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SHAKHNAZARYAN Yu. G.

ANGULAR DISTRIBUTIONS OF THREE-JET EVENTS IN POLARIZED e^+e^- - PAIR ANNIHILATION

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Ю.Г.ШАХНАЗАРЯН

УГЛОВЫЕ РАСПРЕДЕЛЕНИЯ ТРЕХСТРУЙНЫХ СОБЫТИЙ В ПРОЦЕССЕ АННИГИЛЯЦИИ ПОЛЯРИЗОВАННОЙ e^+e^-- ПАРЫ

В первом порядке по "константе" α_s , в рамках квантовой хромодинамики,изучена зависимость от полярного и азимутального углов пространственной ориентации и величины вектора $\vec{T}$ максимально направленного импульса сечения образования трех струй адронов в e^+e^- - аннигиляции в случае учета поляризаций начальных частиц.

Ереванский физический институт

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The dependence of the hadronic three jets production cross section in e^+e^--annihilation, taking into account the primary particles polarization, on polar and azimuthal angles of spatial orientation as well as on the value of the thrust vector $\vec{T}$ is studied in the first order in "constant" α_s in the framework of quantum chromodynamics.

Yerevan Physics Institute

Yerevan 1982

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ANGULAR DISTRIBUTIONS OF THREE-JET EVENTS IN POLARIZED e^+e^- - PAIR ANNIHILATION

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The discovery of three-jet events in e^+e^- annihilation [1] was the first direct experimental proof of the existence of gluon and served a weighty argument in favour of quantum chromodynamics (QCD) with which the hope for the construction of strong interaction theory is connected. At present it is generally accepted that three-jet events of hadron production in e^+e^- annihilation are due to the initial process [2, 3]

$$e^+ + e^- \rightarrow q + \bar{q} + g, \tag{1}$$

in which quark or antiquark emits at short distances hard gluon. Further on, already at sufficiently large distances a fragmentation of the mentioned partons into hadrons occurs that results in three jets of hadrons observed in the experiment. QCD permits one to describe the initial, hard part of the hadron production process as well as to make predictions for a definite class of quantities which are less than others sensitive to the details of quark and gluon transformation into hadrons. Here belong the total cross section of e^+e^--pair annihilation to hadrons calculated [4] already to the second order in α_s as well as the distributions in such parameters as spherocity S [5], thrust T [6], acomplanarity A [7] and some others which are characteristics of jettiness of events.

Beginning from the first works [1, 3, 5-8] up to the present time the process (1) has been intensively studying both experimentally and theoretically. There is already calculated up to the second order in α_s the Sterman-Weinberg type [8] cross section [9] of formation of hadronic three-jets as well as the distribution in variable T [10] . In a number of works the influence of quark mass account [11] on one or another characteristic of process (1), the angular dependences [12] and some other questions were studied. All that was done with the aim to check up the main propositions of QCD, the vector nature of a gluon as well as to find out the parameter α_s .

The object we persue in this work is somewhat different. Assuming that QCD is valid, gluon spin is 1 and the perturbation theory calculations make sense, we are interested in a question whether one can by means of studying angular dependence of the process (1) cross section in the case of polarized primaries claim that the hadronic jet produced at this angle or another is predominantly the quark-antiquark or gluonic one.

In the first order of QCD the color summed differential cross section of process (1) with due regard for the primary particles polarization has the form:

$$d\sigma = \frac{\alpha^2 \alpha_s Q_a^2}{(2\pi)^2} \frac{1}{S} \frac{1}{(1-x_1)(1-x_2)} \Big\{ 2(x_1^2 + x_2^2)(1+\xi_1^{\parallel}\xi_2^{\parallel}) - x_1^2\Big[(1+\vec{\xi}_1\vec{\xi}_2)(1-z_1^2) - 2(\vec{n}_1\vec{\xi}_1^{\perp})(\vec{n}_1\vec{\xi}_2^{\perp})\Big] - x_2^2\Big[(1+\vec{\xi}_1\vec{\xi}_2)(1-z_2^2) - 2(\vec{n}_2\vec{\xi}_1^{\perp})(\vec{n}_2\vec{\xi}_2^{\perp})\Big]\Big\} \cdot dx_1\, dx_2\, dz_1\, d\varphi_1\, d\varphi_2' \,. \qquad (2)$$

Here

$$\alpha_s(S) = \frac{12\pi}{(33-2N_a)\ln\frac{S}{\Lambda^2}} \,,$$

S is the reaction total energy square, Λ is the theory parameter.

N_a is the number of active flavours, Q_a is the charge of q_a quark of a flavour in e units, $\vec{\xi}_{1(2)}$ is the electron (positron) polarization vector in its own rest frame, $x_i = 2E_i/\sqrt{s}$ is a relative energy share of i - parton (i = 1, 2, 3 for quark, antiquark and gluon, respectively), $\vec{n}_i$ is unit vector along i -parton momentum. With these quantities the energy and momentum conservation laws are written down in the form:

$$x_1 + x_2 + x_3 = 2, \qquad x_1 \vec{n}_1 + x_2 \vec{n}_2 + x_3 \vec{n}_3 = 0. \tag{3}$$

The angular variables are defined as follows: $z_i = \cos\theta_i$, θ_i is vector $\vec{n}_i$ polar angle in coordinate frame with the z axis along electron momentum characterized by the unit vector $\vec{v}$, φ_1 is azimuthal angle between electron polarization plane ($\vec{v}$, $\vec{\xi}_1$) and quark production plane ($\vec{v}$, $\vec{n}_1$) in the mentioned coordinates, φ_2' is azimuthal angle between ($\vec{n}_1, \vec{v}$) and ($\vec{n}_1, \vec{n}_2$) planes in coordinates with the polar axis along $\vec{n}_1$ vector.

Integrating the cross section (2) over angular variables results in the well-known expression [3, 5, 6] with an additional factor ($1+\xi_1^{\parallel} \xi_2^{\parallel}$) that reflects the fact of annihilating electron and positron helicity conservation

Our purpose is to study the angular dependence of the process (1) cross section, in particular, the azimuthal dependence in the polarized primary particles case. Since it is unknown so far how one can distinguish between quark and gluonic jets, it is necessary to study spatial orientation of quantities which characterize the jet irrespective of the fact whether it is quark (antiquark) or gluonic. As such quantity we use a thrust $\vec{T}$. For the transition in the cross section (2) to this variable one must divide the energy part of the phase volume into the regions [13]

$$\text{I}.\ x_1 \geq x_2 \geq x_3, \quad \text{II}.\ x_1 \geq x_3 \geq x_2, \quad \text{III}.\ x_3 \geq x_1 \geq x_2. \tag{4}$$

Note that there is no need for one to consider separately also the regions obtained from (4) by the replacement $x_1 \rightleftarrows x_2$, since the cross section (2) is invariant relative to the replacement of variables characterizing quark and antiquark. It is enough but redouble the result for each of the regions (4). If angular distributions allow one to refer one or another event to one of the mentioned regions, then belonging of the event to region I will mean that the least energetic jet is gluonic, and the other two ones are quark-antiquark. In region II the gluonic jet is intermediate in energy, and in region III it is the most energetic one.

Let us find out the $\vec{T}$ axis spatial distribution in separate regions (4). The variable $\vec{T}$ for regions I and II is defined by a quark jet. Taking $x_1 = T,\ dz\, d\varphi_1 = d\hat{\vec{T}}$ and integrating over φ_2' angle at a fixed value of the θ_{12} angle between quark and antiquark momenta for which

$$\cos\theta_{12} \equiv z_{12} = \frac{1}{2x_1x_2}\left(x_3^2 - x_1^2 - x_2^2\right)$$

having in mind that

$$z_2 = z_1 z_{12} + \sqrt{(1-z_1^2)(1-z_{12}^2)}\cos\varphi_2'$$

and

$$\int_0^{2\pi}(\vec{n}_2\vec{\xi}_1^{\perp})(\vec{n}_2\vec{\xi}_2^{\perp})d\varphi_2' = \pi\left[(1-z_{12}^2)(\vec{\xi}_1^{\perp}\vec{\xi}_2^{\perp}) + (3z_{12}^2-1)(\vec{n}_1\vec{\xi}_1^{\perp})(\vec{n}_1\vec{\xi}_2^{\perp})\right]$$

we come to the expression

$$\frac{d\sigma}{dT\,d\hat{\vec{T}}\,dx_2} = \frac{\alpha^2\alpha_s Q_a^2}{2\pi}\frac{1}{s}\frac{1}{(1-T)(1-x_2)}\Big\{\left[(T^2+x_2^2)(1+z_1^2)+\frac{1}{2}x_2^2(1-\right.$$

$$\left.-z_{12}^2)(1-3z_1^2)\right](1+\xi_1^{\parallel}\xi_2^{\parallel}) + \left[T^2+\frac{1}{2}x_2^2(3z_{12}^2-1)\right]\left[2(\hat{\vec{T}}\vec{\xi}_1^{\perp})(\hat{\vec{T}}\vec{\xi}_2^{\perp}) - (1-z_1^2)(\vec{\xi}_1^{\perp}\vec{\xi}_2^{\perp})\right]\Big\} \quad (5)$$

To find out the region I distribution we are interested in, the last cross section should be integrated over x_2 in the limits [13]

$$1-\frac{T}{2}\leq x_2\leq T.$$

After the summation of the obtained expression over all the flavours and its subsequent normalization to the total cross section of the process of $e^+e^-\to$ hadrons in the first order in α_s

$$\sigma_{tot}\equiv\sigma(e^+e^-\to hadrons)=3\sigma_{\mu\mu}\sum_a Q_a^2\left(1+\frac{\alpha_s}{\pi}\right)=\frac{4\pi\alpha^2}{s}\sum_a Q_a^2\left(1+\frac{\alpha_s}{\pi}\right) \quad (6)$$

we come to the following distribution

$$\frac{1}{\sigma_{tot}}\frac{d\sigma_n}{dTd\hat{T}}=\frac{\alpha_s}{4\pi^2}\left(1+\frac{\alpha_s}{\pi}\right)^{-1}\Big\{A_n(T)\Big[(1+z^2)(1+\xi_1^{\parallel}\xi_2^{\parallel})-(1-z^2)(\vec{\xi}_1^{\perp}\vec{\xi}_2^{\perp})+2(\hat{\vec{T}}\vec{\xi}_1^{\perp})\cdot$$
$$\cdot(\hat{\vec{T}}\vec{\xi}_2^{\perp})\Big]+B_n(T)\Big[(1-3z^2)(1+\xi_1^{\parallel}\xi_2^{\parallel})+3\big((1-z^2)(\vec{\xi}_1^{\perp}\vec{\xi}_2^{\perp})-2(\hat{\vec{T}}\vec{\xi}_1^{\perp})(\hat{\vec{T}}\vec{\xi}_2^{\perp})\big)\Big]\Big\}, \quad (7)$$

where the coefficients $A_n(T)$ and $B_n(T)$ dependent only on the vector $\vec{T}$ modulus for the region $n = I$ are equal to

$$A_I=\frac{1}{1-T}\Big[(1+T^2)\ln\frac{T}{2(1-T)}-\frac{1}{8}(3T-2)(6+T)\Big], \quad (8)$$

$$B_I=\frac{1}{4T^2}(3T-2)(5T-2).$$

Here and below through z we denote the angle cosine between the momentum of the most energetic parton and that of electron.

The corresponding distribution in region II can be obtained by integrating (5) over X_2 in the limits [13]

$$2(1-T)\leq X_2\leq 1-\frac{T}{2}.$$

Finally we come to the expression (7) in which

$$A_{II}=\frac{1}{1-T}\Big[(1+T^2)\ln\frac{2(2T-1)}{T}-\frac{5}{8}(3T-2)(2-T)\Big], \quad (9)$$
$$B_{II}=\frac{1}{4T^2}(3T-2)(2-T).$$

To find out the distribution in region III, where the gluonic jet is most energetic, one has to express the initial cross section (2) through the variables of gluon and, for example, of quark using the conservation laws. The phase volume here may be written down as

$$d\phi = dx_1\, dx_3\, dz_3\, d\varphi_3\, d\varphi_1'' ,$$

where $z_3 = \cos\theta_3$, θ_3 and φ_3 are polar and azimuthal angles of gluon emission in coordinate frame with the polar axis along $\vec{v}$, φ_1'' is the azimuthal angle between ($\vec{n}_3, \vec{v}$) and ($\vec{n}_3, \vec{n}_1$) planes in coordinate frame with the polar axis along the $\hat{\vec{n}}_3$ vector. In the region under consideration $X_3 = T$, $dz_3 d\varphi_3 = d\vec{T}$. After integrating over azimuthal angle φ_1'' at fixed value of

$$\cos\theta_{13} \equiv z_{13} = \frac{1}{x_1 x_3}\left[2(1-x_1-x_3) + x_1 x_3\right]$$

we get

$$\frac{d\sigma}{dT\, d\vec{T}\, dx_1} = \frac{\alpha^2 \alpha_s Q_a^2}{2\pi}\,\frac{1}{S}\,\frac{1}{(1-x_1)(T+x_1-1)}\Big\{\Big[\big((2-T-x_1)^2+x_1^2\big)(1+z_3^2)+x_1^2(1-z_{13}^2)(1-$$
$$-3z_3^2)\Big](1+\xi_1^{\parallel}\xi_2^{\parallel})+\left[(2-T-x_1)^2+x_1^2(3z_{13}^2-2)\right]\Big[2(\hat{\vec{T}}\vec{\xi}_1^{\perp})(\hat{\vec{T}}\vec{\xi}_2^{\perp}) -$$
$$-(1-z_3^2)(\vec{\xi}_1^{\perp}\vec{\xi}_2^{\perp})\Big]\Big\} . \qquad (10)$$

Finally, integrating the last expression over X_1 in the limits [13]

$$1-\frac{T}{2} \leq x_1 \leq T$$

and summing up over all flavours, for region III distribution we again come to (7) in which

$$A_{III} = \frac{1}{T}\left[2(1-T)+T^2\right]\ln\frac{2T-1}{1-T} - 3T + 2 , \qquad (11$$

$$B_{III} = \frac{2}{T^2}(3T-2)(1-T).$$

The distribution in momentum and emission angles of the most energetic parton irrespective of the fact whether it is quark, antiquark or gluon one can find by adding together the distributions in separate regions

$$\frac{d\sigma}{dT\, d\vec{T}} = \sum_{n=I,II,III} \frac{d\sigma_n}{dT\, d\vec{T}}$$

i.e. the total distribution is also defined by expression (7) in which one should introduce replacements $A_n \to A$ and $B_n \to B$, where

$$A = \sum_{n=I,II,III} A_n = \frac{2-3T(1-T)}{T(1-T)} \ln \frac{2T-1}{1-T} - \frac{3}{2} \frac{(3T-2)(2-T)}{1-T}, \qquad (12)$$

$$B = \sum_{n=I,II,III} B_n = \frac{1}{T^2}(3T-2)(2-T).$$

As one can readily see, the distributions in separate regions and consequently the total distribution turn to zero at the lower limit of T variation, namely at T = 2/3.

Let us dwell at length on a more interesting case of transverse antiparallel completely polarized primary particles, when

$$\xi_1^{\parallel} = \xi_2^{\parallel} = 0, \quad \vec{\xi}_1^{\perp} = -\vec{\xi}_2^{\perp}, (\vec{\xi}_1^{\perp} \vec{\xi}_2^{\perp}) = -1, \quad (\hat{\vec{T}} \vec{\xi}_1^{\perp}) = -(\hat{\vec{T}} \vec{\xi}_2^{\perp}) = \sin\theta\cos\varphi; \qquad (13)$$

the azimuthal angle φ is referenced from the $(\vec{v}, \vec{\xi}_1^{\perp})$ plane. The distribution we are interested in takes a comparatively simple form:

$$\frac{1}{\sigma_{tot}} \frac{d\sigma_n}{dT\, d\vec{T}} = \frac{\alpha_s}{2\pi^2}\left(1+\frac{\alpha_s}{\pi}\right)^{-1}\left[A_n(T)(1-\sin^2\theta\cos^2\varphi) - B_n(T)(1-3\sin^2\theta\cos^2\varphi)\right], \qquad (14)$$

where coefficients A_n and B_n in the corresponding regions I - III are given by expressions(8), (9) and (11). The total distribution is determined by formulae (14) with coefficients A and B from (12). Note that the angular distribution as presented in(7) or (14) corresponds to the division of the cross section into two parts, one of which omits due to the polar and azimuthal angle integration, and coefficient $A_n(T)$ of the second part characterize the vector $\vec{T}$ modulus distribution in the corresponding region.

Emphasize that the angular dependence in all the cases is given by the $\sin^2\theta\cos^2\varphi$ combination. Therefore at $\varphi=\pi/2$ the cross sections must not depend on polar angle θ. It should be noted that the mentioned combination of the angles is invariant relative to $\theta\to\pi/2-\varphi$, $\varphi\to\pi/2-\theta$ replacements. As a result, the dependences on azimuthal angle φ at fixed θ_0 as well as on polar angle θ at fixed $\varphi_0=\pi/2-\theta_0$ must be determined by the same curves at opposite directions of increasing θ and φ angles These statements are illustrated by the plots in Figs.1-3, where at fixed values of T = 0.7, 0.8 and 0.9 is shown the azimuthal (polar) dependence of the quantity

$$F_n(\theta,\varphi)\equiv\frac{4\pi^2}{\alpha_s}\left(1+\frac{\alpha_s}{\pi}\right)\frac{1}{\sigma_{tot}}\frac{d\sigma_n}{dTd\vec{T}}=2\left[A_n(T)(1-\sin^2\theta\cos^2\varphi)-B_n(T)(1-3\sin^2\theta\cos^2\varphi)\right] \quad (15)$$

in regions I - III as well as in the total region at fixed $\theta(\varphi)$ (lower and upper scales, respectively). We have given the corresponding dependences in the θ and φ angular intervals from 0 to $\pi/2$. It is obvious that at fixed φ the curves defining the θ -dependence in the interval from $\pi/2$ to π will be symmetric to the plotted curves relative to $\theta=\pi/2$, while at fixed θ the curves characterizing the azimuthal dependence in the interval from $\pi/2$ to π will be symmetric to the plotted curves relative to $\varphi=\pi/2$; as to the interval from π to 2π, the mentioned azimuthal dependence will reproduce again.

One may be interested in the θ distribution at all the values of φ :

$$K_n(\theta) \equiv \int_0^{2\pi} F_n(\theta,\varphi)d\varphi = 2\pi\left[A_n(T)(1+\cos^2\theta) - B_n(T)(2-3\sin^2\theta)\right] \quad (16)$$

as well as in the φ distribution at all the values of θ :

$$L_n(\varphi) \equiv \int_0^{\pi} F_n(\theta,\varphi)\sin\theta d\theta = 4\left[A_n(T)(1-\frac{2}{3}\cos^2\varphi) - B_n(T)(1-2\cos^2\varphi)\right]. \quad (17)$$

The corresponding dependences at some values of T are given in Fig.4

After integrating (16) or (17) over the remaining angle we come to the expression

$$\frac{1}{\sigma_{\mu\mu}}\frac{d\sigma_n}{dT} = 4\frac{\alpha_s}{\pi}\sum_a Q_a^2 A_n(T) \quad (18)$$

coinciding with the results of our previous work [13] for the separate regions (taking no account of quark mass) and work [7] for total distribution.

What conclusions can be done on the basis of the given plots? At all the values of T in the whole angular interval region I dominates over region II. At T = 0.7 (see Fig.1) region III contribution is, in fact, independent of angles . At $\varphi \lesssim 30^0$ there is the region of θ angles in which the relative contribution of region III prevails over the regions I and II contributions, achieving 46.2% against 28.8 (I) and 25% (II) at φ = 0 and θ = 90^0. Note that in the other limiting case (φ = 90^0 or θ = 0) the relative contributions of regions I - III are equal to 42.6, 34 and 23.4%, respectively. As one can see, at T = 0.7 the contributions of separate regions I - III do not differ much in magnitude.

A considerable total increase of absolute values of all the regions contributions is noticeable at T = 0.8 (see Fig.2). The angular dependence is rather weak for the region III. The relative contributions of separate regions

I - III in the limiting cases are respectively 60.3, 26.9 and 12.8% at Θ = 0 or φ = 90°; 41.7, 25 and 33.3% at Θ = 90° and φ = 0.

At T = 0.9 (see Fig.3) the absolute contributions of separate regions differ much, therefore, as distinct from the two previous cases, a logarithmic scale is used here. One can readily see that at already $\Theta \gtrsim 45^\circ$ ($\varphi \lesssim 45^\circ$) a rather strong angular dependence takes place in all the regions. The relative contributions of regions I - III in the limiting cases are as follows: 75.2, 19.5 and 5.3% at Θ = 0 or φ = 90°; 56.8, 25 and 18.2% at Θ = 90° and φ = 0.

For the integral dependences $K_n(\Theta)$ and $L_n(\varphi)$ the statistics is noticeably larger (see Fig.4). It should be noted that the maxima for them like those in case of $F_n(\Theta,\varphi)$ are reached, respectively, at Θ = 0 and φ = 90°. As already at one of the mentioned values the angular dependence in $F_n(\Theta,\varphi)$ is absent at all, the maximum relative contributions of regions I - III to the integral dependences $K(\Theta)$ and $L(\varphi)$ will be the same as their contributions in $F(\Theta,\varphi)$ (for definite T values they were given above).

Following the above estimates one may conclude that the most favourable from the viewpoint of the quark-antiquark and gluonic jets identification are the events with possibly large values of T. Thus, if at studying the process (1) at Θ = 0 or φ = 90° we detect the jet with maximum momentum for which $T \doteq 0.9$, then in 95 out of 100 events the jet will be quark or antiquark and in 5 events it will be gluonic. One can assert that under the same conditions the jet with minimum momentum will be gluonic in 75% of events.

We have restricted ourselves to the consideration of the values of $T \lesssim 0.9$ since at $T \to 1$ an infra-red divergence arises, due to which the perturbation theory becomes inapplicable.

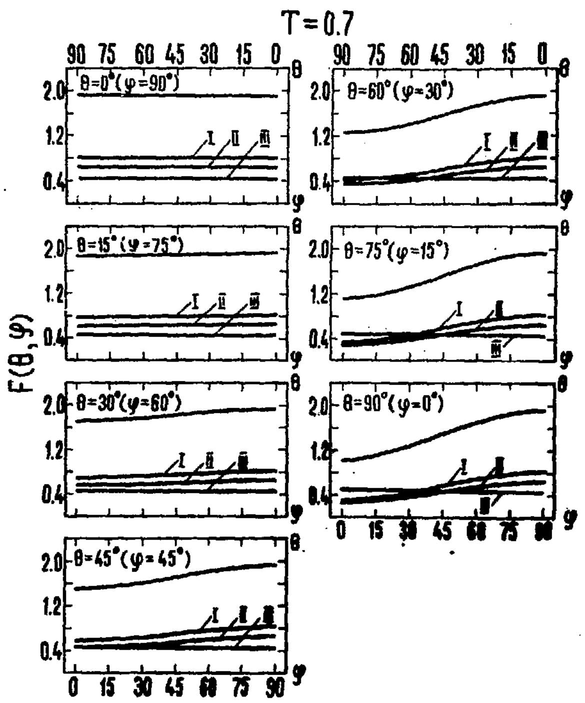
T=0.7
F(θ,φ)
θ=0°(φ=90°)
θ=15°(φ=75°)
θ=30°(φ=60°)
θ=45°(φ=45°)
θ=60°(φ=30°)
θ=75°(φ=15°)
θ=90°(φ=0°)

Рис.I

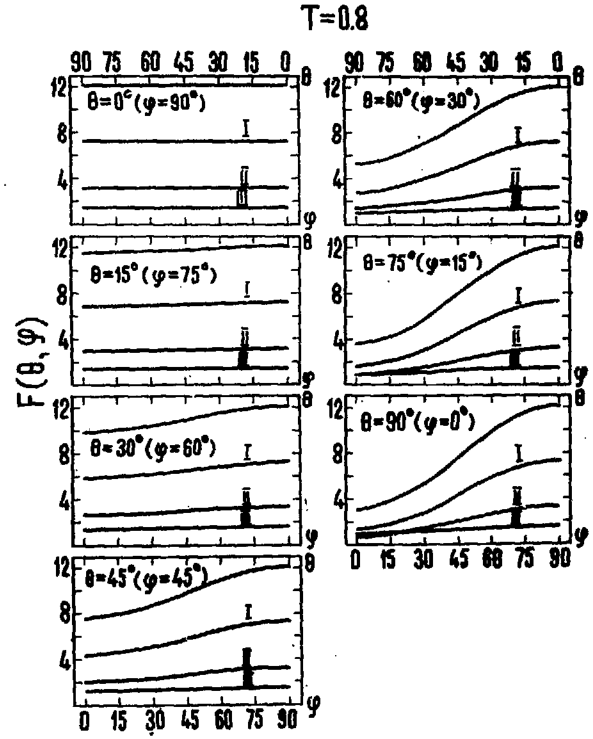
T=0.8
F(θ,φ)
θ=0°(φ=90°)
θ=15°(φ=75°)
θ=30°(φ=60°)
θ=45°(φ=45°)
θ=60°(φ=30°)
θ=75°(φ=15°)
θ=90°(φ=0°)

Рис.2

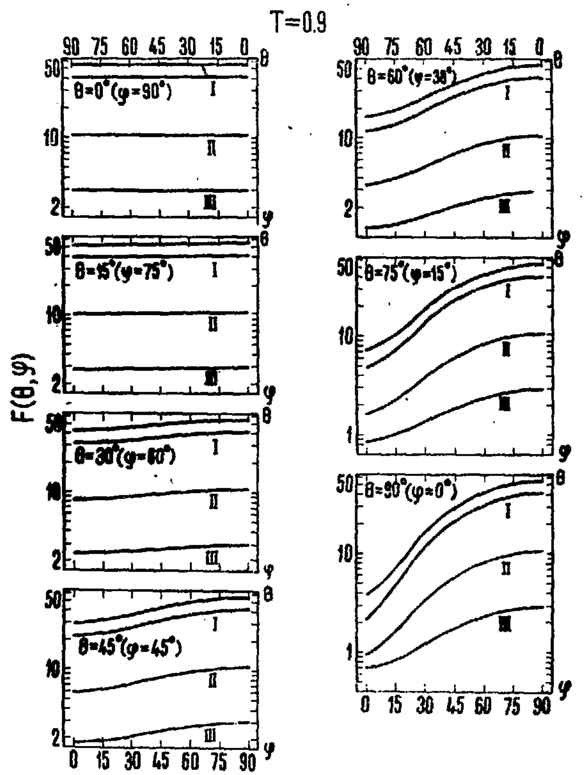
T=0.9
F(θ,φ)
θ=0°(φ=90°)
θ=15°(φ=75°)
θ=30°(φ=60°)
θ=45°(φ=45°)
θ=60°(φ=30°)
θ=75°(φ=15°)
θ=90°(φ=0°)
I
II
III

Рис 3

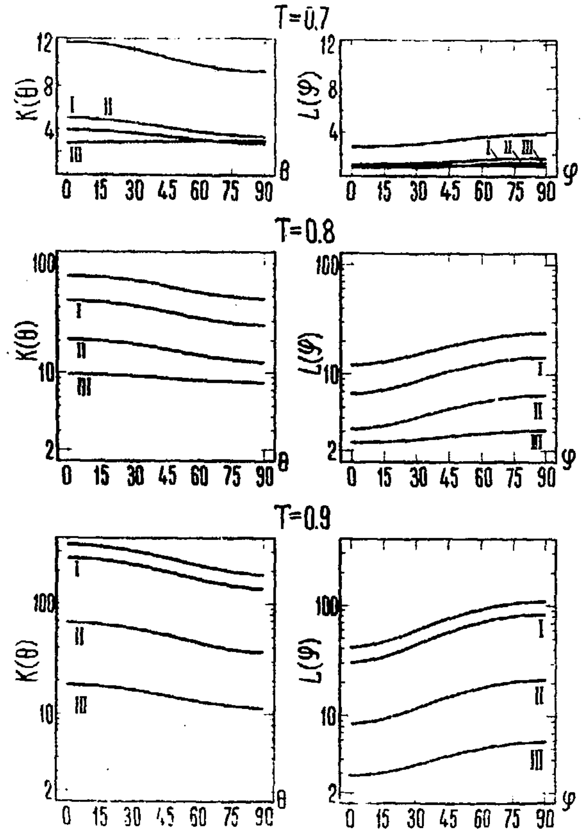
T=0.7
T=0.8
T=0.9
K(θ)
L(φ)
I
II
III

Рис 4

FIGURE CAPTIONS

Fig.1. The dependence of $F(\Theta,\varphi)$, i.e. normalized on ($\frac{\alpha_s}{4\pi^2}\,\frac{\sigma_{tot}}{1+\frac{\alpha_s}{\pi}}$) value differential cross section of process (1) on the azimuthal angle φ at some values of polar angle Θ (lower scale) and on polar angle Θ at some values φ' (upper scale) for the fixed value of T = 0.7; the corresponding dependences for separate regions are marked by I, II and III.

Fig.2. The same as in Fig.1 for T = 0.8.

Fig.3. The same as in Fig.1 for T = 0.9.

Fig.4. The dependence of the process (1) differential cross section on the polar $[K(\Theta)]$ and azimuthal $[L(\varphi)]$ angles at T = 0.7, 0.8 and 0.9; the corresponding dependences for the separate regions are marked by I, II and III.

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СОБЫТИЙ В ПРОЦЕССЕ АННИГИЛЯЦИИ ПОЛЯРИЗОВАННОЙ e^+e^- - ПАРЫ

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