RESEARCH PROPOSAL TO THE U.S. DEPARTMENT OF ENERGY DIVISION OF HIGH ENERGY PHYSICS

PROGRESS REPORT
GRANT DE–FG02–85ER40213

"Theory and Phenomenology of Strong and Weak Interaction High Energy Physics"

DOE/ER/40213--6

DE90 005370

by the

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December 20, 1989

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PROJECT DESCRIPTION

This proposal requests continuing support for the theoretical high energy physics group at the University of Arizona, under Grant DE–FG02–85ER40213. The group consists of Professors Robert L. Thews, Michael D. Scadron, Adrian Patrascioiu, and Peter Carruthers, Associate Professors Doug Toussaint and Anna Hasenfratz, Assistant Professor Ina Sarcevic, postdocs Aleksandar Kocic and Raj Gandhi, and graduate students Erwin Sucipto, Bill Ryan, J. K. Kim, and Robert Karlsen.

Plans for expansion in High Energy Physics have proceeded as anticipated in last year's proposal. Two new faculty members joined our group last fall, Doug Toussaint (Associate Professor with tenure) from UC San Diego, and Ina Sarcevic (Assistant Professor) from Los Alamos. Anna Hasenfratz (Associate Professor with tenure) joined us this fall from Florida State. Their research programs have been initially supported by university startup funds. Due to limited resources, Professors Toussaint and Sarcevic receive only limited travel support from the grant during the current year, with the remainder of their support still taken from temporary university sources. Professor Hasenfratz was supported at Florida State by DOE high energy physics in the Outstanding Junior Investigator program. We propose **as our highest priority** to add their full support to this grant during the upcoming renewal period. One of our postdocs, Dr. Kocic, has returned from his Humboldt fellowship in Regensburg, Germany. A new postdoc, Raj Gandhi, has joined us this fall from Amsterdam (NIKHEF) to work in the area of neutrino physics and phenomenology. With seven faculty currently in our group, **our next priority** is to increase the number of postdoctoral research associates from the present two to four or five, and to bring the total number of supported graduate students up to at least one per faculty member. It should be noted that the supply of high–quality students has increased dramatically since a few years ago, due in no small measure to our grant from the Department of Education for fellowships to support entering students. If these initiatives are successful, we would then plan for one or two more junior faculty appointments after next few years, bringing our total group size to eight or nine faculty. This size will provide a critical mass in areas of both computational field theory and high energy phenomenology. Our group is also benefiting by interactions with other university–supported activities, including research in condensed matter theory and applied mathematics through the Center for the Study of Complex Systems, which was initiated two years ago under the guidance of Prof. Carruthers. The situation in experimental high energy physics has moved forward following the initial appointments of John Rutherfoord from Washington and Michael Shupe from Minnesota. They have been joined this fall by two new Assistant Professors, Ken Johns from Minnesota and Geoffrey Forden from Stonybrook. We hope to propose joining the support of both theory and experimental groups into a single contract after external funding for the experimental effort has been established.

University support for the recent growth in high energy physics has been substantial. All of our new faculty positions have first–year support for travel, operations, summer salary, and significant computer equipment. Approximately $110,000 has been provided for these purposes to our new appointees in high energy theory. The general departmental fund for faculty recruitment has provided us with opportunities to bring in a wide variety of first–rate candidates for periods ranging from a few days to months. Temporary university support for a visitor program has allowed us to bring in research collaborators. This year we have Professors E. Seiler (Max Planck, Munich), J. Stern and G. Clement (CERN), J. Cleymans (Capetown), G. Karl (Guelph), H. Satz (Bielefeld and CERN), S. Gottlieb (Indiana), and M. Blazek (Bratislava). These local sources of support have allowed us to phase in our requests for DOE support.

PROGRESS REPORT AND PROPOSED RESEARCH

Prof. M. D. Scadron: The major research emphasis in 1989 was on chiral symmetry in strong interactions. Based on an invited talk at the QCD Conference at Santa Barbara in January 1988, Scadron and N. Fuchs published two papers in 1989 on current divergences and current quark masses. This analysis follows from Heisenberg equations of motion which are quite general and model independent. The results are that current quark masses are substantially larger than previously believed. Also in early 1989 Scadron (along with A. Kocic and J. Cleymans) published a paper on finite temperature QCD showing that $T_c=2 f_\pi$ in many chiral–symmetric models.

In mid 1989, Scadron and M. Anselmino published work also reported at the Warsaw meeting on the strange quark content in nucleons. Both the strange quark axial spin Δ_s and the strange quark density (sbar s)$_N$ turn out to be very small based on the recent EMC measurement of the polarized proton structure function. Only later did Scadron realize, as discussed in an invited talk at the Hadron conference in Bratislava, that even without the EMC data the neutron and hyperon semileptonic decays require $\Delta d = -1/3$ and $\Delta s = 0$.

Also in mid 1989, Scadron and A. Bramon published two papers on strong interaction phenomenology. One paper focuses on why the measured SU(3) discrepancy between charged and neutral radiative decays $K^* \to K\gamma$ is completely explained by the strange to nonstrange constituents quark mass ratio m_s/m approximately 1.5, the latter also explaining many other SU(3)–breaking effects. The second paper studies the $\eta - \eta'$ mixing angle. Based on all measured two–body decays, Scadron and Bramon conclude that the pseudoscalar mixing angle is -14 ± 2 degrees.

The DGG–Isgur–Karl hyperfine splitting model also allows one to infer the current quark masses. In another work Scadron, Elias and Tong thereby show that current quark masses are additive in Nambu–Goldstone mesons. More recently Scadron gave two talks at the hadron conference in Bratislava on chiral symmetry breaking, both explicit and dynamical. The first shows how the pion gets mass in one–loop order in the linear sigma–model but only including sigma tadpole loops. Further work has been submitted for publication with a student (T. Hakioglu). The second points out the problems encountered if scalar meson tadpoles are ignored. Scadron also stressed these ideas at a summer school in Greece. All of the above approaches to chiral symmetry breaking in strong interactions will be summarized in five talks given at a winter school next month.

Scadron also has an ongoing interest in weak interactions. Gauge invariance issues were worked out for the standard electroweak model in Ref. (15). The origin of the kaon $\Delta I=1/2$ rule and the $K_L - K_S$ mass difference were discussed in two invited talks last summer. Further studies on K, D, B decays is proceeding with a student (R. Karlsen).

Prof. R. L. Thews: This research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Work with graduate student Erwin Sucipto has resulted in a new understanding of patterns of symmetry breaking in radiative decays $V \to P\gamma$. Follow–up work has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (16). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. The long–range collaborative program with Prof. J. Cleymans of Capetown is continuing. Our initial description of nucleon structure functions as a gas of quarks and gluons is being extended in several directions. An application to nuclei and the

EMC effect, initially presented at the Kyoto PANIC conference, awaits further development as a possible student dissertation topic. Mr. Sucipto is making progress on possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. The most recent work with Cleymans is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that most calculations to explain this behavior based on color screening in a quark–gluon plasma have assumed a classical formation time for the resonance. Our quantum–mechanical model calculations show that this picture is incorrect, and that one must work with the time evolution of initial wave functions to calculate relative probabilities for resonance formation after the decay of a plasma background. A simple one–dimensional model was put forward to illustrate these principles (17,19), and current work is aimed at looking for critical kinematic dependencies which might signal plasma formation. This is of special interest now that some alternative explanations based on absorption in dense hadron matter have been proposed. Prof. Thews presented the latest results of this work at the Moriond meeting in March (18), and will present a series of lectures in Capetown in January at a meeting on the phase structure of strongly interacting matter. During that visit, plans will be formulated for future work, while additional results are being developed. Graduate student Bill Ryan is becoming involved in this project with calculations on the effects of time–dependent external potentials on transition probabilities. This is leading toward a dissertation topic in the general area of perturbative QCD and phenomenology at hadron colliders. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. Another graduate student Pete Gugoff (as yet unsupported) is looking at the effects of experimental detector cuts on some previous predictions for discrimination of individual QCD subprocesses.

Prof. Adrian Patrascioiu: A multi–year program is continuing which studies certain properties of some of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills gauge theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagrams and to the possible continuum limits which could be constructed. In particular in a series of papers, Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu argued that probably there is no difference between the abelian and the nonabelian models , contrary to common beliefs based on the so called topological order, which exists in the abelian models at small coupling but not in the nonabelian ones. His heuristic ideas were based on energy–entropy estimates of the type Peierls used to prove the existence of long range order in the Ising model at low temperatures. These ideas were further developed in collaboration with Drs.E.Seiler and I.O.Stamatescu (20) and investigated numerically in a variety of models (6). In every instance, numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. In particular it was concluded that contrary to everybody else's claims, there is a deconfining transition in QCD_4 at zero temperature.

During the last year, this research program has progressed in three major ways:

1) Improved Monte Carlo updating: A major limitation of numerical studies was due to the occurrence of critical slowing down in locally updating algorithms. This limited the numerics to correlation length no larger than 20 lattice units. During the last year Patrascioiu (22) proposed a new type of updating which employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by U. Wolff). With this nonlocal updating critical slowing down is restricted and correlation lengths of 100 lattice units become easily accessible to the numerics. This idea

was applied with great success to investigate a variety of models such as the O(2),O(3),Z(N) and dodecahedron spin models in two dimensions. The data strengthened the evidence that, contrary to common beliefs, the O(3) (nonabelian) model does possess a massless phase at weak coupling and is not asymptotically free.

2) Proof for the existence of a massless phase in the dodecahedron spin model: It has been quite common to assume that one can replace the the O(N) spin model by one of its discrete subgroups and if the latter is sufficiently large, it should exhibit the same phase structure at sufficiently large beta. For O(3), the largest discrete subgroup is the icosahedral Y with 60 elements. It is the invariance group of the dodecahedron, the largest regular polyhedron embedded in S2. In collaboration with Drs.J.–L.Richard and E.Seiler, Patrascioiu (23) derived a rigorous inequality relating the dodecahedron spin model to the Z(10) one. As the latter is known to possess an intermediate massless phase, the inequality suggested a similar property for the dodecahedron. This fact was established numerically (24), employing the new type of Monte Carlo updating described above. It shows that a nonabelian spin model in two dimensions can exhibit algebraic decay of its correlations.

3) Proof of the existence of a massless phase in O(N) models in 2D: The Fortuin–Kasteleyn transformation used for implementing nonlocal Monte Carlo updating can also be used for analytic work. In collaboration with Dr.E.Seiler, Patrascioiu has completed the backbone of a rigorous proof for the existence of a massless phase in all O(N) models at weak coupling. The main tool used is a mapping of the original spin model into a percolation model about which much more is known.

Future plans: Patrascioiu anticipates a fast completion of all the details regarding the absence of a mass gap at sufficiently weak coupling in all O(N) models in two dimension. Thru the use of correlation inequalities, this result also proves rigorously that contrary to indications obtained from perturbation theory, these models are not asymptotically free, but in fact their Callan–Symanzik beta–function vanishes for all N. This results would force a major reconsideration of accepted ideas regarding the properties of QCD_4, which would be the next topic on the agenda.

Prof. Peter Carruthers: In the past few years considerable interest has developed in both experimental and theoretical aspects of multihadron production for all combinations of relativistic projectiles and targets: hadrons on hadrons, hadrons on nuclei and nuclei on nuclei. Besides the ongoing hope to find new phases of hadronic matter, increasing the final state momentum resolution has allowed one to ask new phenomenological questions about the possible fractal or "intermittent" behavior in the longitudinal rapidity and now also the transverse momentum variables. Measurements of multiplicities, particle composition of final states and transverse energy behavior have sharpened theoretical problems and produced several promising lines of theoretical inquiry. The present program involves a combination of basic theory and new phenomenological techniques applied to data analysis in collisions involving relativistic nuclei with hadrons or other nuclei. In addition we continue to develop a field–theoretic description of kinetic and hydrodynamic behavior and collective excitations in excited hadronic matter. Part of this research program has been supported by a grant through the Nuclear Physics division in relativistic heavy ion physics and done in collaboration with Prof. Ina Sarcevic.

The greatest attention recently has been given to the so–called intermittency phenomenon, which means empirically a power law increase of factorial moments with decreasing size of the rapidity bin windows. Although such behavior has been observed by several experimental groups, a saturation occurs for small rapidity bin size. We have studied this behavior from several directions. First of all an extensive analysis (1) was made of possible techniques borrowed from modern nonlinear dynamics for possible applicability to finite samples of possibly fractal sets. Owing to the random shift of impact parameters, energy loss, and quantum number fluctuations from event to event, there is a "noise" effect that interferes with standard time series analysis. It was pointed out that the introduction of successively higher order correlations and conditional probabilities might improve this situation. (In addition we introduced a set of novel set of information correlations analogous to the hierarchy of cumulant moments which allow a new approach to correlation analysis. This method was applied to the forward–backward correlation analysis data in Reference 2.).

While interested for some time in the idea that fractals might manifest themselves in high energy hadronic and nuclear reactions (3) we also have found that current data on the bin size dependence of factorial moments can be explained by fairly conventional approaches. The first of these (5) applied a successful quantum statistical model of multiplicities in which the coherence of emissions from various bins in phase space were tuned to fit a few data points. At the same time several other authors proposed cascading cluster or branching models that have the right qualitative behavior. However we later found (6) a much more general approach which is model independent if one accepts a hierarchical decomposition of cumulant correlation functions into linked pairs in close correspondence to that used in the description of galaxy correlations. The behavior of the second through fifth bin–averaged factorial moments depends on the experimentally determined two–particle correlation length and amplitude in a very simple way. To be explicit, for the three particle correlation function one writes the usual (reduced) rapidity density correlation function as:

$$r_3 (y_1, y_2, y_3) = 1 + k_2(y_1, y_2) + k_2(y_2, y_3) + k_2(y_1, y_3) + k_3(y_1, y_2, y_3)$$

with $k_3 = (a_3)^2 \, [k_2(y_1, y_2) \, k_2(y_2, y_3) + \text{permutations}]/3$

The k_n denote reduced cumulants, with the two particle experimental cumulant represented as $k_2 = \gamma_2 \, e^{-\mathrm{abs}(y_1 - y_2)/\xi}$. Once the coefficient is determined at one energy (e.g. for the NA22 experiment) it also describes the behavior of the three particle correlation function at the much higher energies of the UA5 experiment.

Several authors have observed that standard Monte Carlo event generators do not explain "intermittency". Our work shows this to be non–surprising since few of these codes properly include short range correlations. The same features occur for the fourth and fifth moments. Currently we are extending our analysis to allow for non uniform rapidity densities and to all relevant experiments.

Having found that small rapidity bin variation does not require new physical ideas we explored the possibility of power law asymptotes at large values of the total rapidity interval (45). This approach successfully connects a universal asymptotic power law behavior with scaling exponents in the two dimensional Ising model. In our analysis of the large energy depositions and fluctuations observed in ultrarelativistic heavy–ion collisions at CERN and BNL, we have found strong evidence of the coherence effect. We have predicted the A, B, and rapidity dependence of the fluctuations, which could easily be tested at BNL and CERN energies.

a) The challenge of data analysis presented by typical multiplicities in the hundreds requires new techniques. In addition to the fractal methods mentioned above we have invented (1) a new method based on generalized information correlations. The usual mutual information I(x,y) is computed from a joint probability distribution P(x,y) as $I(x,y) = S(x) + S(y) - S(x,y)$, with S(x,y) the entropy computed from P(x,y), etc. If x and y are statistically independent then I vanishes. We have succeeded in extending this definition to arbitrary order by a one to one map from standard cumulant structures.. But the new information should be less susceptible to experimental error as well as have an absolute information–theoretic significance. All these information correlations have the property that they vanish if any one of the participating variables is statistically independent of the others. The SUNY–Buffalo group has recently applied this method to cosmic ray data. They find a much stronger information correlation between forward and backward hadrons than we determined (2) for UA5 data.

b) For some years we have been developing a field theory formulation of kinetic and transport problems using a generalization of the Wigner phase space distribution. This work followed our 1972–4 work restructuring the Landau hydrodynamical model of hadron production to modern usage, and our 1973 paper on the many body dynamics of nonrelativistic degenerate quark matter. Recently we have been investigating the relation of these structures to the energy–momentum tensor, the virial theorem and the Equation of State of the quark–gluon plasma (7). Another aspect of this program is to derive the existence of quasiparticles and the space–time evolution of a deconfined plasma. Presently the technical aspects of this problem, particularly with regard to gauge invariance, create difficulties. However we continue to consider this as a major long term objective.

c) At very large energies, the multiplicity distribution dN/dy can be measured over the range $0<|y|<Y$, where $Y=\ln s$. We can therefore consider the subdivision of this range into different size intervals Δy, which are larger than the characteristic size of the usual resonance correlations. For the invariant mass of the pion system of the order 0.5–1.0GeV, the corresponding separation of the two pions in rapidity is about $\Delta y_0=1$–2. Therefore the intervals we consider are complementary to our previous study of the intermittency (6). Assuming that we have self–similar cascading pattern in the multihadron production from Y down to the Δy_0, we find that this leads at high energies to the universal power law behavior for the multiplicity moment as a function of relative rapidity $Y/\Delta y$. Such behavior occurs for infinitely large energies and Δy larger than the scale associated with the usual resonance. The experimental data for pp collisions at CERN energies were found to agree very well with this predicted universal behavior (45). We propose to develop Monte Carlo techniques for self–similar cascading, which would contain the necessary short–range correlations, in order to simulate UA5 events and predict power exponents of the moments F_i for even higher energies. We also plan to apply our idea in the case of e^+ e^- collisions, where observed intermittent behavior is much stronger than in the hadronic collisions.

Prof. Doug Toussaint: Research on numerical simulations of quantum chromodynamics continues. These methods allow us to study low energy QCD phenomenology with approximations that are, at least in principle, controllable. In other words, given enough computing power these computations could be made arbitrarily accurate. However, in fact these computations are severely limited by the available computing power, and as a result we are only beginning to get control of the simplest quantities, such as the masses of the hadrons. During this last year, in a continuing collaboration with Steve Gottlieb, Weiqiang Liu, Ray Renken and Bob Sugar, we carried out a simulation of QCD at high temperatures with two flavors of dynamical quarks on a 12^3 x 8 lattice. Most previous work on full QCD at high temperatures has been done with four time slices, so this represents a factor of two decrease in the lattice spacing. We found that at quark masses of $0.025a^{-1}$ and $0.0125a^{-1}$ the transition to manifest chiral symmetry at high temperatures was fairly smooth on this size lattice. Most probably this is a result of the small spatial size, or the large quark mass. However, the possibility that the studies with four time slices were misleading certainly exists, and it is very important to simulate with smaller lattice spacings. Unfortunately, our program to simulate 2 flavor QCD with 16^3 x 8 lattices and smaller quark masses has been aborted due to the demise of the John von Neumann computing center. In a larger collaboration, the so–called "High Energy Monte Carlo Grand Challenge", we are simulating QCD at low temperatures. In the past year we have simulated 12^4 lattices with two flavors of Kogut–Susskind fermions, using dynamical quark masses of $0.025a^{-1}$ and $0.01a^{-1}$. We have measured hadron propagators on 500 lattices at each dynamical quark mass using both Kogut–Susskind and Wilson valence quarks. This is the highest statistics simulation of full QCD with the smallest (though still too large!) quark mass done to date. Preliminary results were reported at the Lattice Gauge Theory Conference in Capri, and a more complete analysis of these results is in progress. We are currently extending this work with a run on 16^4 lattices. This is to check on the effects of finite lattice size, since the physical size of the lattice in the 12^4 run was only about 1.6 fermis. We are also doing another run on 12^4 lattices using a higher accuracy for the propagator computations in the configuration updating. (Our feeling is that the current generation of computations of low temperature QCD will not produce accurate results, and therefore the important thing is to understand the systematic effects of all our approximations. Thus we are trying to change one thing at a time.) Again, due to the demise of ETA computers and the consequent likely removal of the ETA–10 from SCRI, this simulation is unlikely to continue directly. Using the remaining time at JvNC we have begun a simulation of high temperature QCD using dynamical Wilson fermions with four time slices. Most work in high temperature QCD on the lattice has used Kogut–Susskind quarks because of the exact U(1) chiral symmetry on the lattice, and because of the computational simplicity of the Kogut–Susskind quarks. However, in the continuum limit both formulations must give the same answer, and we believe that comparison of the two formulations is a significant test of the reliability of the results on small lattices. Simulations with Wilson quarks with four time slices have been done by Gupta etal and by Bitar etal, and these simulations show that a high temperature transition is accessible with Wilson fermions, contrary to some earlier claims. In our simulation we hope to carefully measure the strength of the jump in measured quantities as we gradually turn the quarks on by lowering their mass from infinity. This is interesting because with Kogut–Susskind quarks as the quarks are turned on the high temperature transition weakens, disappears, and then reappears as the quarks become very light. Also, we plan to measure the spatial screening lengths of hadronic (color singlet) sources in the plasma phase. This is a good test for the restoration of chiral symmetry, which is signalled by the appearance of parity doubling. Since the Wilson quarks do not have any exact chiral symmetry on the lattice, this will probably be more difficult to elucidate with the Wilson quarks than with the Kogut–Susskind quarks.

In addition to these projects with large groups, I have carried out an exploratory simulation of QCD at high baryon number density. This is a notoriously difficult problem

since the fermion determinant becomes complex in this case, and the results obtained are very limited. In particular, on a 4^4 lattice the simulation was controlled up to a density about twice nuclear density, and no phase transition was observed. Most of these simulations were done on the Fermilab lattice gauge machine. I hope to continue these investigations, but it is clear that progress in algorithms is required. Along this line,
I expect to investigate the applicability of the "stationary phase Monte Carlo" methods which have recently been introduced for condensed matter problems with highly oscillatory integrands in the path integrals to the problem of QCD at high density. Finally, Anna Hasenfratz, Dan Stein and I are investigating the behavior of Monte Carlo renormalization group studies of first order phase transitions. These MCRG studies sometimes show a behavior suggesting that they are flowing away from "pseudocritical points" lying beyond the actual critical point, presumably at the end of a metastable region. We hope to understand if this behavior should be generally expected near a first order transition, and if a continuation of the physics across the critical line represents the properties of a metastable phase. It is clear from the above that our ability to do numerical simulations of QCD is dependent on getting (and keeping) large computing power. It appears that the best way to do this is to use commercially produced parallel processing machines that are now becoming available. Together with five other high energy theorists and six condensed matter theorists, I am currently preparing a proposal to purchase such a machine.

Prof. Ina Sarcevic: 1. QCD Minijets and the Rising Cross Section: Most recent UA1 results on minijet cross sections for the CERN pbar–p Collider energies from 200 to 900 GeV have raised the question of the applicability of the perturbative QCD to low p_t physics. The importance of these results has been recognized by many theorists, and some input to this question has already been established. Predictions about minijet production should be useful as large detectors are built. Minijet studies should be possible at Tevatron

Collider energies. They should provide a very valuable testing ground for QCD calculation as presently conducted in the leading logarithm approximation, as well as detailed studies of higher–order effects. Clearly, the mere measurement of low p_t jets should already give much information about the gluon structure of the proton. The energy and luminosity of the pbar–p Collider are such that the accessible p_t range corresponds to a region where gluon jets are expected to dominate ($x_t \leq 0.01$). Any experimental information on low p_t physics at Tevatron Collider energies will therefore have a direct impact on the still–elusive role of gluons. We calculated the jet cross section for different QCD scales, different structure functions, and p_t^{min} (39). We were particularly interested in the relative contribution to the cross section that comes from gluons to that from quarks. The fact that the contribution to the cross section, and therefore multiplicities from the quarks is decreasing with energy has been used to predict interesting behavior of the multiplicity moments and the shape of the KNO scaling function $<n> P_n$. We considered low p_t jets ("minijets," $p_t \simeq$ few GeV) and were interested in finding the energy at which the quark contribution to this "minijet" cross section becomes negligible. The other important problem that we investigated was the choice of the structure function, scale, K factor, and p_t^{min} preferred by the experimental data. It was noted before that, for example, the cross section obtained using the UA1 parameterization of the structure functions does not describe the data. Finding the scale and the value of the K factor preferred by the data gave us very important input to the question of the importance of the higher–order corrections at the Collider energies.

We have recently extend the analysis of the inclusive differential jet cross section to the Tevatron energies. The CDF Collaboration has measured the differential jet cross section up to E_T=400GeV, which has allowed us to compare our theoretical predictions over several orders of magnitude. We have found that the data excludes some choices of the structure function and requires K factor to be E_T dependent (46). With increased statistics at higher E_T (higher luminosity) and better understanding of the CDF and D0 detector response these important QCD tests will become more and more quantitative. Any search of the exotic physics (such as top, Higgs or supersymmetric particles) will depend strongly on this QCD background, especially at SSC energies.

2. Heavy–Quark Production at Collider Energies: We have proposed the way to test structure functions at low x by measuring the heavy quark cross section at Tevatron Collider energies. We have shown that the QCD calculation (through order $O(\alpha_s^3)$ of the total cross section for the bottom and top quark pair cross section is very sensitive to the choice of the structure function at Collider energies (43). Comparison with the UA1 experimental data on the bottom cross section indicates that some choices of the structure functions seem to be preferred by the data. We find that measurements of the bottom quark pair cross section at Tevatron Collider energies should be able to make clear distinction between different choices of the structure functions, therefore providing valuable information about gluon structure function at low x. We have found that the bottom quark cross section at Collider energies is dominated by initial state gluons. At Tevatron energies this contribution becomes 80%, while the rest is due to the quark initiated subprocess. We have shown that the ratio of the cross section calculated through order (α_s^3) to the one calculated through the order (α_s^2), so–called K–factor, is of order 3 for the bottom quark cross section and K is of order 2 for the top quark cross section at Tevatron energies. The theoretical uncertainty due to the choice of the structure function has a significant effect on the experimental lower limit of the top quark mass, which can influence the way of detecting the top quark. We find that theoretical uncertainty due to the choice of the structure function implies about 20% uncertainty in the lower limit of the top mass. This could have an important impact on the way of detecting the top quark. Namely, this could mean the difference between top quark being lighter or heavier than $m_W + m_b$. If the top quark is heavy enough ($m_t > m_W + m_b$, and m_t well above the threshold), then it could be easily detected through the Wb decay of the t. If the top quark mass is close to the threshold ($m_t \simeq 85 - 90$ GeV), the b quarks will be soft and

hard to detect. By measuring the bottom quark pair cross section at Tevatron energies, the uncertainty in the experimental lower limit on the top quark mass could be substantially reduced. Further study of gluon structure functions and top searches is presently under investigation.

3. Unitarity Constrained Photo–nuclear Cross Sections and the Muon Content of Ultra High Energy Gamma–ray Air–showers: In the past few years a number of groups have reported increasingly firm evidence for the observation of the muon excess in the photon–induced air cascade from very high energy point sources. A photon–induced electromagnetic shower proceeds by electron pair production and bremsstrahlung and only develops a muon component via processes characterized by very small cross sections relative to the pair–production cross section, which is 500 mb in air. However, at very high energies, the "hadronic structure" of the photon becomes important and this could be the origin of the large muon content. We have calculated the photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We find that the cross sections are of the order of magnitude large than the ones previously used in the shower calculations for the observed muons. We plan to study the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x, p_t^{min} and higher order corrections) to the number of muons produced in air shower. We will also develop the shower Monte Carlo to simulate the air cascade and determine whether the excess of muons could be explained in the context of conventional physics. Since at HERA energies one would be able to test the idea of the "hadronic structure" of the photon, we intend to do careful study of the differential and total photon–proton cross sections at these energies.

4. Multiparticle Production in QCD–Based Parton Branching Model: This past year has witnessed an impressive renewal of interest in multiparticle production and particularly in Koba–Nielsen–Olesen (KNO) scaling and its violations. The most recent experimental data indicate that the problem of understanding the shape of the hadronic multiplicity

distributions still represents an outstanding problem in strong–interaction physics. We have shown that parton branching distribution P_{mn} of m quarks and n gluons does not obey exact KNO scaling. We have obtained a new non–scaling law for the probability distribution P_{mn}. When quark evolution is neglected, the probability distribution becomes wider as energy increases, in agreement with experimental data. In this model we predict that, due to the dominant role of gluons inside the hadrons, the widening of the probability distribution will stop at Tevatron Collider energies. We also give theoretical predictions for the multiplicities and moments for the Tevatron Collider energies. Since the CDF detector at Fermilab can cover only limited rapidity range, it is very important to give predictions for the multiplicities and moments as a function of rapidity. This work is in progress and I presented preliminary results at the "International Conference on Elastic and Diffractive Scattering" (44).

5. Ultrarelativistic Heavy–Ion Collisions: The study of the fluctuations in transverse energy and multiplicity in ultrarelativistic heavy–ion collisions is a valuable probe of the collision dynamics. Recent experimental data on transverse energy produced in ultrarelativistic heavy–ion collisions at CERN energies, indicate that well over half the beam energy is deposited in the collision volume. The fluctuations in the deposited energy and multiplicity in the central collisions are remarkably large. The first important question that we have addressed is whether the heavy–ion data shows any deviation from simple proton–proton data once a model for multiple collisions is built in. In this case, the possible sources of fluctuations are: 1) the fluctuations of the transverse energy inherent in the individual nucleon–nucleon subcollisions, 2) the fluctuations in the number of primary subcollisions, and 3) the fluctuations due to the successive nucleon rescattering. By carefully incorporating all of the fluctuations, we have found out that the above sources of fluctuations in an independent collision model together fail to account for the observed transverse energy fluctuations (42). Rather, the data suggests that the individual collisions are not independent events, and that the interaction between the target and projectile is to

a degree a coherent or collective process. We have estimated the effective number of statistically independent collisions in O–Au collisions at CERN energy (200 GeV/nucleon), which imply the transverse energy fluctuations in qualitative agreement with the experimental data. We emphasize that fluctuations in E_T and multiplicity are a useful probe of the dynamics underlying nucleus–nucleus collisions. We propose to do quantitative theoretical analysis within the framework of detailed models, which will be able to probe previously inaccessible information on the size and interactions of flux tubes produced in heavy–ion collisions. The qualitative features of the data already indicate the possibility that we are seeing coherent hadron production in the present ultrarelativistic heavy–ion experiments. Understanding the nature of the initial state in these collisions will have important implications for the creation of quark–gluon plasma in future experiments.

Prof. Anna Hasenfratz: In the last year my research has been concentrated on the non–perturbative understanding of the Weinberg Salam model. For small couplings the Weinberg–Salam model can be treated perturbatively. It gives an exceptionally successful description of the weak interactions within the perturbative region. However there are fundamental problems beyond the reach of perturbative expansion. Among the most important questions are the mass of the Higgs particle and the top quark (or heavy quarks).

Recent analytic and numerical works support the almost rigorously proven fact that the φ^4 scalar model is trivial in 4 dimensions, and as a consequence the scalar sector of the Weinberg –Salam model is trivial too. The model can describe an interacting theory only as an effective model with large but finite cut–off. Within this framework the Higgs mass is bounded from above (but it is not predictable).

In recent years I participated in a large scale collaboration where we investigated the

4–component φ^4 model with special emphasis on the triviality and calculated the upper bound of the Higgs particle. The difficulty in these calculations arises from the presence of the massless (or, on a finite lattice, massive but light) Goldstone particles. This year we completed a calculation, where using the theory of chiral perturbation theory we extrapolated the value of the vacuum condensate obtained on finite lattices to infinite volume in a theoretically well controlled way. Other groups addressed the question of the mass of the Higgs particle using different methods. The results are consistent from the different works suggesting that these calculations are under control both theoretically and numerically. The upper bound of the Higgs particle mass within the Weinberg–Salam model is $m_H < 640 \pm 20$ GeV.

A natural extension of the study of the Higgs particle is the study of fermion masses in the standard model. The masses of the fermions are generated via Yukawa coupling. The continuously increasing experimental upper bound on the top quark mass makes it even more important to investigate what can be said about the quark masses within the standard model. While the presence of gauge field is very important, as a first attempt we tried to study simpler, scalar–fermion systems only. The result of these works are quite surprising: unlike the scalar model which turned out to be perturbative to rather large couplings the fermion scalar systems has a very rich, unexpected phase structure. Other groups using different fermion formulations and/or symmetry groups obtained similar results to us indicating a general non–perturbative behavior in scalar–fermion systems. All models studied showed the existence of a new phase with ferrimagnetic symmetry at a Yukawa coupling region not accessible with perturbation theory. In all cases there exist a multiple point where symmetric, ferro and ferrimagnetic phases coexist. This point appears to be critical, it is the endpoint of the second order transition line emerging from the perturbative fixed point at zero Yukawa coupling. That indicates the possibility that a non–trivial continuum theory can be defined by tuning the bare parameters around this point. Until now most of the efforts went into analyzing the phase structure of this theory. The very exciting possibility of the existence of a non–trivial fixed point urges new investigation.

To study the properties of this multiple point, especially the critical exponents and the spectrum of the theory is the next step. That will require numerically more precise calculations. At the same time the analytical challenge is the understanding why such a multicritical point exist in these models and what is the role of the rather unexpected ferrimagnetic phase. The non–trivial phase structure of scalar–fermion models can offer a way to overcome the lattice fermion doubling problem in a new way. In the strongly coupled ferromagnetic phase the fermion masses increase in the continuum limit, the fermions decouple. If one can arrange that only the unwanted doublers decouple while one species remains light, one obtains a new, dynamical way of decoupling. I plan to explore this possibility further too.

Dr. Raj Gandhi: Most recently I have been working on the problem of the observed excess muon content of cosmic ray showers from point sources (with A. Burrows, L. Durand, P. Hong and I. Sarcevic). Although the experimental evidence for a 'hadron–like' muon content of what could only be (within the context of known physics) photon showers is not yet absolutely compelling, it has grown more convincing with the recent simultaneous observation of a muon rich high energy burst from the Crab at both Baksan and KGF. Before one concludes the onset of new physics, it is important to re–examine the assumptions that go into the production and development of air showers. Halzen and collaborators have pointed out the possibility of photons mimicking hadron–like behavior at high energies due to quark pair production and subsequent gluon bremsstrahlung. We are at present doing a detailed analysis of the consequences of this suggestion. Several sources of uncertainty are inherent to the problem, and their importance to the final answer needs to be determined. The photon structure function (and to a lesser extent the hadron structure function) is highly uncertain at the low values of x (the parton fractional momentum) relevant to the problem, i.e. $x \simeq 10^{-4}$. More over it is not known if the 'soft' or non–perturbative part of the total cross–section grows with energy in a way that would appreciably affect the final muon content. Closely related to this is the Ptmin cut used to calculate the jet cross–section, to which the result is highly sensitive. Although the muon problem needs to be explained at relatively low c–m energies, $\simeq$ 1 TeV, the jet cross–section rises very rapidly above this range and unitarity constraints need to be incorporated to examine the effects of higher energy primary photons. We are doing that using eikonal methods, which give good results in the proton–nucleon and proton–nucleus case. Finally, we are working on putting together a shower Monte Carlo to simulate the muon content and determine its sensitivity to the various photon and proton structure functions, the primary energy, the P_t^{min} cut and the 'soft' part of the cross–section and assumptions about its rise with energy. Many of these questions are relevant not only to cosmic ray physics but also to e–p physics at HERA.

I have also been working on and trying to understand certain aspects of the Higgs sector and electro–weak symmetry breaking. The essence of this in the Weinberg–Salam mechanism is Schwinger's linear σ–model. Any effort to tamper with the simple one–doublet Higgs embodied in this model leads to unattractive features or predictions which have not been borne out so far. For instance, a higher Higgs multiplet leads to a photon which is not naturally massless, i.e. the mass may be set to zero but in principle can have any value. The same is true for a two doublet Higgs sector. In some cases massless (barring anomaly and instanton effects) physical Higgs scalars remain, e.g. the axion, which has not been observed so far despite extensive searches over wide mass ranges. In spite of all this, the linear Schwinger e–model has some features which are puzzling, and are linked to our lack of understanding of the Higgs sector. For instance, its full symmetry is SU(2) x SU(2) – a six parameter group. Yet, in nature only four gauge bosons are realized. If one gauges the full symmetry of the σ–model, two additional photon–like bosons are left over. Secondly, and of greater consequence, is the inherent presence of a field independent term, which, when multiplied by the determinant of the metric tensor leads to the cosmological constant. These problems are possibly indications that the σ–model is only approximately realized in nature, and that the Lagrangian needs some modification that would remedy these objections while retaining its desirable features. Pursuing an approach suggested by Veltman, I have been looking at the consequences of introducing a Lorentz symmetry (i.e., a set of three fields with positive energy and one with negative energy) into the Higgs sector of the Lagrangian. Of course, the presence of a field with negative energy has well known problems – positivity of energy is a fundamental postulate of quantum field theory, leading to a stable ground state. In addition it is essential in establishing the second law of thermodynamics. However, there are familiar examples of systems for which degrees of freedom with negative energy are unphysical and can be eliminated using appropriate constraints. One of them is the O(N,1) non–linear σ–model. Maxwell's theory of electromagnetism provides another example of a constrained system with non–compact symmetry but a positive definite Hamiltonian. The same is true of the theory of the relativistic string, which has an invariance under D–dimensional Lorentz transformations. It is well known that at the Lagrangian level, the non–linear compact σ– model is the limit of the linear σ–model as the Higgs mass becomes very large. However, as Veltman and van der Bij have shown, this is not true in terms of higher order diagrams. At two–loop level, one obtains more and more divergent expressions and consequent non– renormalizability in the non–linear case. However, the problem is by no means understood in all generality. For example, it is not known if an appropriate resumming of the perturbation series will not lead to a finite result, or if there is a deeper connection between the compact and non–compact σ–models.

In the recent past I have also worked on the electro–weak interactions of massive Dirac neutrinos (with Jim Lattimer and K.J.F. Gaemers). One of the effects of a mass term is a small but astrophysically and cosmologically significant probability that they will flip spin while undergoing a 'normal' (W or Z mediated) interaction with a nucleon or electron. These interaction are significant in the content of supernova and neutron star formation, where a copious production of neutrinos of all species occurs, which then traverse highly dense matter as they diffuse out of the star subsequent to collapse. A spin flip renders them relatively sterile, and they leave the star within milliseconds rather than seconds, which is the normal cooling time scale. We have examined the mechanisms and consequences of these flips on the energetics of supernovae and used them to put mass limits $\simeq$ 30 KeV on mu, tau and fourth generation neutrinos. In the near future these calculations will be incorporated into Adam Burrows' supernova code to get a firmer grip on the cooling effects of helicity flipped neutrinos and their masses as limited by the general considerations of supernova theory.

Dr. Aleksandar Kocic: 1. Chiral symmetry breaking and QCD vacuum: In (10) I studied the properties of the QCD vacuum and discussed the constraint chiral symmetry places on physical quantities. By studying several chiral models, I found that the restoration temperature in all cases are given by $T_c = 2f_\pi$. My arguments were based on counting rules for the light modes at finite temperature. Their presence was governed by the particular realization of the chiral symmetry and they give the major contribution to the thermodynamic averages. The pion mass was shown to obey the PCAC relation because of the particular geometry of the chiral symmetry breaking vacuum. I argued that it measures the response of the strongly interacting ground state to and electroweak perturbation.

2. Catalyzed symmetry breaking (with E. Dagotto and J. Kogut): In QED at strong couplings composite operators acquire large anomalous dimensions and enter the renormalized theory through the operator mixing. Our arguments that advocated nontriviality of QED beyond the quenched approximation were based on this fact. From

the renormalization group point of view, we interpreted this effect as the nondecoupling of the heavy modes – a maximal violation of the Appelquist – Carrazone theorem. Beyond perturbation theory, the suppression factors for the heavy mode contributions were found. At strong coupling the suppression factors are absent and the heavy modes give O(1) contribution at low energies. This, we pointed out, presents a field theoretical realization of the monopole catalyzed proton decay and is a consequence of the 1/r singularity of the collapsed wavefunction. The consequence of this result is that quantum electrodynamics acts as a microscope of unlimited resolving power for short–distance interactions, and can amplify short–range symmetry breaking effects. We illustrated this point by showing that, at strong couplings, perturbative nonrenormalizable parity–violating interaction survives the continuum limit giving rise to parity–violating mass. We suggested that this effect might have an application in grand unified theories (walking technicolor theories in particular), and could account for a variety of symmetry breaking effects in a natural way.

3. Finite size analysis and zero mass extrapolations in four–dimensional QED (with E. Dagotto and J. Kogut): We pursued the finite size analysis and zero mass extrapolations of the unquenched QED in more detail by studying the theory on larger lattices and for several values of the bare mass to test for the sensitivity to the extrapolation procedure. We found that on larger lattices the scaling window was smaller than before and that the value of the order parameter in the chiral limit was sensitive to the extrapolation procedure. However, our results show substantial deviations from the mean–field behavior supporting our previous (exploratory) studies based on simulations on the smaller lattices. Low–N systematics, we found, was quite similar to that of the quenched theory and qualitatively different from that in the large–N limit. The fits to essential singularity near the critical point were quite compelling, but we think that much more powerful computer simulations would be required in order to make this point precise. This we believe, is of the same degree of difficulty as extracting the asymptotic freedom from lattice QCD. We illustrated our claim by comparing the data for QED near the critical point with those

of the SU(2) gauge theory in four dimensions.

4. QED in three dimensions with N flavors (with E. Dagotto and J. Kogut): We studied massless QED_3 with N flavors using computer simulations and Schwinger – Dyson equation. We found that there exists a critical N ($N_c \simeq 3.5$) beyond which the theory is massless; for low–N chiral symmetry is spontaneously broken. We presented physical arguments for the existence of critical N by understanding the scales of chiral symmetry breaking. In quenched theory we found that chiral symmetry breaking is triggered by the fermion's self–energy which is negative and infrared singular – a mechanism known to occur in two–dimensional QCD. Dynamical fermions cause partial screening of the long range force (from ln r to 1/r) and the 1/r attraction between electrons and positrons drives their condensation. In this way we mapped the theory onto four dimensional QED with coupling proportional to 1/N. From this analogy the critical N emerges clearly. Using the Schwinger – Dyson equations for the fermion and photon propagators we argued that the apparent agreement of simulations with the large–N results was accidental and that the real reason for this lies in the particular momentum scale at which chiral symmetry breaking occurs.

5. Spontaneous parity volitional in QED_3 (with E. Dagotto and J. Kogut): In four component theory there are two types of mass that violate either chiral symmetry or parity. It is believed that the existence of parity violating mass is of some relevance to high temperature superconductivity. Our preliminary calculations using Schwinger – Dyson equation in the quenched theory suggest that parity violating mass can be generated dynamically if the normal mass can. A more difficult problem is to include the effects of the fermion loops because the parity violating mass gives rise to an induced Chern – Simons term in the photon propagator that serves as an additional source of parity violation. (Its strength can be controlled by the number of flavors.) We want to determine how the two effects combine and under what circumstances parity can be broken spontaneously beyond the quenched approximation.

6. Collapse and spin – continuum limit of scalar theories (with E. Dagotto and J. Kogut): although the phase transition in QED was discovered by studying chiral symmetry breaking, our understanding of the nontriviality of the theory was not based directly on this property, but rather on the large anomalous dimensions of the composite operators – a feature intimately related with the non–asymptotically free nature of the vector couplings. In (58) we argued that the similar scenario takes place in quenched scalar theories with vector couplings. For sufficiently large coupling we found that φ^6 and φ^8 become renormalizable and enter the renormalized theory through the operator mixing. The relevance of these operators alters the three important features of scalar theories: triviality of the scalar sector, symmetry breaking due to radiative corrections (Coleman – Weinberg effect) and fine tuning. We suggested that at strong couplings all three issues are resolved in an entirely different manner than in perturbation theory. It is our intention to pursue further these points by analytical techniques and computer simulations of scalar QED. In particular, it is of considerable interest to look for the critical surface in the extended parameter space (including the higher dimensional couplings) and determine the phase diagram and the nature of the continuum limit there.

6. Flavor symmetry breaking (with J. Kogut): We intend to apply the property of amplification of the short–distance symmetry–breaking effects in nonasymptotically free theories to the problem of flavor symmetry breaking. It has been known for some time that, unlike gauge theories, four–fermion models in four dimensions can exhibit spontaneous breaking of vector symmetries if the coupling is chosen appropriately. This choice of coupling favors generation of the isovector and disfavors the isoscalar (chiral symmetry breaking) mass. Because these theories are not renormalizable, their effect at low energies disappears. If a gauge theory like QED is supplemented with such a four–fermi interaction, by tuning the gauge coupling appropriately, it would be possible to amplify whatever is happening in the four–fermi sector and make it apparent at low energies. We want to study how this can happen. In particular, the two couplings should compete with

each other since they favor different masses, and it is not clear whether sufficiently large gauge coupling (necessary for amplification to occur), would tolerate any flavor breaking. Since the flavor symmetry breaking is spontaneous, it will be accompanied by the corresponding Goldstone bosons. Of special interest is their fate within a larger gauge group as used for example in walking technicolor theories. For this purpose, it is also necessary to verify that nonabelian gauge theories with many flavors behave in a similar way as QED.

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