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**THE STRING EFFECT AND INDEPENDENT FRAGMENTATION MODELS:
LORE AND FACTS**

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ABSTRACT

The purpose of this paper is to show that the independent fragmentation model adequately describes the so-called 'string effect', after the Field-Feynman algorithm has been duly corrected for the generation of soft particles. The conclusion is that there is no need to assume a dynamical suppression mechanism to explain the effect.

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1. INTRODUCTION

One of the most popularized results of the experimental physics programmes carried out at PETRA (DESY, Hamburg) and PEP (SLAC, Stanford) is the so-called 'string effect', i.e. the observation in $e^+ + e^- \rightarrow 3$ jets events of a more pronounced minimum in the particle or energy flow between the first and the second leading jet than between the leading and the least energetic jet [1-3]. The JADE and TPC Collaborations have given theoretical importance to this effect by claiming that models based on independent fragmentation of the three partons involved ($q\bar{q}g$) are unable to reproduce it. Their claim was based on the consideration of models that adopted the original Field-Feynman [4] algorithm for jet fragmentation (see refs. [5] and [6] and the independent fragmentation option of ref. [7]). From that consideration it was concluded that a specific dynamical mechanism, such as that provided by the string fragmentation scheme [7, 8] or by QCD coherence cancellations [9, 10], was necessary in order to diminish the production of particles in the region between the two leading jets. Related experimental support for such an interpretation was claimed by the TPC [11] and MARK II [12] Collaborations in comparing their data for $e^+ + e^- \rightarrow 3$ jets and $e^+ + e^- \rightarrow 2$ jets + γ events, showing that the minimum between the two leading jets in 3-jet events is deeper than the one between the two jets in radiative events, for kinematically similar topologies.

A relevant feature of the Field-Feynman algorithm in this context is the treatment of soft particles. The original algorithm uses a strict scaling scheme for the longitudinal dependence, which entails a constant $\langle p_T \rangle$ for particles independently of the longitudinal kinematics. For soft particles, this is clearly in contrast with jet collimation, since such particles can then spread out at quite large angles. An important side effect of the abundant generation of large-angle particles is the inducement of substantial deviations from overall energy and momentum conservation [13]. To some extent such deviations are unavoidable because of the small values of parton masses. However, huge large-angle emission may lead to high values for the invariant jet mass and thus make such deviations especially violent.

Phenomenologically, an indication that the original Field-Feynman algorithm generates too many soft particles at large angles can be obtained from the rapidity distribution at small y (fig. 1). The grey line is a fit with the original Field-Feynman model to data from HRS [14] and MARK II [15]. The characteristic minimum at $y = 0$ exhibited by the experimental data is not, in fact, reproduced.

Biddulph and Thompson have recently developed a modification of the Field-Feynman algorithm, with the aim of reducing energy and momentum fluctuations [13]. Not surprisingly, they have obtained a model in which, at small $p_{\parallel}$, one has approximately

$$\langle p_T^2 \rangle \propto p_{\parallel} / E_{\text{jet}} , \quad (1)$$

which yields a reduction of the angular spread of soft particles. [For a more exact expression, see eq. (2).]

The aim of this note is to show that an independent fragmentation model à la Biddulph and Thompson (IFBT) describes the 'string effect' adequately, without the need for any dynamical suppression mechanism.

In Section 2 the QCD Monte Carlo program used for the calculations is described. The $e^+ + e^- \rightarrow 3$ jets data on the azimuthal particle or energy flow are dealt with in Section 3, and Section 4 is devoted to the comparison of the particle flow in 3-jet and radiative 2-jet events. Section 5 discusses the results, and Section 6 contains the conclusions.

2. THE QCD MONTE CARLO MODEL

The calculations presented here are based on the parton-shower Monte Carlo program of ref. [16]. This was the first parton-shower simulation program developed for e^+e^- annihilation, and its first results were presented at the ECFA-LEP Workshop held in Rome in September 1979 [17]. The basic QCD Monte Carlo algorithm was also developed independently by the authors of ref. [18], although with some substantial differences^{*)}. These approaches then found applications mainly in $p\bar{p}$ collider physics. In recent years, owing to the attainment by PETRA of higher energies, and to the necessity of interpreting events with high jet multiplicities, their use in e^+e^- physics [9, 20, 21] has become more general. At the energies of TRISTAN and LEP, there are no alternatives to the parton-shower approach for handling QCD jet calculations.

A characteristic feature of the parton-shower scheme of ref. [16] is the choice of a gauge that suppresses QCD radiation off one of the members of the original quark-antiquark pair. This eliminates the arbitrariness with which the phase space that is available for radiation is divided between the quark and the antiquark in schemes wherein both of them undergo radiation. Also, the treatment of kinematic bounds becomes much simpler. Of course, radiated partons cannot be associated with the quark or the antiquark in a physically meaningful way, because of gauge invariance. The final state must turn out to be, on the average, symmetric with respect to the inversion of a physical axis such as that of the sphericity or of the thrust. This has been used to check the correctness of the calculational technique employed.

For the present calculations, the parton-level algorithm of ref. [16] has been modified so as to include: i) a matrix element correction for three-parton final states, similar to the correction originally used in ref. [22] for calculating QED radiation effects for leptonic decays of the Z^0 in the leading logarithm approximation; ii) γ - Z^0 interference; iii) initial-state QED radiation, calculated by means of the BKJ program [23].

Independent fragmentation of parton jets is treated with a model of the Field-Feynman type, including heavy-quark fragmentation and baryon production, and modified according to the prescriptions of Biddulph and Thompson [13] as outlined in the Introduction. The corresponding FORTRAN routines have been taken from COJETS, version 5.13 [24], the simulation program for $p\bar{p}$ and pp interactions, wherein full documentation for them can be found. Here we present the main features. The longitudinal part of the model is identical to that of the Field-Feynman model [4], with the adoption of the fragmentation function of ref. [25] for heavy quarks. Quark (or diquark) transverse momenta are also generated as in the Field-Feynman model, i.e. with a Gaussian distribution of constant $\langle p_{q,T}^2 \rangle = \sigma_q^2$. However, the transverse momentum $p_{h,T}$ of the hadron resulting from a $q\bar{q}$ (or quark-diquark) pair, of transverse momentum $p_{q\bar{q},T}$, is obtained from the latter, using a modulation factor depending on longitudinal variables:

$$p_{h,T}^2 = p_{q\bar{q},T}^2 F \frac{xW}{E_{\text{jet}}} \frac{2(1-x)}{(1-x/2)}, \quad (2)$$

where E_{jet} is the total jet energy, W is the residual value of $E + p_{\parallel}$ available for jet fragmentation before the current $q\bar{q}$ pair generation, x is the fraction of W carried by the currently generated hadron, and F is a free parameter. Particle generation goes on until the available energy is exhausted, with only forward-moving particles allowed. The generation of heavy particles is inhibited if the available energy cannot service it. The violation of transverse momentum conservation (also present in the original Field-Feynman model) is corrected at the end by aligning the total momentum of the jet with that of the fragmenting parton. Similarly, a (typically small) Lorentz boost ensures that the

*) For the proper attribution of credits see, for example, ref. [19].

total jet energy is exactly equal to that of the incoming parton. The model presented here is not identical to that of ref. [13], some simplifications having been introduced for algorithmic convenience. In particular, the (small) dependence on quark and particle masses, which is present in the equation of ref. [13] corresponding to our eq. (2), has been dropped. At the end of the generation of an event, exact conservation of total energy and momentum and of charge are ensured by a standard corrective algorithm.

Our results for the IFBT have been obtained with $\Lambda = 0.25$ GeV and a minimum parton-mass cut-off of $Q_0 = 3$ GeV, except for bottom-quarks, which have $Q_0 = 5.4$ GeV. The jet fragmentation parameters that are relevant for this study have been fixed from fits to e^+e^- data. Longitudinal parameters have been left at their standard values (see ref. [24]). For the transverse parameters, we have taken $\sigma_{q,q} = 0.6$ GeV/c for quark jets, $\sigma_{q,g} = 0.9$ GeV/c for gluon jets (which, as customary, are treated as quark jets of random light flavour), and $F = 1.6$ in eq. (2). The higher value of $\sigma_{q,g}$ is needed in order to describe the higher particle $\langle p_T \rangle$ in gluon jets observed by the JADE Collaboration [1]. A fine tuning of the fragmentation-model parameters to e^+e^- data is still pending. Figures 1 and 2 show fits to PEP data for the folded rapidity and p_T^2 distributions [15, 26] with the present parameter values. In particular, the minimum at $y = 0$ in the rapidity distribution is now correctly reproduced.

3. STRING EFFECT IN 3-JET EVENTS

The JADE Collaboration [1] was the first to observe the so-called string effect in $e^+ + e^- \rightarrow 3$ jets events (at $\sqrt{s} = 34$ GeV). This effect amounts to a depletion of particles in the azimuthal region between the two leading jets (predominantly associated with the quark and antiquark jets), relative to the number of particles in the region between the leading jet and the least energetic jet (predominantly associated with the gluon jet). The effect has been reported also by the TPC Collaboration (at $\sqrt{s} = 29$ GeV) [2] and by the TASSO Collaboration (at $\sqrt{s} = 34.6$ GeV) [3]. Magnitudes for the effect observed by the three experiments do not coincide: when counting all particles, the depletion observed by JADE is about twice that seen by TPC and by TASSO (table 1). Also, the increase of the effect when counting only particles with a transverse momentum component that is out of the 3-jet event plane, $p_T^{\text{out}} > 0.3$ GeV/c, although observed by JADE and TPC, is not confirmed by TASSO. This is likely to be due to the different ways of handling the 3-jet event analysis, and to angular acceptance effects. It is unfortunate that, in the extensive discussions devoted by these groups to the theoretical interpretation of the effect, nothing has been said about how much the experimental acceptance limitations affect it. In particular, the blind cones around the beams are likely to play some role. In order to limit their impact, it is customary to consider only events that have a thrust or sphericity axis well away from the beam direction. Therefore, the two blind cones will quite frequently deplete just the regions between jets that are relevant to the string effect.

The results we shall quote do not include corrections for effects from the experimental apparatus, apart from some necessary minimum energy and momentum requirements for counting particles. This is also because we have not found adequate definitions of the geometrical acceptance and experimental resolutions of the JADE experimental set-up. Therefore, the comparison with the data can only be qualitative. More meaningfully, one can compare our IFBT results with the uncorrected Lund parton-shower results quoted in table 1.

Only charged particles with momentum above 0.150 GeV/c and neutral particles with energy above 0.400 GeV are counted (these values are somewhat higher than those used by the JADE experiment, in order to take into account energy resolution effects; they coincide with those of TPC for pions and photons, respectively). The selection of events parallels that made by JADE. The

normalized eigenvalues $Q_1 < Q_2 < Q_3$ of the momentum tensor are computed. Only planar events with $Q_1 < 0.06$ and $Q_2 - Q_1 > 0.07$ are accepted. Particles are attributed to one of the three jets that are obtained by maximizing the triplicity. Jets must contain at least 4 particles and have a total visible energy > 2 GeV. We have furthermore assumed that jets must be at least 60° apart in the event plane, defined by the principal axes of the momentum tensor. Jets are ordered according to their energies, determined from the jet directions projected onto the event plane, with the standard assumptions [1].

Figure 3 shows a (qualitative) comparison between the JADE data and the IFBT energy and particle flows that we have calculated. Experimental depths of minima appear to be reproduced.

Table 1 and fig. 4 show the ratio $n(j_3 - j_1)/n(j_1 - j_2)$ of the particle densities flowing between jets 3 and 1 and between jets 1 and 2 within $0.3 < x_\phi < 0.7$, where

$$x_\phi \equiv \begin{cases} \frac{\phi}{\phi_2} & \text{between jets 1 and 2 ,} \\ \frac{\phi - \phi_3}{2\pi - \phi_3} & \text{between jets 3 and 1 ,} \end{cases} \quad (3)$$

$\phi_1 \equiv 0$, ϕ_2 and ϕ_3 being the azimuthal angles in the event plane of the three jets. The all-particle density ratio from IFBT is even larger than the Lund parton-shower model result (uncorrected for experimental effects) [27]. Also, a similar increase of the effect is obtained when the count is restricted to kaons or to particles with $p_T^{\text{out}} > 0.3$ GeV/c.

4. COMPARISON WITH RADIATIVE 2-JET EVENTS

The TPC [11] and MARK II [12] Collaborations have compared the particle flows in the azimuthal regions between the two leading jets in 3-jet events and between the two jets in 2 jets + γ events, under similar kinematical conditions. The ratio

$$r(x_\phi) \equiv \frac{\left[N_{\text{events}}^{-1} \frac{dn_{\text{tracks}}}{dx_\phi} \right]_{3 \text{ jets}}}{\left[N_{\text{events}}^{-1} \frac{dn_{\text{tracks}}}{dx_\phi} \right]_{2 \text{ jets} + \gamma}} \quad (4)$$

is observed to be somewhat below 1, and to decrease for particles with $p_T^{\text{out}} > 0.3$ GeV/c (fig. 5). It has been claimed that this observation provides further evidence that a dynamical suppression mechanism, such as the string fragmentation model or QCD coherence, is needed in order to explain the particle depletion between the two leading jets in 3-jet events. Neither TPC nor MARK II have compared their $r(x_\phi)$ data with quantitative predictions of such theoretical schemes, though (apart from the TPC comparison with the parton-level, asymptotic QCD coherence predictions of ref. [10]). The effects from the experimental apparatus and the event analysis look far from negligible: the minima in the azimuthal particle flow between the two relevant jets are sensibly deeper for MARK II than for TPC, for both types of events.

Although the comparison of our IFBT results with the data is necessarily qualitative, we shall show that the relevant features of the data are correctly reproduced.

We have patterned the event selection essentially after that of TPC, which relies less than that of MARK II on the jet reconstruction algorithm employed. In fixing it, we have paid special attention to the requirement that the two types of selected events have similar kinematics at the jet or photon level, the radiative photon corresponding to the less energetic jet in 3-jet events. For both types of

events, the normalized eigenvalues $Q_1 < Q_2 < Q_3$ of the momentum tensor must satisfy $Q_1 < 0.06$ and $Q_2 - Q_1 > 0.05$. Radiative 2-jet events must contain a radiative photon with energy > 3.5 GeV, and the remaining events are considered to be 3-jet event candidates. Jets are found by maximizing the triplicity, the radiative photon in 2 jets + γ events being identified with one of the triplicity axes. The triplicity axes must satisfy the planarity condition $|\hat{n}_1 \cdot (\hat{n}_2 \times \hat{n}_3)| < 0.34$, $\hat{n}_i$ being the normalized direction vector of axis i . The event plane is defined by the MARK II thrust tensor [12]. Jets are ordered according to their energies, determined from the jet directions projected onto the event plane, with the standard assumptions. Jets must contain at least 3 particles. The first and second jets must have visible energies > 2.5 GeV, with their sum > 7.25 GeV. The third jet in 3-jet events must have a visible energy > 1.5 GeV, and an energy reconstructed from angles > 4 GeV. The radiative photon in 2 jets + γ events must have an energy reconstructed from angles that is smaller than the energies of the two jets and > 4 GeV.

Table 2 reports the mean values of jet or photon energies, as determined from event-plane azimuthal angles for the accepted events. Corresponding values for 3-jet and 2 jets + γ events differ by less than 2%. Their values are close to those from the TPC event selection (no figures are quoted for MARK II).

In fig. 5 the IFFT results are shown for $r(x_\phi)$, a) including all particles and b) selecting only particles with $p_T^{\text{out}} > 0.3$ GeV/c. The qualitative comparison with the MARK II data shows that their basic features are reproduced: a valley-shaped dependence with a bottom substantially below 1, an increase of the effect for $p_T^{\text{out}} > 0.3$ GeV.

5. DISCUSSION OF THE RESULTS

One might wonder how an independent fragmentation model can account for the particle depletion between the two leading jets. A careful look at the azimuthal particle flow (fig. 3) shows that this question is ill posed. It is clearly not surprising that the minimum between the second and third jets lies above the other two minima, since the two jets are much closer than the other pairs of jets. On the other hand, the azimuthal distance between the first and third jets is shorter, on the average, by $\sim 20^\circ$ than that between the first and second jets. Therefore, one should naturally expect that the minimum between the first and third jets lies somewhat above that between the first and second. The utilization of the original Field-Feynman model, with its huge production of soft, large-angle particles, brings minima to higher levels, the effect being more marked for minima that are distant from the nearest jet axes. This somewhat reduces the disparities between the depths of the minima. That the problem with the original Field-Feynman model is rooted in the generation of soft particles finds confirmation in the TASSO analysis [3] of the $n(j_3 - j_1)/n(j_1 - j_2)$ ratio in bins of p_{in} , the particle momentum component parallel to the event plane. In fact, this analysis shows that for particles with non-small p_{in} , independent fragmentation à la Field-Feynman is in agreement with data (whereas the Lund model disagrees).

The higher value of $n(j_3 - j_1)/n(j_1 - j_2)$ attained for $p_T^{\text{out}} > 0.3$ GeV can be understood in a similar way. For soft particles, this cut translates into the requirement that their transverse momenta be preferentially directed away from the event plane. This further reduces the filling up of minima lying far from jet axes.

The increase of $n(j_3 - j_1)/n(j_1 - j_2)$ for kaons can be seen as a trivial consequence of the richer content in strange particles of the gluon jet, predominantly associated with the third jet.

The apparent directness of the comparison of 3-jet events with radiative 2-jet events is misleading. Hiding behind the topological similarity of the two event samples, which is exhibited by the near equality of corresponding jet or photon energies (table 2), there is the non-negligible difference between the invariant mass of the radiative photon and that of the 'gluon' jet. Angles

between jets, or between jets and the radiative photon, do not determine the actual energies of these objects but rather the relative ratios of their momenta. The finite mass of the 'gluon' jet reduces the energy scale for 3-jet events with respect to radiative 2-jet events having the same angular apertures. This mainly decreases the multiplicity of soft particles, because of the scaling properties of the hard part of the jet particle spectrum. Again, the angular regions far from jet axes are essentially the ones that are affected.

6. CONCLUSIONS

Independent jet fragmentation appears to reproduce the so-called 'string effect' correctly, once the well-known weaknesses of the Field-Feynman model concerning soft-particle generation are removed. Claims that a dynamical suppression mechanism is needed to explain this effect appear to be unsubstantiated.

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Table 1

Ratio $n(j_3 - j_1)/n(j_1 - j_2)$ of the numbers of particles flowing between jets 3 and 1 and between jets 1 and 2 within $0.3 < x_\phi < 0.7$, from various experiments and models. Also listed are the corresponding ratios for particles with $p_T^{\text{out}} > 0.3 \text{ GeV}/c$, for kaons and for the energy flow.

Model/Experiment	All particles	$p_T^{\text{out}} > 0.3 \text{ GeV}/c$	Kaons	Energy
IFBT uncorr.	1.29 ± 0.02	1.42 ± 0.05	1.48 ± 0.08	1.45 ± 0.02
Lund uncorr. ^{a)} [27]	1.22 ± 0.02	1.39 ± 0.05	1.50 ± 0.08	1.47 ± 0.02
JADE [1]	1.39 ± 0.04	1.73 ± 0.13	1.9 ± 0.2	1.56 ± 0.04
TPC ^{b)} [2]	1.19 ± 0.05	1.67 ± 0.24	1.58 ± 0.28	
TASSO ^{c)} [3]	1.19 ± 0.03	^(d)		

- a) Using the parton shower option with ‘local z , $\alpha_s(m^2/4)$ and no coherence’. The Kaons entry refers to $K^\pm$, p , and $\bar{p}$.
- b) The $p_T^{\text{out}} > 0.3 \text{ GeV}/c$ entry actually refers to $\pi^\pm$ with $0.3 < p_T^{\text{out}} < 0.5 \text{ GeV}/c$. The Kaons entry includes protons and lambdas.
- c) $0.25 < x_\phi < 0.75$.
- d) Data do not ‘show any variation’ with respect to the all-particle result [3].

Table 2

Mean values of jet or photon energies as determined from event-plane azimuthal angles for the selected 3-jet and 2-jet + γ events. Values in parentheses are for the TPC event selection [11].

Energy (GeV)	3 jets	2 jets + γ
$\langle E_1 \rangle$	13.0 (12.7)	12.8 (12.7)
$\langle E_2 \rangle$	10.0 (10.2)	10.1 (10.0)
$\langle E_3 \rangle$	6.0 (6.1)	6.1 (6.3)

Figure captions

- Fig. 1 IFBT model fit to the HRS (as quoted in [14]) and MARK II [15] data for the folded rapidity distribution in e^+e^- annihilation at $\sqrt{s} = 29$ GeV. Also shown is a fit with the original Field-Feynman model.
- Fig. 2 IFBT model fit to the HRS [26] and MARK II [15] data for the p_T^2 distribution in e^+e^- annihilation at $\sqrt{s} = 29$ GeV.
- Fig. 3 Qualitative comparison of JADE data [1] with the IFBT results, uncorrected for effects from the experimental apparatus and from event analysis, for the particle and energy flows in the 3-jet event plane, including charged and neutral particles, normalized to the total number of particles in each sample. ϕ is the azimuthal angle in the event plane that is oriented so that the three jets are ordered for increasing energies, with $\phi = 0$ corresponding to the axis of the leading jet. a) Energy flow $(1/E) dE/d\phi$. b) Particle density flow $(1/n) dn/d\phi$. c) Particle density flow for particles satisfying $p_T^{\text{out}} > 0.3$ GeV/c.
- Fig. 4 Ratio $n(j_3 - j_1)/n(j_1 - j_2)$ of the numbers of particles flowing between jets 3 and 1 and between jets 1 and 2 within $0.3 < x_\phi < 0.7$, from various experiments and models. Also shown are the corresponding ratios for particles with $p_T^{\text{out}} > 0.3$ GeV/c, for kaons and for the energy flow.
- Fig. 5 Qualitative comparison of IFBT results, uncorrected for effects from the experimental apparatus and from event analysis, with the MARK II data [12] for the ratio $r(x_\phi)$ of charged track densities in the region between jets 1 and 2 of 3-jet and radiative 2-jet events versus the normalized angle x_ϕ . a) All charged tracks. b) Charged tracks satisfying $p_T^{\text{out}} > 0.3$ GeV/c.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5