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SUMMARY TALK - STRONG INTERACTION PHYSICS

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ABSTRACT

A brief overview of the current status of strong interaction physics is followed by a summary of the numerous contributed papers in this area.

INTRODUCTION AND OVERVIEW

The plan of this summary talk is to begin with an elementary discussion of strong interaction physics. This will give a perspective of the overall situation and set the stage for discussing the large number of contributed talks at this symposium. I have divided these talks into six categories: multiparticle production, heavy ion collisions, parton distributions in nuclei, photon structure function, aspects of QCD theory, other topics. In each category, I will outline the main physics issues of current interest and list the names of all speakers, most of whom have detailed contributions contained in these Proceedings.

The subject matter of this summary is quite traditional, and is complementary to the really "new trends" discussed by Carruthers,[1)]

which are not based on QCD and could possibly develop into important activities of the future. I will come "back to the future" later in this overview, but first let us survey the past and present situation.

About 40 years ago, in contrast to the status of quantum electrodynamics, there was not only no basic quantum field theory for the strong interactions, but furthermore there was no known approach for calculating with Lagrangians containing interactions with large coupling constants. About 20 years ago, it was fashionable to emphasize general properties of the scattering matrix like analyticity and unitarity. It was also the heyday of Regge phenomenology which was successful in describing many facets of the available data, but contained a large number of arbitrary parameters. In particular, the structure and couplings of the Pomeron trajectory were unclear. At the present time, almost everyone accepts quantum chromodynamics as the fundamental theory of strong interactions. The "effective" or "running" coupling constant α_S decreases with increase in the square of the momentum transfer Q^2. Typically, for $Q^2 \simeq 10\ \mathrm{GeV}^2$, the value of α_S is $\simeq \frac{1}{4}$. For hard processes, $[Q^2 \gtrsim 10\ \mathrm{GeV}^2]$, one might expect perturbation theory in α_S to be applicable, whereas for soft processes $[Q^2 \lesssim 10\ \mathrm{GeV}^2]$, ordinary low order perturbation calculations in α_S surely fail. Of course, many physical processes are "mixed" and contain both hard and soft components. For example, electron-positron annihilation into hadrons is thought of as a two step process - color separation, in which the virtual photon produces a quark-antiquark pair, and fragmentation, in which the confinement mechanism converts the separating $q\bar{q}$ pair into a jet of observable hadrons.

Hard Processes: For describing the Drell-Yan process, $R(e^+e^-)$, large-p_T jets, Q^2 evolution of structure functions, etc., low order QCD calculations are generally in very good agreement with experiment. They have been extensively described in many places, and are mainly responsible for our strong belief in QCD as the theory of strong interactions. In recent years, several difficult higher order calculations have been done, and often found to have surprisingly large coefficients. It is also becoming clearer that these coefficients cannot be substantially reduced by varying the

renormalization scheme. The best known and certainly the most disturbing example of large higher order corrections is the three loop level calculation of $R(e^+e^-)$ [2]. This complicated calculation is now known to be in error, and is being repeated by at least two independent groups, with results expected in one or two years.[3] It should be pointed out that such calculations typically involve hundreds of Feynman diagrams which are not only hard to compute, but require skill even for a complete tabulation. In any case, there are indications from several sources that perturbation expansions in α_S are probably not convergent and may in fact be asymptotic. This has motivated the use of "summation" techniques like Padé approximants and Borel summation, but it is not clear how unique or reliable the results are.

Soft Processes: For computing hadron masses, multiparticle production, parton structure and fragmentation functions, etc., low order perturbation theory in α_S makes no sense, and one has to use alternative approaches.

(i) Practical phenomenological approach: This consists of taking input data from one soft process in order to explain others. An example of this is the "universality" of fragmentation functions. The fragmentation functions determined from e^+e^- annihilation (say) are used to describe large-p_T particles in hadronic collisions. Alternatively, it is also possible to develop simple models for fragmentation [like the recursive cascade or Lund models] motivated from QCD parton ideas. Another example of the practical approach is the use of quark and gluon condensates in QCD sum rule applications.[4] The Skyrmion approach and bag models probably fall in this category too. It should also be noted that in the chiral limit of QCD, one can get low energy results using chiral perturbation theory.

(ii) Numerical solution: Solving quantum field theories numerically has been a major activity which began about 10 years ago. Numerical solution involves the use of finite space-time lattices, and this introduces ambiguities in the definition of derivatives and raises questions about taking the limit of zero lattice spacing. Furthermore, the statistical errors which are intrinsically present in Monte Carlo calculations have to be carefully estimated and errors due to finite lattice size have to be kept as

small as possible. There are also technical problems in including quark degrees of freedom and the calculations require enormous computer resources and time. In fact, for all the above reasons, lattice calculations at present are actively pursued by only a few groups of computing experts. Recent results for several fundamental quantities like hadron masses and some meson decay constants are in reasonable accord with data.[5] There is also general agreement that at high energy densities, QCD undergoes a phase transition into a deconfined phase - the quark-gluon plasma. Leaving aside the serious disadvantage of not being analytic, it is very encouraging that lattice gauge theory calculations are beginning to yield physically meaningful soft hadronic physics results starting from the QCD Lagrangian.

(iii) Summing infinite classes of QCD diagrams: This is an attempt to get the main features of soft processes by summing large classes of QCD diagrams using the leading log approximation.[6] It is roughly analogous to the well known result that Regge behavior $s^{\alpha(t)}$ results from summing ladder graphs in ϕ^3 field theory. In particular, the Pomeron is identified with iterations of 2-gluon exchange. Although this approach will probably permit making the transition from hard to "semi-hard" processes, it is probably unreasonable to expect it to work all the way into the soft regime where α_S is large. Aside from the diagrams which are not included and the approximations made in order to compute the diagrams which are included, is the more serious question of the radius of convergence of infinite series in α_S. In fact, it has been argued that the key features of unitarity and color confinement in QCD at the hadronic scale cannot come from a series expansion in α_S.[7] A simple analogy is the quantum mechanical tunneling probability $\exp(-C/\hbar)$ in a double well potential, which cannot be obtained by summing an infinite series in $\hbar$.

(iv) Alternative expansion parameter 1/N: It has been suggested that since the techniques of perturbation theory are well-developed, but α_S is not a good expansion parameter for soft hadronic physics, it would be desirable to use an alternative expansion parameter. It is clearer to describe the general idea in the context of nonrelativistic quantum mechanics.[8] Suppose we are interested in solving the Schrodinger

equation for a three dimensional spherically symmetric potential V(r), for which ordinary coupling constant perturbation theory is not applicable. The procedure is to write the radial Schrodinger equation for V(r) assuming there are N spatial dimensions. The $N = \infty$ limit is easily solved and constitutes the initial unperturbed problem. One then makes a perturbation expansion in 1/N, and ultimately sets N = 3 in order to get results of physical interest. In effect, one has "artificially created" an expansion parameter by exploiting the degree of freedom corresponding to the number of spatial dimensions. With suitable improvements for enhancing the convergence of the 1/N series, this technique yields very accurate analytic expressions for the eigenenergies, and is widely used.[8)]

For quantum field theories, it is also possible to pursue a similar approach by identifying N with an internal degree of freedom. Such an approach has been used in many contexts, most recently in a study of two dimensional quantum gravity. In QCD, one uses the number of colors N_c or the number of flavors N_f for making a 1/N expansion.[9)] Quantitative calculations using a 1/N expansion in quantum field theory are complicated even at the lowest order. However, qualitatively it is easy to see that one gets a topological expansion, implying that diagrams with complicated topologies are suppressed by powers of 1/N. The dual parton model[10)] is a very successful phenomenological scheme motivated by a topological expansion of QCD, which also incorporates unitarity and duality. The leading contribution to elastic scattering has the topology of a cylinder, and corresponds to single Pomeron exchange.

(v) Non-QCD approaches: After noting all the above-described difficulties, many physicists have concluded that the QCD Lagrangian, as formulated in terms of quarks and gluons as the basic fields, is not useful for calculations in the soft regime at the present time. They have chosen to abandon QCD temporarily, and look for more general properties which are independent of the specific choice of Lagrangian, similar to the behavior of a system near a critical point. In the context of multiparticle physics, statistical approaches, intermittency studies and attempts to establish connections with fractal geometry have been actively pursued. These topics are reviewed in Ref. 1.

This concludes a brief overview of the current status and main activities of strong interaction physics. As mentioned at the outset, the intention was to lay a simple framework for discussing the talks at this symposium which are grouped into six categories, and referred to by the name of the contributor.

1. MULTIPARTICLE PRODUCTION {C. C. Shih, U. Sukhatme, F. Takagi, G. Wilk, Z. Wlodarczyk, G. Wrochna}

In high energy collisions, the bulk of the cross section consists of multiparticle production with small transverse momentum with respect to the collision axis. There is plenty of data on all facets of soft processes: average multiplicities, multiplicity distributions, single and two particle inclusive spectra, dependence on rapidity and transverse momentum, charge distributions, short and long range particle correlations, charge distributions, particle ratios, etc. Furthermore, data is available over a large range of energies for a wide variety of incident beams and targets. It is ironic that soft collisions, which are relatively easy to study from an experimental viewpoint, are very hard to describe theoretically from first principles, that is starting from the QCD Lagrangian. However, it is important to note that the models constructed to describe soft hadronic processes are severely constrained and tested by the abundance of available data. I will now mention various models discussed at this symposium, arranged in decreasing order according to the degree of motivation from QCD.

It is well established that the dual parton model[10] gives a very successful overall phenomenological description. Multiparticle production dominantly comes from two chains of hadrons created by the fragmentation of separating colored systems containing valence quarks [with higher order unitarity corrections]. The two chains arise naturally from a unitarity cut of the cylindrical dual Pomeron, which is the leading tern in a 1/N topological expansion of QCD. Another successful phenomenological approach, the Lund-Fritiof model,[11] also has two chains. It was emphasized that charge distributions in rapidity dQ/dy

provide a sensitive test of various models, since they give relatively direct information about the fate of the initial valence quarks in soft hadronic collisions.{Sukhatme} Current data on charge distributions in hadronic collisions and related data from cosmic ray extensive air showers is nicely described by the dual parton model.

Another QCD based model is the recently developed "interacting gluon model". Here it is assumed that when two hadrons collide, they interact via their gluonic components. This produces a number of mini-fireballs which act as sources for hadron production, and give rise to the the experimentally observed linear relationship for long range forward-backward correlations{Wlodarczyk,Wilk}.

Another quantity which indirectly reflects the mechanism of particle production is the multiplicity distribution $P(n,\sqrt{s})$. A successive branching mechanism, applied to e^+e^- collisions, was shown to produce a lognormal multiplicity distribution which fitted available data very well, in fact somewhat better than the more widely used negative binomial distribution{Wrochna}. It was also pointed out that a stochastic branching process could well be underlying previously used two component models for describing multiplicity distributions {Wilk}.

Finally, there were two novel and rather intriguing contributions - one stressing the need to use a quantum statistical ensemble to describe multiplicity distributions and particle correlations {Shih} and the other suggesting that the concept of information dimension used in the theory of fractals is relevant to multiparticle production{Takagi}. As mentioned before, similar ideas are extensively discussed in Ref. 1.

2. HEAVY ION COLLISIONS {H. Bialkowska, A. Solomin}

The study of high energy heavy ion collisions is interesting for both experimental and theoretical reasons. The ability to handle the large multiplicity of produced particles is a challenge for detector technology. The theoretical description of the data in terms of hadronic interactions

and Glauber rescattering provides insight into the space-time development of final state hadrons. However, the main motivation for colliding energetic nuclei is to produce a new phase of matter - the quark-gluon plasma.[12)]

It is widely believed that an ordinary "hadron gas" when compressed to a high baryon density and raised to a high temperature undergoes a deconfinement phase transition to form a quark-gluon plasma. The phase transition can be depicted as a line in the baryon density-temperature plane. Lattice QCD Monte Carlo simulations of the thermodynamics of a gluon gas show that for a baryon density which is a few times nuclear matter density, the critical phase transition temperature is T_c = 200 to 300 MeV. Such conditions are expected to be attainable in ultrarelativistic heavy ion collisions, and a number of experimental signals of deconfinement have been suggested. These include a study of low-p_T lepton pairs, ratios of strange to non-strange hadrons[13)] suppression of J/ψ and its strong p_T -dependence,[14)] etc. None of these signals by themselves is fully convincing, and it will presumably take several of them to establish the existence of a quark-gluon plasma conclusively.

At this symposium, there was a detailed report on the K^+/π^+ ratio {Bialkowska}. This ratio is clearly found to be much larger in relativistic heavy ion collisions [at Brookhaven and CERN] as compared to corresponding pp data. It should be pointed out that experiment E-735 at the Fermilab Tevatron is also attempting to see signs of deconfinement in high multiplicity $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV with as yet inconclusive results.[15)] In any case, the search for a quark-gluon plasma will continue with a large step upward in energy at RHIC - the relativistic heavy ion collider currently in the initial stages of construction at Brookhaven National Laboratory. This facility for the collision of ions with approximately 200 GeV of energy per nucleon, is expected to yield its first physics results in 1997.

3. PARTON DISTRIBUTIONS IN NUCLEI {M. Botje, K. Charcula, G. Mallot, G. Van Middelkoop}

This subject has been of substantial physics interest ever since the EMC measurements in deep inelelastic lepton scattering (DIS) showed that a nucleus could not simply be regarded as a collection of A independent nucleons. Many groups have now taken detailed data on the ratio $F_2(A)/F_2(D)$ for scattering off nuclear targets and deuterium, and established the existence of shadowing for $x < 0.1$. In fact, there is now good data down to $x \simeq 0.001$ from experiment E-665 at Fermilab[16] and NMC {Botje, Mallot, Van Middelkoop}, with even smaller values of x expected to be attainable soon at HERA. Many sources of shadowing have theoretically considered, including parton recombination,[17] pions in nuclei,[18] extended vector dominance,[19] quark clusters,[20] etc.[21] The quark cluster model has a rather simple parametrization which gives a reasonable overall description of the EMC effect at all x.[22] The same framework predicted shadowing effects in the Drell-Yan process, which have recently been confirmed by experiment E-772 at Fermilab.[23]

4. PHOTON STRUCTURE FUNCTION {M. Krawczyk, A. Levy, D. Miller}

Studying the photon structure function has long been suggested as a clean test of QCD.[24] However, this has not turned out to be the case. It is now known that the photon structure function has a point-like [or perturbative] component as well as a hadronic [or non-perturbative] component. The lowest order point-like contribution is calculable in QCD,[24] but the next-to-leading order contribution diverges at small-x.[25] The non-perturbative component , which is usually taken from the vector dominance model, gives an important contribution in currently available experiments {Levy, Krawczyk}. The relative importance of the two components is model-dependent and varies with the parametrization used.[26] Important accurate information about both the photon and proton structure functions is forthcoming from electron-proton collisions at

HERA next year. Currently available LEP data can also be analyzed for two photon scattering events to get fairly high accuracy measurements of the photon structure function, but apparently this is a low priority item at LEP {Levy, Miller}.

5. ASPECTS OF QCD THEORY {J.Baacke, B. Ermolaev,G.Korchemsky, J. Namyslowski, P. Raczka, A. Radyushkin, S. Tamarian}

Various diverse aspects of QCD theory were discussed. These included a discussion of τ-decay after application of the Borel summation technique to the relevant QCD perturbation expansion {Raczka} and a new approach which takes into account the divergences due to gluons which are simultaneously soft and collinear applied to inclusive γ-quark scattering {Ermolaev}. The individual contributions of various speakers should be consulted for more details.

6. OTHER TOPICS {Z. Fodor, N. Ivanov, A. Rimoldi, L. Tikhonova, J. Wdowczyk}

This category contained a variety of miscellaneous topics like a study of diffractive systems in hadronic collisions {Tikhonova} showing good agreement with the dual parton model, and a description of single jet inclusive cross sections measured by UA2 {Rimondi} along with a comparison with QCD calculations.

The topic I would like to focus on is the recent observation of air shower signals associated with astrophysical "point sources" {Wdowczyk}. Careful measurements from several groups seem to confirm the obdervation of energetic air showers coming from the directions of Cygnus X-3, Hercules X-1, etc. These observations, along with phase correlation measurements, imply that the showers must originate from a long lived, neutral, small mass primary hitting the earth's atmosphere. The standard interpretation is to have primary photons of energy 100 GeV $\lesssim$

$\sqrt{s} \lesssim 10$ TeV. However, the observed muon content of the showers is anomalous – it is about one order of magnitude greater than the value expected from a primary photon with known electromagnetic interactions. Therefore, either photons have unusually large [hadronic size?] cross sections at high energies, or there exists a hitherto unknown light neutral primary particle. In either case, there is strong evidence for the occurrence of new physics!

On this upbeat note, I wish to conclude this summary talk with an apology and a "thank you". The apology is to every one whose work I have not described either adequately or correctly – this does not detract from the quality of their work, but merely reflects my ignorance. The "thank you" is for our Polish friends who have worked so hard to make this such an enjoyable symposium.

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