Electro- and neutrinoproduction of resonances

(including the second resonance region)

O.Lalakulich, E.A. Paschos

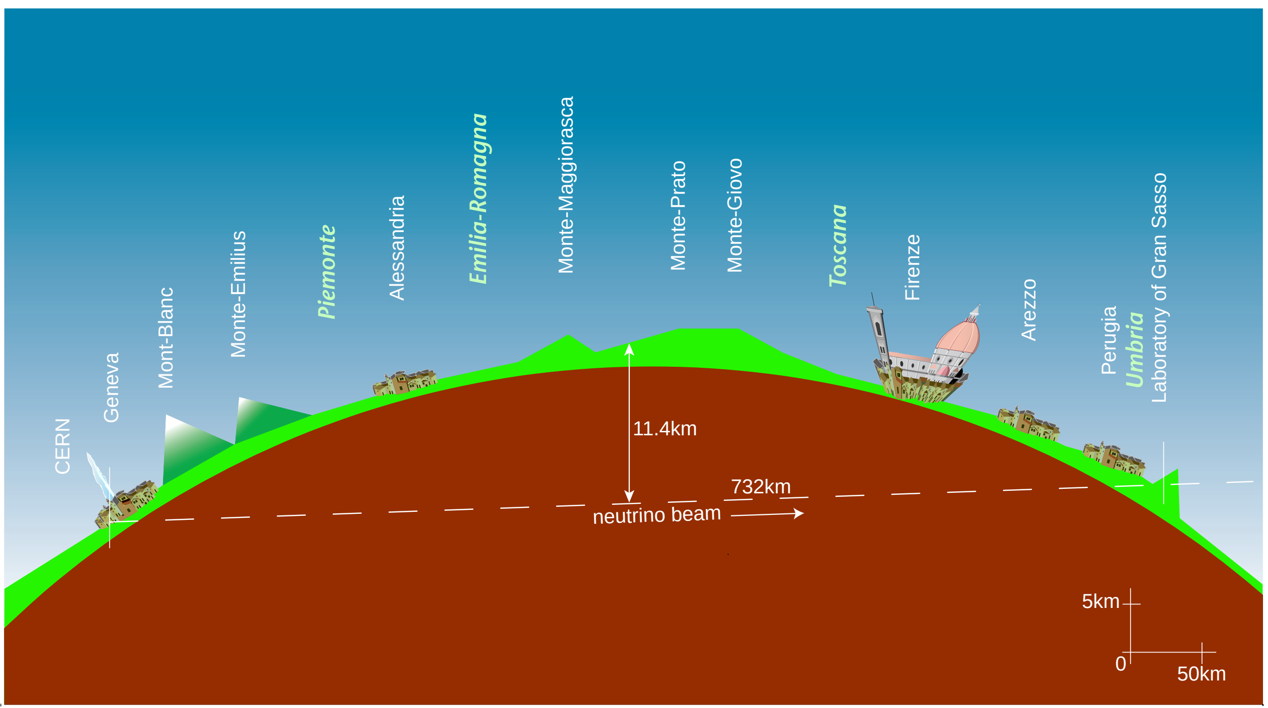
Dortmund University, Germany

Outline

- Why do we need to study weak resonance production and go beyond the Delta-peak
- Electromagnetic and weak vertecies of resonance production: how they are related.
- General way to determine the electromagnetic form factors from JLab and Mainz accelerator electroproduction data: $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$ and $S_{11}(1535)$ resonaces
- Results for the cross section
- Checking quark-hadron duality and Adler sum rules
- Conclusions

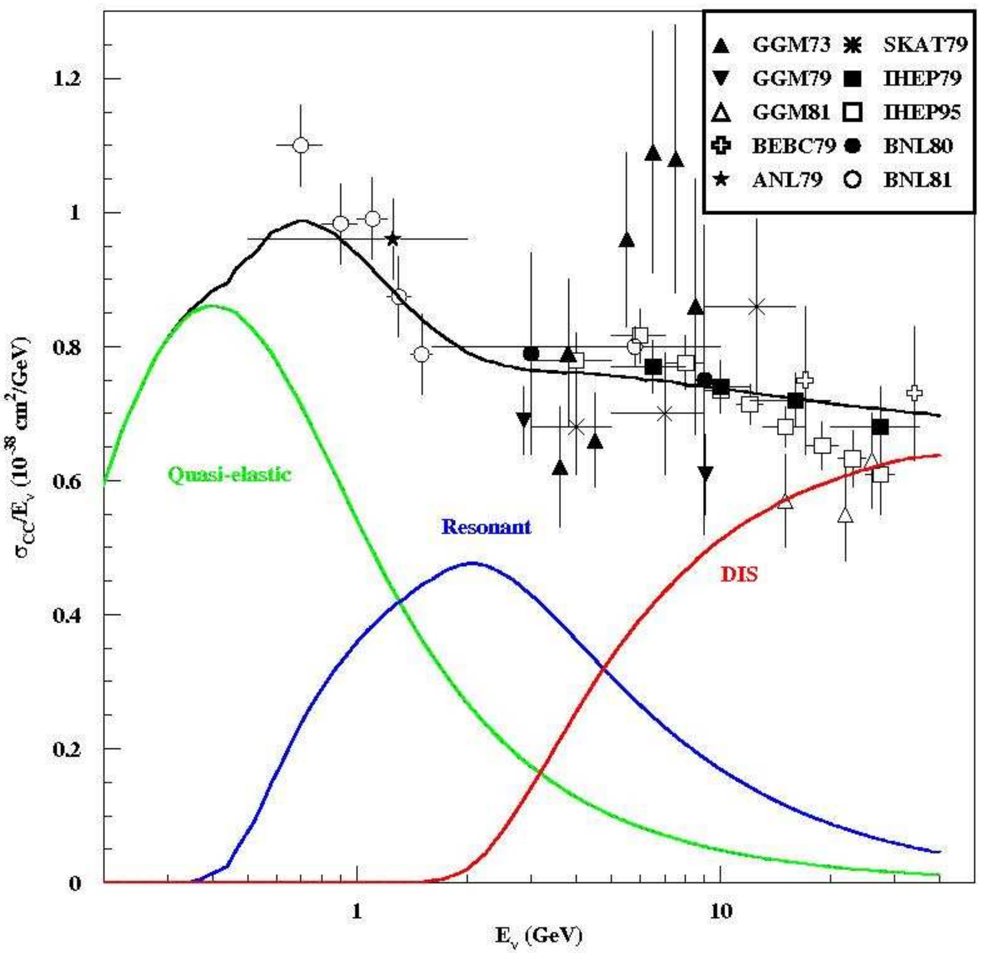
Neutrino oscillations in LBL experiments

- T2K (Tokai to Kamioka) $\langle E_\nu \rangle \sim 0.7$ GeV (planned)
- K2K (KEK to Kamioka) $\langle E_\nu \rangle \sim 1$ GeV (operating)
- MINOS (Fermilab to Soudan) $\langle E_\nu \rangle \sim 3$ GeV (operating)
- CNGS (CERN to GranSasso) $\langle E_\nu \rangle \sim 17$ GeV (under construction)



http://proj-cngs.web.cern.ch/proj-cngs/Download/Download.htm

The total cross section



$\sigma_{tot} = \sigma_{\rm QE} + \sigma_{\rm RES} + \sigma_{\rm DIS}$

1) quasi-elastic (QE)

$\nu_\mu n \to \mu^- p$

2) one-pion-production $\equiv$ resonance production (RES)

$\nu_\mu N \to \mu^- R \to \mu^- N' \pi$

3) deep inelastic (DIS)

$\nu_\mu N \to \mu^- X$

Resonance production

$R_{2I\,2J}$	M_R, GeV	$\Gamma_{R(tot)}$, GeV	$\Gamma_R(R\to\pi N)/\Gamma_{R(tot)}$
$P_{33}(1232)(\Delta^{++},\Delta^{+},\Delta^{0},\Delta^{-})$	1.232	0.120	0.995
$P_{11}(1440)(P_{11}^{+},P_{11}^{0})$	1.440	0.350	0.65
$D_{13}(1520)(D_{13}^{+},D_{13}^{0})$	1.520	0.125	0.56
$S_{11}(1535)(S_{11}^{+},S_{11}^{0})$	1.535	0.150	0.45
$\ldots$			

Accurate measurements and several theoretical approaches are available for the leading $P_{33}(1232)$ resonance for both electro- and neutrino-production

What about resonances with higher masses?

Accurate measurements and several theoretical approaches for electroproduction

Higher mass resonances in neutrinoproduction

1) Old experiments have large errorbars

- ANL ($E_\nu \sim 0.5 - 1.5$ GeV)
- BNL ($E_\nu \sim 1 - 3$ GeV)
- SKAT ($E_\nu \sim 4 - 12$ GeV)
- BEBC ($E_\nu \sim 50$ GeV)

2) Modern experiments intended to study exclusive one-pion production

- K2K ($E_\nu \sim 0.2 - 4$ GeV)
- MiniBOONe ($E_\nu \sim 0.3 - 2.5$ GeV)
- Minerva ($E_\nu \sim 0.3 - 2.5$ GeV; C, Fe, Pb nuclear targets)

3) Theory:

- Rein–Sehgal model (1980), based on the relativistic quark model; update by K.Kuzmin et al (Dubna), K.Hagiwara et al (KEK)
- phenomenological model of Dortmund group (hep-ph/0604132)

Higher mass resonances in neutrinoproduction

4) Fitting the total neutrino cross section $\sigma_{tot} = \sigma_{\rm QE} + \sigma_{\rm RES} + \sigma_{\rm DIS}$: to avoid double counting one should separate RES and DIS invariant-mass regions

- V. Naumov, (Dubna) Max Born Symp, Wroclaw, Dec 2005

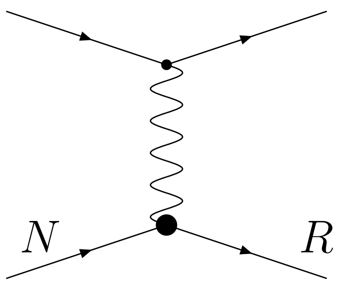
  RES $W < 1.5$ GeV DIS $W > 1.5$ GeV

- Y. Nowak, (Wroclaw) Max Born Symp, Wroclaw, Dec 2005

  Δ resonance and smooth transition to DIS single pion channel

The opportunity to make such separation relies on the phenomenon of quark–hadron duality. It would be nice to study duality in a direct way

Phenomenological description



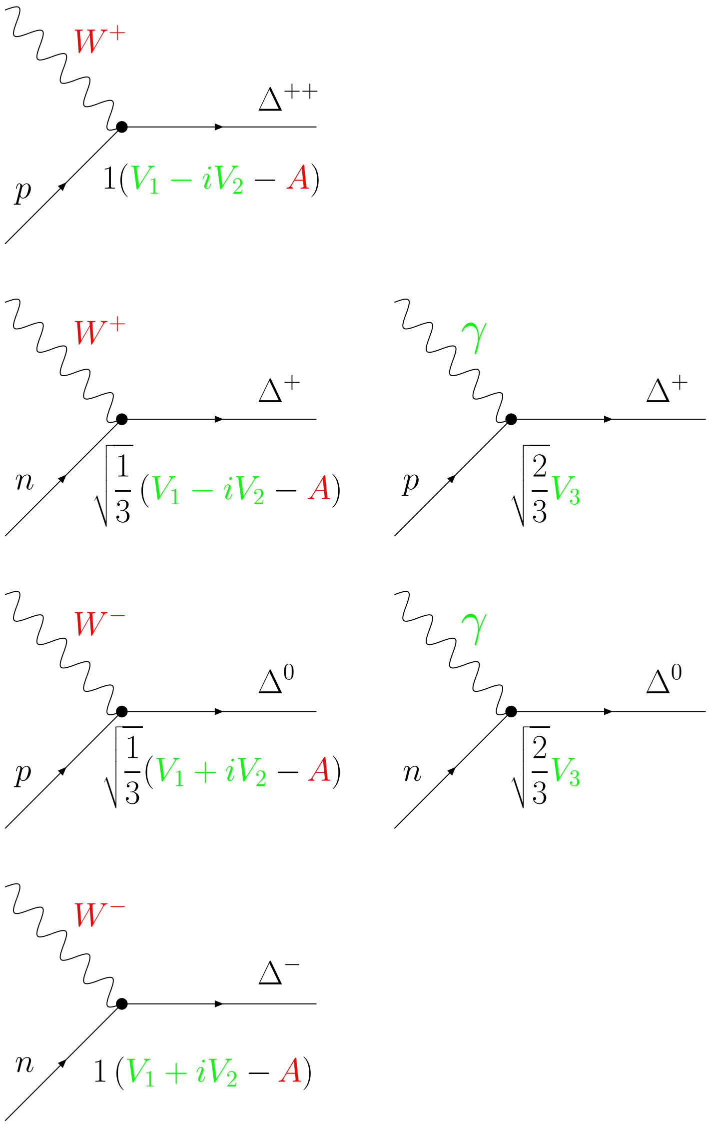
The electromagnetic hadronic vertex is parametrized in terms of the *electromagnetic nucleon-resonance form factors* $C_i^{(p)}$ *and* $C_i^{(n)}$, which depend on the momentum transfered squared $q^2 = -Q^2$ and in general case do not coincide for proton and neutron

The weak hadronic vertex is parametrized in terms of the *weak nucleon-resonance vector* (C_i^V) *and axial* (C_i^A) *form factors*

The form factors characterize the hadronic vertex and are independent of the leptonic one.

R	M_R, GeV	$\Gamma_{R(tot)}$, GeV	elasticity $\Gamma_R(R \to \pi N)/\Gamma_{R(tot)}$
$P_{33}(1232)(\Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-})$	1.232	0.114	0.995
$P_{11}(1440)(P_{11}^{+}, P_{11}^{0})$	1.440	0.350(250 – 450)	0.6(0.6 – 0.7)
$D_{13}(1520)(D_{13}^{+}, D_{13}^{0})$	1.520	0.125(110 – 135)	0.5(0.5 – 0.6)
$S_{11}(1535)(S_{11}^{+}, S_{11}^{0})$	1.535	0.150(100 – 250)	0.4(0.35 – 0.55)

Isospin relations for isospin-3/2 states



1) electromagnetic amplitudes (and as a consequence form factors) are the same for p and n

$$A(\gamma p \to R^+) = A(\gamma n \to R^0)$$

$$C^{(p)} = C^{(n)}$$

2) Isospin triplet $V_a = (V_1, V_2, V_3)$

Weak and el-m amplitudes

$$A(W^+ n \to R^+)^V =$$

$$= \sqrt{\tfrac{1}{3}}\sqrt{2}\,\frac{V_1 - iV_2}{\sqrt{2}} = A(\gamma p \to R^+)$$

Form factors

$$C^{(p)} = C^V$$

Form factors for $P_{33}(1232)$ ($J^P = \frac{3}{2}^+$)

Earlier articles in this notation: Dufner, Tsai, PR 168, 1801; Lewellyn Smith, PR 3 (1972) 261; Schreiner, von Hippel, NPB58 (1983) 333; Paschos, Sakuda, Yu, PRD 69 (2004) 014013; Singh, Athar, Ahmad, hep-ph/0507016;

The resonance field is described by a Rarita-Schwinger spinor $\psi_\lambda^{(R)}$. Quite generally the weak vertex for the resonance production may be written as

$$\langle\Delta|V^\nu|N\rangle = \bar{\psi}_\lambda^{(R)} \left[\frac{C_3^V}{m_N}(\not{q} g^{\lambda\nu} - q^\lambda\gamma^\nu) + \frac{C_4^V}{m_N^2}(q\cdot p g^{\lambda\nu} - q^\lambda p^\nu) + \frac{C_5^V}{m_N^2}(q\cdot p' g^{\lambda\nu} - q^\lambda p'^\nu) + C_6^V g^{\lambda\nu}\right]\gamma_5 u_{(N)}$$

$$\langle\Delta|A^\nu|N\rangle = \bar{\psi}_\lambda \left[\frac{C_3^A}{m_N}(\not{q} g^{\lambda\nu} - q^\lambda\gamma^\nu) + \frac{C_4^A}{m_N^2}(q\cdot p g^{\lambda\nu} - q^\lambda p^\nu) + C_5^A g^{\lambda\nu} + \frac{C_6^A}{m_N^2} q^\lambda q^\nu\right] u_{(N)}$$

dictated by gauge invariance

How the form factors can be determined

Axial FF: PCAC $\quad i\overline{\Delta^+_\mu} q^\mu \left[C_5^A + \frac{C_6^A}{m_N^2} q^2 \right] u_N, = -i\sqrt{\frac{1}{3}} \frac{m_\pi^2 f_\pi}{q^2 - m_\pi^2} \overline{\Delta^+_\mu} g_\Delta q^\mu u_N.$

$$\Longrightarrow C_5^A(Q^2=0) = \frac{g_\Delta f_\pi}{\sqrt{3}} = 1.2 \qquad C_6^A = m_N^2 \frac{C_5^A}{m_\pi^2 + Q^2}$$

Vector FF: CVC $\quad q^\mu J_\mu = 0 \quad \Longrightarrow \quad C_6^V = 0$,

comparison with electroproduction cross section (1968 - 1971) and magnetic multipole dominance leads to $C_3^V(0) = 2.05 \pm 0.04$, $\quad C_4^V(0) = -\frac{m_N}{W} C_3^V$, $\quad C_5^V = 0$

FF fall down with Q^2 faster than dipole $\frac{C_3^V(0)}{D} \frac{1}{1 + \frac{Q^2}{4M_V^2}}$

with $(1 + \frac{Q^2}{M_V^2})^2 \equiv D_V \qquad$ with $\quad M_V = 0.84\ \mathrm{GeV}$

2001: unambigious evidences from the JLab for the contribution of the electric $E2 \sim -2.5\%$, of scalar multipoles $S2 \sim -5\%$. They are taken into account by extracting the form factors from the helicity amplitudes O.L., Paschos, Piranishvili, 2006

Helicity amplitudes for $P_{33}(1232)$

Helicity amplitudes evaluated from the electroproduction data on proton at $W = M_R$ Tiator et al. (Mainz), EPJA 19 (2004); Burkert, Li (JLab), IJMP 13 (2004); Aznauryan (JLab) (private comm, 2005) The relations to C_i^V are calculated by our group at arbitrary Q^2 and W

$$A_{3/2} = \sqrt{\frac{\pi\alpha_{em}}{m_N(W^2-m_N^2)}} \langle R, +\tfrac{3}{2} | J_{em}\cdot\varepsilon^{(R)} | N, +\tfrac{1}{2}\rangle =$$

$$= -\sqrt{N}\frac{|\vec{q}|}{p'^0+M_R}\left[\frac{C_3^{(p)}}{m_N}(m_N+M_R) + \frac{C_4^{(p)}}{m_N^2}(m_N\nu - Q^2) + \frac{C_5^{(p)}}{m_N^2} m_N\nu\right]$$

$$A_{1/2} = \sqrt{\frac{\pi\alpha_{em}}{m_N(W^2-m_N^2)}} \langle R, +\tfrac{1}{2} | J_{em}\cdot\varepsilon^{(R)} | N, -\tfrac{1}{2}\rangle$$

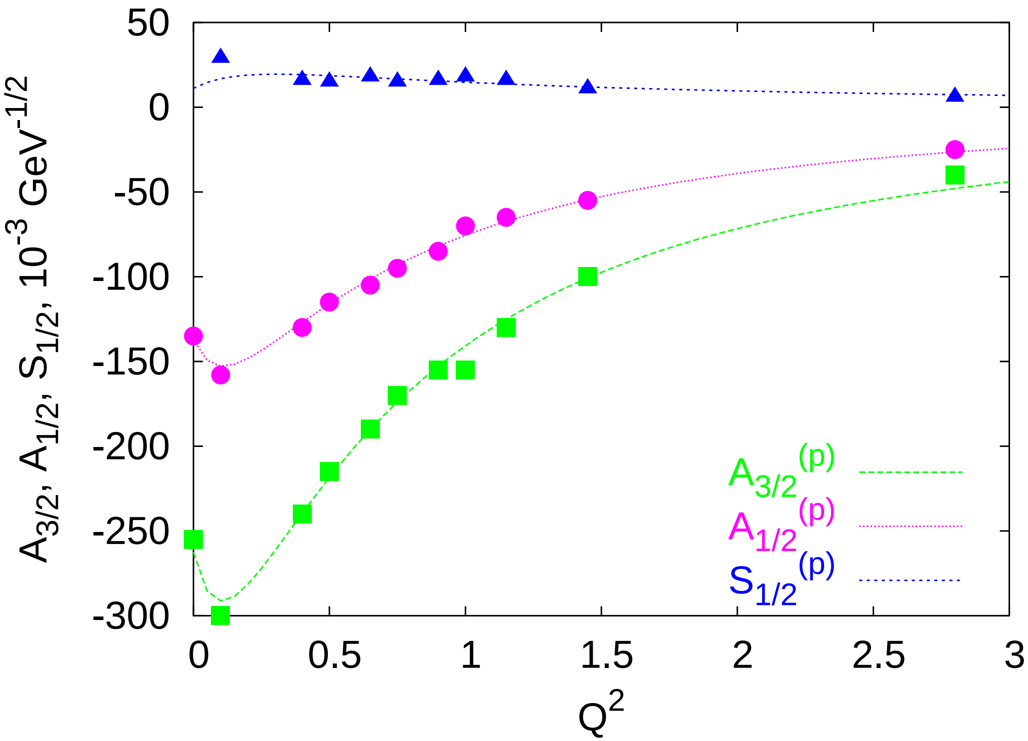
$$= \sqrt{\frac{N}{3}}\frac{|\vec{q}|}{p'^0+M_R}\left[\frac{C_3^{(p)}}{m_N}\left(m_N+M_R-2\frac{m_N}{M_R}(p'^0+M_R)\right) + \frac{C_4^{(p)}}{m_N^2}(m_N\nu - Q^2) + \frac{C_5^{(p)}}{m_N^2} m_I\right.$$

$$S_{1/2} = \sqrt{\frac{\pi\alpha_{em}}{m_N(W^2-m_N^2)}}\frac{q_z}{\sqrt{Q^2}} \langle R, +\frac{1}{2} | J_{em}\cdot\varepsilon^{(S)} | N, +\frac{1}{2}\rangle =$$

$$= \sqrt{\frac{2N}{3}}\frac{|\vec{q}|^2}{M_R(p'^0+M_R)}\left[\frac{C_3^{(p)}}{m_N}M_R + \frac{C_4^{(p)}}{m_N^2}W^2 + \frac{C_5^{(p)}}{m_N^2}m_N(m_N+\nu)\right]$$

$$N = \frac{\pi\alpha_{em}}{m_N(W^2-m_N^2)} 2m_N(p'^0+M_R)$$

Beyond the magnetic dominance



Helicity amplitudes for $P_{33}(1232)$ excitation on proton target at $W = M_{P1232}$

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

$$C_4^V = \frac{-1.5}{D_V} \cdot \frac{1}{1+Q^2/4M_V^2},$$

$$C_5^V = \frac{-0.58}{D_V} \cdot \frac{1}{1+Q^2/0.76M_V^2}$$

where

$$D_V = (1 + Q^2/0.71\ \mathrm{GeV}^2)^2$$

Coincide with the ”magnetic dominance” values with 4% accuracy

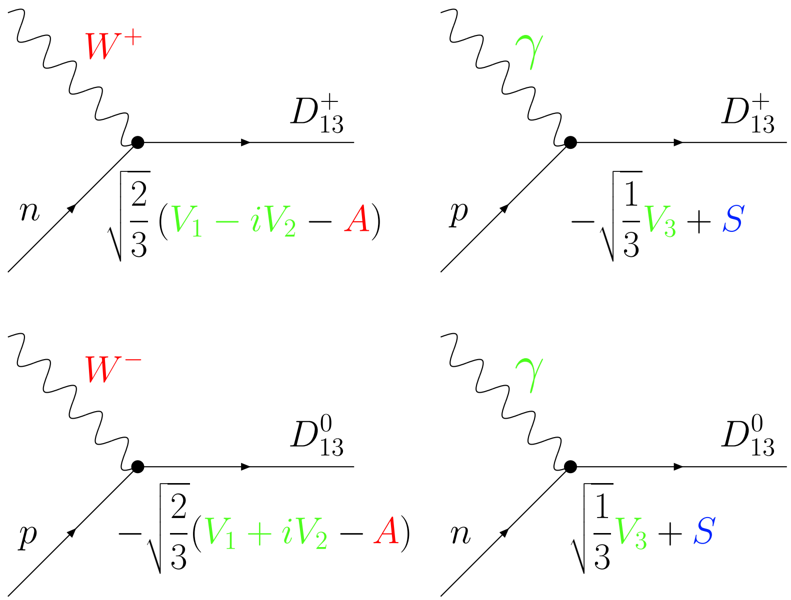
$D_{13}(1520)$: $J^P = 3/2^-, I = 1/2$

The formulas for this resonance are similar to that for P_{33} with the γ_5 changing the place: the are 3 independent vector form factors and 3 independent axial form factors

$$\langle D_{13}|V^\nu|N\rangle = \bar{\psi}_\lambda^{(R)} \left[\frac{C_3^V}{m_N}(\not{q} g^{\lambda\nu} - q^\lambda \gamma^\nu) + \frac{C_4^V}{m_N^2}(q\cdot p g^{\lambda\nu} - q^\lambda p^\nu) + \frac{C_5^V}{m_N^2}(q\cdot p' g^{\lambda\nu} - q^\lambda p'^\nu) \right] u_{(N)}$$

$$\langle D_{13}|A^\nu|N\rangle = \bar{\psi}_\lambda \left[\frac{C_3^A}{m_N}(\not{q} g^{\lambda\nu} - q^\lambda \gamma^\nu) + \frac{C_4^A}{m_N^2}(q\cdot p g^{\lambda\nu} - q^\lambda p^\nu) + C_5^A g^{\lambda\nu} + \frac{C_6^A}{m_N^2} q^\lambda q^\nu \right] \gamma_5 u_{(}$$

Isospin relations for isospin-1/2 states



1) electromagnetic amplitudes (and as a consequence form factors) are different for p and n

2) Isospin triplet $V_a = (V_1, V_2, V_3)$

Weak and el-m amplitudes

$$A(W^+ n \to R^+)^V =$$

$$= \sqrt{\frac{2}{3}}\sqrt{2}\frac{V_1 - iV_2}{\sqrt{2}} = 2\sqrt{\frac{1}{3}}V_3 =$$

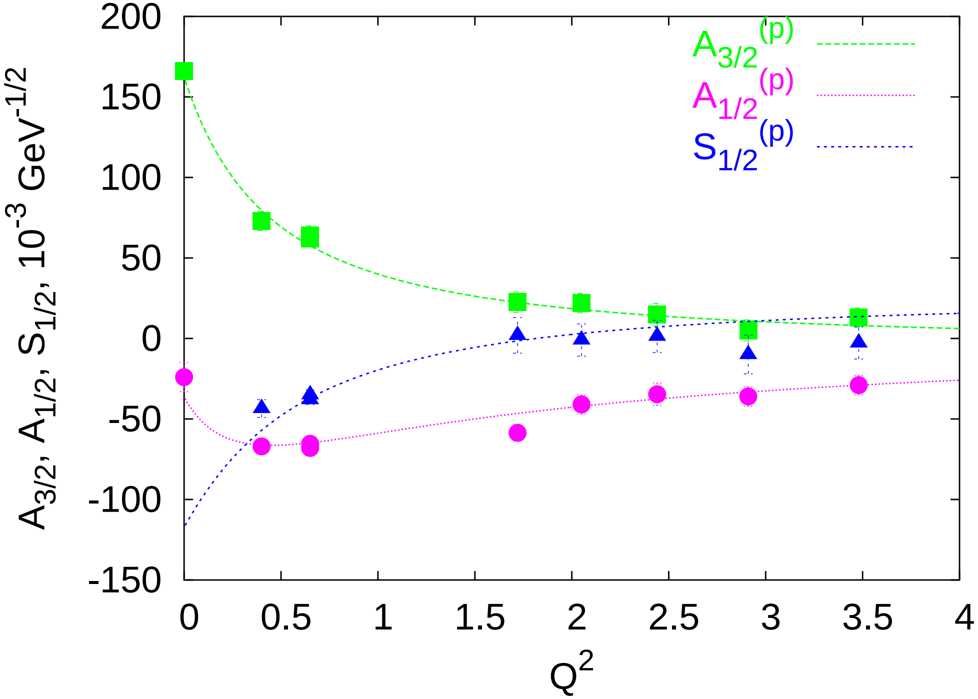
$$= A(\gamma n \to R^0) - A(\gamma p \to R^+)$$

Form factors

$$C^V = C^{(n)} - C^{(p)}$$

$D_{13}(1520)$: Vector form factors

Helicity amplitudes (and as a consequence form factors) for electroproducton are different for the proton and neutron.



Helicity amplitudes for $D_{13}(1520)$ excitation on proton target at $W = M_{D1520}$, latest data from Aznauryan (JLab), 2005, private communication are shown

$$C_3^{(p)} = \frac{2.95}{D_V} \cdot \frac{1}{1+Q^2/8.9M_V^2}$$

$$C_4^{(p)} = \frac{-1.05}{D_V} \cdot \frac{1}{1+Q^2/8.9M_V^2},$$

$$C_5^{(p)} = \frac{-0.48}{D_V}$$

$$C_3^{(n)} = \frac{-1.14}{D_V} \cdot \frac{1}{1+Q^2/8.9M_V^2}$$

$$C_4^{(n)} = \frac{0.46}{D_V} \cdot \frac{1}{1+Q^2/8.9M_V^2},$$

$$C_5^{(n)} = \frac{-0.17}{D_V}$$

where

$$D_V = (1 + Q^2/0.71\ \mathrm{GeV}^2)^2$$

Axial form factors for $D_{13}(1520)$

From PCAC $C_6^A(Q^2) = m_N^2 \frac{C_5^A(Q^2)}{m_\pi^2+Q^2}$, $\quad C_5^A(D_{13}) = -\sqrt{\frac{2}{3}} g_{\pi NR} f_{D13} = -2.1$

The Q^2 dependence for axial form factors cannot be determined from experiment because of the lack of the data.

Instead, we consider two cases: (i) "fast fall-off", in which the Q^2 dependence is choosen the same as for the P_{33} resonance, and (ii) "slow fall-off", in which the Q^2 dependence is flatter and is taken to be the same as for the vector form factors for each resonace.

$$D_{13}(1520): \quad C_5^A = \frac{-2.1/D_A}{1+Q^2/3M_A^2} \text{ ("fast fall-off")}$$

$$C_5^A = \frac{-2.1/D_A}{1+Q^2/8.9M_A^2} \text{ ("slow fall-off") .}$$

with the axial mass common for all the resonances $M_A = 1.05 \text{ GeV}$

We also do not know C_3^A, C_4^A and take $C_3^A(Q^2) = 0$, $C_4^A(Q^2) = 0$.

For more details see O.L., E. Paschos, G. Piranishvili, hep-ph/0602210

$P_{11}(1440)$, $J^P = \frac{1}{2}^+$ and $S_{11}(1535)$, $J^P = \frac{1}{2}^-$

For the spin-1/2 resonances all formulas are simpler

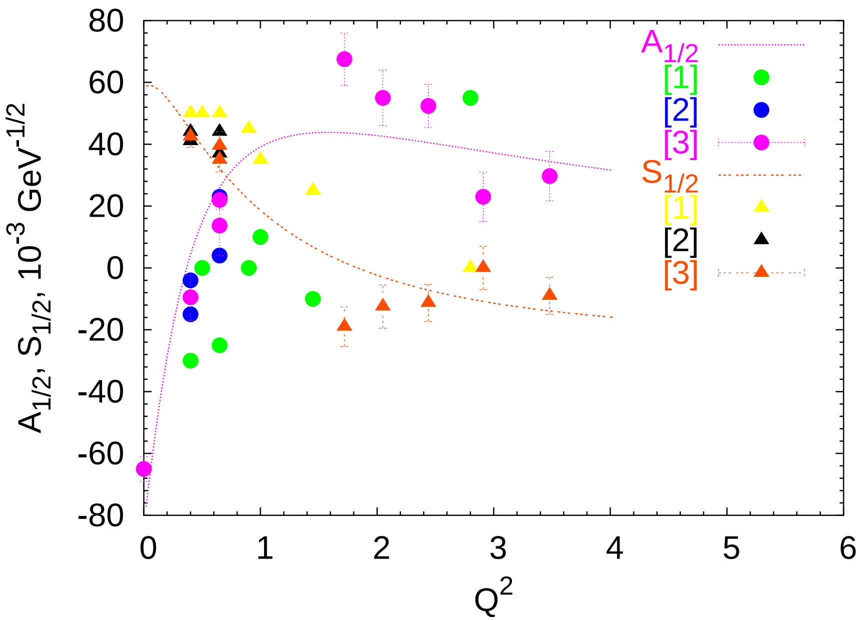
$$\langle P_{11}|J^\nu|N\rangle = \bar{u}(p')\left[\frac{g_1^V}{(m_N+M_R)^2}(Q^2\gamma^\nu + \not{q}q^\nu) + \frac{g_2^V}{m_N+M_R} i\sigma^{\nu\rho}q_\rho \right.$$
$$\left. - g_1^A\gamma^\nu\gamma_5 - \frac{g_3^A}{m_N}q^\nu\gamma_5\right]u(p),$$

where $\sigma^{\nu\rho} = \frac{i}{2}[\gamma^\nu, \gamma^\rho]$.

$$\langle S_{11}|J^\nu|N\rangle = \bar{u}(p')\left[\frac{g_1^V}{(m_N+M_R)^2}(Q^2\gamma^\nu + \not{q}q^\nu)\gamma_5 + \frac{g_2^V}{m_N+M_R} i\sigma^{\nu\rho}q_\rho\gamma_5 \right.$$
$$\left. - g_1^A\gamma^\nu - \frac{g_3^A}{m_N}q^\nu\right]u(p),$$

Vector form factors for $P_{11}(1440)$

Helicity amplitudes (and as a consequence form factors) for electroproducton are different for the proton and neutron, because they include now not only isovector, but also isoscalar part.



Helicity amplitudes for $P_{11}(1440)$ excitation on proton target at $W = M_{P1440}$

[1] Tiator et al. (Mainz), EPJA 19 (2004);

[2] Burkert, Li (JLab), IJMP 13 (2004);

[3] Aznauryan (JLab) (private comm, 2005)

$$g_1^{(p)} = \frac{2.3/D_V}{1 + Q^2/4.3M_V^2},$$

$$g_2^{(p)} = \frac{-0.76}{D_V}\left[1 - 2.8\ln\left(1 + \frac{Q^2}{1\ \mathrm{GeV}^2}\right)\right]$$

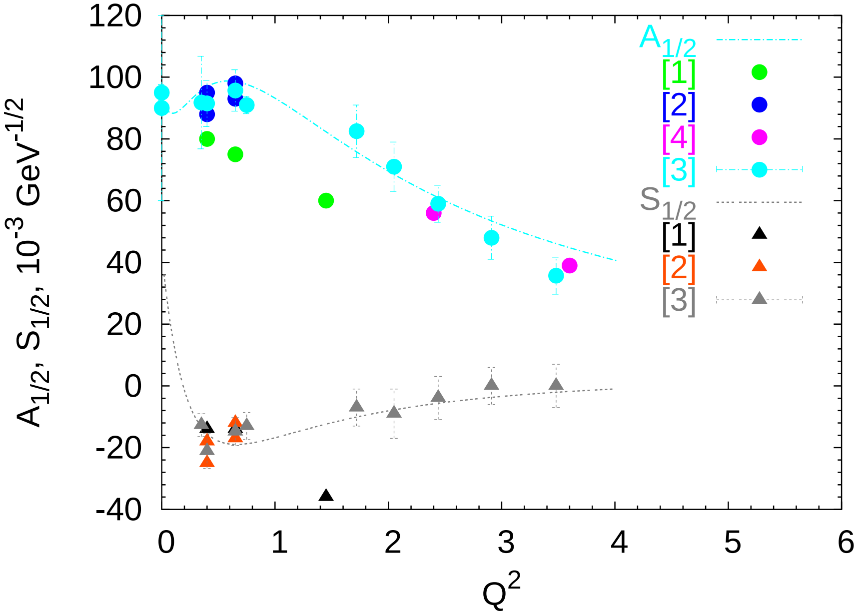
$$g_i^V = g_i^{(n)} - g_i^{(p)}$$

neutron: neglecting isoscalar contribution (which makes sense within the accuracy of the data available)

$$g_i^{(n)} = -g_i^{(p)}$$

Vector form factors for $S_{11}(1535)$

Helicity amplitudes (and as a consequence form factors) for electroproducton are different for the proton and neutron.



$$g_1^{(p)} = \frac{2.0/D_V}{1 + \frac{Q^2}{1.2 M_V^2}} \left[1 + 7.2 \ln\left(1 + \frac{Q^2}{1\ \mathrm{GeV}^2}\right)\right]$$

$$g_2^{(p)} = \frac{0.84}{D_V} \left[1 + 0.11 \ln\left(1 + \frac{Q^2}{1\ \mathrm{GeV}^2}\right)\right]$$

$$g_i^V = g_i^{(n)} - g_i^{(p)}$$

Helicity amplitudes for $S_{11}(1535)$ excitation on proton target at $W = M_{S1535}$

[1] Tiator et al. (Mainz), EPJA 19 (2004);

[2] Burkert, Li (JLab), IJMP 13 (2004);

[3] Aznauryan (JLab)(private comm, 2005)

[4] Armstrong et al. (JLab), PRD 60 (2000)

neutron: neglecting isoscalar contribution (which makes sense within the accuracy of the data available)

$$g_i^{(n)} = -g_i^{(p)}$$

Axial form factors

Axial form factors are related by PCAC to the strong πNR couplings g_{P11} and g_{S11}, which in turn are determined from the elastic resonance width

$$P_{11}(1440): \quad g_3^A(Q^2) = \frac{m_N(M_R+m_N)}{Q^2+m_\pi^2} g_1^A(Q^2), \quad g_1^A(0) = -\sqrt{\frac{2}{3}} \frac{g_{P11} f_\pi}{M_R+m_N} = -0.51$$

$$S_{11}(1535): \quad g_3^A(Q^2) = \frac{m_N(M_R-m_N)}{Q^2+m_\pi^2} g_1^A(Q^2), \quad g_1^A(0) = -\sqrt{\frac{2}{3}} \frac{g_{S11} f_\pi}{M_R-m_N} = -0.21$$

The Q^2 dependence for g_1^A is not known, so we again consider “fast fall-off” and “slow fall-off” cases:

$$P_{11}(1440): \qquad g_1^A(Q^2) = \frac{-0.51/D_A}{1+Q^2/3M_A^2} \text{ (“fast fall-off”)}$$

$$g_1^A(Q^2) = \frac{-0.51/D_A}{1+Q^2/4.3M_V^2} \text{ (“slow fall-off”)},$$

$$S_{11}(1535): \qquad g_1^A(Q^2) = \frac{-0.21/D_A}{1+Q^2/3M_A^2} \text{ (”fast fall-off”)}$$

$$g_1^A(Q^2) = \frac{-0.21/D_A}{1+Q^2/1.2M_A^2} \left[1 + 7.2 \ln\left(1 + \frac{Q^2}{1\ \text{GeV}^2}\right)\right] \text{ (”slow fall-o}$$

How to calculate the cross section

The calculations have been done Schreiner, von Hippel, NPB 58 (1973) 333, neglecting lepton, that is a valid approximation at $Q^2 >> m_\mu^2$. Recent formulas including muon mass Paschos, O.L., PRD 71 (2005) 074003 we present it in a form close to DIS. The cross section in this form is the same for all the resonances

$$\frac{d\sigma}{dQ^2 dW} = \frac{G^2}{4\pi}\cos^2\theta_C \frac{W}{m_N E^2}\left\{\mathcal{W}_1(Q^2+m_\mu^2) + \frac{\mathcal{W}_2}{m_N^2}\left[2(pk)(pk') - \frac{1}{2}m_N^2(Q^2+m_\mu^2)\right] - \frac{\mathcal{W}_3}{m_N^2}\left[Q^2(pk) - \frac{1}{2}(pq)(Q^2+m_\mu^2)\right] + \frac{\mathcal{W}_4}{m_N^2} m_\mu^2 \frac{(Q^2+m_\mu^2)}{2} - 2\frac{\mathcal{W}_5}{m_N^2} m_\mu^2 (pk)\right\}$$

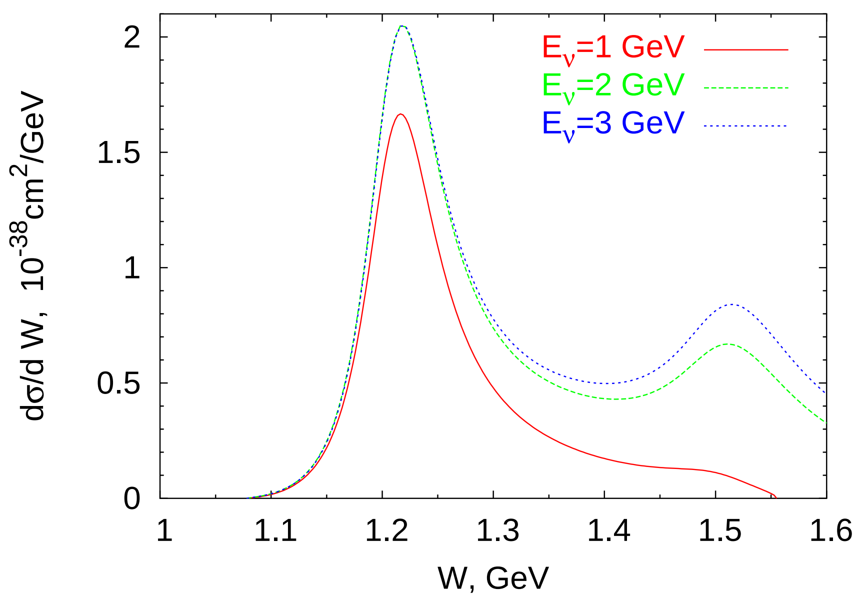
and the hadronic structure functions are defined as usual

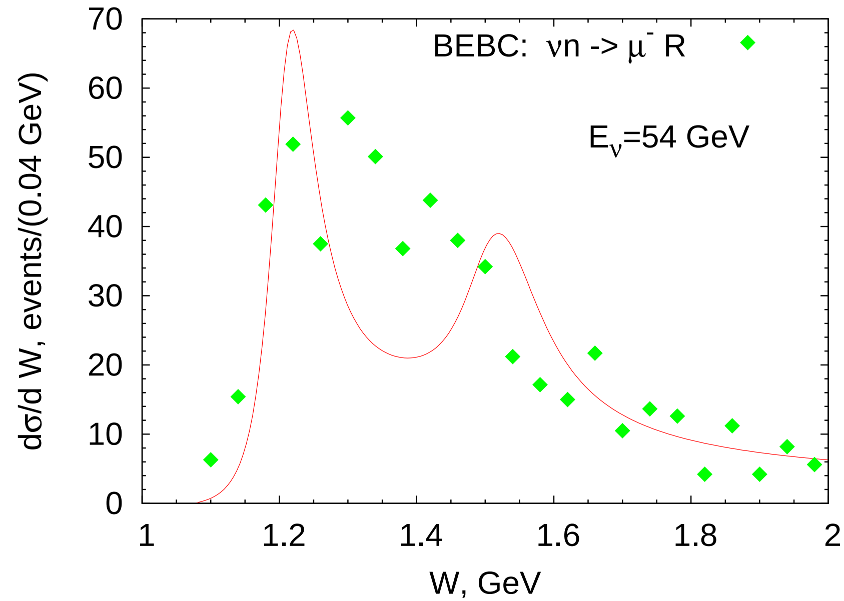
$$\mathcal{W}^{\mu\nu} = -g^{\mu\nu}\,\mathcal{W}_1 + p^\mu p^\nu \frac{\mathcal{W}_2}{m_N^2} - i\varepsilon^{\mu\nu\sigma\lambda} p_\sigma q_\lambda \frac{\mathcal{W}_3}{2m_N^2} + \frac{\mathcal{W}_4}{m_N^2} q^\mu q^\nu + \frac{\mathcal{W}_5}{m_N^2}(p^\mu q^\nu + p^\nu q^\mu)$$

The functional dependence of the structure functions on the form factors vary with resonance.

- $\mathcal{W}_1$, $\mathcal{W}_2$, $\mathcal{W}_3$ give main contribution; $\mathcal{W}_i$ in terms of C_i are given in our paper
- $\mathcal{W}_3$ describe the vector-axial interference
- $\mathcal{W}_4$, $\mathcal{W}_5$ contribute to the Xsec proportional to the lepton mass

Neutrinoproduction at different E_ν

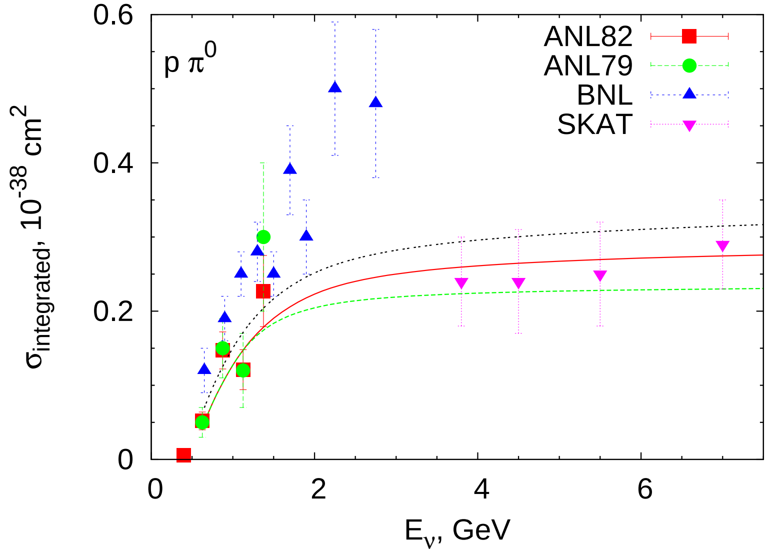


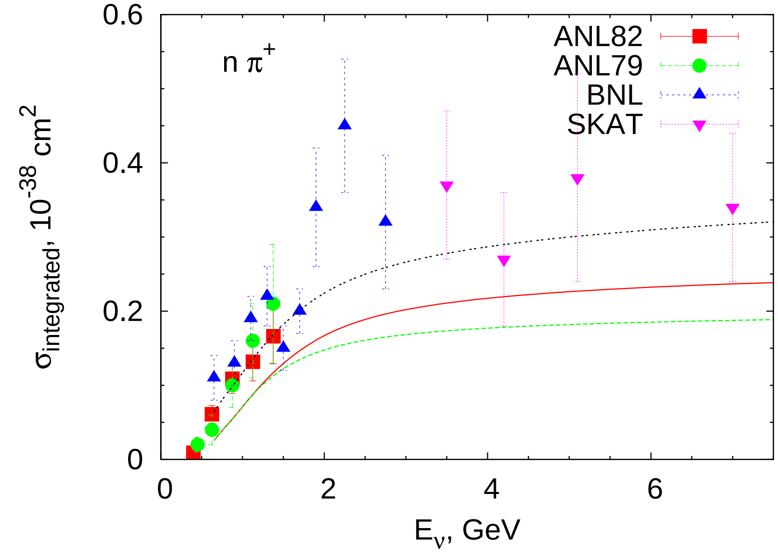


- At $E_\nu < 1\ \mathrm{GeV}$ the second resonance region is negligible in neutrino scattering. It will not be seen in K2K and MiniBOONE.
- At $E_\nu \sim 50\ \mathrm{GeV}$ the two peaks are clearly seen. However, BEBC experiment Allasia et al, NPB 343 (1990) 285 didn't resolve them.

$\nu n \to R^+ \to p\pi^0, \quad \nu n \to R^+ \to n\pi^+$

BNL data points are consistently higher than those of ANL and SKAT, errorbars are large

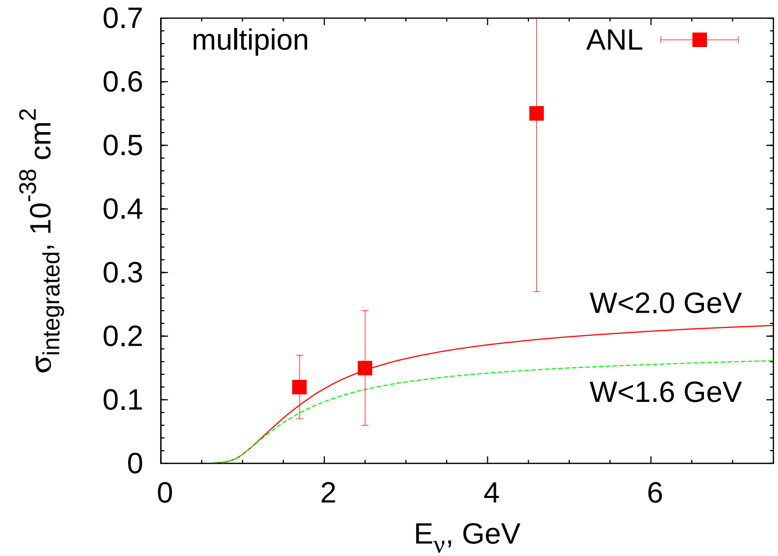




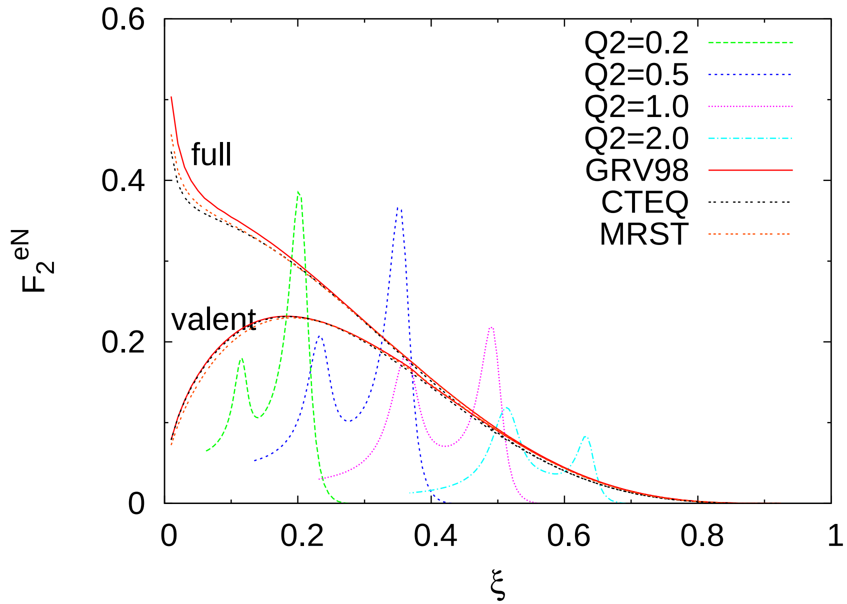
For $\pi^+ n$ channel our curve is a little lower than experimental points: either contributions from higher resonances or a smooth isospin-1/2 incoherent background, for example

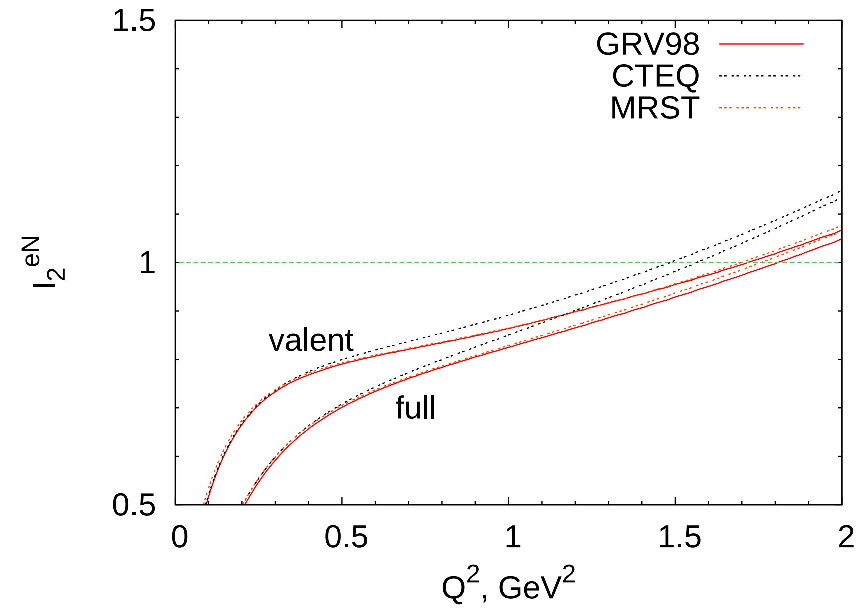
$$\sigma_{bgr}^{\pi^+ n} = 5 \cdot 10^{-40} \left(\frac{E_\nu}{1 \text{ GeV}} - 0.28 \right)^{1/4} \text{cm}^2,$$

$$\sigma_{bgr}^{\pi^0 p} = \frac{1}{2} \sigma_{bgr}^{\pi^+ n}$$



Duality for electron scattering: F_2^{eN}





The use of the Nachtman scaling variable $\xi = \frac{2x}{1+(1+4x^2 m_N^2/Q^2)^{1/2}}$ includes some of the target mass corrections

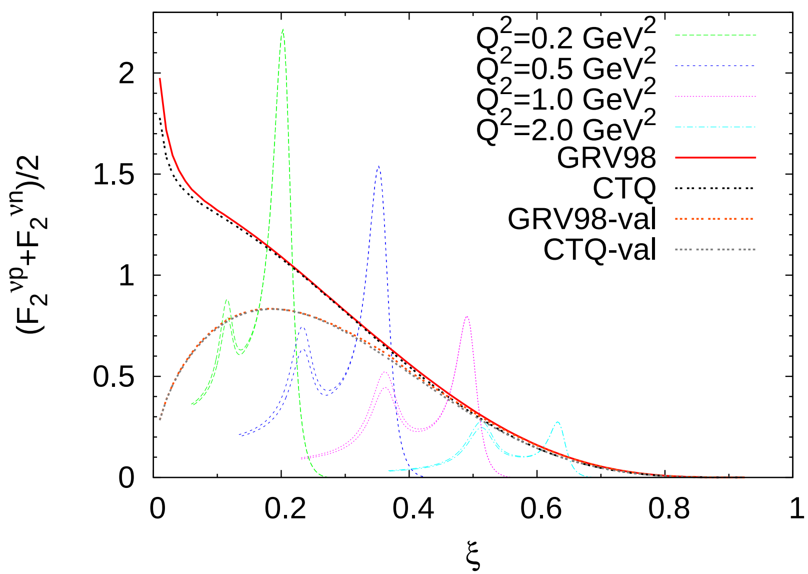
As Q^2 increases, the resonance curves should slide along the DIS curve

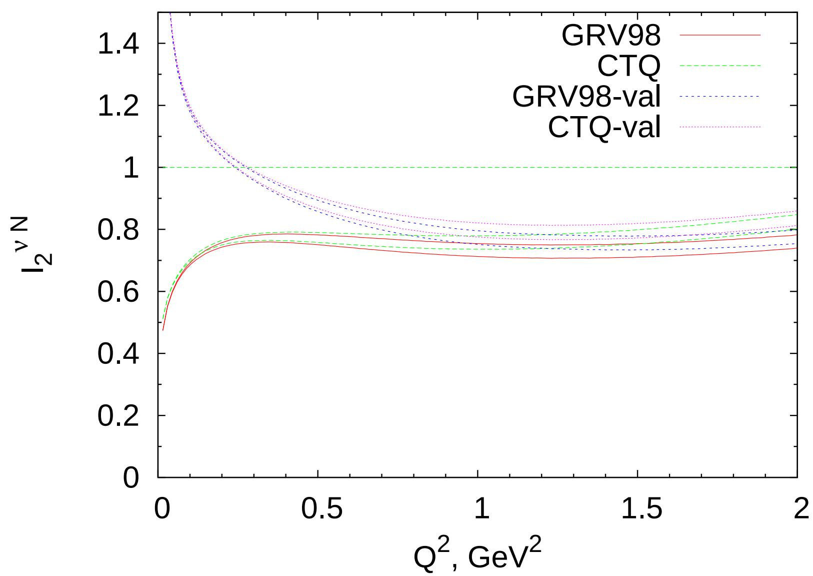
$$I_2^{eN}(Q^2) = \frac{\int_{\xi_i}^{\xi_f} d\xi\ F_2^{eN(\mathrm{res})}(\xi, Q^2)}{\int_{\xi_i}^{\xi_f} d\xi\ F_2^{eN(\mathrm{LT})}(\xi, Q^2)},$$

$$\xi_i = \xi(W = 1.6\,\mathrm{GeV},\ Q^2),$$

$$\xi_f = \xi(W = 1.1\,\mathrm{GeV},\ Q^2)$$

Duality for CC neutrino scattering: $F_2^{\nu N}$





Similar results for $P_{33}(1232)$ are in Matsui, Sato, Lee, PRC 72

and for Rein-Sehgal model in Graczyk, Juszczak, Sobczyk, hep-ph/0601077

$$I_2(\mathrm{res/DIS}) = \frac{\int_{\xi_i}^{\xi_f} F_2^{\mathrm{res}}(\xi, Q^2) d\xi}{\int_{\xi_i}^{\xi_f} F_2^{\mathrm{DIS}}(\xi, Q^2) d\xi},$$

$\xi_i = \xi_i(W = 1.6\,\mathrm{GeV},\, Q^2)$,

$\xi_f = \xi_f(W = 1.1\,\mathrm{GeV},\, Q^2)$.

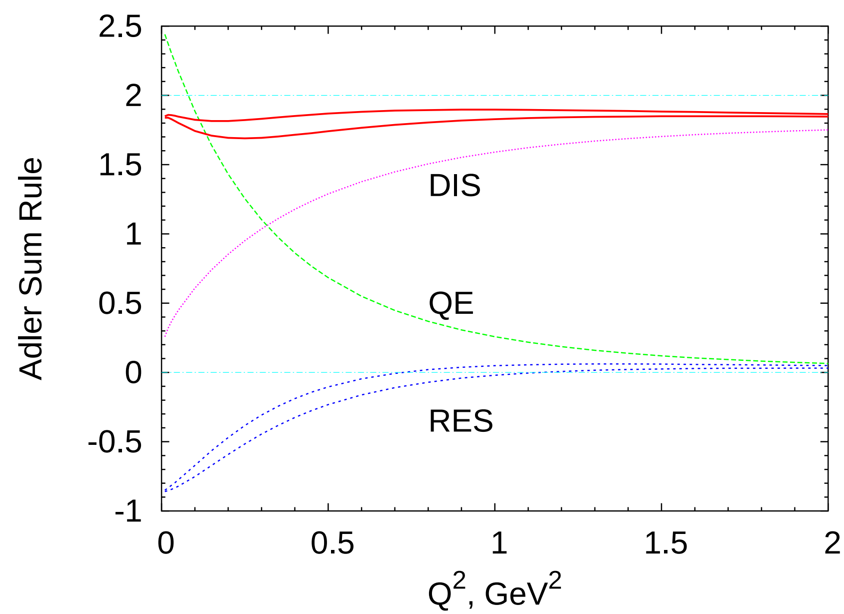
The discrepancy will be eleminated by including other resonances, or background, or modifying the FF at large Q^2.

Resonance contribution to the Adler sum rule

$$\left[g_{1V}^{(QE)}\right]^2 + \left[g_{1A}^{(QE)}\right]^2 + \left[g_{2V}^{(QE)}\right]^2 \frac{Q^2}{2M^2} + \int d\nu \left[W_2^{\nu n}(Q^2,\nu) - W_2^{\nu p}(Q^2,\nu)\right] = 2$$

Using for QE

$$g_{1V}^{(QE)} = \frac{1}{D_V},$$
$$g_{2V}^{(QE)} = \frac{3.7}{D_V},$$
$$g_{1A}^{(QE)} = \frac{1.23}{D_A}.$$



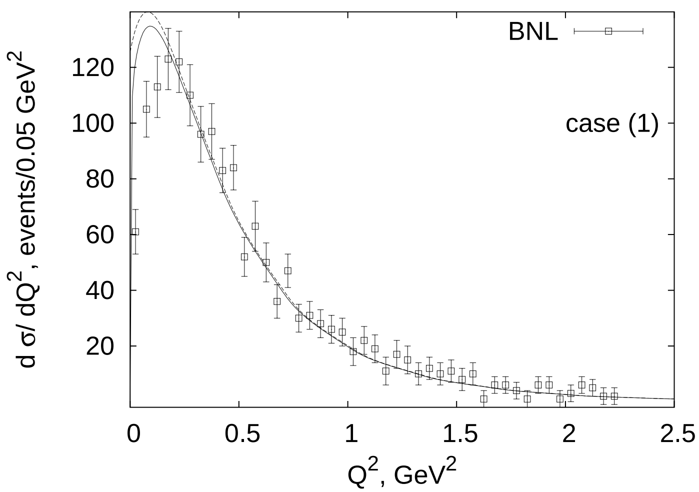
Adler sum Rule is satisfied with a 10% accuracy

Summary

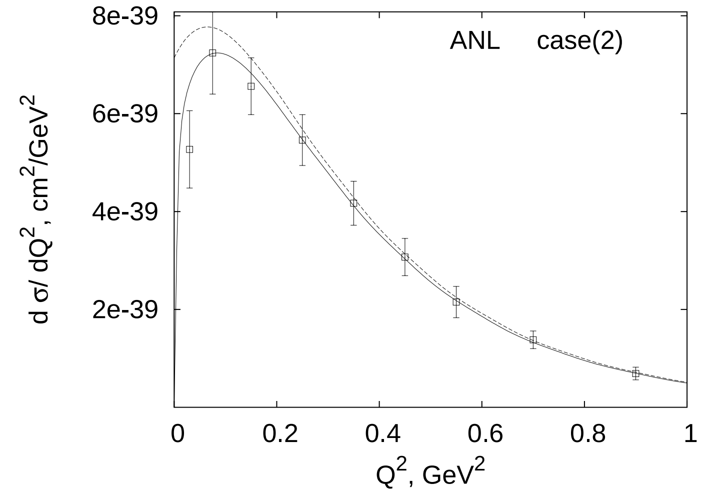
- We present a general formalism for analysing the excitation of resonances by electrons and neutrinos
- We use recent data on helicity amplitudes from JLab and Mainz accelerator to determine the electromagnetic and weak vector form form factors including their Q^2-dependences
- For the isospin-1/2 resonances the form factors fall down not so fast as for the Δ. For $P_{11}(1440)$ and $S_{11}(1535)$ fall off, at small Q^2, is even slower than dipole.
- Δ resonance description shows good agreement with the data, second resonance region must be observable in experiments for $E_\nu > 2\ \mathrm{GeV}$
- Quark–hadron duality for CC neutrino scattering is satisfied in the region $Q^2 = 0.2 - 1.5\ \mathrm{GeV}^2$ for the $(F_2^{\nu p} + F_2^{\nu n})/2$ at the level of $\sim 20\%$. The Adler sum rule is satisfied with a 10% accuracy.

Other topics

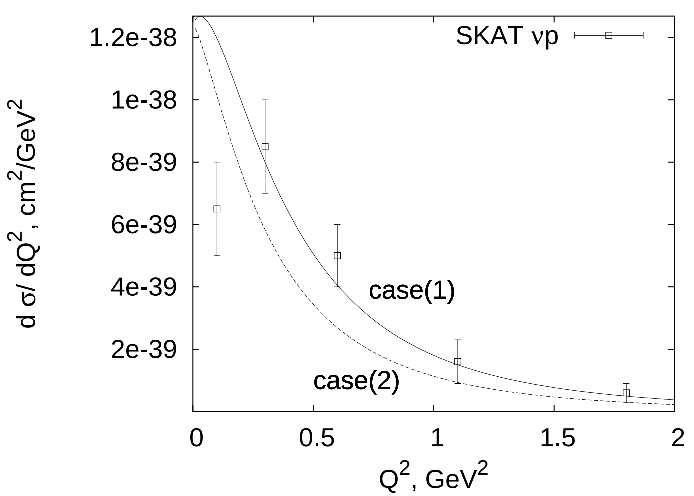
Cross section for $\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- p \pi^+$



$\langle E_\nu \rangle \sim 1$ GeV



$\langle E_\nu \rangle \sim 1$ GeV



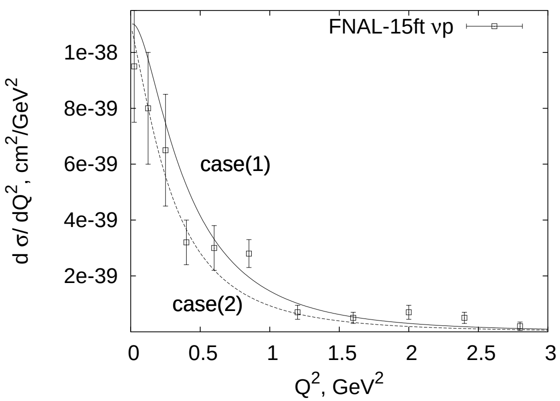
$\langle E_\nu \rangle \sim 7$ GeV

case (1): $C_5^A(Q^2) = \dfrac{C_5^A(0)}{D_A} \cdot \dfrac{1}{1 + \dfrac{Q^2}{\mathbf{3} M_A{}^2}}$

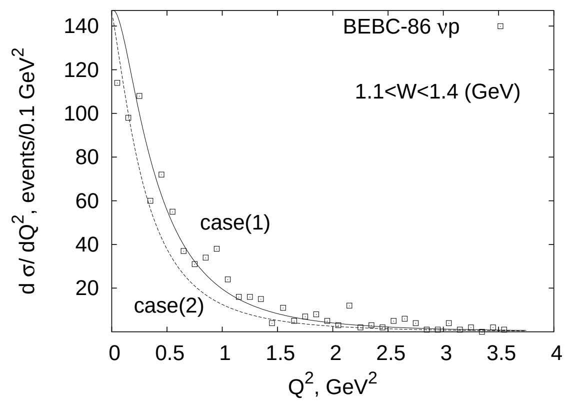
case (2): $C_5^A(Q^2) = \dfrac{C_5^A(0)}{D_A} \cdot \dfrac{1}{1 + \dfrac{\mathbf{2} Q^2}{M_A{}^2}}$

Paschos, O.L. PRD 71 (2005) 074003

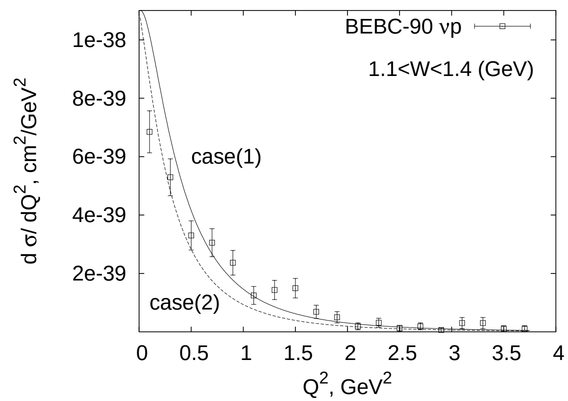
Cross section for $\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- p \pi^+$



$E_\nu \sim 15 - 40$ GeV



$\langle E_\nu \rangle \sim 54$ GeV



$\langle E_\nu \rangle \sim 54$ GeV

The low Q^2 region still to be determined and understood precisely.

Factors, which decrease the cross section are: 1) Pauli blocking Paschos, Sakuda, Yu PRD 69 (2004) 014013 2) muon mass effects Paschos, O.L., PRD 71 (2005) 074003

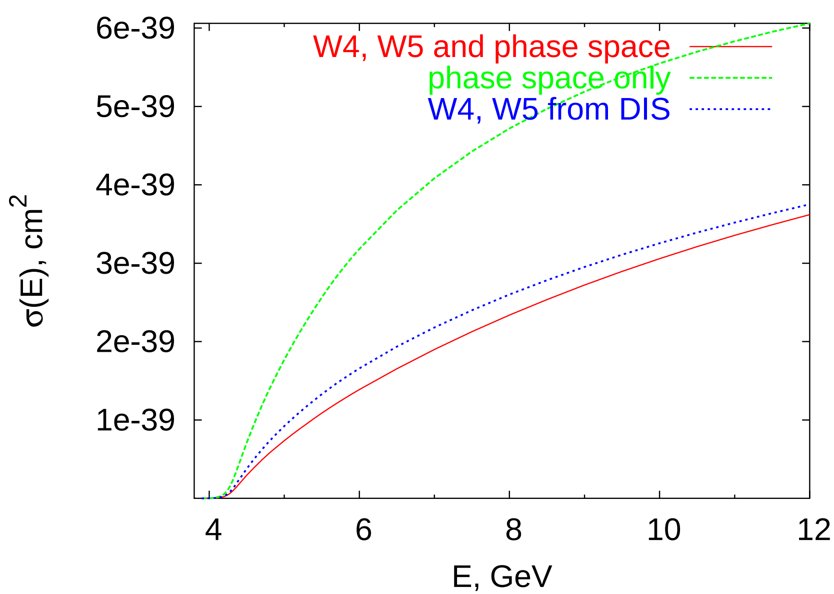
For the $d\sigma/dQ^2$ lepton mass effects are noticable at low Q^2 for small neutrino energies.

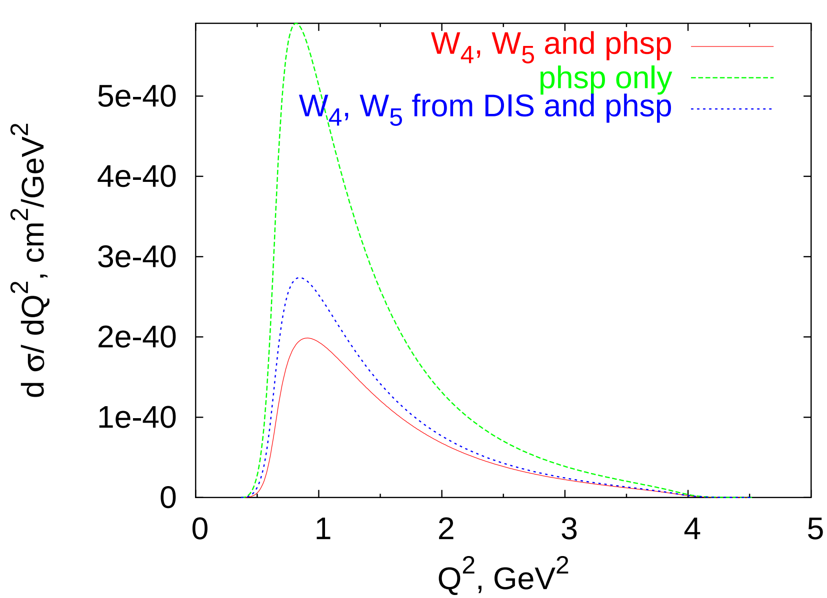
τ-production: $\nu_\tau p \to \tau^- \Delta^{++} \to \tau^- p \pi^+$

Taking into account nonzero mass if the final lepton reduces the cross section in two ways:

1) due to the kinematical restrictions on the phase space available

2) due to the "small" structure functions $\mathcal{W}_4$ and $\mathcal{W}_5$





red line: both effects are taken into account

green line: only the reduction of the phase space is taken into account; ($\mathcal{W}_4 = \mathcal{W}_5 = 0$)

blue line: structure functions in the partonic limit: $\mathcal{W}_4 = 0$, $\mathcal{W}_5 = \mathcal{W}_2/2x$

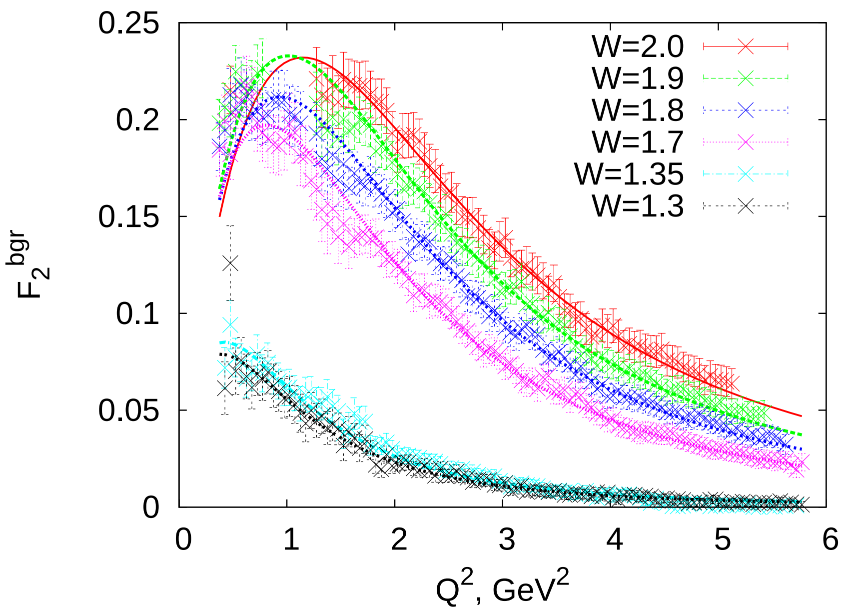
Background (very preliminary !)

Motivation: simplicity, only noninterfering background can be introduced in such a way

Problem: to introduce a single function $background(Q^2, W)$ in such a way that it can be added to any differential ot integrated cross section

Question: for what quantity(ies) should such background be introduced?

My answer: for the structure functions!



$$F_2^{bgr} = F_2^{JLab} - F_2^{RES}$$

F_2^{JLab} is experimental data on the structure function from JLab experiment M. Osipenko et al., PR C73 (2006) 045205; hep-ex/0507098

F_2^{RES} is calculated in our model

Another way to extract F_2^{bgr} — from old virtual photoproduction data F.W. Brasse et al., NP B110 (1976) 413 — gives similar result