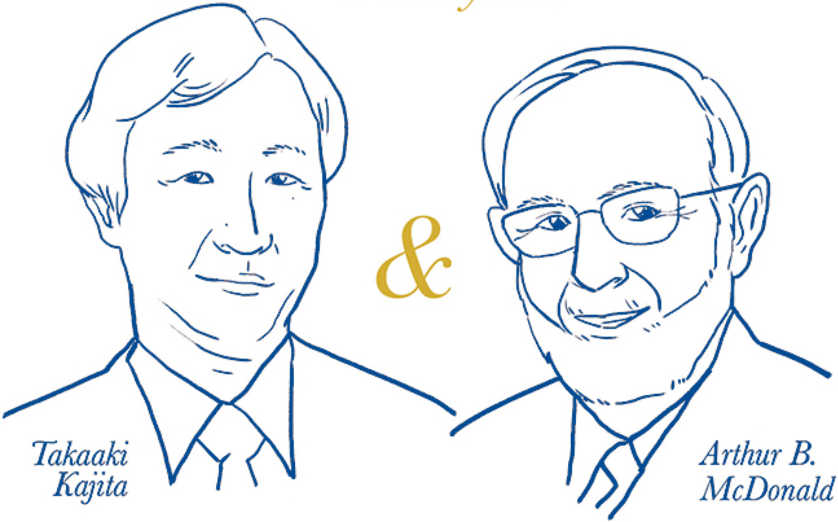
Short-range correlations and two-nucleon knockout in neutrino-nucleus scattering

Tom Van Cuyck, N. Jachowicz, R. González Jiménez
V. Pandey, J. Ryckebusch and N. Van Dessel

BPS meeting 2016

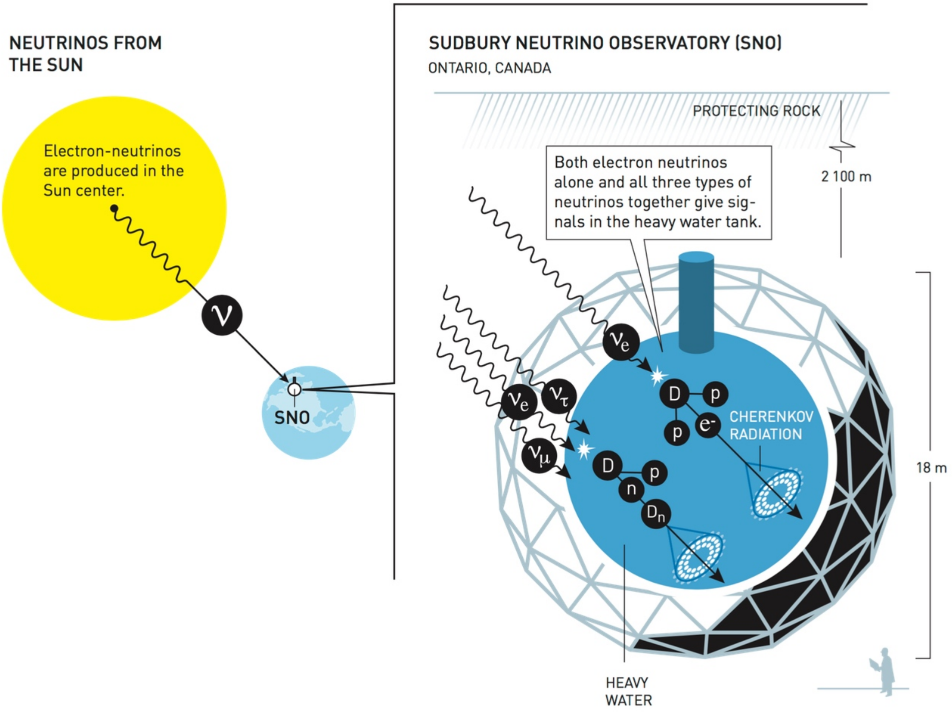
May 18, 2016

2015 NOBEL PRIZE *in Physics*

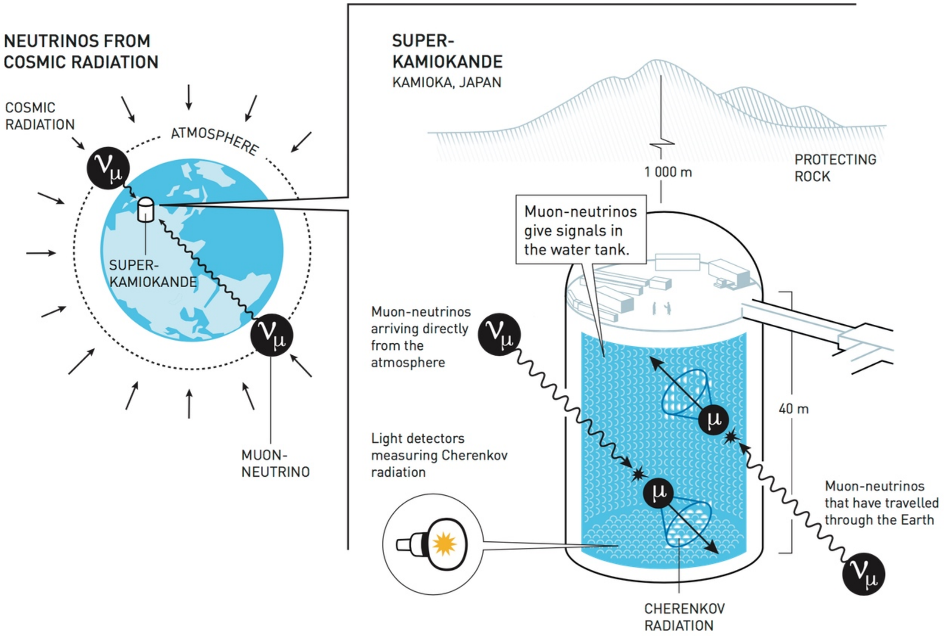


NEUTRINO OSCILLATIONS

The discovery of these oscillations shows that neutrinos have mass.

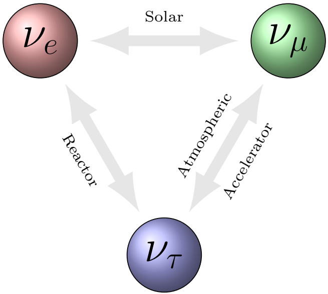


NEUTRINOS FROM THE SUN
Electron-neutrinos are produced in the Sun center.
ν
SNO
SUDBURY NEUTRINO OBSERVATORY (SNO)
ONTARIO, CANADA
PROTECTING ROCK
2 100 m
Both electron neutrinos alone and all three types of neutrinos together give signals in the heavy water tank.
ν_e
ν_τ
ν_μ
D
p
n
D_n
e^-
CHERENKOV RADIATION
18 m
HEAVY WATER


NEUTRINOS FROM COSMIC RADIATION
COSMIC RADIATION
ATMOSPHERE
ν_μ
SUPER-KAMIOKANDE
MUON-NEUTRINO
SUPER-KAMIOKANDE
KAMIOKA, JAPAN
1 000 m
PROTECTING ROCK
Muon-neutrinos give signals in the water tank.
Muon-neutrinos arriving directly from the atmosphere
40 m
μ
Light detectors measuring Cherenkov radiation
Muon-neutrinos that have travelled through the Earth
CHERENKOV RADIATION

Neutrino oscillations

The expected number of neutrinos did not match the actual number number of detected neutrinos – the conclusion being that the expected neutrinos had undergone a transformation on their way to the detector.

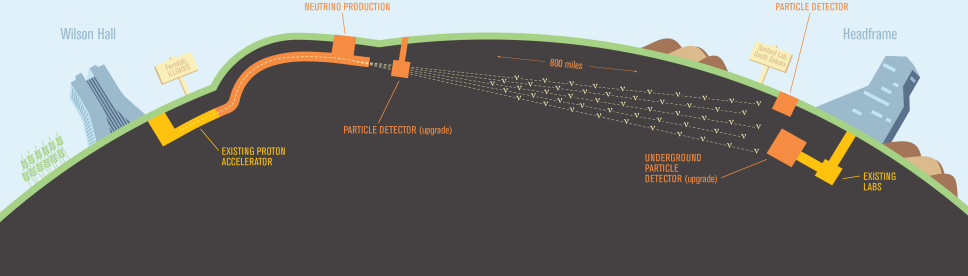


$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

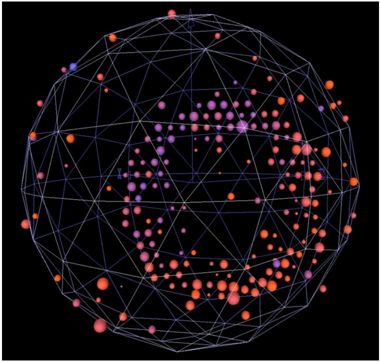
Accelerator-based experiment

1. ν_μ production at near detector
2. neutrino oscillations occur between near and far detector
3. count ν_e, ν_μ and ν_τ at near and far detector
4. extract θ and Δm from differences between near and far detector

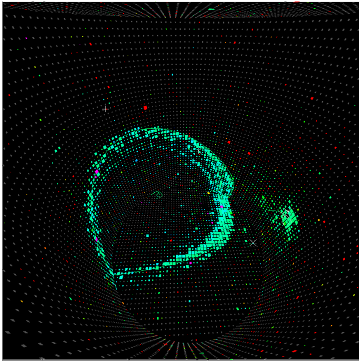
$\rightarrow$ **precise neutrino-nucleus cross-section needed,**
major source of uncertainty is associated with nuclear interactions



Neutrino interaction event



MiniBooNE event

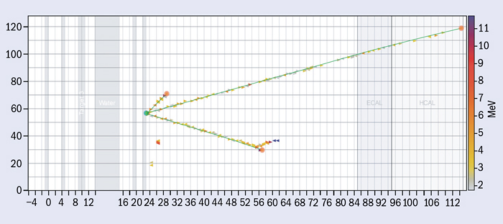


T2K event

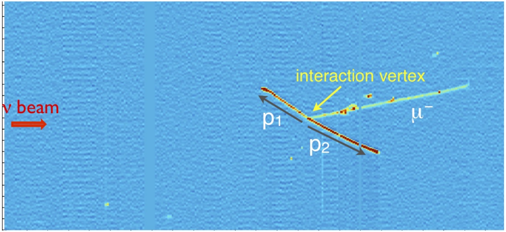
$$\nu_\mu + A \to \mu^- + X$$

Cherenkov detector: only final state lepton is detected

Neutrino interaction event



Minerva event

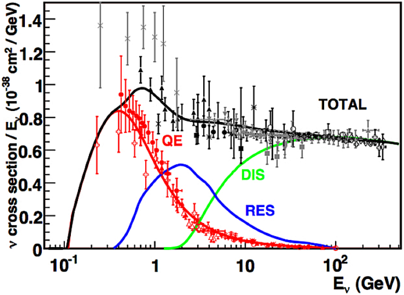


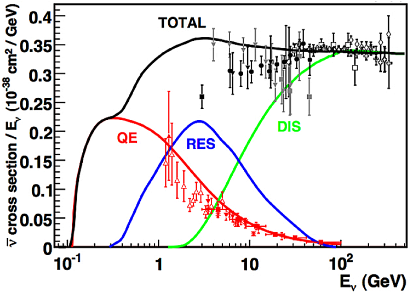
ArgoNeuT event

New generation detector: final state nucleons and pions detected as well

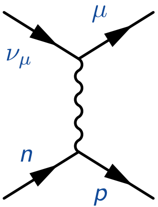
Ref: J.A. Formaggio, *et al.*
Rev.Mod.Phys. 84 (2012) 1307

Cross section

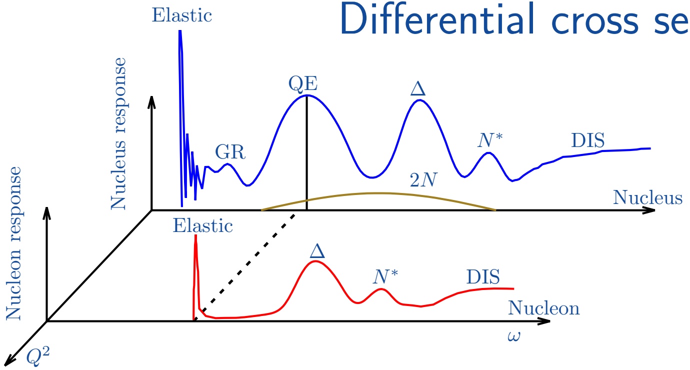




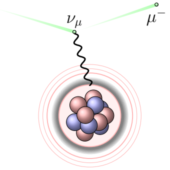
- QE - Quasi-elastic scattering: nucleon stays intact
  $$\nu_\mu + n \rightarrow \mu^- + p$$
- RES - Resonance production: nucleon is excited
  $$\nu_\mu + n \rightarrow \mu^- + \Delta^+$$
  $$\hookrightarrow p + \pi$$
- DIS - Deep inelastic scattering: nucleon breaks up
  $$\nu_\mu + n \rightarrow \mu^- + X$$



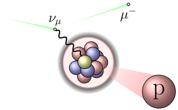
Differential cross section



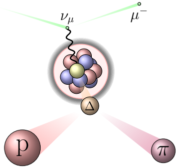
Elastic



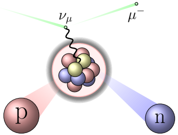
QE



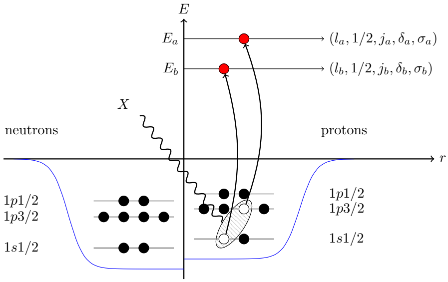
Δ and N^*

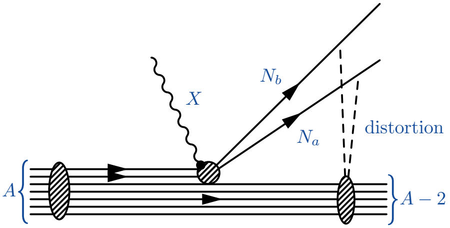


$2N$



Nuclear model

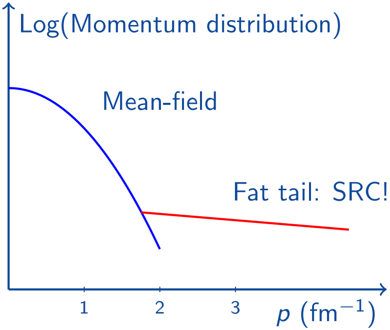


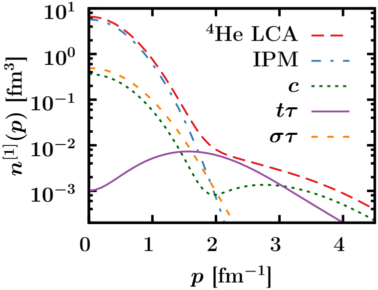


- Ground state nucleus is an IPM
  - Calculated with a Hartree-Fock (HF) approximation using a Skyrme NN force (SkE2)
  - Accounts for binding energies and nuclear structure
  - Pauli-blocking effects included inherently
- Continuum wave functions are calculated using the same NN potential
  - Orthogonality is preserved between initial and final states
  - Distortion effects of the residual nucleus on the ejected nucleons are incorporated

Short-range correlations

Fat tails in the single-nucleon momentum distribution cannot be explained within the impulse approximation (IA)



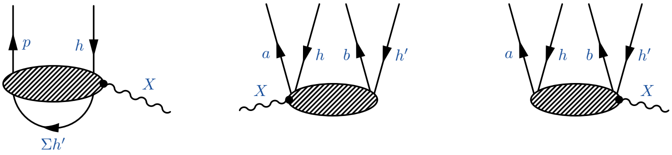


Ref: J. Ryckebusch, *et al.*, J. Phys. G: Nucl. Part. Phys. 42 055104 (2015)

Short-range correlations

Fat tails in the single-nucleon momentum distribution cannot be explained within the impulse approximation (IA)

- Nucleons occur in pairs with high relative momenta and low center-of-mass momenta (SRC pairs)
  - correlations have a short range
  - tensor correlations dominate at intermediate momenta
  - central correlations dominate at high momenta
- A signature of SRC is back-to-back $2N$ knockout
- SRC also have an effect on $1N$ knockout



Ref: J. Ryckebusch, *et al.*, Nucl.Phys. A624, 581 (1997)
S. Janssen, *et al.*, Nucl.Phys. A672, 285 (2000)
(electron-scattering model with SRC + MEC)

Short-range correlations

Correlated wave functions $|\Psi\rangle$ are constructed by acting with a many-body correlation operator $\widehat{\mathcal{G}}$ on the uncorrelated Hartree-Fock wave functions $|\Phi\rangle$

$$|\Psi\rangle = \frac{1}{\sqrt{\mathcal{N}}}\widehat{\mathcal{G}}|\Phi\rangle, \qquad \text{with} \qquad \mathcal{N} = \langle\Phi|\widehat{\mathcal{G}}^\dagger\widehat{\mathcal{G}}|\Phi\rangle.$$

The central (c), tensor $(t\tau)$ and spin-isospin $(\sigma\tau)$ correlations are responsible for majority of the strength. Transition matrix elements between correlated states $|\Psi\rangle$ can be written as matrix between uncorrelated states $|\Phi\rangle$, with an effective transition operator

$$\langle\Psi_f|\widehat{J}_\mu^{\text{nucl}}|\Psi_i\rangle = \frac{1}{\sqrt{\mathcal{N}_i\mathcal{N}_f}}\langle\Phi_f|\widehat{J}_\mu^{\text{eff}}|\Phi_i\rangle.$$

In the IA, the many-body nuclear current can be written as a sum of one-body operators

$$\widehat{J}_\lambda^{\text{eff}} = \widehat{\mathcal{G}}^\dagger\widehat{J}_\mu^{\text{nucl}}\widehat{\mathcal{G}} = \left(\prod_{j<k}^{A}\left[1+\widehat{l}(j,k)\right]\right)^\dagger \sum_{i=1}^{A}\widehat{J}_\lambda^{[1]}(i)\left(\prod_{l<m}^{A}\left[1+\widehat{l}(l,m)\right]\right).$$

Short-range correlations

$$\widehat{J}_\lambda^{\text{eff}} = \widehat{\mathcal{G}}^\dagger \widehat{J}_\mu^{\text{nucl}} \widehat{\mathcal{G}} = \left(\prod_{j<k}^{A} \left[1 + \widehat{l}(j,k) \right] \right)^\dagger \sum_{i=1}^{A} \widehat{J}_\lambda^{[1]}(i) \left(\prod_{l<m}^{A} \left[1 + \widehat{l}(l,m) \right] \right).$$

Use the fact that SRC is a short-range phenomenon to reduce the sums.

- Terms linear in the correlation operator are retained
- A-body operator $\rightarrow$ 2-body operator

$$\widehat{J}_\lambda^{\text{eff}} \approx \underbrace{\sum_{i=1}^{A} \widehat{J}_\lambda^{[1]}(i)}_{\text{one-body (IA)}} + \underbrace{\sum_{i<j}^{A} \widehat{J}_\lambda^{[1],\text{in}}(i,j), + \left[\sum_{i<j}^{A} \widehat{J}_\lambda^{[1],\text{in}}(i,j) \right]^\dagger}_{\text{two-body (SRC)}}$$

where

$$\widehat{J}_\lambda^{[1],\text{in}}(i,j) = \left[\widehat{J}_\lambda^{[1]}(i) + \widehat{J}_\lambda^{[1]}(j) \right] \widehat{l}(i,j)$$

- Effective nuclear current is the sum of a one-body (IA) and two-body (SRC) current

One-nucleon knockout

Directly calculate the double differential cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{l'}\mathrm{d}\Omega_{l'}} = 4\pi\sigma^X \zeta\, f_{rec}^{-1}\left[v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T - h v_{T'} W_{T'}\right],$$

with v and σ^X containing leptonic information, e.g.

$$\sigma^{\text{Mott}} = \left(\frac{\alpha\cos\left(\theta_{e'}/2\right)}{2E_e \sin^2\left(\theta_{e'}/2\right)}\right)^2, \qquad \sigma^W = \left(\frac{G_F\cos\theta_c E_\mu}{2\pi}\right)^2,$$

and the response functions containing the nuclear information

$$W_{CC} = \left|\mathcal{J}_0\right|^2$$
$$W_{CL} = 2\,\mathrm{Re}\left(\mathcal{J}_0\mathcal{J}_3^\dagger\right)$$
$$W_{LL} = \left|\mathcal{J}_3\right|^2$$
$$W_T = \left|\mathcal{J}_+\right|^2 + \left|\mathcal{J}_-\right|^2$$
$$W_{T'} = \left|\mathcal{J}_+\right|^2 - \left|\mathcal{J}_-\right|^2$$

$$\mathcal{J}_0 = \left\langle\Psi_\mathrm{f}\left|\widehat{J}_0(q)\right|\Psi_\mathrm{i}\right\rangle$$
$$\mathcal{J}_+ = \left\langle\Psi_\mathrm{f}\left|\widehat{J}_+(q)\right|\Psi_\mathrm{i}\right\rangle$$
$$\mathcal{J}_- = \left\langle\Psi_\mathrm{f}\left|\widehat{J}_-(q)\right|\Psi_\mathrm{i}\right\rangle$$
$$\mathcal{J}_3 = \left\langle\Psi_\mathrm{f}\left|\widehat{J}_3(q)\right|\Psi_\mathrm{i}\right\rangle$$

SRC results - $1p1h$

The effective two-body operator affects the $1p1h$ cross section

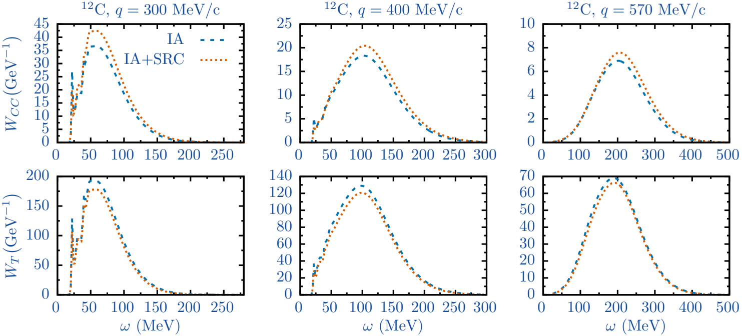


Figure: W_{CC} and W_T response functions for $1p1h$ ^{12}C(ν_μ, μ^-)

- Small increase in longitudinal channel W_{CC}
- Small decrease in transverse channel W_T

Two-nucleon knockout

Start with the 8-fold 'exclusive' differential cross section

$$\frac{d\sigma}{dE_{l'}d\Omega_{l'}dT_a d\Omega_a d\Omega_b} = \sigma^X \zeta f_{rec}^{-1}$$
$$\times \left[v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T + v_{TT}W_{TT} + v_{TC}W_{TC} + v_{TL}W_{TL} - h(v_{T'}W_{T'} + v_{TC'}W_{TC'} + v_{TL'}W_{TL'})\right],$$

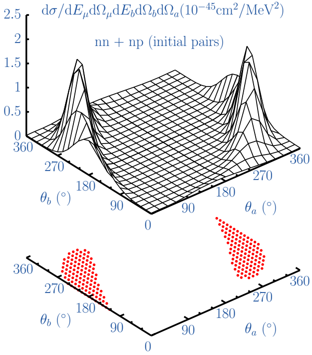
The leptonic factors v and σ^X are independent of the number of knockout particles and five more response functions appear

$$W_{TT} = 2\,\mathrm{Re}\left(\mathcal{J}_+\mathcal{J}_-^\dagger\right)$$
$$W_{TC} = 2\,\mathrm{Re}\left(\mathcal{J}_0\left(\mathcal{J}_+ - \mathcal{J}_-\right)^\dagger\right)$$
$$W_{TL} = 2\,\mathrm{Re}\left(\mathcal{J}_3\left(\mathcal{J}_+ - \mathcal{J}_-\right)^\dagger\right)$$
$$W_{TC'} = 2\,\mathrm{Re}\left(\mathcal{J}_0\left(\mathcal{J}_+ + \mathcal{J}_-\right)^\dagger\right)$$
$$W_{TL'} = 2\,\mathrm{Re}\left(\mathcal{J}_3\left(\mathcal{J}_+ + \mathcal{J}_-\right)^\dagger\right)$$

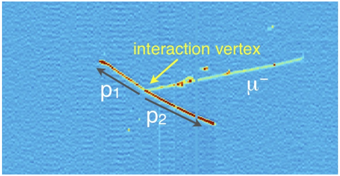
$$\mathcal{J}_0 = \langle \Psi_f | \widehat{J_0}(q) | \Psi_i \rangle$$
$$\mathcal{J}_+ = \langle \Psi_f | \widehat{J_+}(q) | \Psi_i \rangle$$
$$\mathcal{J}_- = \langle \Psi_f | \widehat{J_-}(q) | \Psi_i \rangle$$
$$\mathcal{J}_3 = \langle \Psi_f | \widehat{J_3}(q) | \Psi_i \rangle$$

SRC results - Exclusive $2p2h$

$$\frac{d\sigma}{dE_\mu d\Omega_\mu dT_b d\Omega_b d\Omega_a}(\nu_\mu, \mu^- N_a N_b), \qquad N_a = p, N_b = p', n$$



- exclusive differential cross section shows clear back-to-back knockout signal



ArgoNeuT event

Figure: $E_{\nu_\mu} = 750$ MeV, $E_\mu = 550$ MeV, $\theta_\mu = 15^\circ$ and $T_p = 50$ MeV in lepton scattering plane ($\varphi_a, \varphi_b = 0^\circ$) on ^{12}C.

SRC results - Inclusive $2p2h$

We want to calculate the contribution of the $2N$ knockout channel to the double differential cross section

$$\frac{d\sigma}{dE_{l'}d\Omega_{l'}}(l,l') = \int dT_b d\Omega_b d\Omega_a \frac{d\sigma}{dE_{l'}d\Omega_{l'}dT_b d\Omega_b d\Omega_a}(l,l'N_aN_b)$$

Inclusive $2p2h$

- contribution of $2N$ knockout $A(l,l'N_aN_b)$ to quasielastic $A(l,l')$
- incoherent sum of pp′ and pn knockout
- $2N$ knockout from all possible shell combinations $(1s1/2)^2$, $(1s1/2)(1p3/2)$ and $(1p3/2)^2$

- $\int d\Omega_b$ and $\int d\Omega_a$ analytical integration
- $\int dT_b$ numerical integration

SRC results - Inclusive 2*p*2*h*

Strength of the 2*p*2*h* contribution

- tensor SRC dominates at small to intermediate ω
- central SRC dominates at large ω
- tensor dominated by *pn* pairs

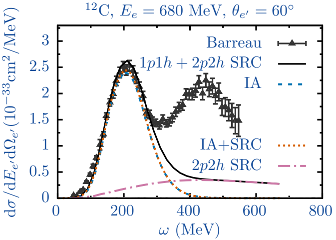


Figure: (e, e') scattering on ^{12}C

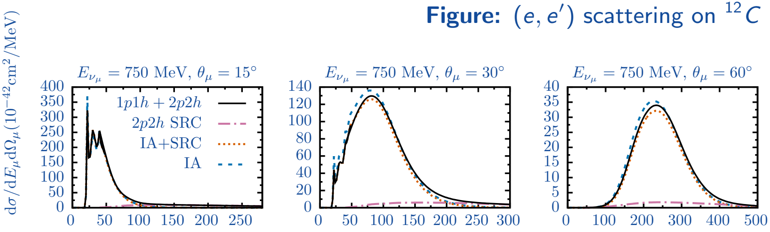


Figure: (ν_μ, μ^-) scattering on ^{12}C

- Inclusive 2*p*2*h* appears as a broad background to 1*p*1*h*

Summary and outlook

Summary

- The model describes the QE peak for electron scattering very well, so it can be expected to work for neutrinos as well
- For the exclusive $2N$ knockout calculations, we started with a model for electron scattering, which was tested against data
- Calculated contribution of SRC to double differential QE cross section
- Inclusive $2p2h$ appears as a broad background to $1p1h$

Outlook

- Extending the model with meson-exchange currents in a consistent approach
  - Vector meson-exchange current model exists for electron scattering
  - Axial meson-exchange currents are *challenging*