HIGH ENERGY HADRON-HADRON COLLISIONS

Final Report

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Abstract

Important results from a study of high-energy collision based on the geometrical model are summarized in three parts, (i) the elastic hadron-hadron collisions, (ii) the inelastic hadron-hadron collisions, and (iii) the e^+e^- annihilation. Results from an investigation on the fullerene molecules are also summarized.

Introduction

This project of studying high energy collision phenomena with the geometrical model has been undertaken and developed by this investigator and collaborators since 1967. Instead of basing conjectures on mathematical extrapolations from some ad hoc theories, our approach was to scrutinize first the general features of the phenomena before going into specific details. This particular method has proved successful in correlating experimental data, suggesting experiments, predicting new phenomena and guiding future experimental studies. In *elastic* hadron-hadron scattering, a theory based on geometrical ideas was first proposed.¹ It was later found to be in very good general agreement with experiments. Additional consequences of this theory for diffraction dissociation as well as fragmentation processes and other phenomena have also been developed. In the past decade, we pushed the geometrical description even further and formulated a theory for high energy *inelastic* collisions. This series of work has provided a *unified physical picture* of multiple particle production which is applicable to both *hadron-hadron* and e^+e^- collisions.

In the following important results of the geometrical model obtained with the support of the DOE grant are summarized in three parts: the elastic hadron-hadron scattering, the inelastic hadron-hadron collision, and the hadronic production in e^+e^- annihilation. The fourth part of this report outlines the results of other topics of investigation. To avoid repetition, only the main physical ideas and essential experimental evidences will be presented, leaving out detailed discussions which can be found in the literature^{2,3} and previous reports.

I. Elastic and quasi-elastic hadron-hadron scatterings.

The geometrical description of elastic hadron-hadron scattering at high energy is based on the fundamental assumption that all hadrons are extended objects with structures. This description provides a direct relationship between the hadronic matter density functions and the elastic differential cross section.

The following results have been obtained from this model and its extensions:

(A) Nucleon and meson form factors.

The hadronic matter distributions can be computed⁴ by using the experimentally measured differential cross section. The proton form factor thus computed at ISR energies agrees amazingly well with the experimental G_E form factor of the proton.⁵ Application of the geometrical model to meson-proton scatterings has also been used to determine⁶ the pion and kaon radii. Theoretical predictions appear in good agreement⁷ with values obtained from direct experimental measurements.

(B) Dip structure in angular distribution of elastic hadron-hadron collisions.

With the proton form factor and the observed total cross section used as input, the model predicted⁸ the pp ($p\bar{p}$) differential cross section, which shows a dip near $-t = 1.4$ (GeV/c)² at ISR energies, and a maximum at a slightly higher $-t$ value. The calculated positions of the minimum and the maximum were in good agreement⁹ with the experimental results. Similar structures were also expected to exist in elastic np and meson-proton scatterings and have since been observed¹⁰ experimentally.

(C) Inward movement of dip structures with increasing energy.

In the geometrical model, the total cross section is related to the opaqueness of the colliding hadrons. With the rising total cross section with increasing energy, the colliding system becomes increasingly opaque. Thus, the model predicted¹¹ an inward shift of the minimum and the maximum positions with energy, and a concurrent rise of the second maximum. These general characteristics are in agreement^{12, 13} with the ISR and SppS experiments.

(D) Existence of many dips in hadron-hadron elastic collisions at ultra high energies.

As the opaqueness increases with the total cross section, the geometrical model predicts¹⁴ the existence of many dips in hadron-hadron elastic scattering at very high energies. Although none of the dips other than the first one has been observed so far, the

development of many dips is inevitable in view of the fact that increasing opaqueness would produce an effective black disk as the scattering center at sufficiently high energies.

(E) Rising X-parameter with total cross section.

An important qualitative feature of the geometrical picture, as distinguished from many other theoretical models, is the increase of the X-parameter ($\equiv \sigma_{el}/\sigma_T$) with increasing total cross sections. In Ref. 14, we predicted in 1979 this parameter to increase from 0.175 at ISR energies to 0.226 at the $\bar{p}p$ S energy of 540 GeV. An accurate measurement of X by the UA4 Collaboration in 1984 confirmed¹⁵ our prediction and thus ruled out many competing theories.

(F) Energy dependence of blackness function at high energies.

The $\bar{p}p$ S Collider data of elastic scattering at 546 GeV revealed that the fractional increase in blackness of the $\bar{p}p$ system with incoming energy is larger at large impact distances than in the central region. This discovery compelled us to modify the opacity function which had been used for the description of the elastic data at ISR energies. While there had been a number of previous fits to the blackness of the $\bar{p}p$ system, we found¹⁶ a simple one-parameter fit which works well for all existing data. This new parametrization for opacity retains the convolution form and the dipole expression for the proton hadronic form factor as in the original geometrical model. The only change is that the radius parameter in the form factor is now energy-dependent. This fit has been extrapolated to the Tevatron energy, and a good agreement with experimental results¹⁷ is obtained.

(G) Concept of matter current in hadrons.

Since geometrical concepts such as size, matter distribution, and the opaqueness distribution of hadrons are very useful in discussing high energy collisions, one may raise the question¹⁸ whether matter current exists inside a polarized hadron. Once we have accepted the concept of an extended hadron with a matter density in it, it seems to us inevitable that we must also accept the existence of a matter current in a polarized hadron. The concepts of matter density and matter current necessarily complement each other,

resulting in a four-vector. We argued that the existence of a matter current can produce observable effects.¹⁹ Experimental test of this idea is possible by utilizing the rising total cross section with increasing incoming energies, but such experiment has not yet been performed.

(H) Dips in diffraction dissociation processes.

One of the conspicuous features of the quasi-elastic diffraction-dissociation processes is the existence of dip or kink structures in the angular distribution similar to that observed in elastic hadron-hadron scattering. We proposed a natural explanation²⁰ of these dip structures in the geometrical model if the source function for the outgoing hadrons is properly chosen. Numerical computations for differential cross section in diffraction dissociation processes have been made. The computation contains no adjustable parameters. The calculated dip positions for both elastic scattering and diffraction dissociation processes are in very good agreement²⁰ with experimental values.

(I) The limiting fragmentation hypothesis for high energy fragmentation processes.

In describing high energy elastic scattering, the geometrical picture envisages the passage of one hadron through another with attenuation. The attenuation factor depends on the impact-parameter b , and not very much on the energy. Since the elastic and inelastic channels are strongly coupled, we argued that in high energy inelastic processes the probability amplitude for the target or the projectile to be excited into any specific mode must also be a function of b alone, and would be largely independent of incident energy, leading to a limiting distribution for fragmentation particles. This hypothesis²¹ was referred to as the hypothesis of limiting fragmentation. Experimental verification²² of the hypothesis has been carried out at the ISR and the $\overline{\text{SppS}}$ Collider.

II. High Energy Inelastic Hadron-Hadron Collisions

In a high energy inelastic hadron-hadron collision, the emitted hadrons can be divided into two groups: the fragmentation particles and the central particles. The

fragmentation particles are few in number. They are, in the geometrical picture, pieces broken off from the chunks of the incoming particles that pass by without meeting very much of the other particle. Their momentum distribution satisfies the hypothesis of limiting fragmentation. On the other hand, the overlapping parts of the incoming particles undergo a more violent collision, yielding a large number of outgoing particles in the central rapidity region. We shall focus our discussion only on the physics of central-particle production.

The injection of new physical ideas into the geometrical model originally proposed for elastic scattering has resulted in a conceptually lucid physical picture for the description of multiple particle production in the central region. The crucial ideas are:

- (i) An inelastic particle production process in hadron-hadron collision is the result of an *incoherent superposition of collisions at different impact-parameters*.
- (ii) At a given impact-parameter, the forward and backward hemispheres have charged-particle multiplicities n_F and n_B distributed in a *stochastic* manner.
- (iii) In the stochastic process the energy partition among particles in each hemisphere is governed mainly by a parameter called the *partition temperature*.

The origins and implications of these ideas are given below together with theoretical predictions of the model and their experimental support.

(A) Multiplicity distribution

The observation at ISR energies that the multiplicity distribution for emitted particles in pp collisions is a broad one, satisfying approximate KNO-scaling,²³ was later confirmed by a higher energy experiment²⁴ at the SppS Collider in 1982. We called these broad distributions *nonstochastic*, since $(\text{the rms fluctuation})/\bar{n}$ is a constant or increases with energy. We suggested²⁵ that the major reason for this large multiplicity fluctuation is the fluctuation of the impact-parameter of the collision or the spread of the total incoming angular momentum. This consideration led us to the idea (i) above.

(B.1) The stochastic and nonstochastic aspects of particle production in hadron-hadron collisions.

Our detailed examination²⁶ of the event distribution $P(n_F, n_B)$ for the forward and the backward multiplicities in a scatter plot at 546 GeV CM energy showed that the distributions with respect to the variables $n_F + n_B$ and $n_F - n_B$ are totally different. While the former is *nonstochastic* as it is expected from the total multiplicity fluctuation, the latter is narrow, i.e., binomial or *stochastic*. This clear separation²⁶ of the stochastic from the nonstochastic elements of the dynamics of multiparticle production is the corner stone of the geometrical description for inelastic process and allows for deeper insight of the physics of hadron-hadron collisions.

(B.2) The forward-backward multiplicity correlation

Because a stochastic distribution becomes increasingly narrower relative to a nonstochastic distribution when the average multiplicity $\bar{n}$ increases, the population of events will increasingly concentrate in an elongated region along the $n_F = n_B$ axis at higher energies. The elongatedness of the two-dimensional $n_F - n_B$ distribution can be related²⁶ to a parameter b_c , which characterizes the correlation of multiplicities in the forward and backward hemispheres. Our prediction that the population will become more and more concentrated in a narrow band as $\bar{n}$ increases means that the forward-backward correlation parameter b_c for hadron-hadron collisions will increase with energy and approaches unity in the ultra high energy limit. The trend of the measured values for b_c from the ISR through the SppS energies²⁶ to the Tevatron energy of 1.8 TeV²⁷ clearly confirms our conjecture.

(B.3) Binomial distribution for the charge asymmetry parameter and the cluster size of the emitted particles.

In the analysis of the distribution function $P(n_F, n_B)$ we found²⁶ that the multiplicity fluctuation with respect to the charge asymmetry variable $n_F - n_B$ is of the

binomial form $C_{n_F/2}^n/2$. The factor 2 in the binomial strongly suggests²⁶ that the positive and negative charged particles are likely produced together in pairs in either the forward or the backward hemispheres. Reasoning along this line, we conjectured²⁶ further that the ratio (the rms *net* charge in each hemisphere)/ $\sqrt{n}$ will approach zero at very high energies. This prediction can be experimentally tested.

(C) Incoherent superposition of collisions at different impact-parameters each with narrow Poisson-like multiplicity fluctuation.

The experimental fact mentioned in (B.2) that both n_F and n_B fluctuate widely, yet in a correlated way, with $n_F \approx n_B$, is very remarkable. A natural explanation for the underlying physical cause for such phenomena lies in the wide fluctuation of the impact-parameter. This assumption is rather natural in view of the fact that both the forward and backward sides share the *same* impact-parameter. Therefore, we concluded^{25, 28} that the physical mechanism for the broad multiplicity fluctuation in hadron-hadron collision is the incoherent superposition of collisions at different impact-parameters, each of which gives a narrow multiplicity distribution. The precise form of this narrow distribution for fixed impact-parameter has been determined³ to be $f(n_0/2, n/2)$, where $f(a, m)$ represents a Poisson with an average $\bar{m} = a$, and n_0 is the *intrinsic multiplicity*. The dependence of the intrinsic multiplicity on b has been determined²⁹ from experimental data for $p\bar{p}$ collisions at 540 GeV CM energy.

(D) Stochastic energy partition, partition temperature and single-particle momentum spectrum.

If at very high energies the population of events in the n_F - n_B plane clusters into a very narrow band, then for given multiplicity in one hemisphere, the charge multiplicity distribution in the other hemisphere would be stochastic. It is therefore natural to assume that the energy and momentum distributions of the emitted particles in that hemisphere is also stochastic, since it was difficult to concoct a mechanism that could single out

multiplicity as the only physical quantity that is stochastic. This idea of energy partition led³⁰ us to a simple expression for the single-particle momentum distribution and a concept of partition-temperature T_p , which is a parameter in the momentum spectrum that governs the stochastic partition of energy in each hemisphere.

The single-particle angular distribution computed with our theory for $\bar{p}p$ collisions at CM energy of 540 GeV was in agreement³⁰ with the preliminary experimental data. In our analysis of the UA5 546-GeV final data, we incorporated in our model the observation³¹ by UA1 experiments that the average transverse momentum varies with multiplicity. The results of our calculation³² are in very good agreement with the experimental data³³ of UA5.

(E) Predictions on single-particle spectra at Tevatron and higher energies.

Encouraged by the agreement of our theory with $\bar{p}p$ experiment at the 540 GeV $S\bar{p}pS$ Collider energy, we have extrapolated²⁸ our result to lower (ISR) and higher (Tevatron and SSC) energies. Recently we have made³⁴ a systematic investigation of the single-particle angular distribution in the entire $S\bar{p}pS$ energy region. Extrapolations based on these new results can lead to more accurate predictions on the momentum distribution at higher energies, which would be helpful to experimentalists in their detector designs.

(F) Further predictions.

1. Decrease of single-diffraction events.

The single-diffraction events are highly forward-backward asymmetrical. If with increasing energy the n_F - n_B multiplicity distribution approaches a narrow band as we predicted, the fraction of single-diffraction events would become²⁸ increasingly rare. This is consistent with the recent observation³⁵ that the ratio of the single-diffraction cross section to the total cross section decreases with increasing energy.

2. Spin—spin correlation of emitted particles.

In a high—energy hadron—hadron collision, the angular momentum in the incoming system is generally very large. Much of it is certainly carried away as orbital angular momenta by the outgoing particles. But the sum of all these orbital angular momenta is not sufficient to make up the original angular momentum. To conserve the total angular momentum of the collision, the difference will have to be contributed by the spin angular momenta of the produced particles. Thus, there is a strong tendency³⁶ for the spins of the outgoing particles to line up parallel to each other in the transverse direction.

III. Inelastic e^+e^- collisions

The physical ideas developed for inelastic hadron—hadron collisions are all applicable to the two—jet events in e^+e^- annihilation, except for one important qualitative difference between these two types of collisions. In e^+e^- annihilation, the reaction goes through an intermediate state of a virtual photon. The angular momentum for the system is thus 0 or $\hbar$, and does not vary over a wide range as in hadron—hadron collisions. The following consequences and predictions have been obtained for e^+e^- annihilation.

(A) Multiplicity distribution.

In the geometrical picture for each angular momentum state of the incoming system, we hypothesized³⁷ that the multiplicity follows a Poisson law. Since in e^+e^- collisions the angular momentum can only be 0 or $\hbar$, the multiplicity being the superposition of two almost identical Poissons is an essentially Poisson distribution,³⁷ i.e., narrow or stochastic.

The above prediction made by us in 1985 was in opposition to popular sentiments which favored KNO—scaling, i.e., nonstochastic multiplicity distribution, for e^+e^- collisions. The experimental data available could not resolve the question whether in e^+e^- collision a Poisson is obtained. But the shapes³⁸ of the multiplicity distribution for $\bar{p}p$ and e^+e^- collisions are distinctively different, with the latter fitting Poisson distribution well. In an

experiment³⁹ by the HRS Collaboration at 29 GeV for e^+e^- collisions, the fit with a Poisson is excellent.

(B) Forward and backward multiplicity correlation.

According to our view for e^+e^- annihilation, the probability distribution with respect to n_F and n_B , the forward and backward (relative to the jet axis) multiplicities, should be a product of two Poissons (each with a cluster size $k = 2$ in analogy with $\bar{p}p$ collisions).

The following consequences have been derived.

(i) The probability distribution with respect to n_F or n_B is a binomial for a fixed $n (= n_F + n_B)$.³⁷

(ii) The net charge³⁷ of each jet should be $\ll \bar{n}$ or $\sqrt{\bar{n}}$.

(iii) Since $P(n_F, n_B)$ is a product distribution, the forward-backward correlation parameter b_c vanishes. This prediction⁴⁰ is supported by the e^+e^- 29-GeV data³⁹ of the HRS Collaboration which yielded a value of $b_c = -0.001 \pm 0.015$.

(iv) Summing $P(n_F, n_B)$ over n_F , but keeping n fixed, we obtain⁴⁰ a Poisson distribution $f(\bar{n}/2, n/2)$ for the total multiplicity. While the experimental distribution is fitted well with a Poisson $f(\bar{n}, n)$, the HRS experiment³⁹ suggested that the cluster size $k = 1$ instead of 2 as predicted by us. But why should the cluster sizes be different for $\bar{p}p$ and e^+e^- has been a puzzling question.⁴¹ (For more results on cluster size, see (F) below.)

(C) Partition temperature and the single-particle momentum spectrum.

Exactly as in hadron-hadron collision the same argument leads to the concept of a partition temperature for e^+e^- annihilation.³⁷ The only differences are: we consider only two-jet events and ignore those with gluon emission; the transverse momentum now refers to the direction perpendicular to the jet axis. As there is only one angular momentum state (mainly $\hbar$ for high-energy e^+e^- annihilation), there is only *one* partition temperature T_p . We found that for each incident energy, excellent fits to the single-particle spectra are obtained³⁷ for one value of T_p .

(D) Prediction for momentum distributions of emitted particles at TRISTAN, SLC and LEP energies.

We have used our theory to extrapolate⁴² the single-particle momentum distribution to higher energies. The general validity of our result is already borne out by the results of the AMY Collaboration⁴³ at TRISTAN and the ALEPH Collaboration⁴⁴ at LEP.

(E) Lack of spin-spin correlation of emitted particles.

The prediction about spin-spin correlation for $\bar{p}p$ collisions was based on the large transverse angular momentum of $\bar{p}p$ events. Since the average transverse angular momentum is small for e^+e^- , we predict⁴⁰ the absence of spin correlation for e^+e^- two-jet events.

(F) Average cluster size of emitted hadrons.

Puzzled by the difference in the cluster size of emitted particles in $\bar{p}p$ collisions and that in e^+e^- annihilation at 29 GeV, we performed a detailed analysis⁴⁵ of all available e^+e^- multiplicity data ranging from the PETRA energy⁴⁶ of 14–44 GeV, through the TRISTAN energy⁴⁷ of 50–60 GeV, to the LEP energy⁴⁸ of 90 GeV. We were surprised to discover that the cluster size in e^+e^- collisions is energy dependent. It increases gradually from $k = 1$ at lower energy to 1.26 at the LEP energy for 2-jet data. Will the average cluster size saturate at $k = 2$ at very high energies? Why does the hadron cluster size change with the collision energy at all? We do not have answers to these questions yet.

IV. Other topics

The discovery of large fullerene molecules has generated enormous interest among physicists and chemists. Though this field is far removed from particle physics per se, we found that some fullerene physics problems can be solved by using general symmetry principles and mathematical methods that have been commonly employed in attacking problems of high energy physics. Our study⁵⁰ of carbon fullerenes has led to a complete analytical solution of the energy eigenvalue problem for carbon-240 molecule, graphene sheet and tubes.

REFERENCES

1. T. T. Chou and C. N. Yang, in *High-Energy Physics and Nuclear Structure*, edited by G. Alexander (North-Holland Publishing Co., Amsterdam, 1967).
2. For a review of the geometrical model for high energy elastic scattering, see T. T. Chou and C. N. Yang, in Proc. of the 1980 Guangzhou Conference on Theoretical Particle Physics, (Science Press, Beijing, 1980).
3. For a review of the geometrical model for multiparticle emission in hadron-hadron and e^+e^- collisions, see T. T. Chou and C. N. Yang, *Int. J. Mod. Phys. A*2, 1727 (1987).
4. T. T. Chou and C. N. Yang, *Phys. Rev.* 170, 1591 (1968).
5. A. W. Chao and C. N. Yang, *Phys. Rev.* D8, 2063 (1973).
6. T. T. Chou, *Phys. Rev.* D11, 3145 (1975) and D19, 3327 (1979).
7. For measurements of pion radius, see E. B. Dally et al., *Phys. Rev. Lett.* 39, 1176 (1977), and 48, 375 (1982); and S. R. Amendolia et al., *Phys. Lett.* 146B, 116 (1984). For measurements of kaon radius, see E. B. Dally et al., *Phys. Rev. Lett.* 45, 232 (1980); and S. R. Amendolia et al., *Phys. Lett.* 178B, 435 (1986).
8. T. T. Chou and C. N. Yang, *Phys. Rev. Lett.* 20, 1213 (1968); L. Durand and R. Lipes, *Phys. Rev. Lett.* 20, 637 (1968).
9. A. Böhm et al., *Phys. Lett.* 49B, 491 (1974).
10. For dip in np scattering, see C. E. DeHaven, Jr. et al., *Phys. Rev. Lett.* 41, 669 (1978). For dip in π^-p scattering, see W. F. Baker et al., *Phys. Rev. Lett.* 47, 1683 (1981). The dip in k^-p scattering was observed by the WA7 Collaboration, 1983.
11. T. T. Chou, unpublished report, University of Denver, 1974; F. Hayot and U. P. Sukhatme, *Phys. Rev.* D10, 2183 (1974).
12. N. Kwak et al., *Phys. Lett.* 58B, 233 (1975); E. Nagy et al., *Nucl. Phys.* B150, 221 (1979).
13. UA4 Collab., M. Bozzo et al., *Phys. Lett.* 147B, 385 (1984) and 155B, 197 (1985).

14. T. T. Chou and C. N. Yang, Phys. Rev. D19, 3268 (1979).
15. UA4 Collab., M. Bozzo et al., Phys. Lett. 147B, 392 (1984).
16. T. T. Chou and C. N. Yang, Phys. Lett. 244B, 113 (1990).
17. N. A. Amos *et al.*, Phys. Lett. 247B, 127 (1990).
18. T. T. Chou, in High Energy Collisions — 1973, edited by C. Quigg (AIP Conf. Proc. No. 15, New York, 1973).
19. T. T. Chou and C. N. Yang, Nucl. Phys. B107, 1 (1976).
20. T. T. Chou and C. N. Yang, Phys. Rev. D22, 610 (1980).
21. J. Benecke, T. T. Chou, C. N. Yang, and E. Yen, Phys. Rev. 188, 2159 (1969).
22. G. Bellettini et al., Phys. Lett. 45B, 69 (1973); and J. G. Rushbrooke, in Proc. XVI Int. Symp. on Multiparticle Dynamics, edited by J. Grunhaus (Editions Frontières, 1985).
23. Z. Koba, H. B. Nielsen and P. Olesen, Nucl. Phys. B40, 317 (1972).
24. UA5 Collaboration, K. Alpgård et al., Phys. Lett. 107B, 310 and 315 (1981); UA1 Collaboration, G. Arnison et al., Phys. Lett. 107B, 320 (1981); and UA5 Collaboration, G. J. Alner et al., Phys. Lett. 160B, 193 and 199 (1985).
25. T. T. Chou and Chen Ning Yang, Phys. Lett. 116B, 301 (1982).
26. T. T. Chou and Chen Ning Yang, Phys. Lett. 135B, 175 (1984).
27. V. Paul Kenney, in Proc. XXV Int. Conf. on High Energy Physics, ed. by K. K. Phua and Y. Yamaguchi (1991).
28. T. T. Chou and Chen Ning Yang, Phys. Rev. D32, 1692 (1985).
29. T. T. Chou, Mod. Phys. Lett. A4, 1079 (1989).
30. T. T. Chou, Chen Ning Yang and E. Yen, Phys. Rev. Lett. 54, 510 (1985).
31. UA1 Coll., G. Arnison et al., Phys. Lett. 118B, 167 (1982).
32. T. T. Chou, in Proc. of Fifth Asia-Pacific Phys. Conf., ed. S. P. Chia et al., (World Scientific, Singapore, 1994) pp. 338–348.
33. UA5 Coll., G. J. Alner et al., Phys. Rep. 154, 247 (1987).

34. T. T. Chou (unpublished).
35. J. G. Rushbrooke, in Proc. of XIV Int. Symp. on Multiparticle Dynamics 1983, edited by P. M. Yager and J. F. Gunion (World Scientific, 1984).
36. Chen Ning Yang and T. T. Chou, J. Phys. Soc. Jpn. 55, Suppl., 53 (1986).
37. T. T. Chou and Chen Ning Yang, Phys. Rev. Lett. 55, 1359 (1985).
38. The TASSO Collaboration, M. Althoff et al., Z. Phys. C22, 307 (1984).
39. M. Derrick et al., Phys. Rev. D34, 3304 (1986).
40. T. T. Chou and Chen Ning Yang, Phys. Lett. 167B, 453 and 171B, 486(E) (1986).
41. T. T. Chou and Chen Ning Yang, Phys. Lett. 193B, 531 (1987).
42. T. T. Chou and Chen Ning Yang, Phys. Lett. 212B, 105 (1988).
43. The AMY Collaboration, Y. K. Li *et al.*, Phys. Rev. D41, 2675 (1990).
44. The ALEPH Collaboration, D. Decamp *et al.*, Phys. Lett. 234B, 209 (1990).
45. T. T. Chou and C. N. Yang, in Proc. XXV Int. Conf. on High Energy Physics, ed. by K. K. Phua and Y. Yamaguchi (1991), p.1013.
46. The TASSO Collaboration, W. Braunschweig *et al.*, Z. Phys. C45, 193 (1989).
47. The AMY Collaboration, H. W. Zheng, *et al.*, Phys. Rev. D42, 737 (1990).
48. The DELPHI Collaboration, P. Abreu et al., Zeit. Phys. C56, 63 (1992).
49. T. T. Chou and Chen Ning Yang, Phys. Rev. D50, 590 (1994).
50. T. T. Chou and Chen Ning Yang, Phys. Lett. A183, 221 (1993); Phys. Lett. A192, 406 (1994).