Neutrino induced pion production at MiniBooNE and K2K

Tina Leitner

Luis Alvarez-Ruso, Oliver Buss, Ulrich Mosel
and
GiBUU team

Institut für Theoretische Physik
Universität Giessen, Germany

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

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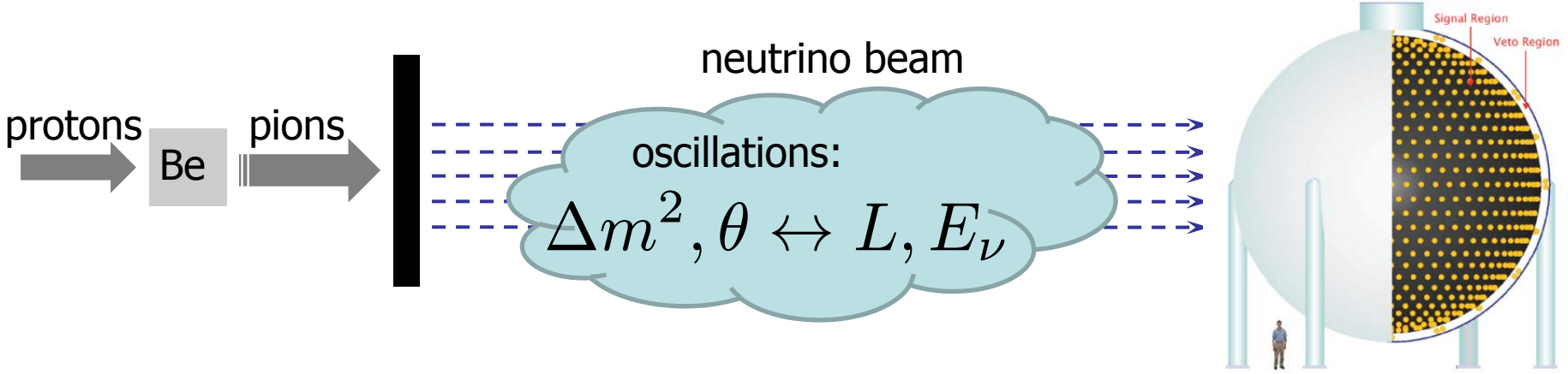
Link between nuclear effects & ν oscillations

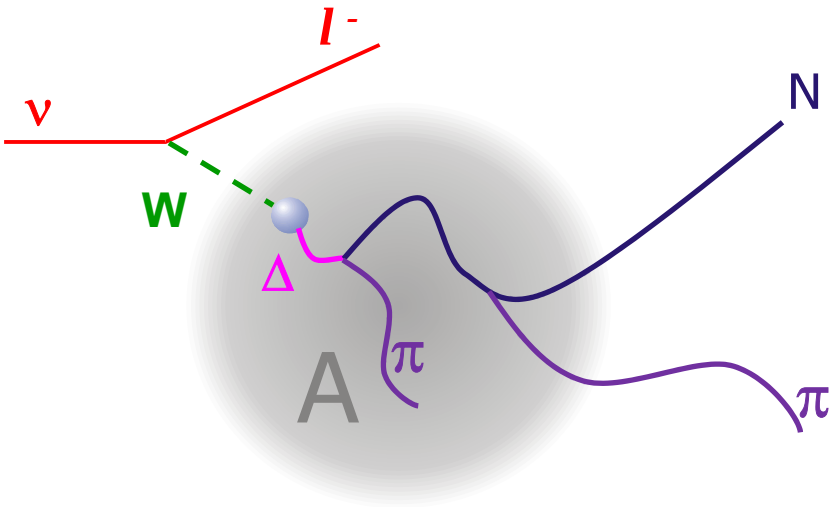


- **particle identification ➔ neutrino flavor**
  - main background for ν_e appearance: **NC $1\pi^0$**

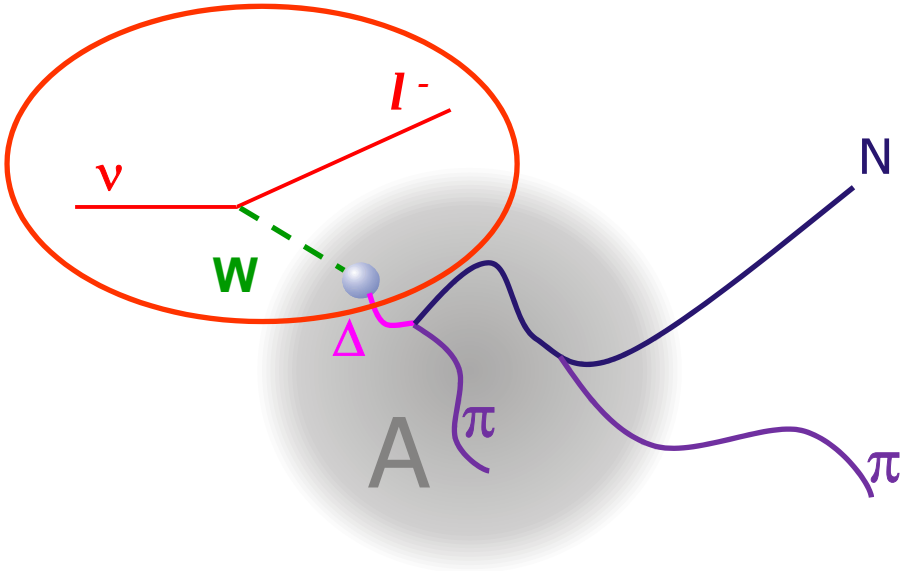
- **reconstruction of neutrino energy via CC QE**
  - main background: **CC $1\pi^+$** with pion being absorbed

➔ **influence of in-medium modifications and final state interactions**

Modelling in-medium reactions



Modelling in-medium reactions



- **Initial state interaction (ISI)**
  - impulse approximation
  - Fermi motion, Pauli blocking
  - self energies: collisional broadening and mean-field potentials
  - medium-modified ν N cross sections

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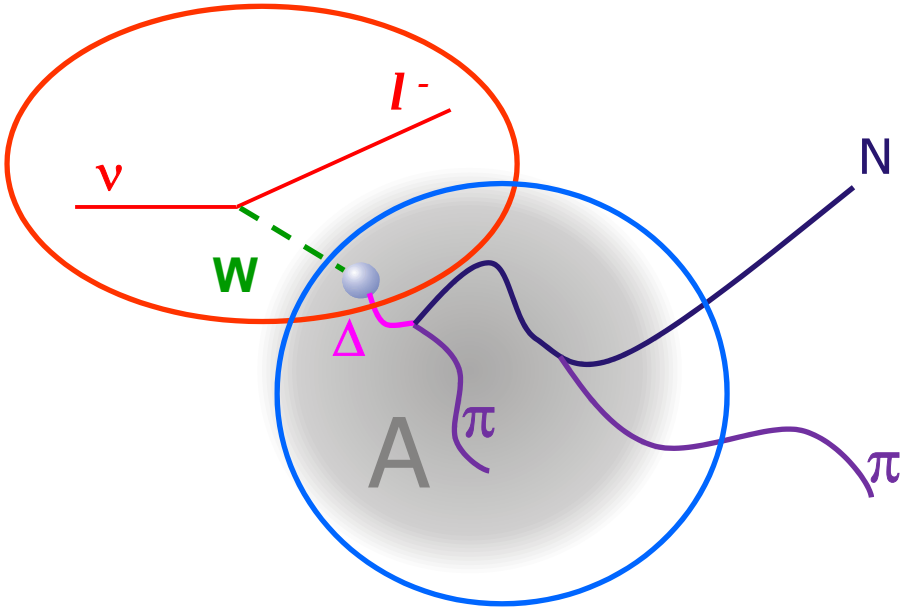

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  - propagation, mean-field potentials
  - absorption
  - particle production, rescattering, …

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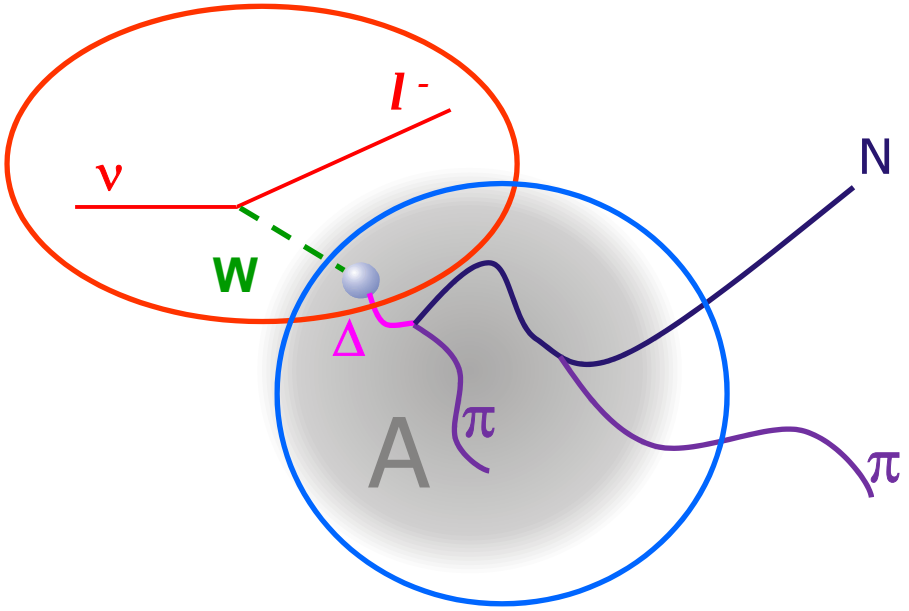

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Consistency:

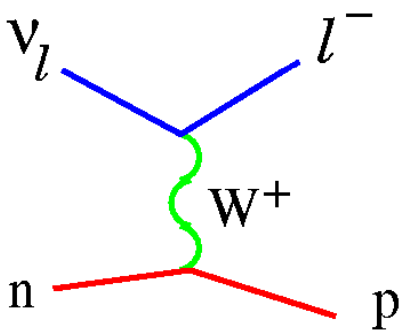
Self energies in the initial state process (e.g., Δ spectral function) should match FSI rates (e.g., ΔN → NN cross sections)

➔ ISI and FSI can only be seperated within the same model

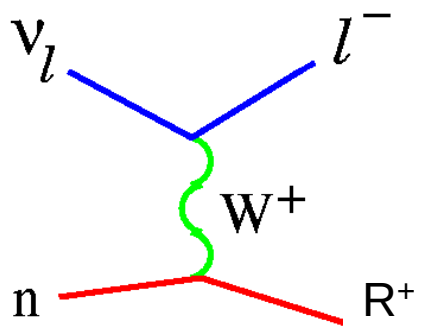
Neutrino nucleon cross section

- **primary interaction** of neutrino with one nucleon at a time

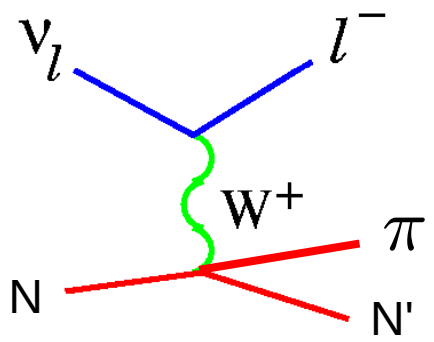
QE



RES



single-π BG



hadronic currents parametrized in terms of form factors:

vector form factors

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

axial form factors

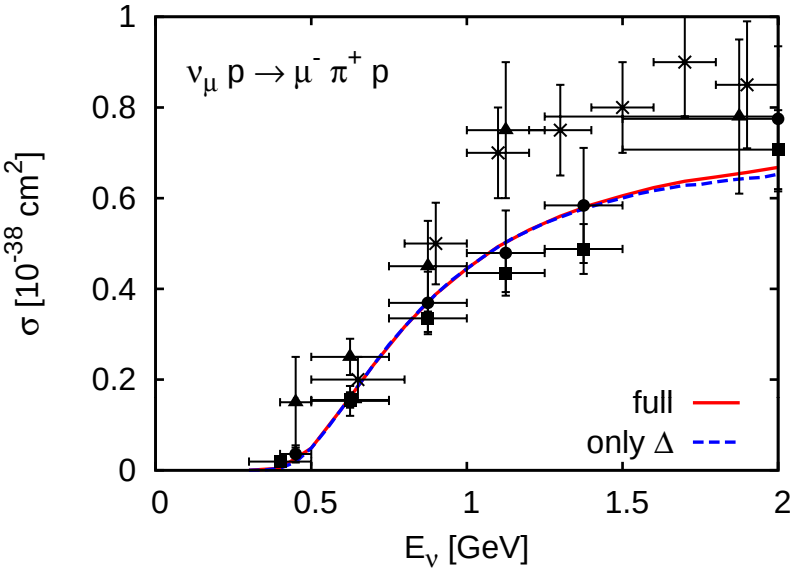
- (dipole) ansatz; related via **PCAC**
- use of **neutrino data** when possible

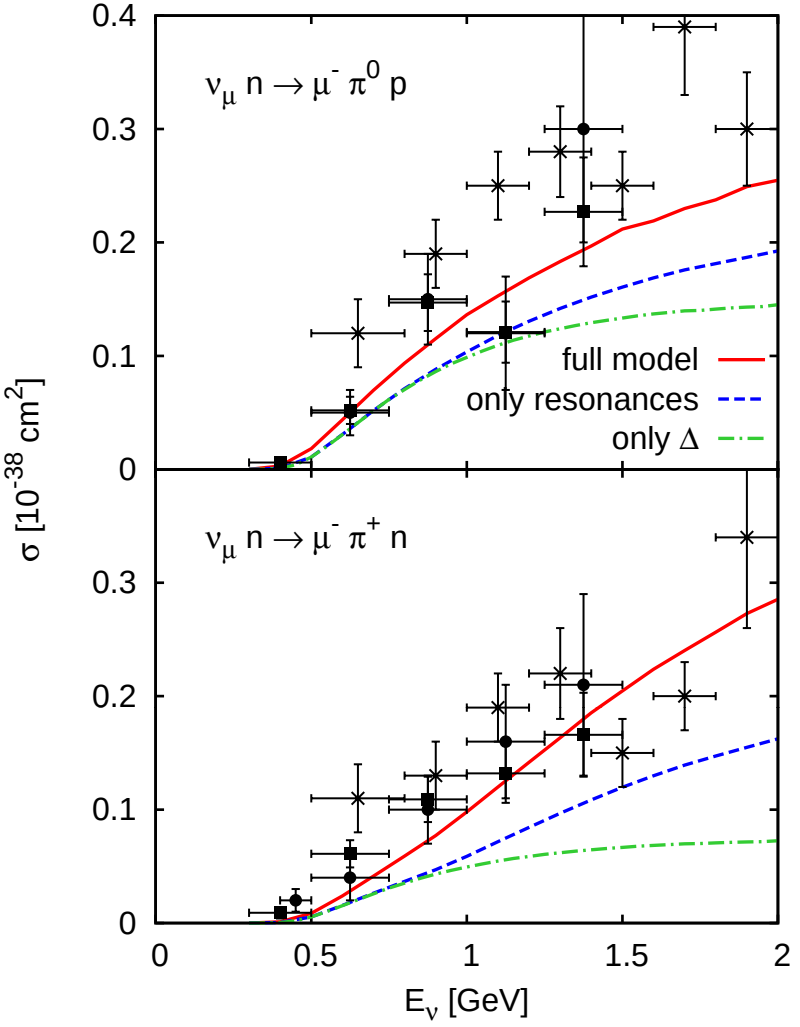
Neutrino induced pion production off nucleons

- QE contributes to pion production only through FSI

- main mechanism at 1 GeV: excitation and subsequent decay of **Delta resonance**

dominant channel:





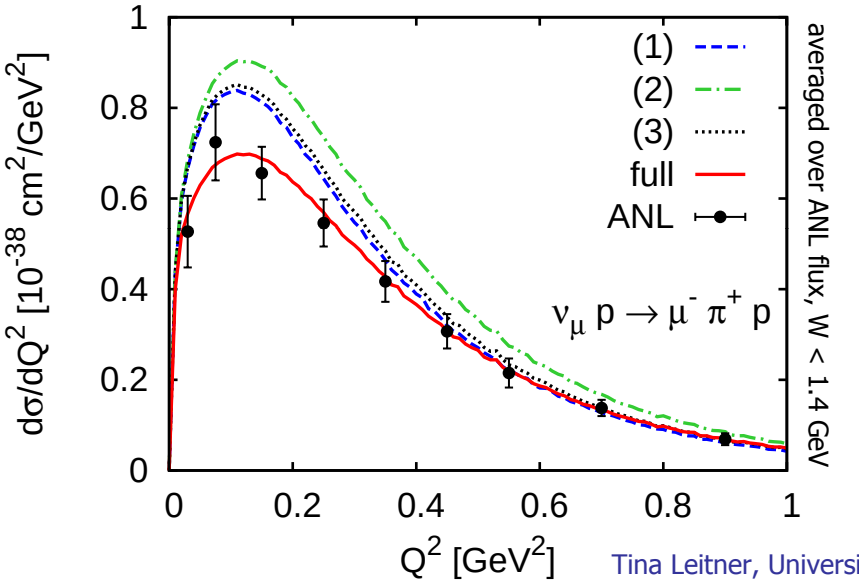
Delta excitation

- hadronic current:

$$J^{\alpha\mu}_{3/2} = \left(\frac{C_3^V}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M_N^2}(g^{\alpha\mu} q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu} q\cdot p - q^\alpha p^\mu) \right)\gamma_5$$
$$+ \frac{C_3^A}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M_N^2}(g^{\alpha\mu} q\cdot p' - q^\alpha p'^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^\alpha q^\mu$$

- **vector form factor**
  - vector form factors ⇔ EM form factors ⇔ **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 factor**
  - modified dipole
  - new vector form factors require refit of C_5^A (axial coupling is kept constant $C_5^A(0) = 1.17$)
  - (1), (2), (3) different Q^2 dependence of C_5^A

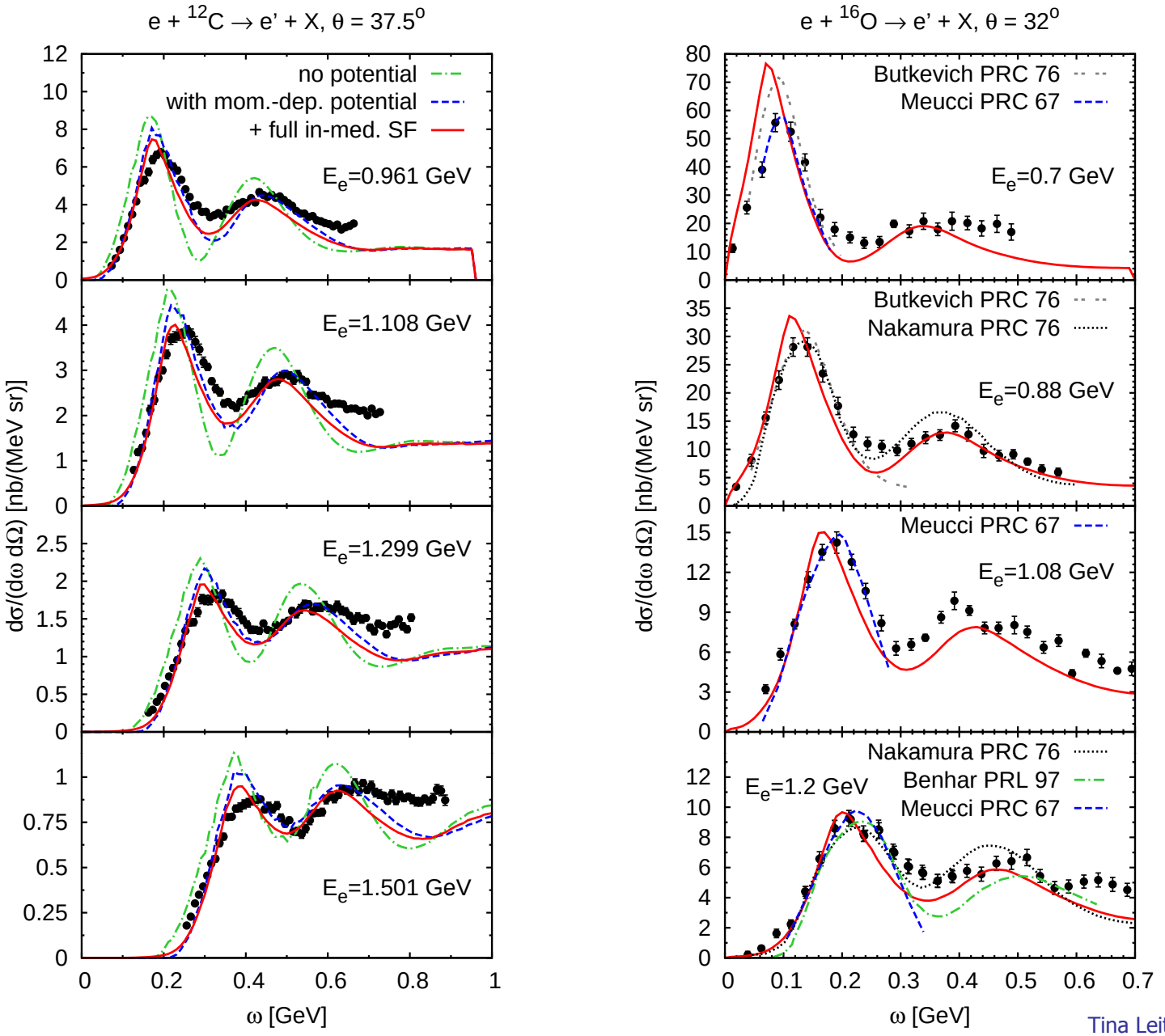


Medium modifications

$$\mathrm{d}\sigma_{\mathrm{tot}}^{\ell A\to\ell'\pi} = \int\limits_{\mathrm{nucleus}} \mathrm{d}^3 r \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \boxed{\Theta(p_F(r)-p)} \frac{k\cdot p}{k^0 p^0} \boxed{\mathrm{d}\sigma_{\mathrm{tot}}^{\mathrm{med}}} \boxed{P_{\mathrm{PB}}(\mathbf{r},\mathbf{p})} M_\pi$$

- **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:** $d\sigma \sim \mathcal{A}(E,\mathbf{p})\,|\bar{\mathcal{M}}|^2$
  - **in-medium self energies / spectral function**
    - density + momentum dependent mean-field potential
    - collisional broadening in low-density approximation: $\Gamma_{coll} \sim \rho\sigma v$
    - Oset /Salcedo prescription for the Δ (including 3-body contributions) NPA468 (1987)
  - **full in-medium kinematics**
  - but: vacuum form factors

ISI model validation: electron scattering – A(e,e')

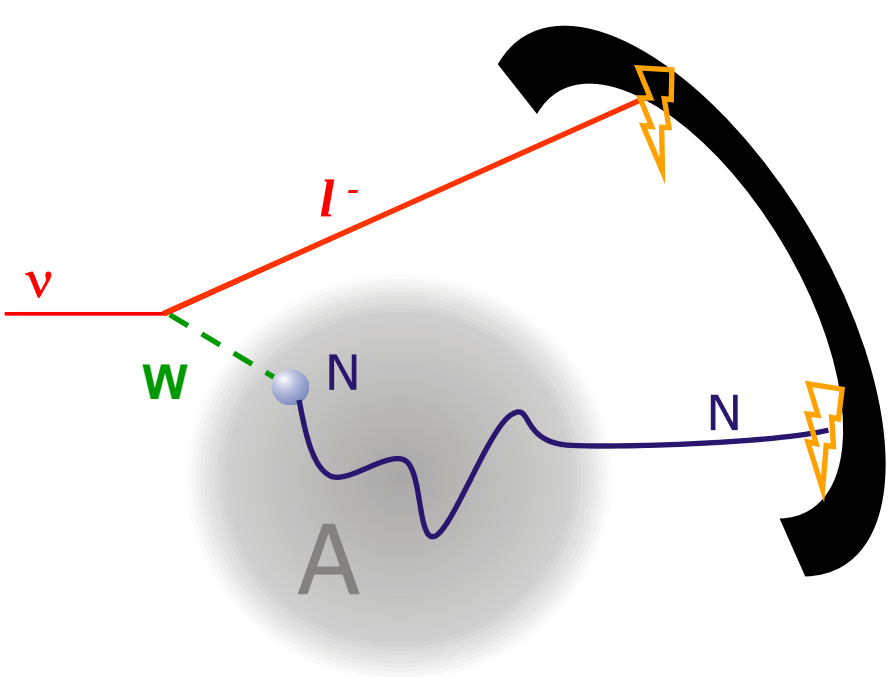


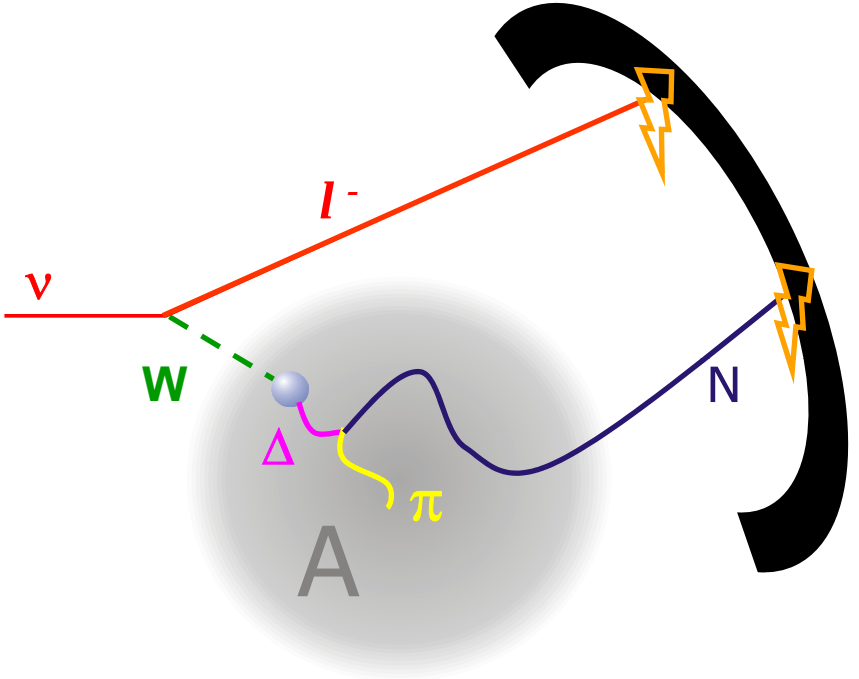
Modelling final state interactions

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

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

- example: **CCQE** is experimentally not observable – masked by FSI
  - experiment measures CCQE-like, defined e.g. as charged lepton but NO pion





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coupled channels: QE ⇔ pion

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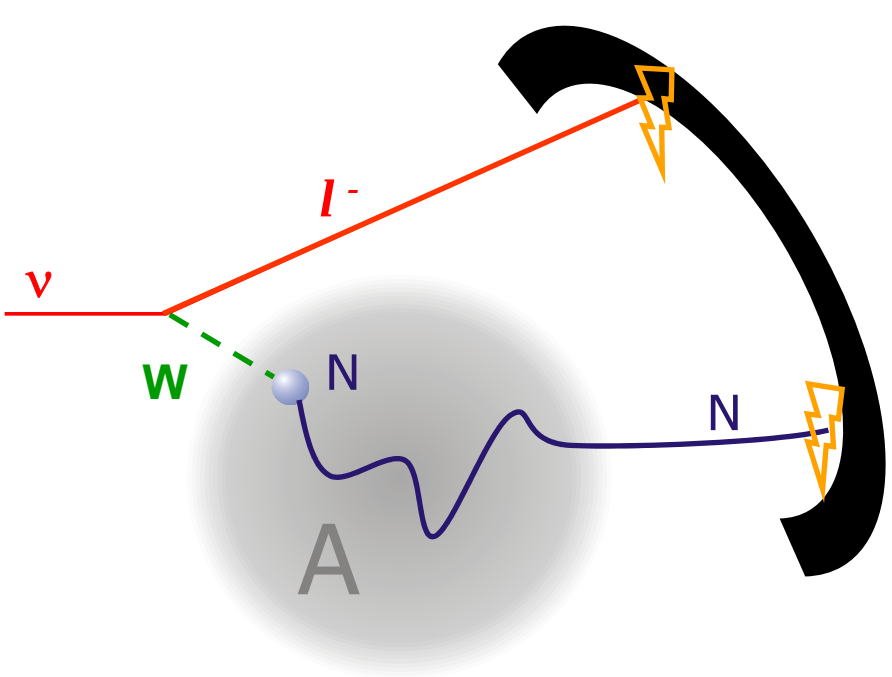
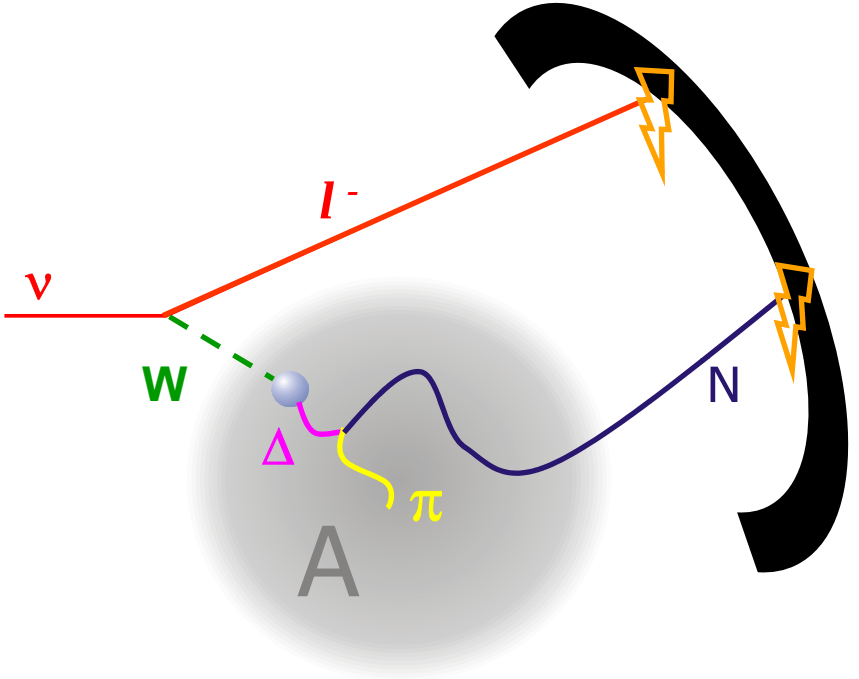
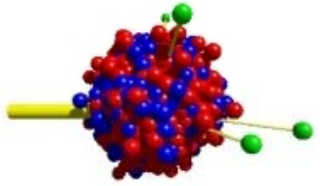




GiBUU model outline

- 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

GiBUU transport model – BUU equation

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

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

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

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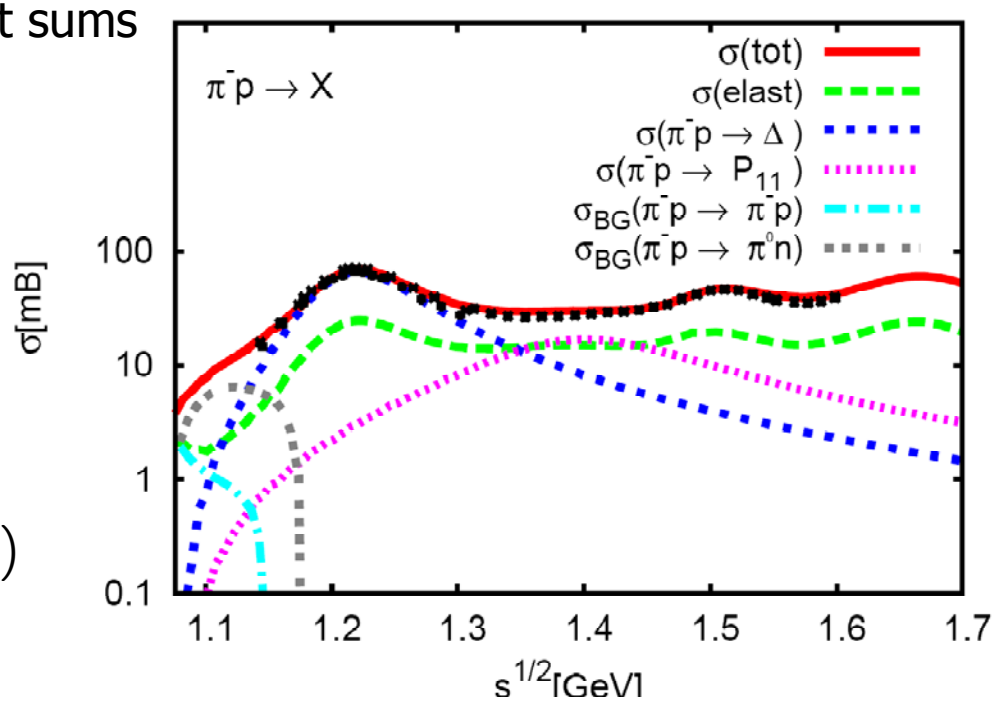
  - elastic and inelastic 2-body scattering
  - decay of unstable particles
  - 3-body reactions through detailed balance
  - Pauli blocking for fermions

GiBUU collision term - cross sections

- **cross sections:** elastic and inelastic scattering
  e.g. $N\,N \to N\,N$, $N\,N \leftrightarrow N\,R$, $N\,\pi \leftrightarrow R$, $\pi\,N \to \pi\,N$, ...

- **resonance model:**
  - cross section based on resonance excitations
  - total cross section as incoherent sums
  - fit to vacuum data by background contributions
  - example: **pion nucleon scattering**

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



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  - density and momentum dependent hadronic mean-field potential
  - Coulomb potential
  - off-shell transport: back to vacuum spectral function when propagating out

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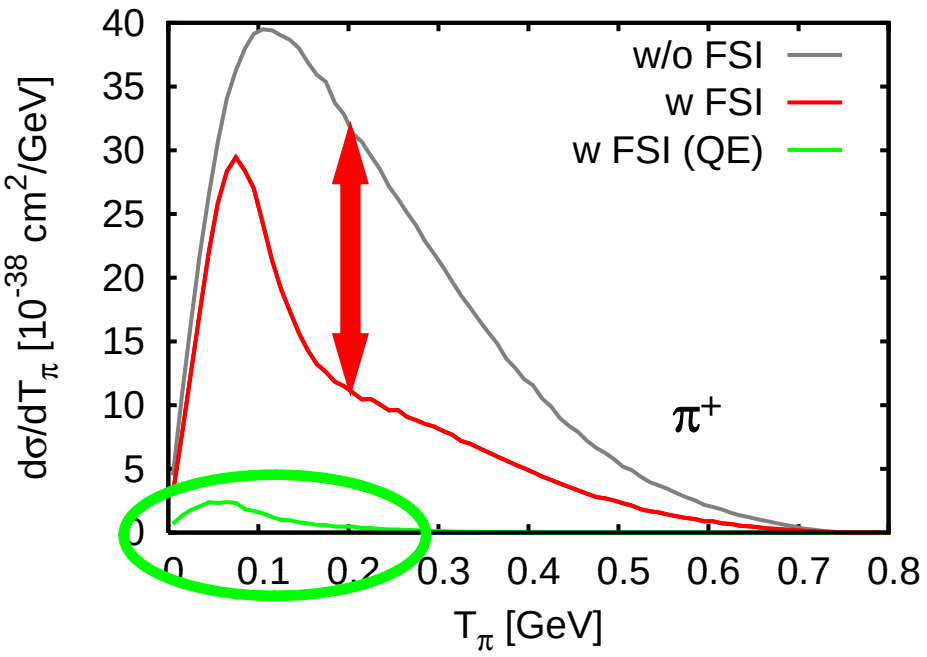
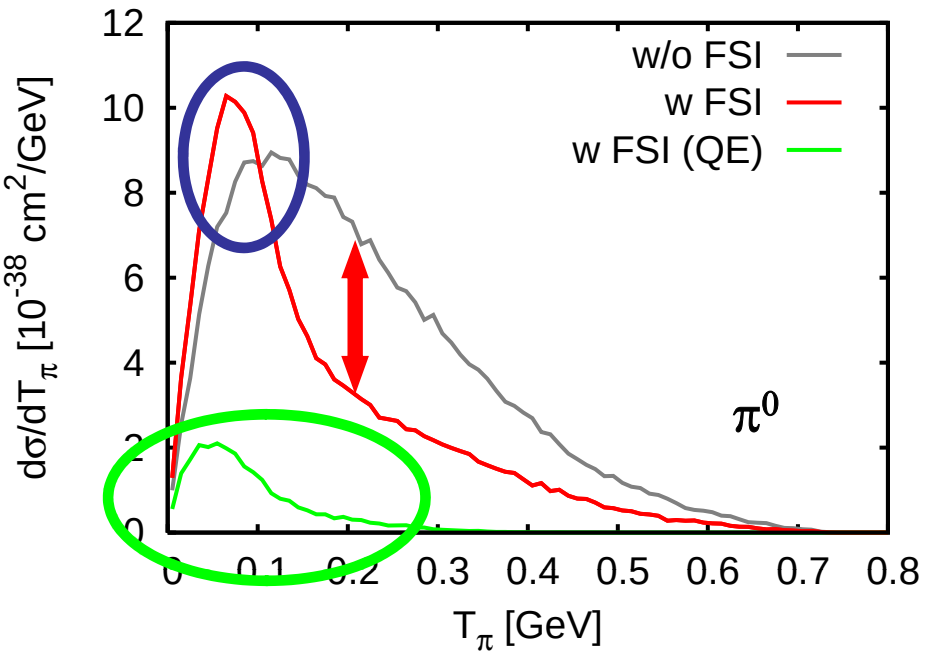
FSI

- **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

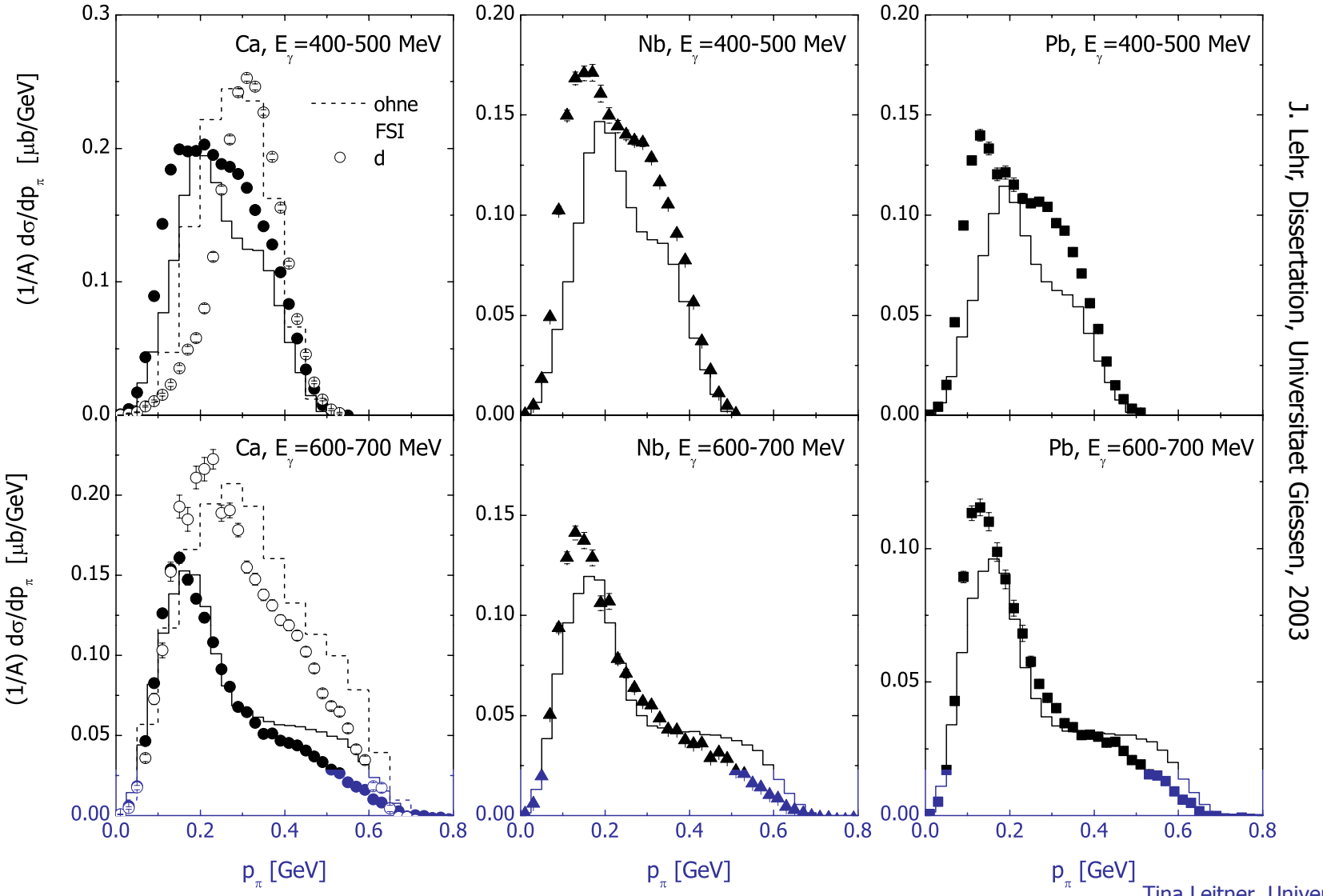




T.L. et al., PRC 73, 065502 (2006)

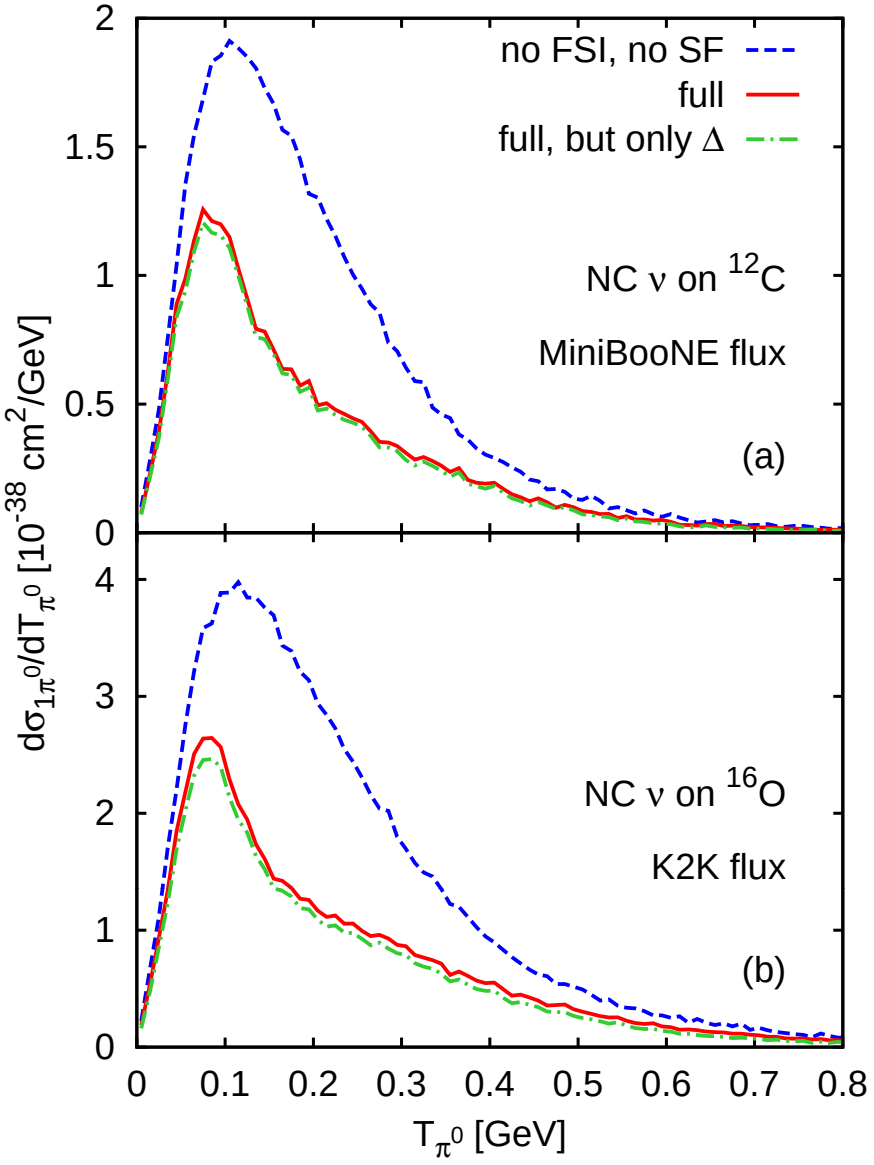
FSI model validation: Photon-induced pion production

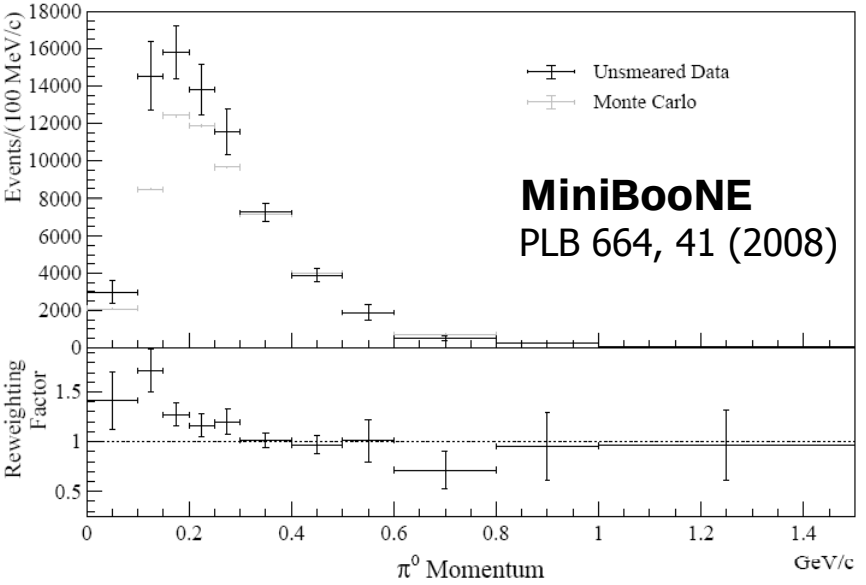
Photoproduction data: $\gamma + A \rightarrow \pi^0 + A^*$, TAPS Eur. Phys. J A22 (2004)

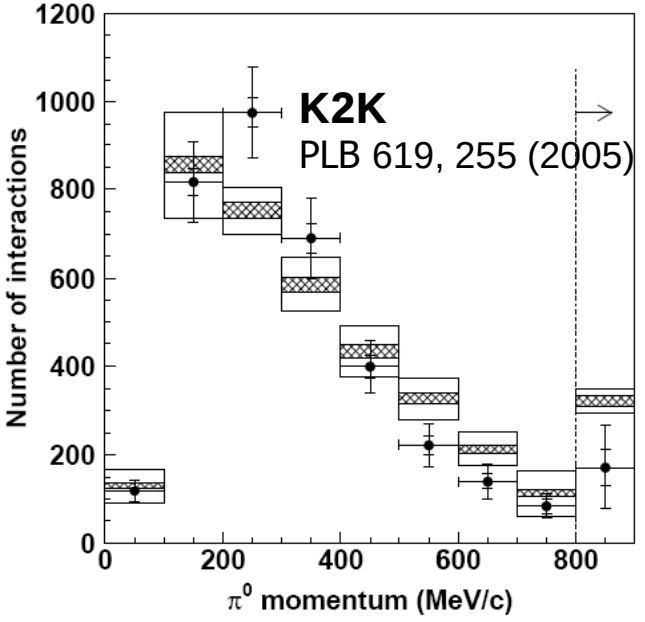


J. Lehr, Dissertation, Universitaet Giessen, 2003

Application: K2K and MiniBooNE NC1π^0







T.L. et al., PRC 79, 038501 (2009)

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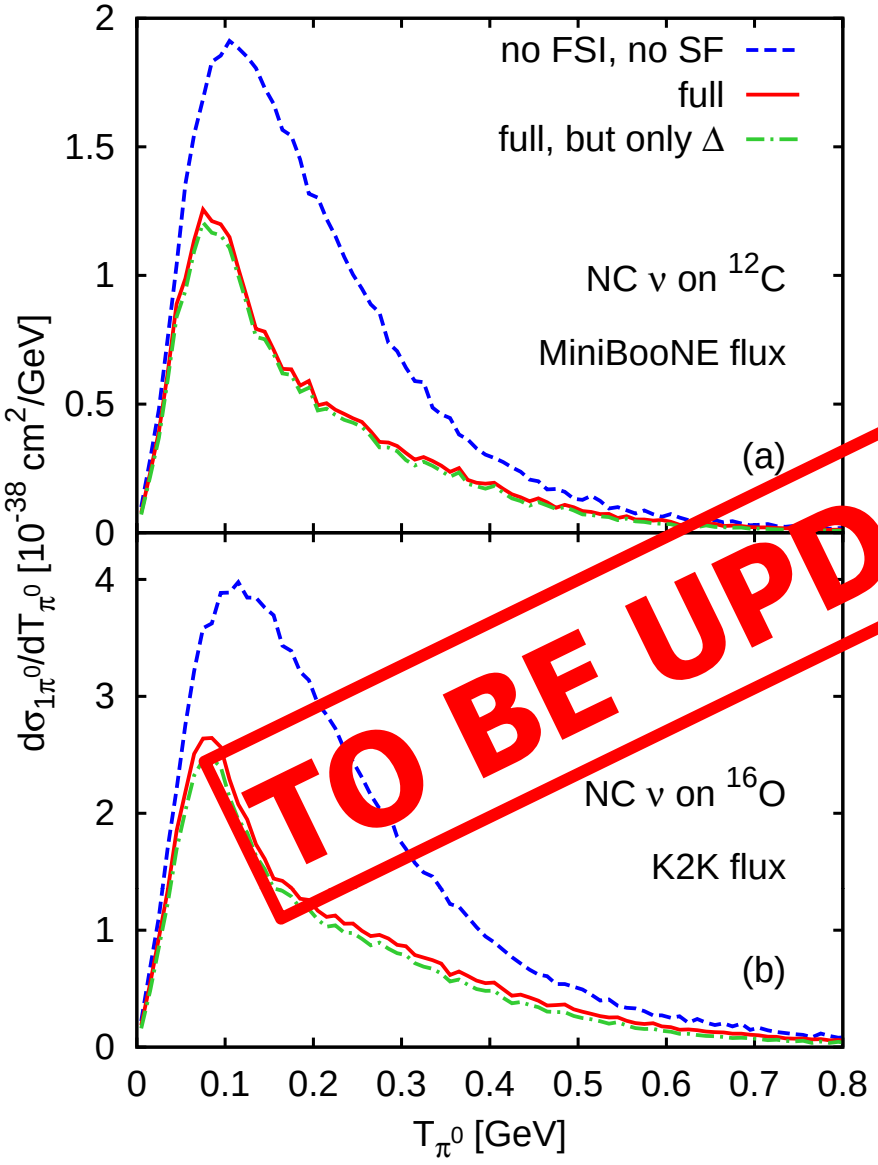

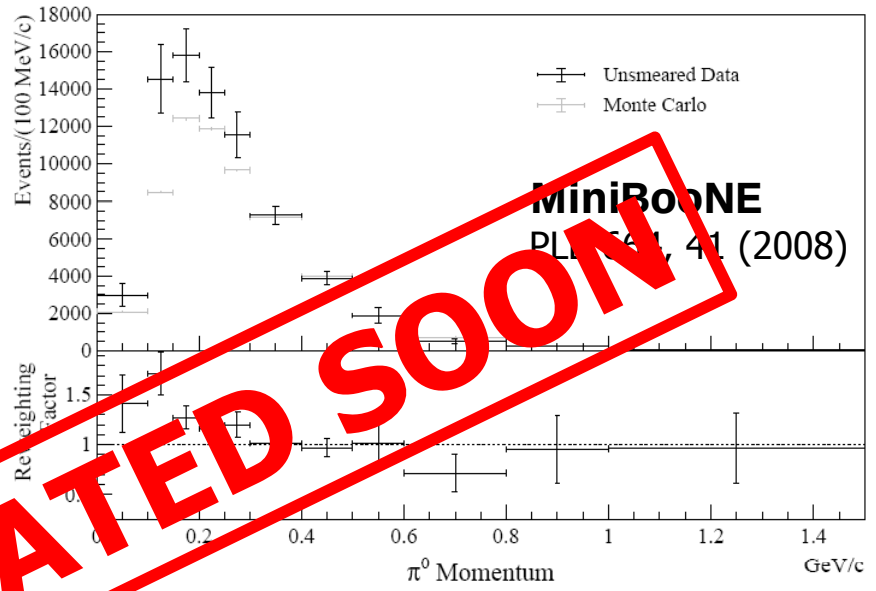

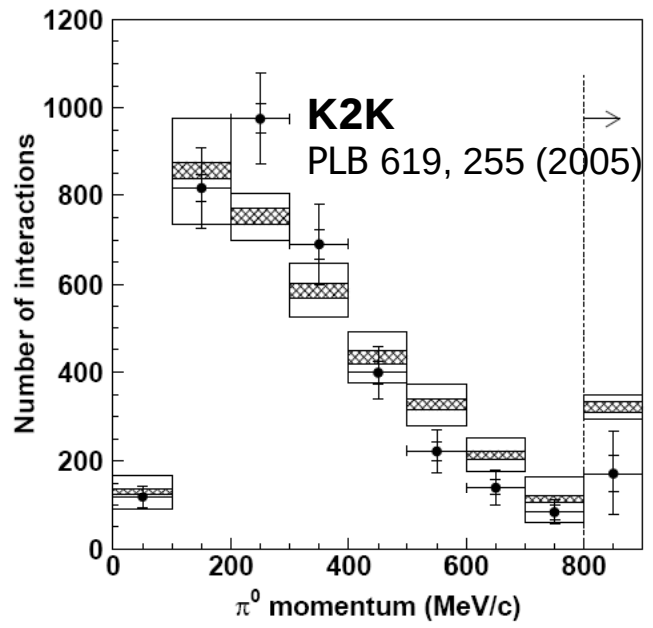

TO BE UPDATED SOON

T.L. et al., PRC 79, 038501 (2009)

Application: K2K and MiniBooNE CC1π^+/QE

- 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:**
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3. $\sigma_{1\pi^+}$ / σ_{QE} **after FSI**

4. $\sigma_{1\pi^+}$ / σ_{QE} **before FSI**
   including nuclear corrections
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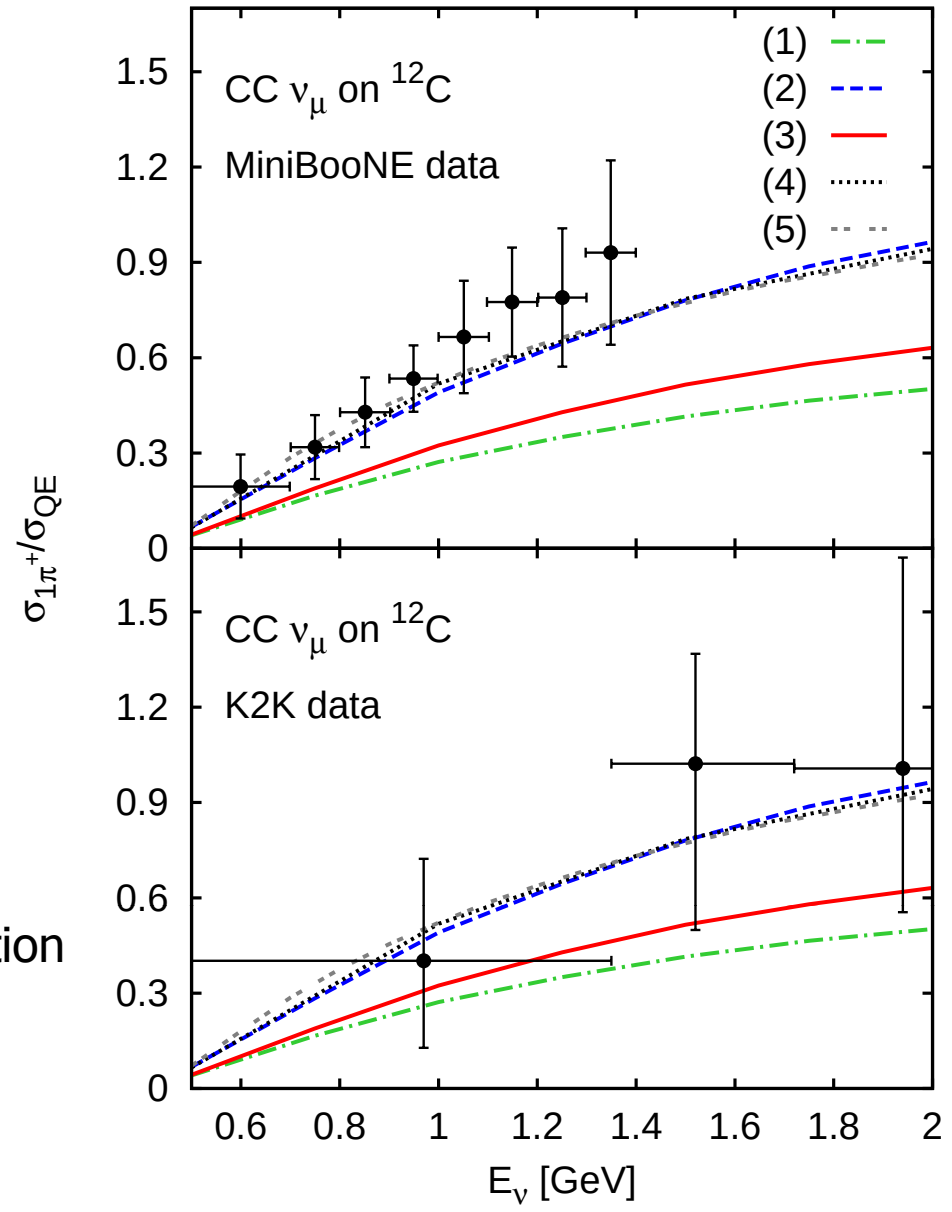
5. $\sigma_{1\pi^+}$ / σ_{QE} **in the vacuum**
   on an isoscalar target.



T.L. et al., PRC 79, 038501 (2009)

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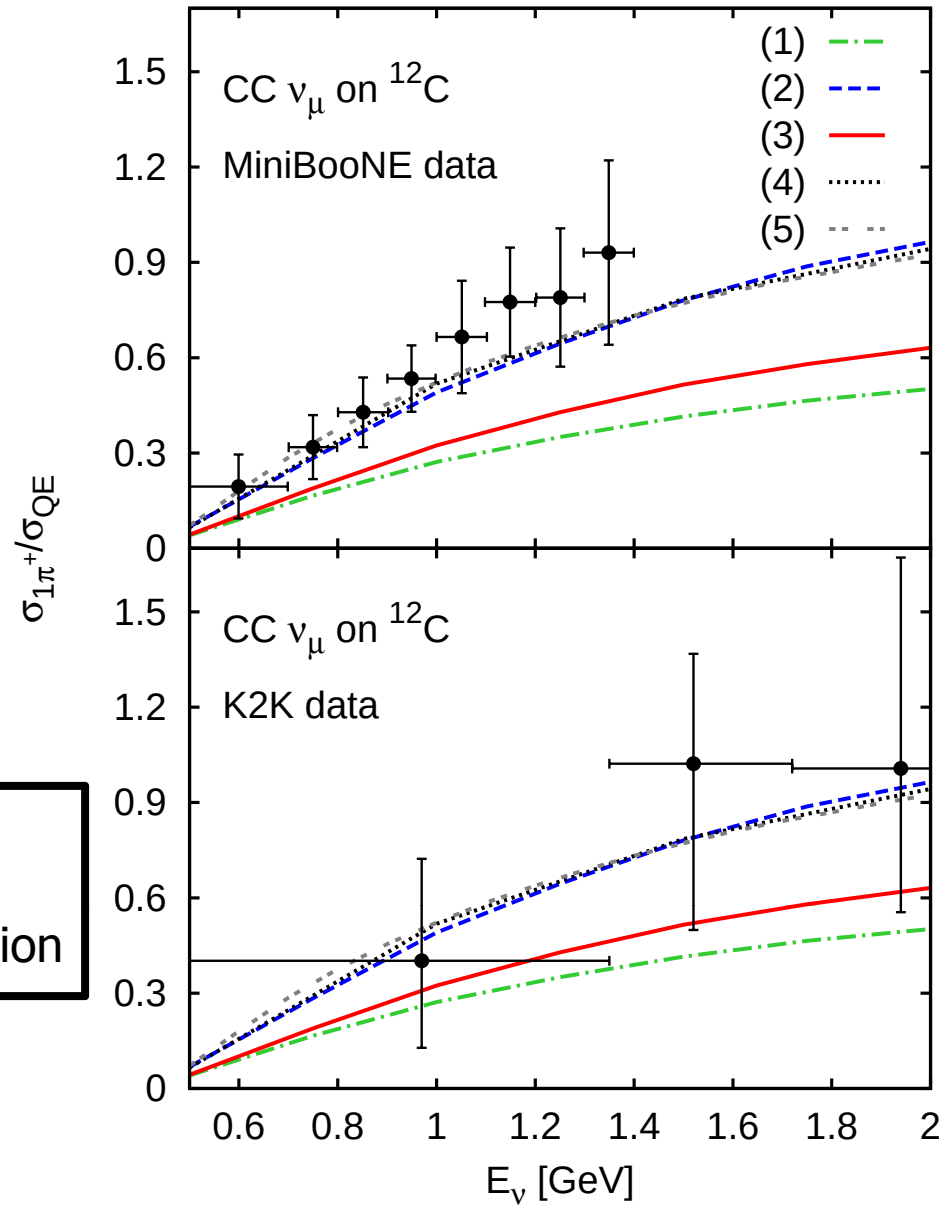
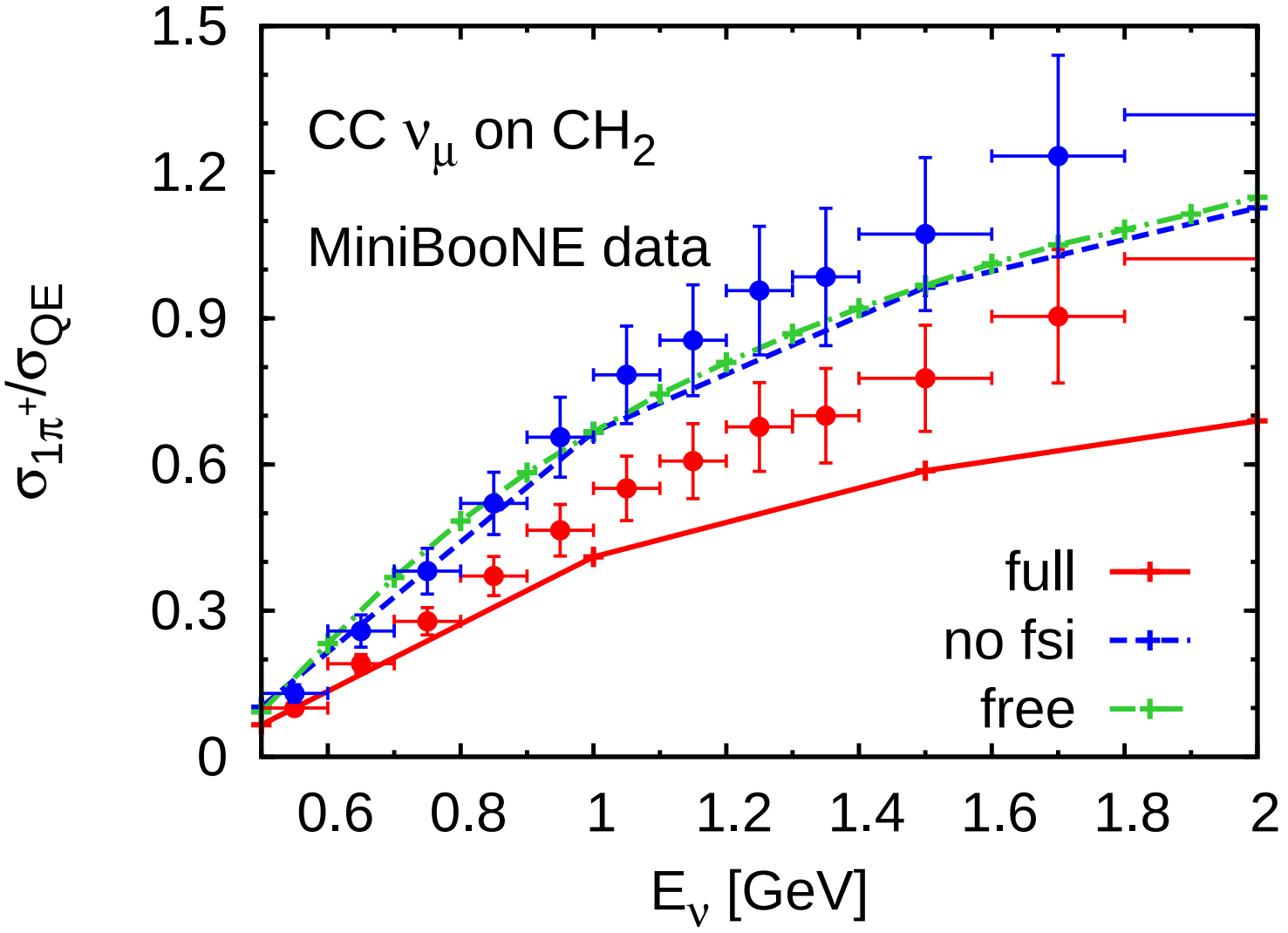


T.L. et al., PRC 79, 038501 (2009)

Application: MiniBooNE CC1π^+/QE NEW!!

- single-π^+-like/QE-like ratio in mineral oil uncorrected for FSI

arXiv:0904.3159



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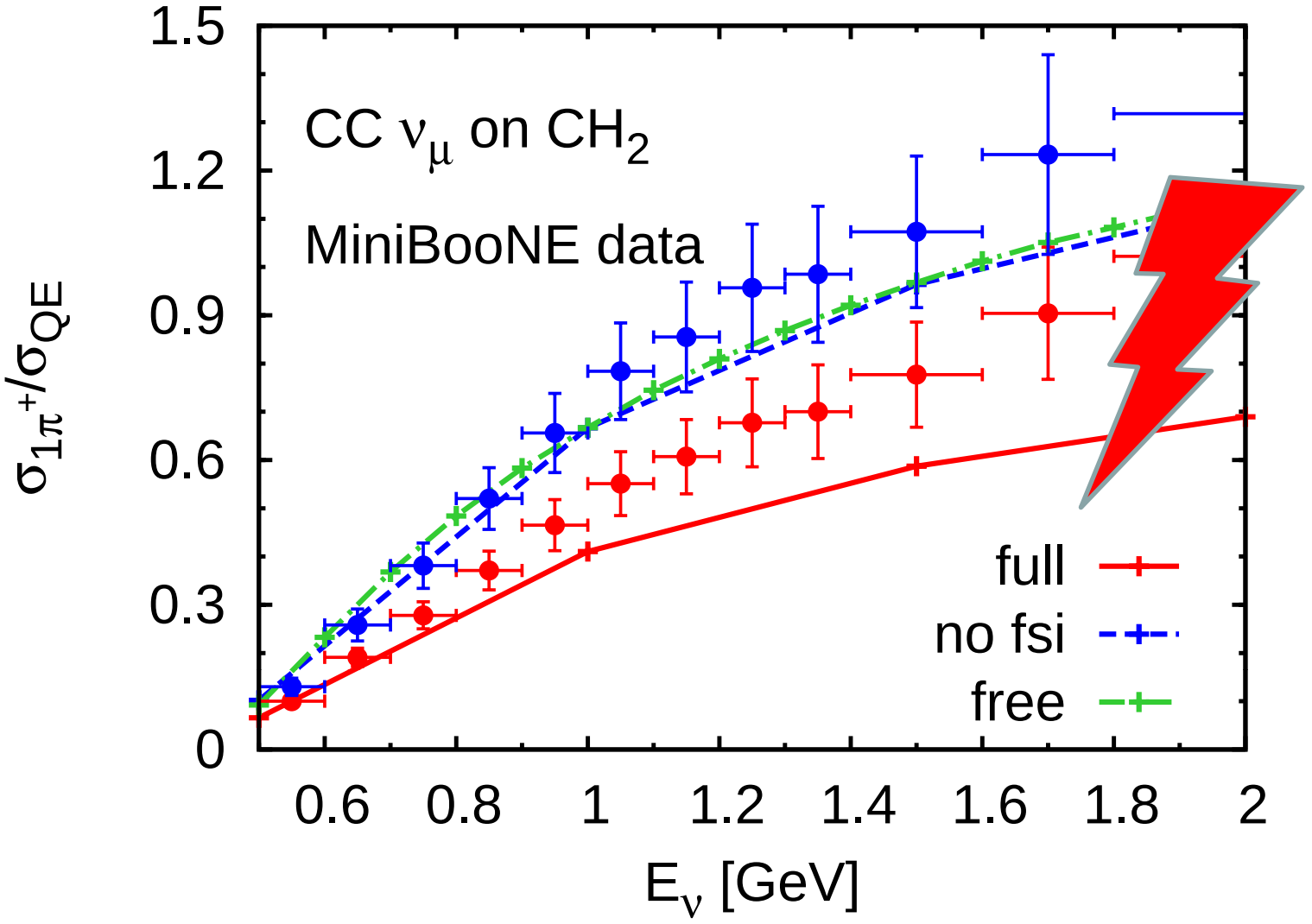

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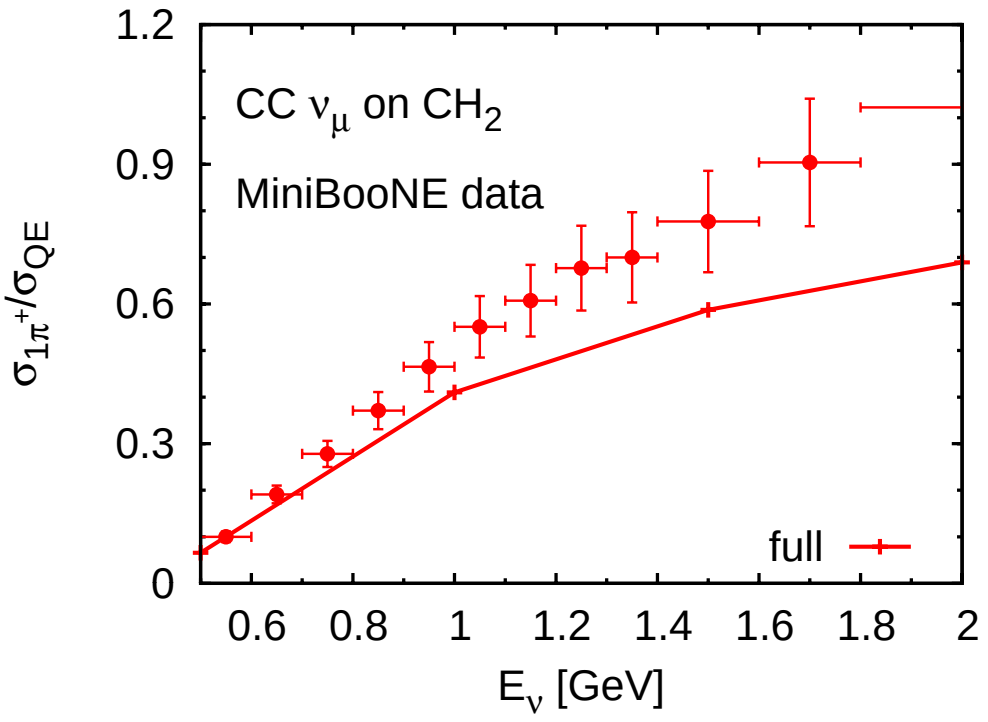

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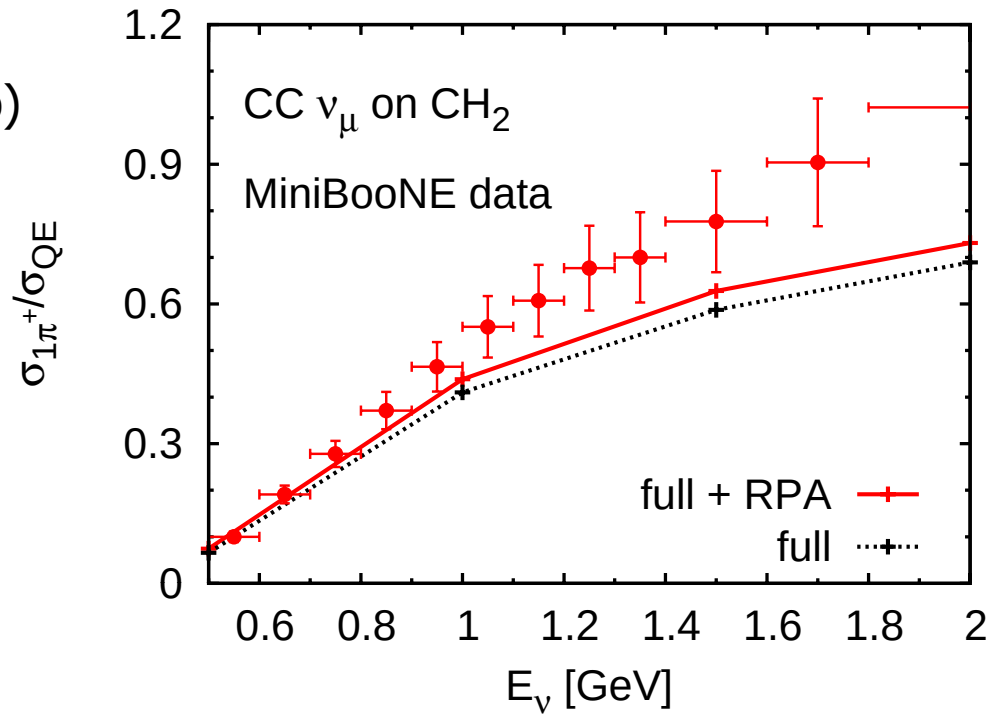

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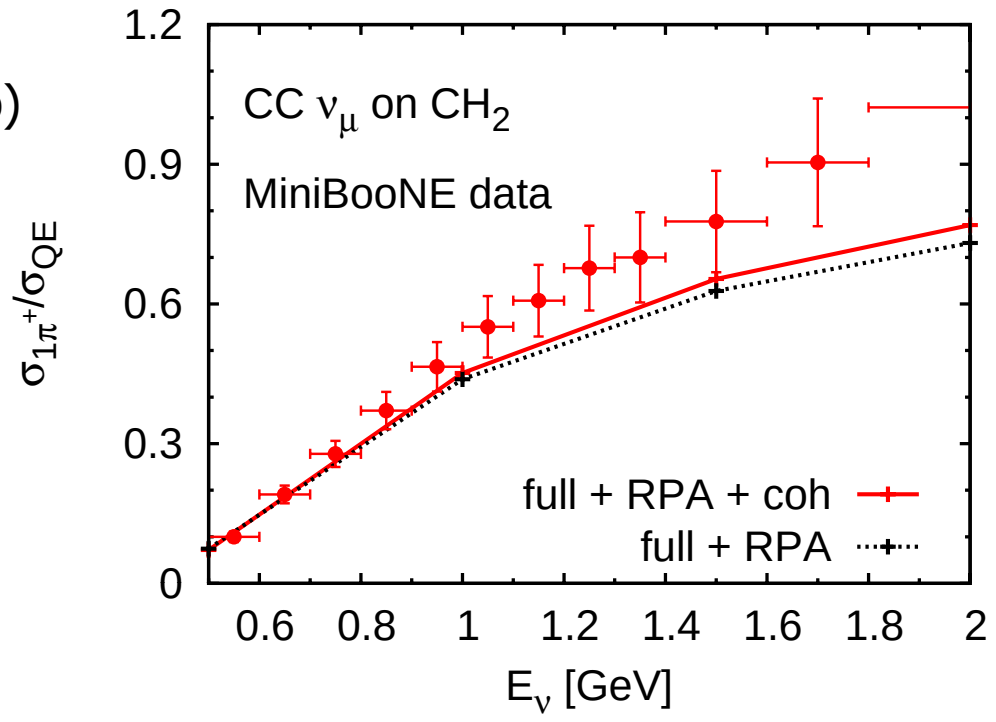

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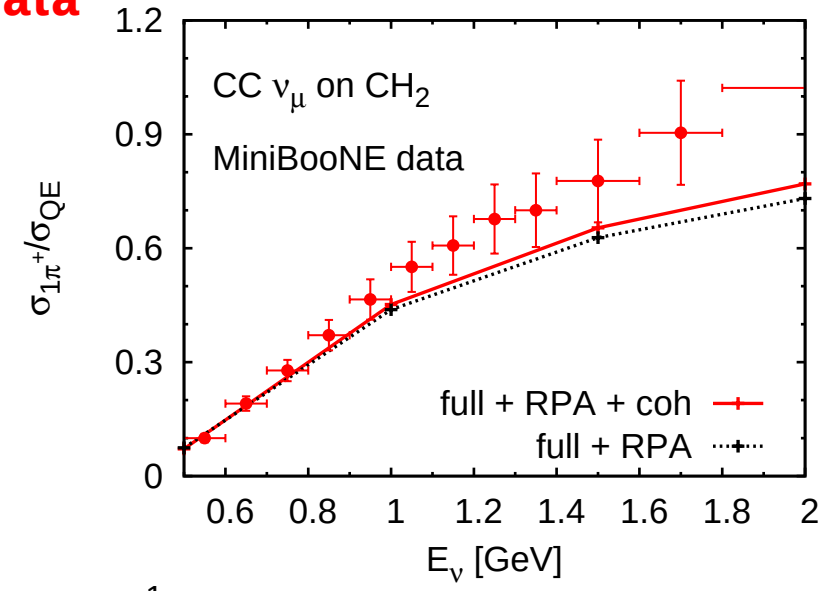

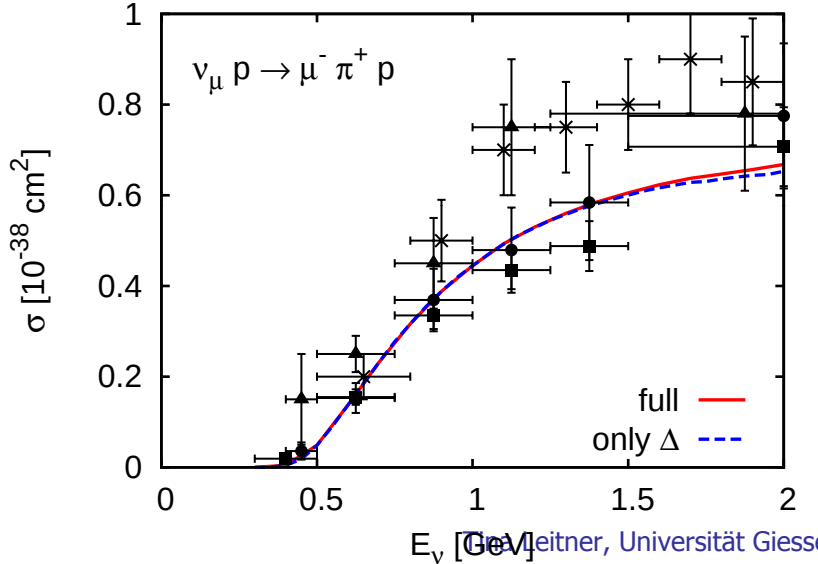

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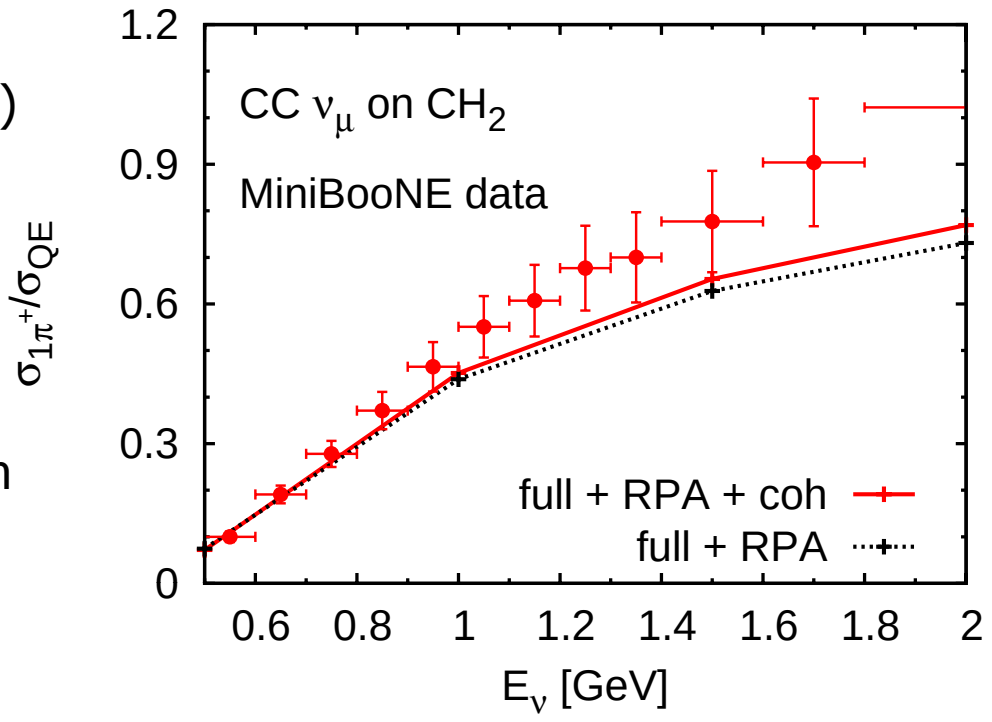
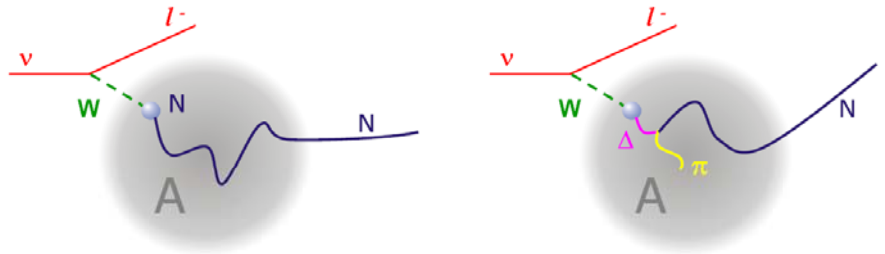
  - **energy reconstruction?**

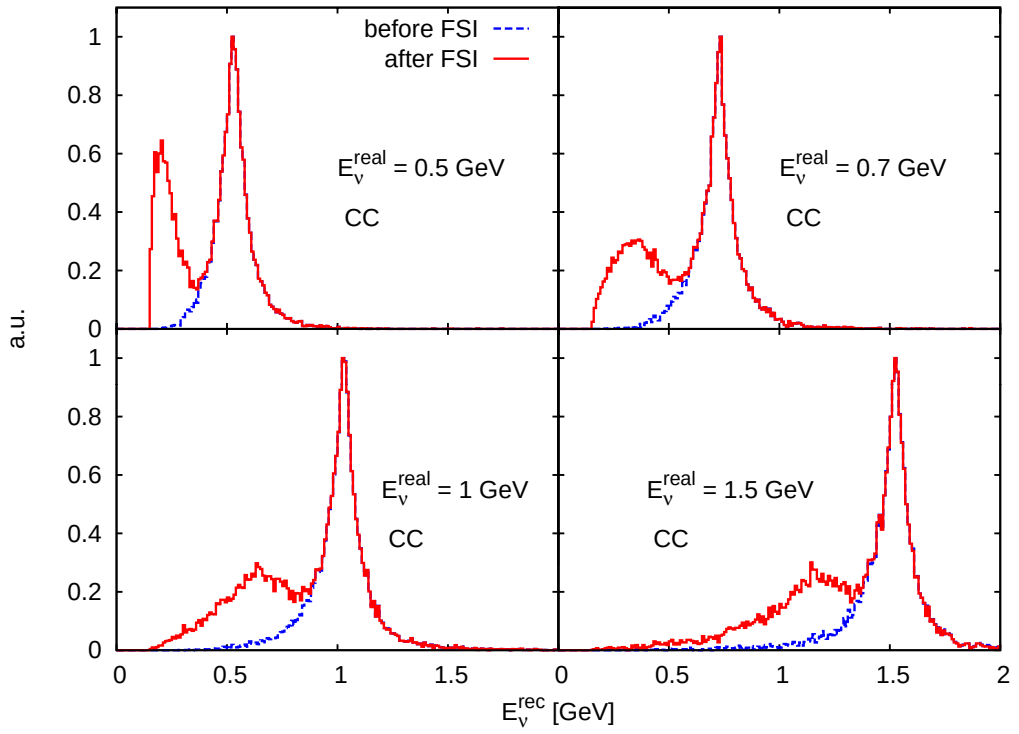


Energy reconstruction via CCQE



CCQE = no pion in final state

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



FWHM ~ 0.1 GeV

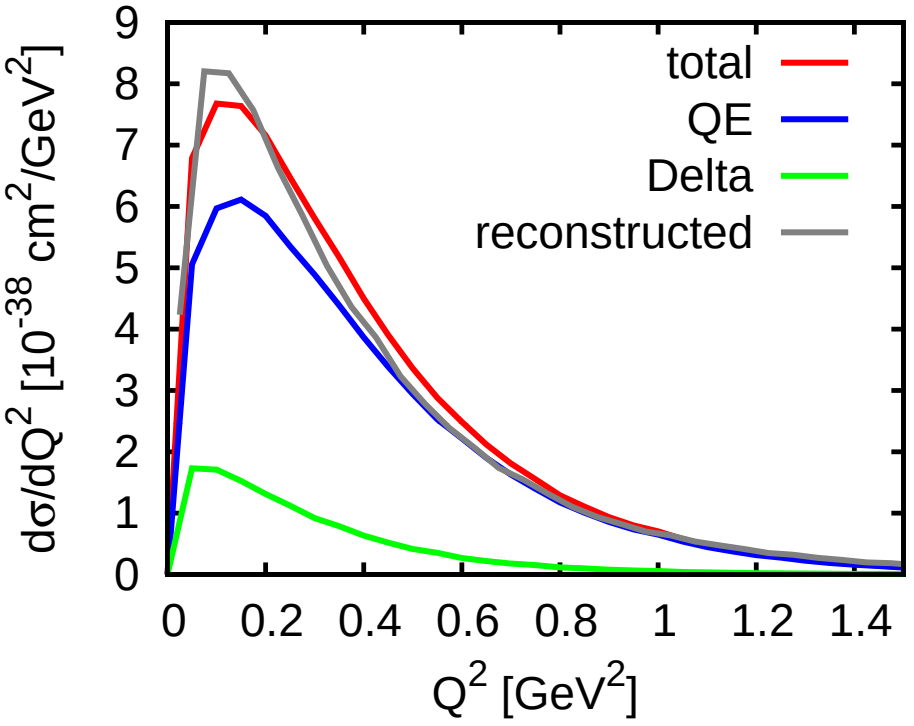
MiniBooNE Q^2 reconstruction

- CC ν_μ on ^{12}C averaged over MiniBooNE flux
  - reconstruction via

$$E_\nu = \frac{2(M_N - E_B)E_\mu - (E_B^2 - 2M_N E_B + m_\mu^2)}{2((M_N - E_B) - E_\mu + p_\mu \cos\theta_\mu)}$$

$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - p_\mu \cos\theta_\mu)$$

  - Fermi gas model of MiniBooNE: E_B = 34 MeV
  - reconstruction changes shape of distribution



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_ν < 1.5 GeV
  - in-medium modifications: local Fermi gas, self energies, …
    - ➔ good description of electroproduction data

K2K, MiniBooNE, SciBooNE, T2K

- 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, …
- work in progress: extension to neutrino energies of up to **~100 GeV**
  - cross section dominated by DIS

Minerva, MINOS, OPERA

- **good understanding of in-medium modifications and FSI necessary to distinguish profane from extraordinary effects**

… NEXT STEP: compare results to data present here