Neutrino induced pion production and nucleon knockout within the GiBUU transport model

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Copenhagen - Gießen - Helsinki - Jyväskylä - Torino

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Motivation

- interest in neutrino cross sections driven by the discovery of oscillations
  - experimental evidence: SNO, Super-Kamiokande, KamLAND and more
  - oscillation probability (2-flavor): $P(\nu_\mu \to \nu_e; t) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4 E_\nu} \right)$
  - oscillation parameters & possible CP phase not known very precisely
  - problems:

neutrino energy E_ν:
flux reconstruction by measuring final state

distance L between production and detection point:
easy at LBL experiments

detector response:
often heavy nuclei

identification of neutrino flavor:
π^0 can fake ν_e appearance signal

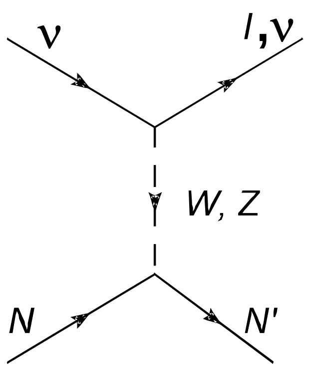
- main source of uncertainties

  - neutrino cross sections
  - nuclear effects

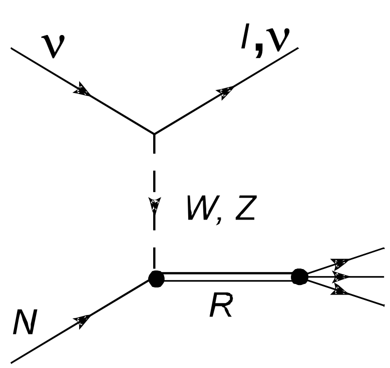
➡ requires coverage by **theory** and experiment

How do neutrinos interact with nucleons?

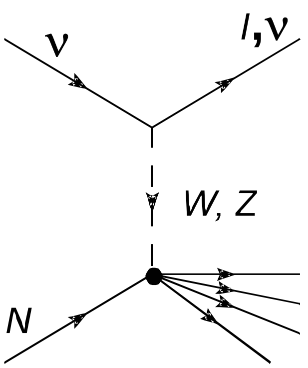
QE



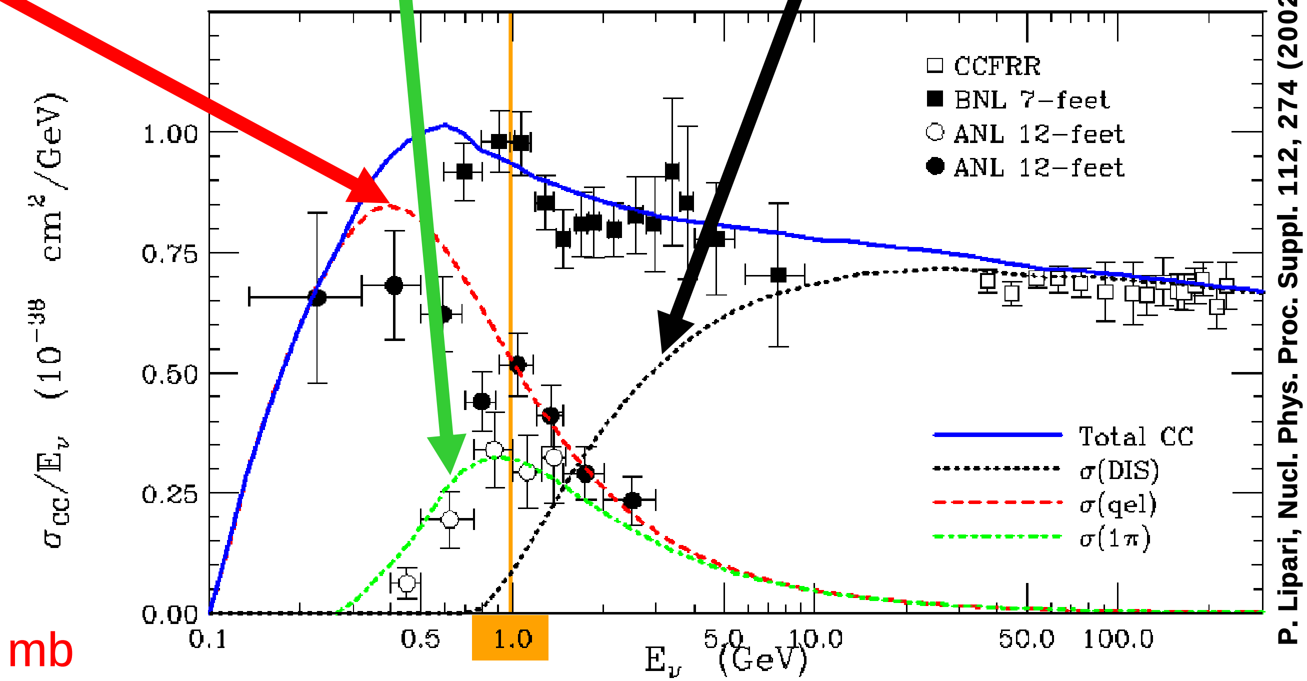
RES



Non-RES/DIS



at ~1 GeV
dominated by
QE
&
Δ resonance



note: 10^{-38} cm² = 10^{-11} mb

Quasielastic scattering

- reactions: CC: $\nu_l\, n \to l^-\, p$
  NC: $\nu\, n \to \nu\, n,\ \nu\, p \to \nu\, p$
- hadronic current: $J_\alpha^{QE} = \langle N'|J_\alpha^{QE}(0)|N\rangle = \bar{u}(p')A_\alpha u(p)$

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

extra term
- ensures vector current conservation for nonequal masses

vector form factors
- related to EM form factors by **CVC**
- **BBA-2003** parametrization

axial form factors
- related by **PCAC**
- dipole ansatz

in addition:
strange vector and axial form factors for NC

Δ resonance production

- reactions:

$$\text{CC: } \nu_l\, n \rightarrow l^- \Delta^+, \quad \nu_l\, p \rightarrow l^- \Delta^{++}$$
$$\text{NC: } \nu\, n \rightarrow \nu\, \Delta^0, \quad \nu\, p \rightarrow \nu\, \Delta^+$$

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

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

$$B_{\beta\alpha} = \left(C_3^V V_3 + C_4^V V_4 + C_5^V V_5 + C_6^V V_6 \right) \gamma_5 + C_3^A A_3 + C_4^A A_4 + C_5^A A_5 + C_6^A A_6$$

with $\mathrm{V_i}$ and $\mathrm{A_i}$ being functions of p, p‘, q

vector form factors

- related by **CVC** to electroproduction
- $C_5^V = C_6^V = 0, \; C_4^V = -\frac{M}{\sqrt{p'^2}} C_3^V$

axial form factors

- related by **PCAC**
- $C_6^A = C_5^A \frac{M^2}{Q^2 + m_\pi^2}, \; C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6} M} \approx 1.2$
- $C_4^A = -\frac{1}{4} C_5^A, \; C_3^A = 0$

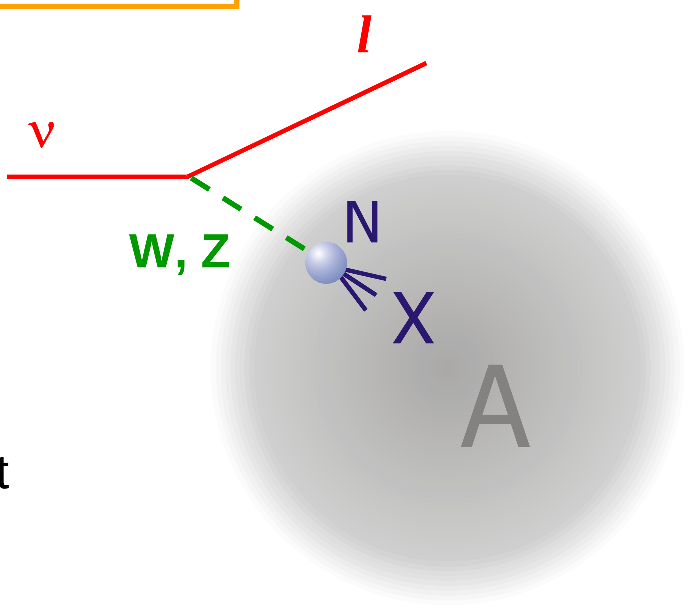
How do neutrinos interact with nuclei?

- neutrino-nucleus reaction: $\nu_l\, A \rightarrow l\ hadrons$

  - scattering off a single nucleon
    - nucleon bound in a nucleus
      - Fermi motion
      - Pauli blocking
      - nuclear binding
      - collisional broadening
      - ...

  ⇛ HK 40.2

  - final state interactions (FSI)
    - **GiBUU** transport model
      - exclusive cross sections:
        pion production & nucleon knockout



GiBUU transport model

- what is GiBUU? **semiclassical transport model in coupled channels**

Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- general information: http://theorie.physik.uni-giessen.de/GiBUU/

- GiBUU describes ...
  - heavy ion reactions (HK 13.4, HK 31.5)
  - pion induced reactions (HK 29.6)
  - low & high energy photon & electron induced reactions (HK 29.6, HK 37.2)
  - **neutrino induced reactions**

... within the same unified framework using the same physics input!

GiBUU transport model – BUU equation

- time evolution of phase space density (for ***i*** = ***N*, Δ, π, ρ, …**) given by BUU eq.:

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

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

one-particle phase space density

mean field: Skyrme type with momentum and density dependence
furthermore: pion potential, Coulomb potential

- one BUU equation for each particle species
  (GiBUU contains 61 baryons and 21 mesons)

- coupled through the potential U_s and the collision integral I_{coll}

GiBUU transport model – collision integral

- **collision term I_{coll}** accounts for changes in phase-space density f_i :
  - "1-body":
    - (strong) decay of unstable particles
  - 2-body:
    - elastic and inelastic scattering
    - $NN \leftrightarrow NN$ $\quad NR \leftrightarrow NR'$

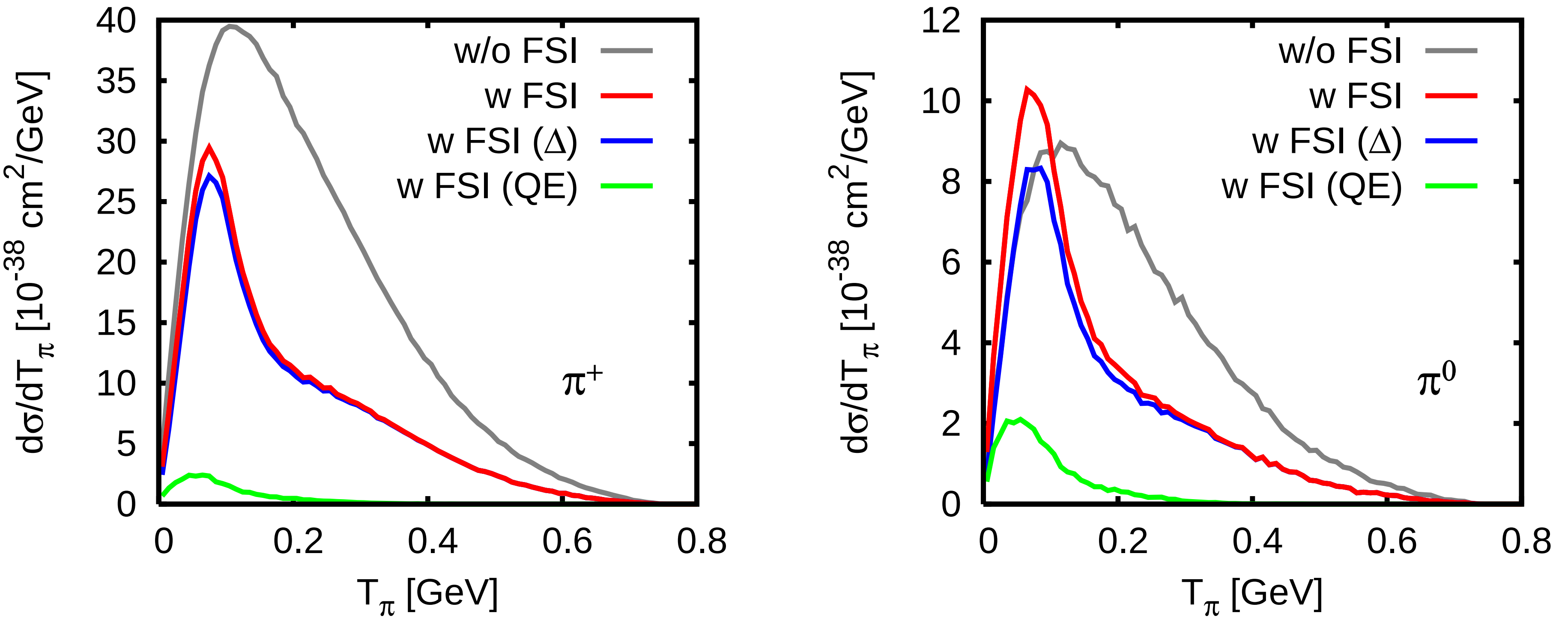
      $NN \leftrightarrow NR$ $\quad mB \leftrightarrow R$, in particular $\pi N \leftrightarrow \Delta$

      $NN \leftrightarrow \Delta\Delta$ $\quad \pi N \leftrightarrow \pi N$
  - 3-body:
    - $\pi NN \rightarrow NN$
    - $NN\Delta \rightarrow NNN$

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

CC pion production: $\nu_\mu {}^{56}Fe \rightarrow \mu^- \pi X$

- effects of FSI on pion kinetic energy spectrum at E_ν = 1 GeV
  - strong absorption in Δ region
  - side-feeding from dominant π^+ into π^0 channel
  - secondary pions through FSI of initial QE protons



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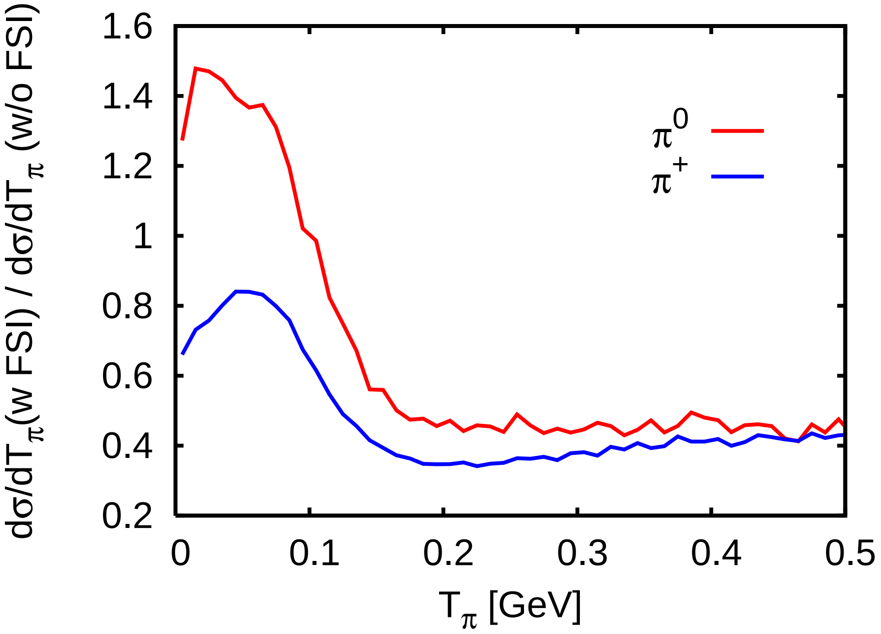

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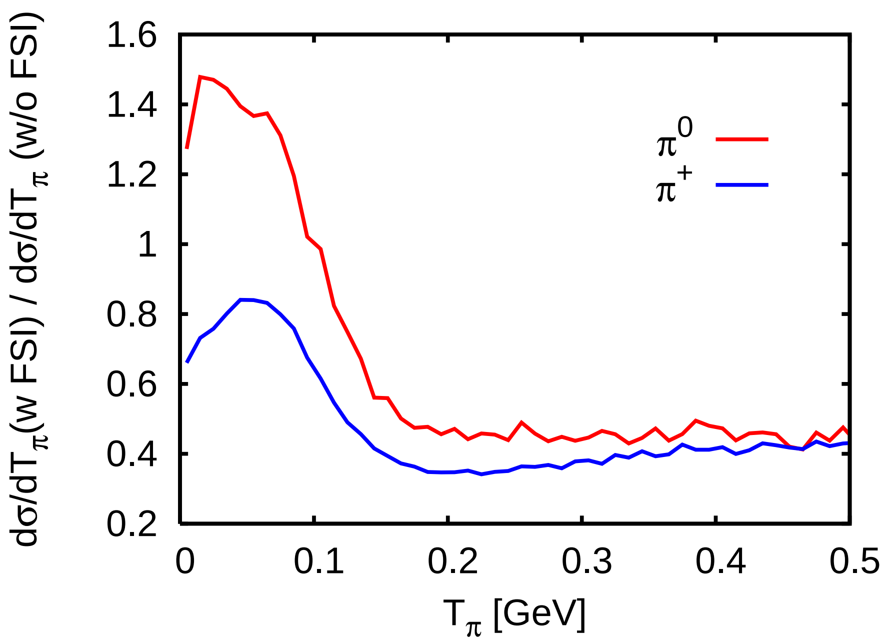
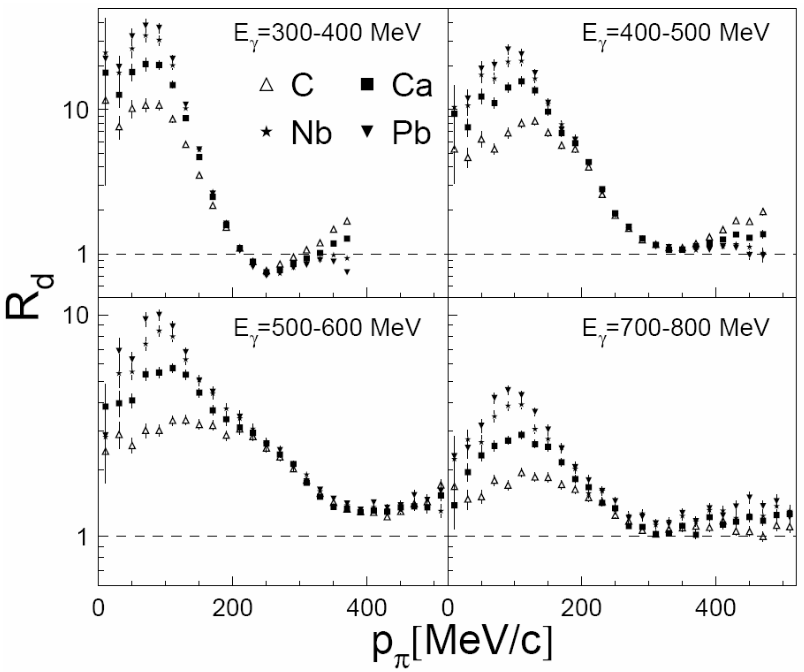
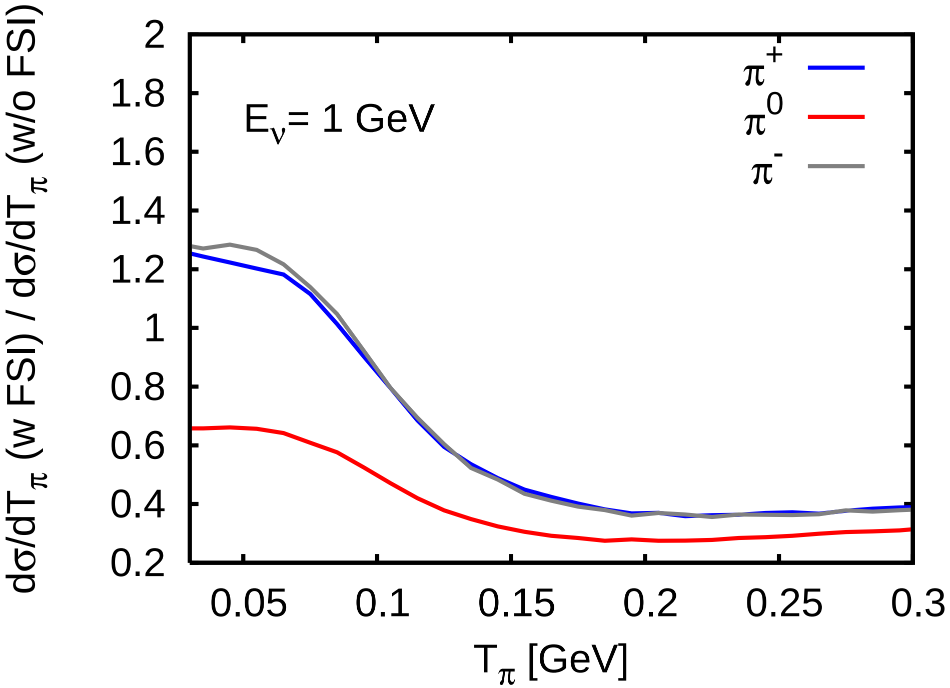




- similar pattern observed in π^0 photoproduction
  - B. Krusche et al., Eur. Phys. J A22 (2004)

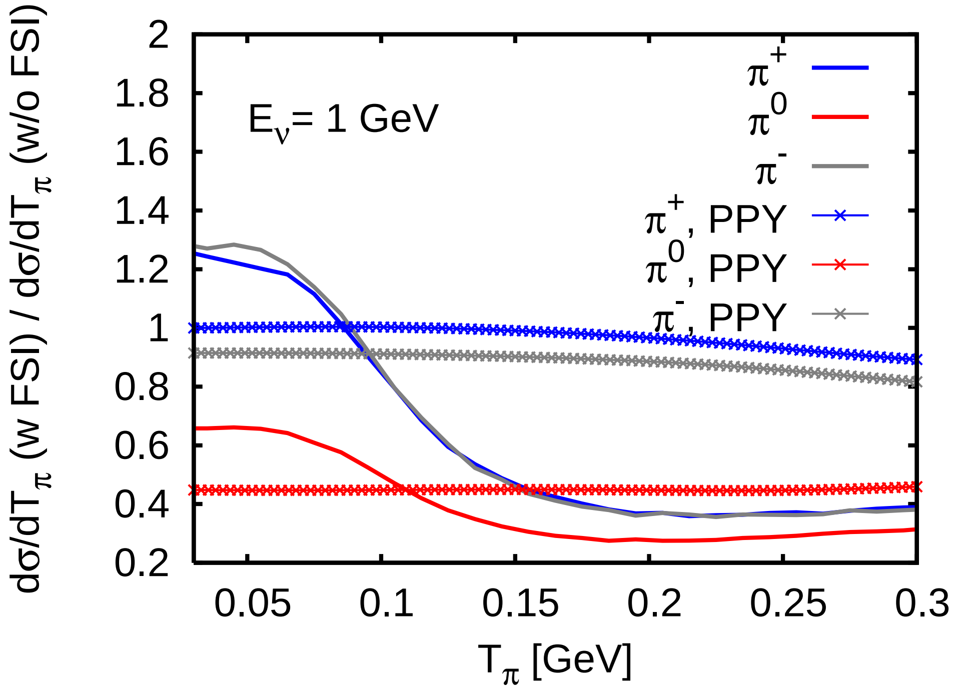
NC pion production: $\nu_\mu\,{}^{56}Fe \rightarrow \nu_\mu\,\pi\,X$

- similar effects of FSI for NC
  - but: side-feeding from dominant π^0 into $\pi^\pm$ channel



NC pion production: $\nu_\mu\, ^{56}Fe \rightarrow \nu_\mu\, \pi\, X$

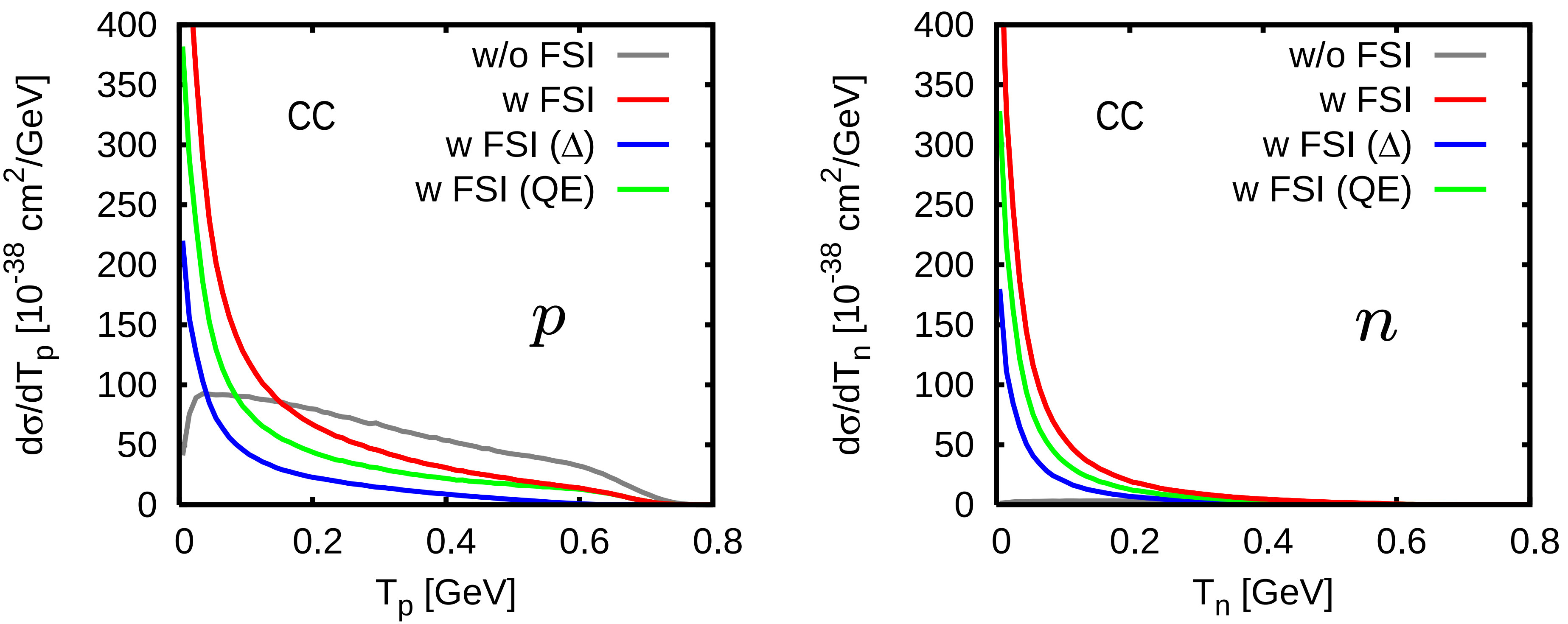
- similar effects of FSI for NC
  - but: side-feeding from dominant π^0 into $\pi^\pm$ channel
  - comparison to random-walk model of Paschos et al. (Nucl. Phys. B 588 (2000) and priv. communication)



ratios of Paschos et al. do **not** reflect the correct properties of $\pi\, N\, \Delta$ dynamics in nuclei

CC nucleon knockout: $\nu_\mu\,{}^{56}Fe \rightarrow \mu^- N X$

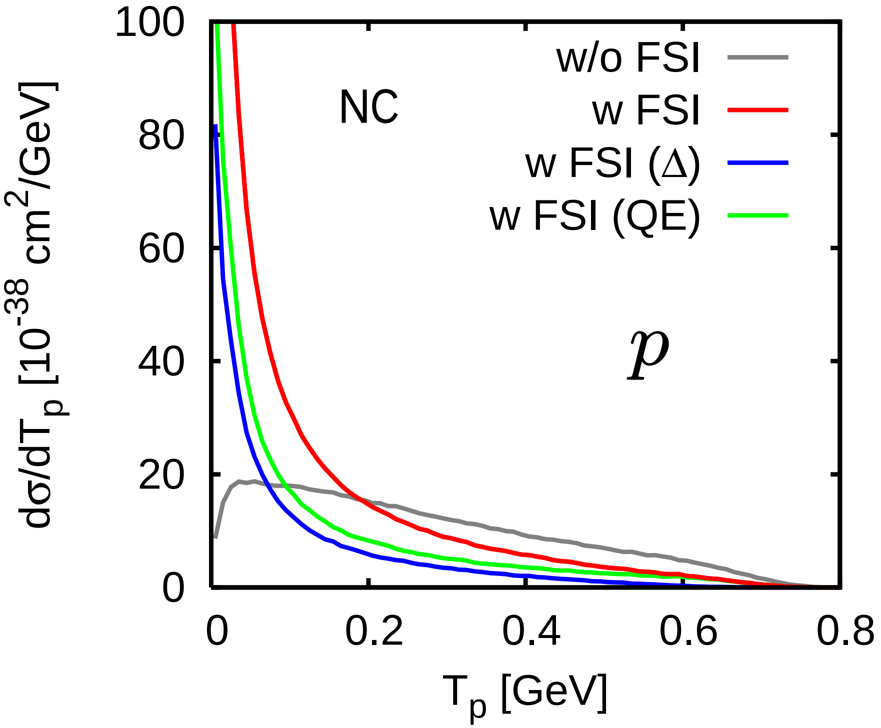
- effects of FSI on nucleon kinetic energy spectrum at E_ν = 1 GeV
  - production of neutrons (in particular in the QE channel)
  - flux reduction at higher energies for protons
  - large number of rescattered nucleons at low kinetic energies
  - FSI **do not cancel** in the p-n ratio (side-feeding!)

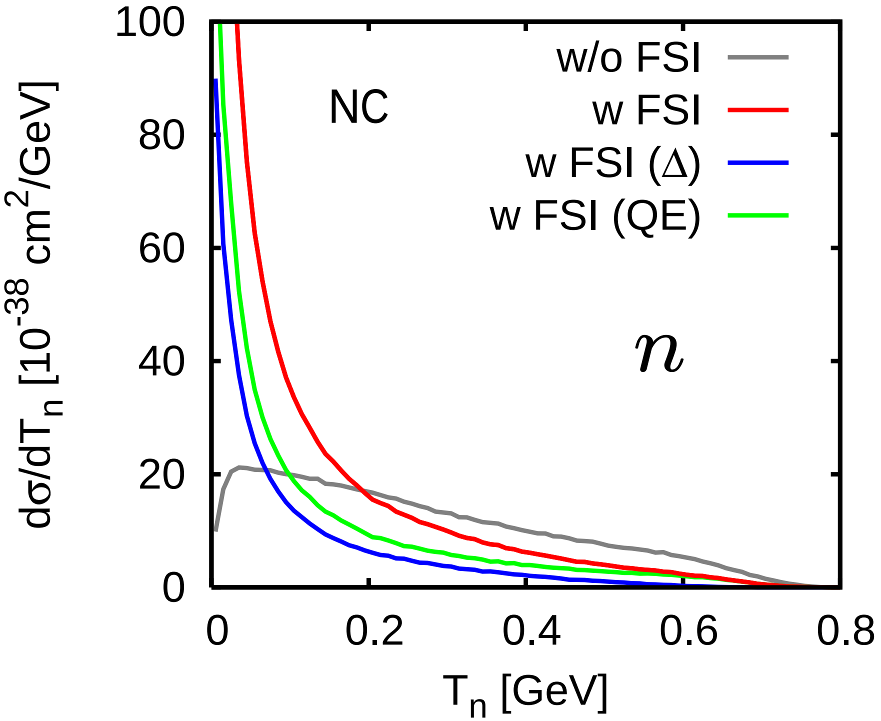


NC nucleon knockout: $\nu_\mu\, ^{56}Fe \rightarrow \nu_\mu\, N\, X$

- similar effects for NC, but:
  - side-feeding only important if proton and neutron yields different
  - NC: starts with comparable yields p : n ~ 1 : 1 (CC: p : n ~ 10 : 1)

Do FSI effects cancel in the p-n ratio? (as claimed e.g. by Alberico, Maieron)





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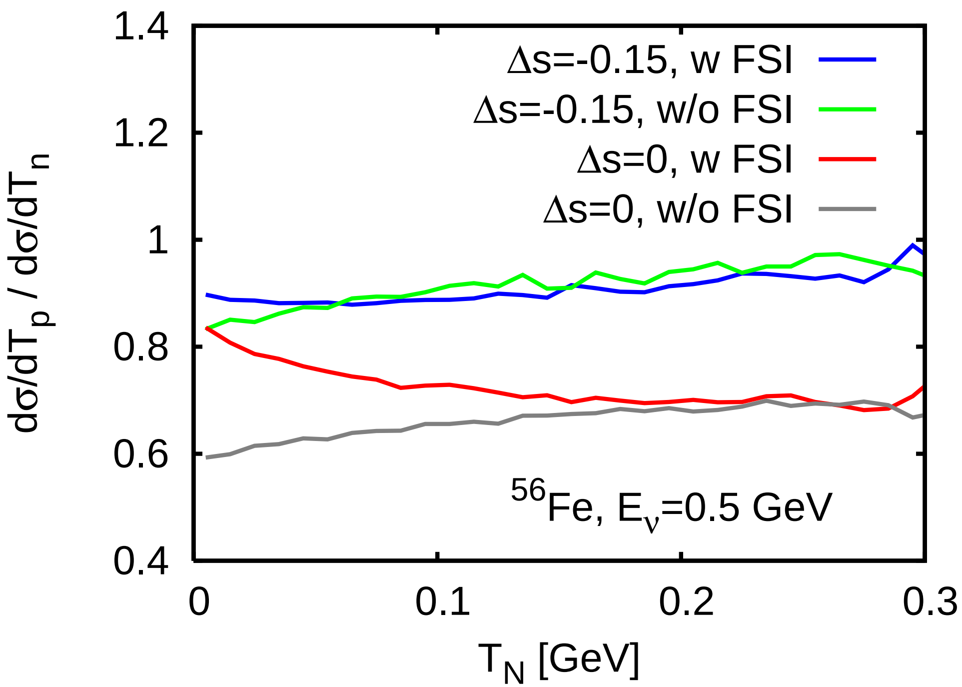


NOT NECESSARILY!

why not?
charge exchange rescattering is very sensitive to differences in initial yields

same effect observed by Nieves et al.

Summary & Conclusions

- neutrino nucleus scattering
  - factorization: νN + in-medium modifications + FSI
- neutrino nucleon reactions
  - at ~1 GeV: dominated by QE scattering & Δ production
  - parametrized in terms of form factors, CVC & PCAC
- neutrino scattering off bound nucleons
  - Fermi motion, Pauli blocking, nuclear binding, modified width → HK 40.2
- final state interactions
  - GiBUU model: reliable model for FSI
- nuclear effects in νA scattering
  - pion production
    - absorption, side-feeding, secondary pions
  - nucleon knockout
    - flux reduction & strong shift to low energies, side-feeding

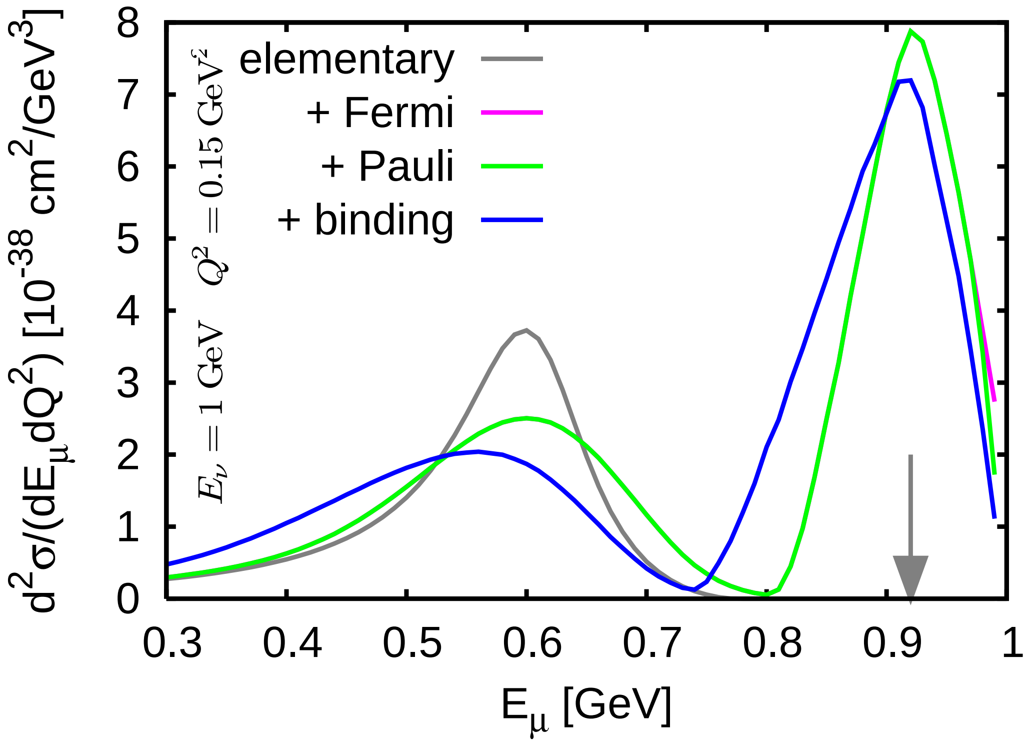
Backup Slides

Medium modifications of the inclusive cross section

ν N cross section is changed if the nucleon is bound in the nucleus!

- **Fermi motion:**
  - local density approximation $p_F(\vec{r}) = \left[\frac{3}{2}\pi^2\rho(\vec{r})\right]^{1/3}$
  - density distribution: Woods-Saxon $\rho(r) = \rho_0\left(1 + \exp\frac{r - r_0}{\alpha}\right)^{-1}$
- **Pauli blocking:**
  - $P_{Pauli} = 1 - \Theta\left(p_F(\vec{r}) - |\vec{p}\,|\right)$
- **nuclear binding:**
  - potential $U_s(\vec{r}, \vec{p})$

➡ affect both QE and Δ



Medium modifications of the inclusive cross section

- Δ cross section is further modified in the nuclear medium:
  - decay might be Pauli blocked: decrease of the free width $\Gamma \rightarrow \tilde{\Gamma}$
  - additional "decay" channels in the medium: collisional width Γ_{coll}

$\Delta N \rightarrow NN$ $\Delta NN \rightarrow NNN$	"pion-less decay"

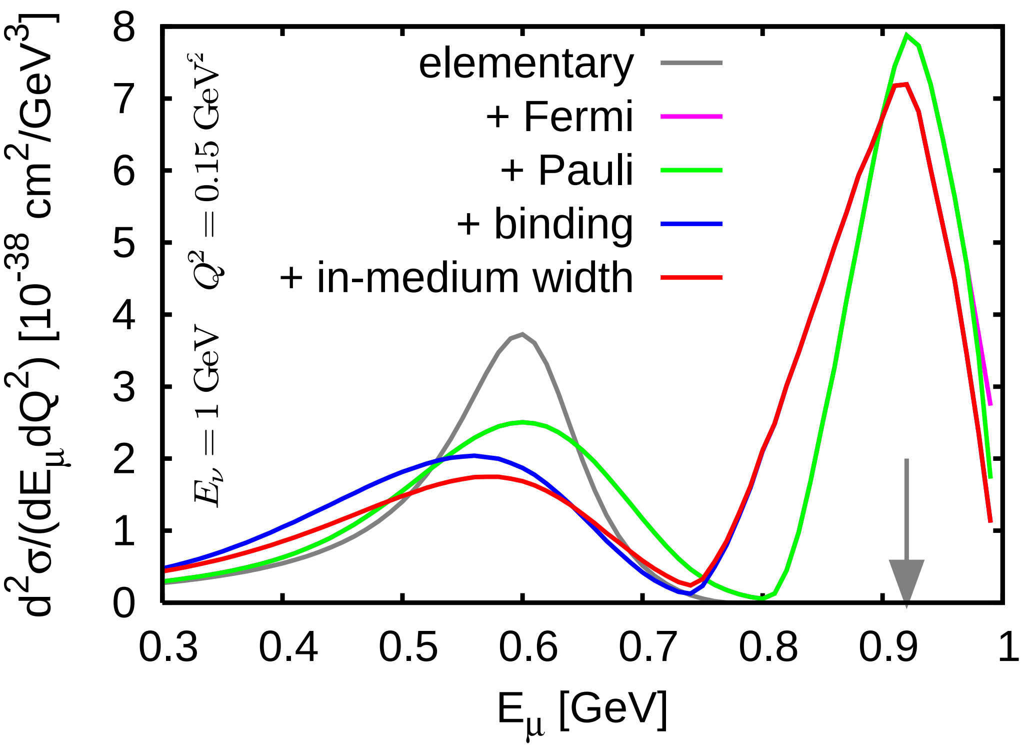
$\Delta N \rightarrow \pi NN$

$\Delta N \rightarrow \Delta N$

  - overall effect:
    increase of the width

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

collisional broadening



CC pion production on free nucleons

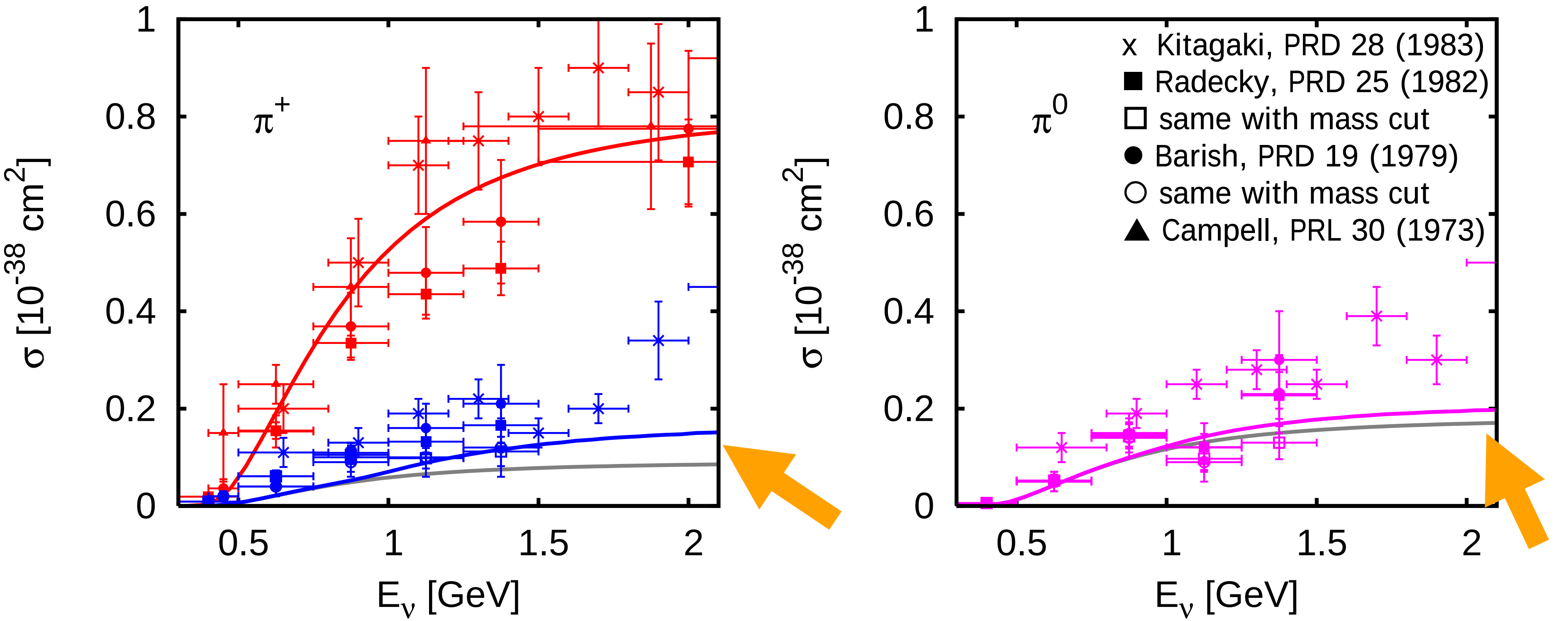
- CC production of Δ^+ and Δ^{++}
  - ➔ subsequent decay into **3** channels: $\nu_l\, p \to l^- p\, \pi^+$

isospin 3/2 state not affected

including higher resonances (isospin ½): $P_{11}(1440), D_{13}(1520), S_{11}(1535)$

$\nu_l\, n \to l^- n\, \pi^+$

$\nu_l\, n \to l^- p\, \pi^0$



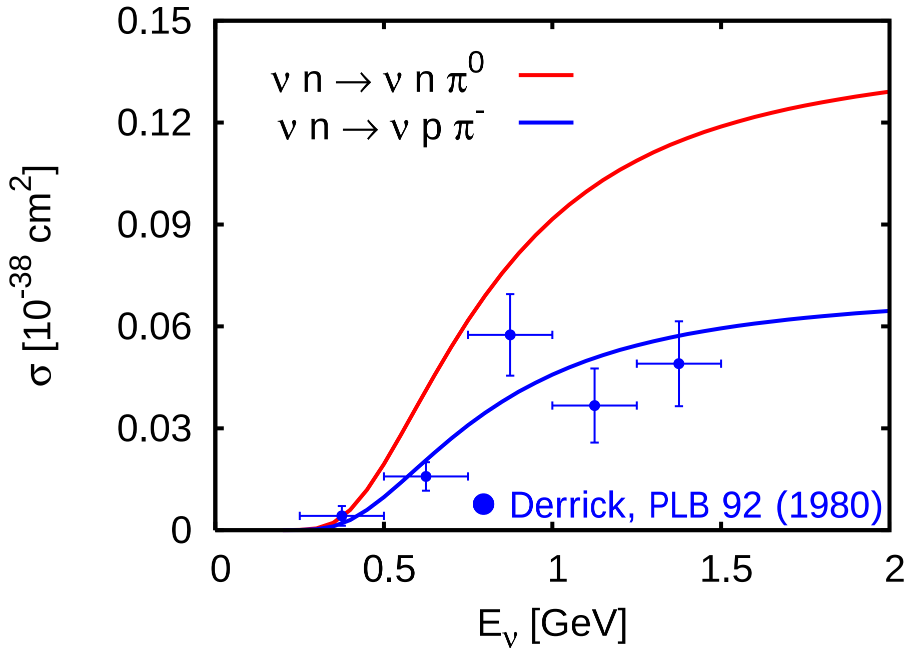
NC pion production on free nucleons

- NC production of Δ^+ and Δ^0
  - ➔ subsequent decay into **4** channels:

$$\nu p \to \nu n \pi^+$$
$$\nu n \to \nu p \pi^-$$
$$\nu p \to \nu p \pi^0$$
$$\nu n \to \nu n \pi^0$$

isoscalar target:

$$\pi^+ : \pi^- : \pi^0 = 1 : 1 : 4$$
$$p : n = 1 : 1$$



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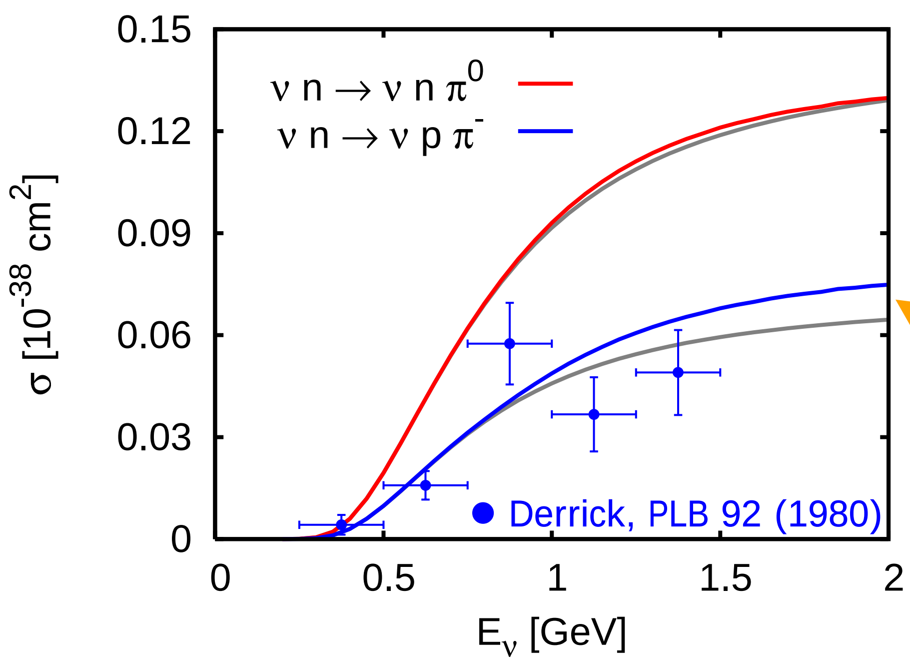
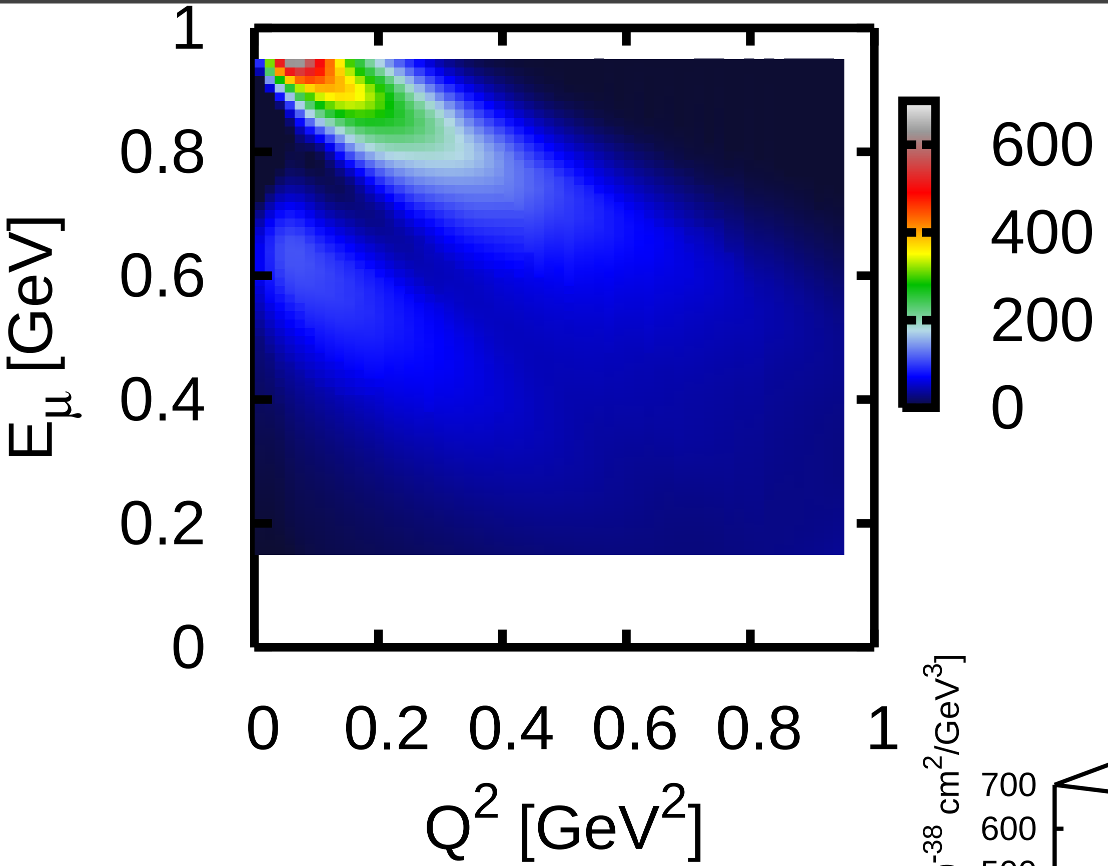


including higher resonances (isospin ½):

$$P_{11}(1440), D_{13}(1520), S_{11}(1535)$$

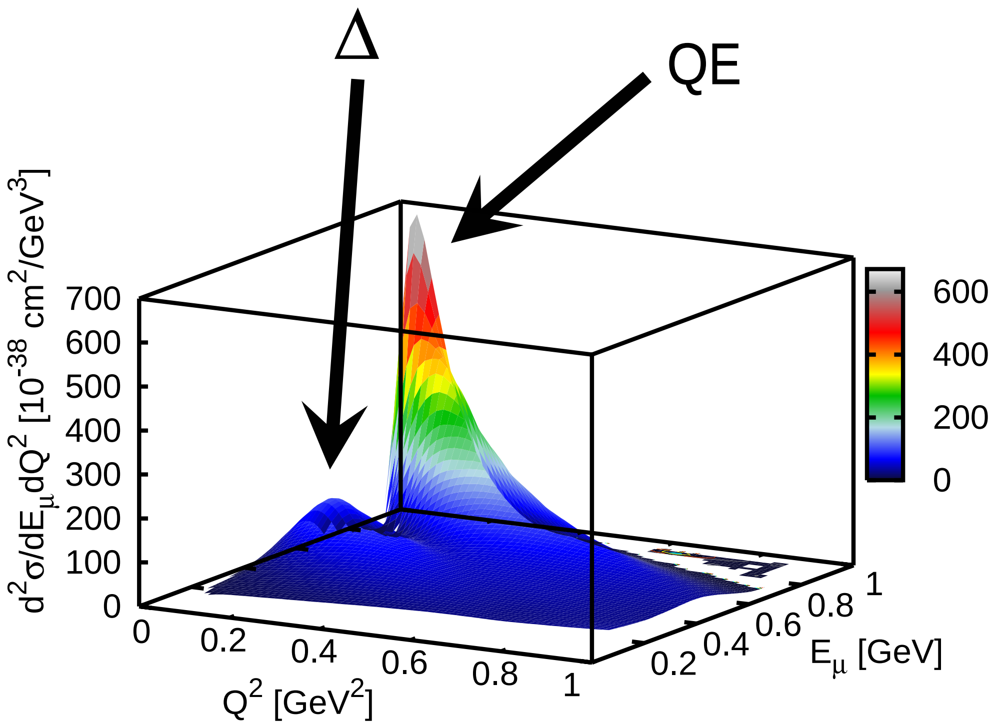
Rein and Sehgal matrix elements
(Ann. Phys. 133, 79 (1981))

Neutrino scattering off bound nucleons

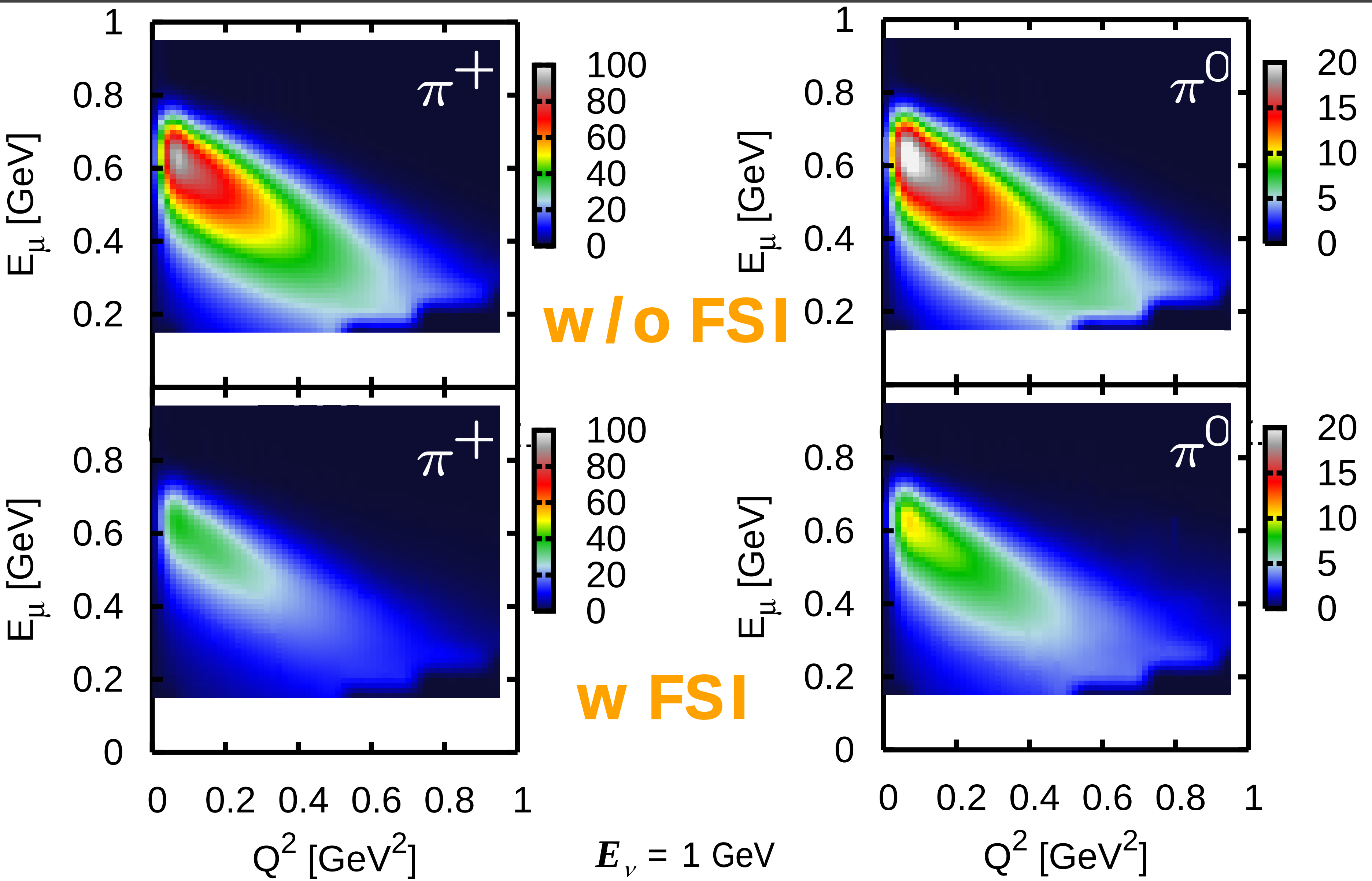


$\nu_\mu\, {}^{56}\mathrm{Fe} \to \mu^- X$

$E_\nu = 1\,\mathrm{GeV}$

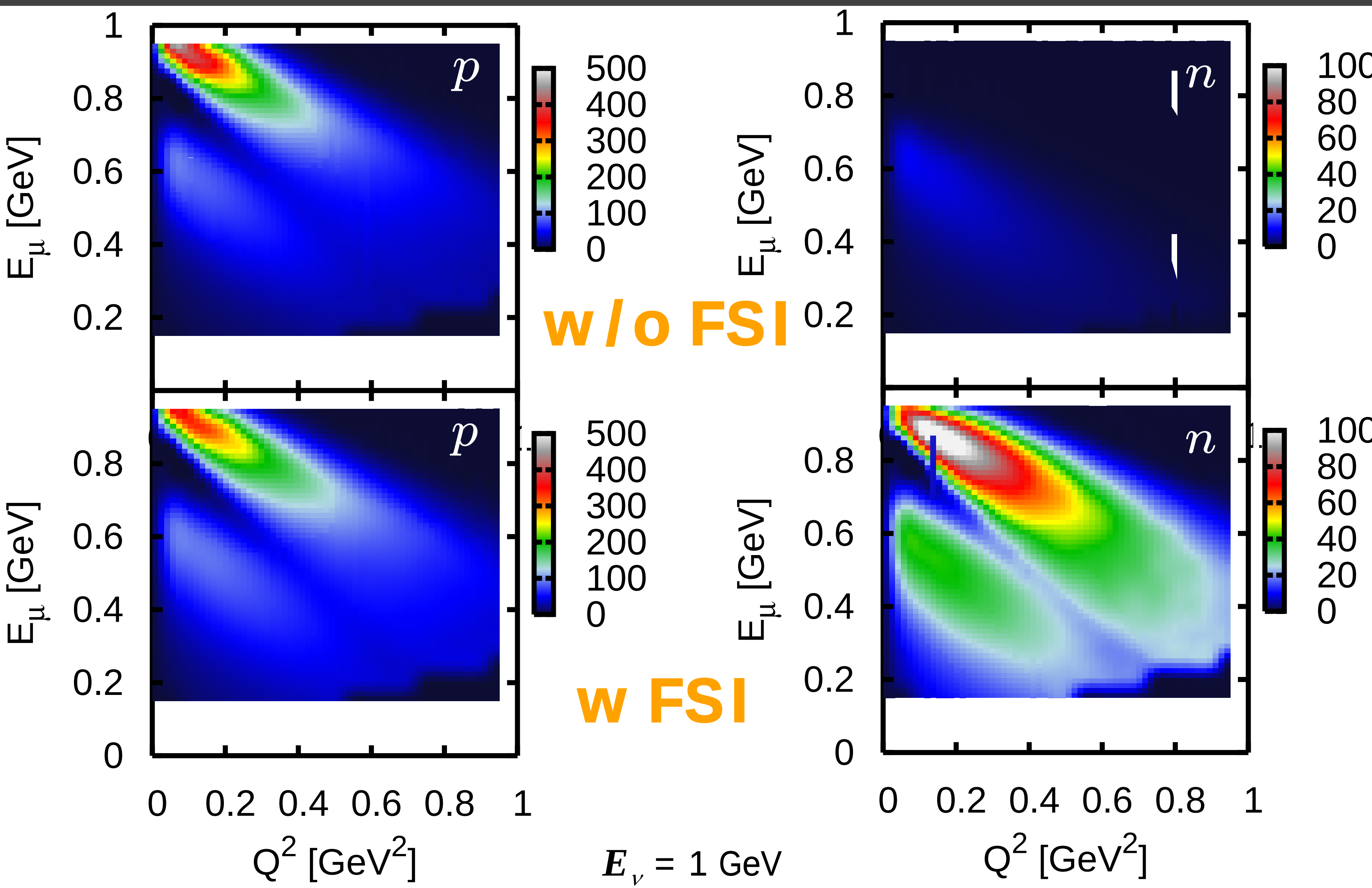


CC pion production: $\nu_\mu {}^{56}Fe \rightarrow \mu^- \pi X$



E_ν = 1 GeV

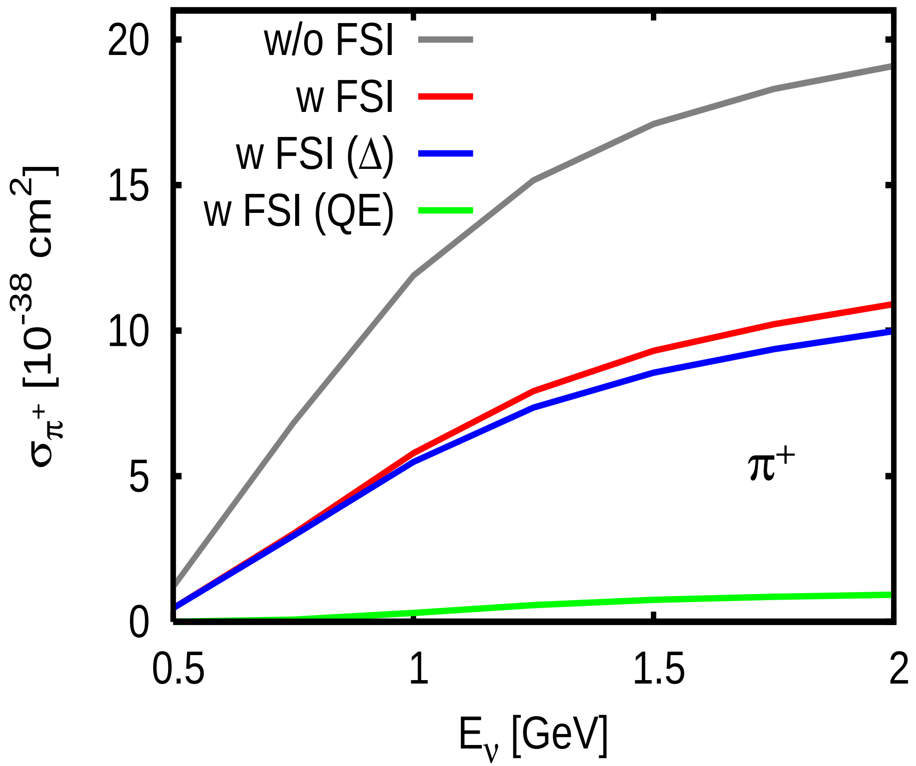
CC nucleon knockout: $\nu_\mu\,^{56}Fe \rightarrow \mu^- N X$

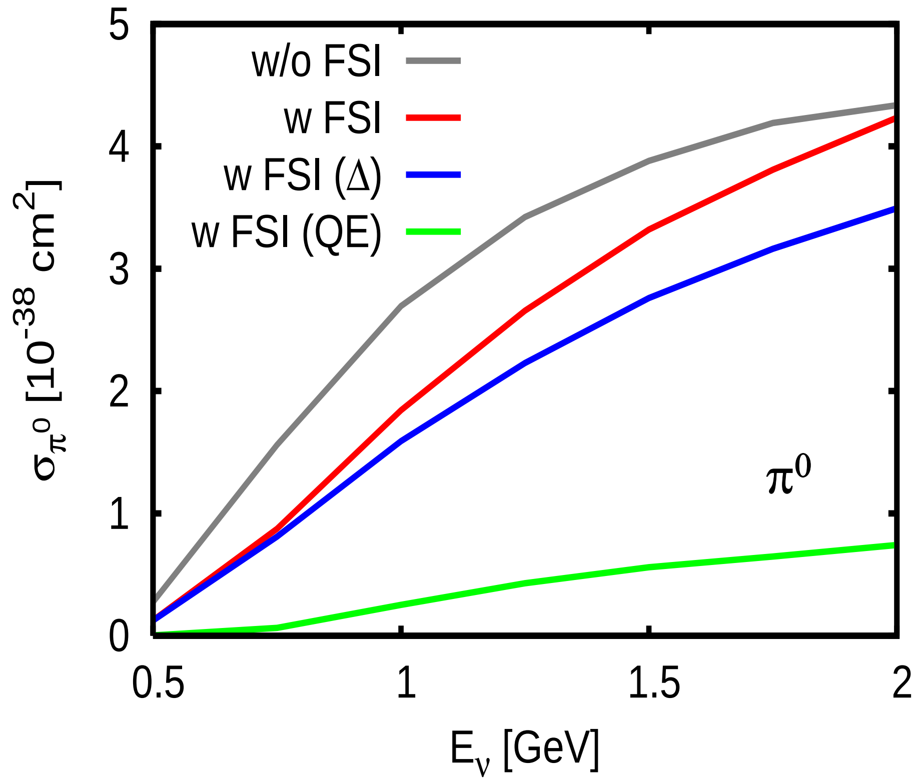


E_ν = 1 GeV

CC pion production: $\nu_\mu\, ^{56}Fe \rightarrow \mu^- \pi X$

$^{56}Fe: \pi^+ : \pi^0 = 4.4 : 1$ (without FSI ➡ FSI change this ratio)



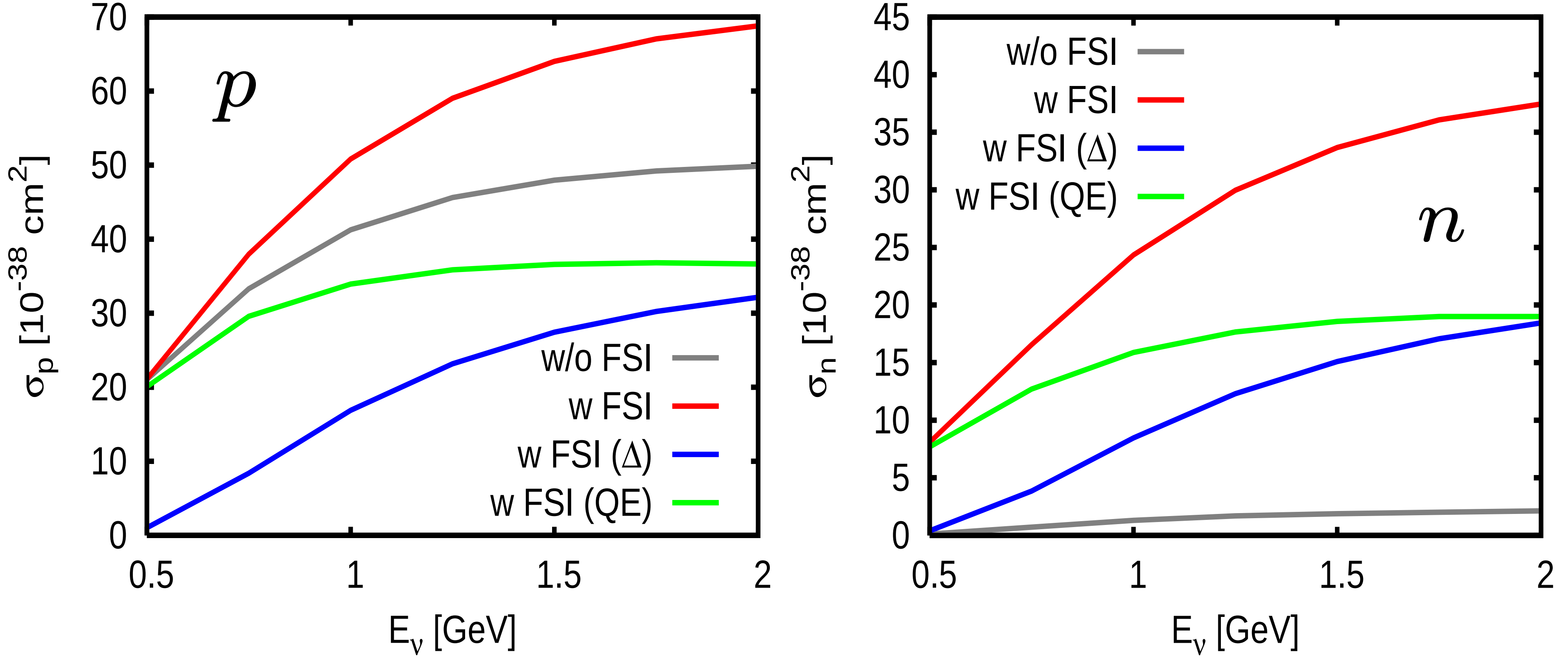


w FSI (Δ): pions through initially produced Δ

w FSI (QE): pions through initially produced QE

CC nucleon knockout: $\nu_\mu {}^{56}Fe \rightarrow \mu^- N X$

^{56}Fe: $p : n = 10 : 1$ (without FSI ➡ FSI change this ratio)



w FSI (Δ): nucleons through initially produced Δ
w FSI (QE): nucleons through initially produced QE

Elementary neutrino nucleon reaction

- cross section for νN reaction $\nu(k) + N(p) \to l(k') + X(p')$:

$$d\sigma = \frac{(2\pi)^4}{4} \frac{\delta^4(k'+p'-k-p)}{\left[(k\cdot p)^2 - m_i^2 M_{eff}^2\right]^{1/2}} \frac{d^4k'}{(2\pi)^3} \delta(k'^2 - m_l^2) \frac{d^4p'}{(2\pi)^3} \delta(p'^2 - M'^2_{eff}) |\bar{\mathcal{M}}|^2$$

- matrix element: $|\bar{\mathcal{M}}|^2 = \frac{G^2}{2} L_{\alpha\beta} H^{\alpha\beta}$

leptonic tensor $L_{\alpha\beta}$

↓

leptonic current j_α

- V – A structure
- includes lepton mass

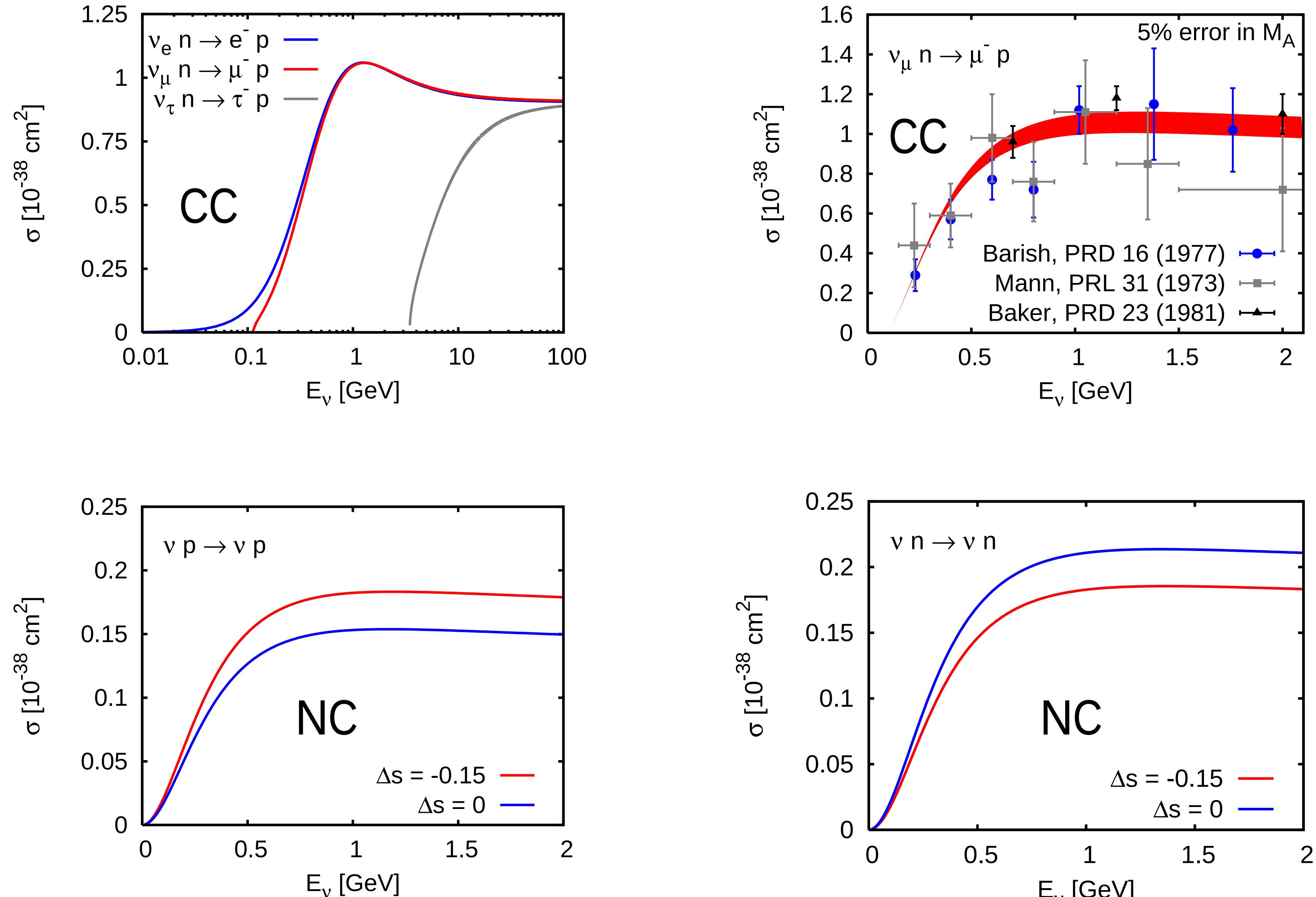
hadronic tensor $H^{\alpha\beta}$

↓

hadronic current J_α^X

- depends on specific reaction
- parametrized with form factors

Quasielastic scattering



Δ resonance production – details

- reactions:
  CC: $\nu_l\, n \to l^- \Delta^+, \quad \nu_l\, p \to l^- \Delta^{++}$
  NC: $\nu\, n \to \nu\, \Delta^0, \quad \nu\, p \to \nu\, \Delta^+$

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

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

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

axial form factors
- related by **PCAC**
- $C_6^A = C_5^A \frac{M^2}{Q^2+m_\pi^2}, \; C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2$

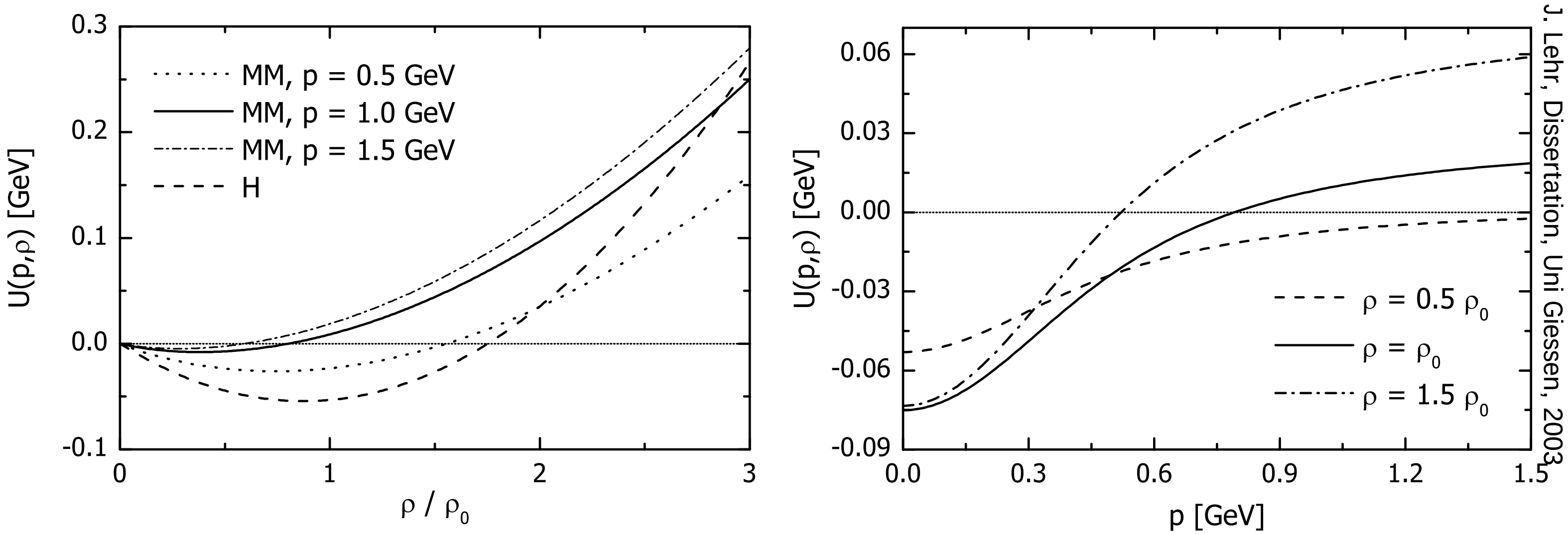
vector form factors
- related by **CVC** to electroproduction
- $C_5^V = C_6^V = 0, \; C_4^V = -\frac{M}{\sqrt{p'^2}} C_3^V$

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

parametrizations: $e\,N$ scattering: C_3^V $\quad \nu\,N$ scattering: C_5^A

GiBUU transport model – potentials

- mean-field potential *U* for nucleons and isospin 1/2 resonances
  - **Skyrme type + momentum dependence**
    - parametrization by Welke et al., Phys. Rev. C38, 2101 (1998)
    - fitted to saturation density of nuclear matter
    - momentum dependence from proton-nucleus scattering data



- mean-field potential for isospin 3/2 resonances
  - 2/3 of the nucleon potential
- furthermore: Coulomb potential, pion potential