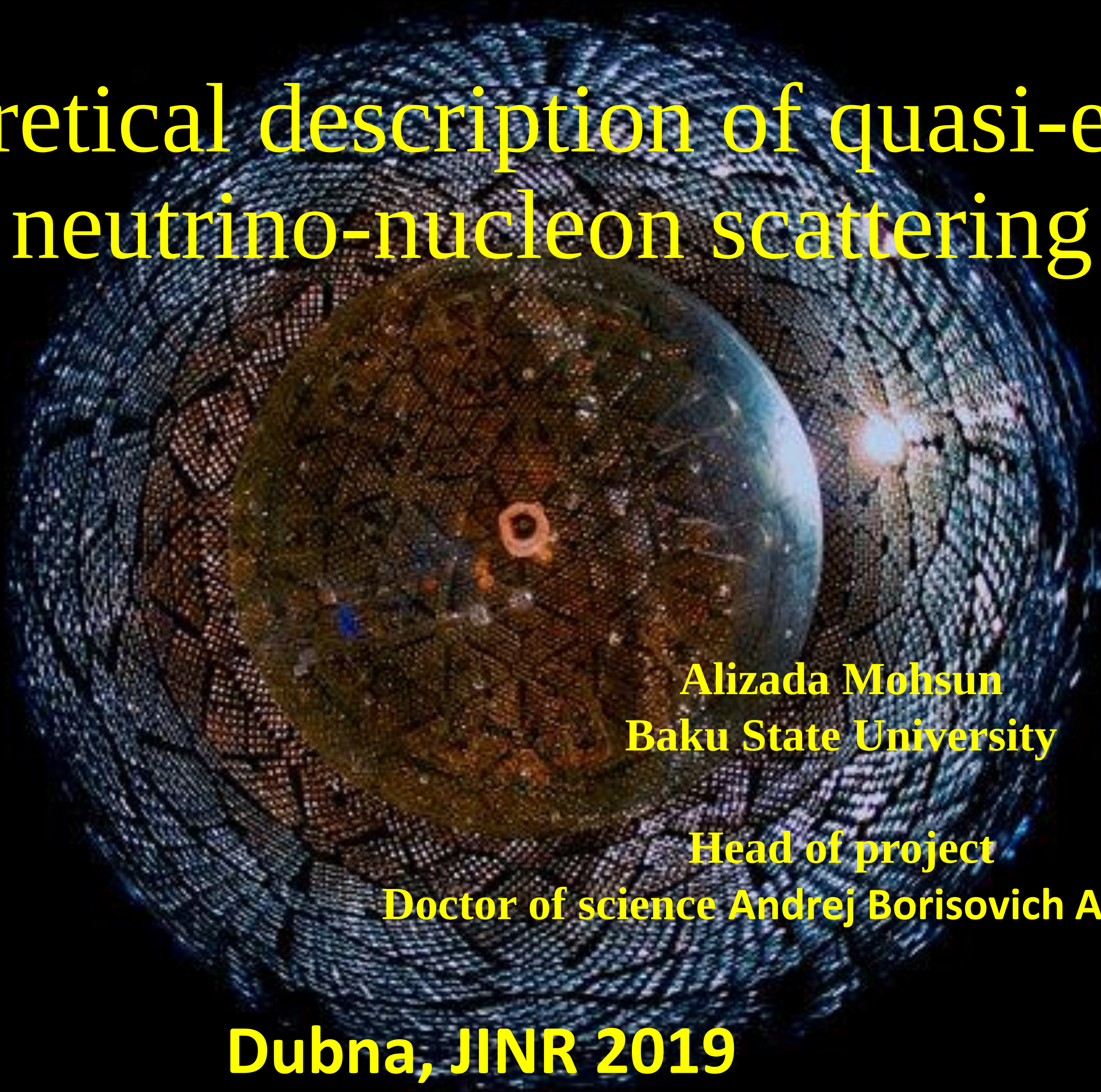

Theoretical description of quasi-elastic neutrino-nucleon scattering

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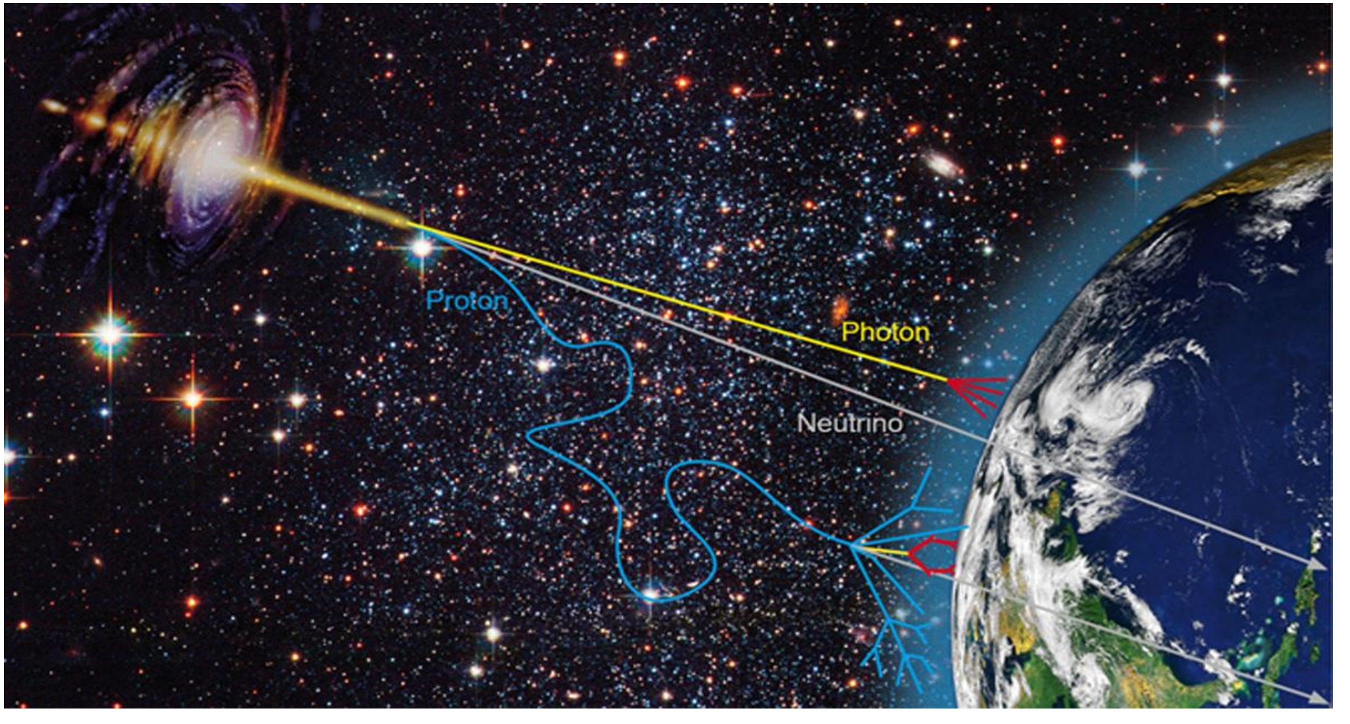
Actuality

- The advantage of neutrinos is that they participate in the weak and gravitational interaction.
- Using neutrinos, one can investigate the weak interaction.
- The Reactor Antineutrino Anomaly.
- Practical application of neutrino is the recently developed neutrino diagnostics of industrial nuclear reactors.



The Reactor Antineutrino Anomaly.

The synthesis of published experiments at reactor-detector distances < 100 m leads to a ratio of observed event rate to predicted rate of 0.976±0.024. Further evaluation of this value leads to the value 0.943±0.023 leading to a deviation from unity at 98,6% which we call the reactor antineutrino anomaly. This value is derived from the ratio of the observed neutrinos to the expected number of neutrinos. The compatibility of results with the existence of a fourth non-standard neutrino state driving neutrino oscillations at short distances is discussed.

Generally reactor neutrino oscillation experiments search for the reaction:

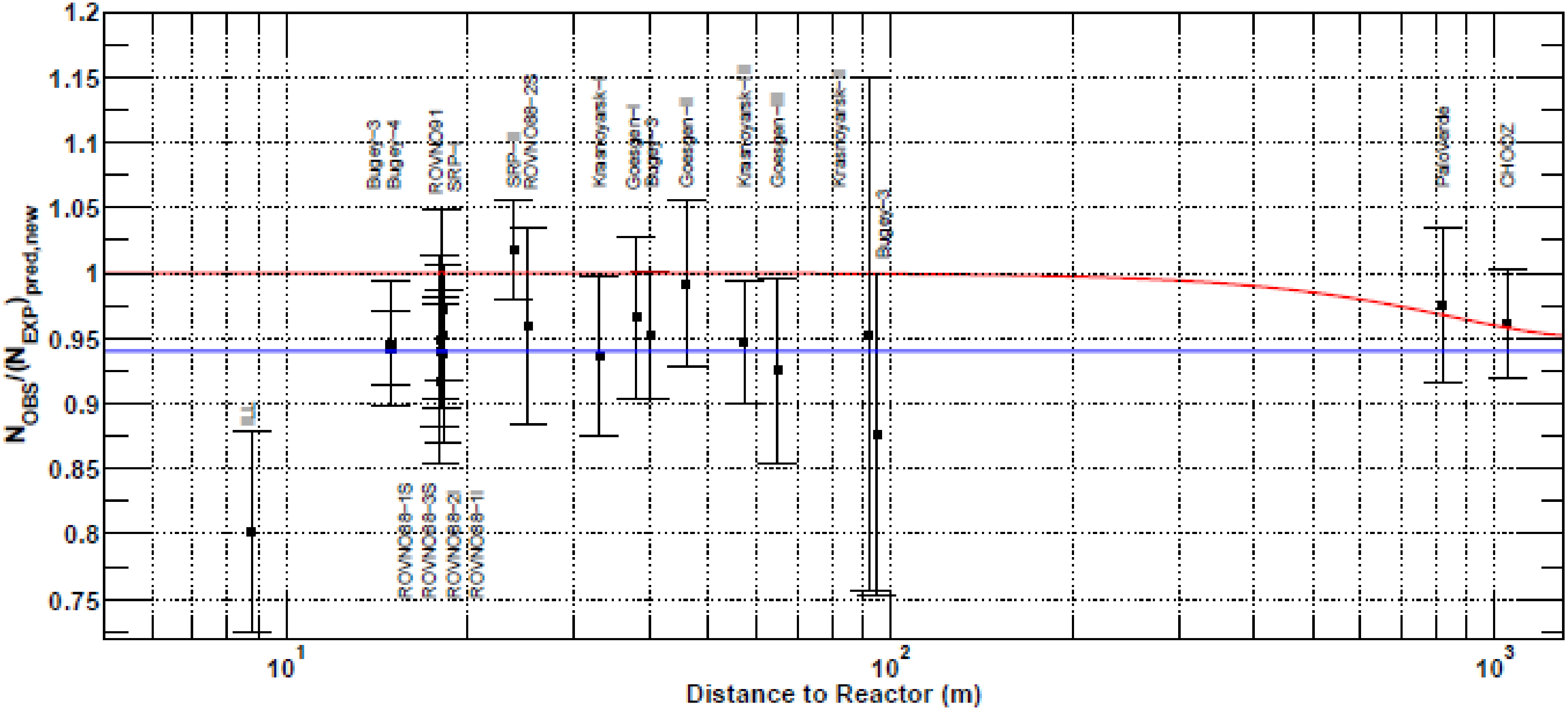
$$\bar{\nu}_e + p \rightarrow e^+ + n,$$

where an electron antineutrino interacts with a free proton in a detector, often filled with scintillator. The reaction cross section can be precisely computed with the V-A theory of weak interaction.

$$\sigma_{\mathrm{V-A}}(E_e) = \kappa p_e E_e (1 + \delta_{\mathrm{rec}} + \delta_{\mathrm{wm}} + \delta_{\mathrm{rad}}),$$

Pe and Ee being the momentum and energy of the positron, and the being the energy dependent recoil (rec), weak magnetism (wm), and radiative (rad) corrections. On the one hand, the prefactor can be written

$$\kappa = \frac{G_F^2 cos^2\theta_C}{\pi}(1 + \Delta^R_{\mathrm{inner}})(1 + 3\lambda^2),$$



1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
$N_{OBS}/(N_{EXP})_{pred,new}$
10^1
10^2
10^3
Distance to Reactor (m)
ILL
Bugey-3
Bugey-4
ROVNO91
SRP-I
SRP-II
ROVNO88-2S
Krasnoyarsk-I
Goesgen-I
Bugey-3
Goesgen-II
Krasnoyarsk-III
Goesgen-III
Krasnoyarsk-II
Bugey-3
PaloVerde
CHOOZ
ROVNO88-1S
ROVNO88-3S
ROVNO88-2I
ROVNO88-1I

Fig1. Ref.[1]

Radiative Corrections

To calculate the effect of radiative corrections on the total quasi-elastic cross-section, we follow the approximate approach of calculating the leading log correction to order $\log Q/m$, where Q is the energy scale of the interaction process . This approach has a calculational advantage in investigating the differences due to the lepton mass, m because the lepton leg leading log only involves sub-processes where photons attach to leptons. The key result from this approach is that the cross-section which allows for the presence of radiated photons, σ_{LLL} is related to the Born level cross-section, σ_B, by

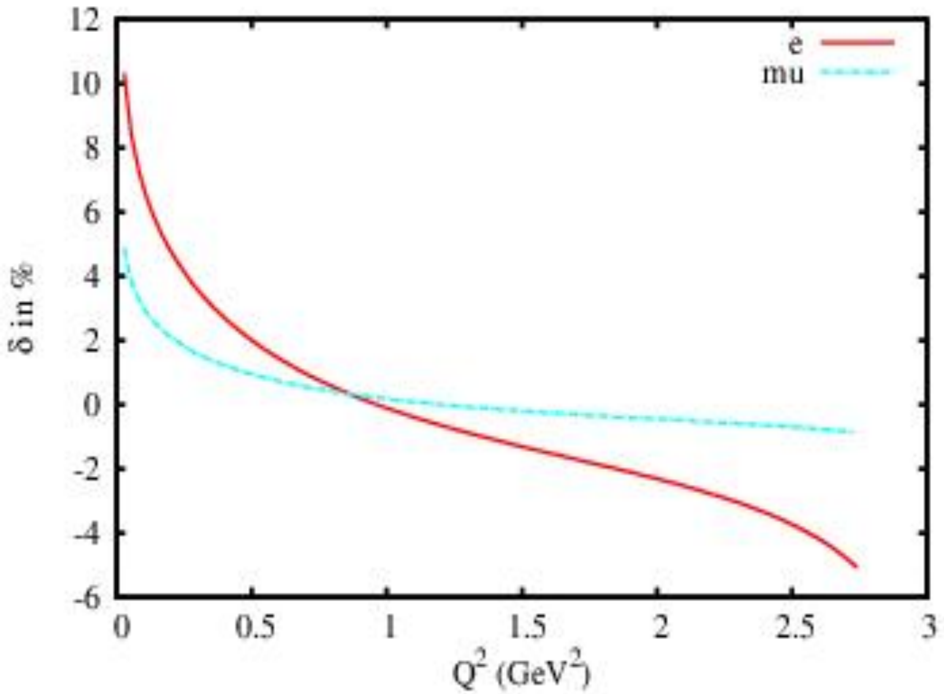


Fig2. Ref.[2]

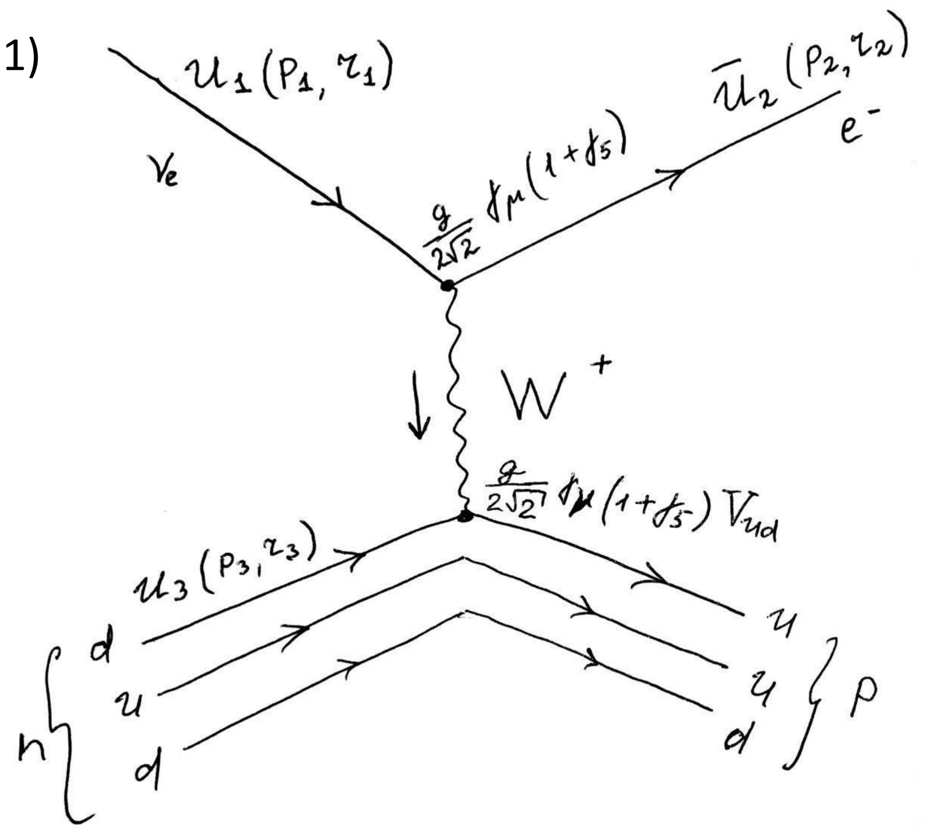
$$\frac{d\sigma_{LLL}}{dE_\ell d\Omega} \approx \frac{d\sigma_B}{dE_\ell d\Omega} + \frac{\alpha_{EM}}{2\pi} \log \frac{4E_\ell^{*2}}{m^2} \int_0^1 dz \frac{1+z^2}{1-z} \times \left(\frac{1}{z} \frac{d\sigma_B}{d\hat{E}_\ell d\Omega} \bigg|_{\hat{E}_\ell = E_\ell/z} - \frac{d\sigma_B}{dE_\ell d\Omega} \right),$$

We have recorded Feynman diagrams and their amplitudes for the following processes:

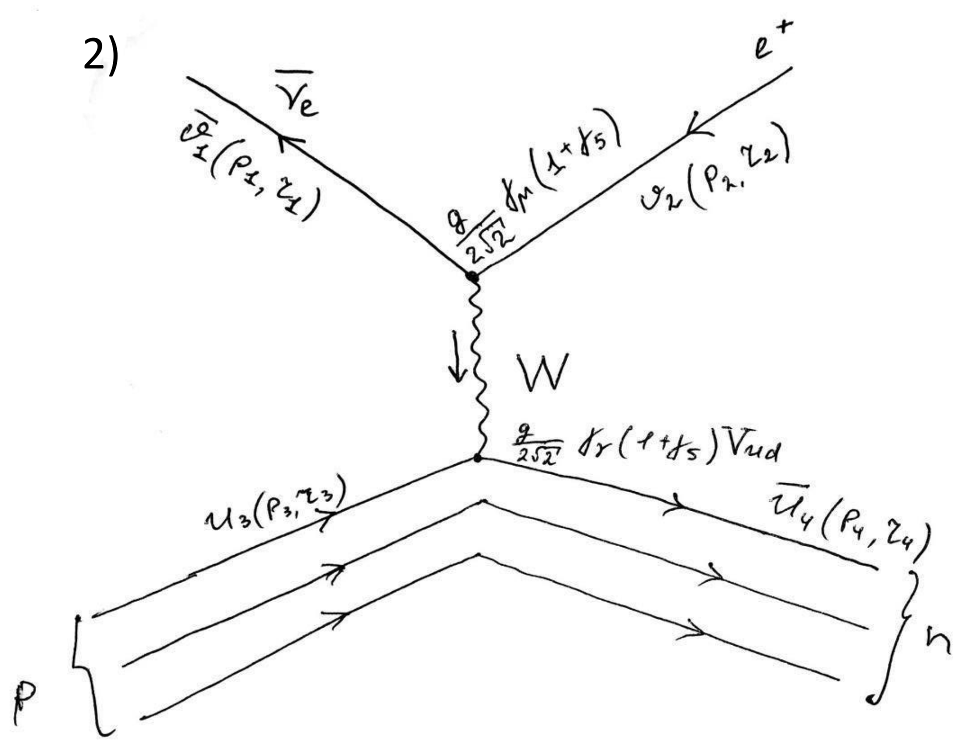
1) $\nu_e + n \to e^- + p,$

2) $\bar{\nu}_e + p \to e^+ + n,$

1)



2)



And this is the amplitude of the transition from the initial state to the final:

1)
$$A_{i\to f}=\frac{g}{2\sqrt{2}}\left[\overline{U_2}(p_2,r_2)\gamma_\mu(1+\gamma_5)U_2(p_2,r_2)\right]\times$$
$$\times\left(iD_{\mu\nu}\right)\times\frac{g}{2\sqrt{2}}\left[\overline{U_4}(p_4,r_4)\gamma_\nu(1+\gamma_5)V_{ud}U_3(p_3,r_3)\right]$$

2)
$$A_{i\to f}=\frac{g}{2\sqrt{2}}\left[\overline{U_4}(p_4,r_4)\gamma_\nu(1+\gamma_5)V_{ud}U_3(p_3,r_3)\right]\times$$
$$\times\left(-iD_{\mu\nu}\right)\times\frac{g}{2\sqrt{2}}\left[\overline{\upsilon_1}(p_1,r_1)\gamma_\nu(1+\gamma_5)V_{ud}\upsilon_2(p_2,r_2)\right]$$

Where :

$$iD_{\mu\nu}=\frac{-i\left(g_{\mu\nu}-\dfrac{q_m q_r}{M_w^2}\right)}{q^2-M_w^2}$$

Calculating the effective cross section.

$$d\Gamma = \frac{d^3q d^3r}{2q^0 2r^0} \times \delta^4\left(p+k-q-r\right)$$

Use the property :

$$d^3r\,\delta^{(3)}\left(\vec{p}+\vec{k}-\vec{q}-\vec{r}\right) \to 1\Big|_{\vec{r}=\vec{p}+\vec{k}-\vec{q}}$$

Receive :

$$d\Gamma = \frac{d^3q}{2q^0 2\sqrt{\left(\vec{p}+\vec{k}+\vec{q}\right)^2+m_r^2}}\delta\left(p^0+k^0-q^0-r^0\right)$$

Decompose :

$$d^3q = \left|\vec{q}\right|^2 dq\,d\varphi\,d\left(\cos\theta\right)$$

From the law of conservation of the equation we obtain square equation.

$$p^0 + k^0 - \sqrt{\vec{q}^2 + m_q^2} - \sqrt{\left(\vec{p} + \vec{k} - \vec{q}\right)^2 + m_r^2} = 0$$

The solution of last equation is:

$$x_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

where:

$$a = 4\left(-E_v^2 + cE_v^2 - 2E_v m_p - m_p^2\right)$$

$$b = 4cE_v\left(m_e^2 - m_n^2 + 2E_v m_p + m_p^2\right)$$

$$c = 4E_v^2 m_p^2 + 4E_v m_p\left(m_e^2 - m_n^2 + m_p^2\right) + \left(m_e^2 - m_n^2 + m_p^2\right)^2 -$$
$$-4m_e^2\left(E_v^2 + 2E_v m_p + m_p^2\right)$$

The discriminante of equation is :

$$D=16c^2E_v^2\left(m_e^2-m_n^2+2E_vm_p+m_p^2\right)^2-16\left(-E_v^2+c^2E_v^2-2E_vm_p-m_p^2\right)\times$$
$$\times\left(4E_v^2m_p^2+4E_vm_p\left(m_e^2-m_n^2+m_p^2\right)+\left(m_e^2-m_n^2+m_p^2\right)^2-4m_e^2\left(E_v^2-2E_vm_p+m_p^2\right)\right)$$

Roots of equation is :

$$q_1=\frac{\left(-4cE_v\left(m_e^2-m_n^2+2E_vm_p+m_p^2\right)\right)+\sqrt{D}}{8\left(-E_v^2+c^2E_v^2-2E_vm_p-m_p^2\right)}$$

$$q_2=\frac{\left(-4cE_v\left(m_e^2-m_n^2+2E_vm_p+m_p^2\right)\right)-\sqrt{D}}{8\left(-E_v^2+c^2E_v^2-2E_vm_p-m_p^2\right)}$$

As see

$$q=q(E_v,c)$$

We will look for solutions in which the discriminant is greater from zero and the roots are non-negative.

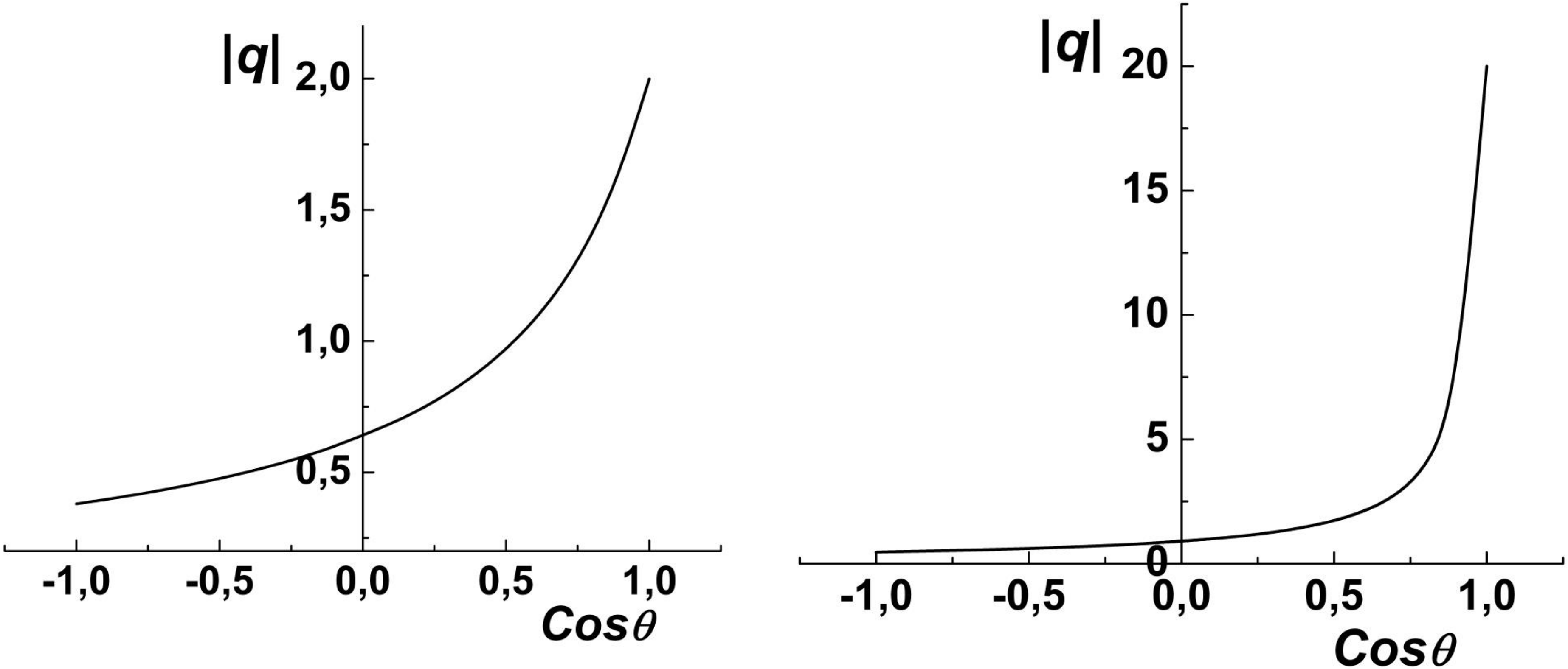


Fig.3

Fig. 3 shows the dependence of the electron impulse on the cos (scattering angle) at the energy E=2 Gev (left) and E=20 Gev (right) of the neutrino.

As see at small scattering angles of the electron, its impulse is greater. The impulse of the electron increases quadratically with decreasing scattering angle.

Using the Lagrangian of the transition we obtain for dΓ:

$$d\Gamma = \frac{2\pi x^2 d\cos\theta}{2q^0 2r^0} \cdot \frac{q^0 r^0}{\left| xr^0 + xq^0 + q^0 \left|\vec{k}\right| c \right|}$$

For effective cross section :

$$\frac{d\sigma}{dQ^2} = \frac{k\left|M\right|^2}{\left(2\left|\vec{k}\right|\left|\vec{k}'\right|\right)} \frac{d\Gamma}{dc}$$

Where Q is the square of the transmitted impulse

$$Q^2 = -\left(k - k'\right)^2$$

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