# EVIDENCE FOR A SPIN-1 GLUON IN THREE-JET EVENTS

TASSO Collaboration

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High-energy $e^+e^-$-annihilation events obtained in the TASSO detector at PETRA have been used to determine the spin of the gluon in the reaction $e^+e^- \to q\bar{q}g$. We analysed angular correlations between the three jet axes. While vector gluons are consistent with the data (55% confidence limit), scalar gluons are disfavoured by 3.8 standard deviations, corresponding to a confidence level of about $10^{-4}$. Our conclusion is free of possible biases due to uncertainties in the fragmentation process or in determining the $q\bar{q}g$ kinematics from the observed hadrons.

The planar events [1–4] with three hadron jets in high-energy $e^+e^-$-annihilation data observed at PETRA give evidence for the gluon bremsstrahlung predicted by perturbative Quantum Chromodynamics (QCD) [5]. More detailed examination [6] of the data shows that QCD supplemented [7,8] with quark and gluon fragmentation models [9] is in excellent agreement with the observed properties of two- and three-jet events including the behaviour of the hadrons within the individual jets. However, since QCD is the theory of coloured spin-1 gluons, establishing that the "observed" gluon has spin 1 is a necessary element in the experimental confirmation of the theory.

There is strong experimental evidence [10] that the quarks responsible for two-jet events in continuum $e^+e^-$ annihilation have spin 1/2. So far there is no direct evidence that the parton responsible for the third jet in three-jet events has spin 1. In this experiment we were able to isolate the individual jets in high-energy three-jet events and measure the correlations between the directions of the three jets. Such angular correlations can discriminate between QCD with its vector gluons and a model with scalar gluons [5,11].

The data used in this analysis were accumulated in the TASSO detector at PETRA. A description of the detector and the selection criteria for hadron event candidates can be found elsewhere [12]. Only charged particle tracks measured in the central detector were used in this analysis. They were accepted over 87% of $4\pi$ solid angle and reconstructed with an efficiency of 97%. A total of 2229 hadron event candidates with total incident energy $W$ in the range $27.4 \leqslant W \leqslant 36.6$ GeV survived all of the cuts described earlier [6]. The total luminosity measured for these runs was 7716 $nb^{-1}$.

The first step in isolating the jets in three-jet events [1] was to determine the event plane by diagonalising the momentum tensor

$$M_{\alpha\beta} = \sum_{i=1}^{N} P_{\alpha i} P_{\beta i} \quad (\alpha, \beta = x, y, z)\,, \tag{1}$$

where the sum runs over all charged hadrons. Events were then eliminated if the angle between the normal to the event plane and the beam direction was greater than 80°. This cut reduced the background of two-jet annihilation events with an additional hard photon emitted. A total of 1869 events were left after this cut. Next the axes of the three jets in the event plane were determined using the method of generalised sphericity described elsewhere [6,13]. Essentially this involves projecting the particle momentum vectors into the event plane and then finding a partition of the particles into three subsets which minimizes the sum of $S = S_1 + S_2 + S_3$, where $S_i$ is the sphericity of the particles in subset $i$. At this stage, no cut was made to ensure that the events were actually three-jet events with a hard gluon.

Before fragmentation the $q\bar{q}g$ Dalitz plot can be described by the fractional energy variables

$$x_i = E_i/E_b\,, \tag{2}$$

where $E_i$ is the energy of quark or gluon $i$ and $E_b$ is the incident beam energy, so that

$$x_1 + x_2 + x_3 = 2\,. \tag{3}$$

We choose to order them such that

$$x_3 \leqslant x_2 \leqslant x_1\,, \tag{4}$$

which implies

$$2/3 \leqslant x_1 \leqslant 1\,. \tag{5}$$

If the quarks and the gluon have negligible masses relative to $E_b$, the $x_i$ are determined by the angles $\theta_i$ shown in fig. 1a:

$$x_i = \frac{2 \sin\theta_i}{\sin\theta_1 + \sin\theta_2 + \sin\theta_3}\,. \tag{6}$$

Furthermore, $x_1$ is then the thrust $T$ of the $q\bar{q}g$ system, and eq. (5) gives the usual range for thrust. Thus, the three jet directions completely define the $q\bar{q}g$ Dalitz plot.

Fig. 1b shows the angle $\tilde{\theta}$ suggested by Ellis and

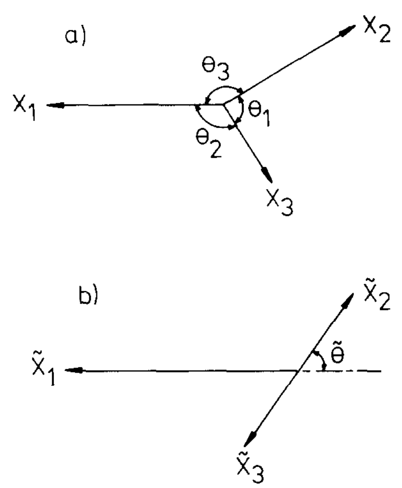


Fig. 1. (a) Momenta and angles of a q$\bar{q}$g final state in the center-of-momentum frame. (b) The q$\bar{q}$g final state transformed to the rest frame of particles 2 and 3.

Karliner [11] to discriminate between vector and scalar gluons. In this figure, the q$\bar{q}$g-system has been Lorentz boosted to the center-of-momentum frame of partons 2 and 3. Assuming negligible quark and gluon masses, $\cos\tilde{\theta}$ is given by

$$\cos\tilde{\theta} = \frac{x_2 - x_3}{x_1} = \frac{\sin\theta_2 - \sin\theta_3}{\sin\theta_1} . \tag{7}$$

The distribution functions for the $x_i$ in QCD and in the scalar-gluon model, after averaging over the production angles relative to the incident e$^+$e$^-$ beams [14], are given by [5]

$$\text{vector:}\quad \frac{1}{\sigma_0}\left(\frac{d\sigma}{dx_1 dx_2}\right)_V$$

$$= \frac{2\alpha_s}{3\pi}\left(\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} + \begin{matrix}\text{cyclic}\\ \text{permut.}\\ \text{of } 1,2,3\end{matrix}\right) , \tag{8}$$

$$\text{scalar:}\quad \frac{1}{\sigma_0}\left(\frac{d\sigma}{dx_1 dx_2}\right)_S$$

$$= \frac{\tilde{\alpha}_s}{3\pi}\left(\frac{x_3^2}{(1-x_1)(1-x_2)} + \begin{matrix}\text{cyclic}\\ \text{permut.}\\ \text{of } 1,2,3\end{matrix}\right) . \tag{9}$$

The infrared divergences in perturbative QCD are expressed by the $(1-x_i)$ denominators. The vector expression has both collinear and soft divergences, while for the scalar case there is only the collinear divergence, causing a somewhat flatter behaviour as a function of $x_i$.

The main experimental difficulty is distinguishing between the vector and scalar cases comes from the fact that the distributions (8) and (9) differ strongly only for large values of thrust $x_1$, where one approaches the collinear two-jet singularity. In this kinematic region, however, the cross section is rapidly varying with $x_1$ and therefore becomes sensitive to smearing effects caused by quark and gluon fragmentation. Moreover, for $x_1$ too close to 1, lowest-order QCD perturbation theory, i.e. eqs. (8) and (9), will become meaningless since higher-order terms and non-perturbative effects come in.

One therefore must restrict the spin analysis to a kinematic region safely away from $x_1 \approx 1$, by a cut in $(1-x_1)$. We placed this cut at a value twice as large as the value $1 - T_0 = 0.05$ found to serve as a useful boundary between the two-jet and three-jet regions in QCD Monte Carlo calculations [6–8]. Thus we used the kinematic region defined by $1 - x_1 > 0.10$. In the three-jet region so defined, the distributions are not strongly peaked either for vector or scalar gluons, making the dependence on fragmentation smearing small. (This will be shown in the discussion of fig. 2 and table 1 below.) As a further precaution we only used distributions *normalized* to the number of events in *this* kinematic region. This means that the distinction between vector and scalar gluons is made only on the basis of the difference in *shape* of the two distributions in the three-jet region. In this way we eliminate, on the parton level, all dependence of our spin analysis on the values of the strong coupling constants $\alpha_s$ and $\tilde{\alpha}_s$ for vector and scalar gluons, respectively. Of course the smearing effects of fragmentation into hadrons will necessarily cause some leakage of two-jet events into the three-jet region and thus lead to a weak dependence on the coupling constants, the effect of which was studied by Monte Carlo calculations.

We used the QCD model of Hoyer et al. [7] to calculate the $x_1, x_2$ distributions expected for vector and scalar gluons including the effects of fragmentation, radiative corrections [15], and detector acceptance. This model includes e$^+$e$^-$ → q$\bar{q}$ and e$^+$e$^-$ → q$\bar{q}$g but not the higher-order process e$^+$e$^-$ → q$\bar{q}$gg that was included in our detailed QCD analysis [6] based on the model of Ali et al. [8]. Since no calculation of these higher-order processes for scalar gluons has been made, we preferred for the present spin analysis to use the Hoyer et al. model [7] for both vector and scalar gluons. (We verified that the inclusion of these higher-order contributions in the vector-gluon case has only a very small effect.) We used the fragmentation parameters $a_F = 0.57$, $\sigma_q = 0.32$ GeV/$c$ and $P/(P + V) = 0.56$ as determined in our QCD analysis of both the two-jet and the three-jet regions [6]. For the QCD coupling constant we used the value $\alpha_s = 0.19$; with this value the Hoyer et al. model gives an excellent description of our combined two-jet and three-jet data ‡1. We repeated the same analysis procedure as that used to determine $\alpha_s$, to obtain the best value for the coupling constant in the scalar model; we found $\tilde{\alpha}_s = 1.6$ ‡2.

From the QCD Monte Carlo calculations we determined that our thrust cut $1 - x_1 > 0.10$ leaves a background of 18% (vector) or 17% (scalar gluons) of two-jet events in the three-jet sample. In order to assess the possible effect of this background on our spin analysis we have varied its size systematically by varying $\alpha_s$ and $\tilde{\alpha}_s$ around their best values as discussed later.

By comparing the Monte Carlo-generated $q\bar{q}g$ state with the result of the analysis after fragmentation into hadrons, we found that the rms error in measuring the angles $\theta_i$ after the thrust cut was in the range of 3° to 8°, depending on the energy of the jet. Events of the following types were eliminated from both the data and the Monte Carlo samples.

(a) All three jet axes lay on the same side of a line in the event plane so momentum conservation was impossible.

(b) One or more of the calculated $x_i$ values were significantly below the total energy of the hadrons assigned to the jet divided by the beam energy.
Both of these difficulties appear only for events with a very soft jet, so that the three jets are not distinct.

‡1 This value of $\alpha_s$ differs from our published value [6] of $\alpha_s = 0.17 \pm 0.02 \pm 0.03$ (systematic) which was obtained including higher-order QCD effects according to the Ali et al. model [8]. The difference effectively compensates for the neglect of these effects in the Hoyer et al. model [7].

‡2 With this value of $\tilde{\alpha}_s$ for scalar gluons, and using a thrust value $T_0 = 0.95$ as the boundary to distinguish between the $q\bar{q}$ and $q\bar{q}g$ regions, the total fraction of $q\bar{q}g$ events in the Hoyer et al. model is 28% and so in spite of the large value of $\tilde{\alpha}_s$ the first-order perturbative contribution is relatively small.

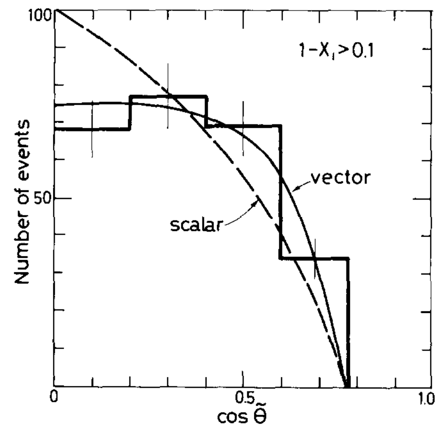


Fig. 2. Observed distribution of the data in the region $1 - x_1 \geq 0.10$, as a function of the cosine of the Ellis–Karliner angle $\tilde{\theta}$ defined in fig. 1b. The solid line shows the QCD prediction, the dotted line the prediction for scalar gluons, both normalized to the number of observed events.

As turned out, in the three-jet region used in our analysis less than 1% of the events had to be eliminated.

Applying the cut $1 - x_1 > 0.10$, the number of hadron events is reduced from 1869 to 248 events. Fig. 2 compares the observed distribution of $\cos\tilde{\theta}$ with the predictions of the Hoyer et al. model for vector and scalar gluons. The model curves are normalized to 248 events ‡3. They have been calculated taking the effects of non-perturbative fragmentation, radiative corrections, jet axes reconstruction, as well as experimental acceptance, efficiency and resolution into account. The distribution of $\cos\tilde{\theta}$ is, however, very insensitive to all these effects, the total correction being less than 10%. The data clearly favour spin 1 over spin 0. The $\chi^2$ values for 3 degrees of freedom calculated taking the finite statistics of the Monte Carlo into account are

$\chi^2 = 1.0$, C.L. = 79% for vector gluons,

$\chi^2 = 14.9$, C.L. = 0.2% for scalar gluons.

Thus, vector gluons are consistent with the data but scalar gluons are disfavoured by 3.1 standard deviations.

‡3 These curves differ qualitatively from the ones in ref. [11]. In particular, the non-zero derivative at $\cos\tilde{\theta} = 0$ is due to condition (4), and the strong decrease at larger values of $\cos\tilde{\theta}$ comes from the $x_1$ dependence of the kinematic limit.

Confidence limits quoted from $\chi^2$ fits for small data samples are somewhat questionable, since changes in binning can affect conclusions. We avoided this problem by using the mean value of $\cos\tilde{\theta}$ as a statistic for comparing the distributions. For 248 events the distribution of the mean is gaussian out to many standard deviations, so we are able to use gaussian confidence limits. From the data

$$\langle\cos\tilde{\theta}\rangle_{\mathrm{exp}} = 0.349 \pm 0.013\,,$$

while for the vector and scalar gluon calculations

$$\langle\cos\tilde{\theta}\rangle_{\mathrm{V}} = 0.341 \pm 0.004\,, \quad \langle\cos\tilde{\theta}\rangle_{\mathrm{S}} = 0.298 \pm 0.003\,.$$

Combining the errors in quadrature, the data differ from the calculation by

0.6 standard deviations (CL = 55%)

for vector gluons ,

3.8 standard deviations (CL = 0.01%)

for scalar gluons ,

again highly favouring spin 1 over spin 0.

In this analysis based on the mean value of $\cos\tilde{\theta}$, it is easy to study the systematic error due to uncertainties in the QCD models and the analysis. Table 1 compares $\langle\cos\tilde{\theta}\rangle_{\mathrm{V}}$ and $\langle\cos\tilde{\theta}\rangle_{\mathrm{S}}$ calculated in different ways. "$q\bar{q}g$" refers to the value obtained directly on the parton level by integrating eqs. (8) and (9) with the cut $1 - x_1 > 0.10$, i.e. without fragmentation or acceptance effects included. "Hoyer et al." refers to calculations using the QCD Monte Carlo model [7] along with acceptance cuts, radiative corrections, and analysis procedures as applied to the data. Further, the strong coupling constants $\alpha_s$ and $\tilde{\alpha}_s$ have been varied by ±20% around the values determined by the fits to the overall data. The close agreement between the different resulting numbers shows again that in our analysis $\langle\cos\tilde{\theta}\rangle$ is insensitive to the details of fragmentation or reconstruction, as well as to the values of $\alpha_s$ and $\tilde{\alpha}_s$.

An analysis of higher moments of the $\cos\tilde{\theta}$ distribution has also been carried out. It supported but did not significantly improve the evidence already found from the first moment $\langle\cos\tilde{\theta}\rangle$.

Although the distribution of $\cos\tilde{\theta}$ is particularly sensitive to the spin of the gluon, other combinations of the $x_i$ contain similar information. For example, the distribution of thrust $x_1$ is spin dependent [5]. While we found it also to favour vector over scalar gluons, we consider this result less significant in view of the dangerous sensitivity of the rapidly varying $x_1$ distribution to experimental resolution effects.

Other distributions, involving angular correlations with the beam direction or requiring polarized beams, have also been proposed as a test of the gluon spin [14,16,17]. The application of these tests requires a larger number of events than presently available.

In conclusion we find that our three-jet data at $W \approx 30$ GeV are consistent with the QCD theory of vector gluons, and exclude the scalar-gluon model at a confidence level of about $10^{-4}$. Previous experimental evidence on the spin of the gluon rested on the interpretation of bound-state $\Upsilon$ decays [18]. Our present analysis provides evidence for the vector nature of the gluon in a high-energy hard process involving clearly distinguished, separable jets.

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Table 1
Average values of the cosine of the Ellis–Karliner angle $\tilde{\theta}$ for $1 - x_1 > 0.10$, calculated for vector (V) and scalar (S) gluons at $W \approx 30$ GeV. (The measured value is 0.349 ± 0.013.)

| Model | $\alpha_s$ | $\langle\cos\tilde{\theta}\rangle_{\mathrm{V}}$ | $\tilde{\alpha}_s$ | $\langle\cos\tilde{\theta}\rangle_{\mathrm{S}}$ |
|---|---|---|---|---|
| $q\bar{q}g$ (partons) | | 0.348 | | 0.298 |
| Hoyer et al. [7] | 0.15 | 0.343 ± 0.004 | 1.26 | 0.301 ± 0.003 |
| ($q\bar{q} + q\bar{q}g$) | 0.19 | 0.341 ± 0.004 | 1.56 | 0.298 ± 0.003 |
| Monte Carlo | 0.23 | 0.339 ± 0.004 | 1.86 | 0.295 ± 0.003 |

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