Neutrino induced pion production at MiniBooNE and K2K

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Link between nuclear effects & $\nu$ oscillations

- particle identification $\rightarrow$ neutrino flavor
  - main background for $\nu_e$ appearance: NC $1\pi^0$

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

$\rightarrow$ influence of in-medium modifications and final state interactions
Modelling in-medium reactions

\[ \nu \rightarrow W \Delta \pi \pi \]
Modelling in-medium reactions

- **Initial state interaction (ISI)**
  - impulse approximation
  - Fermi motion, Pauli blocking
  - self energies: collisional broadening and mean-field potentials
  - medium-modified $\nu$ N cross sections
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**Final state interactions (FSI)**
- propagation, mean-field potentials
- absorption
- particle production, rescattering, ...
Modelling in-medium reactions

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  - impulse approximation
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  - self energies
  - medium-modified $\nu$ N cross sections

- **Final state interactions (FSI)**
  - propagation, mean-field potentials
  - absorption
  - particle production, rescattering, ...

**Consistency:**

Self energies in the initial state process (e.g., $\Delta$ spectral function) should match FSI rates (e.g., $\Delta N \rightarrow NN$ cross sections)

$\Rightarrow$ ISI and FSI can only be separated within the same model

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Neutrino nucleon cross section

- primary interaction of neutrino with one nucleon at a time

**QE**
\[ \nu_l \rightarrow l^-\]
\[ n \rightarrow p \]

**RES**
\[ \nu_l \rightarrow l^-\]
\[ n \rightarrow R^+ \]

**single-\( \pi \) BG**
\[ \nu_l \rightarrow l^-\]
\[ N \rightarrow N' \]

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

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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:**

\[ \nu_\mu p \rightarrow \mu^- \pi^+ p \]

\[ \nu_\mu n \rightarrow \mu^- \pi^0 p \]

\[ \nu_\mu n \rightarrow \mu^- \pi^+ n \]

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Delta excitation

- **hadronic current**:

\[
J_{3/2}^{\alpha\mu} = \left( \frac{C_3^V}{M_N} (g^{\alpha\mu} q - q^\alpha \gamma^\mu) + \frac{C_4^V}{M_N^2} (g^{\alpha\mu} q \cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2} (g_{\alpha\mu} q \cdot p - q^\alpha p^\mu) \right) \gamma_5 \\
+ \frac{C_3^A}{M_N} (g^{\alpha\mu} q - q^\alpha \gamma^\mu) + \frac{C_4^A}{M_N^2} (g^{\alpha\mu} q \cdot p - q^\alpha p^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^\alpha q^\mu
\]

- **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), ...

- **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 \( C_5^A \)

![Graph showing the differential cross section \( \sigma dQ^2 \) against \( Q^2 \)](image)

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Medium modifications

\[
d\sigma_{\text{tot}}^{\ell A \rightarrow \ell' \pi} = \int_{\text{nucleus}} d^3r \int \frac{d^3p}{(2\pi)^3} \Theta(p_F(r) - p) \frac{k \cdot p}{k^0 p^0} d\sigma_{\text{med}}^{\text{tot}} P_{\text{PB}}(r, p) M_\pi
\]

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

- **in-medium \( \nu N \) cross sections:** \( d\sigma \sim A(E, p) |\tilde{M}|^2 \)
  - in-medium self energies / spectral function
    - density + momentum dependent mean-field potential
    - collisional broadening in low-density approximation: \( \Gamma_{\text{coll}} \sim \rho \sigma \nu \)
    - Oset / Salcedo prescription for the \( \Delta \)
      (including 3-body contributions) \( \text{NPA468 (1987)} \)

- full in-medium kinematics
- but: vacuum form factors
ISI model validation: electron scattering – $A(e,e')$

$e + ^{12}\text{C} \rightarrow e' + X, \theta = 37.5^\circ$

- $E_e = 0.961 \text{ GeV}$
- $E_e = 1.108 \text{ GeV}$
- $E_e = 1.299 \text{ GeV}$
- $E_e = 1.501 \text{ GeV}$

$e + ^{16}\text{O} \rightarrow e' + X, \theta = 32^\circ$

- $E_e = 0.7 \text{ GeV}$
- $E_e = 0.88 \text{ GeV}$
- $E_e = 1.08 \text{ GeV}$
- $E_e = 1.299 \text{ GeV}$
- $E_e = 1.501 \text{ GeV}$

Butkevich PRC 76
Meucci PRC 67
Nakamura PRC 76
Benhar PRL 97
Meucci PRC 67

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

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:

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

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**fully-coupled channel problem**

- Hamiltonian $H_i = H_i(f_i, f_{a_i}, f_{b_i}, \ldots)$ connects particle species
- coupled through the collision integral: 61 baryons and 21 mesons
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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
- **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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**GiBUU collision term - cross sections**

- **cross sections**: elastic and inelastic scattering
  
  e.g. \( N N \rightarrow N N, \ N N \leftrightarrow N R, \ N \pi \leftrightarrow R, \ \pi N \rightarrow \pi N, \ldots \)

-resonance model: \( \sqrt{s} \approx 2.4 \text{ GeV} \)

-string model (Pythia): \( \sqrt{s} \)

- **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**

\[
\sigma(\pi N \rightarrow \pi N) = \\
\sigma(\pi N \rightarrow R \rightarrow \pi N) + \sigma_{BG}(\pi N \rightarrow \pi N)
\]
GiBUU transport model – BUU equation

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**fully-coupled channel problem**
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**Hamiltonian**
- 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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GiBUU transport model – BUU equation

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\]

- **fully-coupled channel problem**
  - Hamiltonian \( H_i = H_i(f_i, f_a, f_b, \cdots) \)
  - coupled through **collision integral**:
  - 61 baryons and 21 mesons
  - elastic and inelastic 2-body scattering
  - decay of unstable particles
  - 3-body reactions through detailed balance
  - Pauli blocking for fermions

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

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

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

Tina Leitner, Universität Giessen
T.L. et al., PRC 73, 065502 (2006)
FSI model validation: Photon-induced pion production

Photoproduction data: $\gamma + A \rightarrow \pi^0 + A^*$, TAPS


J. Lehr, Dissertation, Universität Giessen, 2003

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Application: K2K and MiniBooNE NC1\(\pi^0\)

(a) NC \(\nu\) on \(^{12}\)C

MiniBooNE flux

(b) NC \(\nu\) on \(^{16}\)O

K2K flux

\[
d\sigma_{\pi^0}/dT_{\pi^0} \times 10^{-38} \text{ cm}^2/\text{GeV}
\]

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

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Application: K2K and MiniBooNE NC1π^0

no FSI, no SF
full
full, but only Δ

NC ν on ^12C
MiniBooNE flux

NC ν on ^16O
K2K flux

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

TO BE UPDATED SOON

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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. $\sigma_{1\pi^+} / \sigma_{0\pi^+ lp}$ 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.

T.L. et al., PRC 79, 038501 (2009)
Application: K2K and MiniBooNE CC1$\pi^+$/QE

- single-$\pi^+$/QE ratio

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

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

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T.L. et al., PRC 79, 038501 (2009)
Application: MiniBooNE CC1$\pi^+/\text{QE}$  NEW!!

single-$\pi^+$-like/\text{QE-like ratio in mineral oil uncorrected for FSI}

$\sigma_{1\pi^+}/\sigma_{\text{QE}}$

CC $\nu_\mu$ on CH$_2$

MiniBooNE data

$E_\nu$ [GeV]

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Application: MiniBooNE CC1\(\pi^+/QE\) NEW!!

- single-\(\pi^+\)-like/QE-like ratio in mineral oil uncorrected for FSI

CC \(\nu_\mu\) on CH\(_2\)

MiniBooNE data

\[\frac{\sigma_{1\pi^+}}{\sigma_{QE}}\]

\(E_\nu\) [GeV]

Full

No FSI

Free

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arXiv:0904.3159
Application: MiniBooNE CC1\(\pi^+/QE\) NEW!!

- single-\(\pi^+\)-like/QE-like ratio in mineral oil uncorrected for FSI
- **GiBUU underestimates uncorrected data**

- possible origins:

![Graph showing CC \(\nu_\mu\) on CH\(_2\) with MiniBooNE data compared to GiBUU predictions.](image-url)

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Application: MiniBooNE CC1π+/QE NEW!!

- single-π⁺-like/QE-like ratio in mineral oil uncorrected for FSI
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possible origins:

- QE too large?
  - including RPA correlations (cf. talk by L. Alvarez-Ruso)
Application: MiniBooNE CC1$\pi^+/Q$E NEW!!

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- **1$\pi^+$ too small?**
  - coherent pion production estimate based on SciBooNE upper limit

![Graph showing CC $\nu_\mu$ on CH$_2$](image)

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    - elementary $\nu N$ cross section too small; uncertainties in axial form factors

\[\text{CC} \, \nu_{\mu} \text{ on CH}_2\]

\[\nu_{\mu} p \rightarrow \mu^- \pi^+ p\]
Application: MiniBooNE CC1\(\pi^+\)/QE

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- energy reconstruction?
Energy reconstruction via CCQE

CCQE = no pion in final state

reconstruction via

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

\[ E_B = 34 \text{ MeV} \]

FWHM \sim 0.1 \text{ GeV}

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MiniBooNE $Q^2$ reconstruction

- CC $\nu_\mu$ 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 $E_\nu < 1.5$ 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, ...

- work in progress: extension to neutrino energies of up to $\sim 100$ GeV
  - cross section dominated by DIS

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

... NEXT STEP: compare results to data present here