FACULTY OF SCIENCES

Lecture II : Modeling neutrino-nucleus interactions

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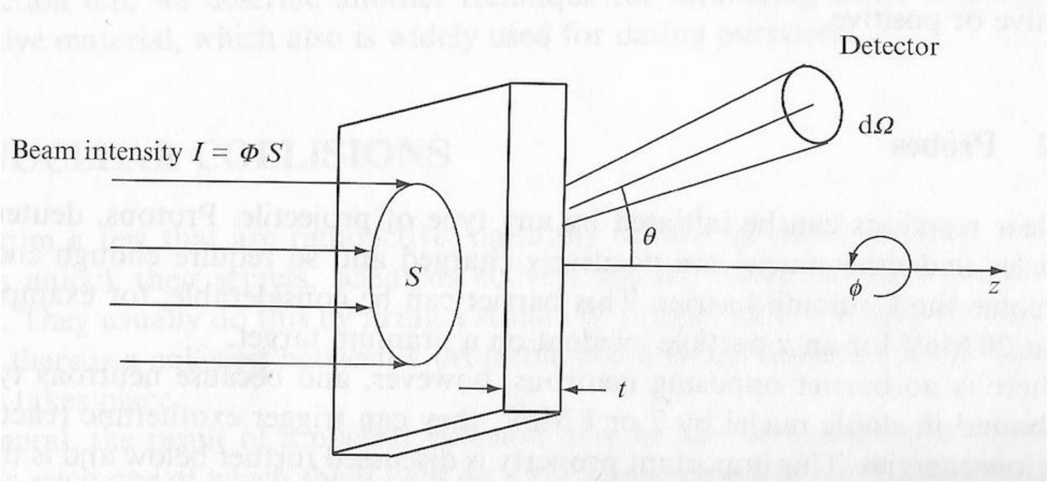
Cross section and reaction rate

Flux=#particles/unit area/unit time



Number density of projectile particles in the beam

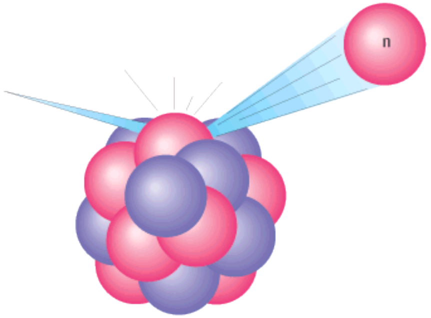
$$\Phi = n_P v \quad \left(= \int v n_P(v) dv\right)$$
$$= \frac{I}{S}$$

Cross section σ = measure of the interaction probability per collision

= # events R / # target nuclei N/incident flux

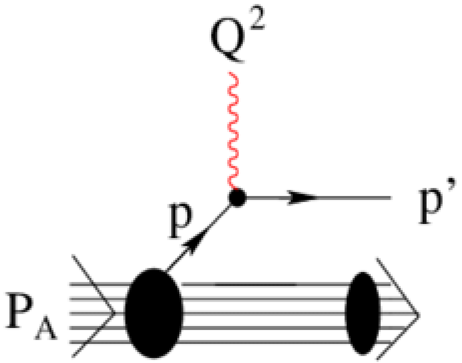
$$R = N\sigma\Phi$$

(Quasi)scattering off a nucleus vs scattering off a nucleon



Impulse approximation : a very important concept !

- The interaction between the projectile and bound target nucleons has essentially the same form as the interaction between two particles in free space
- Often the scattering is dominated by single-collision processes : the lepton most often couples to a single nucleon in the nucleus
- Description assumes that the interaction takes place with 1 nucleon in the nucleus,
- Total cross section is the sum of these lepton-nucleon interactions
- Extra corrections and correlations can be added
- Approach is valid when the momentum transfer is high enough, since then the resolution of the probe is small



Sum over all nucleons !

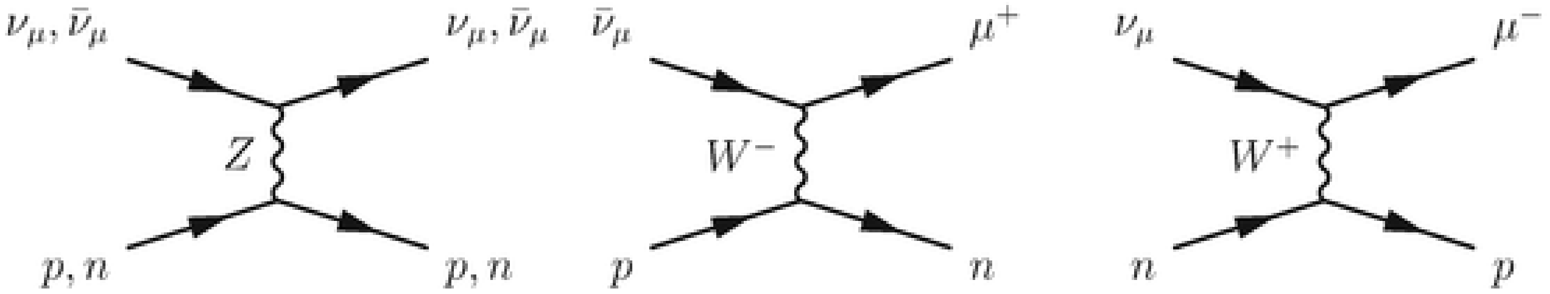
$$\widehat{J}^{\mu}_{nuc}(\boldsymbol{x}) = \sum_{i=1}^{A} \widehat{J}^{\mu}(\boldsymbol{x}_i)\delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}_i)$$

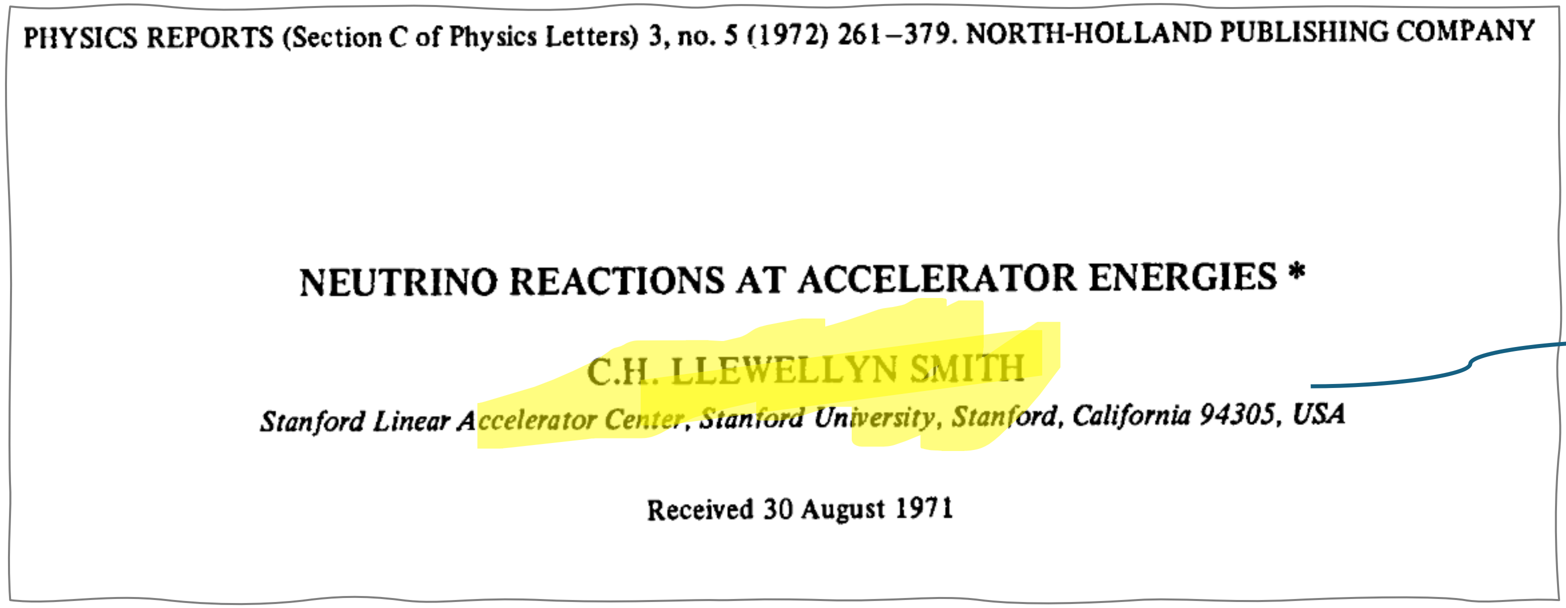
Insert bound nucleons wave functions for the initial nucleon states

The basic ingredient : Scattering off a nucleon

Several options

- Neutral current
- Charged current
- Neutrinos or antineutrinos
- Electron, mu or tauneutrinos ...




PHYSICS REPORTS (Section C of Physics Letters) 3, no. 5 (1972) 261–379. NORTH-HOLLAND PUBLISHING COMPANY

NEUTRINO REACTIONS AT ACCELERATOR ENERGIES *

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Received 30 August 1971

Ingredient for **quasi-elastic** scattering in most generators

The basic ingredient : Scattering off a nucleon

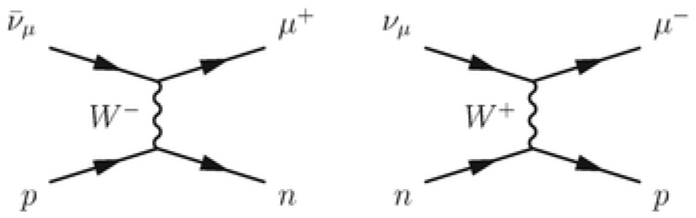
1.3. *The intermediate vector boson (IVB)*

The hypothesis that the weak interactions are mediated by an IVB is very old. The simplest possibility is to introduce two charged vector bosons (W^+ and W^-), which interact only weakly and electromagnetically, and write:

$$\mathcal{L}_{\rm weak} = g_W J_\lambda W^\lambda + \text{hermitian conjugate} . \qquad (1.11)$$

To lowest order in q^2/M_W^2, this generates $\mathcal{L}_{\rm eff}$ above to order g_W^2, with

$$g_W^2/M_W^2 = G/\sqrt{2} .$$



1.1. *The phenomenological theory*

A. *The effective Lagrangian for leptonic and semileptonic processes*

All leptonic and semileptonic interactions directly observed up to now can be described by the phenomenological Lagrangian:

$$\mathcal{L}_{\rm eff} = \frac{G}{\sqrt{2}} \left[(j_\lambda^{(e)} + j_\lambda^{(\mu)})^+ J^{(h)\lambda} + j_\lambda^{(e)+} j^{(\mu)\lambda} + \begin{matrix}\text{hermitian}\\ \text{conjugate}\end{matrix} \right] \qquad (1.1)$$

where G is Fermi's constant

$$G = \frac{(1.023 \pm 0.001) \times 10^{-5}}{M_p^2} ,$$

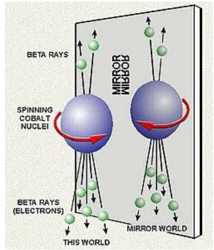
$J_\lambda^{(h)}(x)$ is a current constructed from the hadronic fields and the muon and electron currents are given by

$$j_\lambda^{(\mu),(e)} = \bar{\psi}_{\mu,e}(x)\, \gamma_\lambda (1-\gamma_5)\, \psi_{\nu_\mu,\nu_e}(x) \qquad (1.2)$$

Lepton x hadron current

V-A structure for the lepton current

Leptons : point particles
Weak interaction :
maximal parity violation



The basic ingredient : Scattering off a nucleon

Hadron currents can be constructed from

- Four vectors of incoming and outgoing particles
- Lorentz invariance
- Form factors to take into account the structure and extension of the nucleon (we are not dealing with a quark current !)

A. *General remarks*

The hadronic current describing the process

$$\nu(k_1) + \mathrm{n}(p_1) \rightarrow \ell^-(k_2) + \mathrm{p}(p_2)$$

may be written

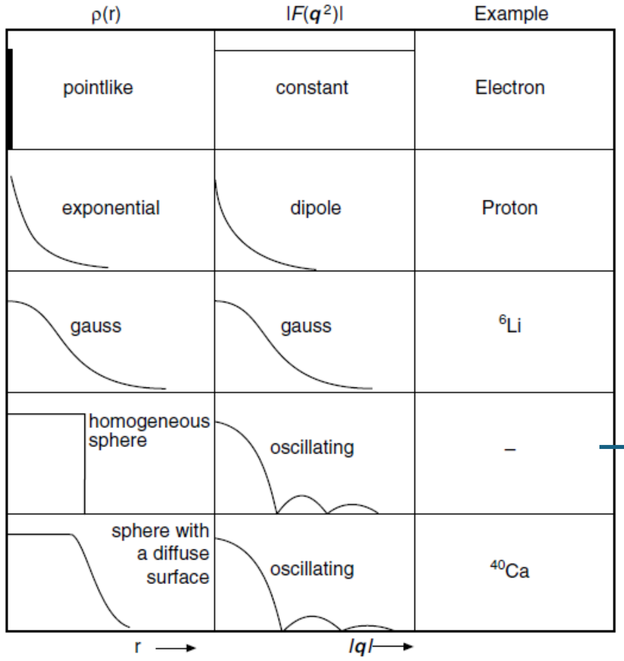
$$\langle \mathrm{p}(p_2)|J^+_\lambda|\mathrm{n}(p_1)\rangle = \cos\theta_c \bar{u}(p_2)\Gamma_\lambda u(p_1)$$

$$\Gamma_\lambda = \gamma_\lambda F^1_V(q^2) + \frac{i\sigma_{\lambda\nu}q^\nu \xi F^2_V(q^2)}{2M} + \frac{q_\lambda F^3_V(q^2)}{M} + \gamma_\lambda\gamma_5 F_A(q^2) + \frac{q_\lambda\gamma_5 F_p(q^2)}{M} + \frac{\gamma_5(p_1+p_2)_\lambda F^3_A(q^2)}{M} \tag{3.13}$$

$$= \gamma_\lambda\left(F^1_V + \frac{(M_1+M_2)\xi F^2_V}{2M}\right) + \frac{q_\lambda F^3_V}{M} - \frac{(p_1+p_2)_\lambda \xi F^2_V}{2M}$$

$$+ \gamma_\lambda\gamma_5\left(F_A + \frac{(M_2-M_1)F^3_A}{M}\right) + i\gamma_5\frac{\sigma_{\lambda\nu}q^\nu F^3_A}{M} + \frac{q_\lambda\gamma_5 F_p}{M}$$

$$\left(q = k_1 - k_2 = p_1 - p_2,\ M = \tfrac{1}{2}(M_1 + M_2)\right).$$



→ Essentially : Fourier transform of density distribution

The basic ingredient : Scattering off a nucleon

Important points to notice about the quasi-elastic process are:

(1) If polarizations are not measured, only 3 combinations of the 6 complex form factors can be determined according to the general theorems in section 2.1. We have

$$\frac{d\sigma}{d|q^2|}\begin{pmatrix}\nu n\to \ell^- p\\ \bar{\nu} p\to \ell^+ n\end{pmatrix} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(q^2)\mp B(q^2)\frac{(s-u)}{M^2}+\frac{C(q^2)(s-u)^2}{M^4}\right] \tag{3.18}$$

$$(s-u = 4ME_\nu + q^2 - m^2)\,.$$

$$\begin{aligned}
A &= \frac{(m^2-q^2)}{4M^2}\Bigg[\left(4-\frac{q^2}{M^2}\right)|F_A|^2-\left(4+\frac{q^2}{M^2}\right)|F_V^1|^2-\frac{q^2}{M^2}|\xi F_V^2|^2\left(1+\frac{q^2}{4M^2}\right)-\frac{4q^2\,\mathrm{Re}\,F_V^{1*}\xi F_V^2}{M^2}\\
&\quad+\frac{q^2}{M^2}\left(4-\frac{q^2}{M^2}\right)|F_A^3|^2-\frac{m^2}{M^2}\left(|F_V^1+\xi F_V^2|^2+|F_A+2F_P|^2+\left(\frac{q^2}{M^2}-4\right)\left(|F_V^3|^2+|F_P|^2\right)\right)\Bigg]\\
B &= -\frac{q^2}{M^2}\,\mathrm{Re}\,F_A^*(F_V^1+\xi F_V^2)-\frac{m^2}{M^2}\,\mathrm{Re}\left[\left(F_V^1+\frac{q^2}{4M^2}\xi F_V^2\right)^* F_V^3-\left(F_A+\frac{q^2 F_P}{2M^2}\right)^* F_A^3\right]\\
C &= \frac{1}{4}\left(|F_A|^2+|F_V^1|^2-\frac{q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2-\frac{q^2}{M^2}|F_A^3|^2\right).
\end{aligned} \tag{3.22}$$

Nucleon Form Factors

- Information about the structure of the nucleon is encoded in form factors
- Neutrino-nucleon form factors constitute a major source of uncertainty in neutrino scattering modeling
- Weak vector form factors are well constrained by electron scattering experiments by CVC

$$\hat{J}^\mu = F_1(Q^2)\gamma^\mu + \frac{i}{2m_N}F_2(Q^2)\sigma^{\mu\nu}q_\nu + G_A(Q^2)\gamma^\mu\gamma_5 + G_P(Q^2)q^\mu\gamma_5$$

$$G_E = F_1 - \tau F_2 \text{ and } G_M = F_1 + F_2 \qquad \tau = Q^2/4m_N^2$$

G :electric and magnetic Sachs form factors

$$F_i = \begin{cases} (\frac{1}{2} - \sin^2\theta_W)F_i^{EM,V}\tau_3 - \sin^2\theta_W F_i^{EM,S} - \frac{1}{2}F_i^s & \text{NC} \\ F_i^{EM,V}\tau_\pm & \text{CC} \end{cases}$$

$$\tau_3|p\rangle = +|p\rangle, \quad \tau_3|n\rangle = -|n\rangle,$$
$$\tau_+|n\rangle = +|p\rangle, \quad \tau_+|p\rangle = 0,$$
$$\tau_-|p\rangle = -|n\rangle, \quad \tau_-|n\rangle = 0.$$

$$G_{Ep} = G_D, \quad G_{Mp} = \mu_p G_D, \quad G_{Mn} = \mu_n G_D$$

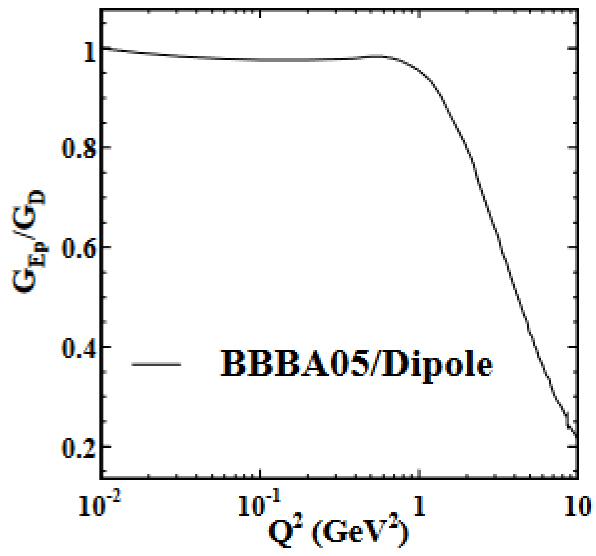
Q^2 dependence Form factor parameterizations !

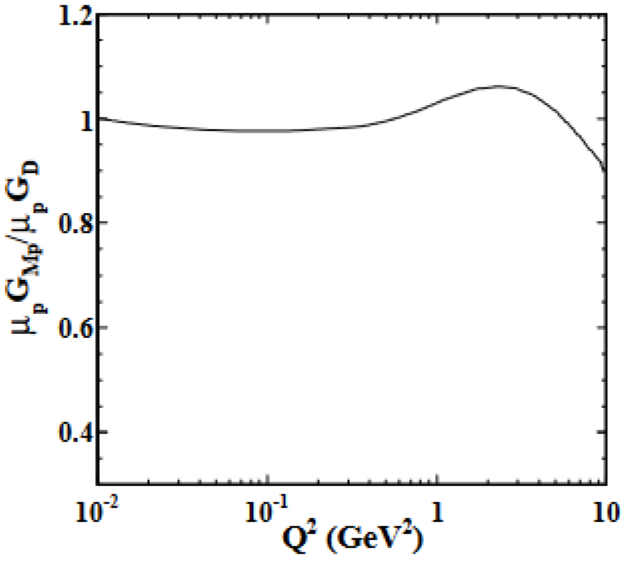
Traditional : Dipole :

$$G_D(Q^2) = \frac{1}{(1+\frac{Q^2}{M_V^2})^2}, \quad M_V = 843 \text{ MeV}$$

$$G_{En}(Q^2) = -\frac{\tau}{1+5.6\tau}G_{Mn}(Q^2)$$

Galster parameterization





Nucleon Form Factors

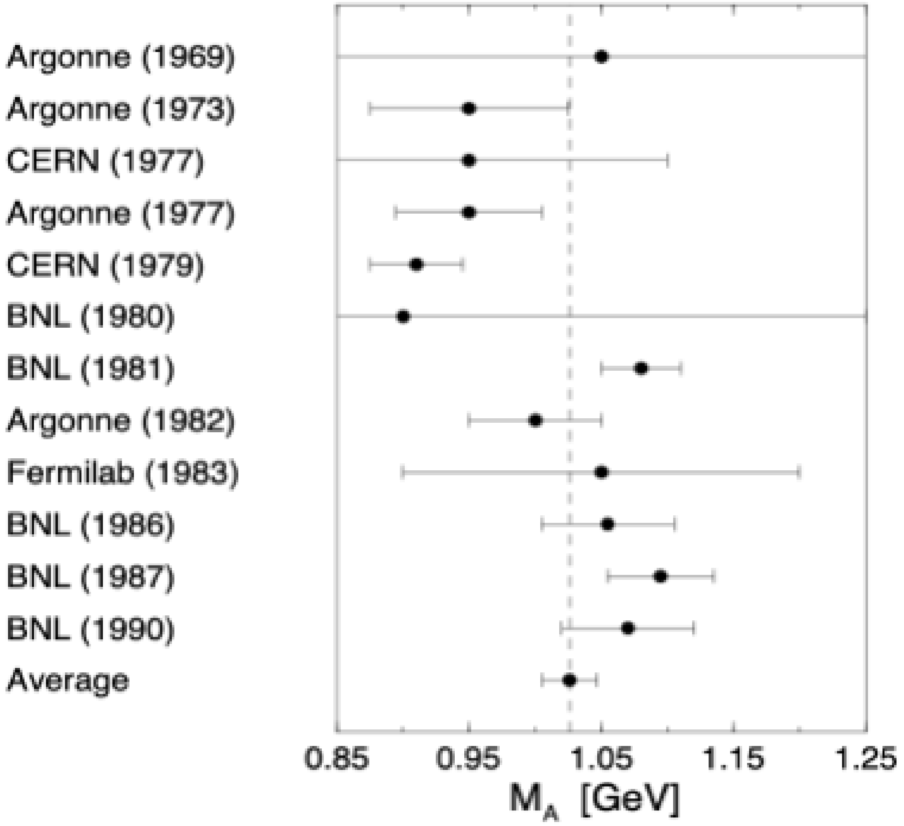
Neutrino-nucleon form factors constitute a major source of uncertainty in neutrino scattering modeling

- Weak vector form factors are well constrained by electron scattering experiments
- Q^2 evolution of the axial form factor is not well-known, mainly based on old bubble chamber data (ANL, BNL, FNAL)

$$G_A = \begin{cases} \frac{-g_A \tau_3 + g_A^s}{2} & \text{NC} \\ g_A \tau_\pm & \text{CC} \end{cases}$$

Axial form factors Q^2 evolution subject to uncertainties

$$G_A(Q^2) = \frac{g_A}{(1+Q^2/M_A^2)^2}$$



Tension with MiniBooNE data : needed higher value to explain data

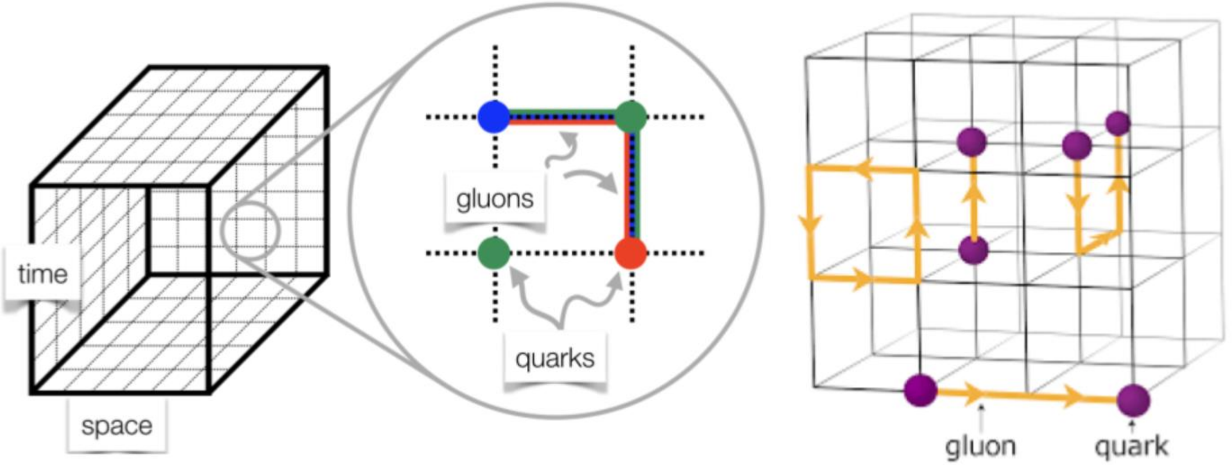
Nucleon Form Factors

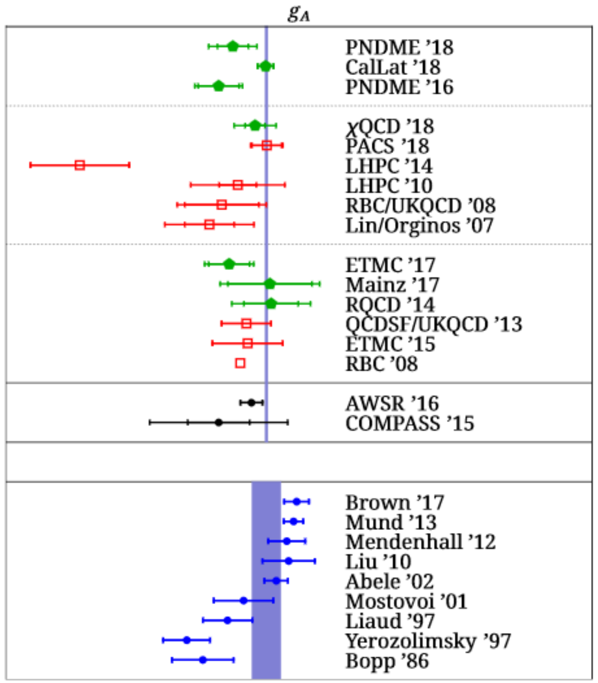
More recent parameterizations :

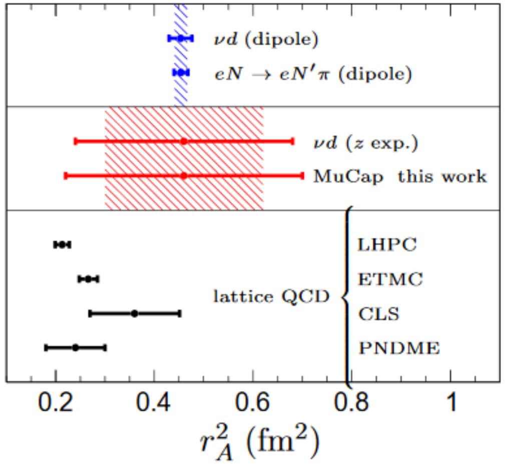
- Lattice QCD efforts : Improved LQCD prediction owing to better control of excited state contamination
- Z-expansion (Meyer et al. PRD84(2011)) :

$$F_A(q^2) = \sum_{k=0}^{k_{\max}} a_k z(q^2)^k$$

Allows for a better quantization of uncertainties

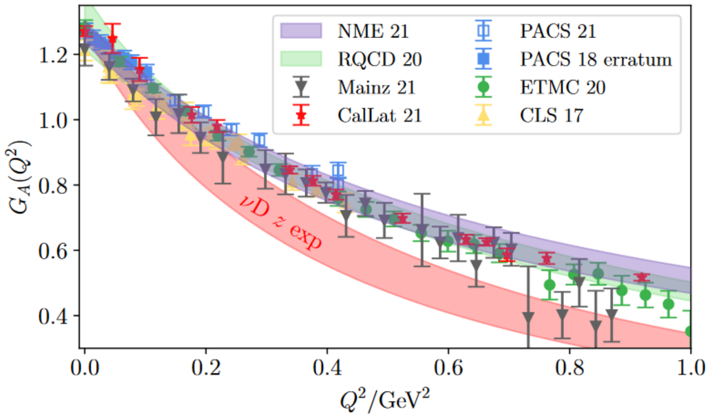


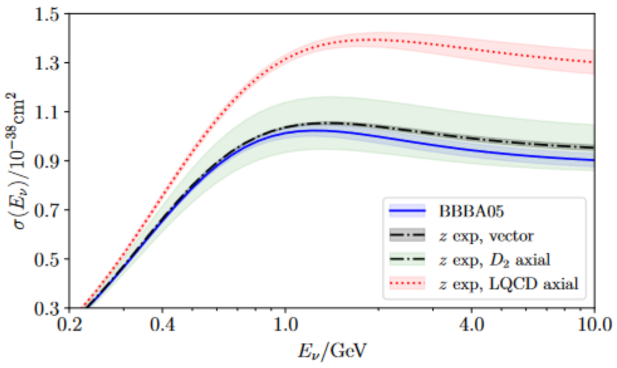




$$r_i^2 \equiv \frac{6}{F_i(0)} \left.\frac{dF_i}{dq^2}\right|_{q^2=0}$$

Nucleon Form Factors

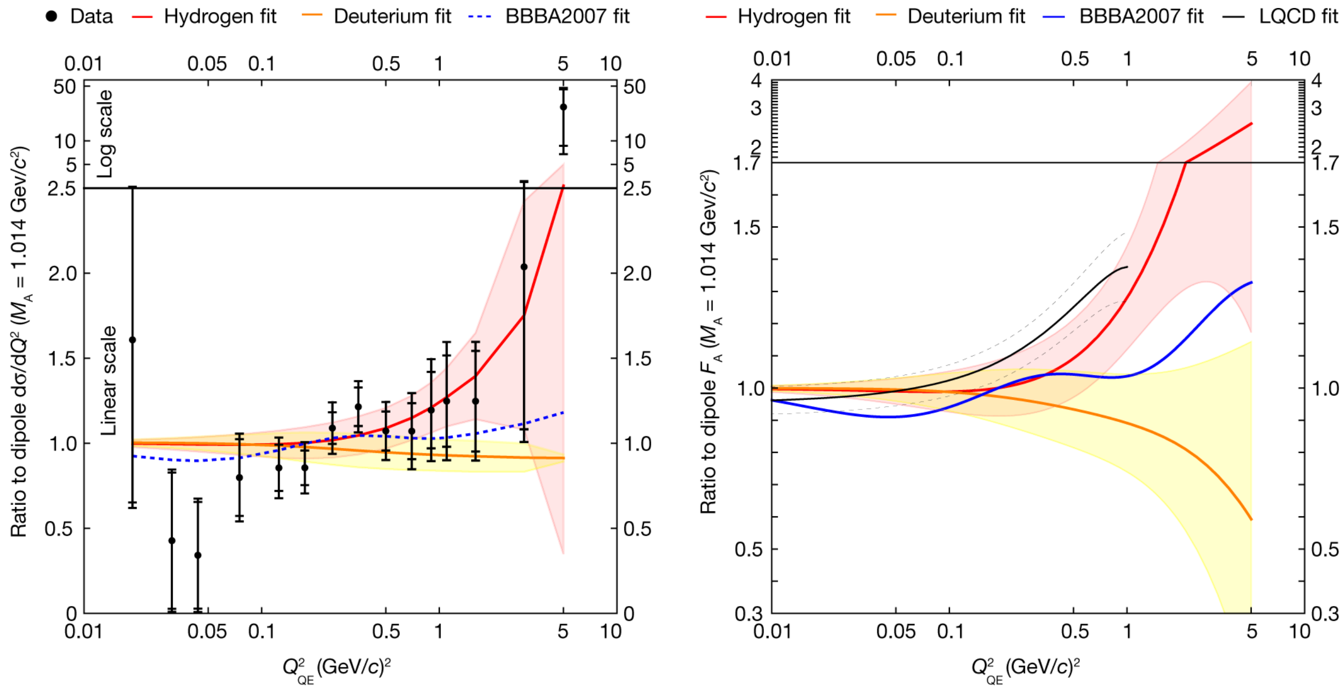




A. Meyer et al arXiv:2201.01839

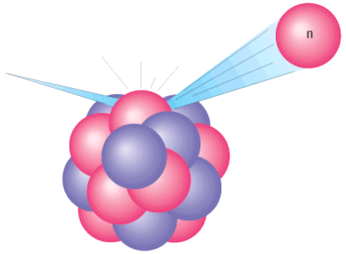
- Softer slope of the axial form factor's Q^2 dependence in LQCD results leads to enhanced cross section on the nucleon

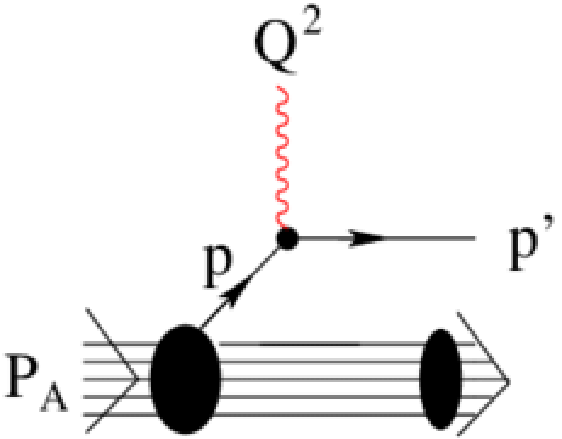
<u>MINERvA, Nature</u> volume 614, pages 48–53 (2023)
New form factor measurement



From scattering off the nucleon to scattering off the nucleus

If the nucleon is bound in a nucleus :





Impulse approximation :

- the interaction between the projectile and target nucleons has essentially the same form as the interaction between two particles in free space
- scattering is dominated by single-collision processes
- the lepton couples to a single nucleon in the nucleus

$$\frac{d^3\sigma}{d\omega d\Omega_f} \propto L_{\mu\nu} W^{\mu\nu}$$
$$\propto v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T + h v_{T'} W_{T'}$$

Sum over all nucleons !

$$\widehat{J}^{\mu}_{nuc}(\boldsymbol{x}) = \sum_{i=1}^{A} \widehat{J}^{\mu}(\boldsymbol{x}_i)\delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}_i)$$

Insert wave functions for nucleons feeling the nuclear potentialfor the nucleon states

More important things you should know about neutrino-nucleus scattering : inclusive vs exclusive

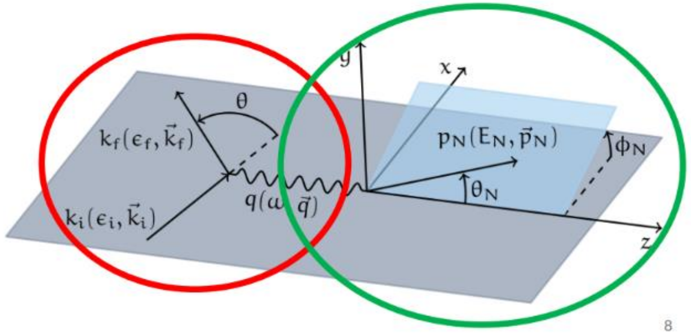
$$\frac{d^3\sigma}{d\omega d\Omega_f} \propto L_{\mu\nu} W^{\mu\nu}$$

$$\propto v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T + h v_{T'} W_{T'}$$

→

$$\frac{d^5\sigma}{d\omega d\Omega_f d\Omega_N} \propto L_{\mu\nu} W^{\mu\nu}$$

$$\propto v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T + v_{TT}W_{TT}$$
$$v_{TC}W_{TC} + v_{TL}W_{TL} + h(v_{T'}W_{T'} + v_{TC'}W_{TC'} + v_{TL'}W_{TL'})$$



leptons

Kinematic factors			Nuclear responses		
v_{CC}	=	$1 + \zeta\cos\theta$	w_{CC}	=	$\lvert\mathcal{J}_0\rvert^2$
v_{CL}	=	$-\left(\frac{\omega}{\lvert\vec{q}\rvert}(1+\zeta\cos\theta) + \frac{m_f^2}{\epsilon_f\lvert\vec{q}\rvert}\right)$	w_{CL}	=	$2\Re\left(\mathcal{J}_0\mathcal{J}_3^\dagger\right)$
v_{LL}	=	$1 + \zeta\cos\theta - 2\frac{\epsilon_i\epsilon_f}{\lvert\vec{q}\rvert^2}\zeta^2\sin^2\theta$	w_{LL}	=	$\lvert\mathcal{J}_3\rvert^2$
v_T	=	$1 - \zeta\cos\theta + \frac{\epsilon_i\epsilon_f}{\lvert\vec{q}\rvert^2}\zeta^2\sin^2\theta$	w_T	=	$\lvert\mathcal{J}_{+1}\rvert^2 + \lvert\mathcal{J}_{-1}\rvert^2$
v_{TT}	=	$-\frac{\epsilon_i\epsilon_f}{\lvert\vec{q}\rvert^2}\zeta^2\sin^2\theta$	w_{TT}	=	$2\Re\left(\mathcal{J}_{+1}\mathcal{J}_{-1}^\dagger\right)$
v_{TC}	=	$-\frac{\sin\theta}{\sqrt{2}\lvert\vec{q}\rvert}\zeta(\epsilon_i + \epsilon_f)$	w_{TC}	=	$2\Re\left(\mathcal{J}_0\left(\mathcal{J}_{+1}^\dagger - \mathcal{J}_{-1}^\dagger\right)\right)$
v_{TL}	=	$\frac{\sin\theta}{\sqrt{2}\lvert\vec{q}\rvert^2}\zeta(\epsilon_i^2 - \epsilon_f^2 + m_f^2)$	w_{TL}	=	$2\Re\left(\mathcal{J}_3\left(\mathcal{J}_{+1}^\dagger - \mathcal{J}_{-1}^\dagger\right)\right)$
$v_{T'}$	=	$\frac{\epsilon_i+\epsilon_f}{\lvert\vec{q}\rvert}(1 - \zeta\cos\theta) - \frac{m_f^2}{\epsilon_f\lvert\vec{q}\rvert}$	$w_{T'}$	=	$\lvert\mathcal{J}_{+1}\rvert^2 - \lvert\mathcal{J}_{-1}\rvert^2$
$v_{TC'}$	=	$-\frac{\sin\theta}{\sqrt{2}}\zeta$	$w_{TC'}$	=	$2\Re\left(\mathcal{J}_0\left(\mathcal{J}_{+1}^\dagger + \mathcal{J}_{-1}^\dagger\right)\right)$
$v_{TL'}$	=	$\frac{\omega\sin\theta}{\sqrt{2}\lvert\vec{q}\rvert^2}\zeta$	$w_{TL'}$	=	$2\Re\left(\mathcal{J}_3\left(\mathcal{J}_{+1}^\dagger + \mathcal{J}_{-1}^\dagger\right)\right)$

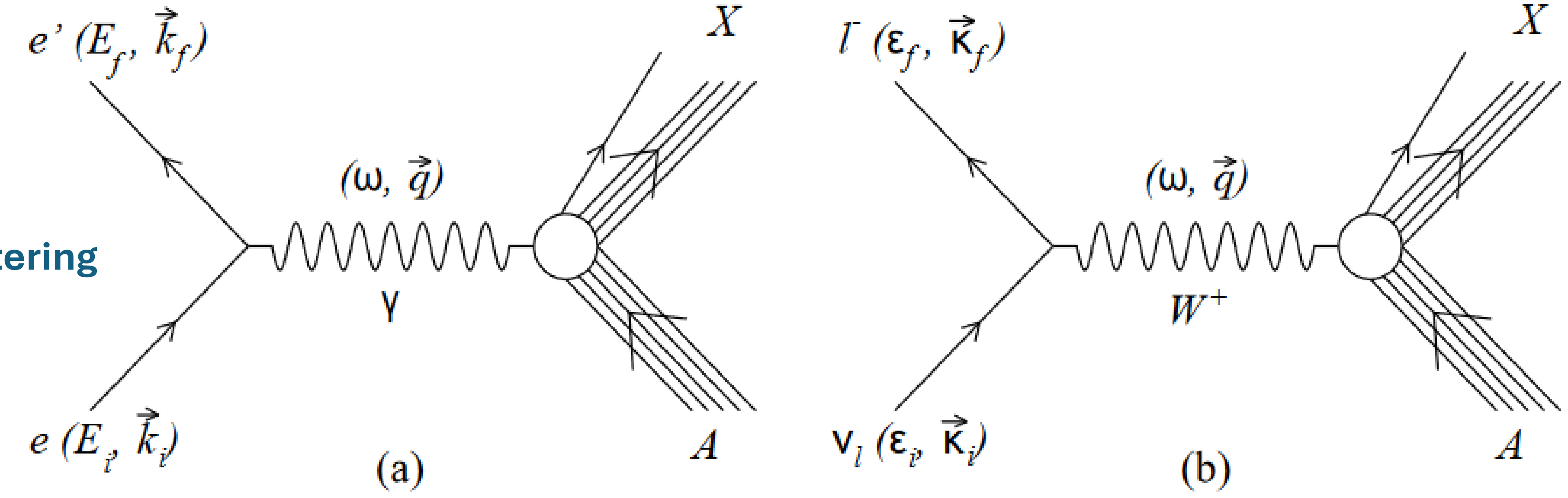
Hadronic tensor

Theoretical extensions needed for exclusive:

- Extra response functions
- Appropriate description of the outgoing nucleon wave function in the nuclear medium
- Contributes to more accurate reconstruction of the neutrino energy

More important things you should know about neutrino-nucleus scattering

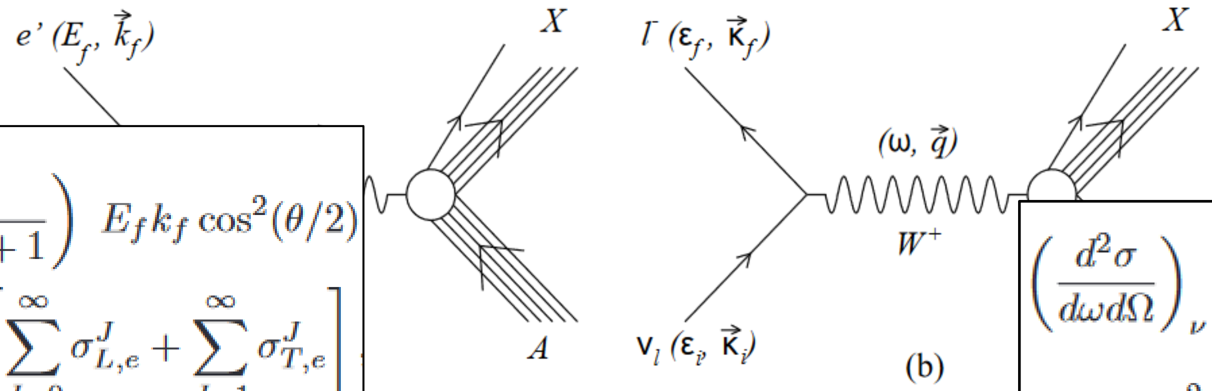
Electron versus neutrino scattering



$$\left(\frac{d^2\sigma}{d\omega d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right) E_f k_f \cos^2(\theta/2) \times \zeta^2(Z', E_f, |q|)\left[\sum_{J=0}^{\infty}\sigma_{L,e}^J + \sum_{J=1}^{\infty}\sigma_{T,e}^J\right]$$

$$\left(\frac{d^2\sigma}{d\omega d\Omega}\right)_\nu = \frac{G_F^2\cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f\kappa_f \times \zeta^2(Z', \varepsilon_f, |q|)\left[\sum_{J=0}^{\infty}\sigma_{CL,\nu}^J + \sum_{J=1}^{\infty}\sigma_{T,\nu}^J\right]$$

Electron versus neutrino scattering



$$\left(\frac{d^2\sigma}{d\omega d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right) E_f k_f \cos^2(\theta/2) \times \zeta^2(Z', E_f, |q|)\left[\sum_{J=0}^{\infty}\sigma^J_{L,e} + \sum_{J=1}^{\infty}\sigma^J_{T,e}\right]$$

$$\left(\frac{d^2\sigma}{d\omega d\Omega}\right)_\nu = \frac{G_F^2 \cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f \kappa_f \times \zeta^2(Z', \varepsilon_f, |q|)\left[\sum_{J=0}^{\infty}\sigma^J_{CL,\nu} + \sum_{J=1}^{\infty}\sigma^J_{T,\nu}\right]$$

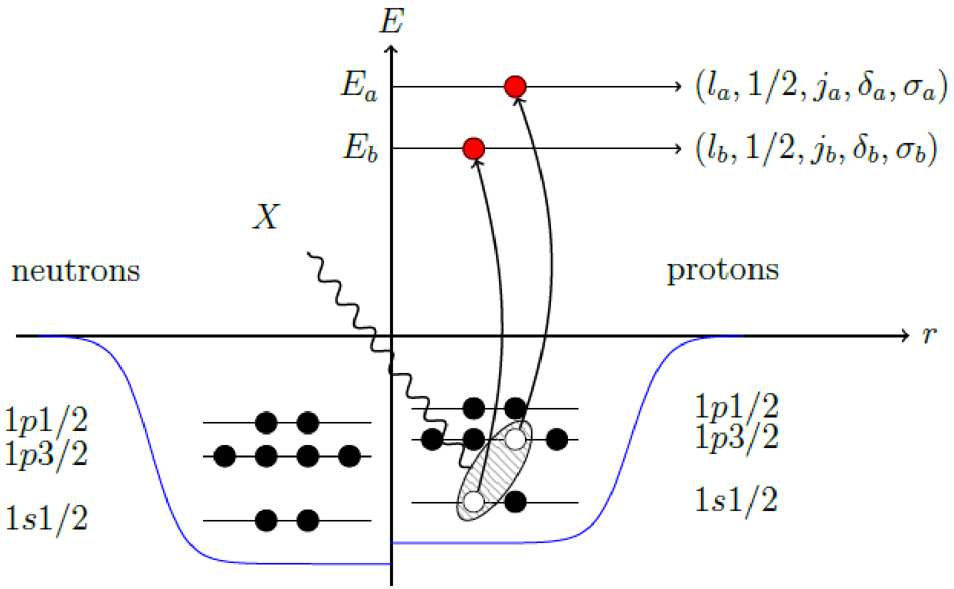
$$\sigma^J_{L,e} = v_e^L R_e^L,$$

$$\sigma^J_{CL,\nu} = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + 2\, v_\nu^{\mathcal{M}\mathcal{L}} R_\nu^{\mathcal{M}\mathcal{L}}\right],$$

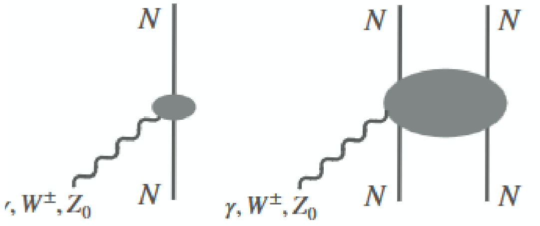
$$\sigma^J_{T,e} = v_e^T R_e^T,$$

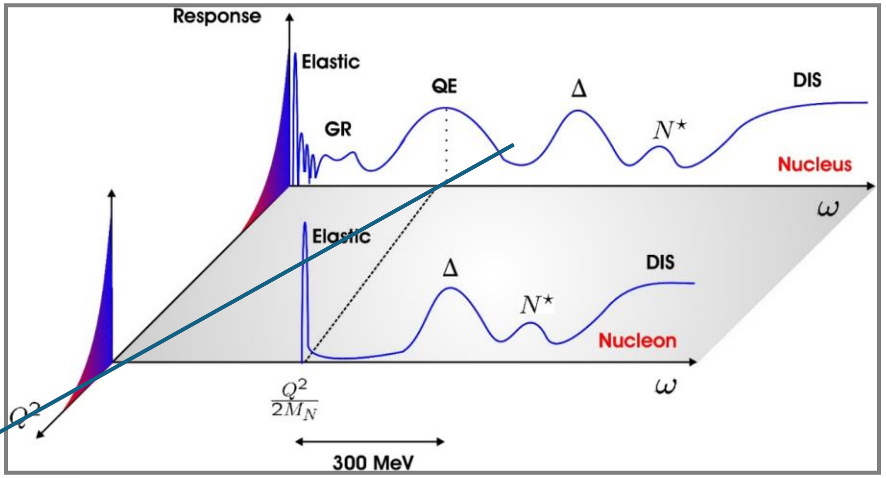
$$\sigma^J_{T,\nu} = \left[v_\nu^T R_\nu^T \pm 2\, v_\nu^{TT} R_\nu^{TT}\right],$$

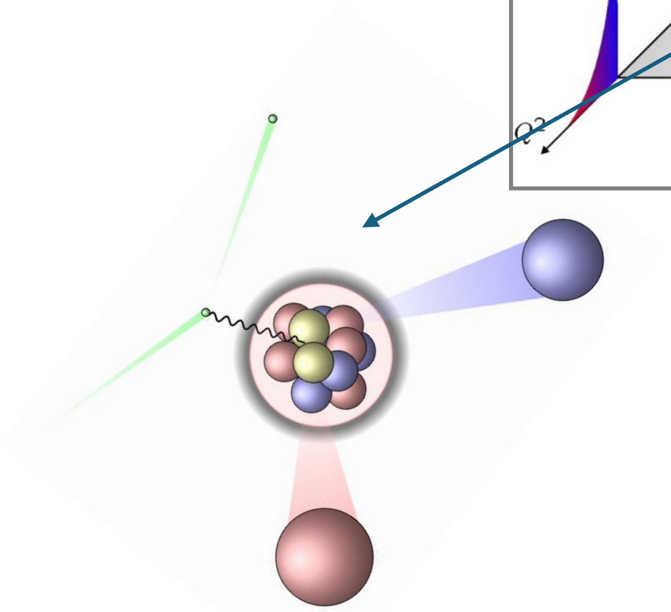
Quasi elastic versus multinucleon knockout processes



$$J = \sum_i j_i + \sum_{i<j} j_{ij} + \dots$$



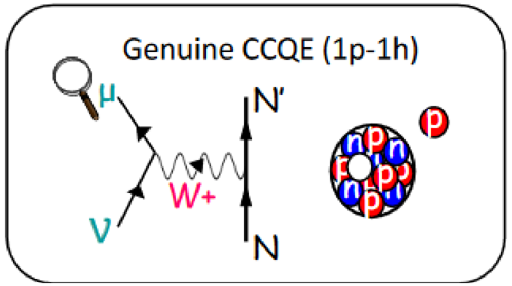


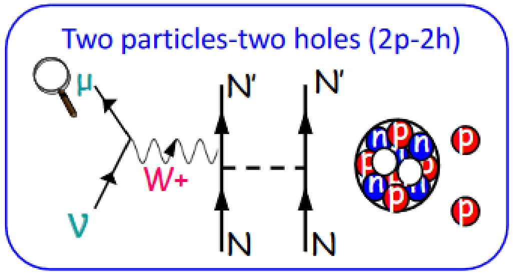


Multi-nucleon effects

- affect 1-nucleon knockout processes
- Cause multi-nucleon knockout processes, filling the dip region between the QE and the Delta peak

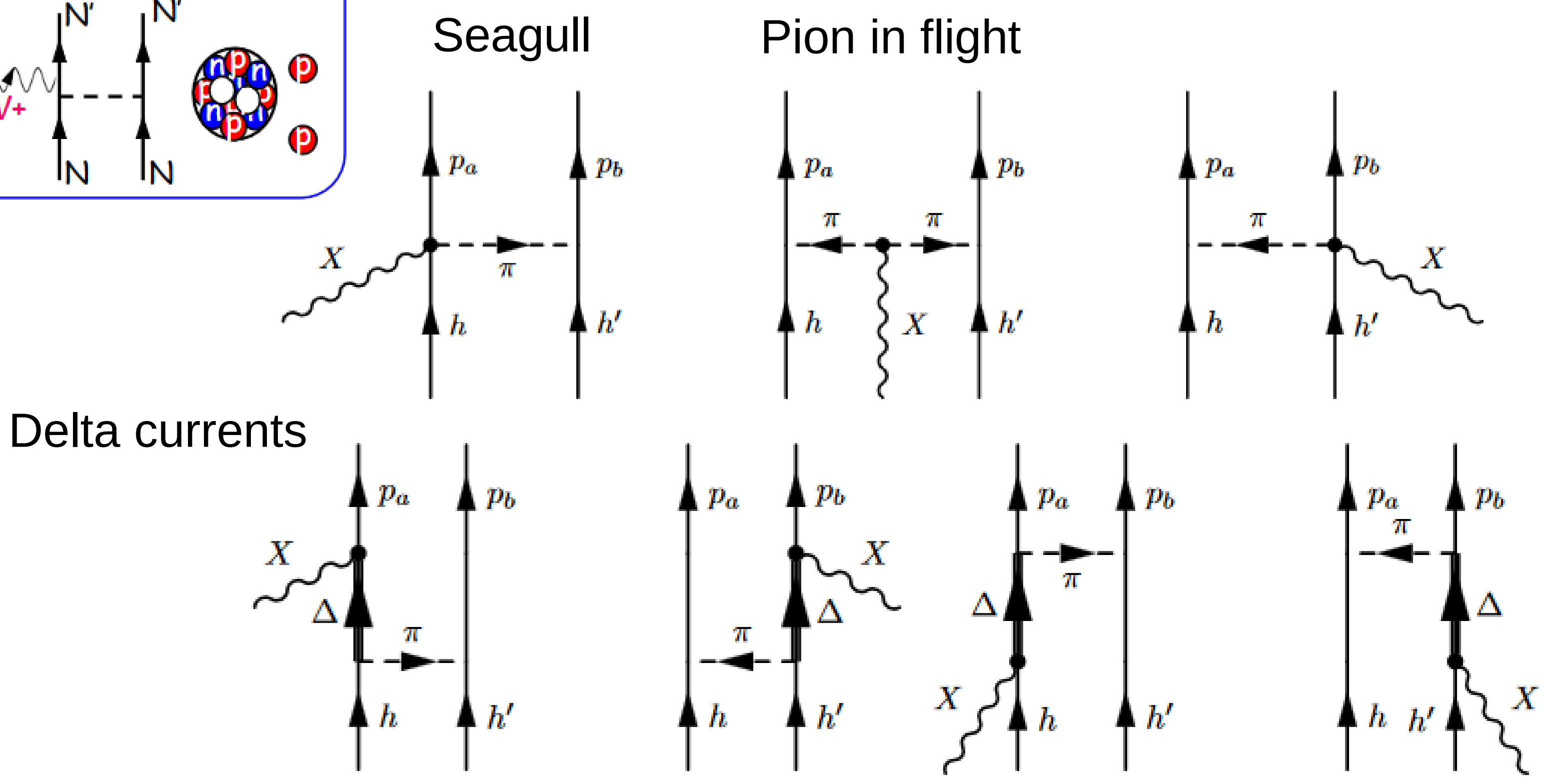
Quasi elastic versus multinucleon knockout processes



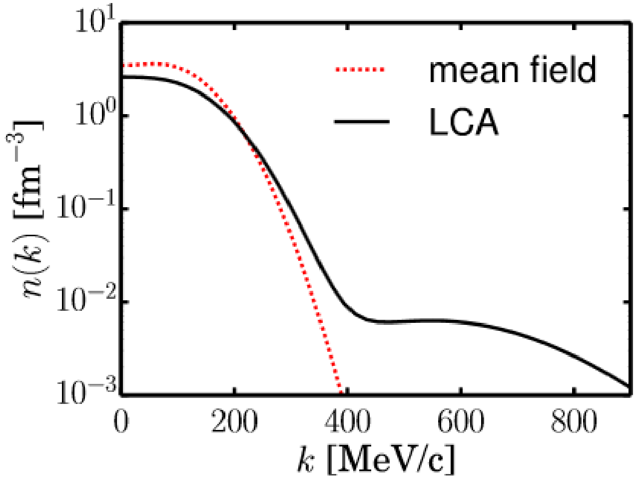


When an electroweak boson interacts with a pair of nucleons which are correlated through short-range correlation or through the exchange of a meson, this will cause the knockout of one or both of the particles from the nucleus. The boson was interacting with a current consisting of two nucleons, a two-body current, called a MEC

Meson-exchange currents

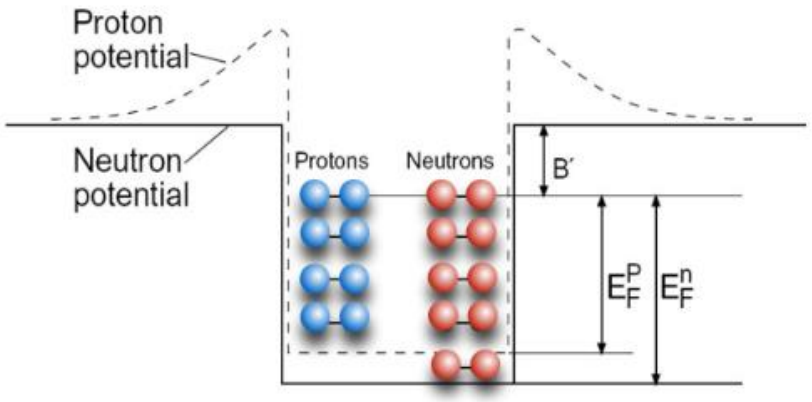


IPM single-particle orbitals are depleted by **short range correlations** and higher momentum states are populated



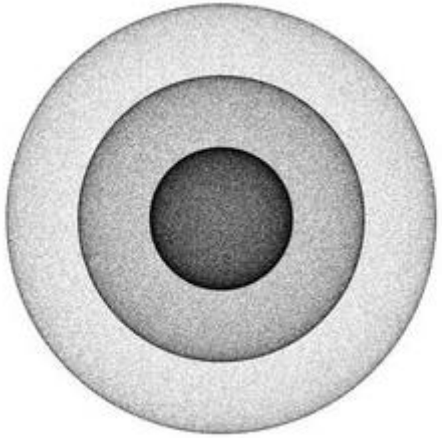
Models you often hear about when working in neutrino physics : Fermi Gas

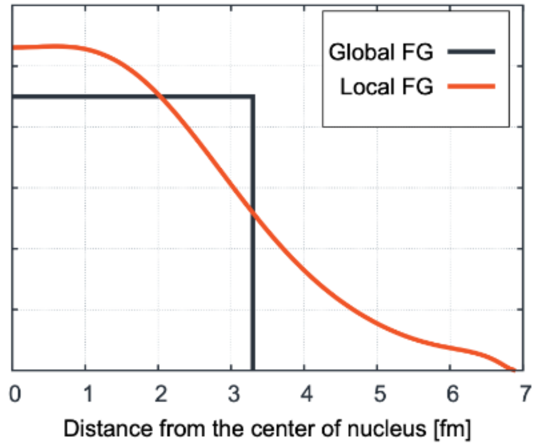
- Nucleons are not interacting, constant average binding energy



- Global Fermi gas :
  - same Fermi momentum for the whole nucleus = uniform density

- Local Fermi gas
  - Density dependent Fermi momentum $p_F \sim \rho(r)^{1/3}$ adjusted to the local density in the nuclear medium



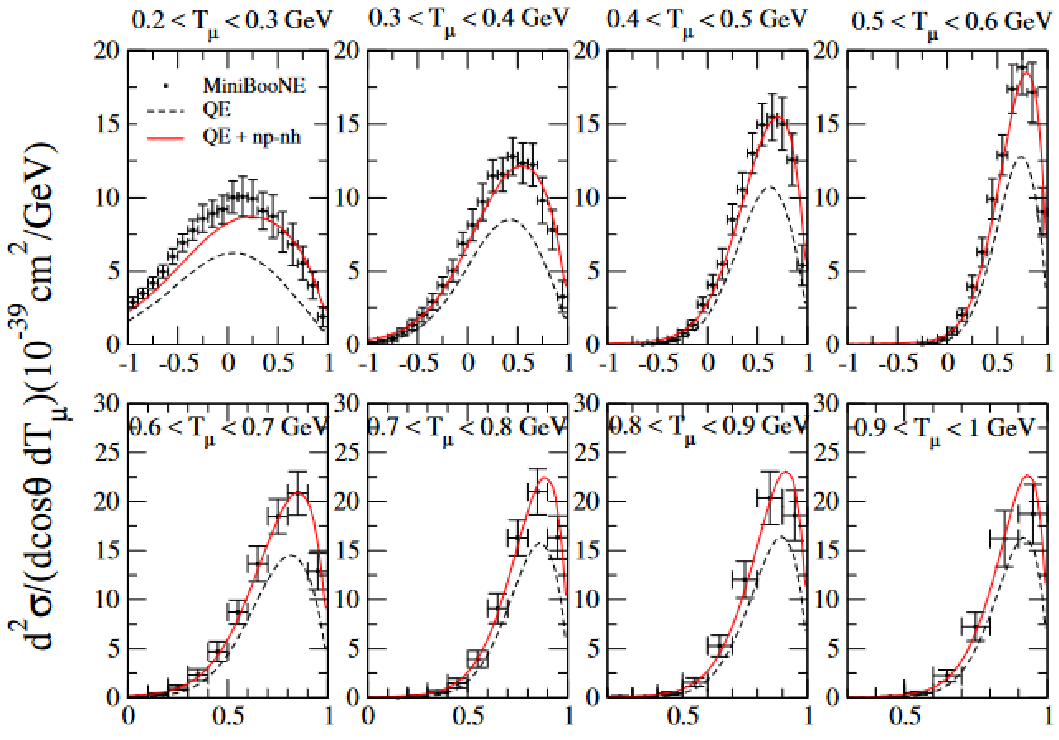


Extra nuclear effects can be added, often labeled FG+RPA e.g. Nieves model (Valencia), Martini model (Saclay Lyon)

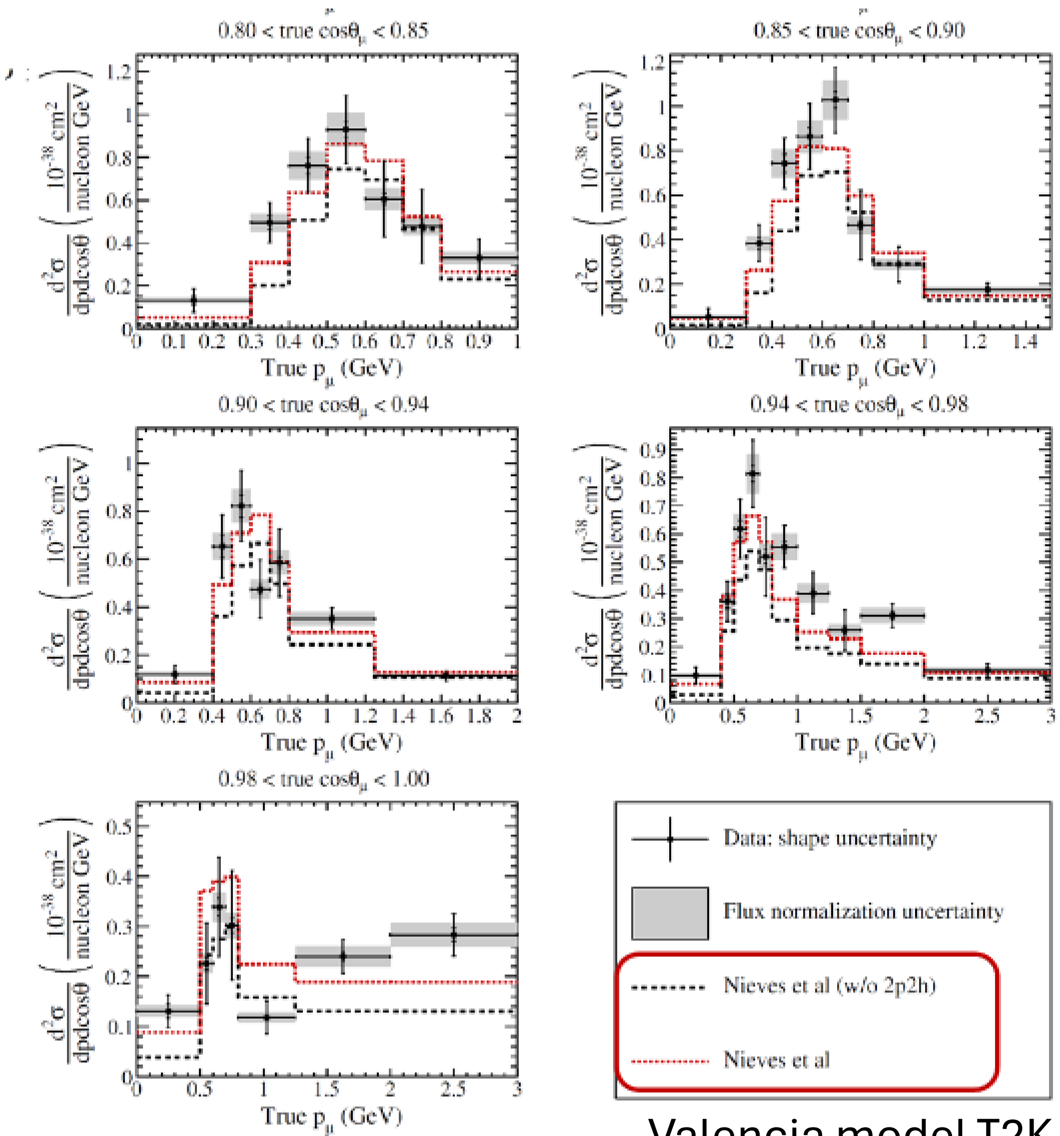
Models you often hear about when working in neutrino physics : Fermi Gas

Fermi gas approaches

- Efficient description of inclusive processes in QE peak region
- Can include extra correlations
- Including np-nh contributions
- often used in generators
- satisfactory agreement with inclusive data



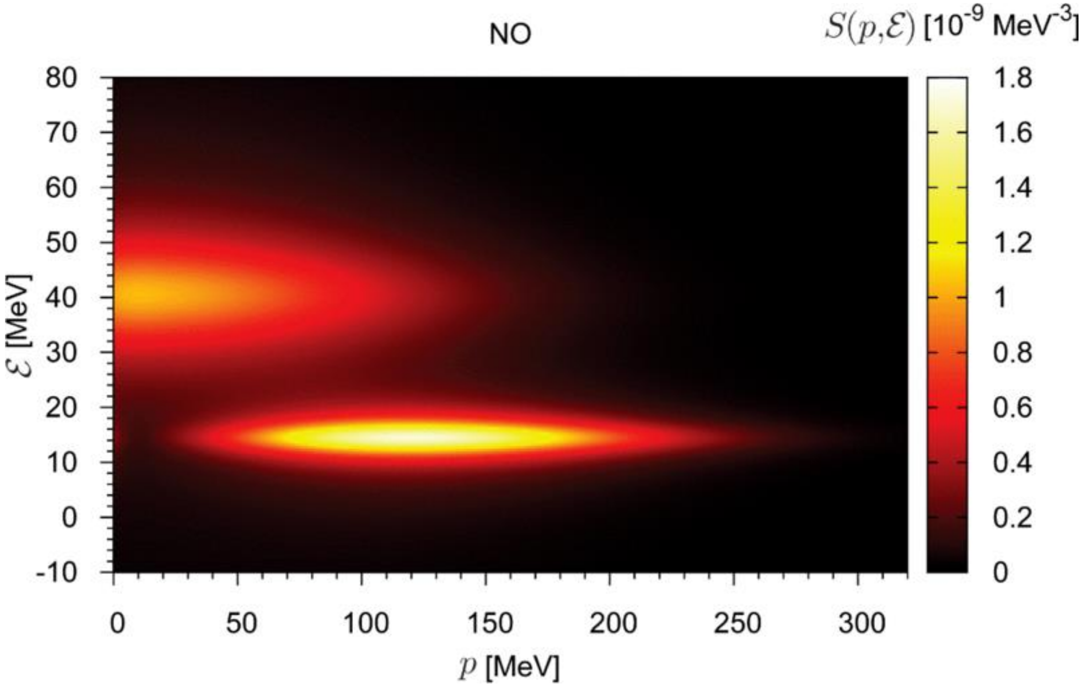
M. Martini et al, PRC84, 055502



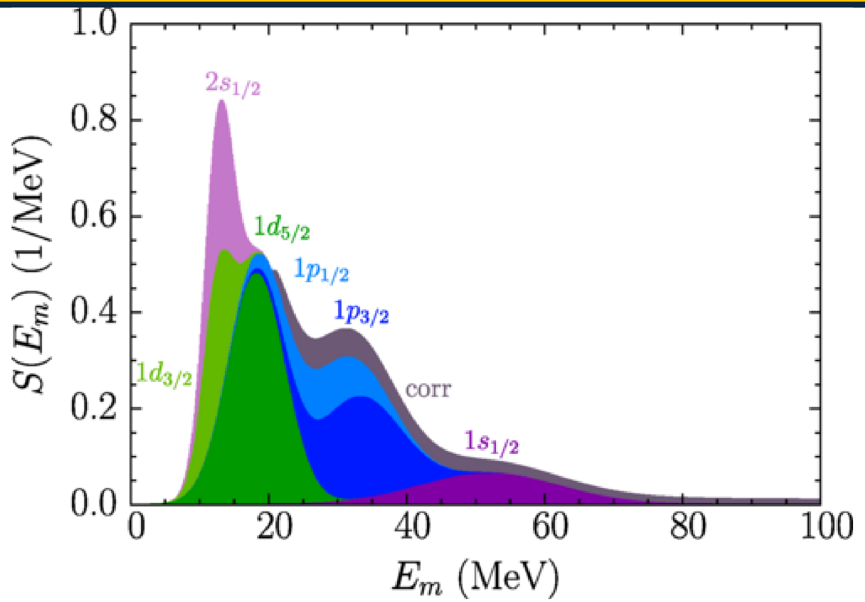
Valencia model T2K

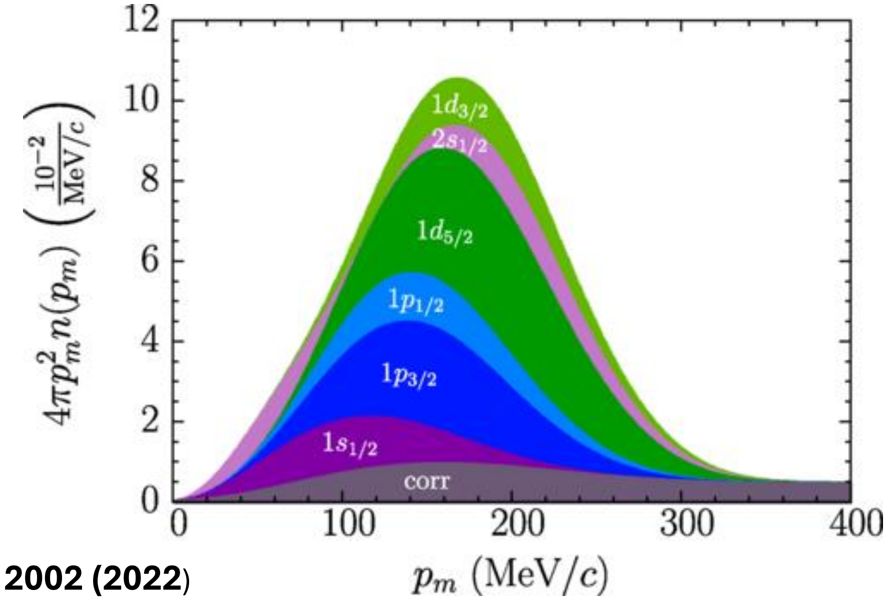
Models you often hear about when working in neutrino physics : Spectral function

- Based on the impulse approximation
- Cross section is factorized : $\sigma_{nucleus}=\sigma_{nucleon}$ x $P(p_m,E_m)$
- The spectral function $P(p_m,E_m)$ provides a probability distribution for removing a nucleon with momentum $p_{m(issing)}$ from the initial nuclear ground state, leaving the final residual nucleus in a state with energy E_m
- The spectral function can be extracted from (electron) scattering data or calculated using a model



PRC91, 034607 (2015)





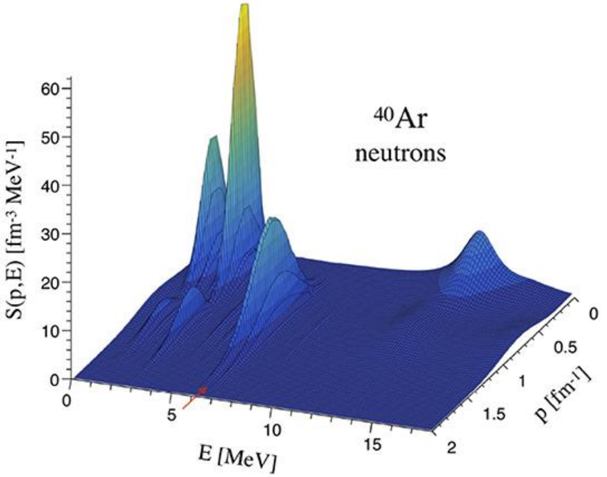
PRD105, 11 2002 (2022)

Determination of the argon spectral function from (*e*,*e*'p) data

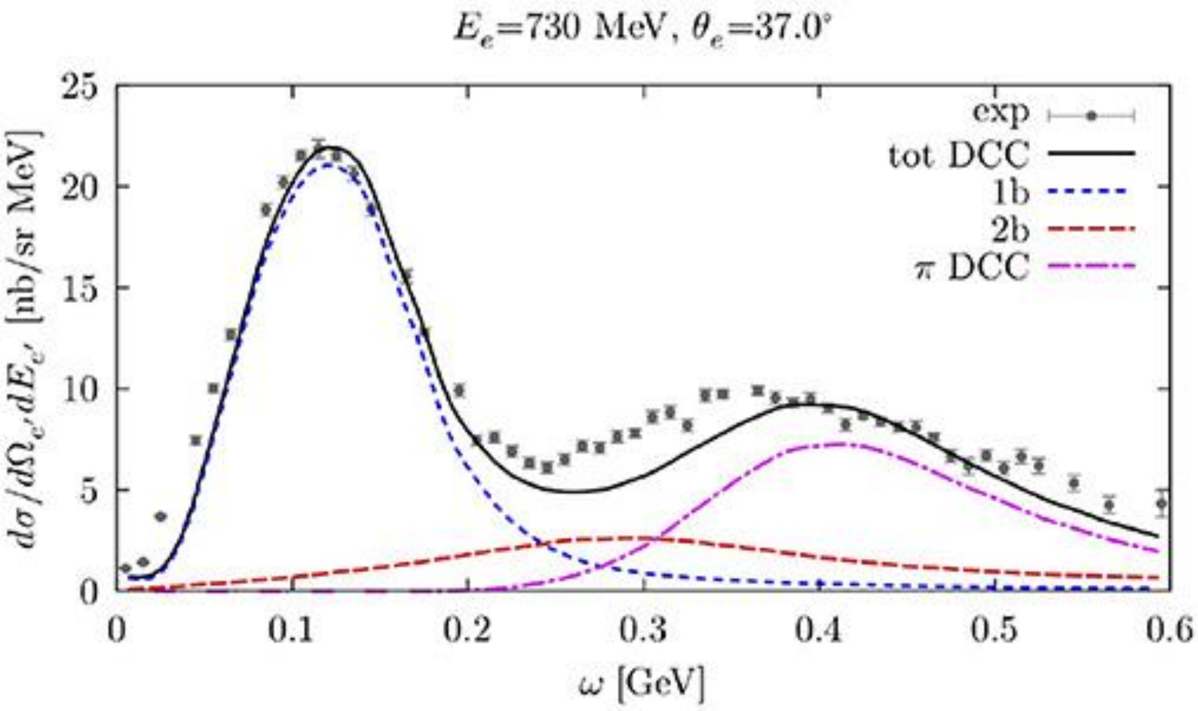
Spectral function

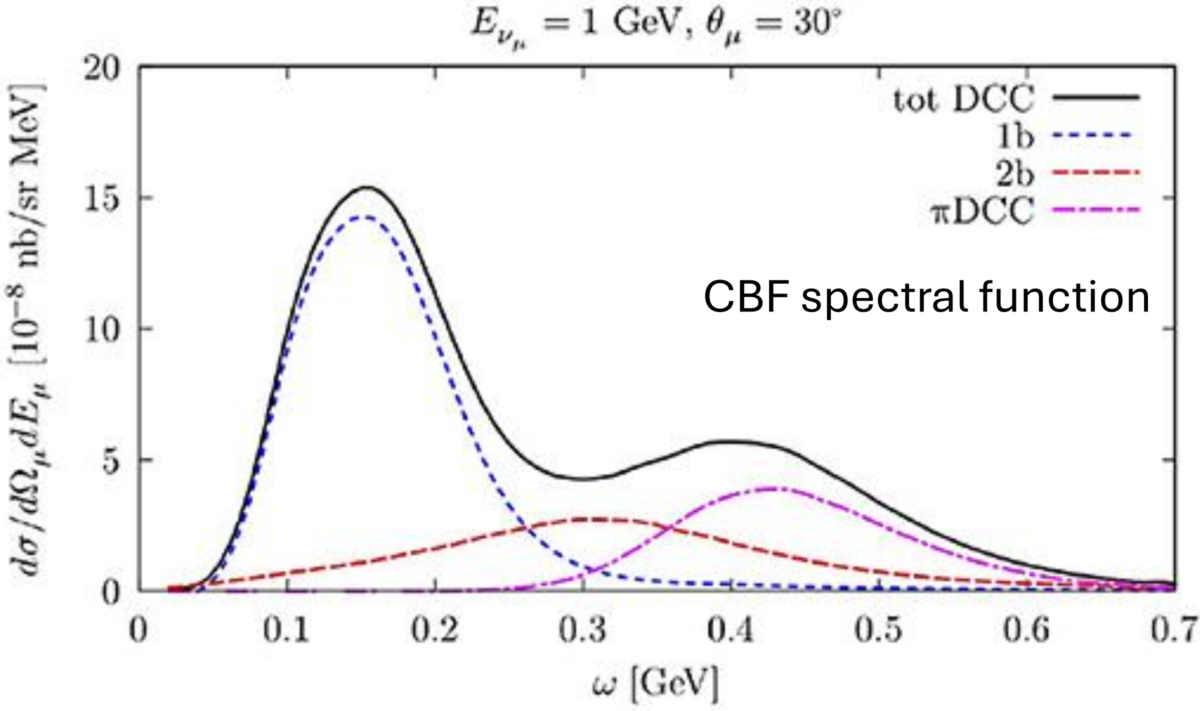
Spectral function calculations

- Factorized approach
- Nuclear medium influence taken into account by spectral function
- Can be extended two 2p2h processes



M. Ivanov et al. PRC91,034607





CBF spectral function

N. Rocco, Front. Phys 8 (2020)

Models you often hear about when working in neutrino physics : (Super)Scaling

Day et al., Annu. Rev. Nucl. Part. Sci. (1990)

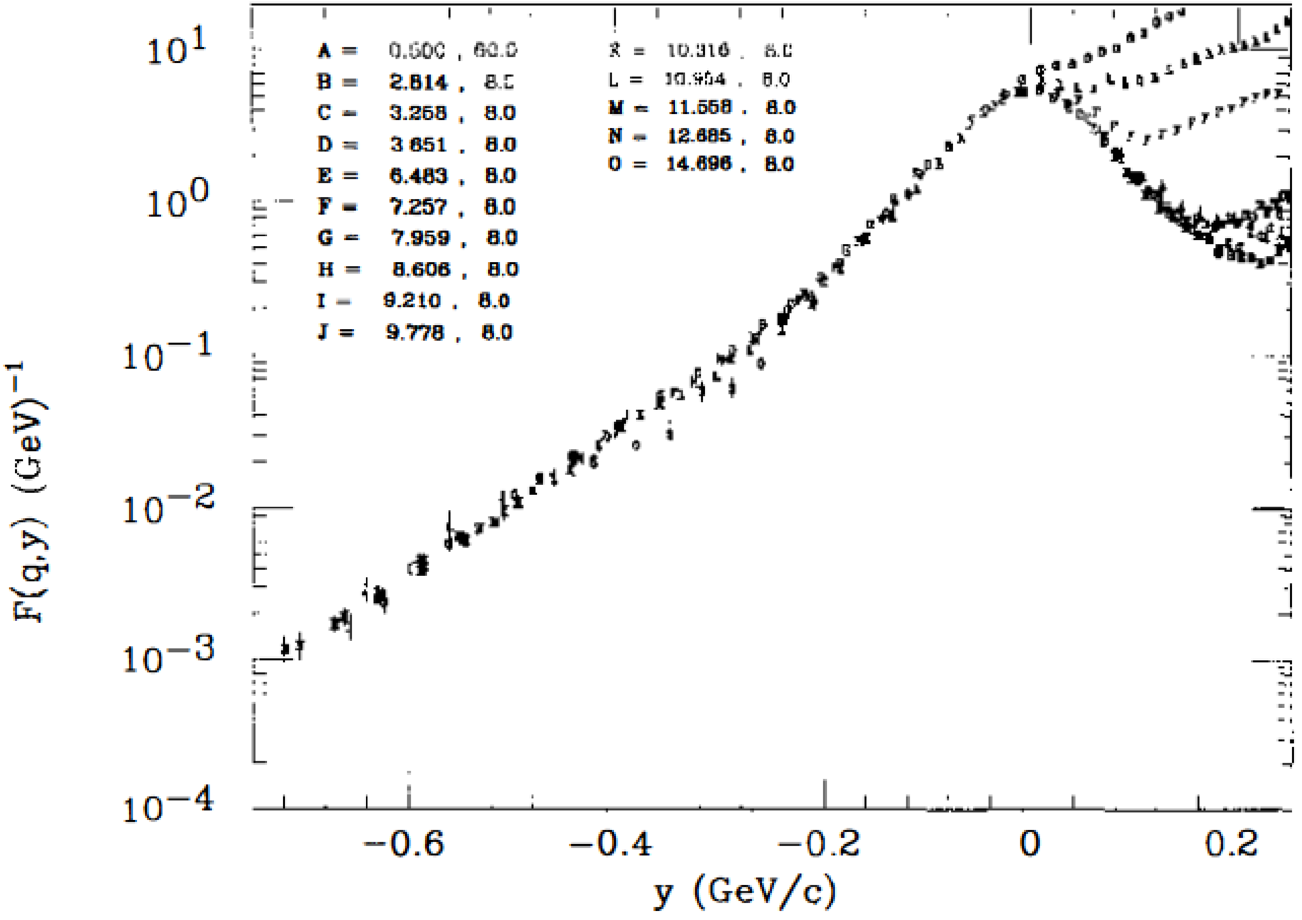


Figure 5 Experimental scaling function for ^{3}He determined from data in Figure 4. The letters label different incident electron energy and scattering angle pairs (ε, θ) in (GeV, degrees).

Based on factorization : separates the QE cross section in an averaged single-nucleon factor and a scaling function encoding the influence of nuclear dynamics

$$\frac{d^2\sigma}{d\Omega\, d\nu} = K \cdot \sigma_{ep}(q, \nu) \cdot F(q, y)$$

→ Scaling of the first kind = independence on q

Scaling variable y ~ minimal longitudinal momentum the bound nucleon had before the interaction

(Super)Scaling

Donnelly and Sick, PRL82 (1999)

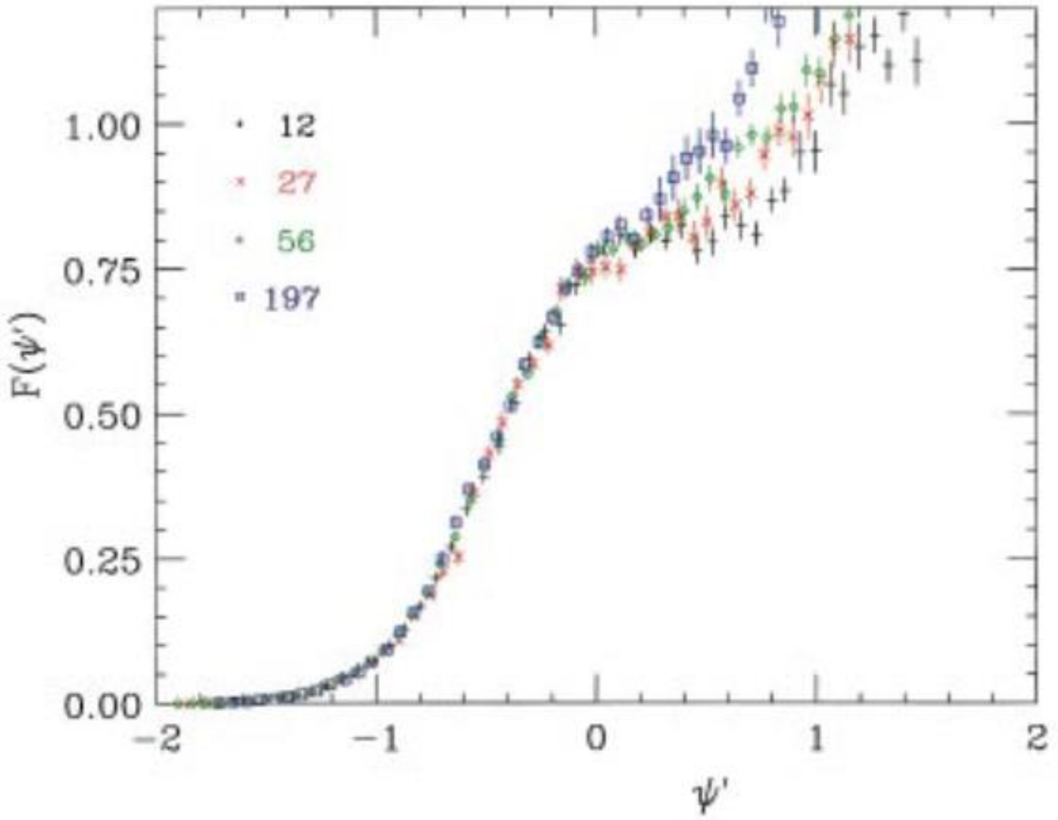


FIG. 2(color). Scaling function for C, Al, Fe, and Au and fixed kinematics [25]. The correspondence of symbol and mass number of the nucleus is also shown.

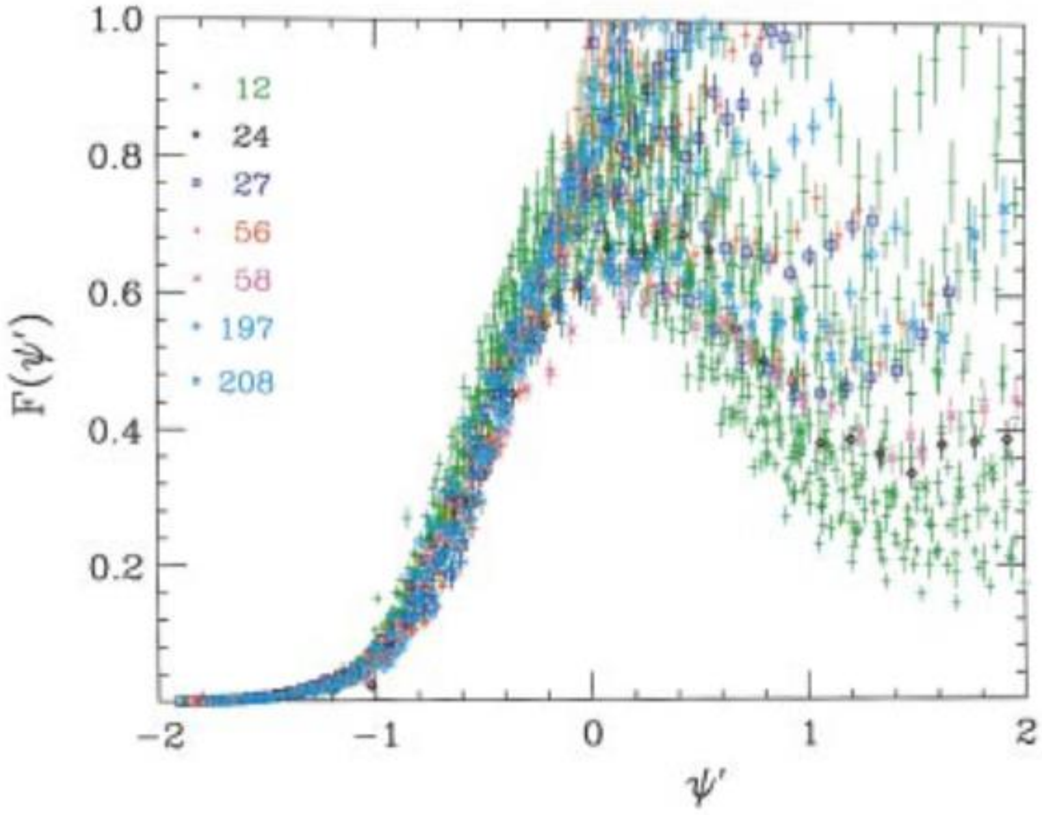


FIG. 1(color). Scaling function $f(\psi')$ as function of ψ' for all nuclei $A \geq 12$ and all kinematics. The values of A corresponding to different symbols is also shown.

Scaling variable Ψ' ~ ratio of threshold nucleon knockout energy to the momentum transfer

→Scaling function independent of A (k_F) = Scaling of second kind

$$f(\psi') = k_F \frac{\sigma_{\text{exp}}}{\sigma_{\text{single-nucleon}}}$$

Models you often hear about when working in neutrino physics : (Super)Scaling

Day et al., Annu. Rev. Nucl. Part. Sci. (1990)

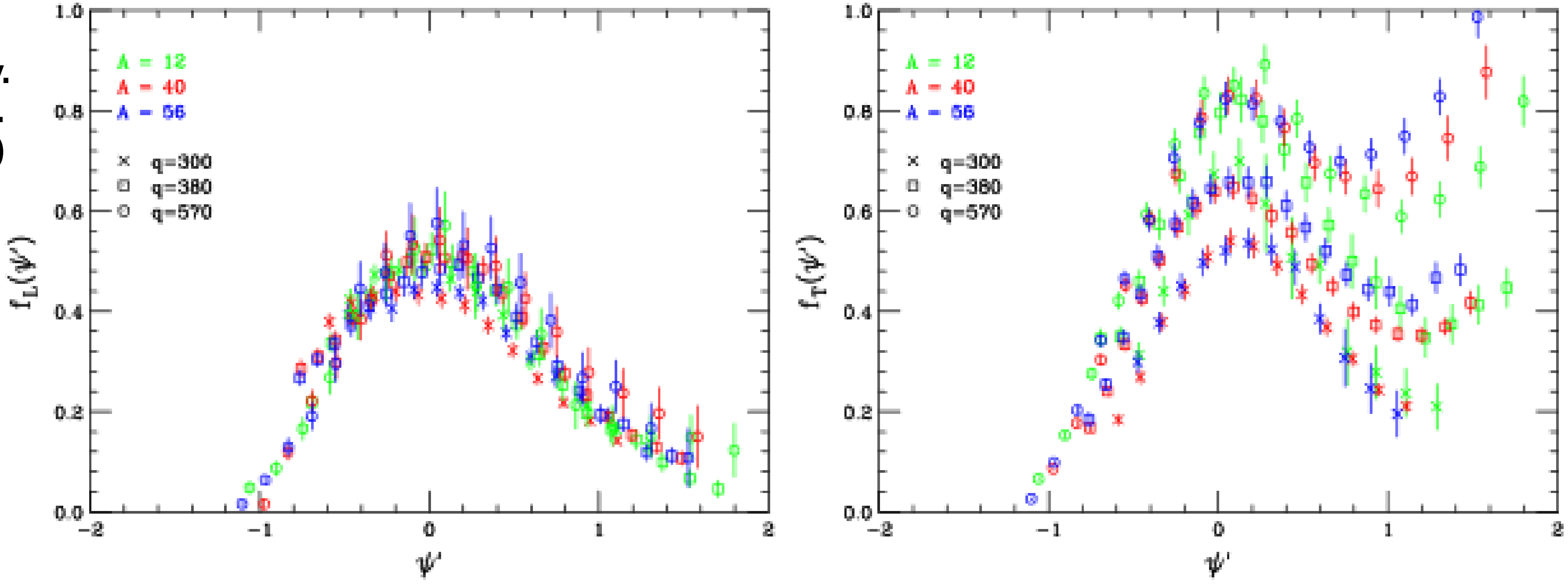


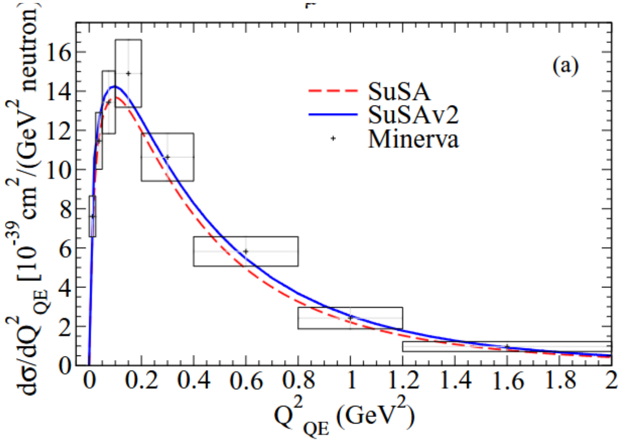
FIG. 15. Scaling function, $f_L(\psi')$ and $f_T(\psi')$, from the longitudinal and transverse response, respectively, as a function of ψ' for different nuclei ($A \geq 12$) and for different values of q (in MeV/c). Data taken from [23].

Scaling of the first kind
+
Scaling of the second kind
=
SuperScaling

Separating longitudinal and transverse contributions :

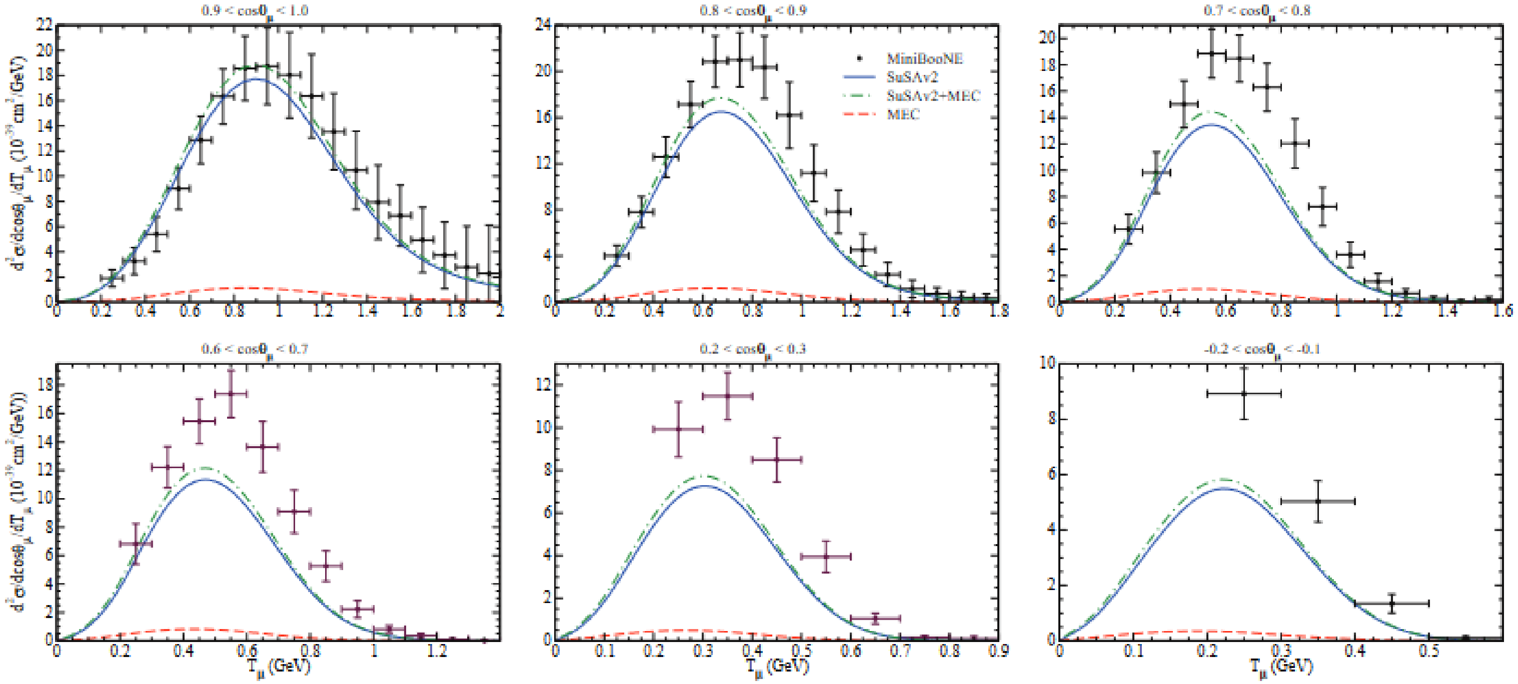
- Allows for a more sophisticated and accurate description
- Shows that transverse channels violate scaling beyond the quasi-elastic peak : multinucleon effects

→ use RMF calculations to determine the scaling functions = SuSAv2



R. Gonzalez-Jimenez PRC90, 035501(2014)

SuSA

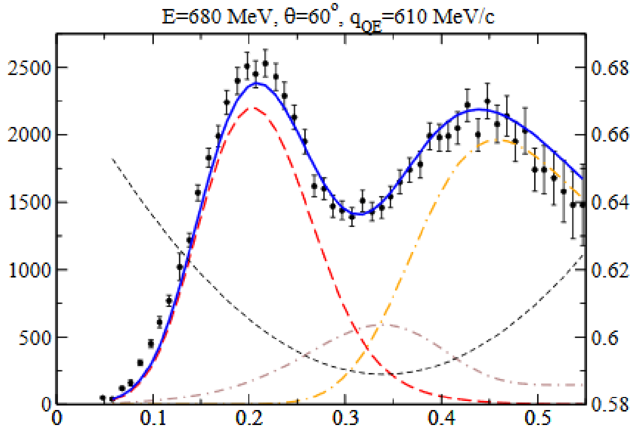


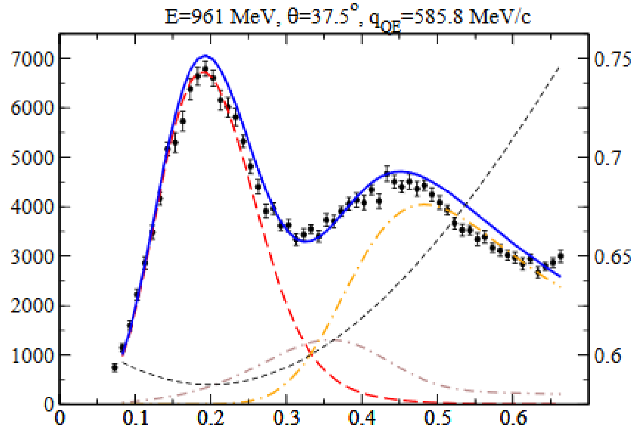
G. Megias et al, PRD 91, 073004

Superscaling approach

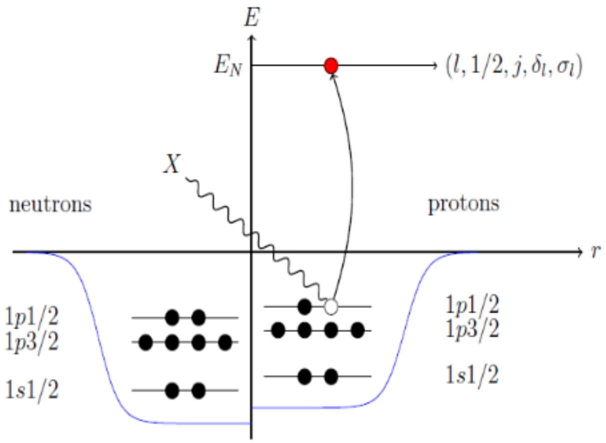
- SuSAv2 based on RMF calculations
- Strong predictive power for inclusive processes
- Including inelastic channels : meson-exchange contributions and pion production

Megias et al., PRD 94, 013012 (2016)





Models you often hear about when working in neutrino physics : Mean Field

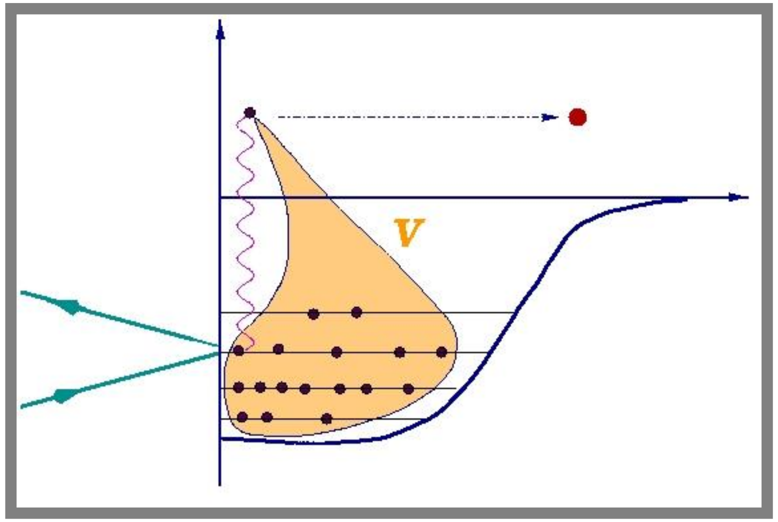


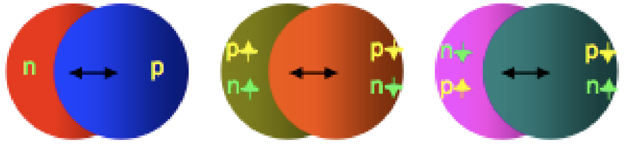
- Mean-field models capture a lot of nuclear medium effects in a natural and efficient way
- For final nucleon wave function distortion is included
- Pauli blocking is included in a natural way
- Can be extended to include long-range CRPA, short-range correlations, MECs
- Non-relativistic e.g. HF and HF-CRPA (Ghent), or relativistic (ED)-RMF (Madrid-Sevilla)

$$\psi_{jm} = \begin{pmatrix} ig(r)\mathcal{Y}_{jlm}(\Omega) \\ -f(r)\mathcal{Y}_{jl'm}(\Omega) \end{pmatrix} = \begin{pmatrix} ig(r)\chi_{\kappa m} \\ -f(r)\chi_{-\kappa m} \end{pmatrix}$$

$$\downarrow$$

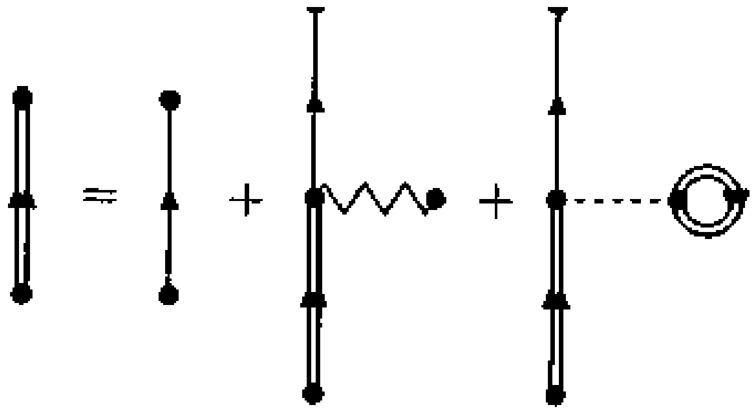
$$\psi_{nl\frac{1}{2}jm}(\vec{r}) = \phi(|\vec{r}|)_{nlj} Y^m_{j(l,\frac{1}{2})}(\Omega_r)$$



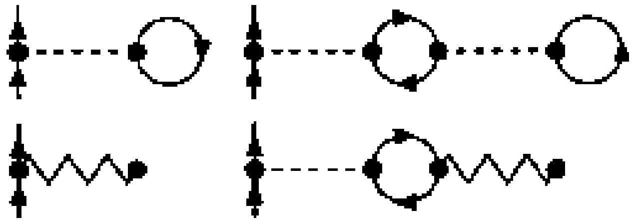


Mean Field

$$G^{HF}(\alpha,\beta;E) = G^{(0)}(\alpha,\beta;E) + \sum_{\gamma,\delta} G^{(0)}(\alpha,\gamma;E)\Sigma^{HF}(\gamma,\delta)G^{HF}(\delta,\beta;E)$$

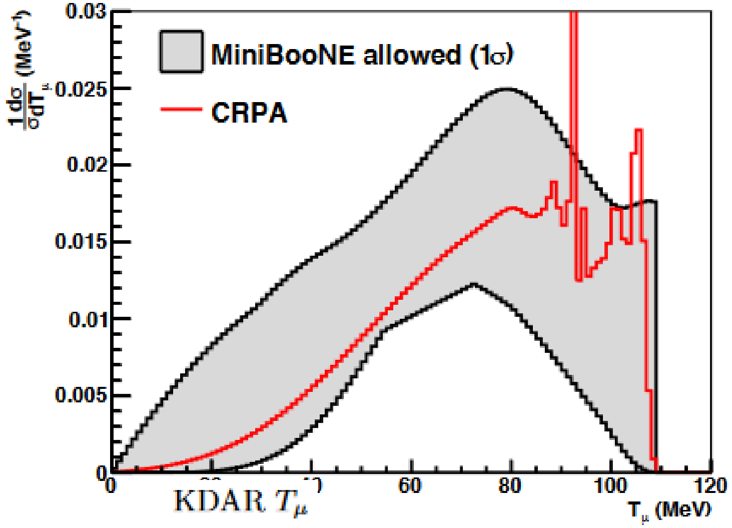


$$\Sigma^{HF}(\gamma,\delta;E) = -\langle\gamma|\,U\,|\delta\rangle - i\int \frac{dE'}{2\pi}\sum_{\mu\nu}\langle\gamma\mu|\,V\,|\delta\nu\rangle\, G^{HF}(\nu\mu;E')$$



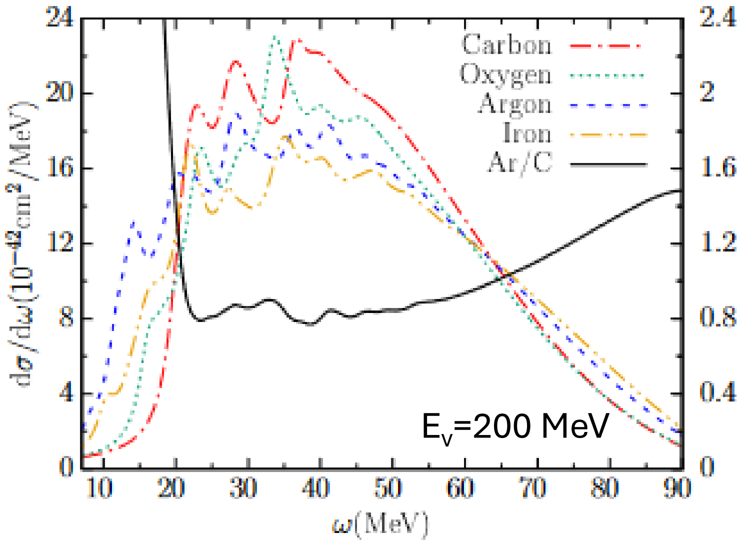
Mean field already contains a lot of correlations !

Mean Field



Ghent group,

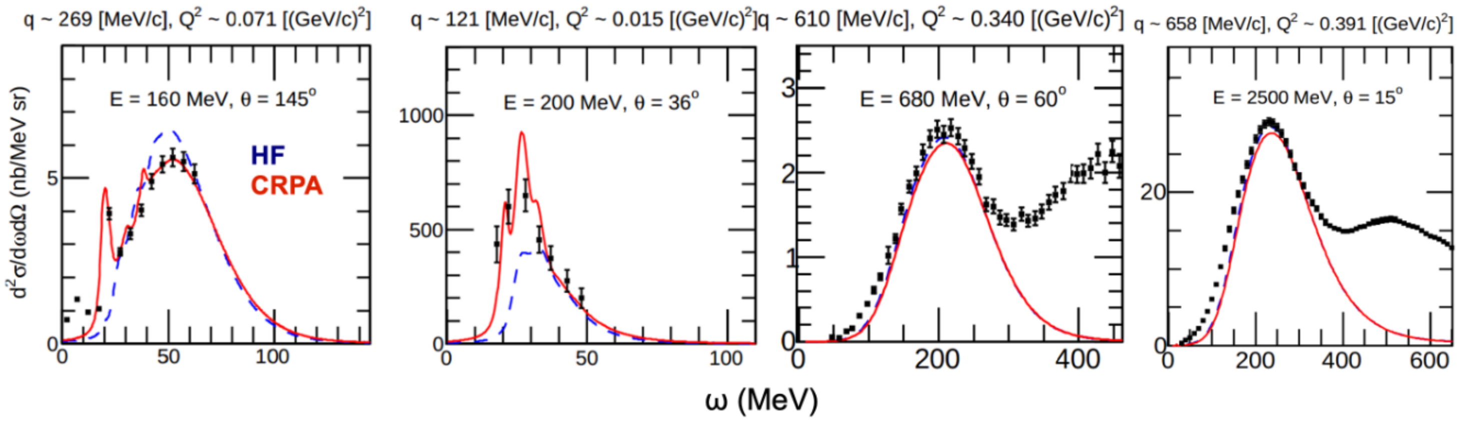
A. Nikolakopoulos et al, PRC103, 064603



N. Van Dessel et al, PRC97, 044616

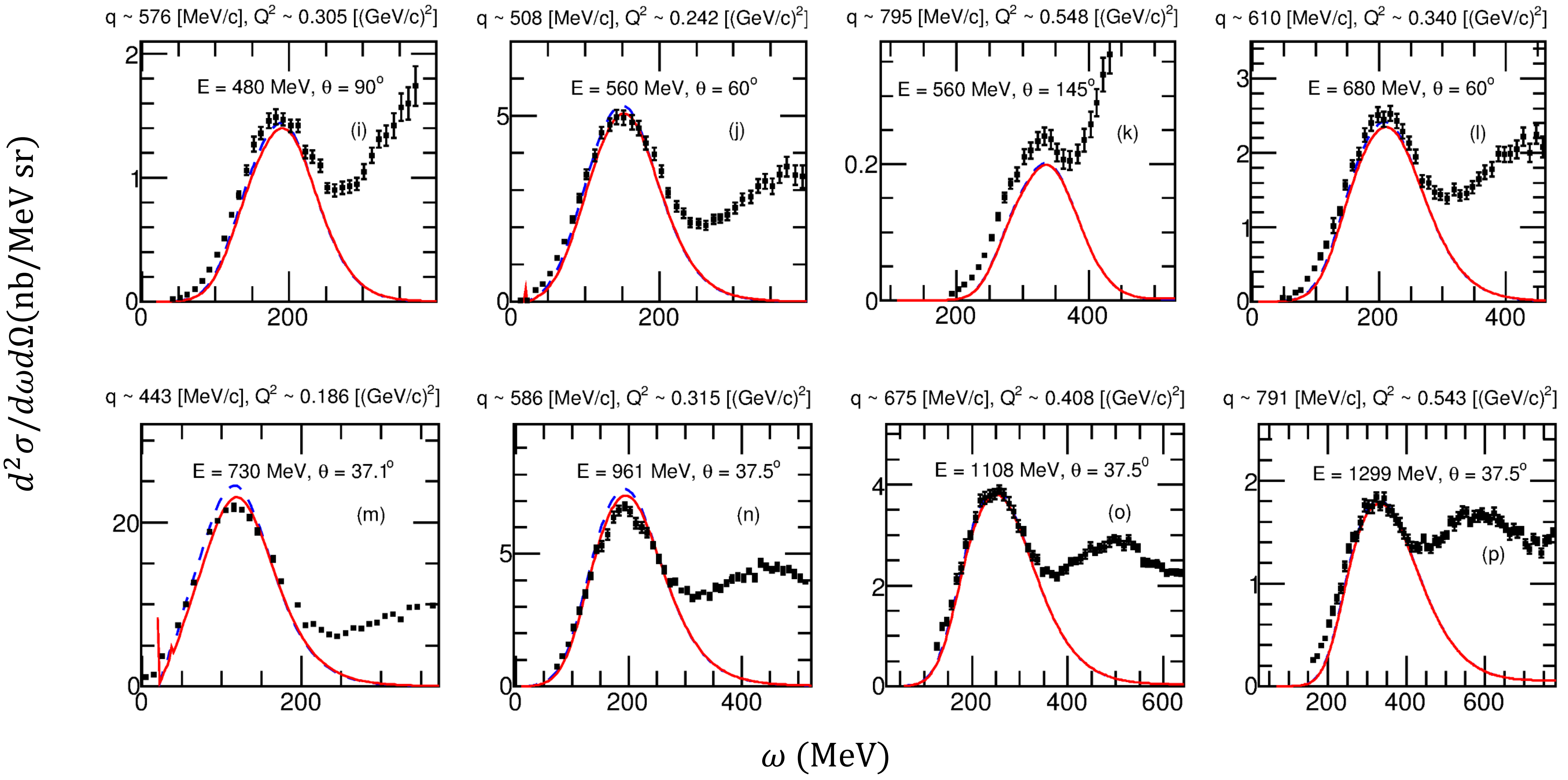
Hartree-Fock **mean field**

- Mean-field models capture a lot of nuclear medium effects in a natural and efficient way
- For final nucleon wave function Pauli blocking is included in a natural way
- Can be extended to include long-range CRPA, short-range correlations, MECs

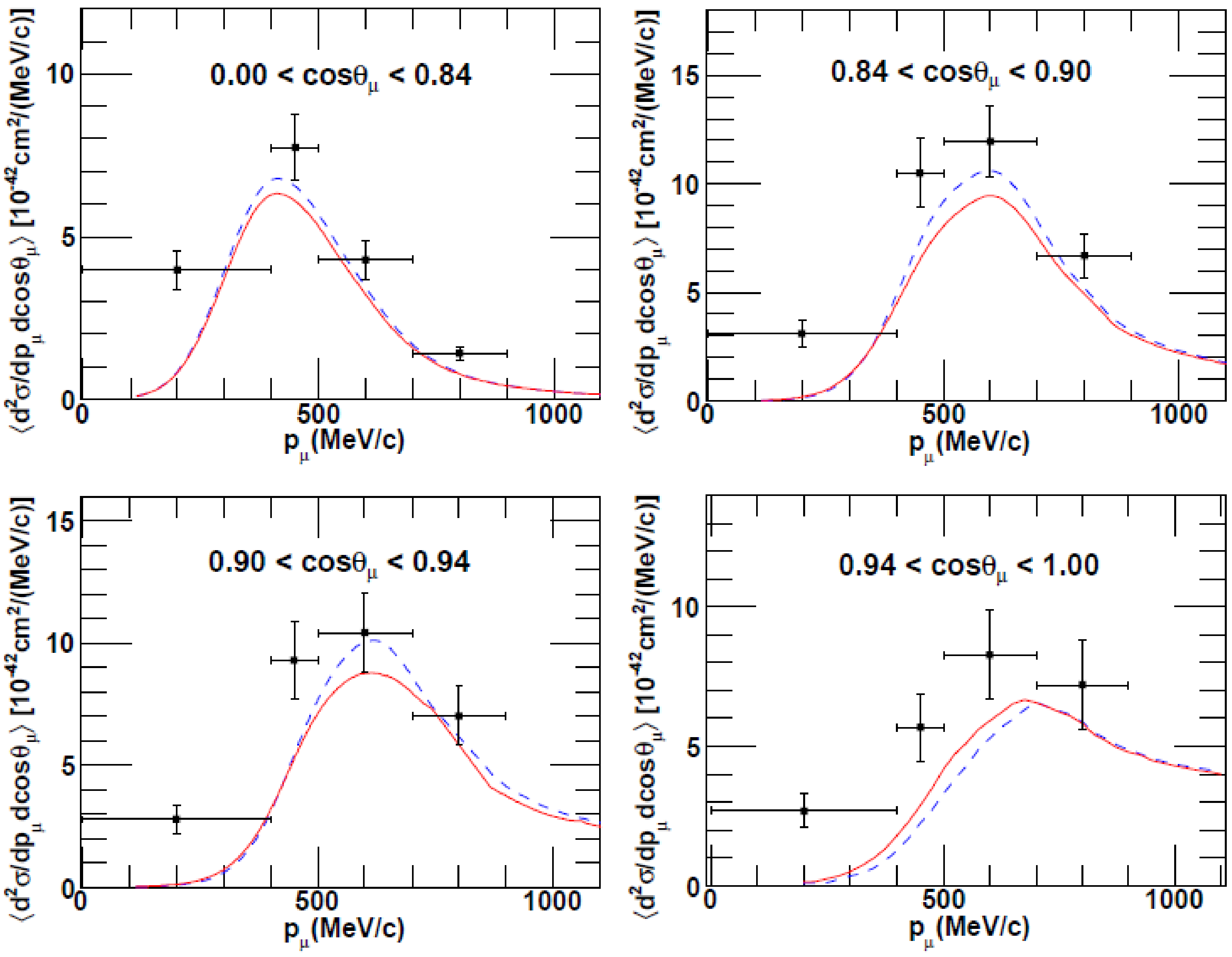


V. Pandey, PhD Thesis UGent 2015

Models you often hear about when working in neutrino physics : Mean Field

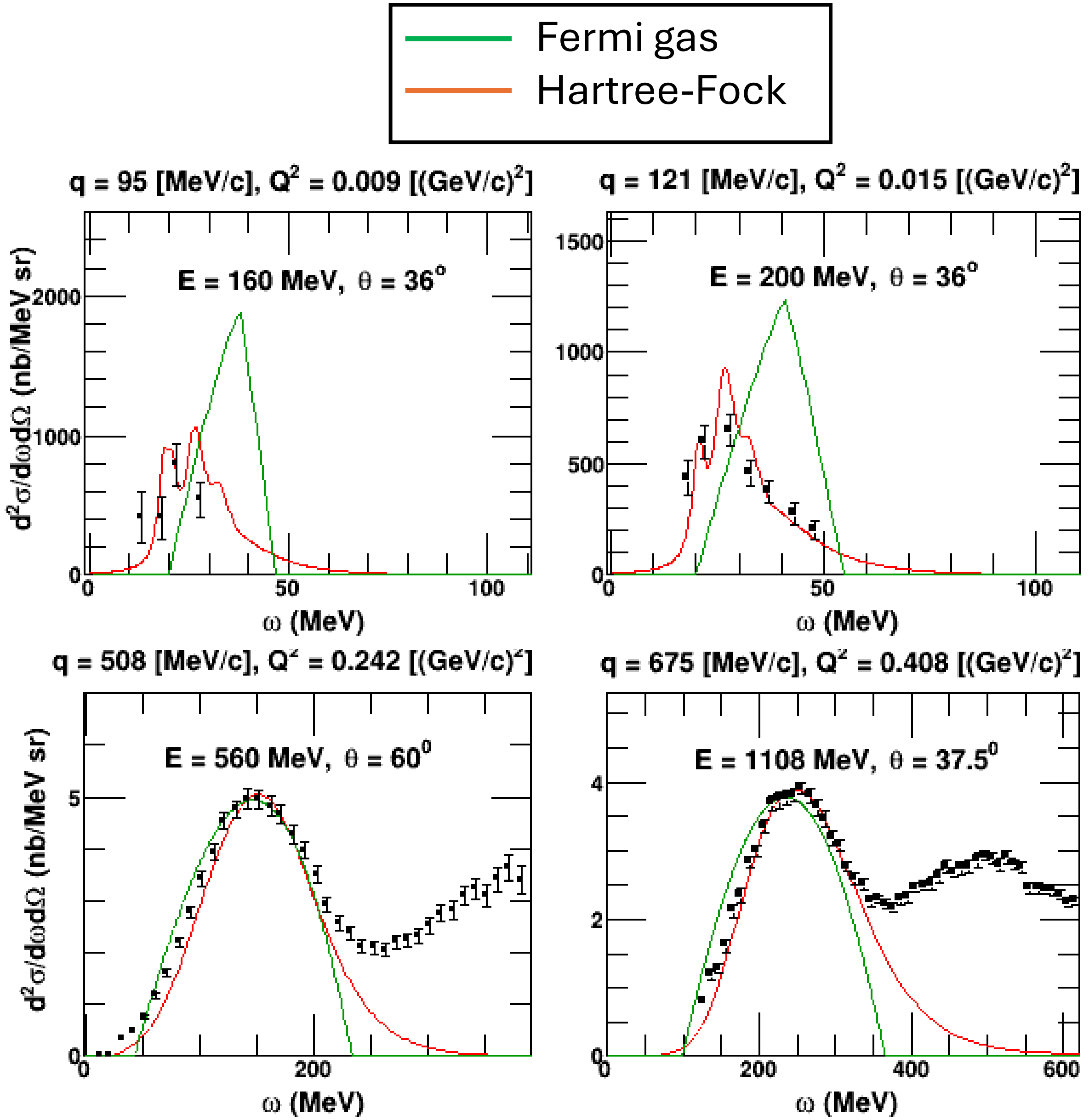


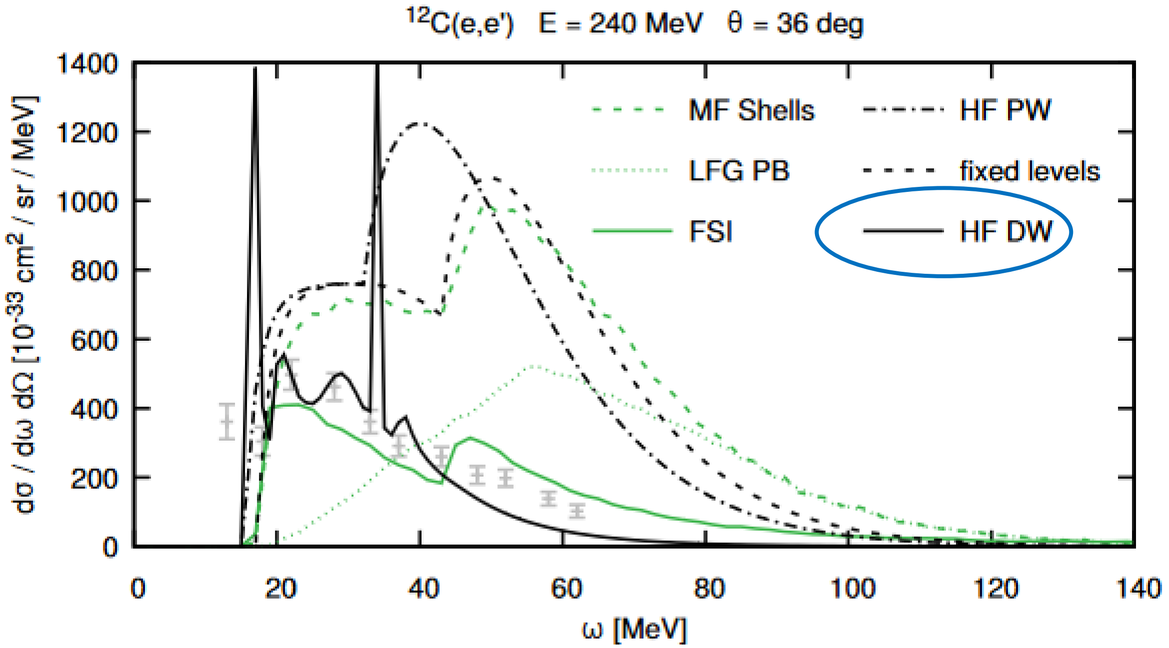
Models you often hear about when working in neutrino physics : Mean Field



T2K ν_μ

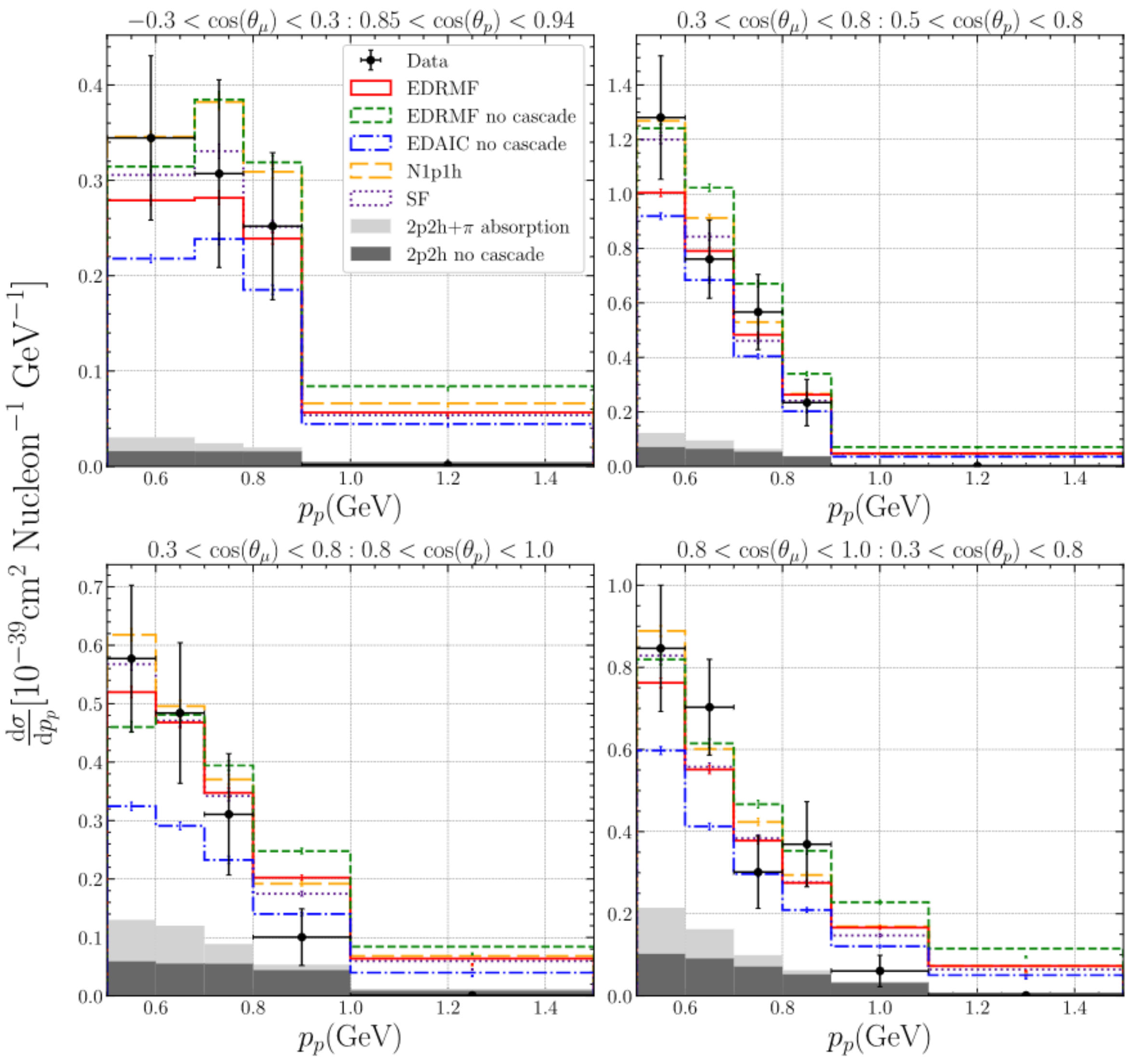
Hartree-Fock MF -CRPA



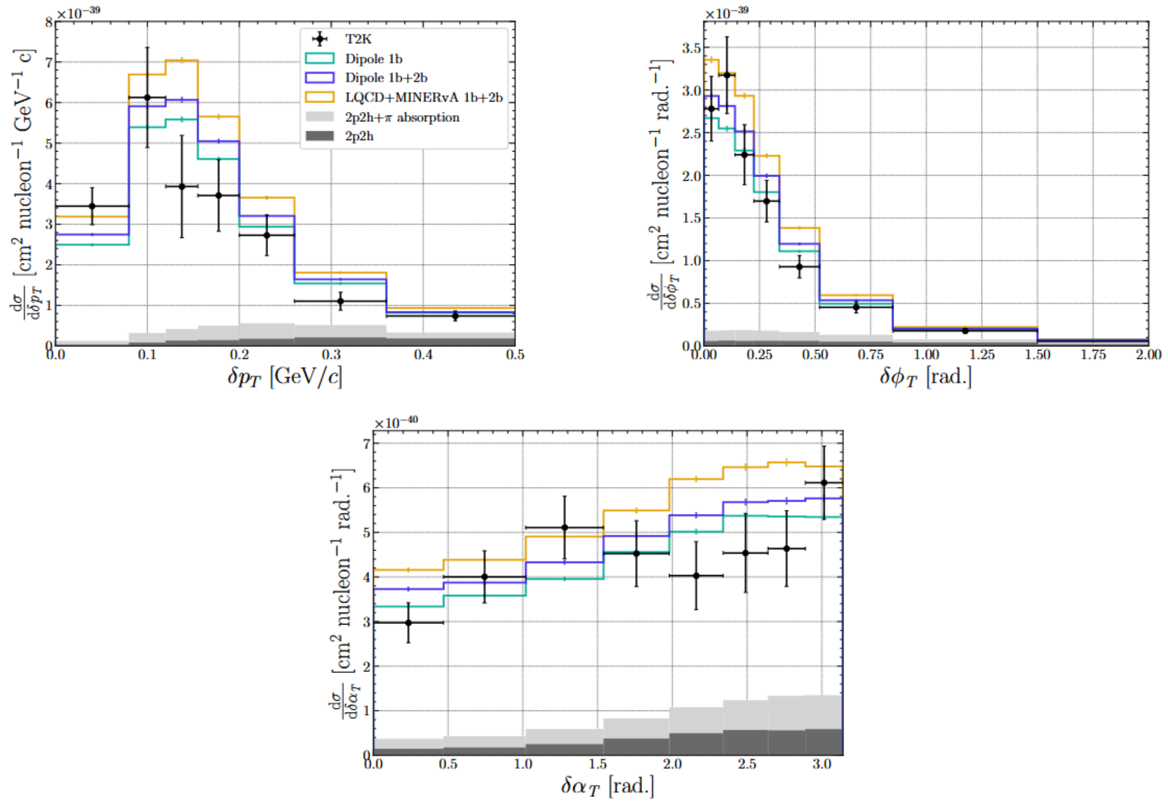


Distortion of the final wave function !

Models you often hear about when working in neutrino physics : Mean Field



Exclusive ED-RMF implementation in NEUT

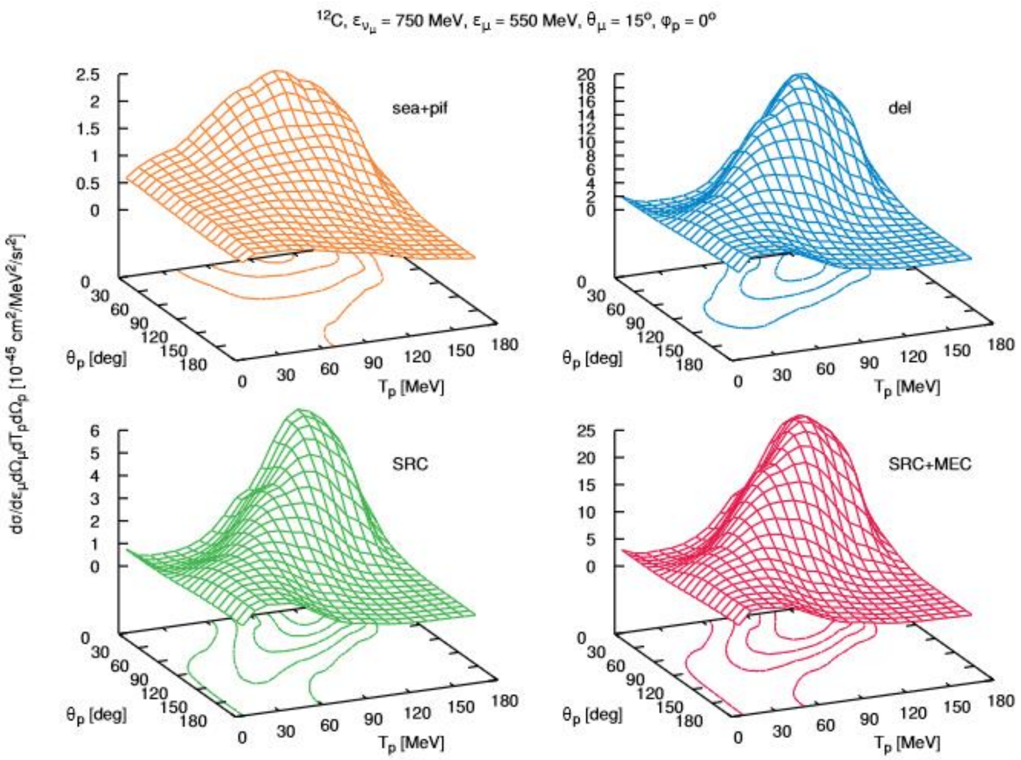


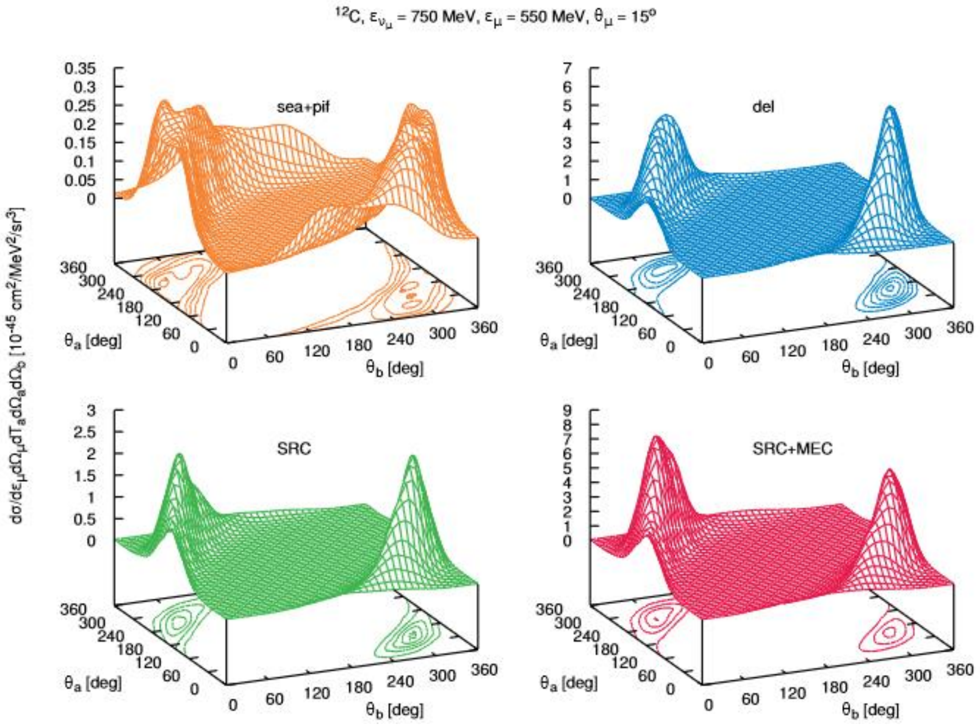
T. Franco-Munoz, J. McKean et al., arXiv:2605.00756

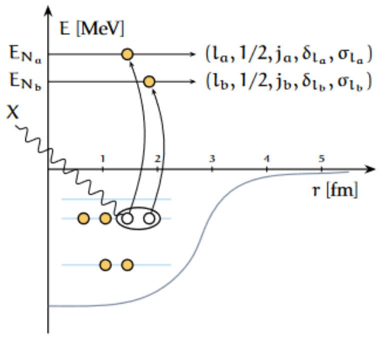
Models you often hear about when working in neutrino physics : Mean Field

Influence of 2-body currents on one-nucleon knockout

2-nucleon knockout



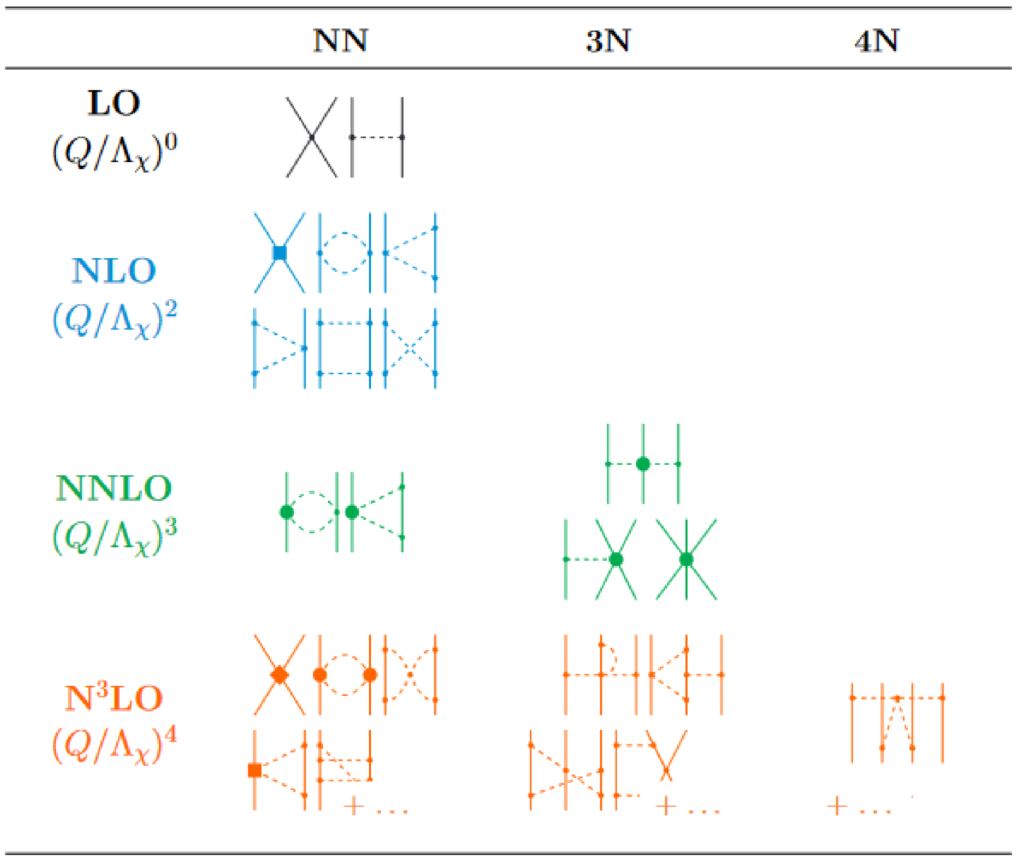




Models you often hear about when working in neutrino physics : Ab Initio

Recent years have seen the coming-of-age of **ab-initio calculations for neutrino-nucleus cross section** predictions and the development of auxiliary techniques to provide predictions for a variety of processes, targets and kinematics

$$H = \sum_i \frac{\mathrm{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

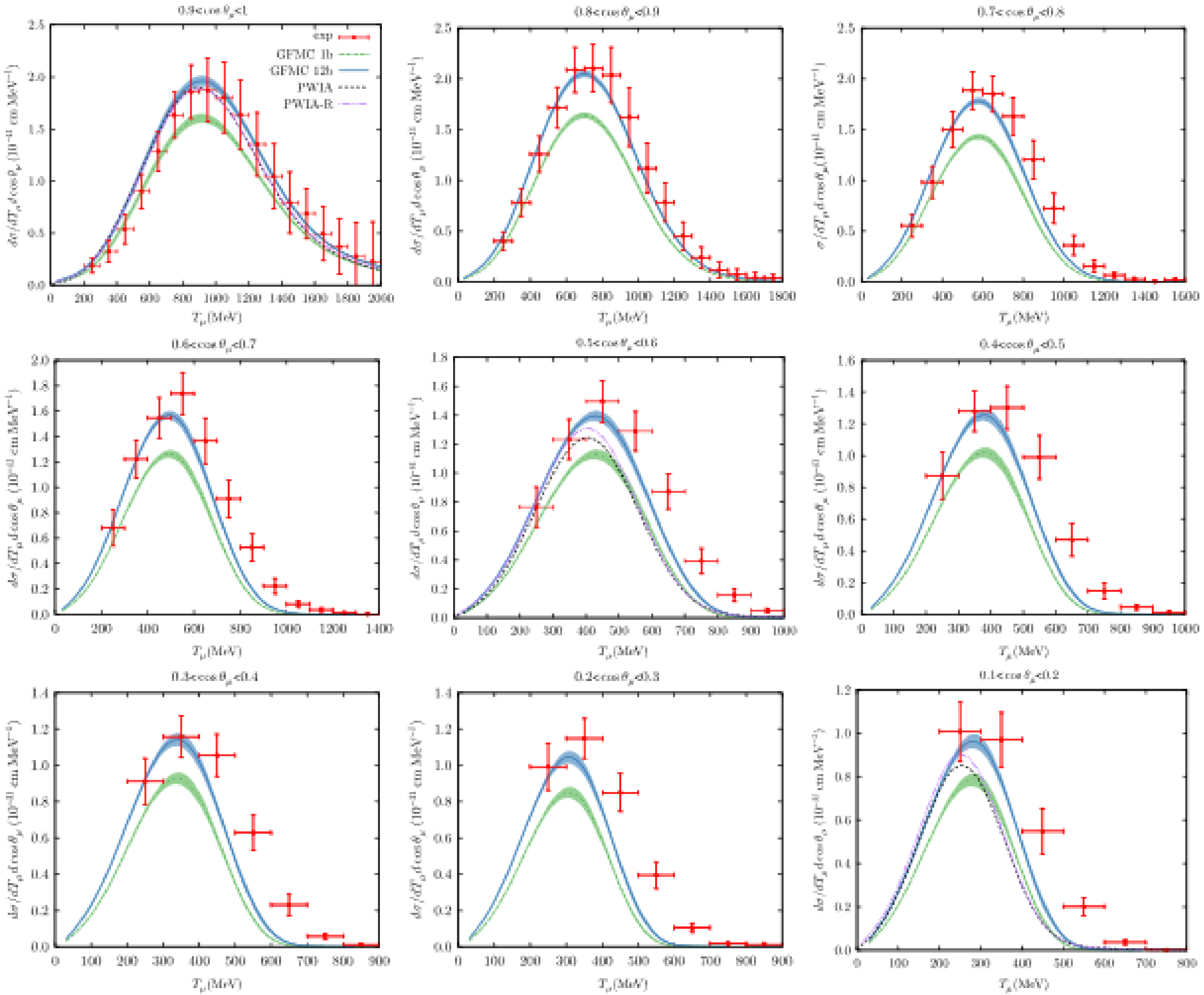


H. Hergert

Ab initio results

- Realistic Hamiltonian e.g. AV18 in GFMC
- Exact (up to the accuracy of the interaction Hamiltonian and order)
- Including multinucleon contributions in a natural way
- Computationally intensive and only applicable to the inclusive response
- Light nuclei
- Non-relativistic

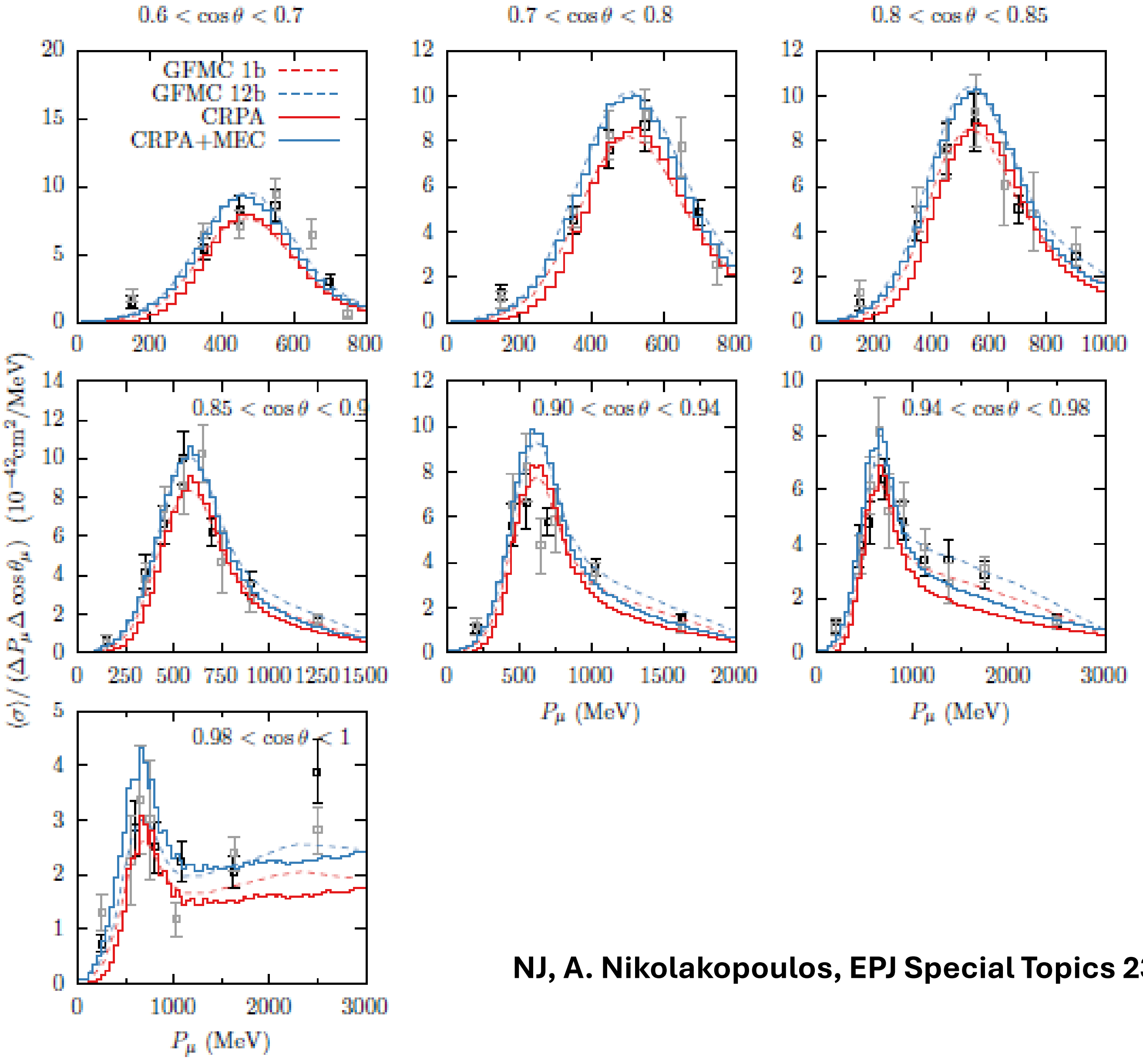
Ab Initio



- MiniBooNE flux-folded double differential cross sections per target neutron for ν_μ-CCQE scattering on ^{12}C in a Green’s Function Monte Carlo approach
- include the effects of many-body correlations induced by the interactions in the initial and final states
- account for the interference between one- and two-body current contributions

A. Lovato et all PRX10, 031068 (2020)

Ab initio

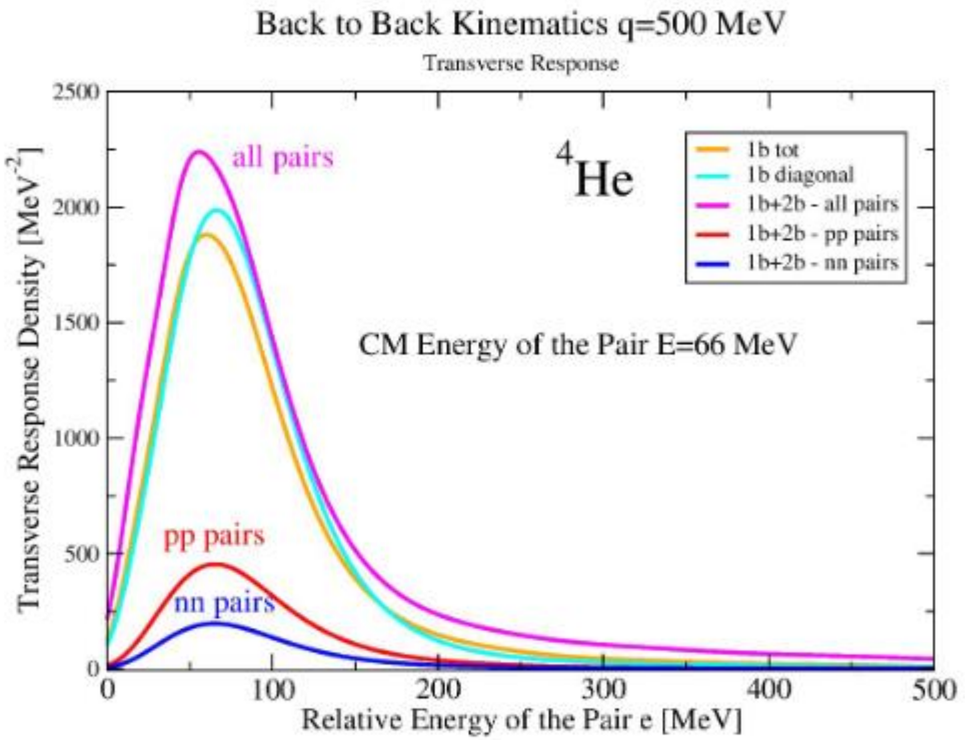


- T2K flux-folded double differential cross sections per target neutron for ν_μ-CCQE scattering on ^{12}C in a Green's Function Monte Carlo approach
- Comparing ab-initio calculations with mean-field-based calculations
- Include long-range correlations in CRPA and added 2p-2h contributions

NJ, A. Nikolakopoulos, EPJ Special Topics 230, 7803

Short Time Approximation STA

Short-time approximation : go beyond the restriction to inclusive processes in ab-initio approaches and provides more exclusive information



S. Pastore et al, PRC101, 044612

- Based on factorization
- Retains 2-body contributions and correctly accounts for interference

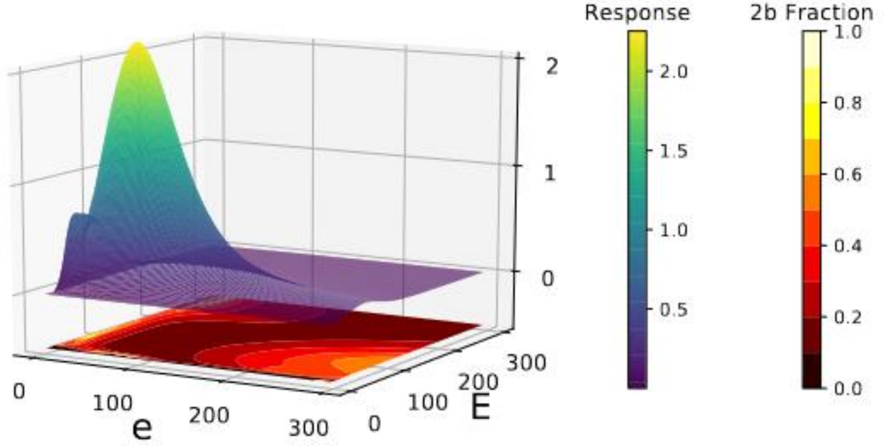
$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij}$$

- Response functions account for scattering off pairs of interacting nucleons

$$R(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right)\, dP'\, dp' \mathcal{D}(p', P'; q)$$

q=500

Transverse response density



Making AI work : Coupled cluster

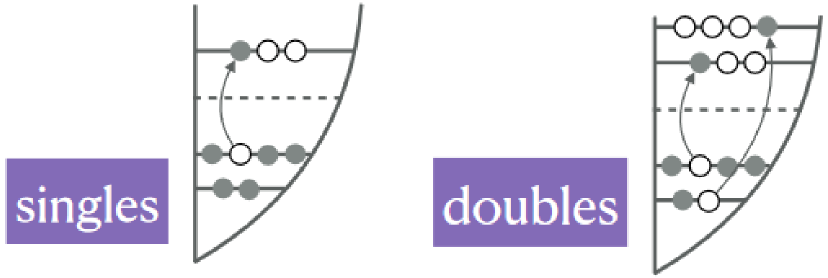
Coupled-cluster theory predictions for **inelastic scattering** processes

$$e^{-T}\mathcal{H}e^{T}|\Psi\rangle \equiv \bar{\mathcal{H}}|\Psi\rangle = E|\Psi\rangle$$

Reference state $|\Psi\rangle$ = mean field

- Operator to include correlations
- Truncation in T controls approximation level

Expansion: $T = \sum t_a^i a_a^\dagger a_i + \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$



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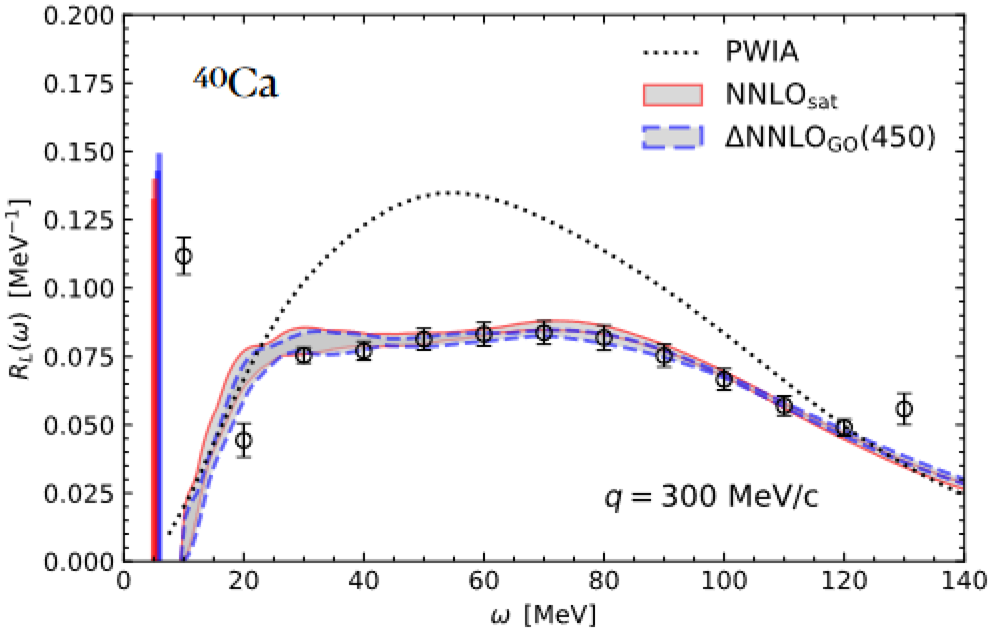
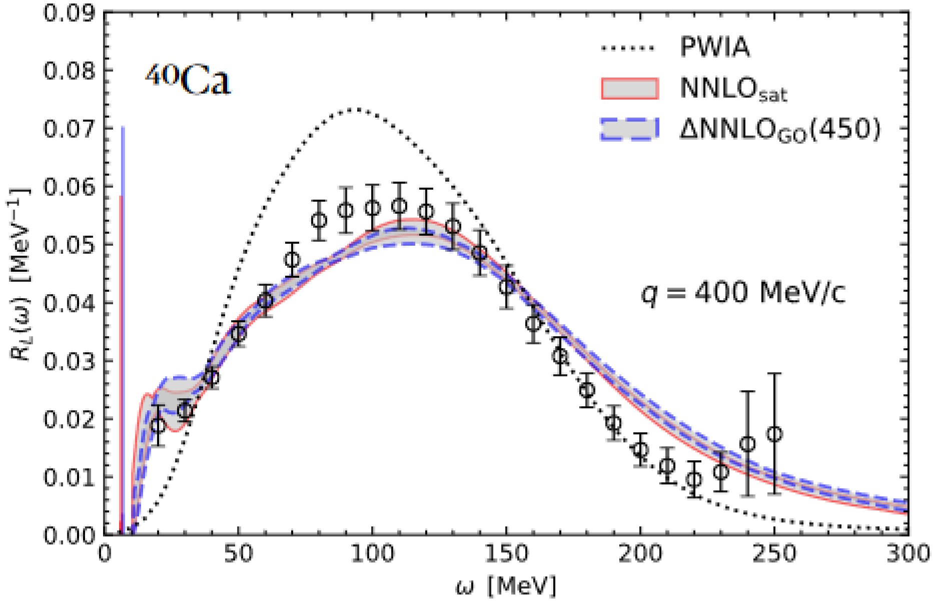


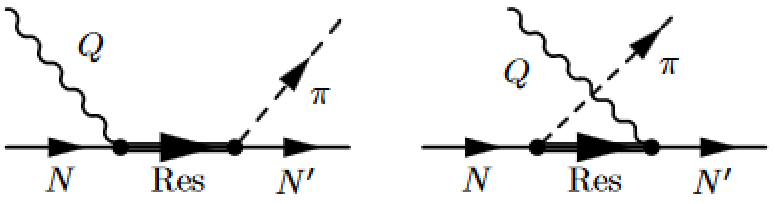


J. Sobczyk et al., PRC 109 (2024) 025502

Beyond nucleon and two-nucleon knockout

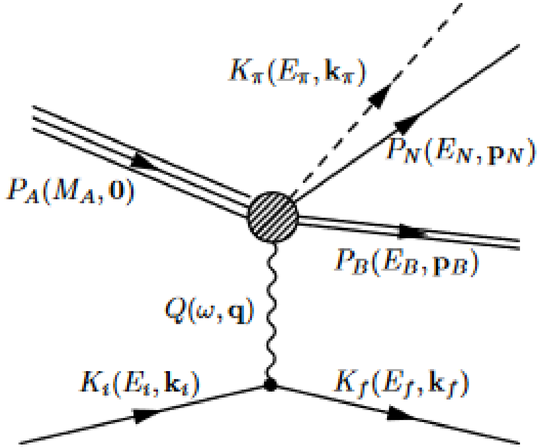
Pion production

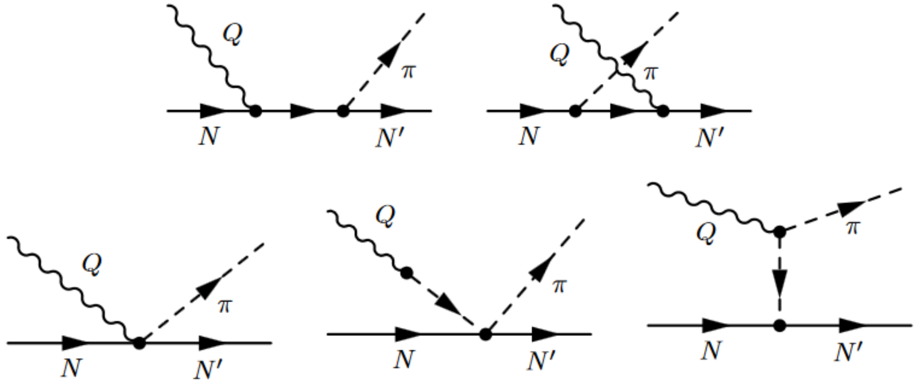
Resonances

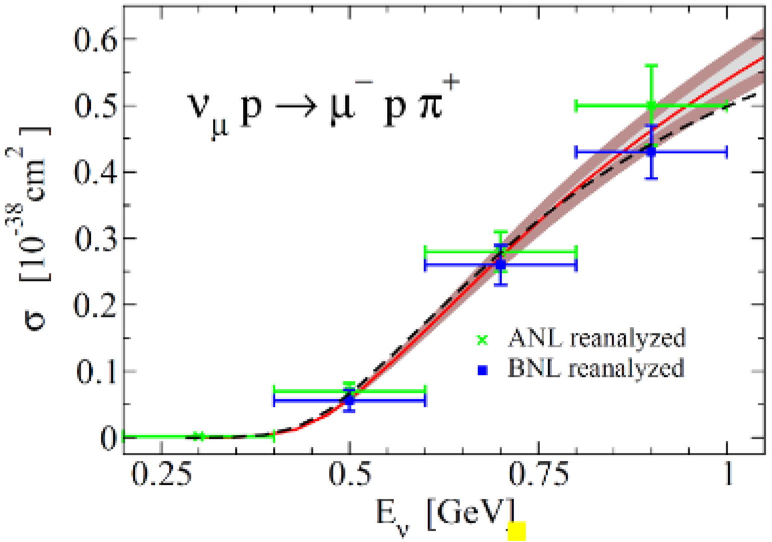


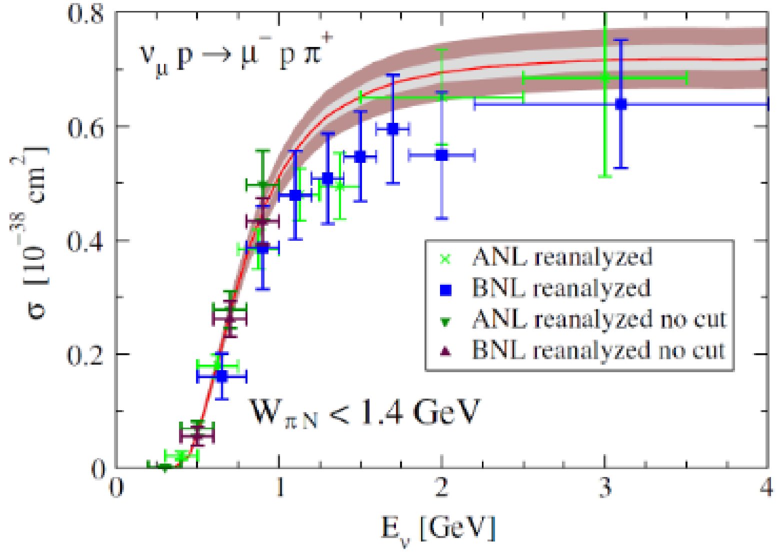
+

ChPT background









Valencia model

- Single pion production in Delta region relatively well understood
- Important background channel for quasi-elastic cross section measurements as the produced pions may be re-absorbed in the nuclear medium or remain otherwise unobserved, leading to a CC0π topology mimicking a QE event

Basic ingredients for modeling single pion production

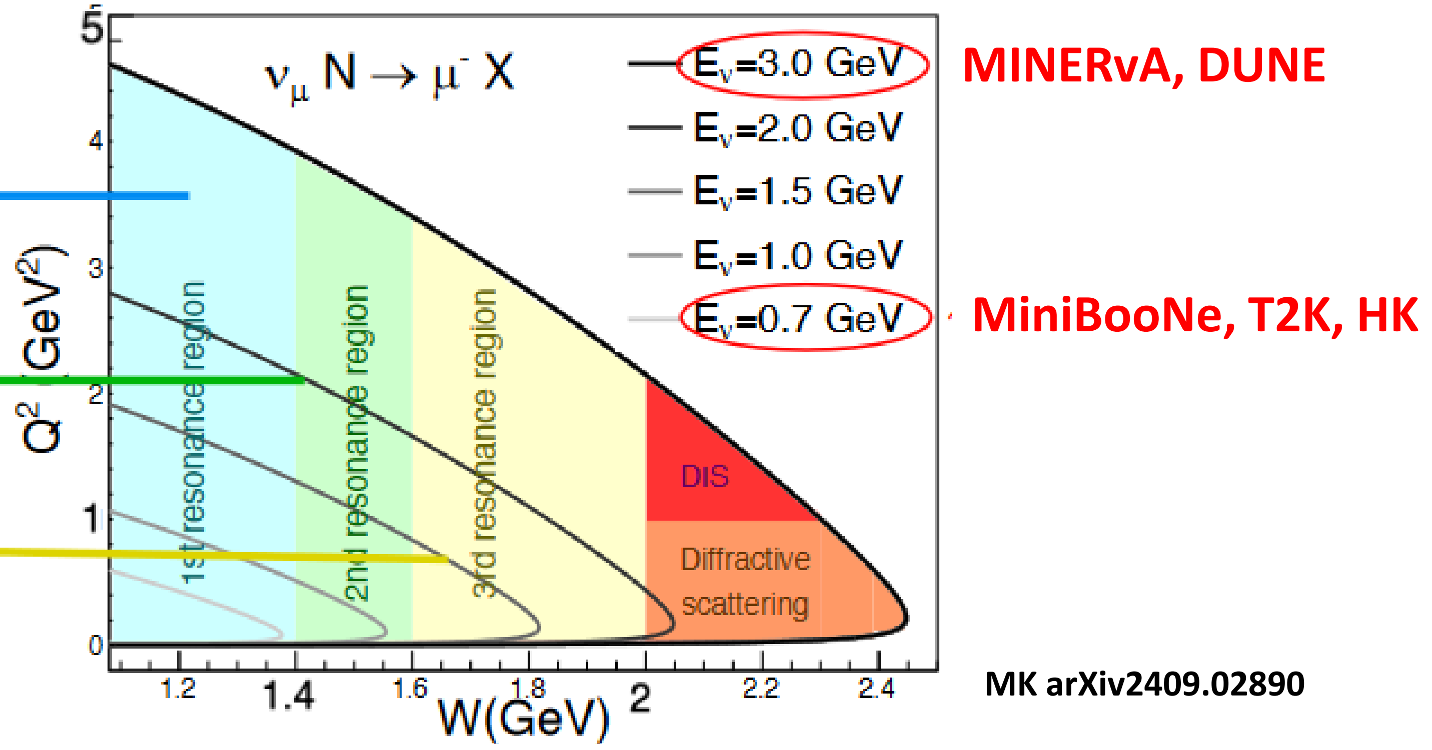
Δ resonance 1pi production

Second resonance region : $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$

2pion, η, ... Production

Third resonance region :

~15 overlapping resonances



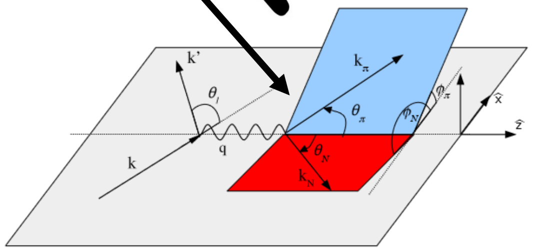
MK arXiv2409.02890

ChPT background

Reggeized background

Basic ingredients for modeling single pion production (off the nucleon !)

$$|\mathcal{M}_W|^2 = \frac{G_F^2 \cos^2\theta_c}{m'm} L^{\mu\nu} H_{\mu\nu}$$



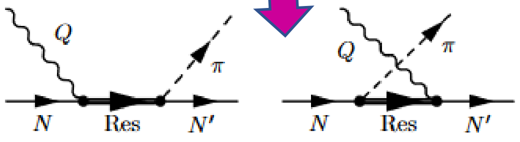
Hadron tensor

$$H^{\mu\nu} = \frac{1}{2}\sum_{s_i,s_f} J^{\mu,*}\left(k_\pi, k_N, Q, s_i, s_f\right) J^{\nu}\left(k_\pi, k_N, Q, s_i, s_f\right)$$

$$J^{\mu}\left(k_\pi, k_N, Q, s_i, s_f\right) = \overline{u}\left(k_N, s_f\right) \mathcal{O}^{\mu}\left(k_\pi, k_N, k\right) u\left(k_i, s_i\right)$$

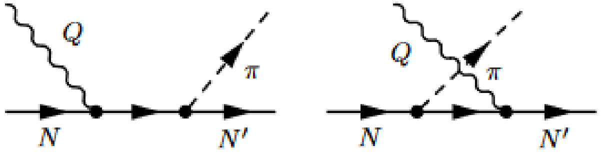
At tree level

Resonances : invariant mass, width Γ, isospin I, spin J, parity P, and for SPP the branching ratio for decay into a pion and nucleon

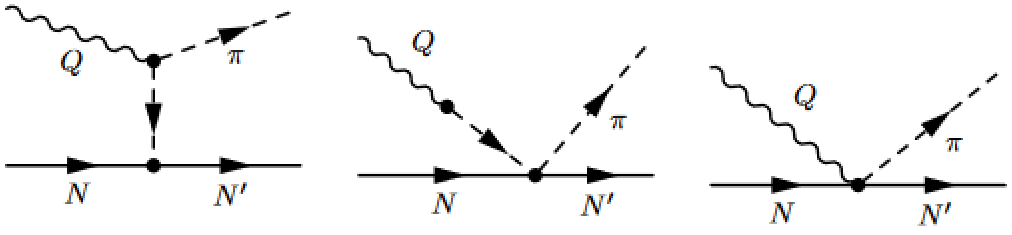


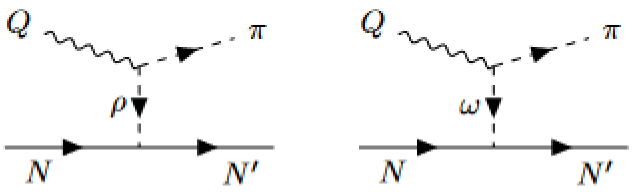
+

Nucleon pole and cross nucleon pole



Non-resonant background

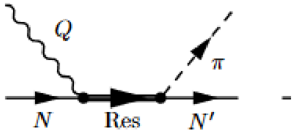
\+ 

\+ 

+ interferences

Basic ingredients for modeling single pion production

$$J^\mu = \sum_n \overline{u}(k_N, s_f)\, \mathcal{O}^\mu_n u(k_i, s_i)$$



$$\mathcal{O}^\mu_{R_{3/2}} = I_{iso,s} \Gamma^\alpha_{R\pi N}\; S_{R,\alpha,\beta}(k_R)\; \Gamma^{\mu\beta}_{QRN}(K_i, Q)$$

Let's pick just one contribution ...
spin 3/2 resonance direct contribution

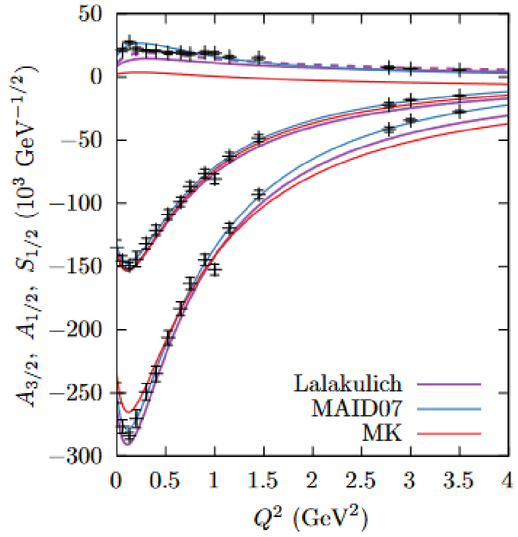
Vertex function for resonance production

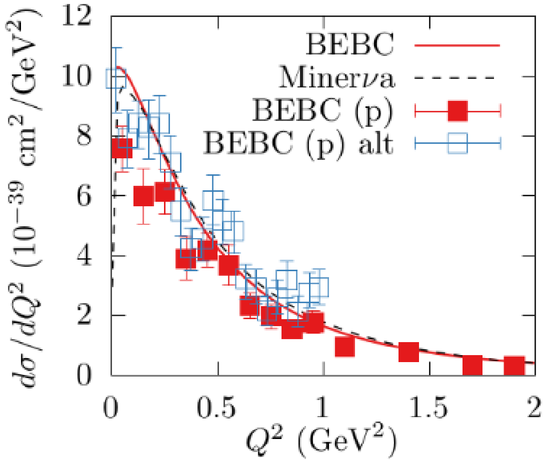
$$\Gamma^{\beta\mu}_{QRN} = \left(\Gamma^{\beta\mu}_{QRN,V} + \Gamma^{\beta\mu}_{QRN,A}\right)\tilde{\gamma}^5$$

- Vector and axial contribution
- Constraint through CVC and PCAC
- Axial form factors not well constrained,
- Large uncertainties on neutrino data

$$\Gamma^{\beta\mu}_V = \left[\frac{C_3^V}{M}\left(g^{\beta\mu}\not{Q} - Q^\beta\gamma^\mu\right) + \frac{C_4^V}{M^2}\left(g^{\beta\mu}Q\cdot k_R - Q^\beta k_R^\mu\right) + \frac{C_5^V}{M^2}\left(g^{\beta\mu}Q\cdot k_i - Q^\beta k_i^\mu\right) + C_6^V g^{\beta\mu}\right]\gamma^5,$$

$$\Gamma^{\beta\mu}_A = \frac{C_3^A}{M}\left(g^{\beta\mu}\not{Q} - Q^\beta\gamma^\mu\right) + \frac{C_4^A}{M^2}\left(g^{\beta\mu}Q\cdot k_R - Q^\beta k_R^\mu\right) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}Q^\beta Q^\mu,$$





e.g. in Lalakulich parametrization

$$C_3 = \frac{2.13/D_V(Q^2)}{1+Q^2/4M_V^2}$$

$$C_4 = -1.51/2.13 C_3$$

$$C_5 = \frac{0.48/D_V(Q^2)}{1+Q^2/0.776M_V^2}$$

Basic ingredients for modeling single pion production

Let's pick just one contribution ...
spin 3/2 resonance direct contribution

$$J^{\mu} = \sum_{n} \overline{u}\left(k_N, s_f\right) \mathcal{O}_n^{\mu} u\left(k_i, s_i\right)$$

$$\mathcal{O}^{\mu}_{R_{3/2}} = I_{iso,s} \Gamma^{\alpha}_{R\pi N} \; S_{R,\alpha,\beta}\left(k_R\right) \; \Gamma^{\mu\beta}_{QRN}\left(K_i, Q\right)$$

Resonance propagator

$$S_3^{\mu\nu} = \frac{\not{k}_R + M_R}{k_R^2 - M_R^2 + iM_R\Gamma(W)} \left[g^{\mu\nu} - \frac{1}{3}\gamma^{\mu}\gamma^{\nu} - \frac{2}{3}\frac{k_R^{\mu}k_R^{\nu}}{M_R^2} + \frac{k_R^{\mu}\gamma^{\nu} - k_R^{\nu}\gamma^{\mu}}{3M_R} \right]$$

Basic ingredients for modeling single pion production

$$J^\mu = \sum_n \overline{u}(k_N, s_f)\, \mathcal{O}_n^\mu u(k_i, s_i)$$

Let's pick just one contribution ...
Spin 3/2 resonance direct contribution

$$\mathcal{O}^\mu_{R_{3/2}} = I_{iso,s}\Gamma^\alpha_{R\pi N}\ S_{R,\alpha,\beta}(k_R)\ \Gamma^{\mu\beta}_{QRN}(K_i, Q)$$

Vertex function for the decay vertex

$$\Gamma^\mu_{\pi NR} = \frac{\sqrt{2} f_{\pi NR}}{m_\pi} k^\mu_\pi \gamma^5 \tilde{\gamma}^5$$

Depends on

- Coupling constant $f_{\pi NR}$
- Resonance width Γ

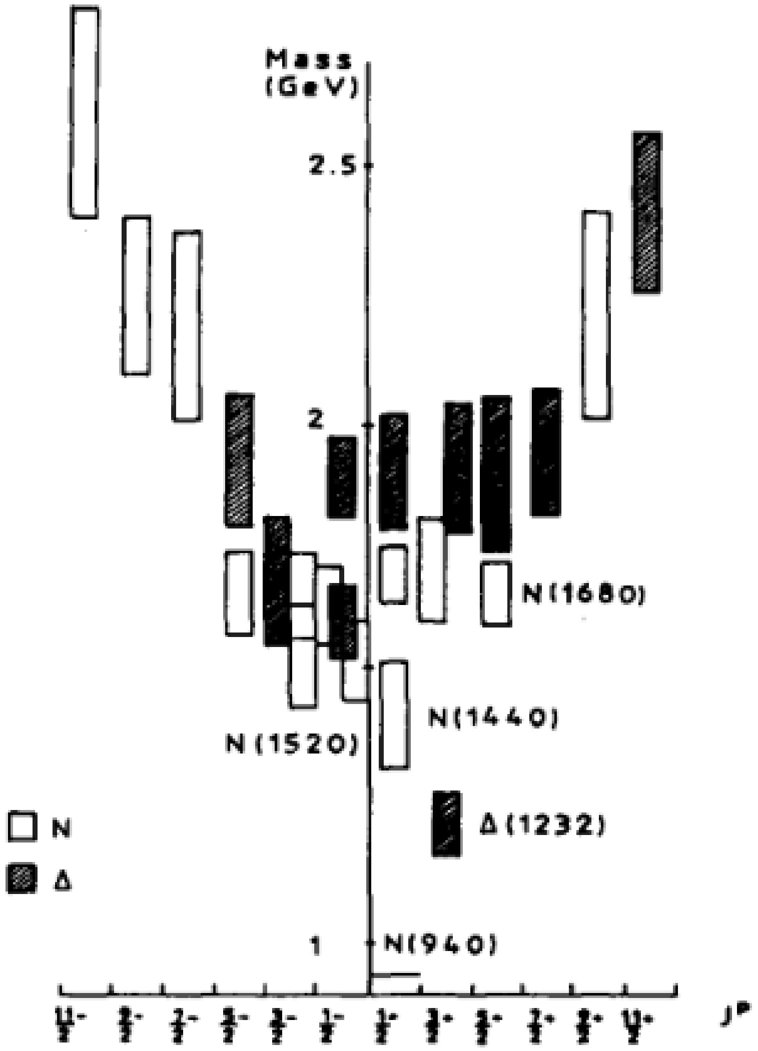
$$\Gamma^{3/2}_{\pi N}(W) = \frac{I_{iso}}{12\pi} \frac{f^2_{\pi NR}}{m^2_\pi} \frac{(k^*_\pi)^3}{W} (E^*_N \pm M_N)$$

	M_R (MeV)	Γ_{exp} (MeV)	$\beta_{\pi N}$	$f_{\pi NR}$
P_{33}	1232	120	1	2.18
S_{11}	1535	150	0.45	0.16
P_{11}	1430	350	0.6	0.49
D_{13}	1515	115	0.6	1.62

$$\Gamma_{\pi N}(M_R) = \beta_{\pi N}\Gamma_{exp}$$

Experimentally determined full width + branching ratio

Basic ingredients for modeling single pion production



M. Giannini, PPNP 24, 253 (1990)

... and these are only resonances ...

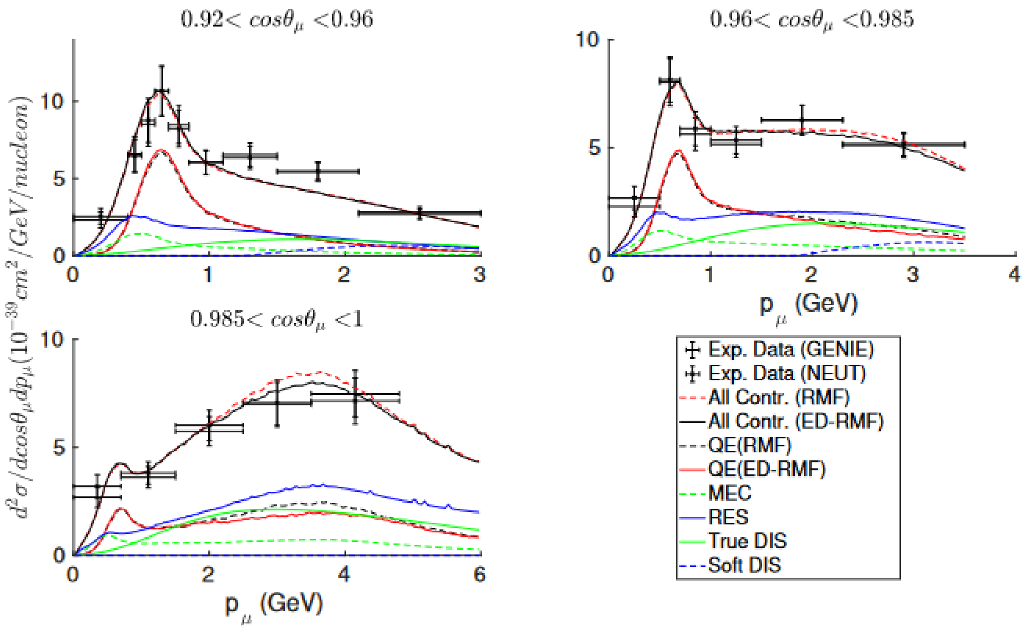
Rein Sehgal model

D. Rein and L.M. Sehgal, Annals of Physics 133, 79 (1981)

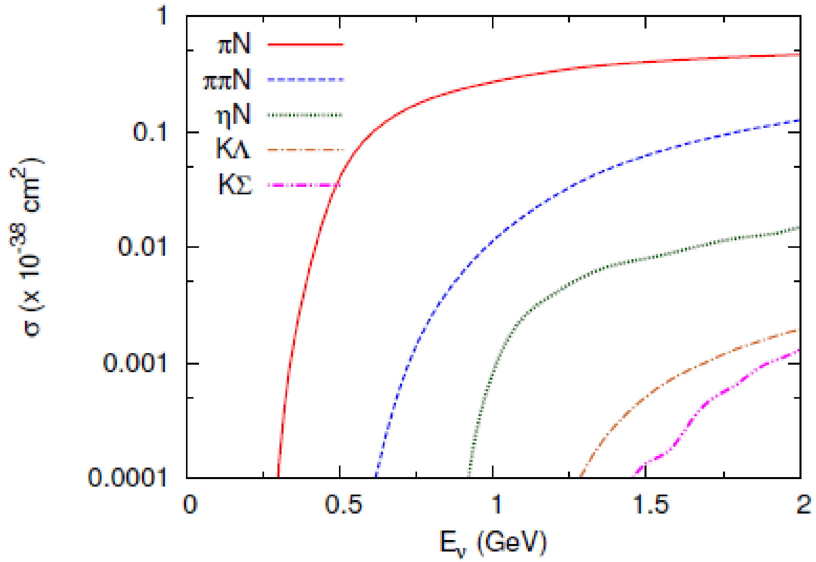
This is an attempt to describe all existing data on neutrino production of single pions in the resonance region up to $W = 2$ GeV in terms of the relativistic quark model of Feynman, Kislinger and Ravndal (FKR). We considered single pion production to be mediated by all interfering resonances below 2 GeV. A simple noninterfering, nonresonant background of isospin $\frac{1}{2}$ was added. It improved agreement with experiment, particularly in the ratio of isospin amplitudes in charged current reactions, at the expense of one additional constant. All total cross sections, cross section ratios and W-distributions are well reproduced at low and high energies, with charged and neutral currents (supposing the Salam–Weinberg theory with $\sin^2 \theta_w \approx \frac{1}{4}$ to be correct), and for neutrinos and antineutrinos, giving predictions where data are lacking. New predictions have been made for complex angular distributions in $\mathcal{N}\pi$ channels exhibiting strong interference between neighbouring resonances. These are sensitive (for 1.1 GeV $\lesssim W \lesssim$ 1.5 GeV) to the sign of the Roper resonance $P_{11}(1450)$ which is controversial in photoproduction experiments.

Models for pion production : ANL-Osaka DCC

- predicts πN, γN partial wave amplitudes used to determine cross sections for πN, ηN, KΛ and KΣ scattering, photoproduction of these channels, 2π production off the nucleon, pion electro- and neutrinoproduction
- Up to W~2 GeV, including ~20 N* states
- Fit to ~30.000 data points for foto pion nucleon, hadron and pion production, and electroproduction for different incoming energies,
- Dynamic coupled channel formalism, different reaction mechanisms contribute in a consistent way to the final state



DCC implementation in SUSA



S. Nakamura, H. Kamano, T. Sato, PRD92, 074024 (2015)

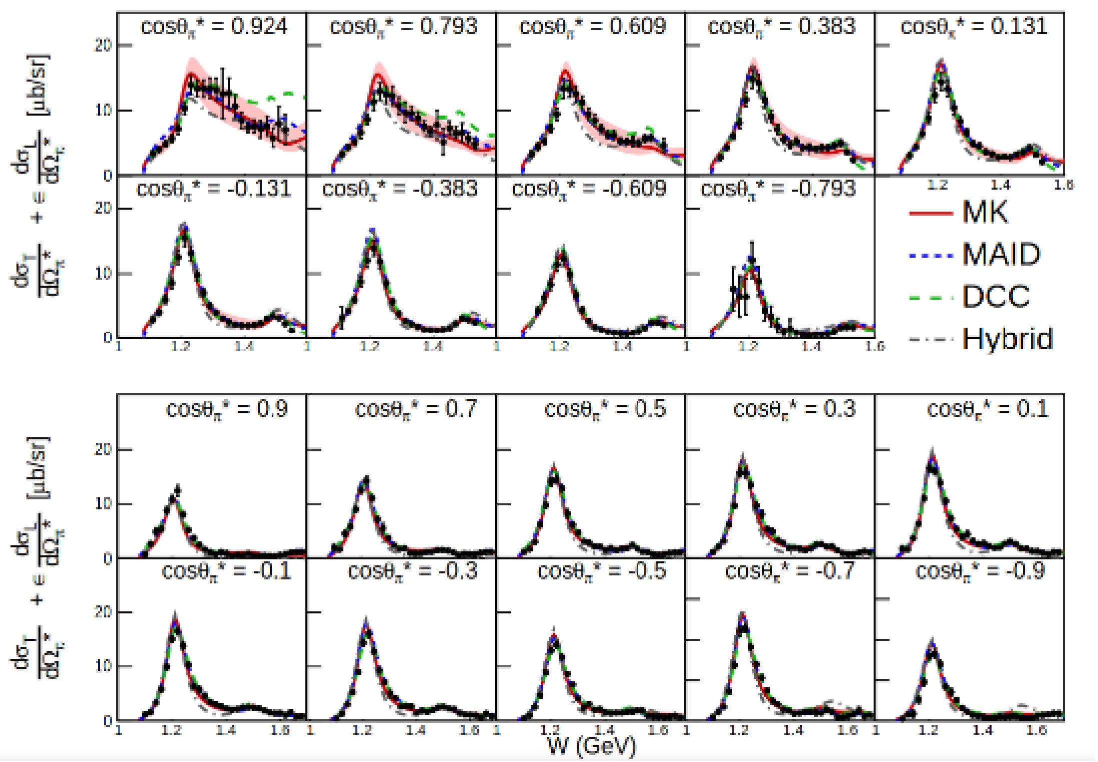
MK model

- Single pion production off the nucleon
- developed aiming at describing neutrino induced processes !
- RS with 17 resonances W<2GeV
- Non-resonant background HNV model
- Fit of a lot of parameters to data
- $d\sigma/dWdQ^2d\Omega_\pi$

# data point	Photon, electron, pion, Neutrino Channels	Q^2 Range $(GeV/C)^2$	W Range GeV	Form Factors	
≈ 9800	$\gamma p \to n + \pi^+$, $\gamma p \to p + \pi^0$	0	1.08 – 2.0	Proton	Vector
≈ 31000	$ep \to en + \pi^+$, $ep \to ep + \pi^0$	0.16 – 6.0	1.08 – 2.0		
≈ 2500	$\gamma n \to p + \pi^-$	0	1.08 – 2.0	Neutron	
≈ 700	NEW $en \to ep + \pi^-$	0.4 – 1.0	1.08 – 1.8		
≈ 400	$\pi^+p \to p + \pi^+$, $\pi^-p \to p + \pi^-$	0	1.08 – 2.0	Axial-Vector	
<100	$\nu N \to l^-N + \pi$, $\bar{\nu}N \to l^+N + \pi$	$Q^2>0$ Integrated	1.08 – 2.0 Integrated		

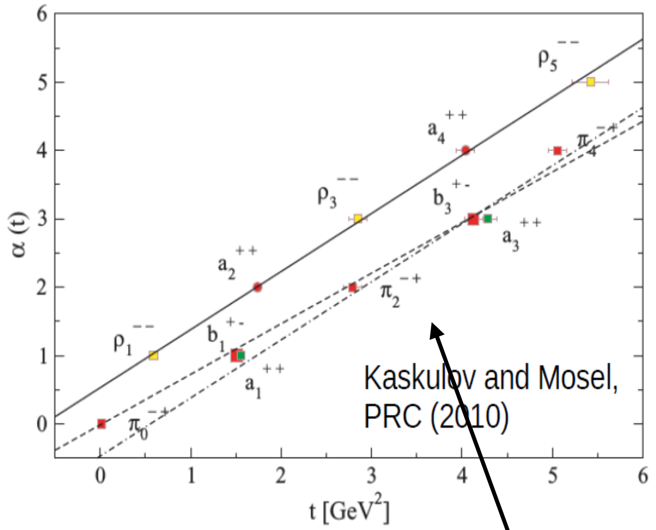
Electron-induced SPP: high quality proton target data

Figures from M. Kabirnezhad [arxiv:2203.15594]

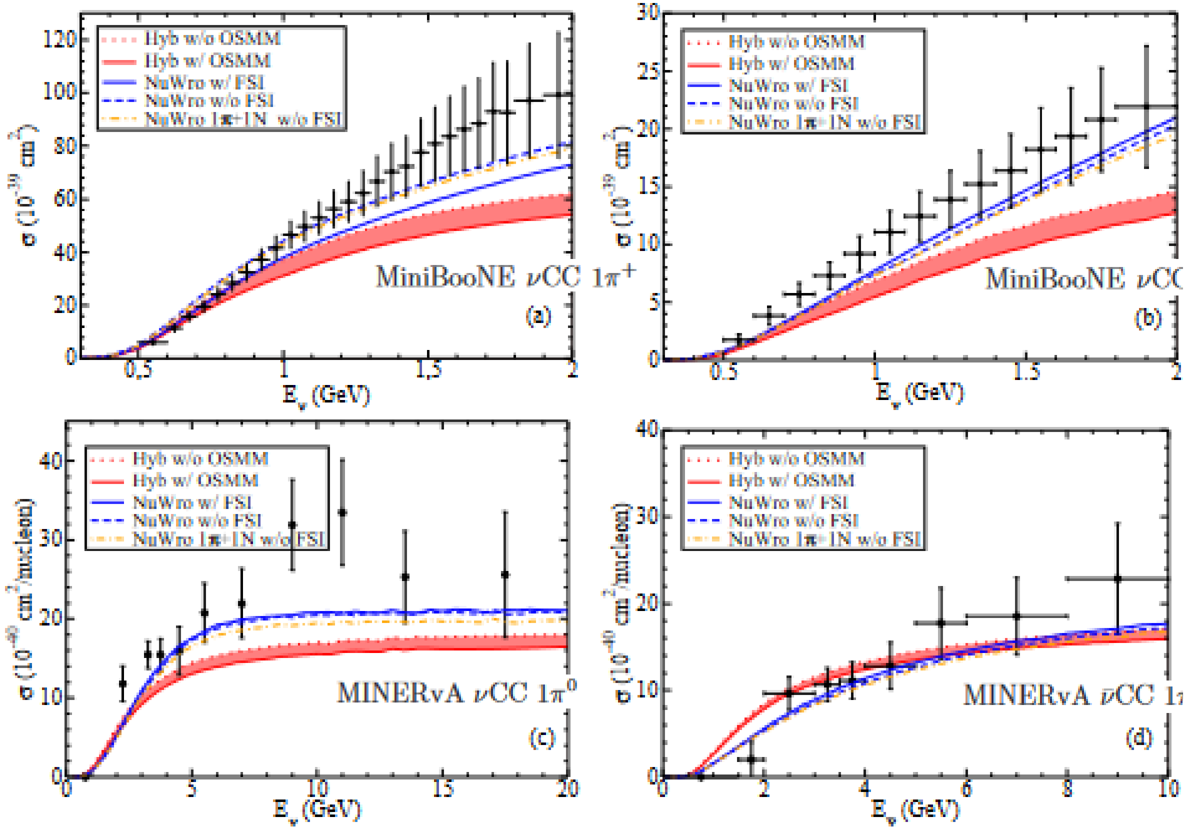


Ghent Hybrid model : single pion production off a bound nucleon

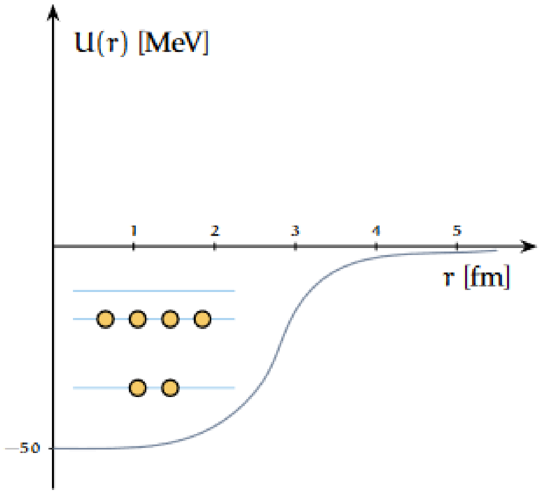
- Designed aiming at the description of pion production off the nucleus
  - Low energy model : resonances + background from ChPT in HNV description
  - High energy model : Reggeized background to overcome shortcomings of the low energy description
- Aiming at fully exclusive description with distorted pion and nucleon wave functions

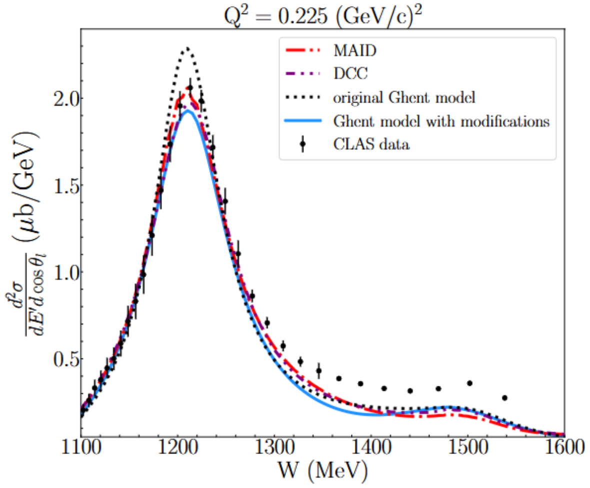


π(140)/b_1(1235) propagator



RMF description for the nucleus



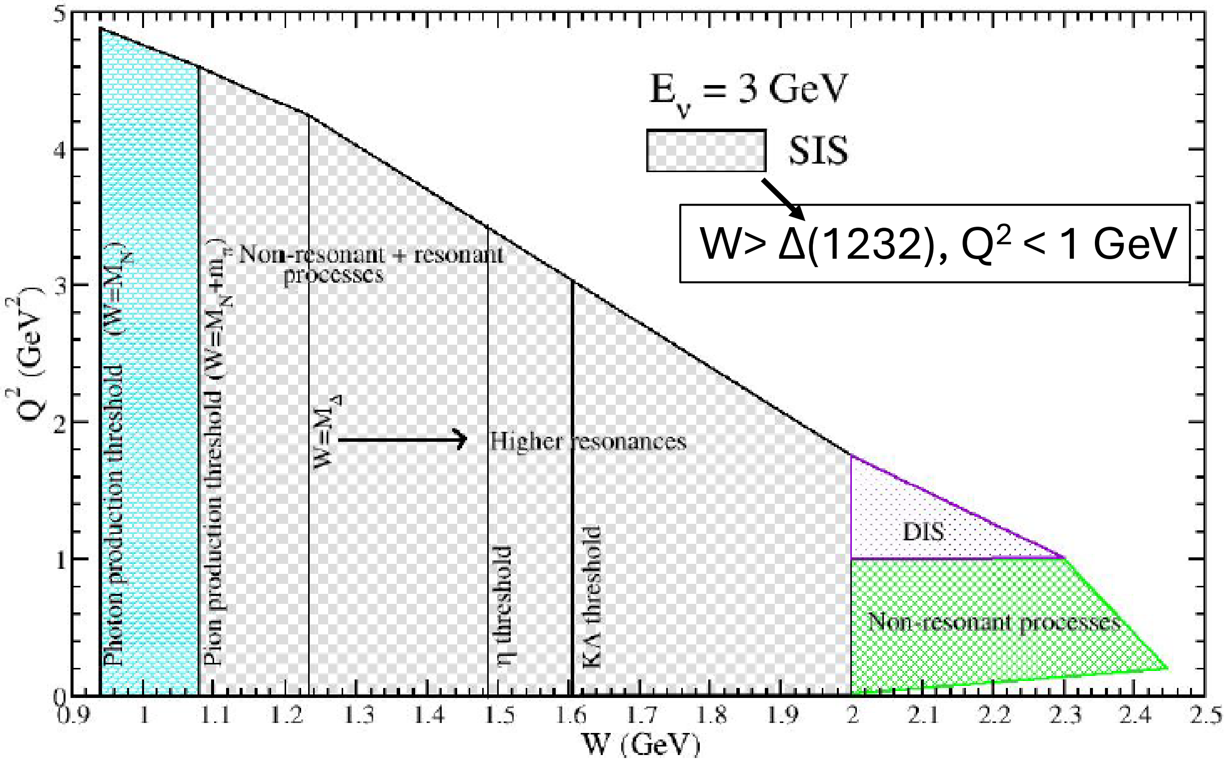


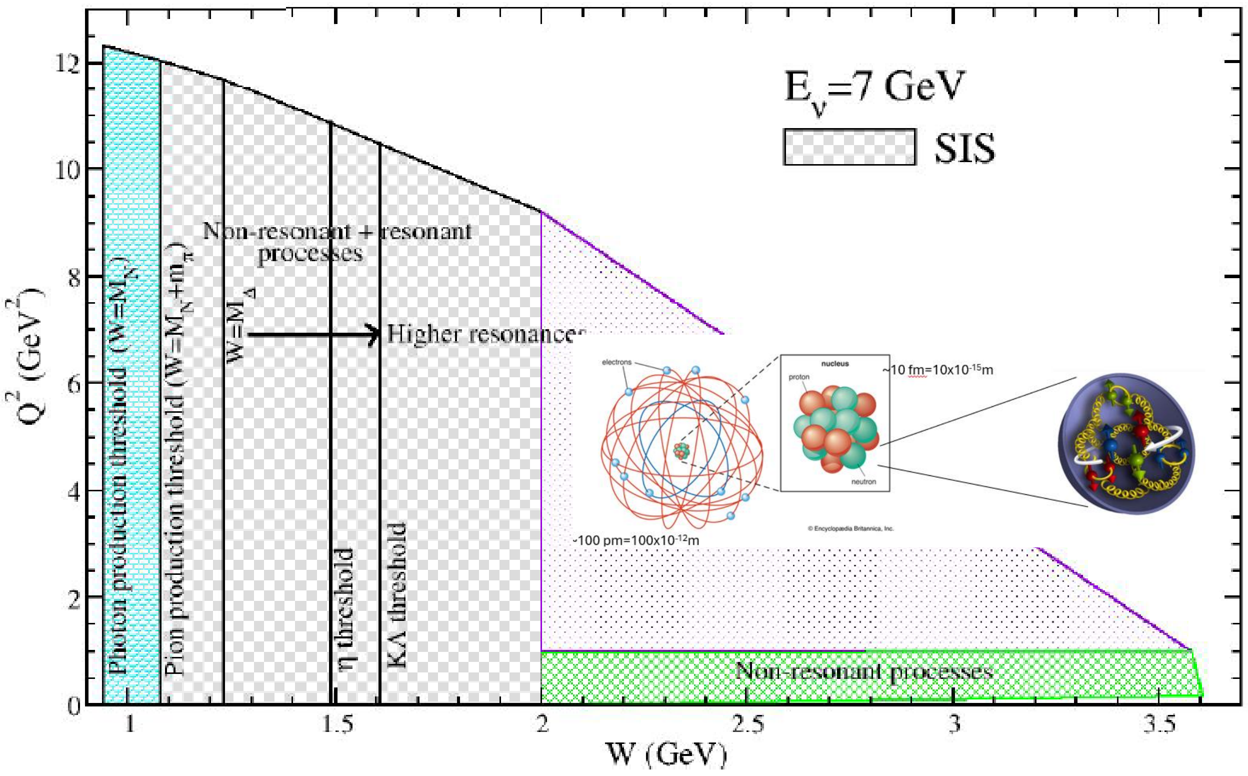
R. Gonzalez-Jimenez et al.,Phys. Rev. D 97

M. Hooft et al., arXiv 2603.29486

Duality and the transition from nucleon to partonic degrees of freedom

- A considerable fraction of events at higher incoming energies are from the SIS (Shallow Inelastic) and D(eep)IS regions
- Important background channel for quasi-elastic cross section measurements as the produced pions may be re-absorbed in the nuclear medium or remain otherwise unobserved, leading to a CC0π topology mimicking a QE event
- A considerable fraction of events at higher incoming energies are from the SIS and DIS regions e.g. around 50% for DUNE





Snowmass WP on theoretical tools for neutrino scattering, L. Alvarez Ruso et al, arXiv:2203.09030

Duality and the transition from nucleon to partonic degrees of freedom

- A considerable fraction of events at higher incoming energies are from the SIS and DIS regions e.g. around 50% for DUNE
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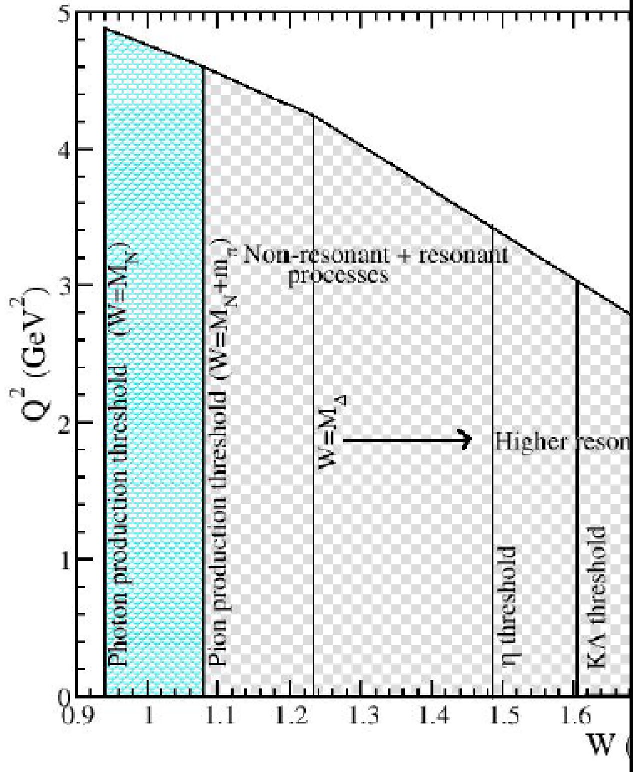
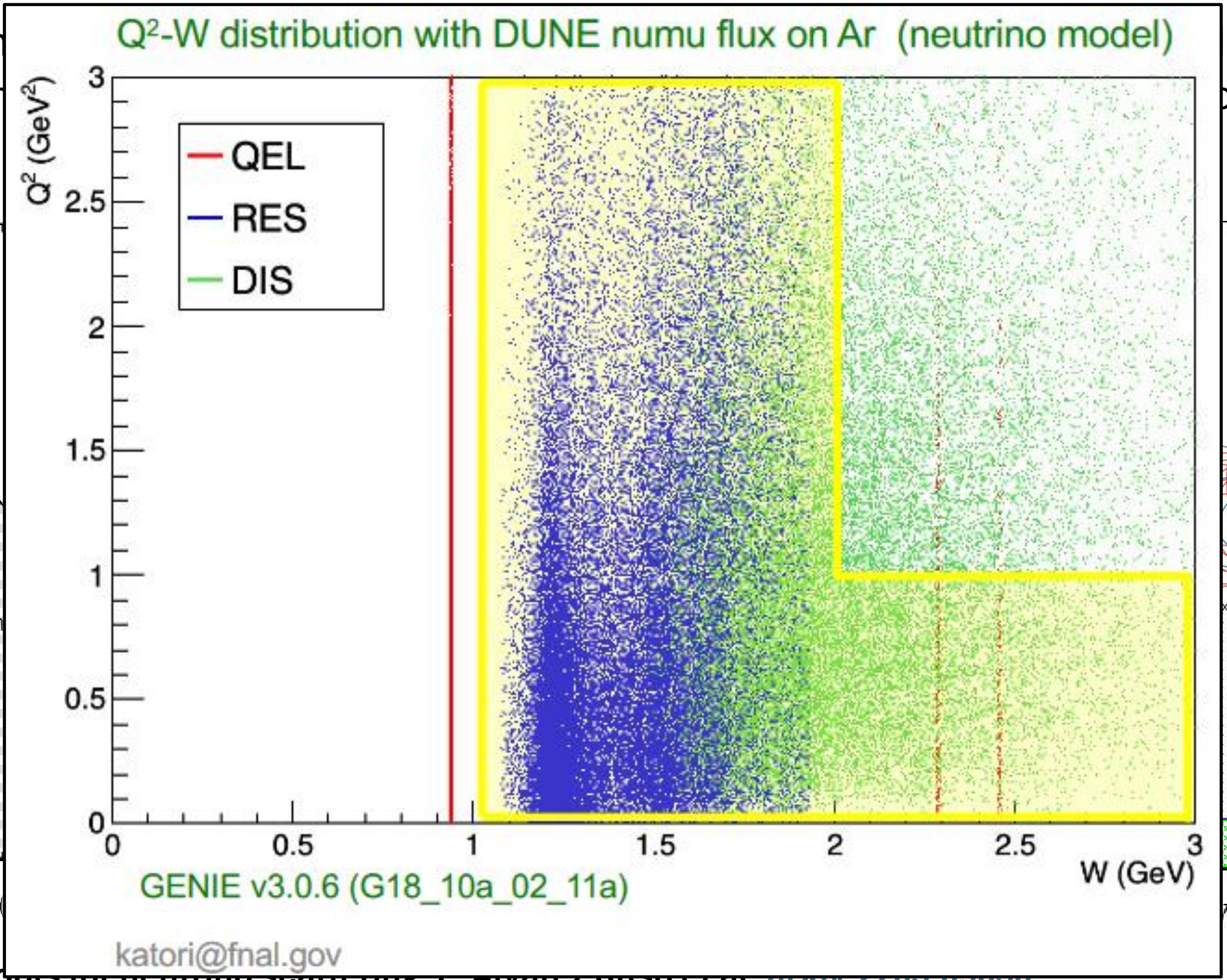
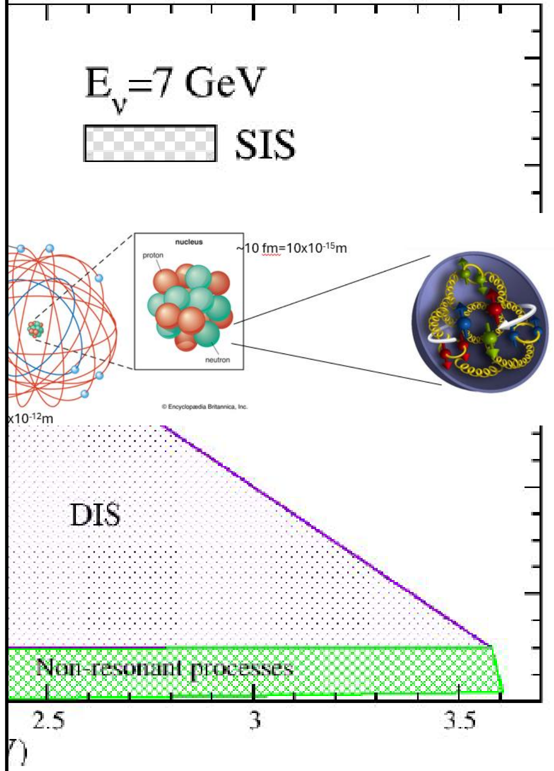




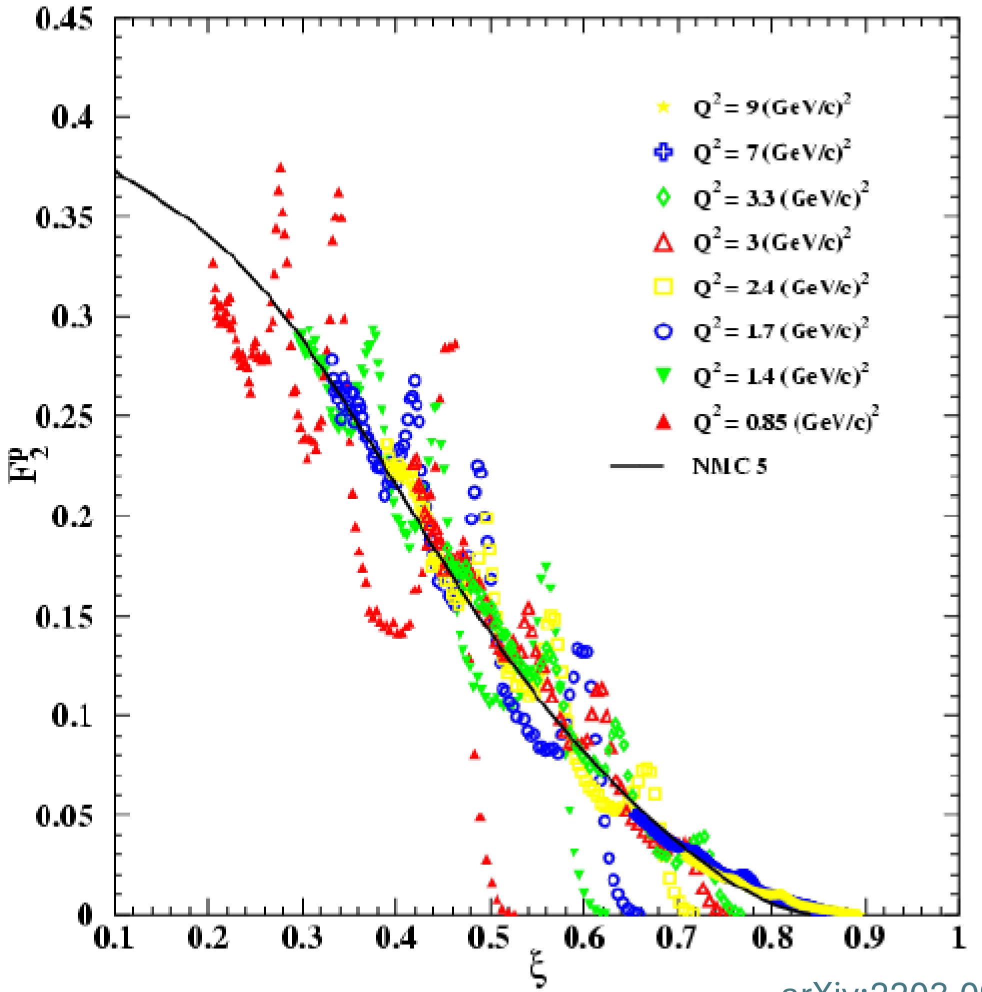


Snowmass WP on theoretical to… …scattering, L. Alvarez Ruso et al, arXiv:2203.09030

Duality and the transition from nucleon to partonic degrees of freedom

The phenomenology of the transition to partonic degrees of freedom is assessed by Bloom-Gillman duality

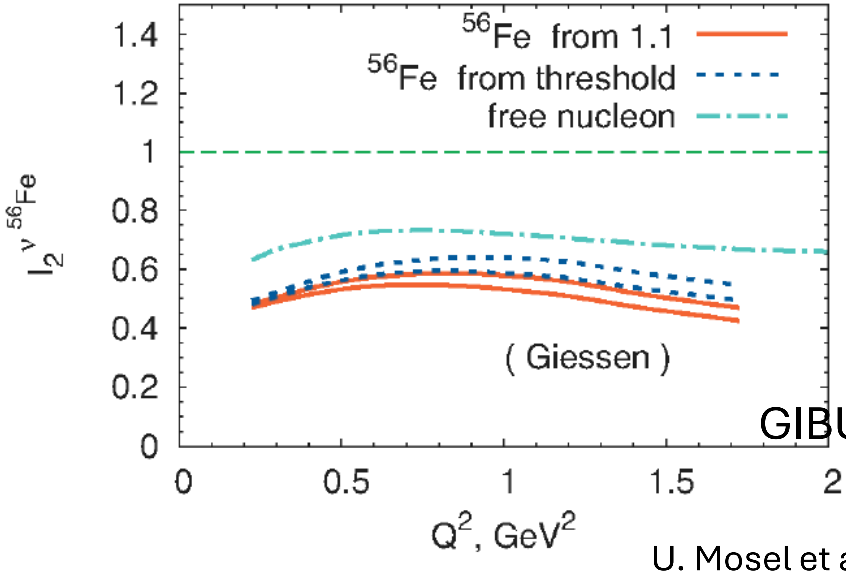
Electron-scattering : resonances (Jlab E94-110 data) follow the extrapolated DIS curve



arXiv:2203.09030

For neutrinos, the situation is less clear :

- Data is limited to low-statistics hydrogen and deuterium bubble chamber data from the 70s and 80s
- For computations the integrated resonance strength tends to account for only ~50% of the observed signal

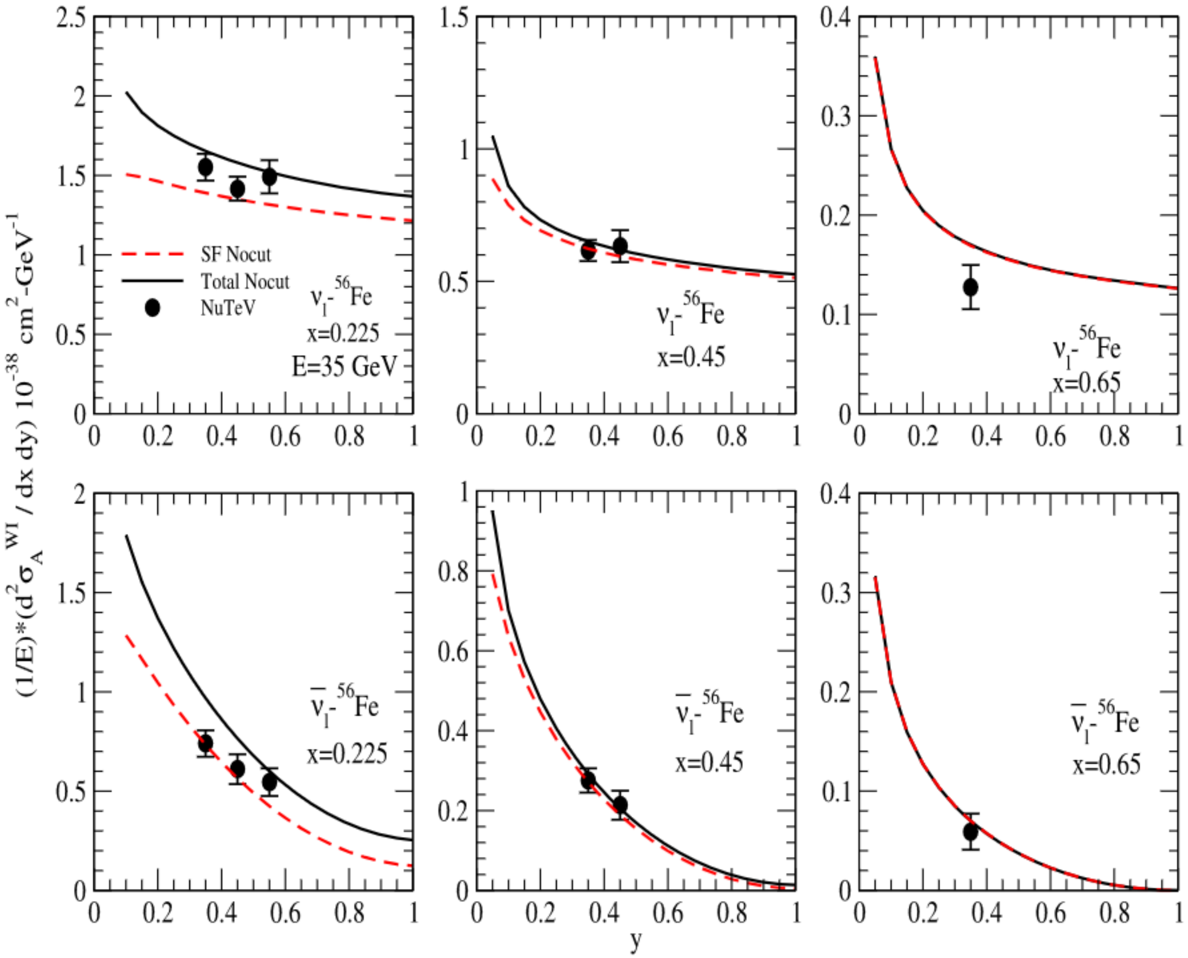


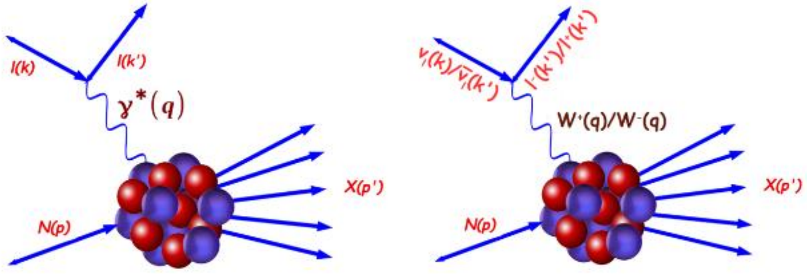
GIBUU

U. Mosel et al, PRC96, 015503 (2017)

$$\mathcal{I}_j(Q^2_{RES}, Q^2_{DIS}) = \frac{\int_{\xi_{min}}^{\xi_{max}} d\xi\, F_j^{RES}(\xi, Q^2_{RES})}{\int_{\xi_{min}}^{\xi_{max}} d\xi\, F_j^{DIS}(\xi, Q^2_{DIS})}$$

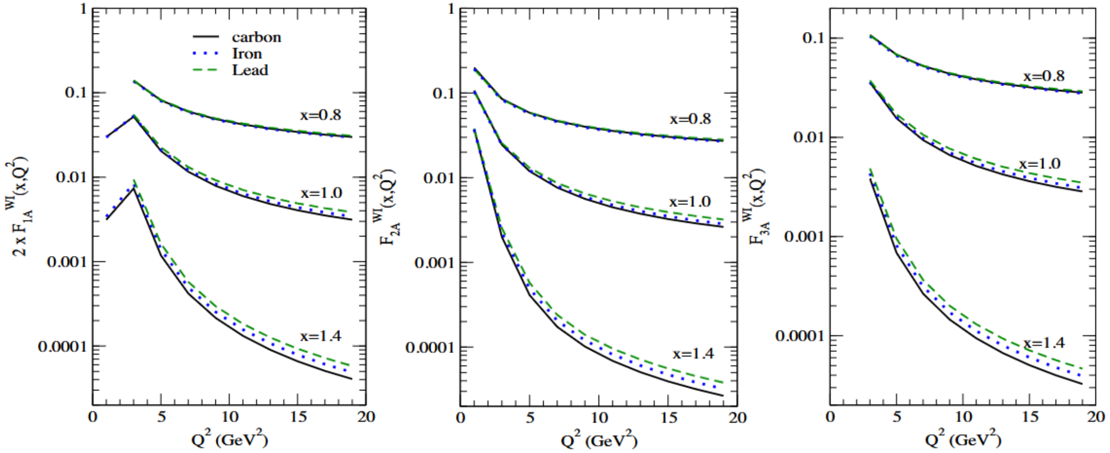
DIS : Deep Inelastic Scattering





$$\frac{d^2\sigma_A^{IC}}{dxdy} = \kappa\left[xy^2 F_{1A}^{IC}(x,Q^2) + \left(1 - y - \frac{M_N xy}{2E_l}\right) F_{2A}^{IC}(x,Q^2) + xy\left(1 - \frac{y}{2}\right) F_{3A}^{IC}(x,Q^2)\right],$$

- Nucleon structure functions
- Encode information about the influence of the nuclear medium

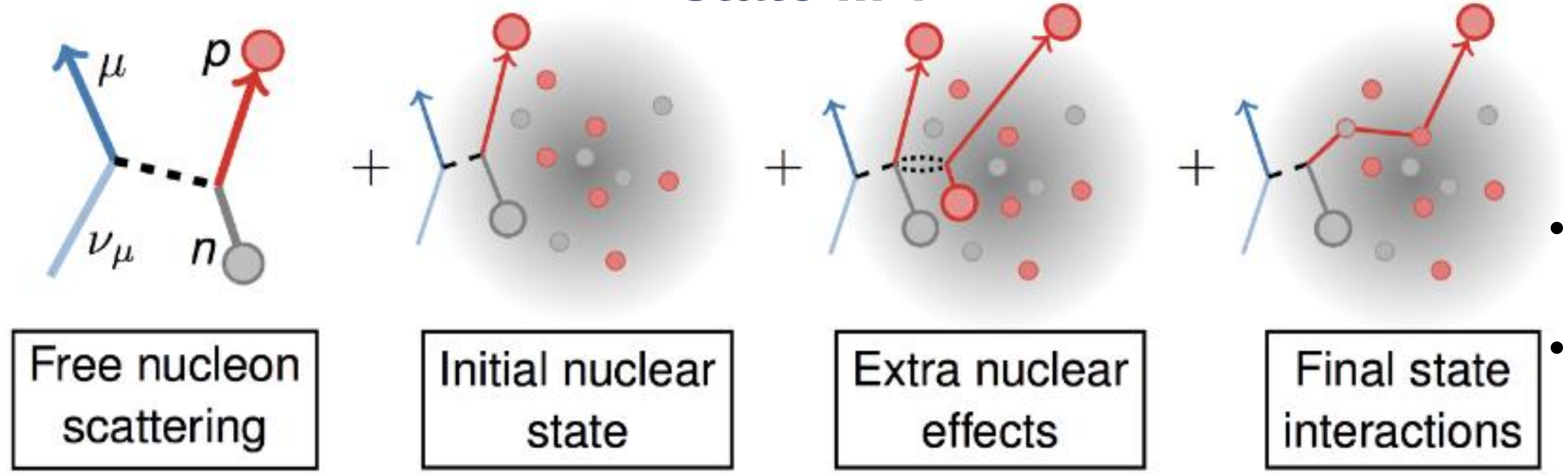


x : Bjorken scaling variable : fraction of the hit nucleon's momentum carried by the struck parton

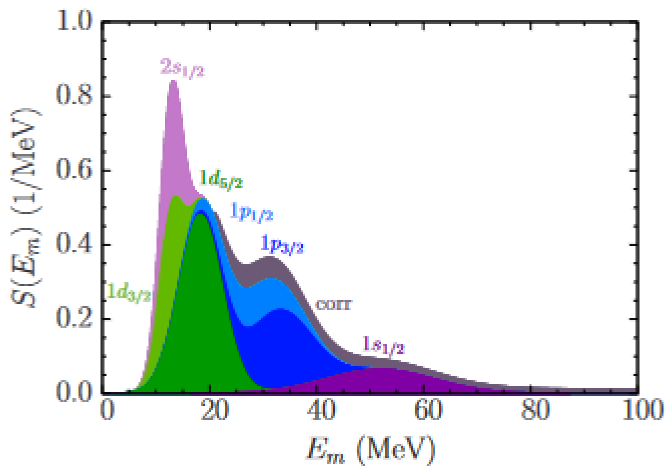
y : fractional energy loss of the probing particle

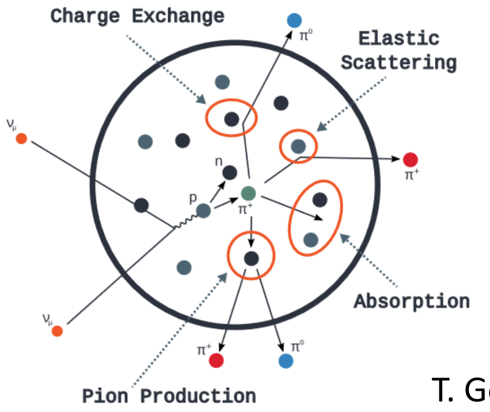
Aligarh group PRD 105, 093002 (2022)

And finally : What is going on between initial and final detected state ... ?



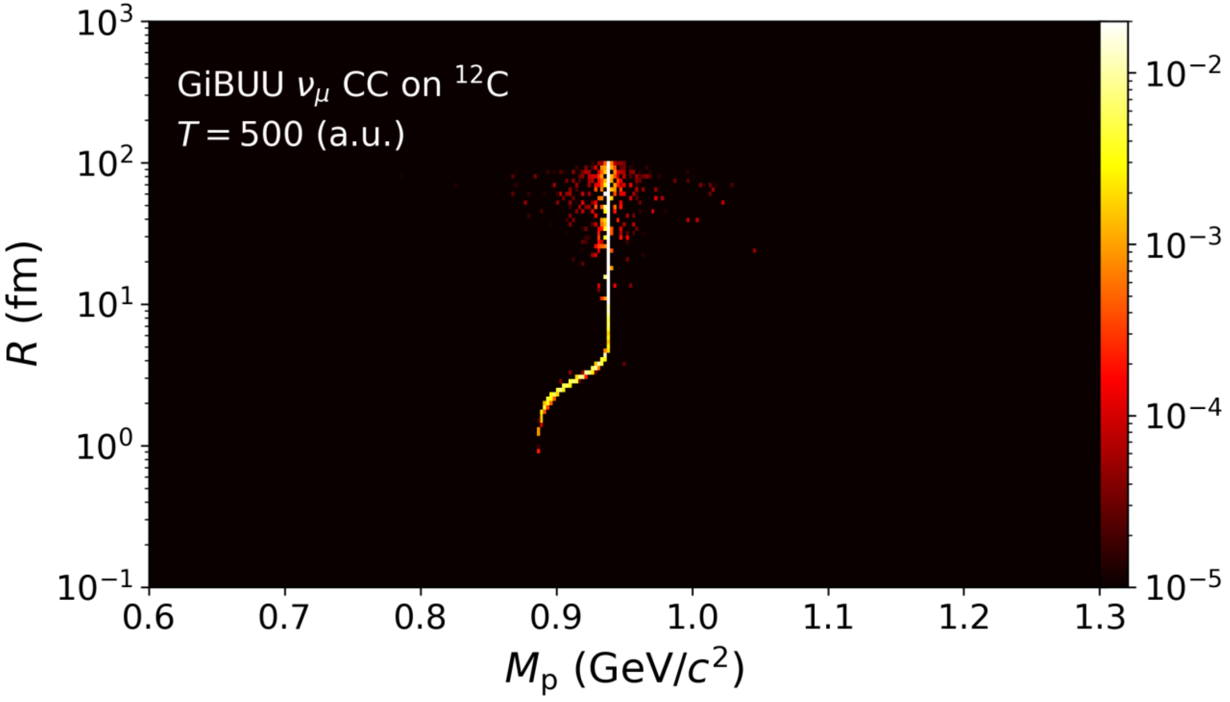
- Partially taken into account by some of the nuclear models
- MC Generators used for oscillation analyses tend to rely on efficient but approximate models

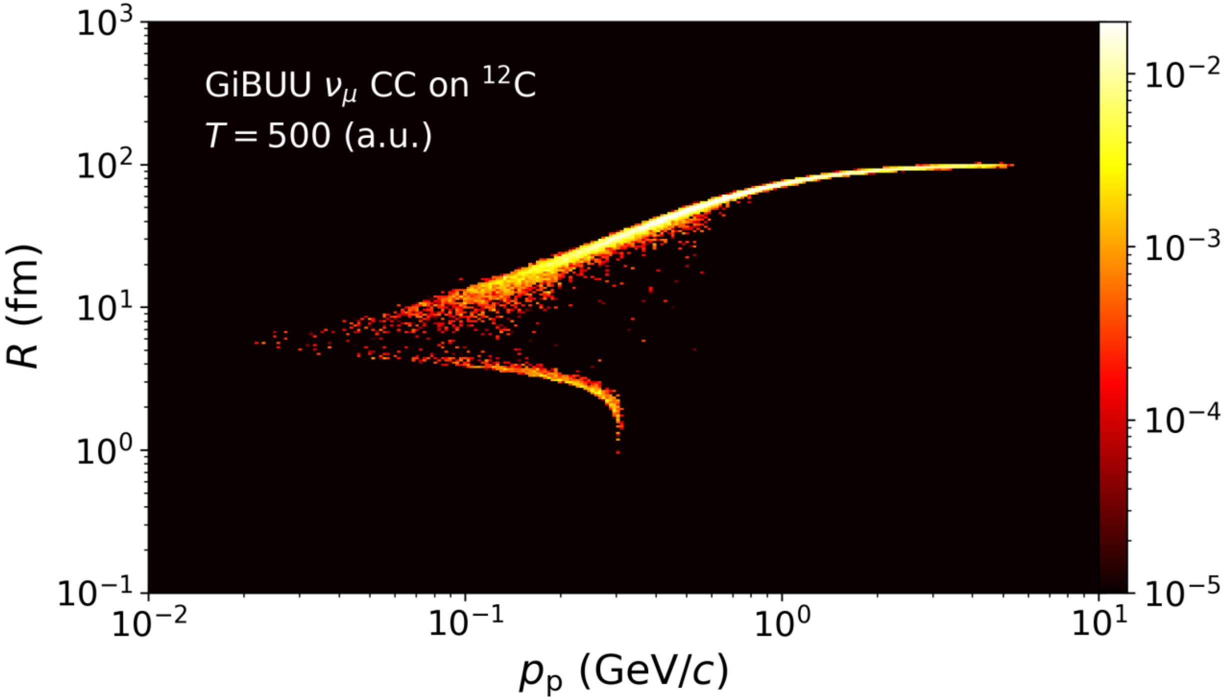




T. Golan

Event generators : bridges between theory and data





Credit: Kaile WEN@IHEP, Xianguo LU@Warwick

† Proton in GiBUU final-state transport
R: radial position, M_p: mass, p_p: momentum

- Theoretical models tend to concentrate on description of the primary vertex
- Generators provide more detailed information about secondary processes obtained in a semi-classical cascade description
- Trade-off between sophistication in models and numerical performance

Event generators : bridges between theory and data

- Theoretical models tend to concentrate on description of the primary vertex
- Generators provide more detailed information about secondary processes obtained in a semi-classical cascade description
- Trade-off between sophistication in models and numerical performance

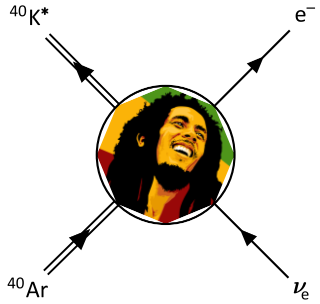
- Number of generators on the market :
    - GENIE, NEUT, NuWro, GIBUU

Challenges in generator developments :

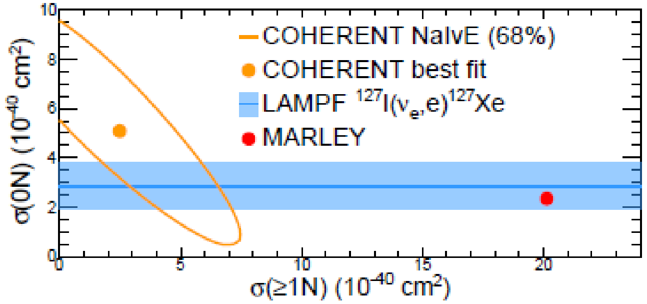
- Standardized interfaces
- Microscopic input for vertex – exclusive description e.g. SuSAv2 and CRPA in GENIE, EDRMF in NEUT, GHENT-HYBRID in NuWro

Event generators : bridges between theory and data

- Number of generators on the market :



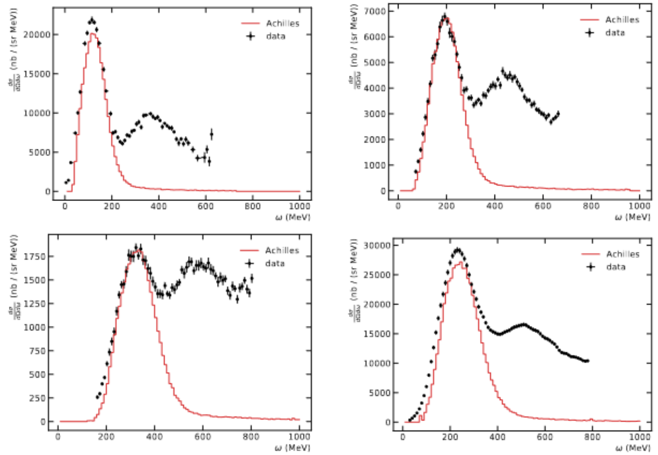
- MARLEY : low energy processes (< 100 MeV) **S. Gardiner PRC103, 044604 (2021)**



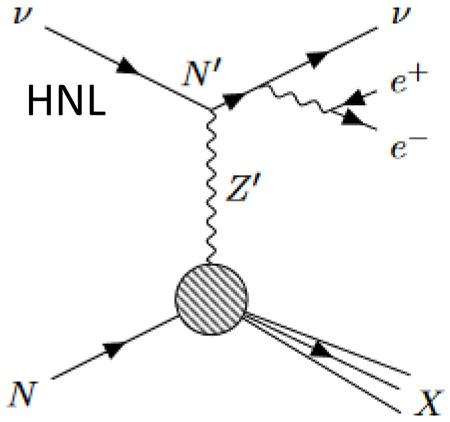
[arXiv:2205.06378](https://arxiv.org/abs/2205.06378)

- INCL : FSI including nuclear clusters and de-excitation

- Achilles : beyond standard model processes, QMC nuclear input



J. Isaacson et al. PRD 107, 033007 (2023)



What you really should take away …

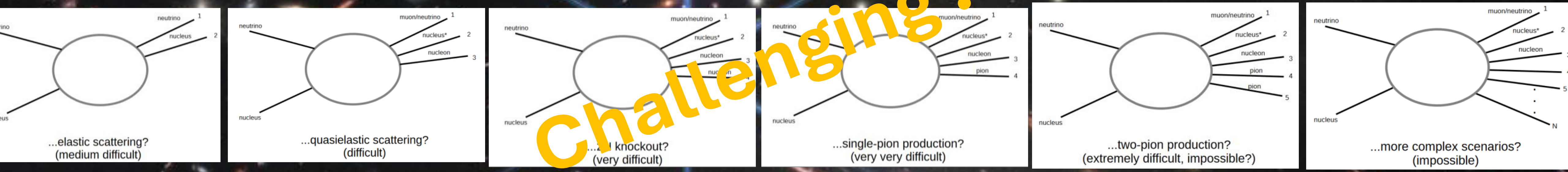
Things to be aware of when working with cross section models :

- Not every model is suitable for the description of any process … What assumptions and approximations are built in ? What is the validity range of the model ?
- Make sure that the model you use is up to the task e.g. exclusive data will need more refined modelling (Is the final state a distorted wave ? Are binding energies and Pauli blocking taken into account ? Angular distributions for hadrons will typically need mean field models to be accurate, ….)

- Descriptions are often based on effective parametrization. As a consequence, results and the separation between various effects are scheme dependent.
- When adding various effects on top of each, make sure you're doing it in a consistent way to avoid double counting. Caring about consistency is a great idea anyhow.

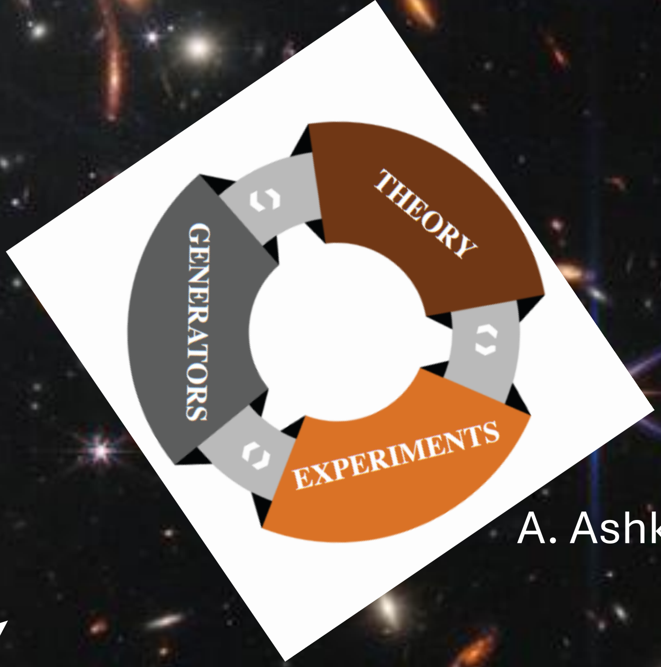
- Making sure that the model is validated against electron scattering data for the type of process and kinematic range you're looking at is a great idea
- Still, be aware that neutrinos are different from electrons … and differences might bias results

Where should we go from here ?



Raul Gonzalez-Jimenez

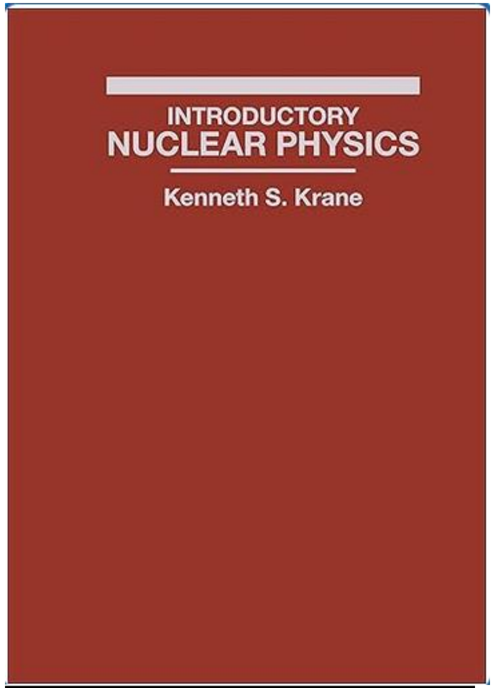
- The upcoming generation of experiments needs cross section calculations with unprecedented accuracy and reliable uncertainty estimates
- We have to tackle the currently existing degeneracy between nucleon uncertainties and nuclear effects, and between cross section and flux uncertainties
- We need calculations for more exclusive processes
- Argon targets
- Especially in the kinematic region beyond the quasielastic and the delta region, and beyond … a lot of open issues remain
- Combine strength of microscopic quantummechanical modeling and generator approaches to FSI and make sure theoretical progress finds it way to generators

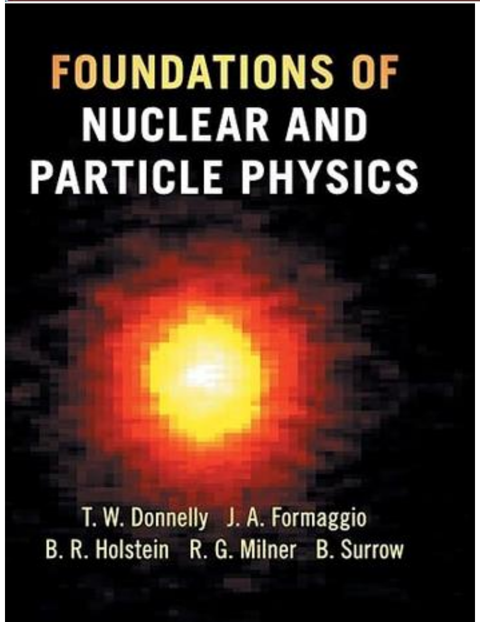


A. Ashkenazi

Snowmass WP on theoretical tools for neutrino scattering, L. Alvarez Ruso et al, arXiv:2203.090

Further reading ...





FERMILAB-PUB-17-195-ND-T
INT-PUB-17-020

NuSTEC[a] White Paper: Status and Challenges of Neutrino-Nucleus Scattering

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(Dated: June 16, 2017)

The precise measurement of neutrino properties is among the highest priorities in fundamental particle physics, involving many experiments worldwide. Since the experiments rely on the interactions of neutrinos with bound nucleons inside atomic nuclei, the planned advances in the scope and precision of these experiments requires a commensurate effort in the understanding and modeling of the hadronic and nuclear physics of these interactions, which is incorporated as a nuclear model in neutrino event generators. This model is essential to every phase of experimental analyses and its theoretical uncertainties play an important role in interpreting every result.

In this White Paper we discuss in detail the impact of neutrino-nucleus interactions, especially the nuclear effects, on the measurement of neutrino properties using the determination of oscillation parameters as a central example. After an Executive Summary and a concise Overview of the issues, we explain how the neutrino event generators work, what can be learned from electron-nucleus interactions and how each underlying physics process — from quasi-elastic to deep inelastic scattering — is understood today. We then emphasize how our understanding must improve to meet the demands of future experiments. With every topic we find that the challenges can be met only with the active support and collaboration among specialists in strong interactions and electroweak physics that include theorists and experimentalists from both the nuclear and high energy physics communities.

[a] Neutrino Scattering Theory Experiment Collaboration http://nustec.fnal.gov

↓

Stay tuned for the new NuSTEC White Paper coming soon !

Journal of Physics G: Nuclear and Particle Physics

TOPICAL REVIEW • OPEN ACCESS

Theoretical tools for neutrino scattering: interplay between lattice QCD, EFTs, nuclear physics, phenomenology, and neutrino event generators

To cite this article: L Alvarez-Ruso *et al* 2025 *J. Phys. G: Nucl. Part. Phys.* **52** 043001

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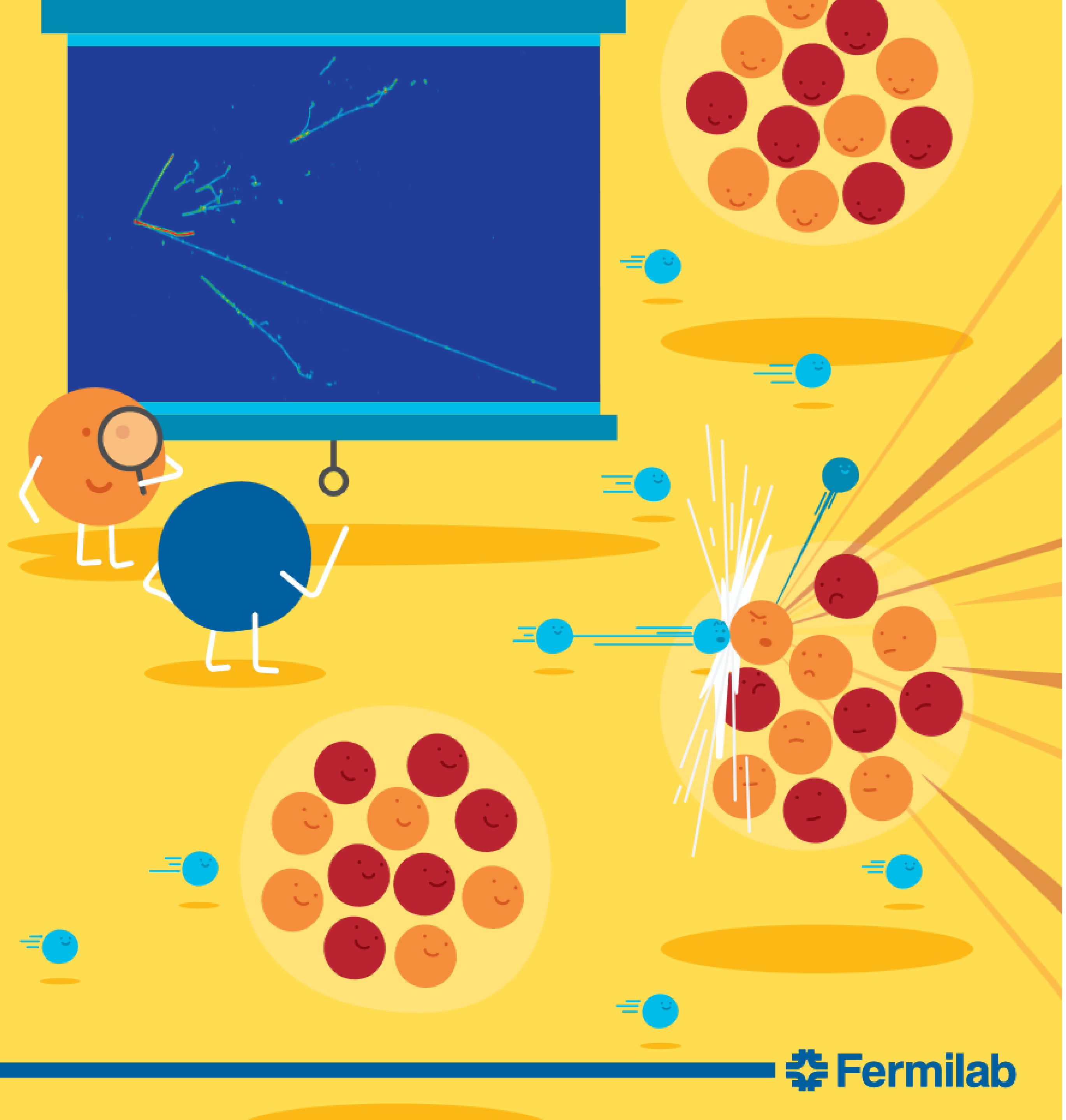
NuSTEC School at Fermilab

November 4–13, 2026

The Neutrino Scattering Theory-Experiment Collaboration School is aimed at graduate students and junior postdocs that will provide an overview of the current status of neutrino-nucleus scattering, highlighting both the experimental and theoretical aspects of the field. Neutrino interaction modeling plays a critical role in current and future neutrino experiments, and this school will include lectures on nuclear models and nuclear effects, the implementation of models, systematic uncertainties associated with neutrino-nucleus scattering, and measurements of neutrino-nucleus scattering. The school will include in-depth discussions, hands-on exercises, including the use of generators, and social events for participants.



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