ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2004. Т. 35. ВЫП. 7

УДК 539.12: 539.171

QED CALIBRATION PROCESSES FOR POLARIZED $\gamma\gamma$ AND γe^- COLLIDERS

E. Bartoš[1,4], *M. V. Galynskii*[2], *S. R. Gevorkyan*[3,4], *E. A. Kuraev*[4]

[1]Department of Theoretical Physics, Comenius University, Bratislava
[2]Stepanov Institute of Physics BAS, Minsk
[3]Yerevan Physics Institute, Yerevan
[4]Joint Institute for Nuclear Research, Dubna

For polarized $\gamma\gamma$ and γe^- high-energy collisions we present the differential cross sections for two different kinematics: emission in large angle for final state of two and three particles and quasi-peripherical final state of three and four particles.

Для поляризованных высокоэнергетических соударений представлены дифференциальные сечения для двух различных кинематик — излучения под большим углом для конечных состояний двух и трех частиц и квазипериферических конечных состояний трех и четырех частиц.

A new laboratory for studying the hadron processes as well as ones with heavy vector beams will be opened with planned linear e^+e^- high-energy colliders [1]. It will provide a possibility (using the backward laser Compton scattering) of obtaining the photon–electron as well as photon–photon colliding beams.

The problem of calibration as well as the problem of measurement of the degree of polarization of photon beams is important for this kind of colliders. The QED processes at $\gamma e^\pm$ collisions are relevant for these purposes. For colliding high-energy electron–photon beams with detections of large-angle emitted final particles, the totally differential cross sections can be useful.

This type of colliders can also investigate similar processes in $\gamma\gamma$ collisions. The general theory of polarization phenomena in colliding photon beams was developed in [2]. The polarization phenomena turn out to be essential in our analysis also.

1. EMISSIONS IN LARGE ANGLES

In this section we will consider photon–photon(electron) collisions with emission of particles into large angles in c.m.s. ($M_i/\sqrt{s} \ll \theta_i \ll 1$, where $\sqrt{s}$ is the total c.m.s. energy and m_i are the masses of particles)

$$\gamma(k_1, \lambda_1) + \gamma(k_2, \lambda_2) \to \mu^+(q_+) + \mu^-(q_-), \tag{1}$$

$$\gamma(k_1,\lambda_1)+\gamma(k_2,\lambda_2)\to\mu^+(q_+)+\mu^-(q_-)+\gamma(k,\lambda), \tag{2}$$

$$\gamma(k,\lambda_\gamma)+e^-(p,\lambda_e)\to e^-(p',\lambda_e)+\gamma(k_1,\lambda_1), \tag{3}$$

$$\gamma(k,\lambda_\gamma)+e^-(p,\lambda_e)\to e^-(p',\lambda')+a(q_-,\lambda_-)+\bar{a}(q_+,\lambda_+),\ a=e^-,\mu^-, \tag{4}$$

$$\gamma(k,\lambda_\gamma)+e^-(p,\lambda_e)\to e^-(p',\lambda')+\pi^-(q_-)+\pi^+(q_+), \tag{5}$$

$$\gamma(k,\lambda_\gamma)+e^-(p,\lambda_e)\to e^-(p',\lambda')+\gamma(k_1,\lambda_1)+\gamma(k_2,\lambda_2). \tag{6}$$

For the matrix elements of processes (1)–(6) we use notation

$$\begin{gathered} M^{\delta}_{\lambda_1\lambda_2},\, M^{\lambda\delta}_{\lambda_1\lambda_2},\, M^{\lambda_\gamma\lambda_1}_{\lambda_e},\, M^{\lambda_-\lambda_+\lambda'}_{\lambda_\gamma\lambda},\, M^{\lambda'}_{\lambda_\gamma\lambda},\, M^{\lambda_1\lambda_2\lambda'}_{\lambda_\gamma\lambda},\\ \lambda,\lambda',\lambda_1,\lambda_2,\lambda_+,\lambda_-,\lambda_\gamma,\delta=\pm1, \end{gathered} \tag{7}$$

with scalar products

$$\begin{gathered} s=2p\cdot p',\quad s_1=2q_-\cdot q_+,\quad t=-2p\cdot q_-,\quad t_1=-2p'\cdot q_+,\\ u=-2p\cdot q_+,\quad u_1=-2p'\cdot q_-,\quad \chi=2k\cdot p,\quad \chi'=2k\cdot p',\\ \chi_{1\pm}=2k_1\cdot q_\pm\,,\quad \chi_{2\pm}=2k_2\cdot q_\pm\,,\\ \chi_\pm=2k\cdot q_\pm,\quad \chi_j=2k_j\cdot p,\quad \chi'_j=2k_j\cdot p',\quad j=1,2. \end{gathered} \tag{8}$$

Photon polarization 4-vectors with the definite chirality λ, $\varepsilon^\lambda_\mu(k)$, $\hat{\varepsilon}^\lambda=\gamma^\mu\varepsilon^\lambda_\mu$ can be put in representation [3]

$$\hat{\varepsilon}_\lambda(k)=N[\hat{q}_-\hat{q}_+\hat{k}\omega_{-\lambda}-\hat{k}\hat{q}_-\hat{q}_+\omega_\lambda]\,,\quad N=[s_1\chi_-\chi_+/2]^{-1/2}. \tag{9}$$

For calculation of the cross sections for processes (1), (2) in the case of partially polarized photon beams with momentum $k_i\,(i=1,2)$ we will use polarization matrices of density $\rho_i=\rho_i(k_i)$ in the helical representation determined by Stokes parameters $\boldsymbol{\xi}^{(i)}$ in the following way [4]

$$\rho_i=\rho_i(k_i)\;=\;\frac{1}{2}\begin{pmatrix}1+\xi_2^{(i)} & i\,\xi_1^{(i)}-\xi_3^{(i)}\\ -i\,\xi_1^{(i)}-\xi_3^{(i)} & 1-\xi_2^{(i)}\end{pmatrix},\ \mathrm{Tr}\,(\rho_i)=1. \tag{10}$$

Let us introduce 2×2 matrix building from the amplitudes of process (1)

$$\mathcal{M}_1^\delta=\begin{pmatrix}M^\delta_{++} & M^\delta_{+-}\\ M^\delta_{-+} & M^\delta_{--}\end{pmatrix}. \tag{11}$$

Then the probability of process (1) will be reduced to calculation of a trace from the product of the next matrices [2] $|M^\delta_{\lambda_1\lambda_2}|^2\to\mathrm{Tr}\,(\rho_1^T\,\mathcal{M}_1^\delta\,\rho_2\,\mathcal{M}_1^{\delta\,\dagger})$.

The cross section in general case has the form [5]

$$\frac{d\sigma^{\gamma\gamma\to\mu\bar{\mu}}_{\boldsymbol{\xi}_1\boldsymbol{\xi}_2\delta}}{d\Omega_{\mu_-}} = \frac{\alpha^2}{4s}\Big\{(1-\xi_2^{(1)}\xi_2^{(2)})R_+ - 2\,(\xi_1^{(1)}\xi_1^{(2)}+\xi_3^{(1)}\xi_3^{(2)}) + \delta(\xi_2^{(2)}-\xi_2^{(1)})R_-\Big\}, \tag{12}$$

where

$$R_\pm = \frac{\chi^2_{1+}\pm\chi^2_{1-}}{\chi_{1-}\chi_{1+}}\ ,\ \chi_{1\pm}=\chi_{2\mp}. \tag{13}$$

For the case of completely circularly polarized photons (right (R): $\xi_2^{(1,2)} = +1$, left (L): $\xi_2^{(1,2)} = -1$) we will have

$$\frac{d\sigma^{\gamma\gamma\to\mu\bar{\mu}}_{LL}}{d\Omega_{\mu_-}} = \frac{d\sigma^{\gamma\gamma\to\mu\bar{\mu}}_{RR}}{d\Omega_{\mu_-}} = 0\,, \quad \frac{d\sigma^{\gamma\gamma\to\mu\bar{\mu}}_{LR}}{d\Omega_{\mu_-}} = \frac{d\sigma^{\gamma\gamma\to\mu\bar{\mu}}_{RL}}{d\Omega_{\mu_-}} = \frac{\alpha^2}{s}R_+\,.$$

The corresponding cross sections for process (2) for definite chiral states of initial photons are

$$\begin{aligned}\frac{d\sigma^{\gamma\gamma\to\mu^-\mu^+\gamma}_{RR(LL)}}{d\Gamma} &= \frac{\alpha^3 s_1}{\pi^2 s}\ \frac{\chi_-\chi_+(\chi_-^2+\chi_+^2)}{D}\ ,\\ \frac{d\sigma^{\gamma\gamma\to\mu^-\mu^+\gamma}_{RL(LR)}}{d\Gamma} &= \frac{\alpha^3 s_1}{\pi^2 s}\ \frac{\chi_{1-}\chi_{1+}(\chi_{1-}^2+\chi_{1+}^2)+\chi_{2-}\chi_{2+}(\chi_{2-}^2+\chi_{2+}^2)}{D}.\end{aligned} \tag{14}$$

For (3)–(6), the matrix elements of the chiral matrix m_{ij} are constructed from the chiral amplitudes of the process $M^{\lambda_-\lambda_+\lambda'}_{\lambda_\gamma\lambda_e}$ as

$$\begin{aligned}m_{11} &= \sum_{\lambda_-\lambda_+\lambda'}\left|M^{\lambda_-\lambda_+\lambda'}_{++}\right|^2, \quad m_{22} = \sum_{\lambda_-\lambda_+\lambda'}\left|M^{\lambda_-\lambda_+\lambda'}_{-+}\right|^2,\\ m_{12} &= \sum_{\lambda_-\lambda_+\lambda'} M^{\lambda_-\lambda_+\lambda'}_{++}\left(M^{\lambda_-\lambda_+\lambda'}_{-+}\right)^*, \quad m_{21}=m_{12}^*.\end{aligned} \tag{15}$$

We put here only half of all chiral amplitudes which correspond to $\lambda_e = +1$. The other half can be obtained from these ones by a space parity operation.

For the case of muon pair production we have

$$\begin{aligned}m_{11} =& 4[s_+][s_-]\frac{u^2+t^2}{ss_1}, \quad m_{22} = 4[s_+][s_-]\frac{u_1^2+t_1^2}{ss_1},\\ m_{12} =& -\frac{4[s_+]^2}{(ss_1)^2}\Big[(ss_1)^2+(tt_1)^2+(uu_1)^2-2tt_1uu_1-\\ &- ss_1(tt_1+uu_1)+4i(tt_1-uu_1)A\Big],\end{aligned} \tag{16}$$

where $A = \varepsilon_{\mu\nu\rho\sigma}q_+^\mu q_-^\nu p^\rho p'^\sigma$ and $[s_\pm] = sN_p + s_1N_q\,\mathrm{e}^{\pm i\varphi_q}$.

For the electron pair production we have

$$m_{11} = \frac{4[s_+][s_-]}{ss_1tt_1}\Big[t^3t_1 + u^3u_1 + s^3s_1\Big], \quad m_{22} = \frac{4[s_+][s_-]}{ss_1tt_1}\Big[t_1^3t + u_1^3u + s_1^3s\Big], \tag{17}$$

$$m_{12} = \frac{4[s_+]^2}{(ss_1tt_1)^2}\Big[(uu_1)^2 - (ss_1)^2 - (tt_1)^2\Big]\Big[\frac{1}{2}((uu_1)^2 + (ss_1)^2 + (tt_1)^2 - 2uu_1(ss_1 + tt_1)) + 2iA(uu_1 - ss_1 - tt_1)\Big].$$

For pions one gets

$$m_{11} = [s_+][s_-]tu, \quad m_{22} = [s_+][s_-]t_1u_1,$$
$$m_{12} = \frac{[s_+]^2}{ss_1}\Big[\frac{1}{2}(uu_1 - tt_1)^2 - ss_1(uu_1 + tt_1) + 2i(tt_1 - uu_1)A\Big]. \tag{18}$$

For the double Compton scattering we have

$$m_{11} = \frac{8s}{D}\Big[\chi_1^3\chi_1' + \chi_2^3\chi_2' + \chi'^3\chi\Big], \quad m_{22} = \frac{8s}{D}\Big[\chi_1'^3\chi_1 + \chi_2'^3\chi_2 + \chi^3\chi'\Big],$$
$$m_{12} = \frac{8s}{D}\Big\{\frac{1}{2}(\chi_1\chi_2' + \chi_2\chi_1')\Big[\chi_1\chi_2' + \chi_2\chi_1' + s(s + \chi' - \chi)\Big] + 2iB(\chi_2\chi_1' - \chi_1\chi_2')\Big\}, \tag{19}$$

with $D = \chi\chi'\chi_1\chi_1'\chi_2\chi_2'$ and $B = \varepsilon_{\mu\nu\rho\sigma}k_2^\mu k_1^\nu p^\rho p'^\sigma$.

The differential cross section of the Compton scattering process (3) has the form

$$d\sigma_{\lambda_e\boldsymbol{\xi}}^{\gamma e^- \to \gamma e^-} = \frac{\alpha^2}{4\chi}\left[\frac{\chi^2 + \chi'^2}{\chi\chi'} + \xi_2\lambda_e\frac{\chi^2 - \chi'^2}{\chi\chi'}\right]dO_\gamma. \tag{20}$$

The cross section of processes (4), (5) has the form

$$\frac{d\sigma}{d\Gamma} = \frac{\alpha^3}{2\pi^2\chi}\Big[m_{11} + m_{22} + \xi_2\lambda_e(m_{11} - m_{22}) - 2\xi_3\,\mathrm{Re}\,(\mathrm{m}_{12}) + 2\xi_1\,\mathrm{Im}\,(\mathrm{m}_{12})\Big],$$
$$d\Gamma = \frac{d^3p'}{p'_0}\frac{d^3q_-}{q_{-0}}\frac{d^3q_+}{q_{+0}}\delta^4(p + k - p' - q_+ - q_-). \tag{21}$$

The cross section of processes (6) has the form

$$\frac{d\sigma}{d\Gamma_\gamma} = \frac{1}{2!}\frac{\alpha^3 s}{2\pi^2\chi D}\Big[\chi\chi'(\chi^2+{\chi'}^2)+\chi_1\chi_1'(\chi_1^2+{\chi_1'}^2)+\chi_2\chi_2'(\chi_2^2+{\chi_2'}^2)+$$
$$+4\xi_1 B(\chi_1\chi_2'-\chi_2\chi_1')-\xi_3(\chi_1\chi_2'+\chi_2\chi_1')(\chi\chi'-\chi_1\chi_1'-\chi_2\chi_2')+$$
$$+\lambda_e\xi_2[\chi\chi'({\chi'}^2-\chi^2)+\chi_1\chi_1'(\chi_1^2-{\chi_1'}^2)+\chi_2\chi_2'(\chi_2^2-{\chi_2'}^2)\Big], \quad (22)$$
$$d\Gamma_\gamma = \frac{d^3p'}{{p'}_0}\frac{d^3k_1}{\varepsilon_1}\frac{d^3k_2}{\varepsilon_2}\delta^4(p+k-p'-k_1-k_2).$$

2. QUASI-PERIPHERICAL COLLISIONS

In this section we will considered quasi-peripherical photon–photon(electron) collisions

$$\gamma(k,\lambda_\gamma)+e^-(p,\lambda_e)\to e^-(p',\lambda')+a(q_-,\lambda_-)+\bar{a}(q_+,\lambda_+), \quad (23a)$$
$$\gamma(k,\lambda_\gamma)+e^-(p,\lambda_e)\to e^-(p',\lambda')+a(q_-,\lambda_-)+\bar{a}(q_+,\lambda_+)+\gamma(k_1,\lambda), \quad (23b)$$
$$a=e^-,\mu^-,$$
$$\gamma(k_1,\lambda_1)+\gamma(k_2,\lambda_2)\to\bar{a}(p_+)+a(p_-)+\bar{b}(q_+)+b(q_-), \quad (23c)$$
$$a,b=e^-,\mu^-,\pi^-,$$

it means, in the case when the $a\bar{a}$, $b\,\bar{b}$ pairs move close to the direction of initial photons. Besides the latter, we will restrict ourselves by the case when the invariant masses $a\bar{a}$ and $b\,\bar{b}$ are large in comparison with the mass of muon and much less than the centre of mass total energy $\sqrt{s}$

$$m_\mu^2 \ll s_1, s_2 \ll s, \quad \chi_\pm \sim s_1, \quad \chi'_\pm \sim s_2. \quad (24)$$

The corresponding matrix elements have a factorized form

$$M(\gamma e^-\to a\bar{a}e^-(\gamma)) = is\frac{2(4\pi\alpha)^{3/2}}{q^2}m_A^{\lambda_1\lambda_\gamma}m_B^{\lambda_e}, \quad m_B^+ = \frac{1}{s}\bar{u}(p')\hat{k}\omega_+u(p),$$
$$M(\gamma\gamma\to e^+e^-\mu^+\mu^-) = is\frac{2(4\pi\alpha)^2}{q^2}\big[m_1^{\lambda_1\lambda_e}m_2^{\lambda_2\lambda_\mu}+m_1^{\lambda_2\lambda_e}m_2^{\lambda_1\lambda_\mu}\big], \quad (25)$$
$$m_1^{\lambda_1\lambda_e} = \frac{1}{s}k_2^\mu\varepsilon_1^\nu(k_1)M_{1\mu\nu}, \quad m_2^{\lambda_2\lambda_\mu} = \frac{1}{s}k_1^\sigma\varepsilon_2^\rho(k_2)M_{2\sigma\rho}.$$

The cross section of process (23a) will be

$$d\sigma = \frac{(2\pi)^4}{\mathbf{q}^4}|m_B^+|^2\,\mathrm{Tr}\,(\rho m_A^{\lambda_1\lambda_\gamma})d^2\mathbf{q}ds_A d\Phi_A ds_B\Phi_B \quad (26)$$

with $s_A=(q+k)^2\approx s\alpha$, $s_B=(p-q)^2\approx s\beta$.

For the elastic subprocess $e^- \to e^-\gamma^*$ one has the integral form $\int ds_B d\Phi_B = (2\pi)^{-3}$ and $|m_B^+|^2 = 1$. For the subprocess $e^- \to e^-\gamma\gamma^*$ (in the process $\gamma e^- \to a\bar{a}e^-\gamma$) one has the integral form $\displaystyle\int ds_B d\Phi_B = \frac{d\alpha_1 d^2k}{2(2\pi)^6\alpha_1\bar{\alpha}_1}$ and

$$|m_B^+|^2 = \frac{2\mathbf{q}^2}{\chi_1\chi_1'}(1+\bar{\alpha}_1^2), \quad \chi_1 = \frac{\mathbf{k}_1^2}{\alpha_1}, \quad \chi_1' = \frac{(\bar{\alpha_1}\mathbf{k}_1 - \alpha_1\mathbf{p}')^2}{\alpha_1\bar{\alpha}_1}. \tag{27}$$

For the upper block the integral equals $\displaystyle\int ds_A d\Phi_A = \frac{d\beta_- d^2q_-}{2(2\pi)^6 x_- x_+}$ and the trace $\mathrm{Tr}\,(\rho m_A^{\lambda_1\lambda_\gamma})$ has the form

$$\mathrm{Tr}\,(\rho m_A^{\lambda_1\lambda_\gamma}) = \frac{2}{\chi_+\chi_-}\left\{\mathbf{q}^2(x_+^2+x_-^2) - \xi_3\left[\mathbf{q}^2 x_- x_+ + 2\frac{(\mathbf{q}\cdot\mathbf{Q})^2}{s_1}\right] + \right.$$
$$\left. + 2\xi_1(x_- - x_+)(\mathbf{q}\cdot\mathbf{Q})\frac{[\mathbf{q}\cdot\mathbf{Q}]_z}{s_1}\right\} \tag{28}$$

with

$$q_\pm = \alpha_\pm p + \beta_\pm k + q_\perp, \quad \mathbf{Q} = \beta_-\mathbf{q}_+ - \beta_+\mathbf{q}_-,$$
$$s_1 = 2q_+q_- = \frac{\mathbf{Q}^2}{\beta_+\beta_-}, \quad x_\pm = \frac{\mathbf{q}_\pm^2}{s\alpha_\pm}. \tag{29}$$

In the case of (25) let us assume that the pair $a(p_-)\bar{a}(p_+)$ belongs to the jet moving along direction of photon k_1 so we have

$$p_\pm = \alpha_\pm k_2 + x_\pm k_1 + p_\pm^\perp, \quad (p_\pm^\perp)^2 = -\mathbf{p}_\pm^2, \quad p_\pm^\perp\cdot k_1 = p_\pm^\perp\cdot k_2 = 0,$$
$$\alpha_\pm \approx \frac{\chi_{1\pm}}{s} = \frac{\mathbf{p}_\pm^2}{sx_\pm}, \; s_1 = (p_+ + p_-)^2 = \frac{\mathbf{Q}_a^2}{x_+x_-}, \; \mathbf{Q}_a = x_+\mathbf{p}_- - x_-\mathbf{p}_+, \tag{30}$$

where $\mathbf{p}_\pm$ are 2-dimensional Euclidean vectors ($\mathbf{p}_- + \mathbf{p}_+ + \mathbf{q} = 0$); $x_\pm = 2k_2p_\pm/s$ are energy fractions of pair components ($x_+ + x_- = 1$), and s_1 is squared invariant mass of the pair.

The similar relations are valid for the pair $b(q_-)\,\bar{b}(q_+)$ from the opposite jet moving in the direction of the photon k_2

$$q_\pm = y_\pm k_2 + \beta_\pm k_1 + q_\pm^\perp\,, \quad q_\pm^\perp = -\mathbf{q}_\pm^2\,, \quad q_\pm^\perp\cdot k_1 = q_\pm^\perp\cdot k_2 = 0\,,$$
$$\beta_\pm \approx \frac{\chi_{2\pm}'}{s} = \frac{\mathbf{q}_\pm^2}{sy_\pm}\,, \; s_2 = (q_+ + q_-)^2 = \frac{\mathbf{Q}_b{}^2}{y_+y_-}\,, \; \mathbf{Q}_b = y_+\mathbf{q}_- - y_-\mathbf{q}_+\,, \tag{31}$$

where energy fractions $y_\pm = 2k_1q_\pm/s$, ($y_+ + y_- = 1$) and $\mathbf{q}_- + \mathbf{q}_+ - \mathbf{q} = 0$.

It is useful to construct 2×2 matrices (see [6])

$$\mathcal{M}^{\pm}_{1(e)} = N_1^2 \mathbf{Q}_a^2 \mathbf{q}^2 \begin{pmatrix} x_\pm/x_\mp & \exp\{\pm 2i\varphi_a\} \\ \exp\{\mp 2i\varphi_a\} & x_\mp/x_\pm \end{pmatrix}, \tag{32a}$$

$$\mathcal{M}_{1(\pi)} = N_1^2 \mathbf{Q}_a^2 \mathbf{q}^2 \begin{pmatrix} 1 & \exp\{2i\varphi_a\} \\ \exp\{-2i\varphi_a\} & 1 \end{pmatrix}, \quad \varphi_a = \widehat{\mathbf{Q}_a \mathbf{q}}. \tag{32b}$$

For the cross section of two different pairs production (i.e., $a \neq b$) one obtains

$$d\sigma(\gamma\gamma \to a\bar{a}b\bar{b}) = \frac{\alpha^4}{\pi} x_+ x_- y_+ y_- \frac{dx_- dy_- d^2p_- d^2q_- d^2q}{\mathbf{p}_-^2 \mathbf{q}_-^2} \times \\ \times \left[\frac{S_{1(a)} S_{2(b)}}{(\mathbf{q}+\mathbf{q}_-)^2 (\mathbf{q}-\mathbf{p}_-)^2} + \frac{S_{1(b)} S_{2(a)}}{(\mathbf{q}-\mathbf{q}_-)^2 (\mathbf{q}+\mathbf{p}_-)^2} \right], \tag{33}$$

and for the case $a = b$

$$d\sigma(\gamma\gamma \to a\bar{a}a\bar{a}) = \frac{\alpha^4}{\pi} x_+ x_- y_+ y_- \frac{dx_- dy_- d^2q_- d^2p_- d^2q}{\mathbf{p}_-^2 \mathbf{q}_-^2} \times \\ \times \frac{S_{1(a)} S_{2(a)}}{(\mathbf{q}+\mathbf{q}_-)^2 (\mathbf{q}-\mathbf{p}_-)^2}, \tag{34}$$

where

$$S_{1(a)} = \frac{\mathrm{Tr}\,(\rho_1\, \mathcal{M}_{1(a)})}{\mathbf{q}^2 \mathbf{Q}^2 N_1^2}, \quad S_{2(a)} = \frac{\mathrm{Tr}\,(\rho_2\, \mathcal{M}_{2(a)})}{\mathbf{q}^2 \mathbf{Q}^2 N_2^2}. \tag{35}$$

REFERENCES

1. *Badelek B. et al.* TESLA Technical Design Report. Part VI. Ch. 1. DESY 2001-011; 2001-209; TESLA Report 2001-23. 2001; hep-ex/0108012;
   Ginzburg I. F. et al. // Nucl. Instr. Meth. A. 1984. V. 219. P. 5.
2. *Ginzburg I. F. et al.* // Yad. Fiz. 1983. V. 38. P. 1021.
3. *de Causmaecker P. et al.* // Nucl. Phys. B. 1982. V. 206. P. 53–60;
   Berends F. A. et al. // Ibid. P. 61–89.
4. *Berestetsky V. B., Lifshitz E. M., Pitaevsky L. P.* Relativistic Quantum Theory. M., 1968. V. IV. Part 1. P. 45.
5. *Bartoš E. et al.* hep-ph/0308045; Nucl. Phys. B. (accepted).
6. *Bartoš E. et al.* hep-ph/0308044; Nucl. Phys. B. (accepted).