(A short) theoretical summary

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INT Workshop, Seattle
Goals:

- not a politically correct resumé with one slide from every talk
- focus on topics that were most intensively discussed
- focus on topics important for users: hints for future MC developments
- hopefully, an introduction to even more discussions!
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- hopefully, an introduction to even more discussions!
I. Treatment of nucleon-nucleon correlations

Ia. Several talks gathered experience from electron scattering experiments:

\textbf{$^{12}\text{C}$ From (e,e$'$), (e,e$'$p), and (e,e$'$pN) Results}

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs (quasi-deuteron)
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
- Less than 1% multi-nucleon correlations
I. Treatment of nucleon-nucleon correlations

Ib. Spectral function approach to describe lepton scattering in impulse approximation was discussed many times:

**Qualitative structure of $S(k, E)$**

**Understanding of structure at high $k$**

large $k$ cannot occur in nuclear mean-field
large $k$ occur in 2N-collisions, scattering N to k outside Fermi sphere
if remove one N with large $k$ then second N is set free
costs energy $E \sim (-k)^2/2M \rightarrow$ large $E$
verified by (e,e’pp) Shneor et al.

Large $k$ only appear at large $E$!!
I. Treatment of nucleon-nucleon correlations

Ic. FG versus SF

For example: The nucleon momentum distribution

\[ P_A(k) = 4\pi \int_0^\infty n_A(k) k^2 \, dk \]

It’s worse than it looks
I. Treatment of nucleon-nucleon correlations

1d. If this were the whole story with correlations, life would be easy:

- SF can be (relatively) easily implemented in MC simulations tools (NuWro, recent work in GENIE and NEUT)
- there are clear ideas how to cook SF for various nuclei
  - correlated contribution is universal, always deuteron-like

Momentum Distributions


At high initial momentums $n_A(p) = N \ast n_D(p)$
I. Treatment of nucleon-nucleon correlations

Ie. Correlations seem to play also a crucial role in two-body current contribution to lepton-nucleus cross section:

<table>
<thead>
<tr>
<th>$q$ (MeV/c)</th>
<th>$^3$He</th>
<th>$^4$He</th>
<th>$^6$Li</th>
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<td>300</td>
<td>0.929</td>
<td>0.893</td>
<td>0.912</td>
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</tr>
<tr>
<td>700</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$q$ (MeV/c)</th>
<th>$\Delta S_L$</th>
<th>$\Delta S_T$</th>
</tr>
</thead>
<tbody>
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<td>300</td>
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<td>600</td>
<td>0.017</td>
<td>0.060</td>
</tr>
<tr>
<td>700</td>
<td>0.024</td>
<td>0.056</td>
</tr>
</tbody>
</table>

J. Carlson
II. Two-body current neutrino computations

II.a A lot of discussion about similariies and differences between existing approaches:

\[ \frac{\partial^2 \sigma}{\partial \Omega \partial k'} = \frac{G_F^2 \cos^2 \theta_c (k')^2}{2 \pi^2} \cos^2 \frac{\theta}{2} \left[ G_E^2 \left( \frac{q^2}{q^2} \right)^2 R_{\tau NN} + G_A^2 \left( \frac{M_\Delta - M_N}{2 q^2} \right) R_{\sigma\tau(L)} + \left( G_M^2 \frac{\tau^2}{q^2} + G_A^2 \right) \left( -\frac{q^2}{q^2} + 2 \tan^2 \frac{\theta}{2} \right) R_{\sigma\tau(T)} \right] \pm 2 G_A G_M \frac{k + k'}{M_N} \tan^2 \frac{\theta}{2} R_{\sigma\tau(T)} \]

**M. Martini, M. Ericson, G. Chanfray, J. Marteau**

Contribution to all terms in $G_M$ and $G_A$

**J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al.**

only to the $G_M^2$ term

**J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al.**

One may add: *transverse enhancement – only all $G_M$ containing terms.*

**J. Carlson:** axial part is enhanced as well!
II. Two-body current neutrino computations

II.b A lot of insight is provided by more rigorous computations

\[ \nu \text{-Deuteron Scattering up to GeV Energy} \]

\[ \text{Shen et al. (2012)} \]

J. Carlson

Good news, because much of what is known about \( M_A \) comes from old deuteron experiments.

Would be nice to see also an impact on \( Q^2 \) distribution.
II. Two-body current neutrino computations

II.c A lot of insight is provided by more rigorous computations

Vocabulary:

\[
\begin{align*}
R_{CC} &= W^{00} \\
R_{CL} &= -\frac{1}{2} (W^{03} + W^{30}) \\
R_{LL} &= W^{33} \\
R_T &= W^{11} + W^{22} \\
R_{T'} &= -\frac{i}{2} (W^{12} - W^{21})
\end{align*}
\]

J. Amaro

On the left enhancement due to two-body current is shown.
II. Two-body current neutrino computations

II.d There is some worry that existing microscopic computations depart from (local) Fermi gas ground state:

- however, computations include contribution from correlation diagrams
  Nucleon-Nucleon
correlations

M. Martini

- is enough correlation introduced via this diagram? is the whole picture consistent?
II. Two-body current neutrino computations

In the Marco Martini model the correlation (N-N) contribution dominates:

\[ E_\nu = 0.7 \text{ GeV} \]

Graph showing differential cross sections for different reactions:
- \( NN \) 2p-2h
- \( N\Delta \) 2p-2h
- \( \Delta\Delta \) 2p-2h
- \( \Delta\Delta \) 3p-3h

\( \sigma / d\omega \) in \( 10^{-38} \text{ cm}^2 / \text{GeV} \) vs. \( \omega \) in [GeV]
II. Two-body current neutrino computations

II.f Another serious source of worries: consistency of existing approaches

- in MCs (also in GiBUU) two body current contribution is always implemented as another independent reaction channel (CCQE, RES, DIS, COH)
- **J. Carlson:** interference with the one body contribution is large
- MCs need a parametrization of both two body current and interference contribution together
- in impulse approximation in SF approach there is a correlation contribution with two nucleon knock out without FSI effects – how wrong is to use this together with Martini/Nieves model?
III. Other topics

III.a A series of presentations on (super-)scaling approach:

A phenomenological super-scaling function has been extracted from the longitudinal $(e,e')$ word data [Jourdan, NPA603, 117 (96)]

\[
f_{\text{RFG}}(\psi') = \frac{3}{4} (1 - \psi'^2) \theta(1 - \psi'^2)
\]

The RFG is very poor

Asymmetric shape with long high energy tail

$q$-independent

A-independent
III. Other topics

III.b It was reminded many times (see also Arie Bodek presentation) that models used in MC should agree with superscaling function:

Only the description of FSI provided by RMF leads to an asymmetric function $f(\psi')$ in accordance with the behavior shown by data. Moreover, $f_T > f_L$

J. Cabbalero

What about LFG+RPA?...
III. Other topics

III.b Pion production (a transition region topic, with presentations in the first and in the second week)

- important to understand CCQE – a background from pion absorption
- precise data is badly needed
- Rein-Sehgal model is not reliable at all
  - nothing new but should be remembered again and again
- important work is being done in GENIE

L. Alvarez-Ruso
IV. A message for MC generators:

- improvements in treatment of nuclear effects (NN correlations) should be done
- spectral function should probably become a default option
- before more rigorous computations are done, existing treatments of two body contribution should be applied
  - comparison to MiniBooNE $\nu_\mu$ and $\bar{\nu}_\mu$ data is a necessary consistency check
- it will be very difficult to get everything that is required in the completely satisfactory way
  - rigorous computations are non-relativistic
  - experimentalists need to know results for oxygen, argon, ...
  - MCs need predictions for final state nucleons
    - any hints from $^3$He and $^4$He computations?...
Summary:
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Correlations have many consequences and must be seriously taken into account!