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Outstanding Junior Investigator Award

John A. Ellison

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1. Introduction

The OJI supported research of J. Ellison has been concentrated in two areas:

- Study of $W\gamma$ and $Z\gamma$ production at the Tevatron, which probes the trilinear boson coupling;
- Design, fabrication and testing of silicon microstrip detectors for the DØ upgrade silicon tracking system.

The $W\gamma$ analysis using data from the first DØ run ($\approx 14 \text{ pb}^{-1}$ integrated luminosity) has been completed – J. Ellison and a postdoctoral researcher working with him (B. Choudhary) were responsible for the muon channel analysis. This analysis is an important test of the Standard Model (SM), since it probes the nature of the $WW\gamma$ coupling, which is related to the W boson magnetic dipole and electric quadrupole moments. Any deviation from the SM value of the $WW\gamma$ coupling would be an indication of either composite structure of the W or higher order loop corrections involving physics beyond the SM. The analysis has resulted in the world's most sensitive limits on the $WW\gamma$ coupling parameters. J. Ellison presented the results at the 1994 APS Division of Particles and Fields Conference [1] and we are in the final stages of writing a paper for submission to Physical Review Letters (PRL). In addition we have also worked on an analysis of $Z\gamma$ production which has yielded sensitive limits on the $ZZ\gamma$ and $Z\gamma\gamma$ couplings. We have completed a second paper on $Z\gamma$ which has been submitted to PRL.

The work on the DØ Silicon Tracker has also make very good progress. J. Ellison presented this work at the 27th International Conference on High Energy Physics in Glasgow [2]. The team led by J. Ellison includes two postdoctoral researchers (A. Bischoff and C. Boswell), one graduate student (M. Mason) and three undergraduate students. We have fully evaluated prototype detectors which were designed at UCR and have completed a detailed simulation study of the detector performance for different strip geometries. The results were used to optimize the design of the final DØ detectors, for which UCR has sole responsibility. We have completed the procurement process resulting in the choice of Micron Semiconductor as the final vendor. We have completed the mask design for the 3-chip barrel detectors and production of the final detectors has now begun.

We have also set up test facilities at UCR to enable testing the large number of detectors which will be produced. We have converted an existing lab into a Class 10,000 clean room (using University funds) and have set up an automated probe station and laser test station.

References

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2. Study of the $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ Trilinear Boson Couplings

The UCR group is playing a leading role in the study of the trilinear vector boson couplings in $D\bar{D}$. We have been studying $W\gamma$ production via the process $p\bar{p} \rightarrow \mu^+\mu^-\gamma + X$ and $Z\gamma$ production via the process $p\bar{p} \rightarrow \mu^+\mu^-\gamma + X$. We have made considerable progress since last year and both these analyses are very close to completion. The results are being written up in two separate papers to be submitted to Physical Review Letters, and are based on approximately 14 pb^{-1} of data collected in Run 1a. In parallel, we are working on the analysis of the data from the current run (1b).

The UCR personnel working on this topic are B. Choudhary, J. Ellison and P. Gartung. Invited talks during the year were: B. Choudhary gave a high energy physics seminar at Argonne in January [1] and at UC Davis in January [2]. He presented results for the collaboration at the Moriond conference in March [3] and also gave a high energy physics seminar at Pavia, Italy, in March [4]. J. Ellison presented the analysis results at the 1994 APS/DPF conference in August 1994 [5]. J. Ellison is also a member of the International Advisory Committee for a Symposium on Trilinear Boson Couplings to be held at UCLA in February 1995.

(a) *Introduction*

In $p\bar{p}$ collisions at the Fermilab Tevatron, the trilinear boson couplings can be probed by diboson production. Measurement of the $WW\gamma$ trilinear coupling is possible by detecting $W\gamma$ production; measurement of the $ZZ\gamma$ and $Z\gamma\gamma$ trilinear couplings is possible via $Z\gamma$ production. Requiring Lorentz covariance and gauge invariance of the on-shell photon, the most general $WW\gamma$ vertex can be parametrized by a Lagrangian which is described by four coupling parameters κ , λ , $\tilde{\kappa}$ and $\tilde{\lambda}$. [6]. The effective Lagrangian is:

$$\begin{aligned} L_{WW\gamma} = & -ie[(W_{\mu\nu}^\dagger W^\mu A^\nu - W_\mu^\dagger A_\nu W^{\mu\nu}) \\ & + \kappa W_\mu^\dagger W_\nu F^{\mu\nu} + \frac{\lambda}{m_W^2} W_{\lambda\nu}^\dagger W_\nu^\mu \tilde{F}^{\nu\lambda} \\ & + \tilde{\kappa} W_\mu^\dagger W_\nu \tilde{F}^{\mu\nu} + \frac{\tilde{\lambda}}{m_W^2} W_{\lambda\nu}^\dagger W_\nu^\mu \tilde{F}^{\nu\lambda}] \end{aligned}$$

where A_μ is the photon field W_μ is the W^- field, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, and $\tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}$.

The first term in the equation for the Lagrangian is the so-called "minimal" coupling term, and the second coefficient κ is conventionally called the "anomalous" magnetic moment of the

W . This term and the third coefficient λ are related to the magnetic dipole moment μ_W and the electric quadrupole moment Q_W of the W by

$$\mu_W = \frac{e}{2m_W}(1 + \kappa + \lambda)$$

$$Q_W = \frac{e}{m_W^2}(\kappa - \lambda)$$

While κ and λ do not violate any discrete symmetries, the $\tilde{\kappa}$ and $\tilde{\lambda}$ terms are P odd and CP violating. They are related to the electric dipole moment d_W and the magnetic quadrupole moment $\tilde{Q}_W$ of the W by

$$d_W = \frac{e}{2m_W}(\tilde{\kappa} + \tilde{\lambda})$$

$$\tilde{Q}_W = \frac{e}{m_W^2}(\tilde{\kappa} - \tilde{\lambda})$$

In the Standard Model at tree level, the $WW\gamma$ coupling is uniquely determined by the $SU(2)_L \otimes U(1)_Y$ gauge symmetry, requiring $\kappa = 1$, $\lambda = 0$, $\tilde{\kappa} = 0$, $\tilde{\lambda} = 0$. Therefore, a measurement of the $WW\gamma$ coupling is a powerful test of the Standard Model gauge symmetry. The consequences of deviations of these parameters from their SM values are:

- The cross section for the process $p\bar{p} \rightarrow W^\pm \gamma$ increases, and thus any excess of events measured will be an indication for physics beyond the SM.
- The differential distributions for some kinematical variables depend strongly on κ , λ , $\tilde{\kappa}$ and $\tilde{\lambda}$. Such variables are, for example, the transverse momentum of the photon ($P_T(\gamma)$), the invariant mass of the $W\gamma$ system ($M_{W\gamma}$) and the angular distribution of the photon in the partonic center of mass system ($\cos \theta^*$).

Anomalous couplings may arise due to radiative loop corrections to the $WW\gamma$ vertex or due to models in which the W is viewed as a composite particle. The experimental signature for anomalous couplings is an increase of the $W\gamma$ production cross section and changes in the kinematic distributions of the final state particles, such as an enhancement of the photon spectrum at high transverse energy [7].

In contrast to the $WW\gamma$ coupling, the coupling of the photon to the Z boson is forbidden in the SM at tree level. However, to allow for the possibility of anomalous couplings, the vertex functions may be parametrized in terms of four parameters ($h_1^Z, h_2^Z, h_3^Z, h_4^Z$) for the $ZZ\gamma$ vertex function and four parameters ($h_1^\gamma, h_2^\gamma, h_3^\gamma, h_4^\gamma$) for the $Z\gamma\gamma$ vertex function [8].

Tree level unitarity requires that the couplings must be described by form factors which vanish when any of the boson momenta become very large. The form factors used for this study are described in references 2 and 3.

In this section, we present measurements of the $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ couplings using $W\gamma$ and $Z\gamma$ events in the electron ($e\bar{\nu}\gamma$ and $e^+e^-\gamma$) and ($\mu\bar{\nu}\gamma$ and $\mu^+\mu^-\gamma$) channels observed by DØ during the 1992-3 run, corresponding to an integrated luminosity of $\sim 14 \text{ pb}^{-1}$.

(b) Event Selection

$W\gamma$ candidates were obtained by searching for events containing an isolated high P_T lepton (electron or muon) and an isolated photon. The events must have large missing transverse energy to signify the presence of a neutrino. Table 1 summarizes the trigger requirements and offline kinematic cuts used.

	$e\nu\gamma$	$\mu\nu\gamma$	$ee\gamma$	$\mu\mu\gamma$
Trigger	$E_T^{em} \geq 20 \text{ GeV}$	$p_t^\mu \geq 5 \text{ GeV}$	$2 \times E_T^{em} \geq 10 \text{ GeV}$	$p_t^\mu \geq 5 \text{ GeV}$
Kinematic cuts:	$\cancel{E}_T \geq 20 \text{ GeV}$	$E_T^{em} \geq 7 \text{ GeV}$		$E_T^{em} \geq 7 \text{ GeV}$
	$E_T^e \geq 25 \text{ GeV}$	$p_T^\mu \geq 15 \text{ GeV}$	$E_T^{e1} \geq 25 \text{ GeV}$	$p_T^{\mu1} \geq 15 \text{ GeV}$
	$\cancel{E}_T \geq 25 \text{ GeV}$	$\cancel{E}_T \geq 15 \text{ GeV}$	$E_T^{e2} \geq 25 \text{ GeV}$	$p_T^{\mu2} \geq 10 \text{ GeV}$
	$E_T^\gamma \geq 10 \text{ GeV}$		$E_T^\gamma \geq 10 \text{ GeV}$	
	$\Delta R \equiv \sqrt{\Delta\phi_{\ell\gamma}^2 + \Delta\eta_{\ell\gamma}^2} \geq 0.7$		$\Delta R \equiv \sqrt{\Delta\phi_{\ell\gamma}^2 + \Delta\eta_{\ell\gamma}^2} \geq 0.7$	

Table 1 $W\gamma$ and $Z\gamma$ selection trigger requirements and offline cuts.

Since anomalous couplings result in an enhancement of events at large $E_T(\gamma)$, lowering the $E_T(\gamma)$ cut below 10 GeV does not increase the sensitivity to anomalous couplings. A further requirement was that the photon be well separated from the lepton ($\Delta R_{l\gamma} \geq 0.7$). This cut suppresses the contribution of the radiative W decay where the photon originates from bremsstrahlung from the final state lepton.

The $W\gamma$ selection criteria yielded 9 candidate events in the electron channel and 10 candidates in the muon channel.

The $Z\gamma$ candidates were obtained by searching for events containing two isolated electrons or muons and an isolated photon (see Table 1). This resulted in 4 candidate events in the electron channel and 2 candidates in the muon channel.

(c) *Background Calculations*

The background estimate for the $W\gamma$ events includes contributions from: W + jets, where a jet is misidentified as a photon; $Z\gamma$, where Z decays to l^+l^- and one of the leptons is missed or mismeasured by the detector and so contributes to the measured E_T ; $W\gamma$ with $W \rightarrow \tau\nu$ followed by $\tau \rightarrow l\nu\bar{\nu}$; and $Z \rightarrow ee$ + jets where an electron is misidentified as a photon due to tracking inefficiency.

We have estimated the W + jets background using the observed E_T distributions of jets in the inclusive W data sample and the measured probability for a jet to fake a photon. This probability was determined as a function of E_T of the jet, using samples of QCD multijet events. The probability was found to be less than 10^{-3} and varied slowly with E_T . The $Z\gamma$ background was estimated using the PYTHIA Monte Carlo generator with a full GEANT simulation of the DØ detector. The remaining backgrounds were much smaller and were estimated from Monte Carlo and data.

Subtracting the estimated backgrounds from the observed number of events, we obtain the number of $W\gamma$ signal events to be $6.5^{+4.0}_{-2.1}^{+1.1}_{-2.1}$ for the electron channel and $7.0^{+4.2}_{-3.1}^{+0.5}_{-1.1}$ for the muon channel, where the first uncertainty is statistical and the second is systematic.

The background estimate for the $Z\gamma$ events includes contributions from Z + jets, where a jet is misidentified as a photon, and $Z\gamma$ with $Z \rightarrow \tau\tau$ followed by $\tau \rightarrow l\nu\bar{\nu}$. These backgrounds were estimated from data and Monte Carlo respectively, as in the $W\gamma$ background study described above.

Subtracting the estimated backgrounds from the observed number of events, we obtain the number of $Z\gamma$ signal events to be $3.8^{+3.2}_{-1.9} \pm 0.09$ for the electron channel and $1.96^{+2.62}_{-1.29} \pm 0.03$ for the muon channel.

(d) *Limits on Anomalous Couplings*

To compare with the SM predictions for $W\gamma$ and $Z\gamma$ production we used the event generator of Baur and Zeppenfeld [7, 8]. This program generates 4-vectors for the $W\gamma$ and $Z\gamma$ processes which were then put through a fast DØ detector simulation. This Monte Carlo simulates the energy and momentum resolutions for electrons, muons and missing E_T and includes fiducial cuts and detector efficiencies.

The predictions for the number of expected $W\gamma$ events using SM couplings are $7.7 \pm 0.8 \pm 0.9$ (e channel) and $6.1 \pm 1.0 \pm 0.7$ (μ channel), where the first error is the systematic error and the second error is due to the uncertainty in the integrated luminosity. For $Z\gamma$ the corresponding predictions are $2.3 \pm 0.4 \pm 0.3$ and $1.84 \pm 0.29 \pm 0.22$.

The systematic error includes the uncertainty in electron efficiency, muon efficiency, photon efficiency including conversion modeling, E_T smearing, choice of structure function, and choice of Q^2 scale. Comparing with the observed signal (section (c)) we see that the data are in good agreement with the SM within errors. Therefore, we see no evidence for anomalous couplings. However, we are able to set limits on the anomalous couplings by comparing our data with the predictions of the event generator for different anomalous couplings.

To set limits on the anomalous couplings, we fit the $E_T(\gamma)$ spectrum using a binned likelihood method (Fig. 1). The $W\gamma$ 95% confidence level (CL) limits derived from this method are $-2.3 < \Delta\kappa < 2.3$ (for $\lambda = 0$) and $-0.75 < \lambda < 0.75$ (for $\Delta\kappa = 0$) as shown in the $\Delta\kappa - \lambda$ contour plot in Fig. 2. The 95% CL limits on the couplings independent of each other are represented by the furthestmost points on the contour: $-3.0 < \Delta\kappa < 3.0$ and $-0.95 < \lambda < 0.95$.

Fig. 1 $E_T(\gamma)$ distribution for $W\gamma$ candidates

Fig. 2 $\Delta\kappa - \lambda$ contour plot from $E_T(\gamma)$ fit.

The same method was used to obtain limits for the $ZZ\gamma$ and $Z\gamma\gamma$ couplings. Because of the form of the vertex functions for these couplings, our measurement is sensitive to the form factor scale Λ and the results given here are for $\Lambda = 500$ GeV. For $ZZ\gamma$ (Fig. 3) we obtain the 95% CL limits $-2.2 \leq h_{30}^Z \leq 2.1$ (for $h_{40}^Z = 0$) and $-0.5 \leq h_{40}^Z \leq 0.5$ (for $h_{30}^Z = 0$) and the independent limits $-3.8 \leq h_{30}^Z \leq 3.8$ and $-1.0 \leq h_{40}^Z \leq 1.0$. For $Z\gamma\gamma$ the limits are only slightly weaker, as shown in Fig. 4.

Fig. 3 Limits on the $ZZ\gamma$ couplings.

Fig. 4 Limits on the $Z\gamma\gamma$ couplings.

(e) Conclusions

The process $p\bar{p} \rightarrow l\bar{\nu}\gamma + X$ and $p\bar{p} \rightarrow l^+l^-\gamma + X$, ($l = e, \mu$) have been observed in DØ and are used to set limits on the $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ vertex couplings. The limits obtained are a considerable improvement on previous measurements (UA2 [9] and the CDF 1988–9 data [10]) and are comparable in sensitivity with the CDF 1992–3 results. Using data from the current Tevatron run 1993–94 and combining results from DØ and CDF, we can expect a significant improvement in sensitivity in the near future.

(f) Future Plans

The major objective for the coming year is the analysis of the data from Run 1b. Since we expect $>100 \text{ pb}^{-1}$ of data, the sensitivity on the anomalous couplings will be greatly increased.

In $W\gamma$ production, a remarkable test of the Standard Model can be made by measuring the angular distribution of the photon in the partonic rest frame. The SM predicts, for $W\gamma$ production, a radiation zero at $\cos\theta_{d\gamma}^* = 1/3$. This is a consequence of gauge cancellations and should be evident experimentally as a dip in the $\cos\theta_{d\gamma}^*$ differential cross section. Large statistics are required, but with 100 pb^{-1} of data we will be able to observe the radiation zero. Anomalous couplings would fill in the radiation zero, and so this analysis will provide a very sensitive test of the Standard Model.

Finally, we hope to work with CDF to combine our results to obtain a significant increase in the sensitivity to anomalous couplings.

(g) *References*

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- 3 B.C. Choudhary, "Measurement of W Mass and $W\gamma$ Couplings at DØ", XXIXth Rencontres de Moriond - International Conference on Electroweak Interactions and Unified Theories, Meribel, Savoie-France, March 12-19, 1994.
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- 5 J.A. Ellison, "Measurement of the W - γ and Z - γ Couplings at the Fermilab Tevatron", 8th Meeting, APS Division of Particles and Fields, Albuquerque, New Mexico, August 2-6, 1994.
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3. The DØ Upgrade

The DØ detector will undergo a major upgrade [1] over the next few years, enabling it to run when the Tevatron luminosity is increased to ten times its present level and the time between bunch crossings is reduced from 3.5 μ s to 132 ns. A 2 T solenoid magnet will be added to extend the physics reach of the experiment, and the entire existing tracking system of gaseous wire chambers will be replaced with an extensive high resolution silicon strip tracking system and a scintillating fiber outer tracker. The upgrades will be installed during 1998, ready for Tevatron Run 2 with the Main Injector. The tracking upgrade will allow DØ to measure the momenta of charged particles, determine the sign of the charge of these particles (for example e^+ will be distinguished from e^-), tag b -jets from top decays using secondary vertex impact parameter measurements within jets, separate multiple interactions within a single beam crossing more effectively, and reduce conversion backgrounds using pulse height information from the silicon.

(a) *The UCR Role in the DØ Upgrade*

The original group working on the hardware for the Silicon Tracker consisted of physicists and engineers from Fermilab, LBL and UC Riverside. The software and hardware activities now include over 100 people from the original three institutions plus 10 other US universities, Moscow State University and the Brazilian Center for Physics Research.

UC Riverside has taken a major role in the Silicon Tracker since its inception by members of this group, and continues to lead many aspects of the designing, prototyping and project management. We have made considerable progress this year, marked by the release of a full Technical Design Report [2] and the movement from the design phase to the construction and testing phase of the project. The major areas of progress for which the UCR group are responsible are:

- Optimization of the tracker geometry
- Design and evaluation of prototype wedge detectors for the silicon disks
- Detector simulations and radiation damage studies
- Development of full specifications for the final DØ silicon detectors
- Procurement of the final barrel and disk detectors
- Mask design for the final barrel and disk detectors
- Preparations for testing large numbers of detectors, including the installation of a clean room at UCR and setting up test facilities.

The members of the UCR high energy physics group who are currently working on the DØ upgrade are John Ellison, Ann Heinson, Andreas Bischoff, Christopher Boswell, one graduate student (Martin Mason) and three undergraduate students (Richel Aguirre, Jean Dionson and Jason Yom). In addition, two other undergraduates worked during last year on the Silicon Tracker (Doug Chapin, now graduated, and Alex Malone); a minority summer research intern (Melvin Vaughn, now graduated); and two high school seniors (Miriosh Higgs and Rina Lim, both now graduated and starting University). A new graduate student (Phi Vu) will start research work on the Silicon Tracker this Fall.

Invited talks given on our work this year were: a presentation of the detector simulation studies [3] by A. Bischoff at the Third International Workshop on Vertex Detectors (Bloomington, in May); a talk on the evaluation of DØ prototype detectors [4] by C. Boswell at the same workshop; a talk on the physics capabilities of the DØ upgrade [5] by J. Ellison at the International Conference on High Energy Physics (Glasgow in July); and a talk on the redesign of the DØ Silicon Tracker [6] by A. Heinson at the 1994 DPF meeting (Albuquerque in August). In addition, three abstracts for papers [7] have been submitted to the IEEE Nuclear Science Symposium in Norfolk, Virginia in November.

Details of work by the UCR group are presented below.

(b) Optimization of the Silicon Tracker Design and Geometry

In March 1993, a two stage design for the DØ Silicon Tracker was presented to the collaboration in a Technical Design Report and approved after internal review. The first stage was a small vertex detector, covering 48 cm of the beamline in z , with three layers of single-sided detectors in the barrels and three double-sided disks on each end. This was intended for use during the 1995 run just before the installation of the Main Injector. A much more ambitious design was proposed for use with the full DØ upgrade in 1997 after Main Injector installation. This tracker, with nearly one million readout channels, covered 96 cm of the beamline, and had an extensive forward tracking system for $2.5 < |\eta| < 3.5$ with 20 double-sided disks and 8 large very-forward single-sided disks. However, after approval of these staged detectors, it became apparent that the physics goals, Tevatron schedule and amount of money available had changed dramatically. No Tevatron run was scheduled before Main Injector installation, leading to no clear purpose in building a small first stage detector. In addition, the cancellation of the SSC meant that the high p_T area of physics research would be wide open until LHC operation from ~2004. Therefore, the UCR group undertook to re-examine the silicon tracker design to move the emphasis from forward (b -quark) physics to central (t -quark) physics.

Figure 5 shows r - z views of the new DØ Silicon Tracker, with its focus on central, high p_T physics, and for comparison, the former Step 1 and Step 2 DØ Silicon Trackers and the CDF

SVX and SVX II trackers. The new DØ tracker now covers the interaction region, shown shaded at 1σ and 2σ regions inside the beam pipe. It has four layers for good track finding efficiency, and interspersed disks to retain some forward tracking capability. Layers 2 and 4 of the barrel are double-sided with small angle stereo strips, to aid pattern recognition. The barrel segments are only 12 cm long, which is half the length of the former design, in order to allow the disks to lie close enough together. The disks are squeezed between the barrel segments without impacting significantly on the acceptance of the tracker with large cracks, through the development of a new thinner assembly. The readout electronics now lie off the active detector surface, at larger radius than the outer barrel layer. This detector has been documented in the Technical Design Report [2] of July 1994, and the barrels and six end disks have full funding approval.

The UC Riverside acceptance studies of tracker geometries for top quark physics [8] have lead to improvement of the geometrical acceptances for $t\bar{t}$ events from 58% for the former Step 1 tracker and 79% for the former Step 2 tracker, to 94% for the new design. When hit efficiencies of $\sim 96\%$ per layer are considered as well as geometrical acceptances, then the fourth barrel layer of the new tracker design improves the event-finding probability by an even larger factor. DØ will now be able to compete effectively with CDF in the search for the top quark and the study of its properties.

Fig. 5 A comparison of silicon tracker designs at the Tevatron collider.

The tracker geometry is currently being re-examined by a forward tracking group, to optimize the placement of the disks. Some of the central disks may be moved out to the ends of the barrels, to improve the tracking efficiency in the very forward direction where particles do

not pass through many barrel layers. To compensate for the loss of hits with excellent z resolution near the interaction point, layers 1 and 3 of the three inner barrels may become double-sided detectors with 90° stereo, instead of single-sided detectors as in the baseline design. The UC Riverside group will examine this proposal very carefully over the next few months, as the technologies for double-sided detectors are immature and need careful design and prototyping work to assure feasibility.

(c) *The DØ Silicon Tracker*

The Silicon Tracker consists of barrels made of silicon ladders, and of disks made of silicon wedge-shaped wafers. It will provide high resolution tracking for $|\eta| < 3.2$. An $r-z$ view of the full upgrade DØ tracking system is shown in Fig. 6 and a cross section in the $r-\phi$ plane of the Silicon Tracker is shown in Fig. 7. The small disks and some of the barrel layers are double-sided and the large disks and the rest of the barrel layers are single-sided.

Fig. 6 DØ upgrade half $r-z$ view showing the inner Silicon Tracker with four of the seven barrel segments and six of the full twelve disks, the outer Scintillating Fiber Tracker, with all four superlayers of fibers. A possible forward tracking system is also shown.

Fig. 7 DØ Silicon Tracker barrel $r-\phi$ view, showing four layers of ladders, (layers 2 and 4 double-sided), with good overlaps in all layers, including on the z side of the double-sided layers. There is an approximate 12-fold geometry which will be used to form trigger towers.

(d) *Design and Evaluation of Prototype Wedge Detectors at UCR*

This year we have completed the evaluation of the prototype F-disk wedge detectors which were designed at UCR and fabricated at Micron Semiconductor, UK [9] (11 detectors) and SINTEF SI, Norway [10] (9 detectors). The results are presented below and are being used to optimize the design of the final detectors for DØ. We found that almost all the prototypes fabricated at Micron were well within our specifications but only one out of nine of those fabricated at SI had leakage currents within the specifications. This was a major consideration when selecting the vendor for the final detectors. Unless specifically indicated, all of the results below refer to the detectors fabricated by Micron, since these detectors met all our design specifications.

The wedge detectors are double-sided with height 7.5 cm, active area 24.5 cm^2 and 1024 readout strips on each side. The readout pitch is $50 \mu\text{m}$ on both sides. The strips on the p-side are at a stereo angle of $+15^\circ$ and those on the n-side are at -15° . The strip length varies across the detector, as shown in Fig. 8.

Fig. 8 Layout of the strips on a double-sided wedge detector.

The detectors are fabricated on n-type silicon of thickness $300 \mu\text{m}$ and resistivity $> 5 \Omega\text{cm}$. They are ac-coupled to the readout electronics by capacitors integrated directly onto each strip.

The capacitor is formed by a thin dielectric layer between the strip implant and the aluminum metallization. Polysilicon resistors are used to bias the strips since this technology has been shown to be radiation hard [11].

Figure 9 shows a schematic of the p-side of the wedge detector mask layout. The p^+ strips are at a pitch of $50\text{ }\mu\text{m}$. The strips are metallized and the bond pads are angled at 15° to allow parallel wire-bonding to the SVX II chips. The effective bonding pitch is defined as $51.8\text{ }\mu\text{m}$. On the n-side, the n^+ implants are at a pitch of $50\text{ }\mu\text{m}$. On both sides, the implanted strips are connected via polysilicon resistors to a bias line. The polysilicon resistors have a nominal design value of $2\text{ M}\Omega$.

Fig. 9 Schematic of a wedge detector layout with polysilicon biasing (p-side).

The nominal implant strip width for the readout strips on the p-side and n-side is $10\text{ }\mu\text{m}$. This value was chosen to give a small interstrip capacitance and a reasonably large value for the

coupling capacitance. The coupling capacitors are formed by growing a 200 nm silicon dioxide layer over the implanted strip.

For n-type bulk silicon, the positive fixed oxide charge can create an accumulation layer at the silicon surface, causing a very low impedance path between neighboring n^+ strips. To circumvent this, p^+ isolation implants have been introduced between the n^+ strips in the prototypes fabricated at Micron Semiconductor.

Fig. 10 Cross section of the double-sided detector design. All dimensions are in microns.

The width of this implant (24 μm) was chosen to be as wide as possible to achieve a low interstrip capacitance [12]. Figure 10 shows a schematic cross section through the silicon wafer transverse to the strip direction for the prototype wedge detectors.

(d-i) *Depletion Voltages*

A measurement of the full depletion voltage is necessary to determine a suitable operating voltage for the detectors. Since it is desirable that all detectors in a barrel layer or F-disk have approximately the same operating voltage, we require the detector depletion voltages to be uniform to within ± 15 V.

We have determined the full depletion voltages of the prototype detectors by capacitance measurements directly on the detectors (Fig. 11), without the need for test structures. Although the measurements show a dependence on frequency, this is well understood and we were able to extract the full depletion voltage from these measurements. For our prototypes, the full depletion voltages fell in the range 18–50 V.

Fig. 11 Total detector capacitance vs. bias voltage for a prototype wedge detector.

(d-ii) *Leakage Current and Breakdown Voltage*

Shot noise due to the detector leakage current contributes to the overall noise of the readout electronics and should therefore be minimized in the detector fabrication process. Figure 12 shows a measurement of active area leakage current versus bias voltage for one of the wedge detector prototypes. The breakdown voltage (defined at a current of $10\text{ }\mu\text{A}$) is approximately 85 V , well above the full depletion voltage (20 V).

Fig. 12 Active area leakage current vs. applied voltage for a prototype wedge detector.

In our specifications we require that the active area leakage current per unit area be less than 120 nA cm^{-2} . For the wedge detectors, this is equivalent to a total current of about $3\text{ }\mu\text{A}$, or 3 nA per strip. The leakage current shot noise is then negligible compared with the series noise due to the detector capacitance.

(d-iii) *Breakdown Voltage of the Coupling Capacitors*

One of the important design parameters of the detectors is the breakdown voltage of the coupling capacitors. This must be well above the detector full depletion voltage to ensure reliable long term operation. Also, since the depletion voltage increases with time due to radiation damage, a high coupling capacitor breakdown voltage is necessary to ensure radiation hardness throughout the anticipated very long run.

Figure 13 shows a measurement of the leakage current as a function of applied voltage for two types of capacitors, one with a silicon dioxide dielectric, the other with both silicon dioxide and silicon nitride. The simple silicon dioxide capacitors have a breakdown voltage of 80 V. For the final detectors we will increase this to 100 V by increasing the thickness of the oxide layer or use the silicon nitride.

Fig. 13 Breakdown voltage determination for two types of coupling capacitors.

(d-iv) *Capacitance of the Coupling Capacitors*

To avoid loss of signal from the detector we require $C_C \gg C_D$ where C_C is the capacitance of the coupling capacitor and C_D is the detector strip capacitance. This requirement is a trade off with the requirement of high capacitor breakdown voltage. For the prototype wedge detectors, we used a 200 nm silicon dioxide layer as capacitor dielectric. For a 10 μm strip width, this results in a predicted breakdown of ≈ 100 V and a coupling capacitance of ≈ 17 pF/cm.

The coupling capacitance is shown as a function of measurement frequency in Fig. 14 for a typical coupling capacitor. The decreasing effective capacitance with increasing frequency was due to the finite resistance of the strip implantation, which became significant at higher frequencies [13]. This can be well modeled using an equivalent circuit network and it is found that the true capacitance is the value at low frequency. Therefore, the coupling capacitor capacitance can be measured directly, without requiring a test structure. The measured coupling capacitance for the prototype detectors was 160 pF, i.e. 21 pF/cm.

Fig. 14 Measured coupling capacitance vs. test frequency for a full length (7.5 cm) strip. The solid line is the prediction from a circuit model with the strip implant resistance included.

(d-v) *Bias Resistors*

Polysilicon resistor biasing was chosen since this method has been shown to be sufficiently radiation hard. The choice of resistance value is a trade off between minimizing the Johnson noise contribution of the resistor (favoring high values) and minimizing the voltage drop across the resistor due to radiation-induced leakage currents (favoring low values). A design value of $2\text{ M}\Omega$ has been chosen. We estimate a $2\text{ M}\Omega$ resistor will result in a noise contribution of 131 e^- rms (227 e^- rms) for a 132 ns (398 ns) sampling time. Since the expected noise is about 1000 e^- rms (disk detectors), the noise due to the bias resistor will contribute less than 2.5 % to the total noise.

We measured values of $4.6\text{ M}\Omega$ for the p-side resistors and $3.4\text{ M}\Omega$ for the n-side resistors. The uniformity between adjacent channels on each detector side was within 3 %. For the final detectors the manufacturer will be able to tune the polysilicon doping to get the correct value of $2\text{ M}\Omega$ on both sides. This was not possible for the prototypes because of the very small number of detectors produced.

(d-vi) *n-Side Interstrip Resistance*

As discussed above, to obtain a high interstrip resistance on the n-side, we used a $24\text{ }\mu\text{m}$ width p^+ isolation implant between the n^+ strips. The n-side interstrip resistance for the prototype wedge detectors was measured on a probe station by contacting dc probe pads on the n^+ strips. Figure 15 shows a result of such a measurement. The measured resistance is $20\text{ G}\Omega$. This demonstrates that the p^+ isolation implantation results in a high n-side interstrip resistance, as expected.

Fig. 15 Measurement of the interstrip resistance on the n-side of a prototype wedge detector.

(d-vii) *Detector Strip Capacitance*

The capacitance at the input of the SVX II is the total capacitance of one strip of the detector. Our design goal for the capacitance is 1.6 pF/cm for the p-side and 2.0 pF/cm for the n-side.

The interstrip capacitance was measured on the detector by probing a strip and its two nearest neighbors. The measured capacitance between the strip and neighbors is affected by the polysilicon resistors, which act as a shunt to ground at low frequencies, as well as the finite implant resistance. Figure 16 shows the measured capacitance of a DC strip to the two nearest neighbors.

Fig. 16 Measurement of the interstrip capacitance on the n-side of a prototype wedge detector.

Clearly evident is the effective capacitance falling off at higher frequencies due to the implant resistance, and the falling off at low frequencies due to the polysilicon resistors. Work is in progress to finalize these measurements.

(e) *Detector Simulations*

In order to predict the characteristics of silicon microstrip detectors for different layout geometries and fabrication techniques, we have performed detailed simulations using the packages DIOS and TOSCA. These are sophisticated semiconductor modeling packages using a finite element method to solve the semiconductor equations on a 2-d grid. Although these programs are *highly* CPU intensive, the use of such tools is important since it provides a method of evaluating designs without having to fabricate detectors, which is both expensive and time consuming. We have used these packages to simulate different detector geometries, primarily focusing on the most important properties – the interstrip capacitance and the interstrip resistance. This study is still in progress and we give some preliminary results below.

One of the parameters affecting the detector performance is the interstrip resistance for both sides of the detector. If the interstrip resistance is too small, all strips are effectively connected and the signal is spread over all strips, so that no position resolution can be obtained from the detector.

Fig. 17 Interstrip resistance vs. electron lifetime for a hole lifetime of $100 \mu s$

Figure 17 shows the interstrip resistance as a function of the electron lifetime for the n-side of the detector. For this simulation, the hole lifetime was fixed at 100 μs and the strip length was taken as 7.5 cm (the longest strips in our wedge detectors). For $\tau_n \gg \tau_p$ the interstrip resistance is dominated by the hole lifetime τ_p and therefore almost constant. On the other hand, for $\tau_n \ll \tau_p$ the interstrip resistance is dominated by the electron lifetime τ_n and therefore increases with τ_n .

Using $\tau_{eff} = 3$ ms, a typical value for the prototype detectors, the resulting interstrip resistance is about 20 G Ω . This is in reasonable agreement with the measured value of 25 G Ω .

To study the effect of different p-side strip layouts on the effective strip capacitance, we varied the strip pitch and the strip width on the p-side, using three different combinations:

- strip pitch 25 μm , strip width 10 μm ,
- strip pitch 50 μm , strip width 10 μm ,
- strip pitch 50 μm , strip width 16 μm .

A definition of the different capacitors contributing to the overall strip capacitance is presented in Fig. 18. After performing a TOSCA simulation it is possible to obtain the capacitance matrix between all ohmic contacts. Therefore we can obtain the capacitances shown in Fig. 18 as a function of the detector bias voltage. The results for the p-side with 25 μm strip pitch and 10 μm strip width are shown in Fig. 19. As expected, the capacitance C_{sb} decreases with increasing bias voltage proportional to $1/\sqrt{V_{bias}}$. This is due to the increase of the depletion zone, the depth of which is proportional to $\sqrt{V_{bias}}$. It reaches a constant level at full depletion, which is for this case about 65 V. The capacitance C_{is} also decreases with increasing bias voltage due to the decreasing of C_{sb} . This is due to the fraction of C_{is} that is formed as a series capacitance from both strips through the non-depleted part of the silicon. The capacitances C_{is2} and C_{is3} stay almost constant after an initial depletion needed to separate the individual strips.

Fig. 18 Individual capacitances contributing to the total strip capacitance.

Fig. 19 Capacitances for 25 μm strip pitch and 10 μm strip width on the p-side.

To investigate the effect of varying the p-side strip pitch and width, we performed several simulations with varying geometries. The results are summarized in Table 2. Note that the design with a strip pitch of 50 μm and a strip width of 16 μm has a similar total strip capacitance as the design with 25 μm pitch and 10 μm width. The design with the larger strip width would yield a higher coupling capacitance for a given oxide thickness.

detector side	strip width [μm]	strip pitch [μm]	C_{is} [pF/cm]	C_{is2} [pF/cm]	C_{sb} [pF/cm]	C_{tot} [pF/cm]
n-side	10	50	0.67	0.175	0.07	1.76
p-side	16	50	0.57	0.18	0.14	1.64
p-side	10	25	0.63	0.13	0.09	1.61
p-side	10	50	0.42	0.165	0.11	1.28

Table 2 Summary of silicon microstrip detector strip capacitances for different geometries. C_{is} , C_{is2} and C_{sb} are defined in Fig. 32, and C_{tot} is the total strip capacitance.

The results obtained from the simulations are in good agreement with the values measured on the prototype detectors. The results for different geometries are being used to optimize the final design of the microstrips.

(f) *Radiation Damage Studies*

Over the last year, the UC Riverside group (A. Heinson, J. Ellison) have examined the radiation environment that the Silicon Tracker will have to operate in, in the light of new higher luminosities predicted for the Tevatron Main Injector run, and using the results on depletion voltage change, annealing and anti-annealing from SDC radiation damage studies [15]. This work has lead to a decision on the maximum operating temperature of the Silicon Tracker of 10°C to ensure survival of the inner barrel detectors throughout Run 2 with the Main Injector. The radiation damage predicted for this barrel layer at such small radius from the beamline is comparable to that predicted for SDC silicon detectors operated at 20 cm radius for a 10 year SSC lifetime.

The radiation dose from accumulating 2 fb^{-1} of data has been calculated to be $\sim 1.1\text{ Mrad}$ (31.6×10^{12} charged particles / cm^2) on the inner barrel layer at 2.77 cm radius, plus an additional 3.6×10^{12} neutrons / cm^2 [3]. This amount of radiation will raise the noise by ~ 800 electrons. When added in quadrature to the initial detector noise and SVX II chip noise, the signal to noise ratio is expected to decrease from 17 to 15 which will not have a significant effect on the efficiency of the tracker. The main effect of the 1.1 Mrad dose will be the rise of the depletion voltage to $\sim 130\text{ V}$ if the detectors are operated at $\sim 20^{\circ}\text{C}$. The breakdown voltage of the coupling capacitors is $\sim 100\text{ V}$, and so the inner barrel layer detectors will become inoperable about half way through the run if they are inadequately cooled. If the silicon detectors are operated at $\sim 0\text{--}10^{\circ}\text{C}$, and kept at that temperature between running periods, then the anti-annealing will be controlled and the full depletion voltage will be kept below $\sim 80\text{ V}$.

Over the next few months, the UC Riverside group plans to finish the radiation damage calculations and fully document them. The results were presented at the DPF 94 meeting by Heinson [6].

(g) *Detector Procurement and Mask Design*

The UCR group, in collaboration with the DØ management and the Fermilab Purchasing department, are responsible for the procurement of all the silicon detectors for the silicon tracker. Due to the large number of detectors required and the large cost, the organization of this procurement is crucial to the success of the silicon tracker project. Based on our evaluation of the prototypes and the simulation studies, we have developed full specifications for the detectors [14] for use in the procurement process. Bids were received from three manufacturers and were evaluated by us in collaboration with Fermilab. The final contract was given to Micron Semiconductor – this decision was based on the low cost and the fact that Micron could meet all

our specifications. We have now placed orders for 600 single-sided detectors for the barrel layers 1 and 3, and 600 double-sided detectors for barrel layers 2 and 4 at a total cost of \$1.3M.

We are currently working with Micron on the design of the masks for the fabrication of the single-sided detectors for layers 1 and 3 of the barrel. The design is well underway and is expected to be finished by November 1994, after which production of detectors will begin. The next step will be to work on the design of the double-sided detectors for the barrel and disks.

(h) *Specification of Production Tests*

The first single-sided detectors should arrive in Spring 1995. To prepare for this we have set up test facilities at UCR, including a 500 ft² Class 10 000 clean room. The cost of this facility was approximately \$60,000 – funding came from J. Ellison's University initial complement. We are also in the process of setting up a computer controlled automatic probe station test facility which will be used for testing the silicon detectors when they arrive. We will test properties such as the leakage current and full depletion voltage and for each strip we will test the coupling capacitor to check for shorts. This information will be entered into a database for future reference during construction and running of the silicon tracker.

(i-i) *Laser Test Station*

In this section we describe the development and testing of an automated laser test station for testing and calibrating the modules of the DØ silicon tracker. Such a system is critical for quality assurance of the large number of silicon detector modules needed for future silicon trackers. Since the number of modules is so large, testing cannot be done in a test beam. Therefore, we have developed a test system capable of (a) testing and calibrating the electronics alone and (b) testing the response of detector modules to ionizing radiation. Our initial work has been concentrated on the latter subject.

(i-ii) *Conceptual Design of the Laser Test Station*

Module testing will be done using an automated laser test station. The module tester is based on the fact that a laser of the correct wavelength and power can simulate fairly closely the ionization profile of a minimum ionizing particle. Using a precision x-y translation stage, the laser can be directed at a single strip of the detector and can be stepped from strip to strip very quickly with 1 µm precision. By controlling the x-y stage and the data acquisition system by computer, every channel of the module can be tested automatically. This will immensely speed up the testing of modules compared with more conventional test methods such as test beams,

cosmic rays or radioactive sources. Ultimately, all the silicon detector modules of a large silicon tracking system could be tested with the laser station.

We have completed a conceptual design of the laser test station. The laser chosen has a wavelength of 1064 nm and a mean free path of about 200 μm (see section (c)) so that it probes the whole thickness of the silicon detector. The laser is coupled through the port of a microscope on a semiconductor probe station producing a circular spot of diameter 10 μm . The detector module is placed on a custom jig attached to the probe station x-y stage which allows the detector to be moved with respect to the laser spot via a GPIB interface. The whole system is controlled by a data acquisition computer (Macintosh or Sun). The detector module is read out using the VME DRS module and CIB cable interface. Detector bias and front end electronics power is supplied by GPIB power supplies and a GPIB controlled cooling system.

(i-iii) *Evaluation of Laser and Optics System*

Evaluation of a suitable laser has been completed. We selected a 1064 nm wavelength laser combined with a fast (< 1 ns) risetime pulse generator. For shorter wavelengths (e.g. 820 nm, a typical commercial IR wavelength) the photon mean free path is too short (about 20 μm for a 820 nm wavelength) so that almost all the photons interact in the surface region of the silicon detector. Therefore, only the surface can be probed and the laser is not sensitive to charge collection from the bulk of the silicon. However, the 1064 nm wavelength was expected to have a photon mean free path comparable to the typical thickness of a silicon detector (300 μm). This was verified by measuring the intensity of the laser beam after passing it through varying thicknesses of silicon. Figure 34 shows the measured intensity (pulse height in a photodetector) as a function of the thickness of silicon absorber. A fit to an exponential decay gives the photon mean free path. The measured value was 206 μm . As is evident from the figure, the photon intensity is reduced to $> 20\%$ after traversing 300 μm of silicon.

In order to test one channel at a time the laser spot should have a spatial size much less than the typical detector strip pitch (50 μm). The BNC laser is coupled to a 100 μm diameter optical fiber and therefore a method of focusing the laser light is necessary. To achieve this we studied two methods: one using a simple lens and another utilizing a high magnification microscope. Although both methods gave similar spot sizes we chose the latter option. This allows us to couple the optical fiber to the microscope of a semiconductor probe station, using the microscope objective lens to focus the laser light producing a 10 μm diameter spot. We designed a simple optical coupling system consisting of two lenses to produce an image at the focal plane of the microscope objective lens. This system was tested and implemented on our Alessi probe station. To allow easy imaging of the final laser spot we designed the optical coupling so that we could easily switch between the 1064 nm laser and a conventional visible light emitting diode. We

could then view the spot using the camera port on the microscope. Figure 35 shows an image of the spot on the surface of a silicon detector. The image of the spot is a uniform circle with a diameter of 10 μm . Another significant advantage of using this system, rather than a simple lens is that it allows easy viewing of the surface of the silicon detector. This is particularly important for diagnosis of the cause of bad channels.

Fig 34 Measured laser intensity as a function of silicon absorber thickness. Three separate measurements are shown.

Fig 35 Photomicrograph of the laser spot on the surface of a silicon detector. The light circle is the laser spot.

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OJI continuation proposal

**A study of quark and gluon jets and of the long
distance QCD force field at the Z^0**

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MASTER

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(1) Introduction

Quantum Chromodynamics (QCD) is widely accepted as the correct theory of the strong nuclear force in elementary particle physics. The precision to which QCD has been tested is relatively limited, however, compared to the precision to which other interactions such as the electro-weak one have been tested. In part, this is because the large value of the QCD coupling constant, α_s , renders theoretical calculations based on perturbation theory relatively imprecise. The confinement of quarks and gluons inside hadrons also leads to uncertainty because the theoretical predictions cannot, in general, be tested directly against the experimental measurements but are subject to hadronization corrections. From an experimental standpoint, it has proven difficult to isolate gluon jets inside multi-jet events in an unbiased manner so as to determine gluon jet properties using model independent methods. Basic quark-gluon interactions such as the four-jet matrix element in e^+e^- annihilations have been relatively untested due to the lack of a data sample with sufficient statistics. Perturbation theory has essentially nothing to say about the properties of the hadronization process itself. It is for these reasons that QCD has remained relatively untested.

In the absence of precise theoretical predictions, experiment can play an important role in exploring the nature of strong interactions through a study of the phenomenology of quark and gluon hadronization, by providing detailed and model independent measurements of quark and gluon jet properties and by a quantitative test of the production matrix elements for multi-jet final-states. The e^+e^- collider LEP offers a unique opportunity for these investigations because of the very large data samples collected at the Z^0 peak and because of the excellent detector capabilities. Theoretical uncertainties are not as large at the Z^0 energy as they are at the lower energies of previous e^+e^- colliders because α_s , and thus unknown higher order terms, are smaller

for LEP. The hadronization correction is also smaller for LEP's larger energy because it decreases like the inverse power of the center-of-mass energy. The larger jet energies at LEP mean that gluon jets evolve to an advanced stage through multiple soft gluon emission so that their properties exhibit the full structure that can be expected perturbatively. The large data samples at LEP permit original analysis strategies to be developed, leading to new possibilities for conclusive tests of the theory. Thus, the physics potential for QCD studies at LEP is very high.

It was to initiate a program of research to investigate quark and gluon jets and the hadronization mechanism using Z^0 data that a proposal for funding was submitted to the Department of Energy in October 1991, for the benefit of John William Gary, Assistant Professor of Physics at the University of California, Riverside. This funding for a three year grant was requested under the Outstanding Junior Investigator program and received approval in June 1992. The program was based on analysis of the multihadronic Z^0 sample of the OPAL detector at LEP. In the current document, we submit a continuation request for OJI support for the coming year, covering the period from February 1, 1994 to January 31, 1995. In section 2, the goals of the proposed research program are restated. The progress made during 1993 towards the achievement of those goals is summarized in section 3. Section 4 states our goals for the upcoming year. Section 5 contains a summary. The budget request is given in section 6.

(2) Research program

The study of multihadronic final-states in e^+e^- annihilations has contributed much to the experimental verification of QCD. Examples include the first observation of jet structure in high energy collisions, the measurement of the gluon spin and the demonstration that the coupling strength of QCD decreases in value for smaller distance scales. Many important features of QCD have remained essentially untested, however, for the reasons outlined in the introduction. There are three related fields of study which we are pursuing, using novel techniques in part introduced by us. All three utilize the OPAL data statistics and detector capabilities to their full potential. They are structured so as to yield direct, model independent and definitive results: (1) quark-gluon jet differences using rare events with special geometric properties, such as three-jet events in which a high energy gluon jet recoils against two identified quark jets, (2) angular correlations between jets in four jet events, as a means to test the four-jet matrix element, determine the gauge group "color factors" and demonstrate the non-Abelian character of QCD in a quantitative manner, and (3) multi-particle correlations between identified large mass hadrons such as protons, Δ^{++} baryons, Λ hyperons and ϕ mesons, as indicators of the dynamics of the underlying QCD field.

The first major area of investigation in our program is the detailed measurement of differences between quark and gluon jets using model independent techniques. Despite the large numbers of three-jet events recorded at PEP, PETRA and TRISTAN, it proved difficult to establish whether differences were present between quark and gluon jets as expected from QCD. The studies at these lower energy colliders employed jets which did not have the same energy or event environment. Thus, quark jets in two-jet events were compared to gluon jets in three-jet events or else gluon jets in

three-jet events were identified by requiring that they have the least energy of the three jets. As a result, these studies were model dependent, largely inconclusive and sometimes contradictory. I introduced a new analysis strategy to study quark and gluon jet properties, utilizing rare events in which quark and gluon jets had the same energy and environment within an event. Two-fold symmetric three-jet events were employed, in which the angles between the highest energy jet and each of the two lower energy jets were the same. For the configuration chosen, the highest energy jet was known to be a quark or antiquark jet with high probability, because of the nature of the gluon radiation spectrum. In some cases, one of the two lower energy jets could be identified as a heavy quark jet by the presence of a high energy lepton. The lepton tag on the quark jet marked the other lower energy jet as a gluon jet. The properties of these anti-tagged gluon jets were compared to those of the unbiased sample of quark and gluon jets from the untagged sample. Since the quark and gluon jets being compared had the same energy, event environment and selection criteria, they could be compared directly, with no need for Monte Carlo calculations to establish the results. This analysis strategy was used in two OPAL physics publications [1, 2], both of which are entirely my work. It was observed that gluon jets were broader and yielded a softer particle energy spectrum than quark jets, in agreement with the expectations of QCD. The pursuit of the study of gluon jet properties using the innovative techniques introduced by these two papers continues to be a major element of our program, as presented in sections 3 and 4.

The second major area of investigation in our program is the study of angular correlations between jets in four jet events. The purpose of this study is to determine the color factors of QCD and test the four jet matrix element. Measurement of the color factors is equivalent to a direct observation of the triple gluon vertex and so this study also constitutes a quantitative test of the non-Abelian aspect of QCD.

This investigation comprises the principal thesis matter for Shun-Lung Chu, a UCR Ph.D. candidate for whom I am thesis advisor. Details of this analysis are presented in section 3.

The third major area of investigation in our program is the study of the transformation of the long distance QCD force field into hadrons. The essential tool for this study is correlations between two or more large mass particles such as protons, Δ^{++} baryons, Λ hyperons and ϕ mesons. Large mass hadrons preserve the momentum information of the particles produced in the breakup of the QCD field. As such, they map out the field which connects the quarks and gluons, acting as probes of how the QCD field hadronizes. Light particles such as π mesons arise primarily from resonance decays and do not preserve this information as well. Correlations between large mass hadrons, such as the location in phase space of an anti-baryon relative to a baryon that has been identified in an event, test mechanisms for how basic quantum numbers such as baryon number or strangeness are created from the QCD vacuum. Such information, for which little experimental data currently exist, should provide considerable information about the phenomenology of quark and gluon confinement and result in strong constraints on popular models of hadronization such as the string [3], cluster [4] and UCLA [5] models. We are presently working to reconstruct the Δ^{++} resonance in our data and to measure its decay properties, as discussed in section 3.

(3) Progress report to October 1993

In this section, we summarize the progress that has been made towards realizing the goals of our research program.

After the grant of the OJI award, an advertisement was issued for a postdoc position in my research group. This resulted in the recruitment of Dr. Paul Schenk, a recent Ph.D. recipient whose UCR contract began December 1, 1992. Dr. Schenk has a background in system management of distributed workstation systems and in e^+e^- physics at the Z^0 pole. He has become rapidly integrated into my OJI program. In addition to Dr. Schenk, a second postdoc, Charles Jui, and a UCR Ph.D. student, Shun-Lung Chu, are full time members of my research group. Dr. Schenk and Mr. Chu are compensated 50% from my OJI contract and 50% from funds provided to me by the University. Dr. Jui is compensated 50% from my University funds and 50% from the main UCR-OPAL contract with DOE.

Using OJI grant money and University funds, I purchased eleven HP PA-RISC workstations. These workstations form a Monte Carlo farm, known as the RSF or "Riverside Snake Farm," to produce large samples of simulated Z^0 hadronic decay events. This farm has been in operation for about one year and three months and has been essentially trouble free. Several million simulated multihadronic Z^0 decays have been generated with this facility. The generated samples have been extremely helpful to my research and to the OPAL Collaboration as a whole. Dr. Jui was instrumental in the set-up and initial operation of this farm. Currently, Drs. Jui and Schenk take on joint responsibility to manage this cluster, which constitutes a major contribution of my OJI program to OPAL. Dr Schenk presented a conference report on the architecture and operation of the RSF cluster at the Conference on Computing in High Energy Physics held at Florida State University in February 1993.

This past year, we continued our program to compare quark and gluon jet properties using the model independent techniques invented by us. We studied new ways to identify the quark jets in two-fold symmetric three-jet events, using reconstructed secondary vertices from heavy quark decay in place of the leptons used in the first analyses. Reconstruction of secondary vertices in jets permits bottom quark jets to be identified and the methods we developed in our earlier studies of two-fold symmetric three-jet events [1, 2] to be applied. The data sample in our new study is about seven times larger than that which we used previously, allowing more detailed and quantitative tests of quark and gluon jet differences. The paper containing this new analysis was recently published in *Zeitschrift für Physik C* [6]. This new work is entirely the product of my OJI program.

As an example of the new results, fig. 1 (a) shows the inclusive scaled energy distribution, $(1/n_{total}) dn_{total}/dx_E$, for particles assigned to the quark and gluon jets in our study. From comparison of these curves, a substantially softer particle energy spectrum of the gluon jets, relative to the quark jets, is quite clear. This feature is expected in QCD due to the larger color charge of gluons compared to quarks. The ratio of the gluon to the quark jet distribution is shown in fig. 1 (b), from which the softer particle energy spectrum of the gluon jets is again very clear. Shown in comparison to the data in fig. 1 (b) are the predictions of Monte Carlo calculations which incorporate perturbative QCD along with different assumptions about the hadronization process. The three models Jetset-Peterson [7], Herwig [8] and Cojets623 [9], all of which include differences between quark and gluon jets, provide adequate descriptions of the data, while the model Cojets612 [9], which does not contain significant quark and gluon jet differences, is in clear disagreement with the data, as expected. This illustrates the sensitivity of our analysis to differences between quark and gluon jet structure.

Figure 1: (a) Inclusive scaled particle energy distributions of the quark and gluon jets, corrected for quark and gluon jet misidentification. (b) Ratio of the two curves in (a).

Since the quark and gluon jets in our study have the same energy, while the particle energy spectrum of the gluon jets is observed to be softer, the gluon jets can be expected to exhibit a larger mean multiplicity. This is indeed the case, as is shown in figure 2: the difference in mean multiplicity between quark and gluon jets is determined to be $1.27 \pm 0.04 (\text{stat.}) \pm 0.06 (\text{syst.})$, which is the first significant difference between quark and gluon jet multiplicities ever reported.¹ Again the models, with the exception of Cojets612, provide a satisfactory description of the data, although the quark jet is better described by Jetset and Herwig than it is by Cojets623.

The results from this paper were chosen to be some of the principal ones from

¹Prior to the OPAL work, the only published value for this ratio was $1.29^{+0.21}_{-0.41} \pm 0.20$ from the HRS Collaboration [10]

Figure 2: (a) and (b): Multiplicity distributions of the quark and gluon jets, corrected for quark and gluon jet misidentification. The Monte Carlo results include detector simulation and the same selection criteria as the data, except the quark and gluon jets are identified using Monte Carlo information.

OPAL for 1993. Dedicated conference talks were given on this analysis at the DPF meeting held at Fermilab in November 1992 and at the plenary sessions of the La Thuile and Moriond Conferences in March 1993. No other single OPAL publication received as much attention during this period. The presentation at the DPF meeting mentioned above was given by my postdoc Charles Jui on my behalf. At the request of the OPAL physics coordinator, Dr. Jui also presented my results at a CERN seminar in February 1993. I presented these results myself in seminars at Caltech, UCLA and LBL given in May, June and September 1993, respectively, and at the Multiparticle Dynamics meeting held in Aspen in September 1993.

This past year, we also continued our study to measure the QCD color factors

using angular correlations in four jet events. This study leads to a quantitative demonstration of the non-Abelian character of QCD. The values of the color factors, denoted C_F , C_A and T_F , are physical manifestations of the underlying structure of the group in which a gauge theory is embedded. For QCD, based on $SU(3)$, the color factors are $C_F=4/3$, $C_A=3$ and $T_F=1/2$, while for the Abelian gluon theory, based on $SU(1)_1$, $C_F=1$, $C_A=0$ and $T_F=3$. The ratios of the color factors, C_A/C_F and T_F/C_F , are sufficient to distinguish between the different gauge groups.

A measurement of the color factor ratios C_A/C_F and T_F/C_F at e^+e^- colliders is possible through the study of processes at order α_s^2 or higher. The most straightforward case is the study of angular correlations between jets in four-jet events. Four jet production in e^+e^- annihilations occurs through double gluon bremsstrahlung, the triple gluon vertex and four quark production. These three processes lead to different angular correlations between the four jets while their relative contributions depend on the values of the color factors. Using distributions sensitive to the angular correlations, the relative contributions of the three different processes can be separated and the color factor ratios determined.

We choose three experimental variables for our analysis, each of which has a different dependence on the three processes leading to four-jet final states. These experimental variables are constructed from the angles between jets in four-jet events. The three variables are: (1) the cosine of the Bengtsson-Zerwas angle, $\cos \chi_{BZ}$ [11], (2) the modified Nachtmann-Rieter variable, $|\cos \theta_{NR}^*|$ [12], and (3) the cosine of the angle between the two lowest energy jets, $\cos \alpha_{34}$ [13]. The analysis is based upon a simultaneous fit of the theoretical predictions for χ_{BZ} , $|\cos \theta_{NR}^*|$ and $\cos \alpha_{34}$ to the measured distributions, after the data have been corrected for detector and hadronization effects and for background from two- and three-jet events. The color factor ratios C_A/C_F and T_F/C_F and the overall normalization are used as the fit

parameters. An innovative feature of our study is the use of calculated jet energies. By using jet energies calculated from the directions of the jets, we achieve superior jet energy resolution and more reliable results than are attainable using visible jet energies. Use of calculated jet energies is a standard technique in three-jet analyses, but ours is the first experimental study to introduce it to four-jet kinematics.

The preliminary results of this analysis are now in the form of an OPAL physics note draft. They should be available as an official OPAL result for presentation at conferences and seminars in the near future. A publication containing the final results is expected within a few months time. Full details will be contained in the thesis of Shun-Lung Chu, for whom this analysis is the principal Ph.D. subject matter.

The use of calculated jet energy in four-jet events is a new technique introduced in this study. As an example of the benefit of this technique, fig. 3 shows the measured distributions of $\cos \chi_{BZ}$ and $|\cos \theta_{NR}^*|$ in comparison to various Monte Carlo curves. The parton level Monte Carlo curve, shown by the histogram, is included to serve as a reference representing the ideal case of a perfect detector with no hadronization uncertainty. The uncorrected data spectra of $\cos \chi_{BZ}$ and $|\cos \theta_{NR}^*|$ are shown by the circular symbols while the corresponding Monte Carlo plots, including simulation of the detector and the same analysis procedures as the data, are shown by the square symbols. The distributions constructed using calculated jet energies, shown by the filled circles for the data and filled squares for the Monte Carlo, are in good agreement with the histograms representing the parton level Monte Carlo, while the distributions constructed using the traditional method of visible jet energies, shown by the open circles for the data and open squares for the Monte Carlo, show considerable distortion relative to the parton level reference curve. Thus we obtain much smaller hadronization and detector corrections by introducing calculated jet energies into our analysis. It is also seen from fig. 3 that the filled squares agree with the filled

Figure 3: Comparison of distributions, from both data and Monte Carlo, constructed using visible jet energies and calculated jet energies, for (a) $\cos \chi_{BZ}$ and (b) $|\cos \theta_{NR}^*|$.

circles better than the open squares agree with the open circles: thus we obtain a better description of the data by the detector level Monte Carlo using calculated jet energies instead of visible jet energies, again leading to smaller uncertainties in the data corrections.

Our preliminary results for the color factor ratios C_A/C_F and T_F/C_F are shown in fig. 4. The measured values, $C_A/C_F = 2.168 \pm 0.156(stat.) \pm 0.221(syst.)$ and $T_F/C_F = 0.416 \pm 0.092(stat.) \pm 0.222(syst.)$ (preliminary), are in good agreement with the SU(3) values of QCD, which are $C_A/C_F = 9/4$ and $T_F/C_F = 3/8$, indicated by the filled star in fig. 4. Also shown in fig. 4 are the color factor ratios from other gauge groups than SU(3). Of these groups, only the $U(1)_3$ Abelian gluon model and SO(3) are realistic since it is only they which include three color degrees-of-freedom

Figure 4: Measured values of the color factor ratios C_A/C_F and T_F/C_F with 68% and 95% confidence-level contours. Expectations from various gauge models are also shown.

and which therefore describe the measured value of $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$: both these groups are excluded by our analysis by more than four standard deviations.

The third major area in which we have invested effort this past year is the investigation of heavy baryon production in multihadronic Z^0 decays. This effort has concentrated on the Δ^{++} baryon since we find its production rate in the Monte Carlo to be very sensitive to the assumptions about the baryon production mechanism. Furthermore, the Δ^{++} is one of the most important hadrons which has never been observed in e^+e^- annihilations above the Υ region. The Δ^{++} is also interesting because it is a spin 3/2 particle. A measurement of its production rate would allow the suppression factor for spin 1 diquarks, relative to spin 0 diquarks, to be determined:

this would be the first such measurement for non-strange baryons. Our first goal is to measure and publish the total production rate and differential energy spectrum of the Δ^{++} and its anti-particle. Following this, we intend to investigate multi-particle correlations involving the Δ^{++} and other large mass hadrons. This investigation is expected to yield further, detailed information about the mechanism of quark and gluon confinement.

Figure 5 shows some preliminary results from this study. The points with errors

Figure 5: Δ^{++} ($\bar{\Delta}^{--}$) mass peak for $0.1 < x_E$.

show the experimental data for proton-pion $p\pi^+$ mass combinations for which the proton has been identified using energy loss dE/dx information. The charge conjugate

states $\bar{p}\pi^-$ are also included. The p and π^+ are both required to emanate from the beam constrained primary event vertex point since the Δ^{++} decays strongly. For figure 5, the scaled energy, $x_E = 2 \cdot E_{p\pi^+}/E_{c.m.}$, is selected to be larger than 0.1. The shaded histogram in figure 5 shows the Monte Carlo prediction from Jetset with the Δ^{++} signal removed. Away from the region of the Δ^{++} mass, for values of $m_{p\pi^+}$ smaller than about 1.15 GeV/ c^2 or larger than about 1.35 GeV/ c^2 , the Monte Carlo and data are in good agreement, which demonstrates that the combinatoric background is well modeled. In the region of the Δ^{++} mass, for $m_{p\pi^+} \approx 1.15 - 1.35$ GeV/ c^2 , the data are in excess of the shaded Monte Carlo, which we interpret to be the first signal for Δ^{++} production ever observed in e^+e^- annihilations above the $\Upsilon(1S)$. Including the Δ^{++} in the Monte Carlo leads to the hatched histogram in figure 5, which agrees well with the measured distribution.

(4) Program for the next budget period

In the next budget period, our program will be to continue to expand our investigations in the research areas outlined in sections 2 and 3 above.

First, we intend to pursue our study of quark and gluon jet properties using model independent techniques. There are several extensions to our present analysis which we expect to investigate. One involves identified particles in multihadronic events. We intend to extend our earlier studies to examine the relative production rates of identified charged pions, charged and neutral kaons, protons and lambda hyperons in quark and gluon jets. Such differences in the relative abundances of different particle species in quark and gluon jets, should they exist, are expected to have a non-perturbative origin. Our results should therefore help to further establish the phenomenology of quark and gluon jet hadronization. A second aspect of quark and gluon jet differences which we expect to pursue involves the tagging of light quark flavors, instead of the exclusive reliance on heavy quark flavor tagging as we have done in the past. Use of a three-jet data sample with quark and gluon jet identification based on tagging light quark jet flavors will help to establish the universality of our results and to better assess systematic effects related to the tagging techniques, using the data alone. For example, one light quark tagging strategy involves the reconstruction of high energy K_s^0 mesons in jets to identify those which are initiated by strange quarks. A third aspect of quark and gluon jet differences which we expect to pursue involves the selection of different symmetric event topologies than those used in our present study. The principal reason for this is to obtain quark and gluon jets with larger energies than in our current analysis, since quark and gluon jet differences are expected to become larger as the jet energy increases. By using three-jet events with two tagged quark jets recoiling against the gluon jet, we could

conceivably obtain gluon jet samples with energies up to about 43 GeV, which is significantly larger than the jet energies of about 24 GeV used in our present study. Furthermore, a double tagged sample can be used to identify gluon jets in a manner which is independent of the particular jet finding algorithm chosen for the analysis, as is discussed in a recent article which I wrote [14]. A fourth aspect of the quark-gluon jet analysis which we intend to pursue is to repeat our recently published analysis [6] using a "cone" definition of the jets, similar to the jet definitions used at $p\bar{p}$ colliders. Use of the cone definition should allow a more direct comparison of our data with QCD analytic formulae and to jet data from the Fermilab Tevatron. First results on this last topic are expected for the near future.

Second, we intend to complete and publish our four jet event analysis and determination of the QCD color factors in the next budget year. We have written an OPAL physics note draft which is now being presented to the Collaboration. Once approved, our analysis will become an official OPAL result for presentation at conferences and in seminars. The current results are based on massless quarks in the four jet matrix element, valid to order α_s^2 . We next wish to perform additional analysis to ascertain the effects of massive quarks in the propagators. Furthermore, a new four-jet matrix element calculation, valid to order α_s^3 , may soon become available, which will allow the assessment of the next-to-leading order corrections to our results. If this new calculation becomes available on a timely basis, we may include it in our analysis before proceeding to publication.

Third, we intend to complete and publish our investigation of the production rate and inclusive energy spectrum of the Δ^{++} baryon. Once this analysis is completed, we will then initiate a study of correlations between the Δ^{++} and other baryons and large mass hadrons.

(5) Summary

In the next year we propose to continue our research program in the study of quark and gluon jet properties, four jet angular correlations, and the hadronization mechanism, using funds provided through the OJI program of the Department of Energy. Our program will be based on novel analysis strategies with the purpose of obtaining direct and model independent results. This study is to be performed using the data sample of the OPAL detector at the CERN e^+e^- collider LEP. In the past year, we have prepared and published a major study [6] on differences between quark and gluon jets, prepared a draft physics note on four jet angular correlations and the determination of the QCD color factors and have initiated an investigation into the production properties of the Δ^{++} baryon. We have presented conference talks at the DPF meeting at Fermilab, the Conference on Computing in High Energy Physics at Florida State University, the Multiparticle Dynamics conference at Aspen and the Meeting on QCD at 2 TeV at Michigan State University. In addition, we have presented research seminars on our results at CERN, Caltech, UCLA and LBL. In the next budget period, we intend to extend our program to include the study of identified mesons and baryons in quark and gluon jets, to test methods of tagging light quark jet flavors in three-jet events, to obtain tagged quark and gluon jet samples with higher energies than in our previous study, and to complete and publish our measurements of the QCD color factors and the Δ^{++} production properties.

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JOHN WILLIAM GARY
FEBRUARY 1, 1994 THROUGH JANUARY 31, 1995

	1994-1995
I. SALARIES	
A. SENIOR PERSONNEL	
1. J. W. Gary, Assist Prof. IV, 9 mo appt 1 1/2 mo Summer (\$40,500) 100%	\$7,088
B. OTHER ACADEMIC & STAFF	
1. Schenk, Postgraduate Researcher VI (\$32,688) 65%	\$21,867
2. S. L. Chu, Research Assistant\Grad. Student Researcher (\$24,864\34,212 on 9/94) 10 mos @ 50%; 2 mos @ 100%	\$16,659
TOTAL SALARIES	<u>\$45,614</u>
II. BENEFITS	
A. SENIOR PERSONNEL	
1. Gary, 9.5%	\$673
B. OTHER ACADEMIC AND STAFF	
1. Schenk, 20%	\$4,373
2. Chu, PFR, GSHIP, 1.74%	\$3,184
TOTAL BENEFITS	<u>\$8,230</u>
TOTAL SALARIES & BENEFITS	<u>\$53,844</u>
IV. TRAVEL	
A. Domestic (APS Mtg, FNAL, SLAC, SSC)	\$1,110
B. Foreign (HEP Mtgs, CERN Switzerland)	\$4,000
TOTAL TRAVEL	<u>\$5,110</u>
V. SUPPLIES & EXPENSES	\$1,500
TOTAL DIRECT COSTS	<u>\$60,454</u>
INDIRECT COSTS (25.4% MTDC - ON \$57,270)	\$14,547
TOTAL COST	<u><u>\$75,000</u></u>