Theory Prospects for Neutrino Nucleus Cross Sections

Saori Pastore

51st Annual Fermilab Users Meeting, Batavia IL, June 2018

Open Questions in Fundamental Symmetries and Neutrino Physics

Majorana Neutrinos, Neutrinos Mass Hierarchy,
CP-Violation in Neutrino Sector, Dark Matter

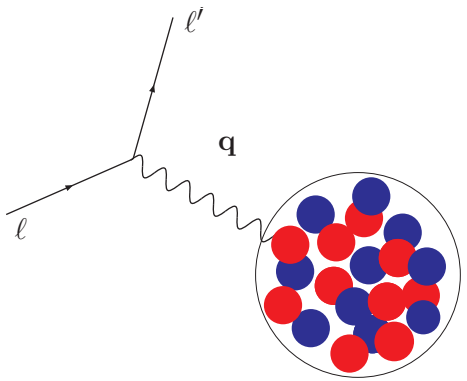
with

Carlson & Gandolfi (LANL) & Baroni (USC) & Schiavilla (ODU+JLab)
Pieper & Wiringa (ANL) & Piarulli (ANL+WashU) & Lovato (ANL+INFN) & Rocco (ANL+FNAL)

and with

Mereghetti & Dekens & Cirigliano & Graesser (LANL)
de Vries (Nikhef) & van Kolck (AU+CNRS/IN2P3)

Nuclear Physics for the Neutrino Program



* Accurate calculations of ν-nucleus cross-sections in a wide range of energy/momentum transfer

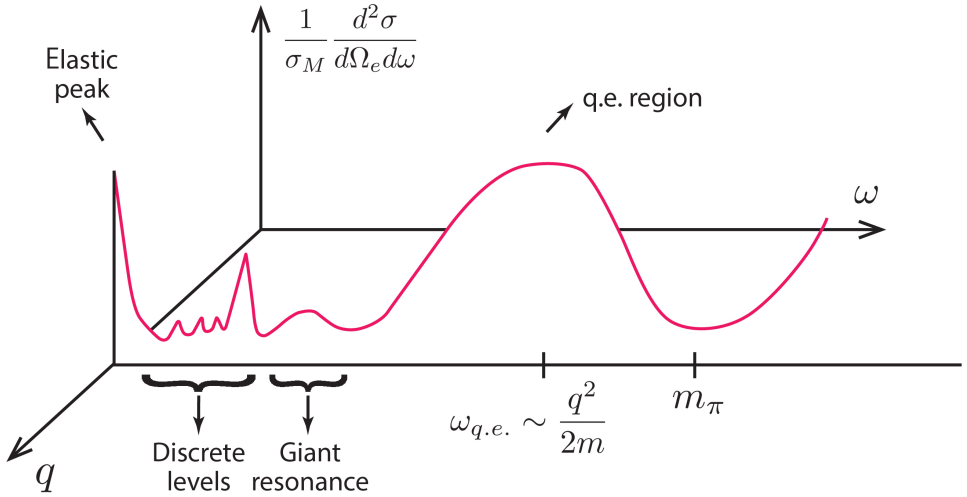
* Targets: from d to ^{40}Ar and more

* (More) Exclusive Channels

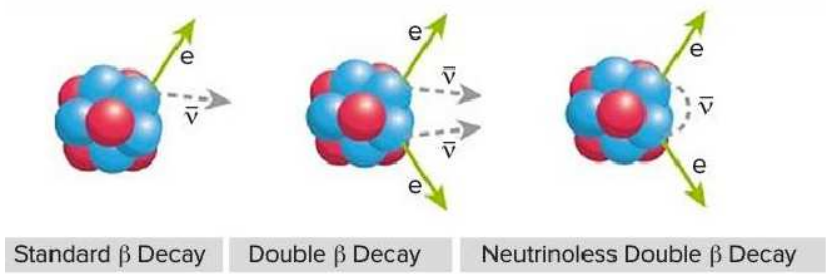
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2_{21} L}{2E_\nu} \right)$$

* In this talk: The Quantum Monte Carlo community's effort *

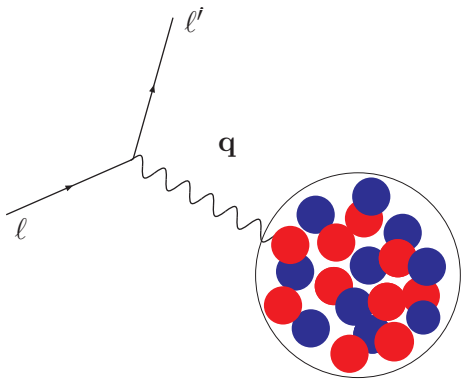
Towards a coherent and unified picture of neutrino-nucleus interactions



* $\omega \sim$ few MeV, $q \sim 0$: β-decay, $\beta\beta$-decays
* $\omega \sim$ few MeV, $q \sim 10^2$ MeV: Neutrinoless $\beta\beta$-decays
* $\omega \lesssim$ tens MeV: Nuclear Rates for Astrophysics
* $\omega \sim 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering $\Leftarrow$



The Microscopic (or *ab initio*) Description of Nuclei



Develop a comprehensive theory that describes quantitatively and predictably all nuclear structure and reactions

* Accurate understanding of interactions between nucleons, p's and n's
* and between electrons and neutrinos with nucleons, nucleons-pairs, ...
* Electroweak Nucleonic Form Factors are inputs of the *ab initio* framework

$$H\Psi = E\Psi$$

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A, s_1, s_2, \ldots, s_A, t_1, t_2, \ldots, t_A)$$

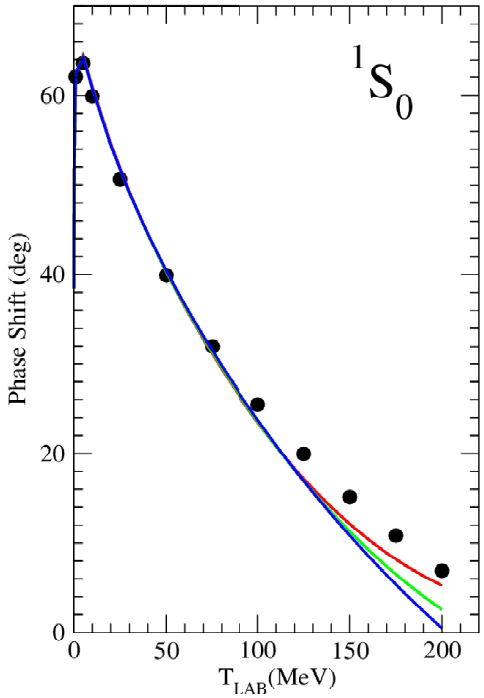
Erwin Schrödinger

Nuclear Interactions

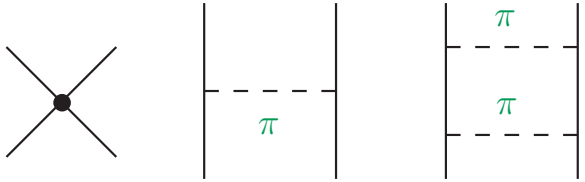
The nucleus is made of A non-relativistic interacting nucleons and its energy is

$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} \upsilon_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

where υ_{ij} and V_{ijk} are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD

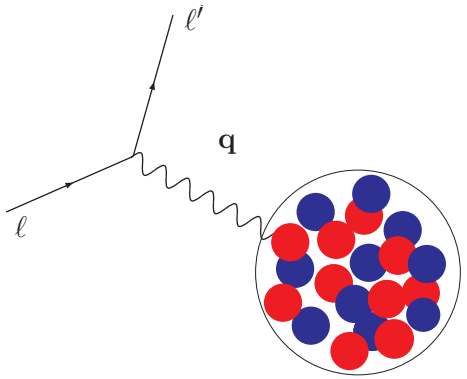


Pastore *et al.* PRC80(2009)034004



* QMC: AV18+UIX / AV18+IL7
  Wiringa+Schiavilla+Pieper *et al.*
* QMC: NN(N2LO)+3N(N2LO) (π&N)
  Gerzelis+Tews+Epelbaum+Gandolfi+Lynn *et al.*
* QMC: NN(N3LO)+3N(N2LO) (π&N&Δ)
  Piarulli *et al.*

Quantum Monte Carlo Methods



Solve numerically the many-body problem

$$H\Psi = E\Psi$$

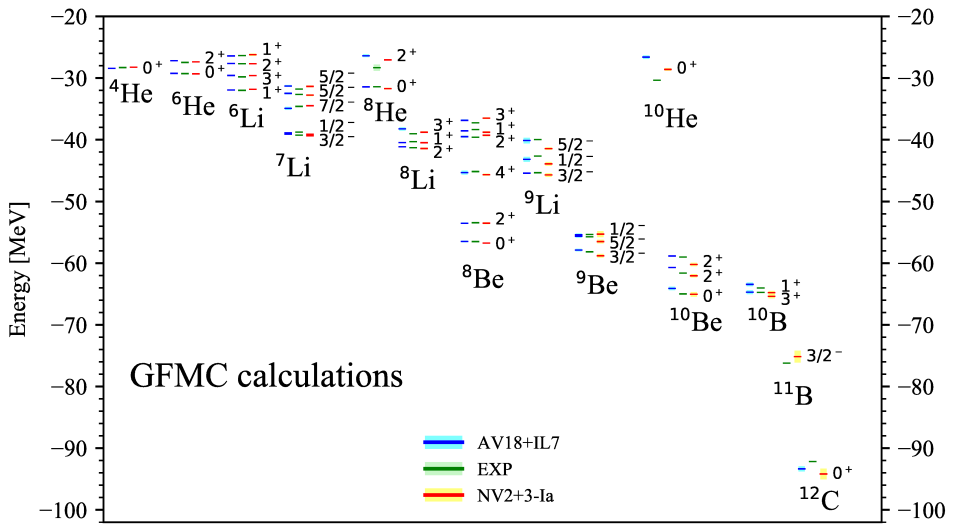
$$\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A, s_1, s_2, ..., s_A, t_1, t_2, ..., t_A)$$

Ψ are spin-isospin vectors in $3A$ dimensions with $2^A \times \frac{A!}{Z!(A-Z)!}$ components

^{4}He : 96
^{6}Li : 1280
^{8}Li : 14336
^{12}C : 540572

using Variational and Green's Function MC Methods
one ^{12}C energy calculation takes $\sim$ 15k core hours in VMC
and $\sim$ 75k core hours in GFMC

Energy Spectrum and Shape of Nuclei

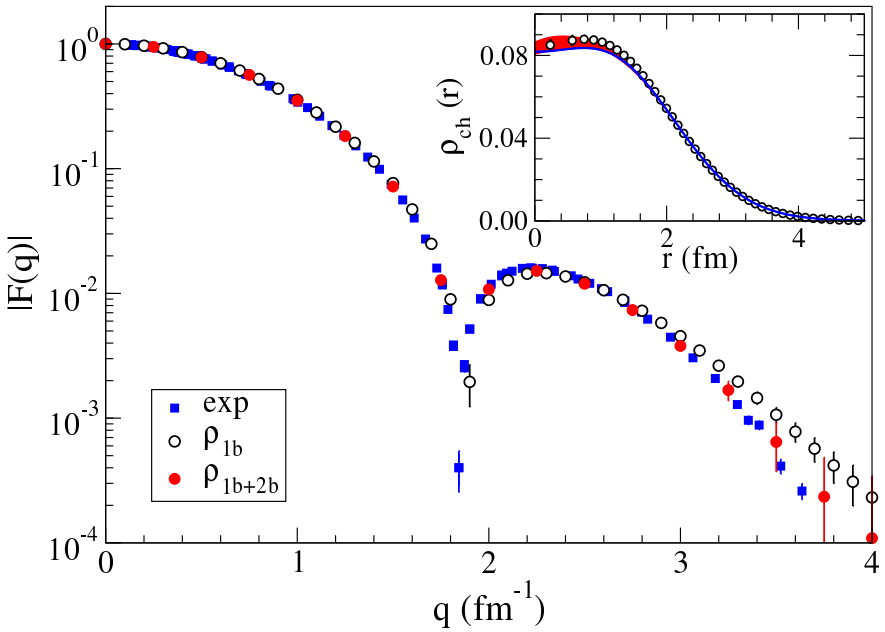


Piarulli *et al.*

PRL120(2018)052503

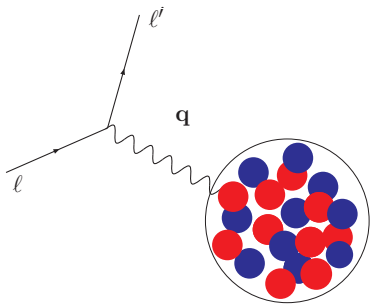
Lovato *et al.*

PRL111(2013)092501

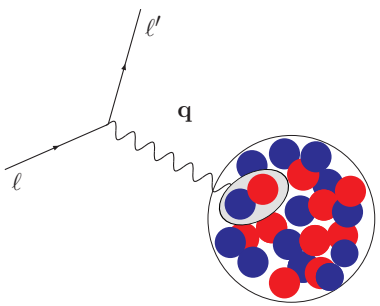


Nuclear Currents

1b



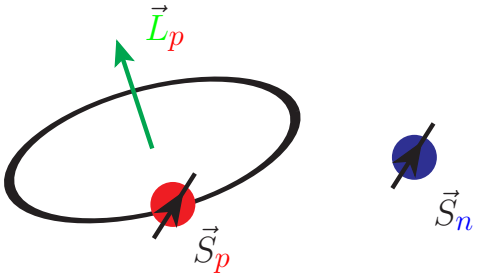
2b



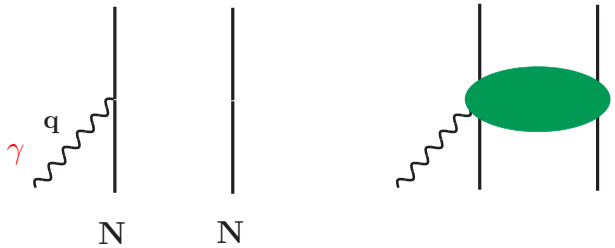
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \dots ,$$

$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \dots$$

* Nuclear currents given by the sum of p's and n's currents, one-body currents (1b)



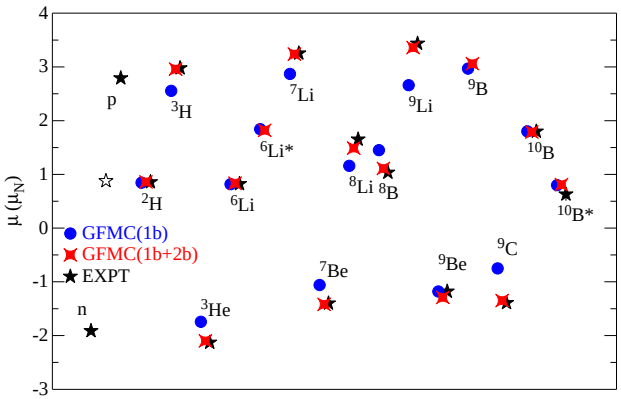
* Two-body currents (2b) essential to satisfy current conservation
* We use Meson-Exchange Currents (MEC) or χEFT Currents

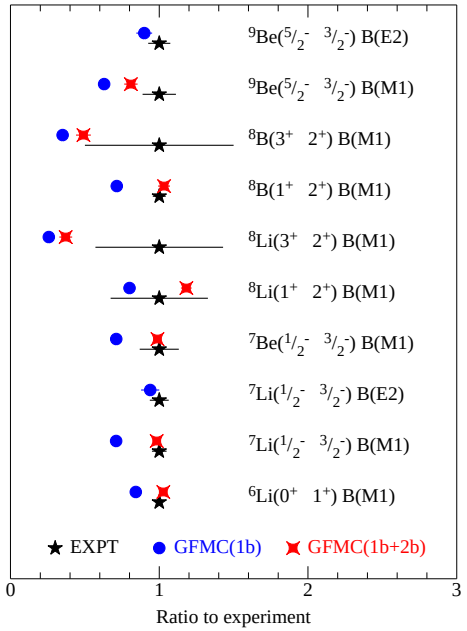


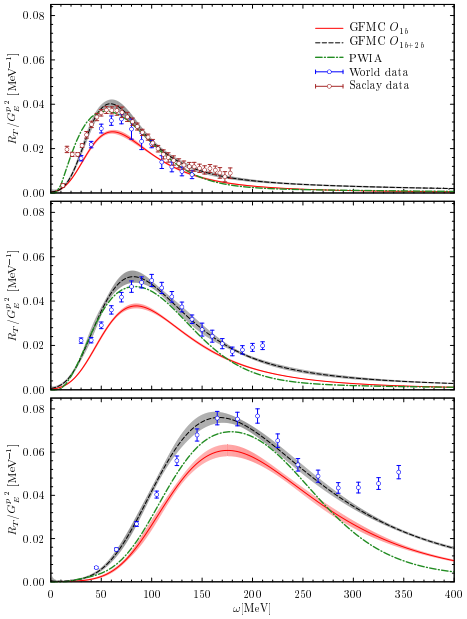
$+ \dots$

$$\mathbf{q}\cdot\mathbf{j} = [H, \rho] = [t_i + v_{ij} + V_{ijk}, \rho]$$

EM Moments, EM Decays and *e*-scattering off nuclei







Pastore *et al.* PRC87(2013)035503

Lovato *et al.* PRC91(2015)062501

Electromagnetic data are explained when
two-body correlations and currents are accounted for!

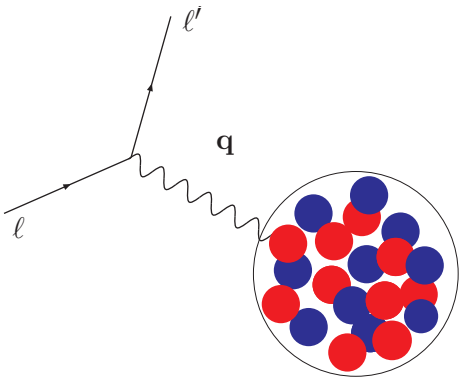
Inclusive (e,ν) scattering

* inclusive xsecs *

$$\frac{d^2\sigma}{dE\prime d\Omega_{e\prime}} = \sigma_M \left[v_L R_L(q,\omega) + v_T R_T(q,\omega) \right]$$

$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f | O_\alpha(\mathbf{q}) | 0 \rangle|^2$$

Longitudinal response induced by $O_L = \rho$
Transverse response induced by $O_T = \mathbf{j}$
... 5 nuclear responses in ν-scattering...



* Sum Rules *

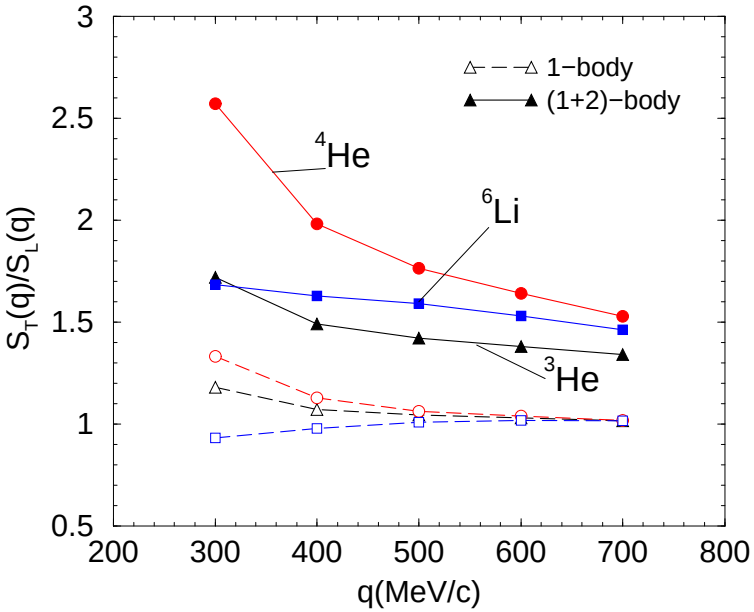
Exploit integral properties of the response functions + closure to avoid explicit calculation of the final states

$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

$$S_\alpha(q) = \int_0^\infty d\omega\, R_\alpha(q,\omega) \propto \langle 0 | O_\alpha^\dagger(\mathbf{q}) O_\alpha(\mathbf{q}) | 0 \rangle$$

Sum Rules and Two-Body Physics

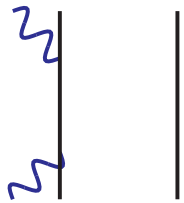


Carlson *et al.* PRC65(2002)024002

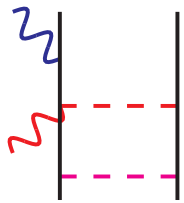
$$S_T(q) \propto \langle 0|\mathbf{j}^\dagger\,\mathbf{j}|0\rangle$$
$$\propto \langle 0|\mathbf{j}_{1b}{}^\dagger\,\mathbf{j}_{1b}|0\rangle + \langle 0|\mathbf{j}_{1b}{}^\dagger\,\mathbf{j}_{2b}|0\rangle + \ldots$$

- $\mathbf{j} = \mathbf{j}_{1b} + \mathbf{j}_{2b}$

• enhancement of the transverse response is due to interference between 1b and 2b currents AND presence of two-nucleon correlations •



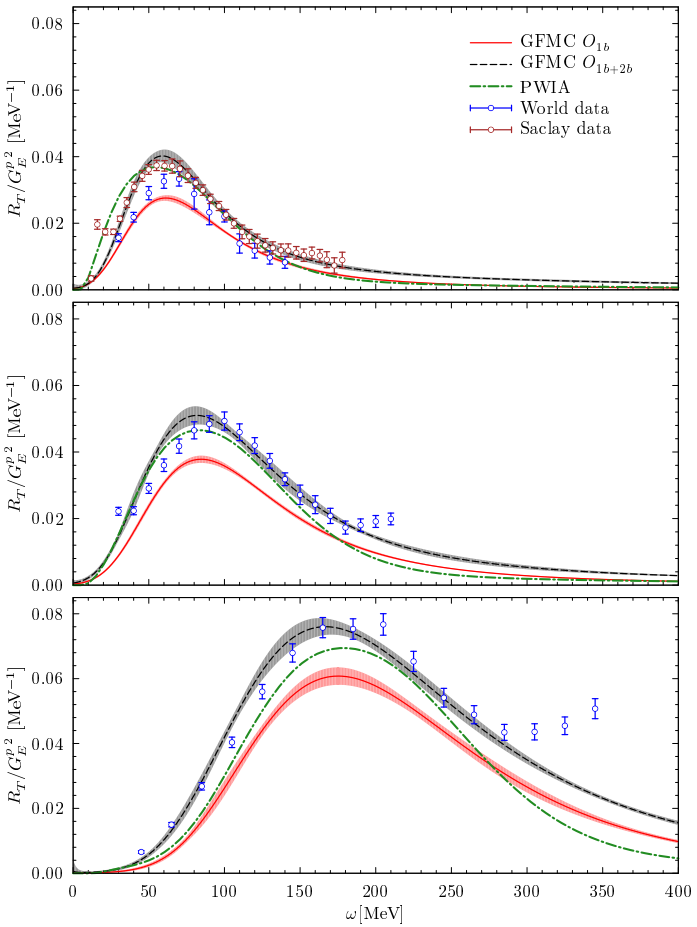
$$\langle \mathbf{j}_{1b}^\dagger\ \mathbf{j}_{1b}\rangle > 0$$



$$\langle \mathbf{j}_{1b}^\dagger\ \mathbf{j}_{2b}\ v_\pi\rangle \propto \langle v_\pi^2\rangle > 0$$

Recent Developments on Inclusive Electron Scattering off ^{12}C

Electromagnetic Transverse Responses



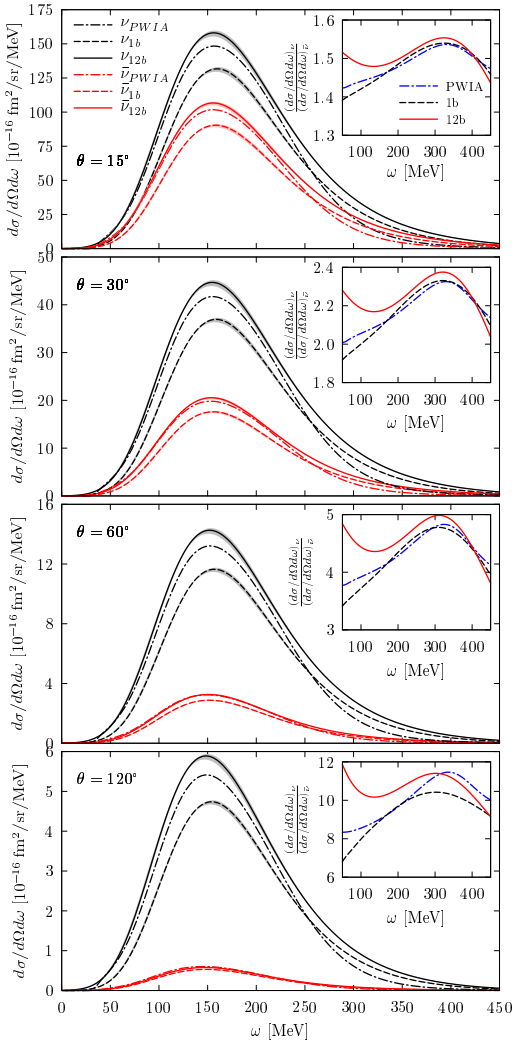
$q = [300 - 750]$ MeV

Lovato & Gandolfi *et al.* PRC91(2015)062501 & arXiv:1605.00248

Electromagnetic data are explained when
two-body correlations and currents are accounted for!

Recent Developments on Inclusive Neutrino Scattering off ^{12}C

NC Inclusive Xsec



$q = 750$ MeV

Lovato & Gandolfi *et al.* PRC97(2018)022502

$\sim$ 100 million core hours

Challenges and Opportunities

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1. How to describe electroweak-scattering off $A > 12$ without losing two-body physics (*i.e.*, two-body correlations and currents)?

2. How to incorporate (more) exclusive processes?

3. How to incorporate relativistic effects?

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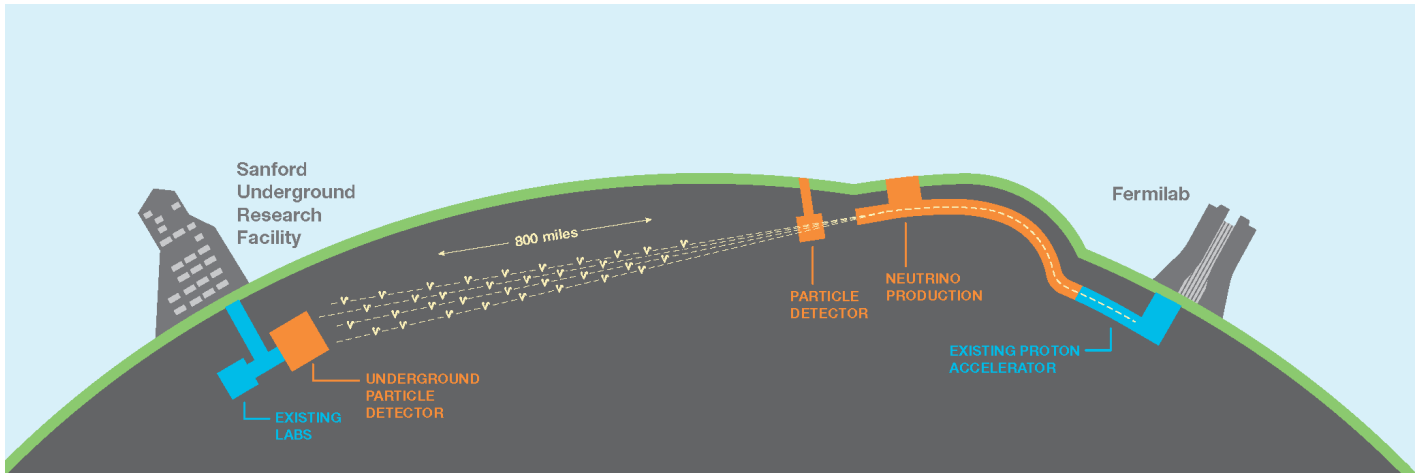
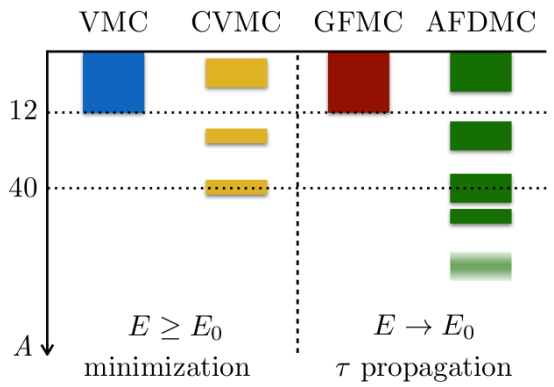


The Present and Future of Quantum Monte Carlo Calculations

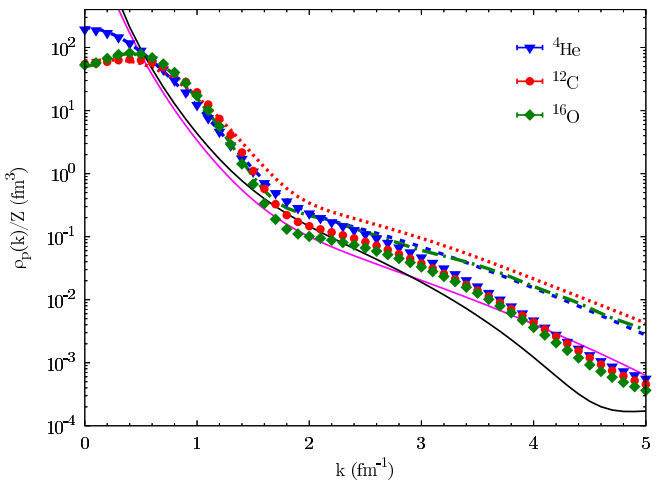


(C)VMC GFMC AFDMC	light systems	$A \leq 12$
CVMC AFDMC	light to medium-mass nuclei	$A \sim 50$
AFDMC	infinite matter	$A \to \infty$

figure by Lonardoni

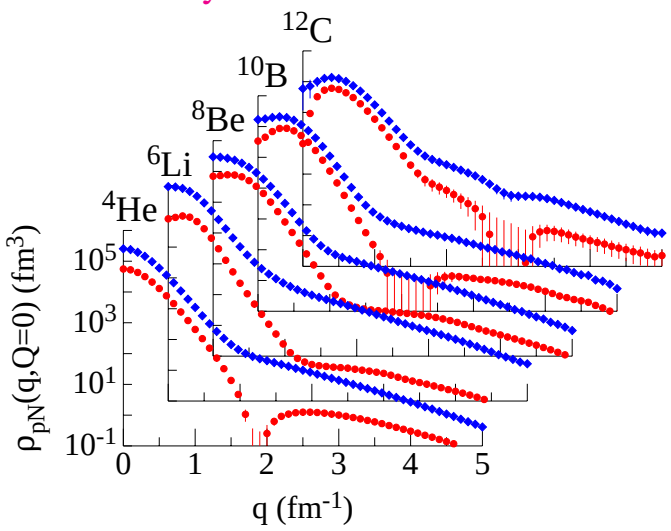
Use of Quantum Computers is being also explored - Roggero, Baroni, Carlson, Perdue *et al.*

One-body momentum distributions



Lonardoni *et al.* to appear on PRC arXiv:1804.08027

Two-body momentum distributions



Wiringa *et al.* PRC89(2014)024305

One-body momentum distributions http://www.phy.anl.gov/theory/research/momenta/
Two-body momentum distributions http://www.phy.anl.gov/theory/research/momenta2/

Factorization: The Short-Time Approximation

$$R(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle\, 0|O^\dagger(\mathbf{q})|f\rangle\langle f|O(\mathbf{q})|0\rangle$$

$$R(q,\omega) = \int dt \langle\, 0|O^\dagger(\mathbf{q})\, e^{i(H-\omega)t}\, O(\mathbf{q})|0\rangle$$

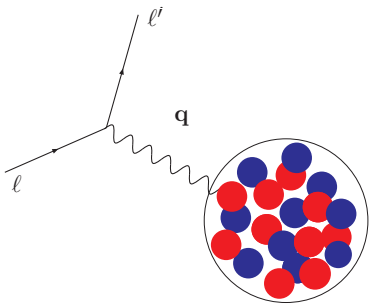
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

$$H \sim \sum_i t_i + \sum_{i<j} \upsilon_{ij}$$

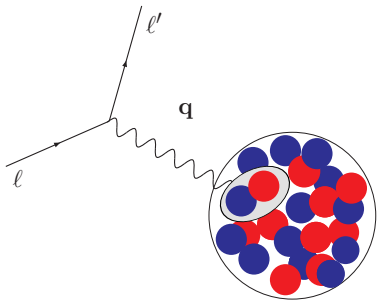
and

$$O_i^\dagger P(t) O_i + O_i^\dagger P(t) O_j + O_i^\dagger P(t) O_{ij} + O_{ij}^\dagger P(t) O_{ij}$$

1b



2b

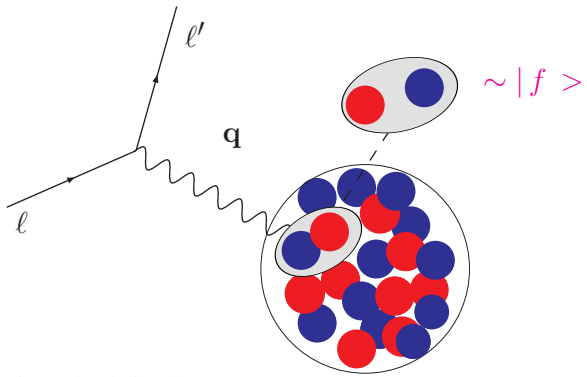


WITH

Carlson & Gandolfi (LANL) & Schiavilla (ODU+JLab) & Wiringa (ANL)

Factorization up to two-body operators: The Short-Time Approximation (STA)

Response functions are given by the scattering off pairs of fully interacting nucleons that propagate into a correlated pair of nucleons



$$R(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle 0|O^\dagger(\mathbf{q})|f\rangle\langle f|O(\mathbf{q})|0\rangle$$

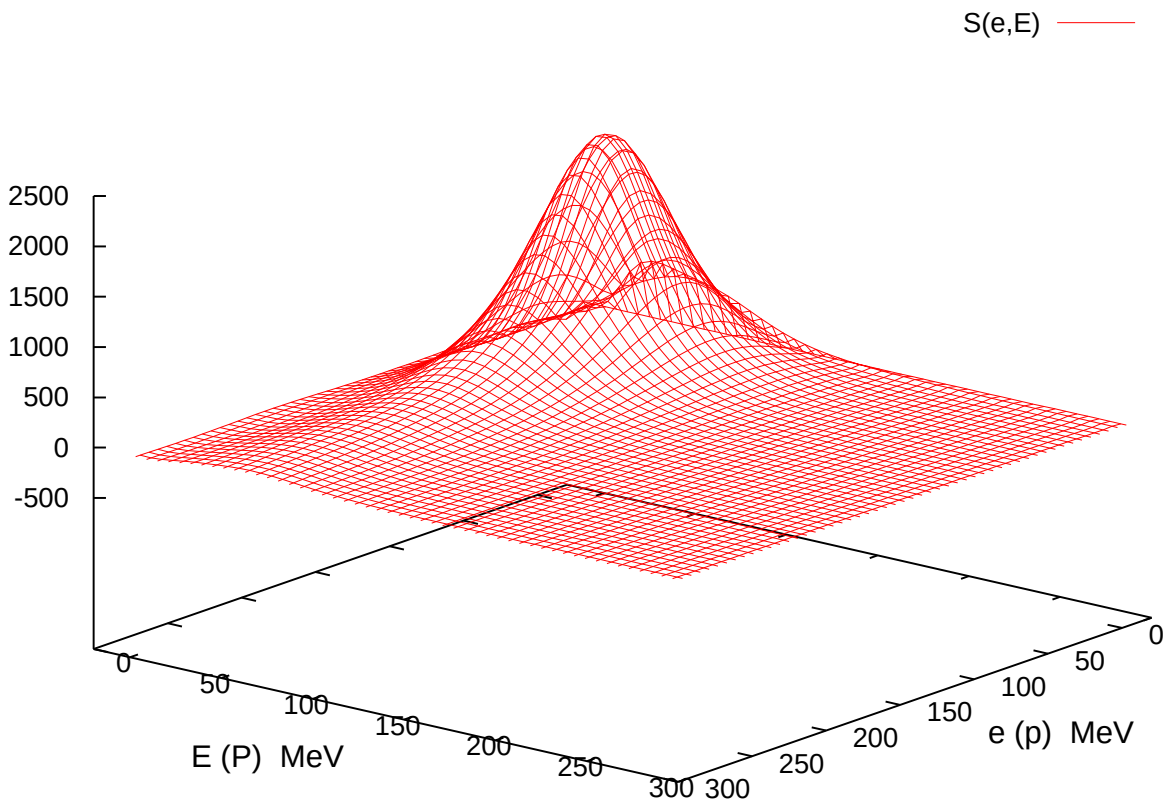
$$O(\mathbf{q}) = O^{(1)}(\mathbf{q}) + O^{(2)}(\mathbf{q}) = \text{1b} + \text{2b}$$

$$|f\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two} - \text{nucleon w.f.}$$

* We retain two-body physics consistently in the nuclear interactions and electroweak currents
* STA can describe more two-body physics, *e.g.*, pion-production induced by e and ν

$$R(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P\, d\Omega_p\, dP\, dp \left[p^2 P^2 \langle 0|O^\dagger(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle \mathbf{p},\mathbf{P}|O(\mathbf{q})|0\rangle\right]$$

The Short-Time Approximation

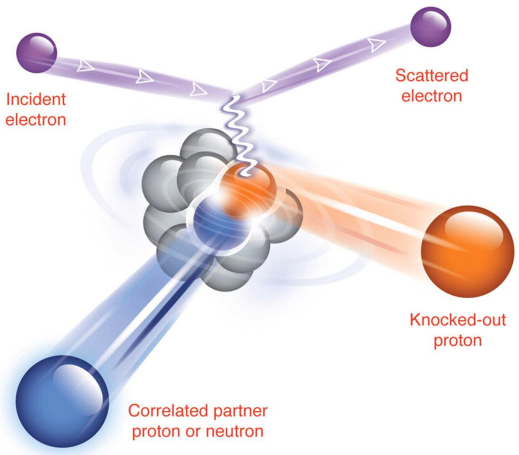


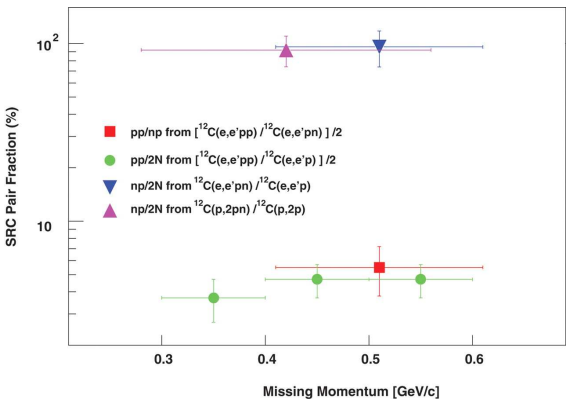
Transverse "response-density" 1b + 2b for ^4He

$$R(q,\omega) \qquad \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P \, d\Omega_p \, dP \, dp \left[p^2 P^2 \langle 0|O^\dagger(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle \langle \mathbf{p},\mathbf{P}|O(\mathbf{q})|0\rangle \right]$$

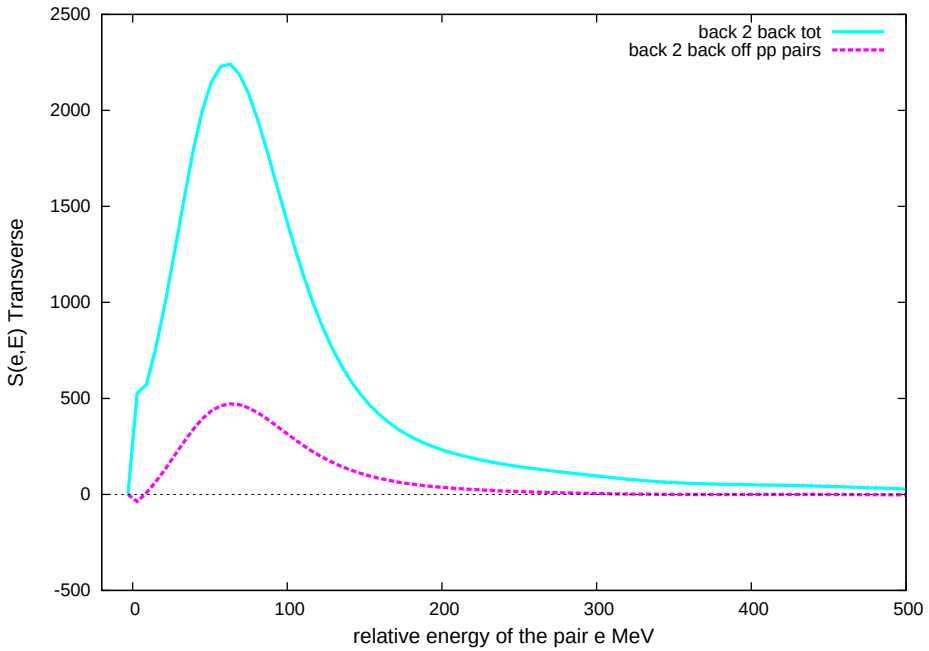
* Preliminary results *

STA back to back scattering





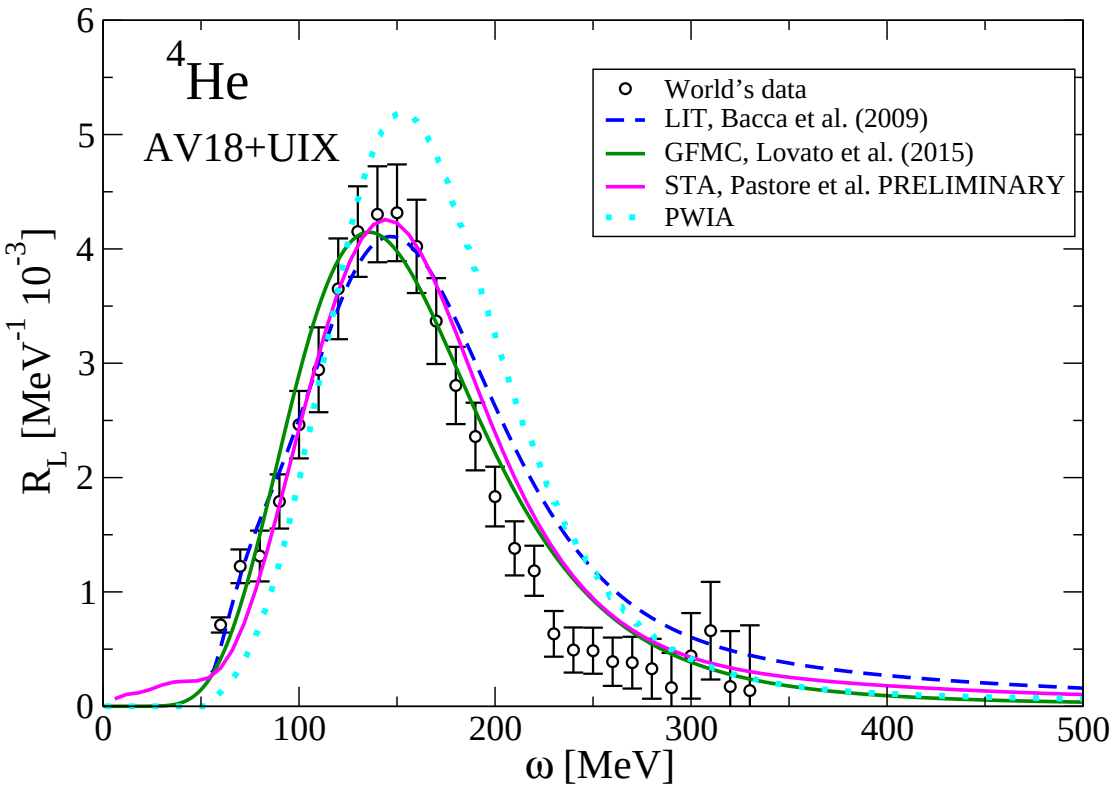
JLab, Subedi *et al.* Science320(2008)1475



$q = 500$ MeV, $E = 69$ MeV *pp* vs tot

* Preliminary results *

The Short-Time Approximation



Longitudinal Response function at $q = 500$ MeV

* Preliminary results *

Quantum Monte Carlo Studies for the Neutrino Program

Two-nucleon correlations and two-body electroweak currents
are crucial to explain available experimental data

* Exact GFMC calculations of inclusive NC xsecs off ^{12}C are available

* Quantum Monte Carlo Calculations extended to nuclei with $A \leq 40$

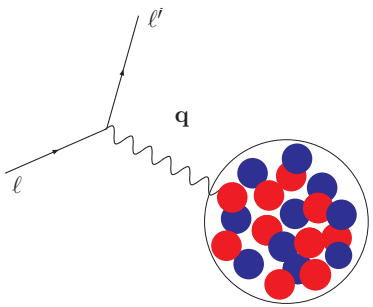
* Short-Time-Approximation developed to evaluate υ-A scattering in $A > 12$ nuclei

* STA retains two-body physics in the inter-nucleon interactions and currents

* STA is in excellent agreement with both exact calculations and data

* STA susceptible of describing exclusive processes, *e.g.*, pion-production

* We are joining the efforts of Betancourt *et al.* and Perdue *et al.*

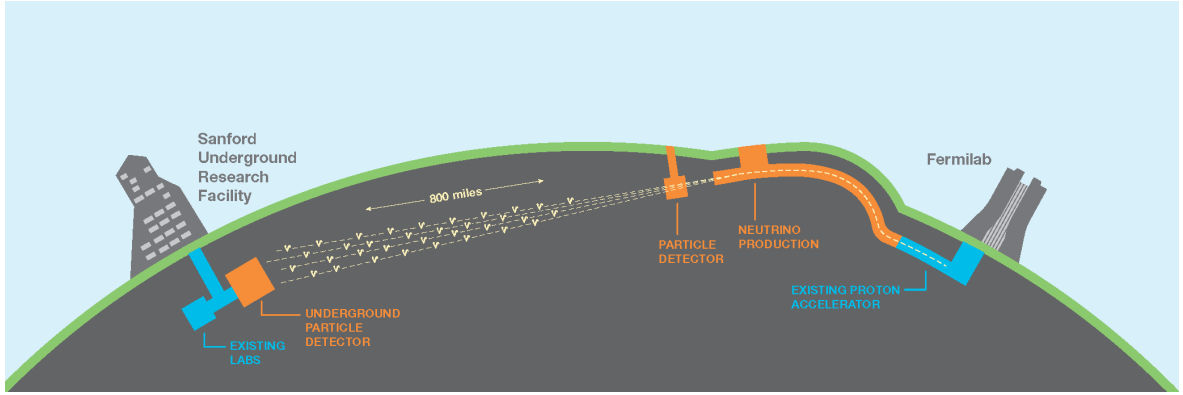


Nuclear Physics for the Neutrino Program

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

* Accurate calculations of ν-nucleus cross-sections in a wide range of energy/momentum transfer

* Targets: from d to ^{40}Ar and more

* (More) Exclusive Channels

$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2_{21} L}{2E_\nu} \right)$$