CONF-850869--12

THE STATUS OF PERTURBATIVE QCD

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CONF-850869--12

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ABSTRACT

Progress in QCD in the past year in reviewed.

1. INTRODUCTION

Over the past year, work on perturbative QCD has shown much vitality. A big impetus has come from the studies that have been made for the SSC, at Snowmass and Oregon, and from the results coming in from the Sp$\bar{p}$S. There is an interesting statistic: At the conference concluding the workshop here, on Super-High Energy Physics[1], 40% of the talks were on perturbative QCD.

Since new accelerators are supposed to look for new physics, this appears paradoxical until one reminds oneself of some of the important properties of QCD. Suppose one produces a Higgs particle that decays to a $t\bar{t}$ pair, which ultimately decays to several light quarks. As these emerge from th scattering they radiate gluons readily, for the QCD coupling is not very small. The gluons themselves radiate more gluons, and as the process gets to longer distances, the effective coupling gets bigger. Eventually they reach the confinement scale, when the large number of partons then turns into a collection of jets of ordinary hadrons.

We all know how cleanly jets appear at the Sp$\bar{p}$S, and they obviously correspond to partons coming out of the the elementary processes inside a collision. But they are not nearly so clean when one wishes to examine them in detail. QCD effects persist to the highest energies in distorting signatures for new physics. As Gunion, Kunszt, and Soldate[2] recently showed, the most serious background to finding the Higgs particle is just ordinary QCD jet production.

The problems in making improved predictions for high energy scattering are all to do with soft partons (especially gluons). Much of the work now is on the small-x problem, which consists of studying the soft partons directly, rather than indirectly through their recoil effects on the hard partons. Not only are these problems of great intrinsic interest, but the answers are vitally needed by experimentalists. In solving the problems, we are going away from the places where one makes the easiest tests of QCD to where the cross-sections are biggest.

Specific areas in which there has been progress are as follows: At last we have a proof[3] of factorization for hadron-hadron collisions - for the Drell-Yan process etc. There are

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Talk given at DPF Conference Eugene, OR. Aug. 12-15, 1985.

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AC02-80ER10712

greatly improved techniques for the fast calculation of higher order graphs[4]. Perturbative Monte-Carlo calculations for hadron-hadron scattering have come considerably closer to real QCD[5],[6]. We now understand the applicability of perturbative methods to heavy quark production[7].

Finally, there has been progress in understanding the small-x problem[8],[9], and this subject is making a take-over bid for Regge theory.

2. PROOF OF FACTORIZATION

Proofs of the classical factorization theorem for hadron-hadron collisions have been given[3] by Bodwin, and by Soper, Sterman and myself. These lay to rest the controversy that was started by Bodwin, Brodsky and Lepage[10] as to whether factorization is true. Almost all QCD calculations of cross-sections for high-energy hadron-hadron collisions use factorization, so without the theorem, the predictive power of the theory is lost. The original proofs[11] were known to be incomplete shortly after their publication. When Sterman and myself[12] completed the proof for e^+e^- annihilation, we explicitly did not cover the hadron-hadron case (i.e., the Drell-Yan process etc).

2.1 Factorization

The factorization theorem that we discuss here asserts that the cross-section for a process like Drell-Yan is given as a convolution of a hard scattering cross-section, σ_{hard}, with parton distribution functions, $f(x, Q)$.

The original proofs[11] did not properly treat the cancellation of the effects of soft gluons. At first sight, one appears to have a particular case of the Kinoshita-Lee-Nauenberg and Bloch-Nordsieck cancellations, as has been stated in the literature. However, the simple $O(\alpha_s)$ calculations with incoming partons are misleading in this respect, for soft gluons can be emitted off internal as well as external lines. A simple graph demonstrating this fact is given in Fig. 1. Cancellations of the Bloch-Nordsieck type, such as we are all used to in QED, involve only emission off external lines.

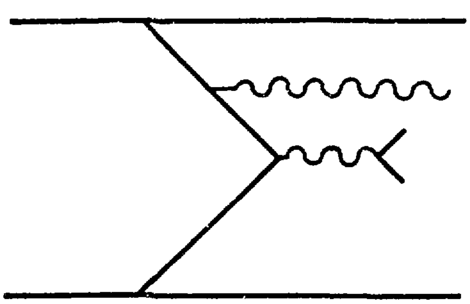

Fig. 1. Emission of soft gluon from internal line.

2.2 The proof

The physics of the proof is roughly as follows. First, we know that final-state interactions cancel. The basic ideas come from Ref. 13], and embody the fact that we sum over the possible happenings in the final-state.

Then comes the fact that soft gluons cannot resolve the details of jets. This permits a coherent sum over the emission of soft gluons from different lines in a jet. At the level of Feynman graphs, this is seen as the use of a "soft approximation", after which a certain kind of Ward identity can be used.

After using the Ward identities, we find that the soft gluons factorize: Their emission is effectively off the holes left in the incoming hadrons by the partons that went into the hard scattering. The proof of cancellation of soft-gluon effects for jet production in e^+e^- annihilation now applies[12],[14].

The difficulty raised by Bodwin, Brodsky and Lepage is that the soft approximation is not valid in certain non-negligible momentum regions. Because both initial- and final-state interactions are present, one cannot avoid this region by the trivial contour deformation one uses in e^+e^- annihilation[12]. One must first invoke the cancellation of final-state interactions. Unfortunately, the treatment of the final-state cancellations is most easily made in time-ordered perturbation theory, while the Ward identities are only conveniently treated in Feynman perturbation theory. What makes a proof so hard to construct is to combine these ideas in the right order to give both a robust and correct proof, which is what we believe we now have.

2.3 Implications

The techniques used in constructing a full proof of factorization are of general applicability to soft-gluon physics. especially to cases where the effects of the soft gluons do not cancel. The methods apply to all orders, and not merely to the leading logarithm approximation. Already there have been important applications to transverse momentum distributions. The techniques are also crucial in treating the small-x problem.

The proofs are now given in Feynman gauge, rather than in a non-covariant gauge.

3. CALCULATING HIGH ORDER GRAPHS

There were great improvements in techniques to compute high order tree graphs in QCD[2]. The basic ideas have been known for a little while.

First, instead of calculating cut graphs for cross-sections, which is what one normally does, one should calculate amplitudes first. This is because there are many fewer terms to handle. Then one chooses bases for the gluon polarizations cunningly, thus eliminating most of the terms in the couplings. Finally one uses a helicity basis for the fermions; combined with the choice of gluon-polarization basis, this avoids the γ-matrix sprawl that happens so readily when using the traditional methods. The progressive improvements are listed in Ref. 15].

There is hope of extending the methods to treat graphs with massive quarks and rather importantly with loops. To do this would be very valuable, for otherwise we will be deluged with calculations of multi-jet production and the like, from tree-graphs, but with the calculations being incomplete without the virtual corrections. Almost all results for new physics involve heavy fields, of course.

4. MONTE-CARLO PROGRAMS FOR HADRON-HADRON COLLISIONS

There are two methods of making perturbative QCD calculations – the "analytic" methods and the Monte-Carlo methods.

Analytic calculations result in closed formulae for cross-sections, and the numerical work is confined to solving simple differential equations and performing low-dimensional integrals. The basic quantities in this approach are non-logarithmic terms obtained from Feynman graphs; they are capable of systematic improvement by calculating higher orders. But the cross-sections are typically given only for certain inclusive processes, and there is no information on the rest of the event.

The Monte-Carlo approach turns the Feynman graphs, suitably approximated, into a probabilistic algorithm, which can then be used to generate whole events. This approach is therefore very helpful for experimentalists, because the results are easy to compare with their data and fit in well with Monte-Carlo simulations of the apparatus. However, the approximations have often been not very good. Also, it has been difficult to incorporate the full results of perturbative QCD into the algorithms, especially the new results on soft gluons.

The workshops at Snowmass last summer and at Oregon this spring have stimulated much work on improvement in the Monte-Carlos. The aim is to include much more of the known soft gluon physics, and to do this correctly. Initial-state gluon radiation was incorporated in the Monte-Carlos for hadron-hadron scattering. Paige[6] summarized this work in his talk here.

5. PRODUCTION OF HEAVY QUARKS ETC

Another issue that was more-or-less resolved was the applicability of perturbative methods to the production of heavy strongly interacting particles (anything from the charmed quark to possible super-symmetric partners of the usual quarks and gluons). Unfortunately, no one has written down a proof of factorization for these processes. Furthermore, the predictions for total charm cross-sections are notoriously below the quoted experimental values[16]. (At the ISR one talks of experimental cross-sections of between 100 μb and 1 mb, but of theoretical predictions of tens of μb.)

Therefore, many people have proposed that the standard factorization fails for heavy quark production, and have suggested alternative mechanisms for enhancing the charm cross-section. (Examples: flavor excitation, intrinsic charm, pre-binding distortion à la Bethe-Heitler, diffractive excitation.) These proposals have considerable impact on the design of experiments for looking for new heavy flavors. The cross-sections are much larger than from the conventional gluon-fusion mechanism and are typically large contributions in the forward direction.

At the Oregon workshop these issues were investigated. Ultimately, agreement was reached that the standard perturbative mechanism gives the correct QCD prediction. This conclusion[7] was based on an analysis of low-order Feynman graphs and of the coordinate-space physics in the light of what is necessary to make a proof of factorization[3].

Some of the proposed alternative mechanisms are higher twist – like intrinsic charm or pre-binding distortion. These mechanisms might be important for charm production, but not for top production. Others of the proposed mechanisms are actually included in the gluon fusion mechanism, and sometimes, as in the case of flavor excitation, omit relevant graphs.

If there is a substantial fraction of a heavy quark cross-section that is diffractive, as has been suggested from the ISR data[16], then it is a part of the gluon-fusion contribution. This needs further investigation. At the time of writing, the subject of diffractive hard scattering[17] appeared poised for take-off.

The problem with the charm data apparently still remained. Possible explanations are the following: 1. QCD is wrong. 2. The data are wrong. 3. The higher twist corrections are unusually large. 4. The charmed hadron distributions do not follow the charmed quark distributions very well. 5. Higher order corrections bring in larger K-factor than we are used to.

At this meeting, data[18] was presented by the LEBC collaboration. Their cross-section is in agreement with the gluon-fusion predictions, but with a significant excess in the forward region. This is modeled correctly by a Lund string Monte-Carlo calculation for the final-state interactions. The excess forward production is a higher twist effect, according to our new QCD results[7]. But for partons of a couple of GeV, it is not unreasonable to expect such distortions in the final-state interactions.

There are also indications[19],[20] that the higher-order corrections to the gluon-fusion process are unusually large. A full calculation of the $O(\alpha_s^3)$ corrections to heavy quark production would be especially useful. The tree graphs are known, but the virtual corrections are not.

The conclusion then is that the standard perturbative methods for heavy flavor production are reliable, and can be used with confidence to predict cross-sections for new heavy flavors.

6. SMALL X

I will briefly discuss here the progress that has been made in the study of hard collisions whose typical transverse momenta, Q, are much less than the overall center-of-mass energy, $\sqrt{s}$. The quantity x is the ratio $Q/\sqrt{s}$. The motivations for this study I explained in the introduction. Mueller gave a fuller discussion in his talk[8] at this conference, as I did in the proceedings of the workshop conference[9].

The fundamental theoretical issue comes from the logarithms of x that occur in higher order corrections, and from the question of whether factorization is actually true. The logarithms must be resummed in some fashion, for otherwise they ruin the convergence of the perturbation series. The Russian work summarized in the paper of Gribov, Levin and Ryskin[21] led the way. Factorization appears to hold, and there are ways of controlling the logarithms. The techniques that are used are those of the soft gluon type, but mostly so far in leading logarithm approximation. Considerable resummations are need to get final results.

The main phenomenological issues stem from the fact that the Altarelli-Parisi evolution generates a large number of gluons at small x and even not very large Q. The result is that the cross-section for making jets with transverse momenta of a few GeV is of the order of the total hadronic cross-section, at current collider energies. Thus there is a change in the character of minimum bias events: they include perturbative hard scatterings typically. Moreover multiple hard scattering ("parallel") may be common[22], and will have its effect on violations of KNO scaling and the like.

More results can be expected in this field. There is an obvious overlap with Regge theory, which will be explored. Further exploration of the region where partons become overcrowded and recombine within a hadron is continuing; this region sets the ultimate limit that we have at present for the applicability of factorization. This and the study of multiple hard scattering will bring in the need to understand the two-parton correlation functions better. We hope to gain more control over the approximations used. More work on the phenomenology of multiple hard scattering is needed.

7. CONCLUSIONS

1. Perturbative QCD is on solid ground, now that we have a proof of factorization.
2. The range of its applicability is growing. The small-x work is most significant here.
3. The particularly interesting problems that need more work are:
   a. The small-x problem.
   b. More QCD input to the Monte-Carlos.
   c. Understanding the sizes of higher-order graphs. I did not discuss this, but there are many next-to-lowest order corrections that are comparable to the lowest order graphs. Frequently we have plausible excuses as to why this does not wreck the applicability of the perturbation expansion, but it would be nice to work the excuses into a systematic treatment. I am speaking here of the large constant terms, rather than of the large logarithms, which are often well understood.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of Energy under contracts DE-AC02-80ER-10712 and DE-AC02-76ER-02220. I would like to thank the organizers for running such a superb conference.

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