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How to Find the Gluon Jets in e^+e^- Annihilation.

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Abstract: We point out an asymmetry in the combined multiplicity and angular distributions of the final state mesons in a quark-antiquark-gluon fragmentation event from e^+e^- annihilation. The asymmetry is characteristic for the gluon jet in the model for soft hadronisation of coloured objects which we have developed based on the semiclassical treatment of a stringlike colour force field (a stretched-out bag) without excited transverse modes.

The essentially one-dimensional structure of the jets in leptoproduction and in e^+e^- annihilation is an indication of a stringlike character of the colour force field or colour flux tube (a stretched-out bag). At the highest PETRA energies, however, the one-dimensional structure is broken by a set of 3 jet events [1]. This is interpreted as signs of the emergence of gluon jets.

We note that the massless relativistic string provides a relativistically invariant and causal generalization to three dimensions of a linear force field in one dimension [2,3]. Inside the string dynamics, it is possible for a small pointlike part to carry a finite amount of energy and momentum. Such a "kink" mode is a localized amount of field energy. It is acted upon by the string by twice the force acting upon an endpoint quark. These modes have therefore many features in common with massless gluons - in QCD with N colours the corresponding force ratio is expected to be $2/(1 - \frac{1}{N^2})$.

In refs [3,4,5] we have developed models for the soft hadronisation of confined quarks and gluons based on a stringlike force field without excited transverse degrees of freedom. The assumption that the force field during the hadronisation process contains no transverse excitations is strongly supported by the experimentally observed polarization of inclusively produced Λ particles [6].

In this note we will apply our model to the e^+e^- annihilation events in the present PETRA and PEP energy regime. We assume that at these energies $q\bar{q}$ and $q\bar{q}g$ states dominate, and will therefore neglect events with four or more jets. The matrix element for the production of quarks and gluons on a short time scale will be taken from perturbative QCD [7]. We will.then use our model for the long time soft hadronisation to study the properties of the final state. In Fig. 1 we illustrate how the force field in a $q\bar{q}g$ system is stretched and how it breaks up into pieces, hadrons, by the production of quark-antiquark pairs. Due to the stochastic nature of the model, it lends itself to an implementation in terms of a Monte Carlo simulation process. The details of this Lund Jet Monte Carlo generation program (LUJMC) will be presented elsewhere [8].

We will in particular address the question of how to identify the gluon jet on an event for event basis in a sample of 3 jet events. Most gluon jet models, including our own, predict that a gluon jet contains more particles with smaller energies than a corresponding quark jet. Monte Carlo calculations, however, show that this difference is hidden by the statistical fluctuations from jet to jet. Now we note that if a gluon acts like a kink on a stringlike force field, as in Fig. 1, then the produced particles will in momentum space appear along two hyperbolae as shown in Fig. 2. The typical distance from the hyperbolae to the origin will in our model be ~ 300 MeV for primary mesons, i.e. of the same order of magnitude as the typical $p_\perp$ in a jet. Therefore this particular gluon model predicts more particles in the angular range between the gluon and the quark (or antiquark) than between the quark and the antiquark. Again, this effect in itself is too small to give a clear separation between quark jets and gluon jets. The two effects may however be combined to define an asymmetry, to be described below, which we predict to be of the order of 16%. This should be observable in a sample of a few hundred three jet events. Assuming that the asymmetry is found, we may then give recipes for identifying the gluon jet on an event for event basis. Before defining the asymmetry, we will briefly present a few details of the model.

In ref. [4] we have studied how the force field between an original quark-antiquark pair breaks up by the production of new massless $q\bar{q}$ pairs in the field. Although the model is of an "inside-out" nature, in the sense that in every Lorentz frame those mesons which are slow in that frame are formed first, the predictions of the model have in general a close similarity to the iterative cascade jet models [9].

In ref. [5] we introduce the masses and the transverse degrees of freedom in the production of the $q\bar{q}$ pairs as zero-point fluctuations in a stringlike force field with no excited degrees of freedom. Then the quark and the antiquark will occur with equal and oppositely directed transverse momenta ($\bar{k}_\perp$ and $-\bar{k}_\perp$, respectively) and we show that each production vertex should be weighted by

$$\left| g\left(\frac{\kappa\tau}{\mu_\perp}\right)\right|^2 \cdot h\left(\frac{\pi\mu_\perp^2}{\kappa}\right) \qquad (1)$$

$$h(z) = \exp(-z) \qquad (2)$$

where $\mu_\perp$ is the transverse mass of the q $(\bar{q})$ $\mu_\perp = \sqrt{\mu^2 + \bar{k}_\perp^2}$ and τ is the invariant distance to the production vertex from the production of the original $q_o\bar{q}_o$ pair. The factor h is the same as obtained in an early calculation by Schwinger [10], recently reconsidered by several authors [11], and corresponds to the probability for a virtual pair to tunnel out through a linear potential (force κ).

For a virtual pair to tunnel out, the field must be so large that the field energy can be transformed into mass (or transverse mass). If $\tau < \mu_\perp/\kappa$ the pair cannot be produced classically inside the field. From the investigation of a simple quantum mechanical model for the production matrix element we show in ref. [5] that this gives rise to a suppression factor $|g|^2$ in eq.(1). The model independent properties of $|g|^2$ are that

1. $|g(\alpha)|^2$ is small for small α
2. $|g(\alpha)|^2$ approaches 1 rapidly when $\alpha \gg 1$
3. $|g(\alpha)|^2$ is smoothly varying in between.

The precise behaviour of $|g|^2$ is not independent of the details of the model, but we have found [5] that widely different functions $|g|^2$ with the properties 1-3 above result in essentially the same final state single particle distributions.

Before we extend the model to gluon jets as well, we would like to comment upon a particular problem in the generation of a complete two jet e^+e^- event - the question of joining the jets characteristic for the q_o and the $\bar{q}_o$ in the centre. The prescription used in the LUJMC is that we generate randomly (with probability 1/2) particles from either end of the total jet, weighting each vertex according to eq.(1), and keeping track of $W_+ = E+p_z$ and $W_- = E-p_z$ which remain after each step. When the remaining mass W_+W_- is below a given value (approximately 4 GeV^2), we generate a final $q\bar{q}$ pair which is used to produce the final two mesons. The two possible kinematical solutions (if no solution, we start all over again) are weighted with a probability that gives the right average difference in rapidity. This way we will at each step conserve energy, momentum and flavour, and we also obtain a smooth joining prescription in the centre (e.g. a flat rapidity distribution at large energies).

In ref. [3] we have studied the fragmentation of a gluon jet. If we make a boost along the gluon direction, the angle between the two string pieces in Fig. 1 becomes small and it looks like a hairpin. Two breaks, one in each "leg", will now cut off the "first rank" meson, leaving behind two ordinary quark jets. In a $q\bar{q}g$ situation we first study the breaks closest to the kink. What then remains in each leg is, in the respective rest frame, just ordinary quark-antiquark jets. The details on how to ensure conservation of energy and momentum in the formation of the "first rank" meson will be described elsewhere [8].

When implementing the QCD matrix element [7] we recognize two different cuts, which taken together give a smooth transition between $q\bar{q}g$ and $q\bar{q}$ events [8]. Firstly, if a gluon and a quark (or antiquark) are so collinear that $M_{qg} \lesssim 3$ GeV (for $m_q \approx 0$), almost all particles will be produced in the other $(\bar{q}g)$

"leg" and we approach a two jet situation. Secondly, consider the event in a frame where the quarks go out in opposite directions and the gluon goes out perpendicularly to them. If then $E_g \lesssim 2$ GeV, the gluon will lose its energy before the longtime hadronisation starts and only remain as a transverse excitation on the $q\bar{q}$ string, giving a negligible increase in average transverse momentum.

Using the LUJMC we find our model to be in fair agreement (within experimental uncertainties) with PETRA results [1,12] on charged multiplicity, sphericity, thrust, $p_\perp^2$ distributions etc. This is also true e.g. for a model (which we will denote A for alternative) in which the quark, the antiquark and the gluon fragment independently of each other and where the gluon fragments "as a quark" (which we take as $u, \bar{u}, d, \bar{d}, s$ or $\bar{s}$ in the ratio 2:2:2:2:1:1). In this model, however, the gluon jet will not have a larger multiplicity than a quark jet, neither will the angular range between the q and the $\bar{q}$ contain fewer particles than between the g and the q or $\bar{q}$.

We now proceed with a more quantitative study of the differences noted above. For this purpose we have compared the two models at a CM energy of 30 GeV. No radiative corrections or detector acceptance cuts have been applied. Charged as well as neutral particles (except neutrinos) are used. We start by selecting clear three-jet event candidates and proceed by aligning them in a uniform way. This can be done according to various schemes. We have chosen to apply cuts in thrust ($T < 0.9$), angular separation (the two weak jets should be within 150^0 of the strongest jet) and energy ($\Sigma|p| > 5$ GeV for each jet). The event plane is defined by the thrust axis and the axis perpendicular to this which has the largest thrust (the major axis). This plane is chosen to be the xz-plane, with the "slim jet" side of the thrust axis in the +z-direction. Then components p_y will in this context contain no interesting physical information, and are henceforth neglected. Since our model does not at present include $q\bar{q}gg$ or $q\bar{q}q\bar{q}$ events, we leave the questions of cuts in e.g. acoplanarity open.

With the introduction of these cuts, about 10% of all events are remaining. These can be divided into three classes.

I. Misidentified $q\bar{q}$ events (mostly of $b\bar{b}$-character, which probably could be dismissed by more elaborate analysis) and $q\bar{q}g$ events where the event plane or the jet directions were not reconstructed satisfactorily - about 6%.

II. Correctly identified $q\bar{q}g$ events, where the gluon is giving rise to the strongest jet - about 11%.

III. Correctly identified $q\bar{q}g$ events, where the gluon is giving rise to one of the two weaker jets.

Our analysis method will be constructed to work for class III events, but we have to consider the background given by the classes I and II.

The two weaker jets we number 1 (lying somewhere in the $p_z < 0, p_x > 0$ quadrant) and 2 ($p_z < 0, p_x < 0$). We make the following definitions. The multiplicities n_1 and n_2 on the two sides ($p_x > 0$ and $p_x < 0$, respectively) are defined as the number of charged or neutral particles with $|p_z| < 2$ GeV and $|p_x| > 0.2$ GeV. The areas A_1 and A_2 on the two sides are defined by $\sqrt{p_x^2 + p_z^2} > 0.2$ GeV, $\theta > 30^0$ (counted from the +z axis in the xz-plane) and $|p_x| > 0.2$ GeV if $p_z > 0$. For these we define (putting all $p_y = 0$)

$$\bar{P}_k^{(i)} = \sum_{\bar{p}_j \in A_k} |\bar{p}_j|^{i-1} \, \bar{p}_j \qquad (3)$$

$$k = 1, 2$$

$$\cos \theta_k^{(i)} = \frac{(\bar{P}_k^{(i)})_z}{|\bar{P}_k^{(i)}|} \qquad (4)$$

With this definition high i-values favour fast particles in the jets while low i-values favour particles with small momenta. This means that, in our model, e.g. $\theta_k^{(2)} - \theta_k^{(0)}$ tends to become more positive with a gluon jet on side k than with a quark jet there. If the two weaker jets are not equally strong, corrections have to be made for this. We choose to add a term linear in

$$\Delta P = \sum_{\bar{p}_j \in A_1} |\bar{p}_j| - \sum_{\bar{p}_j \in A_2} |\bar{p}_j| \qquad (5)$$

to give corrected measures

$$\Delta n = n_1 - n_2 + a \cdot \Delta P \qquad (6)$$

$$\Delta \theta = (\theta_1^{(2)} - \theta_1^{(0)}) - (\theta_2^{(2)} - \theta_2^{(0)}) + b \cdot \Delta P \qquad (7)$$

with $a = 0.08 \text{ GeV}^{-1}$ and $b = -0.032$ radians $\cdot \text{ GeV}^{-1}$. It should be noticed that a and b not only depend on the choice of CM energy 30 GeV but also could depend on detector acceptance cuts and so forth. They have been chosen in such a way that in the A-model both $(\Delta n)_A$ and $(\Delta\theta)_A$ as a function of ΔP vanish in the mean. The corrections to Δn are rather small for this particular definition of n_1 and n_2, but are still included to break the deadlock $n_1 = n_2$.

The recipe that the gluon jet is jet no. 1 if $\Delta n > 0$ and jet no. 2 if $\Delta n < 0$ then identifies the gluon correctly in 70% of the class III events. The same applies to $\Delta\theta$. It should be noted that several alternative multiplicity or angular variables give reliabilities of the same order.

Combining the two measures, we obtain an asymmetry, so that $\Delta n \cdot \Delta\theta > 0$ is expected for 60% of the class III events, which reduces to 58% with the inclusion of class I and II events. The definitions of Δn and $\Delta\theta$ were chosen to maximize this asymmetry. If either or both of the two features we predict does not hold true, the asymmetry will disappear and $\Delta n \cdot \Delta\theta > 0$ in 50% of the cases (provided that bias arising from unequally strong jets is removed correctly). On the other hand, if the asymmetry is there, one can within the subsample $\Delta n \cdot \Delta\theta > 0$ identify the gluon correctly in 80% of the class III events. To increase the asymmetry, one may impose cuts on $|\Delta n|$ and $|\Delta\theta|$, but then at the cost of a greatly reduced rate.

The asymmetry prediction in this note is a crucial test for the gluon jet model in ref. [3]. This model is in a sense the simplest dynamically consistent way to introduce the degrees of freedom of a stringlike force field.

The conclusion, in case the asymmetry is not seen in experimental data, is evidently that a confining force field may contain further interesting and nontrivial dynamics!

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Figure captions

Fig. 1 The space-time development of a quark-antiquark-gluon event. The quark and antiquark move along the directions marked q and $\bar{q}$ and are at the endpoints of a string field. The gluon is a pointlike energy-momentum carrying piece of the string moving along the directions g, thereby causing a triangular shape of the outmoving string field. The field breaks by the production of $q\bar{q}$-pairs and the directions of the final state mesons are marked by arrows when they become independent entities. (Note that the slowest mesons in the cms are the first ones to emerge, and also take the largest pieces of the string.)

Fig. 2 The momentum space distribution of the final state particles which appear in the mean along two hyperbolae The size of the strokes indicates the size of the transverse momentum fluctuations in a string field without excited transverse degrees of freedom.

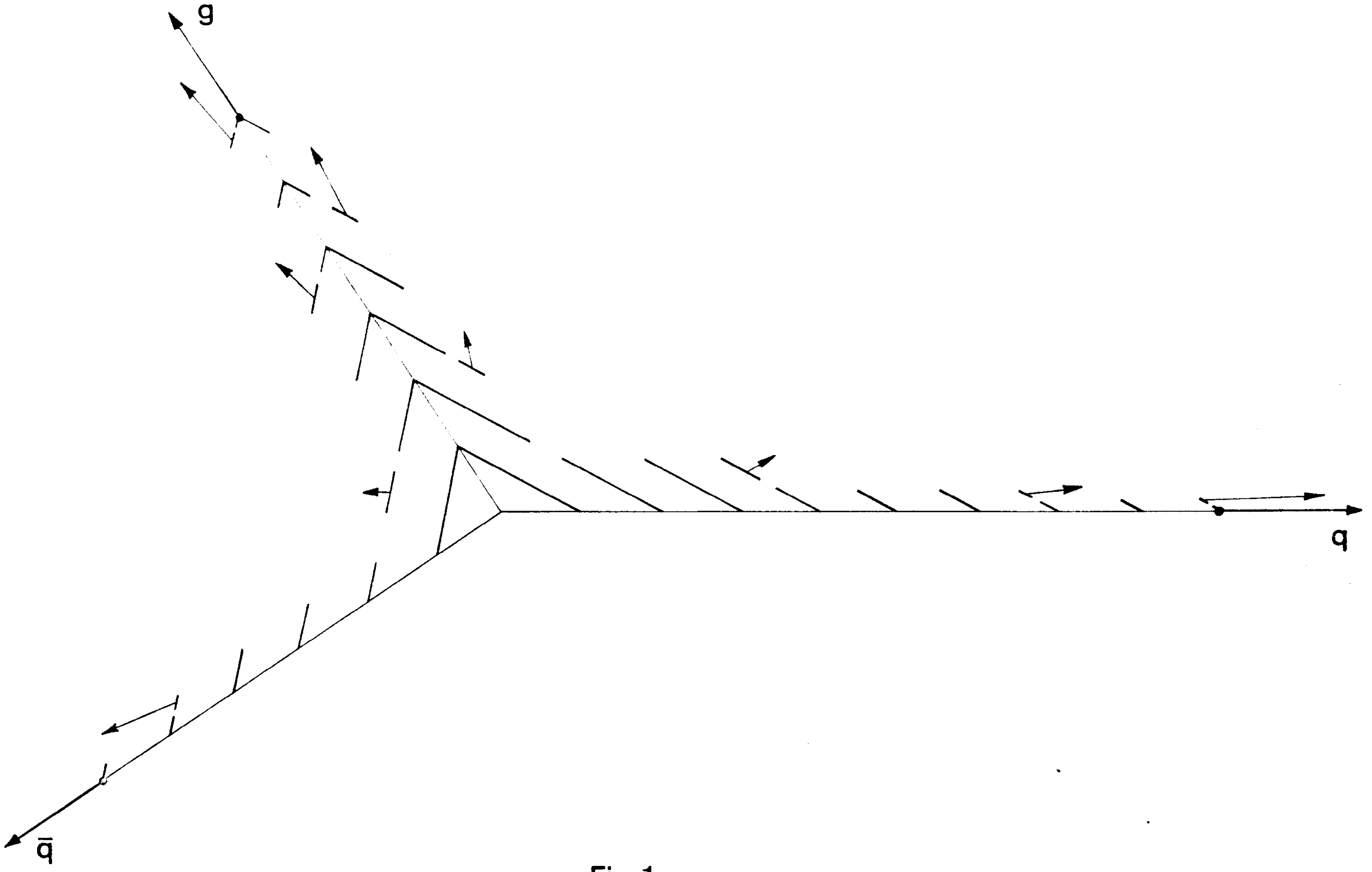

Fig.1

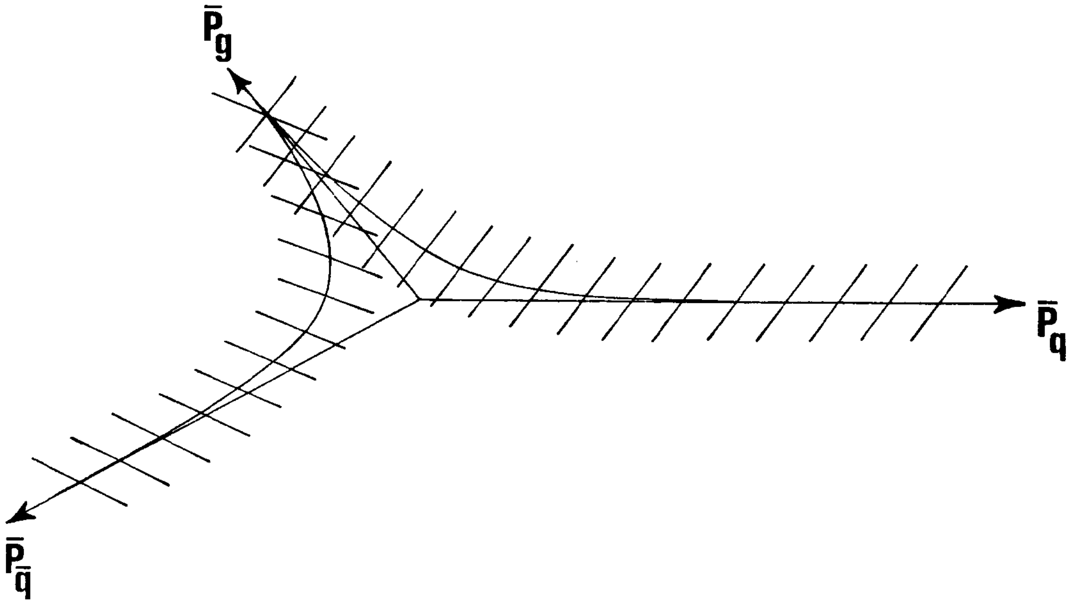

Fig. 2