DOE/ER/40224-248

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RESEARCH REPORT

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N. G. Deshpande

This is a summary of some of the work carried out in electroweak physics by me in collaboration with postdoctoral fellows and students at Oregon, and other colleagues around the world. The past five years have been extraordinarily productive with over thirty refereed publications and over ten presentations in major conferences. The impact of the work on the field has been very significant, especially that related to B physics. In most cases the work is either inspired by experiments or has important consequences for future experiments. The postdoctoral fellows working with me have all found permanent or long-term positions, and continue to be active in the field. The work completed covers a broad spectrum of topics, and can be divided roughly into the following four categories.

- Rare B decays and methods of measuring CP violation at B factories
- Models of CP violation and their consequences
- Neutrino properties
- Grandunification and its low energy consequences

I. Rare B Decays and CP Violation at B Factories

1. Electroweak Penguin Process

Observation of the first direct one loop process $B \to K^*\gamma$ and $b \to s\gamma$ at CLEO has had a stimulating effect on studies of models beyond the standard model, where useful limits on heavy particles can be derived from the fact that the above processes agree so closely with the standard model. Similar useful bounds can be derived from the process $b \to s\ell^+\ell^-$ which has not been observed yet. In collaboration with Trampetic and Panose, we have carried out a detailed analysis of this process in the standard and the two Higgs extension of the standard model. Unlike $b \to s\gamma$, this process is very sensitive to the mass of the top quark. With knowledge of top mass, observation of $b \to s\ell^+\ell^-$ is likely to severely constrain non standard models.

"The decay $b \to s\ell^+\ell^-$ and the enlarged Higgs sector," Phys. Lett. **B308**, 322 (1993) (with K. Panose and J. Trampetic).

2. Hadronic Penguin Processes and CP Phases

Observation of purely hadronic penguin process is clearly an important test of the standard model at one loop. With Trampetic we had estimated a number of processes of this type.

"Penguin-mediated exclusive hadronic weak B decays," Phys. Rev. **D41**, 895 (1990) (with J. Trampetic).

In an attempt to refine these predictions, I undertook a study of the weak Hamiltonian in collaboration with Xiao-Gang He. A complete next to leading order calculation was undertaken including electroweak penguin processes. A similar calculation was also performed by Fleischer based on the work of Buras. We found that in the next to leading order electroweak penguins were significantly enhanced for heavy top quark. We applied this calculation to the pure penguin process $b \to s\phi$ and $B \to K^+/K\phi$. The net decrease in the rate was found to be about 20%.

> "Hadronic penguin B decays in the standard and the two-Higgs-doublet models," Phys. Lett. **B336**, 471 (1994) (with X-G. He).

This work was also presented at the XXVII International High Energy Physics Conference at Glasgow.

We realized immediately the importance of electroweak penguin contributions to the other B decays. In particular the iso-spin properties of hadronic penguins were significantly altered. The process $b \to s$ had a sizable $\Delta I = 1$ admixture to the $\Delta I = 0$ gluonic contribution. This had the effect that many of the techniques in the literature to measure CP violating angle γ were incorrect. Further, penguin contributions also contaminated $B \to \pi\pi$ decays so that measurement of α had significant error. These results were pointed out in an important paper:

> "Isospin Structure of Penguin Diagrams and Their Consequences in B Meson Physics," Phys. Rev. Lett. **74**, 26 (1995) (with X-G. He) .

Testing standard model of CP violation thus presented new difficulties. Two new ways of testing the standard model were discovered by us. We proved that if SU(3) symmetry is assumed, the rate differences between B, $\overline{B}$ mesons to $K\pi$ states can be related to $\pi\pi$ states. These relationships depended only on the unitarity of the CKM matrix.

> "CP Asymmetry Relations Between $\overline{B^\circ} \to \pi\pi$ and $\overline{B^\circ} \to K\pi$ Rates," Phys. Rev. Lett. **75**, 1703 (1995) (with X-G He).

We also estimated SU(3) breaking effects for the above processes. Again, using SU(3) we found a triangular relation between $B \to K\pi$ and $B \to K\eta$ modes. Using these rates, and combining with $B \to \pi\pi$ rates, it is possible to determine gamma free from the earlier criticism.

> "A method for Determining CP Violating Phase γ," Phys. Rev. Lett. (to be published) (with X-G. He)

The presence of electroweak penguin diagrams lead to certain rare process which would be highly suppressed otherwise. For example in $b \to s$ penguin process, electroweak penguin diagrams contribute to $\Delta I = 1$ transitions. Thus, process like $B_s \to \pi\eta$ or $\pi\phi$, which are pure $\Delta I = 1$, only proceed through electroweak penguin. We have estimated decay rates for these processes:

"Unique Signature of Electroweak penguin in Pure Hadronic B Decays," Phys. Lett. **B345**, 547 (1995) (with X-G. He and J. Trampetic)

The search for pure penguin semi-inclusive process $b \to s\phi$ can be measured. Similar to $b \to s\gamma$, one needs to calculate the energy spectrum ϕ to enable experimentalists to select the correct events. We have carried out a calculation which includes gluon emission and the fermi momentum of b to obtain the ϕ energy spectrum

"Energy distribution of ϕ in Pure Penguin Induced B Decays," Phys. Lett. (to be published) (with G. Eilam, X-G. He and J. Trampetic)

3. Determination of V_{td}

Parameters of the Cabibbo-Kobayaski-Maskawa (CKM) matrix play a central role in the standard model. It is extremely difficult to determine the element V_{td} directly. However, there are loop processes where the top quark dominates. Such is the case for the rare process $b \to d\nu\overline{\nu}$. This process gives rise to $B \to \pi\nu\overline{\nu}$ and $B \to \rho\nu\overline{\nu}$ decay modes. Feasibility of an experiment to detect those modes was examined by me in collaboration with two experiments, Schwartz and Urheim. This resulted in a Snowmass Conference report and a journal article.

"$B \to \pi\nu\overline{\nu}, \rho\nu\overline{\nu}$ and determination of V_{td}," Phys. Rev. **D44**, 291 (1991) (with A. Schwartz and J. Urheim)

II. Models of CP Violation and Their Consequences

The origin of CP violation is still an unresolved problem. So far CP violation has only been observed in the neutral kaon system. In the standard model this is accounted ted for through a phase in the CKM matrix. This model, though consistent with observation, is largely untested. It is thus important to construct other models of CP violation to see how they differ in their predictions. We have made a detailed study a multi-Higgs model. Although this model is based on a discrete symmetry $S_3 \times Z_3$, the main features of the model are expected to be valid for any Higgs-based model with flavor changing interactions.

"Flavor-changing process and CP violation in $S_3 \times Z_3$ model ," Phys. Rev. **D45**, 953 (1992) (with M. Gupta and P. B. Pal).

"CP violation in a multi-Higgs-doublet model with flavor changing neutral currents ," Phys. Rev. **D49**, 4812 (1995) (with X-G. He).

The main feature that emerges is that flavor charging Higgs masses are generally in the TeV range for consistency with known limits on $K-\overline{K}$ and $B-\overline{B}$ mass differences. The CP violation the K and B system is of the superweak type. Thus ϵ'/ϵ would be generally zero and the measurement of the unitarity triangle at B factories would give $\beta = -\alpha$ and $\alpha + \beta + \gamma \neq 180°$. The e. d. m. of neutron and electron is in the range of $10^{-27} \sim 10^{-28}$ e. c. m. and should be observable with improved experiments.

Prediction of ϵ'/ϵ in the standard model are sensitive to the top quark mass. The electroweak penguin contribution cancels the gluonic contribution for $M_t \approx 220$ GeV. Even for 176 GeV top quark mass, the contribution is diminished substantially. When this happens, gluon dipole contributions, which are normally neglected, become important. This operator also contributes to CP violation in hyperon decays. We have estimated the effect of this operator.

> "Gluon dipole penguin contribution to ϵ'/ϵ and CP violation in hyperon decays in the Standard Model ," Phys. Lett. **B326**, 307 (1994) (with X-G. He and S. Pakvasa).

III. Neutrino Properties

1. Sterile Neutrino Solution to Solar Neutrino Problem

The varying deficiencies of the solar neutrino flux usually explained by ν_e oscillations into ν_μ or ν_τ. The favored mechanism for oscillations in the MSW matter enhanced one. Detectors capable of detecting ν_μ or ν_τ are being constructed. However, the intriguing possibility of ν_e oscillations into a sterile species, like a singlet neutrino, is generally considered. In a collaboration with Barger, Phillips, Whisnant, and Pal we considered allowed parameter space in Δm^2 and mixing angle for this possibility.

> "Sterile-Neutrino Solution to the Solar Puzzle," Phys. Rev. **D43**, 1759 (1991) (with V. Barger, P. Pal, R. J. N. Phillips and K. Whisnant).

At that time large mixing and small mixing solutions were both allowed. New Gallian results however eliminate the large mixing solution, and only the small mixing solution with $\Delta m^2 \approx 10^{-5} ev^2$ is allowed. This solution can be ruled out when detectors capable of detecting ν_μ and ν_τ through their neutral currents are built.

2. Limit on ν_τ magnetic moment.

Not much is known about the properties of ν_τ directly from experiment. Since the mass of ν_τ could be much larger than the other species, one can speculate that it may have a larger magnetic moment. With Sarma from the Tata Institute, we were able to obtain limits on the magnetic moment of ν_τ by observing that if ν_τ had a magnetic moment, it would affect the process $Z \rightarrow \nu_\tau \overline{\nu}_\tau$. Since very accurate limits have been obtained on the invisible width of Z, this can be converted into useful limits on the magnetic moments.

> "Limits on Tau-neutrino Magnetic Moment from Neutrino Counting," Phys. Rev. **D43**, 943 (1991) (with KVL Sarma).

The limit obtained was $4.3 \times 10^{-6} \mu_B$.

As limits on the invisible width improve, we expect an order of magnitude improvements in the limit.

IV. Grandunification and its low energy consequences

1. The groups SU(15) and SU(16)

The grandunification groups SU(5) and SO(10) have received most of the attention in recent years. We have studied grandunification based on alternate groups SU(15) and SU(16). In these groups the chain of symmetry breaking can be so chosen that the unification scale can be as low as 10^7 GeV. With a scale that low, there is no fine tuning problem and no need of supersymmetry. The low energy group structure is much richer, with many gauge bosons present at the TeV scale. At low energy the gauge structure corresponds to "ununified model" where quarks and leptons belong to separate $SU(2) \times U(1)$ groups. Even the SU(3) color group can be richer with $SU(3)_L \times SU(3)_R$ structure. We have studied proton decay and neutrino masses in such models. In spite of low energy unification scale, proton decay is suppressed and neutrino masses are naturally small.

> "Neutrino Mass in Grand Unified SU(15)," Phys. Rev. **D44**, 3702 (1991) (with P. B. Pal and H. C. Yang) .

> "SU(16) grand unification: Breaking scales, proton decay and neutrino magnetic moment," Phys. Rev. **D47**, 2894 (1993) (with E. Keith and P. B. Pal).

An interesting feature of the SU(16) model is the possibility of having a significant magnetic moment and at the same time having a naturally small mass for neutrinos. This is accomplished by having an SU(2) group for neutrinos similar to one postulated by Voloshin naturally present in the SU(16) gauge group.

2. Non supersymmetric SO(10)

Much has been made from the precision data from LEP about the incompatibility of simple SU(5) with values of gauge couplings extracted at M_Z. A strong case for supersymmetric SU(5) with relatively low energy for susy scale of about 1 TeV has been made. In a series of papers we point out that SO(10) with one or more intermediate scales between the unification scale and the electroweak breaking scale offers as good a solution. These solutions also lead to naturally small neutrino masses with the see-saw mechanism.

> "Implications of the CERN LEP results for SO(10) grand unification," Phys. Rev. **D46**, 2261 (1992) (with E. Keith and P. B. Pal).

"Implications of results from the CERN e^+e^- collider LEP for SO(10) grand unification with two intermediate stages," Phys. Rev. **D47**, 2892 (1993) (with E. Keith and P. B. Pal).

Our analysis shows that in the two stage breaking, many scenarios allow an extra Z' gauge boson to emerge at the low energy scale. Properties of this Z' boson are also discussed.

Many authors have tried to predict masses and mixing angles by making different ansatze at the unification scale. These have been studied in supersymmetric theories. Since no evidence for supersymmetry exists at present, we have examined to what extent such ansatze work in ordinary SO(10). we have made a comprehensive study of this problem assuming either standard Higgs doublet at low energy, or two Higgs doublets. In general we find that the ansatze work quite well. They typically predict 13 parameters with eight inputs.

"Predictive fermion mass matrix Ansatze in nonsupersymmetric SO(10) grand unification ," Phys. Rev. **D50**, 3513 (1994) (with E. Keith).

3. Supersymmetric SO(10)

Many authors have considered the possibility of a low energy $SU(2)_R$ group. We have examined in detail the low energy phenomenology based on this group.

"Left-Right-symmetric electroweak models with triplet Higgs fields," Phys. Rev. **D44**, 837 (1991) (with J. Gunion, B. Kayser and F. Olness).

A particularly useful part of this study is the discussion of the Higgs structure. A conclusion that was shown was that the new Higgs meson masses generally are in the 10^7 GeV range.

An outstanding problem has been of how to make $SU(2)_R$ a low energy symmetry in grandunification context. Although a three stage SO(10) breaking could allow this, no simple way was known. For the first time we were able to show that in a supersymmetric SO(10) a low energy $SU(2)_R$ can arise naturally with a simple Higgs choice.

"SO(10) Grand Unification with a Low-Energy $SU(2)_R$-Symmetry-Breaking Scale M_R," Phys. Rev. Lett. **780**, 3189 (1993) (with E. Keith and T. G. Rizzo).

The unification scale in this scheme is consistent with limits on proton decay. The scheme also permits neutrino masses to emerge naturally to account for the solar neutrino deficiency. The mass of tau-neutrino is in the correct mass range to account for some part of the dark matter in the universe.

4. Proton life time in finite grand unified theories

Many authors have considered constructing a theory free of any infinities. Such theories are supersymmetric and have extra constraints on couplings and particle content to cancel all divergences. Although theoretically attractive, we point out a severe theoretical problem with this class of theories. Because all interaction are related to gauge interactions, the Higgs interactions with fermions are quite strong, and the proton decay turns out to be extremely fast.

> "Proton life-time problem in finite grand unified theories," Phys. Lett. **B332**, 88 (1994) (with X-G. He and E. Keith).

At present no known way to circumvent this problem is known.

Talks given at conferences

1. "CP Asymmetries in charged B decays"
   Talk given at BNL Summer Study. Published in BNL Summer Study Proceedings, page 249. (1990)
2. "Rare Decays and CP Asymmetries in Charged B Decays"
   Talk given at Beyond Standard Model II. Published in proceedings of Beyond Standard Model II. (1990)
3. "Overview of the Left-Right Extension of the Standard Model"
   Talk given at the XXV International Conference on High Energy Physics, Singapore. (1990)
4. "Proton Decay in Supersymmetric Finite Grandunification"
   Talk at Division of Particles and Fields, Alburquerque, NM. (1994)
5. "CP Violation in Multi-Higgs Doublet Model"
   Talk given at III Workshop in HIgh Energy Physics, Madras, India. (1994)
6. "Penguin B Decays $b \to s\ell^+\ell^-$ and $b \to sg^*$"
   Talk at XXVII International Conference on High Energy Physics, Glasgow, Scotland. (1994)
7. "Penguin Decays of B Meson"
   Talk given at High Energy Symposium, Bombay, India. (1993). Published in proceedings, page 249.
8. "Hadronic Penguins in B Decays and Extraction of α, β and γ"
   Talk at IV International Conference on Physics Beyond the Standard Model. (1994)

Davison E. Soper

During the five years since September 1990, I have been engaged in a number of investigations of QCD, with applications to experiments at the Fermilab collider, at LEP, and at HERA. In addition, I have made some contributions to particle physics in service roles and have given a number of invited talks, sometimes on my own research, sometimes on broader topics. In this section, I outline these activities.

I. Service contributions

1. Physical Review Letters, 1992-present

Since July 1992, I have been a Divisional Associate Editor of Physical Review Letters. There are two parts to this job. First, the editors in New York send me (by fax) papers that have been submitted on a range of subjects in theoretical QCD. I send back (by email) some impressions of what editorial issues might arise from the paper and several suggestions of appropriate referees. Second, in cases in which the paper is rejected on the basis of the referees' opinions, the authors may appeal the decision. In this case, I read the entire file that has been generated and write my own recommendation, which is sent over my signature to the authors (and usually also to the referees).

2. CTEQ Handbook of Perturbative QCD

I am a member of the CTEQ Collaboration, a group of XX theorists and experimentalists with an interest in QCD. One of our activities has been to publish a Handbook of Perturbative QCD, first as a Fermilab publication, and now in Reviews of Modern Physics:

> "Handbook of Perturbative QCD," Rev. Mod. Phys. **67**, 157 (1995), by the CTEQ Collaboration (Raymond Brock, *et al.*).

This handbook is designed to be an introduction and reference to the field containing the main theoretical ideas and an account of the experimental results. The group hopes that the document can evolve and expand in scope in future editions.

3. CTEQ Summer Schools on QCD

The CTEQ Collaboration has held summer schools of ten days duration, addressing mostly the interests of young Ph.D. experimentalists but of use also to young theorists. We have had about eighty students at each school. The schools were supported at first by the Texas Accelerator Commission, then by the DOE, the NSF, the DOE national laboratories, and by DESY. Our first school was in 1992 at Mackinac Island, MI. The second was in 1993 at Lake Monroe, IN. The third was in 1994 at Lake of the Ozarks, MO. In 1995, we held our fourth summer school at Bad Lauterberg, Germany. I helped to organize these schools and gave lecture series (listed below under Invited Talks) at all of them.

4. TASI 95

I was the program director for the 1995 Theoretical Advanced Studies Institute summer school. The TASI summer schools are funded by the DOE and the NSF and are held in Boulder Colorado for four weeks each June. Each year, there is a different theme, combined with lectures on core subjects in particle theory. About fifty advanced graduate students in theoretical physics attend the school each year. In addition, the proceedings are published, forming a series of pedagogical introductions to the various subfields of particle theory. In 1995, the theme of the school was QCD. I organized series of lectures on the basics of the standard model, renormalization, factorization, calculational methods, applications to heavy quark physics, and the phenomenology of QCD at Fermilab, LEP, and HERA. In addition, there were courses on supersymmetry and on duality within supersymmetric theories.

II. Invited talks

- Opal experimental group, CERN, Geneva, January 1991, "The Energy-Energy Correlation Function in the Back-to-Back Region."
- Bielefeld University, Germany, February 1991, "Jet Production in Hadron Collisions."
- Dortmund University, Germany, February 1991, "Jet Production in Hadron Collisions."
- XXVI Rencontre de Moriond, QCD Session, Les Arcs, France; March 1991, "Jet Production in Hadron Collisions."
- University of Pisa, Italy, March 1991, "Jet Production in Hadron Collisions."
- Physics Colloquium, DESY laboratory, Hamburg, Germany, April 1991, "The Final State in Deeply Inelastic Scattering at HERA."
- CERN Theory Division seminar, April 1991, "Jet Production in Hadron Collisions."
- University of Florence, Italy, April 1991, "Jet Production in Hadron Collisions."
- Workshop on Perturbative Quantum Chromodynamics, University of Lund, Sweden, May 1991, "Jet Production in Hadron Collisions."
- LAPP laboratory, Annecy, France, May 1991, "Jet Production in Hadron Collisions."

- Conference on Gauge Field Theory on the Light Cone, University of Heidelberg, Germany, June 1991, "Challenges of Light-Cone Gauge."
- UA2 experimental group, CERN, Geneva, July 1991, "Measurement of Jet Cross Sections in Hadron Collisions."
- Oregon State University, Corvallis OR, February 1992, "Jet Physics."
- American Physical Society Washington Meeting, April 1992, "Jet Physics as a Probe of New Interactions."
- CTEQ Summer School on QCD Phenomenology and Analysis, Mackinac Island, MI, May 1992, "QCD Jets" (two lectures).
- Workshop on Light-Cone QCD, Telluride, CO, August 1992, "Use of the Leibbrandt-Mandelstam Gauge Prescription in the Null-Plane Schroedinger Equation."
- Workshop on Small-x and Diffractive Physics at the Tevatron, Fermilab, Batavia, IL, September 1992, "Diffractive Hard Scattering as a Probe of the Parton Content of the Pomeron."
- Argonne National Laboratory, Argonne IL, October 1992, "Jet Physics."
- Workshop on New Techniques for Calculating Higher Order QCD Corrections, ETH, Zurich, December 1992, "Calculation of Jet Cross Sections in Hadron Collisions."
- CTEQ Summer School on QCD, Lake Monroe, IN, July 1993, five lectures on "Introduction to the Parton Model and Perturbative QCD" (five lectures), "Determination of the Strong coupling from Experiment."
- International Symposium on Multiparticle Dynamics, Aspen, CO, September 1993, "Multiparticle Dynamics 1983 - 1993."
- Aspen Winter Physics Conference, Aspen, CO, January 1994, "The Past and Future of the Determination of Parton Distributions."
- Workshop on Light Cone Field Theory, University of Washington, Seattle, June 1994, "Use of Light Cone Field Theory for Parton Phenomenology."
- Physics Department Seminar, University of Washington, Seattle, June 1994, "Diffractive Jet Production at HERA."
- CTEQ Summer School on QCD, Lake of the Ozarks, MO, August 1994, "Diffractive and Hard Diffractive Scattering" (three lectures).

- Workshop on QCD, Gran Sasso National Laboratory, L'Aquila, Italy, August 1994, "Diffractive jet production at HERA", "Determination of Parton Distributions", "Jet Definition for Triply Differential Jet Cross Sections in Hadron Collisions."

- Workshop on QCD, DESY Laboratory, Hamburg, Germany, September 1994, "Diffractive Jet Production at HERA."

- Meeting of the QCD Group of the D0 Collaboration, Tuscon, AZ, January, 1995, "Triply Differential Jet Cross Sections."

- XXX Rencontre de Moriond, QCD Session, Les Arcs, France, March 1995, "Conference Summary."

- Argonne National Laboratory, Argonne, IL, April 1995, "Diffractive Hard Scattering."

- University of Minnesota, Minneapolis, April, 1995, "Rencontre de Moriond Summary Talk."

- International Symposium On Particle Theory and Phenomenology, Iowa State University, Ames, IA, May 1995, "Exploring Hadrons and QCD with Hard Scattering Processes."

- Meeting on Deep Inelastic Scattering at HERA, Christ's College, Cambridge, England, July 1995, "Diffractive Deeply Inelastic Scattering."

- CTEQ/DESY Summer School on QCD Analysis and Phenomenology, Bad Lauterberg, Germany, July 1995, "Summation of logarithms in QCD" (two lectures).

III. Composite Models

Most current particle physics experiments explore an energy range of around 100 GeV or less. (Here $p\bar{p} \to jets$ is an exception, with a wider reach.) It is an attractive idea to suppose that the physics we see at this scale is that of a low energy effective theory, the shadow of a more complete theory with a characteristic energy scale of a couple of TeV. Furthermore, this more complete theory could have strong interactions and a rich structure of particles with masses in the TeV range. We may further suppose that the particles we call quarks and leptons may be composites of the fundamental fields of the TeV theory. They would be nearly massless because of a chiral symmetry of the theory. The longitudinal modes of the W and Z bosons would be Nambu-Goldstone bosons corresponding to spontaneous symmetry breaking in the TeV theory. Building on ideas along these lines in the literature, Jon Rosner and I explored such models in the paper

"Tests of a Composite Model of Quarks and Leptons," Phys. Rev. D**45**, 3206 (1992), with J. Rosner.

It is, of course, not easy to be very specific in such a discussion since the models considered are strongly interacting and highly relativistic. Not much is known about this kind of dynamics. Nevertheless, the general picture is attractive enough as an alternative to supersymmetric models that one wants to be alert to possible experimental signatures of the picture. Working mostly with group theory to describe the TeV scale symmetries and their breaking, we found that we could make at least a little headway in describing features of such a composite model. We then used this information to make predictions for experiments in the energy/transverse momentum range of a 0 to 300 GeV. We looked at $e^+e^- \to b\bar{b}X$, $e^+e^- \to \ell\bar{\ell}X$ and $e^+e^- \to hadrons$ and at $\bar{p}p \to e^+e^-X$ and $\bar{p}p \to e^-\bar{\nu}_eX$.

IV. Jets at hadron colliders

Steve Ellis, Zoltan Kunszt, and I have worked over a period of years on the calculation of jet cross sections in high energy hadron-hadron collisions.

The main motivation has been to probe possible physics beyond the standard model. We share the widely held belief that there is new physics at small distance scales, probably on the order of $1/(1\ \text{TeV})$. Present accelerators cannot quite produce parton-parton collisions with c.m. energies $\hat{s} \sim 1\ \text{TeV}^2$, so as to produce directly new particles or resonances with a 1 TeV mass. However, the new physics will produce new terms in the low energy effective lagrangian that are not present in the standard model. A typical such term might be

$$\frac{\tilde{g}}{M^2}\left[\bar{\Psi}\Psi\right]^2, \tag{1}$$

where $M \sim 1$ TeV is the new physics scale and $\tilde{g}$ is a new physics coupling. It may be possible to observe the effect of such a term on a cross section involving $\hat{s} < M^2$. One needs to look carefully at a cross section that probes the structure of the partons at the smallest distance scale possible. The jet cross section is a good candidate: CDF and D0 can measure a jet cross section out to a jet E_T of about 400 GeV. This corresponds to $\hat{s} \sim 800$ GeV. Any deviation of the observed cross section from the standard model prediction is a signal for new physics.

Of course, such a comparison requires a reasonably precise theoretical prediction. Various arguments suggest that Born level QCD predictions should not be considered to have a residual theoretical error of much smaller than a factor 2. To do better than this (perhaps 20%), one needs a one loop calculation. That has been the purpose of our work.

Our method entails carefully defining what one means by a jet cross section (with a definition that is quite close to what CDF actually measures), and then using the matrix elements calculated by R. K. Ellis and Sexton to calculate this cross section at the parton level. Since the integrals are divergent, a certain amount of work was necessary to calculate the divergent pieces analytically and show that they cancel from the physical cross section, leaving finite integrals that are much to complicated to calculate analytically but which can be calculated numerically.

1. One jet cross section

In 1990, just before the beginning of the period covered by this report, we completed the calculation of the one jet inclusive cross section $d\sigma/dE_T$:

> "The One Jet Inclusive Cross Section at Order α_s^3: Quarks and Gluons," Phys. Rev. Lett. **64**, 2121 (1990), with S. D. Ellis and Z. Kunszt.

A European group consisting of Aversa, Chiappetta, Greco, and Guillet also calculated a jet cross section and published its results later that same year [1]. Their first results were for a different jet definition than is now standard, but they subsequently adapted their calculation to the same definition. While I was at CERN, I was able to collaborate with Guillet to verify that our results agreed at the level of our numerical accuracy, about 1%.

2. Two jet cross section

One of the most interesting applications of jet physics at order α_s^3 is the comparison of theory and experiment for the cross section to make two jets plus anything. As soon as we had a program powerful enough to do this calculation (Spring 1991), we did it and made the results available to the experimental groups and to the general community at conferences. There are two main cross sections to be examined. First, one can examine at the cross section as a function of the jet-jet mass, $d\sigma/dM_{JJ}$ looking for any sort of resonant behavior or for a deviation from the QCD prediction at the highest jet-jet mass. Second, one can fix a bin of jet-jet mass and look at the distribution of the two jets as a function of the rapidity difference $2y_* = (y_1 - y_2)$ between the jets,

$$\left[\frac{d\sigma}{dM_{JJ}}\right]^{-1} \frac{d\sigma}{dM_{JJ}dy_*} \tag{2}$$

Here one is examining the angular distribution of parton-parton scattering. One expects to find the very strong forward peak produced by the exchange of spin-1 gluons. In 1992 we published a phenomenological analysis for the angular distribution:

> "Two jet production in hadron collisions at order α_s^3 in QCD," Phys. Rev. Lett. **69**, 1496 (1992), with S. D. Ellis and Z. Kunszt.

In 1992, we also published a detailed exposition of our method:

"Calculation of Jet Cross Sections in Hadron Collisions at Order a_s^3," Phys. Rev. D46, 192 (1992), with Z. Kunszt.

This paper serves as documentation for the algorithm that lies behind the computer code that we use in the numerical calculation. It also can serve as a template for new applications.

3. Jet structure

When one calculates a cross section to make jets using an order α_s^3 calculation, the result depends on the definition of a jet – for example, if the jet is defined as particles inside a cone of angular radius R, then the cross section depends on R. This is because the theoretical cross section is sensitive to the internal structure of the (theoretical) jets, just as the physical cross section is sensitive to the internal structure of the real jets. It therefore makes sense to check how well the internal structure of theoretical jets (which, at order α_s^3 can contain one or two partons) matches that of physical jets. In the paper

"Jets at Hadron Colliders at Order a_s^3 : A Look Inside," Phys. Rev. Lett. **69**, *3615 (1992)*, with S. D. Ellis and Z. Kunszt.

we examine the energy flow within jets. We found something interesting: a mismatch between the energy flow in the experimental jets and that in the theoretical jets that suggests that the jet algorithm as actually implemented in the CDF experiment may have missed including some groups of particles that should have been counted as jets according to the "Snowmass Accord" jet definition. (However, the number of missed jets suggested by this analysis is not great enough to seriously affect the cross section.) The internal structure of jets has been investigated recently in a DO preprint [2].

4. Jet definitions

Jets are found in both electron-positron annihilation events at LEP and SLC and in hadron-hadron scattering events at Fermilab. In both cases, the measurement of jet production cross sections provides an important test of quantum chromodynamics. In both cases, the algorithm used to define the the jets is a crucial part of the measurement when one wants to make a quantitative comparison between theory and experiment. However, the definitions used in the two cases are quite different from each other. In hadron-hadron collisions, the standard is to use a cone definition, in which a jet consists of particles whose momentum vectors lie inside an appropriately defined cone. In electron-positron annihilation, the experimental groups use a successive combination algorithm, along the lines introduced by the JADE group at PETRA. Here one combines two particles that are nearby in momentum space to form a protojet. One continues combining particles and protojets until all suitably nearby particles have been combined into a few jets.

Why has a successive combination algorithm not been used in hadron-hadron collisions? In large part, it is because it has not been evident how the successive combination algorithms could be adapted to the circumstances of hadron-hadron collisions. First, the kinematics are different in hadron-hadron collisions. Second, electron-positron annihilation events are relatively clean while hadron-hadron collision events contain, in addition to some occasional high P_T jets that are of interest, many low P_T particles that are not associated with the jets.

Building upon an idea of B. Webber *et al.*[3], Steve Ellis and I have proposed a jet algorithm that follows the successive combination model, is adapted for the special nature of hadron collisions, and, we argue, has important advantages over the standard cone algorithm:

> "Successive Combination Jet Algorithm for Hadron Collisions," Phys. Rev. D**48**, 3160 (1993), with S. D. Ellis.

We calculate the one-jet-inclusive cross section at next-to-leading order using the new algorithm and find that the new algorithm works as well as the cone algorithm in this perturbative calculation.

5. Triply differential jet cross sections

Consider an idealized hadron-hadron collision in which two partons elastically scatter to produce two high E_T jets. There are three variables necessary to specify the jet momenta, for instance E_{T1}, y_1, y_2. For this reason, it is possible to define "infrared safe" cross sections to make two jets that are differential in three jet variables. In the two jet cross sections discussed in earlier subsections, one or two of the jet variables are integrated out, leaving cross sections that are differential in fewer variables.

I have consulted with the experimental groups CDF and D0 about what measurements of triply differential two jet cross sections might be possible experimentally and what can be learned. It is indeed possible to measure three variables at once, and both groups have done it. What can be learned, I think, is information about the distribution of partons in the proton. With three variables, one can essentially select independently the momentum fractions x_a and x_b of the participating partons.

The computer program that Ellis, Kunszt and I wrote was not designed to handle three variables at once, so I worked to revise it. Certain rather major structural changes in the program were required.

We needed more, however, than a revised program. I quickly discovered that there was an important physics problem: much of the point of the investigation was to experimentally investigate the jet cross section rather near the edge of phase space, where either x_a or x_b is near 1. In this region, the QCD prediction for $d\sigma/dE_{T1}\,dy_1\,dy_2$ turns out to be imprecise because the dominant contribution comes from graphs with three partons in the final state instead of two. Unfortunately, we have no next-to-leading order (α_s^4) calculation of the cross section for three parton final states, so the

α_s^3 calculation has potentially large unknown corrections. Kosower, Giele, and Glover have written a new program that can perform jet calculations and have compared the QCD prediction to the measurement for $d\sigma/dE_{T1}\,dy_1\,dy_2$ [4]. Within the errors, the agreement is good. However, for the reasons stated above, Steve Ellis, with whom I worked on this project, and I have wanted to do better.

We have found that it is possible to do better. The method involves a simple change of the experimental definition of the jet cross section to be measured. With the revised definition, the cross section is dominated by two-jet-like events instead of three-jet-like events, even near the edge of phase space. We calculated the cross section with the revised definition and published the results in

> "Triply Differential Jet Cross Sections for Hadron Collisions at Order α_s^3 in QCD," Phys. Rev. Lett. **74**, 5182 (1995), with S. D. Ellis.

V. Jets in e^+e^- annihilation

Measurements of cross sections to make jets are quite important in electron-positron annihilation, first at PETRA and now at LEP and SLAC. A typical example is the measurement of α_s using the ratio of the cross section to make three jets to the total hadronic cross section. Of course, this measurement depends on the algorithm used to define the number of jets in an event. The experimental groups use jet algorithms similar to the algorithm introduced by the JADE group at PETRA. As discussed in Sec. above, one combines two particles that are nearby in momentum space to form what might be called a protojet. One successively combines particles and protojets until all of the particles have been merged into a few jets.

There are several variations of this algorithm, including an improved version known as the Durham algorithm, which has some theoretical advantages. Bethke, Kunszt, Stirling and I investigated the advantages and disadvantages of the available algorithms (including one we invented) in the paper

> "New Jet Cluster Algorithms: Next-to-Leading Order QCD and Hadronization Corrections," Nucl. Phys. **B370**, 310 (1992), with S. Bethke, Z. Kunszt, and W. J. Stirling.

We were particularly concerned with estimates of the theoretical error entailed in the calculation of the jet cross section (for an assumed value of α_s), including both the error from not using perturbative contributions beyond order α_s^2 and the error from neglecting nonperturbative effects.

VI. Determination of Parton Distributions

John Collins and I have worked on the proper method for determining parton distribution functions from the data, including propagating the experimental statistical and systematic errors and an estimate of the theoretical errors into the distribution functions. Our analysis is contained in a working paper of the CTEQ Collaboration,

> "Issues in the Determination of Parton Distribution Functions," e-Print Archive: hep-ph@xxx.lanl.gov - 9411214, (an electronic paper, not submitted to any journal), with J. C. Collins.

Collins and I chose an unusual format for disseminating this paper, guided by the following considerations. Parton distributions with a complete error matrix would be of interest to most of the particle physics community and would surely warrant publication in Physical Review Letters with a longer analysis in Physical Review. However, we have taken only a preliminary step toward such an analysis. Preliminary steps are mainly of interest to physicists who might take the next steps. The CTEQ Collaboration is one group with the capability to undertake complete analysis, so a CTEQ working paper was surely called for. However, other groups, particularly Martin, Roberts, and Stirling, could do it also. We therefore chose to put our paper on methodology on the hep-ph archive where it is accessible to everyone, but we did not submit it to a paper journal.

VII. Semi-inclusive deeply inelastic scattering

What can one observe in deeply inelastic electron proton scattering at HERA if, in addition to detecting the scattered electron, one examines the distribution of hadronic energy in a calorimeter? In DIS events, there is a nominal jet direction defined by the momentum transfer from the electron. This is the direction (θ_*, ϕ_*) defined by the direction of the outgoing struck quark in the parton model diagram $e + q \to e + q$. In most events, there should be a single narrow jet in this direction. However, in a fraction α_s of the events, gluon bremsstrahlung can produce jets in substantially different directions. Thus, by examining the final state, one can test QCD experimentally in some detail.

Ruiben Meng, Fred Olness and I have examined the possibilities for such tests. In particular, we consider the cross section for $e + p \to e + hadron + X$, weighted by the energy of the hadron, summed over hadron types, and integrated over the hadron energy. Thus we have a distribution of energy as a function of angles, analogous to the energy-energy correlation function in electron-positron annihilation.

1. The energy distribution at large angles

In the paper

> "Semi-Inclusive Deeply Inelastic Scattering at Electron-Proton Colliders," Nucl. Phys. **B371**, 79 (1992), with R. Meng and F. Olness.

we consider the distribution of hadronic energy at angles (θ, ϕ) that are far from the parton model jet direction (θ_*, ϕ_*). The contributing Feynman diagrams involve hard QCD subprocesses such as $e + q \to e + q + g$ and $e + g \to e + q + \bar{q}$. QCD evolution of $F_2(x, Q^2)$ involves these same hard processes. By examining the hadronic energy distribution, one directly probes the processes that underlie this evolution. In addition, this examination should provide a rather direct way of measuring the distribution of gluons in the proton, since scattering away from the nominal jet direction is just as likely to result from incoming gluons as from incoming quarks.

We analyzed the cross section in terms of Lorentz invariant hadronic functions and angular functions that reflect the photon or Z-boson spin. There is a rather rich structure, with nine hadronic structure functions. Then we computed the hadronic structure functions in lowest order QCD.

The experimental investigation that we advocated requires quite good luminosity. We are encouraged that the luminosity of HERA is improving into the range that should make the investigation possible.

2. The energy distribution at small angles

As I write, Olness, Meng and I are just completing a companion paper on the hadronic energy distribution in the region $(\theta, \phi) \approx (\theta_*, \phi_*)$:

> "Semi-Inclusive Deeply Inelastic Scattering at Small q_T," preprint OITS 590 (to be submitted), with R. Meng and F. I. Olness.

In this region, low order perturbation theory does not suffice because the emission of many soft gluons is important. Thus one must sum the contributions from soft gluons at all perturbative orders. The situation is closely analogous to the Z-boson production in hadron collisions when the P_T of the Z is small compared to M_Z; similarly, it is analogous to the energy-energy correlation function in electron-positron annihilation in the back-to-back region. We draw on this analogy in order to make predictions for the case of deeply inelastic scattering.

VIII. Null-plane field theory

There has been quite a lot of work over the past several years undertaken with the aim of using QCD quantized on the null-plane $x^+ \equiv (t + z)/\sqrt{2} = 0$ as the starting point for calculation of bound state masses. The hope is that the simplified vacuum structure obtained in null-plane field theory may make treatment of the bound state problem more tractable. However, this is by no means a simple problem, and there are several obstacles to be overcome. With graduate student H. Liu, I wrote a paper addressed to one of these obstacles:

> "Implementation of the Leibbrandt-Mandelstam Gauge Prescription in the Null-Plane Bound State Equation," Phys. Rev. D48, 1841 (1993), with H. H. Liu.

In gauge theories in null-plane gauge, infinities can arise from the $1/n\cdot q$ singularity in the gauge boson propagator. Leibbrandt and Mandelstam have given a prescription for defining this singularity so as to give finite results for the four-dimensional loop integrals in Feynman diagrams. However, this prescription is not directly applicable to calculations based on x^+ ordered perturbation theory, and in particular to the the null-plane bound state equation. We show how the prescription can be applied, at least in the simplest version of this kind of calculation.

IX. Top quark contribution to the cross section for $e^+e^- \to$ *hadrons*

Measurement of the total cross section for $e^+e^- \to hadrons$ at LEP provides one of the better measurements of the value of the strong coupling α_s. The estimated errors in the theory for this process are very small, so that the error in the measurement of α_s comes mostly from the experimental errors. This situation stands in sharp contrast to the situation for other quantities used to measure α_s, where the theoretical errors dominate. For this reason, the total cross section may become the best way to measure α_s as the experimental errors are reduced.

The most important contributions to the $e^+e^- \to hadrons$ cross section have been calculated to order α_s^3. (The first correct calculation was by Levan Surguladze in a paper with Mark Samuel.) However, there was a *lower* order, α_s^2, contribution that was not fully calculated. This contribution involves the production of a light quark-antiquark pair, which exchange a virtual gluon. The gluon propagator has an insertion of a top quark loop. The problem arises from the mass of the top quark. If M_t could be regarded effectively zero, the diagram is quite standard. If M_t could be regarded as very heavy (compared to $\sqrt{s} = 91$ GeV) one can use an expansion about $M_t = \infty$, and the results can be found in the literature. However, M_t is really around 170 GeV. Thus it is not obvious that either of these limits applies. Estimates based on the small M_t and large M_t limits indicate that the contribution of this diagram are fairly small. Nevertheless, it appeared important to Surguladze and me to get this diagram correctly.

The calculation involves three loop diagrams containing massive propagators, for which standard methods do not apply. We developed numerical integration methods that give good results. Indeed, part of our aim was to develop such methods, which can be adapted to other circumstances. We found two independent methods, one based on the $\overline{\text{MS}}$ renormalization prescription and the other on the Collins-Wilczek-Zee renormalization prescription (with results of both expressed in terms of the standard five flavor $\overline{\text{MS}}$ version of α_s.) The numerical results with these two methods agree. Our results are published in

> "Top Quark Contribution to Hadronic Decays of the Z Boson at α_S^2 in QCD," Phys. Rev. Lett. **73**, 2958 (1994), with L. Surguladze.

In addition, Surguladze has made use of the methods of this paper in other investigations, as described in his report.

X. Diffractive jet production at HERA

The Zeus group at HERA, and later the H1 group, has reported finding deeply inelastic scattering events in which the proton appears to be diffractively scattered. That is, they see evidence for the process $e + p \to e + p + X$ where the momentum transfer Q^2 is moderately large and the proton, instead of being broken up, is scattered through a small angle with a modest energy loss ($< 10\%$). In the data reported so far, the diffractively scattered proton is not seen directly. Rather the experimental groups see no particles with transverse momenta greater than 400 MeV in the region of the detector where the beam jet from a broken-up proton should be found. Thus they see a "rapidity gap."

This general phenomenon of diffractive hard scattering was predicted in 1985 by Ingelman and Schlein, and has been seen by the UA8 group at the CERN collider in the process $p + \bar{p} \to p + jets + X$. It is of interest because the diffractive scattering indicates that the proton has "exchanged a pomeron" with the rest of the system, while the hard scattering (jet production or deeply inelastic electron scattering) indicates that the pomeron is made of pointlike partons. By studying the process, one may hope to learn in what sense the pomeron is to be understood as the exchange of quarks and gluons.

The Ingelman-Schlein model can be interpreted as consisting of two steps. First, the cross section has a factorized form in which one of the factors is the partonic hard scattering cross section and the other factor is a function $df^{\rm diff}_{a/A}(x;t,x_{\mathcal{P}})/dt\,dx_{\mathcal{P}}$ that tells the probability for finding a parton carrying momentum fraction x in the proton while the proton is diffractively scattered with invariant momentum transfer t and the loss of a fraction $x_{\mathcal{P}}$ of its longitudinal momentum. Berera and I call this step "diffractive factorization." The second step in the Ingelman-Schlein model consists of relating $df^{\rm diff}_{a/A}(x;t,x_{\mathcal{P}})/dt\,dx_{\mathcal{P}}$ to some factors that derive from Regge theory times a "distribution of partons in the pomeron." This step may be called "Regge factorization."

These ideas are closely related to a recent proposal by Trentadue and Veneziano to measure "fracture functions" [5]. These functions are essentially the functions $df^{\rm diff}_{a/A}(x;t,x_{\mathcal{P}})/dt\,dx_{\mathcal{P}}$ integrated over t.

1. Factorization breaking

Arjun Berera and I studied the validity of the first part of the Ingelman-Schlein model, the hypothesis of diffractive factorization, in the paper

> "Diffractive Jet Production in a Simple Model with Applications to HERA," Phys. Rev. D **50**, 4328 (1994), with A. Berera.

An earlier study by Collins, Frankfurt, and Strikman indicated that this hypothesis was likely to break down. Berera and I studied the issue with the help of a simple model in which one can see rather completely what happens. We confirmed that the factorization should break down for diffractive hard scattering with two hadrons in the initial state. We found, furthermore, that the factorization-breaking terms have an interesting structure. Abstracting from our simple model, we proposed a test for this structure in HERA experiments. The proposal is to look for the process $\gamma + p \to p + jets + X$. Since a real photon can act as a hadron, this process has two hadrons in the initial state. Thus the factorization breaking terms, with a particular signature, should be found. However, by tagging the final state electron one can select photons with virtualities Q that are one the order of a GeV (less than the many GeV for the jet transverse momenta.) Such a photon is still hadronic in the sense that it consists of quarks with some probability. However, the quarks are separated by a small transverse distance on the order of $1/Q$. We predict that when $1/Q$ is smaller than the transverse size characterizing the pomeron, the breaking of diffractive factorization should disappear.

The experiment with tagged electrons may be difficult until the luminosity of the machine improves. However, it does appear possible to compare diffractive photoproduction of jets (factorization breaking) with diffractive deeply inelastic scattering (no factorization breaking).

2. Behavior of diffractive parton distribution functions

Berera and I have continued this line of investigation in the paper

> "Behavior of Diffractive Parton Distribution Functions," e-Print Archive: hep-ph/9509239, submitted to Physical Review, with A. Berera.

We provide, first of all, a general analysis of the theory of diffractive hard scattering in general and diffractive deeply inelastic scattering in particular. Much of this analysis assembles results that were already in the literature, but we have also filled in some gaps.

We first give operator definitions of the diffractive parton distribution functions and argue that these functions obey the usual Altarelli-Parisi evolution equations. (There had been some doubt about this point among theorists in the field.)

Next, we address the hypothesis of diffractive factorization. Our first paper demonstrated that the diffractive parton distribution functions do not factor out of hard scattering cross sections in the case that there are two hadrons in the initial state. On the other hand, for deeply inelastic scattering, with one hadron in the initial state, the factorization, we argue in this paper that diffractive factorization hypothesis.

Turning to specific features of the diffractive parton distribution functions $df_{a/A}^{\rm diff}(x;t,x_P)/dt\, d$ we briefly review the ideas, based on Regge theory, for the behavior of these functions in the limit of small $\beta = x/x_{\mathbb{P}}$. Then we analyze the behavior of these functions for values of β that are near to 1. This analysis is similar in spirit to the analysis of the behavior of ordinary parton distributions $f_{a/A}(x)$ for x near 1, which yields the so-called "constituent counting rules." The analysis is based on perturbative QCD, but contain a certain measure of conjecture. The result is that the diffractive parton distributions fall off only slowly as $\beta \to 1$.

XI. Perturbative expansion for $e^+e^- \to$ hadrons

What are the limits to the accuracy QCD perturbation theory, given that one is able to calculate only a finite number of terms in the perturbative series? How can this accuracy be improved? This is a deep question in quantum field theory. One limitation relates to classical solutions of the field equations, "instantons." Another limitation relates to the influence of physical processes at distance scales that are much larger or much smaller than the scale of the physical process being considered. This limitation, which has received a lot of attention recently, goes under the name of "renormalons." A third limitation comes from large terms that are proportional to π^2 and are associated with analytic continuation in momentum space.

The QCD perturbative expansion for the width for $Z \to$ hadrons is an example in which three nontrivial terms are known and in which the series appears to be quite well behaved. Working with this expansion, Surguladze and I have investigated the size of the error associated with QCD theory and how this error can be reduced. The paper, which we are just now completing, is

> "On the QCD Perturbative Expansion for $e^+e^- \to$ Hadrons," preprint OITS 589, (to be submitted) with L. Surguladze.

In this paper, we sum a class of large "π^2 terms" and reorganize the series so as to minimize "renormalon" effects. We also consider the renormalization scheme-scale ambiguity of the perturbative results. We find that, with three nontrivial known terms in the perturbative expansion, the treatment of the π^2 terms is quite important, while renormalon effects are less important.

The measured hadronic width of the Z is often used to determine the value of $\alpha_s(M_Z^2)$. A standard method is to use the perturbative expansion for the width truncated at order α_s^3 in the $\overline{\rm MS}$ scheme with scale $\mu = M_Z$. We estimate that the determined value of $\alpha_s(M_Z^2)$ should be increased by 0.6% compared to the value extracted with this standard method. After this adjustment for π^2 and renormalon effects, we estimate that the uncertainty in $\alpha_s(M_Z^2)$ arising from QCD theory is about 0.4%. This is, of course, much less than the experimental uncertainty of about 5%.

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Xiao-Gang He

I joined the High Energy Physics Group in September, 1993 as a research associate. The last two years has been the high light of my research carrier. With professor N.G. Deshpande and collaborators from other institutions, I published 15 research papers in refereed journals, three are being considerd for publication, and 7 in conference proceedings.

The following is a brief description of the research programs I have carried out in the last two years.

B physics

Rare B decays have been subject of considerable theoretical and experimental interest recently. They provide tests for the Standard Model at the loop level and new phsyics beyond the Standard Model. My research concentrated on the possible pegnuin effects on various B decays and the determination of the fundamental CKM parameters. We were the first to point out the importance of the electroweak penguin effects on B decays and problems caused by the electrowek penguin in the determination of the CKM parameters. We then proposed new methods to overcome difficulties associated with the electroweak penguin effects. We also worked on other B related physics. The principle results in each of the paper are given below.

[OITS-538] **Hadronic Penguin B Decays In the Standard And the Two Higgs Doublet Models**
With N. Deshpande, Phys. Lett. **B336**, 471(1994).

In this paper we studied in next-to-leading order QCD hadronic penguin B decays in the Standard and two-Higgs-doublet models. Although the gluonic penguin dominates, we found the electroweak contribution non-negligible. In the Standard Model, the branching ratio for $B \to X_s\phi$ is predicted to be in the range $(0.6 \sim 2) \times 10^{-4}$. The ranges of branching ratios for $B \to K\phi$, $B \to K^*\phi$, and $B_s \to \phi\phi$ are $(0.4 \sim 2) \times 10^{-5}$, $(0.2 \sim 1) \times 10^{-5}$, and $(0.15 \sim 0.5) \times 10^{-5}$, respectively. The contribution from the charged Higgs boson in two Higgs doublet models depend on $cot\beta$, and can be as large as 40%.

This work was reported by Deshpande at the 27th International Conference on High Energy Physics in Glasgow, August, 1994. The report [OITS-555] is published in the conference proceedings.

[OITS-553] **Isospin structure of penguins and their consequences in B physics**
With N.G. Deshpande, Phys. Rev. Lett. **74**, 26(1995).

Isospin structure of electroweak penguin diagrams is different from the gluon mediated or strong penguin. Given the large top mass these electroweak contributions are significant. This has the consequence that some previous analyses which relied on a simple isospin structure in charmless B decays become inapplicable. We presented the general Hamiltonian in next-to-leading order QCD, and illustrated our conclusion quantitatively for $B \to \pi\pi$ and $B \to K\pi$ decays in the factorization approximation. Some remarks on CP asymmetries in B decays are also made.

This work was reported by Deshpande at the Beyond the Standard Model IV Conference in Lake Tahoe, Califirnia, Dec. 1994. The report [OITS-572] will be published in the conference proceedings.

[OITS-560] **Unique signature of electroweak penguin in pure hadronic B decays**

With N.G. Deshpande and J. Trampetic, Phys. Lett.**B345** 547(1995)

The elelctroweak penguin contributions in pure hadronic B decays in the Standard and two-Higgs-doublet models are studied. We find that in $B_s \to \pi^0(\eta\,,\phi)$ and $B_s \to \rho^0(\eta\,,\phi)$ decays, the electroweak penguin contributions dominate over all other contribuitons. These processes provide unique signatures of electroweak penguin in pure hadronic processes. These modes could be in measureable range of future B facilities.

[OITS-564] **Long distance contributions to penguin processes $b \to s\gamma$ and $b \to d\gamma$**

With N.G. Deshpande and J. Trampetic, Phys. Lett. B in press.

In this paper we considered the long distance contributions to inclusive penguin processes through processes like $b \to sV$ and $b \to dV$ where V are ${}^3S_1(c\bar{c})$ states ψ_i in the former case and include ρ, ω for the latter case. We carefully examine vector dominance for $\bar{c}c$ states, and conclude that there is a large suppression of $\psi \sim \gamma$ transition when ψ is at $q^2 = 0$. The long distance effects can be at most 7% in the amplitude for $b \to s\gamma$. The long distance contribution to $b \to d\gamma$ is also found to be small.

[OITS-566] **CP asymmetry relations between $\bar{B} \to \pi\pi$ and $\bar{B} \to \pi K$ rates**

With N.G. Deshpande, Phys. Rev. Lett. **75**, 1703(1995).

In this paper we proved that CP violating rate difference $\Delta(\pi^+\pi^-) = \Gamma(\bar{B}^0 \to \pi^+\pi^-) - \Gamma(B^0 \to \pi^-\pi^+)$ is related to $\Delta(\pi^+K^-) = \Gamma(\bar{B}^0 \to \pi^+K^-) - \Gamma(B^0 \to \pi^-K^+)$ in the three generation Standard Model. Neglecting small annihilation diagrams, and in the SU(3) symmetry limit, we show that $\Delta(\pi^+\pi^-) = -\Delta(\pi^+K^-)$. The SU(3) breaking effects are estimated using factorization approximation, and yield $\Delta(\pi^+\pi^-) \approx -(f_\pi/f_K)^2\Delta(\pi^+K^-)$. Usefulness of this relation for determining phases in the CKM unitarity triangle is discussed.

[OITS-571] **The Nonresonant Cabibbo Suppressed Decay $B^\pm \to \pi^+\pi^-\pi^\pm$ and Signal for CP violation**

With N. Deshpand, G. Eilam and J. Trampetic, Phys. Rev. D in press.

We considered various contributions to the nonresonant decay $B^\pm \to \pi^+\pi^-\pi^\pm$, both of the long-distance and short-distance types with the former providing for most of the branching ratio, predicted to be $BR(B^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}) = (1.5-8.4)\times 10^{-5}$. We also discuss an application to CP violation resulting from the interference of that nonresonant background (with $m(\pi^+\pi^-) \approx 3.4$ GeV) and $B^{\pm} \rightarrow \chi_{c0}\pi^{\pm}$ followed by $\chi_{c0} \rightarrow \pi^+\pi^-$. The resulting value of the partial rate asymmetry is $(0.40 \sim 0.48)\sin\gamma$, where $\gamma = \arg(V_{ub}^*)$.

[OITS-575] **Energy Distribution of ϕ in Pure Penguin Induced B Decays**
With N. Deshpande, G. Eilam and J. Trampetic, Submitted to Phys. Lett. B.

We studied the energy distribution of ϕ in pure penguin induced $B \rightarrow X_s\phi$ taking into account the fermi motion of b inside B meson for $b \rightarrow s\phi$ and also modification due to gluon bremsstrahlung process $b \rightarrow s\phi g$. We find that the contribution to $B \rightarrow X_s\phi$ from $b \rightarrow s\phi g$ is less than 3%. This study providès a criterion for including most of the ϕ's produced in a penguin process.

[OITS-576] **A Method for Determining CP Violating Phase γ**
With N.G. Deshpande, Phys. Rev. Lett. in press.

In this paper we proposed a new way of determining the phases of weak amplitudes in charged B decays based on SU(3) symmetry. When electroweak penguin effects are included, previous proposed method using $B \rightarrow \pi K$ to measure the CP violating phase γ becomes invalid. The new method introduced here overcomes the difficulties associated with electroweak penguins.

[OITS-582] **Importance of Dipole Penguin Operator in B Decays**
With N.G. Deshpande and J. Trampetic, Submitted to Phys. Rev. Lett.

The importance of dipole penguin operator, $O_{11} = (g_s/8\pi^2)m_b\bar{s}\sigma_{\mu\nu}RT^a bG_a^{\mu\nu}$, on B decays is demonstrated. It is shown that branching ratios for the inclusive decay $b \rightarrow ss\bar{s}$, the semi-inclusive decay $b \rightarrow s\phi$, and the exclusive decay $B \rightarrow \pi K$ are enhanced by 20% to 30%. A useful consequence of this calculation is the inclusive $b \rightarrow ss\bar{s}$ spectrum which will be essential in isolating pure penguin process.

CP Violation

CP violation is still a mystery of elementary particle physics. So far CP violation has only been observed in neutral kaon system. In order to isolate the source (or sources) of CP violation, it is necessary to observe CP violation in other systems and to study different theories of CP violation. In the last two years I have focused on CP violation in Kaon decays, hyperon decays and other low energy systems. I published 6 research papers and the results are reported at three conferences.

[OITS-519] **CP violation in fermion pair decays of neutral boson particles**
With J.P. Ma and B. McKellar, Phys. Rev. **D49**, 4548-4552(1994).

We studied CP violation in fermion pair decays of neutral boson particles with spin 0 or 1. We study a new asymmetry to measure CP violation in $\eta, K_L \to \mu^+\mu^-$ decays and discuss the possibility of measuring it experimentally. For the spin-1 particles case, we study CP violation in the decays of J/ψ to $SU(3)$ octet baryon pairs. We show that these decays can be used to put stringent constraints on the electric dipole moments of Λ, Σ and Ξ.

[OITS-529] **CP violation in a multi-Higgs doublet model with flavour changing neutral current**
With N.G. Deshpande, Phys. Rev. D49, 4812(1994)

We studied CP violation in a multi-Higgs doublet model based on a $S_3 \times Z_3$ horizontal symmetry where CKM phase is not the principal source of CP violation. We consider two mechanisms for CP violation in this model: a) CP violation due to complex Yukawa couplings; and b) CP violation due to scalar-pseudoscalar Higgs boson mixings. Both mechanisms can explain the observed CP violation in the neutral Kaon system. ϵ'/ϵ due to neutral Higgs boson exchange is small in both mechanisms, but charged Higgs boson con-tributions can be as large as 10^{-3} for a), and 10^{-4} for b). CP violation in the neutral B system is, however, quite different from the Minimal Standard Model. The neutron Electric Dipole Moment can be as large as the present ex- perimental bound, and can be used to constrain charged Higgs boson masses. The electron EDM is one order of magnitude below the experimental bound in case b) and smaller in case a).

This work was reported by Deshpande at the WHEPP-3 Conference in India, Dec. 1993. The report [OITS-551] is published in the conference proceedings.

[OITS-533] **Gluon dipole penguin contributions to ϵ'/ϵ and CP violation in hyperon decays**
With N. Deshpande and S. Pakvasa, Phys. Lett. B326, 307-311(1994)

In this paper we considered the gluon dipole penguin operator contributions to ϵ'/ϵ and CP violation in hyperon decays. It has been proposed by Bertolini et al. that the contribution to ϵ'/ϵ may be significant. We show that there is a cancellation in the leading order contribution and this contribution is actually suppressed by a factor of order $O(m_\pi^2, m_K^2)/\Lambda^2$. We find that the same operator also contributes to CP violation in hyperon decays where it is not suppressed. The gluon dipole penguin operator can enhance CP violation in hyperon decays by as much as 25%.

[OITS-541] **ϵ'/ϵ and anomalous gauge boson couplings**
With B. McKellar, Phys. Rev. D51, 6484-6489(1995).

We studied ϵ'/ϵ in the Standard Model and ϵ'/ϵ due to anomalous $WW\gamma$ and WWZ interactions

This work was reported by Xiao-Gang He at the Physics Doesn't Stop Conference in Madison, Wisconsin, April, 1994. No written paper for this report.

[OITS-563] **CP Violation In Hyperon Decays Due To Left-Right Mixing**
With D. Chang, S. Pakvasa, Phys. Rev. Lett. **74**, 3927(1995).

In this paper we considered CP violating asymmetry A in polarization in hyperon and anti-hyperon decays due to left-right mixing in a class of Left-Right symmetric models. We find that the gluon dipole penguin operator dominates the contributions to CP violating asymmetry. For $\Lambda \to p\pi^-$, even though the S-wave contribution to A is constrained from experimental data on ϵ'/ϵ, A can be as large as 10^{-4}. For P-wave, the contribution is not directly related to ϵ'/ϵ. A can be even larger, and may reach 6×10^{-4}. This is much larger than the value expected for A in the Standard Model.

This work and [OITS-533] were reported by Xiao-Gang He at the Eighth Meeting of the Division of Particles and Fields of American Physical Society in Albuquerque, New Mexico, Aug. 1994, and the Beyond the Standaard Model IV Conference in Lake Tahoe, California, Dec. 1994. The reports [OITS-550] and [OITS-573] are published in the conference proceedings.

[OITS-579] **CP Violation in $\Lambda \to p\pi^-$ Beyond the Standard Model**
With G. Valencia, Preprint ISU-HET-95-3, OITS-579 (Phys. Rev. D in press).

The CP violating asymmetry $A(\Lambda^0_-)$ has been estimated to occur at the level of a few times 10^{-5} within the minimal standard model. The experiment E871 expects to reach a sensitivity of 10^{-4} to the asymmetry $A(\Lambda^0_-) + A(\Xi^-_-)$. In this paper we study some of the implications of such a measurement for CP violation beyond the minimal standard model. We find that it is possible to have $A(\Lambda^0_-)$ at the few times 10^{-4} level while satisfying the constraints imposed by the measurements of CP violation in kaon decays.

Research in other areas

In the past two years, I have also carried out research in other areas which are described in the following.

[OITS-532] **Model for a light Z'**
With R. Foot, H. Lew and R. Volkas, Phys. Rev. **D50**, 4571-4580(1994)

A model of a light Z' boson is constructed and phenomenological bounds are derived. This Z' boson arises from a very simple extension to the Standard Model, and it is constrained to be light because the vacuum expectation values which generate its mass also break the electroweak gauge group. It is difficult to detect experimentally because it couples exclusively or primarily (depending on symmetry breaking details) to second and third generation leptons. However, its effects may be observable in the NOMAD experiment being developed at CERN.

This work was reported by Xiao-Gang He at the Eighth Meeting of the Division of Particles and Fields of American Physical Society in Albuquerque, New Mexico, Aug. 1994. The report [OITS-549] is published in the conference proceedings.

[OITS-540] **Proton Life-time Problem In Finite Grand Unified theories**
With N. Deshpande, E. Keith, Phys. Lett. **B332**, 88-92(1994).

We studied proton decay in finite supersymmetric SU(5) grand unified theories in this paper. We find that the dimension-five operators due to color triplet higgsino induce too rapid a proton decay. This behaviour can be traced to the large Yukawa couplings to the first generation that are necessary for finiteness.

This work was reported by Xiao-Gang He at the Eighth Meeting of the Division of Particles and Fields of American Physical Society in Albuquerque, New Mexico, Aug. 1994. The report [OITS-548] is published in the conference proceedings.

[OITS-559] **Amplitude Zero in radiative decays of scàlar particles**
With N.G. Deshpande and Sechul Oh, Phys. Rev. **D51**, 2295-2301(1995).

In this paper we studied amplitude zeros in radiative decay processes with a photon or a gluon emission of all possible scalar particles(e.g. scalar leptoquarks) which may interact with the usual fermions in models beyond the standard model. For the decays with a photon emission, the amplitudes clearly exhibit the factorization property and the differential decay rates vanish at specific values of a certain variable which are determined only by the electric charges of the particles involved and independent of the particle masses and the various couplings. For the decays with a gluon emission, even though the zeros are washed away, the differential decay rates still have distinct minima. The branching ratios as a function of leptoquark masses are presented for the scalar leptoquark decays. We also comment on the decays of vector particles into two fermions and a photon.

Work in progress

With Professor Deshpande and Mr. Oh, we are continuing our investigations in B decays. We are currently studying theoretical errors in several methods proposed to measure CKM parameters. We hope to provide better understanding of theoretical and experimental aspects of these methods.

With Dr. Babu from the Institute of Advanced Studies at Princeton, I am currently studying possible neutrino self interactions. In the Standard Model, interaction among neutrinos is mediated by Z boson. There are only bounds on possible neutrino self interaction which are about 100 times of the strength predicted by the Standard Model. Our study will concentrate on theoretical models which predict large neutrino self interaction and possible ways to test the models.

Levan R. Surguladze

Decay Rates of the Higgs Boson

- QUARK MASS EFFECTS IN FERMIONIC DECAYS OF THE HIGGS BOSON IN $O(\alpha_s^2)$ PERTURBATIVE QCD [1]

In this work the results of analytical evaluation of $O(\alpha_s^2)$ QCD contributions due to the nonvanishing quark masses to $\Gamma_{H\to q_f\bar{q}_f}$ are presented. The "triangle anomaly" type contributions are included. As a byproduct the $O(\alpha_s^3)$ logarithmic contributions are evaluated. The results are presented both in terms of running and pole quark masses. The partial decay modes $H \to b\bar{b}$ and $H \to c\bar{c}$ are considered. The calculated corrections decrease the absolute value of large and negative $O(\alpha_s^2)$ massless limit coefficient by $\leq 1\%$ in the intermediate mass region and by 1%–20% in the low mass region which, however, is experimentally ruled out. The results are relevant for $H \to t\bar{t}$ decay mode for the higher Higgs mass region where the calculated mass effects are very large and important. The high order corrections remove a very large discrepancy between the results for $\Gamma_{H\to q_f\bar{q}_f}$ in terms of running and pole quark masses almost completely and reduce the scale dependence from about 40% to nearly 5%. The remaining theoretical uncertainties are discussed.

- MINIMAL SUPERSYMMETRIC HIGGS BOSON DECAY RATE IN $O(\alpha_s^2)$ PERTURBATIVE QCD [2]

In this work the $O(\alpha_s^2)$ QCD contributions in the fermionic decay rates of a CP-odd pseudoscalar Higgs boson (such as is found in the minimal supersymmetric model) are evaluated analytically. The corrections due to the nonvanishing quark masses are included. The results are presented both in terms of running and pole quark masses.

e^+e^- Annihilation and Z Boson Decay at LEP

- TOP QUARK CONTRIBUTION TO HADRONIC DECAYS OF THE Z BOSON AT α_s^2 IN QCD [3]

In this work we (Professor D.E.Soper and I) evaluate the effect of a virtual top quark on the coefficient of α_s^2 in the decay rates $\Gamma(Z \to \text{hadrons})$ and $\Gamma(Z \to b\bar{b})$. We treat the dependence on the top quark mass exactly instead of using a large mass expansion. The present work completes the evaluation of the α_s^2 contributions to these quantities. The calculation uses both the $\overline{\text{MS}}$ and Collins-Wilczek-Zee renormalization prescriptions. The results can be applied to the hadronic decays of the τ-lepton.

- QUARK MASS CORRECTIONS TO THE Z BOSON DECAY RATES [4]

In this work the results of perturbative QCD evaluation of the $\sim m_f^2/M_Z^2$ contributions to the $\Gamma(Z \to hadrons)$ and $\Gamma(Z \to b\bar{b})$ for the quark masses $m_f \ll M_Z$ are presented. Some of the recent results which were obtained using the combination of renormalization group constraints and the results of several other calculations have been independently confirmed by the direct computation. Some existing confusion in the literature is clarified. In addition, the calculated $O(\alpha_s^2)$ correction to the correlation function in the axial channel is a necessary ingredient to the yet uncalculated $O(\alpha_s^3)$ mass correction to the Z decay rates. The results can be applied to the τ hadronic width.

Review Articles

- PERTURBATIVE QCD CALCULATIONS OF TOTAL CROSS-SECTIONS AND DECAY WIDTHS IN HARD INCLUSIVE PROCESSES [5]

In this work we (Professor M.A.Samuel and I) present a detailed summary of the current understanding of methods of analytical higher order perturbative computations of total cross-sections and decay widths in the Standard Model. As an example the quantities $\sigma_{tot}(e^+e^- \to hadrons)$; $\Gamma(\tau^- \to \nu_\tau + hadrons)$ and $\Gamma(H \to hadrons)$ up to $O(\alpha_s^2)$ and $O(\alpha_s^3)$ are considered. The evaluation of four-loop QED β - function at an intermediate step of the calculation is briefly described. The problem of scheme-scale dependence of perturbative results is considered and some of the existing possible solutions are discussed. The problem of estimation of theoretical uncertainty in perturbative calculations of various physical observables within the Standard Model is briefly discussed.

- STATUS OF PERTURBATIVE QCD EVALUATION OF HADRONIC DECAY RATES OF THE Z AND HIGGS BOSONS [6]

In this talk at the *Rencontres de Moriond* conference (France, 1995), we (Professor Soper and I) review the current status of the high order perturbative QCD evaluation of the hadronic decay rates of the Z and Higgs bosons. A systematic classification of the various types of QCD corrections to $O(\alpha_s^2)$ and $O(\alpha_s^3)$ is made and their numerical status is clarified.

- COMPUTER PROGRAMS FOR ANALYTICAL PERTURBATIVE CALCULATIONS IN HIGH ENERGY PHYSICS [7]

In this work a review of the present status of computer packages for the high order analytical perturbative calculations is presented. The mathematical algorithm and the quantum field theory methods used are briefly discussed. Our most recent computer package HEPLoops for analytical computations in high energy physics up to four-loops is discussed in detail.

- METHODS AND ALGORITHMS FOR ANALYTICAL PERTURBATIVE CALCULATIONS IN HIGH ENERGY PHYSICS AND THEIR COMPUTER IMPLEMENTATIONS [8]

In this talk, given at the International Workshop on *Software Engineering and Artificial Intelligence Systems for High Energy and Nuclear Physics* (Pisa, Italy, 1995), I have presented a review of the present status of the methods and algorithms for analytical high order perturbative calculations in high energy physics and their computer implementations for the algebraic programming systems like REDUCE, SCHOONSCHIP and FORM. A possible future developments were also discussed.

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