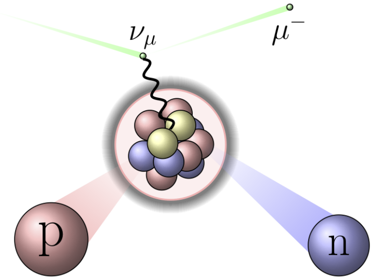

Modeling two-nucleon knock-out in neutrino-nucleus scattering

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Uniwersytet Wrocławski

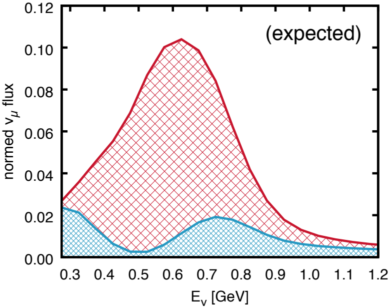
T2K

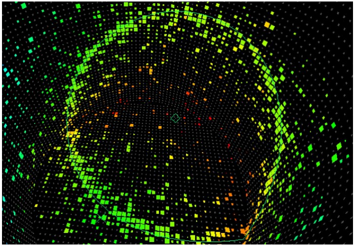
UNIVERSITEIT GENT

Neutrino oscillation experiments

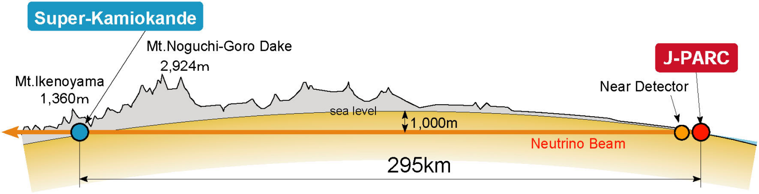
T2K

$$P_{2\mathrm{f}}(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$





$$E_\nu^{\mathrm{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2)}{2[M_n - E_B - E_\mu + |\vec{k}_\mu|\cos\theta_\mu]}$$



Detected rate of ν_α events

$$R_{\nu_\alpha} \sim \Phi_{\nu_\mu}(E_\nu) \times P_{\nu_\mu \to \nu_\alpha}(\{\Theta\}, E_\nu) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon_{\text{det.}}$$

Event **rate** | Incoming **flux** | Oscillation **probability** | **Cross section** | **Efficiency**

Knowledge of neutrino-nucleus **cross sections**:

→ allows to **reconstruct neutrino energy** from the detected **final states**,

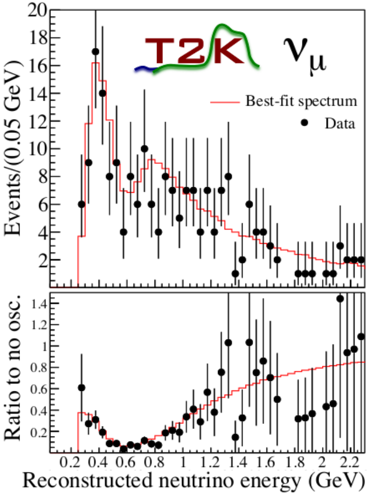
→ is the **crucial uncertainty** in **oscillation analyses**,

but...

→ is an **advanced** computational **problem**,

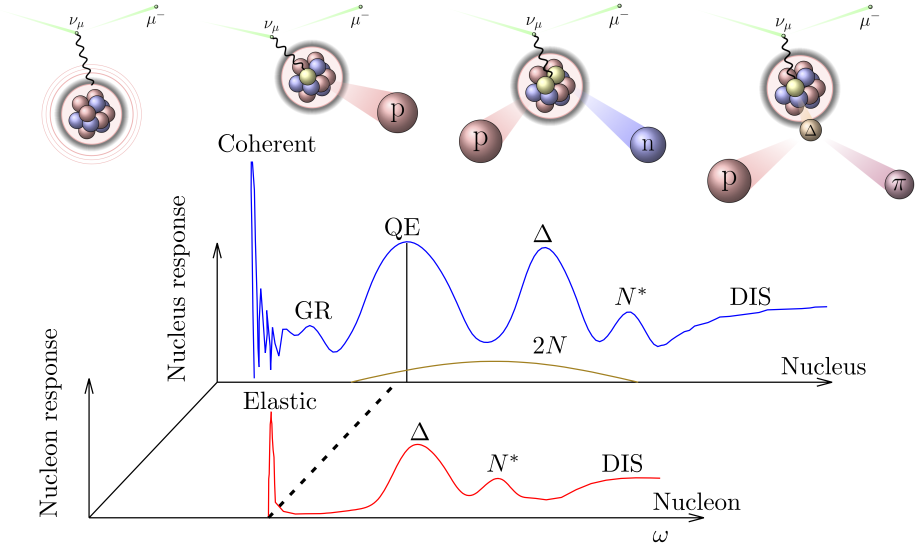
→ current **precision** is not exceeding **20%**,

→ **constraints** from **ND** are **not enough**.



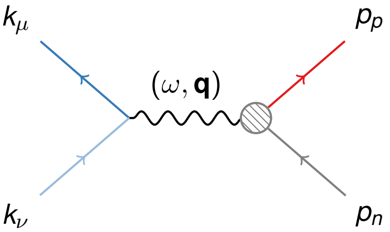
K. Abe et al., Phys.Rev.Lett. 121 (2018) 171802 (edited)

Nuclear response



T. Van Cuyck

Dimensionality of the problem



any binary scattering with on-shell particles

4 four-vectors = **16 variables**

- **- 4** : on-shell relations
- **- 4** : 4-mom. conservation
- **- 3** : nucleon rest frame
- **- 2** : neutrino along $\hat{z}$

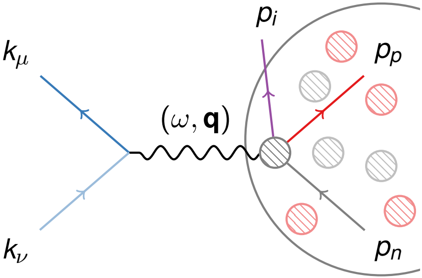
3 independent **variables**

$\rightarrow$ we can fix incoming energy (E_ν)

$\rightarrow$ the cross section is rotationally invariant (ϕ_μ)

$\rightarrow$ the final formula is 1-dimensional, e.g. $\mathrm{d}\sigma/\mathrm{d}q^2$

Dimensionality of the problem



scatterings including an off-shell target

3 independent **variables**

+ 3 : nucleus rest frame

+ 1 : off-shell nucleon

7 independent **variables**

+ 3 : every on-shell particle

$\rightarrow$ we can fix incoming energy (E_ν)

$\rightarrow$ the cross section is rotationally invariant (ϕ_μ)

$\rightarrow$ the final formula is at least 5-dimensional

Computing νA cross section

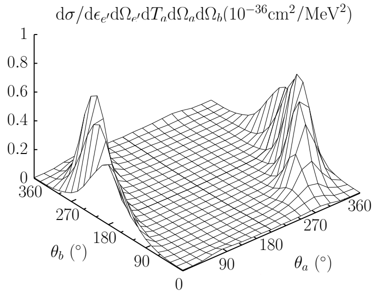
Monte Carlo generator

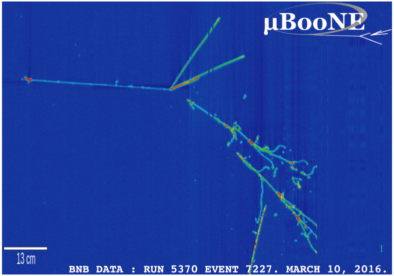
→ generate **events**

→ cover **whole phase space**

→ useful but **approximated**

e.g. **NuWro**





Detailed calculation

→ compute **cross sections**

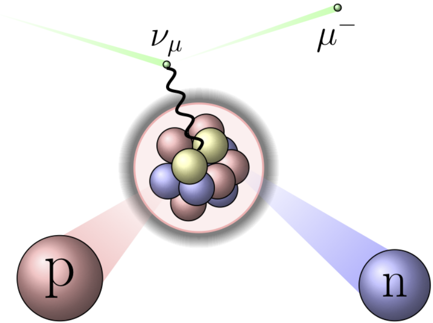
→ **fixed kinematics**

→ precise but **expensive**

e.g. **Ghent** group

Contents

- History of 2p2h modeling
- Theoretical formalism of the Ghent group
  - Kinematics
  - Nucleon wave functions
  - Short-range correlations
  - Meson-exchange currents
- Experimental prospects

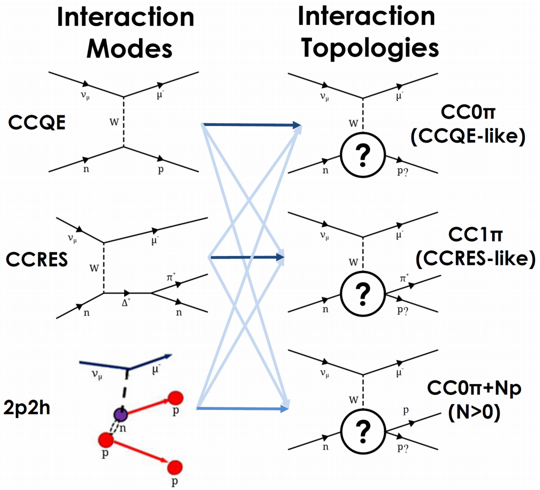


T. Van Cuyck, N. Jachowicz, R. González-Jiménez et al., Phys.Rev.C 95 (2017) 054611

T. Van Cuyck, N. Jachowicz, R. González-Jiménez et al., Phys.Rev.C 94 (2016) 024611

The MiniBooNE puzzle

An attempt to make a **pure CCQE measurement**...

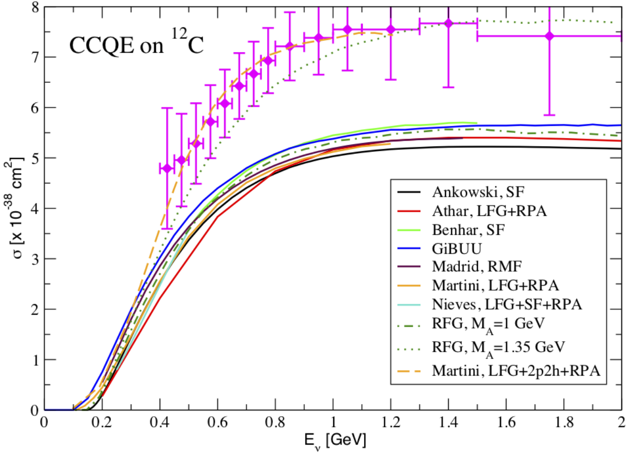


S. Dolan

The MiniBooNE puzzle

An attempt to make a **pure CCQE measurement**...

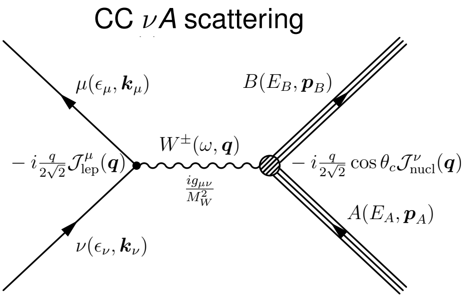
$\rightarrow$ suffered from huge **model dependencies**

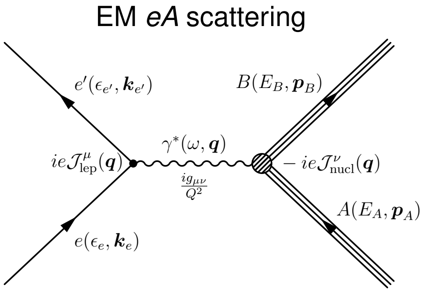


L. Alvarez-Ruso, Nucl.Phys.B Proc.Suppl. 229-232 (2012) 167-173 (Neutrino 2010)

The theoretical framework: language of response functions

Cross section formula





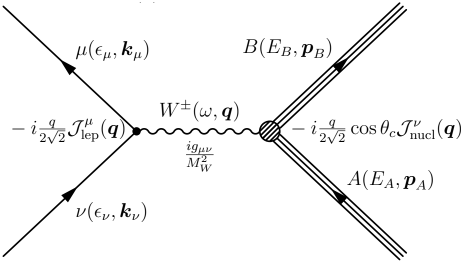
Currents:

$$\begin{aligned}
\mathcal{J}^{\rm lep}_\mu(q) &\equiv \bar{u}(k_f, s_f)\hat{J}^{\rm lep}_\mu u(k_i, s_i) = \bar{u}(k_f, s_f)\gamma_\mu(1 + h\gamma^5)u(k_i, s_i) \\
\mathcal{J}^{\rm nuc}_\mu(q) &\equiv \langle\Psi_f|\, \hat{J}^{\rm nuc}_\mu \,|\Psi_i\rangle
\end{aligned}$$

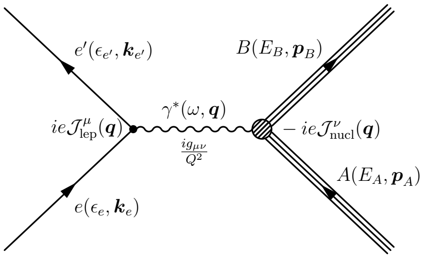
where $h = 0$ for (unpolarized) electrons, and $h = -(+)$ for (anti)neutrinos

Cross section formula

CC νA scattering



EM *eA* scattering

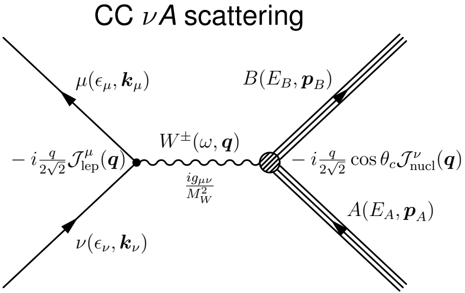


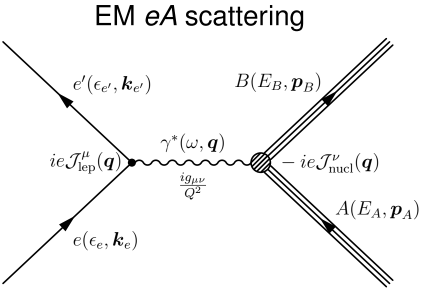
Matrix elements:

$$\mathcal{M}_{fi}^{W} = -i\frac{G_F}{\sqrt{2}}\cos\theta_c \mathcal{J}_{\nu}^{\mathrm{lep}}(q)\mathcal{J}_{\mathrm{nuc}}^{\nu}(q)$$

$$\mathcal{M}_{fi}^{\gamma} = -i\frac{e^2}{Q^2}\mathcal{J}_{\nu}^{\mathrm{lep}}(q)\mathcal{J}_{\mathrm{nuc}}^{\nu}(q)$$

Cross section formula





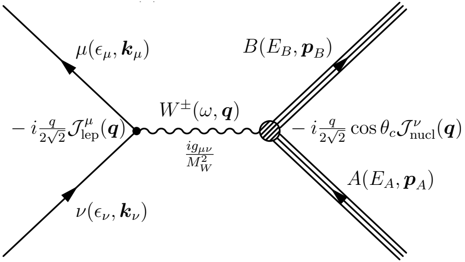
The cross section is propotional to the square:

$$\overline{\sum}_{if} \left|\mathcal{M}^W_{fi}\right|^2 = \frac{G_F^2}{2}\cos^2\theta_c L_{\mu\nu}H^{\mu\nu}$$

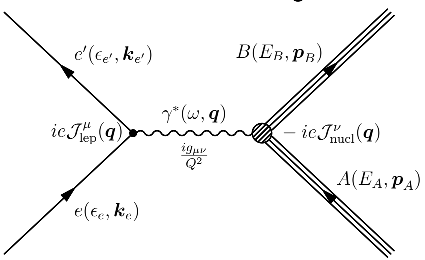
$$\overline{\sum}_{if} \left|\mathcal{M}^\gamma_{fi}\right|^2 = \frac{e^4}{4Q^2} L_{\mu\nu}H^{\mu\nu}$$

Cross section formula

CC νA scattering



EM *eA* scattering

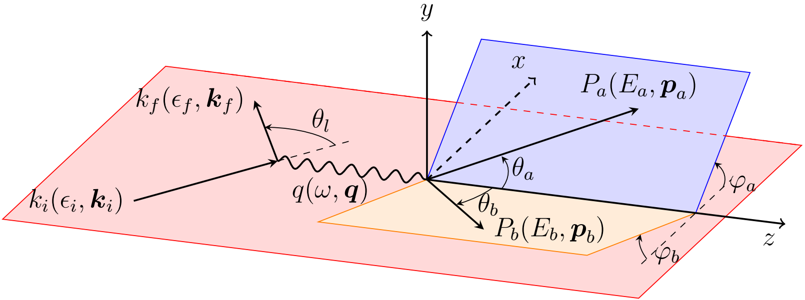


Leptonic tensor:

$$L_{\mu\nu} \propto \left(k_{i,\mu}k_{f,\nu} + k_{f,\nu}k_{i,\mu} + g_{\mu\nu}m_i m_f - g_{\mu\nu}k_i \cdot k_f - ih\epsilon_{\mu\nu\alpha\beta}k_i^\alpha k_f^\beta \right)$$

the axial term ($-ih\epsilon_{\mu\nu\alpha\beta}k_i^\alpha k_f^\beta$) drops down for electrons ($h = 0$)

Cross section formula



In such frame of reference:

$$L_{\mu\nu}W^{\mu\nu} = \frac{2\epsilon_i\epsilon_f}{m_i m_f} \quad [v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T + v_{TT}W_{TT} + v_{TC}W_{TC} + v_{TL}W_{TL} + h\,(v_{T'}W_{T'} + v_{TC'}W_{TC'} + v_{TL'}W_{TL'})]$$

Lepton responses

$$v_{CC} = 1 + \zeta \cos\theta$$

$$v_{CL} = -(\frac{\omega}{q}(1 + \zeta \cos\theta) + \frac{m_f^2}{\epsilon_f q})$$

$$v_{LL} = 1 + \zeta \cos\theta - \frac{2\epsilon_i \epsilon_f}{q^2} \zeta^2 \sin^2\theta$$

$$v_T = 1 - \zeta \cos\theta + \frac{\epsilon_i \epsilon_f}{q^2} \zeta^2 \sin^2\theta$$

$$v_{TT} = -\frac{\epsilon_i \epsilon_f}{q^2} \zeta^2 \sin^2\theta$$

$$v_{TC} = -\frac{\sin\theta}{\sqrt{2}q} \zeta(\epsilon_i + \epsilon_f)$$

$$v_{TL} = \frac{\sin\theta}{\sqrt{2}q^2} \zeta(\epsilon_i^2 - \epsilon_f^2 + m_f^2)$$

$$v_{T'} = \frac{\epsilon_i + \epsilon_f}{q}(1 - \zeta \cos\theta) - \frac{m_f^2}{\epsilon_f q}$$

$$v_{TC'} = -\frac{\sin\theta}{\sqrt{2}} \zeta$$

$$v_{TL'} = \frac{\omega}{q} \frac{\sin\theta}{\sqrt{2}} \zeta$$

$\rightarrow$ **dimensionless kinematical factors**

One-nucleon knockout

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

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

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

and the response functions W_i containing the nuclear information

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

$$\begin{aligned} \mathcal{J}_0 &= \langle\Psi_\mathrm{f}|\,\hat{J}_0(q)\,|\Psi_\mathrm{i}\rangle \\ \mathcal{J}_+ &= \langle\Psi_\mathrm{f}|\,\hat{J}_+(q)\,|\Psi_\mathrm{i}\rangle \\ \mathcal{J}_- &= \langle\Psi_\mathrm{f}|\,\hat{J}_-(q)\,|\Psi_\mathrm{i}\rangle \\ \mathcal{J}_3 &= \langle\Psi_\mathrm{f}|\,\hat{J}_3(q)\,|\Psi_\mathrm{i}\rangle \end{aligned}$$

Two-nucleon knockout

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{l'}\mathrm{d}\Omega_{l'}\mathrm{d}T_a\mathrm{d}\Omega_a\mathrm{d}\Omega_b} = \sigma^X \zeta\, g_{rec}^{-1} \times \Big[v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T + v_{TT}W_{TT} + v_{TC}W_{TC} + v_{TL}W_{TL} + h(v_{T'}W_{T'} + v_{TC'}W_{TC'} + v_{TL'}W_{TL'}) \Big],$$

$$W_{TT} = 2\Re\left(\mathcal{J}_+\mathcal{J}_-^\dagger\right)$$

$$W_{TC} = 2\Re\left(\mathcal{J}_0\left(\mathcal{J}_+ - \mathcal{J}_-\right)^\dagger\right)$$

$$W_{TL} = 2\Re\left(\mathcal{J}_3\left(\mathcal{J}_+ - \mathcal{J}_-\right)^\dagger\right)$$

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

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

$$\mathcal{J}_0 = \langle \Psi_\mathrm{f} | \widehat{J}_0(q) | \Psi_\mathrm{i} \rangle$$

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

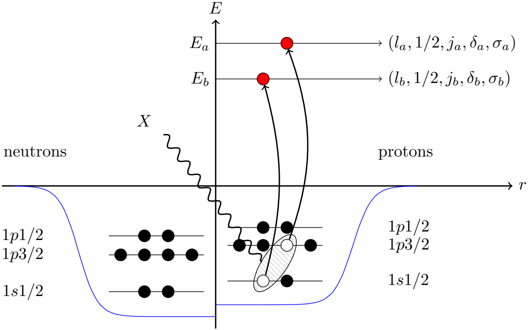
$$\mathcal{J}_- = \langle \Psi_\mathrm{f} | \widehat{J}_-(q) | \Psi_\mathrm{i} \rangle$$

$$\mathcal{J}_3 = \langle \Psi_\mathrm{f} | \widehat{J}_3(q) | \Psi_\mathrm{i} \rangle$$

$\rightarrow$ integrate over outgoing nucleons $\int \mathrm{d}T_a\, \mathrm{d}\Omega_a\, \mathrm{d}\Omega_b$

The theoretical framework:
nuclear modeling

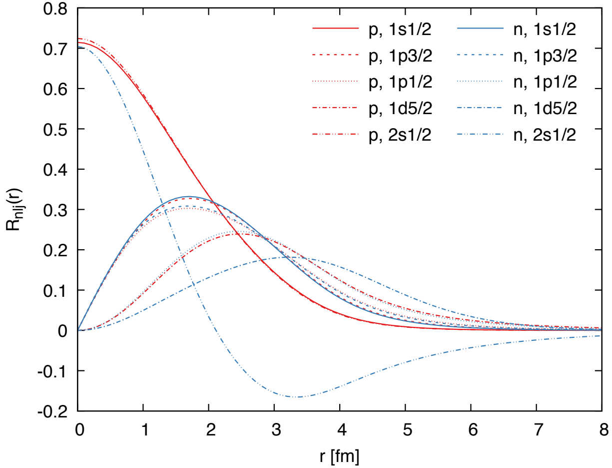
Nuclear model: initial state



- Ground state nucleus is an **independent-particle model** (IPM)
  - **Mean-field potential** results in a **shell model**
  - Calculated with a **Hartree-Fock** (HF) **approximation** using a Skyrme NN force (SkE2)
  - Accounts for **binding energies** and **nuclear structure**

Nuclear model: initial state

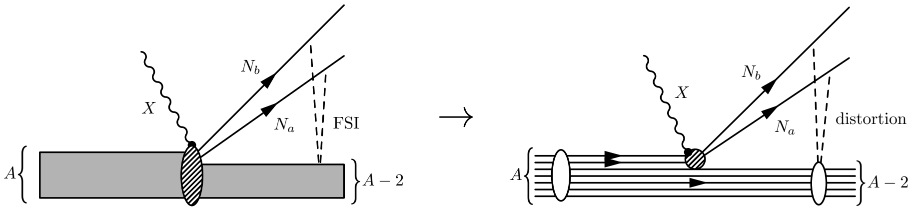
→ we iteravitely solve a **radial Schrödinger equation** for R_{ljm}



→ **carbon wave functions** for particular shells

Nuclear model: final state

- **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
  - Pauli-blocking effects included inherently



Multipole expansion

$\rightarrow$ we perform **non-relativistic reduction of operators**

$\rightarrow$ simplify integrals with **multipole expansion**

$$\hat{\rho}(\mathbf{q}) \rightarrow \hat{M}_{JM}^{\mathrm{Coul}}(q) = \int \mathrm{d}\mathbf{r}\,[j_J(qr)Y_{JM}(\Omega_r)]\,\hat{\rho}(\mathbf{r})$$

$$\hat{J}_3(\mathbf{q}) \rightarrow \hat{L}_{JM}^{\mathrm{long}}(q) = \frac{i}{q}\int \mathrm{d}\mathbf{r}\,[\nabla(j_J(qr)Y_{JM}(\Omega_r))]\cdot\hat{J}(\mathbf{r})$$

$$\hat{J}_{\pm}(\mathbf{q}) \rightarrow \hat{T}_{JM}^{\mathrm{elec}}(q) = \frac{1}{q}\int \mathrm{d}\mathbf{r}\left[\nabla\times(j_J(qr)\mathbf{Y}_{J(J,q)}^{M}(\Omega_r))\right]\cdot\hat{J}(\mathbf{r})$$

$$\rightarrow \hat{T}_{JM}^{\mathrm{magn}}(q) = \int \mathrm{d}\mathbf{r}\left[j_J(qr)\mathbf{Y}_{J(J,q)}^{M}(\Omega_r)\right]\cdot\hat{J}(\mathbf{r})$$

$\rightarrow$ summation over J increases the accuracy of our results

Nuclear currents in the IA

$$\hat{\rho}_V(\mathbf{r}) = \sum_i^A F_1(Q^2)\delta^{(3)}(\mathbf{r}-\mathbf{r}_i)\tau_\pm(i)$$

$$\hat{\rho}_A(\mathbf{r}) = \sum_i^A \frac{G_A(Q^2)}{2m_N i}\sigma_i \cdot \left[\delta^{(3)}(\mathbf{r}-\mathbf{r}_i)\overrightarrow{\nabla}_i - \overleftarrow{\nabla}_i\delta^{(3)}(\mathbf{r}-\mathbf{r}_i)\right]\tau_\pm(i)$$

$$\hat{J}_V(\mathbf{r}) = \hat{J}_{\rm con}(\mathbf{r}) + \hat{J}_{\rm mag}(\mathbf{r})$$

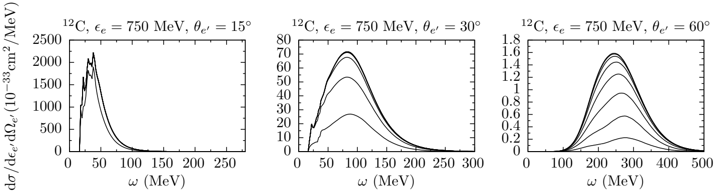
$$= \sum_i^A \frac{F_1(Q^2)}{2m_N i}\left[\delta^{(3)}(\mathbf{r}-\mathbf{r}_i)\overrightarrow{\nabla}_i - \overleftarrow{\nabla}_i\delta^{(3)}(\mathbf{r}-\mathbf{r}_i)\right]\tau_\pm(i)$$

$$+ \sum_i^A \frac{F_1(Q^2)+F_2(Q^2)}{2m_N}\left(\overrightarrow{\nabla}\times\sigma_i\right)\delta^{(3)}(\mathbf{r}-\mathbf{r}_i)\tau_\pm(i)$$

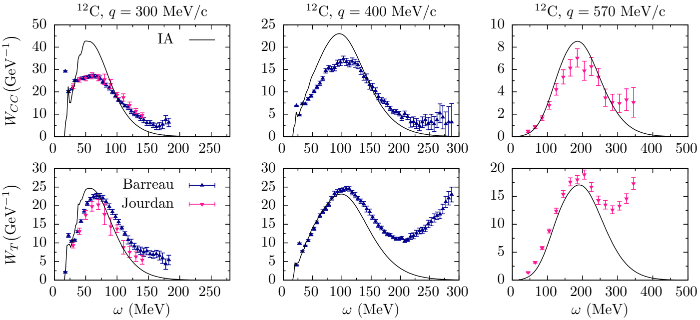
$$\hat{J}_A(\mathbf{r}) = \sum_i^A G_A(Q^2)\delta^{(3)}\sigma_i(\mathbf{r}-\mathbf{r}_i)\tau_\pm(i)$$

One-nucleon knockout

→ multipoles contribution

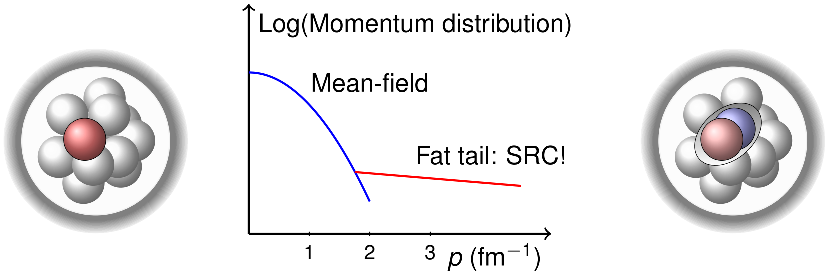


→ comparison to electron scattering data



Short-range correlations

Fat tails in the single-nucleon momentum distribution cannot be explained within an independent-particle model (IPM)



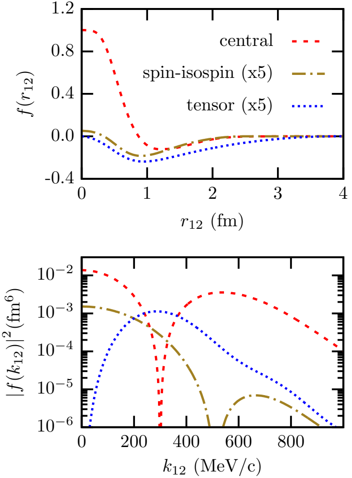
→ **Nucleons occur in pairs** with **high relative momenta** and **low center-of-mass momenta** (SRC pairs)

→ **Mean-field**: momenta **below** k_F, **SRC pairs**: momenta **above** k_F

→ A signature of SRC is back-to-back $2N$ knockout

→ SRC also have an effect on $1N$ knockout

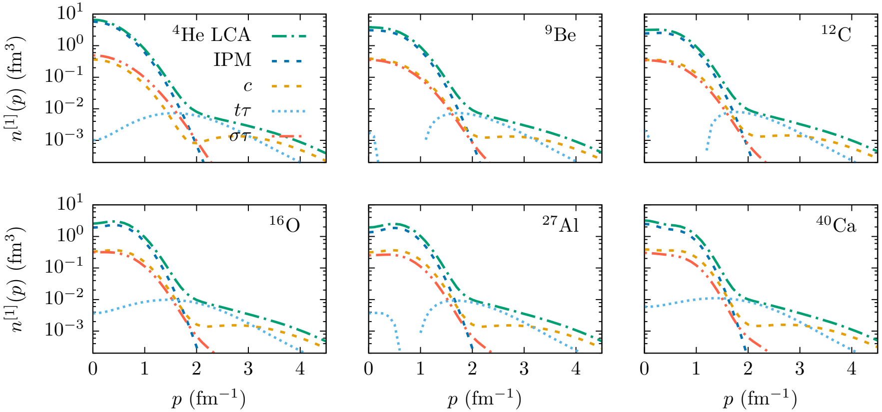
Short-range correlations



- The correlations have a short range: $f(r_{ij}) \to 0$ at $r_{ij} > 3$ fm
- Tensor correlation function dominates for intermediate relative momenta $200 - 400$ MeV/c
- Central correlation function dominates at high relative momenta
- Spin-isospin correlation function overall relatively small
- These correlation functions are input

(Gearhart, 1994), (Pieper, Wiringa, and Pandharipande, 1992)

Short-range correlations



Single-nucleon momentum distribution

J.Phys.G 42 (2015) 5, 055104

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

$$\widehat{\mathcal{G}} \approx \widehat{\mathcal{S}}\left(\prod_{i<j}^{A}\left[1+\widehat{l}(i,j)\right]\right)$$

with $\widehat{\mathcal{S}}$ the symmetrization operator and

$$\widehat{l}(i,j) = -g_c(r_{ij}) + f_{t\tau}(r_{ij})\widehat{S}_{ij}\left(\vec{\tau}_i\cdot\vec{\tau}_j\right) + f_{\sigma\tau}(r_{ij})\left(\vec{\sigma}_i\cdot\vec{\sigma}_j\right)\left(\vec{\tau}_i\cdot\vec{\tau}_j\right).$$

$g_c(r_{ij})$, $f_{t\tau}(r_{ij})$ and $f_{\sigma\tau}(r_{ij})$ are the respective correlation functions

Correlation functions: (Gearhart, 1994), (Pieper, Wiringa, and Pandharipande, 1992)

Short-range correlations

Transition matrix elements between correlated states $|\Psi\rangle$ can be written as ones between uncorrelated states $|\Phi\rangle$, with an effective transition operator

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

with

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

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

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

Short-range correlations

Use the fact that SRC is a short-range phenomenon

→ Terms linear in the correlation operator are retained

→ A-body operator → 2-body operator

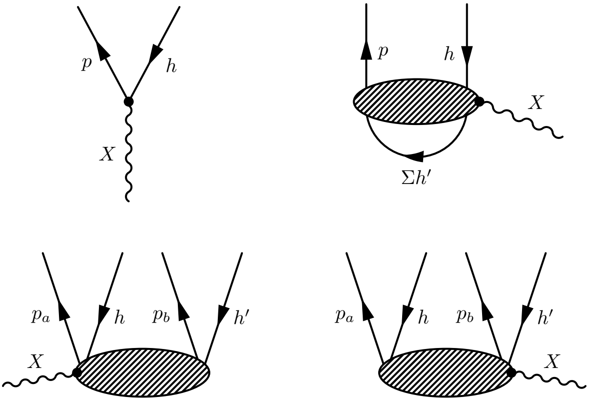
$$\widehat{J}_{\lambda}^{\text{eff}} \approx \underbrace{\sum_{i=1}^{A} \widehat{J}_{\lambda}^{[1]}(i)}_{\text{one-body(IA)}} + \underbrace{\sum_{i<j}^{A} \widehat{J}_{\lambda}^{[1],\text{in}}(i,j), + \left[\sum_{i<j}^{A} \widehat{J}_{\lambda}^{[1],\text{in}}(i,j)\right]^{\dagger}}_{\text{two-body(SRC)}}$$

where

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

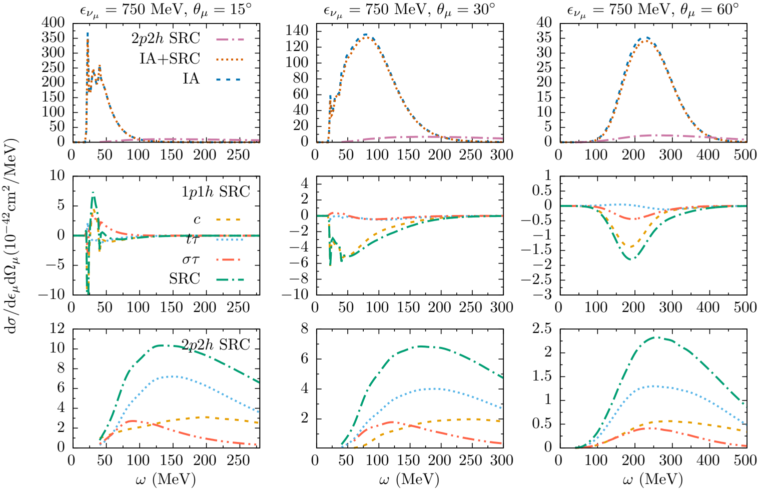
→ Effective nuclear current is the sum of a one-body (IA) and two-body (SRC) current

Short-range correlations



The 1p1h (top) and 2p2h (bottom) diagrams considered. The top left diagram shows the 1p1h channel in the IA.

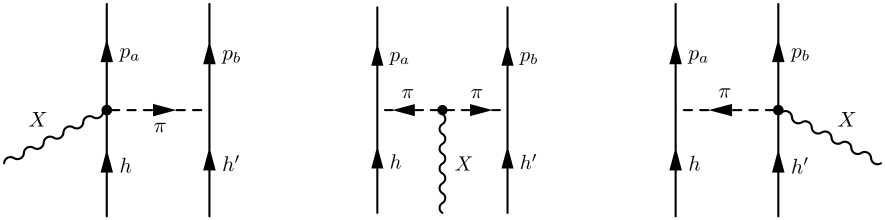
SRC results - Inclusive ^{12}C(ν_μ, μ^-)



→ Small decrease of 1p1h channel due to SRCs

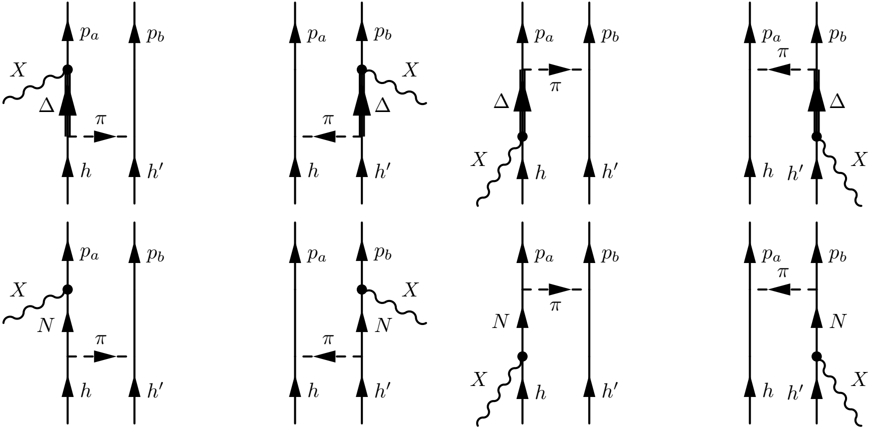
→ Inclusive 2p2h appears as a broad background to 1p1h

Meson-exchange currents



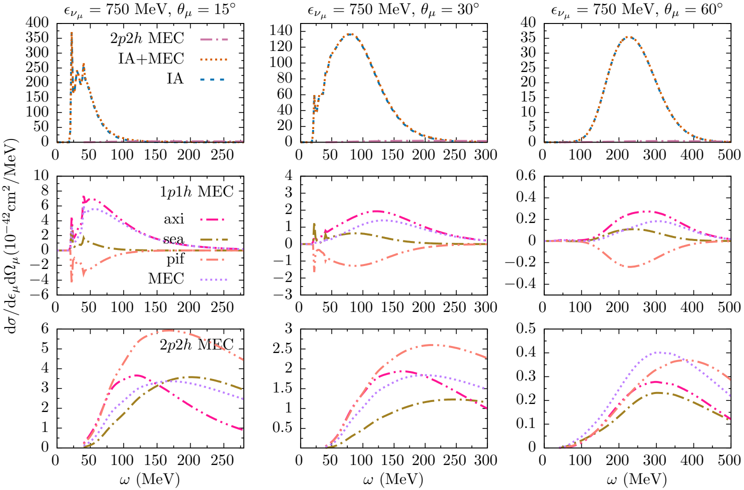
The seagull and pion-in-flight currents.

Meson-exchange currents



The Δ currents (top) and correlation currents (bottom).

MEC results - Inclusive ^{12}C(ν_μ, μ^-)



→ Small increase of 1p1h channel due to MECs

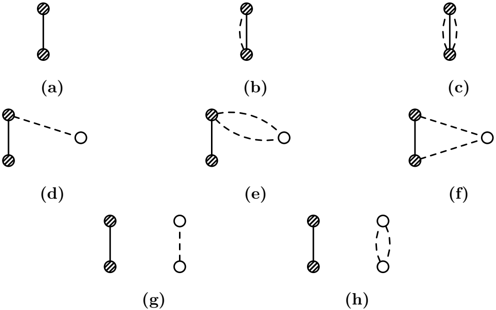
→ Inclusive 2p2h appears as a broad background to 1p1h

SRS + MEC

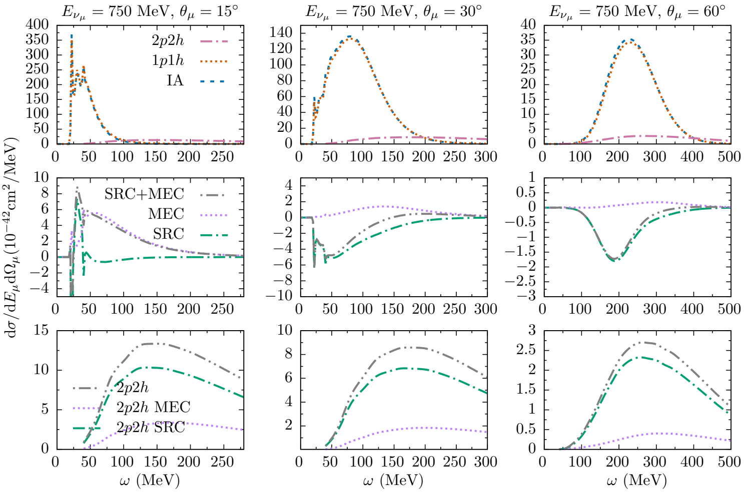
Extend the current model with MECs

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

$$+ \underbrace{\sum_{i<j}^{a} \widehat{J}^{[2],\text{sea}}_{\lambda}(i,j) + \sum_{i<j}^{a} \widehat{J}^{[2],\text{pif}}_{\lambda}(i,j)}_{\text{two-body(MEC)}}$$



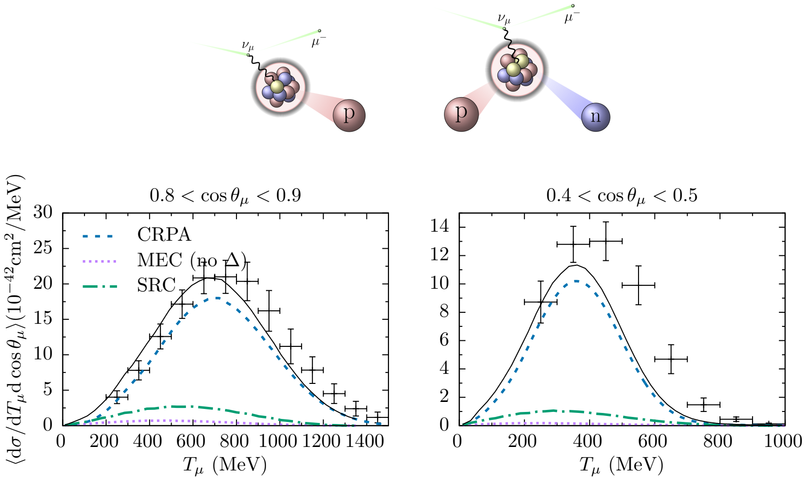
SRC + MEC results - Inclusive ^{12}C(ν_μ, μ^-)



→ Effect of MECs largest for small θ_μ, SRCs for larger θ_μ in 1*p*1*h* channel

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

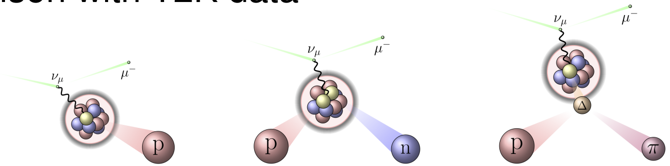
Comparison with MiniBooNE data

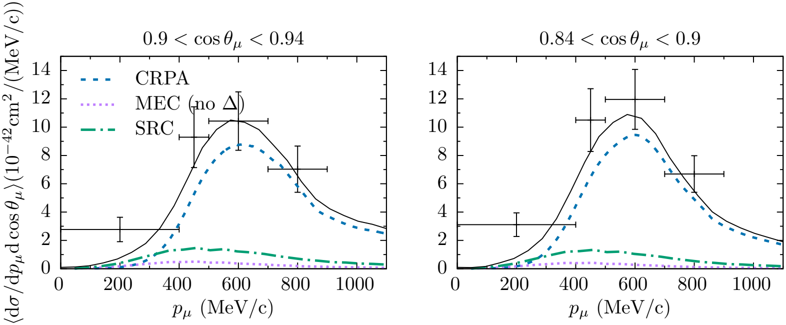


MiniBooNE 'CCQE-like' data from Phys.Rev.D 81 (2010) 092005

CRPA results are from Phys.Rev.C 94 (2016) 054609

Comparison with T2K data

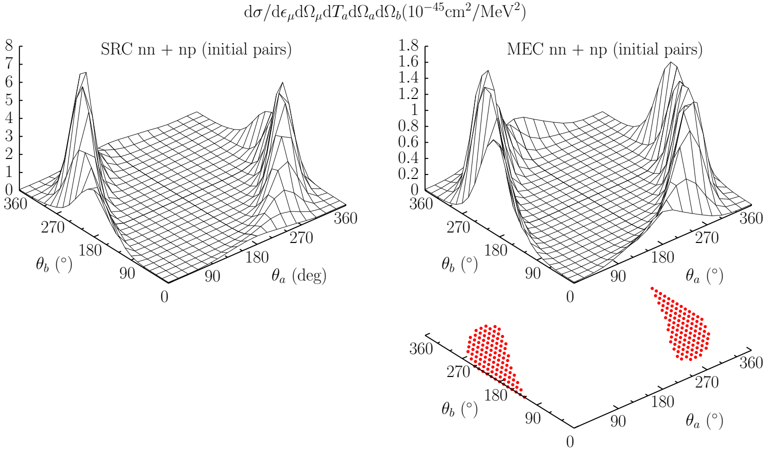




Inclusive T2K data from Phys.Rev.D 87 (2013) 092003

CRPA results are from Phys.Rev.C 94 (2016) 054609

Exclusive $A(\nu_\mu, \mu^- N_a N_b)$



The ^{12}C$(\nu_\mu, \mu^- N_a N_b)$ cross section at $\epsilon_{\nu_\mu} = 750$ MeV, $\epsilon_\mu = 550$ MeV, $\theta_\mu = 15^\circ$ and $T_p = 50$ MeV for in-plane kinematics ($q = 268$ MeV/c, $x_B = 0.08$). The bottom panel shows $P_{12} < 300$ MeV/c.

Summary

→ The **Ghent group** provides a **powerful model** capable of calculating various contributions to the **2p2h final states**

→ The **MEC calculation misses Δ-currents** and needs to be further developed

→ Efforts are done to **implement** such model in **Monte Carlo event generators** so it can be used in **experimental analyses**

Collaborators

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  - Nils Van Dessel

and many more...