Modeling neutrino-nucleus interactions in the few-GeV regime

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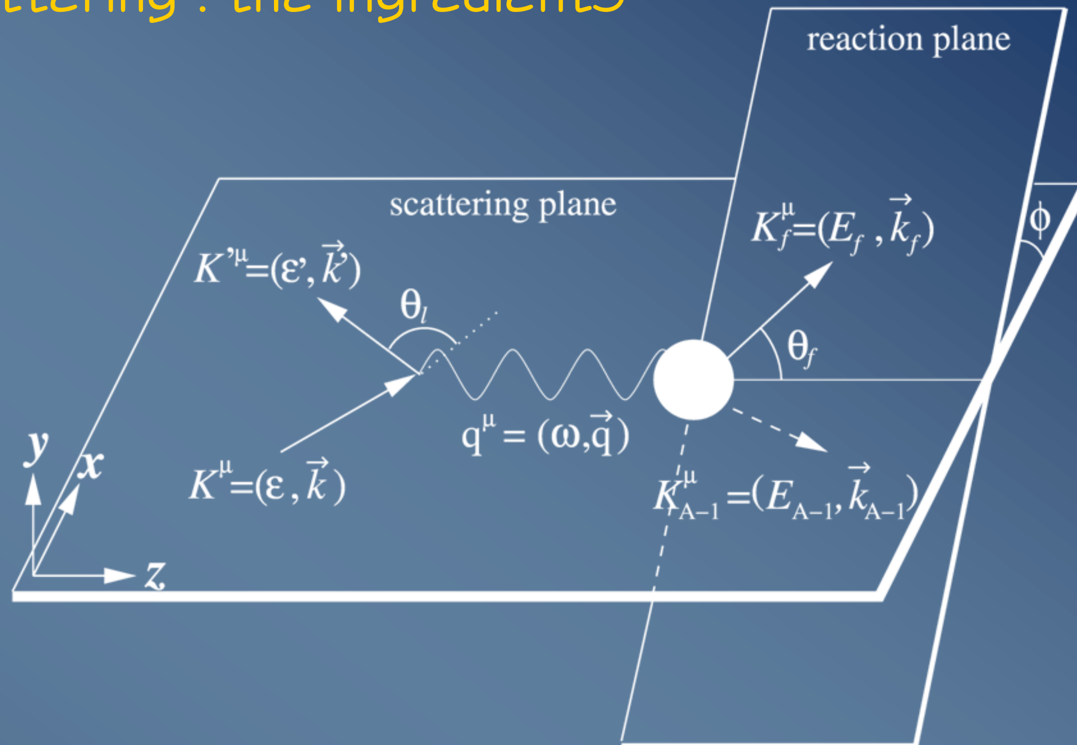
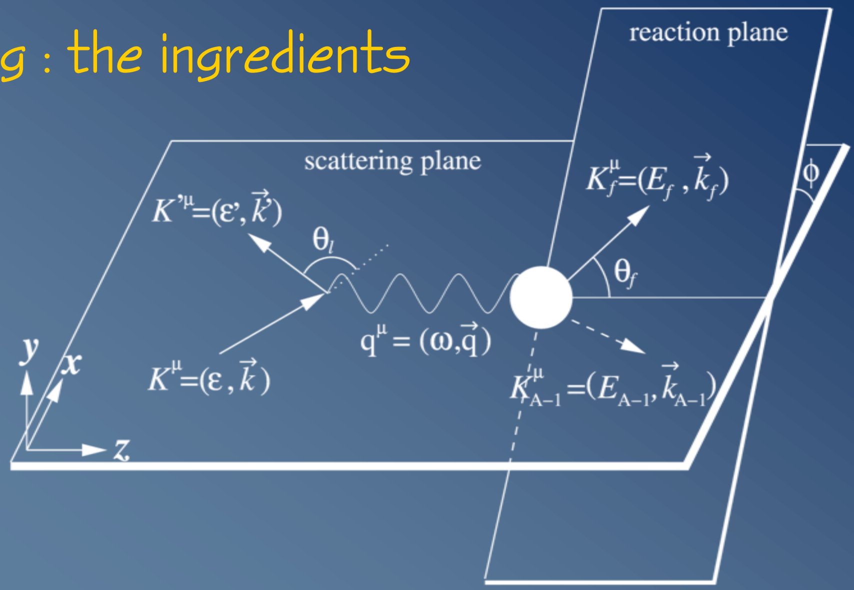
Neutrino-nucleus scattering : the ingredients



Neutrino-nucleus scattering : the ingredients



Cross section :

$$d\sigma = \frac{1}{\beta}\overline{\sum_{if}}|M_{fi}|^2 \frac{M_l}{\varepsilon'}\frac{M_{A-1}}{E_{A-1}}\frac{M_N}{E_f} d^3\vec{k}_{A-1} d^3\vec{k}' d^3\vec{k}_f$$

$$(2\pi)^{-5}\delta^4(K^{\mu}+K_A^{\mu}-K'^{\mu}-K_{A-1}^{\mu}-K_f^{\mu})$$

$$\Downarrow$$

$$\frac{d^5\sigma}{d\varepsilon' d^2\Omega_l d^2\Omega_f} = \frac{M_l M_N M_{A-1}}{(2\pi)^5 M_A \varepsilon'} k'^2 k_f f_{rec}^{-1} \overline{\sum_{if}}|M_{fi}|^2$$

with $$\overline{\sum_{if}}|M_{fi}|^2 = \frac{G_F^2}{2}\left[\frac{M_B^2}{Q^2+M_B^2}\right]^2 l_{\alpha\beta}W^{\alpha\beta}$$

lepton tensor

hadron tensor

Lepton tensor :

$$l_{\alpha\beta} \equiv \overline{\sum_{s,s'}} [\overline{u}_l \gamma_\alpha (1-\gamma_5) u_l]^\dagger [\overline{u}_\nu \gamma_\beta (1-\gamma_5) u_\nu]$$

Hadron tensor :

$$W^{\alpha\beta} = \overline{\sum_{if}} \langle \Delta^{\alpha\mu} J_\mu \rangle^\dagger \langle \Delta^{\beta\nu} J_\nu \rangle = \overline{\sum_{if}} \langle \mathcal{J}^\alpha \rangle^\dagger \langle \mathcal{J}^\beta \rangle$$

$$\langle \mathcal{J}^\alpha \rangle \equiv \left\langle (A-1)(J_R M_R), K_f(E_f, \vec{k}_f) m_s \left| \Delta_{\alpha\mu} \hat{J}^\mu \right| A(0^+, g.s.) \right\rangle$$

$$J^\mu = F_1(Q^2)\gamma^\mu + i\frac{\kappa}{2M_N} F_2(Q^2)\sigma^{\mu\nu} q_\nu + G_A(Q^2)\gamma^\mu\gamma_5 + \frac{1}{2M_N} G_P(Q^2) q^\mu \gamma_5$$

Cross section :

$$\frac{d^5\sigma}{d\varepsilon' d^2\Omega_l d^2\Omega_f} = \frac{M_N M_{A-1}}{(2\pi)^3 M_A} k_f f_{rec}^{-1} \sigma_M^{Z,W^\pm}$$

$$[v_L R_L + v_T R_T + v_{TT} R_{TT} \cos 2\phi + v_{TL} R_{TL} \cos\phi + h(v'_T R'_T + v'_{TL} R'_{TL} \cos\phi)]$$

Kinematic factors	Response functions
$v_L = 1,$	$R_L = \left\| \langle \mathcal{J}^0(\vec{q}) \rangle - \frac{\omega}{\|\vec{q}\|} \langle \mathcal{J}^z(\vec{q}) \rangle \right\|^2,$
$v_T = \tan^2 \frac{\theta_l}{2} + \frac{Q^2}{2\|\vec{q}\|^2},$	$R_T = \left\| \langle \mathcal{J}^+(\vec{q}) \rangle \right\|^2 + \left\| \langle \mathcal{J}^-(\vec{q}) \rangle \right\|^2,$
$v_{TT} = -\frac{Q^2}{2\|\vec{q}\|^2},$	$R_{TT} \cos 2\phi = 2\Re \left\{ \langle \mathcal{J}^+(\vec{q}) \rangle^* \langle \mathcal{J}^-(\vec{q}) \rangle \right\},$
$v_{TL} = -\frac{1}{\sqrt{2}} \sqrt{\tan^2 \frac{\theta_l}{2} + \frac{Q^2}{\|\vec{q}\|^2}},$	$R_{TL} \cos\phi = -2\Re \left\{ \left[\langle \mathcal{J}^0(\vec{q}) \rangle - \frac{\omega}{\|\vec{q}\|} \langle \mathcal{J}^0(\vec{q}) \rangle \right] \left[\langle \mathcal{J}^+(\vec{q}) \rangle - \langle \mathcal{J}^-(\vec{q}) \rangle \right]^* \right\}$
$v'_T = \tan \frac{\theta_l}{2} \sqrt{\tan^2 \frac{\theta_l}{2} + \frac{Q^2}{\|\vec{q}\|^2}},$	$R'_T = \left\| \langle \mathcal{J}^+(\vec{q}) \rangle \right\|^2 - \left\| \langle \mathcal{J}^-(\vec{q}) \rangle \right\|^2,$
$v'_{TL} = \frac{1}{\sqrt{2}} \tan \frac{\theta_l}{2}.$	$R'_{TL} \cos\phi = -2\Re \left\{ \left[\langle \mathcal{J}^0(\vec{q}) \rangle - \frac{\omega}{\|\vec{q}\|} \langle \mathcal{J}^z(\vec{q}) \rangle \right] \left[\langle \mathcal{J}^+(\vec{q}) \rangle + \langle \mathcal{J}^-(\vec{q}) \rangle \right]^* \right\}$

transition matrix elements

$$\langle J^\mu \rangle = \int d\vec{r}\, \overline{\phi}_F(\vec{r}) \hat{J}^\mu(\vec{r}) e^{i\vec{q}.\vec{r}} \phi_B(\vec{r})$$

RPWIA : relativistic wave functions obtained within the Hartree-approximation to the Walecka-Serot σ-ω model

\+

Final state interactions :

Quasi-elastic processes : one-step single-nucleon knockout contribution to the inclusive cross sections

Intermediate energies : beyond the nuclear resonance region

RMSGA

relativistic multiple scattering Glauber approximation

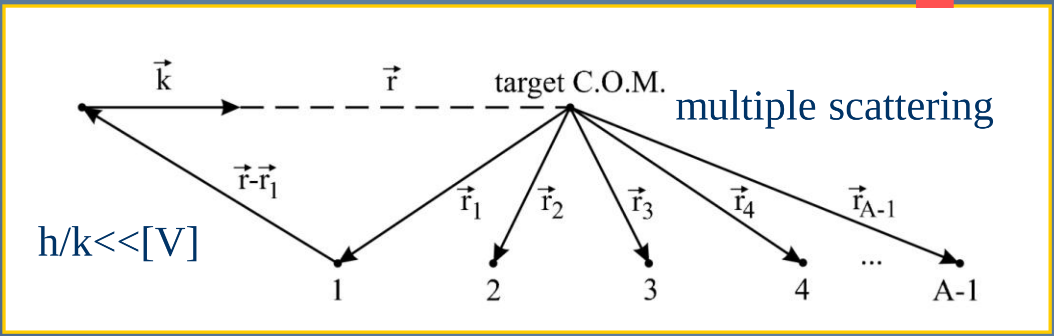
- semi-classical approach
- ‘high’ energies
- nucleon-nucleon data

M.C. Martínez et al PRC73, 024607 (2006)

Final State Interactions

$$\langle J^\mu \rangle = \int d\vec{r}\, \overline{\phi}_F(\vec{r}) \hat{J}^\mu(\vec{r}) e^{i\vec{q}.\vec{r}} \phi_B(\vec{r})$$

scattering wave function



$$\phi_F(\vec{r}) \equiv \mathcal{G}(\vec{b}, z)\phi_{k_f, s_f}(\vec{r})$$

Glauber phase

- eikonal approach
- linear trajectories
- ‘frozen spectators’ approximation

$$\mathcal{G}(\vec{b}, z) = \prod_{\alpha \neq B} \left[1 - \int d\vec{r}\,'|\phi_\alpha(\vec{r}\,')|^2 \theta(z' - z) \Gamma(\vec{b}' - \vec{b}) \right]$$

$$\mathcal{G}(\vec{b}, z) \approx \left\{ 1 - \frac{\sigma_{NN}^{tot}(1 - i\epsilon_{NN})}{4\pi\beta_{NN}^2} \int_0^\infty b' db' T_B(b', z) \exp\left[-\frac{(b-b')^2}{2\beta_{NN}^2} \right] \int_0^{2\pi} d\phi_{b'} \exp\left[\frac{-2bb'}{\beta_{NN}^2} \sin^2\left(\frac{\phi_b - \phi_{b'}}{2} \right) \right] \right\}^{A-1}$$

Summarized : included in the description of the nucleus and the reaction are :

-nuclear binding : energy levels, missing momentum distributions for the bound nucleons

-Pauli blocking

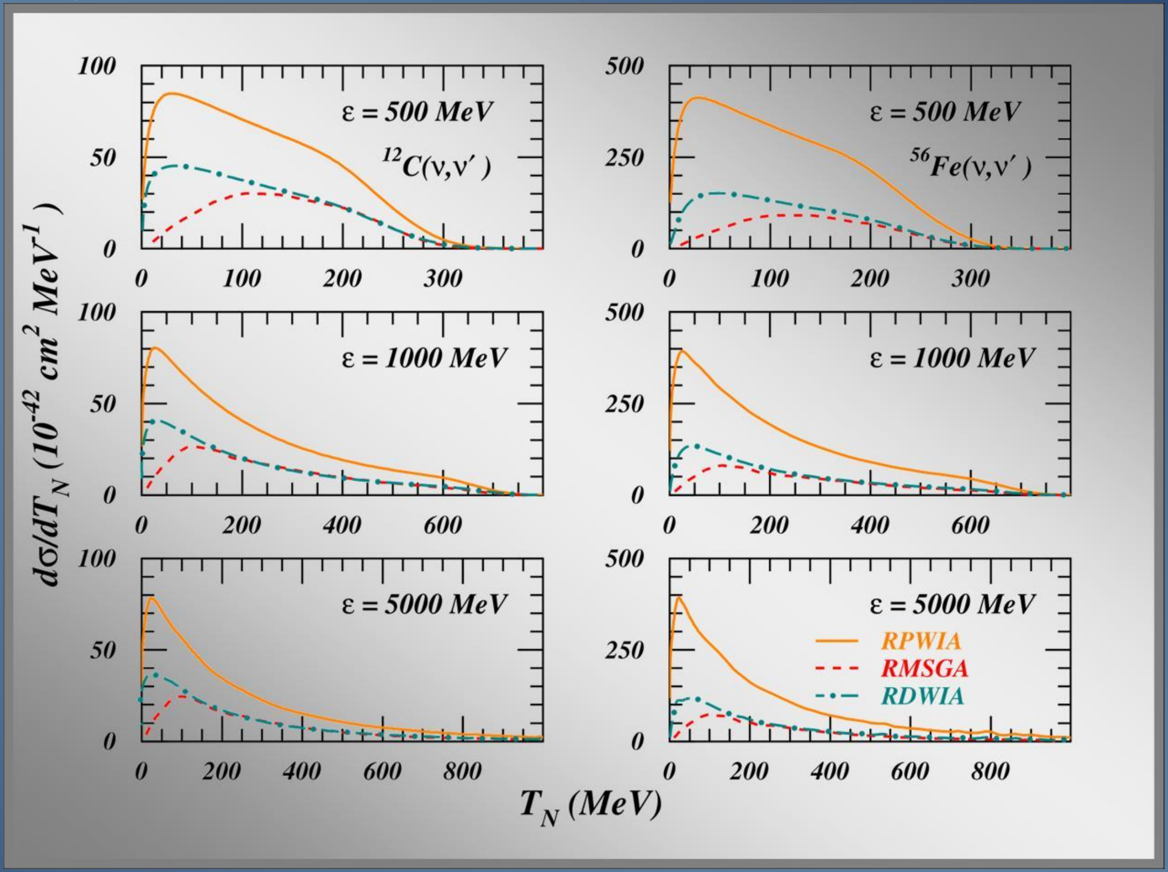
-relativistic description

-final-state interactions

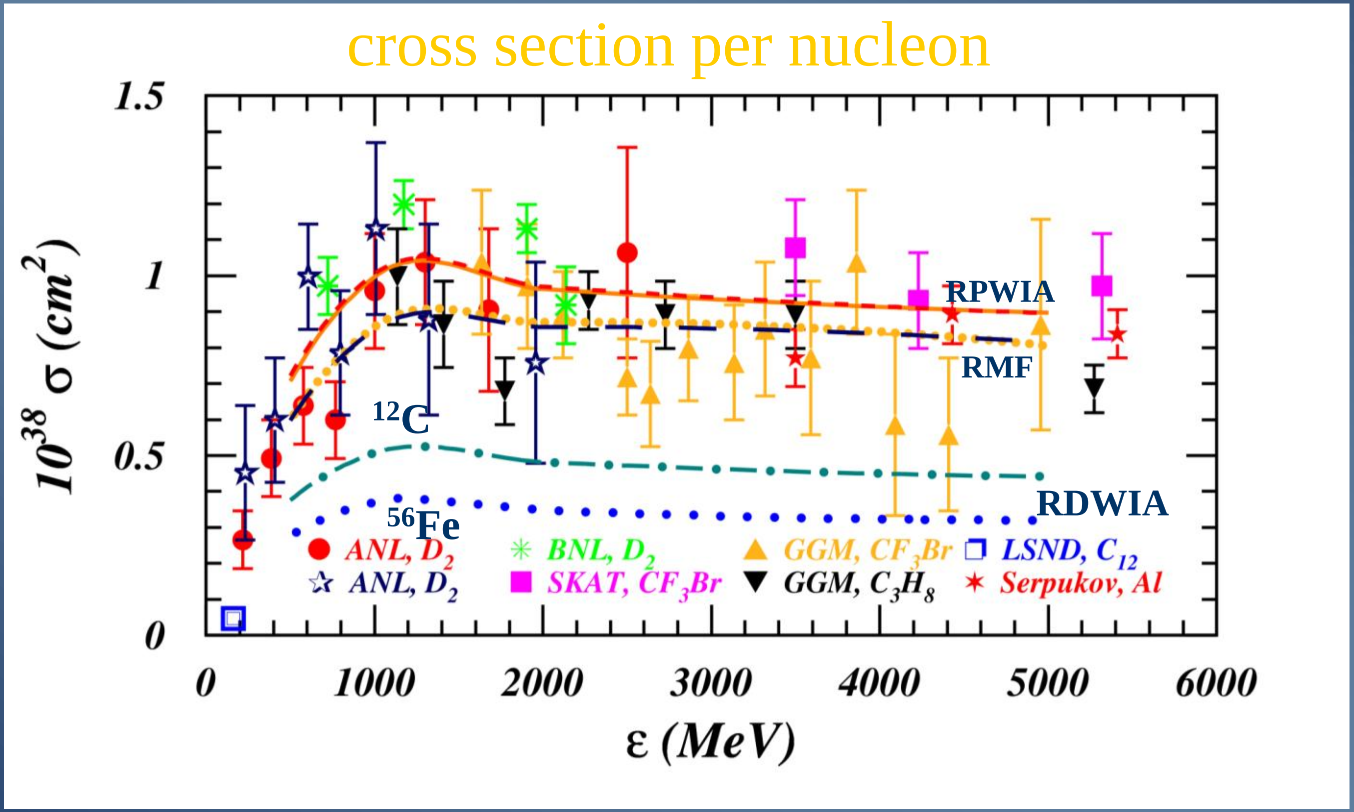
-full implementation of hadronic current with axial, and weak vector contributions and their interference terms, Q^2 dependence of the form factors

•neutral current neutrino scattering off ^{12}C

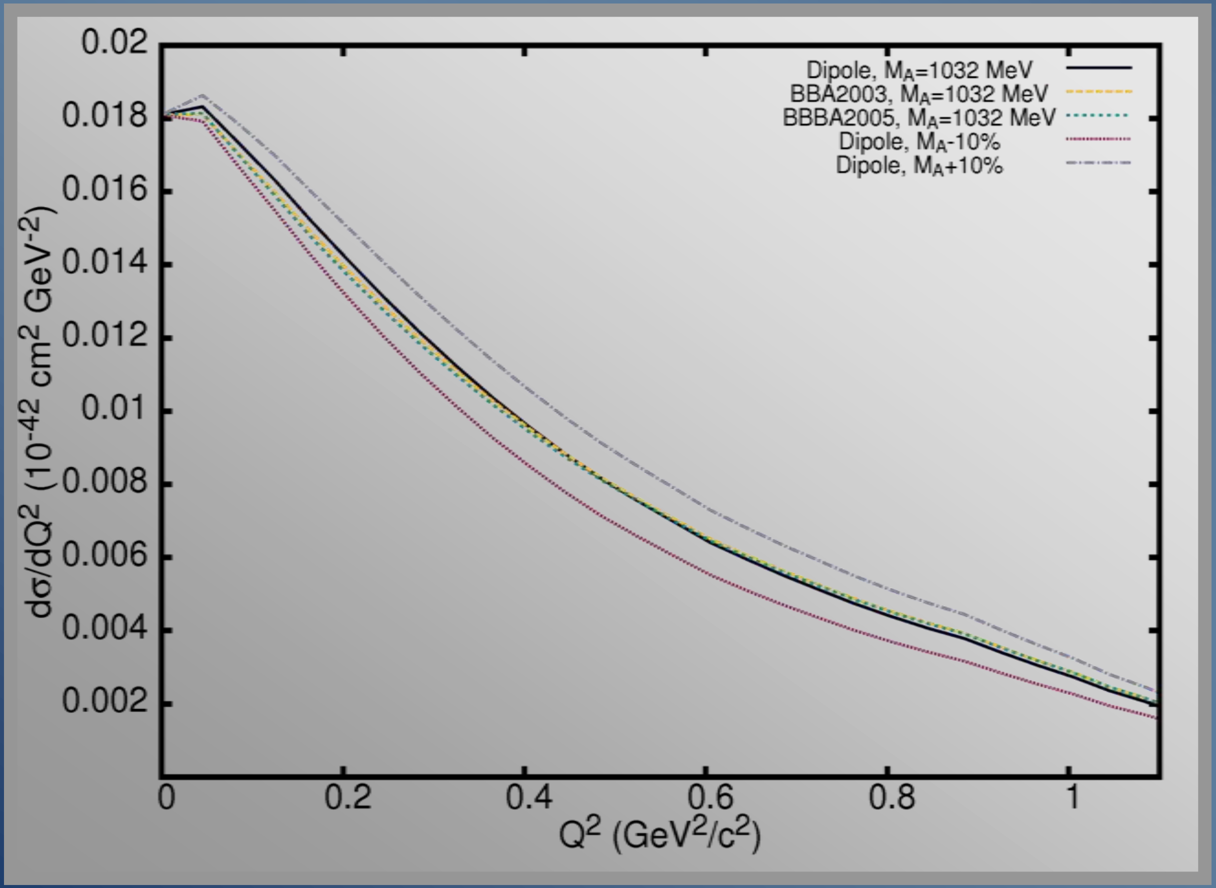
•comparing relativistic plane wave impulse approximation (RPWIA-no final state interactions), final state interactions implemented using a relativistic distorted wave approximation (RDWIA) and a relativistic multiple scattering Glauber approximation (RMSGA).



- The results are in good agreement with those obtained with other models e.g. M.C. Martínez et al., PRC73, 024607 (2006) ; A. Meucci et al., NPA773, 250 (2006) ; J.E. Amaro et al., PRL98, 242501 (2007).
- Agreement with data ….



Influence of the Q^2 dependence of the form factors and the value of M_A on RPWIA cross sections for charged-current quasi-elastic neutrino scattering off ^{12}C for an incoming neutrino energy of 1 GeV.

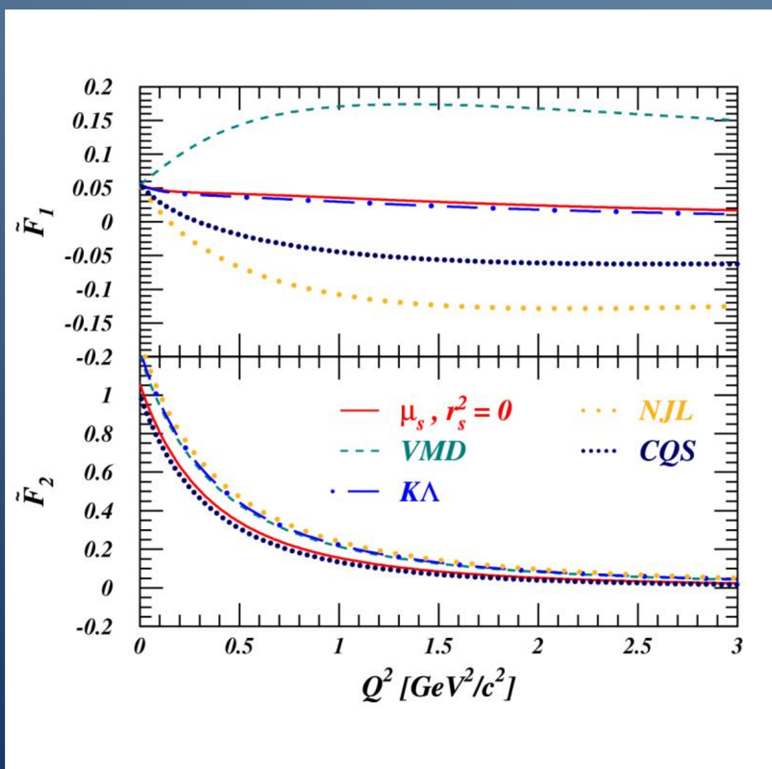


Strangeness in the nucleon

Axial form factor : $$G_A(Q^2) = -\frac{(\tau_3 g_A - g_A^s)}{2} G(Q^2), \qquad g_A = 1.262$$

$$G(Q^2) = (1 + Q^2/M^2)^{-2}, \qquad M = 1.032$$

→the net strangeness effect is very small for isoscalar targets



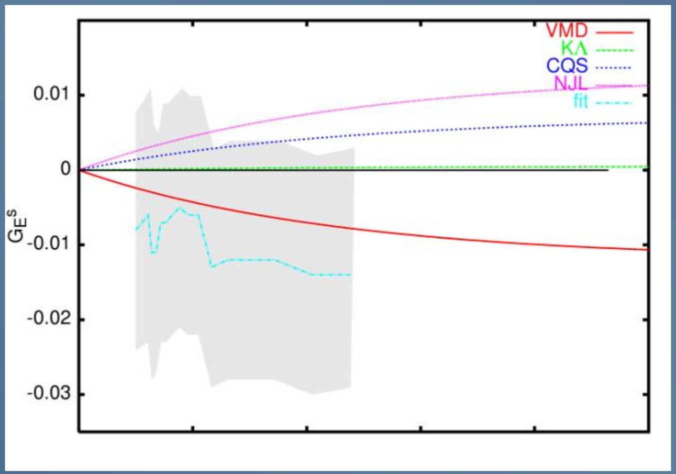
Weak vector form factors :

$$F_i^Z = \left(\frac{1}{2} - \sin^2\theta_W\right)\left(F_{i,p}^{EM} - F_{i,n}^{EM}\right)\tau_3 - \sin^2\theta_W\left(F_{i,p}^{EM} + F_{i,n}^{EM}\right) - \frac{1}{2}F_i^s$$

$$F_1^s = \frac{1}{6}\frac{-r_s^2 Q^2}{(1 + Q^2/M_1^2)^2}, \qquad M_1 = 1.3$$

$$F_2^s = \frac{\mu_s}{(1 + Q^2/M_2^2)^2}, \qquad M_2 = 1.26$$

Model	$\mu_s(\mu_N)$	$r_s^2(\text{fm}^2)$
VMD	-0.31	0.16
$K\Lambda$	-0.35	-0.007
NJL	-0.45	-0.17
CQS (K)	0.115	-0.095



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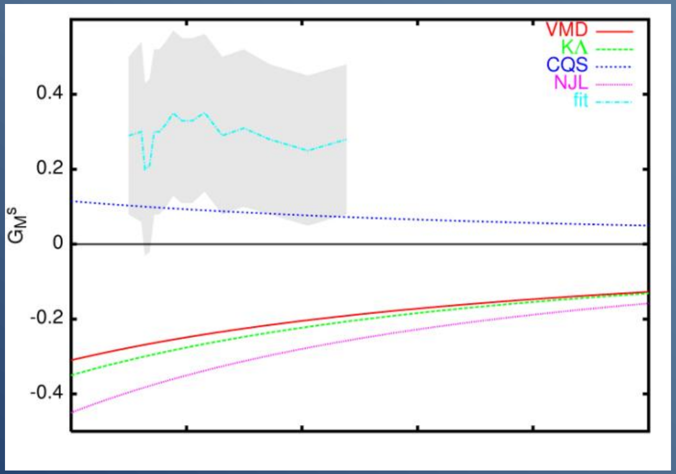
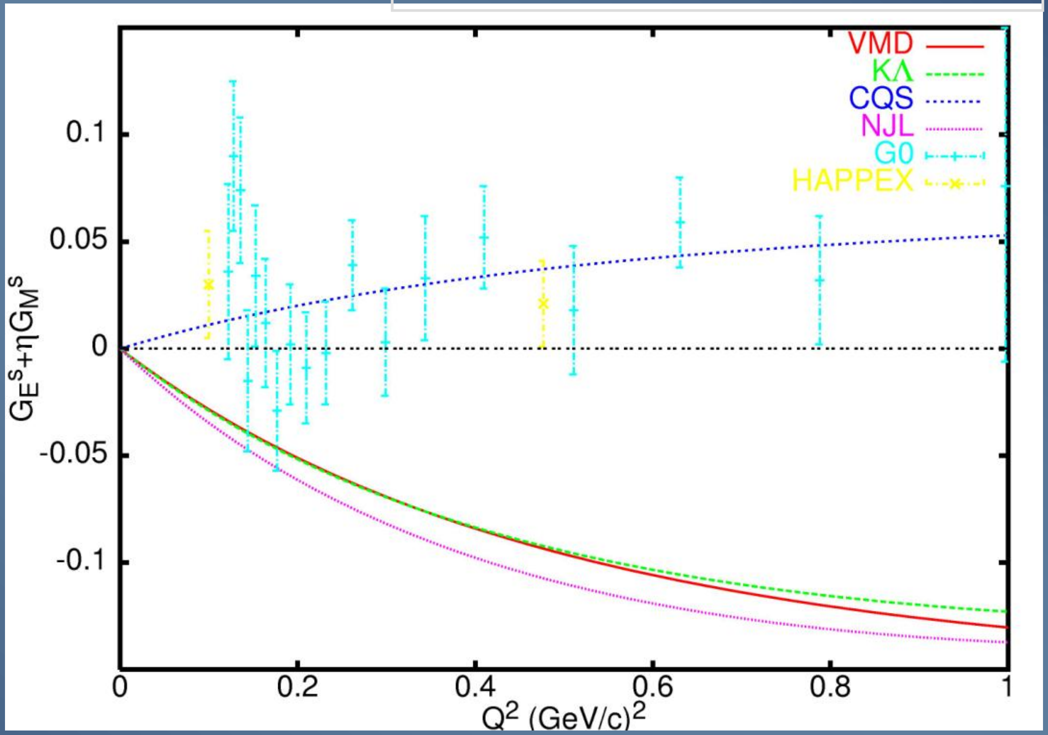
Data and fit from 'Global analysis of nucleon strange form factors at low Q^2', J. Liu, R.D. Mckeown, R.D. Ramsey-Musolf, PRC76, 025202 (2007).





Traditionally :

•strangeness contribution to the ***weak vector formfactors*** : Parity Violating Electron Scattering (Sample, Happex, G0, …)

Correlated !

•strangeness contribution to the ***axial current*** : neutrino scattering

-vector current contributions are suppressed

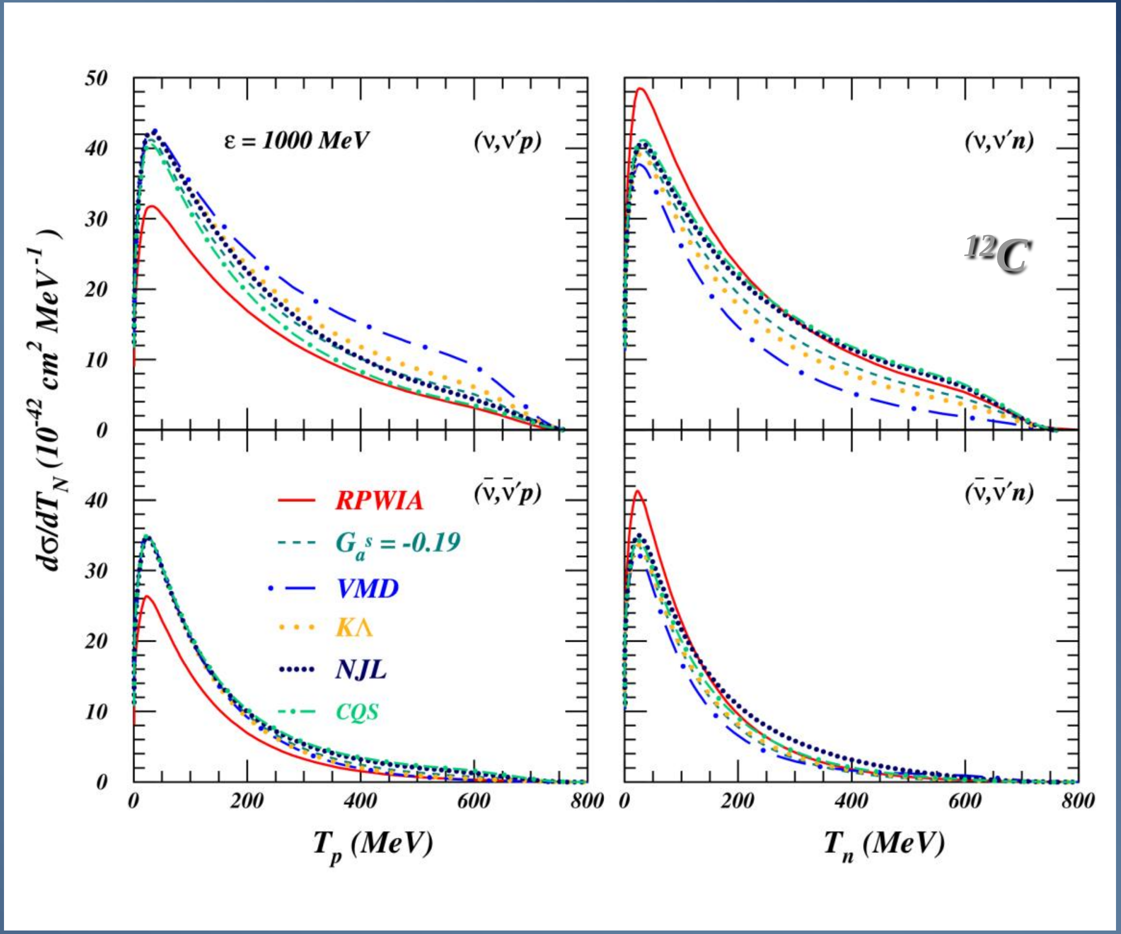
-no radiative corrections

→ systematic overview of the sensitivity of cross-section ratios to the strange-quark content of the nucleon

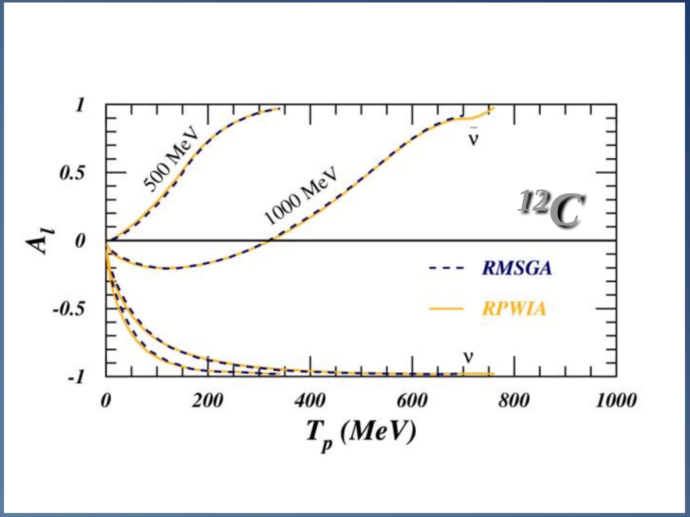
→compare the influence of axial as well as vector strangeness

→in terms of ejectile energies and Q^2 values

Influence of strangeness on cross sections at intermediate energies

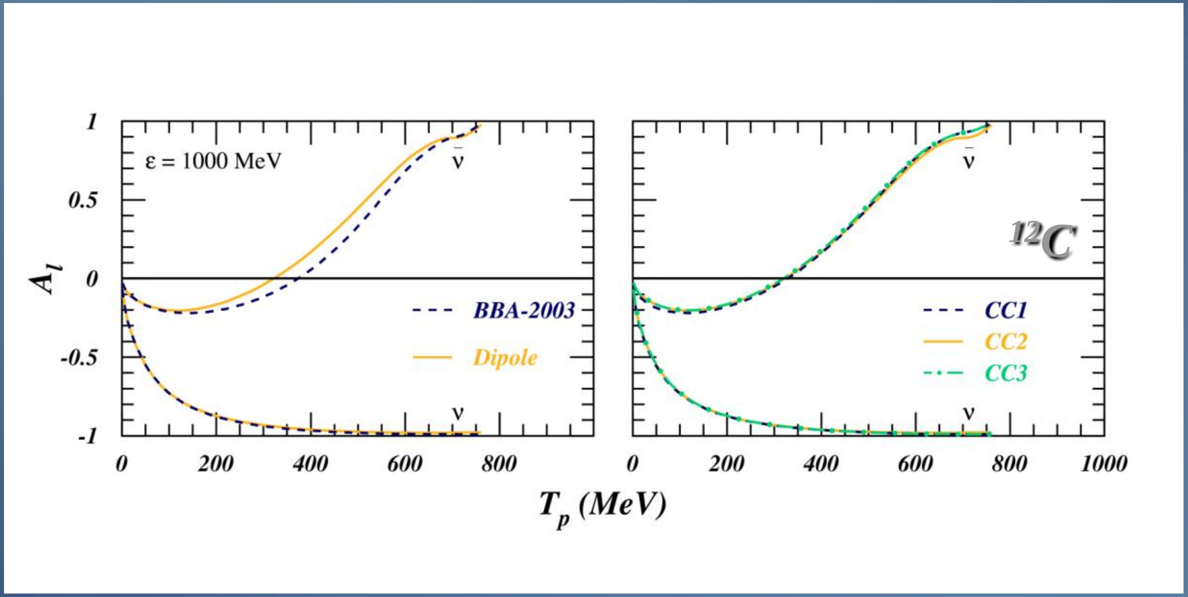


Cross section ratios



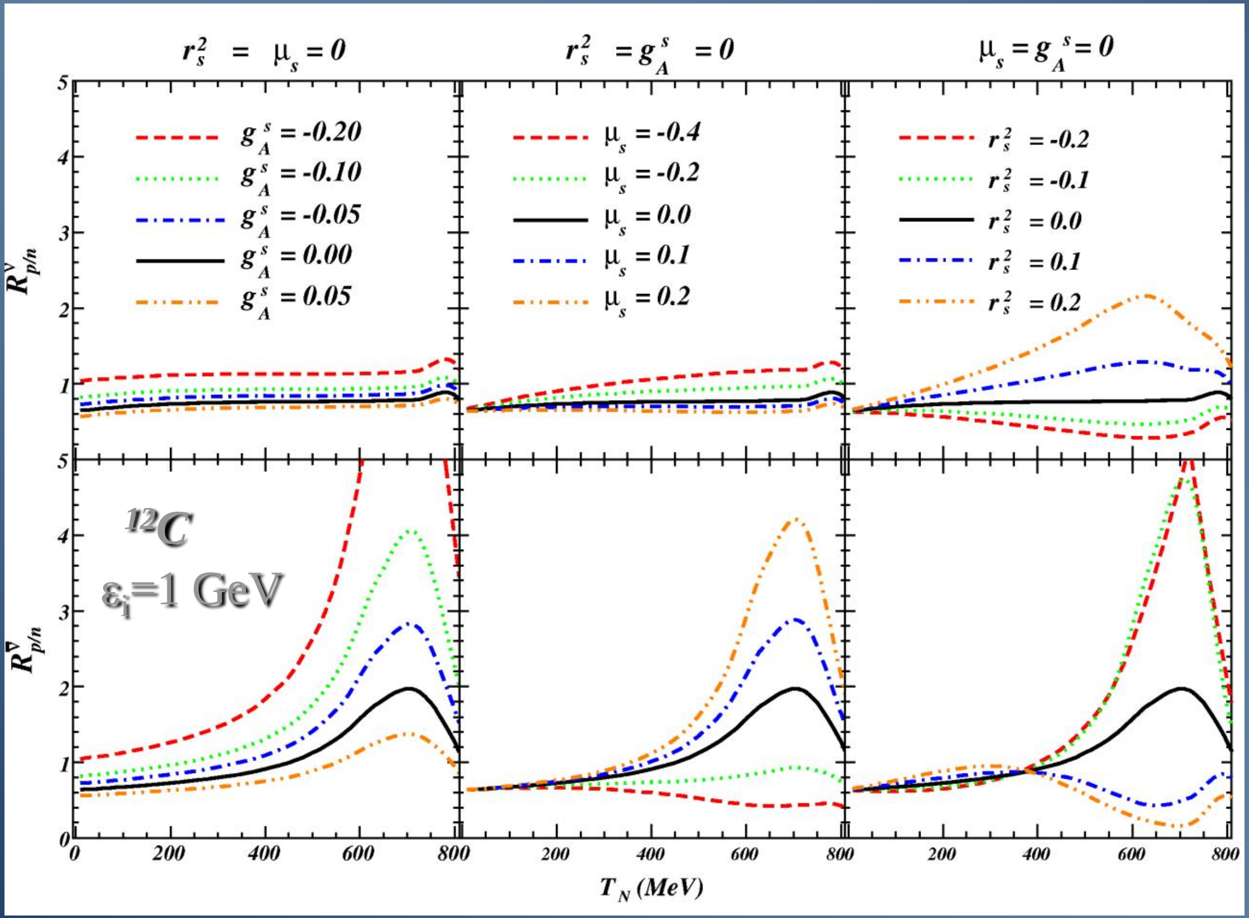
- ratios stable against the influence of final state interactions, uncertainties in the description of the Q^2 dependence of the vector form factors, off-shell ambiguities.

Ratios are robust observables, which makes them very suitable quantities to study strange-quark contributions to the nucleon



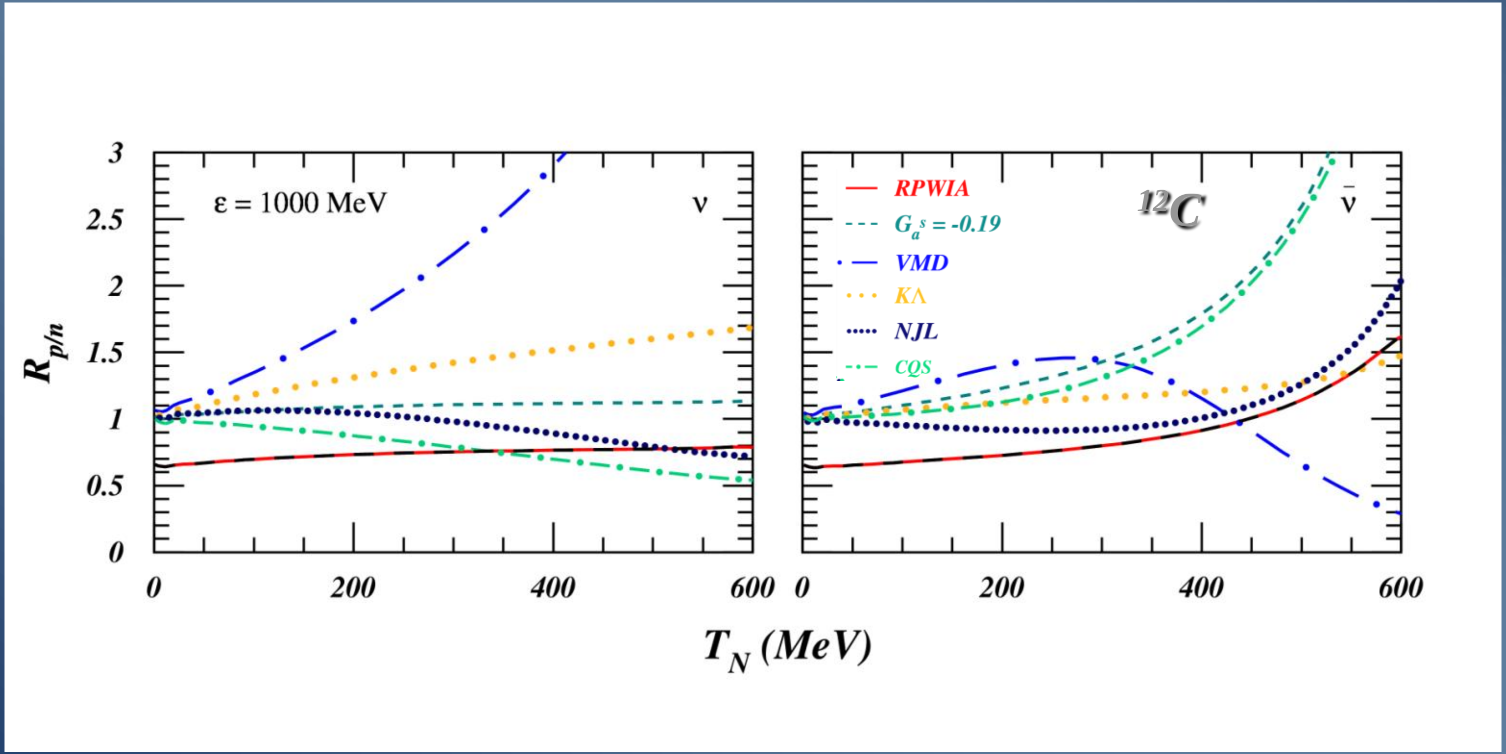
Ratio of neutral current neutrino scattering off a proton/neutron

$$R_{p/n} = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,n)}$$



$$R_{p/n} = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} / \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,n)}$$

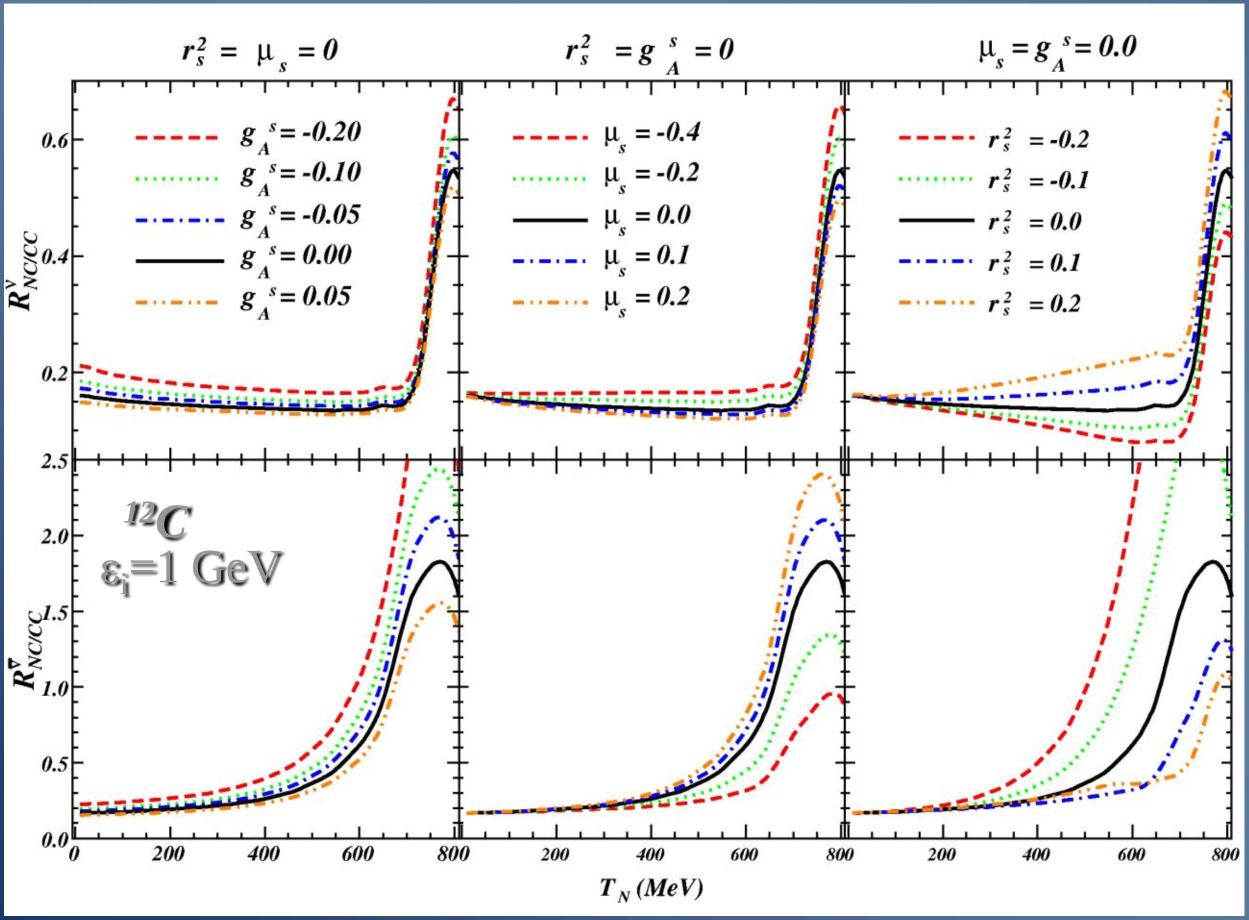
… continued



Ratio of neutral-to-charged current neutrino scattering

$$R_\nu = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\nu,p)}$$

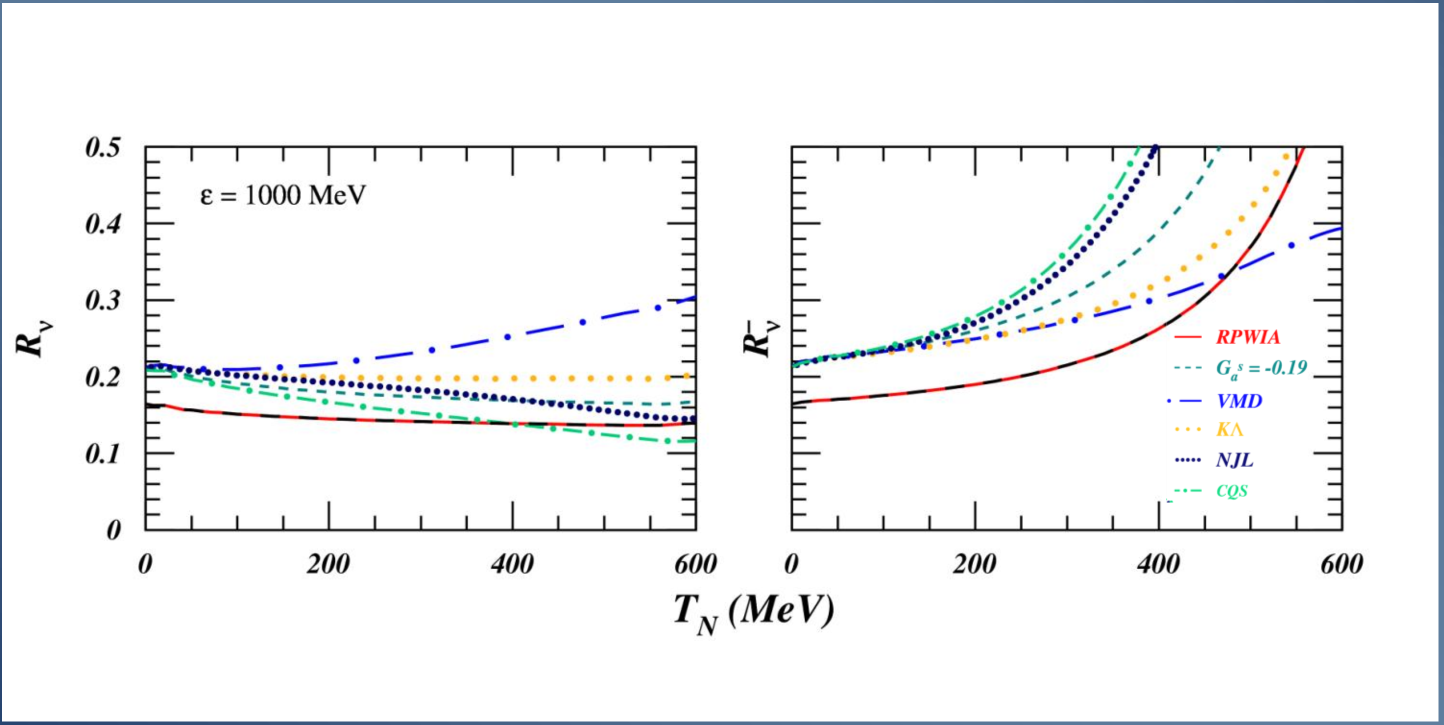
$$R_{\overline{\nu}} = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\overline{\nu},p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\overline{\nu},n)}$$



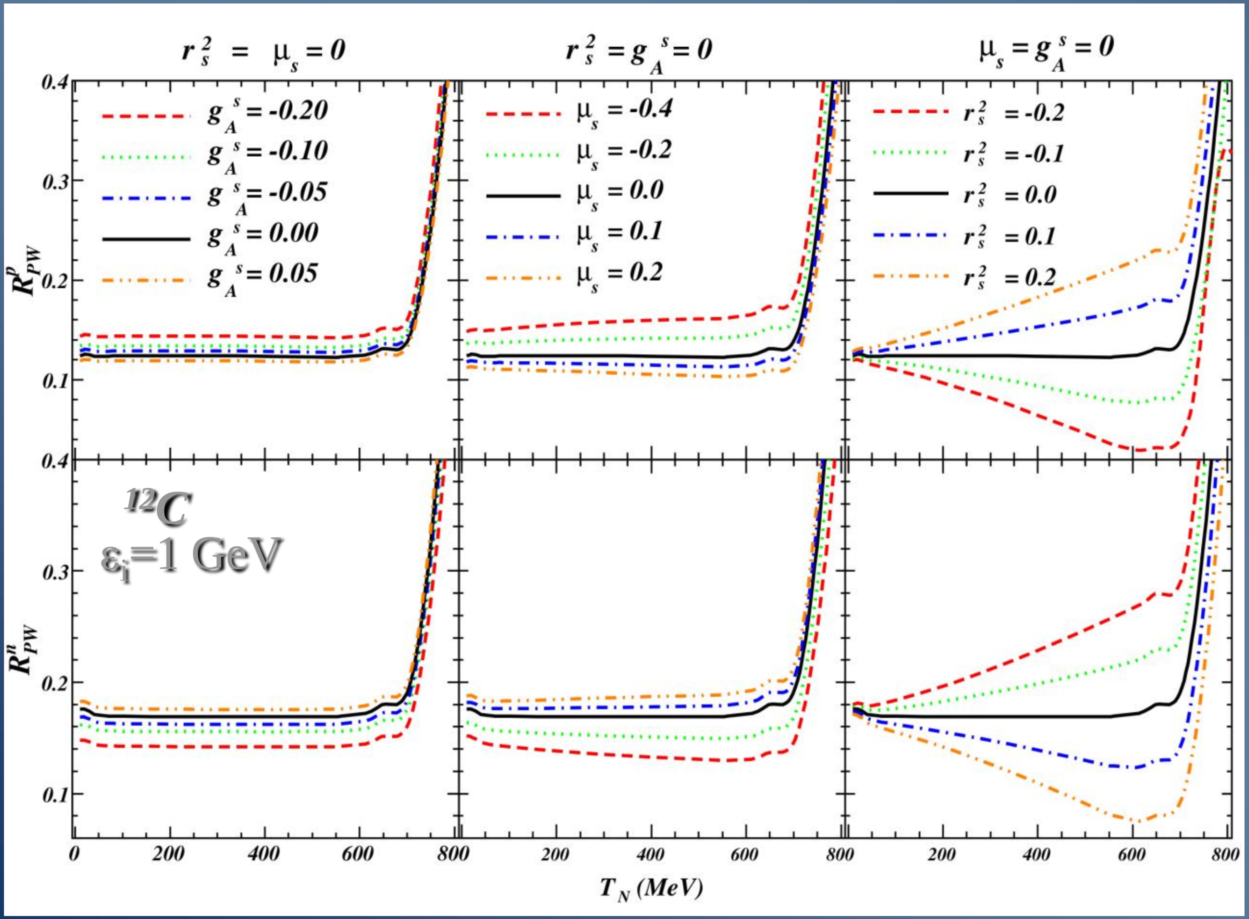
Ratio of neutral-to-charged current neutrino scattering … continued

$$R_\nu = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\nu,p)}$$

$$R_{\overline{\nu}} = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\overline{\nu},p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\overline{\nu},n)}$$



$$A_p = \frac{\left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} - \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\overline{\nu},p)}}{\left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\nu,p)} - \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\overline{\nu},n)}}$$

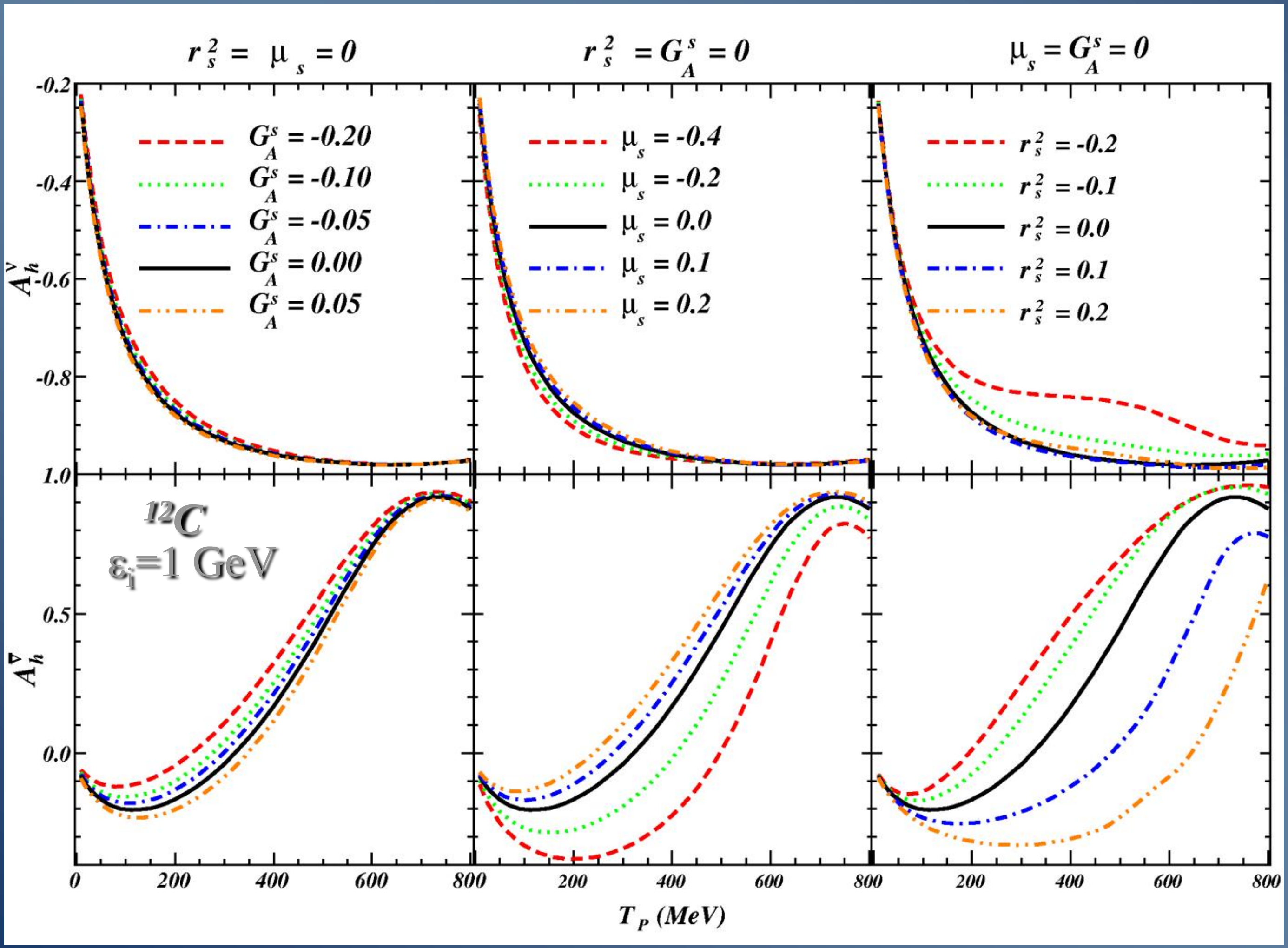


Paschos-Wolfenstein relation in a hadronic framework

C. Praet et al, PRC74, 065501 (2006)

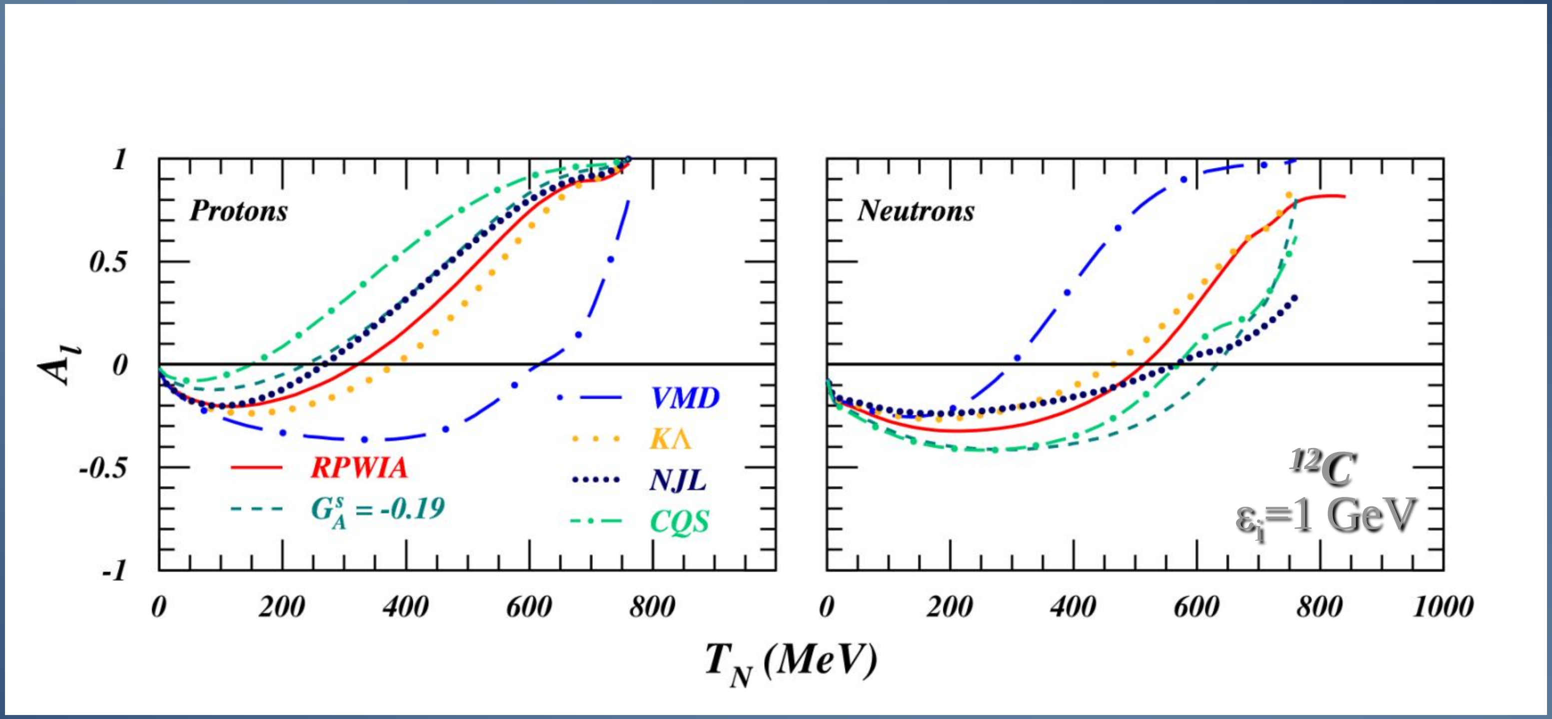
Helicity asymmetries

$$A_l(T_N) = \frac{\frac{d\sigma}{dT_N}(h_N=+1) - \frac{d\sigma}{dT_N}(h_N=-1)}{\frac{d\sigma}{dT_N}(h_N=+1) + \frac{d\sigma}{dT_N}(h_N=-1)}$$



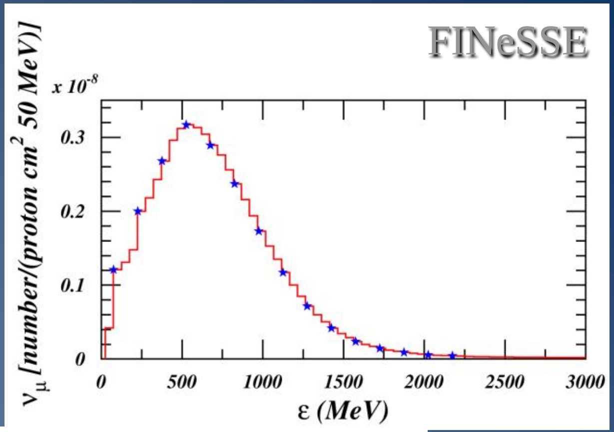
Helicity asymmetries

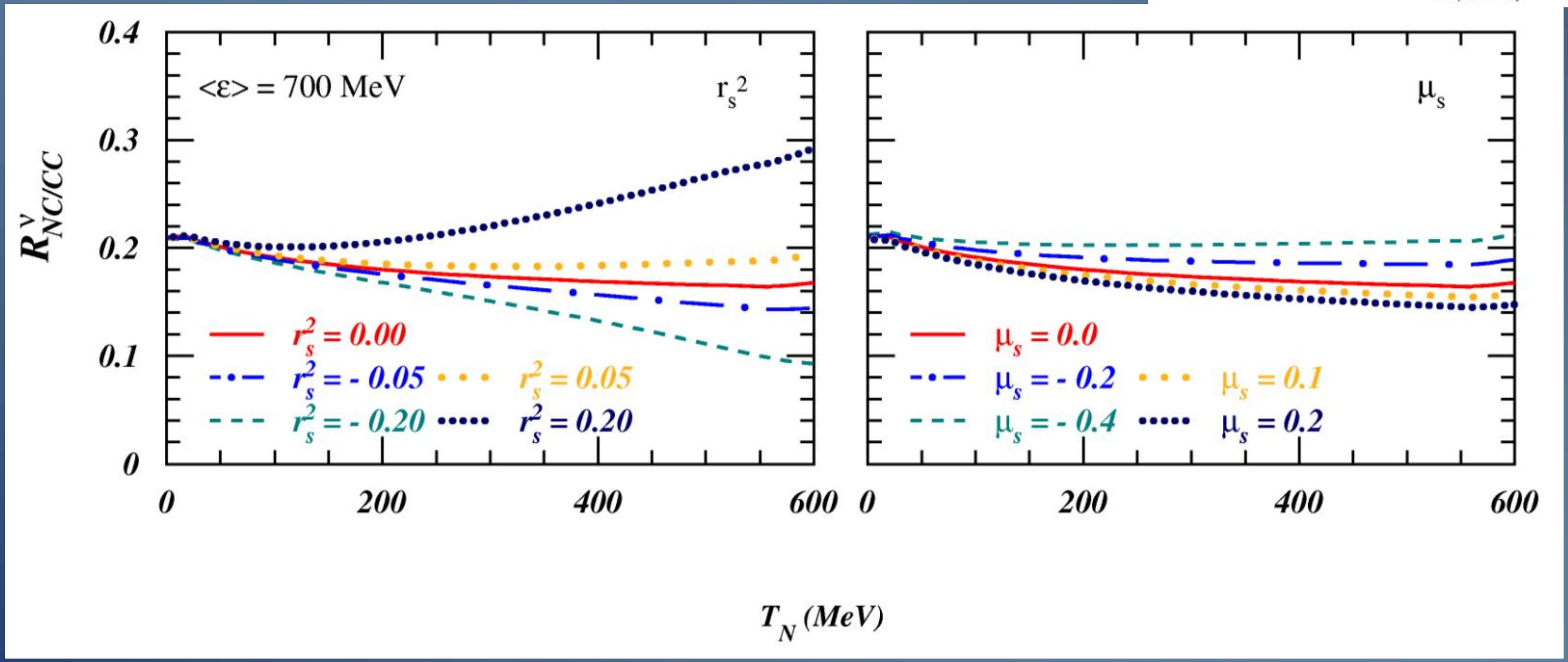
P. Lava et al, PRC73, 064605 (2006)



→This ratio is very sensitive to the weak vector form factors !

The influence of the neutrino energy distribution on the ratios and strangeness influence

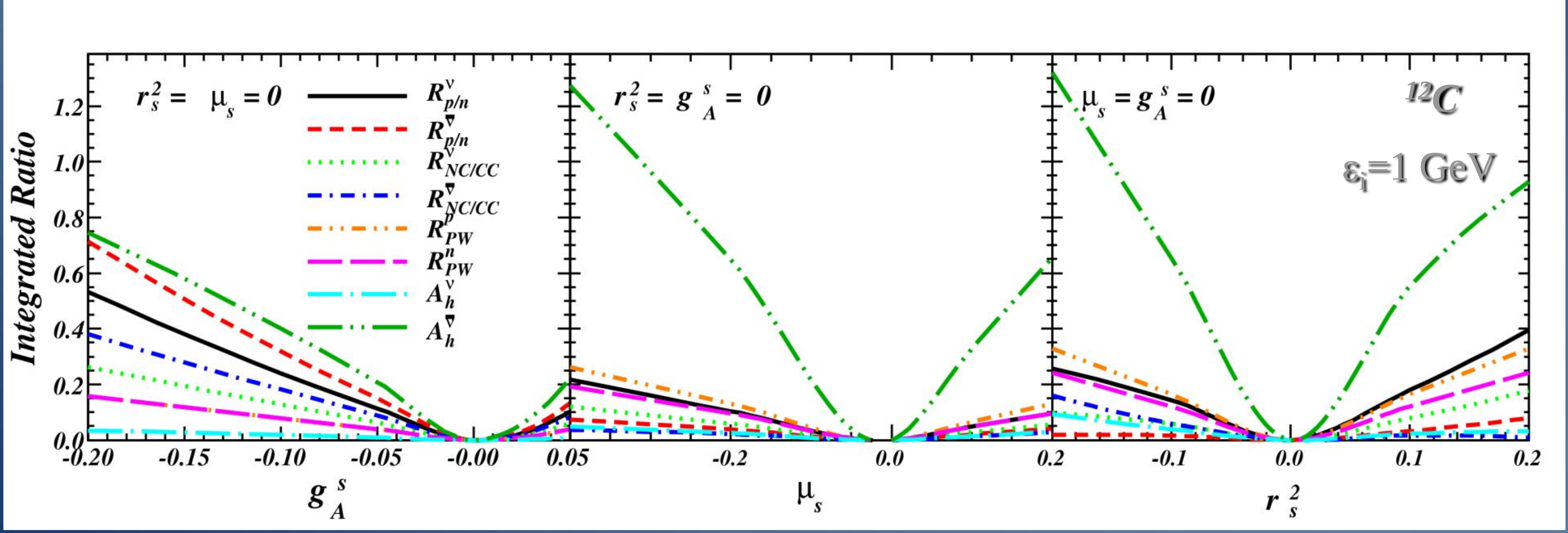




→ Folding has no qualitative influence on the overall sensitivity to strangeness mechanisms

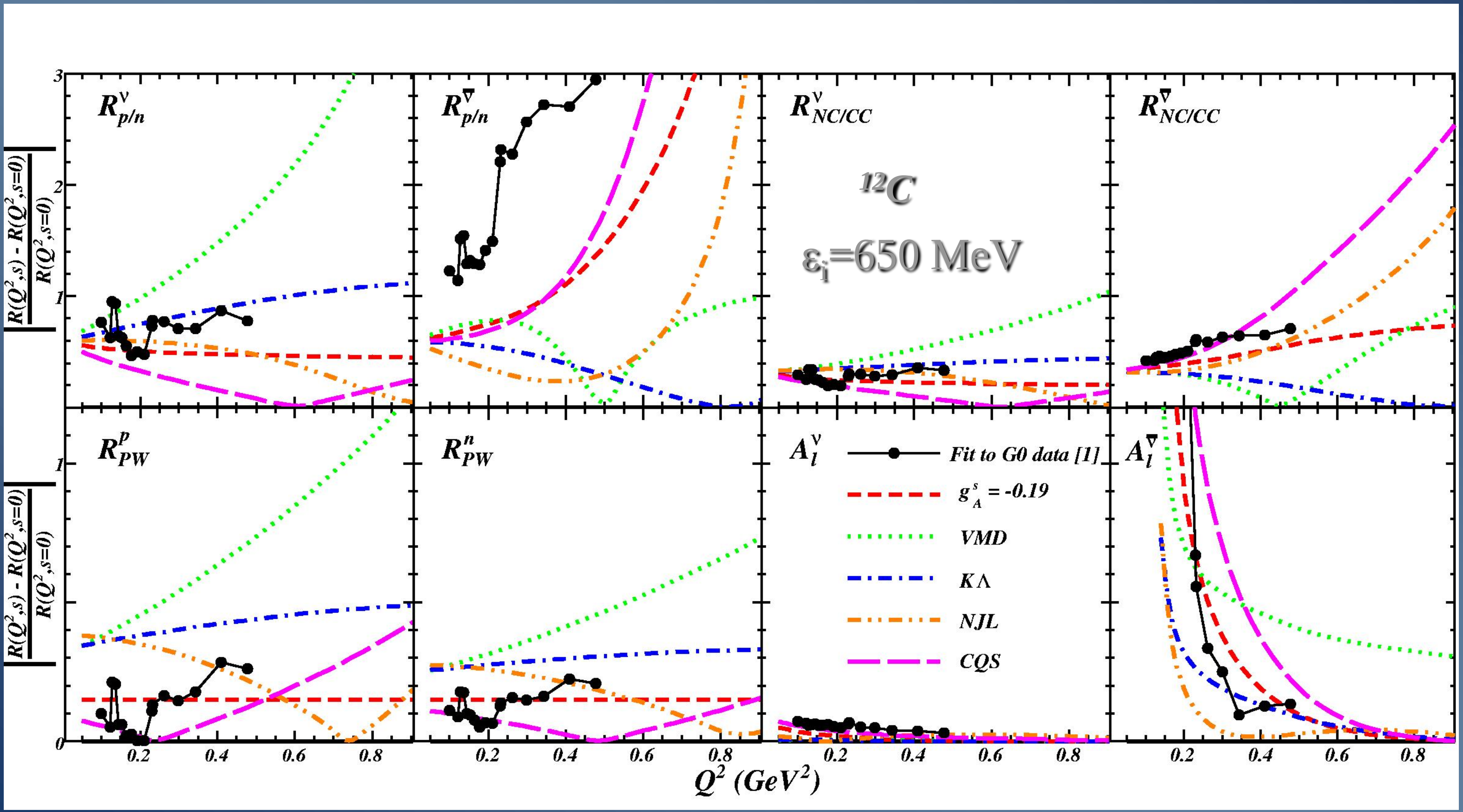
Comparing the sensitivity of the ratios :

$$\left| \frac{R(s=0) - R(s)}{R(s=0)} \right|$$



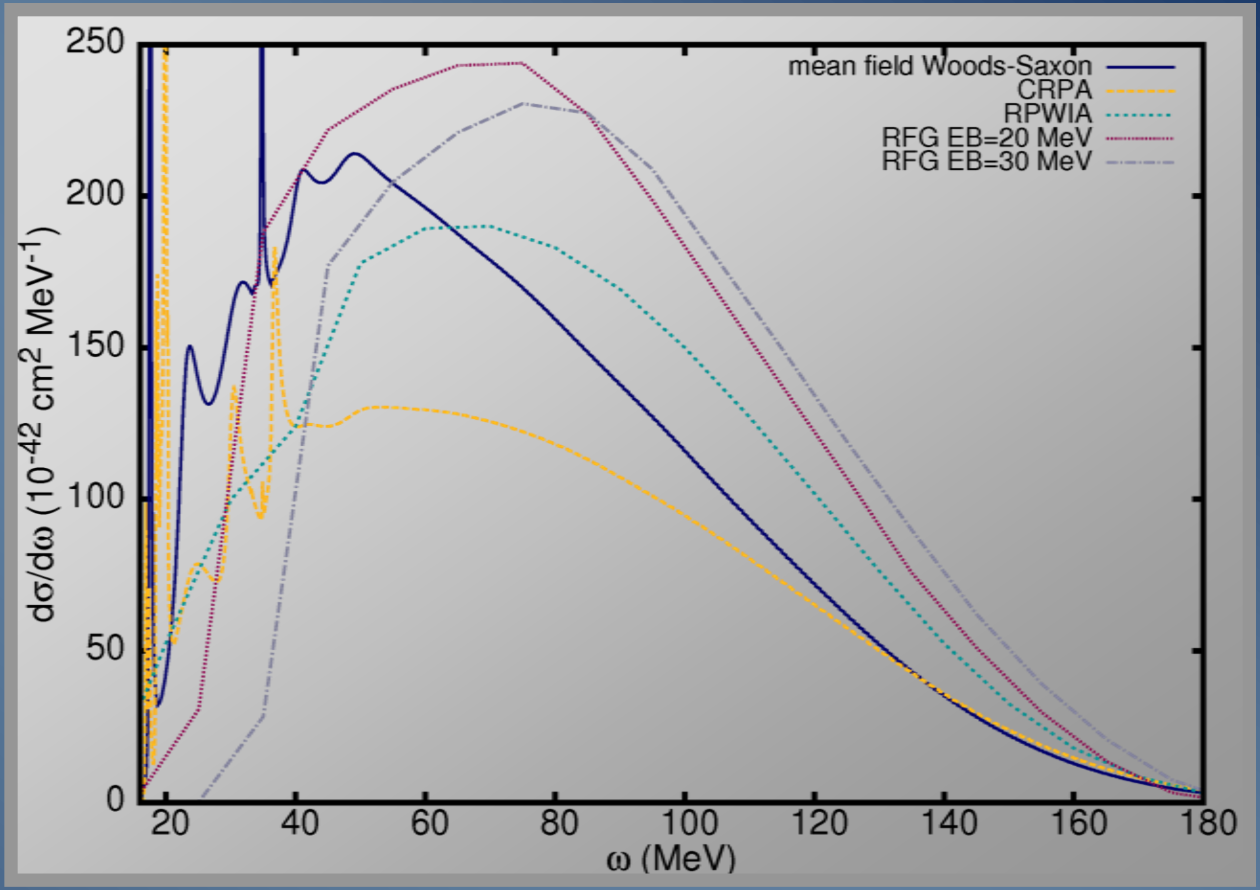
Q^2 dependence of the strangeness sensitivity

$$\left|\frac{R(Q^2, s=0) - R(Q^2, s)}{R(Q^2, s=0)}\right|$$



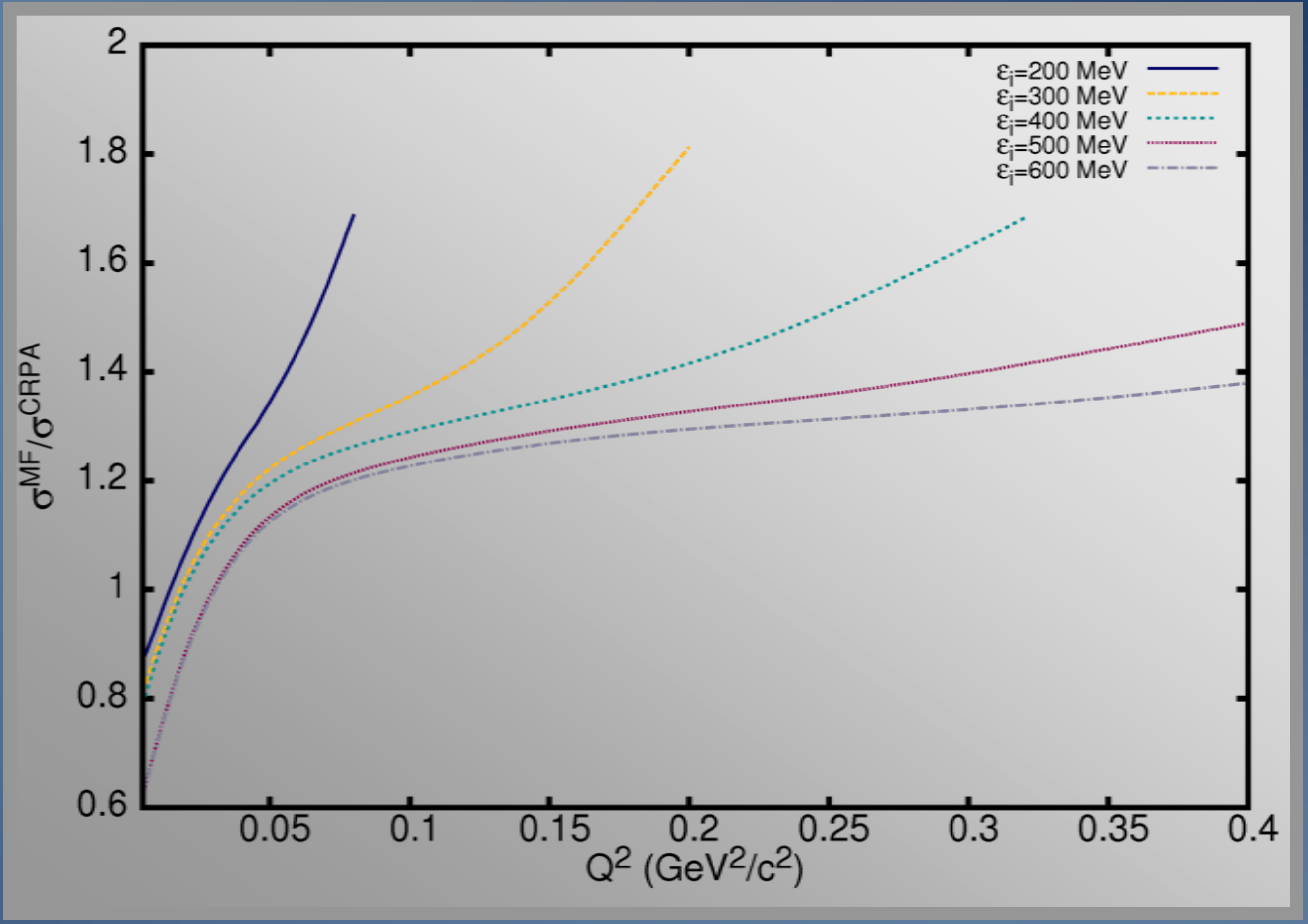
Cross sections at low Q^2

→Comparison between inclusive cross sections obtained within a relativistic Fermi gas calculation, a relativistic plane wave impulse approximation (RPWIA) approach, a mean-field calculation, and a calculation including CRPA correlations implemented using a Skyrme parametrization as residual interaction.



Cross sections at low Q^2

→ Q^2 dependence as a function of incoming energy



Conclusions

• The influence of the Q^2 parametrization on cross sections is modest ; cross sections are sensitive to the exact value of M_A

• (anti)neutrino cross section ratios are relatively free of ambiguities and well-suited to extract strangeness information from data

  • antineutrinos cross-section ratios are more sensitive to strangeness influences than neutrino cross-section ratios

  • vector strangeness effects are large and strongly Q^2 dependent

  • Helicity asymmetries are most sensitive to strangeness contributions in the weak form factors

  • The overall sensitivity of $R_{NC/CC}$ ratios to strangeness effects is considerably smaller than that of $R_{p/n}$, but at small Q^2, the strangeness contributions to $R_{NC/CC}$ are more strongly dominated by the axial channels

Conclusions

•For inclusive cross sections, especially at higher energies, the Fermi gas model is remarkably accurate. At lower energies however, nuclear effects become preponderant and their influence cannot be neglected. CRPA correlations account for a cross section reduction of approximately 25% at incoming energies of 600 MeV and up to 35% for cross sections induced by 200 MeV neutrinos.

References : P.Lava, N.Jachowicz, M.C. Martínez, J. Ryckebusch, 'Nucleon helicity asymmetries in quasielastic neutrino-nucleus scattering', PRC73, 064605 (2006) ; M.C. Martínez, P.Lava, N. Jachowicz, J.Ryckebusch, J.M. Udías, 'Relativistic models for quasielastic neutrino scattering', PRC73, 024607 (2006) ; C.Praet, N.Jachowicz, J.Ryckebusch 'Paschos-Wolfenstein relation in a hadronic picture', PRC74, 065501 (2006) ; N. Jachowicz, P. Vancraeyveld, P. Lava, C. Praet, J. Ryckebusch, 'Strangeness content of the nucleon in quasielastic neutrino-nucleus reactions', PRC76, 055501 (2008) ; N. Jachowicz, C. Praet, J. Ryckebusch, in preparation.