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JET PHYSICS IN e^+e^- INTERACTIONS

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JET PHYSICS IN e^+e^- INTERACTIONS

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The status of QCD predictions for jets in e^+e^- interactions is reviewed.

Jet physics in e^+e^- interactions has played an important role in the development of the standard model. The observation of jets at SPEAR¹ was one of the early pieces of evidence for the parton model, while the three-jet events from PETRA² gave direct evidence for QCD processes beyond the parton model. It now seems reasonably clear that the hadronic events observed in e^+e^- annihilations are in qualitative agreement with expectations from QCD. The remaining question is whether this qualitative agreement can be turned into a quantitative test of QCD.

The difficulties of making a quantitative test all stem from the familiar fact that jet processes involve a wide range of distance scales. The e^+e^- annihilation occurs at short distances of order $1/Q$. Because of asymptotic freedom we expect that short-distance cross sections can be calculated using QCD perturbation theory as a power series in the running coupling constant^{3,4}

$$\alpha_{\overline{MS}}(Q^2) = \frac{4\pi}{b_0} \frac{1}{\ln(Q^2/\Lambda^2)} \left[\frac{1}{1 + \frac{b_1}{b_0^2} \frac{\ln \ln(Q^2/\Lambda^2)}{\ln(Q^2/\Lambda^2)}} + \dots \right]$$

$$b_0 = 11 - \frac{2}{3} n_f, \quad b_1 = 102 - \frac{38}{3} n_f.$$

For the total cross section the Kinoshita-Lee-Nauenberg⁵ theorems guarantee that this series is insensitive to infrared scales, at least in perturbation theory.

Partial cross sections, however, can be sensitive to the distance scales of order $1/\Lambda$ at which hadrons form. The physics of hadron formation is certainly not perturbative and hence is poorly understood. We expect that color confinement will lead to a flux tube with a fixed transverse size between separated color charges. As this tube is stretched, it becomes energetically favorable for it to break, giving hadrons with a limited p_T distribution set by the size of the flux tube. There is some theoretical evidence for this picture from lattice QCD calculations,⁶ but there is currently no description of particle production derived directly from QCD.

In this situation we are forced to rely on models. Such models are certainly very useful for estimating the signatures and backgrounds for various processes, and some of them (e.g. the Lund model)⁷ are based rather explicitly on theoretical guesses about non-perturbative QCD effects. However, while testing a model may help to refine the parameters, it is unlikely to teach us anything fundamental about the underlying physics. The hope of learning

something fundamental from jet physics therefore must rely on finding quantities which are insensitive to the hadronization model used. The basis hypothesis is that quantities which are insensitive to small masses in perturbation theory are also insensitive to non-perturbative effects. This is certainly physically plausible.

Sensitivity to small mass scales in QCD perturbation theory always appears as logarithmic singularities of the Feynman integrals as the relevant mass μ vanishes. Then the expansion parameter is not $\alpha_{\overline{MS}}(Q^2)$ but rather

$$\alpha_{\overline{MS}}(Q^2) \ln(Q^2/\mu^2)$$

which is not small for any value of Q^2 . Such singularities are of two different types. Infrared singularities⁵ arise as the momentum k of a gluon attached to an external line becomes small:

$$p^2 = m^2, \quad k^2 = 0, \quad k \rightarrow 0$$

Then the cross section contains a factor of the form

$$\int \frac{d^3k}{2k} \frac{1}{((p+k)^2 - m^2)^2} = \int \frac{d^3k}{2k} \frac{1}{(2p \cdot k)^2}$$

which is logarithmically divergent as $k \rightarrow 0$. In QED such singularities cancel between real and virtual processes when integrated over a suitable interval. Physically this just reflects the fact that a zero-energy photon is not observable. In QCD the situation is more complicated,⁸ but a similar cancellation seems to work for the leading power of $1/Q^2$.

Collinear singularities⁵ arise from the emission of one massless parton parallel to another:

$$p^2 = k^2 = 0, \quad \theta \rightarrow 0$$

This leads to a factor in the cross section of

$$\int d\cos\theta \frac{\sin^2\theta}{((p+k)^2)^2} = \int d\cos\theta \frac{\sin^2\theta}{p_0^2 k_0^2 (1-\cos\theta)^2}$$

where the extra $\sin^2\theta$ in the numerator arises because for $\theta \rightarrow 0$ a spin-1 gluon must flip the helicity. Again the integral is logarithmically divergent. These divergences do not cancel. However, because the singularities arise from partons going on shell, they should factorize.⁹ That is, the singularities can be associated with jet fragmentation functions -- or in hadronic processes with structure functions -- in a universal, process-independent way. The general proof of this factorization is fraught with difficulties, but it has been checked explicitly to two-loop order.¹⁰ To leading order, the result is very simple: each collinear singularity contributes to the cross section a factor

$$\frac{\alpha_s((p+k)^2)}{2\pi(p+k)^2} P(z), \quad z = \frac{|p|}{|p+k|}$$

where $P(z)$ is the appropriate Altarelli-Parisi function,¹¹

$$P_{q \rightarrow qg}(z) = \frac{4}{3} \left[\frac{1+z^2}{1-z} \right],$$

$$P_{g \rightarrow gg}(z) = 6 \left[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right]$$

$$P_{g \rightarrow qq}(z) = \frac{1}{2} \left[z^2 + (1-z)^2 \right].$$

Thus these singularities, which are responsible for the leading-log QCD scaling violations, have a simple form of classical probabilities.

The basic assumption made in all QCD jet models is that the singularities of perturbation theory are a reliable guide to the effects of non-perturbative physics. Then for e^+e^- annihilation all non-perturbative effects must behave like collinear singularities and so can be lumped into jet fragmentation functions. Because of factorization these are universal: each jet fragments independently, at least for the fast particles. Higher order graphs generate scaling violations. The splitting of one parton into two obviously softens the fragmentation, and because of the collinear singularities such splittings are not negligible corrections.

There is one technical complication. So far, only singularities producing powers of $\ln(Q^2/\mu^2)$ have been discussed. This is fine when studying scaling violations at fixed z , but for small z or for the multiplicity powers of $\ln(1/z)$ are comparable to powers of $\ln(Q^2/\mu^2)$. When only the sum of the $\ln(Q^2/\mu^2)$ terms is considered, the resulting scaling violations produce a multiplicity growth like¹²

$$\bar{n}(Q^2) \sim \exp \left\{ \left[\frac{4CA}{\pi b_0} \ln \frac{Q^2}{\Lambda^2} \right]^{\frac{1}{2}} \right\}.$$

When the $\ln(1/z)$ terms are taken into account,¹² this growth is reduced to

$$\bar{n}(Q^2) \sim \exp \left\{ \left[\frac{2CA}{\pi b_0} \ln \frac{Q^2}{\Lambda^2} \right]^{\frac{1}{2}} \right\}.$$

Physically the reason is that in the leading $\ln(Q^2/\mu^2)$ approximation each parton radiates independently; since the initial qq state is a color singlet, coherent effects must reduce the number of soft gluons. To leading order in $\ln(1/z)$ these coherent effects can be included by using the factorized Altarelli-Parisi form for the cross section but restricting the gluon emission angles to satisfy^{12,13}

$$\theta_1 > \theta_2 > \theta_3 > \dots$$

Thus the probabilistic interpretation is retained.

All of the jet models of direct experimental interest are based on Monte Carlo simulation. Each model contains a part describing the hard QCD process and a part describing the formation of hadrons.

In existing models three different choices have been used for the perturbative QCD part. The first is simply to truncate QCD perturbation theory at some given order, typically including two, three, and perhaps four jets. The exact QCD cross sections can then be used for each topology, so the only model dependence comes from the way in which the singularities are cut off as two jets merge into one. This sounds innocuous but can actually have a large effect. A good example is provided by calculations of the higher order corrections to the thrust distribution, which is supposed to be insensitive to small mass scales. Ellis, Ross, and Terrano¹⁴ (ERT) and Vermaseren, Gaemers, and Oldham¹⁵ (VGO) calculated this correction in the limit of zero cutoff, while Fabricius, Kramer, Schierholtz, and Schmidt¹⁶ (FKSS) kept a finite cutoff. All the calculations were correct, but ERT and VGO found large corrections, while FKSS found much smaller corrections. Nevertheless, the finite-order approach puts in the most correct information about the jet cross sections to the given order. Since at PEP/PETRA energies there is no need for more than four jets, it is not surprising that the most widely used e^+e^- models (Ali,¹⁷ Hoyer,¹⁸ and Lund⁷) all adopt this approach.

The second choice for treating perturbative QCD is the branching approximation originally proposed by Fox and Wolfram.¹⁹ It allows an arbitrary number of jets but used for the multijet cross sections on approximation given by a product of factors of the form

$$\frac{\alpha_s((p+k)^2)}{2\pi(p+k)^2} P(z)$$

to reproduce the correct collinear singularities. Exact, noncollinear kinematics are taken into account. This makes the choice of z ambiguous; the most common choice is¹⁹

$$z = \frac{p_0 + |\vec{p}|}{(p_0 + k_0) + |\vec{p} + \vec{k}|}.$$

The branching approximation correctly describes the perturbative QCD scaling violations and multiple jets close in angle. For widely separated jets it has the right powers of α_s and of $1/(p+k)^2$, but it differs from the exact QCD cross sections by factors of about two.²⁰ Because it allows an arbitrary number of jets, it is most appropriate at high energy. (It is also useful for hadronic reactions, for which even the three-jet cross sections are complicated and the four-jet ones have not yet been calculated.) It is used by the Field,²¹ Gottschalk,²² Odorico,²³ and ISAJET²⁴ models.

The third approach is a modification of the second in which the coherent corrections to the branching approximation are included. This should provide a better approximation to the multiplicity and to the soft particle distributions at very high energy. Simple estimates, however, suggest that even for $Q = 10$ TeV the difference in the multiplicity is only about a factor of two. This approach has been used only by Webber,¹³ but it perhaps deserves wider application.

Once the perturbative QCD hard scattering has been generated, the partons must be turned into hadrons. There are also three approaches which have been used for this. Perhaps the simplest is to fragment each parton independently using some variant of the original Field-Feynman model.²⁵ Because of the factorization of collinear singularities, this is expected to describe correctly at least the fast particles in the jets. Indeed, the Ali and Hoyer models, which are of this type, do describe most of the e^+e^- data very well. However, in such models soft particles are typically treated in a somewhat arbitrary way and energy conservation is imposed by hand. More significantly, when two jets become parallel the single-jet result is not automatically obtained.²⁶ Nevertheless, independent fragmentation does incorporate most of the essential physics, and it is used in the Ali, Hoyer, Odorico, and ISAJET models.

String fragmentation models are somewhat closer to the usual picture of non-perturbative QCD. For a qqg event the simplest approach of this type is to split the gluon into $q'\bar{q}'$ and to fragment each qq' system in its own center of mass using the Field-Feynman model. The Lund model, the most widely used example of this type, is more complicated and attempts to put in more of QCD string dynamics. But the main effect is the same: in three-jet events the gluon jet is spread out, so a larger value of α_s is needed to fit the data.^{27,28} It seems that such models describe the very slow particles in three-jet events somewhat better²⁹ than do independent fragmentation models. However, both types fit most of the data quite well.

The final type²¹ of hadronization model uses the branching approximation down to masses of order 1 GeV. Then color neutral clusters are turned into hadrons with some trivial model, e.g., phase space. Such models reproduce the data remarkably well with very few parameters. It is important to realize, however, that they are models; the use of perturbation theory at such low masses is totally unjustified. Also, these models do contain nonperturbative

parameters, e.g., the cutoff mass at which the branching is stopped. The Field, Gottschalk, and Webber models are all of this type.

Of all the existing models, only the Ali and Hoyer independent fragmentation models and the Lund string model have been tuned to the data well enough to attempt to make a quantitative test of the underlying perturbative QCD cross sections. This test is conveniently parameterized by the value of α_s obtained in fitting the data. The results from the four PETRA groups at $Q \sqrt{s} \approx 30$ GeV are given in the following table:

	α_s (Indep. frag.)	α_s (String frag.)
DESY	$.12 \pm .02$	$.19 \pm .02$
JADE	$.16 \pm .015 \pm .03$	$.16 \pm .015 \pm .03$
Mark J	$.12 \pm .01$	$.14 \pm .01$
TASSO	$.16 \pm .02$	$.21 \pm .02$

Two conclusions are evident. First, the string models generally give larger values of α_s . This is easily understood: in the string models the fragmentation is done in the color separation frame and the hadrons are then boosted back to the lab frame. The fast hadrons follow the jet directions, but the slow ones get spread out, so more three-jet events are needed to fit the data. Second, the differences between different experiments are comparable to the differences between the models. Either something is very wrong with some of the detector simulation programs or supposedly small differences between versions of the models have a substantial effect on the results.

Perhaps we should be satisfied that all of the experiments agree that

$$\alpha_s = .16 \pm .04 .$$

After all, for hadronic physics a 25% error is not bad! But to make a quantitative test of QCD we would like to do better. In the absence of real theoretical progress on the confinement problem only two approaches seem at all promising. One is to study a wider variety of models. It is sometimes said that the independent fragmentation and string models represent extreme limits, but with only two models it is hard to find a model in the middle. It would therefore be desirable to tune (say) one of the branching models to fit the data as well as the present ones do. Unfortunately, this requires a lot of work with no guarantee of useful results.

The only other approach is to go to higher energy. The differences between the various hadronization models are clearly higher twist effects and should scale roughly like

$$\frac{\langle n \rangle \langle p_T \rangle}{Q} .$$

All of the existing three jet analyses have been done for $Q \approx 30$ GeV. Even a comparison with $Q \approx 45$ GeV might help, and a comparison with $Q \approx 90$ GeV would surely be useful. But since these are large, unexplained differences among the experimental groups, the analysis must be done with a consistent set of assumptions. The best hope for this in the near future may be a comparison of PEP and SLC data.

The SppS collider³¹ has already observed jets at Q values which will not be available in e^+e^- collisions until LEP-II. Hadron colliders may well be the best way to look for certain kinds of deviations from QCD, e.g., scaling violations coming from quark substructure.³² But hadron colliders do not seem to be a good way to make precise tests of QCD. One problem is that many more graphs contribute even in lowest order, so that higher order calculations are more difficult.³³ Presumably this could be overcome with enough work. The other, more fundamental problem is that jet cross sections vary rapidly with p_T , so the results are sensitive to the p_T scale and hence to the treatment of soft particles. Such particles are not well understood.

In the present state of theoretical understanding, it is unlikely that we will soon have a single decisive test of QCD. We can hope to test QCD only by studying a wide variety of processes. Jets in e^+e^- reactions are certainly one of the processes that should be vigorously pursued.

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