DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 80/103
October 1980

A QCD ANALYSIS OF JETS IN e^+e^- ANNIHILATION

by

A. Ali

NOTKESTRASSE 85 · 2 HAMBURG 52

DESY 80/103
October 1980

A QCD Analysis of Jets in e^+e^- Annihilation *

A. Ali

Deutsches Elektronen-Synchrotron DESY, Hamburg

* Invited talk at the XXth International Conference on High Energy Physics, held in Madison, Wisconsin, July 17-23, 1980.

A QCD ANALYSIS OF JETS IN E^+E^- ANNIHILATION

A. Ali
Deutsches Elektronen-Synchrotron DESY, Hamburg,
Federal Republic of Germany

Jets in e^+e^- annihilation are discussed in the context of perturbative Quantum Chromodynamics. Topics discussed include higher twist contribution, effects of quark masses and fragmentation on the 3 and 4 jet rates and some distributions bearing on the experimental verification of 4 jet events at the PETRA/PEP energies.

It is now almost five years that the idea of observing gluon jets in e^+e^- annihilation was first discussed [1]. Since then a lot of water has gone down the river Elbe. Several independent groups at DESY have presented independent and convincing evidence [2] bearing on the existence of gluon bremsstrahlung as a physical phenomenon. There is even a prima facie case [3] for the spin-1 nature of gluon [4] and indeed there is ample evidence [5] that the first estimates [6] of the effective quark gluon coupling, $\alpha_s(Q^2)$, are in conformity with the expectations of asymptotic freedom.

The triumph of the Born estimates, impressive as it is, however, by itself does not constitute a satisfactory quantitative description of the experimental data in terms of the underlying theory, QCD. The hurdles that prevent such a direct comparison are:

i) Non-perturbative effects, both related to confinement and to the breakdown of perturbation theory in certain kinematic domains.

ii) Influence of higher order effects on the normalization and shape of the lowest order distributions.

Clearly (i) is the more formidable of the two, since calculation of higher order effects in a theory does not involve any matter of principle once you admit the Born(term) philosophy. I would like to report some work related to points (i) and(ii) above from a practitioner's point of view. Most of it, if not all, is related to the determination of $\alpha_s(Q^2)$ from e^+e^- jet data.

First, let me discuss the effects of the higher twist terms in e^+e^- annihilation. In deep inelastic reactions, the term higher twist is almost synonymous with mass effects. In e^+e^- annihilation, there is no target mass and the final quark mass effects can perhaps be calculated in the context of perturbative QCD. What is generally understood by higher twist effects in e^+e^- annihilation are effects related to non-perturbative phenomenon, for example the process

$$e^+e^- \to q + \bar{q} + \text{large } p_T \text{ hadron(s)} \qquad (1)$$

which competes with the QCD process

$$e^+e^- \to q + \bar{q} + G \qquad (2)$$

The higher twist process (1) can be calculated in model field theories. A σ-model type estimate gives [7]:

$$\frac{1}{\sigma_{pt.}} \frac{d\sigma(1)}{dx_1 dx_2} \simeq \frac{\alpha_{HT}}{16\pi^2} \frac{1}{Q^2} \left(\frac{x_2^{\ 2}}{(1-x_2)^2} + \frac{x_1^{\ 2}}{(1-x_1)^2} \right)$$

$$\sigma_{pt.} = \frac{4\pi\alpha}{3s} \Sigma Q_i^2 \ , \ x_i = E_i/E_{beam} \qquad (3)$$

where α_{HT} is the effective quark-meson coupling constant. This has to be compared with the QCD estimate:

$$\frac{1}{\sigma_{pt.}} \frac{d\sigma(2)}{dx_1 dx_2} = \frac{2}{3} \frac{\alpha_s(Q^2)}{\pi} \frac{x_1^{\ 2} + x_2^{\ 2}}{(1-x_1)(1-x_2)} \qquad (4)$$

(3) gives rise to a p_T-behaviour $\frac{d\sigma}{dp_T^{\ 2}} \sim \frac{1}{p_T^{\ 4}}$ as compared to the $O(\alpha_s)$ QCD prediction $\frac{d\sigma}{dp_T^{\ 2}} \sim \frac{1}{p_T^{\ 2}}$. Of course, intrinsic to both (1) and (2) is a non-perturbative p_T dependence, for which there is convincing experimental evidence that it is sharply peaked. Both the low-p_T hadron data[8] as well as the low energy e^+e^- data[9] suggest, though do not prove, that a Gaussian distribution

$$\frac{d\sigma}{dp_T^{\ 2}} \sim e^{-bp_T^{\ 2}} \qquad (5)$$

with $b \simeq 6\text{-}8$ GeV^{-2} describe the p_T distributions and $\langle p_T \rangle$ adequately. The question is how important could be the contribution from (3) or in other words how big is α_{HT}? It has been suggested[7] that the Spear p_T-distributions in the energy region 3.0 GeV<Q<7.4 GeV are well accounted for if one takes $b \cong 6$ GeV^{-2} in (5) and $\alpha_{HT} \cong 220$ GeV^2. However, this analysis ignores the charm quark production and weak decay effects.

I have redetermined the strength of the effective coupling α_{HT} by taking into account charm production and decay at DORIS and SPEAR.[16] Using still $b = 6$ GeV^{-2}, I get

$$\alpha_{HT} \lesssim 10 \text{ GeV}^2 \qquad (6)$$

Note that neither $\langle p_T \rangle$ nor the p_T-distributions can be explained in terms of the higher twist process (1) and the non-perturbative p_T distribution (5) in the entire DORIS/SPEAR, PETRA range. The multiplicity of the third jet also mutilates against a q + $\bar{q}$ + "meson" interpretation of these events. My contention here is that the bound (6) together with the $\frac{1}{Q^2}$ behaviour of (3) leads to the result that the contribution of the higher twist/CIM diagrams is $\lesssim$ 1 % of the contribution due to the perturbative QCD process (2) at $Q \gtrsim 30$ GeV.*

* This is correlated with the value of $\alpha_s(Q^2)$ and b. I have taken $\alpha_s(Q^2) = 0.15$ and b = 6 for this estimate.

Next, I would like to discuss the effects of quark masses on the 3 and 4 jet rates. Implicit in these estimates is the tacit assumption that the quark mass effects may be incorporated via perturbation theory. In $q\bar{q}$ production, these kinematic mass effects are not a faithful approximation since the resonances in the $q\bar{q}$ channel vitiate this simple quark model picture. One does not anticipate resonances in the $q\bar{q}G$ channel, more so when the three partons are so far apart in phase space. There is thus a hope that taking into account the quark mass effects in the 3 and 4 jet processes, using perturbation theory, may be a more meaningful exercise. I adopt this philosophy and present in tables I and II the effects of charm and bottom quark masses on the rates of 3 and 4 jet events. One could use the Sterman-Weinberg[11] variables to define finite 3 and 4 jet events, or equivalently the variable thrust, T[12] and acoplanarity, A,[13] to define the 3 and 4 jets respectively. The variables T and A are defined as:

$$T = \max(x_1, x_2, x_3)$$
$$A = 4 \min \frac{\Sigma p^i_{out}}{\Sigma |\vec{p}^{\,i}|} \qquad (7)$$

The ratios $R_{3jet} \equiv \sigma(3jet,\ T<T_c)/\sigma_{total}$ and $R_{4jets} \equiv \sigma(4jet,\ A>A_c)/\sigma_{total}$ are presented in table I, where σ_{total} is the expression derived in ref. (14):

$$\sigma_{total} = \sigma_o\left(1 + \frac{\alpha_s(Q^2)}{\pi} + (1.98 - .116 n_f)\left(\frac{\alpha_s(Q^2)}{\pi}\right)^2\right) \qquad (8)$$

and $\alpha_s(Q^2)$ is the quark gluon coupling constant in the so-called $\overline{MS}$ scheme. The entries in table II are obtained by imposing cuts on each invariant mass pair.

Table I. Fraction of 3 and 4 jet events with thrust and acoplanarity variables

Q (GeV)	T_c	R_{3jet} $n_f=3$	R_{3jet} $n_f=5$	A_c	R_{4jet} $n_f=3$	R_{4jet} $n_f=5$
20	.95	.30	.27	.05	.045	.035
	.90	.13	.12	.03	.085	.07
30	.95	.28	.26	.05	.04	.03
	.90	.12	.11	.03	.07	.06
40	.95	.26	.25	.05	.035	.03
	.90	.115	.11	.03	.065	.06

Table II. Fraction of 3 and 4 jet events with invariant mass cuts

Q (GeV)	M_{ij} (GeV)	R_{3jet}		R_{4jet}	
		$n_f=3$	$n_f=5$	$n_f=3$	$n_f=5$
20	5	.24	.28	4.5×10^{-3}	5×10^{-3}
	6	.155	.165	6.0×10^{-3}	7×10^{-3}
30	5	.445	.48	.038	.04
	6	.34	.36	.015	.018
40	5	.59	.62	.09	.10
	6	.48	.50	.05	.055

Note that the entries in tables I and II have been calculated for equal value of $\alpha_s(Q^2)$ for $n_f=3$ and $n_f=5$.* Also note that the quark mass effects are still $\sim$ 10-12 % in the range of PETRA jet experiments, and they introduce a substantial difference in the value of the QCD scale parameter, Λ.[15] I would also like to point out that only fixed angle type variables like the Sterman-Weinberg variables or T give cross sections proportional to $(\ln Q^2/\Lambda^2)^{-1}$ for the process $e^+e^- \to Q\bar{Q}G$, as opposed to the fixed p_T cuts, like the invariant masses, where the use of perturbation theory becomes suspect. This can be seen through the rapid growth of R_{3jets} and R_{4jets} with energy in table II. The entries for R_{4jets} are exact to $O(\alpha_s^2)$ but those for R_{3jets} are subject to $O(\alpha_s^2)$ virtual gluon corrections, whose exact contribution is controversial at the moment[16]. In any case, an $O(\alpha_s^2)$ calculation for 3jets including the quark masses has yet to be done.

The next point I would like to discuss concerns the effects of quark and gluon fragmentation. That there is a definite correlation between the fragmentation parameters and the value of $\alpha_s(Q^2)$ extracted from an experiment was first pointed out in ref. (6). Needless to say that the exact correlation is model dependent, and one should undertake a more detailed study of these matters than has been done so far. My purpose here is to show, by example of the model in ref. 6, the extent of one of such correlations namely between the intrinsic quark p_T parameter $\sigma_q \equiv \frac{1}{\sqrt{2b}}$ and the value of $\alpha_s(Q^2)$. The model described in ref. 6 is a modified Field and Feynman model[17] with a primordial p_T distribution as in (5), and a longitudinal fragmentation described in ref. (17) and specified through the parameter A_F. The fragmentation is then completely specified by stating the pseudoscalar, P, to vector meson, V, decay ratio from a $q\bar{q}$ pair. The residual $\sigma_q - \alpha_s(Q^2)$ correlation is shown in Fig. 1. The data comes from the TASSO collaboration[5,18]. I agree that the correlation is somewhat disconcerting in the absence of any other constraints. The fragmentation effects are important also for the so called "infra-red-safe fragmentation-insensitive variables" like thrust and acoplanarity. The distribution in acoplanarity is shown in Fig. 2. Note the effect of fragmentation on the 4jet distribution. Incidentally, Fig. 2 is a prediction of $O(\alpha_s^2)$ effects in e^+e^- annihila-

* The entries correspond to using $\Lambda_{\overline{MS}}$ = 350 MeV, $n_f=3$, $m_u=m_d=m_s=0$ m_c = 1.8 GeV and m_b = 4.5 GeV.

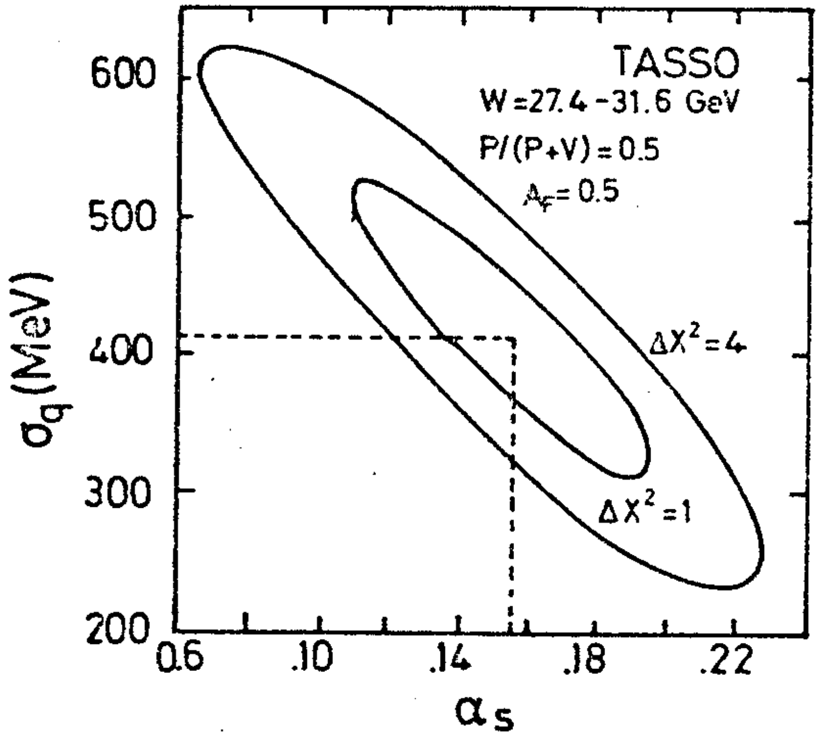

Fig. 1. The correlation between the intrinsic parameter σ_q and the quark gluon coupling constant $\alpha_s(Q^2)$ based on the model in ref. (6). The data includes events with sphericity ≥ 0.25. $\Delta\chi^2_{\pm} = 1,4$ correspond to ± 1σ and ± 2σ respectively.

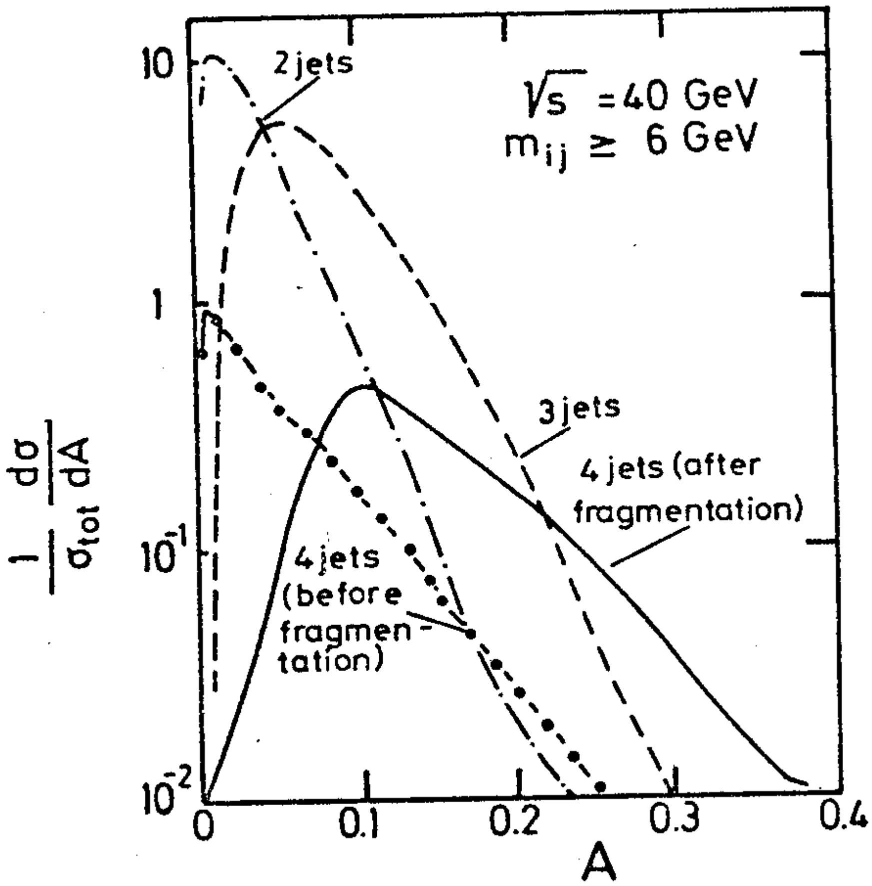

Fig. 2. Acoplanarity distributions for 2, 3 and 4 jets where invariant mass cuts are used to define finite 3 and 4 jets and fragmentation effects are included using ref. (6).

tion [19] -- perhaps the distributions $\frac{1}{\sigma}\frac{d\sigma}{dp^2_{out}}$ and $\frac{1}{\sigma}\frac{d\sigma}{dp^4_{out}}$ are more sensitive to the effects of 4jets. The rise of heavy quark multiplicity in e^+e^- annihilation [19] is another $O(\alpha_s^2)$ effect which might be observable at PETRA/PEP energies.

The extent of the non-perturbative effects at PETRA/PEP energies is a reminder that the determination of $\alpha_s(Q^2)$ from e^+e^- data is a somewhat model dependent enterprise.

I gratefully acknowledge useful and productive discussions with my colleagues at DESY. I would especially like to thank Gustav Kramer and Esko Pietarinen for sharing their insight with me.

REFERENCES

1. J. Ellis, M.K. Gaillard and G.G. Ross, Nucl. Phys. B111, 253 (1976).
2. For an exhaustive list of experimental references see the talk of B. Wiik in the Proceedings of this Conference.
3. V. Hepp, PLUTO Collaboration, DESY 80/84 (1980), TASSO Collaboration, R. Brandelik et al., DESY 80/80 (1980).
4. A. De Rujula, J. Ellis, E.G. Floratos and M.K. Gaillard, Nucl. Phys. B138, 387 (1978). J. Ellis and I. Karliner, Nucl. Phys. B148, 141 (1979). K. Koller and H. Krasemann, Phys. Lett. 88B, 119 (1979).
5. MARK J Collaboration, D.P. Barber et al., Phys. Lett. 89B, 139 (1979); TASSO Collaboration, R. Brandelik et al., Phys. Lett. 94B, 437 (1980).
6. A. Ali, E. Pietarinen, G. Kramer, J. Willrodt, Phys. Lett. 93B, 155 (1980) and A. Ali, E. Pietarinen and J. Willrodt, DESY Report T-80/01 (1980).
7. T.A. DeGrand, Y.J. Ng and S.-H.H. Tye, Phys. Rev. D16, 3251 (1977).
8. See, for example, L. Di Lella, CERN-EP/79-145 (1979).
9. See for example G.G. Hanson, SLAC-Reports SLAC-PUB-1814 (1976), SLAC-PUB-2118 (1978); PLUTO Collaboration, R. Brandelik et al., DESY 79/73 (1979).
10. A. Ali (unpublished calculation)
11. G. Sterman and S. Weinberg, Phys. Rev. Lett. 39, 1436 (1977).
12. E. Farhi, Phys. Rev. Lett. 39, 1587 (1977). See also S. Brandt et al., Phys. Lett. 12, 57 (1964).
13. A. De Rujula et al. in ref. (4).
14. M. Dine and J. Sapirstein, Phys. Rev. Lett. 43, 668 (1979); W. Celmaster and R.J. Gonsalves, Phys. Rev. Lett. 44, 560 (1980); K.G. Chetyrkin, A.L. Kataev and F.V. Tkachov, Phys. Lett. 85B, 277 (1979).
15. This for example is one of several differences between the model of ref. 6 and the one described in P. Hoyer, P. Osland, H.G. Sander, T.F. Walsh and P.M. Zerwas, Nucl. Phys. B161, 349 (1979).
16. R.K. Ellis, D.A. Ross and A.E. Terrano, Caltech Reports CALT-68-783 and CALT-68-785 (1980); K. Fabricius, I. Schmitt, G. Schierholz and G. Kramer, DESY Report 80/91(1980)
17. R.D. Field and R.P. Feynman, Nucl. Phys. B136, 1 (1978).
18. TASSO Collaboration and J. Freeman, Ph.D. thesis (under preparation), Univ. of Wisconsin. I am grateful to Jim Freeman for supplying fig. 1.
19. A. Ali, J.G. Körner, Z. Kunszt, J. Willrodt, G. Kramer, G. Schierholz and E. Pietarinen, Nucl. Phys. B167, 454 (1980).