From electron- to neutrino-nucleus scattering
Do we need a new paradigm ?

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Based on work done in collaboration with A. Ankowski, D. Meloni and N. Farina

ECT*, Trento. October 26, 2009

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- The paradigm* of electron-nucleus scattering

*a philosophical or theoretical framework of any kind

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  - extracting *nucleon* properties from *nuclear* cross sections
- Summary and conclusions: do we need a new paradigm ?

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- Elementary interaction vertex largely determined by electron-proton and electron-deuteron data
- Nuclear effects described using a variety of dynamical models and the formalism of many-body theory
- The large body of available data is used to test the validity of the dynamical models and the accuracy of the computational techniques

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- All the information on target structure is contained in $W^{\mu\nu}$

$$W^{\mu\nu} = \sum_X \langle 0|J^\mu|X\rangle\langle X|J^\nu|0\rangle \delta^{(4)}(p_0 + q - p_X)$$

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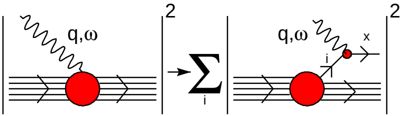
- ⋆ At large momentum transfer, electron-nucleus scattering reduces to the incoherent sum of elementary scattering processes involving individual nucleons, whose momentum ($\mathbf{k}$) and removal energy (E) distribution is described by the hole spectral function $P(\mathbf{k}, E)$

The impulse approximation (IA) regime

- ⋆ At $|\mathbf{q}|^{-1} \lesssim d$



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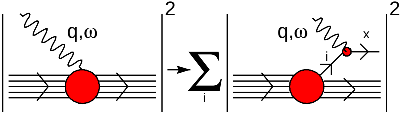

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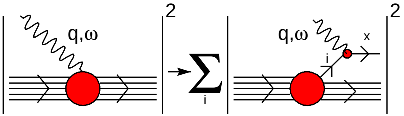

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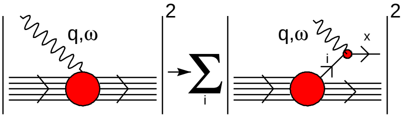

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▹ neglect final state interactions (FSI) between the hadron X produced at the em interaction vertex and the spectator nucleons

The IA cross section

- Within IA

$$\langle 0|J^\mu|X\rangle = \frac{m}{\sqrt{|\mathbf{p}_\mathcal{R}|^2 + m^2}} \langle 0|\mathcal{R}, \mathbf{p}_\mathcal{R}; \mathrm{N}, -\mathbf{p}_\mathcal{R}\rangle \sum_i \langle -\mathbf{p}_\mathcal{R}, N|j_i^\mu|x, \mathbf{p}_x\rangle$$

where $|\mathrm{N}, \mathbf{k}\rangle$ is the state describing a *free* nucleon carrying momentum $\mathbf{k}$

$$W^{\mu\nu}(\mathbf{q}, \omega) = \int d^3k \, dE \left(\frac{m}{E_\mathbf{k}}\right) \left[ZP_p(\mathbf{k}, E) w_p^{\mu\nu}(\widetilde{q}) + NP_n(\mathbf{k}, E) w_n^{\mu\nu}(\widetilde{q})\right]$$

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- The IA x-section is determined by
  - The nucleon energy and momentum distribution, described by the hole spectral functions
  - The em tensor describing a *free* nucleon carrying momentum $\mathbf{k}$

$$w_N^{\mu\nu} = \sum_x \langle \mathbf{k}, \mathrm{N}|j_N^\mu|x, \mathbf{k}+\mathbf{q}\rangle\langle \mathbf{k}+\mathbf{q}, x|j_N^\nu|\mathrm{N}, \mathbf{k}\rangle \delta(\widetilde{\omega} + E_\mathbf{k} - E_x)$$

$$\widetilde{\omega} = E_x - E_\mathbf{k} = E_0 + \omega - E_\mathcal{R} - E_\mathbf{k} = \omega - E + m - E_\mathbf{k}$$

The IA cross section (continued)

- The nucleon tensor can be written as $(\widetilde{q} \equiv (\widetilde{\omega}, \mathbf{q}))$

$$w_N^{\mu\nu} = w_1^N \left(-g^{\mu\nu} + \frac{\widetilde{q}^\mu \widetilde{q}^\nu}{\widetilde{q}^2} \right) + \frac{w_2^N}{m^2} \left(k^\mu - \frac{(k\widetilde{q})}{\widetilde{q}^2} \widetilde{q}^\mu \right) \left(k^\nu - \frac{(k\widetilde{q})}{\widetilde{q}^2} \widetilde{q}^\nu \right)$$

- In principle, the structure functions w_1^N and w_1^N can be extracted from electron-proton and electron-deuteron data
- In the case of quasielastic (QE) scattering

$$w_1^N = -\frac{\widetilde{q}^2}{4m^2} \, \delta \left(\widetilde{\omega} + \frac{\widetilde{q}^2}{2m} \right) \, G_{M_N}^2$$

$$w_2^N = \frac{1}{1 - \widetilde{q}^2/4m^2} \, \delta \left(\widetilde{\omega} + \frac{\widetilde{q}^2}{2m} \right) \left(G_{E_N}^2 - \frac{\widetilde{q}^2}{4m^2} G_{M_N}^2 \right)$$

where G_{E_N} and G_{M_N} are the nucleon electric and magnetic form factors

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- The measured inelastic cross sections have allowed for a systematic study of the dynamic response over a broad range of momentum and energy transfer
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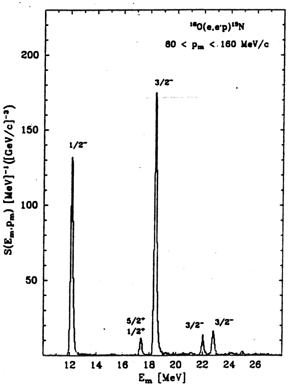
- Single nucleon knock out $(e, e'p)$ experiments have provided a wealth of information on mean field dynamics
- The emerging picture suggests that, in spite of its ability to account for a number of nuclear properties, the shell model approach fails to explain important features of the data, whose description requires that nucleon-nucleon (NN) *correlations* be taken into account
  - Not a novel issue ! Back in 1952 Blatt & Weiskopf pointed out that “The limitation of any independent particle model lies in its inability to encompass the correlation between the positions and spins of the various particles in the system”

Evidence of correlation effects

- The spectral lines corresponding to shell model orbitals are clearly seen in the missing energy spectra of $(e, e'p)$ experiments



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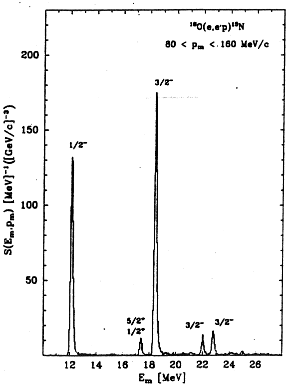
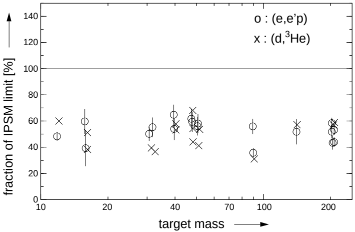
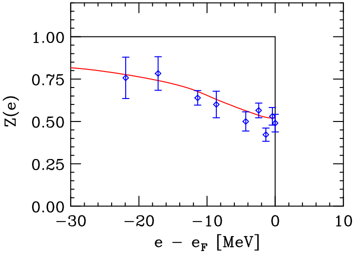


- The measured strengths of the peaks corresponding to shell model states are significantly less than unity ($\lesssim 0.6$ for valence states)



Evidence of correlation effects (continued)

- Energy dependence of the spectroscopic strengths of the shell model states of ^{208}Pb, measured in high resolution $(e, e'p)$ at NIKHEF-K



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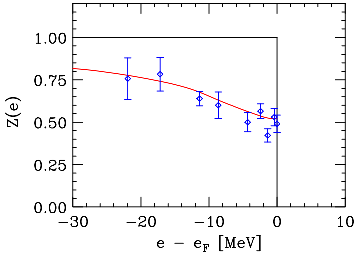
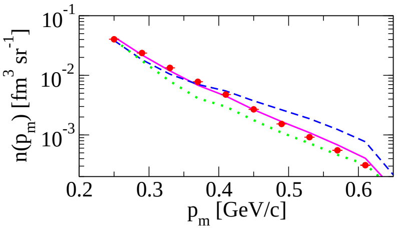
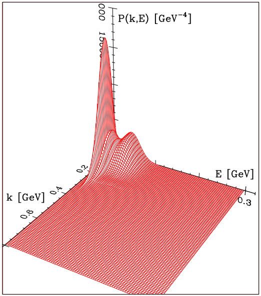
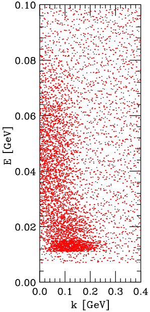


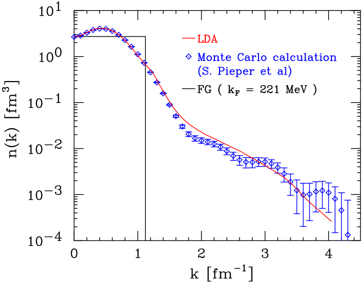
- The missing strength is pushed to large momentum and removal energy. Carbon momentum distribution measured by the JLab E97-006 collaboration.



Oxygen spectral function and momentum distribution







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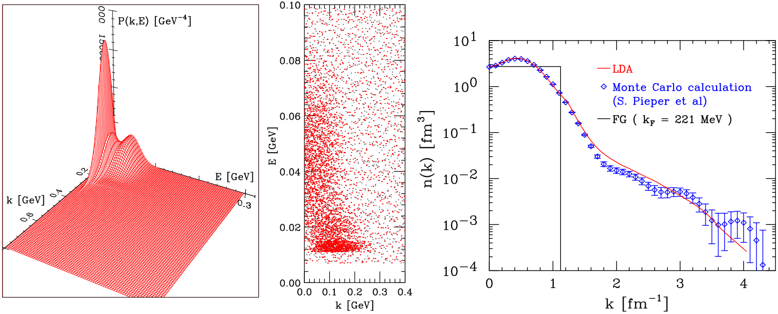
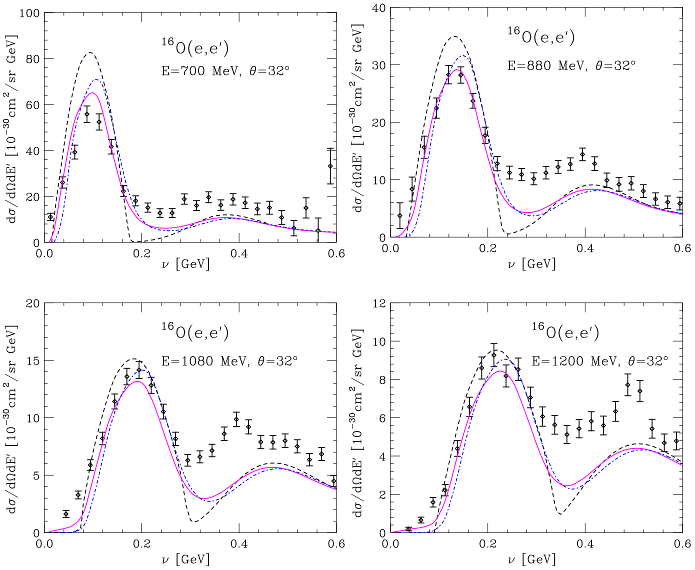


- Fermi Gas (FG) model: $P_h(\mathbf{k}, E) \propto \theta(k_F - |\mathbf{k}|)\, \delta(E - \sqrt{|\mathbf{k}|^2 + m^2} + \epsilon)$
- shell model states account for $\sim$ 80% of the strenght
- the remaining $\sim$ 20%, arising from NN correlations, is located at high momentum *and* large removal energy ($\mathbf{k} \gg k_F, E \gg \epsilon$)

Comparison to oxygen data @ $0.2 \lesssim Q^2 0.6$ GeV^2



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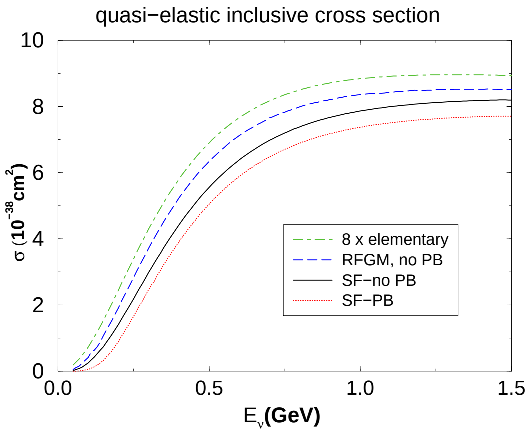
- Most experimental analyses are based on the Fermi Gas model
- Implementation of more realistic models in simulation codes is strongly needed (and under way)

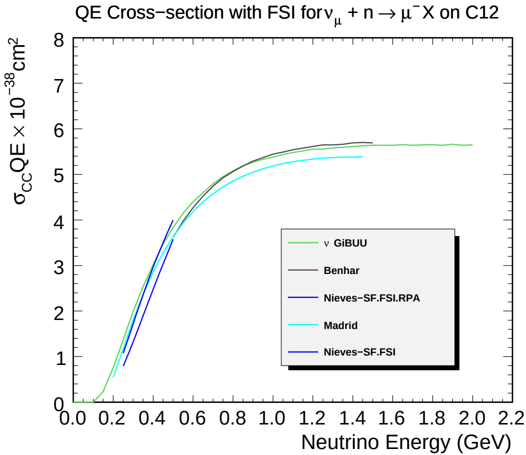
Gauging nuclear effects in quasielastic scattering

★ Total x-section of the process $\nu_e +^{16} O \rightarrow e^- + X$



Model dependence

★ Total x-section of the process $\nu_e +^{12} C \rightarrow e^- + X$



Q^2-distributions and the nucleon axial mass

- ⋆ K2K and MiniBooNE have reported a large value of the nucleon axial mass, $M_A \sim 1.2$ GeV, extracted from the analysis of neutrino interactions with oxygen and carbon, to be compared to $M_A \sim 1.0$ GeV obtained using a deuterium target

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- ⋆ To what extent is the determination of M_A from nuclear data biased by the treatment of nuclear effects in the analysis ?

Experimental determination of the axial mass

★ Both K2K and MiniBooNE search for signatures of neutrino oscillations using Charged Current Quasi Elastic (CCQE) interactions

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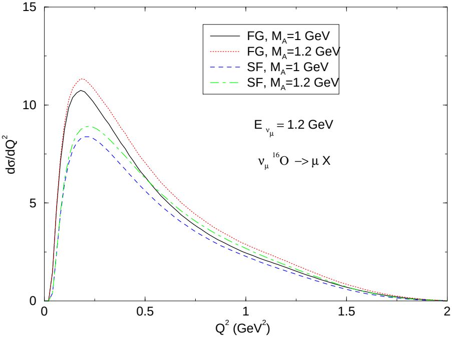
- ⋆ the neutrino energy is reconstructed from

$$E_\nu = \frac{2(m_n - E_B)E_\mu - (E_B^2 - 2m_n E_B + m_\mu^2 + \Delta m^2)}{2(m_n - E_B - E_\mu + |\mathbf{p}_\mu| \cos\theta_\mu)} \ ,$$

  with $|\mathbf{p}_\mu| = \sqrt{E_\mu^2 - m_\mu^2}$ and $E_B \sim 25 \div 35$ MeV

Q^2-distributions at fixed neutrino energy

- Comparison between the FG model and the approach based on a more realistic spectral function (SF), including correlation effects, at fixed neutrino energy E_ν



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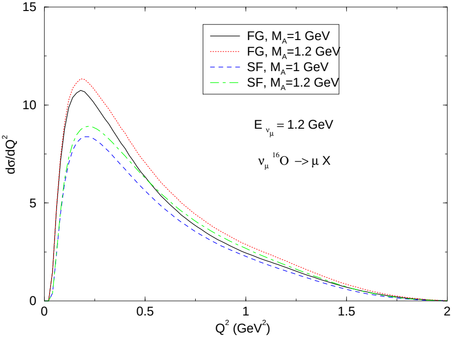
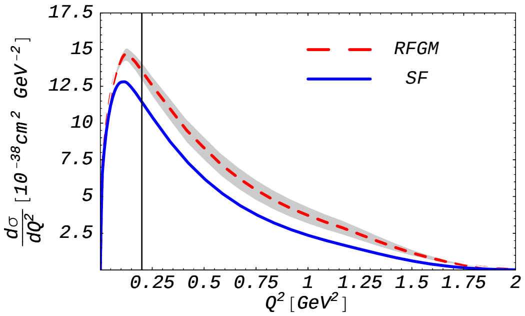


- Using a realistic spectral function and increasing M_A lead to changes of opposite sign

Q^2-distributions at fixed neutrino energy (continued)

- ⋆ Comparison between FG with $M_A = 1.0$ GeV and SF with $M_A = 1.2$ GeV. Neutrino energy $E_\nu = 1.2$ GeV



- ⋆ The vertical line shows the boundary of the kinematical region $Q^2 < 0.2$ GeV^2, excluded from the data set analyzed by the K2K collaboration.

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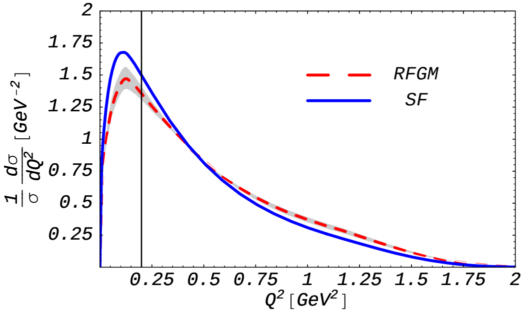

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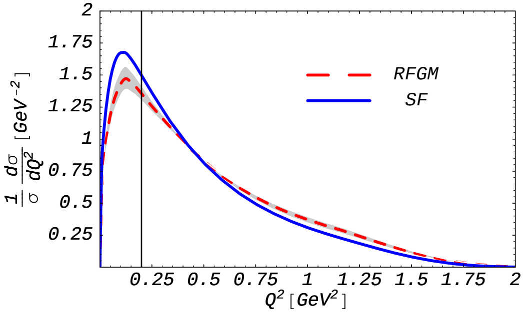
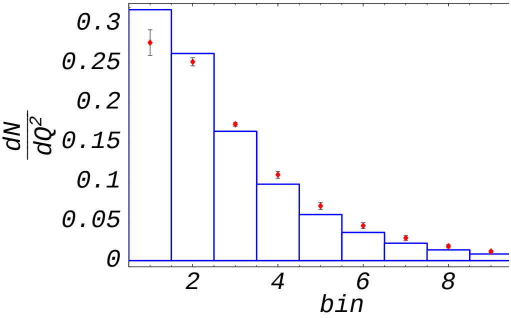
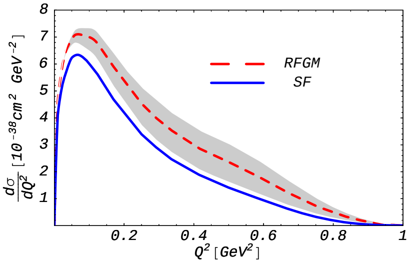


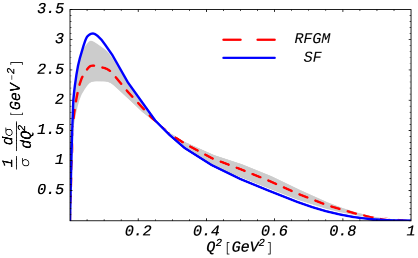
- ⋆ The explanation of the large M_A suggested in the MiniBooNE paper does not appear to be viable

K2K flux-integrated Q^2-distribution



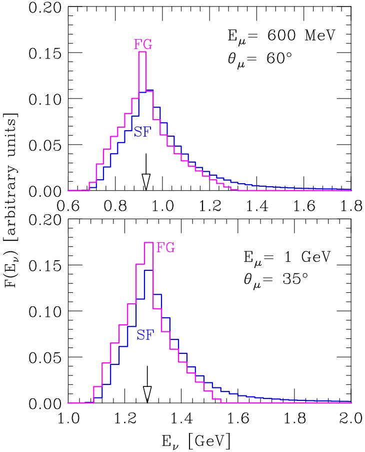
Q^2-distributions at $E_\nu = 700$ MeV





Uncertainty in the reconstructed E_ν

- ⋆ Distribution of the reconstructed E_ν obtained from the FG and SF approaches



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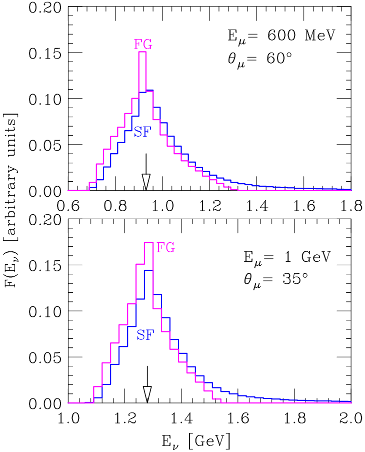

- ⋆ Note: a larger E_ν leads to predict an even larger M_A

Comparing physical and reconstructed Q^2

- ⋆ The reconstructed neutrino energy is used in the determination of Q^2

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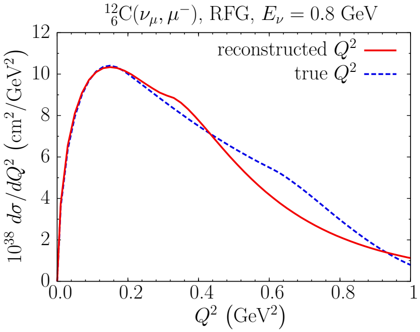
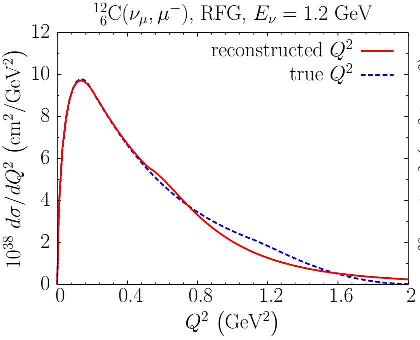
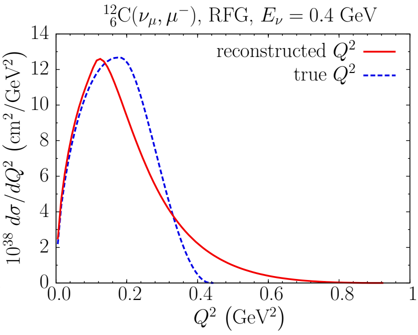


Comparing physical and reconstructed Q^2 (continued)





Twisting the FG model at low Q^2

- ⋆ The MiniBooNE analysis introduces in the FG model the additional parameter κ, leading to an increase of the lower energy integration limit

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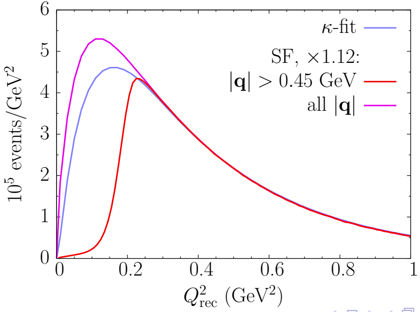
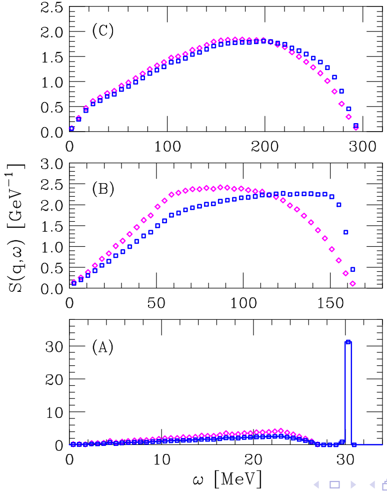
- ★ κ quenches the contributions corresponding to $|\mathbf{q}| \lesssim 0.45$ GeV



Where does the IA picture break down ?

- Interplay between short- and long range correlation effects on the weak response of nuclear matter: (A), (B) and (C) correspond to $|\mathbf{q}|$ =60, 300 and 475 MeV



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- The analysis of neutrino-nucleus scattering observables involve additional difficulties
  - lepton kinematics not fully determined
  - elementary interaction vertex not extracted from neutrino-nucleon data
- More work is likely be required, to make the models of nuclear effects more flexible, and applicable to a broad kinematical range