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ANGULAR DISTRIBUTIONS OF HADRON JETS IN e^+e^- ANNIHILATION FROM QCD: γ-Z INTERFERENCE

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Abstract:

Angular correlations and asymmetries of $q\bar{q}$ and $q\bar{q}g$ initiated jets are calculated including the Z - boson besides the virtual photon. A sizable forward-backward and azimuthal asymmetry due to the weak neutral current is predicted already for upper PETRA and PEP energies.

The study of hadron jets in $e^+ e^-$ annihilation provides one of the cleanest tests of perturbative QCD. With higher energies coming in sight, there will be an increasing admixture of the weak neutral current. This will give additional information on the dynamics of quarks and gluons at short distances. Beyond that, we expect to get a glimpse of the Z-boson long before it will be produced.

At lower energies ($\sqrt{q^2} \lesssim 50$ GeV) the relative contribution of the Z is roughly $\sim 1/|Q|$ where Q is the charge of the particle being produced. Hence, for $Q = -1/3$ ($Q = 2/3$) quark production the γ - Z interference effects are ~ 3 (3/2) times larger than for $e^+ e^- \to \mu^+ \mu^-$, which favours $e^+ e^-$ annihilation into hadrons to search for the Z-boson, in spite of the somewhat lower statistics ($\sim Q^2$).

In this letter we shall extend our previous work [1] on the topology of hadron jets in $e^+ e^-$ annihilation by considering the process

$$e^+ e^- \to \gamma, Z \to q \bar{q} g , \tag{1}$$

which also includes the zeroth order process $e^+ e^- \to \gamma, Z \to q \bar{q}$ as a limiting case.

The electromagnetic and weak (neutral current) couplings are defined by [2]

$$\mathcal{L}_{e.m.} = i|e|\{-\bar{e}\gamma_\mu e + \sum_{f(\text{lavour})} \sum_{c(\text{olour})} Q_f \bar{q}_{fc} \gamma_\mu q_{fc} \} A^\mu ,$$

$$\mathcal{L}_{n.c.} = i|e| M_Z \sqrt{g} \{\bar{e}\gamma_\mu(v + a\gamma_5)e + \sum_f \sum_c \bar{q}_{fc}\gamma_\mu(v_f + a_f\gamma_5) q_{fc}\} Z^\mu , \tag{2}$$

whereas the strong interaction between the quarks and gluons is described by conventional QCD (coloured vector gluons). In eq. (2) M_Z is the mass of the Z-boson and $g = G_F(8\sqrt{2}\pi\alpha)^{-1} \approx 4.49\ 10^{-5}\ \mathrm{GeV}^{-2}$ ($\alpha = e^2/4\pi$), G_F being the Fermi weak coupling constant. In the Weinberg-Salam model, e.g., we have

$$M_Z \sqrt{g} = 1/2 \sin 2\theta_W \,,$$

$$v = -1 + 4 \sin^2\theta_W \,, \qquad a = -1$$

(3)

$$v_f = \begin{cases} 1 - \frac{8}{3}\sin^2\theta_W \\ -1 + \frac{4}{3}\sin^2\theta_W \end{cases} , \quad a_f = \begin{cases} 1 & Q_f = \frac{2}{3} \\ -1 & Q_f = -\frac{1}{3} \end{cases}$$

with Θ_W being the Weinberg angle.

Let Θ be the angle between the incoming electron beam and the direction $\vec{Oz}$ (Fig. 1) of either the quark, antiquark or gluon, and χ be the azimuthal angle as defind in Fig. 1 which fixes the orientation of the $q\bar{q}g$ production plane with respect to the scattering plane. The cross section then reads

$$2\pi \frac{d^4\sigma}{d\cos\Theta \, d\chi \, dx_1 dx_2} = \frac{3}{8}(1+\cos^2\Theta)\frac{d^2\sigma_U}{dx_1 dx_2}$$

$$+ \frac{3}{4}\sin^2\Theta \frac{d^2\sigma_L}{dx_1 dx_2} + \frac{3}{4}\sin^2\Theta \cos 2\chi \frac{d^2\sigma_T}{dx_1 dx_2} \qquad (4)$$

$$- \frac{3}{2\sqrt{2}}\sin 2\Theta \cos\chi \frac{d^2\sigma_I}{dx_1 dx_2} - \frac{3}{\sqrt{2}}\sin\Theta\cos\chi \frac{d^2\sigma_A}{dx_1 dx_2}$$

$$+ \frac{3}{4}\cos\Theta \frac{d^2\sigma_P}{dx_1 dx_2}$$

where *) $x_i = 2\, p_i / \sqrt{q^2}$ $(x_1 + x_2 + x_3 = 2)$ and p_1, p_2, p_3 being the quark, antiquark and gluon momenta, respectively.

The cross sections σ_U, σ_L, σ_T and σ_I are the same as before apart from the replacement $\sum_f Q_f^2 \rightarrow G_1$:

---

*) All quark masses are taken to be zero, i.e., we assume $4\, m_f^2 / q^2 \ll 1$.

$$\frac{d^2\sigma_U}{dx_1 dx_2} = G_1 \tilde{\sigma}^{(1)} \frac{1}{(1-x_1)(1-x_2)} \frac{1}{2}\left[x_1^2(1+\hat{p}_{1z}^2)+x_2^2(1+\hat{p}_{2z}^2)\right] ,$$

$$\frac{d^2\sigma_L}{dx_1 dx_2} = G_1 \tilde{\sigma}^{(1)} \frac{1}{(1-x_1)(1-x_2)} \frac{1}{2}\left[x_1^2(1-\hat{p}_{1z}^2)+x_2^2(1-\hat{p}_{2z}^2)\right] ,$$

$$\frac{d^2\sigma_T}{dx_1 dx_2} = \frac{1}{2} \frac{d^2\sigma_L}{dx_1 dx_2} , \tag{5}$$

$$\frac{d^2\sigma_I}{dx_1 dx_2} = G_1 \tilde{\sigma}^{(1)} \frac{1}{(1-x_1)(1-x_2)} \frac{1}{2\sqrt{2}}\left[x_1^2\hat{p}_{1x}\hat{p}_{1z}+x_2^2\hat{p}_{2x}\hat{p}_{2z}\right] ,$$

$$\vec{p}_i = \frac{\sqrt{q^2}}{2}\hat{p}_i , \quad \hat{p}_{iy} = 0 , \quad \hat{p}_{ix}^2 + \hat{p}_{iz}^2 = 1 .$$

Here $\tilde{\sigma}^{(1)} = 2\frac{\alpha_s}{\pi}\sigma_{\mu\mu}$, $\sigma_{\mu\mu}$ being the cross section for $e^+e^- \to \mu^+\mu^-$ and α_s the QCD running coupling constant, whereas

$$G_1 = \sum_f G_1^f ,$$

$$G_1^f = Q_f^2\,\Xi - 2Q_f \,\mathrm{Re}\,\rho(v\,\Xi - a\,\xi)v_f + |\rho|^2\left[(v^2+a^2)\,\Xi - 2va\,\xi\right](v_f^2+a_f^2) , \tag{6}$$

$$\rho = \rho(q^2) = g\, M_Z^2 \frac{q^2}{q^2 - M_Z^2 + i M_Z \Gamma_Z} ,$$

$$\Xi = 1 + \xi^{(-)}\xi^{(+)} , \quad \xi = \xi^{(-)} + \xi^{(+)} .$$

Here $\xi^{(-)}$ and $\xi^{(+)}$ denote the longitudinal polarization of the electron and positron beam *), respectively, such that for pure helicity states $\xi^{(\pm)} = \mp h^{(\pm)}$. The cross sections σ_A and σ_P which give rise to an angular asymmetry in ($\Theta \to \pi - \Theta$, $\chi \to \pi - \chi$) correspond to the helicity amplitudes (in the notation of Ref.3) $b^1_{+1} + b^1_{-1}$ and b^1_0 , respectively. They have the form

$$\frac{d^2\sigma_A}{dx_1 dx_2} = G_5 \tilde{\sigma}^{(1)} \frac{1}{(1-x_1)(1-x_2)} \frac{1}{2\sqrt{2}} \left[x_1^2 \hat{p}_{1x} - x_2^2 \hat{p}_{2x} \right] , \tag{7}$$

$$\frac{d^2\sigma_P}{dx_1 dx_2} = G_5 \tilde{\sigma}^{(1)} \frac{1}{(1-x_1)(1-x_2)} \left[x_1^2 \hat{p}_{1z} - x_2^2 \hat{p}_{2z} \right] ,$$

where

$$G_5 = \sum_f G_5^f ,$$

$$G_5^f = -2 Q_f \,\mathrm{Re}\,\beta (a\Xi - v\xi) a_f + |\beta|^2 \left[2va\Xi - (v^2+a^2)\xi \right] 2 v_f a_f . \tag{8}$$

The cross section for producing one sort of flavour only is given by replacing $G_{1,5}$ by $G^f_{1,5}$. Equation (5) is a short-hand notation of eqs. (2) -(4) of Ref.1 with

$$\hat{p}_{ix} = \sin \Theta_{ik} , \quad \hat{p}_{iz} = \cos \Theta_{ik} , \quad i = 1,2 , \tag{9}$$

$$\cos \Theta_{ik} = \hat{p}_i \cdot \hat{p}_k = 1 - \frac{2}{x_i x_k} (x_i + x_k - 1) ,$$

where k labels the reference parton pointing into the z-direction, i.e., $\hat{p}_k = (0, 0, 1)$.

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*) Having integrated over ϕ , the azimuthal angle around the beam axis, the transverse polarization drops out.

The contribution (7) to the cross section constitutes (i) an azimuthal asymmetry of the event plane with respect to the scattering plane (term $\sim$ $\sin\Theta\cos\chi$) and (ii) a forward-backward asymmetry of the $\vec{Oz}$ axis with respect to the electron beam direction (term $\sim\cos\Theta$), both coupled with a charge asymmetry of quark versus antiquark distributions (alternate sign in eq. (7)). If quarks and antiquarks are not distinguished as is, e.g., the case if the final state is analyzed in terms of thrust, these asymmetries will vanish. Thus it will be necessary to tell at least which jet is the quark jet or which the antiquark jet.

How big an effect do we expect now? The three-jet events are found to have for various thrust (T) values, on the average, the following form [4), *)] ("typical event"):

$$
\begin{aligned}
&\underline{T = 0.7}: && \langle\cos\vartheta\rangle = -0.59, \\
& && T_2 = 0.68,\ T_3 = 0.62 \\
&\underline{T = 0.8}: && \langle\cos\vartheta\rangle = -0.78, \\
& && T_2 = 0.69,\ T_3 = 0.51 \\
&\underline{T = 0.9}: && \langle\cos\vartheta\rangle = -0.92, \\
& && T_2 = 0.74,\ T_3 = 0.36
\end{aligned}
\tag{1o}
$$

where ϑ is the angle between the thrust axis and the second most energetic jet, and T_2 (T_3) the thrust of the second most (least) energetic jet. Let us select those events in which the quark jet is most energetic (i.e., $T = x_1$) and has the direction $+\vec{Oz}$ (Fig.1). For the "typical event" we then obtain the following angular distributions:

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*) First we have calculated $\langle\cos\vartheta\rangle$. In the next step T_2 and T_3 have been determined from T and $\langle\cos\vartheta\rangle$.

$\underline{T = 0.7:}$

$$\sim\ 1 + \begin{pmatrix}0.44\\0.44\end{pmatrix}\cos^2\Theta + \begin{pmatrix}0.14\\0.14\end{pmatrix}\sin^2\Theta\cos 2\chi + \begin{pmatrix}0.18\\0.04\end{pmatrix}\sin 2\Theta\cos\chi$$

$$+\ \frac{G_5^f}{G_1^f}\left[\begin{pmatrix}0.67\\0.07\end{pmatrix}\sin\Theta\cos\chi + \begin{pmatrix}1.36\\1.36\end{pmatrix}\cos\Theta\right]$$

$\underline{T = 0.8:}$

$$\sim\ 1 + \begin{pmatrix}0.67\\0.67\end{pmatrix}\cos^2\Theta + \begin{pmatrix}0.08\\0.08\end{pmatrix}\sin^2\Theta\cos 2\chi + \begin{pmatrix}0.17\\0.10\end{pmatrix}\sin 2\Theta\cos\chi$$

$$+\ \frac{G_5^f}{G_1^f}\left[\begin{pmatrix}0.48\\0.20\end{pmatrix}\sin\Theta\cos\chi + \begin{pmatrix}1.64\\1.64\end{pmatrix}\cos\Theta\right] \qquad (11)$$

$\underline{T = 0.9:}$

$$\sim\ 1 + \begin{pmatrix}0.87\\0.87\end{pmatrix}\cos^2\Theta + \begin{pmatrix}0.03\\0.03\end{pmatrix}\sin^2\Theta\cos 2\chi + \begin{pmatrix}0.12\\0.10\end{pmatrix}\sin 2\Theta\cos\chi$$

$$+\ \frac{G_5^f}{G_1^f}\left[\begin{pmatrix}0.28\\0.19\end{pmatrix}\sin\Theta\cos\chi + \begin{pmatrix}1.87\\1.87\end{pmatrix}\cos\Theta\right]$$

where the upper (lower) values correspond to the case where $\vec{Ox}$ (Fig.1) points into the hemisphere of the antiquark (second most energetic) jet, henceforth called case A_1 (case B_1).

The quantities G_1^f and G_5^f have been shown in Figs. 2 and 3 for $Q_f = 2/3$ and $Q_f = -1/3$ and $\sin^2\Theta_W = 1/4$ *) (M_Z = 86.14 GeV). The width is taken to be Γ_Z = 2.24 GeV which corresponds to three lepton and three quark doublets [2]. For events in which the antiquark jet is the most energetic (i.e., $T = x_2$) and along $\vec{Oz}$ the terms proportional to G_5^f / G_1^f change sign while the rest remains the same. The case where the gluon jet is most energetic has relatively low weight ($\lesssim$ 10 %) so that it can be disregarded.

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*) For a summary on the Weinberg angle see Ref.5.

At lower energies $Q_f = -1/3$ quarks give rise to a larger effect than $Q_f = 2/3$ quarks ($\sim 1/ |Q_f|$) as can be deduced from Fig.3. For $Q_f = -1/3$ quark production and case A_1 the asymmetry should clearly be seen already at the upper PETRA and PEP energies where it is of the same order of magnitude as the symmetric counterpart. In passing to case B_1 the azimuthal correlation is somewhat reduced (a factor ~ 2 at T = o.8) while the rest remains unchanged. Above $\sim$ 7o GeV $Q_f = 2/3$ quarks begin to dominate. Right on the Z-resonance the asymmetry vanishes for $\sin^2\Theta_W = 1/4$ (cf. Fig.3). The measurement of the asymmetry at various energies can also be looked at as a test of the Weinberg-Salam model. From the energy dependence of G_1^f and of G_5^f/G_1^f all the v_f and all the a_f can be determined [2)], whereby longitudinal beam polarization is needed only in order to determine the signs of the v_f relative to the a_f.

In practice one will test <u>one</u> angular distribution at a time rather than the whole angular distribution displayed in eqs. (4) and (11). From eq. (4) we obtain (for one flavour production)

$$\frac{d^3\sigma^f}{d\cos\Theta\, dx_1 dx_2} = \frac{3}{8}\, \frac{d^2(\sigma_U^f + 2\sigma_L^f)}{dx_1\, dx_2}\left(1+\alpha_f \cos^2\Theta + 2\epsilon_f \cos\Theta\right), \tag{12}$$

$$\alpha_f = \frac{d(\sigma_U^f - 2\sigma_L^f)}{d(\sigma_U^f + 2\sigma_L^f)}, \quad \epsilon_f = \frac{d\sigma_T^f}{d(\sigma_U^f + 2\sigma_L^f)},$$

and

$$\frac{d^3\sigma^f}{d\chi\, dx_1 dx_2} = \frac{d^2(\sigma_U^f + \sigma_L^f - \sigma_T^f)}{dx_1\, dx_2}\left(1+\beta_f \cos^2\chi + 2\eta_f \cos\chi\right), \tag{13}$$

$$\beta_f = 2\, \frac{d\sigma_T^f}{d(\sigma_U^f + \sigma_L^f - \sigma_T^f)}, \quad \eta_f = \frac{3\pi}{4\sqrt{2}}\, \frac{d\sigma_A^f}{d(\sigma_U^f + \sigma_L^f - \sigma_T^f)}.$$

Note that due to the relation $\sigma_L = 2\,\sigma_T$, eq. (5), we have

$$\beta_f = \frac{2(1-\alpha_f)}{5+3\alpha_f} \quad . \tag{14}$$

For the various coefficients we predict, again based on the "typical three-jet event" (1o) and $T = x_1$, $\hat{p}_1 = (\,o, o, 1\,)$:

$\underline{T = 0.7}$:

$$\alpha_f = \begin{pmatrix}0.37\\0.37\end{pmatrix},\ \epsilon_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}0.68\\0.68\end{pmatrix},\ \beta_f = \begin{pmatrix}0.18\\0.18\end{pmatrix},\ \eta_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}-0.25\\-0.03\end{pmatrix}$$

$\underline{T = 0.8}$:

$$\alpha_f = \begin{pmatrix}0.67\\0.67\end{pmatrix},\ \epsilon_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}0.82\\0.82\end{pmatrix},\ \beta_f = \begin{pmatrix}0.09\\0.09\end{pmatrix},\ \eta_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}-0.16\\-0.07\end{pmatrix} \tag{15}$$

$\underline{T = 0.9}$:

$$\alpha_f = \begin{pmatrix}0.87\\0.87\end{pmatrix},\ \epsilon_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}0.93\\0.93\end{pmatrix},\ \beta_f = \begin{pmatrix}0.03\\0.03\end{pmatrix},\ \eta_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}-0.09\\-0.06\end{pmatrix}$$

where the upper (lower) numbers correspond to case A_1 (case B_1). Only η_f changes in passing from case A_1 to case B_1. For the average quantities

$$\langle\cos\Theta\rangle_f = \frac{1}{2}\,\frac{d\sigma_P^f}{d(\sigma_U^f+\sigma_L^f)} \quad , \quad \langle\cos\chi\rangle_f = \frac{3\pi}{4\sqrt{2}}\,\frac{d\sigma_A^f}{d(\sigma_U^f+\sigma_L^f)} \tag{16}$$

we obtain

$$\underline{T = 0.7}: \quad \langle\cos\Theta\rangle_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}0.39\\0.39\end{pmatrix},\ \langle\cos\chi\rangle_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}-0.23\\-0.02\end{pmatrix}$$

$$\underline{T = 0.8}: \quad \langle\cos\Theta\rangle_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}0.45\\0.45\end{pmatrix},\ \langle\cos\chi\rangle_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}-0.15\\-0.06\end{pmatrix} \tag{17}$$

$$\underline{T = 0.9}: \quad \langle\cos\Theta\rangle_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}0.48\\0.48\end{pmatrix},\ \langle\cos\chi\rangle_f = \frac{G_S^f}{G_1^f}\begin{pmatrix}-0.09\\-0.06\end{pmatrix}$$

Again, the effect is quite large even far below the Z-pole.

So far our analysis was based on the assumption that at least the quark and/or antiquark jet were located and that one could tell if it had charge $Q_f = 2/3$ or $Q_f = -1/3$. In principle this should be possible by looking at the net charge of the jet and the jet fragments. Here, heavy quarks (e.g., c quarks)have a slight advantage as they can relatively easy be reconstructed.

A different approach would be to study semiinclusive hadron production, i.e., to weight quarks and antiquarks by their fragmentation functions and sum over quarks and antiquarks which go together with the selected hadron. This leaves a final effect due the fact that the fragmentation functions for a quark and antiquark into the same hadron h, D_q^h and $D_{\bar q}^h$, are different for $h \neq \bar h$. Let us assume that $\vec{Oz}$ is the thrust axis and define $\vec{Ox}$ to point into the hemisphere of the second most energetic jet (similar to the case B_1). Then the various cross sections for finding a hadron h along the thrust axis, i.e., arising from the most energetic parton, with fractional momentum $z = x/T$, T fixed, read

$$\frac{d^2(\sigma_U^h+\sigma_L^h)}{dT\,dz} = G_1^f\tilde\sigma^{(1)}\Big\{\Big[-\frac{(4-T)(3T-2)}{2(1-T)}+\frac{1+T^2}{1-T}\ln\Big(\frac{2T-1}{1-T}\Big)\Big]\big(D_{q_f}^h(z)+D_{\bar q_f}^h(z)\big)$$
$$-\Big[-2(3T-2)+\frac{2(2-2T+T^2)}{T}\ln\Big(\frac{2T-1}{1-T}\Big)\Big]D_g^h(z)\Big\},$$

$$\frac{d^2\sigma_L^h}{dT\,dz} = G_1^f\tilde\sigma^{(1)}\Big\{\frac{(3T-2)}{T}\big(D_{q_f}^h(z)+D_{\bar q_f}^h(z)\big)+\frac{4(1-T)(3T-2)}{T^2}D_g^h(z)\Big\},$$

$$\frac{d^2\sigma_T^h}{dT\,dz} = \frac{1}{2}\,\frac{d^2\sigma_L}{dT\,dz},$$

$$\frac{d^2\sigma_I^h}{dT\,dz} = G_1^f\tilde\sigma^{(1)}\Big[\frac{2}{T}\sqrt{2T-1}-\frac{1}{\sqrt{1-T}}\Big]\Big[\frac{1}{\sqrt2}\big(D_{q_f}^h(z)+D_{\bar q_f}^h(z)\big)+\sqrt2\,\frac{(1-T)(2-T)}{T}D_g^h(z)\Big], \tag{18}$$

$$\frac{d^2\sigma_A^h}{dT\,dz} = G_5^f\tilde\sigma^{(1)}\frac{1}{\sqrt2}\Big[\frac{2}{T}\sqrt{2T-1}-\frac{1}{\sqrt{1-T}}\Big]\big(D_{q_f}^h(z)-D_{\bar q_f}^h(z)\big),$$

$$\frac{d^2\sigma_P^h}{dT\,dz} = G_5^f\tilde\sigma^{(1)}\Big[-\frac{(4-2T+T^2)(3T-2)}{2T(1-T)}+\frac{1+T^2}{1-T}\ln\Big(\frac{2T-1}{1-T}\Big)\Big]\big(D_{q_f}^h(z)-D_{\bar q_f}^h(z)\big).$$

The different terms in (18) are self-explanatory. The cross sections (18) inserted into eqs. (4), (12), (13) and (16) will give the corresponding angular distributions and asymmetries. It should be noted that these cross sections are smaller than the jet cross sections discussed before. The jet cross sections associated with the various species of partons (forming the thrust axis), where the momenta of the recoiling less energetic jets have been integrated out, are given by the coefficients multiplying $D^h_{q_f}$, $D^h_{\bar{q}_f}$ and D^h_g, respectively.

In zeroth order perturbation theory (naive parton model) there will be a forward-backward asymmetry $\sim \cos\Theta$. This asymmetry can be derived from eq. (18) by letting $T \to 1$, i.e., when the internal quark goes on mass shell. In this order we obtain the distribution *)

$$\sim (1+\cos^2\Theta)\left(D^h_{q_f}(x)+D^h_{\bar{q}_f}(x)\right)+2\cos\Theta\,\frac{G_5^f}{G_1^f}\left(D^h_{q_f}(x)-D^h_{\bar{q}_f}(x)\right). \qquad (19)$$

Here the polar asymmetry is of the same order of magnitude as found in (15).

For the time being we conclude that the γ - Z interference should become visible with reasonable statistics already at the upper PETRA and PEP energies.

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*) For details see Ref.6.

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Figure Captions

Fig. 1 Definition of angles Θ and χ . The q, $\bar{q}$ and g momenta lie in the (x,z) plane. The z-axis ($+\overrightarrow{Oz}$) is along the direction of either the quark, antiquark or gluon. In our numerical analysis this will be the thrust axis, i.e., the direction of the most energetic jet. If the partons going into the $-\overrightarrow{Oz}$ direction are distinguished, the x-axis can be defined by either one of them. Another possibility is to define $\overrightarrow{Ox}$ to be in the direction of the fastes among the partons going into the hemisphere $-\overrightarrow{Oz}$ (i.e., the second most energetic jet if $\overrightarrow{Oz}$ is the thrust axis). For the actual definition see text.

Fig. 2 G_1^f as a function of $\sqrt{q^2}$ for $Q_f = 2/3$ and $Q_f = -1/3$ quarks.

Fig. 3 The ratio G_5^f/G_1^f as a function of $\sqrt{q^2}$ for $Q_f = 2/3$ and $Q_f = -1/3$ quarks.

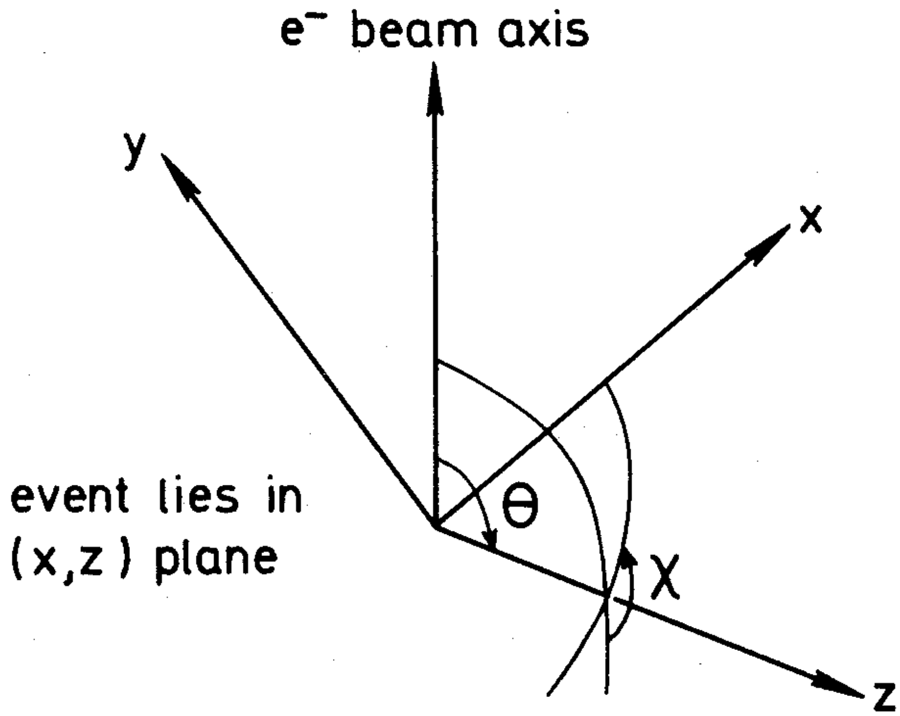
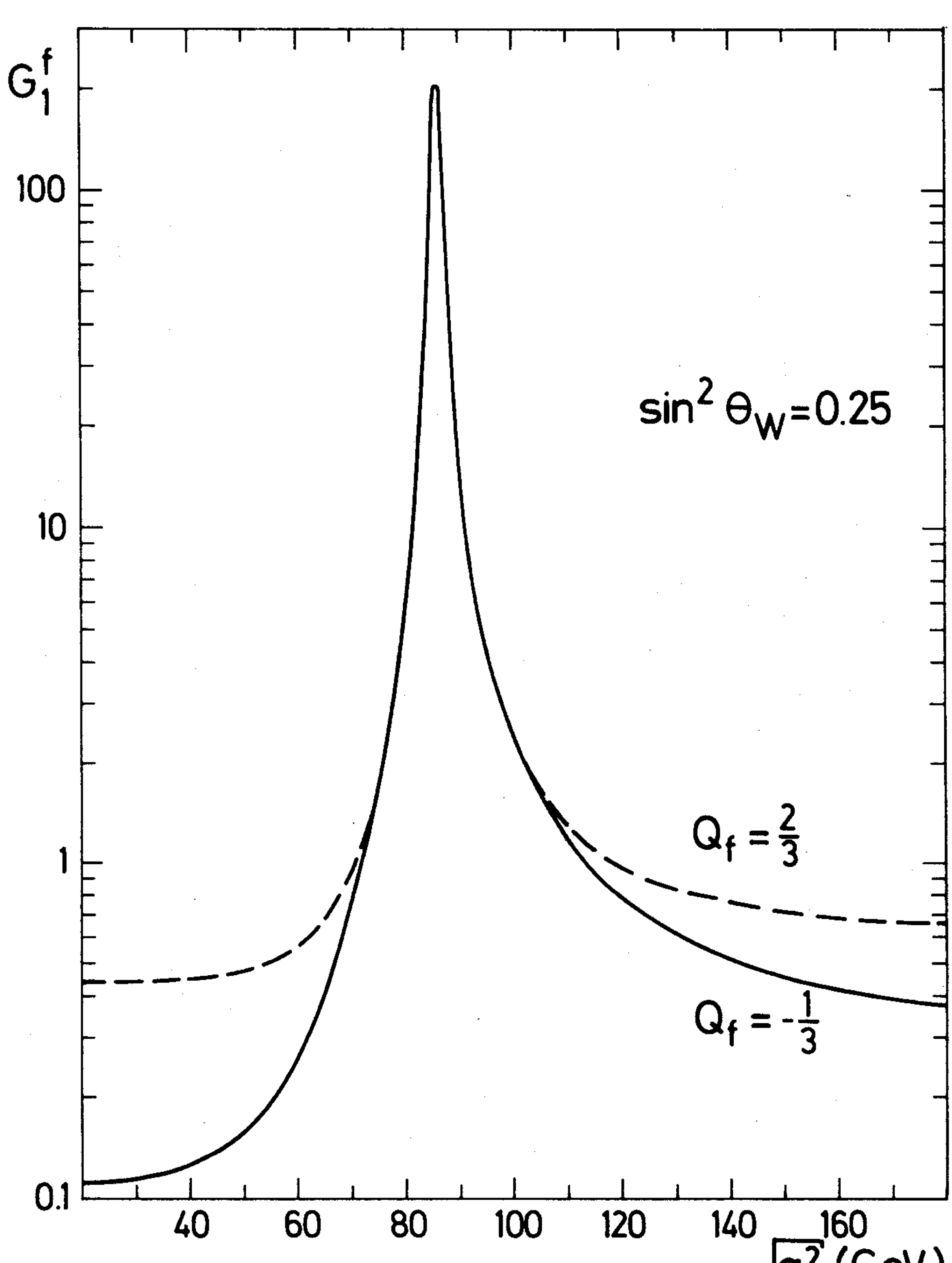


Fig. 1



G_1^f
100
10
1
0.1
$\sin^2\theta_W = 0.25$
$Q_f = \frac{2}{3}$
$Q_f = -\frac{1}{3}$
40
60
80
100
120
140
160
$\sqrt{q^2}$ (GeV)

Fig. 2

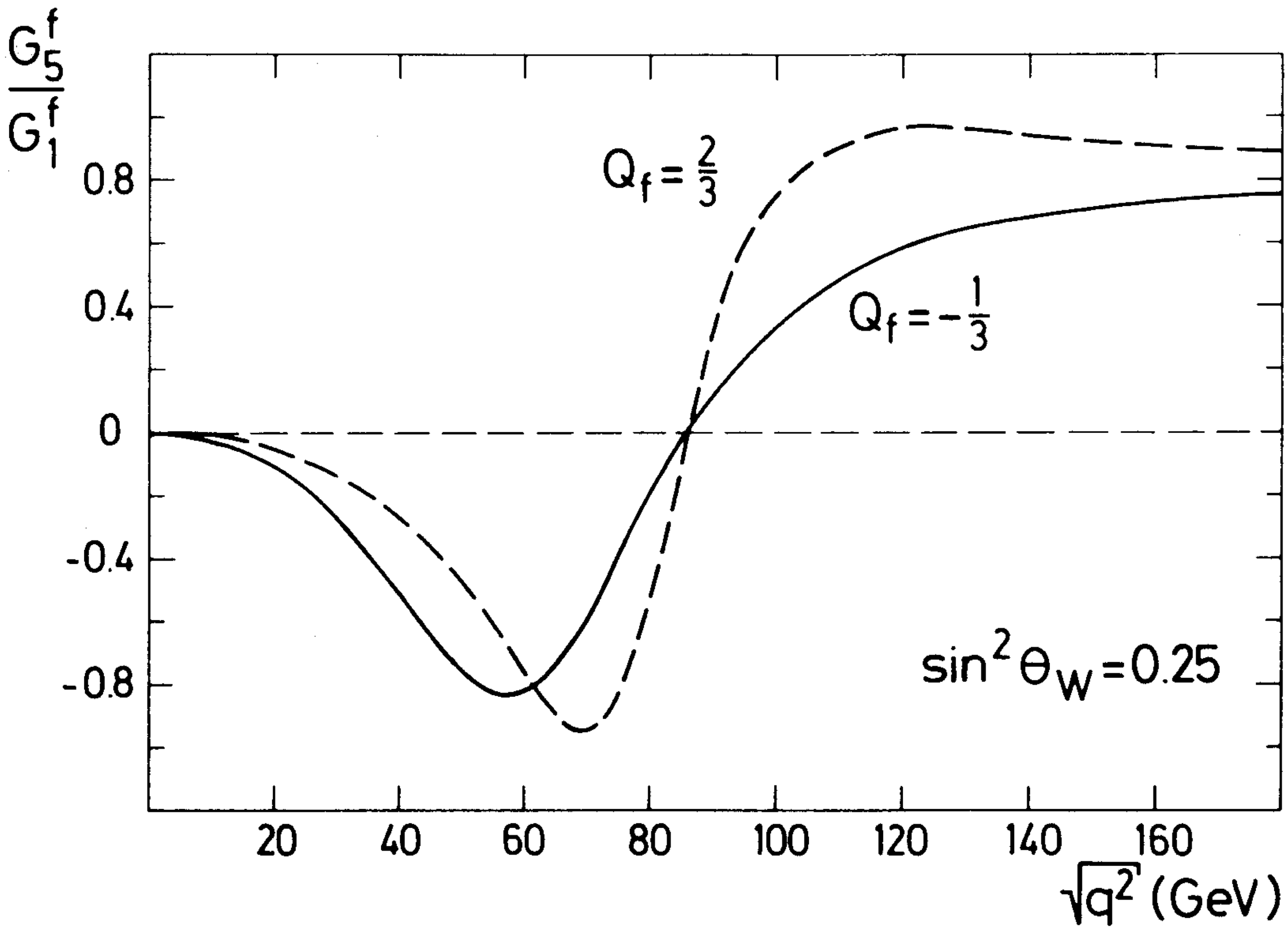

$\frac{G_5^f}{G_1^f}$
0.8
0.4
0
-0.4
-0.8
$Q_f = \frac{2}{3}$
$Q_f = -\frac{1}{3}$
$\sin^2\theta_W = 0.25$
20
40
60
80
100
120
140
160
$\sqrt{q^2}$ (GeV)

Fig. 3