Modelling neutrino-nucleus interactions: status and perspectives

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What Next: Sezioni d'urto dei neutrini
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Outline

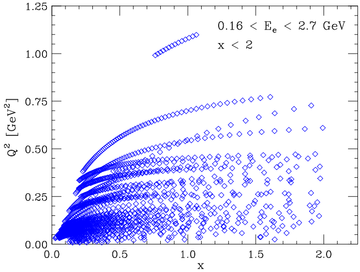
- Understanding the neutrino-nucleus cross section at *fixed* beam energy between few hundreds MeV and few GeV: lessons from electron scattering data
  - Quasi elestic (zero-pion) events: single nucleon knock out, two-nucleon knock out and meson-exchange currents
  - Resonance production & deep inelastic scattering
- Understanding the flux integrated cross section
- Impact on the determination of oscillation parameters
- Where are we? What next?

Electron-nucleus scattering at ~ 1 GeV

- Large supply of precise data available

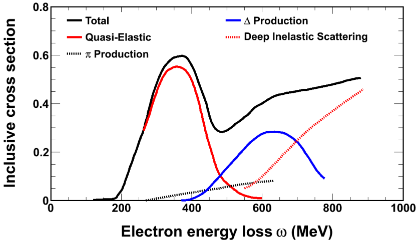
$$Q^2 = 4E_e E_{e'} \sin^2 \frac{\theta_e}{2} \quad , \quad x = \frac{Q^2}{2M\omega}$$

- Carbon target



- Different rection mechanisms contributimg to the mesured cross sections can be readily identified

$$e + A \to e' + X$$



Preamble: the lepton-nucleus x-section

⋆ Double differential cross section of the process $\ell + A \to \ell' + X$

$$\frac{d\sigma_A}{d\Omega_{k'} dk'_0} \propto L_{\mu\nu} W_A^{\mu\nu}$$

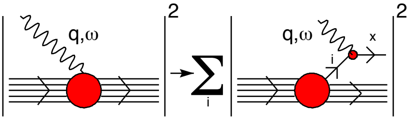
- ▷ $L_{\mu\nu}$ is fully specified by the lepton kinematical variables
- ▷ The determination of the target response tensor

$$W_A^{\mu\nu} = \sum_N \langle 0 | J_A^{\mu\,\dagger} | N \rangle \langle N | J_A^\nu | 0 \rangle \delta^{(4)}(P_0 + k - P_N - k')$$

  requires a consistent description of the target initial and final states and the nuclear current. Accurate calculations are feasible in the non relativistic regime, corresponding to $|\mathbf{q}| \lesssim 500$ MeV
- ▷ In the kinematical regime in which relativistic effects become important, approximations are needed to describe the $|\mathbf{q}|$-dependent current operator and final state

THE IMPULSE APPROXIMATION (IA)

⋆ At $\lambda = 2\pi/|\mathbf{q}| \ll d_{\rm NN}$, the average NN distance in the target nucleus



▷ neglect the contribution of the two-nuleon current

$$J_A^\mu(q) = \sum_i j_i^\mu(q) + \sum_{j>i} j_{ij}^\mu(q) \approx \sum_i j_i^\mu(q)$$

▷ write the final state in the factorized form

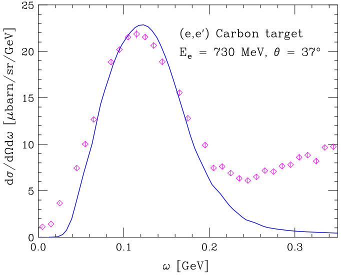
$$|N\rangle \to |\mathbf{p}\rangle \otimes |n_{(A-1)}, \mathbf{p_n}\rangle \ .$$

▷ at zero-th order, neglect final state interactions (FSI) between the outgoing nucleon and the spectator particles

IA quasi elastic results compared to data

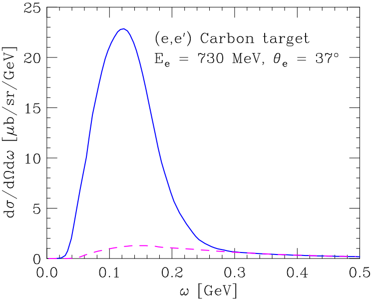
- ⋆ Nuclear x-section $d\sigma_A = \int d^3k dE \, d\sigma_N \, P(\mathbf{k}, E)$

- ⋆ QE (nucleon-only final states) only

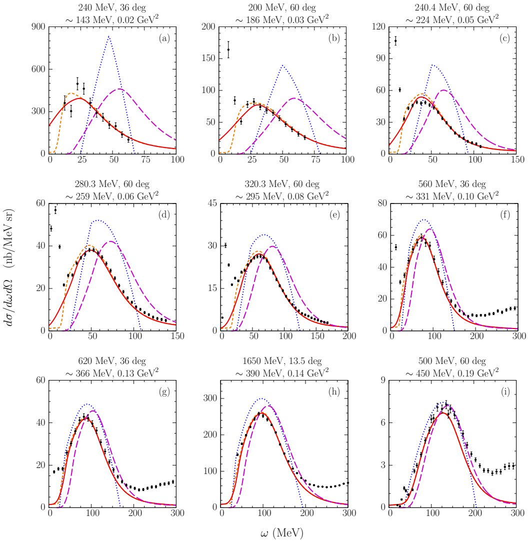


- ⋆ Position and width of the peak are reproduced

- ⋆ Correlation tail (∼ 10 % of total strength), corresponding to events with 2p2h final states, cleary visible

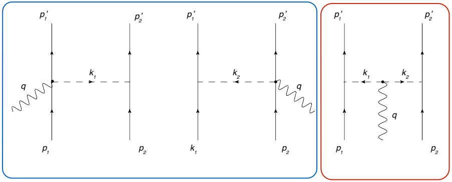


Carbon quasi elastic cross section within IA



⋆ FSI corrections included [A. Ankowski et al, PRD 91 033005, (2015)]

TWO-NUCLEON MESON-EXCHANGE CURRENT (MEC)



Seagull
or
contact
term

Pion
in
flight
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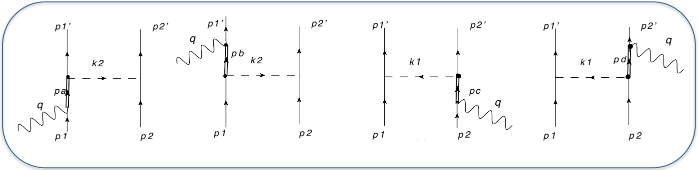


$|0\rangle \to |2p2h\rangle$ TRANSITION PROBABILITY

- ⋆ Esisting calculations of processes involving 2p2h final states are based on oversimplified models of the initial and final states
- ⋆ In interacting many body systems 2p2h states can be excited through the action of both one- and two-body transition operators

$$|\langle 2p2h| \, J \, |0\rangle|^2 = |\langle 2p2h| \, J_1 \, |0\rangle|^2 + |\langle 2p2h| \, J_2 \, |0\rangle|^2 + 2 \, \mathrm{Re} \, \langle 2p2h| \, J_1 \, |0\rangle^\star \langle 2p2h| \, J_2 \, |0\rangle$$

- ⋆ Within the independent particle model (either FG or shell model)

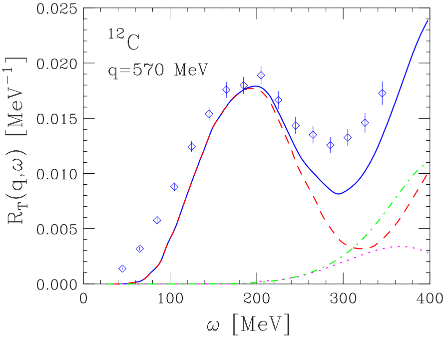
$$\langle 2p2h| \, J_1 \, |0\rangle = 0$$

- ⋆ Strong nucleon-nucleon correations lead to the appearance of sizable interference contributions to the $|0\rangle \to |2p2h\rangle$ transition probability

Contribution of the two-nucleon current

- ⋆ Electromagnetic response of ^{12}C in the transverse channel [PRC 92, 024602 (2015), data from the global analysis of J. Jourdan]

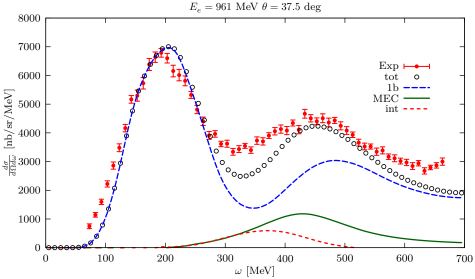
$$\frac{d^2\sigma}{d\Omega_{e'} dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{\mathbf{q}^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{\mathbf{q}^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

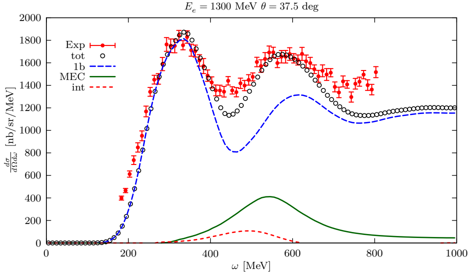


- ⋆ Sizable interference contribution peaked at $\omega > \omega_{QE} = Q^2/2m$

COMPARISON TO MEASURED CROSS SECTIONS

⋆ N. Rocco, PhD Thesis, Sapienza Università di Roma, 2015

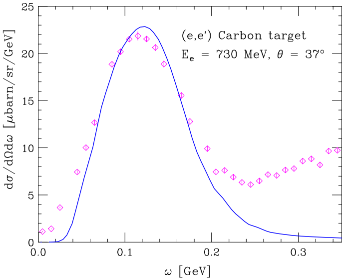


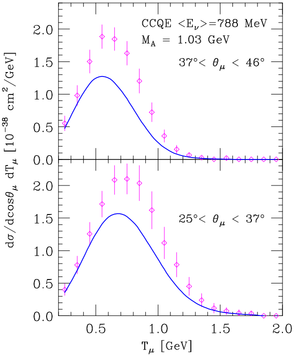


COMPARE e- AND ν_μ-CARBON QE CROSS SECTIONS

⋆ Double differential CCQE neutrino x-section (MiniBooNE)

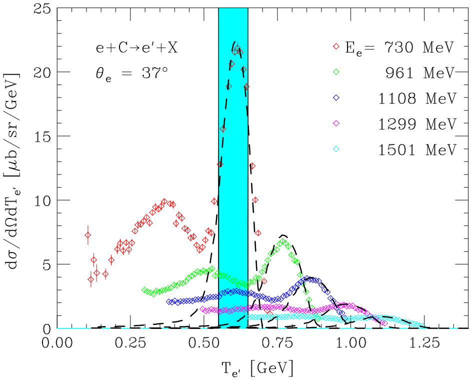
$$\frac{d\sigma_A}{dT_\mu d\cos\theta_\mu} = \frac{1}{N_\Phi}\int dE_\nu \Phi(E_\nu) \frac{d\sigma_A}{dE_\nu dT_\mu d\cos\theta_\mu}$$





"FLUX AVERAGED" ELECTRON-NUCLEUS X-SECTION

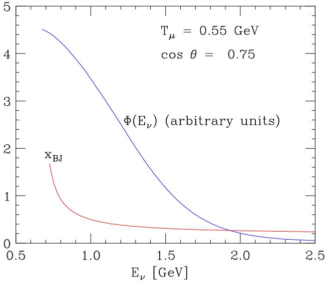
- ⋆ The electron scattering x-section off Carbon at θ_e= 37 deg has been measured for a number of beam energies

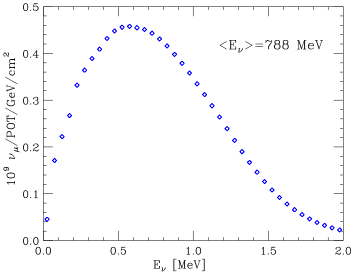


- ⋆ In the flux-averaged cross section, each bin of kinetic energy and scatering angle of the outgoing lepton picks up contributions arising from different reaction mechanisms

The issue of flux average

- ⋆ The *flux-averaged* cross sections at fixed T_μ and $\cos\theta_\mu$ picks up contributions at different beam energies, corresponding to different reaction mechanisms not taken into account in the IA scheme

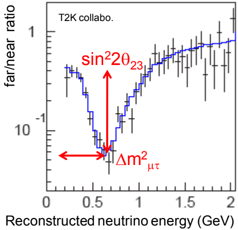




- ▷ $x = 1 \to E_\nu$ 0.788 GeV , $x = 0.5 \to E_\nu$ 0.975 GeV
- ▷ For MiniBooNE flux $\Phi(0.975)/\Phi(0.788) = 0.83$

Neutrino energy reconstruction

$$P_{\alpha\to\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



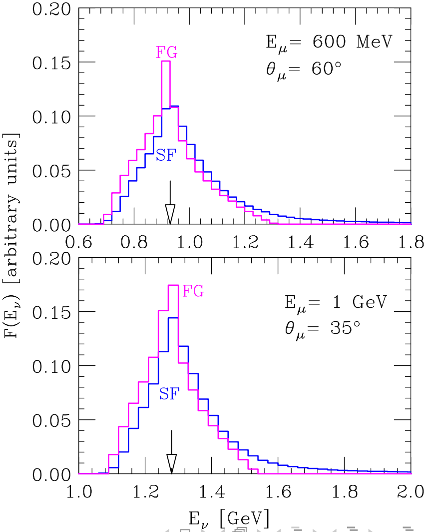
- ⋆ In the charged current quasi elastic (CCQE) channel, assuming single nucleon single knock out, the *reconstructed* of neutrino energy is

$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)} ,$$

where $|\mathbf{k}_\mu|$ and θ_μ are measured, while $\mathbf{p}_n$ and E_n are the *unknown* momentum and energy of the interacting neutron

Distribution of reconstructed neutrino energy in the QE channel

- ⋆ Neutrino energy reconstructed using 2×10^4 pairs of $(|\mathbf{p}|, E)$ values sampled from realistic (SF) and FG oxygen spectral functions
- ⋆ The average value $\langle E_\nu \rangle$ obtained from the realistic spectral function turns out to be shifted towards larger energy by ~ 70 MeV



Impact on the determination of oscillation parameters

- ⋆ Analysis carried out by the Virginia Tech group [PRL 111, 221802 (2013); PRD 89, 073015 (2014)]
  - ▷ Study the impact of nuclear models on the determination of the atmospheric parameters Δm^2_{31} and θ_{23}
  - ▷ Consider a typical ν_μ disappearance experiment consisting of two detectors, identical in terms of both composition and detection properties

	Baseline	Fid. mass	Flux peak	Beam Power	Run. time
Far	295 km	22.5 kt	0.6 GeV	750 kW	5 yrs
Near	1.0 km	1.0 kt			

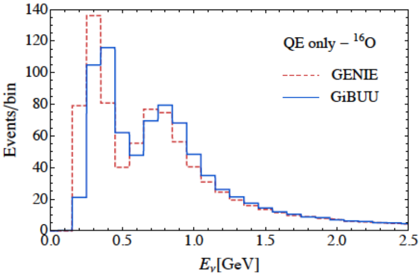
  - ▷ Take into account all events identified as QE, including single nucleon knock out (true QE), "stuck pion" and and 2p2h (QE-like) events

- ⋆ Simulations performed using GENIE (Generates Events for Neutrino Interaction Experiments) and GiBUU (Giessen Boltzmann Uehling Uhlenbeck)

Energy distribution of QE events

	QE	RES	non-RES	MEC/2p2h	Total
GiBUU	870	152	32	214	1268
GENIE	877	221	11	249	1358

- ⋆ Expected number of events at the far detector



- ⋆ The observed $\sim 10\%$ shift is likely to be ascribed to a different description of final state interactions of the knocked out nucleon

Oscillation parameters

- Three different analyses
  - Use different models to generate the events and extract the oscillation parameters
  - Remove the effects of 2p2h events
  - Change nuclear target
- In all instances, the bias on the determination of the oscillation paraeters is found to be comparable to the statistical errors
  - Input "true" values

$$\begin{array}{llll} \theta_{12} = & 33.2^\circ & \Delta m^2_{21} = 7.64 \times 10^{-5}\,\mathrm{eV}^2 \\ \theta_{13} = & 9^\circ & \Delta m^2_{31} = 2.45 \times 10^{-3}\,\mathrm{eV}^2 \\ \theta_{23} = & 45^\circ & \delta = 0^\circ \end{array}$$

  - Fitted values

True	Fitted	$\theta_{23,min}$	$\Delta m^2_{31,min}[\mathrm{eV}^2]$
GENIE (^{16}O)	GENIE (^{12}C)	44°	2.49×10^{-3}
GiBUU (^{16}O)	GENIE (^{16}O)	41.75°	2.69×10^{-3}
		47°	2.55×10^{-3}
GiBUU (^{16}O)	GiBUU (^{16}O) w/o MEC	42.5°	2.44×10^{-3}
GENIE (^{16}O)	GENIE (^{16}O) w/o MEC	44.5°	2.36×10^{-3}

Kinematic and calorimetric reconstruction

- ⋆ The reconstructed neutrino energy of a generic event can be written in the form

$$E_\nu = E_\ell + E + T_{A-n} + \sum_i (E_{\mathbf{p}'_i} - M) + \sum_j E_{\mathbf{h}'_j}$$

- ⋆ Experiments with neutrino beams peaked at $E_\nu \sim 600\text{–}800$ MeV, such as T2K and MiniBooNE, determine E_ν from the kinematics of the outgoing charged lepton

$$E_\nu^{\rm kin} = \frac{2(nM - \epsilon_n)E_\ell + W^2 - (nM - \epsilon_n)^2 - m_\ell^2}{2(M - \epsilon - E_\ell + |\mathbf{k}_\ell| \cos\theta)}$$

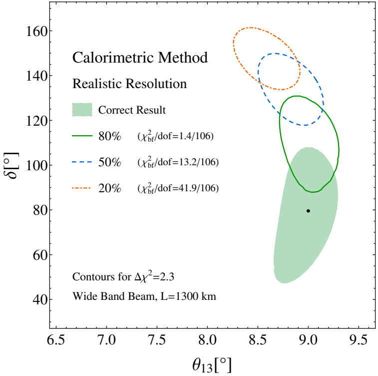
- ⋆ At energies $E_\nu \gtrsim 1$ GeV inelastic processes become larger and eventually dominant. In this regime E_ν can be reconstructed measuring the visible energy associated with each event

$$E_\nu^{\rm cal} = E_\ell + \epsilon_n + \sum_i (E_{\mathbf{p}'_i} - M) + \sum_j E_{\mathbf{h}'_j}$$

IMPACT OF MISSING ENERGY

- ⋆ The calorimetric technique rests on the ability of fully reconstructing the final state, which largely depends on the detector design and performance, as well on the understanding of nuclear effects that may lead to a sizeable amount of missing energy, hindering the reconstruction of the neutrino energy (production of neutrons, pion absorption . . .) [RM-VT, PRD 92, 073014 (2015)]

- ⋆ A 20% underestimated missing energy introduces a sizable bias in the extracted δ_{CP} value. [RM-VT, arXiv:1507.08561; PRD, in press]

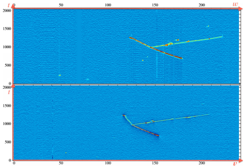


SUMMARY . . .

- ⋆ Over ghe past decade, the understanding of the mechanisms contributing to the flux-integrated neutrino-nucleus cross-sections at energies between few hundreds MeV and few GeV has significantly improved.
- ⋆ Both new data (MiniBooNE, Minerν, . . .) and new theoretical models have appeared
- ⋆ The large body of electron-nucleus scattering data is being exploited to validate theretical models.
- ⋆ In many instances the prediction of different models, some of them based on conflicting assumptions, are very close to one anohter
- ⋆ Implementation of 21st century models in MC event generators is slowly starting, but is still in its infancy
- ⋆ INFN-related groups (Lecce, Pavia, Roma, Torino) have provided substantial contributions to the development of the field. They are involved in a number of international collaborations and their work is widely recognized within the community.

. . . & Outlook

- ⋆ The degeneracy between different models must be resolved, testing their ability to explain selected sets of data. For example, the longitudinal and transverse electromagnetic responses, or two-nucleon emission processes [see, e.g. ArgoNeuT, PRD 90, 012008 (2014)].

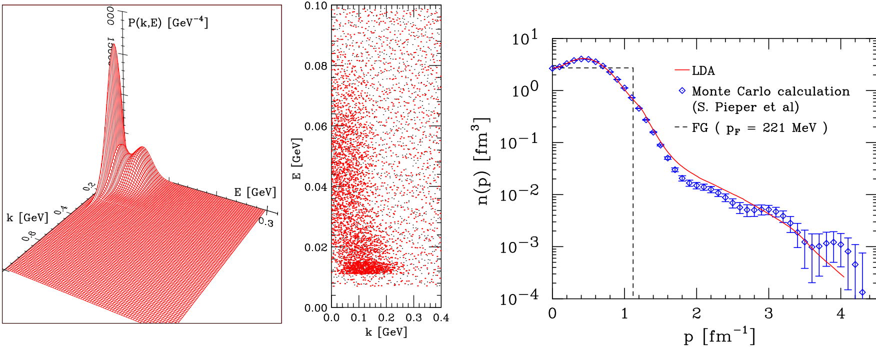


- ⋆ New electron data will be needed to build accurate models of neutrino- and antineutrino-argon interactions. A dedicated $(e, e'p)$ experiment on argon has been approved at JLab and will take data next September. A second experiment using a titanium target will be proposed in 2016.
- ⋆ The effort aimed at consistently implementig the models in event generators must go on in a more organized and effective fashion. Serious sociological problems need to be be solved.

Backup slides

SPECTRAL FUNCTION OF ^{16}O

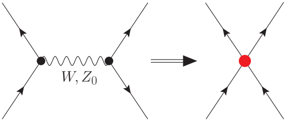
- ⋆ The spectral function of medium-mass nuclei has obtained combining $(e, e'p)$ data and results of theoretical nuclear matter calculations within the Local Density Approximation (LDA)



- ⋆ 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 ($\mathbf{k} \gg k_F, E \gg \epsilon$)

Neutrino-nucleon interactions

- ⋆ In the regime of momentum transfer (q) discussed in this talk Fermi theory of weak interaction works just fine



- ⋆ x-section of the charged-current process $\nu_\ell + n \to \ell^- + X$

$$d\sigma \propto L_{\lambda\mu} W^{\lambda\mu}$$

  - ▷ $L_{\lambda\mu}$ is determined by the lepton kinematical variables (more on this later)

$$W^{\lambda\mu} = -g^{\lambda\mu} W_1 + p^\lambda p^\mu \frac{W_2}{m_N^2} + i\,\varepsilon^{\lambda\mu\alpha\beta} q_\alpha p_\beta + \frac{W_3}{m_N^2} + q^\lambda q^\mu \frac{W_4}{m_N^2} + (p^\lambda q^\mu + p^\mu q^\lambda) \frac{W_5}{m_N^2}$$

- In principle, the structure functions W_i can be extracted from the measured cross sections
- In the elastic sector $\nu_\ell + n \to \ell^- + p$ they can be expressed in terms of vector ($F_1(q^2)$ and $F_2(q^2)$), axial ($F_A(q^2)$) and pseudoscalar ($F_P(q^2)$) *form factors*

$$W_1 = 2 \left[-\frac{q^2}{2} \, (F_1 + F_2)^2 + \left(2\, m_N^2 - \frac{q^2}{2} \right) \, {F_A}^2 \right]$$

$$W_2 = 4 \left[{F_1}^2 - \left(\frac{q^2}{4\, m_N^2} \right) \, {F_2}^2 + {F_A}^2 \right] = 2W_5$$

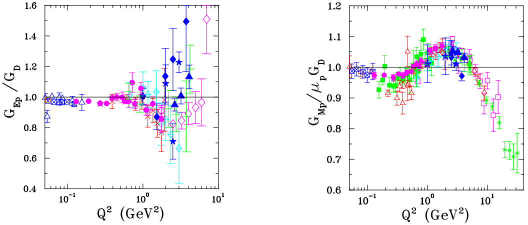
$$W_3 = -4 \, (F_1 + F_2) \, F_A$$

$$W_4 = -2 \left[F_1 \, F_2 + \left(2\, m_N^2 + \frac{q^2}{2} \right) \frac{{F_2}^2}{4\, m_N^2} + \frac{q^2}{2} \, {F_P}^2 - 2\, m_N \, F_P \, F_A \right]$$

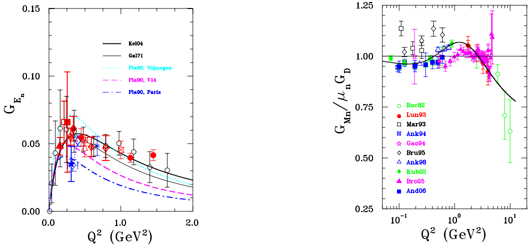
- according to the CVC hypothesis, F_1 and F_2 can be related to the electromagnetic form factors, measured by electron-nucleon scattering, while PCAC allows one to express F_P in terms of the axial form factor (more on this later)

Vector Form Factors

- ⋆ Proton data



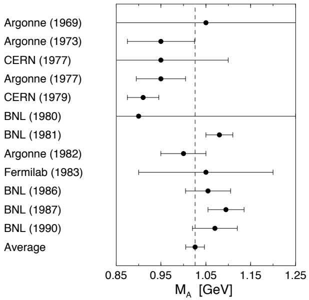
- ⋆ Neutron (deuteron) data



Axial form factor

⋆ Dipole parametrization

$$F_A(Q^2) = \frac{g_A}{\left[1 + (Q^2/M_A^2)\right]^2}$$



- ▷ g_A from neutron β-decay
- ▷ axial mass M_A from (quasi) elastic ν- and $\bar{\nu}$-deuteron experiment

Two-body currents within the spectral function formalism

- ⋆ The generalisation of the factorisation scheme allows for a consistent treatment of ground state correlations and fully relativistic two-body currents
  - ▷ Rewrite the final state $|N\rangle$ in the factorized form

$$|N\rangle \rightarrow |\mathbf{p}, \mathbf{p}'\rangle \otimes |n_{(A-2)}, \mathbf{p}_n\rangle$$

$$\langle N|{j_{ij}}^{\mu}|0\rangle \rightarrow \int d^3k d^3k' M_n(\mathbf{k}, \mathbf{k}') \langle \mathbf{p}\mathbf{p}'|{j_{ij}}^{\mu}|\mathbf{k}\mathbf{k}'\rangle$$

The amplitude

$$M_n(\mathbf{k}, \mathbf{k}') = \{\langle n_{(A-2)}|\langle \mathbf{k}, \mathbf{k}'|\} \otimes |0\rangle$$

is independent of $\mathbf{q}$, and can be obtained from non relativistic many-body theory