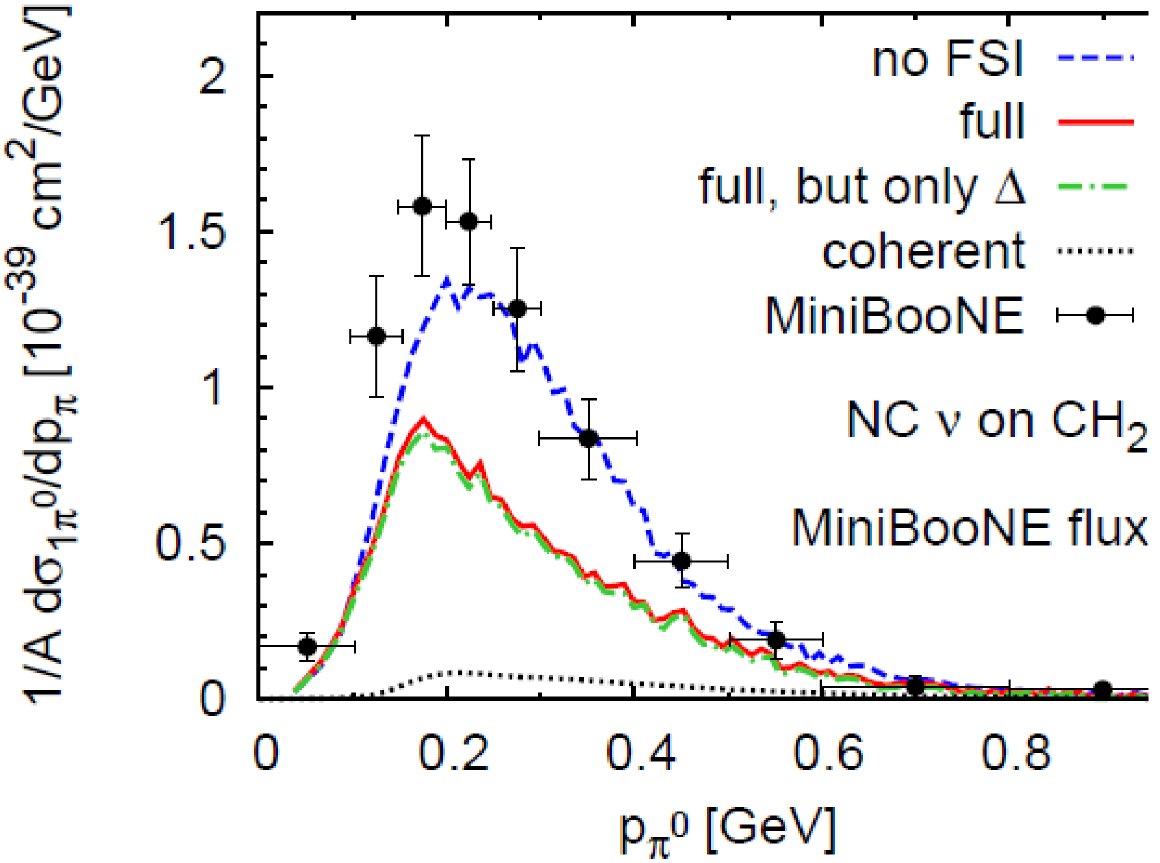
- NC π^o production at MiniBooNE



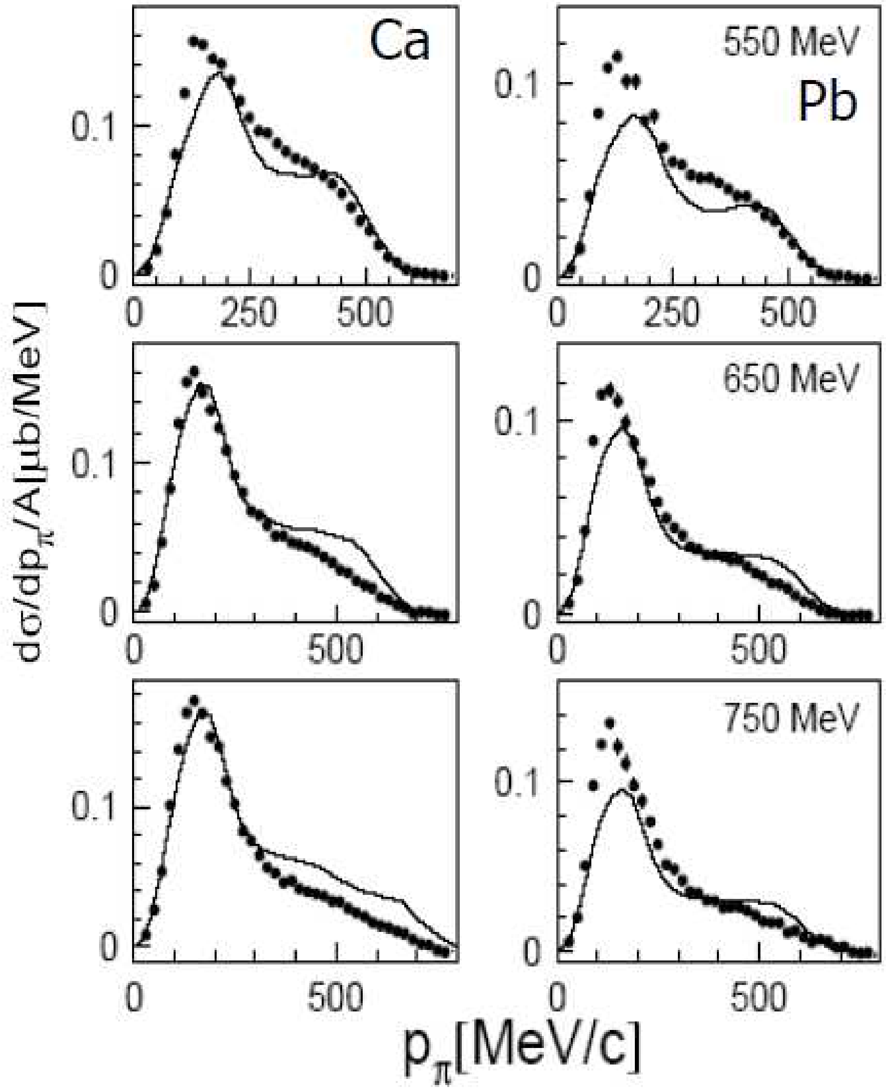
- Good description of shape
- Integrated σ : factor 2 smaller

1π production

- NC π^o production at MiniBooNE



$\gamma\, A \rightarrow \pi^0\, X$



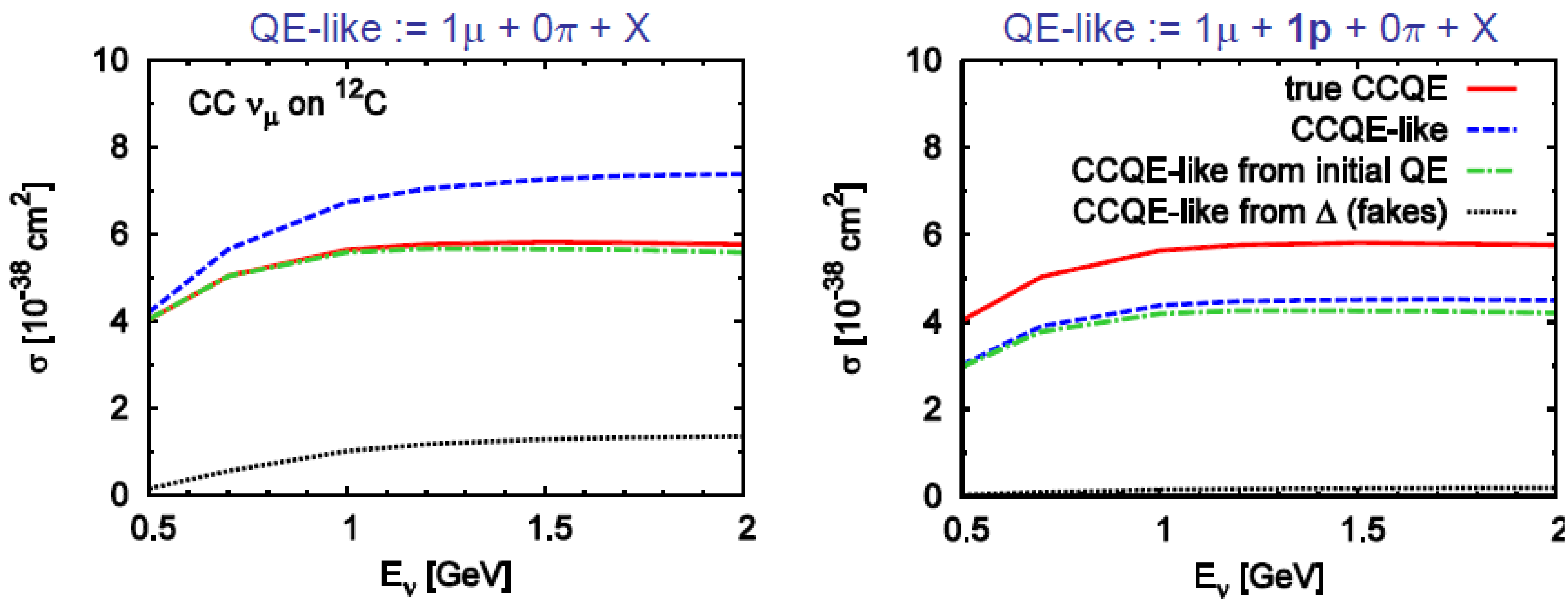
TAPS, EPJA 22 (2004)

- Good description of shape
- Integrated σ : factor 2 smaller
- Better agreement in π^o photoproduction

QE & 1π entanglement

- Clean separation between QE and 1π in nuclei is hard to achieve
- Depends on the detection technique
- For example:

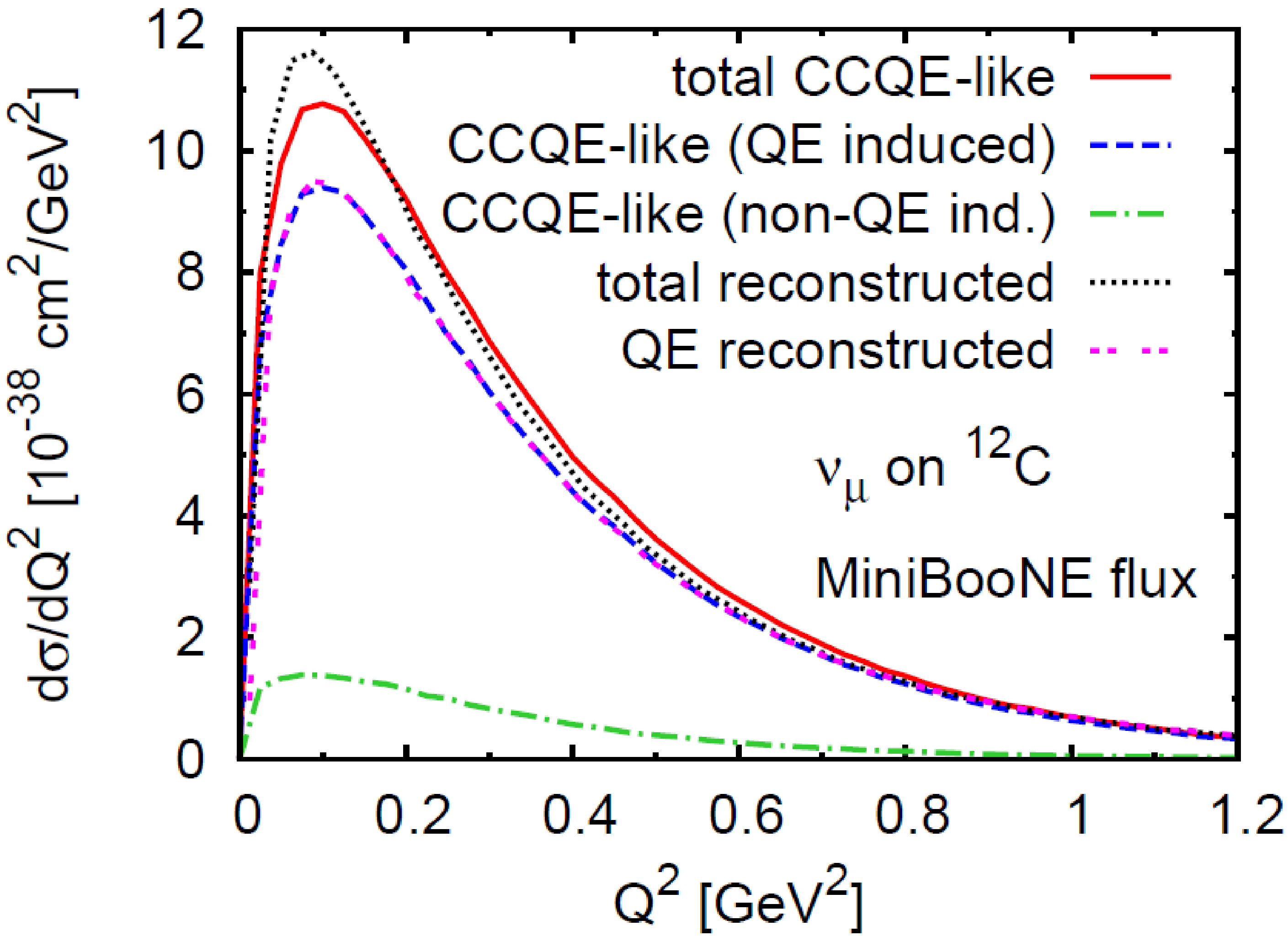
Cherenkov type | Tracking type



- ~ 20% of CCQE events are misidentified: has to be corrected with MC

E_ν reconstruction

- Influenced by QE & 1π entanglement



Conclusions

- GiBUU provides a framework to study different processes:
  - Heavy ion collisions, pA, πA ,γA, eA
  - νA (inclusive and exclusive) without new parameters
- FSI modifies considerably the distributions through rescattering, charge-exchange and absorption
- A realistic description of FSI is important to oscillation experiments