European Graduate School
Complex Systems of Hadrons and Nuclei
Copenhagen - Gießen - Helsinki - Jyväskylä - Torino

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

# Nuclear effects in neutrino scattering

L. Alvarez-Ruso, T. Leitner, U. Mosel

- Introduction
- Neutrino-nucleon reactions: QE and $\Delta$ (1232)
- Inclusive nuclear cross section
- In-medium modifications
- Final state interactions
- Exclusive channels: $\pi$ production and nucleon knockout
- QE scattering at MiniBooNE
- Conclusions

# Introduction

Neutrino nucleus interactions are relevant for:

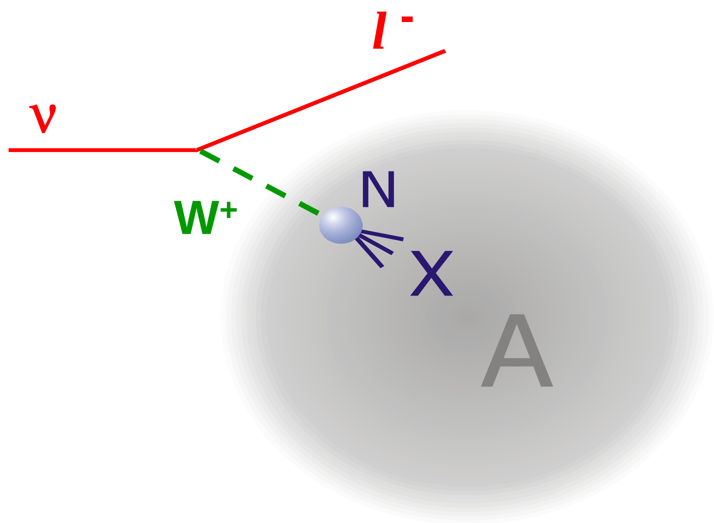
- Oscillation experiments: systematic uncertainties
  - neutrino fluxes
  - backgrounds
  - detector responses
- Hadron structure:
  - nucleon axial form factor
  - N-R axial transitions
  - strangeness in the nucleon spin
- In-medium modifications:
  - form factors
  - spectral functions
  - nuclear correlations

⬇

- Experiments: MINERνA, FINeSSE with a high intensity ν beam

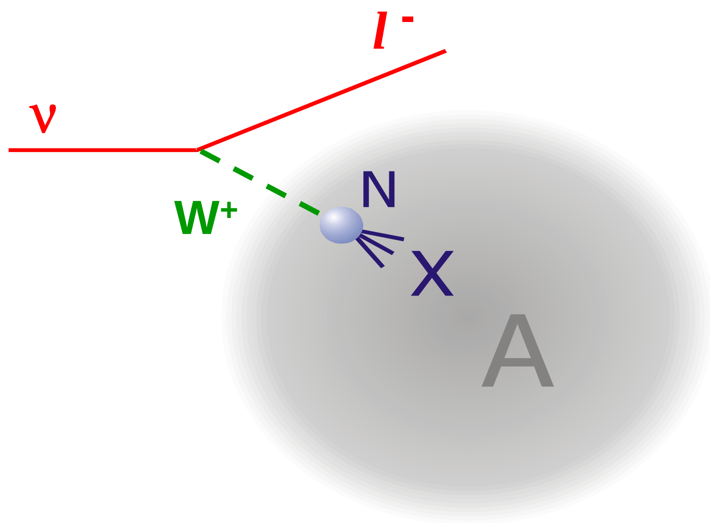
Understanding nuclear effects is essential for the interpretation of the data and represents both a challenge and an opportunity

# Neutrino-nucleus scattering



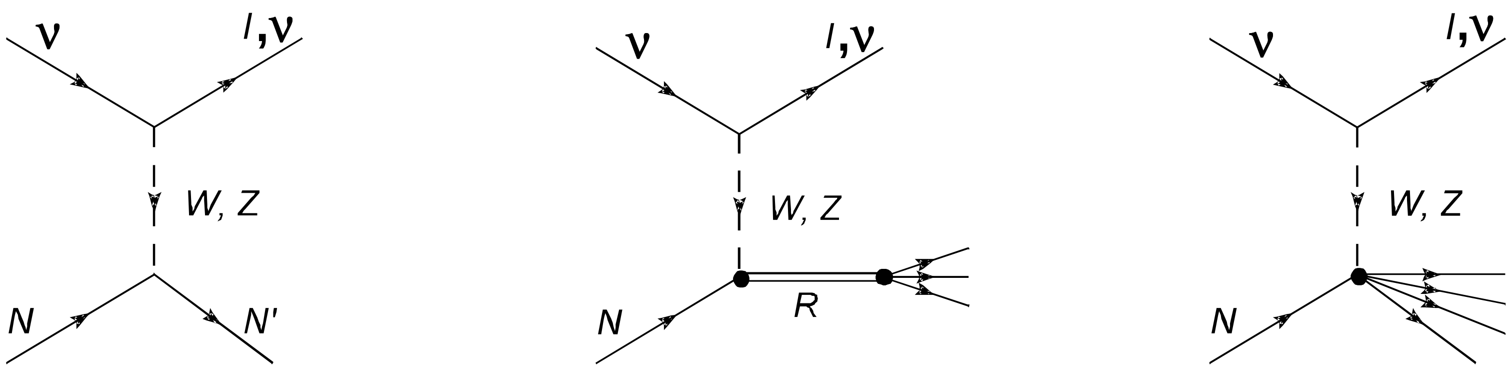

1. Elementary reactions: $\nu_l\, N \to l^- X$
2. In-medium modifications of the elementary cross sections
3. Propagation of the final state X ⟺ **FSI**

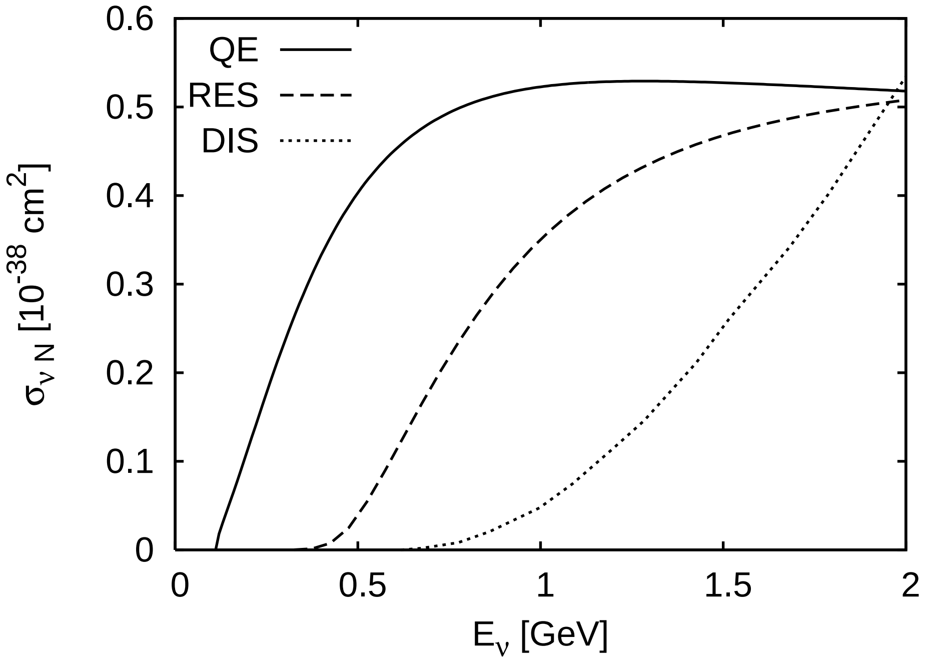
# Neutrino-nucleus scattering




1. Elementary reactions: $\nu_l \, N \rightarrow l^- X$
2. In-medium modifications of the elementary cross sections
3. Propagation of the final state X ⟺ FSI

# Elementary neutrino-nucleon reactions




we consider **QE** & **Δ** **:**

$$\nu\, n \to l^- p$$

$$\nu\, n \to l^- \Delta^+$$

$$\nu\, p \to l^- \Delta^{++}$$

# Quasielastic scattering

- $\nu(k) + N(p) \to l^-(k') + X(p')$ :

$$\frac{d^2\sigma_{\nu N}}{dQ^2 dE_l} = \int d\phi \, \frac{1}{64\pi^2} \frac{1}{|k \cdot p|} \frac{1}{E_\nu} \delta\left(p'^2 - M'^2\right) |\bar{\mathcal{M}}|^2$$

- matrix element for CC: $|\bar{\mathcal{M}}|^2 = \frac{G_F^2 \cos^2\theta_C}{2} L_{\alpha\beta} H^{\alpha\beta}$

| leptonic tensor $L_{\alpha\beta}$ | hadronic tensor $H^{\alpha\beta}$ |
|---|---|
| ↓ | ↓ |
| $j_\alpha = \bar{\nu}_l \gamma_\alpha (1-\gamma_5) l$ | hadronic current: $J_\alpha^X$ |
| V – A structure | • depends on the specific reaction<br>• parametrized in terms of form factors |

# Quasielastic scattering

- hadronic current:

$$J_\alpha^{QE} = \langle p | J_\alpha^{QE} | n \rangle = \bar{u}(p') A_\alpha u(p)$$

$$A_\alpha = \left( \gamma_\alpha - \frac{\not{q}\, q_\alpha}{q^2} \right) F_1^V + \frac{i}{2M} \sigma_{\alpha\beta} q^\beta F_2^V + \gamma_\alpha \gamma_5 F_A + \frac{q_\alpha \gamma_5}{M} F_P$$

- vector form factors $F_{1,2}^V(Q^2) = F_{1,2}^p - F_{1,2}^n$
  - related to electric & magnetic form factors by **CVC**
  - **BBA-2003** parametrization
- axial form factors $F_A(Q^2)$, $F_P(Q^2)$
  - related by **PCAC**
  - dipole ansatz
- extra term $-\not{q}\, q_\alpha / q^2$
  - ensures vector current conservation for nonequal masses

# Δ resonance production

- hadronic current: $J_\alpha^\Delta = \langle \Delta^+ | J_\alpha^\Delta(0) | n \rangle = \bar{\psi}^\beta(p') B_{\beta\alpha} u(p)$

  $\bar{\psi}^\beta(p')$ ← Rarita-Schwinger spinor

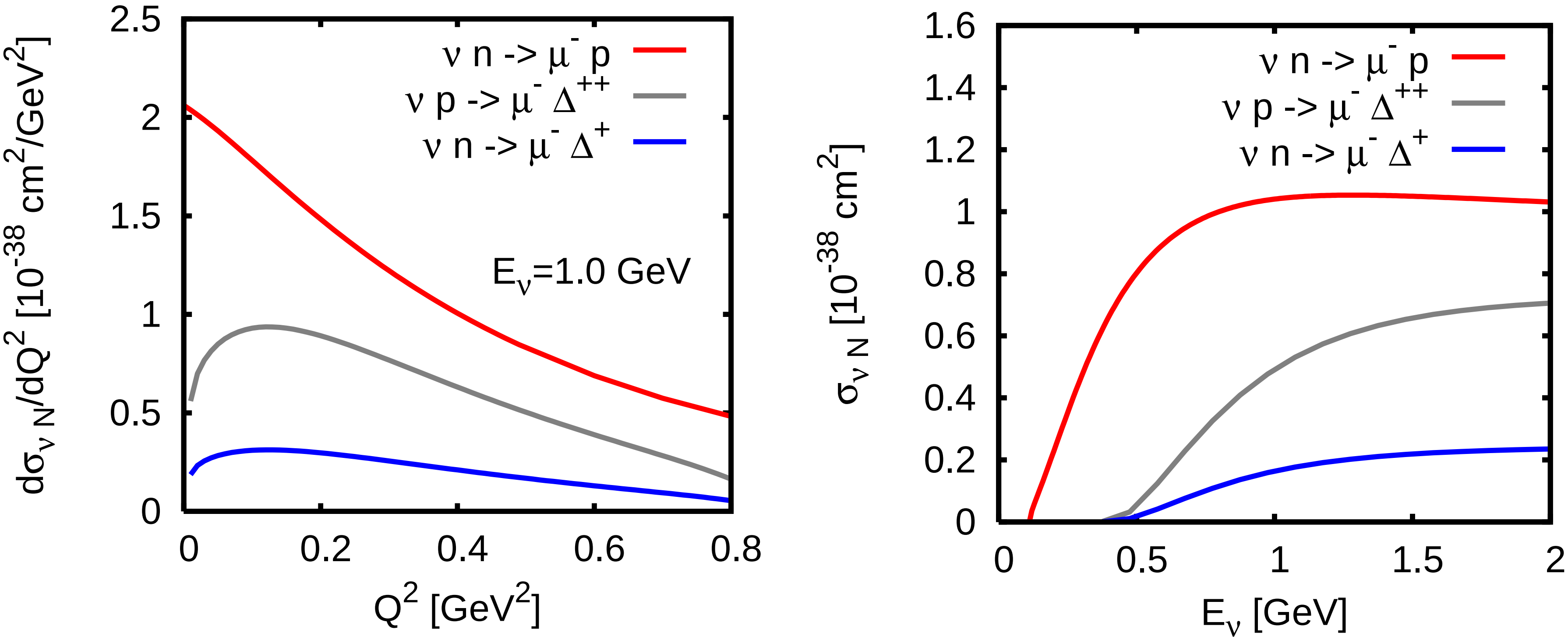
$$B_{\beta\alpha} = \left( \frac{C_3^V}{M}(g_{\alpha\beta}\not{q} - q_\beta\gamma_\alpha) + \frac{C_4^V}{M^2}(g_{\alpha\beta}q\cdot p' - q_\beta p'_\alpha) + \frac{C_5^V}{M^2}(g_{\alpha\beta}q\cdot p - q_\beta p_\alpha) + g_{\alpha\beta}C_6^V \right)\gamma_5$$
$$+ \frac{C_3^A}{M}(g_{\alpha\beta}\not{q} - q_\beta\gamma_\alpha) + \frac{C_4^A}{M^2}(g_{\alpha\beta}q\cdot p' - q_\beta p'_\alpha) + C_5^A g_{\alpha\beta} + \frac{C_6^A}{M^2}q_\beta q_\alpha$$

| CVC & $M_{1+}$ dominance | PCAC | Adler model |
|---|---|---|
| $C_4^V = -\frac{M}{W}C_3^V$ $C_5^V = 0$ $C_6^V = 0$ | $C_6^A = C_5^A \frac{M^2}{Q^2+m_\pi^2}$ | $C_4^A = -\frac{1}{4}C_5^A$ |
| $C_3^V$ ← *e N* scattering | $C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2$ | $C_3^A = 0$ |

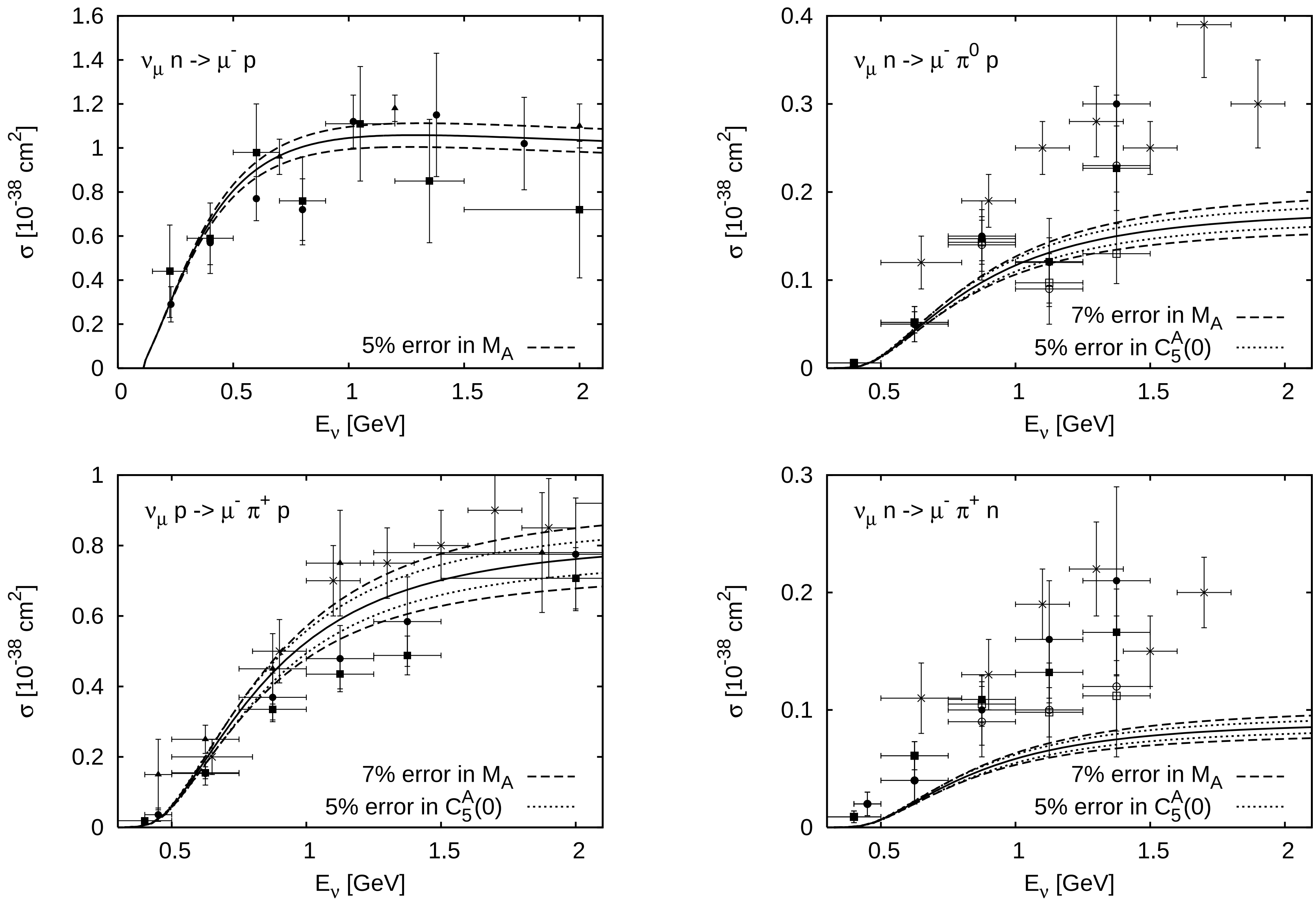
dominant contribution: $C_5^A$, $C_3^V$

- Δ width: **p-wave** $\Gamma \sim q_{CM}^3$ ← π momentum in the Δ rest frame

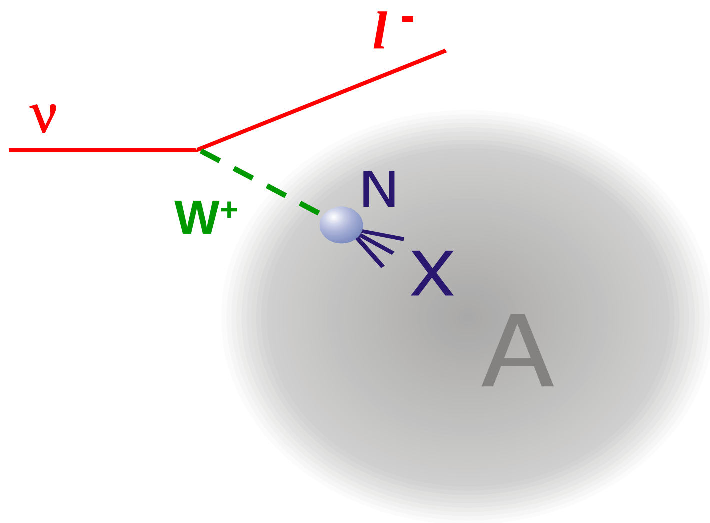
# Elementary cross sections



# Elementary cross sections

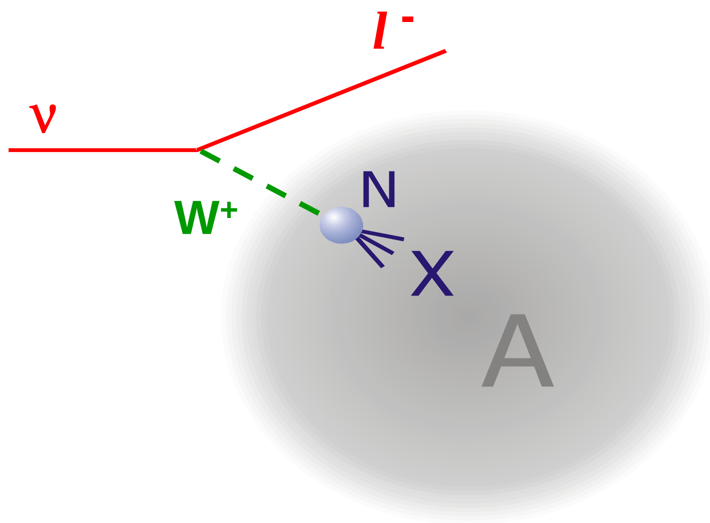


# Neutrino-nucleus scattering




1. Elementary reactions: $\nu_l\, N \rightarrow l^- X$
2. In-medium modifications of the elementary cross sections
3. Propagation of the final state X ⟷ **FSI**

# Neutrino-nucleus scattering

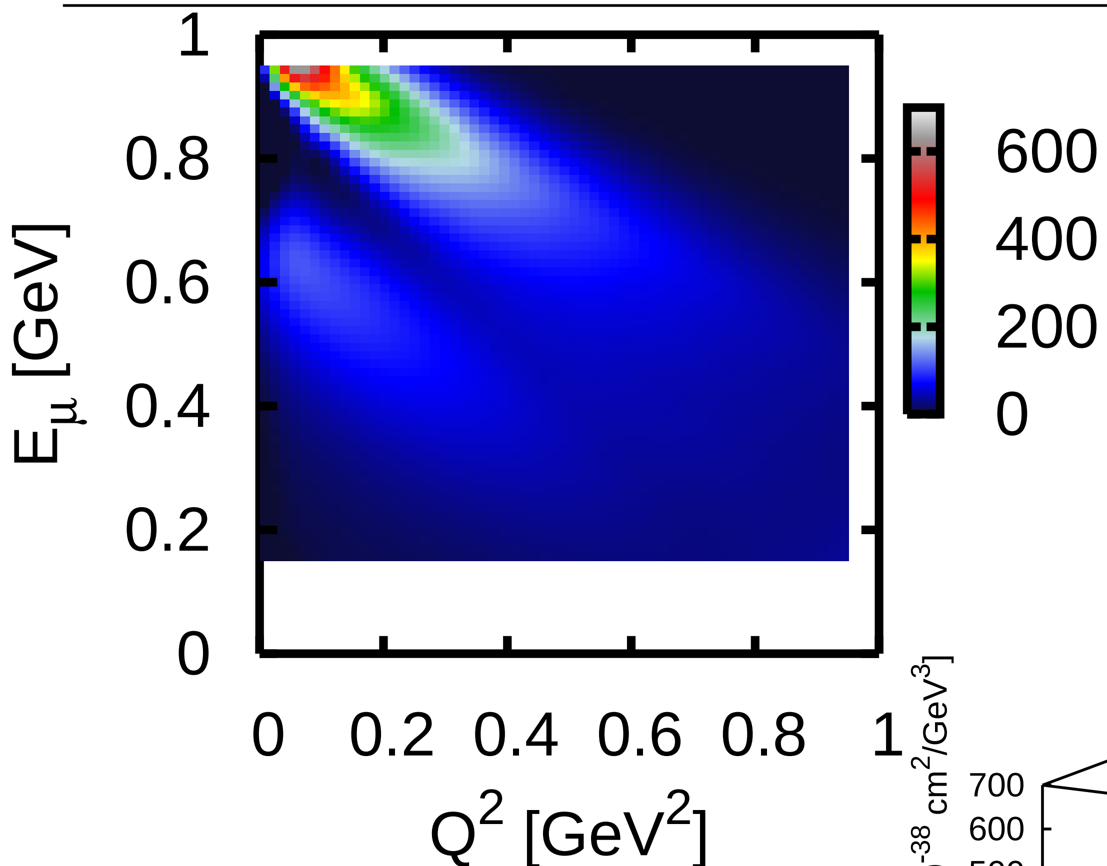



- Fermi motion
- Pauli blocking
- Nuclear binding
- In-medium $\Delta$ width:

$$\Gamma \to \Gamma^{med} = \tilde{\Gamma} + \Gamma_{coll}$$

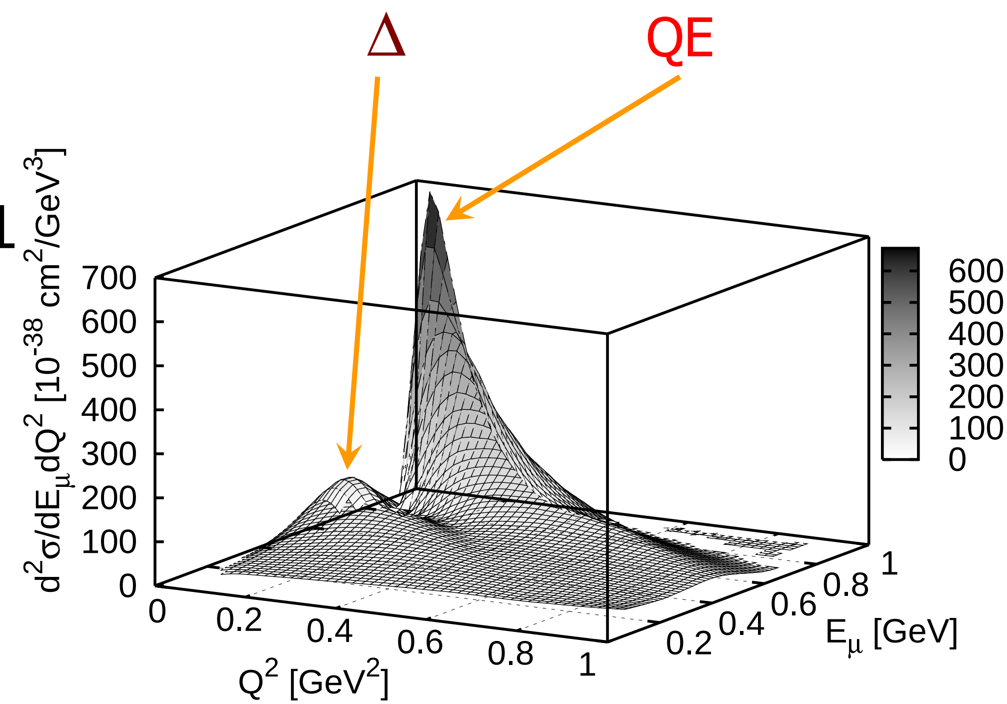
1. Elementary reactions: $\nu_l N \to l^- X$
2. In-medium modifications of the elementary cross sections
3. Propagation of the final state X ⟺ FSI

# Inclusive cross section



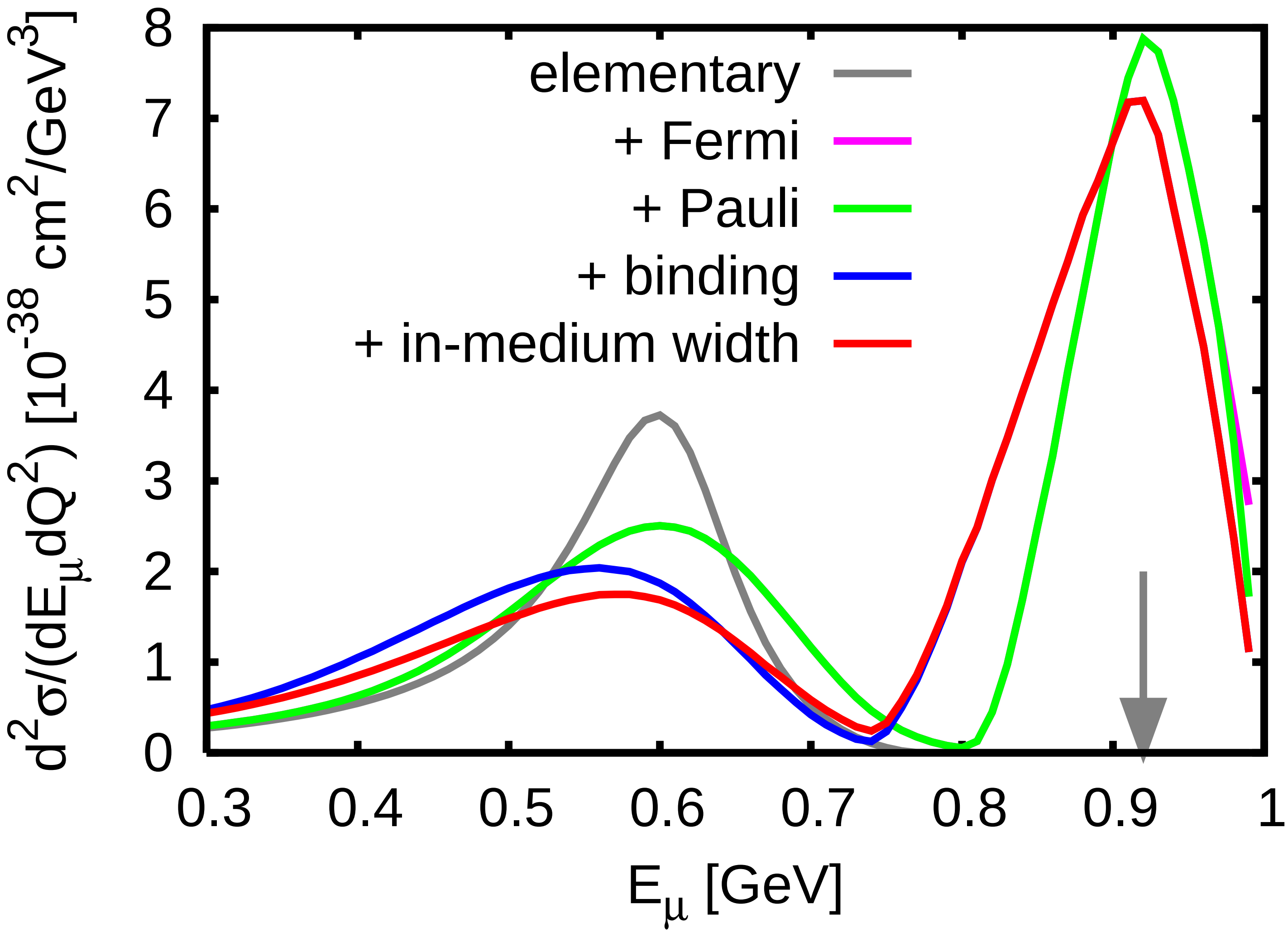

$\nu_\mu\,{}^{56}\mathrm{Fe} \rightarrow \mu^- X$

$E_\nu = 1$ GeV

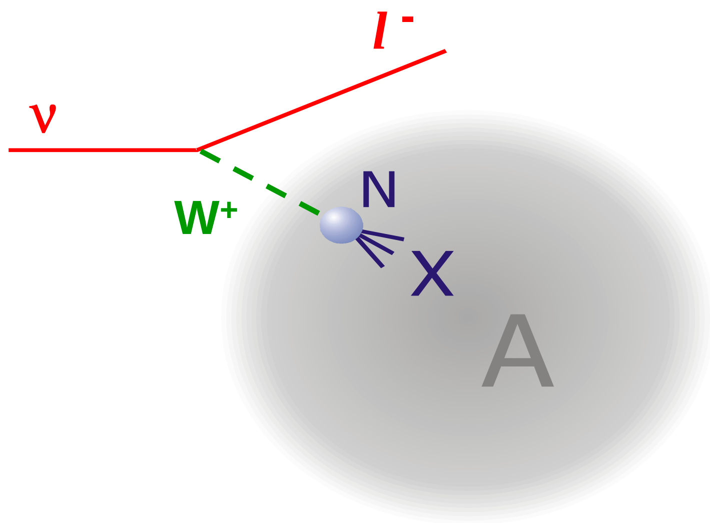


# In-medium effects

- $\nu_\mu {}^{56}\text{Fe} \to \mu^- X$ $E_\nu = 1\,\text{GeV},\ Q^2 = 0.15\,\text{GeV}^2$

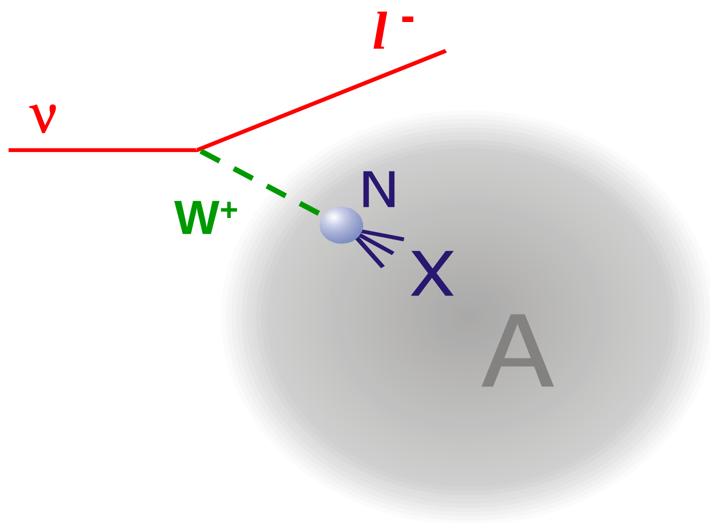


# Neutrino-nucleus scattering




1. Elementary reactions: $\nu_l \, N \rightarrow l^- X$
2. In-medium modifications of the elementary cross sections
3. Propagation of the final state X ⟷ **FSI**

# Neutrino-nucleus scattering




1. Elementary reactions: $\nu_l N \to l^- X$
2. In-medium modifications of the elementary cross sections
3. Propagation of the final state X ⟷ **FSI**

# GiBUU Transport Model

- Semiclassical transport model in coupled channels
- Previously applied to heavy-ion collisions, $e\,A$, $\gamma\,A$, $\pi\,A$ reactions
- Particles ($i$=$N$, $\Delta$, $\pi$, $\rho$, …) propagate according to the **B**oltzmann-**U**ehling-**U**hlenbeck equation:

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

$H = \sqrt{(m_i + U_s)^2 + \vec{p}^{\,2}}$ ← Hamiltonian

$U_s(\vec{r},\vec{p})$ ← non-local mean field potential

$f_i(\vec{r},\vec{p},t)$ ← phase space density for particle species $i$

- Set of BUU equations coupled via $I_{coll}$

# GiBUU Transport Model

- **Collision integral** accounts for changes in $f_i$ :
  - elastic and inelastic scattering
  - Pauli blocking for fermions
  - decay of unstable particles
- most important processes:

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

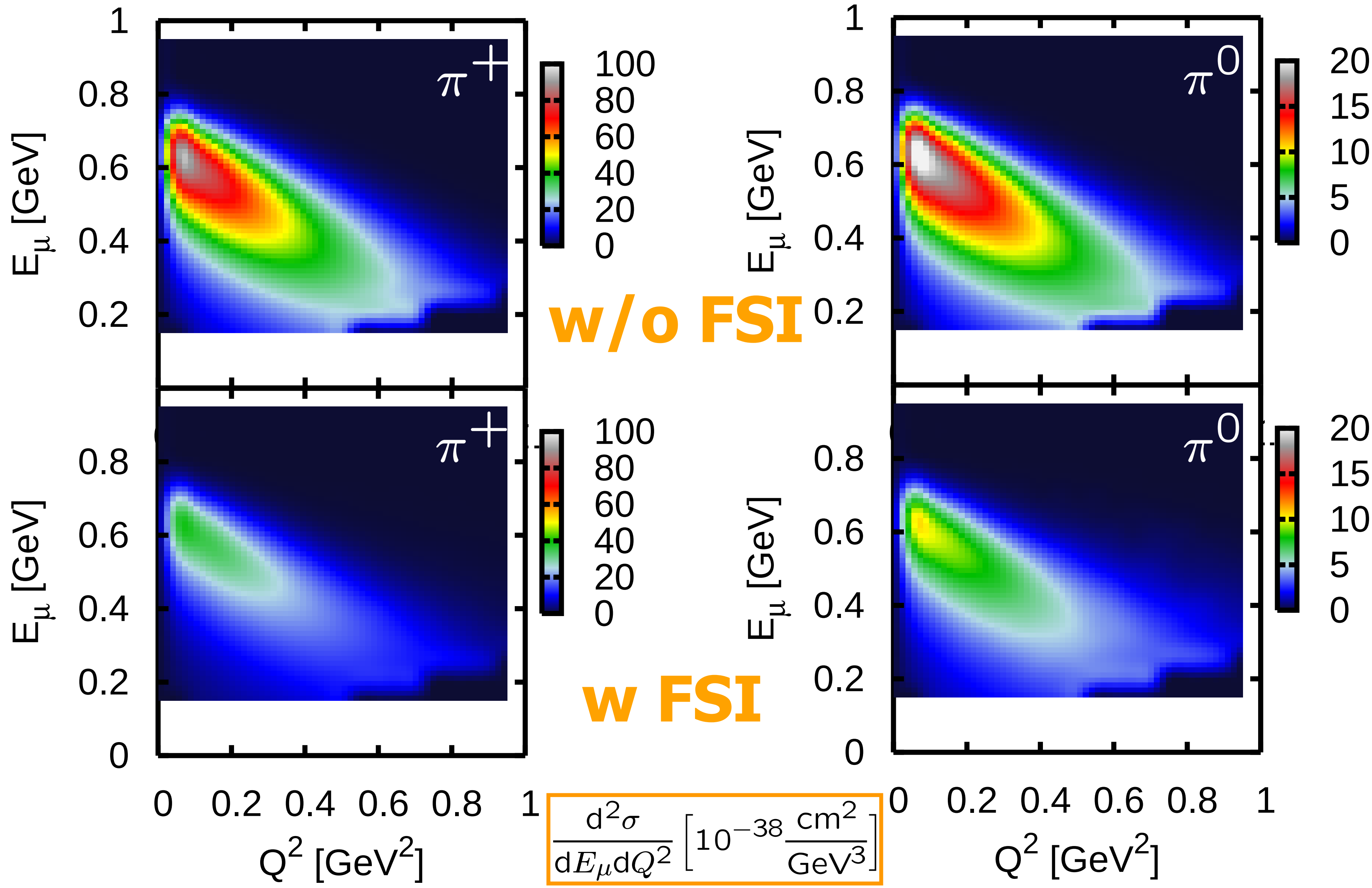
$$NN\pi \leftrightarrow NN \qquad \pi N \leftrightarrow \Delta$$

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

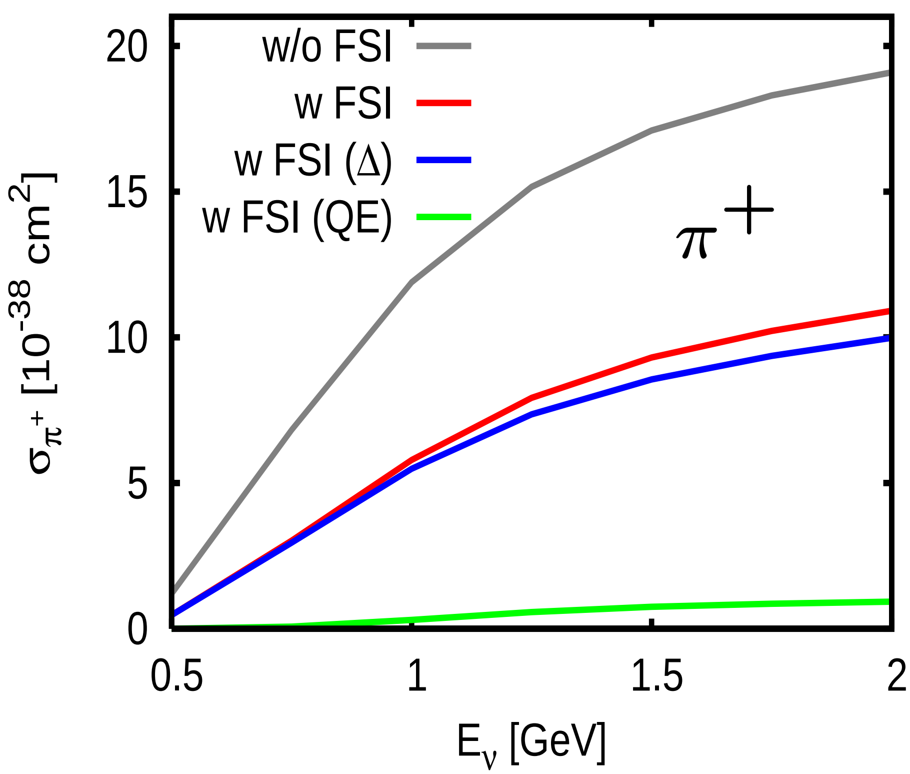
$$NN \leftrightarrow \Delta\Delta \qquad \pi N \leftrightarrow \pi\pi N$$

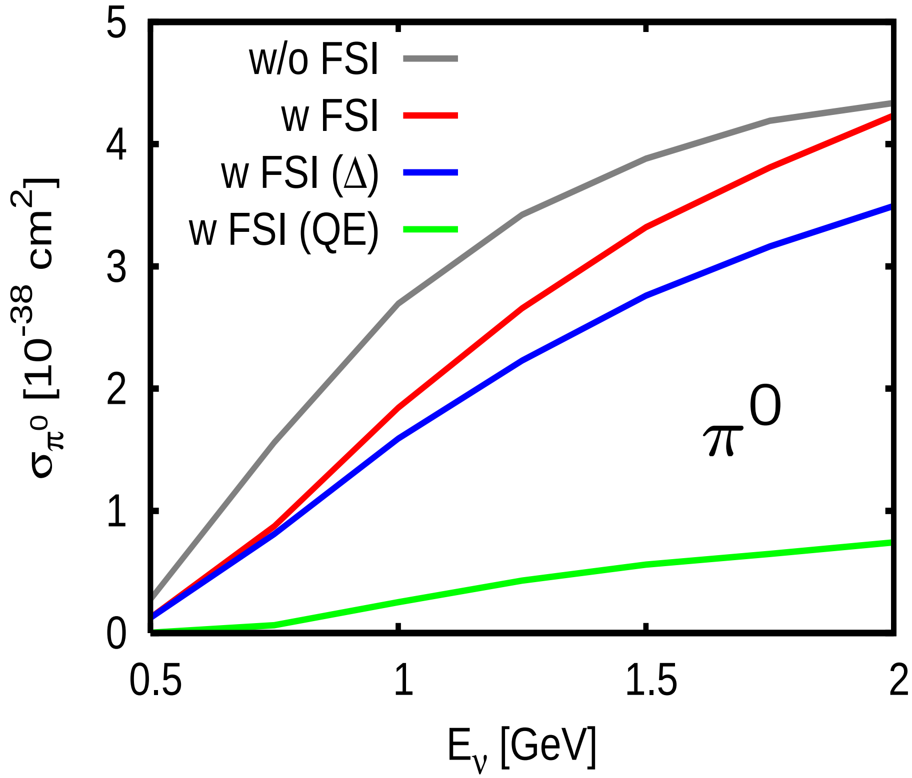
**FSI** ⟶
- **absorption**
- **charge exchange**
- **redistribution of energy**
- **production of new particles**

## Pion production $\nu_\mu\, {}^{56}\text{Fe} \to \mu^- \, \pi \, X$ at $E_\nu = 1$ GeV



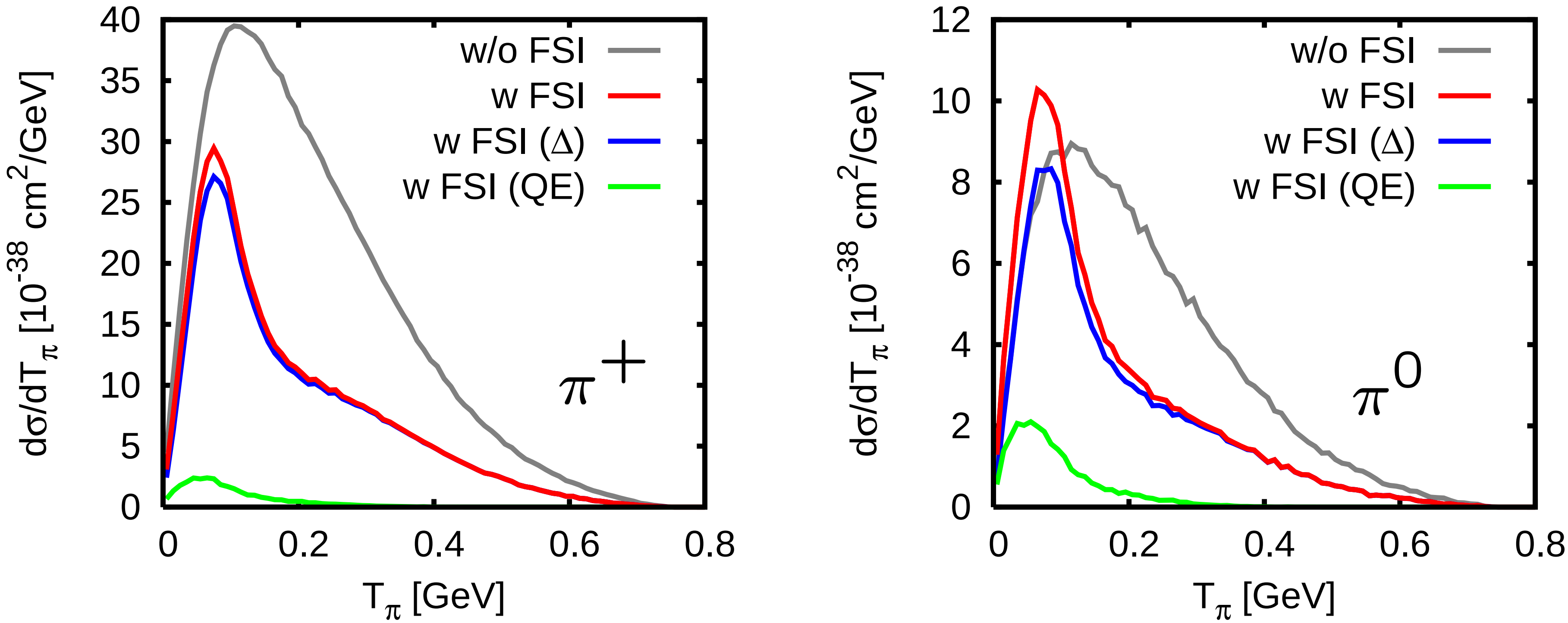
# Pion production $\nu_\mu\,^{56}\text{Fe} \rightarrow \mu^-\,\pi\,X$



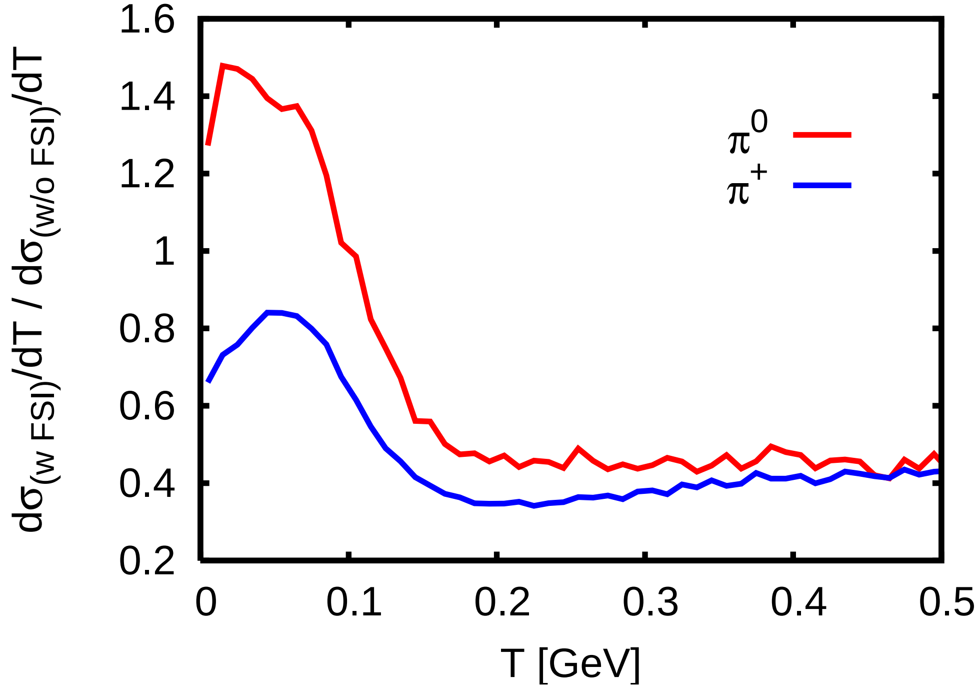
# Pion Production $\nu_\mu\, {}^{56}\mathrm{Fe} \to \mu^- \,\pi\, X$

- Pion kinetic energy spectrum at $E_\nu = 1$ GeV
  - strong absorption ( $\pi N \to \Delta$ followed by $\Delta\ N \to N\ N$)
  - side-feeding from $\pi^+$ into the $\pi^0$ channel via charge exchange
  - secondary pions from initial QE protons: $pN \to \Delta N \to N N \pi$
  - shift to lower energies due to elastic $\pi N \to \pi N$



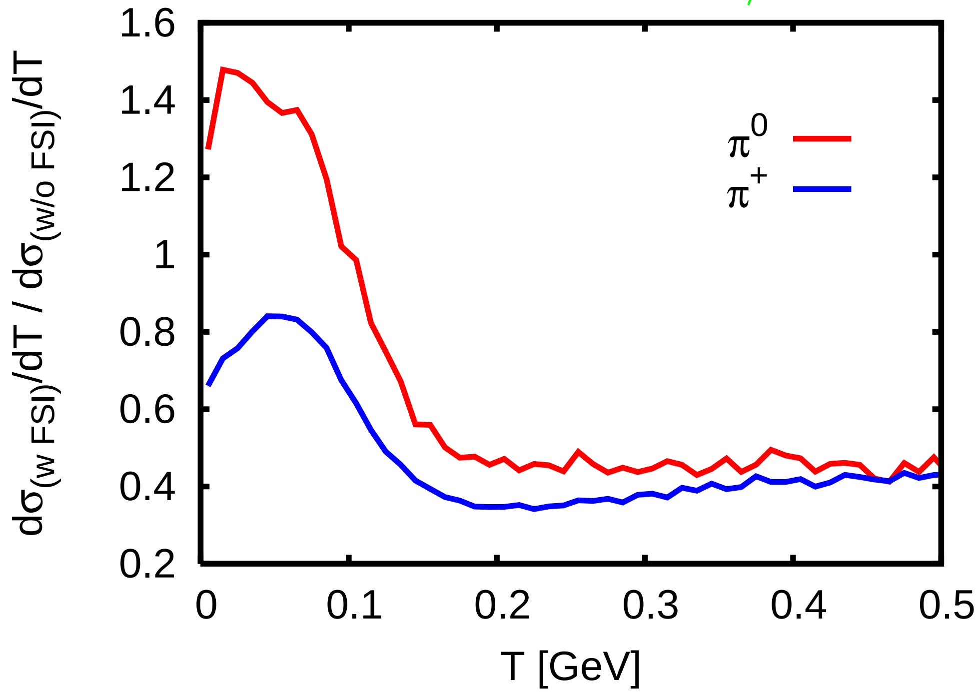
# Pion Production $\nu_\mu\, {}^{56}\mathrm{Fe} \to \mu^- \, \pi \, X$

- Ratio $R = \frac{(d\sigma/dT)_{\text{w FSI}}}{(d\sigma/dT)_{\text{w/o FSI}}}$

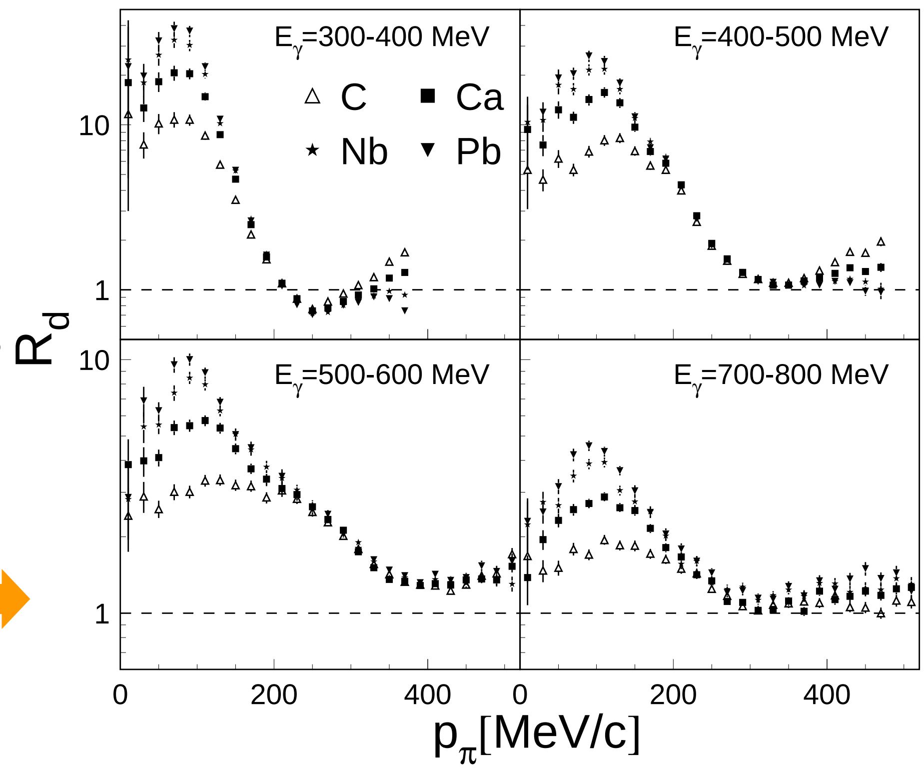


# Pion Production $\nu_\mu\,{}^{56}\mathrm{Fe} \to \mu^- \,\pi\, X$

- Ratio $R = \dfrac{(d\sigma/dT)_{\mathrm{w\ FSI}}}{(d\sigma/dT)_{\mathrm{w/o\ FSI}}}$



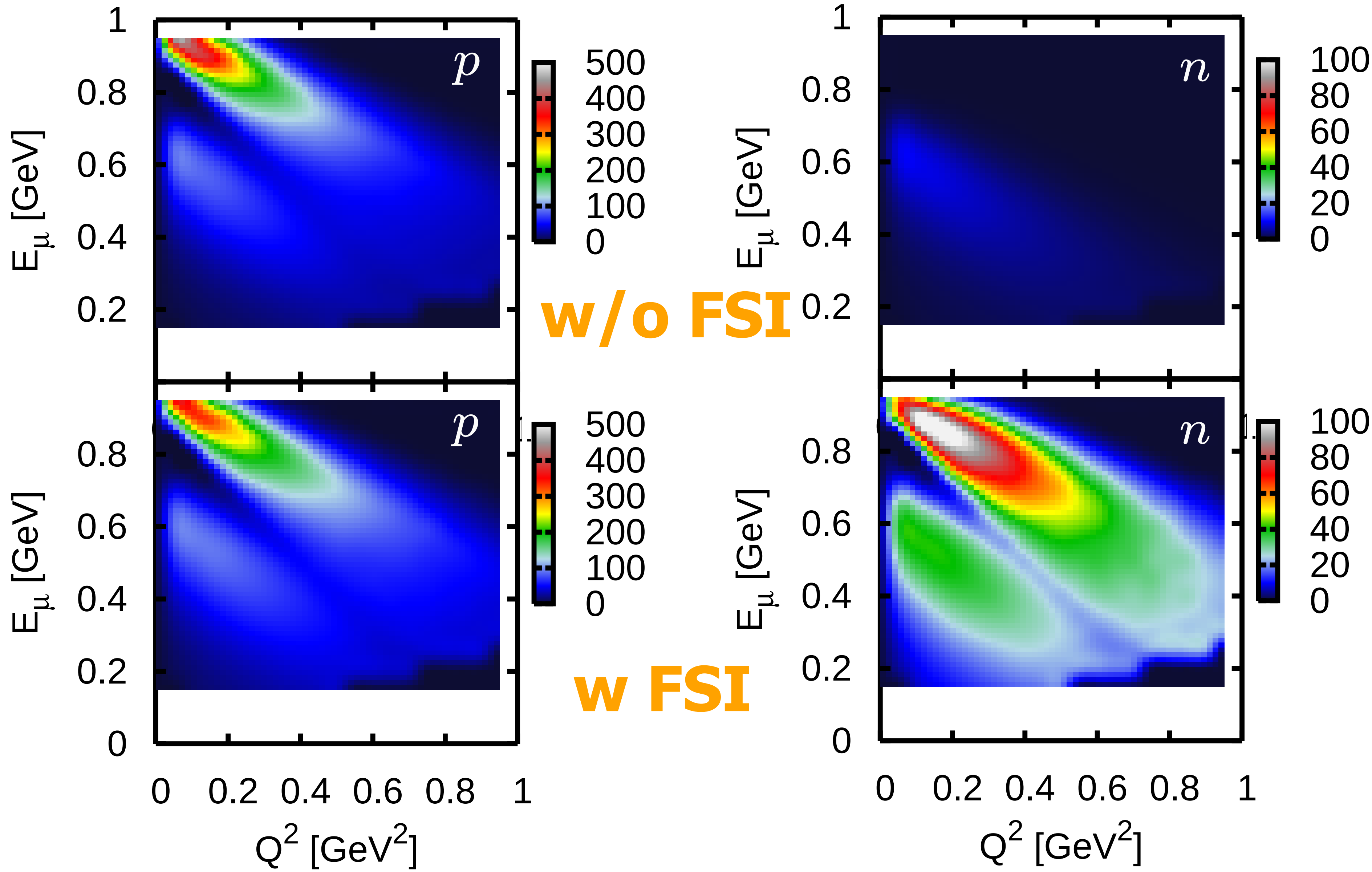

$$R_d = \frac{(d\sigma/dp_\pi)_A / A^{2/3}}{(d\sigma/dp_\pi)_d / 2}$$



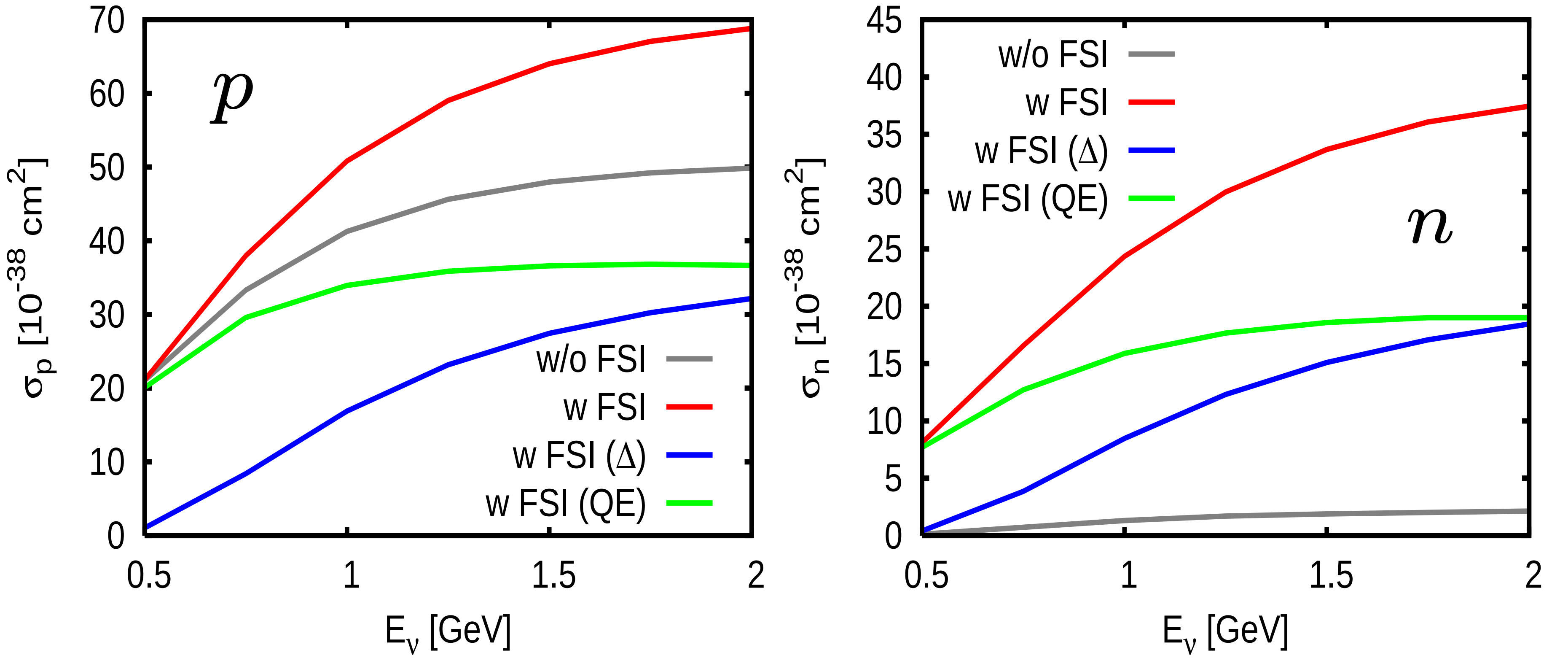

- Similar pattern observed in $\pi^0$ photoproduction

B. Krusche et al., Eur. Phys. J A22 (2004)

## Nucleon Knockout $\nu_\mu\, ^{56}\mathrm{Fe} \to \mu^- N X$ at $E_\nu = 1$ GeV



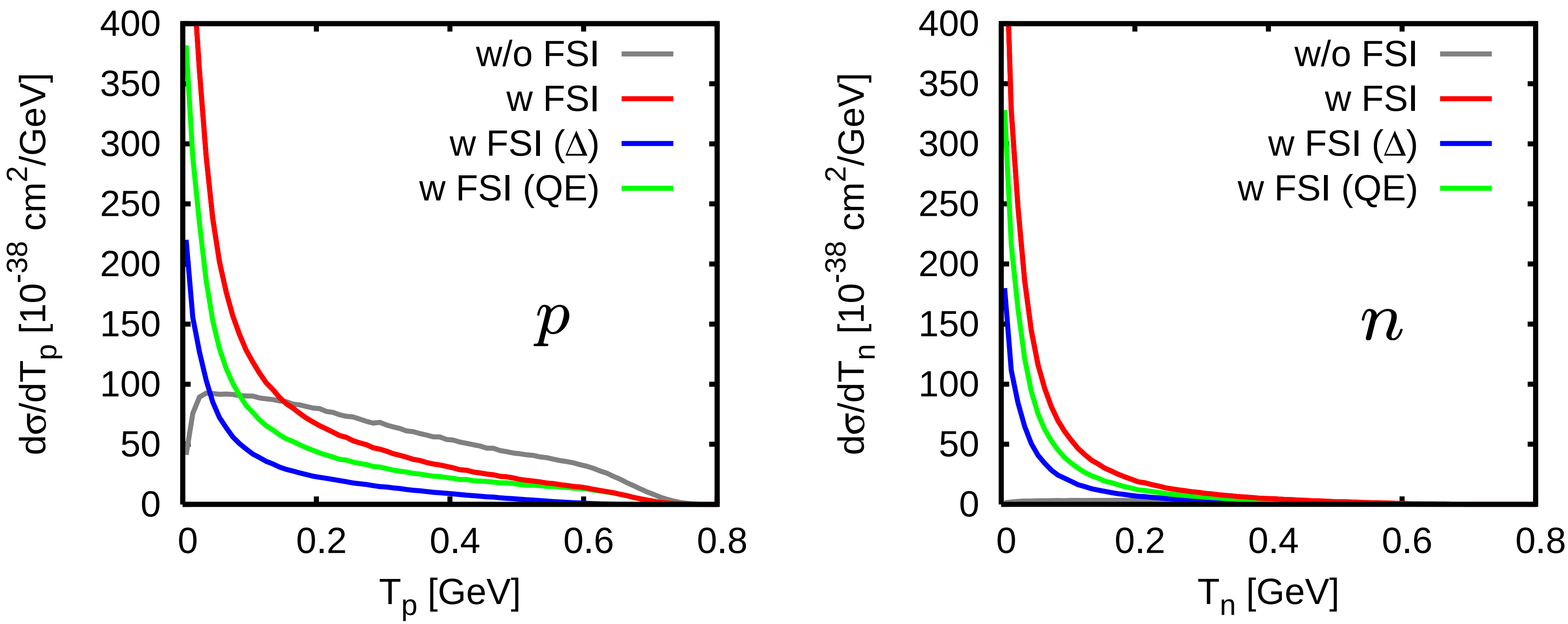
# Nucleon knockout $\nu_\mu \, ^{56}\mathrm{Fe} \rightarrow \mu^- \, N \, X$




- Enhancement due to secondary interactions ( $N\,N \rightarrow N\,N$, $\Delta\,N \rightarrow N\,N$, ...)

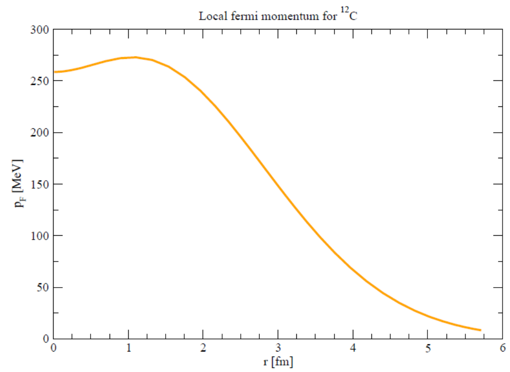
# Nucleon Knockout $\nu_\mu\, {}^{56}\mathrm{Fe} \to \mu^- \, N \, X$

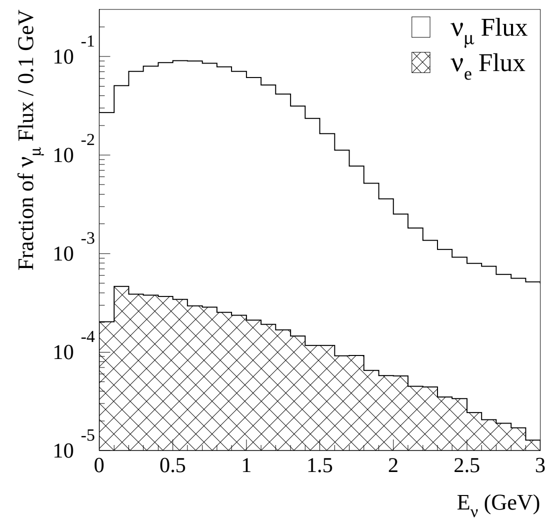
- Nucleon kinetic energy spectrum at $E_\nu = 1$ GeV
  - large number of nucleons at low kinetic energies
  - flux reduction of high-energy protons
  - Strong $p \to n$ side-feeding



# QE scattering at MiniBooNE

- Reaction: $\nu_\mu + {}^{12}C \rightarrow \mu^- + X$
- Observables averaged over MiniBooNE ν flux
- Fermi motion & Pauli blocking
- Local density approximation

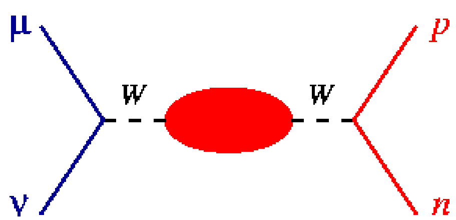


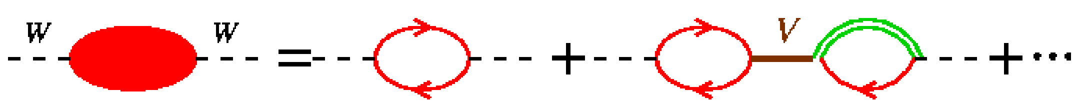




J. Monroe, hep-ex/0408019

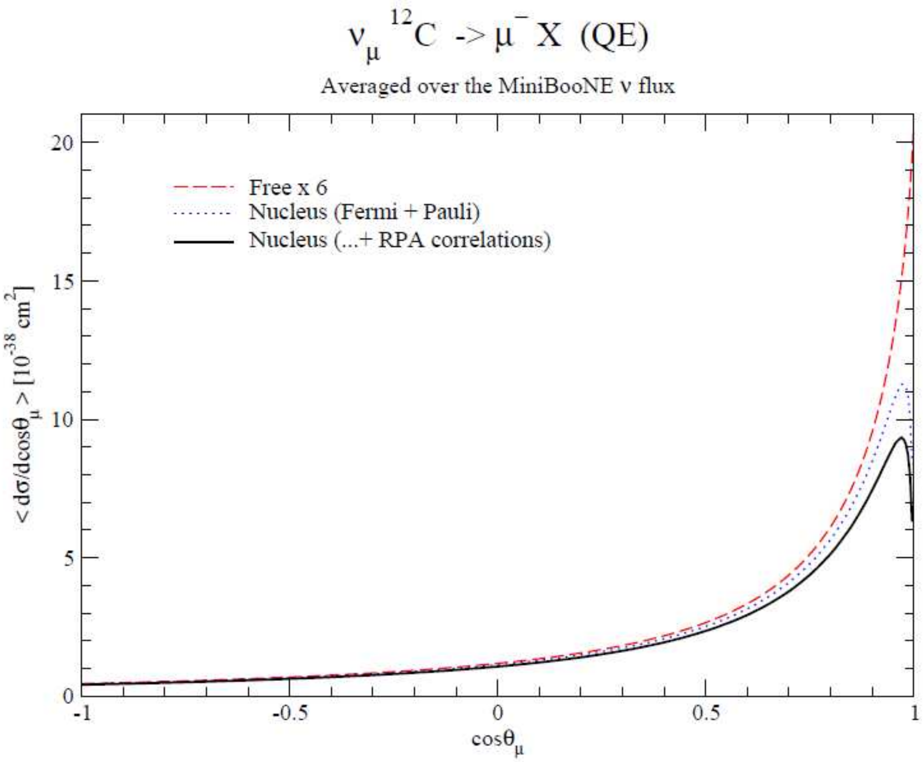
- Polarization effects (nuclear RPA correlations)

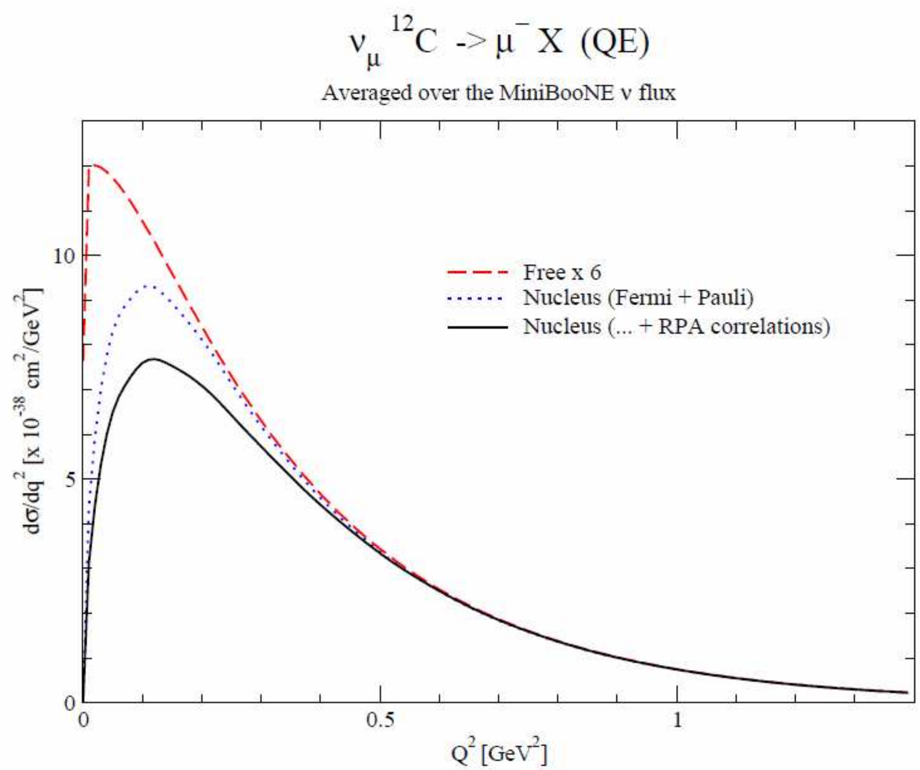
Following Singh & Oset NPA 542 (1992) :



# QE scattering at MiniBooNE



## Conclusions

- A model for neutrino interactions with nuclei have been developed
- Elementary processes:
  - both QE and Δ(1232) considered
  - state-of-the-art form-factors (CVC & PCAC)
- Nuclear effects:
  - Fermi motion, Pauli blocking, Binding
  - Collisional broadening of the Δ resonance
- FSI implemented by means of a semiclassical coupled-channel transport model (BUU)
- Combined description of
  - Inclusive nuclear cross-section
  - Exclusive channels: pion production, nucleon knockout
- FSI modifies considerably the distributions through rescattering, side-feeding and absorption
- Nuclear correlations are important are low Q2