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

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Neutrino interactions with nucleons and nuclei at intermediate energies

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Overview:

- Motivation & Introduction
- Neutrino Nucleon Reactions
- BUU Transport Model
- Nuclear Effects in νA Scattering
- Summary & Outlook

Motivation & Introduction

- past, current & future experiments
  - neutrino oscillations ✓
  - neutrino mass ✓
  - precision measurement of oscillation parameters ✗

- problems
  - uncertainties due to neutrino cross sections & nuclear effects
    → detector response
  - neutrino energy reconstruction
  - proposed experiments: MINERνA, FINESSE

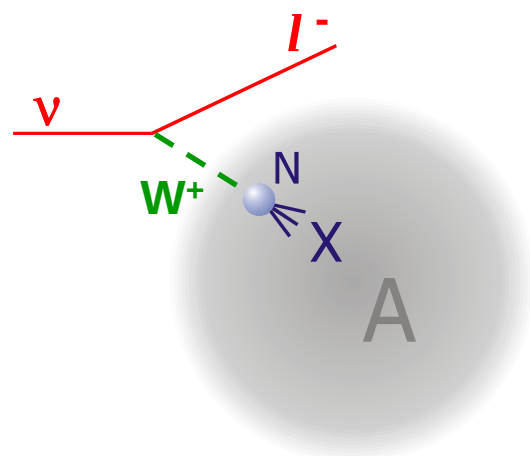
→ better understanding of nuclear effects is crucial for existing & future neutrino experiments

Neutrino Nucleus Scattering

- νA reaction is factorized using **impulse approximation**:
  - $\nu_l N \rightarrow l^- X$

    with consideration of
    - Fermi motion
    - Pauli blocking
    - binding energies
    - in-medium modified Δ width

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



  - propagation of final state X within **BUU transport model** with consideration of FSI

- most general: all neutrino flavors, all nuclei, CC & NC

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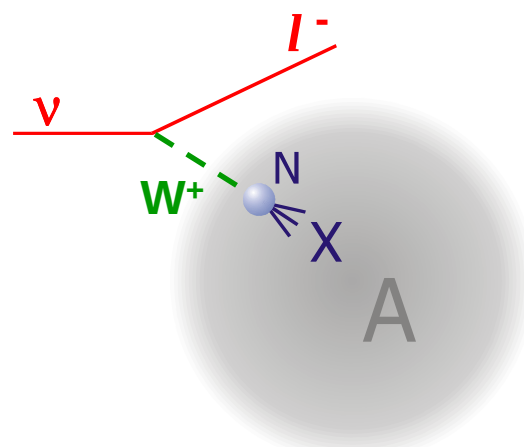

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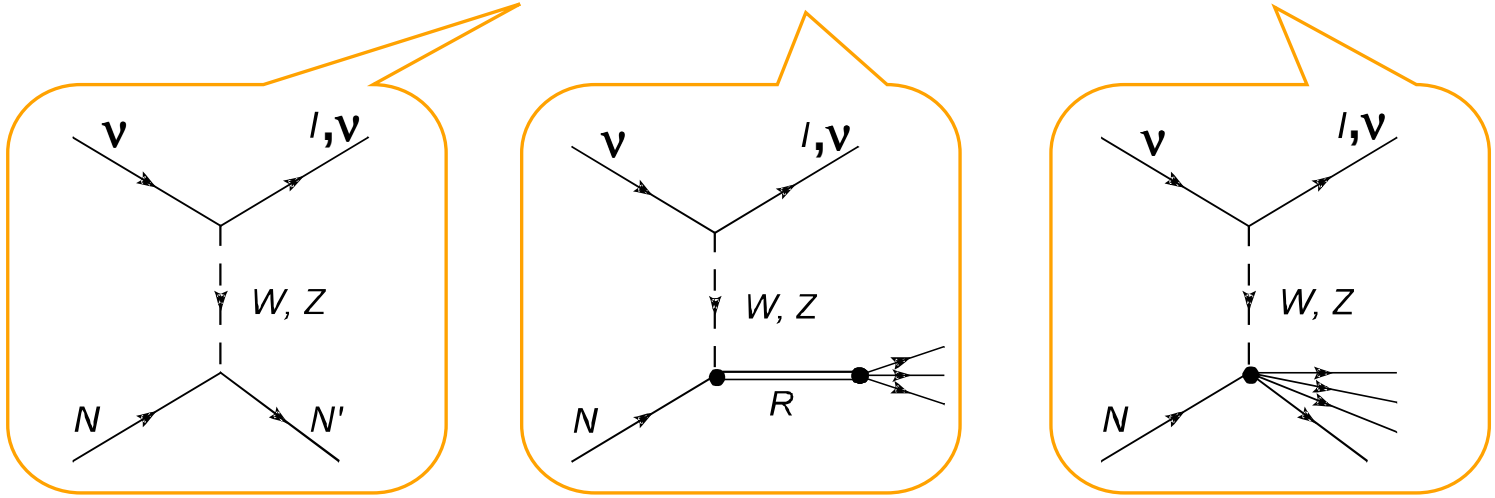
Neutrino Nucleon Scattering

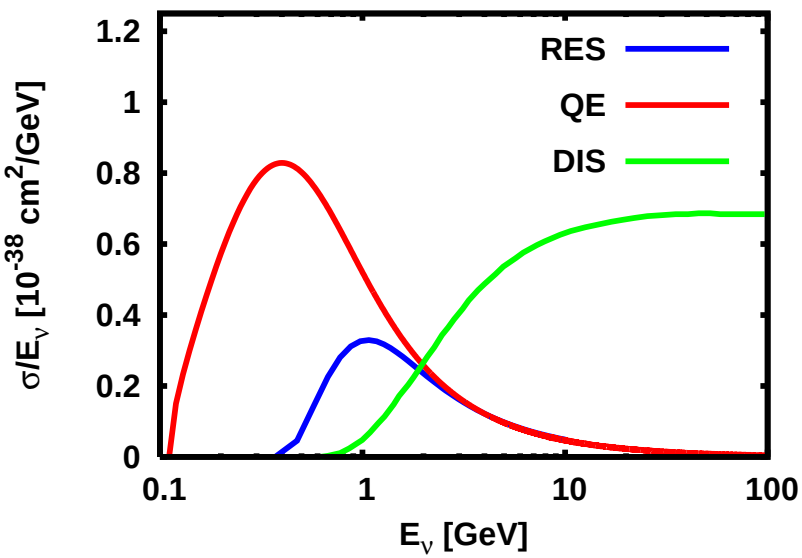
- elementary processes: $\sigma = \sigma(QE) + \sigma(RES) + \sigma(Non - RES/DIS)$



- dominated by **QE** & **Δ resonance**

CC:

$$\nu n \rightarrow l^- p$$
$$\nu n \rightarrow l^- \Delta^+$$
$$\nu p \rightarrow l^- \Delta^{++}$$



Quasielastic Scattering

- hadronic current for $\nu_l\, n \to l^- p$

$$J^\alpha = \cos\theta_C \bar{u}_p \left(\gamma^\alpha F_1^V(Q^2) + \frac{i\sigma^{\alpha\beta} q_\beta}{2M} F_2^V(Q^2) + \gamma^\mu \gamma^5 F_A(Q^2) + \frac{q^\alpha \gamma^5}{M} F_P(Q^2) \right) u_n$$

CVC

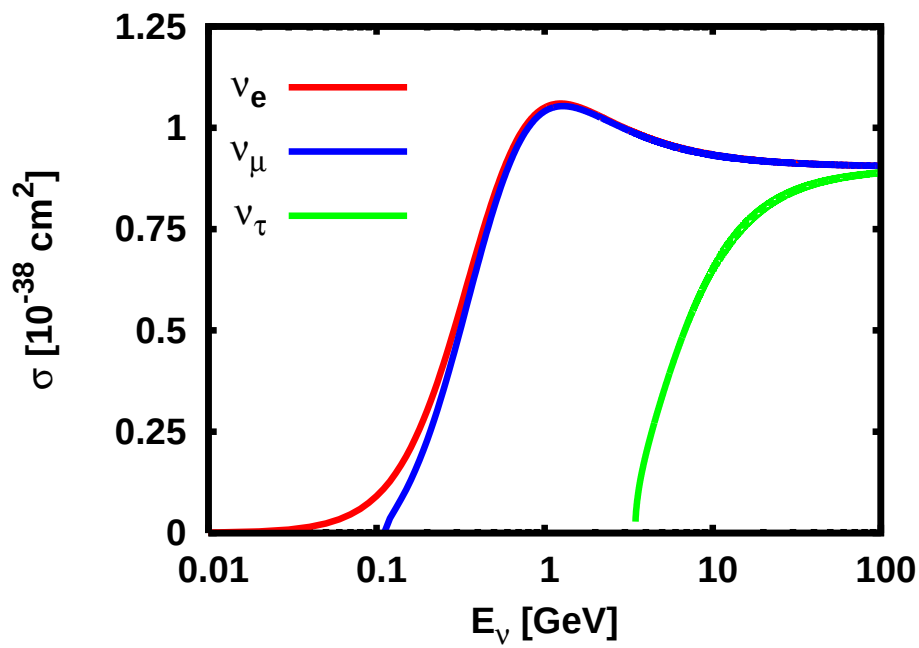
$$F_{1,2}^V(Q^2) = F_{1,2}^p(Q^2) - F_{1,2}^n(Q^2)$$

PCAC

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

- BBA-2003 parametrization for $F_{1,2}^{n,p}$ and

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$



Δ Resonance Production

- hadronic current for $\nu_l\, n \to l^- \Delta^+$

$$J_\alpha = \cos\theta_C \bar{\psi}^\beta(p') D_{\beta\alpha} u(p)$$

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

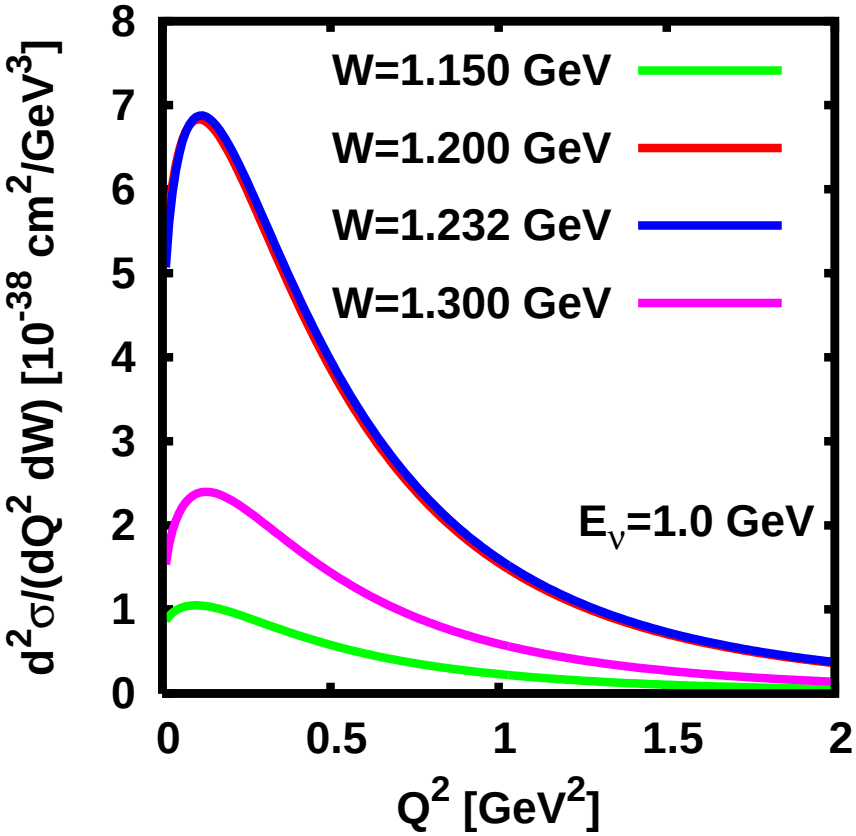
$$D_{\beta\alpha} = \left(\frac{C_3^V}{M}(g_{\alpha\beta}\not{q} - q_\beta\gamma_\alpha) + \frac{C_4^V}{M^2}(g_{\alpha\beta} q\cdot p' - q_\beta p'_\alpha) + \frac{C_5^V}{M^2}(g_{\alpha\beta} q\cdot p - q_\beta p_\alpha) + g_{\alpha\beta} C_6^V \right)\gamma_5$$
$$+ \frac{C_3^A}{M}(g_{\alpha\beta}\not{q}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

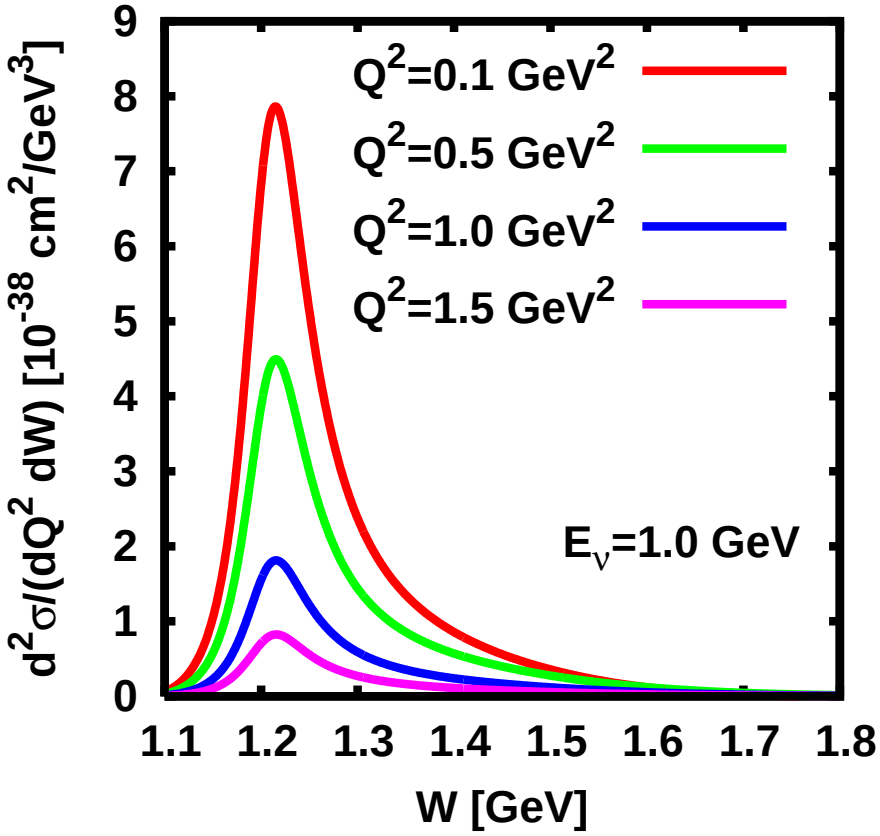
CVC & M_{1+} dominance	PCAC	parametrization
↓	↓	↓
$C_4^V \sim C_3^V$ $C_5^V = 0$ $C_6^V = 0$	$C_6^A \sim C_5^A$	C_3^V
$C_3^V \to eN$		C_5^A C_4^A C_3^A

- Δ width: **p-wave** $\Gamma \sim q_{CM}^3$

Δ Resonance Production Cross Section

- double differential cross section $\frac{d^2\sigma}{dQ^2 dW}$ for $\nu_\mu p \to \mu^- \Delta^{++}$





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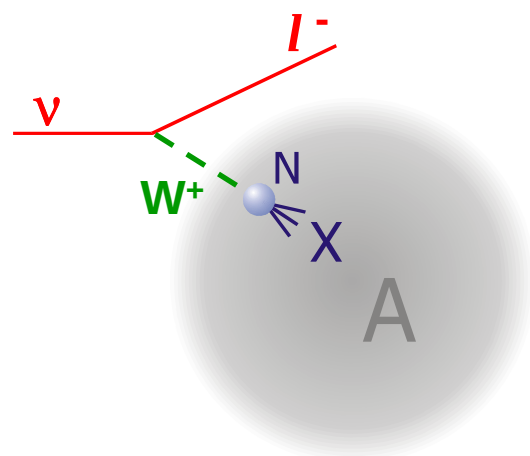

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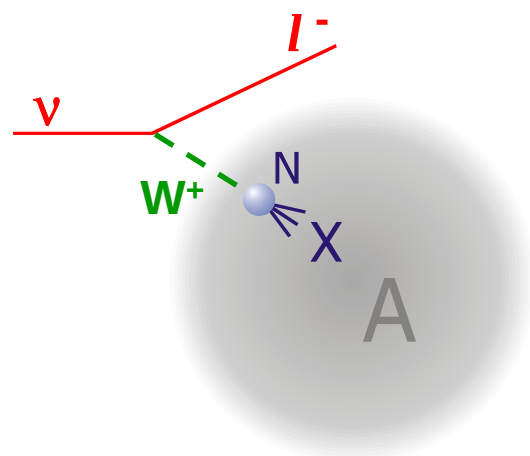

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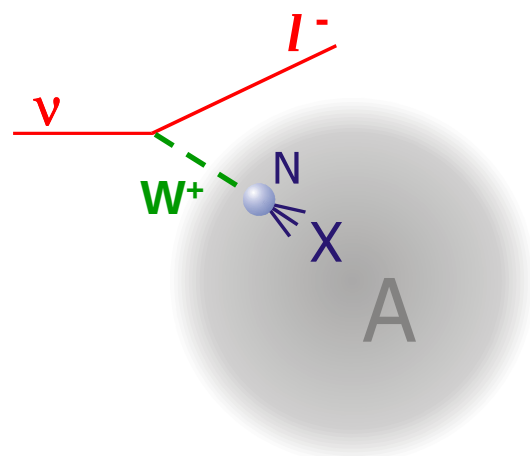

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BUU Transport Model

- description of heavy ion collisions, *e A*, γ *A* and ν *A* reactions with **one** code
- compared experimental data, in particular for $\gamma^{(*)}$ *A*
- coupled channel semiclassical transport model
  - **B**oltzmann-**U**ehling-**U**hlenbeck equation
    for each particle species i ($i = N, R, \pi, \rho, K, \ldots$):

$$\frac{df_i}{dt} = \left(\partial_t + (\nabla_{\vec{p}} H)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H)\nabla_{\vec{p}}\right) f_i(\vec{r}, \vec{p}, t) = I_{coll}\left[f_1, \ldots, f_i, \ldots, f_M\right]$$

Hamiltonian: $H = \sqrt{(\mu + U_s)^2 + \vec{p}^{\,2}}$ f_i : phase space density

mean field for baryons

Skyrme type with momentum dependence

- set of BUU equations coupled via I_{coll} and mean field

BUU Transport Model – Collision Term

- **collision integral** : 2 particle collisions:
  - elastic and inelastic scattering (coupled channels)
  - Pauli blocking for fermions

FSI ⟷

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

- most important scattering processes:

$$NN \leftrightarrow NN \qquad NR \leftrightarrow NR'$$

$$NN\pi \leftrightarrow NN \qquad mB \leftrightarrow R, \text{ in particular } \pi N \leftrightarrow \Delta$$

$$NN \leftrightarrow NR \qquad \pi N \leftrightarrow \pi N$$

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

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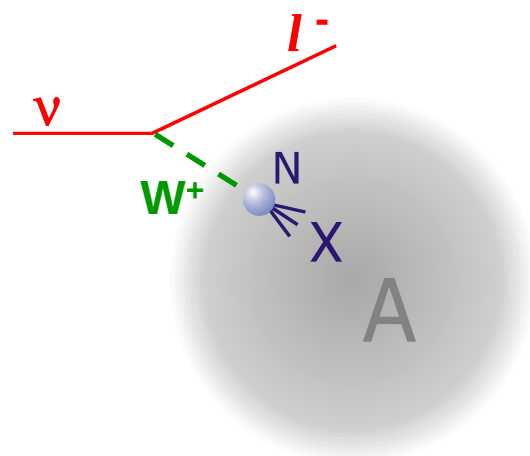

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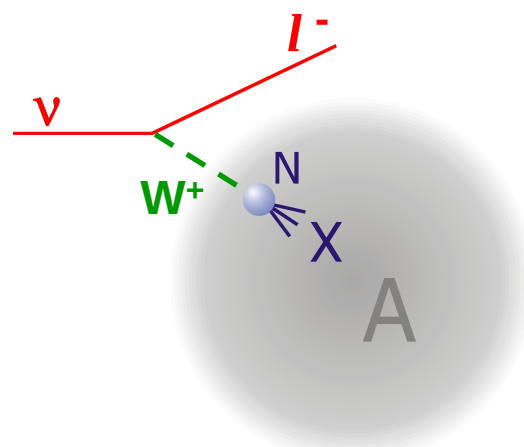

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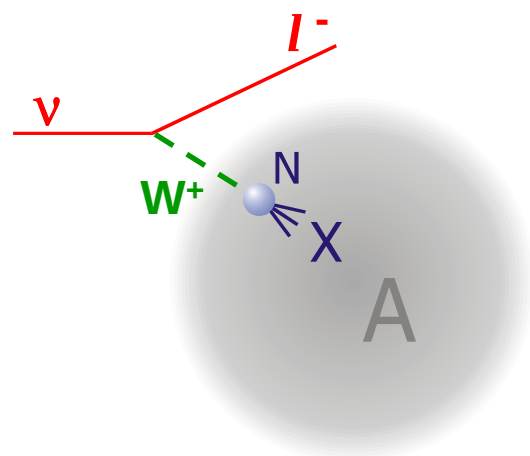


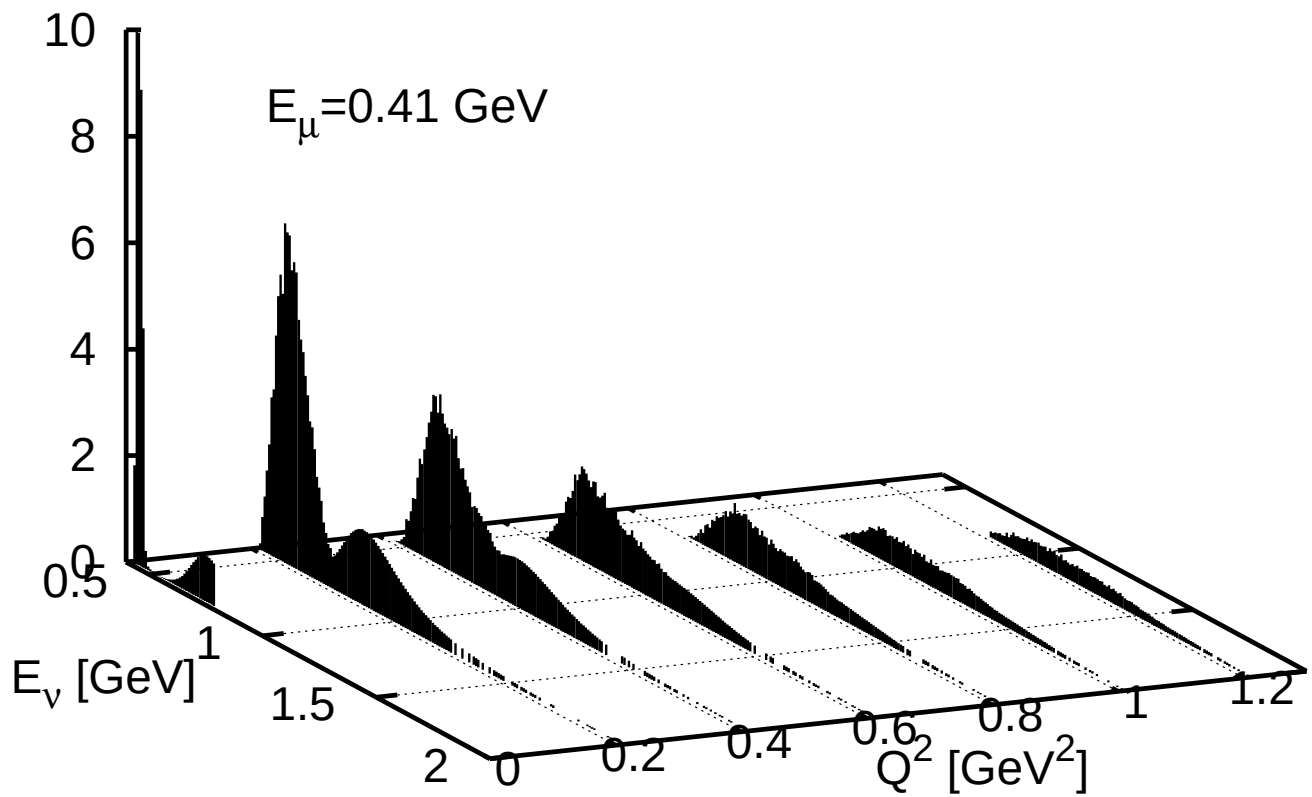
  - propagation of final state X within the **BUU transport model** taking into account FSI

- example: $\nu_\mu {}^{56}\mathrm{Fe} \to \mu^- X$ at E_ν = 0.4 – 2 GeV

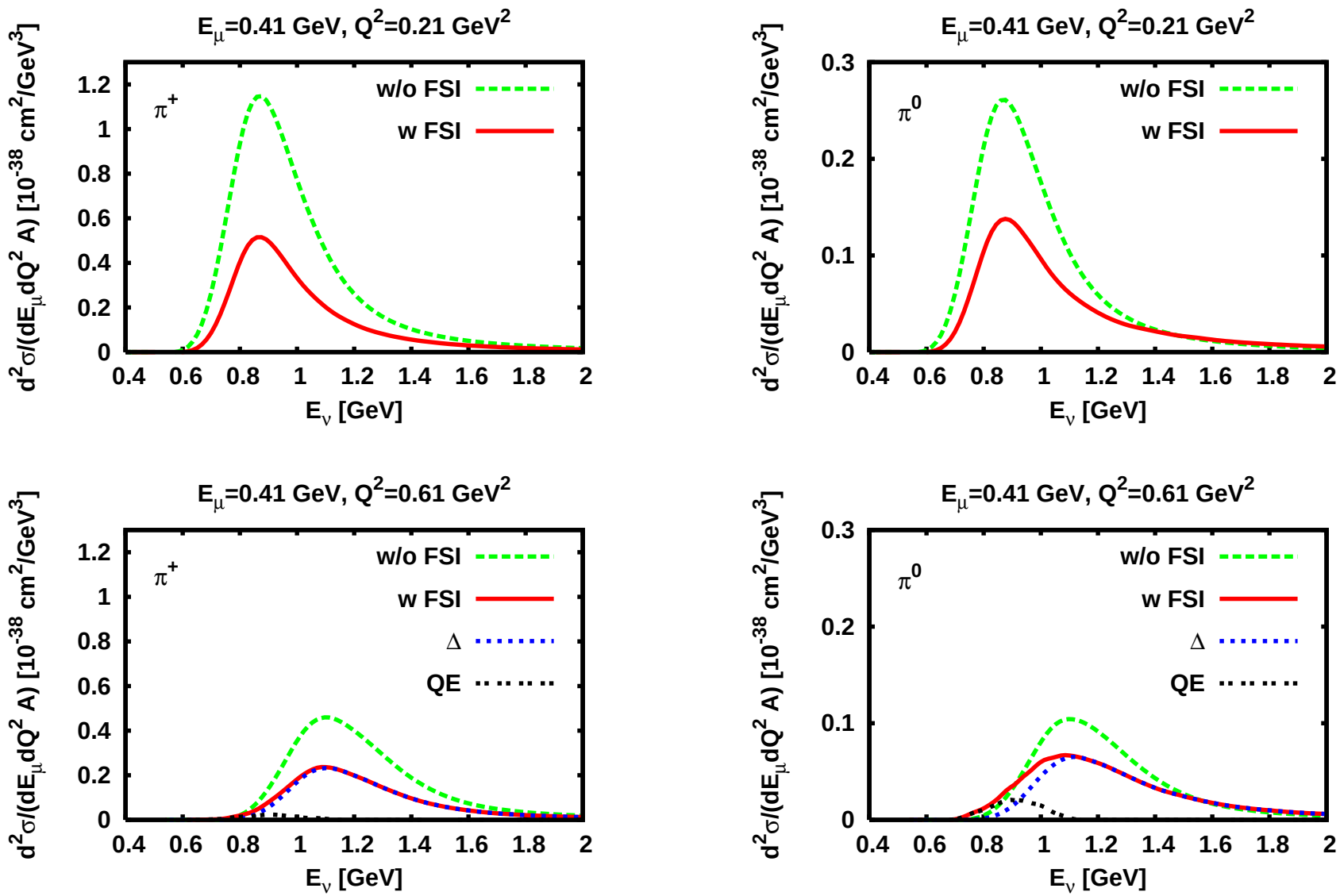
Inclusive Cross Section $\nu_\mu\, {}^{56}\mathrm{Fe} \to \mu^- X$

- double differential cross sections per nucleon: $\frac{\mathrm{d}^2\sigma}{\mathrm{d}E_\mu \mathrm{d}Q^2\, A}$
- inclusive cross section:

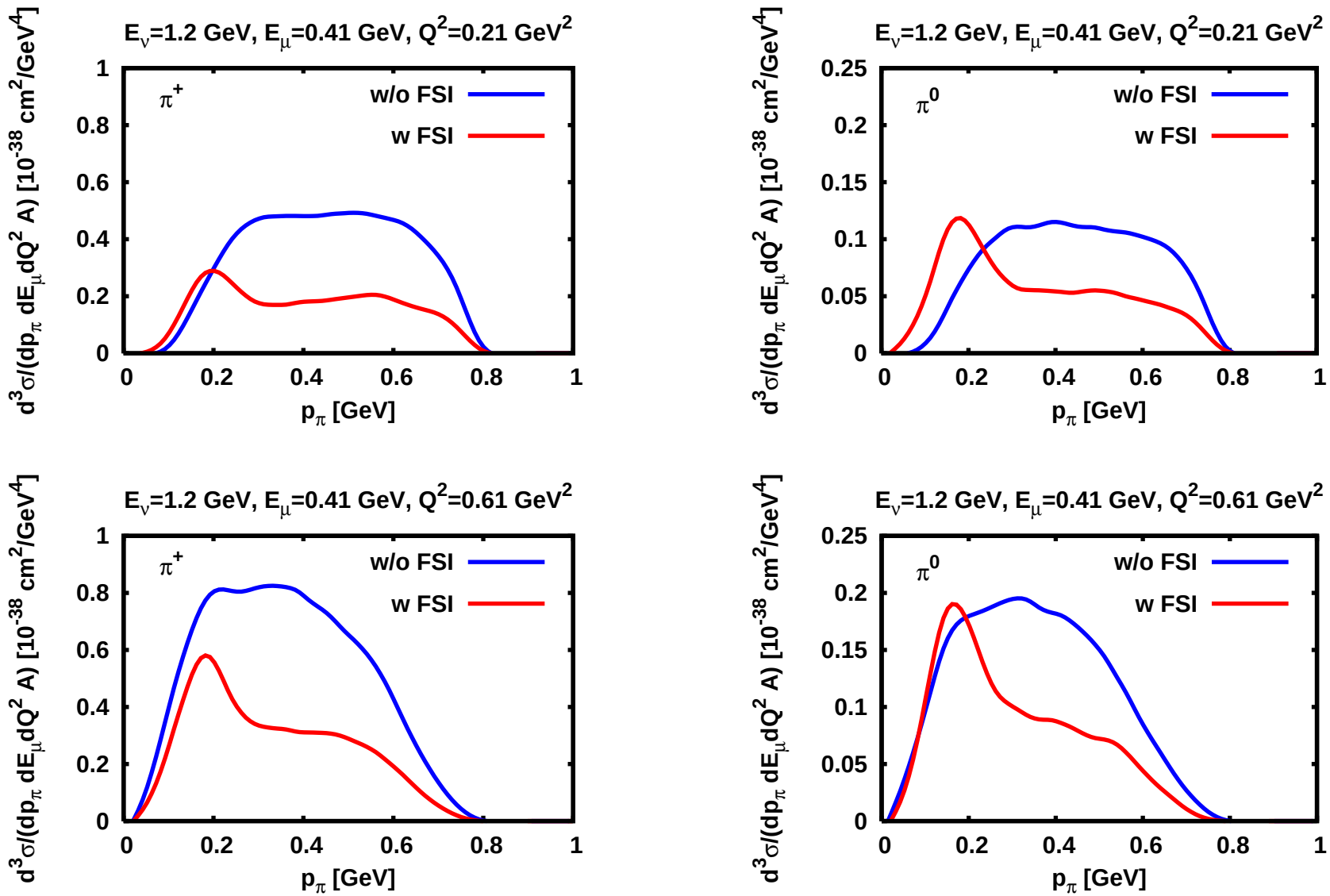
$d^2\sigma/(dE_\mu dQ^2\ A)$ [10^{-38} cm^2/GeV^3]



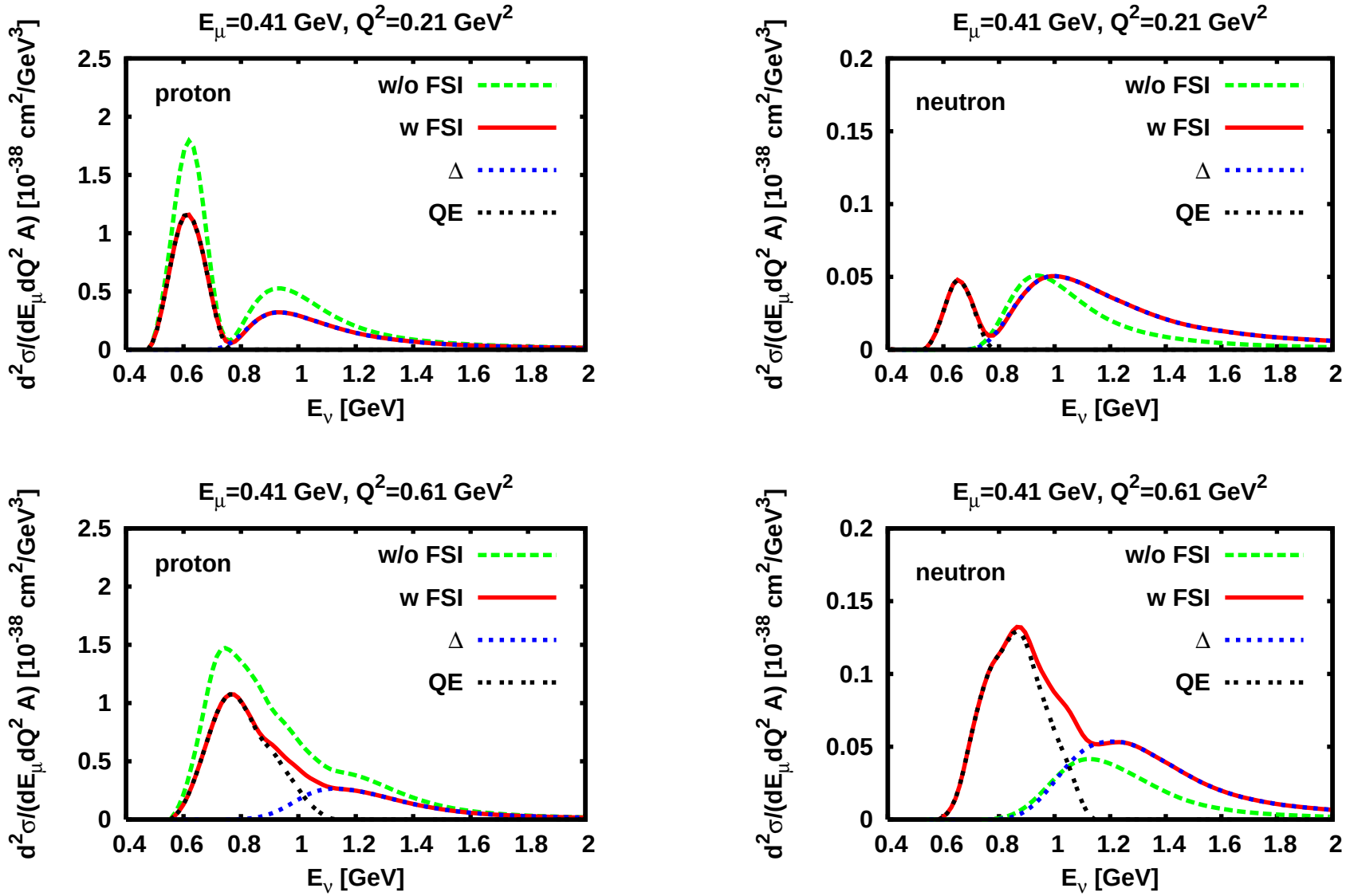
Pion Production $\nu_\mu\, {}^{56}\mathrm{Fe} \rightarrow \mu^- \pi X$



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



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



Summary & Outlook

- **neutrino nucleus scattering**
  - impulse approximation
  - νN followed by FSI
- **neutrino nucleon reactions**
  - quasielastic scattering & Δ production
  - vector form factors extracted from electron scattering
- **BUU model**
  - extended to νA
  - important in-medium effects are taken into account
- **nuclear effects in νA scattering**
  - inclusive scattering, pion production & nucleon knockout
  - in-medium effects, in particular FSI, are not negligible