FOUR-JET EVENTS IN e^+e^- ANNIHILATION: TESTING THE THREE-GLUON VERTEX ☆

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The distribution of the azimuthal angle between the planes formed by the two highest energy jets and the two lowest energy jets in four-jet events of e^+e^- annihilation, depends characteristically on the triple-gluon vertex.

A key property of quantum chromodynamics is the self-interaction of gluons, a consequence of the nonzero color charges of the gauge particles. This self-coupling is a necessary ingredient to overcome the fermionic screening of color sources, rendering the quark–gluon interactions asymptotically free. A variety of tests of the triple-gluon vertex have been discussed in the past decade, comprising deep-inelastic lepton–nucleon scattering, high-transverse momentum jets in hadron–hadron collisions and heavy quarkonium decays. However, due to the complexity of QCD all such analyses are based on a mixture of assumptions so that only the diversity of independent processes can put the theory on a firm basis. A qualitatively new test ground will shortly open with the huge number of high-energy jet events expected in e^+e^- annihilation at LEP and SLC. Sufficiently large invariant masses of all jet pairs ensure that jets truly reflect the distribution of quark and gluon quanta in the femto-universe, revealing the basic couplings in the QCD lagrangian.

Several methods have been proposed that exploit characteristic features of gluon dynamics in QCD, as opposed to abelian vector theories, to isolate the triple-gluon vertex in four-jet events of e^+e^- annihilation. Two proposals are physically most transparent. (i) The "gluon alignment" [1] in the splitting process $g \to gg$ forces the two planes, each formed by a high-energy jet together with a low-energy jet, to orient preferentially parallel, with the low-energy jets pointing into the same hemisphere. (ii) Virtual helicity-zero gluons of low invariant mass that are radiated from almost back-to-back high-energy quark–antiquark jets cannot decay into gluon jets at 90° relative to the quark direction [2]. Cleverly exploiting the only zero in the spin-one rotation matrix, the large polar angle range is depleted from low-energy jets in QCD (accumulating at small angles). This is just opposite to virtual gluon decays into quark pairs (and phase space distributions) [#1]. In this note, we propose a different observable that is complementary to the previously discussed examples, yet also based on angular asymmetries due to polarization effects.

Gluons radiated from quarks and antiquarks in $e^+e^- \to q\bar{q}g$ are linearly polarized to a high degree *in* the $q\bar{q}g$ final state plane [4]. Denoting the cross sections for polarizations in and perpendicular to this plane by $d\sigma_\parallel$ and $d\sigma_\perp$, respectively, QCD predicts

$$P(x_g) = (d\sigma_\parallel - d\sigma_\perp)/(d\sigma_\parallel + d\sigma_\perp) = 2(1-x_g)/(x_q^2 + x_{\bar{q}}^2) , \quad (1)$$

where, as usual, $x_i = 2E_i/\sqrt{s}$ are the scaled quark and gluon energies in the laboratory frame. The fragmentation of a linearly polarized gluon into daughter partons depends on the azimuthal angle χ between the final state plane and the polarization vector. The

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[#1] Methods based solely on invariant jet measures are not useful for isolating the triple-gluon coupling. A summary is given in ref. [3], and a comprehensive systematic comparison of all methods is in preparation.

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asymmetric term is just opposite in sign for gg and $q\bar{q}$ decays [5],

$$D_{g\to gg}(z,\chi) = \frac{6}{2\pi}\left(\frac{(1-z+z^2)^2}{z(1-z)} + z(1-z)\cos 2\chi\right),$$

$$D_{g\to q\bar{q}}(z,\chi) = \frac{N_F}{2\pi}\{\tfrac{1}{2}[z^2+(1-z)^2] - z(1-z)\cos 2\chi\}. \qquad (2)$$

Quark jets accumulate perpendicular to the polarization vector [6] with a maximal asymmetry $\sim[1-\cos 2\chi]$ for $z=\frac{1}{2}$. The asymmetry for gluon jets is less pronounced, $\sim[1+\frac{1}{9}\cos 2\chi]$ even for $z=\frac{1}{2}$, so that the angular distribution in QCD is quite distinct from abelian theories [#2]. In four-jet events of e^+e^- annihilation, fig. 1, we therefore expect the angle between the plane formed by the two low-energy jets (generated preferentially in the virtual gluon decays) and the plane formed by the high-energy jets (mostly identical with the primordial quark–antiquark pair) to be distributed nearly isotropically in QCD while these planes should be preferentially perpendicular in abelian theories [#3].

We have checked that this difference between QCD and abelian theories survives the transition to a full-scale four-jet analysis including all diagrams for $e^+e^-\to q\bar{q}gg$ and $q\bar{q}q'\bar{q}'$. The abelian theory has been defined with a fixed coupling $\alpha_* = \frac{3}{4}\alpha_s$ in order to correctly reproduce the two- and three-jet rate, and quarks were endowed with three (ungauged) degrees of freedom. Introducing a minimum jet–jet invariant mass $m_{jj}^2 \geqslant y_{min}s$, we ensure that the lifetime and flight distance of all virtual quarks and gluons $d\sim\frac{1}{2}\sqrt{s}/m_{jj}^2$ will be short enough so that parton showers do not expand yet and the "naive" Feynman diagram calculation in the femto-universe will be valid. We have chosen $y_{min}=0.02$ setting an upper limit of $d\sim\frac{1}{20}$ fm at $\sqrt{s}\sim m_Z\sim 94$ GeV. The resulting jj invariant mass of ~ 14 GeV is sufficient to resolve the jets so that all the problems occurring at low e^+e^- energies [8] are avoided.

The actual Monte Carlo calculation was performed by adopting the four-jet QCD matrix elements [9] as implemented in ref. [10], modified appropriately for the abelian model. Because the azimuthal angle χ is not defined for back-to-back jets (1 antiparallel to 2, or 3 antiparallel to 4), angular cuts of 160° between 1 and 2 and 100° between 3 and 4 have been imposed. The qualitative differences between QCD and the abelian model are not affected by these cuts.

The χ distributions are displayed in fig. 2 for QCD (full line) as well as the abelian model (dashed line). (The distribution for a simple phase space model where the particles 3 and 4 are lumped together into a massive cluster decaying isotropically, is similar to the abelian model, yet with a somewhat less steep slope.) The slope of the curves is a monotonic funtion of the angular cuts imposed. A qualitatively characteristic difference between the models is ap-

[#2] Adding up gluons, quarks and antiquarks in QCD, the coefficient of the $\cos 2\chi$ term is proportional to $(3-N_F)$ so that asymmetry effects vanish for $N_F=3$ quark degrees of freedom [7].

[#3] Note that for isotropical phase space decays of a virtual gluon to two jets, these planes are oriented preferentially perpendicular. This is due to the fact that the minimum value required for the invariant mass of jet pairs, is very restrictive when the two planes coincide. This cut affects χ distributions in QCD much less as a consequence of the gluon alignment.

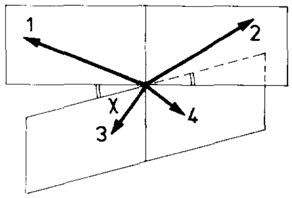

Fig. 1. Definition of the azimuthal angle χ between the planes formed by the two high-energy and the two low-energy jets in $e^+e^-\to$ fourjets.

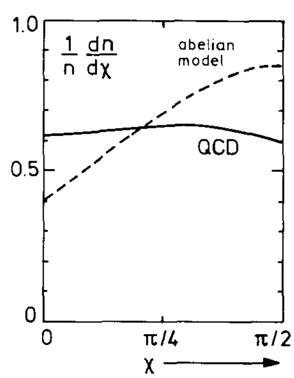

Fig. 2. Distribution of the azimuthal angle χ in QCD (in contrast to an abelian vector theory).

parent so that they are easy to separate. The χ distribution is sensitive to the triple-gluon vertex.

All conclusions so far have been derived for four-jet events on the parton level. We therefore need to check whether the four-jet rate is sufficiently large if our restrictive cuts are imposed, and whether jet fragmentation and c, b quark decays do not spoil these effects. To study these problems, the Lund string fragmentation model [11] has been used as an example, together with a jet finding algorithm [12]. Choosing the resolution parameter $d_{\rm join} = 5$ GeV in this algorithm, the sample of four-jet events at $y \geqslant 0.02$ on the hadron level is not contaminated by three-parton events after fragmentation (faithfulness $\sim 99\%$), parton and jet angles coincide within 4°, and deviations of the reconstructed jet energies from the parton energies are less than 6%. The χ distributions for approximately 7 000 Monte Carlo events are displayed in fig. 3. The jet finding algorithm unravels the original parton distributions very accurately. The relative four-jet cross section (including angular cuts) amounts to 4% for $y \geqslant 0.02$ and $\alpha_s^{\rm eff} = \alpha_s(ys)$ so that,

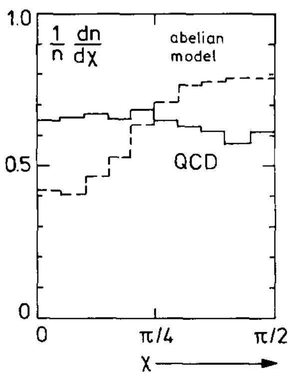

Fig. 3. χ distributions for 7 000 Monte Carlo events, based on the jet finding algorithm of ref. [12]. (The statistical error in each bin is approximately 3%.)

for example, $\sim 40\,000$ events can be used for the analysis out of 10^6 Z decays. We have also checked that parton showers do not spill over into the regime of well-separated jets. Imposing our standard cuts the four-jet cross section is fully covered by the hard four-parton cross section derived at short distances [#4]. Hence the jet distributions reflect the distributions of the partons in the femto-universe and allow us to isolate effects of the triple-gluon coupling.

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[#4] This is based on choosing a physically meaningful scale $M^2 \sim ys$ in the argument of the running coupling constant (see also ref. [13]).