SOFT QCD AND MONTE CARLO

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The models for soft QCD used in in Monte Carlo event generators are described briefly, together with some related topics of current experimental and phenomenological interest.

1 Introduction

QCD dynamics in the regime of long distances and low momentum transfers is an important ingredient of many processes, but we do not yet have many theoretical tools for making predictions in this regime. The techniques of lattice QCD are mostly applicable to static properties such as mass spectra. For dynamical processes like hadron formation in jets (hadronization) we have only some general ideas, which form the basis of phenomenological models implemented in Monte Carlo simulation programs. These are in fact surprisingly successful, indicating that the underlying ideas may indeed have some fundamental validity.

In the present talk I give a brief introduction to the current ideas and models for hadronization, and mention some areas of experimental and phenomenological study which seem likely to shed further light on the dynamics of soft QCD.

2 Hadronization models

2.1 General ideas

Local parton-hadron duality.[1] Hadronization is a long-distance process, involving only small momentum transfers. Hence the flows of energy-momentum and flavour quantum numbers at hadron level should follow those at parton level. Results on inclusive spectra and multiplicities support this hypothesis.

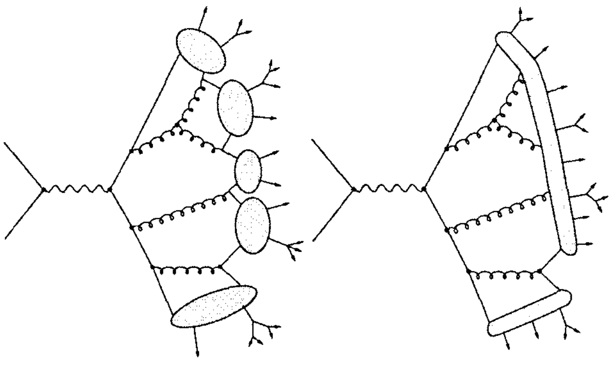

Figure 1: Cluster and string hadronization models.

Universal low-scale α_S.[2,3] Perturbation theory works well down to low scales, $Q \sim 1$ GeV. Assume therefore that $\alpha_S(Q^2)$ can be defined non-perturbatively for all Q, and use it in evaluation of Feynman graphs. This approach gives a good description of heavy quark spectra and event shapes.

2.2 *Specific models*

The above general ideas do not try to describe the mechanism of hadron formation in any detail. For this we must resort to models, the main ones being cluster and string hadronization, shown schematically in fig. 1, used in the HERWIG and JETSET Monte Carlo event generators, respectively.

The *cluster model*[4,5] starts by splitting gluons non-perturbatively, $g \to q\bar{q}$, after the parton shower. Colour-singlet $q\bar{q}$ combinations have lower masses and a universal spectrum due to the *preconfinement*[6] property of the shower. These colour-singlet combinations are assumed to form clusters, which mostly undergo simple isotropic decay into pairs of hadrons, chosen according to the density of states with appropriate quantum numbers. This model has few parameters and a natural mechanism for generating transverse momenta and suppressing heavy particle production in hadronization. However, it has problems in dealing with the decay of very massive clusters, and in adequately suppressing baryon and heavy quark production.

The *Lund string model*[7,8] is based on the dynamics of a relativistic string, representing the colour flux stretched between the initial $q\bar{q}$. The string produces a linear confinement potential and an area law for matrix elements:

$$|M(q\bar{q} \to h_1 \cdots h_n)|^2 \propto e^{-bA}$$

where A is the space-time area swept out. The string breaks up into hadrons via $q\bar{q}$ pair production in its intense colour field. Gluons produced in the parton shower give rise to 'kinks' on the string. The model has extra parameters for the transverse momentum distribution and heavy particle suppression. It has some problems describing baryon production, but less than the cluster model.

The *UCLA string model*[9] is a variant of the Lund model which takes the above area law for matrix elements more seriously, using it to determine the relative rates of production of different hadron species. This results in heavy particle suppression without extra parameters, the mass-squared of a hadron being proportional to its space-time area. At present the model still uses extra parameters for p_T spectra, and again has some problems describing baryon production.

More detailed discussion of these models and quantitative comparisons may be found in refs. [10,11].

3 Event shapes and power corrections

Comparisons between data on e^+e^- hadronic event shapes and the best available perturbative calculations reveal large non-perturbative and/or higher-order contributions, which generally decrease inversely with energy ($1/Q$ corrections).[12] Although these power corrections are well reproduced by the Monte Carlo models, it would be good to have a more basic understanding of them. In the universal low-scale α_S model, they measure the mean value of α_S at low scales,

$$\alpha_0(\mu_I) = \frac{1}{\mu_I}\int_0^{\mu_I} d\mu\, \alpha_S(\mu^2)\ .$$

The values obtained for α_0 appear consistent with universality to ±20%: for $\mu_I = 2$ GeV, $\alpha_0 \simeq 0.5 \pm 0.1$ Similar results are obtained in deep inelastic lepton scattering.[13]

4 Heavy quark fragmentation

New high-precision $b \to$ B fragmentation data from SLC [14] strongly constrain models of heavy quark hadronization. The most complete perturbative calculations [15,16] suggest that including more perturbative QCD leads to a reduction in the amount of non-perturbative smearing required. The form ot the non-perturbative contribution looks different from the Peterson parametrization [17] normally used (fig. 2). In the universal low-scale α_S model, the perturbative prediction is extrapolated smoothly to the non-perturbative region, with no explicit smearing function.[3] Thus in this model the new data will constrain the low-energy behaviour of α_S.

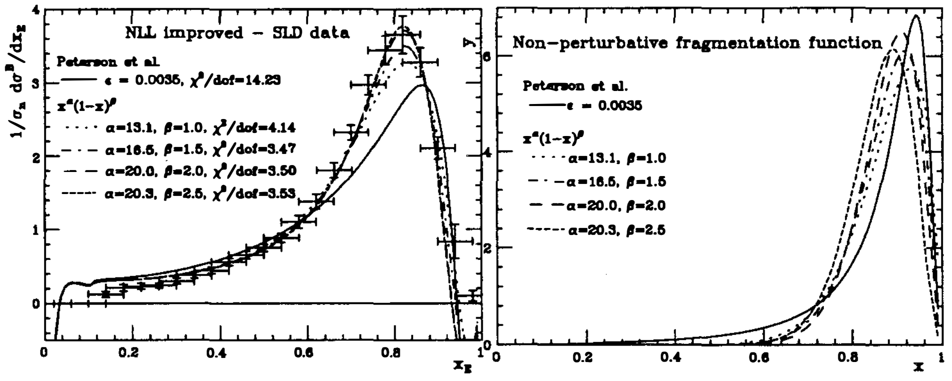

Figure 2: B hadron fragmentation function and fits to its non-perturbative component.

5 Bose-Einstein correlations

Experimental studies of $\pi^\pm\pi^\pm$ correlations which distinguish between directions along and perpendicular to the thrust axis find definite evidence for elongation of the source region along that axis.[18] This has a good explanation in the Lund string model, in terms of the change of the space-time area A when identical bosons are interchanged.[19] In the cluster model the space-time elongation of the cluster formation zone along the jet axis also leads to such an effect.

6 WW fragmentation

In $e^+e^- \to$ WW, there could be correlations between W hadronic decays due to overlap of the hadronization volumes. The Monte Carlo models allow for the possibility of such *reconnection effects* by allowing clusters or strings to form differently in the overlap region. This leads to discrepancies between hadron distributions in semi-leptonic and fully hadronic decays, especially at low momenta. So far, no strong effects are apparent in the data.[20] If present, they could affect the measurement of the W mass from fully hadronic final states.[21]

Bose-Einstein correlations between hadrons from different W's are also being looked for.[22] They would lead to an increase in the correlation function for WW relative to that for a single W, which could again affect the W mass determination.

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