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JETS IN HADRON COLLISIONS IN QCD

MICHAEL H. SEYMOUR
Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire. OX11 0QX. England.

I briefly discuss three topics related to the hadroproduction of jets: jet definitions; jet structure; and the underlying event.

1 Introduction

Jets of hadrons are one of the most striking features of hadronic collisions. They also provide much of the interesting physics, both directly in QCD studies, and indirectly in reconstruction of particles that decay to jets, for example the top quark. In recent years, we have grown increasingly optimistic that jet physics is entering a new era of 'precision measurements', based on the increasing precision of perturbative calculations and parton distribution functions on the one hand, and the experimental data on the other. In this talk, I would like to discuss three potential flies in the ointment – areas in which soft or semi-soft physics might spoil the connection between the hard parton-level calculations and the hadron-level data.

It has recently been realized that the jet definition in current use, the Snowmass-inspired iterative cone algorithm, is not infrared safe. This means that we cannot calculate jet cross sections perturbatively. In section 2 I briefly discuss why not, what this might mean, and how we can rectify it.

Modelling the internal structure of jets well is important, because this determines the dependence of jet cross sections on the jet definition and, to some extent, the systematic errors on jet measurements. Direct measurement of the jet structure is therefore important as a cross-check of this modelling, as well as as a test of QCD in its own right. In section 3 I discuss the measurements that have been made to date, and prospects for improved measurements using better observables.

One of the biggest uncertainties in jet physics is the correction due to the 'underlying event', the soft collision undergone by the hadron remnants in addition to the hard parton scattering that produces the jets. In section 4 I discuss why this is so important, and how we can constrain current models better.

Finally in section 5 I draw some conclusions.

2 Jet definitions

The 'Snowmass Accord'[1] was the first serious attempt to standardize jet definitions across different experiments and between theory and experiment. It defined a jet as a direction that maximizes the amount of transverse energy flowing through a cone centred on its direction. The transverse energy, E_T of the jet is simply the scalar sum of the transverse energies of the particles in it and its direction in pseudorapidity, η, and azimuth, ϕ, space is given by the E_T-weighted averages of the particles in it.

However, this definition suffers from two main problems, the solution of which have lead to more-or-less each experiment using a slightly different definition. Firstly, a global maximization is far too costly in computer time, so a local maximization is used, starting from a 'seed' direction. Typically, every calorimeter cell above a given E_T is used as a seed. Secondly, after doing this maximization, several jets can be overlapping, sharing some particles in common. The way this is resolved depends on the amount of shared energy: if it is above some threshold, the jets are merged together; and if it is below, they are split, with the particles being shared out according to which jet they are nearest. The precise details of the versions used by CDF[2] and D0[3] are summarized in Ref. [4].

Unfortunately, it turns out that the precise definition of the seeds makes the merging/splitting step infrared-unsafe. In order to calculate cross sections in perturbation theory, the jet definition must be insensitive to the presence of infinitely soft gluons. This is not the case in the algorithm as defined above, which is manifested as a logarithmic dependence on the seed cell energy threshold. If this is set to zero, corresponding to an infinitely good detector, the cross section is infinite at NNLO, as shown in Fig. 1. This problem had not previously been noticed because it

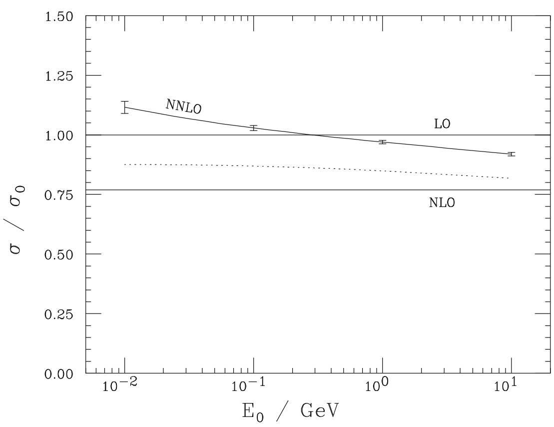

Figure 1: *The seed cell threshold dependence of the inclusive jet cross section in the DØ jet algorithm with* $R = 0.7$ *in fixed-order (solid) and all-orders (dotted) calculations. Taken from [4].*

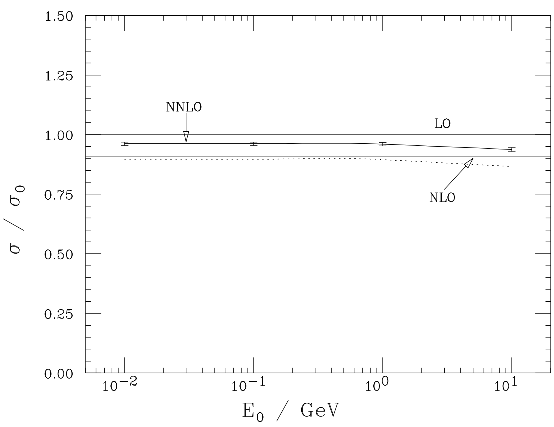

Figure 2: *As Fig. 1, but in the improved iterative cone algorithm, in which midpoints of pairs of jets are used as additional seeds for the jet-finding. Taken from [4].*

is first manifested in four-parton final states. Exact order-by-order calculations for two-jet cross sections have only reached NLO, corresponding to three-parton final states. However, a partial calculation of the three-jet cross section to NLO, corresponding to four-parton final states, has recently been completed[5], and a negative-infinite cross section was found. This is a direct reflection of the positive-infinite inclusive two-jet cross section I found, as the sum of the two is finite. Furthermore, as explained in Ref. [4] Sudakov suppression prevents this effect from being visible in the all-orders result (also shown in Fig. 1), so this problem was not identified using parton shower Monte Carlo programs either.

A simple solution is to add a new step to the clustering process: after iterating from the seed cells but before resolving overlapping jets, consider the midpoint of every pair of jets found so far as a seed direction and iterate again. As shown in Fig. 2, this solves the problem and gives a cross section that is finite in any order of perturbation theory. In my simplified approximation to higher orders, it also gives a smaller correction from one order to the next, but this will not necessarily be the case in the full calculation.

Despite this making the cross section finite, the fact that it makes no difference at NLO means that the full dynamics are not well described by NLO calculations. A better solution is to use an algorithm in which there is no merging/splitting ambiguity, such as the $k_\perp$ algorithm[6,7]. As shown in Ref. [7], this is extremely similar to the iterative cone algorithm at NLO, provided one sets the radius-like parameter about 1.35 times bigger in the $k_\perp$ algorithm than in the cone algorithm. They also studied the distribution of energy within the jet and found that more is concentrated near the centre in the $k_\perp$ algorithm, meaning that it 'pays more attention' to the hard core of the jet and less to the soft tails. This is probably why it is superior to the cone for reconstructing the masses of particles decaying to jets like the top quark and Higgs boson[8].

3 Jet structure

In leading order perturbation theory, jets are infinitely narrow. A NLO calculation of a jet cross section gives the first non-zero contribution to the width. At higher perturbative orders this width is increased by multiple gluon emission, and ultimately by non-perturbative hadronization effects. Therefore by studying the internal structure of jets, we are probing the details of the confinement mechanism by which a hard parton evolves to a jet of hadrons. This picture is somewhat complicated by the underlying event, as I will discuss more in the next section.

The simplest probe of jet structure is the jet shape, essentially a map of how the jet's energy is distributed as a function of angle from its centre. The first perturbative calculation of the jet shape was made in Ref. [9]. It was found that it does not describe the data[10,11] very well at all, which was attributed to the merging/splitting problems I mentioned earlier. To get around this, an adjustable parameter "R_{sep}" was introduced to simulate the effect of higher orders in a NLO calculation. More recently, and particularly with the advent of good quality data from HERA[12], it was found that R_{sep} had to vary as a function of essentially all the kinematic variables available in order to fit the data, thus losing all predictivity[13]. Since these are only LO calculations of the jet structure, it is perhaps not surprising that they do not do very well, particularly since it was already known that their scale-dependence was large.

In Ref. [4], I used a simple model[a] of the NLO matrix elements to estimate the effect of higher order corrections, resummation of large logs to all orders, and hadronization. The conclusion, shown in Fig. 4, is that these effects combined roughly double the amount of energy near the edge of the jet, and give a dramatic overall change in shape. We should therefore not be too surprised that the LO calculations fail. On the contrary, we should treat this as an indication that we can really learn some physics from the jet shape.

A great deal of progress has recently been made in understanding power corrections to semi-inclusive jet quantities in e^+e^- annihilation and DIS where the primary jets are principally quarks. Jet structure at hadron colliders offers a unique opportunity to make similar studies of gluon-dominated jets and first studies in this direction were made in Refs. [4,14].

In comparison with Monte Carlo models, the results of Refs. [10,11] show that HERWIG's jets are always too narrow, by an amount that varies with the jet kinematics. Given that the

[a] A comparison of the model with the exact matrix elements is shown in Fig.3, where it can be seen to be essentially perfect.

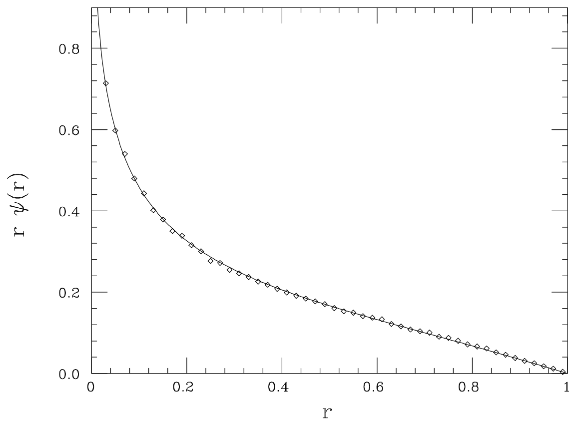

Figure 3: *The jet shape at leading order in the $k_\perp$ algorithm for a 50 GeV jet at $\eta = 0$ according to the exact tree-level matrix elements (points) and the MLLA formula (curve). Taken from [4].*

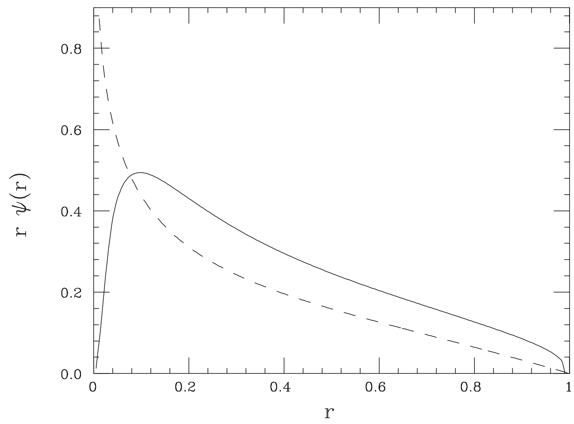

Figure 4: *Total effect of running coupling, power corrections and resummation on the shape of a 50 GeV jet in the $k_\perp$ algorithm: LO (dashed) and with everything (solid). Taken from [4].*

description of jets in e^+e^- annihilation is almost perfect (at least on the scale of the disagreement in hadron collisions), it is surprising that the description is so poor. Asking what is new in hadron collisions relative to e^+e^-, three features come to mind: gluon jets rather than quark jets; initial state radiation; and the underlying event. As shown by OPAL[15], one can implement cone algorithms in e^+e^- annihilation and use vertex tagging to isolate a very pure sample of gluon jets. These are well-described by the parton shower models. CDF made a very detailed study of the distribution of the softest jet in three-jet events[16], which is very sensitive to the treatment of initial-state radiation, and even interference between initial- and final-state. This was also well-described by HERWIG. Therefore we are left with the underlying event as the most viable culprit, which I will discuss more in the next section.

It is also known from e^+e^- annihilation that the energy spread of a jet is not the best probe of its structure. By resolving the jet into subjets using a cluster algorithm such as the $k_\perp$, a much more direct reflection of the underlying parton structure is obtained. The simplest such quantity is the average number of subjets, calculated in Ref. [17]. The factorizing property of the $k_\perp$ algorithm means that leading and next-to-leading logs can be summed to all orders, which is extremely important for small resolution criteria, y_{cut}, as shown in Fig. 5. So far, the subjet

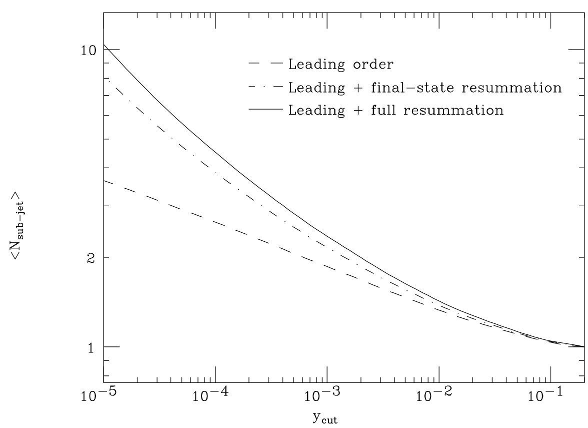

Figure 5: *Leading order (dashed) and resummed results for the subjet multiplicity in a 100 GeV jet at the Tevatron. Taken from [17].*

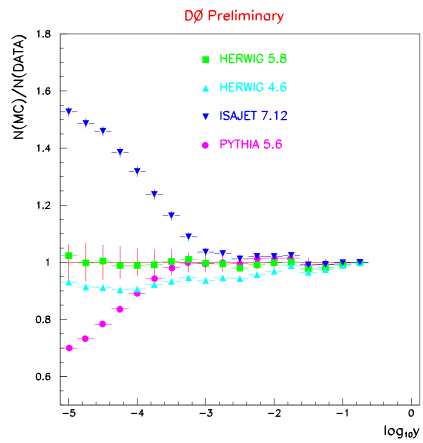

Figure 6: *The subjet multiplicity in a 300 GeV jet at detector level in various models, normalized to the data. Taken from [18].*

multiplicity has only been measured at detector level[18], only allowing comparison with Monte Carlo models. There the agreement seen in Fig. 6 is quite remarkable, at least in HERWIG, given that at the left of the plot, 300 GeV jets are being probed at a scale of only 1 GeV.

4 The Underlying Event

To leading twist, final state properties in hadron collisions are determined by the collision of a single parton from each hadron. However, to give a complete description of the final state, one must go beyond leading twist and consider how the rest of each hadron interacts (producing the 'underlying event'). This is an area of QCD that is poorly understood both theoretically and experimentally, and a great deal more study is warranted from both sides. It is the source of the majority of hadrons in an event and, although they are typically soft, they have a major impact on jet physics.

At present we have two very different models for the underlying event: 'soft' and 'hard'. The soft model, implemented in HERWIG[19], treats the collision of the two remnants exactly like a minimum bias event at the same energy, which is parametrized from UA5 data[20]. The hard model, implemented in PYTHIA[21] and as an add-on package for HERWIG called JIMMY[22], uses multiple perturbative scattering ('minijets') to produce the underlying event. Both give good descriptions of the average properties of events and even correlations like the pedestal effect[23,24]. However, they give very different probabilities for rare upward fluctuations in the amount of activity, which is what is most important for determining jet cross sections.

The typical E_T density produced by the underlying event is of order 1 GeV per unit $\eta \times \phi$, so one would naïvely expect it to have only a small effect on high E_T jets. This is not however the case, because the perturbative jet spectrum falls so rapidly with E_T. Therefore, although it is very rare for a jet to have its energy increased by several GeV, at any given E_T there are so many more jets a few GeV below that the small fraction of them that get shifted up in E_T become a large fraction of the jets at that E_T.

It is predominantly the high k_t tail of the underlying event distribution that produces this shift, which is the feature that differs most between the hard and soft models. It would help to pin this high k_t tail down if the test proposed in Ref. [24] was carried out. Instead of just measuring the amount of E_T in the tails of the jet, the idea is to measure correlations between the E_T on either side of the jet, giving a probe of the 'jetiness' of the pedestal. The proposal of Ref. [24] has been updated and adapted to Tevatron-type analyses in Ref. [25], and it is hoped that it will soon be measured.

The underlying event also has an important practical consequence for Monte Carlo event generators because many events above a given E_T come from partons at much lower p_t. This means that the minimum p_T of scatters must be set much lower than the minimum jet E_T in order for it to have no effect, but then the efficiency is very low, as most jets do not make it over the E_T cut. Unfortunately no solution to this problem is foreseen at present.

5 Conclusions

Despite the great advances made in jet physics in recent years, we should not be over-complacent about our accuracy. Non-perturbative effects can be large, and must be understood before a connection can be made between the precise parton-level calculations and the precise hadron-level measurements. The precision of both sides can be viewed as an opportunity to learn more about QCD, but if on the other hand we really want to test our perturbative calculations and measure α_s and the parton distribution functions, we need to constrain and improve our models of the non-perturbative corrections. Doing so will require greater theoretical and experimental understanding.

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