

Influence of the local approximation on neutrino induced coherent pion production

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45th Karpacz Winter School in Theoretical Physics, Lądek-Zdrój, Poland
February 09, 2009



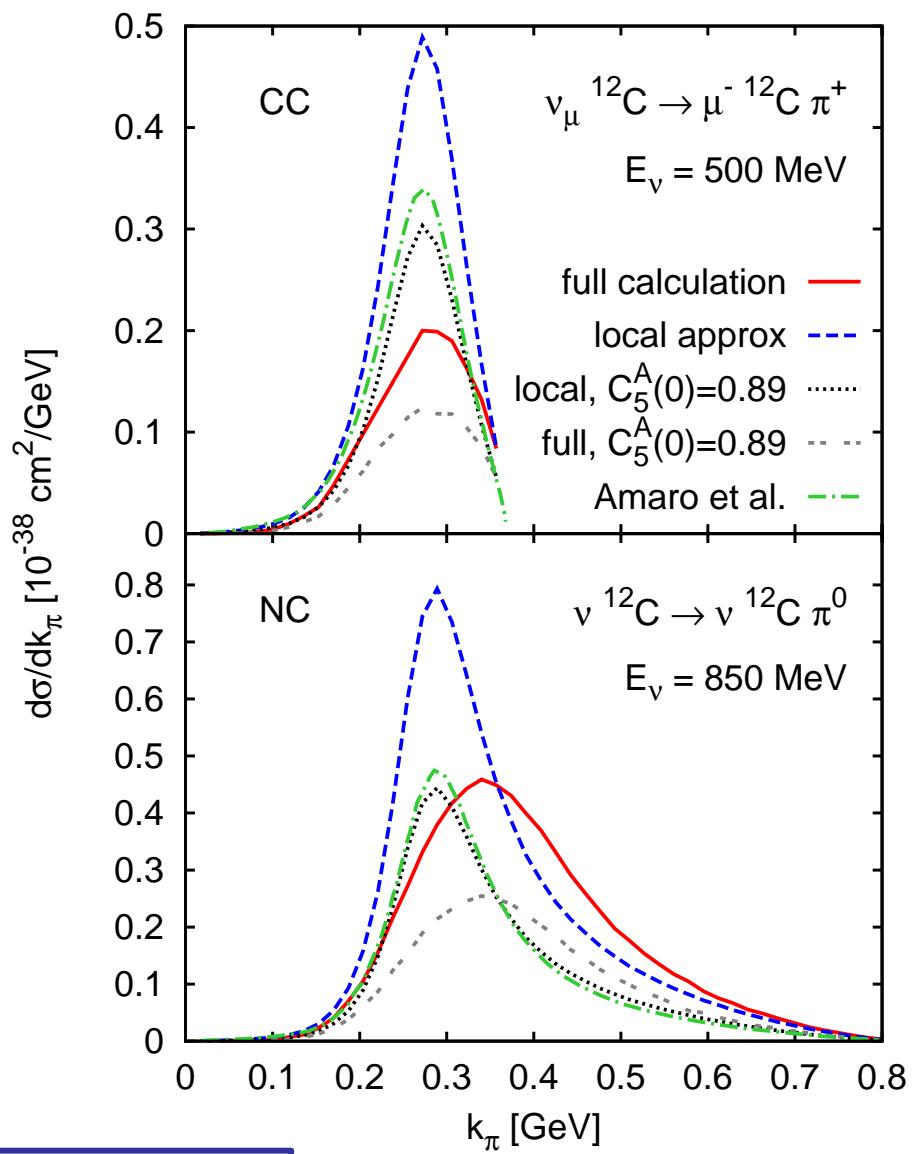
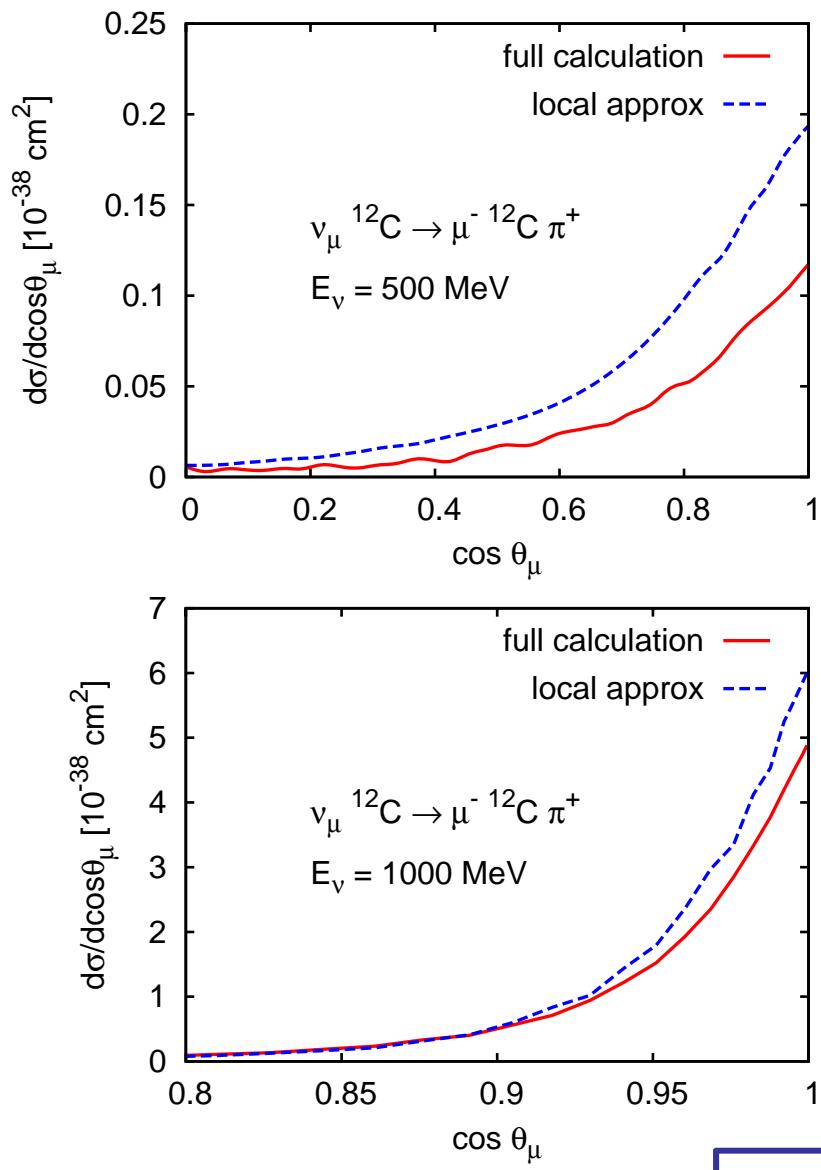
Local approximation

- available theories generally fall into two categories:
 - **PCAC models** (e.g. Rein-Sehgal):
coherent pion production is related to a pion forward scattering amplitude via PCAC assuming that the process is dominated by the axial current and that specific nuclear effects play no role, besides providing nuclear size information
 - **nuclear structure models** (cf. talk by M. Valverde):
start from a theoretical description of the nuclear structure and sum the pion production amplitude coherently over all target nucleon states
- all rely on **local approximation**:
factorizes pion production amplitude into a part that contains the pion production amplitude and one that contains the nuclear size information

$$J_{\text{nucleus}}^\mu(q) \sim \sum_i \int d^3p \bar{\psi}_i(\vec{p}') k_\pi^\alpha G_{\alpha\beta}(p_\Delta) \Gamma^{\beta\mu}(p, q) \psi_i(\vec{p})$$

$$\tilde{J}_{\text{nucleus}}^\mu(q) \sim k_\pi^\alpha \int d^3r e^{i(\vec{q}-\vec{k}_\pi)\cdot\vec{r}} \text{tr} (\rho(\vec{r}, \vec{r}) G_{\alpha\beta}(p_\Delta^0) \Gamma^{\beta\mu}(p^0, q))$$

Local vs. full



no pion FSI, only Δ

Hadronic transport approach to neutrino nucleus scattering: The Giessen BUU model and its applications

Tina Leitner

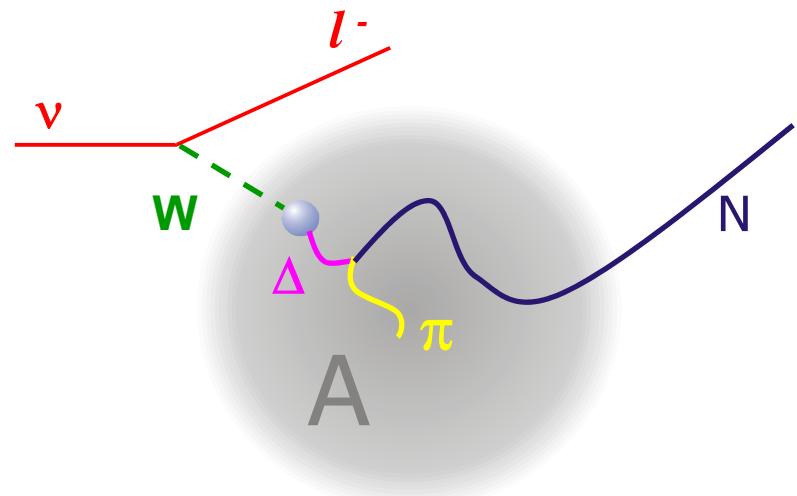
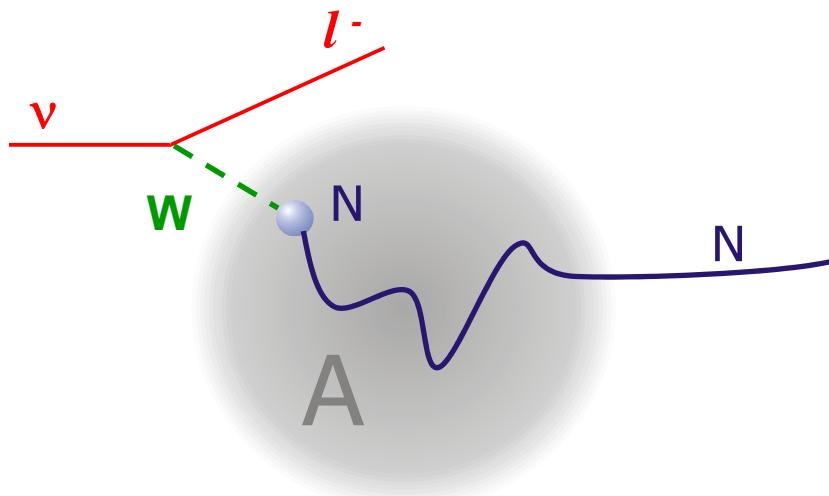
Oliver Buss, Ulrich Mosel, and Luis Alvarez-Ruso

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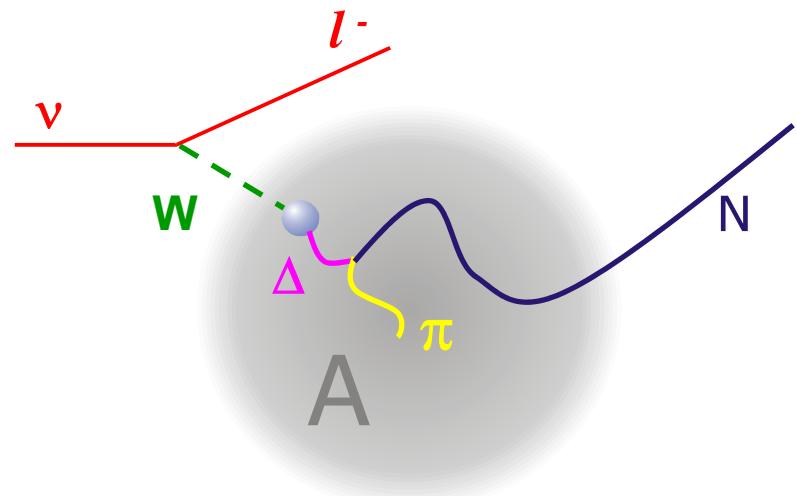
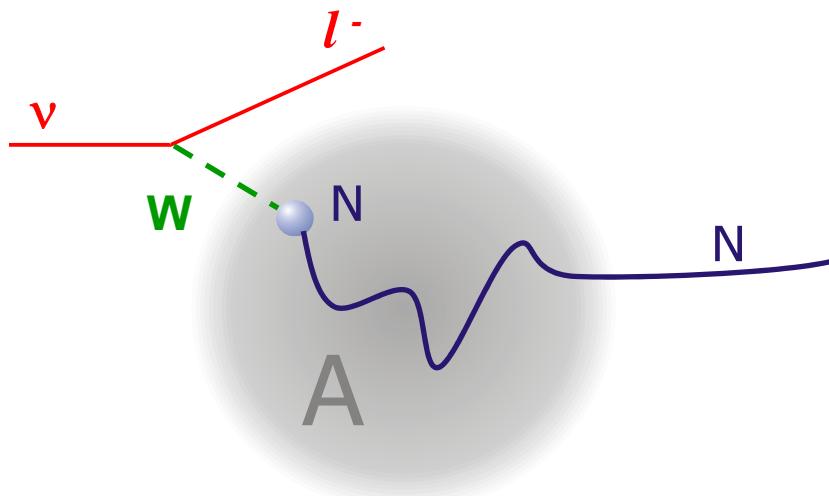


Motivation: Link between nuclear effects and ν oscillations



- **particle identification**
 - identify neutrino flavor, CCQE, π^0 background, ...
- **reconstruction of neutrino quantities**
 - important for oscillations and cross section measurements: E_ν & Q^2
- ➔ **influence of in-medium modifications and final state interactions**

Outline

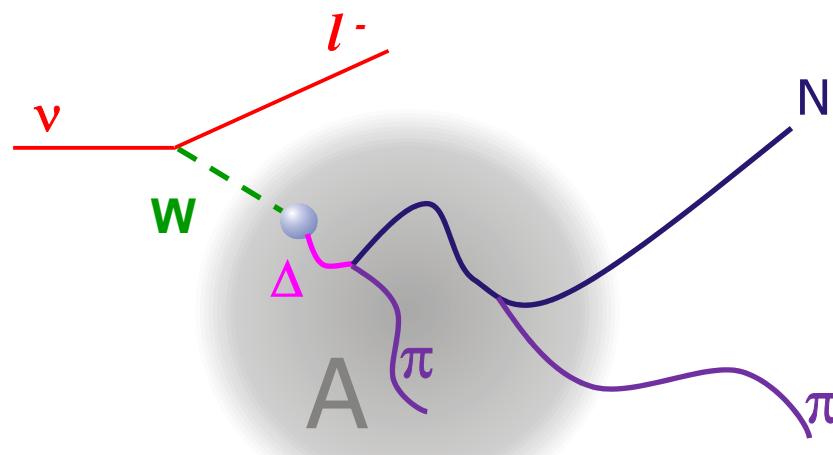


- **GiBUU model**
 - initial state interactions, final state interactions

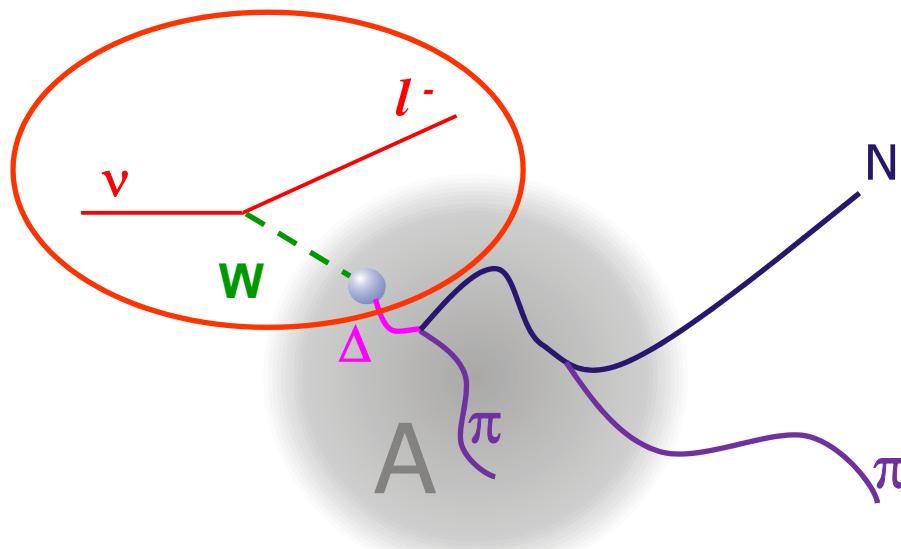
- **general results**
 - inclusive and semi-inclusive

- **applications**
 - MiniBooNE, K2K

Modelling in-medium reactions



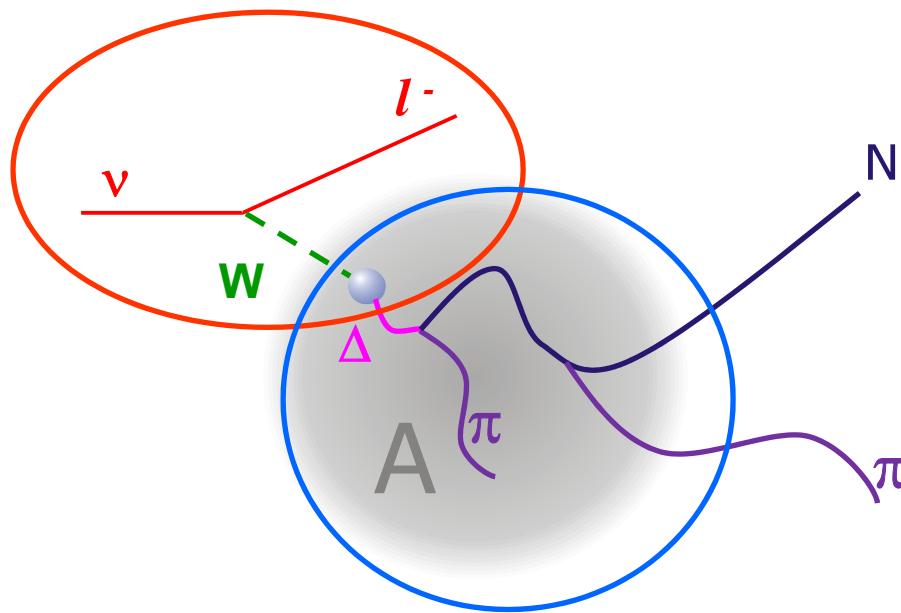
Modelling in-medium reactions



■ Initial state interaction (ISI)

- impulse approximation
- Fermi motion, Pauli blocking
- self energies
- medium-modified ν N cross sections

Modelling in-medium reactions



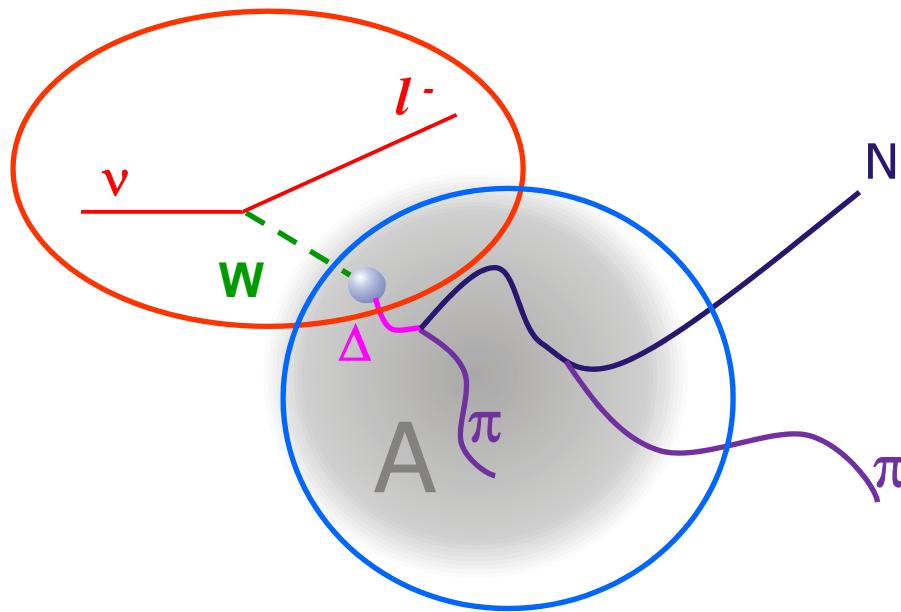
■ Initial state interaction (ISI)

- impulse approximation
- Fermi motion, Pauli blocking
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- medium-modified ν N cross sections

■ Final state interactions (FSI)

- absorption
- particle production, rescattering, ...

Modelling in-medium reactions



■ Initial state interaction (ISI)

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■ Final state interactions (FSI)

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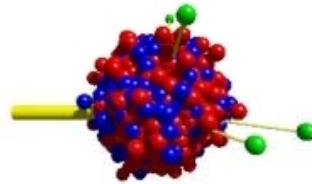
Consistency:

Self energies in the initial state process should match FSI rates

→ ISI and FSI can only be separated within the same model

GiBUU model outline

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



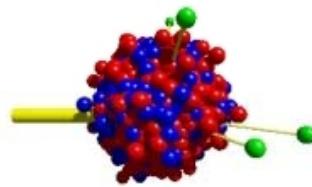
Institut für Theoretische Physik, JLU Giessen
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- more information & code download: <http://theorie.physik.uni-giessen.de/GiBUU/>
- GiBUU describes ...
 - heavy ion reactions
 - pion and proton induced reactions
 - low and high energy photon and electron induced reactions
 - neutrino induced reactions**

... within the same unified framework using the same physics input!
- GiBUU allows to describe specific experiments (inclusion of detector acceptances)
- GiBUU has been checked extensively against experimental data for heavy-ion collisions, eA , γA , pA , πA reactions
- aim: describe many nuclear reactions within one microscopic model
 - no parameter tuning to match one particular data set

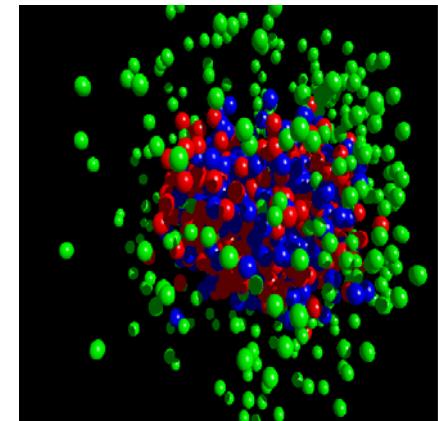
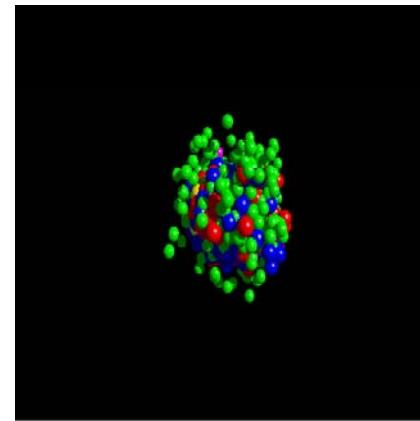
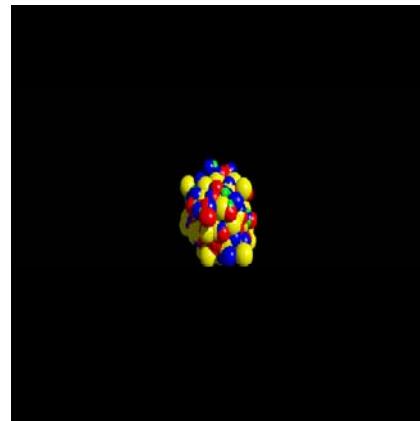
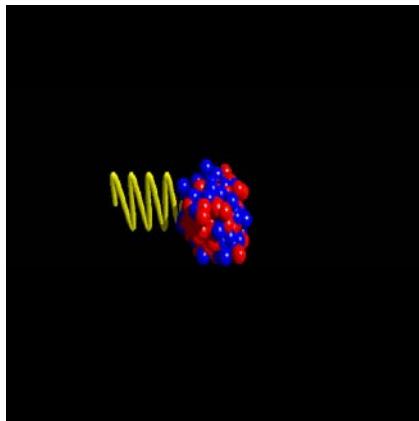
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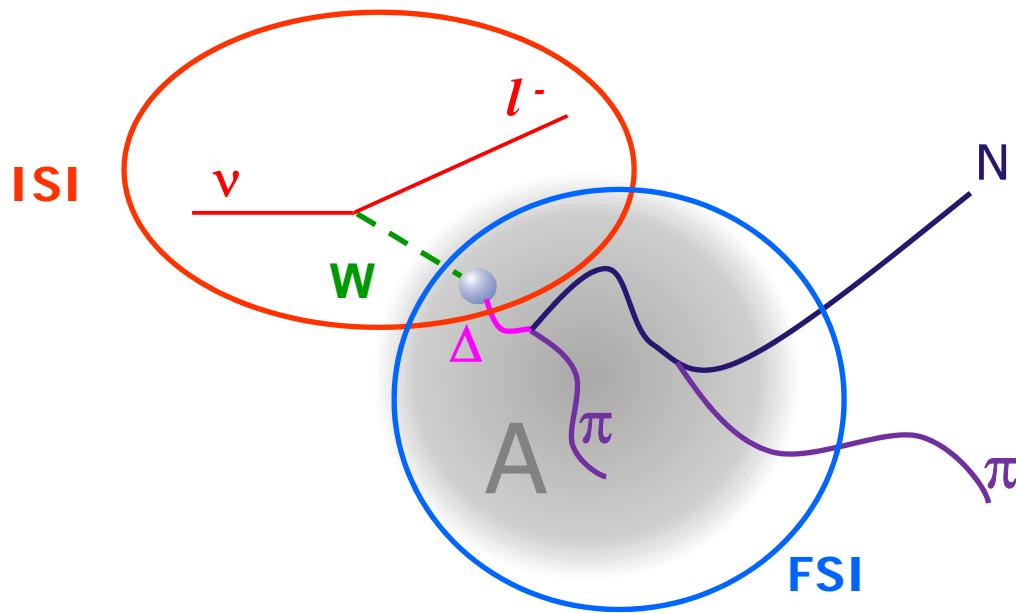


Institut für Theoretische Physik, JLU Giessen
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- more information & code download: <http://theorie.physik.uni-giessen.de/GiBUU/>
- visualized example: photo absorption



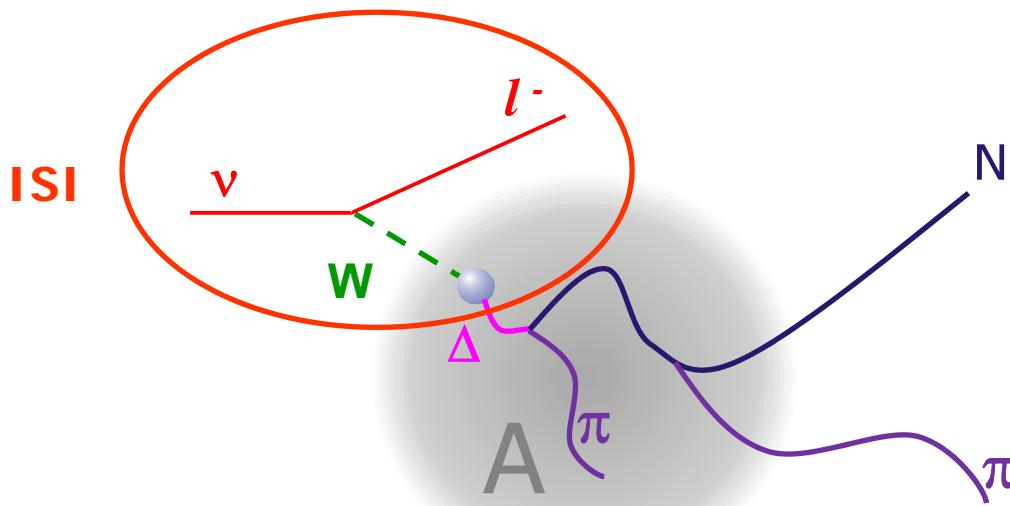
GiBUU model outline



$$d\sigma_{\text{tot}}^{\ell A \rightarrow \ell' X} = g \int_{\text{nucleus}} d^3r \int \frac{d^3p}{(2\pi)^3} \Theta(p_F(r) - p) \frac{1}{v_{\text{rel}}} \frac{k \cdot p}{k^0 p^0} d\sigma_{\text{tot}}^{\text{med}} P_{\text{PB}}(\mathbf{r}, \mathbf{p}) M_X$$

→ impulse approximation to factorize primary interaction and FSI

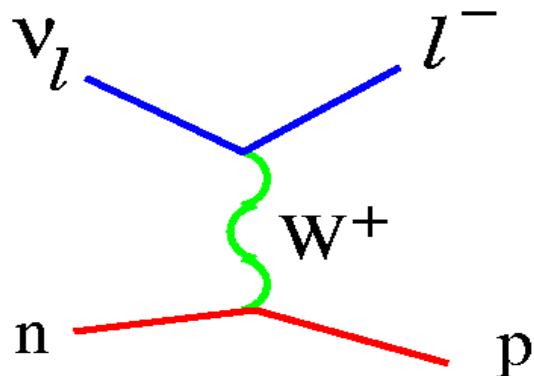
GiBUU model outline: ISI



$$d\sigma_{\text{tot}}^{\ell A \rightarrow \ell' X} = g \int_{\text{nucleus}} d^3r \int \frac{d^3p}{(2\pi)^3} \Theta(p_F(r) - p) \frac{1}{v_{\text{rel}}} \frac{k \cdot p}{k^0 p^0} d\sigma_{\text{tot}}^{\text{med}} P_{\text{PB}}(\mathbf{r}, \mathbf{p}) M_X$$

- **primary interaction** of neutrino with one nucleon at a time
 - QE, resonance excitation, non-resonant pion background
- **medium modifications**
 - local Fermi gas, Pauli blocking
 - full in-medium kinematics with nuclear potentials
 - in-medium spectral functions

Quasielastic scattering



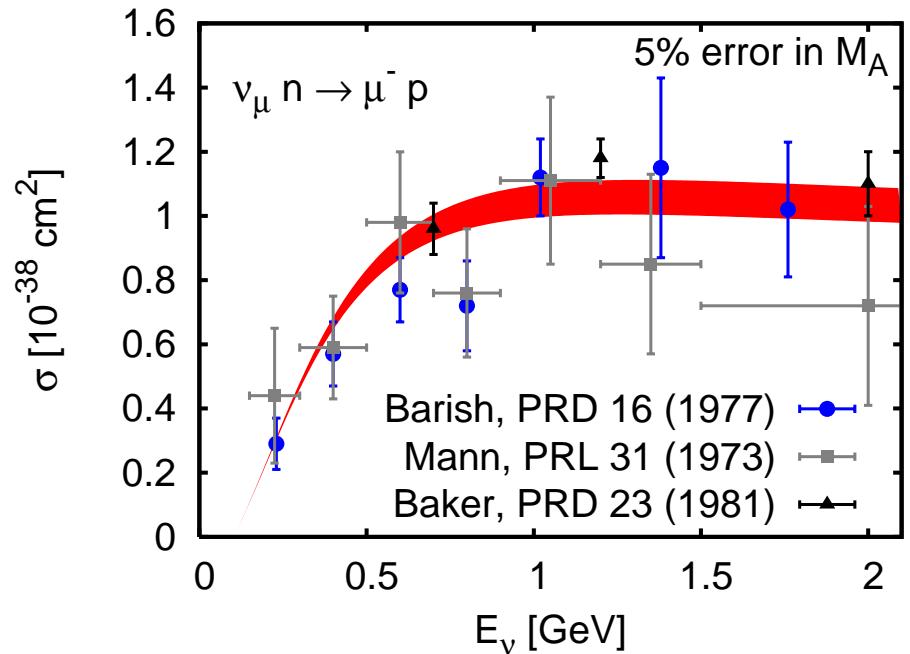
$$J_{QE}^\mu = \left(\gamma^\mu - \frac{q^\mu q^\alpha}{q^2} \right) F_1^V + \frac{i}{2M_N} \sigma^{\mu\alpha} q_\alpha F_2^V + \gamma^\mu \gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P$$

vector form factors

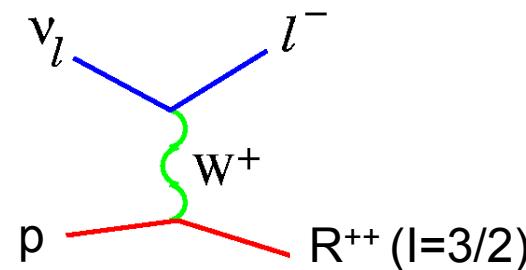
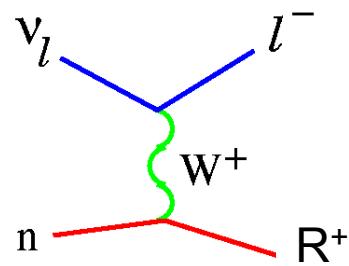
- related to EM form factors by **CVC**
- **BBBA-2007** parametrization

axial form factors

- related by **PCAC**
- dipole ansatz with **$M_A = 1 \text{ GeV}$**



Resonance excitation: Hadronic currents



- **spin 1/2 resonances:** $P_{11}(1440)$, $S_{11}(1535)$, $S_{31}(1620)$, $S_{11}(1650)$, $P_{31}(1910)$

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

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

$$\begin{aligned} J_{3/2}^{\alpha\mu} = & \left[\frac{C_3^V}{M_N} (g^{\alpha\mu} \not{q} - q^\alpha \gamma^\mu) + \frac{C_4^V}{M_N^2} (g^{\alpha\mu} q \cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2} (g_{\alpha\mu} q \cdot p - q^\alpha p^\mu) \right. \\ & \left. + \left(\frac{C_3^A}{M_N} (g^{\alpha\mu} \not{q} - q^\alpha \gamma^\mu) + \frac{C_4^A}{M_N^2} (g^{\alpha\mu} q \cdot p' - q^\alpha p'^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^\alpha q^\mu \right) \gamma_5 \right] \begin{Bmatrix} \gamma_5 \\ 1 \end{Bmatrix} \end{aligned}$$

- **spin > 3/2 resonances:** $D_{15}(1675)$, $F_{15}(1680)$, $F_{35}(1905)$, $F_{37}(1950)$
analogous to spin 3/2 resonances

Resonance excitation: Form factors

■ vector form factors

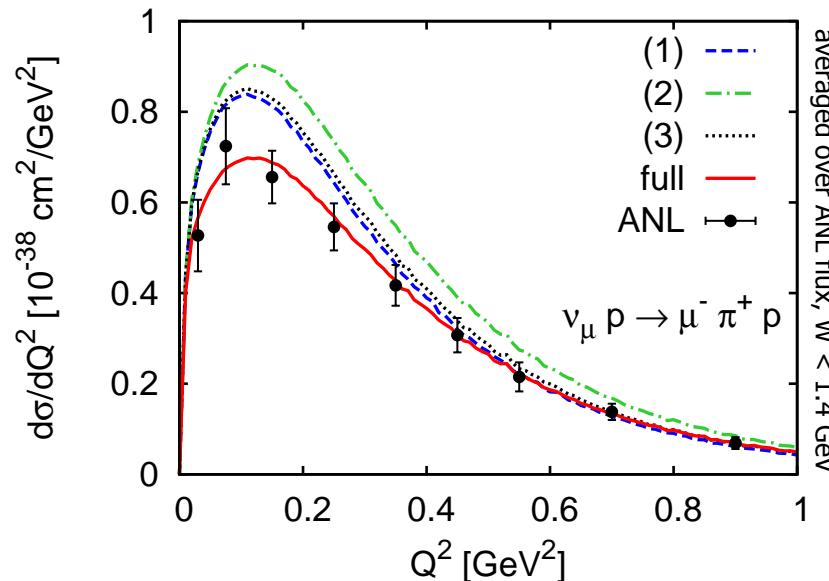
- vector form factors $C_i^V \Leftrightarrow$ EM form factors $C_i^{\text{EM}} \Leftrightarrow$ **helicity amplitudes**

Fogli et al. NPB160 (1979), Alvarez-Ruso et al. PRC57 (1998), Lalakulich et al. PRD71 (2006), ...

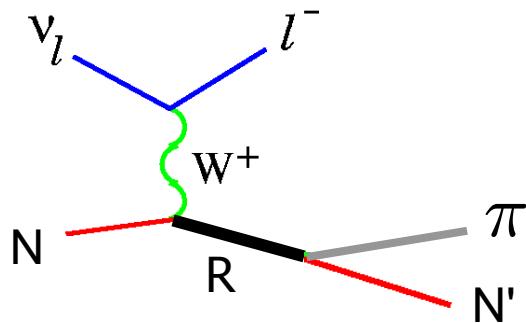
- helicity amplitudes from **MAID analysis** Drechsel et al. Eur. Phys. J. A 34 (2007)

■ axial form factors

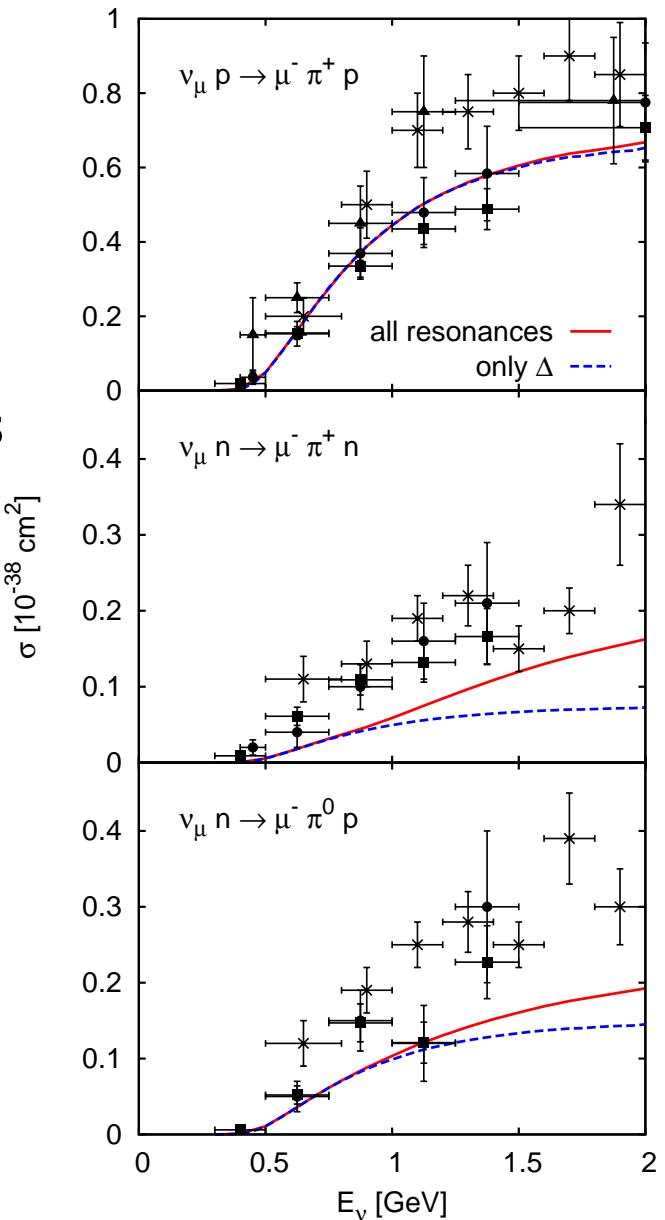
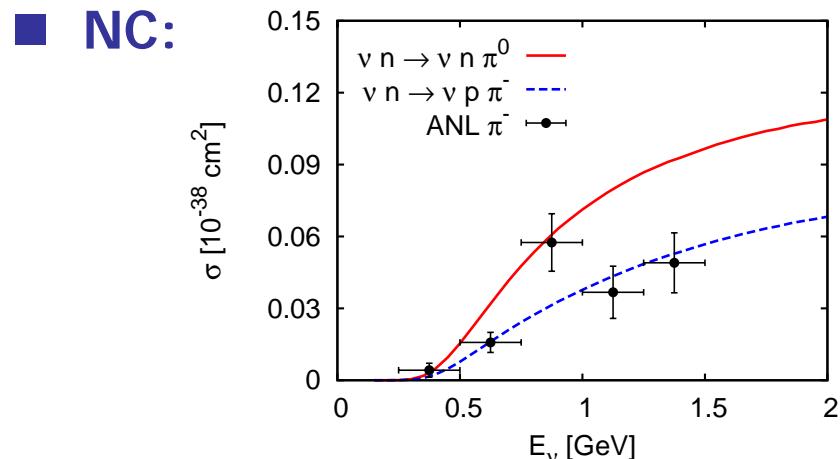
- axial coupling strength \Leftrightarrow **PCAC**
- dipole ansatz for all resonances except $P_{33}(1232)$
- refit of axial form factor required for $P_{33}(1232)$ (data!):



Pion production through resonance excitation



- CC: underestimation in isospin $1/2$ channels
→ non-resonant background
but: small compared to total yield



Non-resonant single pion background

- microscopic models: Δ and non-resonant terms

Fogli and Nardulli / Nieves et al. / Sato and Lee

talk by Olga Lalakulich on Wednesday

- phenomenological model:

$$\begin{aligned} d\sigma_{BG} &= d\sigma_{BG}^V + d\sigma_{BG}^A + d\sigma_{BG}^{V/A} \\ &= d\sigma_{BG}^V + d\sigma_{BG}^{\text{non-}V} \\ &= (1 + b^{N\pi}) d\sigma_{BG}^V \end{aligned}$$

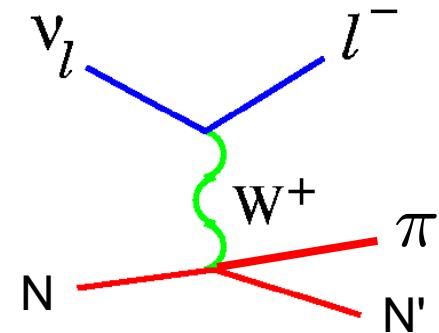
vector current is known:

invariant amplitudes

fixed by EM data from MAID

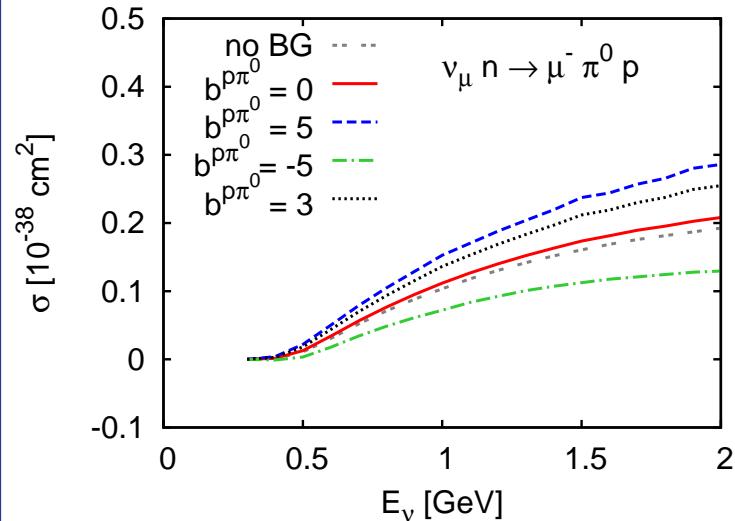
$$\mathcal{V}_{N\pi}^\mu = \sum_{i=1}^6 A_i^{N\pi} M_i^\mu$$

→ subtract resonance contribution



axial part:

$b^{N\pi}$ have to be fitted to data



Non-resonant single pion background

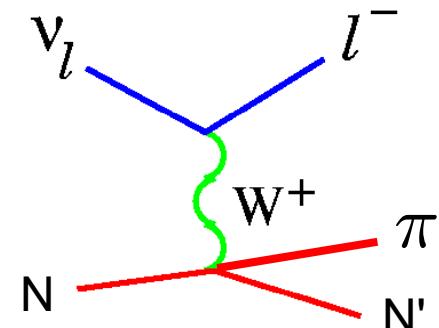
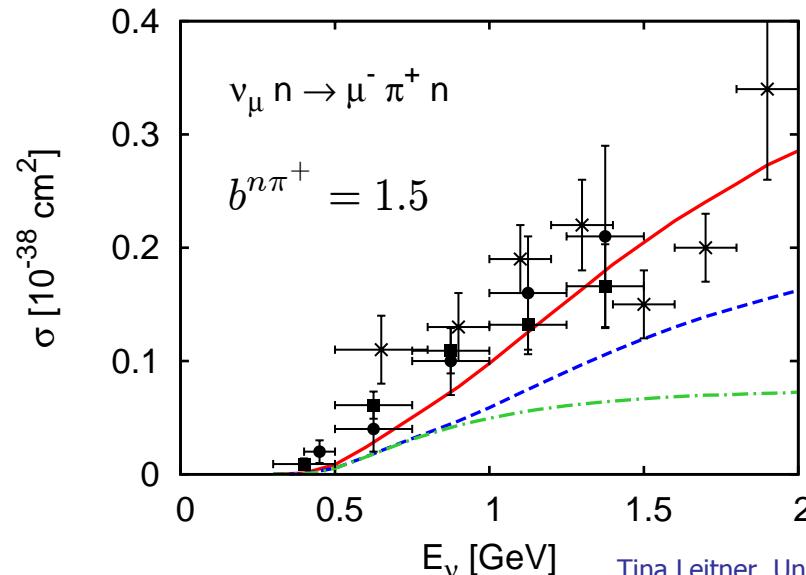
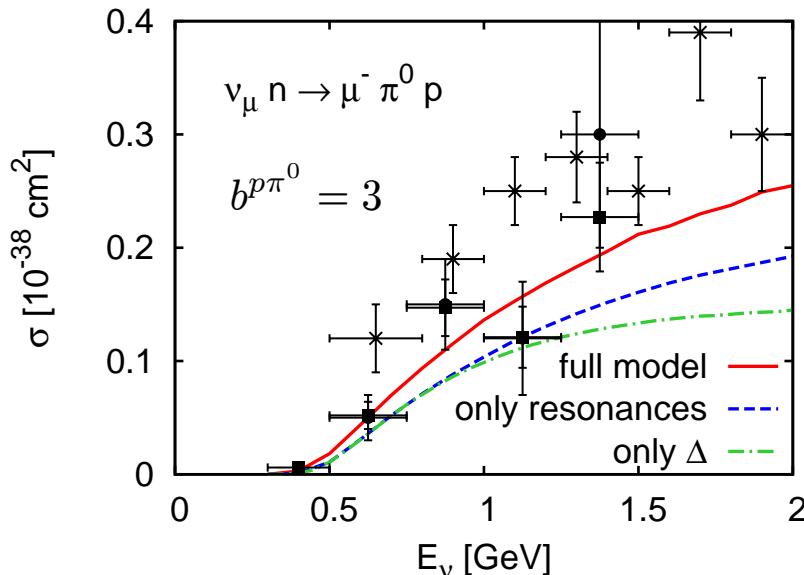
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- good agreement to ANL data:



Medium modifications

$$d\sigma_{\text{tot}}^{\ell A \rightarrow \ell' X} = g \int_{\text{nucleus}} d^3r \int \frac{d^3p}{(2\pi)^3} \Theta(p_F(r) - p) \frac{1}{v_{\text{rel}}} \frac{k \cdot p}{k^0 p^0} d\sigma_{\text{tot}}^{\text{med}} P_{\text{PB}}(\mathbf{r}, \mathbf{p}) M_X$$

■ local Fermi gas

- local density approximation with realistic density profiles: $p_F(\vec{r}) = \left[\frac{3}{2} \pi^2 \rho(\vec{r}) \right]^{1/3}$
- **Pauli blocking**

■ in-medium ν N cross sections

□ in-medium self energies

- density + momentum dependent mean-field potential
- collisional broadening

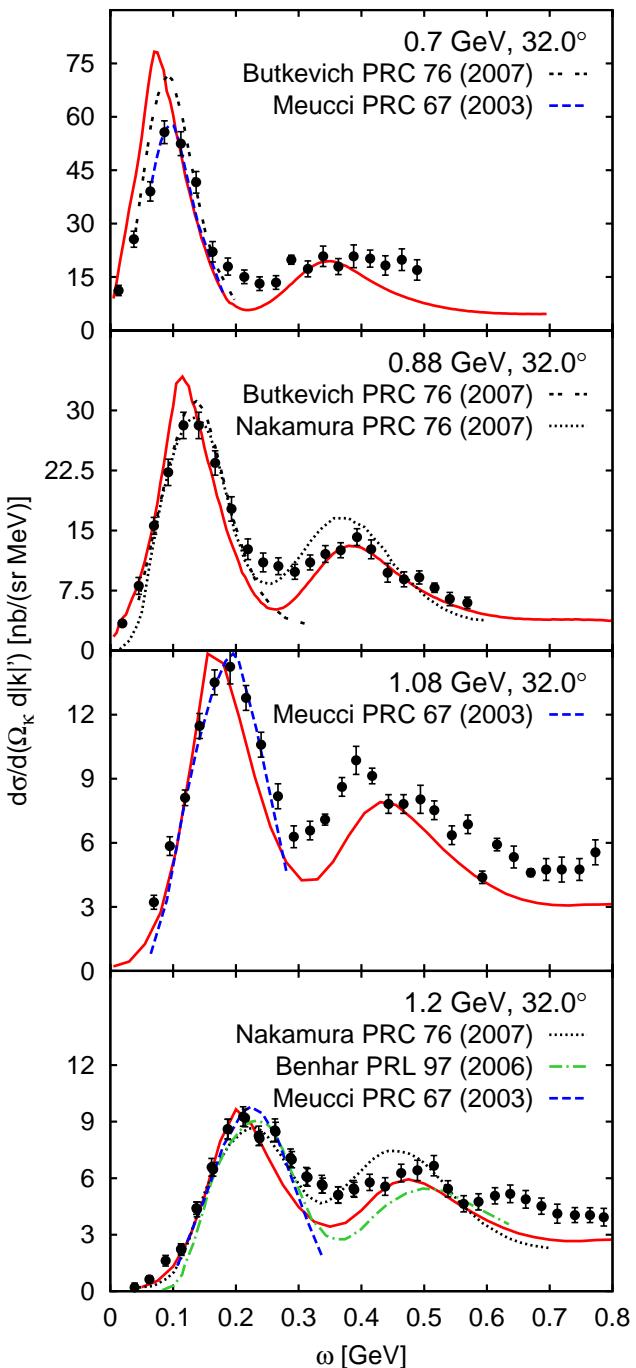
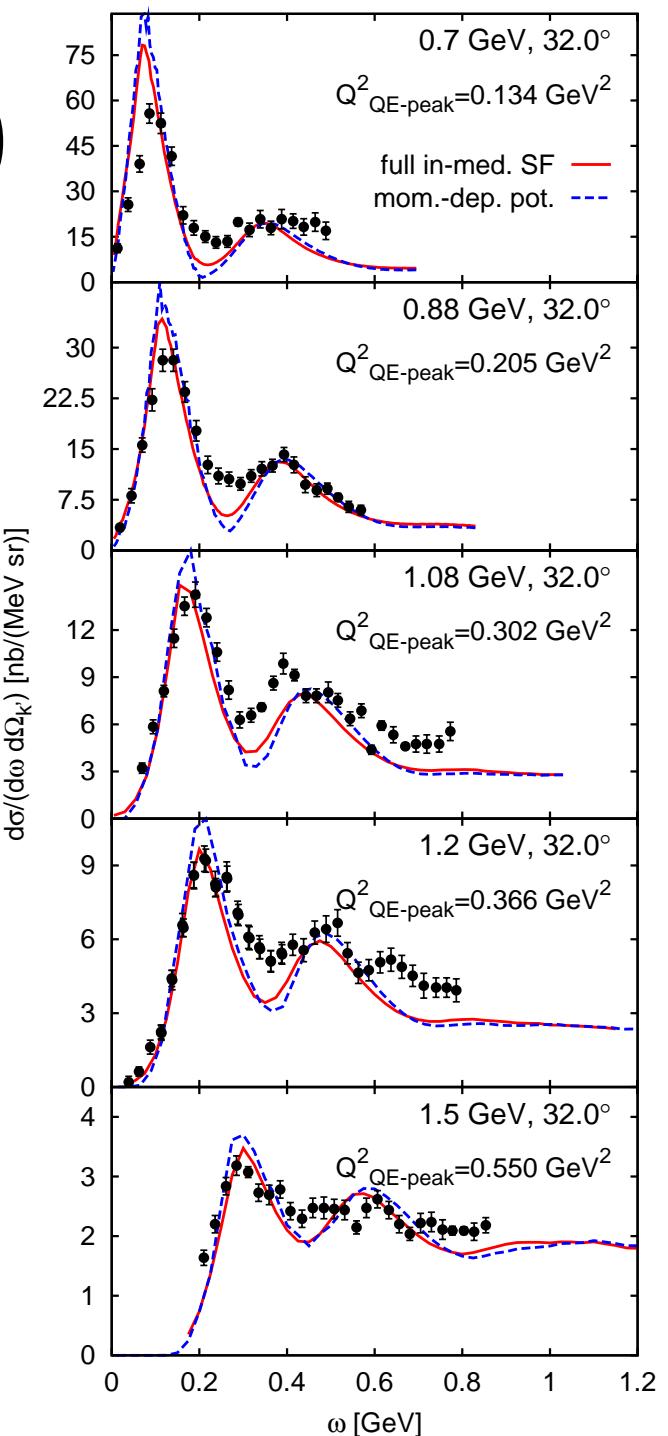
$$\Gamma_{\text{tot}} = \Gamma_{\text{PB}} + \Gamma_{\text{coll}}$$

collisional width in low-density approximation using GiBUU xsections

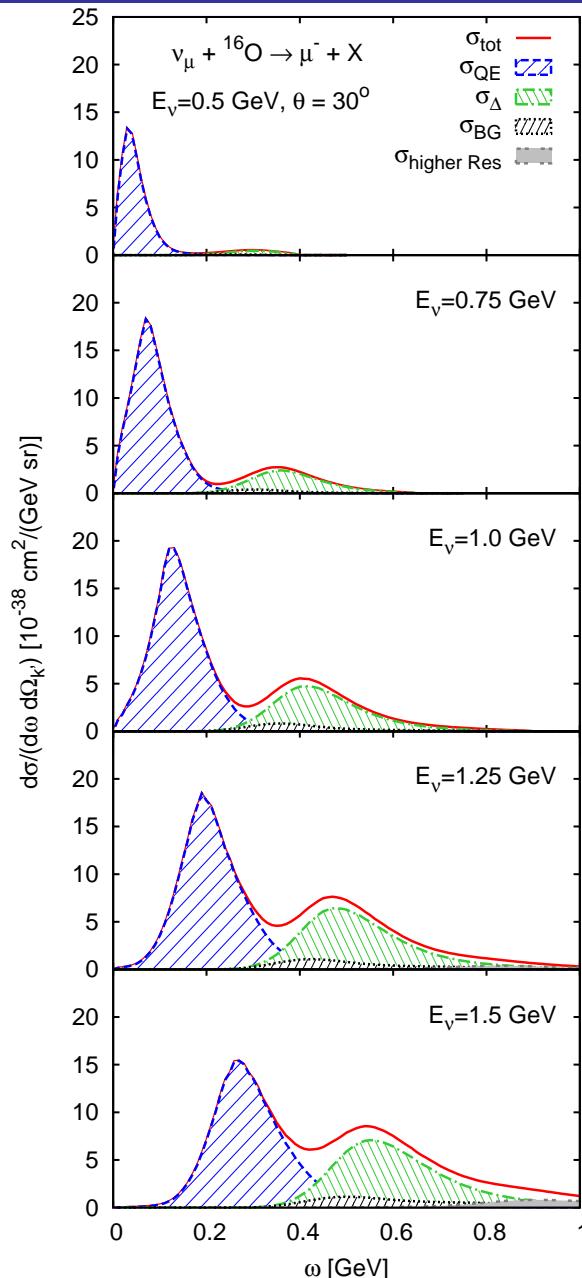
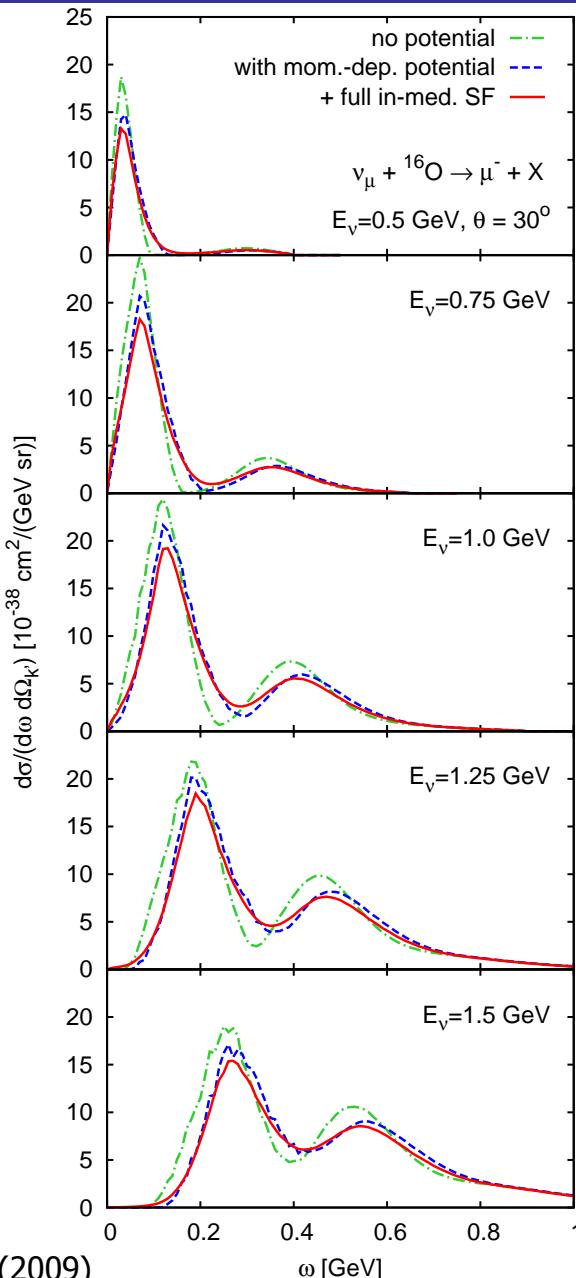
$$\Gamma_{\text{coll}} \sim \rho \sigma v$$

■ full in-medium kinematics, Fermi motion

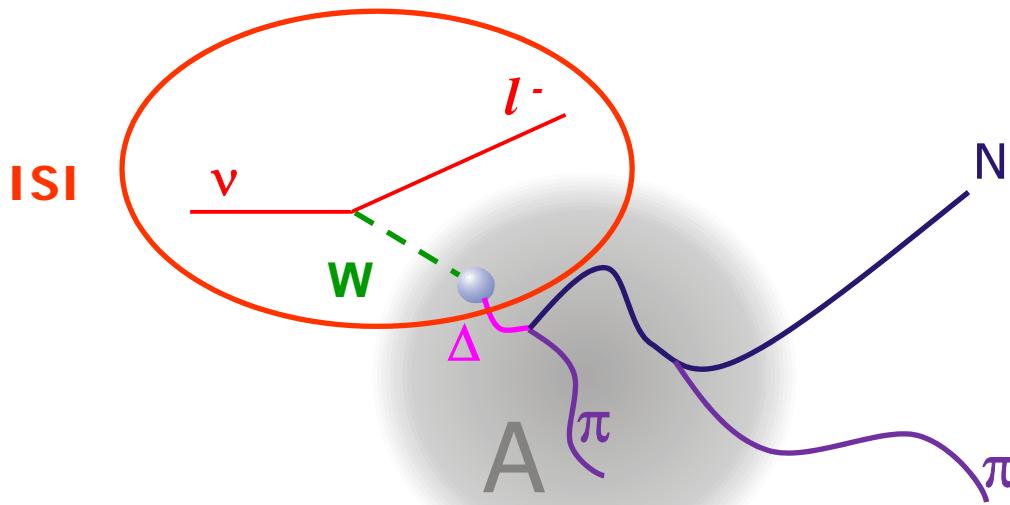
$^{16}\text{O}(\text{e},\text{e}')$



Neutrino inclusive scattering



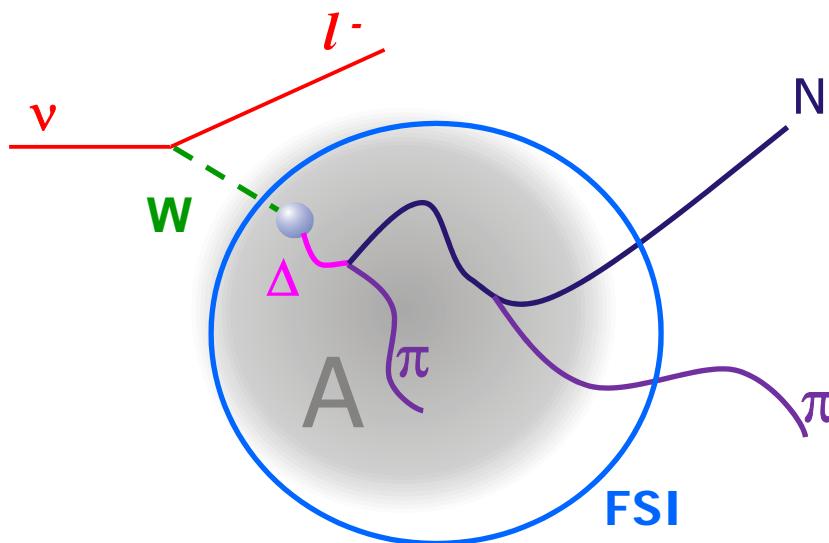
GiBUU model outline: ISI



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GiBUU model outline: FSI



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- wishlist of experimentalists
 - reliable FSI
 - tracking of particles
 - identification/multiplicities



- ways to model FSI
 - Glauber/eikonal approximation
 - optical model
 - hadronic transport**

Transport theory



- Kadanoff-Baym models
 - full solution
 - can not be solved yet – thus not feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models
 - Boltzmann equation as gradient expansion of Kadanoff-Baym equations
 - include mean-fields
 - realizations: HSD, UrQMD, Valencia-Code, **GiBUU**
- Cascade models
 - no mean-fields, no Fermi motion
 - NEUT, hN in GENIE, NUWRO cascade, FLUKA

GiBUU transport model – BUU equation

- time evolution of phase space density $f_i(\vec{r}, p, t)$ (for $i = N, \Delta, \pi, \rho, \dots$) under influence of Hamiltonian H given by **BUU equation**:

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

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- **fully-coupled channel problem**
 - Hamiltonian $H_i = H_i(f_i, f_a, f_b, \dots)$ connects particle species
 - coupled through the collision integral: 61 baryons and 21 mesons

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 - coupled through the collision integral: 61 baryons and 21 mesons
- **collision integral** accounts for changes in f_i (gain and loss term):
 - elastic and inelastic 2-body scattering
 - decay of unstable particles
 - 3-body reactions through detailed balance
 - Pauli blocking for fermions

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- **collision integral** accounts for changes in f_i (gain and loss term):
 - elastic and inelastic 2-body scattering
 - decay of unstable particles
 - 3-body reactions through detailed balance
 - Pauli blocking for fermions
- **Hamiltonian**
 - density and momentum dependent hadronic mean-field potential
 - Coulomb potential
 - off-shell transport: back to vacuum spectral function when propagating out

GiBUU transport model – BUU equation

- time evolution of phase space density $f_i(\vec{r}, p, t)$ (for $i = N, \Delta, \pi, \rho, \dots$) under influence of Hamiltonian H given by **BUU equation**:

$$\frac{df_i}{dt} = (\partial_t + (\nabla_{\vec{p}} H_i) \nabla_{\vec{r}} - (\nabla_{\vec{r}} H_i) \nabla_{\vec{p}}) f_i(\vec{r}, p, t) \quad \dots]$$

- **fully-coupled channel problem**
 - Hamiltonian $H_i = H_i(f, \dots)$
 - coupled through detailed balance
 - **collision integral**
 - scattering
 - absorption
 - charge exchange
 - redistribution of energy
 - production of new particles
 - **Hadronic Hamiltonian**
 - density and momentum dependent hadronic mean-field potential
 - Coulomb potential
 - off-shell transport: back to vacuum spectral function when propagating out
- FSI

GiBUU collision term: 2-body cross sections

■ cross sections: elastic and inelastic scattering

e.g. $N N \rightarrow N N$, $N N \leftrightarrow N R$, $N \pi \leftrightarrow R$, $\pi N \rightarrow \pi N$, ...



■ resonance model:

□ meson baryon cross sections based on resonance model

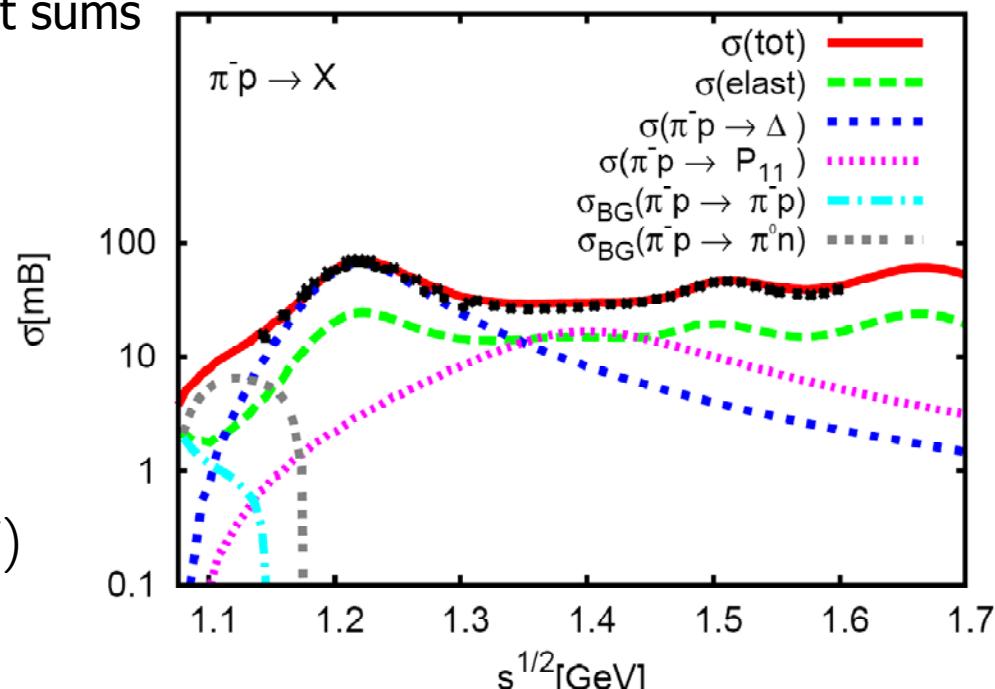
□ total cross section as incoherent sums

□ fit to vacuum data by
background contributions

□ example:
pion nucleon scattering

$$\sigma(\pi N \rightarrow \pi N) =$$

$$\sigma(\pi N \rightarrow R \rightarrow \pi N) + \sigma^{BG}(\pi N \rightarrow \pi N)$$

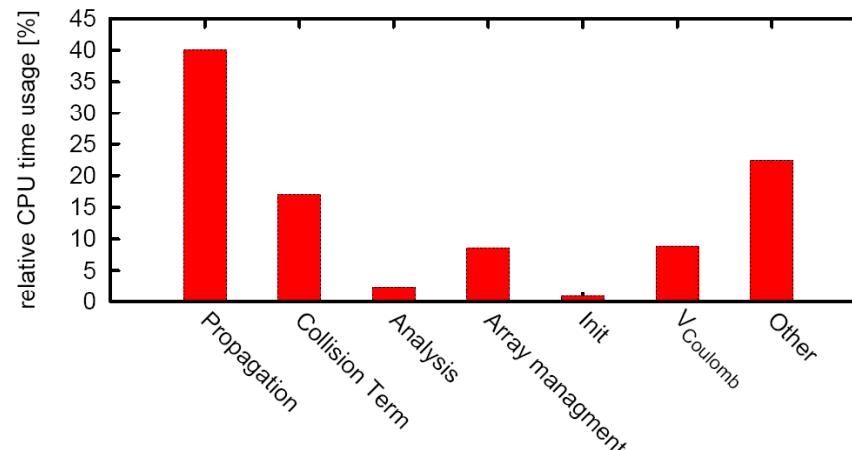


GiBUU transport model – numerical realization

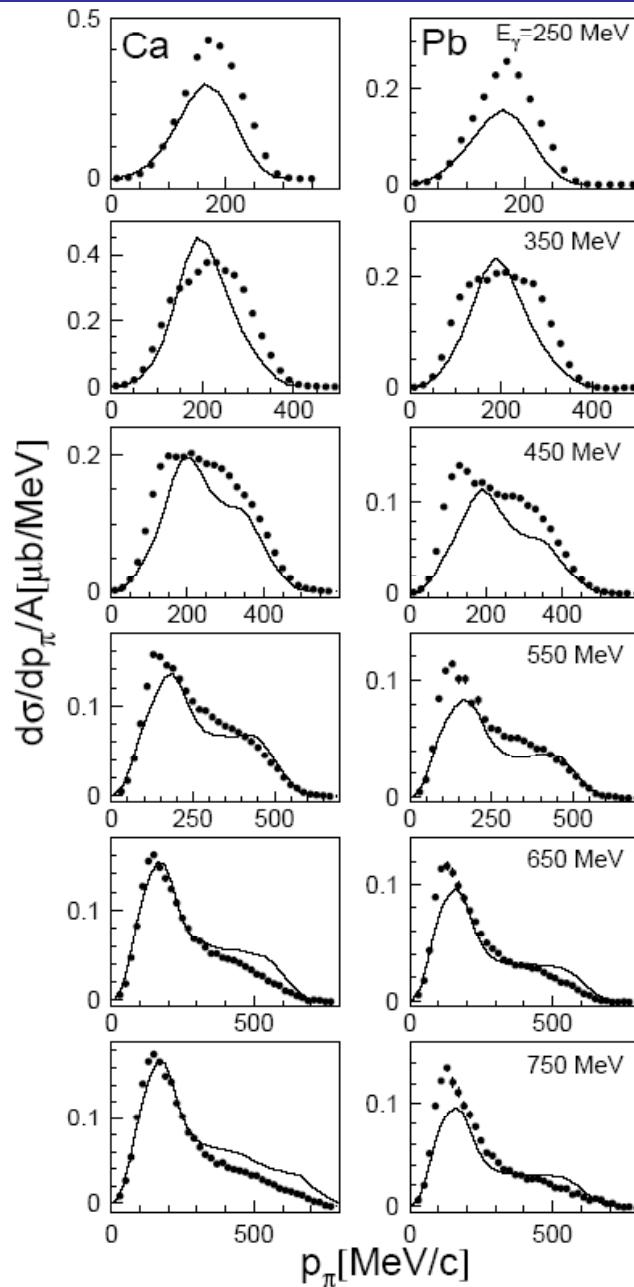
- task: solve set of 8-dimensional integral-differential equations which are coupled through the collision integral and the mean-field
- solution: **test particle ansatz** → discretize phase-space density

$$f_1(\vec{r}, p, t) = \frac{(2\pi)^4}{N} \sum_{i=1}^{n(t)} \delta(\vec{r} - \vec{r}_i(t)) \delta(p - p_i(t))$$

- N is number of test particles per physical particle (ensembles)
- $n(0) = A \times N$
- solving BUU eq. with test particle ansatz yields Hamilton eqs. of motion
(note: off-shell transport!)
- collision integral is sampled with Monte Carlo method
- timing:
~ 1 CPU day for 1 photon energy in $\gamma^{40}\text{Ca} \rightarrow \pi^0 X$
- all details:
PhD thesis of O. Buss



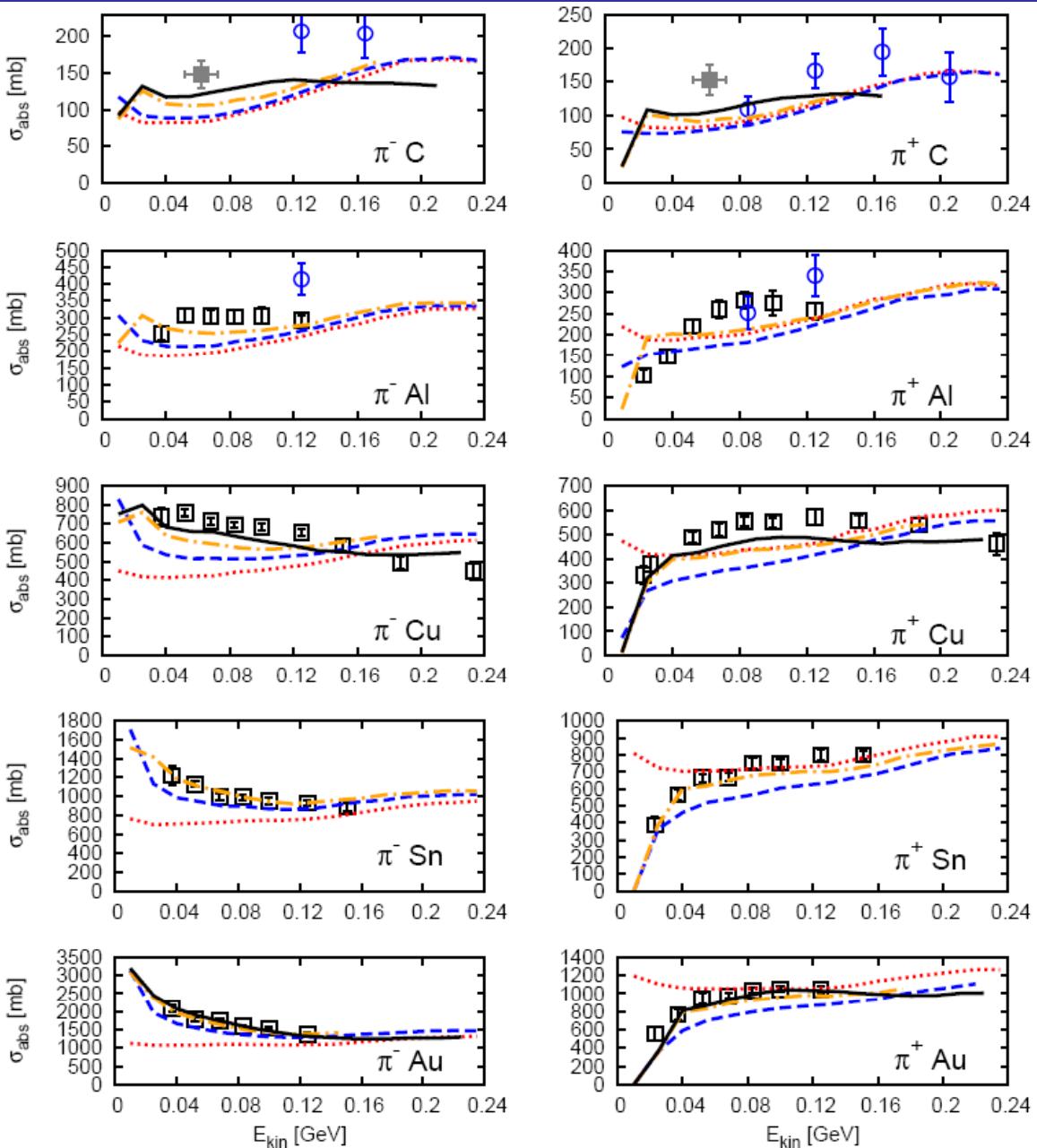
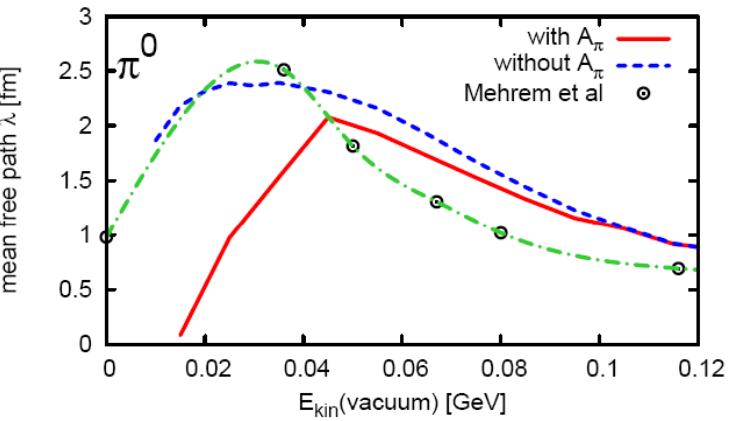
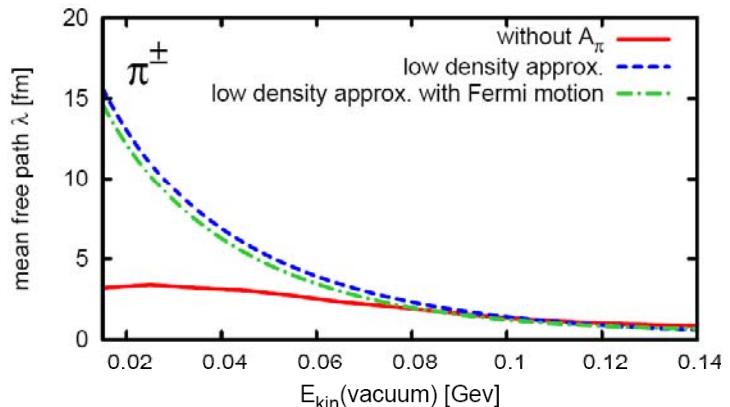
π^0 photoproduction



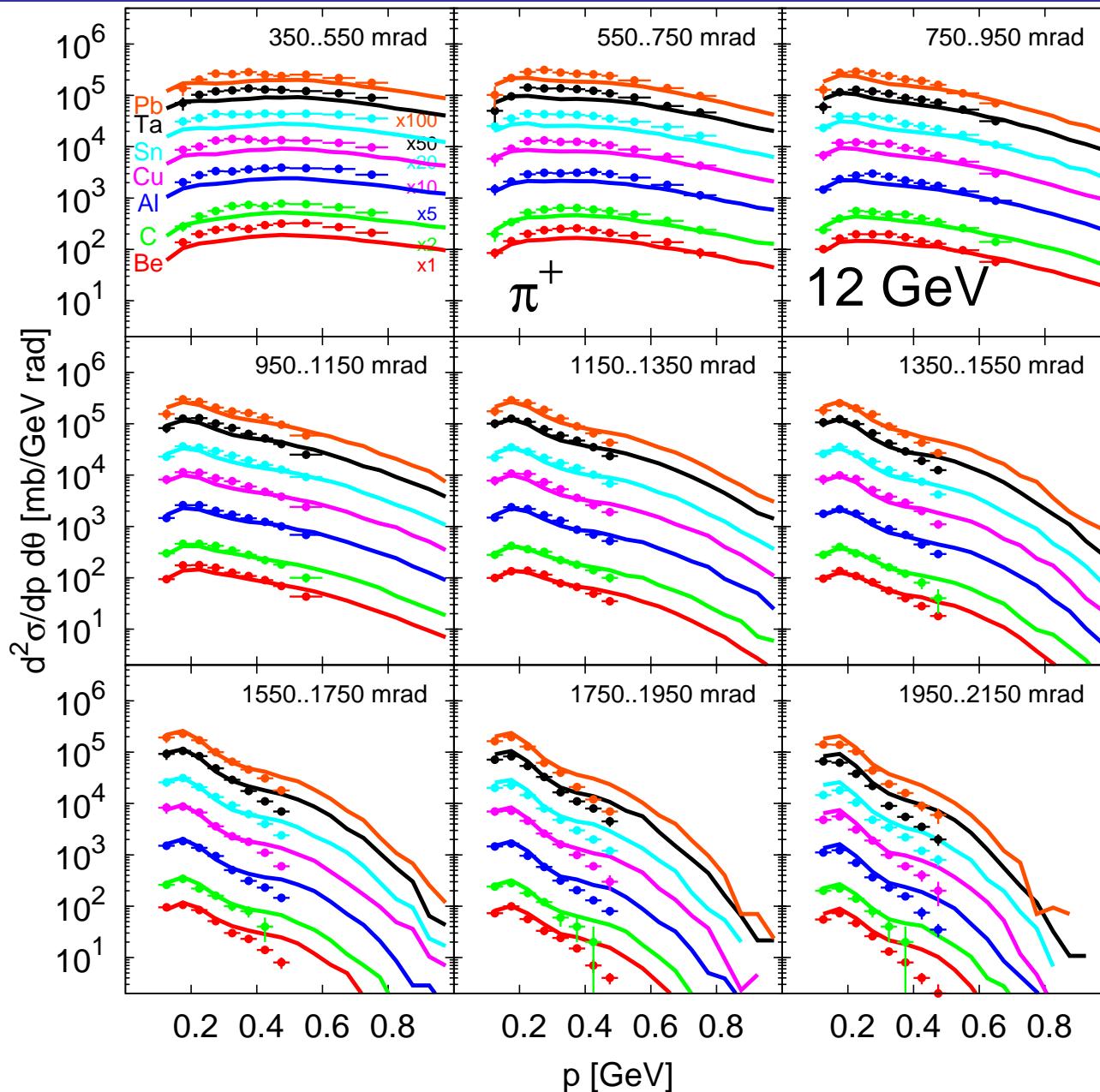
TAPS data
Eur. Phys. J A22 (2004)

Pion absorption and mean free path

Buss et al., EPJ A29(2) (2006)



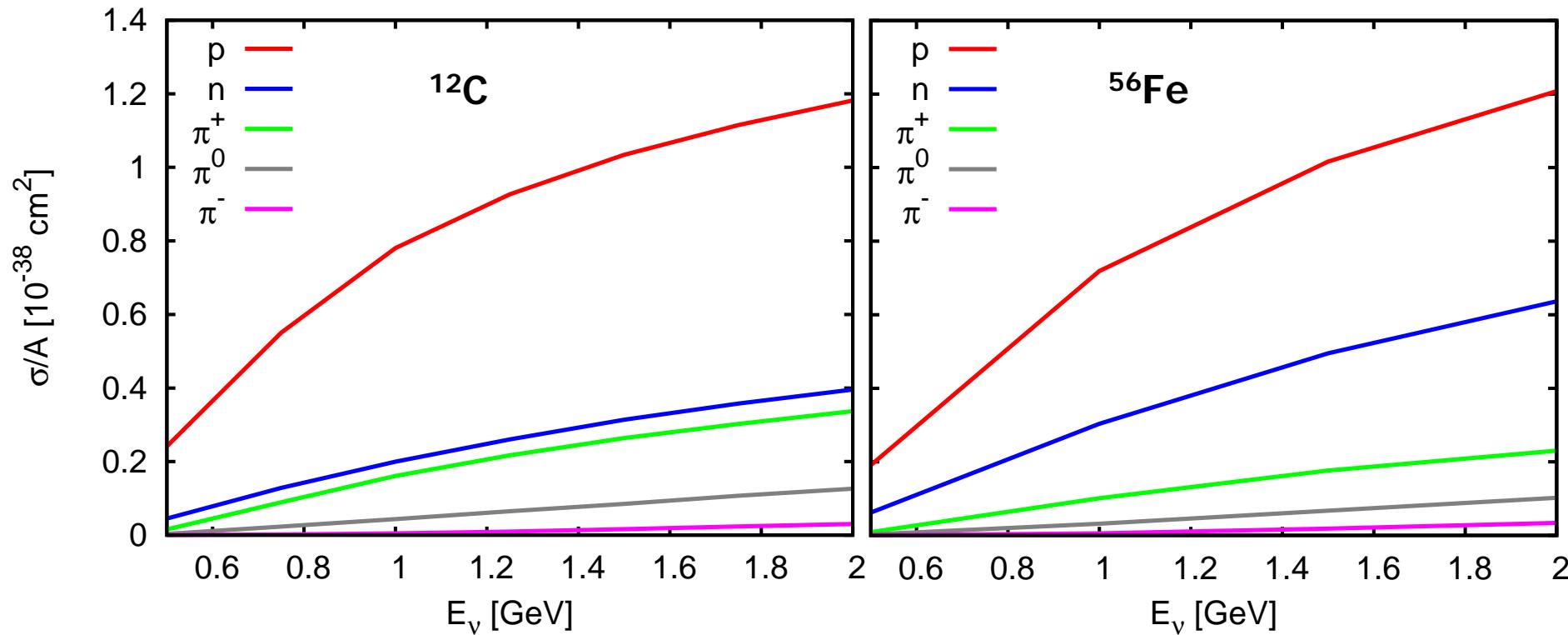
HARP



K. Gallmeister and U. Mosel,
arXiv:0901.1770

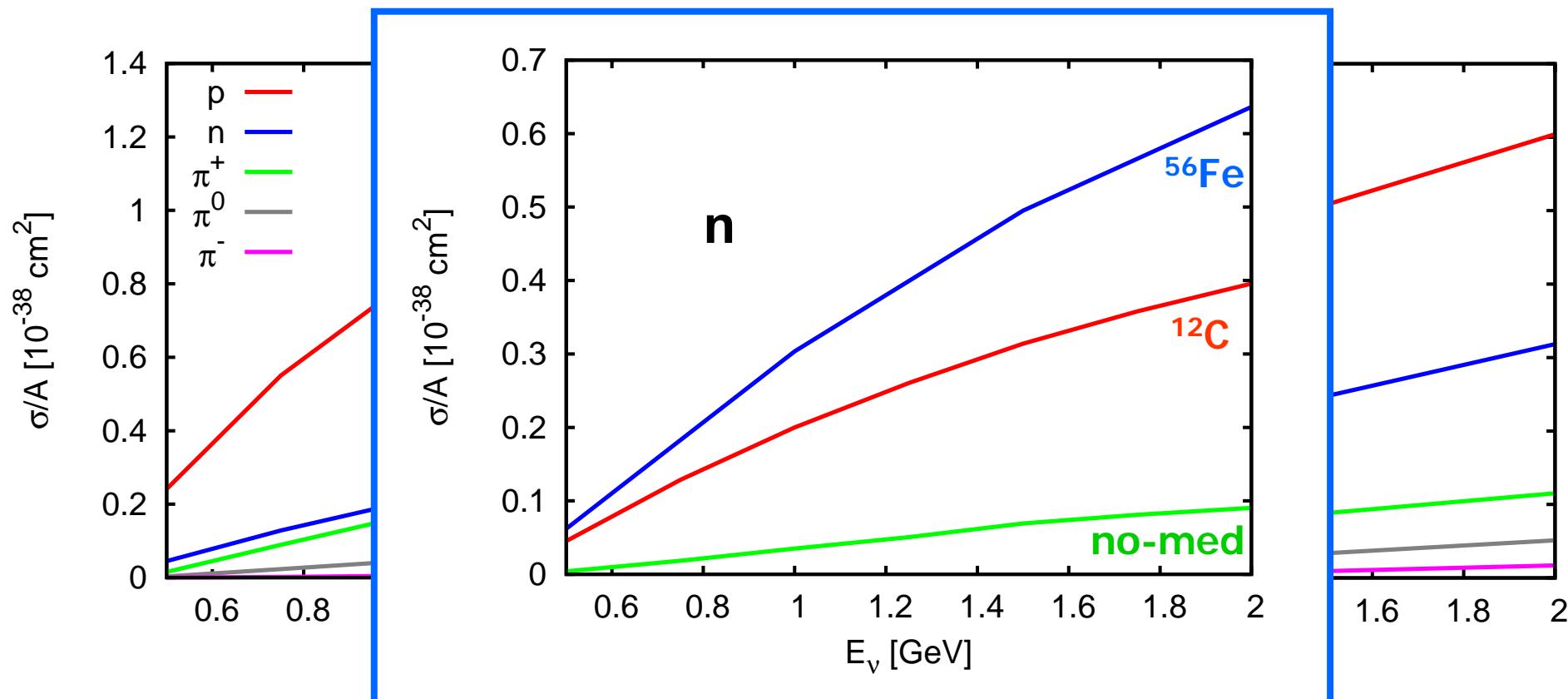
Particle yields for CC scattering

■ CC ν_μ on ^{12}C and ^{56}Fe



Particle yields for CC scattering

- CC ν_μ on ^{12}C and ^{56}Fe

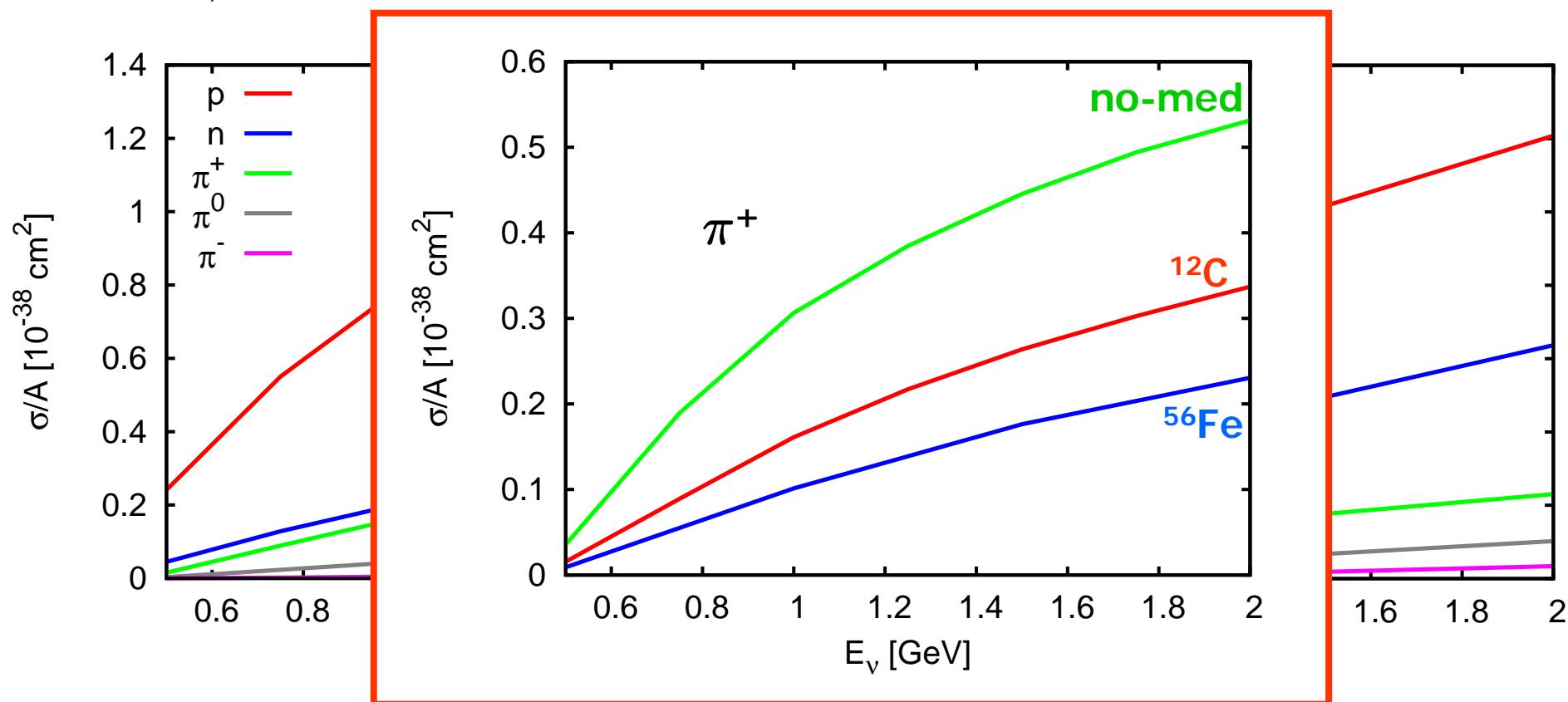


- main differences

- side-feeding: $p \text{ N} \rightarrow n \text{ N}$

Particle yields for CC scattering

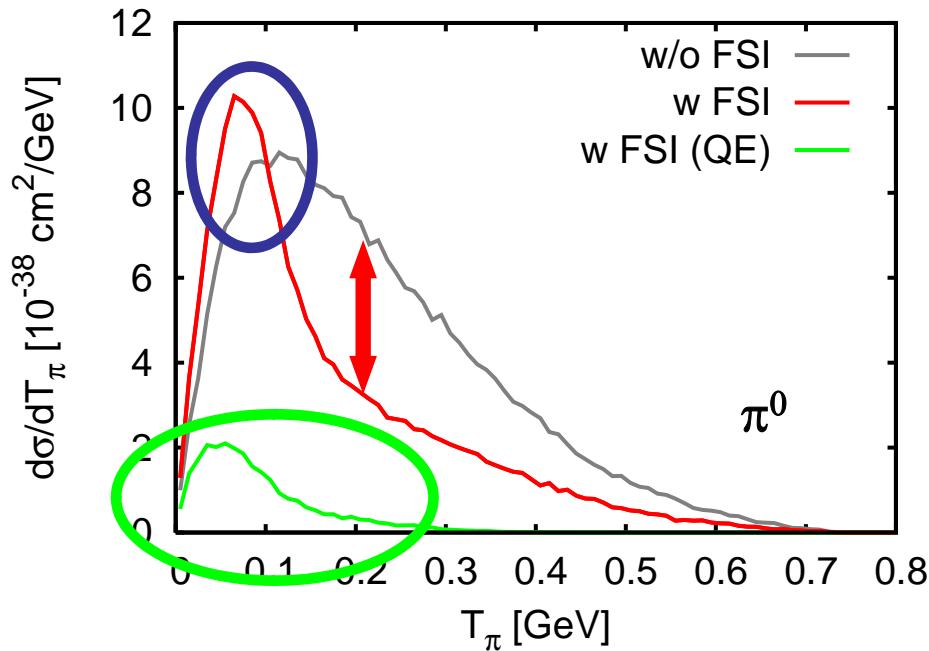
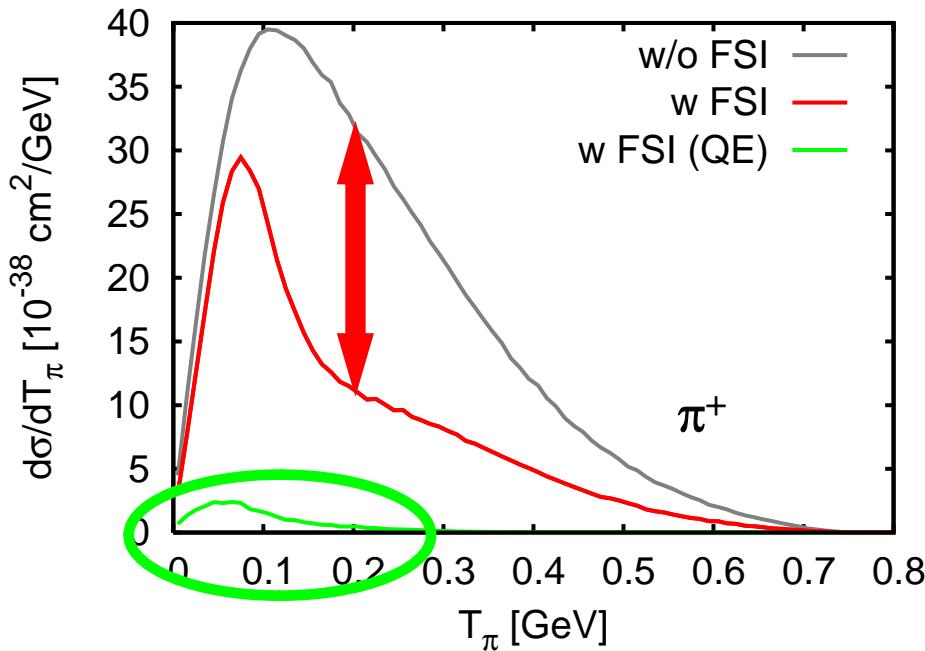
- CC ν_μ on ^{12}C and ^{56}Fe



- main differences
 - side-feeding: $\text{p } \text{N} \rightarrow \text{n } \text{N}$
 - absorption: $\pi \text{ N} \rightarrow \Delta, \Delta \text{ N} \rightarrow \text{N N}$

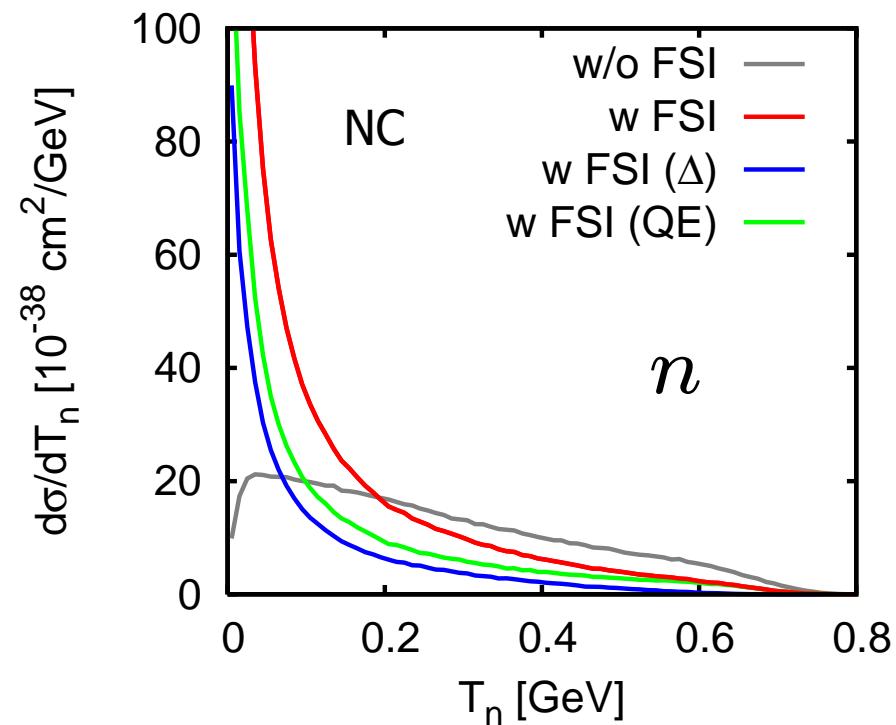
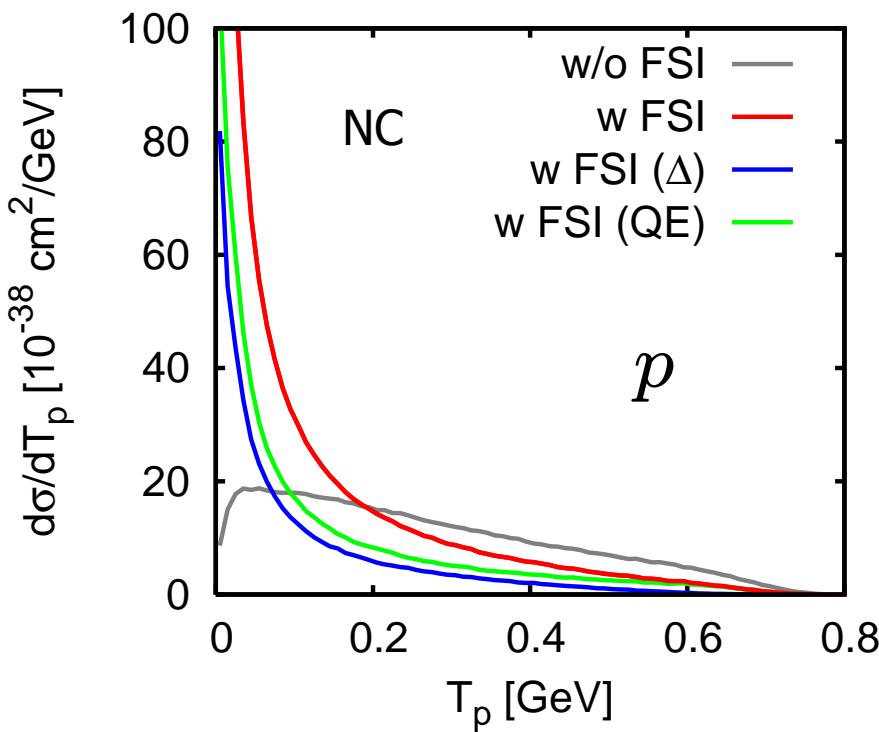
CC pion production: $\nu_\mu {^{56}\text{Fe}} \rightarrow \mu^- \pi X$

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



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

- effects of FSI on nucleon kinetic energy spectrum at $E_\nu = 1 \text{ GeV}$
 - flux reduction at higher energies
 - large number of rescattered nucleons at low kinetic energies

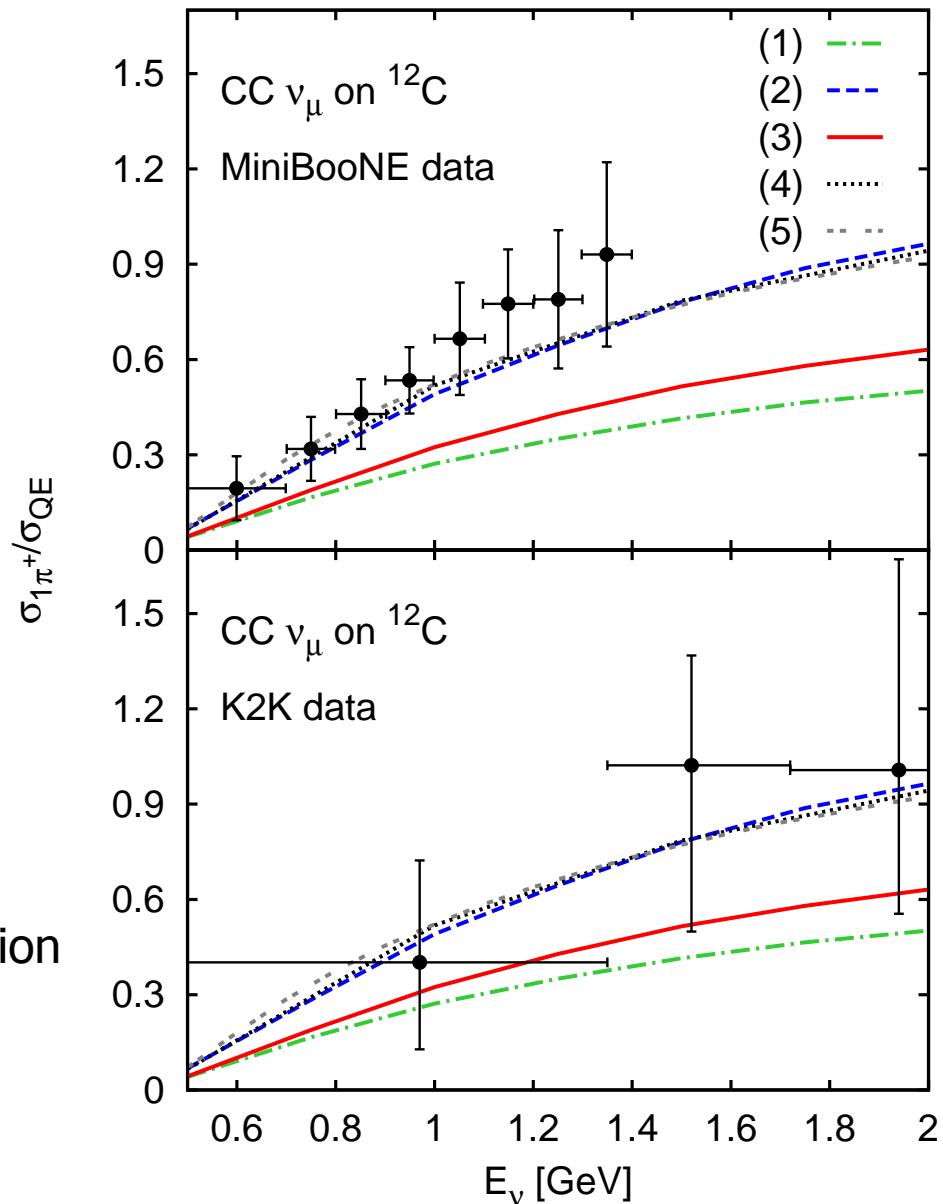


**Δ contribution to knock-out almost equals QE contribution
(increases with E_ν) !**

K2K and MiniBoonE CC1 π^+

■ single- π^+ /QE ratio

1. $\sigma_{1\pi^+} / \sigma_{0\pi^+}$ after FSI:
MiniBooNE definition for
CCQE-like cross section
2. $\sigma_{1\pi^+} / \sigma_{0\pi^+ p}$ after FSI:
K2K definition for
CCQE-like cross section
3. $\sigma_{1\pi^+} / \sigma_{QE}$ after FSI
4. $\sigma_{1\pi^+} / \sigma_{QE}$ before FSI
including nuclear corrections
like mean fields and Fermi motion
5. $\sigma_{1\pi^+} / \sigma_{QE}$ in the vacuum
on an isoscalar target.



K2K and MiniBoonE CC1 π^+

■ single- π^+ /QE ratio

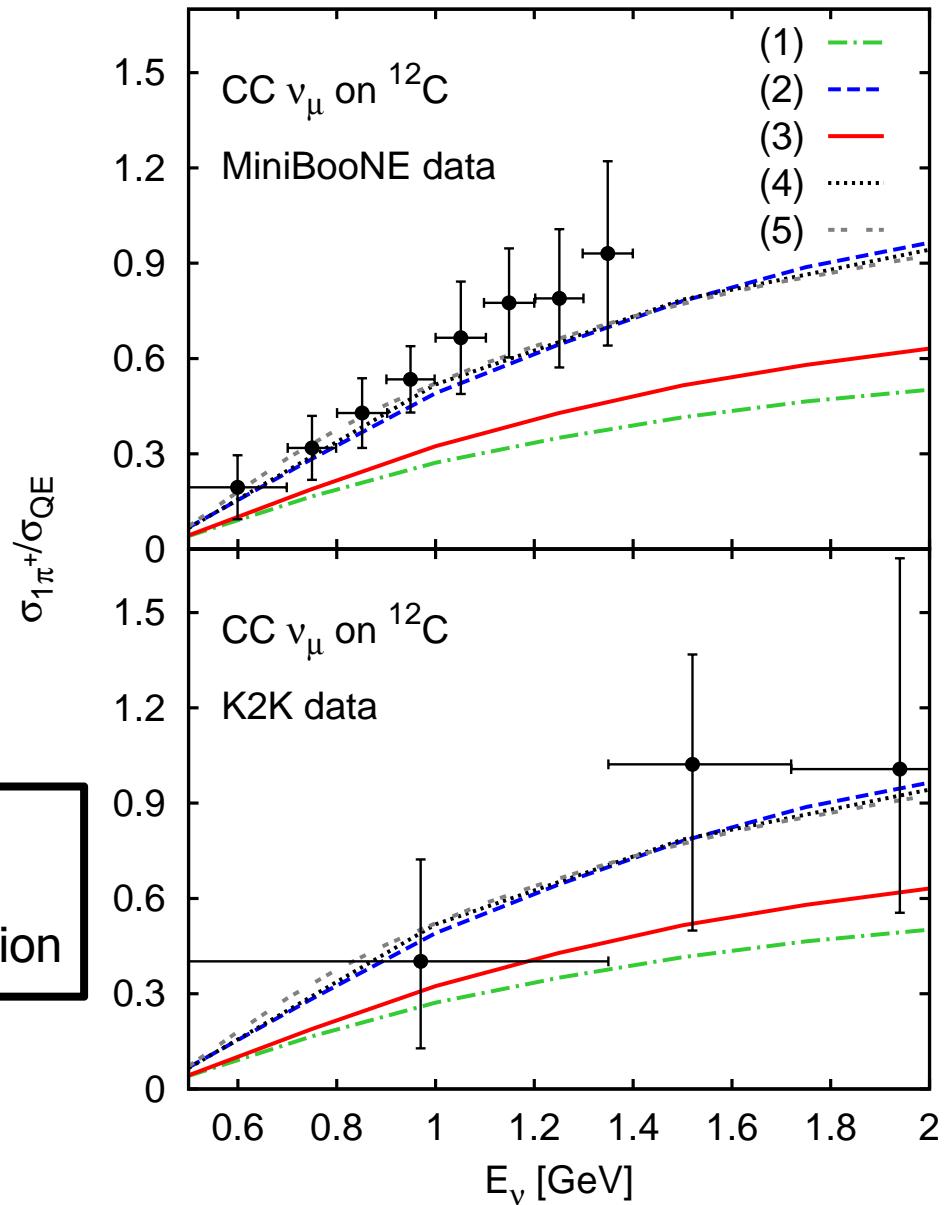
1. $\sigma_{1\pi^+} / \sigma_{0\pi^+}$ after FSI:
MiniBooNE definition for
CCQE-like cross section

2. $\sigma_{1\pi^+} / \sigma_{0\pi^+ + 1p}$ after FSI:
K2K definition for
CCQE-like cross section

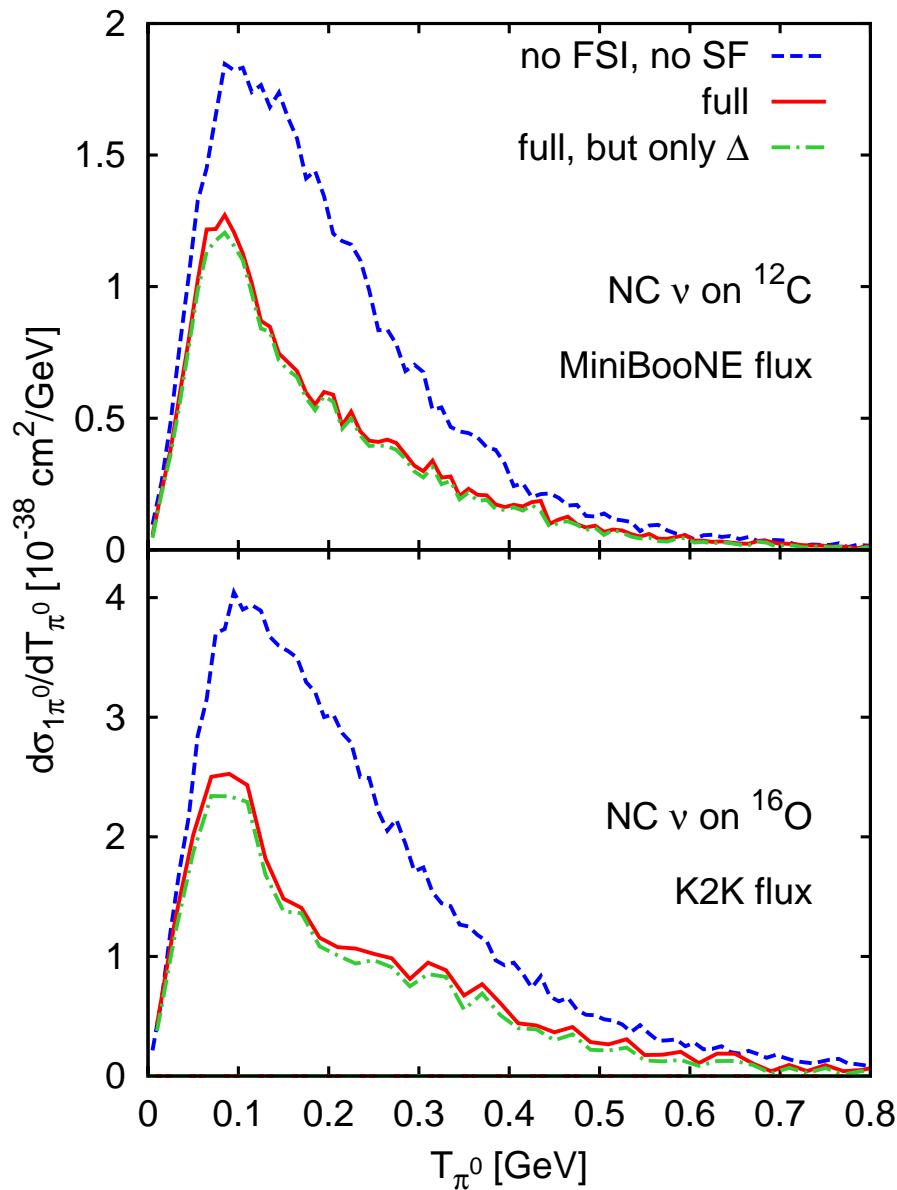
3. $\sigma_{1\pi^+} / \sigma_{QE}$ after FSI

4. $\sigma_{1\pi^+} / \sigma_{QE}$ before FSI
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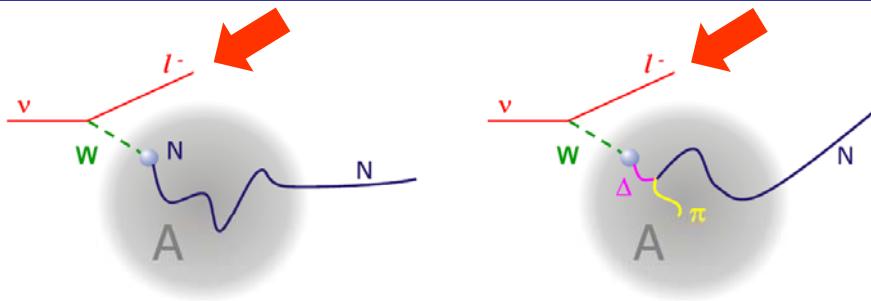
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K2K and MiniBoonE NC1 π^0

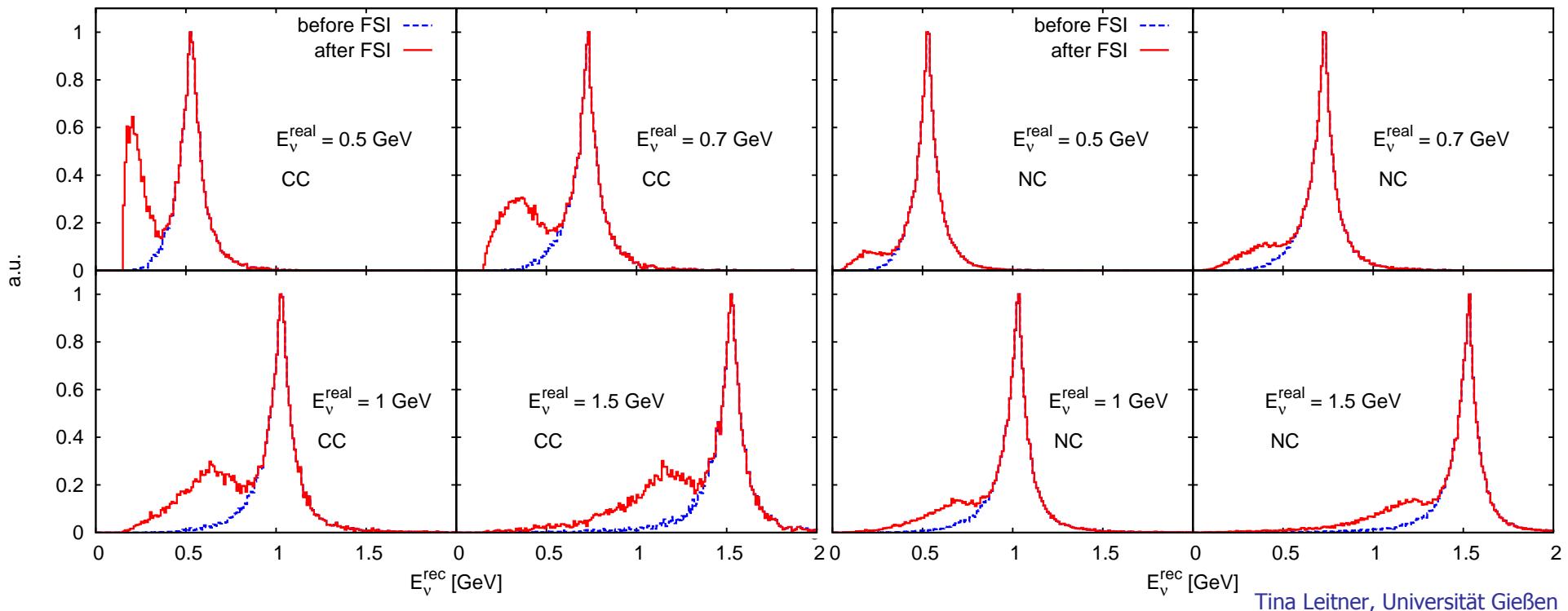


MiniBooNE energy reconstruction



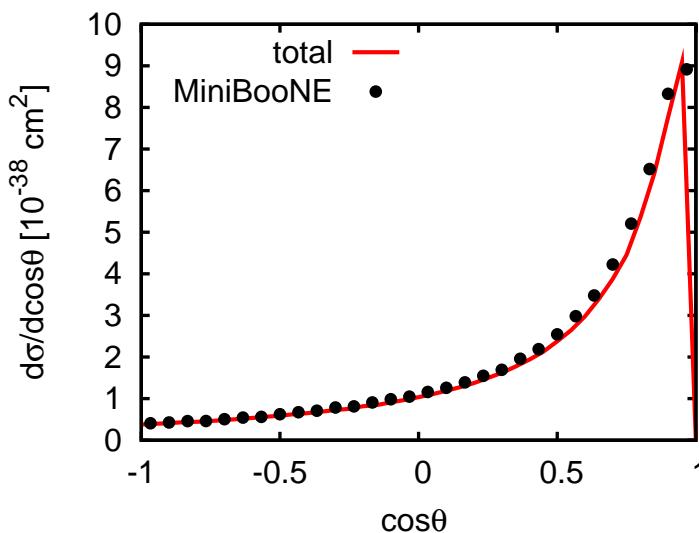
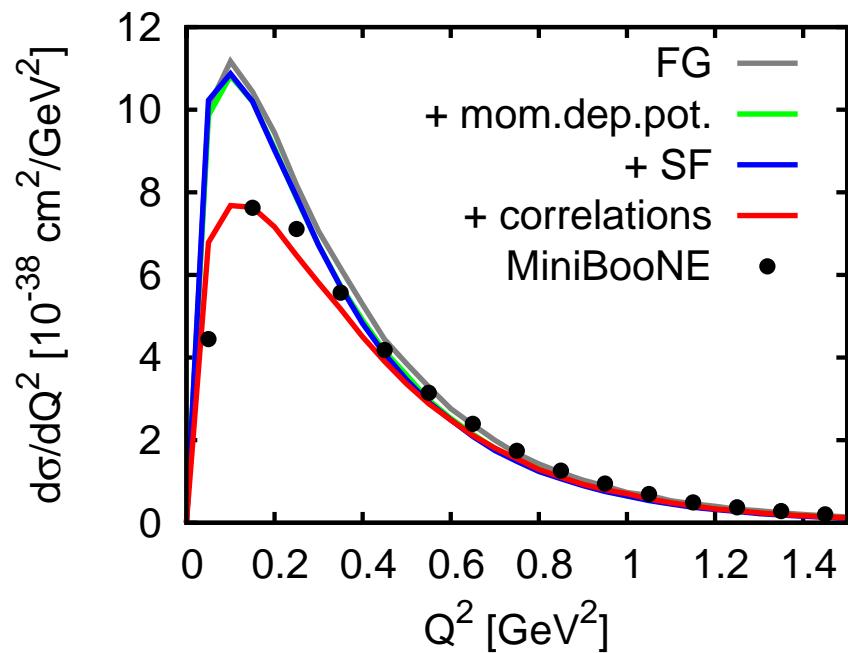
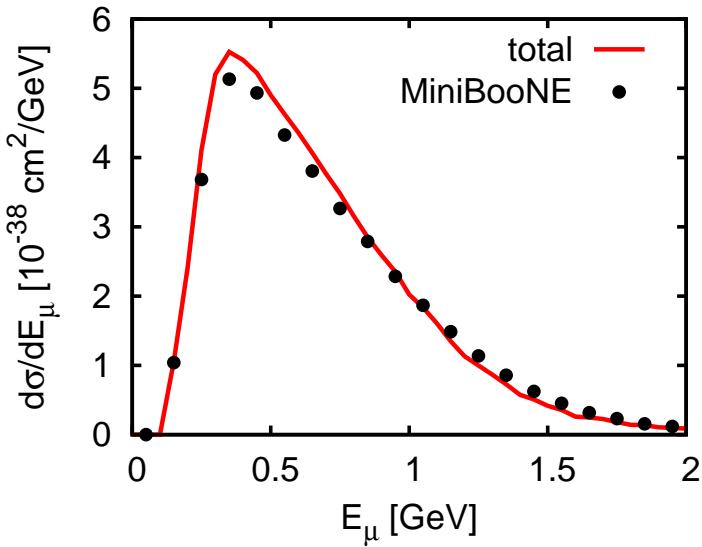
QE-like = no pion in final state

- reconstruction via $E_\nu = \frac{2(M_N - E_B)E_\mu - (E_B^2 - 2M_NE_B + m_\mu^2)}{2((M_N - E_B) - E_\mu + p_\mu \cos \theta_\mu)}$ $E_B = 34 \text{ MeV}$



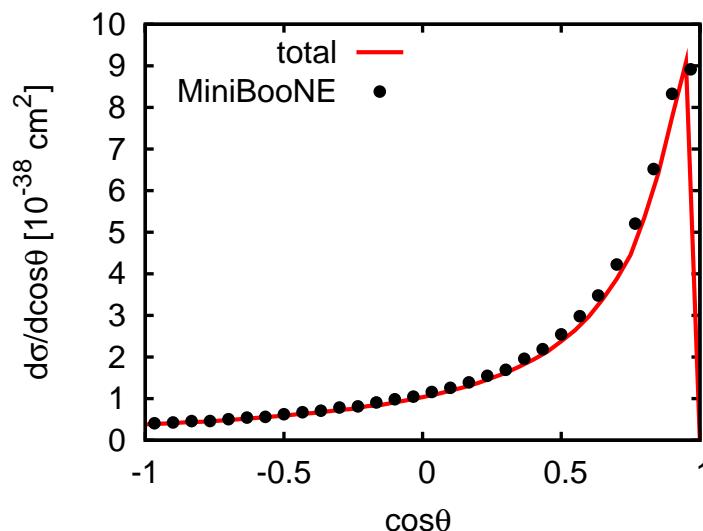
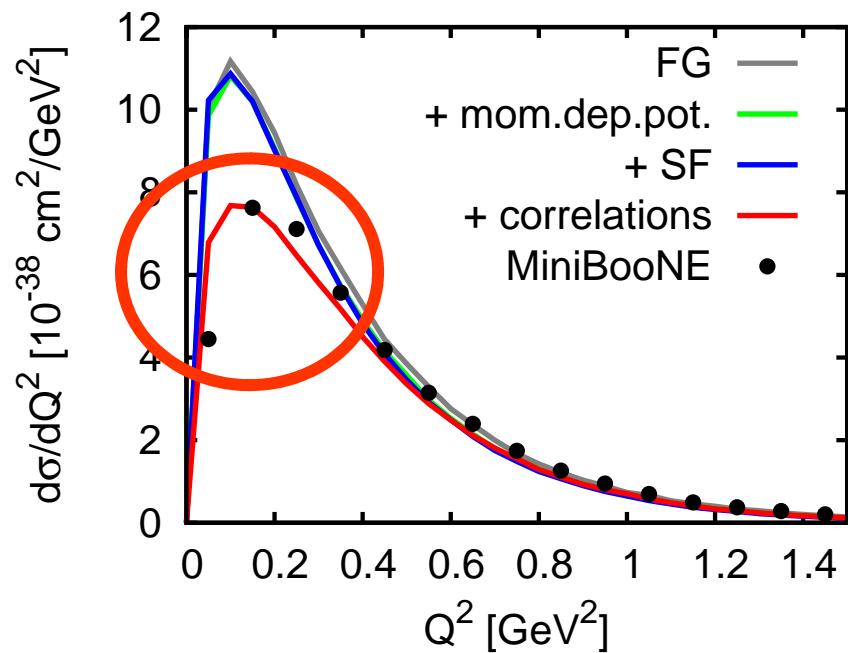
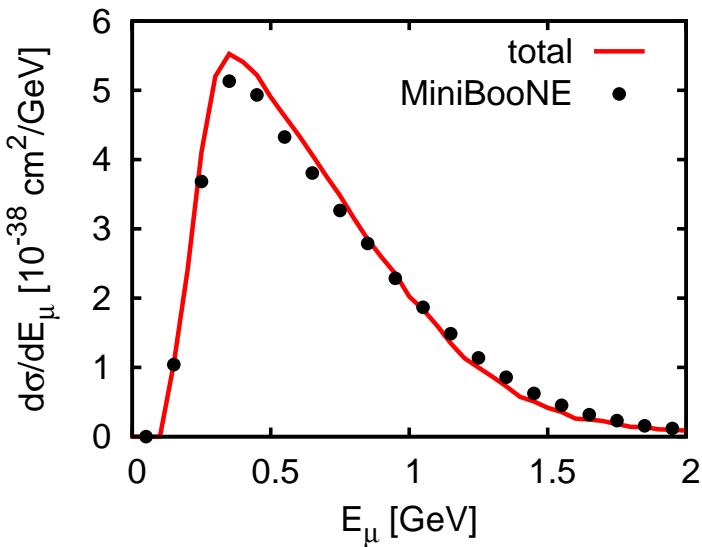
MiniBooNE CCQE

- CCQE (like)
 - full GiBUU in-med mod. + FSI
 - $M_A = 1 \text{ GeV}$
 - no parameter tuning
 - in addition:
RPA correlations by
Nieves et al. PRC73 (2006)
 - compared to MiniBooNE
Monte Carlo output (T. Katori)



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Summary & Conclusions

- **GiBUU** is a multi-purpose theory to describe final state interactions including
 - elastic and inelastic scattering
 - side feeding (charge exchange)
 - method allows to propagate particles out to detector
- cross section **dominated by QE contribution & Δ excitation** for $E_\nu < 1.5 \text{ GeV}$
 - in-medium modifications: local Fermi gas, self energies, ...
 - ➔ good description of electroproduction data
- LBL experiments need to
 - **identify initial process and produced hadrons**
 - **reconstruct neutrino quantities**from observables for both cross section & oscillation measurements
 - simulate impact of in-medium modifications and FSI with GiBUU
 - ➔ absorption, secondary particles, Δ induced nucleon knockout, ...

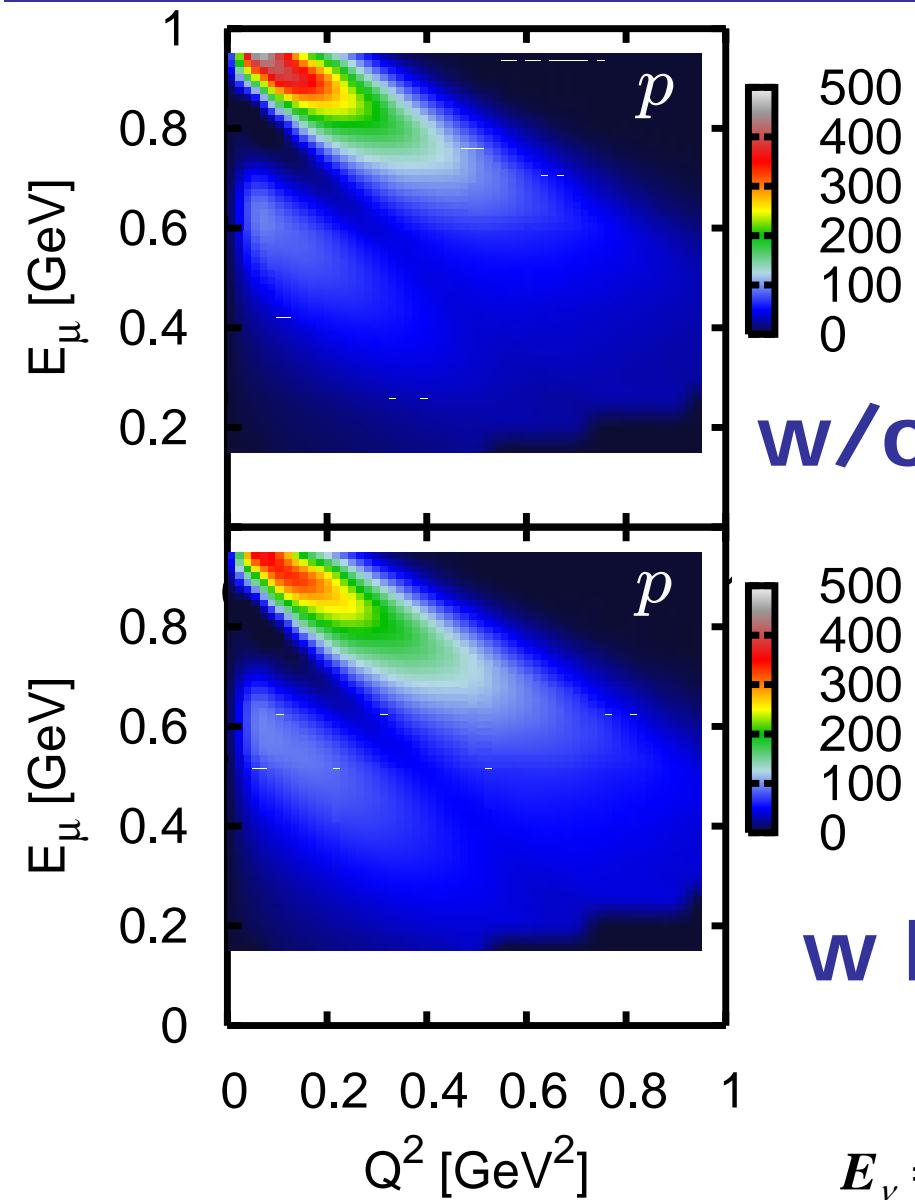
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 - simulate impact of in-medium modifications and FSI with GiBUU
 - absorption, secondary particles, Δ induced nucleon knockout, ...
- **good understanding of in-medium modifications and FSI necessary to distinguish profane from extraordinary effects**

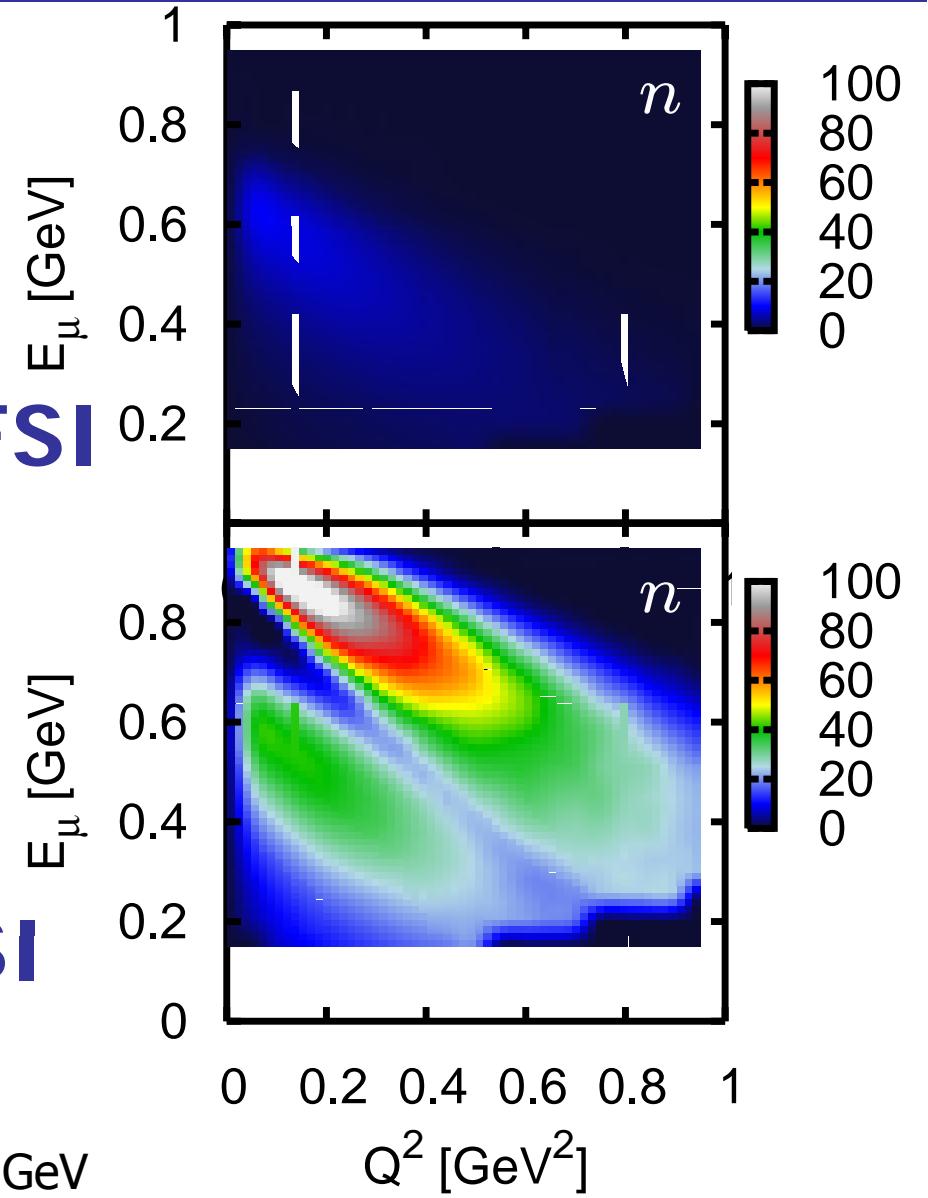
Backup Slides

■ Backup slides

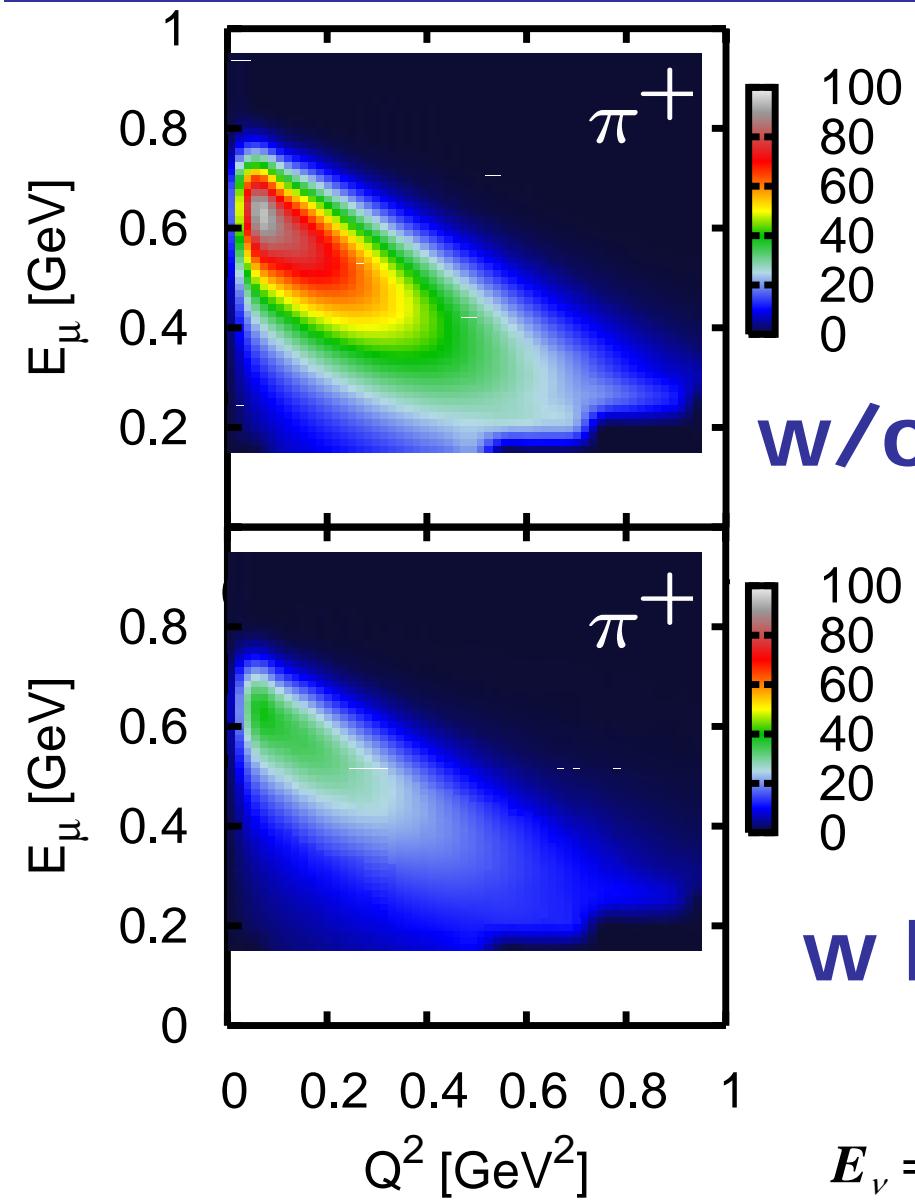
CC nucleon knockout: $\nu_\mu^{56}\text{Fe} \rightarrow \mu^- N X$



$E_\nu = 1 \text{ GeV}$



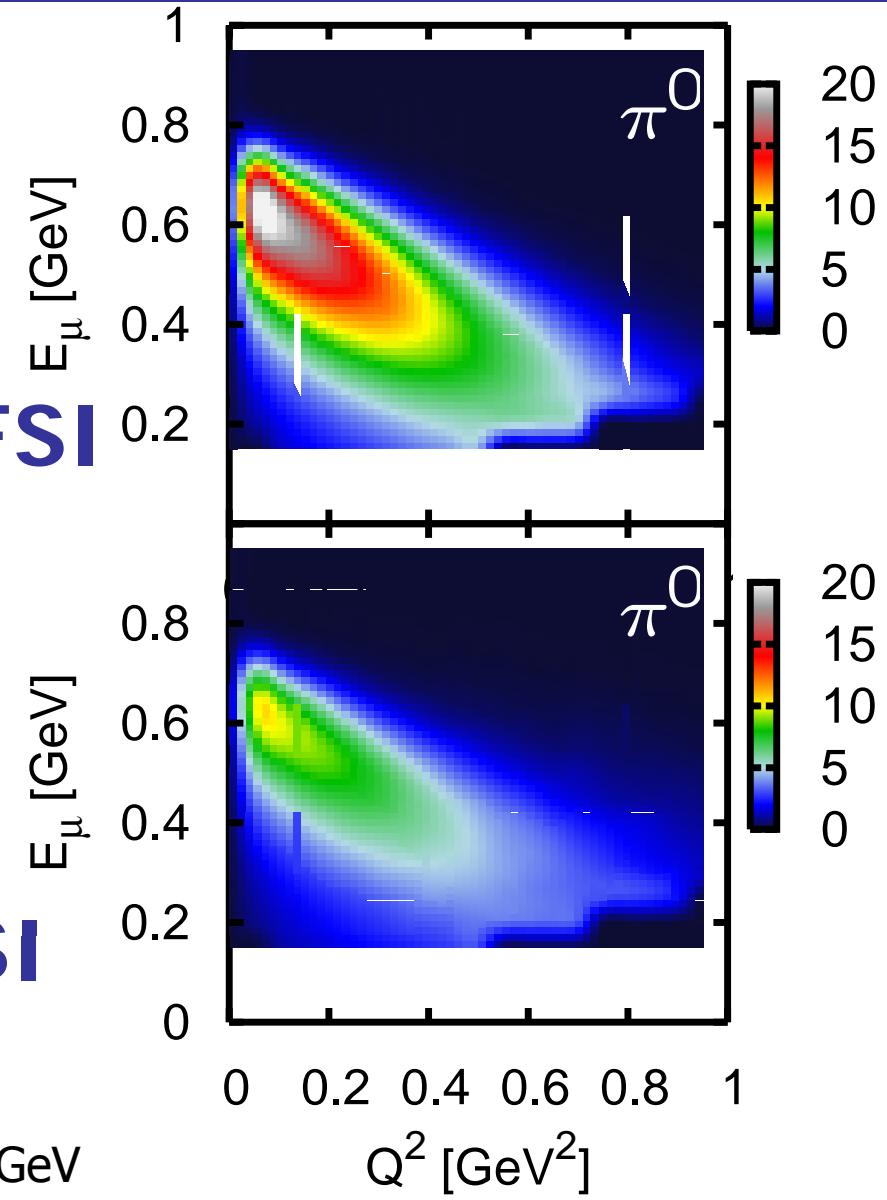
CC pion production: $\nu_\mu {}^{56}\text{Fe} \rightarrow \mu^- \pi X$



w/o FSI

w FSI

$E_\nu = 1 \text{ GeV}$



Lepton nucleon cross section

- cross section for l N reaction $\ell(k) + N(p) \rightarrow \ell'(k') + X(p')$:

$$d\sigma_{\text{tot}} = d\sigma_{\text{QE}} + \sum_{\text{R}} d\sigma_{\text{R}} + d\sigma_{\text{BG}}$$

- **dynamics of the interaction:** $|\bar{\mathcal{M}}_{\text{QE,R,BG}}|^2 = C_{\text{EM,CC,NC}}^2 \ L_{\mu\nu} \ H_{\text{QE,R,BG}}^{\mu\nu}$

□ with: $C_{\text{EM}} = 4\pi\alpha/q^2$, $C_{\text{CC}} = G_F \cos \theta_C / \sqrt{2}$, $C_{\text{NC}} = G_F / \sqrt{2}$

leptonic tensor $L_{\mu\nu}$



leptonic current j_μ

- simple V – A structure
- includes lepton mass

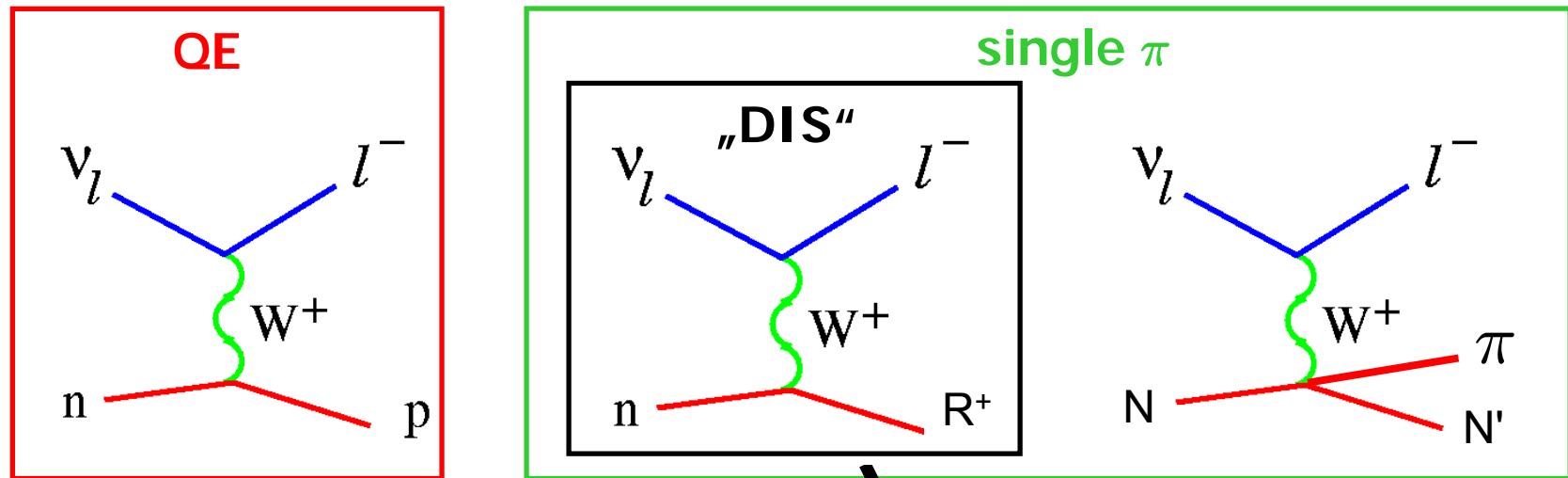
hadronic tensor $H_{\text{QE,R,BG}}^{\mu\nu}$



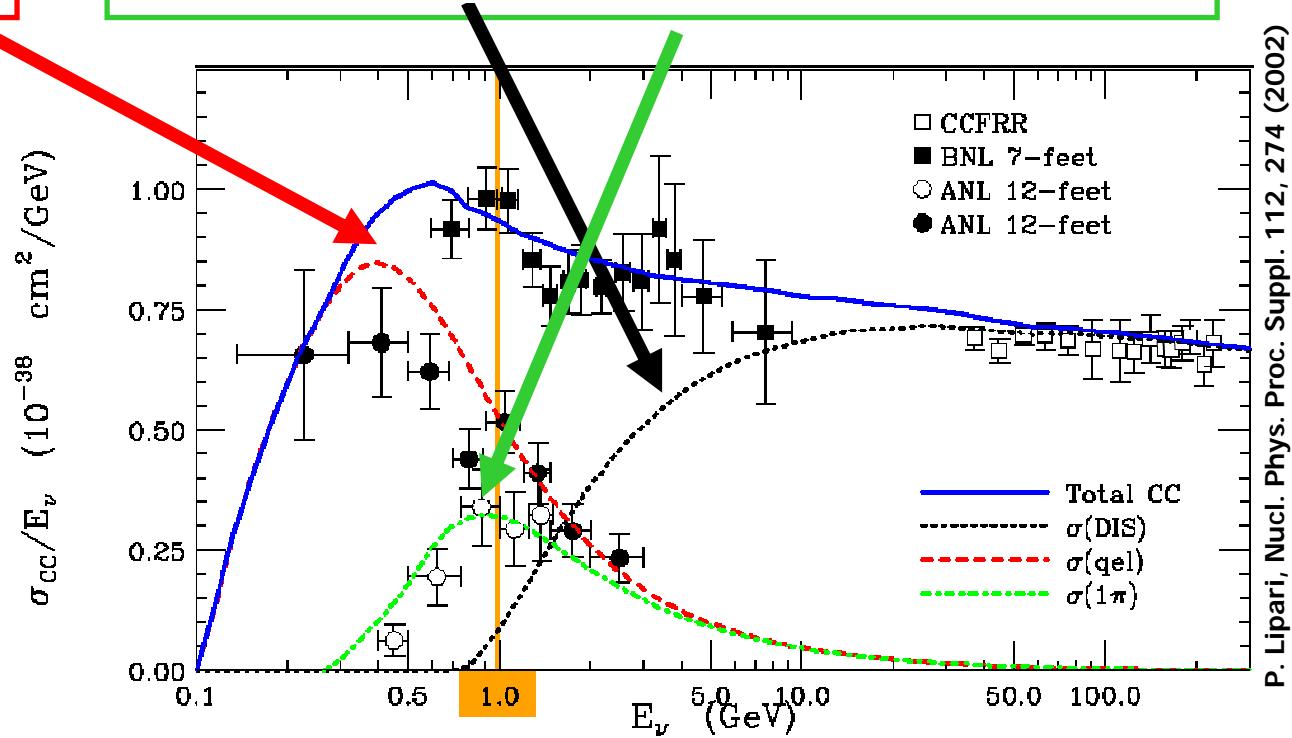
hadronic current $J_{\text{QE,R,BG}}^\mu$

- depends on specific reaction
- parametrized with form factors

Lepton nucleon cross section



“real DIS” neglected



In-medium spectral function I: real part

- cross section proportional to **spectral function**: $d\sigma \sim \mathcal{A}(E, \mathbf{p}) |\bar{\mathcal{M}}|^2$ given by

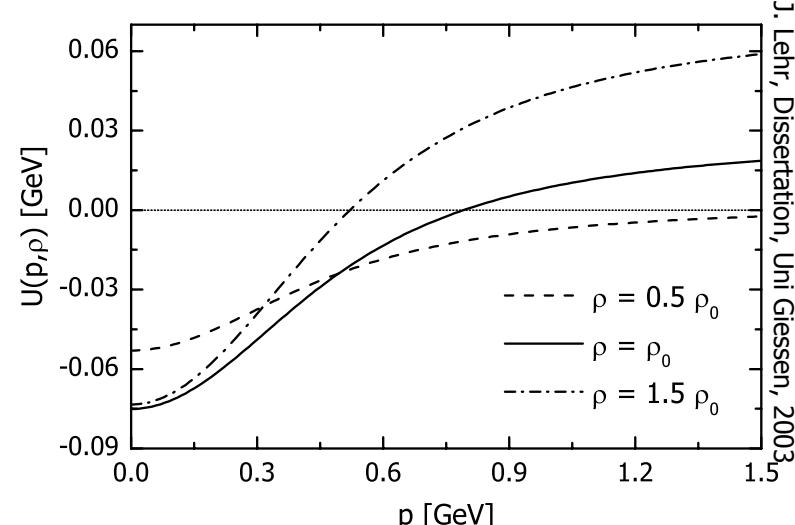
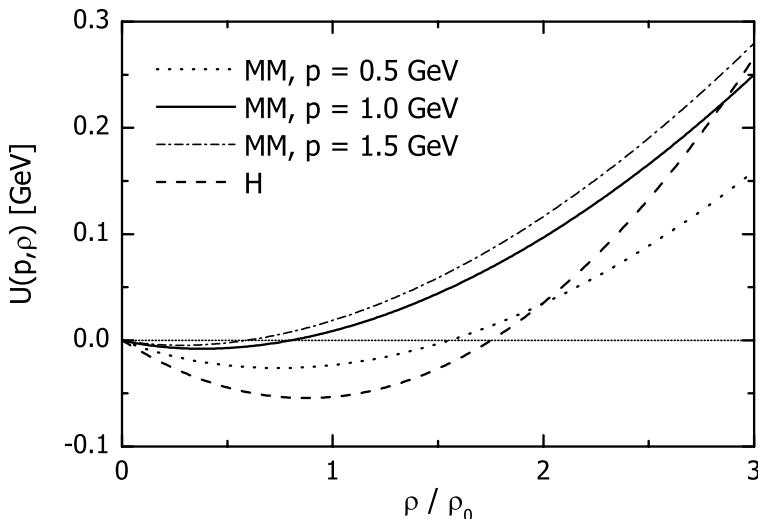
$$\mathcal{A}(E, \mathbf{p}) = \frac{1}{\pi} \frac{-\text{Im}\Sigma(E, \mathbf{p})}{(M^2 - M_0^2 - \text{Re}\Sigma(E, \mathbf{p}))^2 + (\text{Im}\Sigma(E, \mathbf{p}))^2},$$

- **real part** fixed by **hadronic mean-field potential**

- **Skyrme type + momentum dependence** (Welke et al., PRC 38, 2101 (1998))

- momentum dependence from proton-nucleus scattering data
 - same potential for nucleon and isospin $\frac{1}{2}$ resonances
for isospin $3/2$: $\frac{2}{3}$ of the nucleon potential

- ensures normalization of spectral function



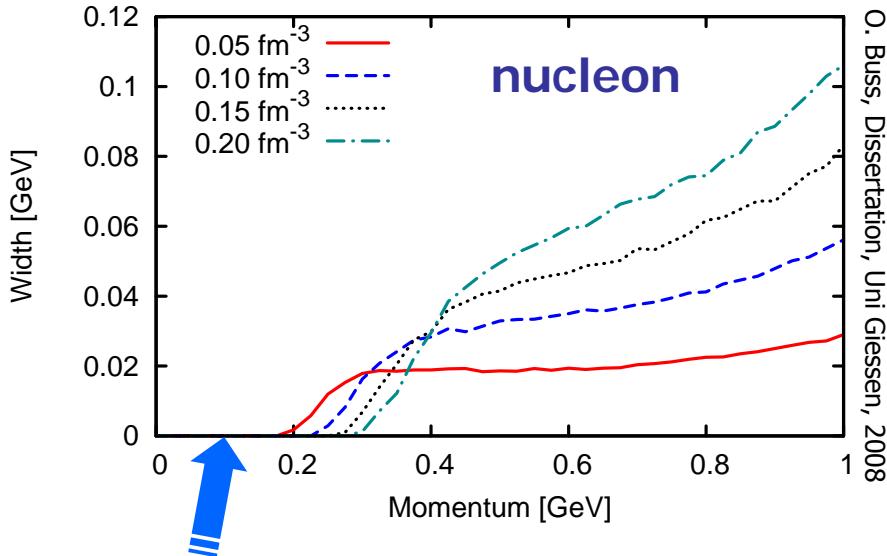
Collisional broadening

■ imaginary part of in-medium self energy

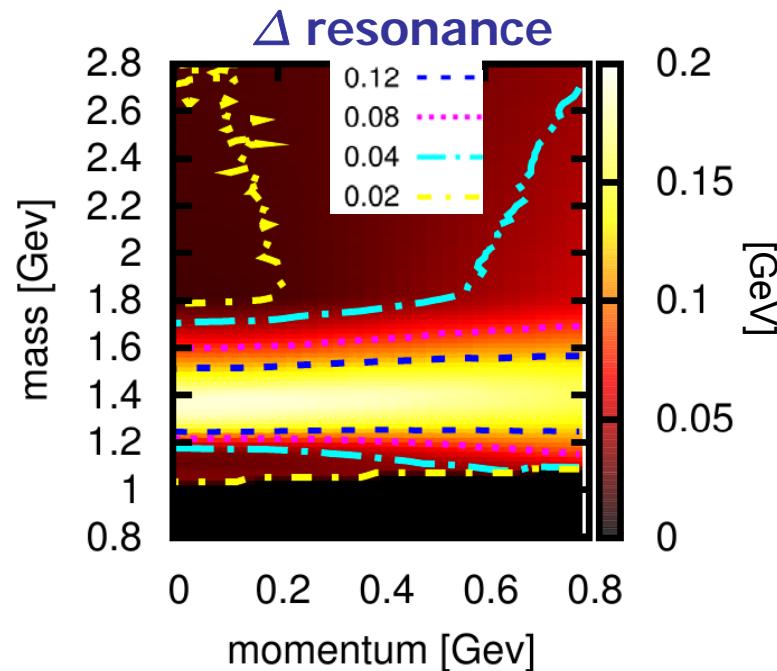
□ $Im\Pi(\vec{r}, p) \sim \Gamma_{free, Pauli\ blocked}(\vec{r}, p) + \Gamma_{coll}(\vec{r}, p)$

with approximate ansatz for **collisional broadening**

$$\Gamma_{coll}(\vec{r}, p) = \int_{Fermi\ sea\ at\ \vec{r}} \sigma(p, p') v_{rel}(p, p') dp'$$



vanishing width below Fermi momentum



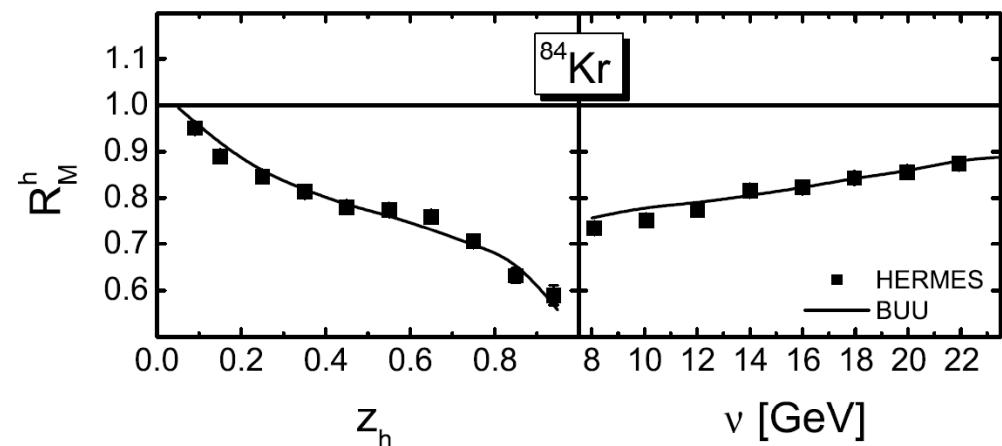
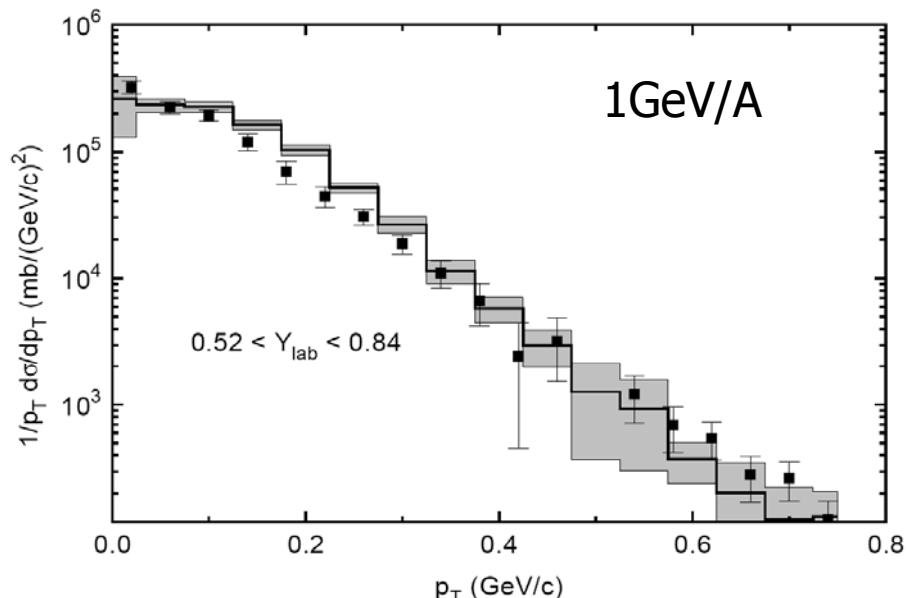
Boltzmann-Uehling-Uhlenbeck (BUU) models

- how-to?
 - solve set of coupled transport equations which are based on the BUU equation
 - **BUU** equation:
 - Boltzmann equation modified by Nordheim, Uehling and Uhlenbeck to describe fermionic systems
 - describes space-time evolution of a many-body system under the influence of potentials and a collision term
- short history:
 - transport models based on the BUU equation are used since the 1980's for heavy-ion collisions
 - since the mid-1990's: BUU models were also successfully applied to calculate particle production in pion- or (virtual) photon-nucleus reactions
 - in particular with EM probes BUU was applied to many experiments (JLAB, TAPS, HERMES) (range of bombarding energies \sim 100 MeV – many GeV)
- advantage:
 - description of final state interactions (FSI): in principle no limitation
 - important advantage compared to other models (e.g. Glauber) which only include absorptive FSI

GiBUU describes ...

■ heavy ion reactions:

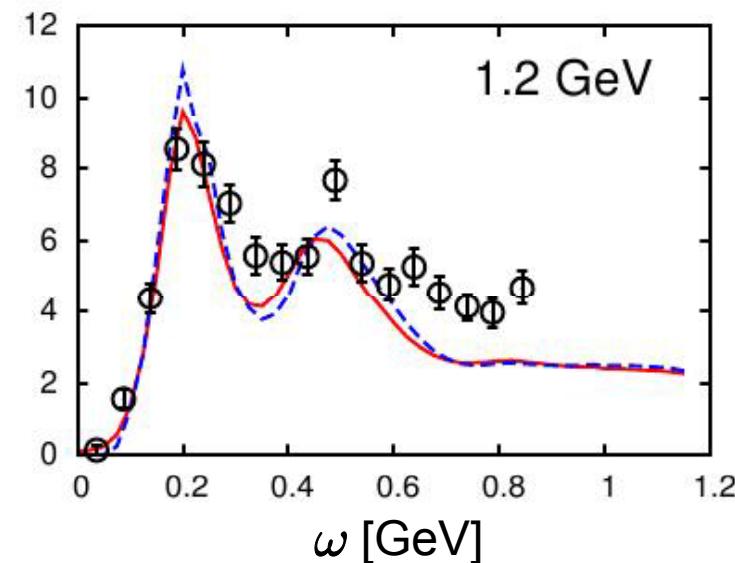
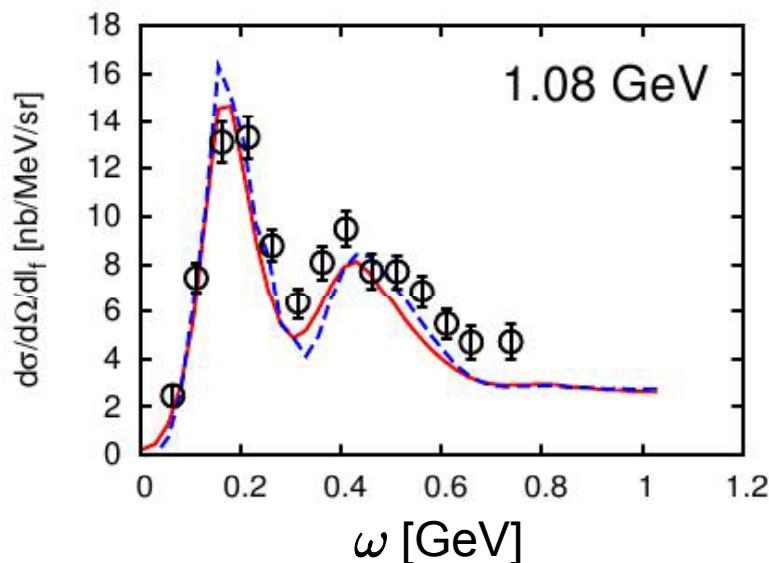
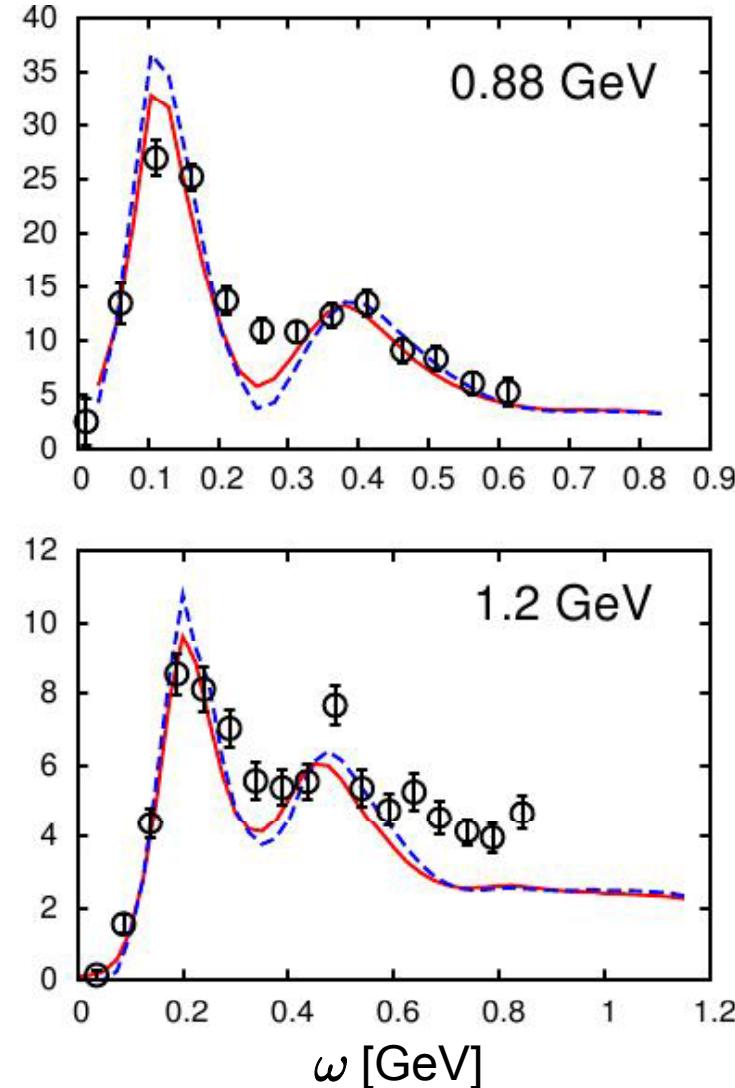
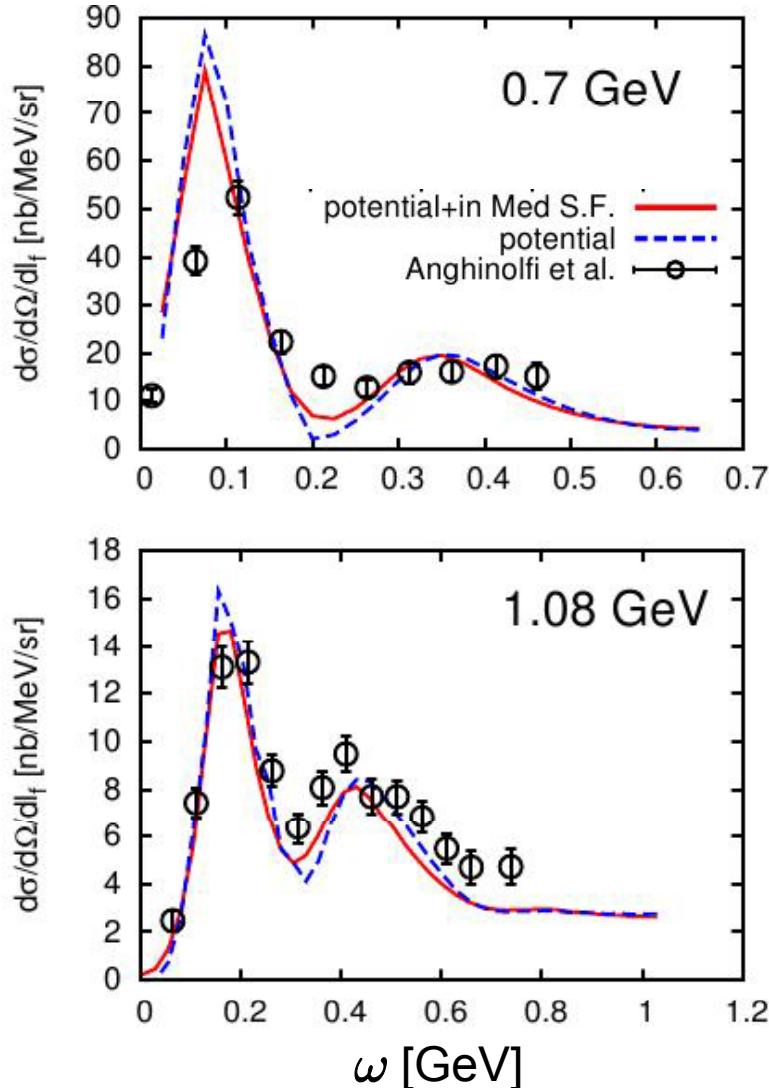
π^0 production in Au+Au collisions
(Teis et al., Z. Phys. A 356 (1997))



■ **high energy electron scattering:**
hadron multiplicity ratio compared to
Hermes data (27.5 GeV electron beam)
(Falter et al., PRC 70 (2004),
Gallmeister et al., nucl-th/0701064)

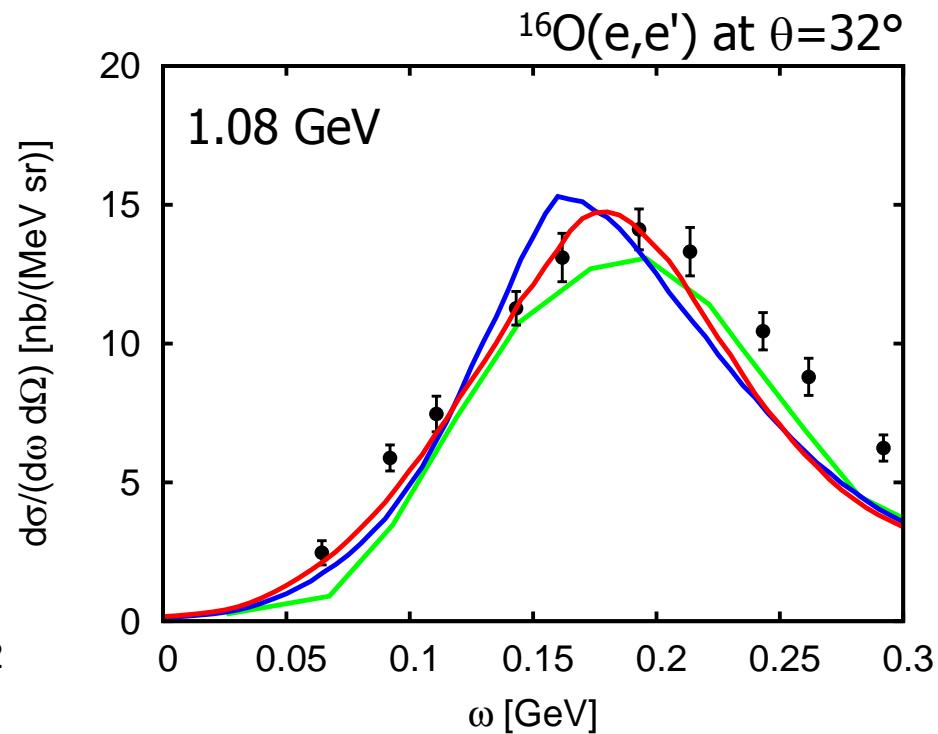
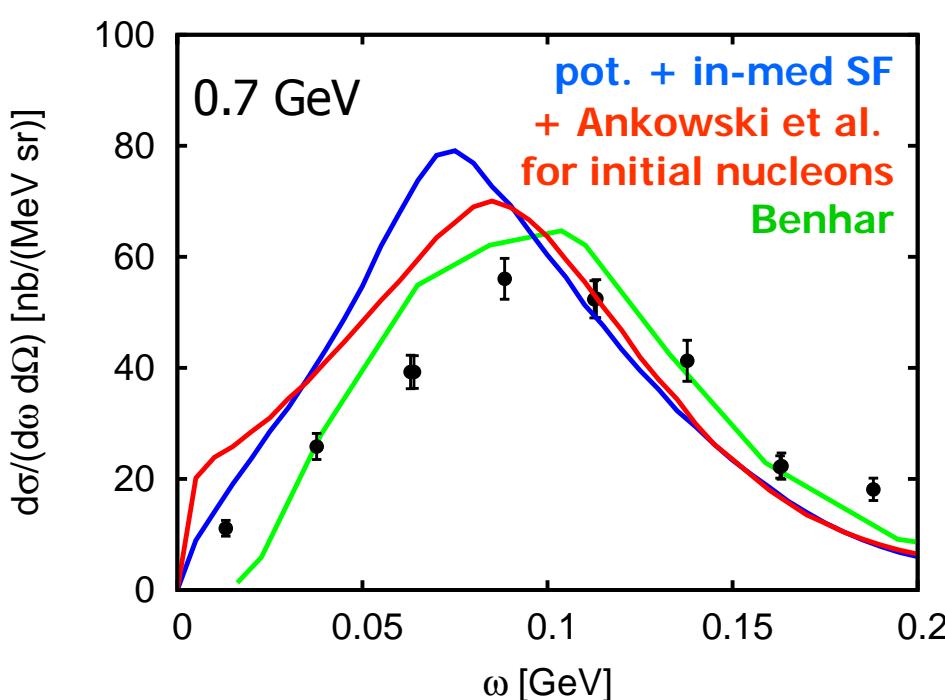
Inclusive cross section: Electroproduction

- first check for every neutrino calculation: electron scattering – $^{16}\text{O}(\text{e},\text{e}')$ at $\theta=32^\circ$



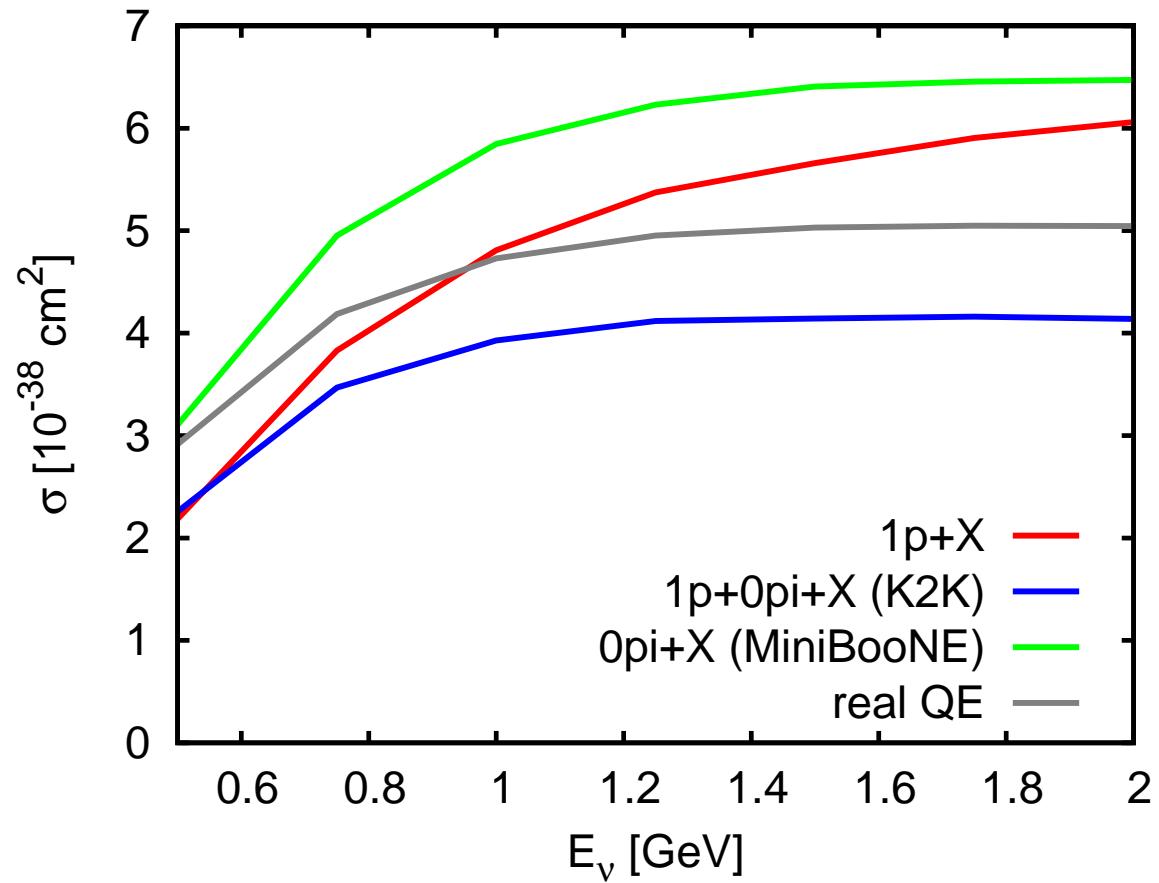
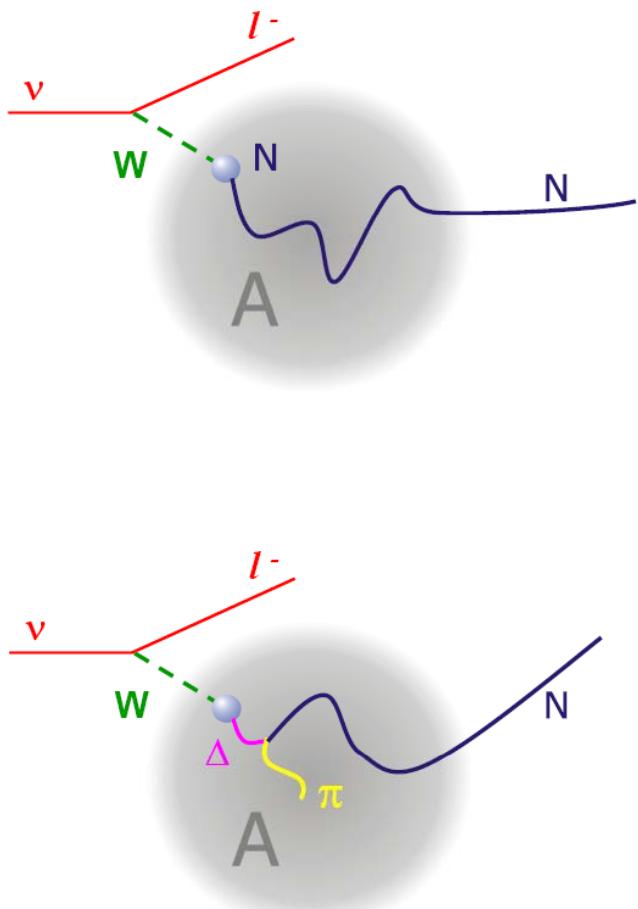
Low Q^2 discrepancy

- in addition: spectral function for nucleons in the Fermi sea
 - using approach of **Ankowski et al.** → fit to **Benhars NMBT calculation**

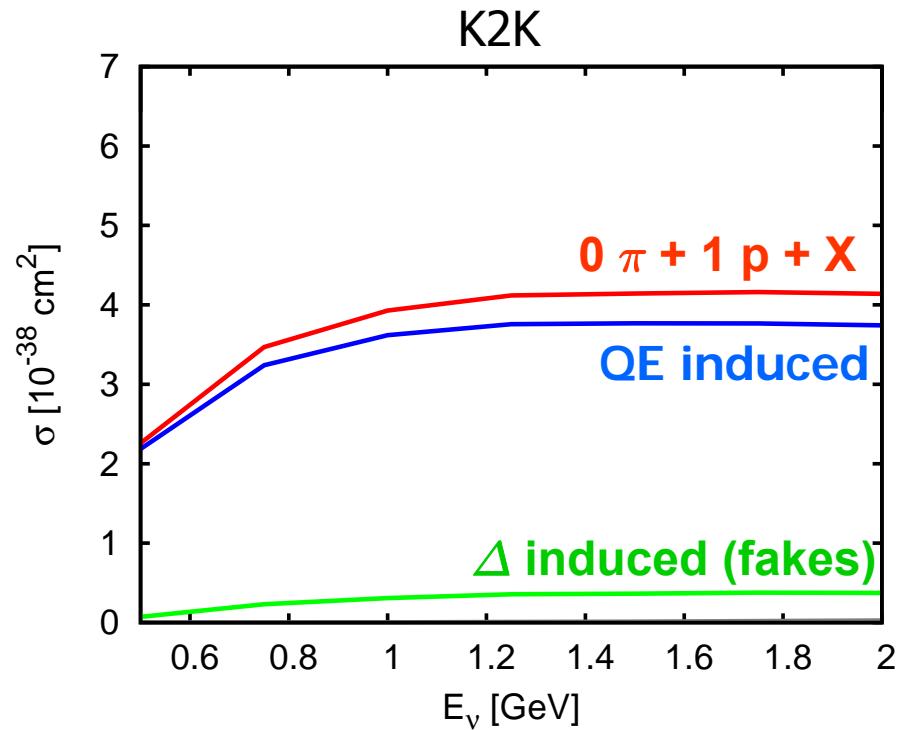
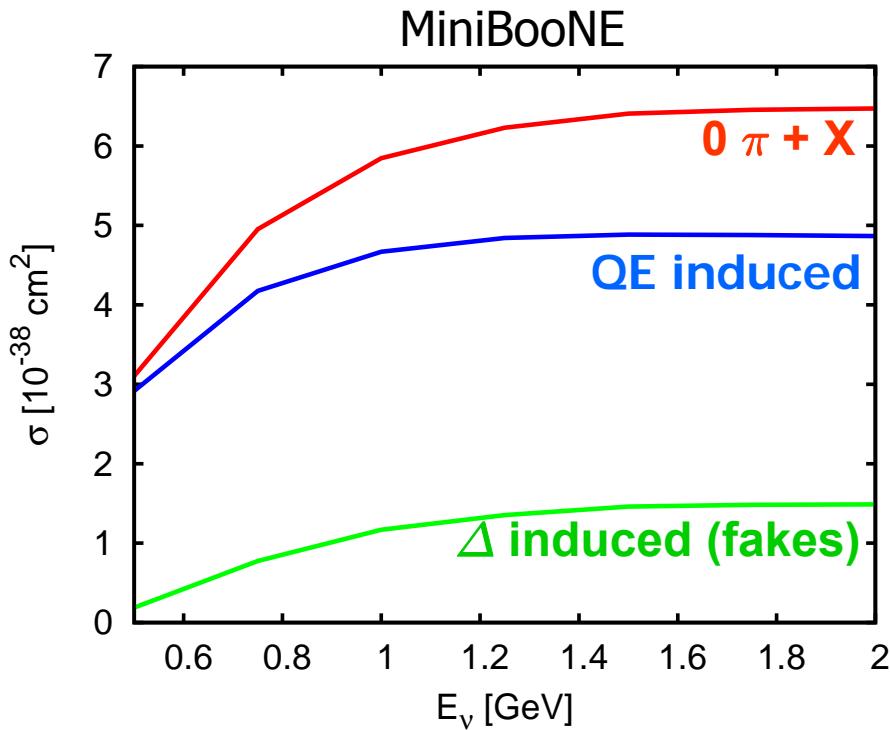


- beam energies < 0.88 GeV: unresolved discrepancy, potentials?
- beam energies > 0.88 GeV: simple ansatz for collisional width describes data as well as sophisticated model of Benhar et al.

CCQE – How to identify?



Different approaches to real CCQE



- K2K methods gives cleaner sample
- influence on observables?
 - e.g. reconstruction of neutrino quantities via CCQE