Quasi-elastic neutrino-nucleus scattering and the strangeness content of the nucleon

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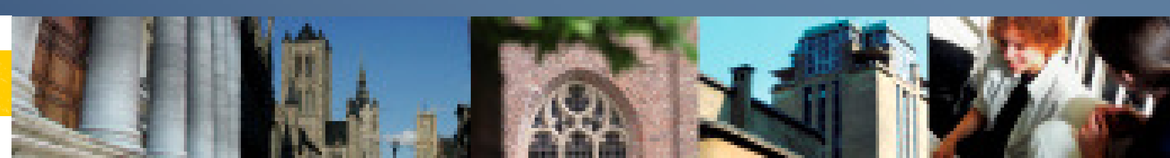
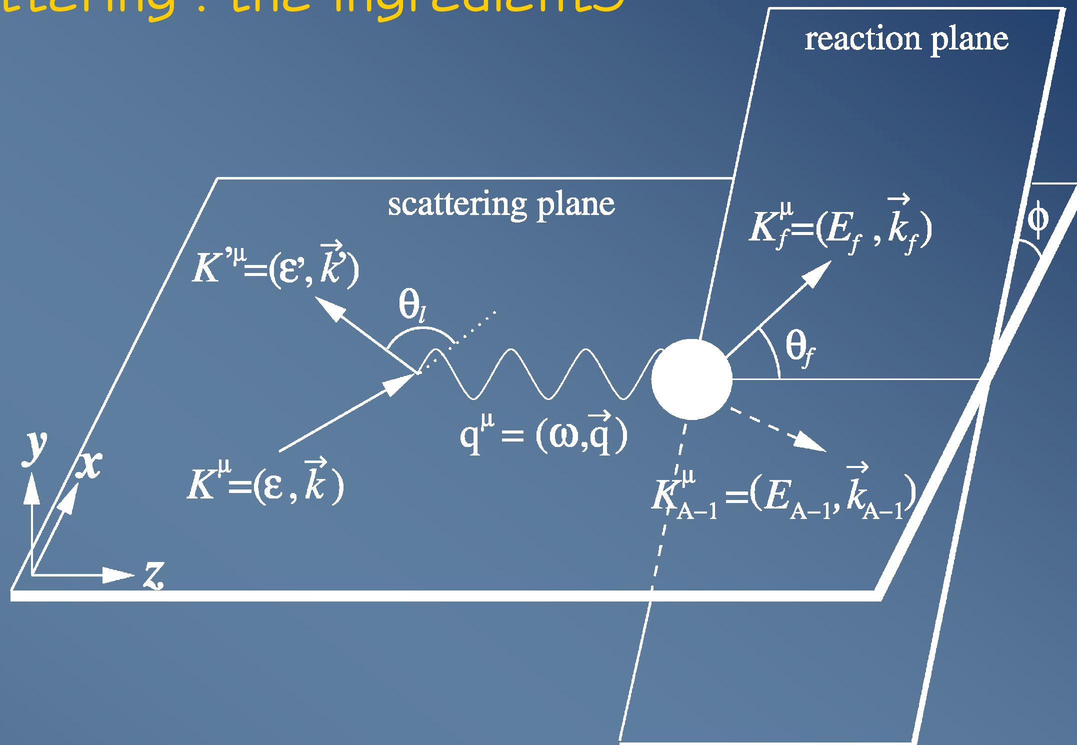


Neutrino-nucleus scattering : the ingredients



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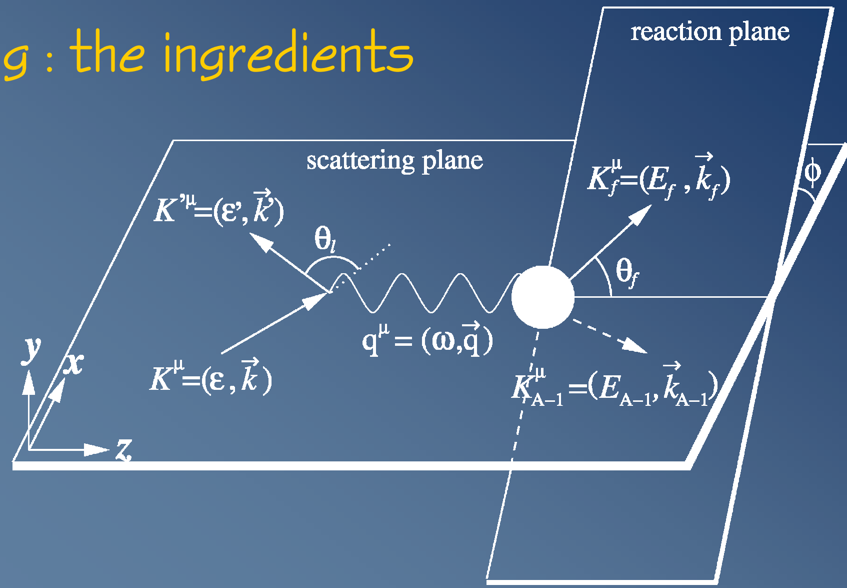


Cross section :

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

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

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

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 :

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

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

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

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

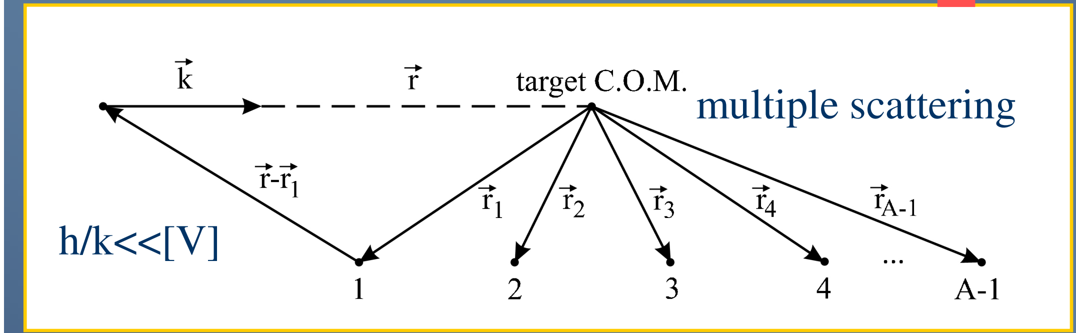
- semi-classical approach
- ‘high’ energies
- nucleon-nucleon data

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

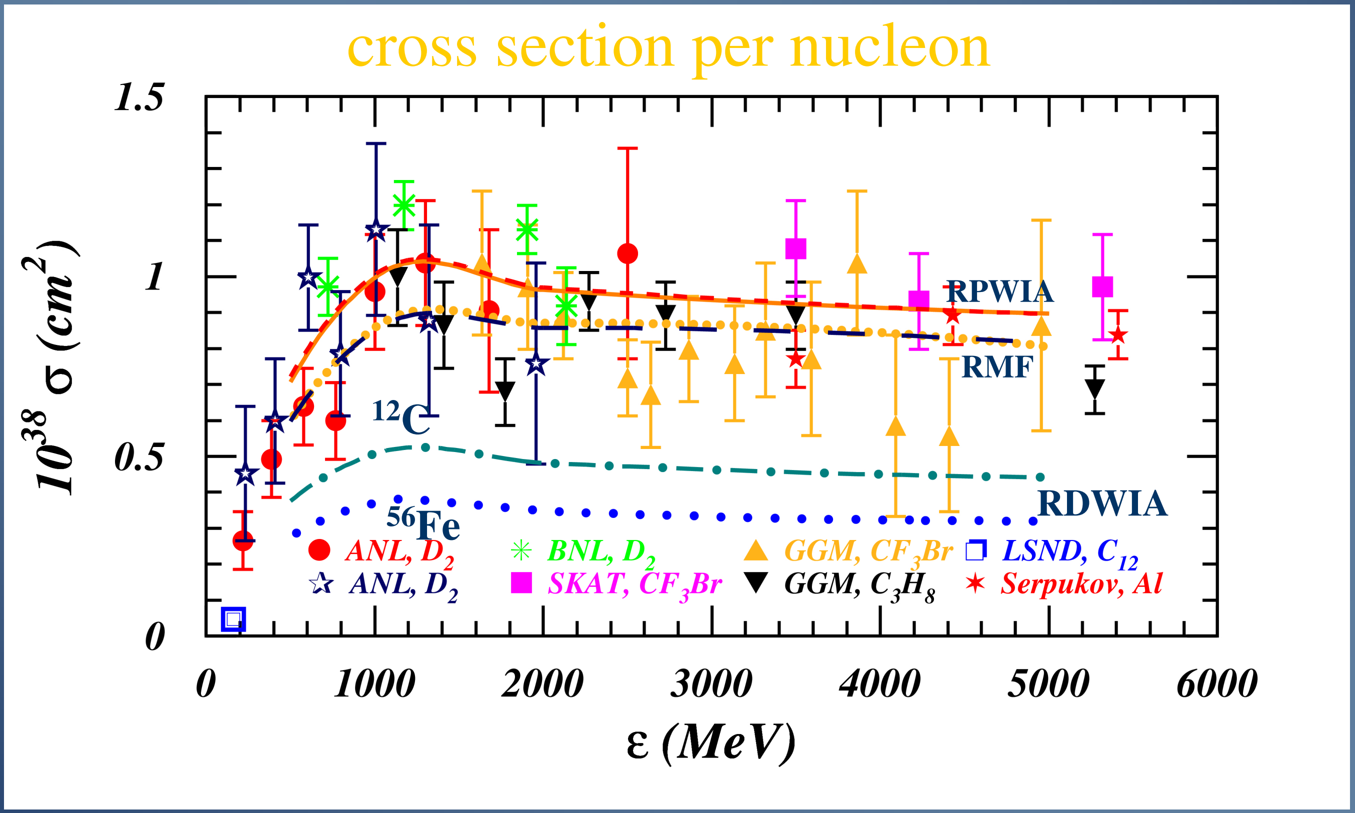
$$\mathcal{G}(\vec{b}, z) = \prod_{\alpha \neq B} \left[1 - \int d\vec{r}\,' |\phi_\alpha(\vec{r}\,')|^2 \theta(z' - z) \Gamma(\vec{b}' - \vec{b}) \right]$$

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

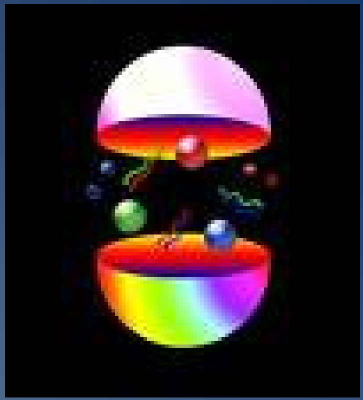
Summarized : included in the description of the nucleus and the reaction are :

- -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

- 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 ….



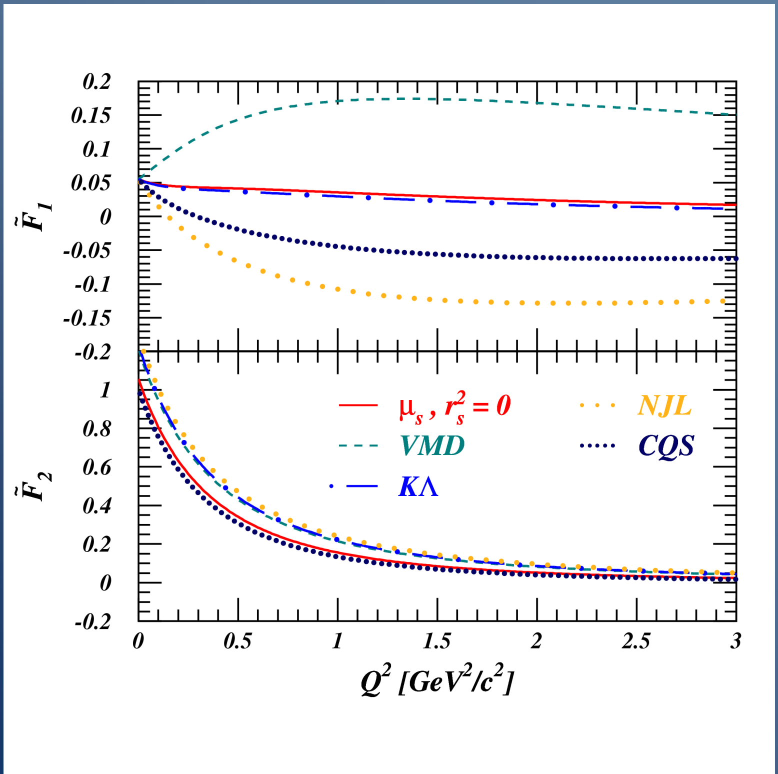
Strangeness in the nucleon



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



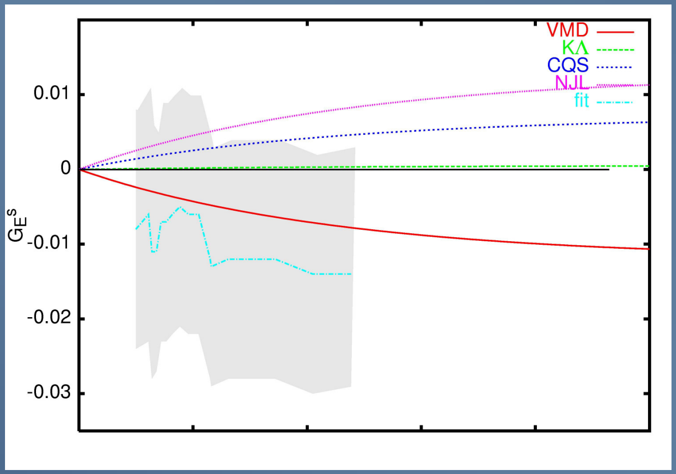
Weak vector form factors :

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

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

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

Model	$\mu_s(\mu_N)$	$r_s^2(\mathrm{fm}^2)$
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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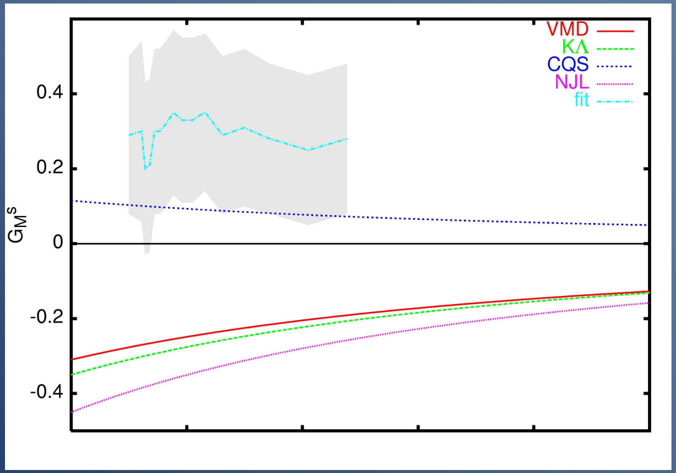
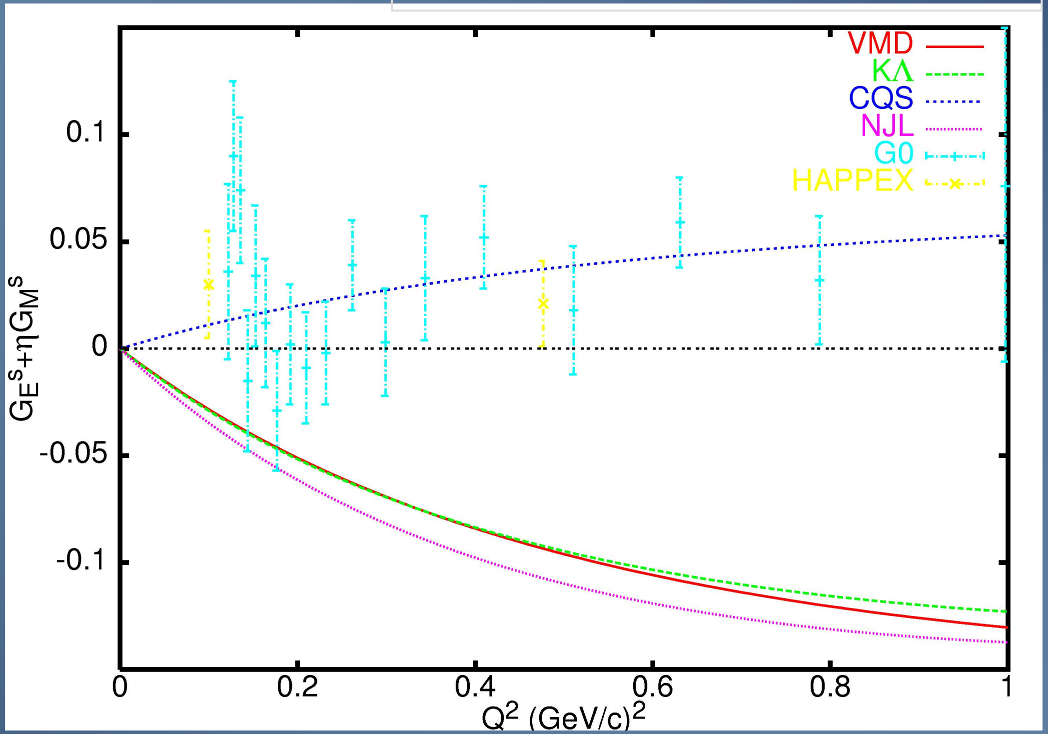
Data and fit from 'Global analysis of nucleon strange form factors at low Q^2', J. Liu, R.D. Mckeown, R.D. Ramsey-Musolf, PRC76, 025202 (2007).





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

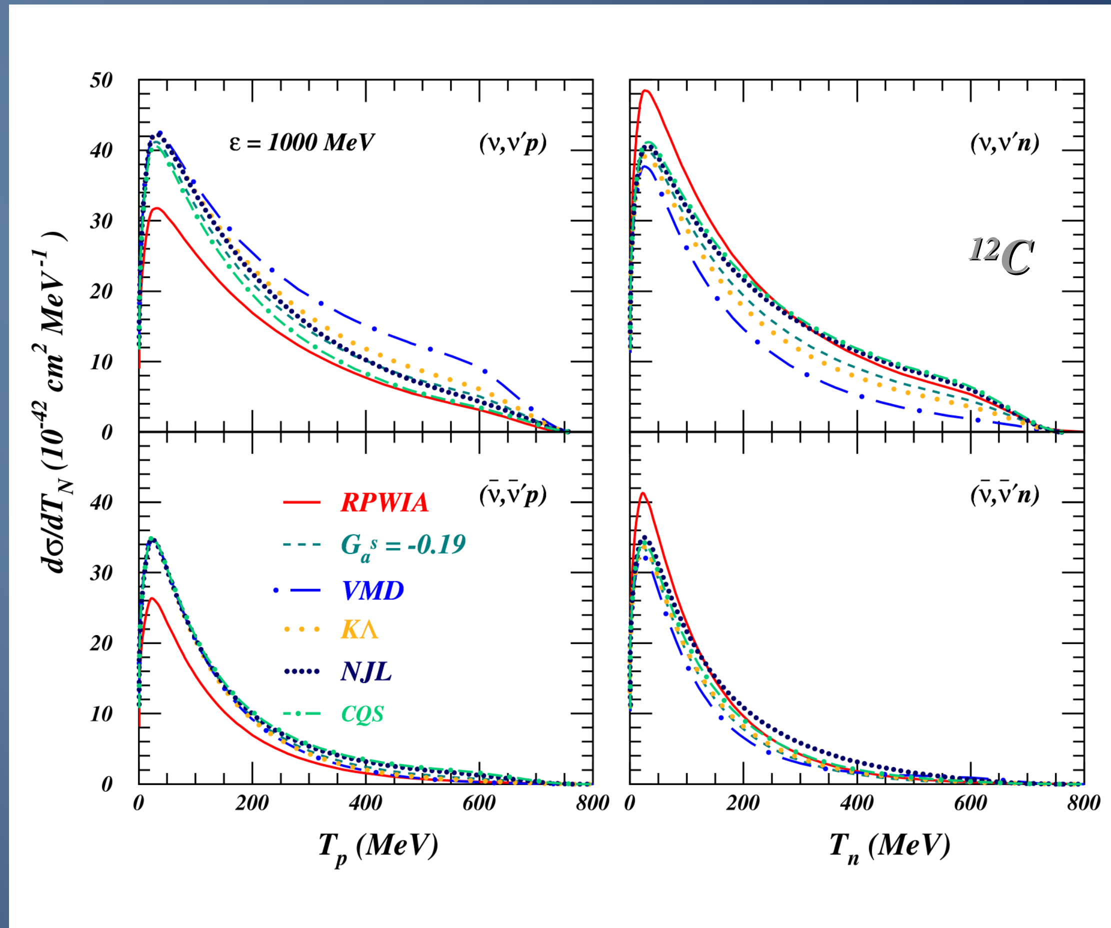
  -no radiative corrections

→ 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

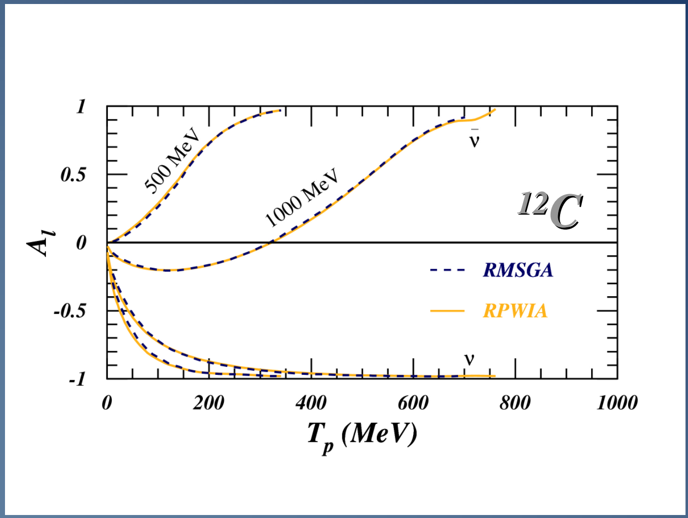
→in terms of ejectile energies and Q^2 values

Influence of strangeness on cross sections at intermediate energies

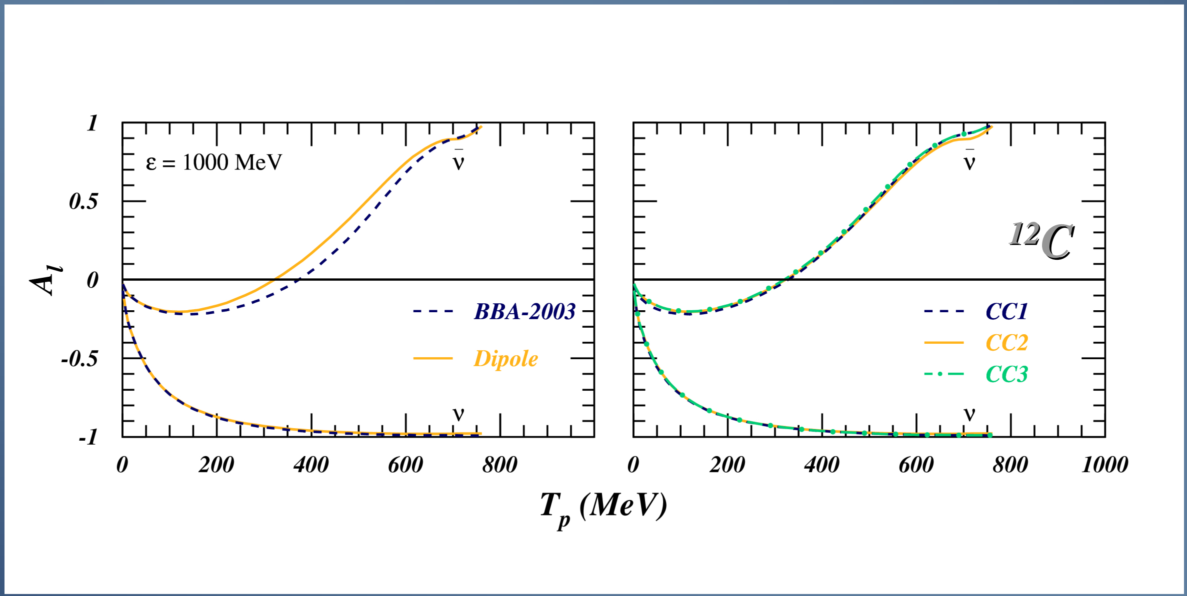


Cross section ratios

- 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.

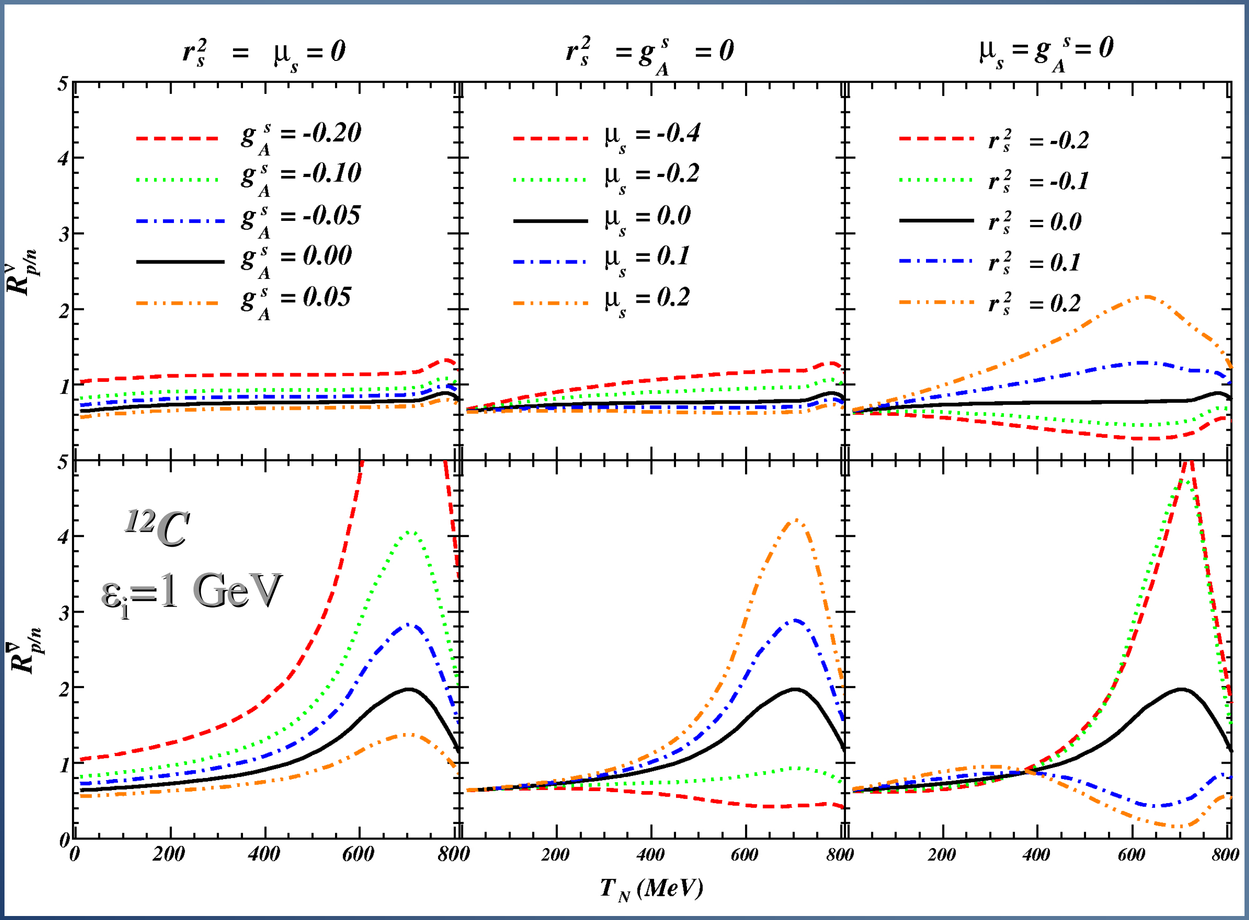


Ratios are robust observables, which makes them very suitable quantities to study strange-quark contributions to the nucleon



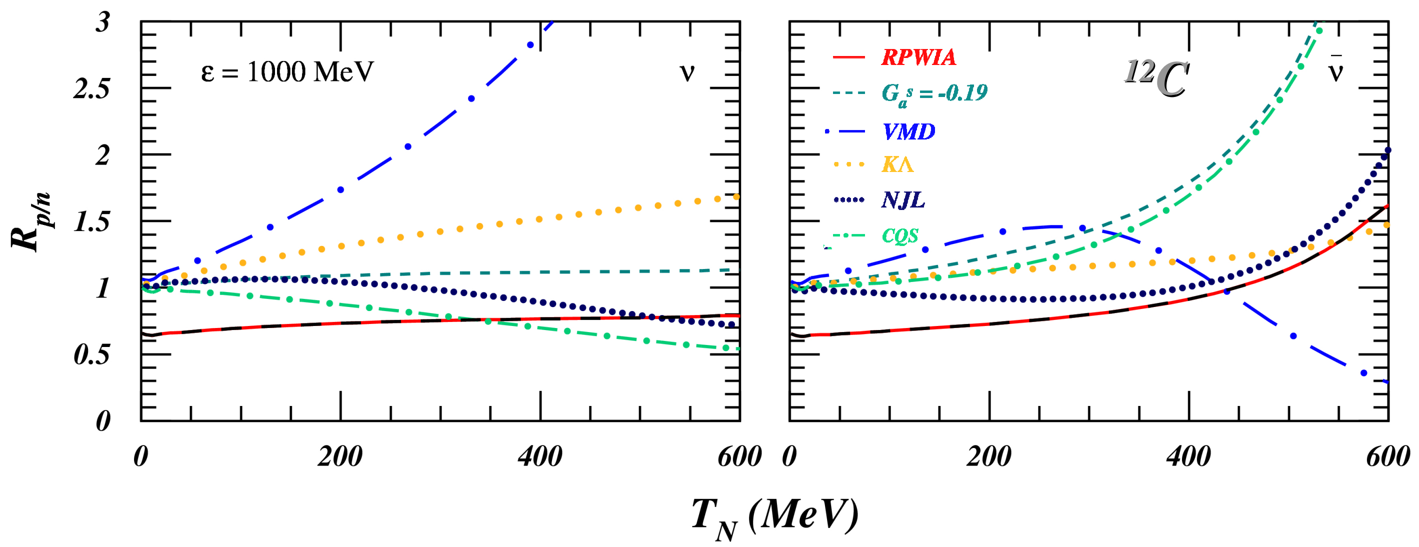
Ratio of neutral current neutrino scattering off a proton/neutron

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



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

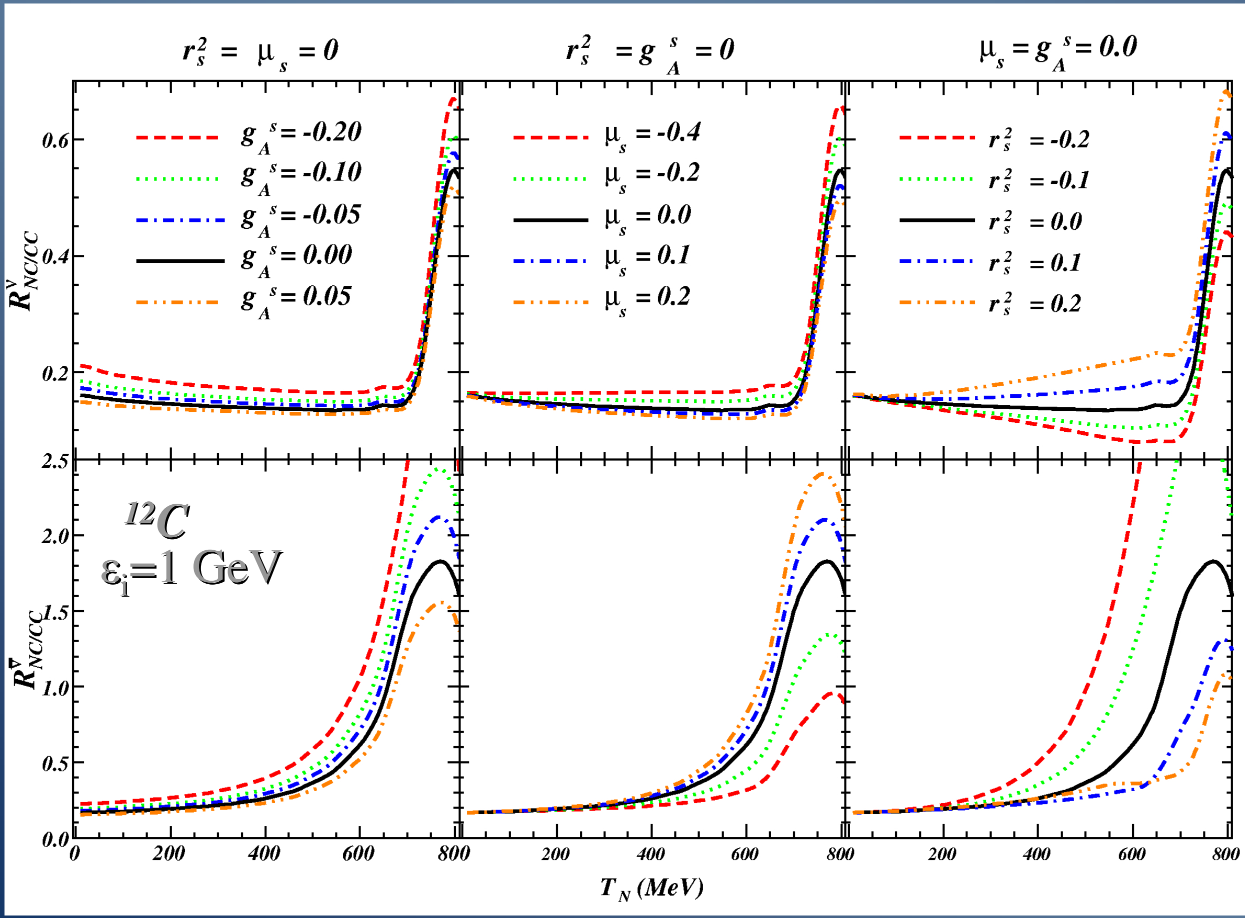
… continued



Ratio of neutral-to-charged current neutrino scattering

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

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



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

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

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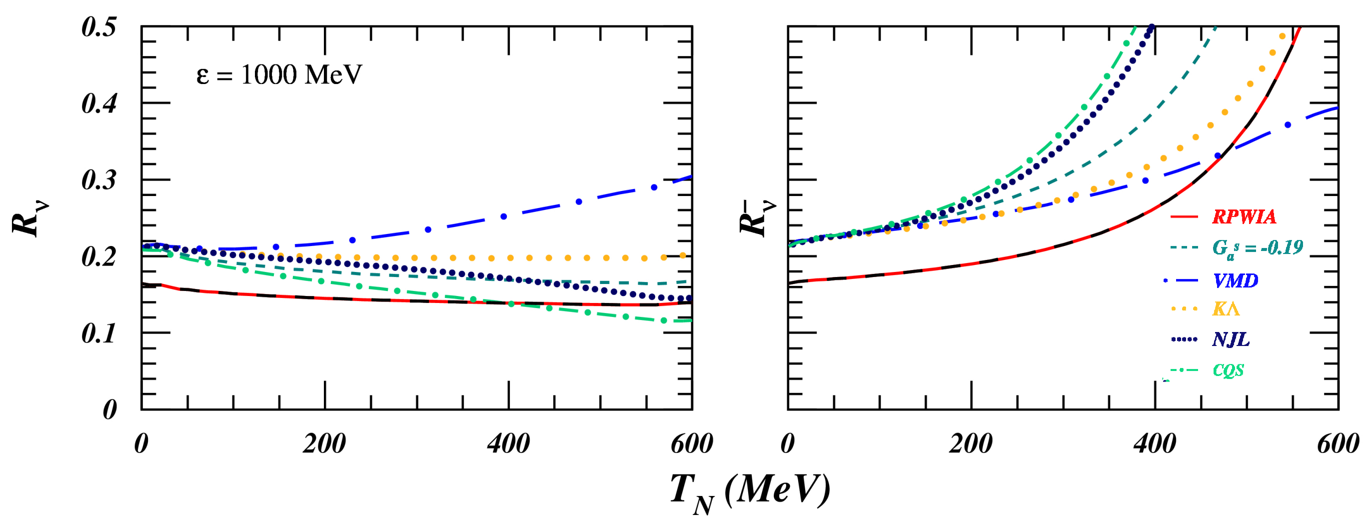
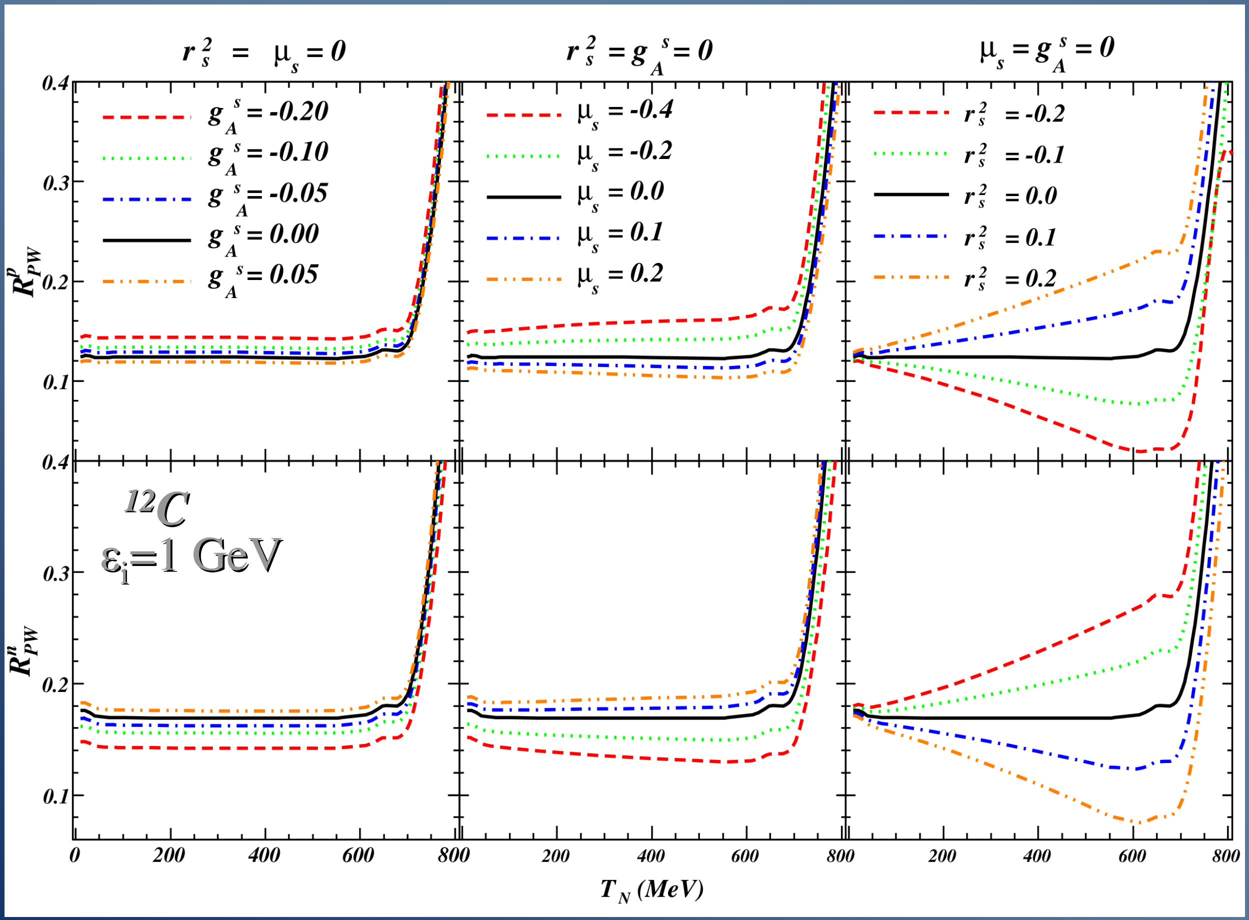


$$A_p = \frac{\left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} - \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\overline{\nu},p)}}{\left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\nu,p)} - \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\overline{\nu},n)}}$$

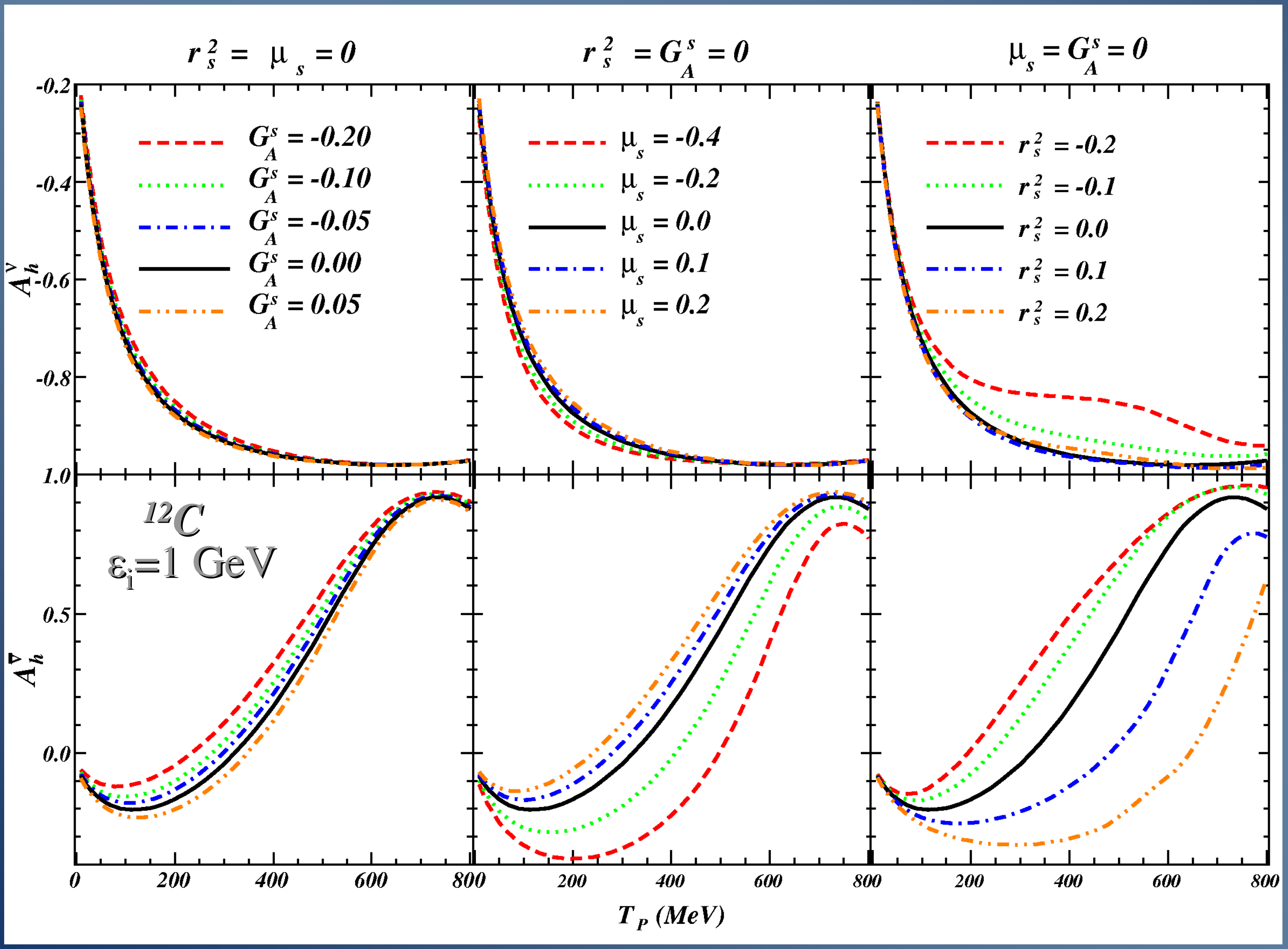


Paschos-Wolfenstein relation in a hadronic framework

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

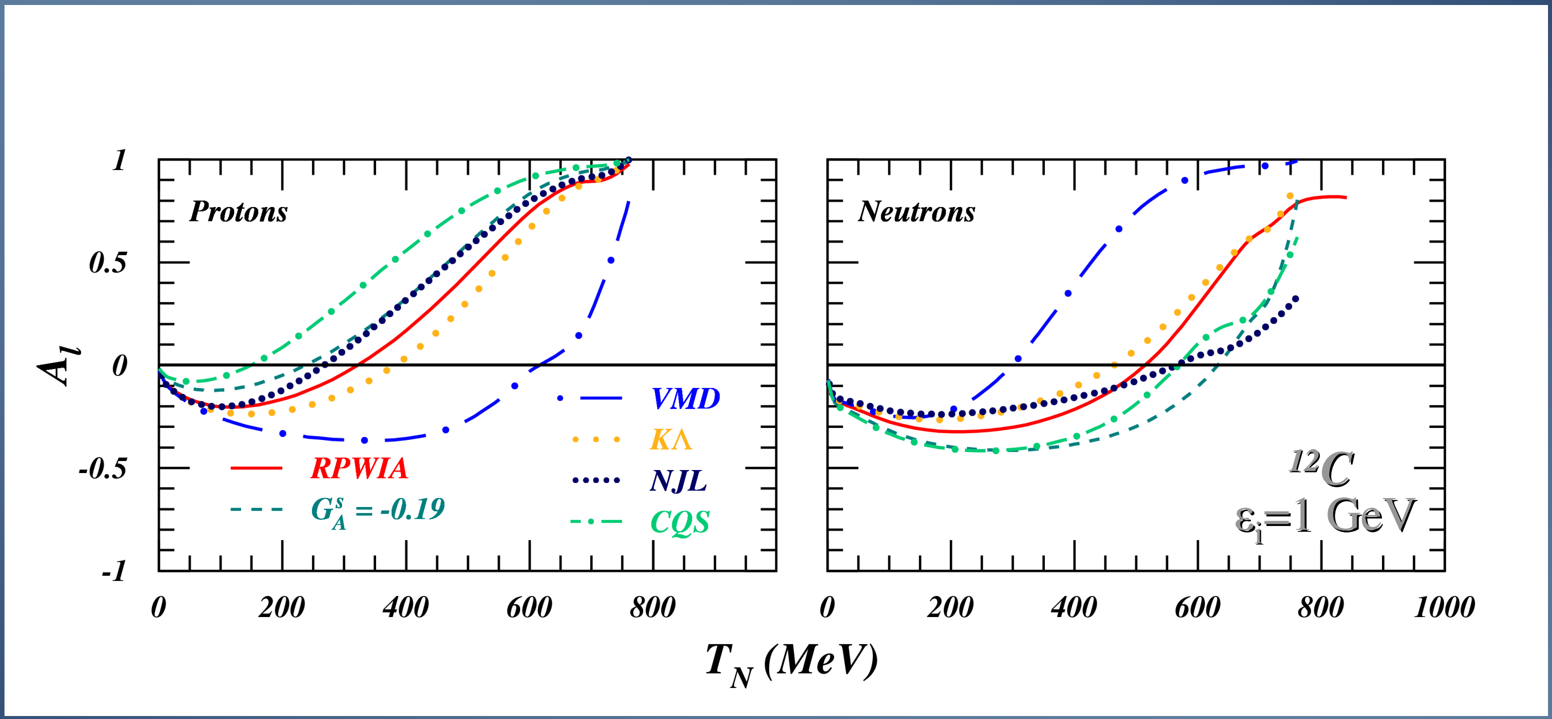
Helicity asymmetries

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



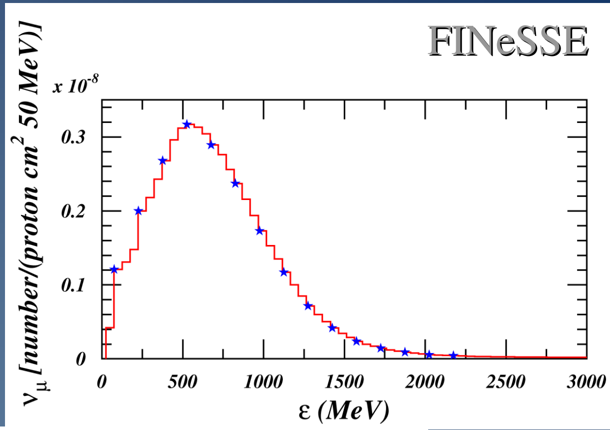
Helicity asymmetries

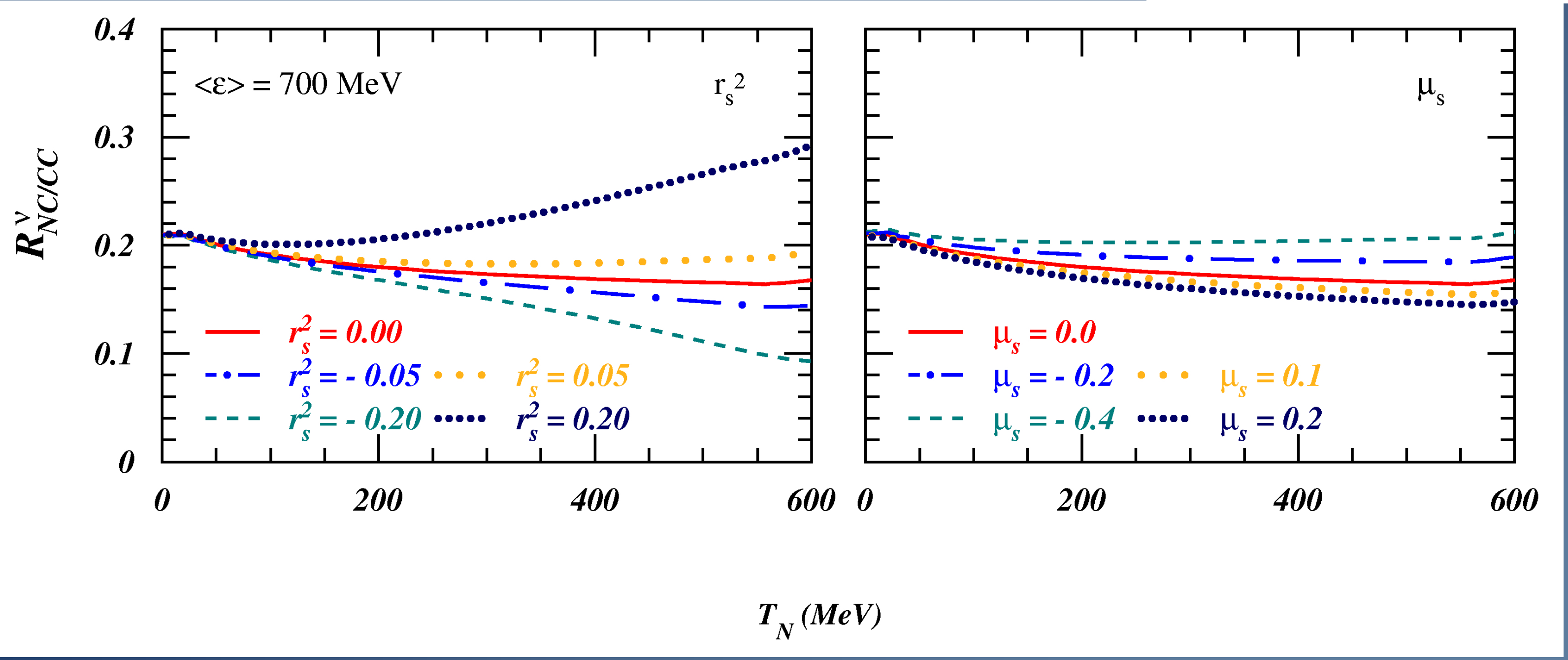
P. Lava et al, PRC73, 064605 (2006)



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

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

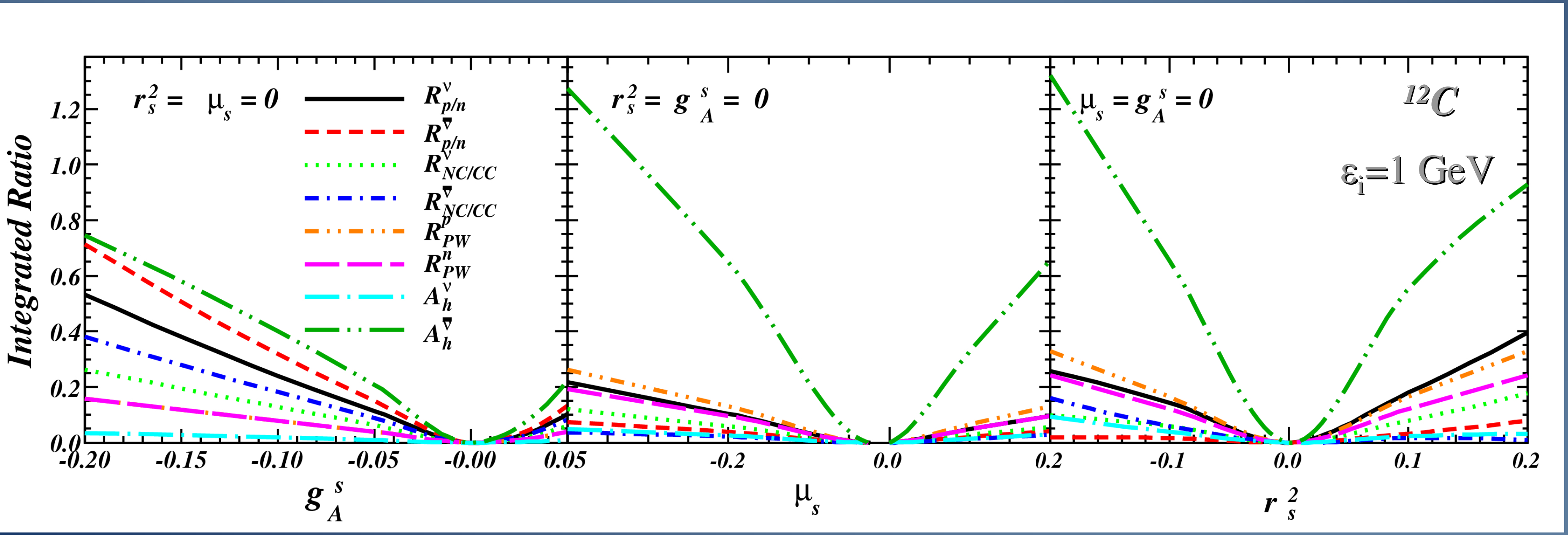




→ Folding has no qualitative influence on the overall sensitivity to strangeness mechanisms

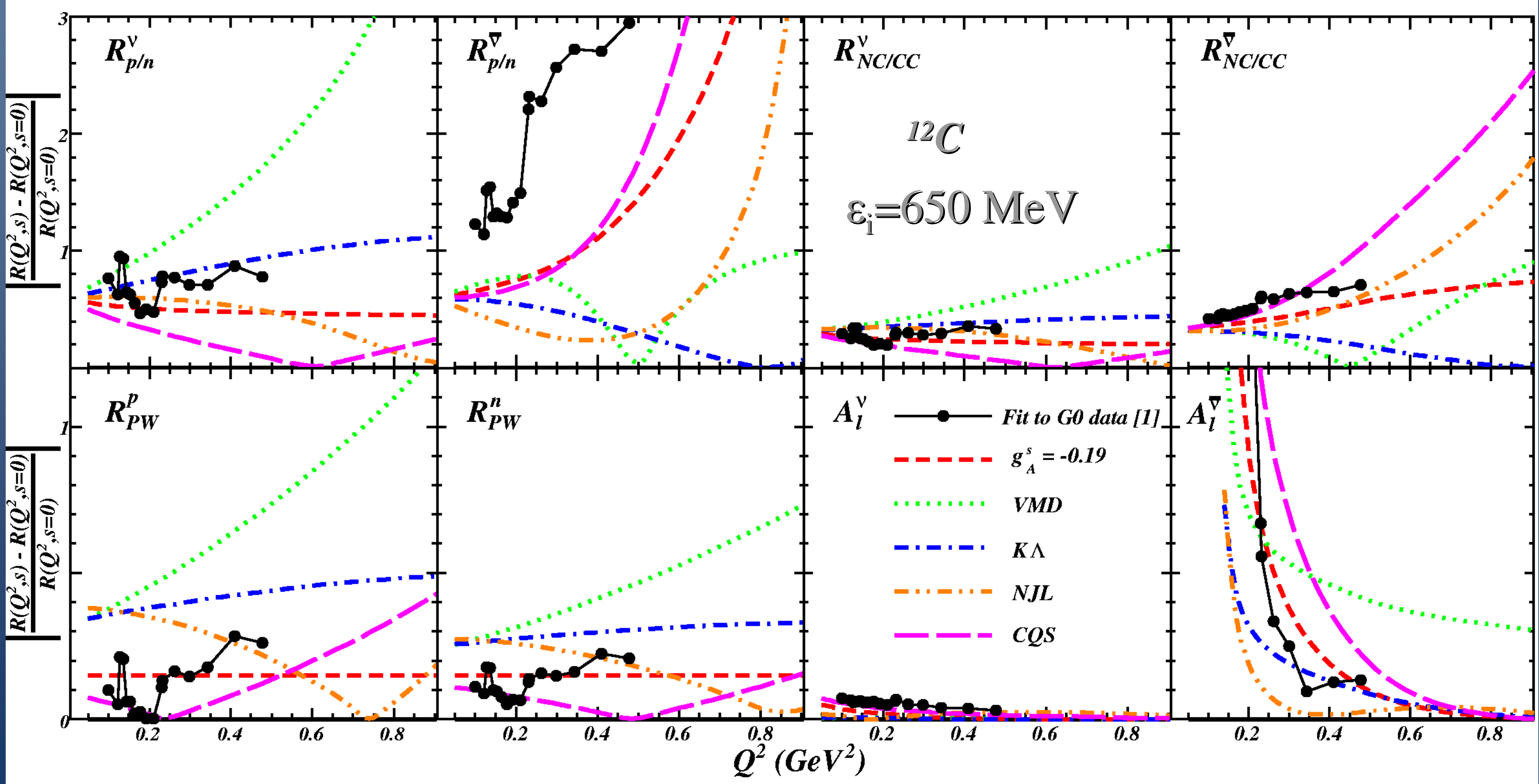
Comparing the sensitivity of the ratios :

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



Q^2 dependence of the strangeness sensitivity

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



Conclusions

- (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

Ref : N. Jachowicz, P. Vancraeyveld, P. Lava, C. Praet, and J. Ryckebusch, PRC76, 055501 (2007)