HIGH ENERGY HADRON-HADRON COLLISIONS

Annual Progress Report

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Date Submitted -- December 1991

PREPARED FOR THE

U. S. DEPARTMENT OF ENERGY

UNDER GRANT NO. DE-FG09-84ER40160

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Abstract

Results of a study on high energy collision with the geometrical model are summarized in three parts: (i) the elastic hadron-hadron collision, (ii) the inelastic hadron-hadron collision, and (iii) the e^+e^- annihilation. More recent results are highlighted below.

For elastic scattering, a modified form for the hadronic matter form factor of the proton was proposed which remains to be dipole in form but contains an energy-dependent range parameter. This new expression of the opacity function fits the elastic $\bar{p}p$ scattering very well from the ISR to $S\bar{p}pS$ energies. Extrapolation of this theory also yielded results in good agreement with the $\bar{p}p$ differential cross section measured at the Tevatron. For inelastic hadron-hadron collisions, we have made a systematic investigation of the single-particle momentum spectra in the entire $S\bar{p}pS$ energy region. Results are useful for the extrapolation of angular distribution to the higher SSC energies. In e^+e^- annihilation, a detailed analysis of all available experimental multiplicity data from PETRA to LEP energies has been performed. We discovered that the cluster size of emitted hadrons increases steadily with energy and is close to 2 as we predicted.

The current project of studying high energy collision phenomena with the geometrical model has been undertaken and developed by this investigator and collaborators for the past two decades. 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 very 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 several years we pushed the geometrical description even further and formulated a theory for high energy *inelastic* collisions. This recent 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 we summarize important theoretical results from the geometrical model on three general areas, the elastic hadron-hadron scattering, the inelastic hadron-hadron collision, and the hadronic production in e^+e^- annihilation. To avoid excessive repetition, only the main physical ideas and essential experimental evidence will be presented, leaving out detailed discussions which can be found in the literature.^{2,3}

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 seem to be 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 $-t = 1.4$ $(\text{GeV}/c)^2$ 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 $S\bar{p}pS$ 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 ($\equiv \sigma_{\text{el}}/\sigma_{\text{T}}$) 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 SppS 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 SppS 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 a 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 carried out.

(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 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 $n_F \cong n_B$, 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 what we called 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 excellent agreement³⁰ with experimental data.

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

The agreement of our theory with $\bar{p}p$ experiment at the 540 GeV $S\bar{p}pS$ Collider energy was very encouraging. We have extrapolated²⁸ our result to lower (ISR) and higher (Tevatron and SSC) energies. These results would be helpful to experimentalists in their designs of particle detectors.

Recently we have made a systematic investigation of the single-particle angular distribution in the entire $S\bar{p}pS$ energy region. The result³¹ will be published. Extrapolations based on these new results can lead to more accurate predictions on the momentum distribution at the SSC energies.

(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 observation³² 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 tendency³³ 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 hypothesized³⁴ 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,³⁴ 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 shapes³⁵ of the multiplicity distribution for $\bar{p}p$ and e^+e^- collisions are distinctively different, with the latter fitting Poisson distribution well. In an experiment³⁶ 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 $n (= n_F + n_B)$.³⁴

(ii) The net charge³⁴ 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 prediction³⁷ is supported by the e^+e^- 29-GeV data³⁶ 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 obtain³⁷ 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 experiment³⁶ 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.³⁸ (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.³⁴ 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 obtained³⁴ 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 extrapolate³⁹ the single-particle momentum distribution to higher energies. The general validity of our result is already borne out by the results of the AMY Collaboration⁴⁰ at TRISTAN and the ALEPH Collaboration⁴¹ 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 predict³⁷ 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 analysis⁴² of all available e^+e^- multiplicity data ranging from the PETRA energy⁴³ of 14--44 GeV, through the TRISTAN energy⁴⁴ of 50--60 GeV, to the LEP energy⁴⁵ of 90 GeV. We were surprised to discover that the cluster size in e^+e^- collisions is energy dependent. It increases steadily from $k = 1$ at lower energy to a value close to 2 at the LEP energy. 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.

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