NEUTRINO INTERACTIONS WITH NUCLEAR MATTER AT LOW ENERGIES AND WITH NUCLEONS AT HIGH ENERGIES

Gennady Lykasov

in collaboration with Vadim Bednyakov, V.V.Uzhinsky

Joint Institute for Nuclear Research, Dubna

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The main goal is to construct a new generator simulating neutrino interaction within a detector

G.I.Lykasov, V.A.Bednyakov, Phys.Rev. C **014622** *(2007); G.I.Lykasov, E.Olsson, C.J.Pethick, Phys.Rev.C* **72** *025805 (2005); G.I.Lykasov, C.J.Pethick, A.Schwenk, Phys.Rev.C* **78** *045803 (2008).*

The main inputs are the neutrino-nucleus cross sections in a wide energy region.
The rate of neutrino-nucleon scattering in a medium at low energies can be presented in the following form

$$W_{fi} = \frac{G_{\mathrm{F}}^2 n}{4V} \left[C_V^2 (1 + \cos\theta) \mathcal{S}_V(\mathbf{q}, \omega) + C_A^2 (3 - \cos\theta) \mathcal{S}_A(\mathbf{q}, \omega) \right]$$

where θ is the scattering angle, V is the normalized volume, n is the nuclear density.

The FF $\mathcal{S}_{V,A}$ are related to the corresponding response function $\chi_{V,A}$

$$\mathcal{S}_{V,A}(\omega,\mathbf{q}) = \frac{2}{n}\frac{\mathrm{Im}\chi_{V,A}(\omega,\mathbf{q})}{1-\exp(-\omega/T)}.$$

The Dyson type perturbation equations over the spin-independent $\mathcal{F}$ and spin dependent $\mathcal{G}$ interactions of quasiparticles presented in the matrix form.

$$\begin{aligned}\chi_V &= \chi^0 - \chi_V\mathcal{F}\chi^0,\\ \chi_A &= \chi^0 - \chi_A\mathcal{G}\chi^0,\end{aligned}$$

Here χ^0 is the diagonal 2×2 matrix consisting of χ^0_p and χ^0_n which being the zero approximations of the proton and neutron response functions over the interaction. For isospin-symmetric nuclear matter $\mathcal{F}$ and $\mathcal{G}$ become also 2×2 matrices

$$\begin{aligned}\chi^p_V(1+f_{nn}\chi^0_n) \; + \; \chi^n_V f_{pn}\chi^0_p \; &= \; \chi^0_p\\ \chi^p_V f_{pn}\chi^0_n \; + \; \chi^n_V(1+f_{pp}\chi^0_n) \; &= \; \chi^0_n\end{aligned}$$

and

$$\begin{aligned}\chi^p_A(1+g_{nn}\chi^0_n) \; + \; \chi^n_A g_{pn}\chi^0_p \; &= \; \chi^0_p\\ \chi^p_A g_{pn}\chi^0_n \; + \; \chi^n_A(1+g_{pp}\chi^0_n) \; &= \; \chi^0_n \;,\end{aligned}$$

where f_{pp}, f_{nn}, f_{pn} and g_{pp}, g_{nn}, g_{pn} are the spin-independent and spin-dependent amplitudes of pp, nn and pn interactions, respectively.

Note, that the amplitude of interaction between two quasi-particles q and q' with three-momenta $\mathbf{p}$

and $\mathbf{p}'$ neglecting the tensor forces has the following form

$$f_{qq'}(\mathbf{p},\mathbf{p}') = f + f'(\tau\cdot\tau') + g(\sigma\cdot\sigma') + g'(\sigma\cdot\sigma')(\tau\cdot\tau')$$

where q and q' can denote p, n, and f, f', g, g' are the Landau parameters, σ and τ are the spin and isospin Pauli matrices, respectively.

$$\begin{aligned} f_{pp} &= f_{nn} = f + f', \\ g_{pp} &= g_{nn} = g + g', \\ f_{pn} &= f_{np} = f - f', \\ g_{pn} &= g_{np} = g - g'. \end{aligned}$$

L.D.Landau, Sov.Phys.JETP, **5**, *101(1957)*
A.B.Migdal, "Theory of Finite Fermi Systems and Application to Atomic Nuclei", Interscience, New York, 1962
G.Baym, C.J.Pethick, "Landau Fermi-Liquid Theory:Concepts and Applications", New York, 1991
*N.Iwamoto, C.J.Pethick, Phys.Rev. D***25**, *313 (1982)*
*G.L., E.Olsson, C.J.Pethick, Phys.Rev. C***72**, *02805 (2005)*
*S.Reddy, M.Prakash & J.M.Lattimer, Phys.Rev. C***59**, *2888 (1999)*

Application of the FLT to the analysis of $\nu - A$ interactions

$$1/l = V \int \frac{d^3q}{(2\pi)^3} W_{fi}.$$

With this quantity one can estimate the cross section of the elastic neutrino interaction with a heavy nucleus σ_{el}

$$\sigma_{el} = \frac{V_A}{l} \; = \; V_A \int \frac{d^3q}{(2\pi)^3} \tilde{W}_{fi}$$

where $\tilde{W}_{fi} = V_A \cdot W_{fi}$ and $V_A = A \cdot v_N$. Here A is the number of nucleons in a nucleus and $v_N = 4\pi/3r_N^3$ is the nucleon volume, r_N is the nucleon radius about 0.8 fm. To estimate the number of neutrino interactions $\mathcal{R}$ per 1 second within a target T we use the simple formula

$$\mathcal{R} \; = \; P_{targ} N_A \sigma_{\nu A} f_\nu$$

Here f_ν denotes the initial neutrino flux.

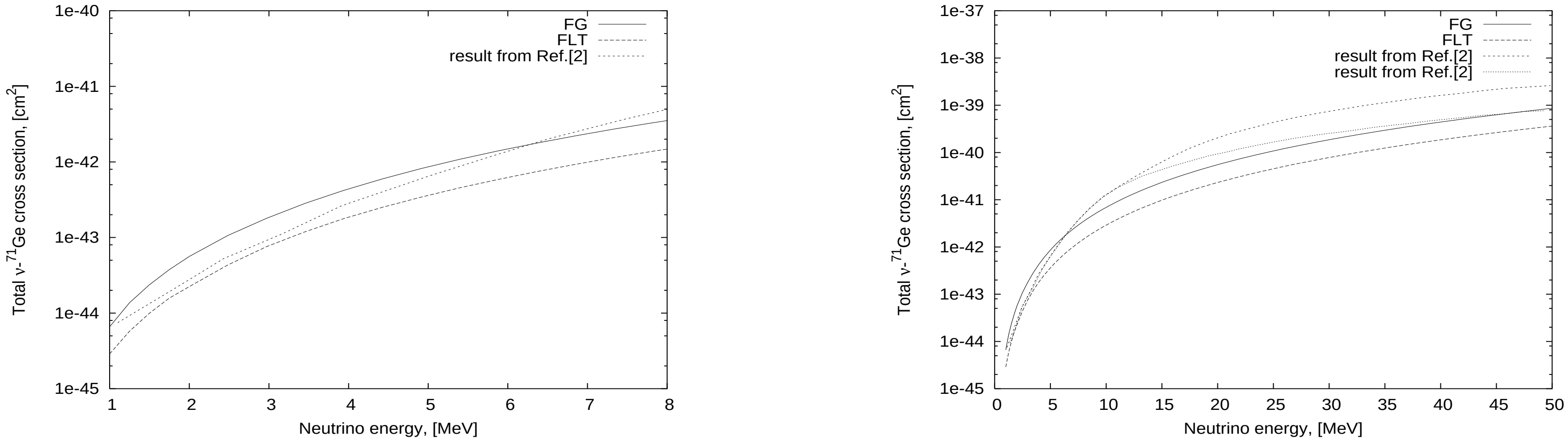

Figure 1: The total ν-^{71}Ge cross section as a function of the neutrino energy E_ν.

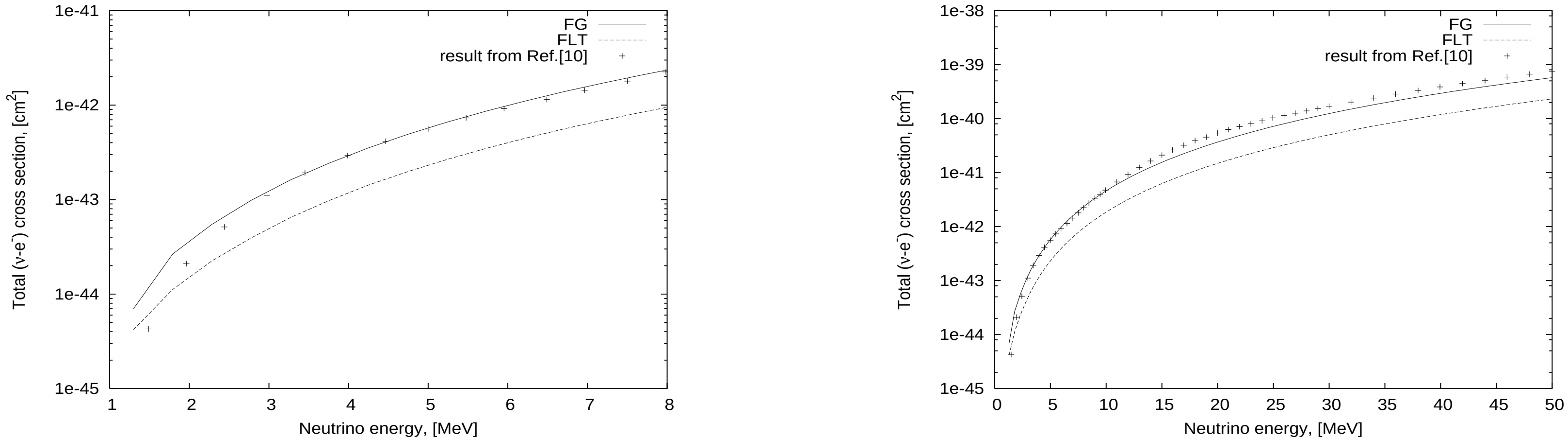

Figure 2: The total absorption ν-^{40}Ar cross section as a function of the neutrino energy E_ν.

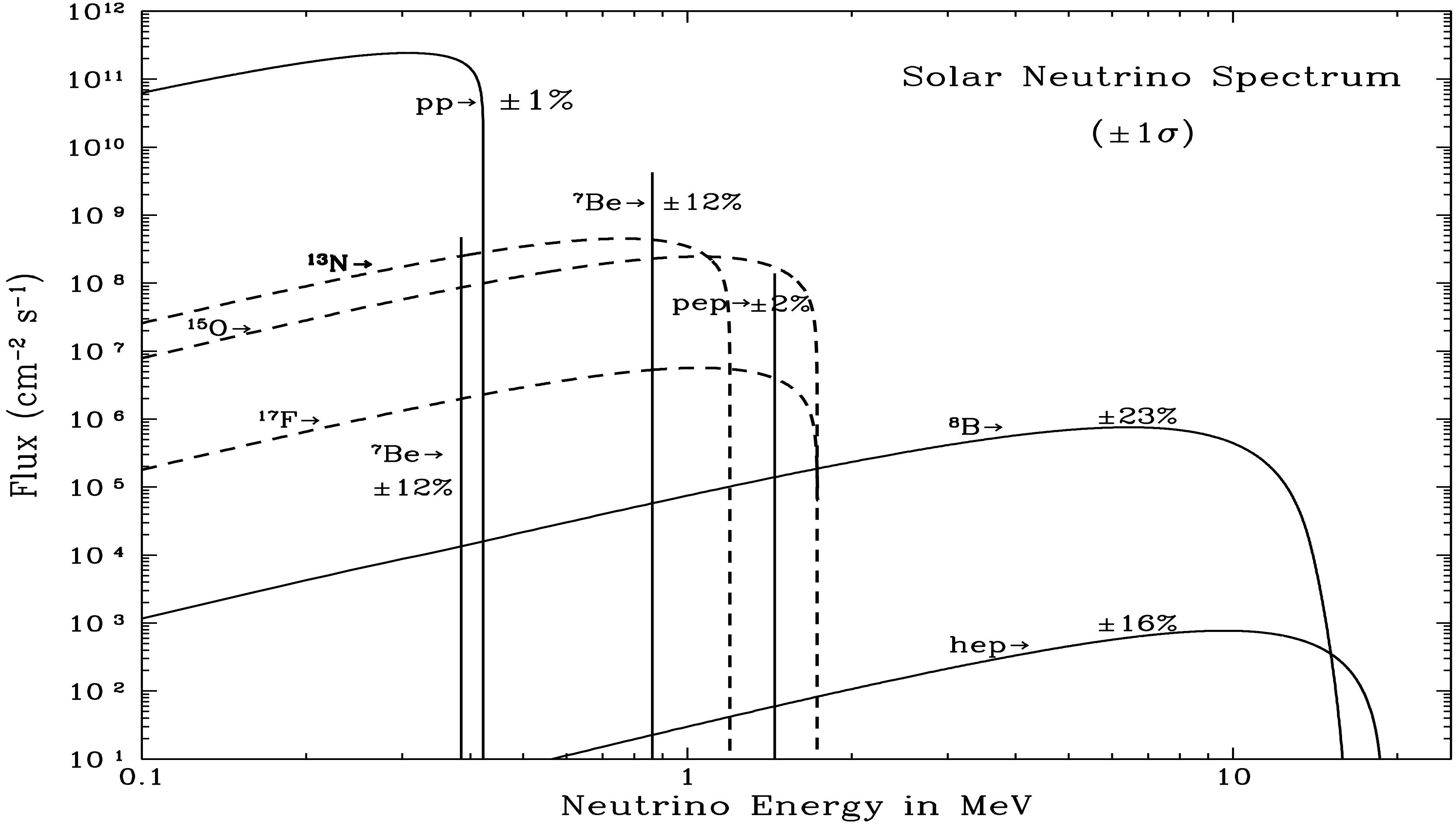

Figure 3: The flux continuum $[cm^{-2}sec^{-1}MeV^{-1}]$ as a function of the neutrino energy E_ν.

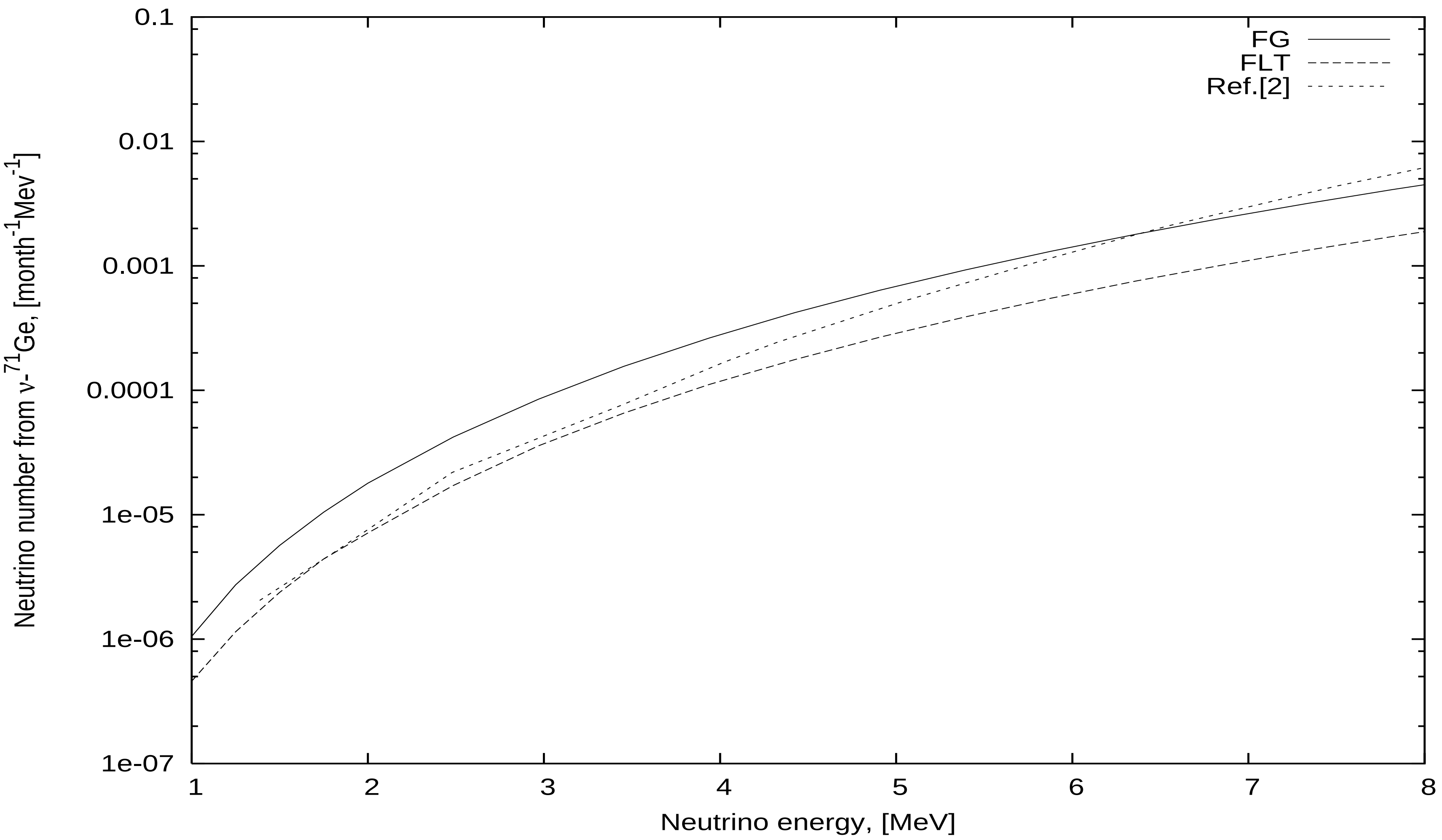

Figure 4: The total neutrino number per a month and MeV produced from ^{8}B-ν flux interacting with 1.kg ^{71}Ge target as a function of the neutrino energy E_ν.

G.I.Lykasov, U.Sukhatme, V.V.Uzhinsky, Phys.Lett. B **553** *217 (2003); O.Benhar, S.Fantoni, G.I.Lykasov, U.Sukhatme, V.V.Uzhinsky, Eur.Phys.J., A* **19** *147 (2004); O.Benhar, S.Fantoni, G.I.Lykasov, U.Sukhatme, Phys.Lett. B* **527** *73 (2002); O.Benhar, S.Fantoni, G.I.Lykasov, Eur.Phys.J. A* **7** *415 (2000).*

Planar and cylinder graphs

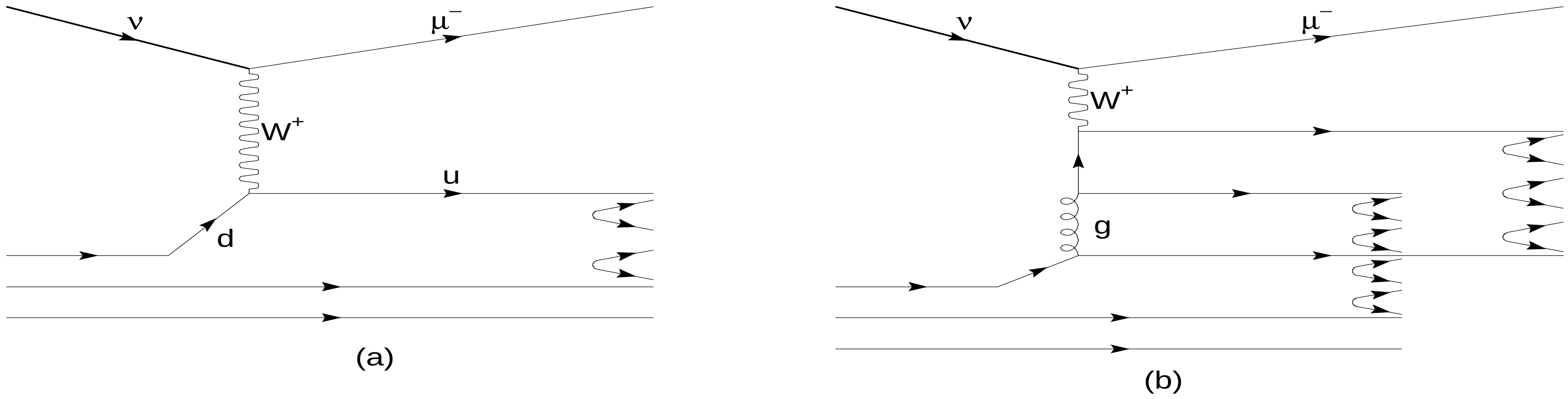

Figure 5: The planar graph (left panel) and the cylinder graph (right panel). *G.Veneziano, Phys.Lett., B52,220 (1974)*

Semi-inclusive process $\nu(\bar{\nu})p \to \mu^-(\mu^+)hX$

$$\rho_{nu(\bar{\nu})p\to\mu^-(\mu^+)hX} = \Phi(Q^2)\left\{F_P(x,Q^2;z,p_t) + F_C(x,Q^2;z,p_t)\right\}$$

with

$$\Phi(Q^2) \ = \ mE\frac{G^2}{\pi}\frac{m_W^2}{Q^2+m_W^2} \ ,$$

where G is the Fermi weak coupling constant, E is the energy of incoming neutrino, m and m_W are the nucleon and the W-boson masses respectively. $x = Q^2/2(p_\nu \cdot k)$ is the Bjorken variable, p_ν and k are the four-momenta of the initial neutrino and nucleon, $z = (E_h + p_{hz})/(E + p_z)$ is the light cone variable.

The variable z can be treated also as the Feynman variable $x_F = \frac{2p_L^*}{W_X}$ defined as the longitudinal momentum fraction in the hydronic center mass system (h.c.m.s.), p_L^* is the longitudinal hadron momentum in the h.c.m.s. (*G.L., U.Sukhatme, V.V.Uzhinsky, Phys.Lett.*__B553__*,217 (2003)*)

Mean multiplicity of charged hadron in the current fragmentation region

The multiplicity $< n_c h >$ measured by NOMAD is close to $< n_c h > /2$ results from e^+e^- experiment at $E = \sqrt{s}$ and $< n_c h >$ from ep and $\bar{\nu}p$ at $E = Q$. **QCD fit for $< n_c h >$**

$$< n_c h^{QCD} > = \ a \ + \ bexp(c\sqrt{ln(Q^2/Q_0^2)}) \ ,$$

where a=2.257, b=0.094, c=1.775, Q_0=1GeV.c. (*W.Furmanski, R.Petronzio, S.Pokorski, Nucl.Phys.***B155***,253 (1979); A.Bassetto, M.Ciafaloni, G.Marchesini, Phys.Lett.***B83***, 207(1979);K.Konishi, Rutherford Report RL 79-035 (1979); A.H.Mueller, Phys.Lett.***B213***, 85(1983)*)

Multiple hadron production in $\nu - p \to \mu^- + X$ process

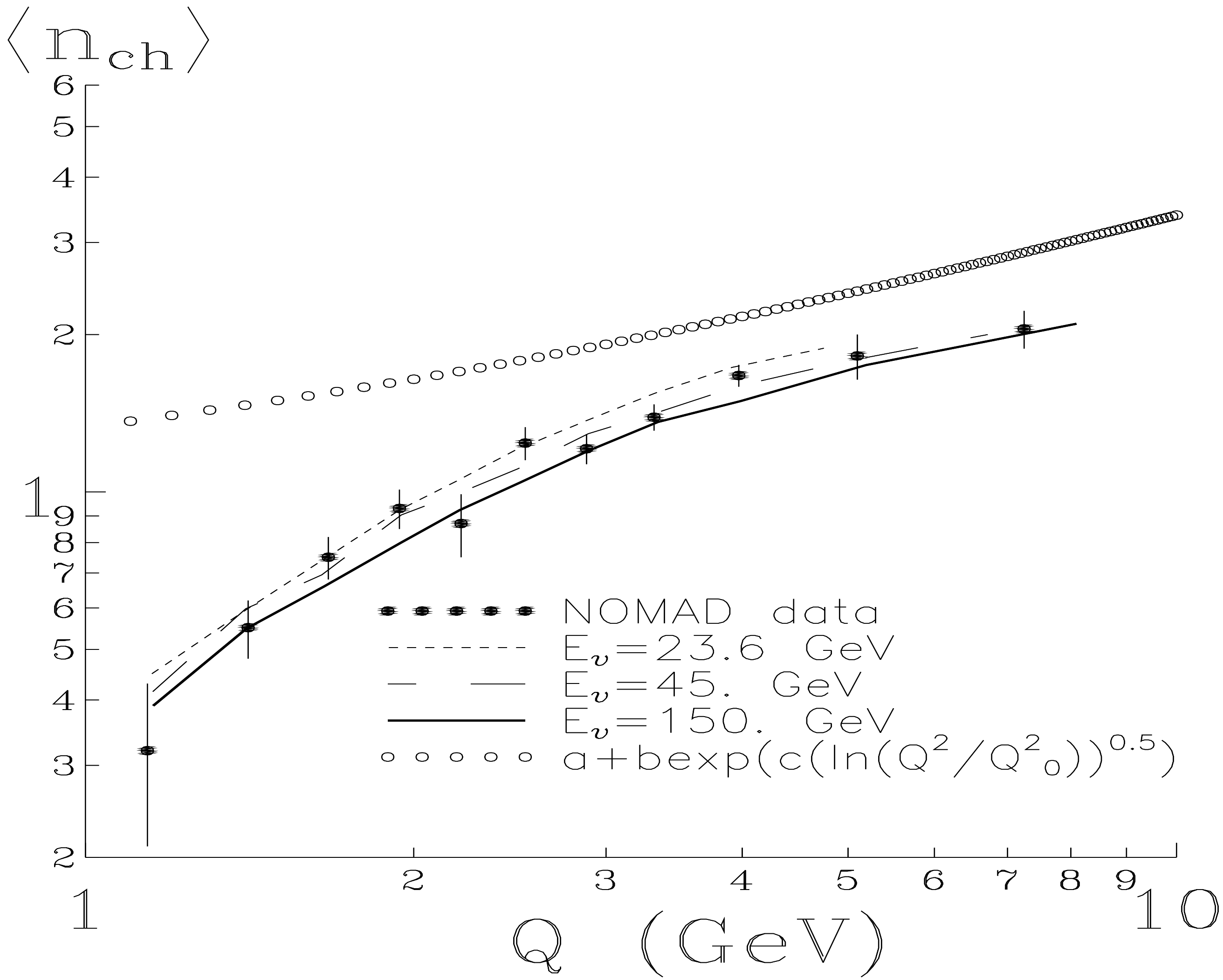

Figure 6: Mean multiplicity of charged hadron in the current fragmentation region as a function of the momentum transfer Q. The open circles correspond to the QCD fit; the solid, long dash and short dash lines correspond to our calculations at E_ν=150.GeV, 45.GeV and E_ν=23.6.GeV respectively. The experimental points are the NOMAD data.

Q^2-inclusive spectrum

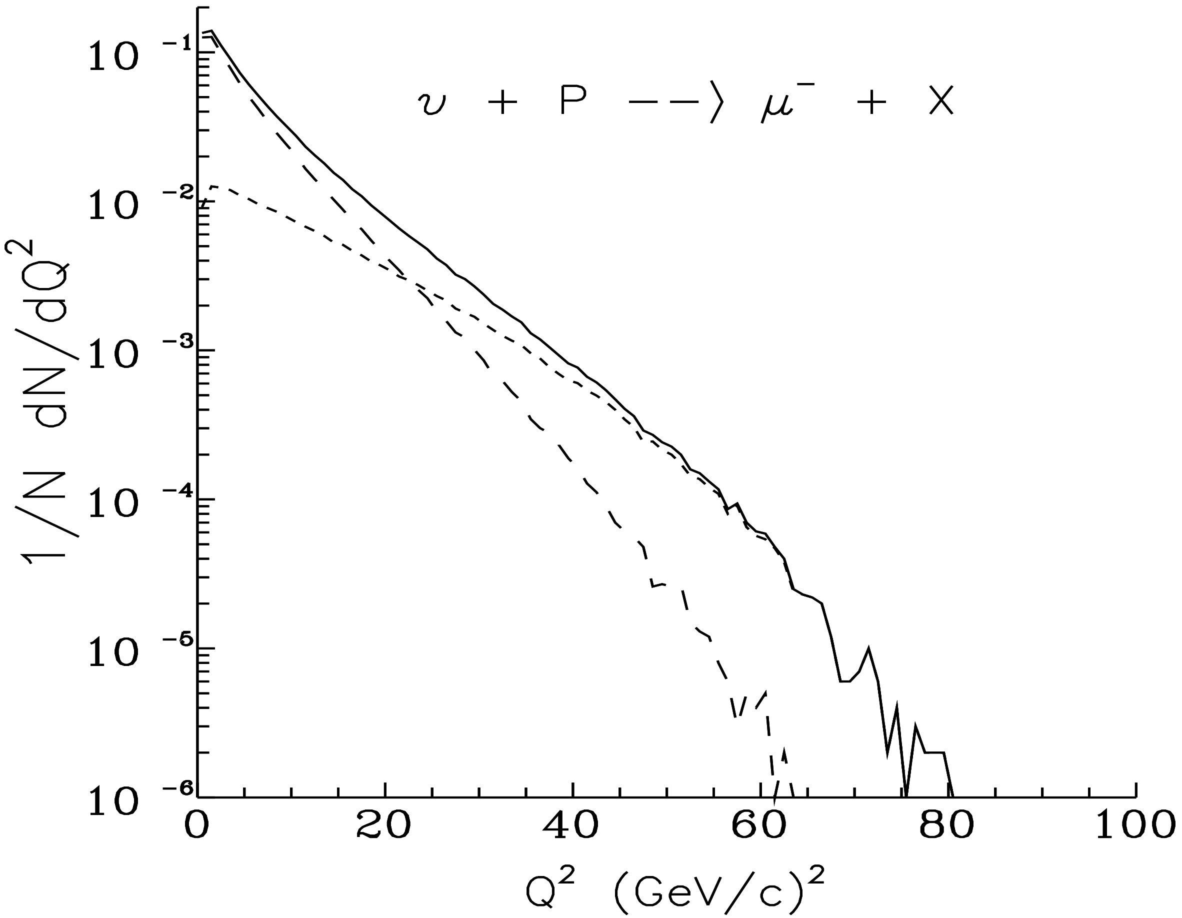

Figure 7: The Q^2-distribution $\frac{1}{N}\frac{dN}{dQ^2}$ of muons produced in $\nu\ p \to \mu^-\ X$ reaction. The long dash and short dash lines correspond to the contributions of the cylinder and planar graphs respectively. The solid line is the sum of these contributions.

x_F-distributions of strange hadron

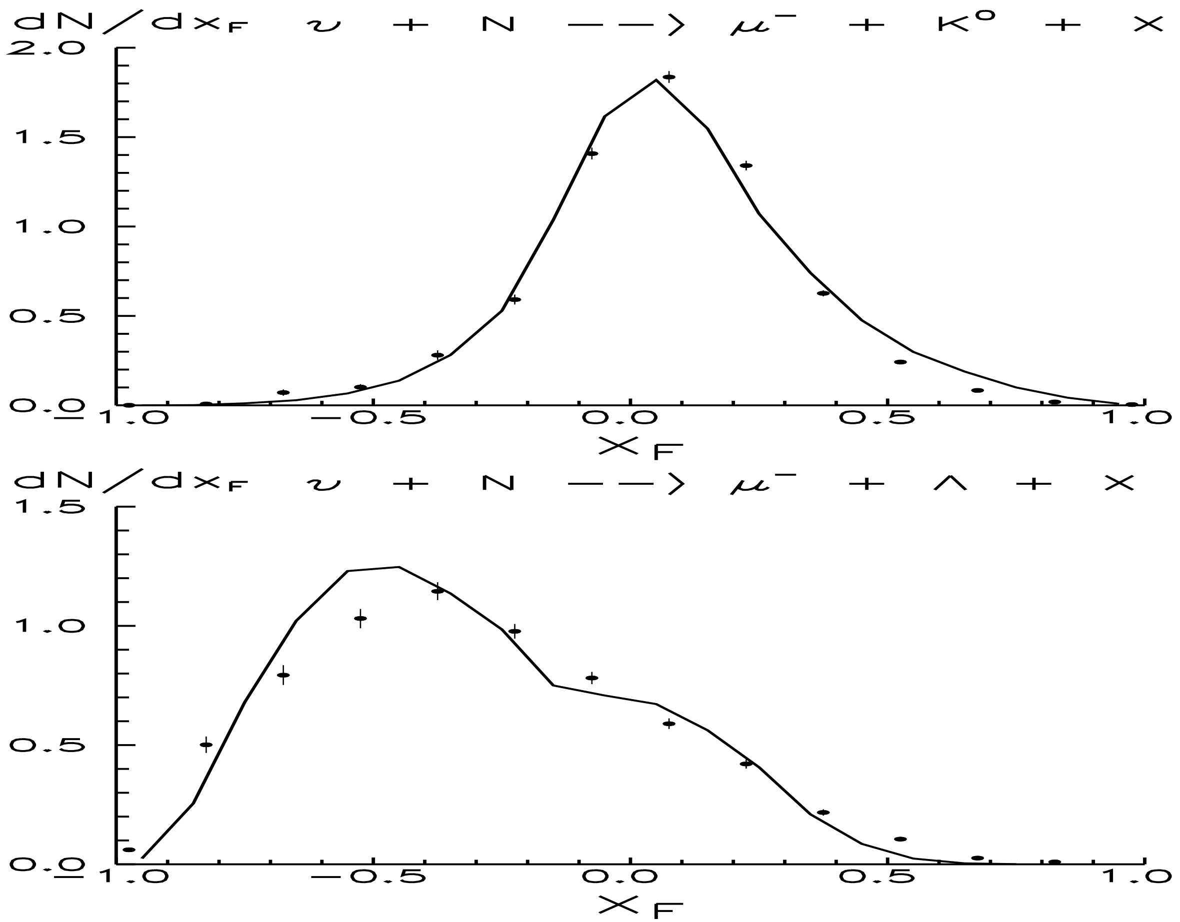

Figure 8: The x_f-distribution of strange hadron DN/dx_F. produced in $\nu\ p \to \mu^-\ X$ reaction.

Multiplicity of strange hadron

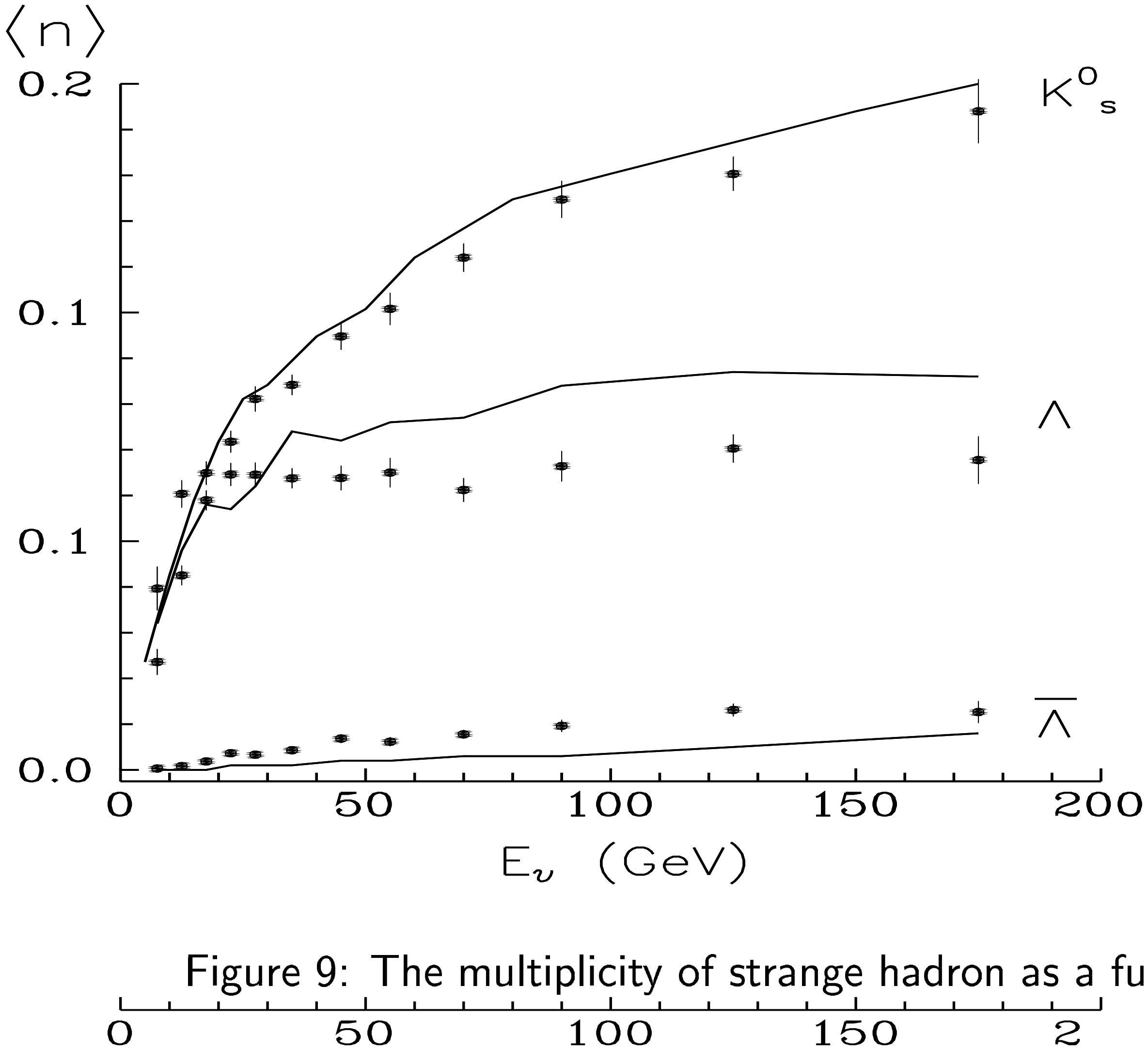

Figure 9: The multiplicity of strange hadron as a function of neutrino energy E_ν.

Multiplicity of backward going charged pions

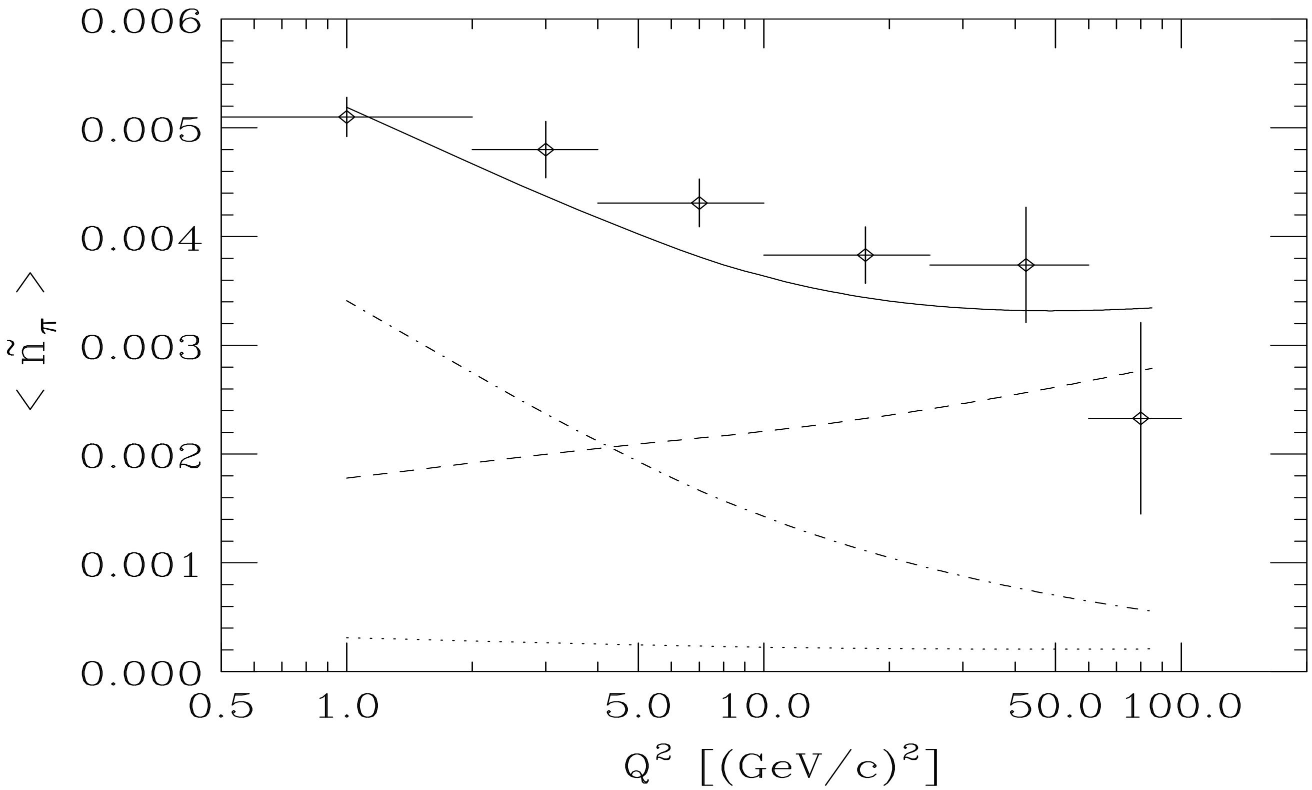

Figure 10: Mean multiplicity of charged pions produced in backward semi-sphere in $\nu^{12}C \to \mu^- \pi X$ process

(*P.Astier, et al., (NOMAD Coll.) Nucl.Phys..**B609**,255 (2001)*)

Our calculations

(*O.Benhar,S.Fantoni, G.L., U.Sukhatme, Phys.Lett.**B527**,73 (2002)*)

Backward going pions

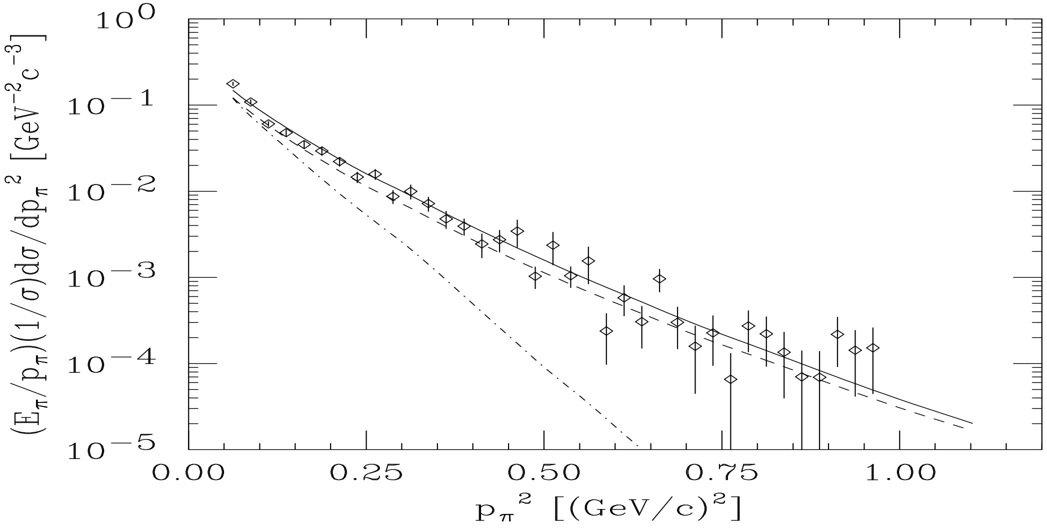

Figure 11: Comparison of our calculations (solid line) with the NOMAD data (full circles) and the MC calculation (open circles)

MC calculation and NOMAD data

(*P.Astier, et al., (NOMAD Coll.) Nucl.Phys..***B609***,255 (2001)*)

Our calculations

(*O.Benhar,S.Fantoni, G.L., Eur.Phys.J.***A7***,415 (2000);*
*O.Benhar,S.Fantoni, G.L., U.Sukhatme, V.V.Uzhinsky, Eur.Phys.J.***A19***,147 (2004)*)

SUMMARY (Low energies)

I. The FLT can be applied to compute total cross sections for neutrino scattering off heavy nuclei at low neutrino energies.

II. The obtained cross sections do not contradict to other calculations within different nuclear models.

III. The suggested approach is much simple in comparing to other models.

IV. The cross sections obtained within the FLT are different from the results obtained within the Fermi gas approximation in a factor 2.5-3 at $E_\nu \leq 5 - 6 MeV$.

V. At higher energies such difference becomes smaller.

VI. The suggested approach can be applied to compute the background from solar neutrinos interacting within a detector.

SUMMARY (High energies)

I. The standard QCD model analyzing the multiple hadron production in lepton-proton interactions has to be corrected at $Q^2 < 10(GeV/c)^2$.

II. The non perturbative corrections can be included applying the $1/N$ expansion in QCD.

III. The inclusion of cylinder graphs or one-Pomeron exchange diagrams leads to satisfactory description of existing experimental data.

IV. Application of suggested approach and assuming an existence of non nucleon degrees of freedom in nuclei allows us to describe the NOMAD data on pion production in backward semi-sphere in $\nu - A$ semi-inclusive processes.

V. The suggested approach can be applied to analyze experiments like OPERA performed at the LNGS.