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HIGH ENERGY ACCELERATOR AND COLLIDING BEAM USER GROUP

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A. Introduction

Since our last report, LEP at CERN and the OPAL detector have fulfilled a large part of their promised programs. From the first Z° event recorded at LEP by OPAL on August 13th, 1989 to the end of June 1990, OPAL has recorded ~120,000 multihadron events on tape. These events together with the several thousand lepton pair events have extended our critical tests of the standard model very substantially and have not found it wanting in any particular. The number of light neutrinos is found to be three, the mass of the Z° and the partial widths of the Z° to multihadrons, to e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ have been measured with precision, fixing $\sin^2\theta_W$ to 2% accuracy. The forward backward asymmetry and the partial hadronic widths agree well with the Standard Model (SM). QED works perfectly at LEP energies for $e^+e^- \rightarrow \gamma\gamma$ reactions. OPAL has pioneered stringent tests of QCD which the data has passed with flying colors, independent of the recombination schemes used. Asymptotic Freedom, that is a strong coupling constant that decreases as the energy increases, has been demonstrated to many standard deviations. The top quark mass been shown to be > 45 GeV independent of decay mode. An intensive search for Higgs scalar mesons has been carried out without success. The current OPAL lower limit is ~40 GeV for the standard Higgs, and close to that for the lightest minimum supersymmetric Higgs particles. No non-SM particles have been found: No b′, no excited leptons no new heavy charged or neutral leptons, no supersysmmetric particles, no technipions, etc. The mass limits for these conjectured particles tend to be close to the kinematical limit of ~ 45 GeV available in Z° decays.

The Maryland High Energy Physics Group has taken leadership roles in the OPAL luminosity monitor (R. Kellogg) and in the large Hadron

Calorimeter (A. Ball). Both instruments have been performing well. Dr. Alfred Lee, IV has been leading the luminosity working group and has made improvements in the on-line and off-line system used to obtain the luminosity's measurements and to make these results accessible to the whole collaboration. Mr. Wayne Springer played a crucial role in bringing on the hadron calorimeter on-line system in a timely manner. The trigger electronics for the hadronic calorimeter has been delivered to CERN but it will not be incorporated into the OPAL trigger matrix until the next run in 1991. Prof. A. Jawahery has been in residence at CERN since January, 1990. He has been leading the $b\bar{b}$ working group for OPAL, and will present their first results at the Singapore Conference. Dr. Austin Ball will present OPAL's results on the search for Higgs particles at the Singapore Conference. Dr. R. Kellogg gave an invited paper on OPAL's physics results at the Spring meeting of the American Physical Society in Washington, D. C.

Dr. Andrew Baden hs been appointed an Assistant Professor, effective July 1, 1990. He has joined Prof. Hadley on the Dϕ experiment at Fermilab after helping to set limits on the top mass with CDF. He has also begun to play a significant role in the SDC proposal to the SSC that our group has joined. Prof. Hadley has recruited a research associate, Dr. Kathleen Streets, and at least two graduate students to work with him on the Dϕ project alongside Drs. A. Baden and S. Kunori. Part of our technical staff has been engaged in constructing current monitoring electronics at Maryland for Dϕ and Professor Hadley is playing a leading role in planning for Dϕ upgrades.

The E665 experiment has begun to present physics results on deep inelastic muon interactions on nucleons and nuclei from data taken in the 1987-88 FNAL fixed taget cycle, e.g. an invited paper and eight contributed papers at the April 1990 Washington APS meeting. A second run is underway now and is going well. Erik Ramberg has completed his Ph.D. thesis on π° production and is now working at Fermilab. Our two other graduate students, S. Aid and S. O'Day, are expected to complete their Ph.D. theses on this experiment during the current contract period. Dr. S. Kunori has played a crucial role in this experimental program since its inception.

Dr. A. Jawahery and his student Chul Park have completed an analysis of the 1988 CESR run on the 5S $\Upsilon(b\bar{b})$ state, obtaining evidence for the production of the B_s meson at this resonance. Mr. Park will soon complete his Ph.D. thesis on this subject and has taken a job at Fermilab.

Prof. C. Y. Chang, besides participating strongly in the OPAL experiment, continues to participate in the CYGNUS experiment at Los Alamos. The Air Shower Array has been increased by ≥ 2 in number of counters and by 4 in total area. Despite this, no new burst signals have been recorded. One cute new result that confirms the angular sensitivity of the detector is the observation of the attenuation of cosmic rays by the moon, which subtends only 0.2 square degrees of the sky. A new efficient on-line system has been installed that allows study of the data at Maryland nearly in real time.

The final results of $\nu_e e^-$ elastic scattering experiment carried out by Dr. R. Talaga and D. Krakauer with collaborators have been published. They were highlighted in the review talk given by Dr. P. Vilain at the ν'90 Conference in CERN in June. A new limit to the neutrino magnetic moment is a by product of this experiment. Dr. Krakauer has received his Ph.D. for this work at Maryland and is now employed at ANL.

The experimental test of the Pauli Principle to a level of ~ 10^{-26} has been published in Physics Letters and was one of the contributed papers at a special session on the subject held at the 1990 Washington APS meeting. A few more papers from the JADE collaboration have been published with the participation of G. T. Zorn.

A great deal of time, energy and travel funds have gone into our efforts with respect to the SSC. The Maryland group has joined the Solenoidal Detector Collaboration and has helped to write the EOI for that consortium. Prof. Skuja is the leader in this effort and has organized a team to design the forward muon detectors for SDC. Prof. Baden is a leader of the software design team for SDC.

Dr. Douglas Fong and our student managers have successfully completed the upgrade of the Maryland HEP Computer System allowing our VAX 780 to be retired.

Since Prof. George Snow is approaching retirement age, it is wise to submit this proposal with a younger Co-Principal Investigator, namely Prof. Andris Skuja. This choice has been discussed with all the co-investigators and has their approval.

B. OPAL Experiment at LEP. (A. Ball, C. Y. Chang, D. Fong, S. Hou, A. Jawahery, R. G. Kellogg, A. Lee, IV, J. Lorah, A. Skuja, G. A. Snow, and R. W. Springer at the U. of Maryland in collaboration with physicists from Birmingham, Bologna, Bonn, Cambridge, Carleton, CERN, Chicago, Freiburg, Heidelberg, QMC London, London Birckbeck, London Brunel, UC London, Manchester, Montreal, NRC of Canada, Rutherford Lab., Saclay, Technion, Tel-Aviv, Tokyo, UC Riverside and Weizmann Inst.

B.1 Physics with OPAL

As of July 25, 1990 OPAL had recorded 122,000 Z° hadronic decays and 12,000 leptonic decays, almost equally divided in the e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states. A wide variety of physics subjects have been addressed this past year with subsets of this data. Twenty-one papers have been published or submitted for publication in refereed journals and many more are in pro= gress. The topics range from testing the Standard Model by detailed studies of the mass, width and decay properties of the Z°, searching for the Higgs scalar, testing QCD in the Z° mass region and determining the strong coupling constant $\alpha_s(M_z)$, searching for rare decay modes of the Z° and for new heavy particles. All the searches have been without success. The data supports very strongly the Standard Model with three light neutrinos, and the Quantum Chromodynamics theory of the strong interactions. QED without modification at the 100 GeV/c momentum region is also confirmed. Important new lower limits have been set for the mass of the Higgs scalar meson and the possibility that the dark matter in the universe consists of wimps in the Gev mass region has been virtually eliminated. It has been an exciting year. In what follows we will touch on some highlights leaving out most of the experimental details which are given in the published papers.

(a). Analysis of Z° Couplings to Hadrons and Charged Leptons

We report on an improved measurement of the mass of the Z° boson, its total width and its partial decay widths into hadrons and leptons. On the basis of 112,237 hadronic decays and 11,327 decays into electrons, muons and taus, selected at center of mass energies near to the mass of the Z° we obtain from a combined fit to hadrons and leptons a mass of $M_Z = 91.174 \pm 0.011$ (exp) ± 0.021 (LEP) GeV, and a total width of $\Gamma_Z = 2.505 \pm 0.020$ GeV. The errors on M_Z have been separated into the experimental error and the uncertainty due to the LEP beam energy. The measured leptonic partial widths are $\Gamma_{ee} = 82.7 \pm 1.3$ MeV, $\Gamma_{\mu\mu} = 85.9 \pm 2.0$ MeV, and $\Gamma_{\tau\tau} = 83.9 \pm 2.3$ MeV, consistent with lepton universality. From a fit assuming lepton universality we obtain $\Gamma_{l^+l^-} = 83.6 \pm 1.0$ MeV. The hadronic partial width is $\Gamma_{had} = 1778 \pm 26$ MeV. The ratio of the hadronic to the leptonic partial width of the Z° is measured as $R_Z = 21.26 \pm 0.32$. From the measured total and partial widths a model independent value for the invisible width is calculated to be $\Gamma_{inv} = 476 \pm 25$ MeV, corresponding to $N_\nu = 2.86 \pm 0.15$.

The couplings of the Z° to charged leptons are studied using measurements of the lepton pair cross sections and forward-backward asymmetries of the lepton pairs. Using a parametrisation of the lepton pair differential cross section which assumes tha the Z° has only vector and axial vector couplings to leptons, the square of the product of the effective axial vector and vector coupling constants of the Z° to charged leptons is determined to be $\hat{a}_l^2\hat{v}_l^2 = 0.0039 \pm 0.0033$, in agreement with the Standard Model. A parametrisation in the form of the improved Born approximation gives effective leptonic axial vector and vector coupling constants $\hat{a}_l^2 = 1.005 \pm 0.012$ and $\hat{v}_l^2 = 0.0038 \pm 0.0033$. In the framework of the Standard Model, the values of the parameters ρ_Z and $\sin^2\bar{\theta}_W$ are found to be $\rho_Z = 1.005 \pm 0.012$ and $\sin^2\bar{\theta}_W = 0.2346^{+0.0095}_{-0.0057}$ respectively. Using the relationship in the minimal Standard Model between ρ_Z and $\sin^2\bar{\theta}_W$, the result $\sin^2\bar{\theta}_W^{SM} = 0.2315 \pm 0.0028$ is obtained.

This is the third paper by the OPAL collaboration on this important subject. It was presented at the 25th International Conference on High Energy Physics, Singapore, August 1990.

Table 15 displays the numerical results mentioned above in tabular form. Note that the dominant error on the mass of the Z° is now the error in the LEP machine energy. To give a more graphical form to some of these results we display in Fig. 5 how well the OPAL values for Γ_Z and σ_{had} at the Z pole agree with the Standard Model with three light neutrinos. Fig. 6 shows the energy dependence of the four reactions $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ and hadrons in the total 1989 + 1990 data sample. Fig. 7 shows the Forward-backward charge asymmetries A_{FB} for the three reactions: (a) $e^+e^- \rightarrow e^+e^-$, $|Cos\theta_{e^-}| \leq 0.7$ (b) $e^+e^- \rightarrow \mu^+\mu^-$, $|Cos\theta_{\mu}| < 0.95$, and (c) $e^+e^- \rightarrow \tau^+\tau^-$ $|Cos\theta_{\tau}| < 0.90$. In this figure, the $e^+e^- \rightarrow e^+e^-$ cross sections and asymmetries are corrected for the t-channel contributions. The solid lines are the results of the fit to the combined set of leptonic and hadronic data with the parameters listed in Table 15. Table 15 also shows that the luminosity measurement has reduced its error to 1.6% overall (< 0.8% point to point). Some details about how this was accomplished is given in Section B.2. Figure 8a shows how well the OPAL results for the product of the (vector coupling x axial vector coupling)^2 and the average leptonic width Γ_{ll} as measured by OPAL agrees with the Standard Model prediction for $50 < m_t < 250$ GeV/c^2 and $20 < M_H < 1000$ GeV/c^2. Figure 8b shows a similar comparison on the Γ_{hadron} vs Γ_{lepton} plane. Again one sees that the Standard Model and the OPAL data agree within a standard deviation.

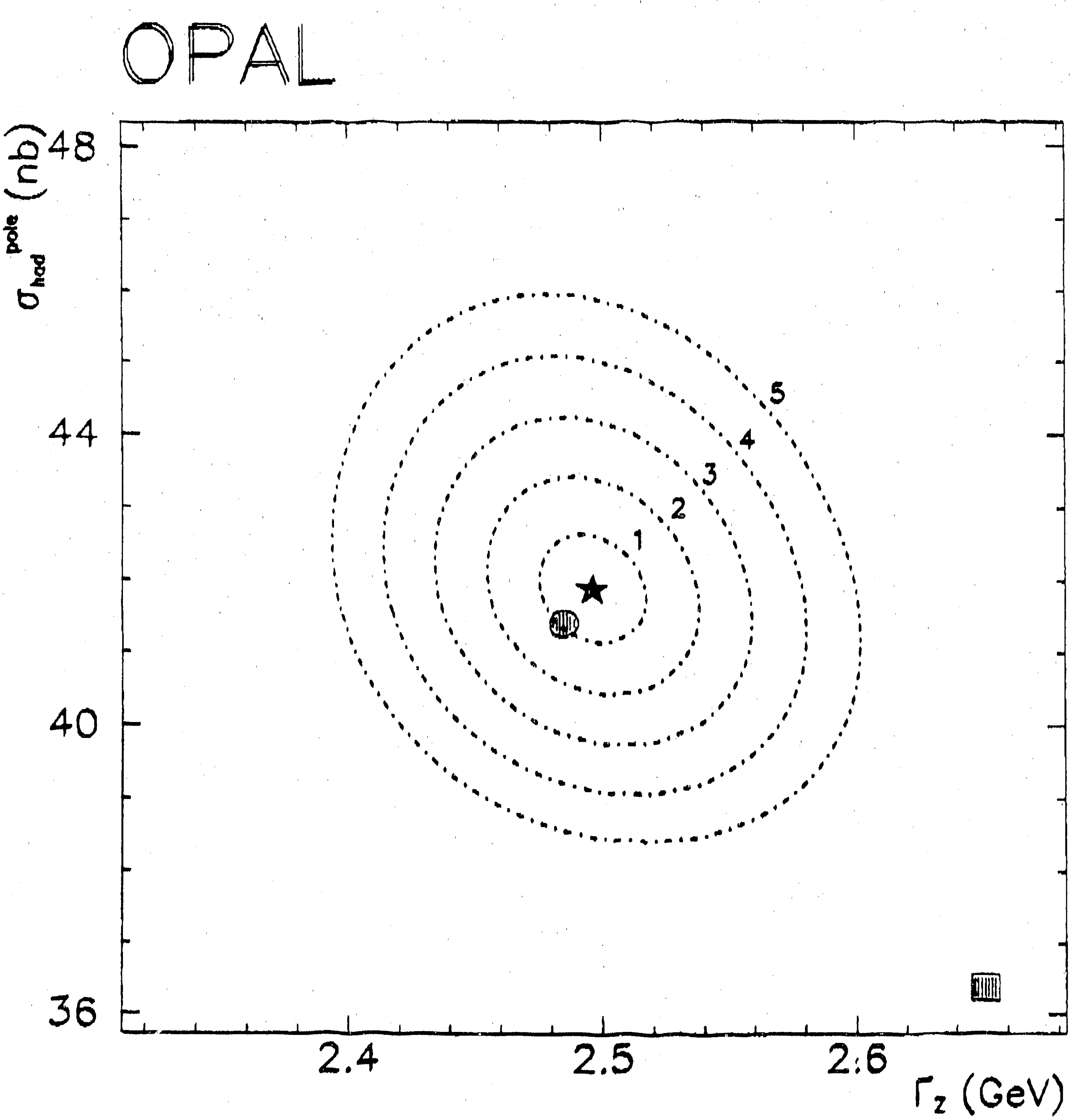
If one uses the <u>Standard</u> <u>Model</u> one loop calculations together with the data, one can obtain an estimaate of the top quark mass by combining Γ_{had} and $\Gamma_{l\bar{l}}$. One finds $M_T = 154^{+55}_{-94}$ GeV including an error on α_s of ± 0.02. By

parameter	value (now)	value (Phys in Coll)	comments
N_{had}	112,237	82,100	
N_{ee}	3,263	1,800	
$N_{\mu\mu}$	4,642	3,050	
$N_{\tau\tau}$	3,412	2,550	
N_{ll}	11,327	7,400	
Γ_{ee}	82.7±1.3		
$\Gamma_{\mu\mu}$	85.9±2.0		
$\Gamma_{\tau\tau}$	83.9±2.3		
$\Gamma_{l^+l^-}$	83.6±1.0	83.1±1.5	
$\hat{a}_l^2 \hat{v}_l^2$	0.0039±0.0033	0.0054±0.0046	
$\hat{a}_l^2$	1.005±0.012	0.9964±0.018	
$\hat{v}_l^2$	0.0038±0.0033	0.0056±0.0046	
ρ_Z	1.005±0.012	0.996±0.018	from fit to ρ_Z and $\sin^2\overline{\theta}_W$
$\sin^2\overline{\theta}_W$	0.2346±0.0076	0.2310±0.0090	from fit to ρ_Z and $\sin^2\overline{\theta}_W$
$\sin^2\overline{\theta}_W$	0.2315±0.0028	0.2321±0.0044	from fit to $\sin^2\overline{\theta}_W$ alone
M_Z [GeV]	91.174±0.011	91.171±0.019	
Γ_Z [GeV]	2.505±0.020	2.496±0.029	
Γ_{had} [GeV]	1.778±0.026	1.766±0.034	
σ_{had}^{pole} [GeV]	41.88±0.74	41.5 ±1.0	
R_Z	21.26±0.32	21.25±0.49	
Γ_{inv} [MeV]	476±25	481±34	
N_ν from Γ_{inv}	2.86±0.15	2.89±0.20	

errors	σ_{tot}^{90}	σ_{tot}^{89}	σ_{corr}
Lumi (overall)	1.6%	2.2%	1.25%
Lumi (ptp)	< 0.8%	1% - 3%	
hadron selection	0.8%	0.8%	0.8%
electron selection	1.0%		1.0%
muon selection	0.9%	2.3%	0.0
tau selection	1.6%	3.6%	1.9

Table 15: Comparison of the fits to the hadronic cross section and to the combined e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ cross sections and forward-backward asymmetries based on the improved Born approximation.

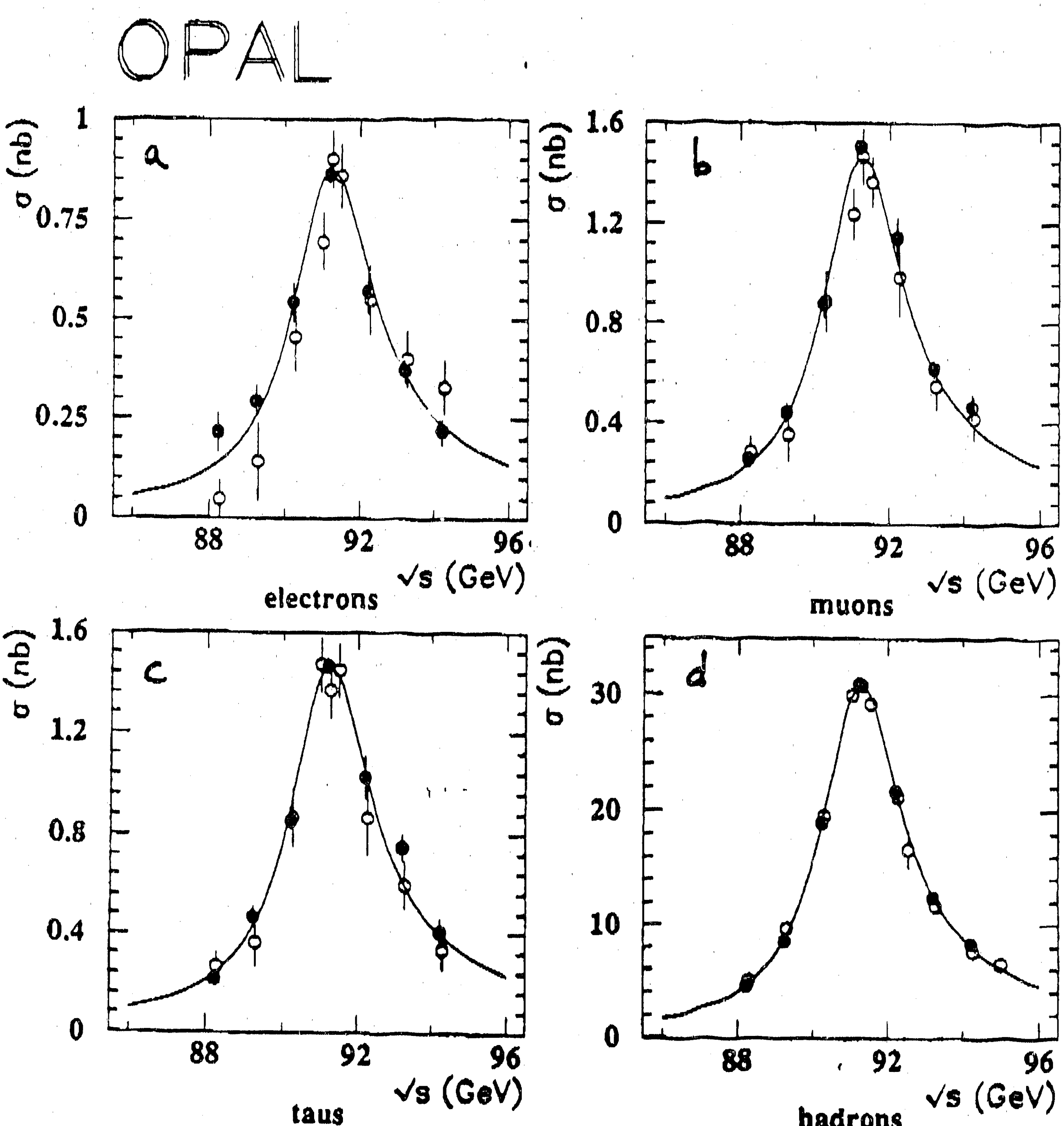
Fig. 5



1989 DATA

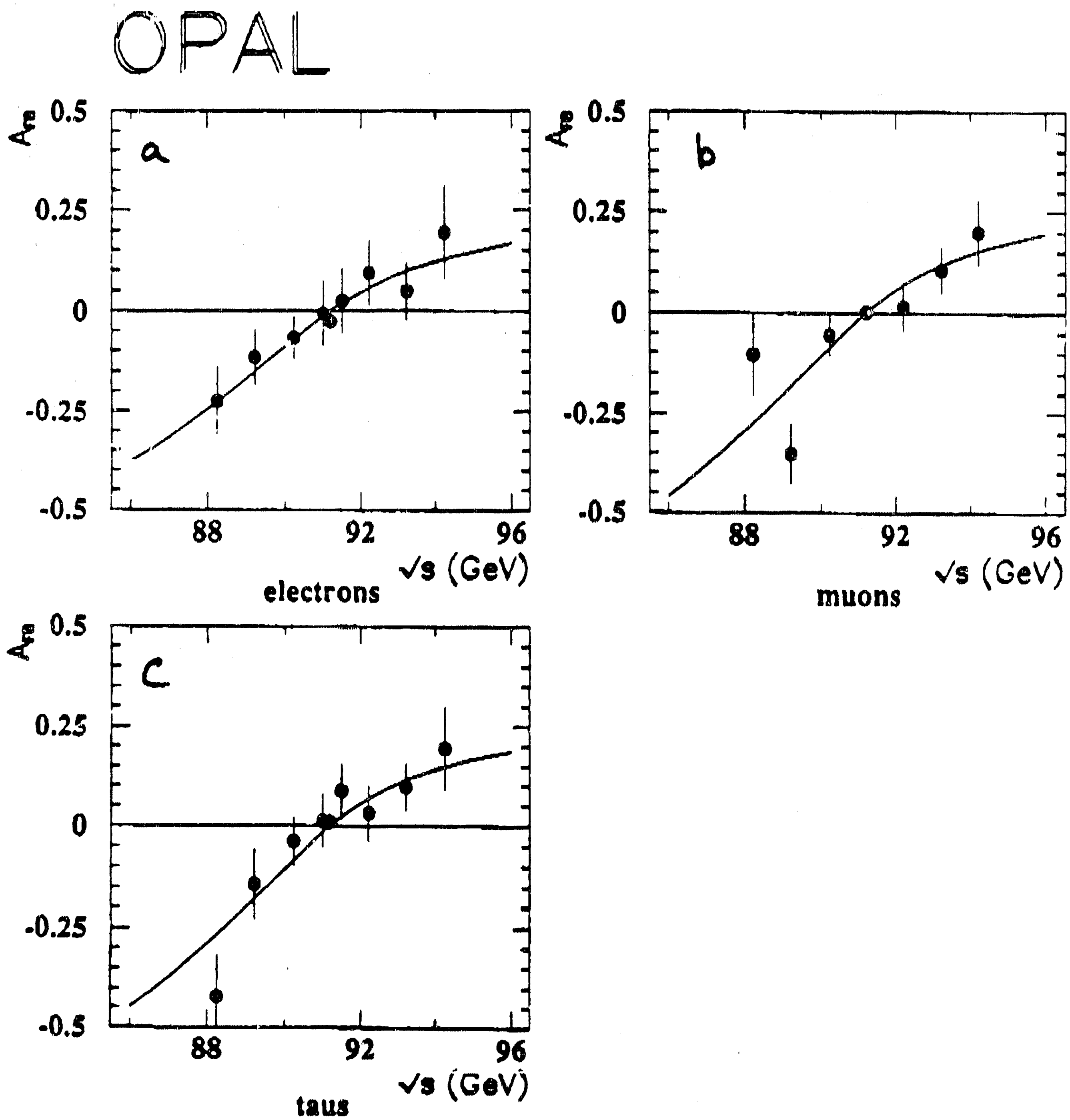
1990 DATA

FIG. 6



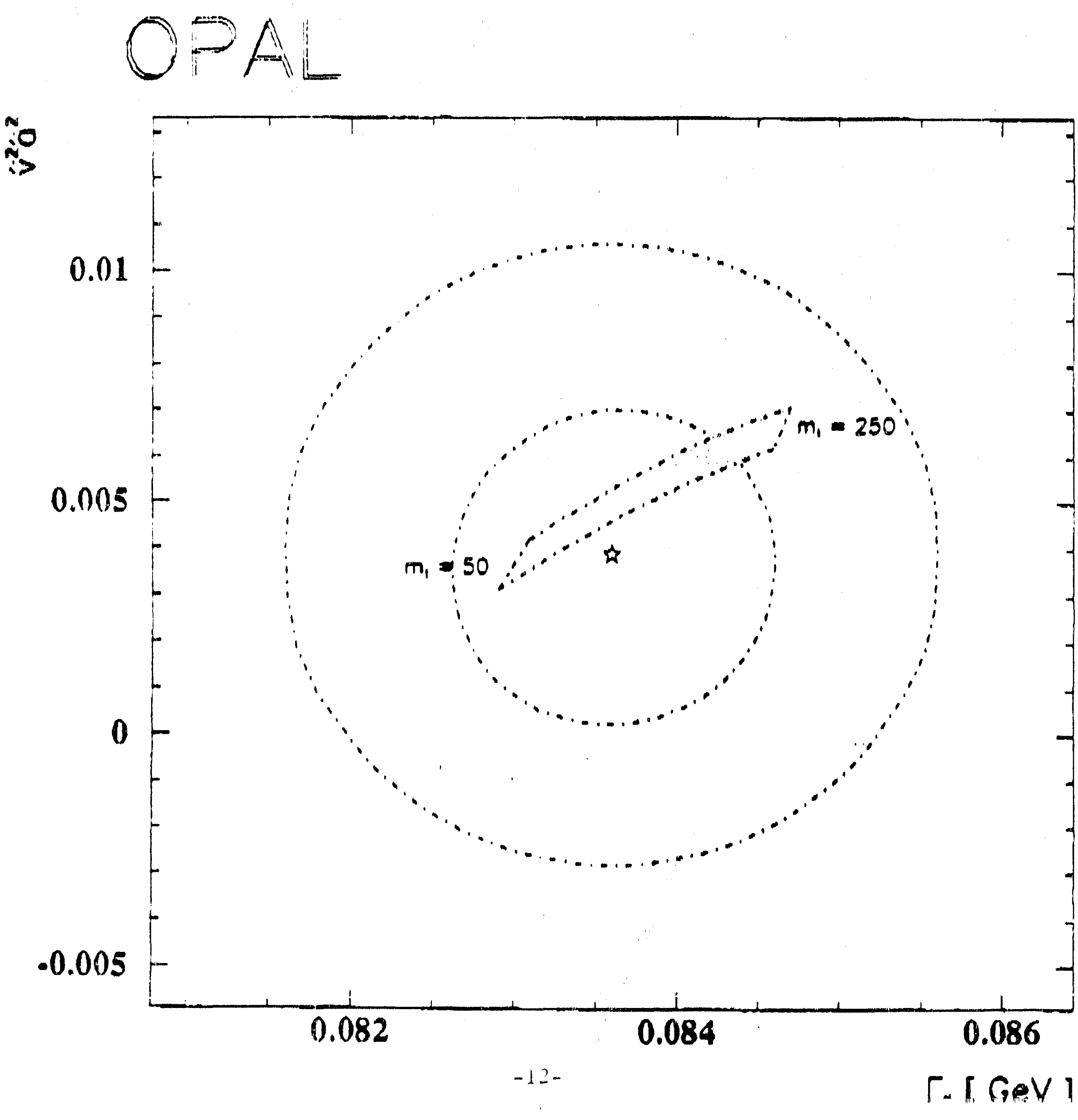
1989 + 1990 DATA COMBINED

FIG. 7



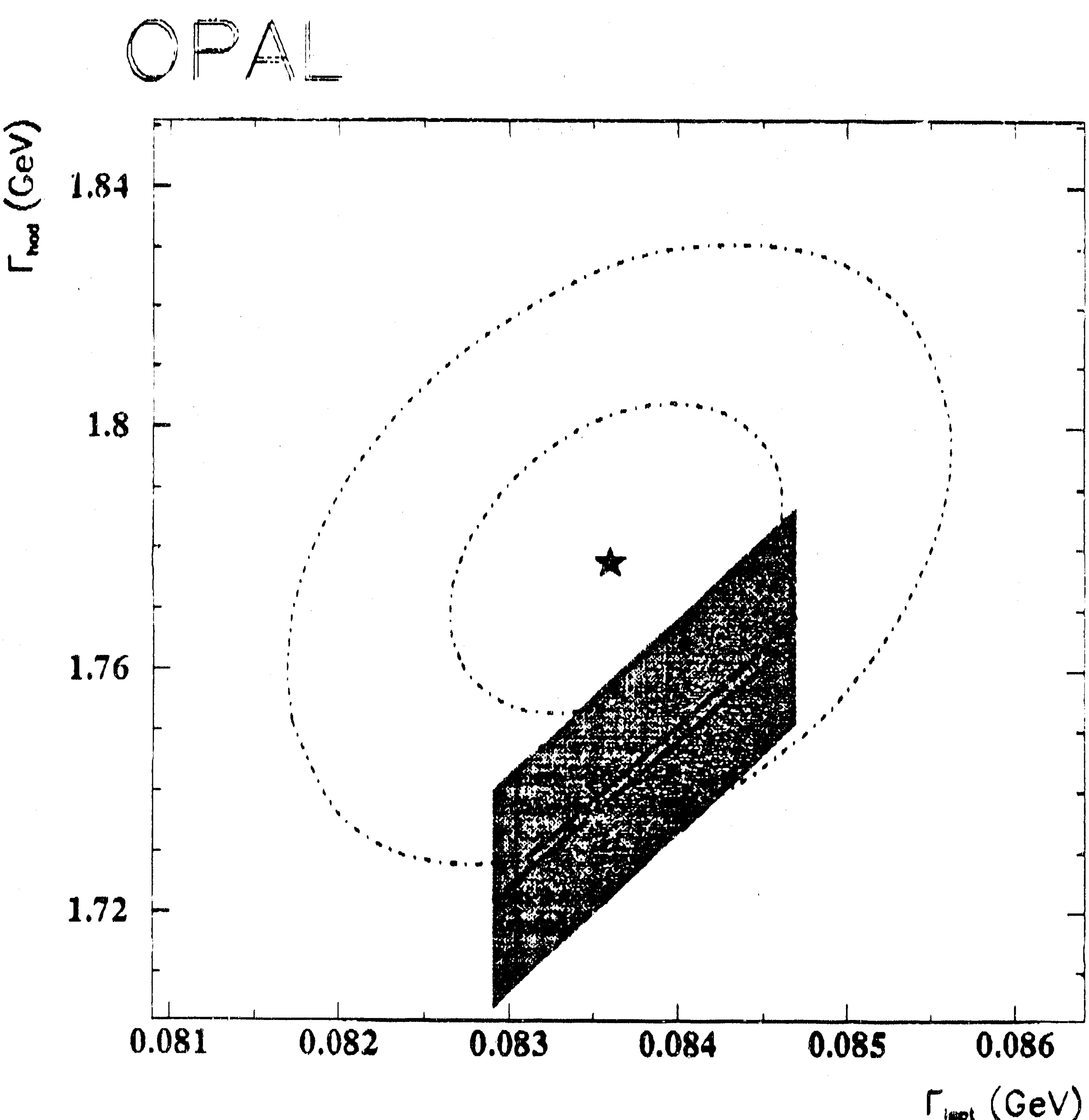
1989 + 1990 DATA

FIG. 8 a



1989 + 1990 DATA

FIG. 8b



combining OPAL data with the CDF and UA2 data on M_W/M_Z $(1 - M_W^2/M_Z^2 = 0.2254 \pm .0065)$, one can deduce $M_T = 144\ ^{+39}_{-50}$ GeV. A still lower upper limit for the mass of the top is obtained if the OPAL LEP data is combined with low energy data of νq, νe and eq scattering, i.e. $M_T = 106\ ^{+61}_{-\,..}$ GeV. All of the above estimates assumed M_H = 100 GeV and $\rho_{tree} = 1$. Allowing M_H to vary from 40 to 1000 GeV, as has been studied by J. Ellis and G. L. Fogli, CERN-Th 5817/90, degrades the upper limits quoted by about 20 GeV.

(b) Search for Higgs bosons.

One of the major thrusts of the OPAL experiment at LEPI is to search for the Higgs boson via the reaction $e^+e^- \rightarrow Z^\circ \rightarrow Z^* + H^\circ$ where the $Z^* \rightarrow \nu\bar{\nu}$, $l\bar{l}$ or jetjet and the $H^\circ \rightarrow \tau\bar{\tau}$ or $b\bar{b}$. As more data is accumulated, the mass limit of the standard Higgs boson is constantly being pushed higher. For the Singapore Conference analyses were carried out on 3.9 pb^{-1} of data from the 1990 run and were combined with the earlier 1.27 pb^{-1} of data from 1989. A new search method was used to optimize the search in the mass region $M_H > 30$ GeV/c^2. The result is that a Standard Model Higgs boson with mass in the range $3.0 \le m_{H^\circ} \le 39.4$ GeV/c^2 is excluded at the 95% confidence level.

The most sensitive reaction for this search is that in which the Z^* is invisible ($Z^* \rightarrow \nu\bar{\nu}$). The idea in the search is to look for acoplanar events in which the Higgs decays into one or two jets with a large missing transverse momentum. A large number of cuts are imposed that eliminate standard Z° hadronic decay events but have the $\nu\bar{\nu}\ H^\circ$ events with an efficiency $\gtrsim 60\%$. Tables 1, 2 and 3 exhibit these phenomena for the OPAL data sample, the QCD Monte Carlo events and for a sample of generated high mass Higgs events. Zero events were found after cuts in the data in the three samples $\nu\bar{\nu}$ jet jet, $l\bar{l}$ jet jet where l = e or μ, and $\tau\bar{\tau}$ jet jet. Combining

Table 1: Effects of the cuts for the $\nu\bar{\nu}$ search channel for periods 5 - 13. The cuts are described in detail in the text. The MC events, based on a sample of 40,000 JETSET 7.2 and HERWIG 4.3 multihadrons, have been normalized to the integrated luminosity of the data. The signal MC makes use of GOPAL in the "full" mode.

Cut	Data	QCD MC	H^0 of mass 36 GeV/c^2	H^0 of mass 40 GeV/c^2
–	2.7M	70332	400	398
A0 (Preselection)	62677	63726	365	353
A1 (θ_{GCE})	57455	58611	352	337
A2 ($\theta_{hemi\ 1,2}$)	49573	50257	346	320
A3 ($E_{endcap\ region}$)	48405	49148	310	289
A4 ($p_T > 6\ GeV/c$)	23225	21495	298	270
A5 (Acolinearity)	161	117	277	240
A6 (M_{inv})	25	19	277	239
A7 ($M_{hemi\ 1,2}$)	15	11	274	236
A8 ($E_{back,HC}$)	2	7	268	227
A9 ($E_{back,CD,EM}$)	0	0	268	222

Table 2: Number of events passing all cuts, except the one indicated, for the $\nu\bar{\nu}$ search channel for a sample of 400 MC Higgs bosons. The cuts are described in detail in the text.

Cut	Data	H^0 of mass 36 GeV/c^2	H^0 of mass 40 GeV/c^2
A1 (θ_{GCE})	1	2	1
A2 ($\theta_{hemi\ 1,2}$)	0	1	2
A3 ($E_{endcap\ region}$)	6	32	28
A4 ($p_T > 6\ GeV/c$)	47	6	11
A5 (Acolinearity)	4	7	13
A6 (M_{inv})	1	0	1
A7 ($M_{hemi\ 1,2}$)	2	3	3
A8 ($E_{back,HC}$)	4	6	9
A9 ($E_{back,CD,EM}$)	2	0	5

Table 3: Efficiency of the $\nu\bar{\nu}$ search. The efficiencies were obtained using approximately 400 full-GOPAL and 2000 "smear"-GOPAL events at each mass; the latter was used to establish the m_{H^0} dependence of the acceptance, and the former for the absolute acceptance.

m_{H^0} (GeV/c^2)	efficiency (%)
36	64 ± 2
38	62 ± 2
40	60 ± 2
45	57 ± 2
50	43 ± 2

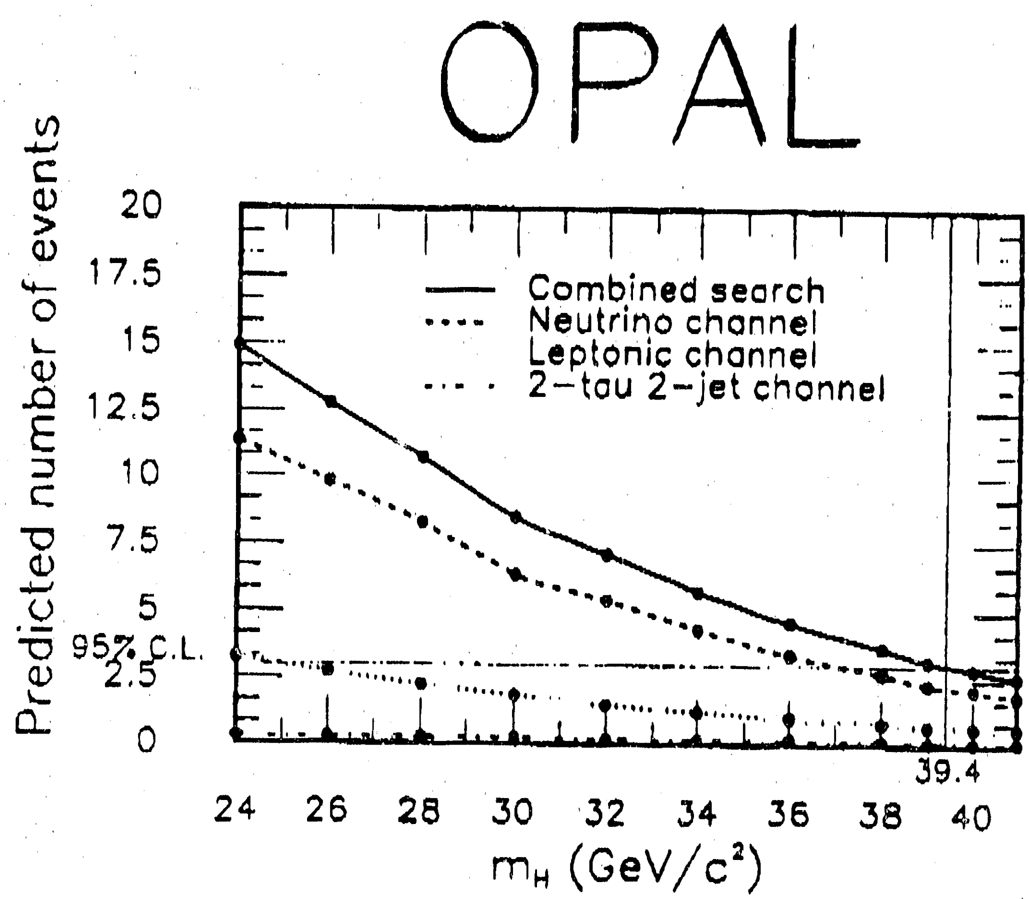
these results and allowing for theoretical and systematic uncertainties one obtains the predicted number of events shown in Fig. 1, which leads to the mass limits already quoted. A separate analysis has eliminated a very light Standard Model Higgs with $M_{H^\circ} < 2\ m_\mu$ in which the H° is invisible or decays into e^+e^- or $\gamma\gamma$.

Other important theoretical possibilities for Higgs bosons lie in the minimal supersymmetric theories. In this case the lightest of three "Higgs" bosons is less massive than the Z° and one of these three bosons is a pseudo scalar so that the decay $Z^\circ \rightarrow h^\circ + A^\circ$ can occur with an appreciable probability if allowed kinematically. This decay has been searched for in the 4 jet, 2 jet + $\tau\bar{\tau}$ and 2 $\tau\bar{\tau}$ configuration but without success. A detailed paper on the techniques used in this search has been submitted to Zeits. fur Phys. C. The results have again been updated for the Singapore Conference and are displayed in Figs. 2a and 2b for the two regions of vacuum exploration value parameter space $\tan\beta > 1$ and $\tan\beta < 1$ respectively. Almost the entire kinematically allowed region of phase space is now eliminated at the 95% confidence level.

(c) Test of Quantum Chromodynamics

A study of multijet production rates hs been carried out in the Z° boson sample decaying into multihadrons. The number of two, three, four and five jet events vary with the jet resolution parameter y_{cut}, as first used by JADE, but in each case, the distribution of the number of jets found is in excellent agreement with the prediction of QCD when calculated to $\theta(\alpha_s^2)$. This is shown in Fig. 2a. The QCD theory when cut-off at second order contains two parameters $\Lambda_{\overline{MS}}$ and a renormalization scale parameter μ^2. When these are varied for a best fit one finds $\mu^2 \sim 0.002$ and $\Lambda_{\overline{MS}}$ = 80-180 MeV. If μ^2 is fixed at $E^2_{CM} = M^2_{Z^\circ}$, the result for $\Lambda_{\overline{MS}}$ = 200-450 meV or $\sigma_s(91\ \text{GeV}) = 0.124 \pm .008$,

FIG. 1



OPAL
Predicted number of events
20
17.5
15
12.5
10
7.5
5
95% C.L.
2.5
0
Combined search
Neutrino channel
Leptonic channel
2-tau 2-jet channel
39.4
24
26
28
30
32
34
36
38
40
m_H (GeV/c^2)

FIG. 2A

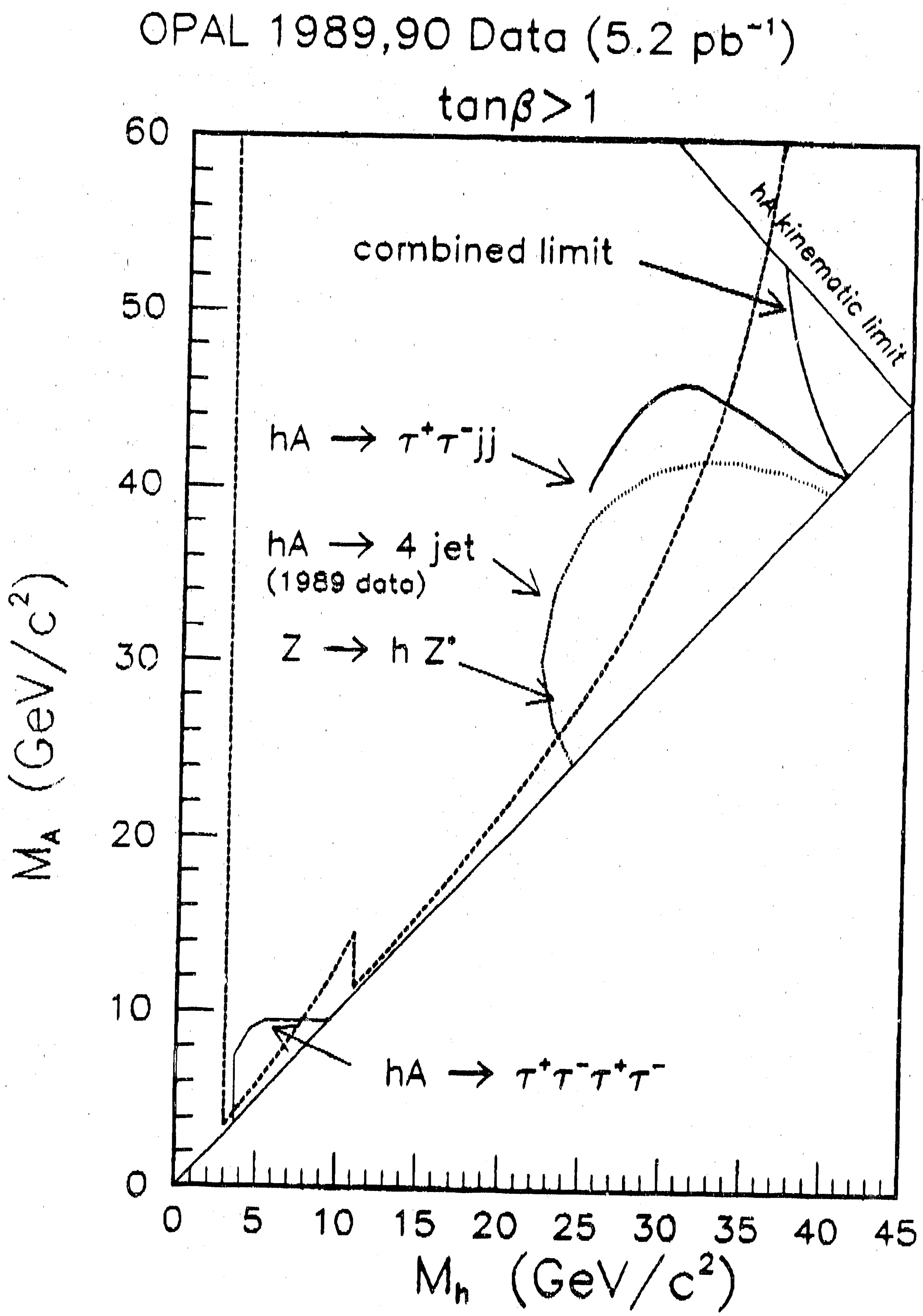
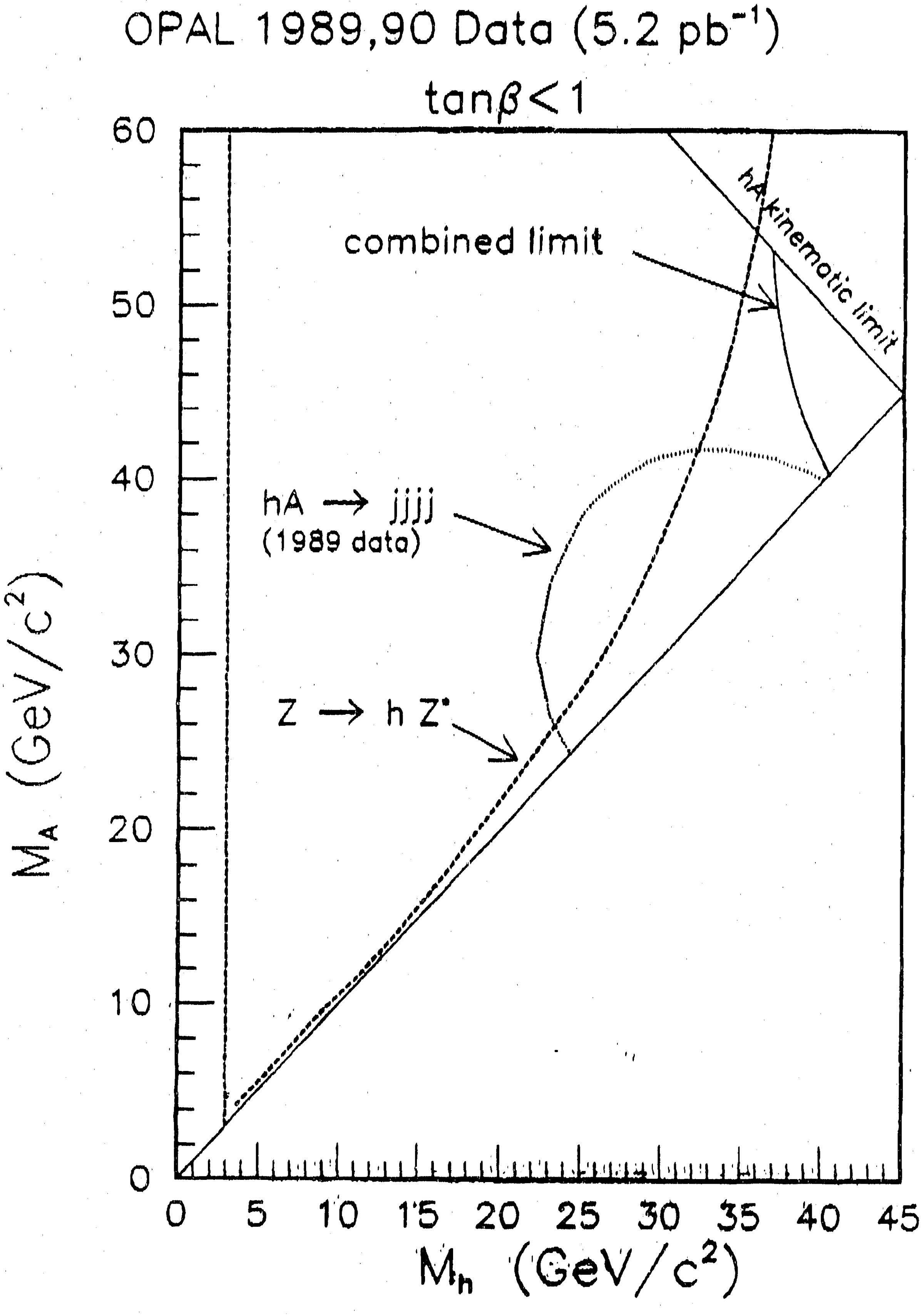

OPAL 1989,90 Data (5.2 pb⁻¹)
tanβ>1
combined limit
hA kinematic limit
hA → τ⁺τ⁻jj
hA → 4 jet
(1989 data)
Z → h Z*
hA → τ⁺τ⁻τ⁺τ⁻
M_A (GeV/c²)
M_h (GeV/c²)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45

FIG. 2B



OPAL 1989,90 Data (5.2 pb^{-1})
$\tan\beta<1$
combined limit
hA kinematic limit
hA → jjjj
(1989 data)
Z → h Z*
M_A (GeV/c^2)
M_h (GeV/c^2)
0
10
20
30
40
50
60
5
15
25
35
45

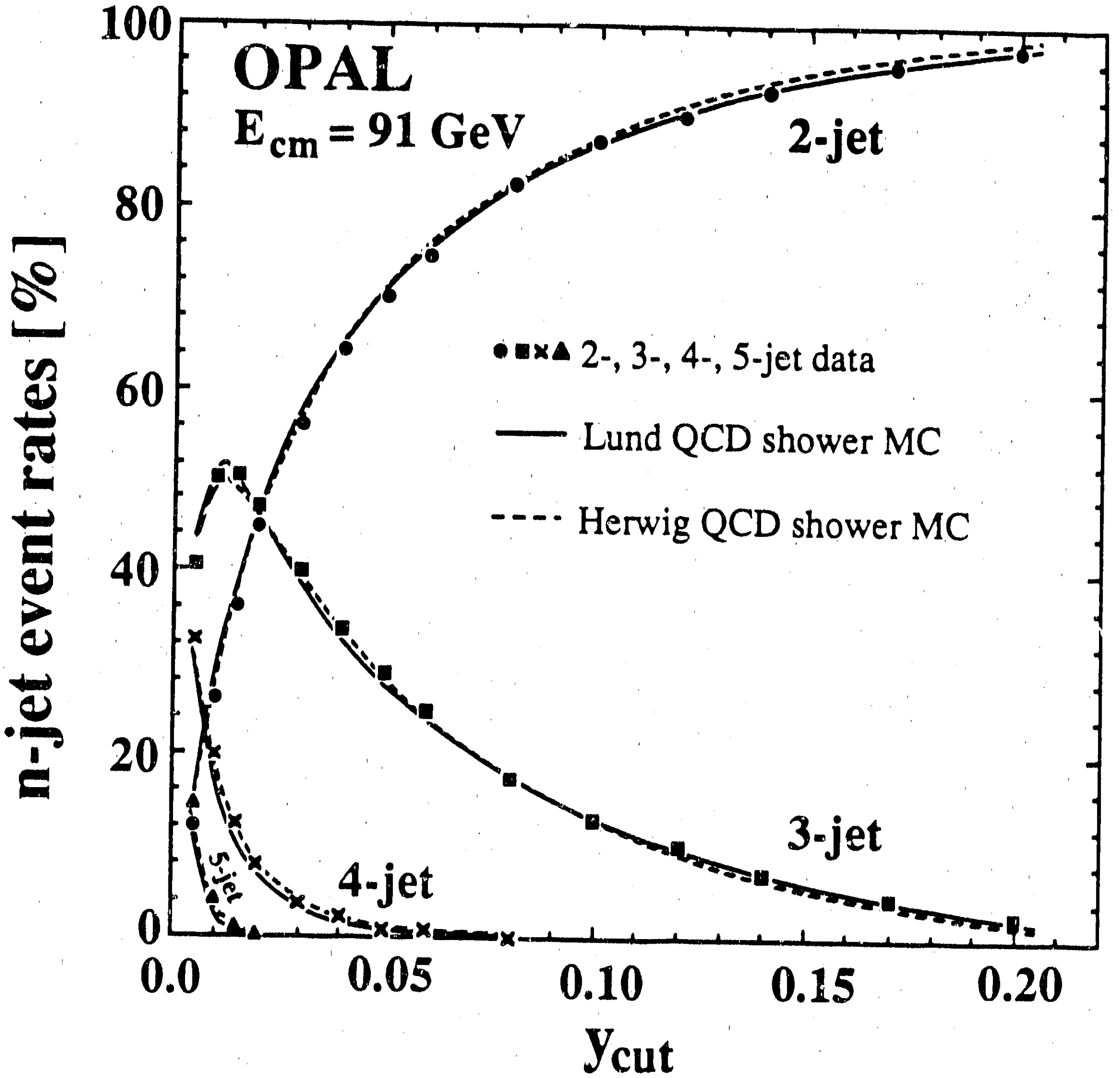


Fig. 2a. Two-, three-, four- and five-jet event rates observed at E_{cm} = 91 GeV as a function of the jet resolution parameter y_{cut}, compared to two different QCD model calculations.

providing a good description of the data for jet resolution parameters $y_{cut} \geq 0.05$.

QCD predicts that $\alpha_s(E)$ falls as E increases. A robust test of this prediction can be carried out by plotting the fraction of 3 jet events, R_3, as a function of energy when the jet definition used has the same y_{cut} parameter throughout. This is shown in Fig. 4b when the OPAL data result has been added to the PEP, PETRA and TRISTAN data published earlier. The dependence of R_3 on E_{CM} that is observed agrees very well with QCD and excludes an energy independent strong coupling constant with a significance of 5.7 standard deviations. The evidence for the "running" of α_s with energy does not depend on the choice of the renormalization scale μ^2 used in the theoretical calculations.

Since the above result was published (Phys. Lett. B235, 389 (1990)), an investigation has been carried out on the systematic uncertainty due to different recombination schemes. Using more data and correcting for acceptance and hadronization for each scheme, one obtains a new more reliable result for the QCD strong coupling constant, namely, $\alpha_s(M_Z^2) = 0.116 \pm 0.016$. G. Altarelli stressed at the ν'90 conference how good the agreement of this result is with the QCD predictions made from low energy experiments that $\alpha_s^{Pred.}(m_Z^2) = 0.11 \pm 0.01$.

Another test of QCD has been carried out by OPAL by analyzing the four-jet final hadronic states of the Z° decay in terms of observables that are sensitive to the non-abelian gauge structure of QCD. The basic QCD diagrams for four jet events are shown in Fig. 1. The definitions of the angle variables x_{Bz} and θ^{*}_{NR} used in the analysis are illustrated in Fig. 2. The results for the average values of these two angles in the 4 jet events vs. y_{cut} are shown in Fig. 6 together with the QCD predictions and a prediction

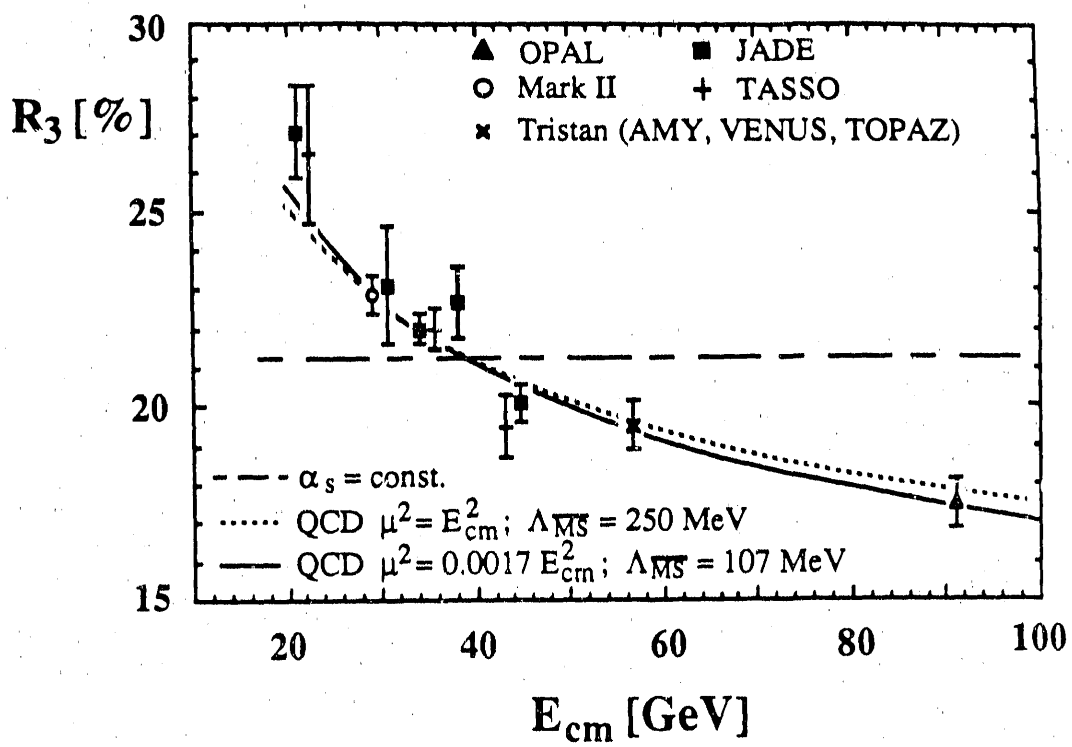


Fig. 4b. The energy dependence of the three-jet event production rates at $y_{cut} = 0.08$, compared with several assumptions about the energy dependence of α_s. The data points at 22 GeV are not included in the fits [5]. The errors shown are statistical only.

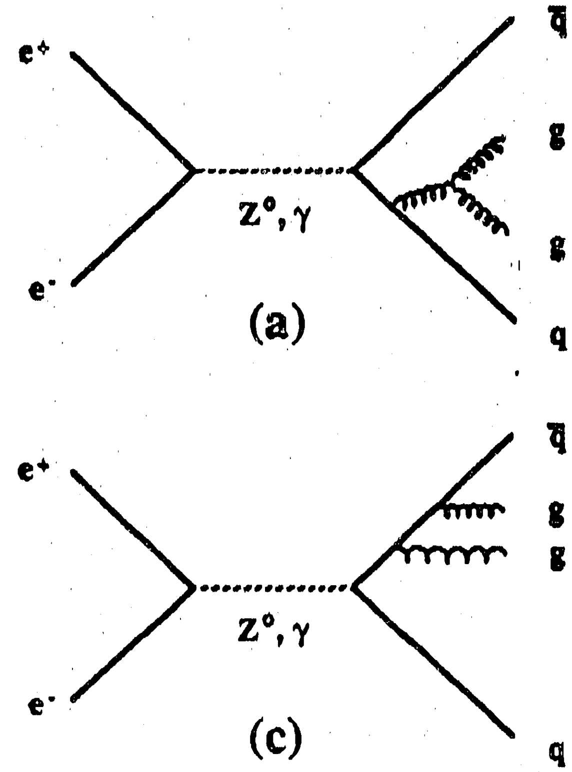


Figure 1: Basic Feynman diagrams for the process $e^+e^- \to 4$ jets.

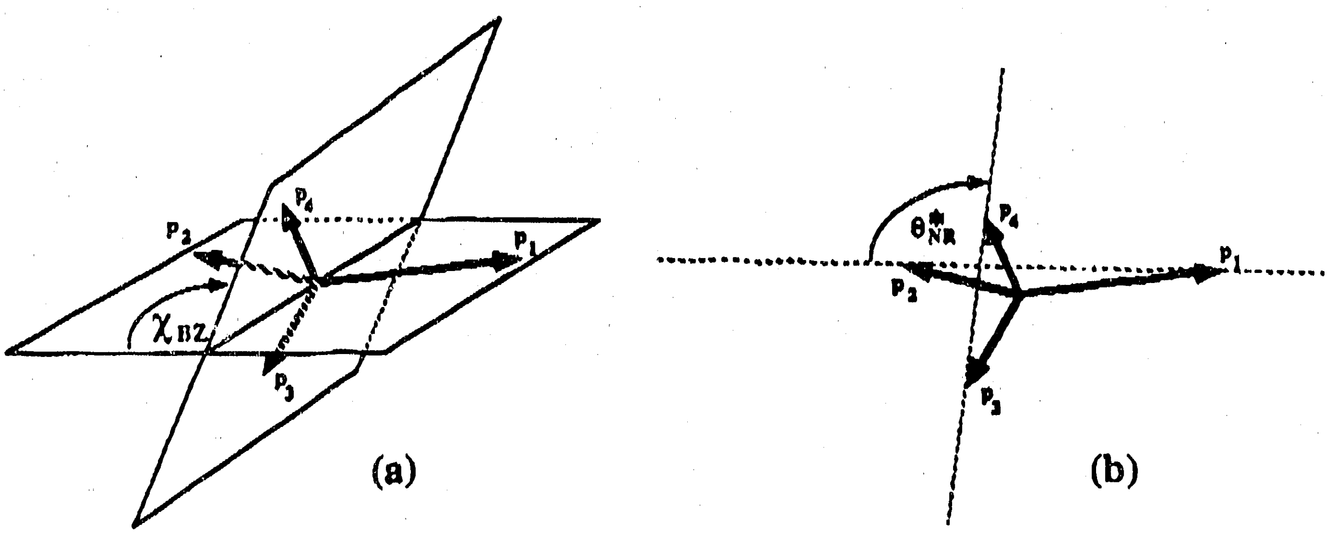


Figure 2: Definitions of χ_{BZ} (a) and of θ^*_{NR} (b) for a typical 4-parton event configuration.

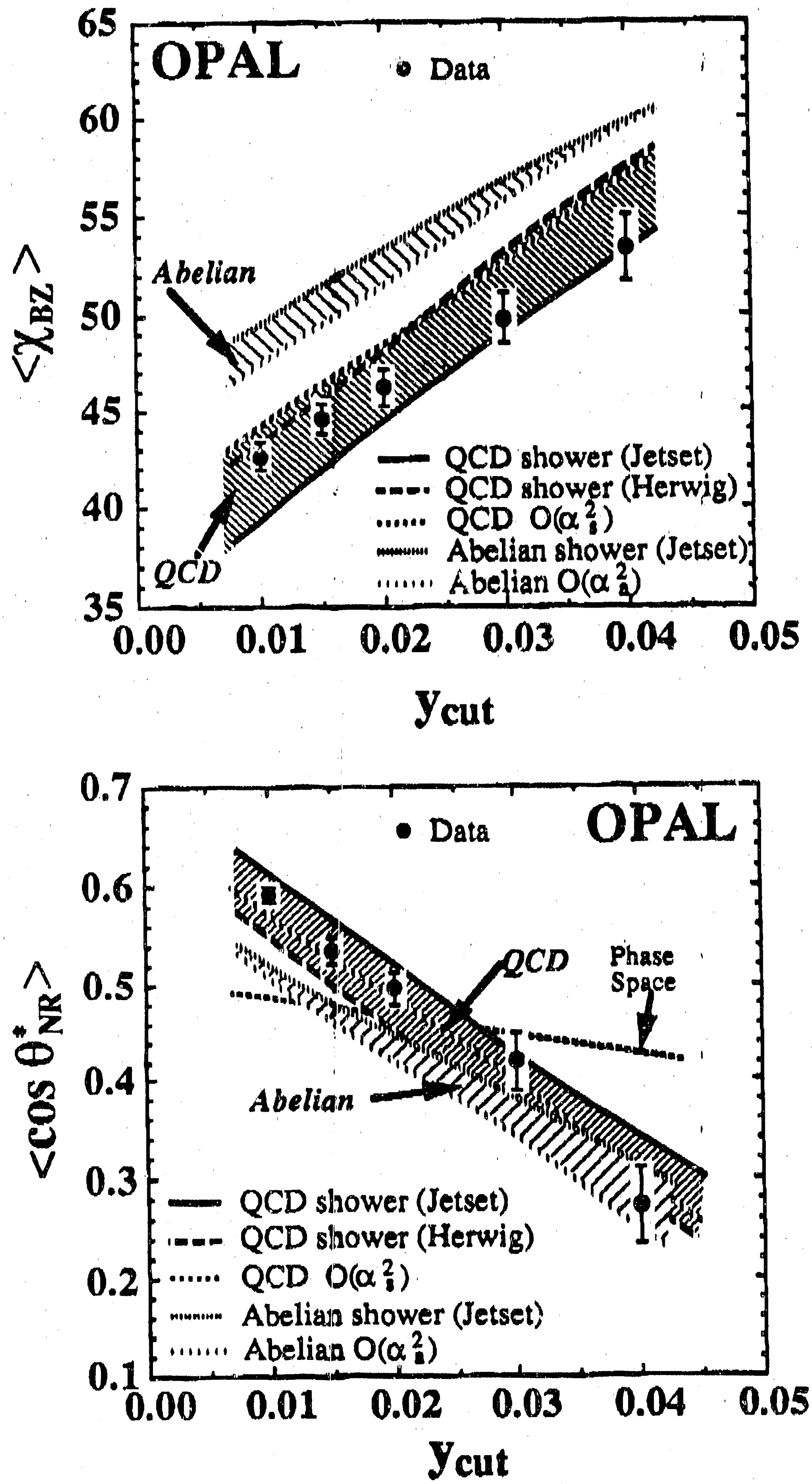


Figure 6: Mean values of the χ_{BZ} and $\cos\theta^*_{NR}$ distributions as a function of the jet resolution parameter y_{cut}; the data are corrected for detector and hadronisation effects.

for abelian gluons. The data and QCD are in very good agreement and the abelian theory is ruled out.

Another test of QCD follows from a study of the inclusive momentum distribution of charged particles in multihadronic events at the Z°. The data shows good agreement with QCD predictions for the height and the peak position of the particle momentum distribution. This QCD prediction is sensitive to the phenomena of soft gluon interference. Simple non-coherent models with independent fragmentation fail to reproduce the energy dependence and momenta spectra.

(d) Couplings of $Z^\circ \to q\bar{q}$.

(i) The first method that OPAL has used to obtain information the decay of Z° into different types of $q\bar{q}$ is via the reaction $Z \to q\bar{q} + \gamma$. The idea behind this technique is to note tha' the probability for final state γ emission is four times larger for up type quarks $\sim (\frac{2}{3})^2$, than for down type quarks $\sim (1/3)^2$. By combining the data on $Z^\circ \to q\bar{q}$ and $Z^\circ \to q\bar{q}\gamma$, one can find the strength of the Z° couplings to up + charm quarks separately from the strength of Z° coupling to down + strange + bottom quarks. In particular $\Gamma_{Z^\circ} \propto 3C_d + 2C_u$, while

$$N(Z^\circ \to \gamma q\bar{q}) \sim 3C_d + 8C_u, \text{ where}$$

C_d denotes the $\sum_{i=1}^{3} (v_i^2 + a_i^2)$, $i = 1,2,3$ corresponding to d, s, b quarks.

and C_u denotes the $\sum_{i=1}^{2} (v_j^2 + a_j^2)$, $j = 1,2$ corresponding to u, c.

Clearly with two equations and two unknowns, C_u and C_d, one can solve for the two unknowns and compare the results with the standard model.

The experimental method looks for high energy isolated γ-rays ($E_\gamma > 10$ GeV) at $p_T > 5$ GeV relative to the thrust axis. The details are given in a paper soon to be published in Phys. Lett. B that was based on 27,309 multi-hadron events from 1989. For the Singapore Conference the sample has been updated by 49,869 events from 1990. OPAL finds 78 isolated photons. Of these 5.1 ± 1.4 are estimated to come from initial state radiation and 8 ± 5 to be background events from isolated π°'s or neutral hadrons, thus yielding N_{γ} = 64.9 ± 10.2 photons from other sources. Using the QCD Monte Carlo based on the standard model, one predicts 61.0 photons from final state radiation in very good agreement with the observed number. Turning the argument around, one can use the data to determine the widths for $\Gamma_{d\bar{d}}$ and $\Gamma_{u\bar{u}}$. One finds $\Gamma_{d\bar{d}}$ = 369 ± 67 MeV and $\Gamma_{u\bar{u}}$ = 330 ± 99 MeV using the intersections of the two bands shown in Fig. 3. Fig. 4 shows how these errors compare with recent measurements of partial widths of Z° to $b\bar{b}$ and $c\bar{c}$ made by other LEP experiments. The isolated γ method is limited by statistics rather than by systematics so it should at least remain competitive with the other methods of determining partial decay widths of the Z° as the statistics of Z° events grow.

(ii) $Z^{\circ} \rightarrow b\bar{b}$ decays

Recently OPAL has developed methods to measure the branching ratio of $Z \rightarrow b\bar{b}$ decays from inclusive muon data. A very large effort was necessary to optimize the information from the muon barrel and endcap chambers with the information from the jet chamber and from the strips in the hadron barrel and endcaps. This has lead to an algorithm for the selection of tracks as inclusive muon candidates with a global efficiency of 73.9 ± 1.% ± 1%. With this algorithm the fake rate per pion track has been measured to be 1.1 ± 0.3% using known pions from $K_s^{\circ} \rightarrow \pi^+\pi^-$ decays and estimated from Monte Carlo to be 0.9 ± .1%.

Using this inclusive muon algorithm, a search for large p_T muons was

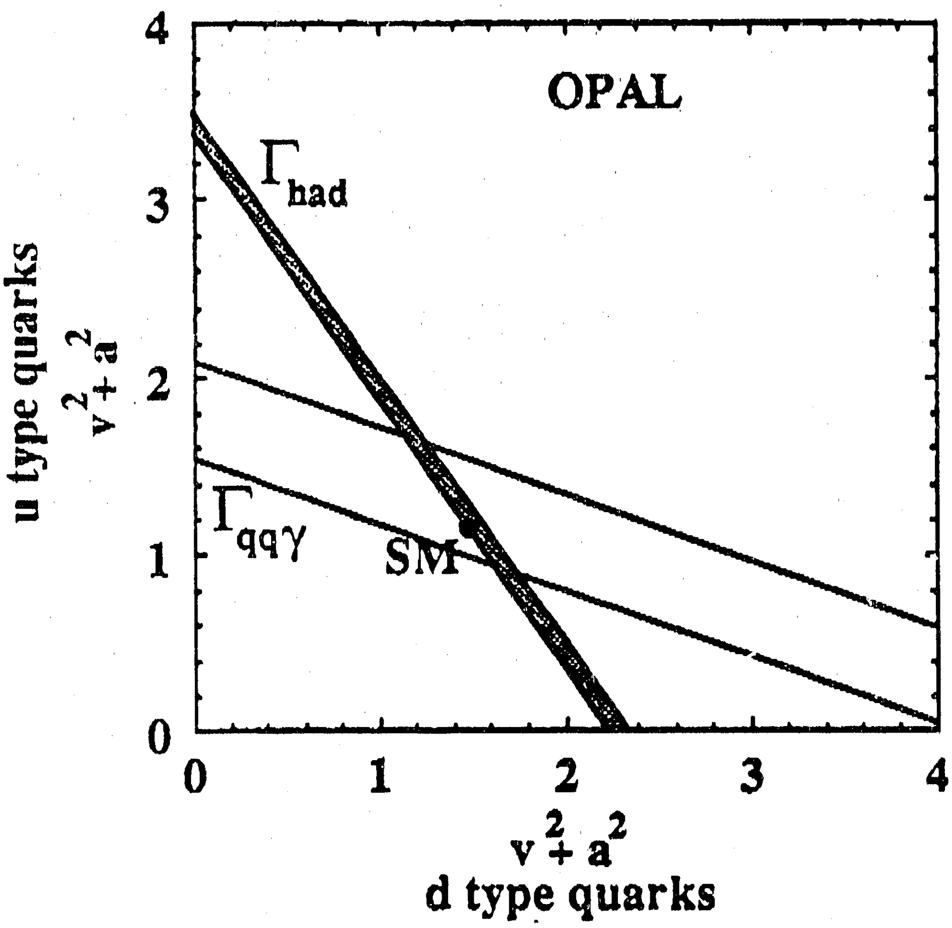

OPAL
Γ_{had}
$\Gamma_{qq\gamma}$
SM
u type quarks
v^2+a^2
v^2+a^2
d type quarks
0
1
2
3
4
0
1
2
3
4

Fig. 3

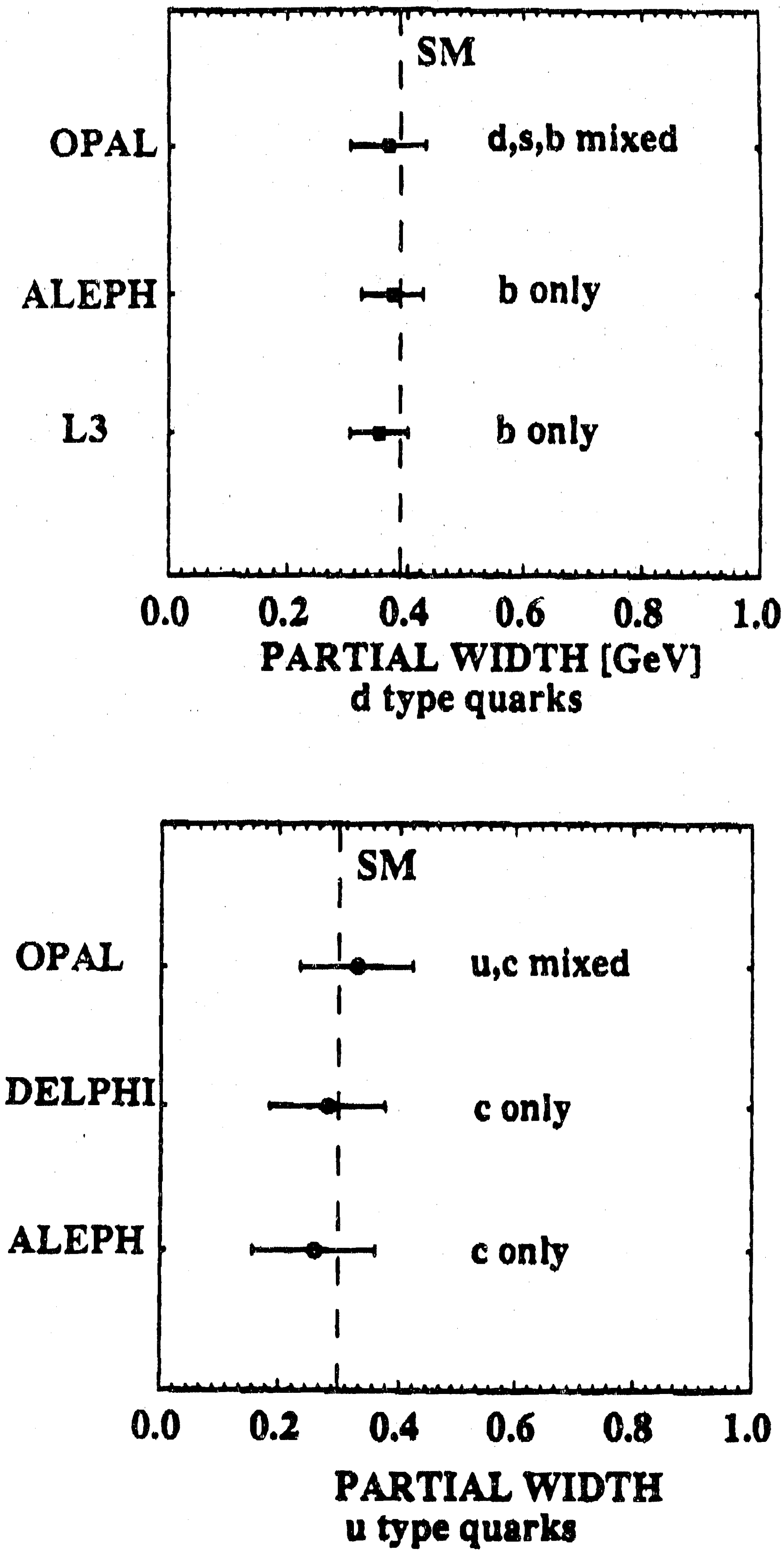

SM
OPAL
d,s,b mixed
ALEPH
b only
L3
b only
0.0
0.2
0.4
0.6
0.8
1.0
PARTIAL WIDTH [GeV]
d type quarks
SM
OPAL
u,c mixed
DELPHI
c only
ALEPH
c only
0.0
0.2
0.4
0.6
0.8
1.0
PARTIAL WIDTH
u type quarks

Fig. 4

carried out by OPAL in 71,106 multihadronic Z° events collected in 1990. A total of 7029 muon candidates passed the criteria. Fidicial cuts of $|\cos\theta_\mu| < 0.9$ and $|\cos\theta_{jet}| < 0.8$ were imposed. To reduce direct charm and $b \to c \to \mu$ decay contributions a cut of $p > 4.5$ GeV/c was imposed. To improve signal to noise further a cut of $p_T > 1$ Gev/c was made. 1168 muon candidates remain. The Monte Carlo prediction for the background is 403.1 non-prompt and fake muons plus 49.7 $c \to \mu$ tracks, leaving 715.2 $b \to \mu + b \to c \to \mu$ decay candidates. Applying correction factors for the muon detection efficiency, angular acceptance and kinematic acceptance plus experimental smearing, one can obtain the best estimate of the number of $b \to \mu + b \to c \to \mu$ decays. The $b \to c \to \mu$ decays are estimated by Monte Carlo and are quite small given the p and p_T cuts mentioned before. The result obtained is

$$BR(b \to \mu) \times \frac{\Gamma(Z^\circ \to b\bar{b})}{\Gamma(Z^\circ \to \text{hadrons})} = 0.0206 \pm 0.0010 \pm 0.0018$$

The largest contribution to the systematic error comes from the estimate of the non-prompt and fake muon subtraction (± .0017). Assuming a b semileptonic branching ratio of 0.102 ± .010 gives $\frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} = 0.202 \pm .010 \pm .028$, in good agreement with Standard Model prediction of 0.217.

A study was also carried out on the forward backward angular distrtibution of this sample. Using only the multihadron sample (52036) of Z°'s obtained at the Z° peak, one finds

	# forward	# backward	Total
Muon candidates	434	449	883
Expected fakes	151	154	305
Expected charm	19	31	50

Expected cascade	31	32	63
B signal	233	232	465
B signal (corrected for eff.)	278	274	552

Asymmetry calculated for $|\cos\theta_{jet}| < 0.8$

$$A_{fb} = \frac{278 - 274}{278 + 274} = 0.01 \pm 0.07,$$

Extrapolating to $|\cos\theta| \leq 1.0$, one obtains $A_{fb} = 0.01 \pm 0.08$, compared to the Standard Model prediction of $A_{fb}^{SM} \doteq 0.108$. Clearly this is only the opening shot of a long compaign to study $Z^\circ \to b\bar{b}$ decay.

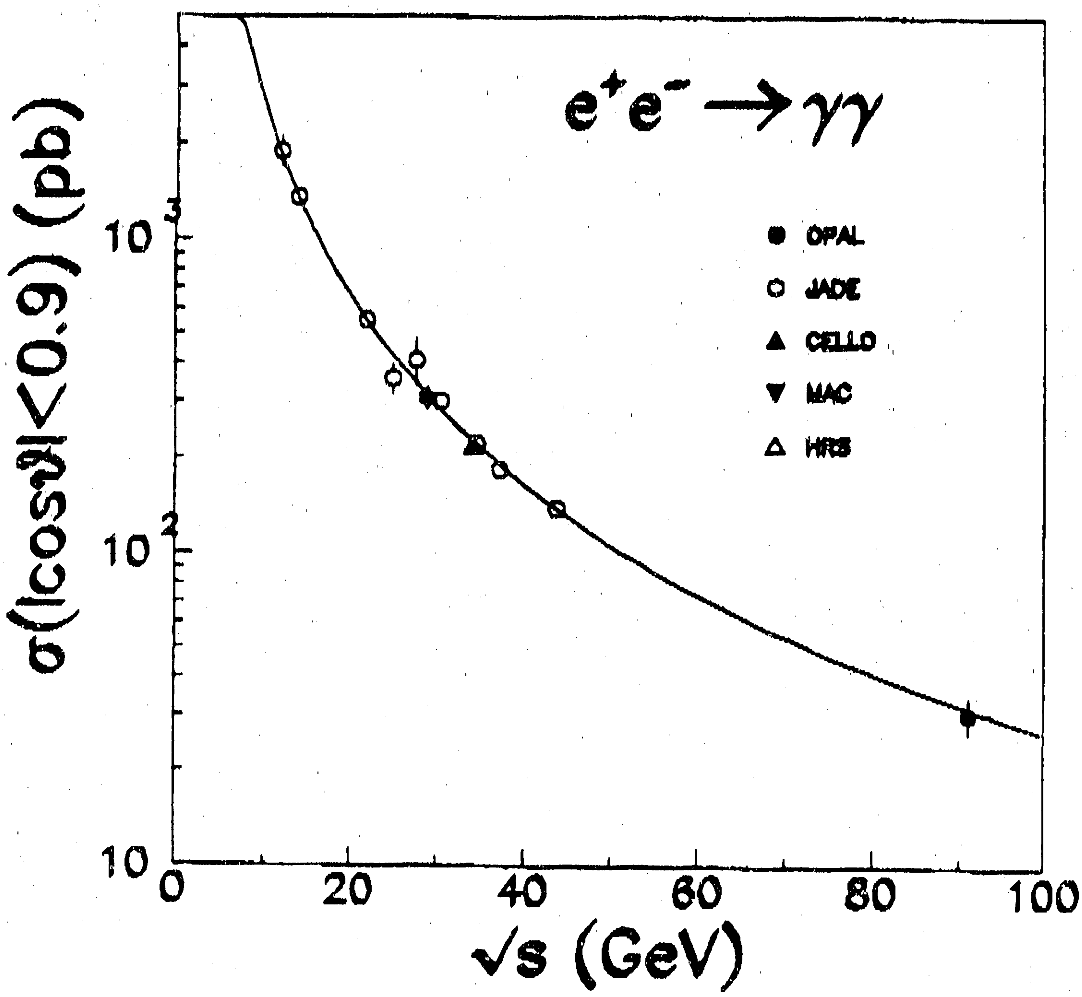
(e) A Study of the Reaction $e^+e^- \to \gamma\gamma$ at LEP

The first analysis of the QED reaction at LEP was carried out by OPAL using a sample with integrated luminosity 0.7 pb^{-1}. This analysis has been upgraded for the Singapore Conference with a sample of integrated luminosity 3.8 pb^{-1}. The selection criteria for $e^+e^- \to \gamma\gamma$ was slightly changed from those used in the paper, to avoid some uncertainty in the forward region. The results for the total cross section and the angular distribution are in excellent agreement with the predictions of Quantum Chromodynamics. This can be seen in Figs. 2 and 4. Introducing deviations from QED in terms of cut-off parameters that modify the electron propagator, one finds the limits $\Lambda_+ > 110$ GeV and $\Lambda_- > 95$ GeV.

The same data set can be used to set upper limits on the branching ratios of $Z^\circ \to \gamma\gamma$, $Z^\circ \to \pi^\circ\gamma$ and $Z^\circ \to \eta\gamma$. These are found to be 1.3×10^{-4}, 1.3×10^{-4}, and 1.9×10^{-4} respectively, at the 95% confidence level.

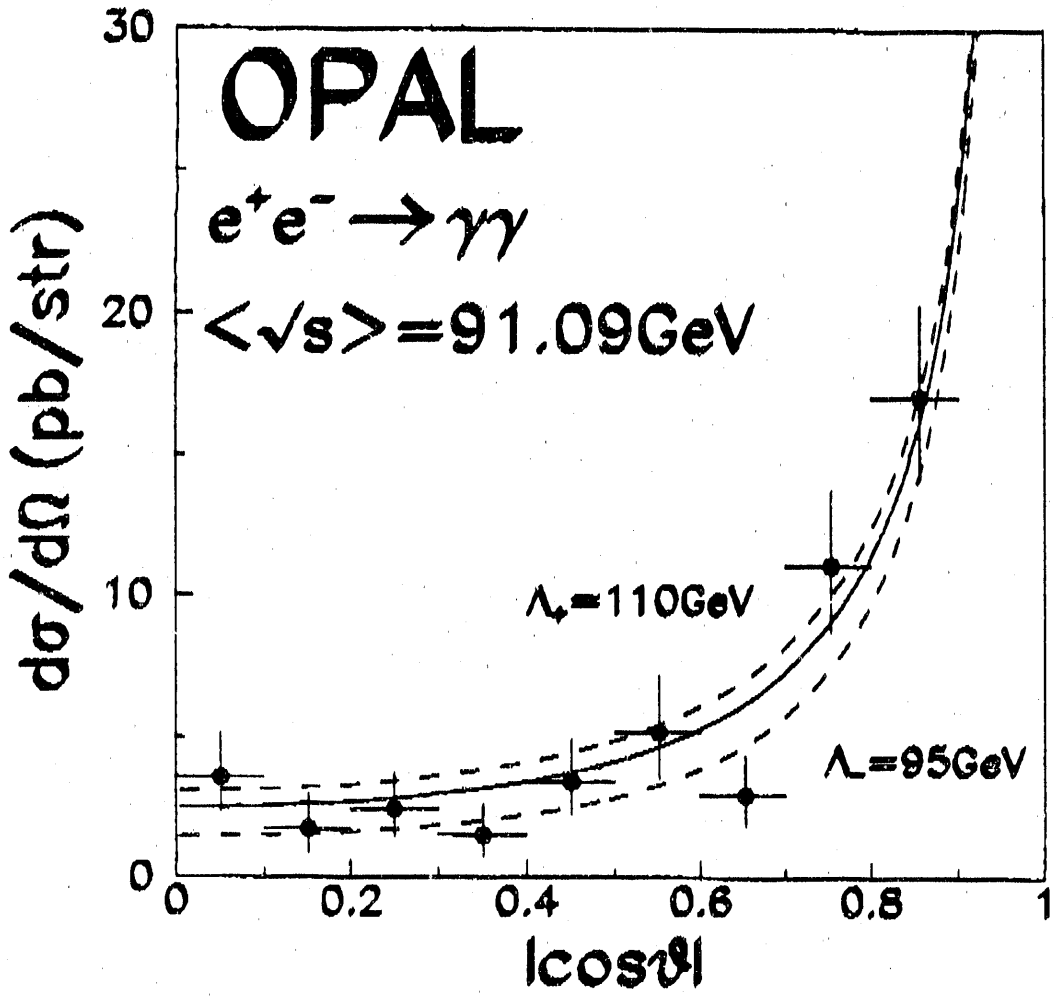
(f) Search for New Particles with OPAL at LEP

OPAL has carried out systematic searches for the quarks t and b', technipions $H^\pm$, heavy leptons $L^\pm$, L°, excited leptons l^* and wide variety



$e^+e^- \rightarrow \gamma\gamma$
OPAL
JADE
CELLO
MAC
HRS
σ(|cosϑ|<0.9) (pb)
10^3
10^2
10
0
20
40
60
80
100
√s (GeV)

Fig. 2



OPAL
e⁺e⁻ → γγ
<√s>=91.09GeV
Λ₊=110GeV
Λ₋=95GeV
dσ/dΩ (pb/str)
|cosϑ|
0
10
20
30
0.2
0.4
0.6
0.8
1

Fig. 4

of supersymmetric particles $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$, $\tilde{W}$, $\tilde{H}^{\pm}$, $\tilde{W}^{\pm}$ and $\tilde{\chi}$. Unfortunately none of these searches have found evidence for the existence of the particles sought. LEP as a Z° factory has proved to be an exceptionally clean place to look for all these particles but apparently if any exist they seem to be too massive to be produced (usually in pairs) at the CM energy of 91 GeV.

For b′ and t particles one looks for spherical events; for excited leptons, one looks for leptons + gammas; for heavy leptons and SUSY particles one looks for acolinear and acoplanar events with missing energy; and so on. The lower limits for all the particles searched for are usually in the mass range ≥ 40-45 GeV. In the case of neutral lepton production one expresses the results in terms of mixing angles rather than masses as shown in the next Figure for (i) $e^+e^- \to L^{\circ}\bar{L}^{\circ}$ and (ii) $e^+e^- \to \nu\bar{L}^{\circ}$ or $\bar{\nu}L^{\circ}$. In these cases the 95% limit to the lepton branching ratios are ~ 3×10^{-4} to 10^{-3} for L° masses up to 45 or 88 GeV in the cases (i) and (ii) respectively.

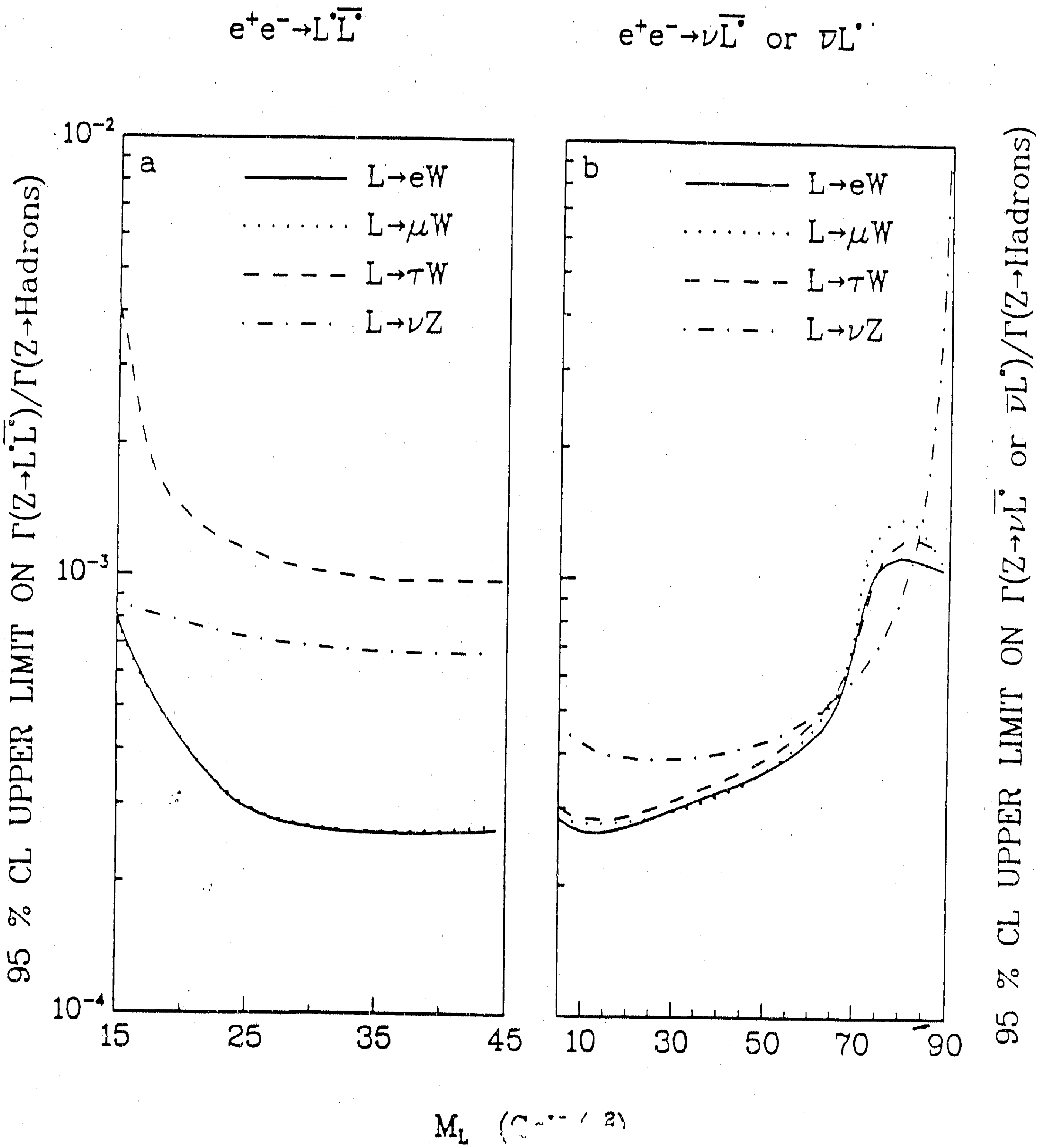
The next figure illustrates OPAL's limits for a charged scalar meson that decays as expected either into $c\bar{s}$ or $\tau\nu$.

The next figure illustrates how a b′ or a top would distort the acoplanarity distribution of multihadronic events from the Z°, independent of the details of the b′ and t decay modes.

Finally the last figure shows that the OPAL data is incompatible with the acoplanarity distributions that would be produced by SUSY particles $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$ and $\tilde{\chi}$ respectively.

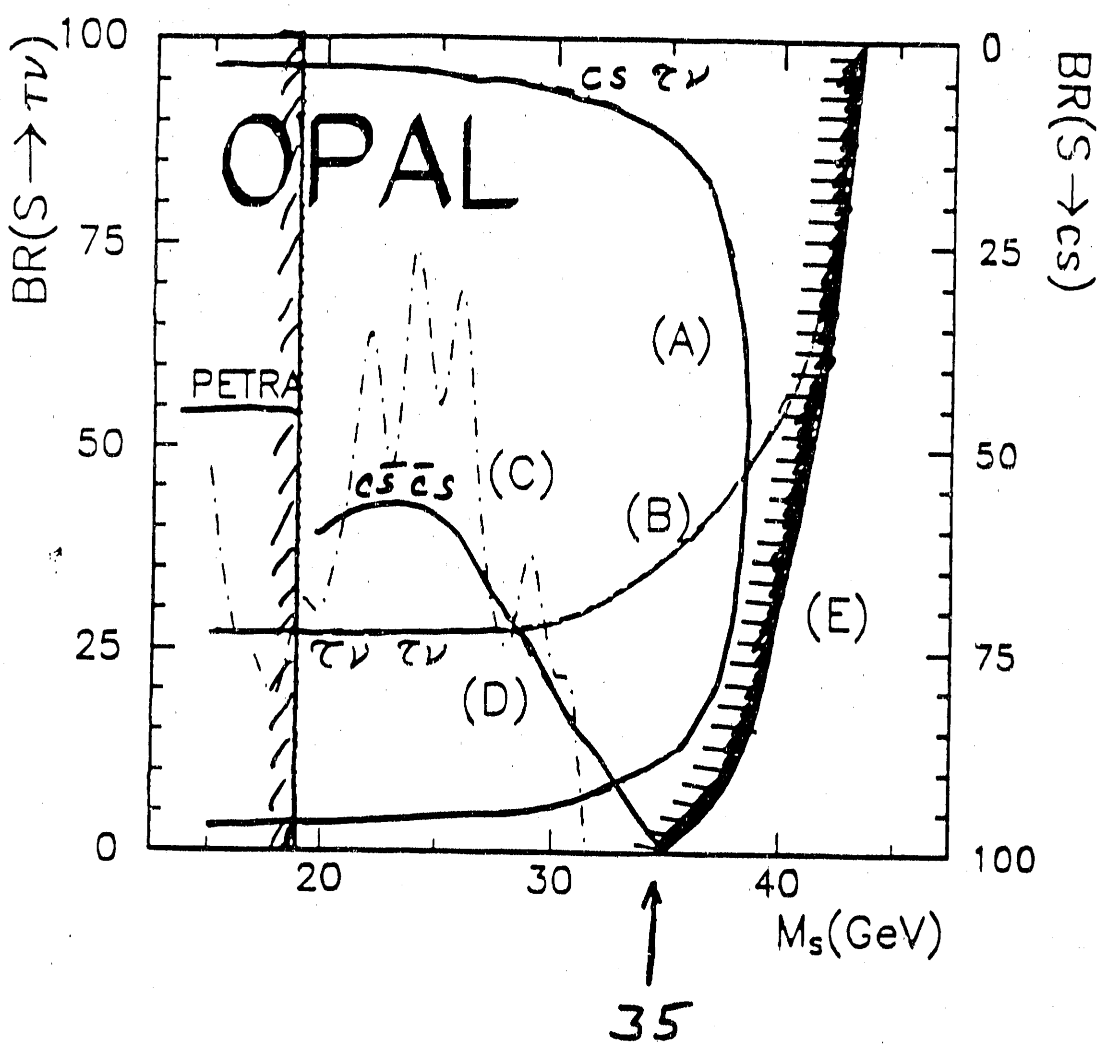
A quantitative summary of these searches was presented by M. J. Oreglia at the ν'90 Conference and also at the Singapore Conference.

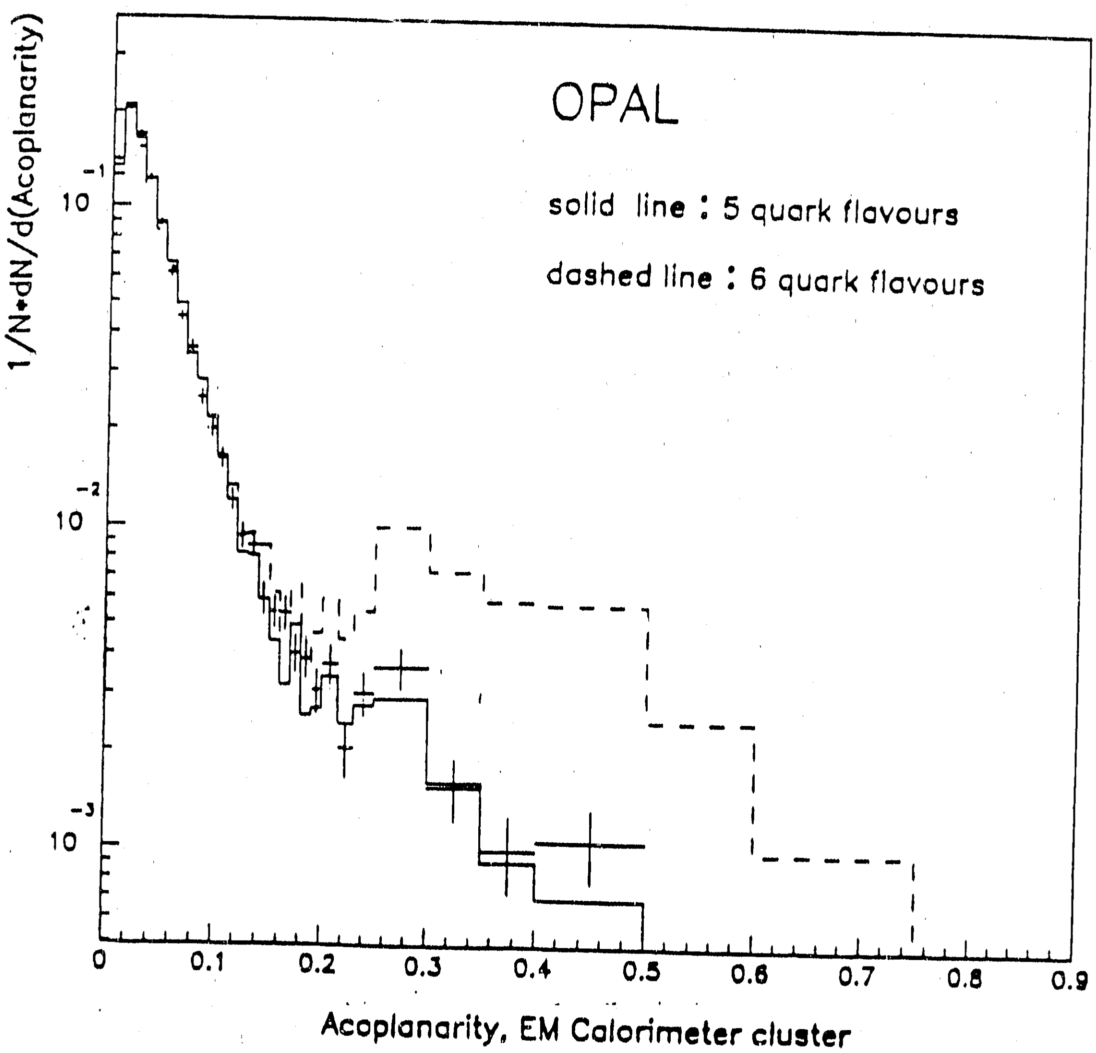
OPAL

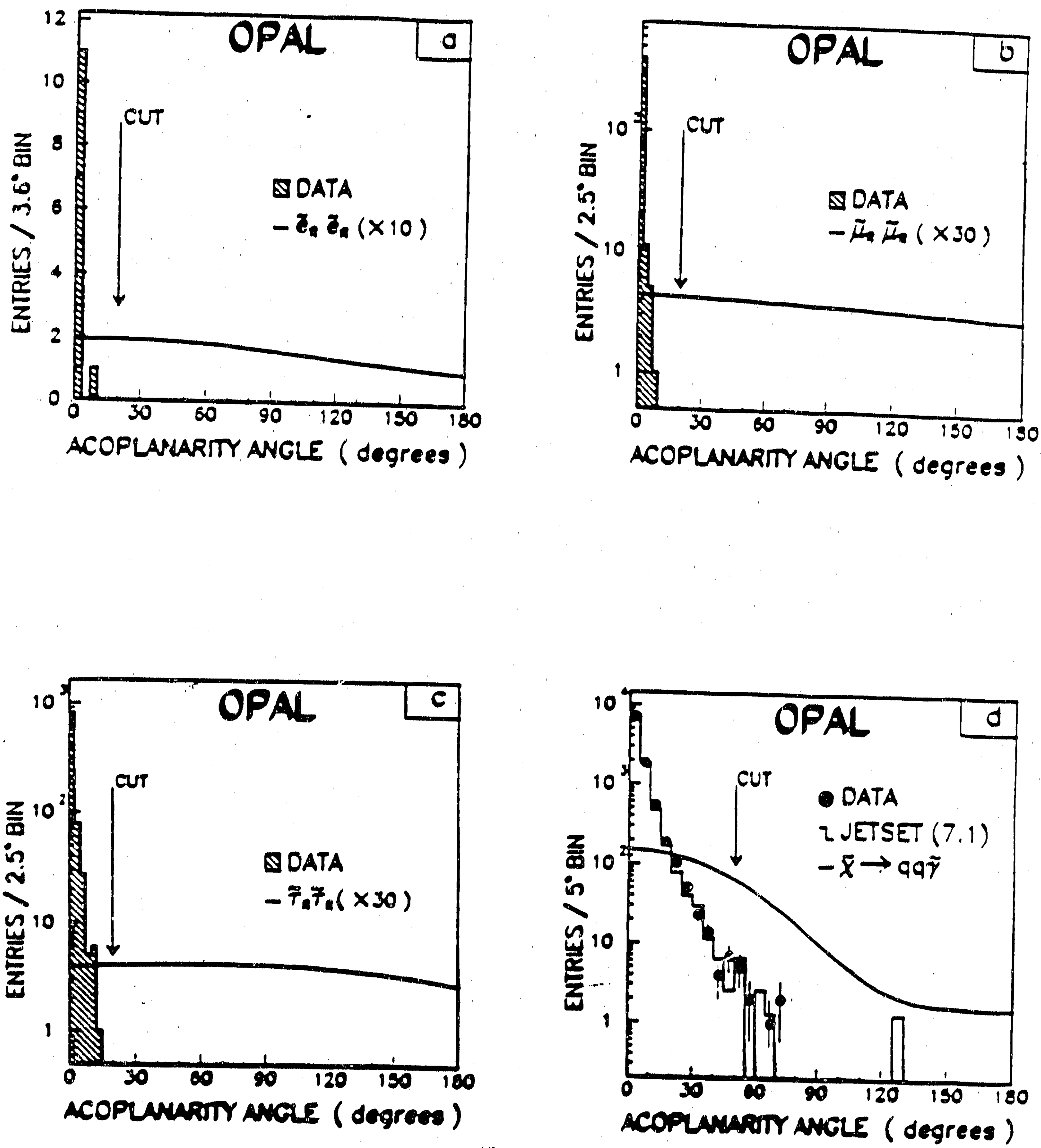


$e^+e^- \to L^*\overline{L^*}$
$e^+e^- \to \nu\overline{L^*}$ or $\overline{\nu}L^*$
a
b
L→eW
L→μW
L→τW
L→νZ
95 % CL UPPER LIMIT ON Γ(Z→L*L̄*)/Γ(Z→Hadrons)
95 % CL UPPER LIMIT ON Γ(Z→νL̄* or ν̄L*)/Γ(Z→Hadrons)
10⁻²
10⁻³
10⁻⁴
15
25
35
45
10
30
50
70
90
M_L

TECHNIPION SEARCH




OPAL
solid line : 5 quark flavours
dashed line : 6 quark flavours
1/N*dN/d(Acoplanarity)
10⁻¹
10⁻²
10⁻³
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Acoplanarity, EM Calorimeter cluster


OPAL
a
CUT
DATA
ENTRIES / 3.6° BIN
ACOPLANARITY ANGLE (degrees)
OPAL
b
CUT
DATA
ENTRIES / 2.5° BIN
ACOPLANARITY ANGLE (degrees)
OPAL
c
CUT
DATA
ENTRIES / 2.5° BIN
ACOPLANARITY ANGLE (degrees)
OPAL
d
CUT
DATA
JETSET (7.1)
ENTRIES / 5° BIN
ACOPLANARITY ANGLE (degrees)

B.2 Luminosity Monitor Performance. (S. Hou, R. Kellogg, A. Lee, IV, plus physicists from London and Bologna).

In the first OPAL paper on the mass and width of the Z° (Oct. 13, 1989) the systematic error of the luminosity measurement was estimated to be 5%. By the second OPAL paper on the same subject (Feb. 23, 1990) this error was reduced to 2.2%, and in the most recent paper for the Singapore Conference the luminosity systematic normalization error has decreased to 1.6%.

The integrated luminosity of the colliding beams is determined by the measurement of small angle Bhabha scattering, a process insensitive to Z° effects. The measurement uses the forward detector, consisting of two identical elements placed around the beam pipe at either end of the central tracking chambers. In this analysis two components of this detector are used in a complementary manner: (i) a calorimeter provides a high statistics measurement of the relative luminosity at each beam energy; (ii) a set of proportional tube chambers with a well defined geometry and acceptance provides the absolute luminosity calibration.

Each calorimeter consists of a cylindrical lead-scintillator sandwich divided into 16 azimuthal segments and two longitudinal sections: a presampler of 4 radiation lengths (X_o) and a main calorimeter of 22 X_o. For 45 GeV electrons, the energy resolution of the calorimeter was measured to be 1.3 GeV ($19\%/\sqrt{E}$), with 84% of the energy deposited in the main calorimeter. Light sharing between adjacent segments and between inner and outer readouts of the main calorimeter is used to determine the center of the showers. The polar angle resolution varied between 1 and 10 mrad, being best near the inner edge of the calorimeter, while the resolution in azimuth varied between 3.5 and 35 mrad, being best at the segment boundaries. The acceptance of the calorimeter extends from 39 to 155 mrad, and is essentially complete in azimuth.

The proportional tube chambers are positioned between the presampler and main sections of the calorimeter. These chambers each consist of a vertical, horizontal, and diagonal plane of proportional tubes of 1 cm^2 cross section. The positions of the centroids of showers from incident electrons or photons are measured using the pulse height information from the tubes. For 45 GeV electrons, the tube chambers have 1.3 mrad resolution in θ and ϕ and detect 99.3% of the showers. The tube chamber acceptance extends from 50 mrad to 135 mrad in polar angle, and covers 95% in azimuth. The positions of the tube chambers were surveyed to 1.0 mm and were checked with electron tracks measured in drift chambers in front of the calorimeter.

To select events for the absolute luminosity calibration a fiducial region is defined well within the tube chamber and calorimeter acceptance, extending from 58 mrad to 124 mrad in polar angle from the nominal beam axis, and excluding azimuthal angles within 10 degrees of the horizontal and vertical planes. Particles emitted from the interaction point in this angular region traversed only a minimum of material before reaching the forward detectors (less than 0.2 X_o). The average of the angles measured on the two sides of the event is required to lie within this fiducial reigon. Therefore the acceptance is largely independent of the position and size of the beam intersection region. To reject background due to off-momentum beam particles, the difference in the azimuthal angles between the two ends, $\Delta\phi$, is required to be in the range between 160° and 200°. Finally, the average of the energies of the largest cluster in each calorimeter is required to be larger than 2/3 of the beam energy.

The detector read-out was triggered when the energy sum in each forward calorimeter exceeded 15 GeV overall, or 12 GeV in back-to-back clusters. The overall trigger efficiency was found to be 99.0 ± 0.3% for the events selected by these cuts.

The relative luminosity between points of different beam energy was measured using the main calorimeters only. Events were selected in which the average energy of the largest clusters seen in the main sections of each calorimeter exceeded 70% of the beam energy. This requirement was high enough to eliminate the background, but was 3 standard deviations below the peak from well contained Bhabha events. It rejected Bhabha events only partially contained due to the radiation of an energetic photon or shower leakage at the edges of the calorimeter.

The acceptance of the calorimeter selection is normalized to the tube chamber acceptance. The stability of the measurement is checked by comparing the tube chamber and calorimeter luminosities as a function of LEP fill and beam energy. No statistically significant systematic differences were observed.

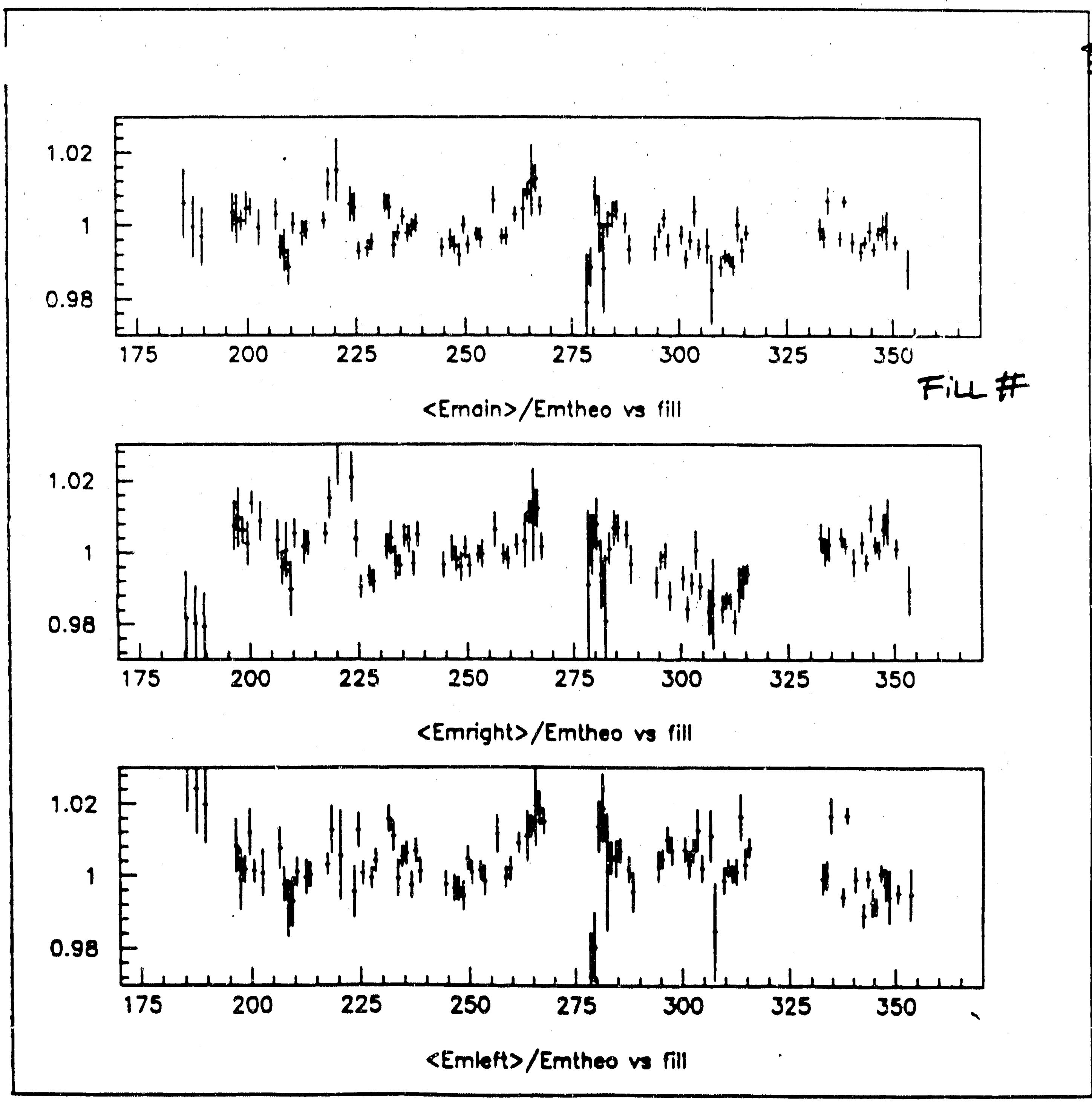
Significant improvements in three aspects of the OPAL luminosity measurement have reduced our estimated systematic errors in 1990.

(1) An improved calibration procedure for the calorimeter allows the energy scale to be held constant with an rms spread at 0.5% fill-to-fill. (Fig. 1). This results in a point-to-point error in the luminosity measured over the Z° line shape of

$$\frac{0.8\%}{\sqrt{N_{\mathrm{Fill}}}}$$

Since there are only ~ 1000-4000 FD Bhabhas/Fill, the systematic point-to-point error is never dominant. In 1989, we quoted a 1% point-to-point

Fig. 1 <E_{main}> stability

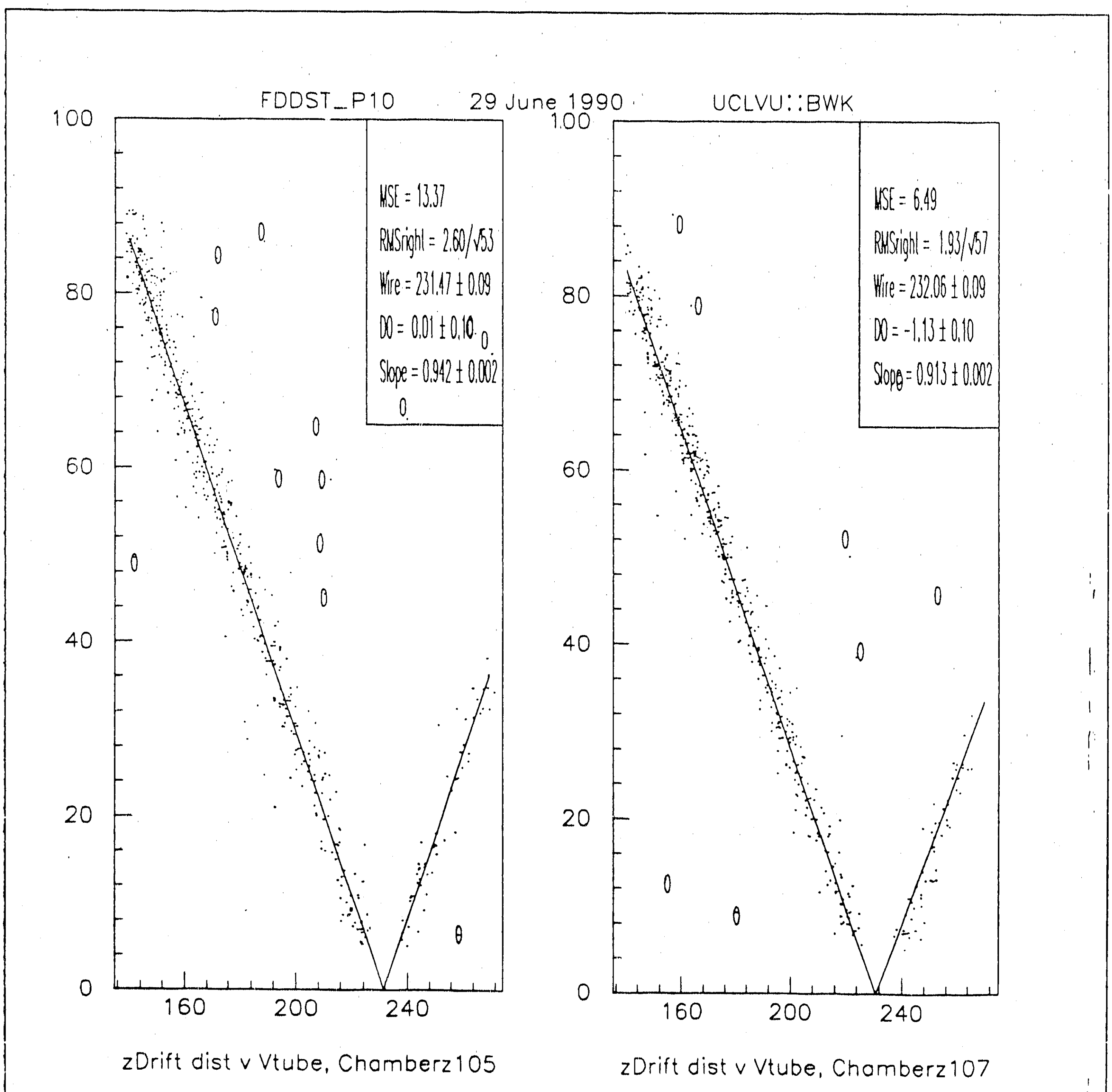


luminosity error, independent of the number of fills.

(2) Drift Chambers in front of the forward calorimeter have been used to survey the position at the Tube Chambers. The drift chamber positions are known to a precision of 150μ, and the fits which transfer the drift chamber wire position into the tube chamber system add additional errors at typically 350μ. (Fig. 2). Seven of the eight tube chamber quadrants have been so surveyed. The precision of the resulting tube chamber coordinates has been evaluated by checking the interaction point position reconstructed by each of the four tube chamber quadrant-pairs independently. The resulting quadrant-to-quadrant discrepancies lead to the estimate of an 800μ random survey error in the coordinates of each of the eight tube chamber quadrants. The error in the average radius of the two scattered electrons in a Bhabha event is then 600μ, which corresponds to a 1% uncertainty in the acceptance. The corresponding numbers in 1989 were 1mm and 1.5%, which were derived from mechanical survey information of the tube chambers alone. The net correction to the tube chamber positions introduced by using the drift chambers was only 600μ, well within the expected error.

(3) The tube chamber luminosity measurement has been improved by incorporating more information from the calorimeter. In order to eliminate the necessity for determining the inefficiency of the tube chambers in each measurement period (~ 2%), the coordinate from the calorimeter is used whenever an event lacks a single coordinate from the tubes. A more fundamental improvement is the use of the calorimeter coordinate in every case when it lies below 53 mrad. This eliminated the class of mismeasured events (1.5%) in the 1989 measurement where electrons scattering in the support ring, at 47

Fig. 2, Drift Chamber vs. Tube Chamber Coordinates

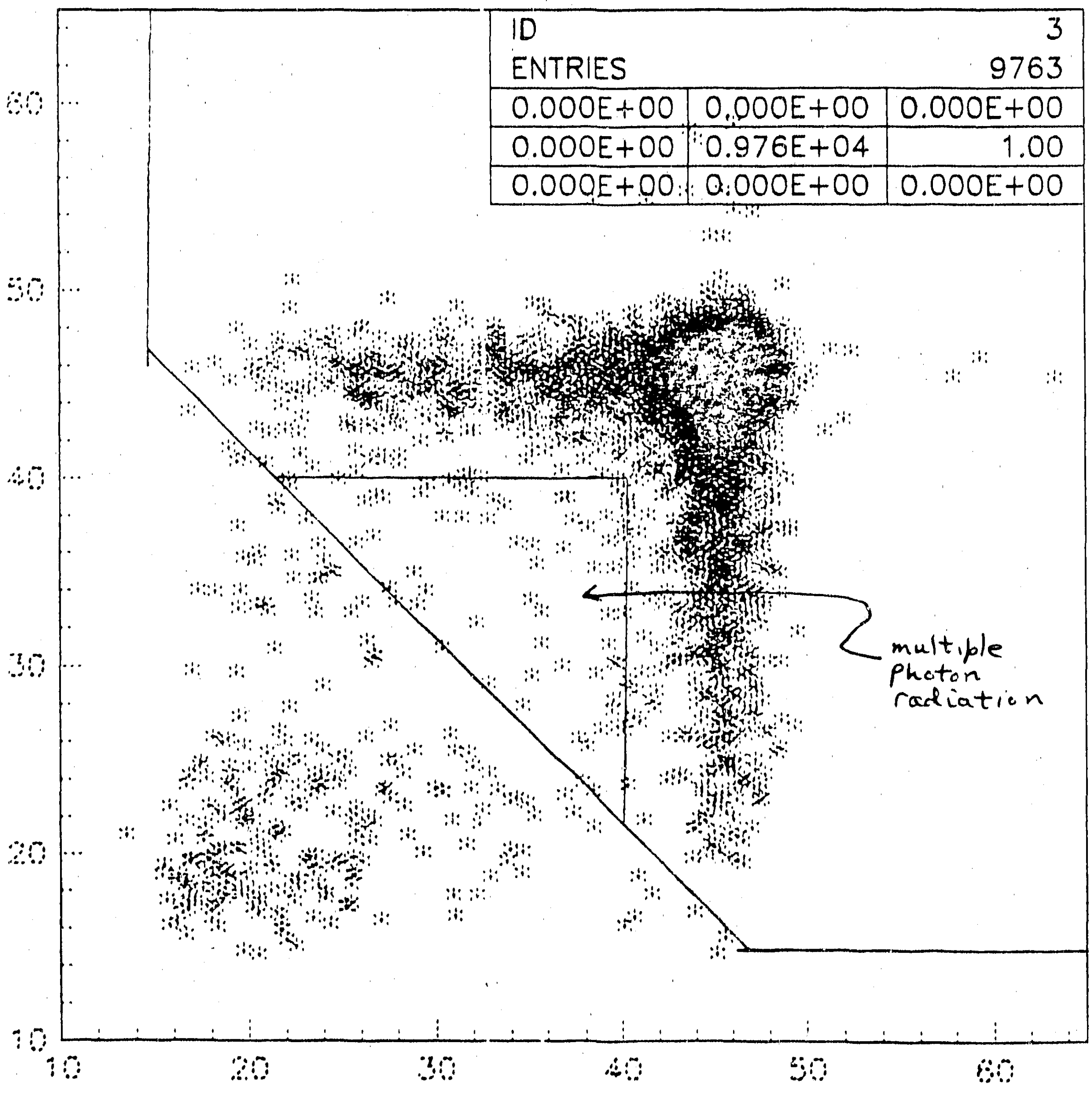


mrad, caused spurious tube coordinates at higher angles. The use of the calorimeter introduces some new uncertainty due to the increased systematic error in its coordinates, but since this influenced only a small number of events, the effect is small (0.4%). The advantage of using the calorimeter is that it eliminates the 0.5% tube efficiency error and the 0.5% uncertainty in the 1.5% background subtraction which was necessary in 1989 to account for the event scattering in the support ring. A significant bound is that in 1990 less than 1% of the events in the tube chamber sample is poorly reconstructed. In particular the population of events between the radiative tail of the E_R vs. E_L correlation plot is truly due to multiple photon emission, rather than poor reconstruction. 0.5% of all tube events lie in the triangle drawn in Fig. 3, while BHLUMI, a Monte Carlo which simulates multiple photon emission in small-angle Bhabha scattering predicts 0.5 ± 0.2% in the same region. (This simulation was carried out by C. Y. Chang and C. Grandi).

The estimated systematic errors on the absolute luminosity are as follows:

	1989 data	1990 data (Singapore '90)
Tube survey	1.5%	1.0%
Tube efficiency	0.5%	—
Trigger efficiency	0.3%	—
$E_{\bar{TOT}}$ cut	0.5%	0.5%
$\bar{R}$ cut	0.5%	0.2%
Calorimeter coordinates	—	0.4%
Background subtraction	0.5%	—
Theory	1.0%	1.0%
TOTAL	2.2%	1.6%

Fig. 3



E_{Left} vs. E_{Right} for Tube Events (new selection)

The luminosity measurements were carried out by a team of Maryland, London and Bologna physicists, and have been a crucial ingredient in many of OPAL's physics results. The Maryland personnel at CERN concerned with the forward detector are Dr. Richard Kellogg, Dr. Alfred Lee, IV and Mr. Suen Hou, with some part time assistance from Prof. C. Y. Chang and Prof. Andris Skuja. Mr. Hou will base his Ph.D. thesis on the luminosity measurements at OPAL.

B.3 Hadron Calorimeter Performance (A. Ball, P. Goldey, A. Jawahery, J. Lorah, W. Springer, University of Maryland, with U. of Bologna and U. of California, Riverside)

a) Introduction

Since commissioning in September 1989, the hadron calorimeter hardware and data acquisition systems have performed reliably, and the data provided have played a crucial role in several physics analyses, notably the measurement of the $Z^{\circ} \rightarrow b\bar{b}$ branching ratio, and the search for Higgs bosons.

The hardware configuration is essentially complete, with the tower and strip readout having functioned since the beginning of LEP physics, and the trigger having been recently commissioned for testing.

b) Hardware and Data Acquisition

The 7500 7- and 8-cell streamer chambers have settled into stable operation with a total of 3% inoperative due to gas circulation problems or instability at high voltage. Front end readout failures have been insignificant by comparison. Isolation of the approximately 200 rogue channels was possible because the onboard housings give, albeit with some difficulty, access to each individual chamber and readout channel.

Typical LEP operating schedules during 1990 gave an opportunity for access once every 2 weeks. Interventions (involving retracting the endcap muon chambers and inserting scaffolding) were made in all but one of these maintenance periods. Without this work, an estimated 10% of channels would have been inoperative by the end of the 1990 data-taking.

The gas mixing and circulation system required extensive modifications after the operational experience gained during 1989. Since the gas flow rate normally results in only one volume change per day, initial filling is very slow and recovery from an incorrect mixture takes several days, resulting in significant data losses during 1989. Modifications made during the 1989-90 winter shutdown have eliminated most of the problems. The isobutane supply batteries are now maintained at a constant temperature of 35°C using forced air circulation. A new, purely mechanical system handles automatic changeover between working and reserve batteries, and a pressure-driven switch isolates the detector and underground gas distribution in case of a loss in isobutane pressure. Additionally, the "slow controls" safety system monitors argon and isobutane flows, once again isolating the underground system in case of a deviation from nominal flow values. The 256 parallel underground flow comparator channels were completely overhauled and re-calibrated, so that deviations from normal flow of more than 30% in an individual channel can now be used to trigger safety actions. A high flow return bypass has been installed to allow twice the normal gas flow to be maintained, at the expense of monitoring, during filling and purging. A gas composition monitor, based on speed of sound measurement, allows the evolution of the mixture emerging from the detector to be monitored.

Clearly, more improvements are necessary. Spare electronic flow controllers are needed, since the existing ones failed near the end of 1990 data taking. An underground gas-gain monitor will be needed to eliminate gain uncertainties due, for instance, to differences in temperature between the surface gain monitor and the detector itself. Tests have begun on a system to recuperate isobutane from the return gas by condensation. 90 hours of successful operation have been achieved, but the device is far from sufficiently reliable to permit use of recuperated isobutane in the mixer. Responsibility for the further development of this device is shared with CERN.

The data acquisition system has achieved a high level of reliability, contributing less than 2% of all OPAL DAQ problems during 1990. Automatic recalculation of both tower and trigger pedestals now occurs during re-starts of the HCAL subdetectors.

c) Hadronic Energy Measurement

The detector was operated at constant gain throughout the 1990 data taking period, by adjustment of the operating voltage so as to compensate for effects such as atmospheric pressure fluctuations. The appropriate voltage was defined as that needed to make the surface gas-gain monitor (consisting of 12 chambers in a cosmic ray telescope) register an average charge per cell of 30 +/- 2 pc. for a normally incident cosmic ray muon. Constant gain operation eliminates most offline corrections to the tower energy and maintains at constant values quantities such as strip cross-talk and efficiency. These are crucial parameters for the effectiveness of the muon-finding algorithm.

Fig 1 (solid line) shows the tower energy calibration, presented as the energy deposit per hit layer for muon tracks from muon pair events corrected to normal incidence. This is compared (dotted line) with the same distribution for muons in the 1987 HCAL test-beam module, where the energy scale was obtained by comparison with the response to pions of known energies. This calibration remained stable throughout the whole 1990 data-taking period.

Fig 2 shows the distribution of the total energy deposited in the HCAL (including the pole-tip calorimeter) for multihadronic events at the Z° peak. The data are in remarkably good agreement with the Monte-Carlo predictions (solid line) based on test-beam data.

FIG 1

Energy Per Layer Deposited By Muons Traversing The Hadron Calorimeter

(a correction Q0 = Q(theta)/(1+0.82cos(theta)) has been applied to the charge registered at a polar angle theta in order to derive the expected charge at normal incidence Q0. The energy conversion is chosen to match the observed distribution with that seen in a test module (dotted line), where the response to muons was compared with that to pions of known energy.)

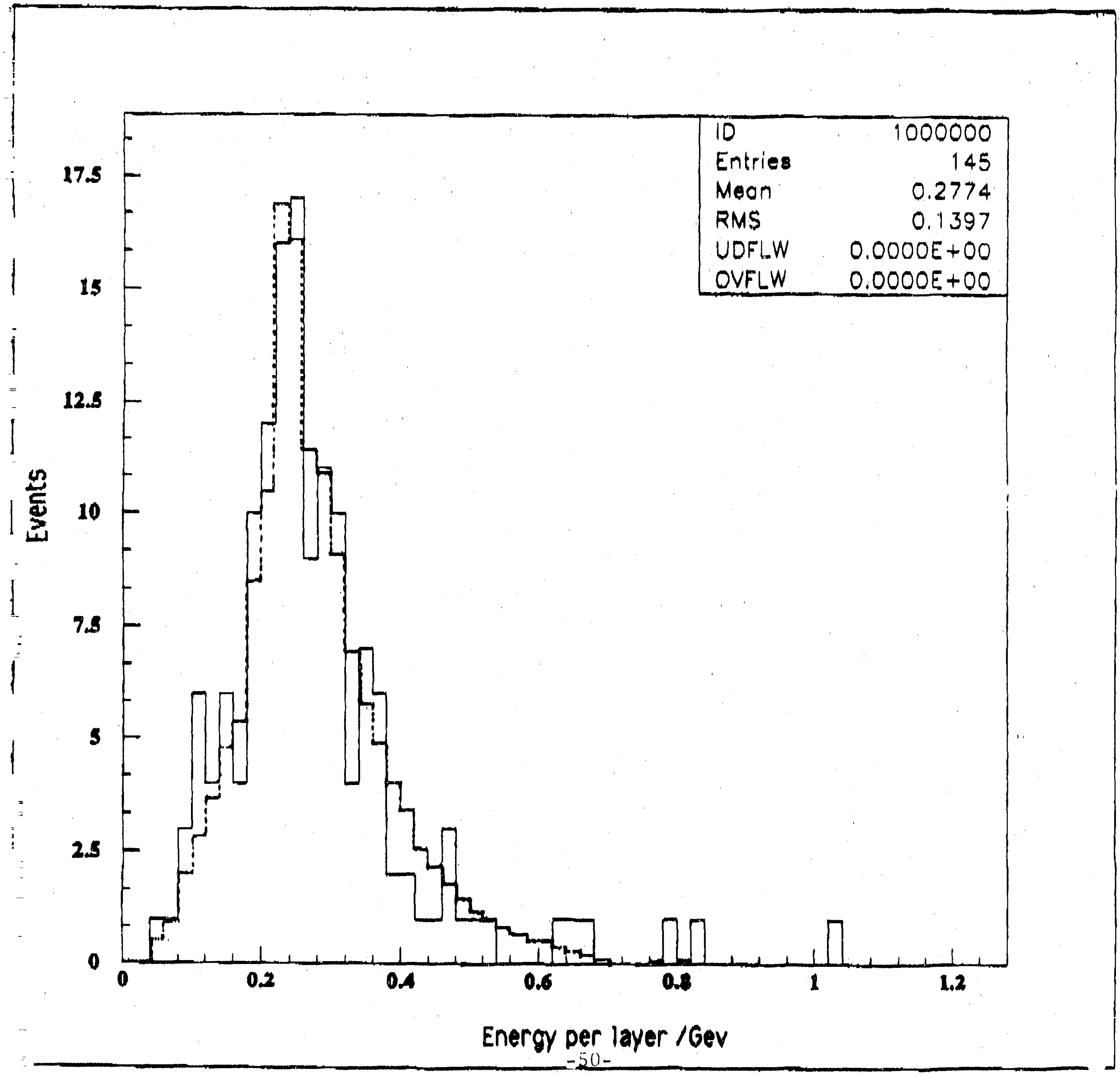
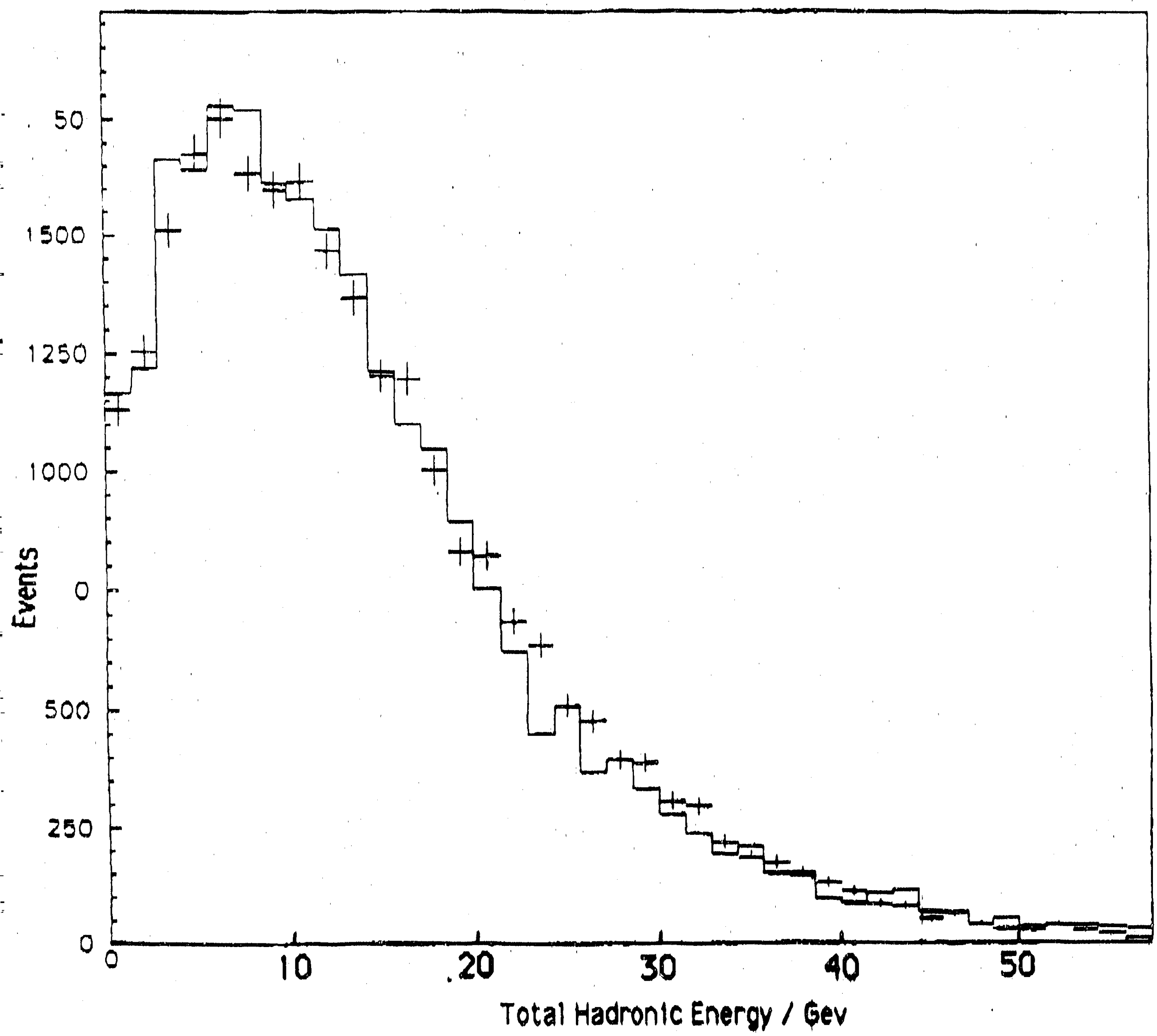


FIG 2

Total Energy Per Event Seen In The
Hadron Calorimeter For Z^0--> Multihadrons

The Solid Line Is The Prediction Of Jetset 7.2
Plus A Full Detector Simulation



d) Muon Identification

The generalized HCAL strip clustering algorithm includes a package for identifying penetrating tracks. The basic idea is to find a series of hit-strip clusters, each with no more than 3 hits, and each in a separate layer of the HCAL, which fit well to a straight line pointing towards the origin. Such a muon segment is required to contain a minimum of 4 layers, to have penetrated to at least layer 5, to have no more than 4 consecutive missing layers, and to have less than 9 nearby hits, summed over all layers.

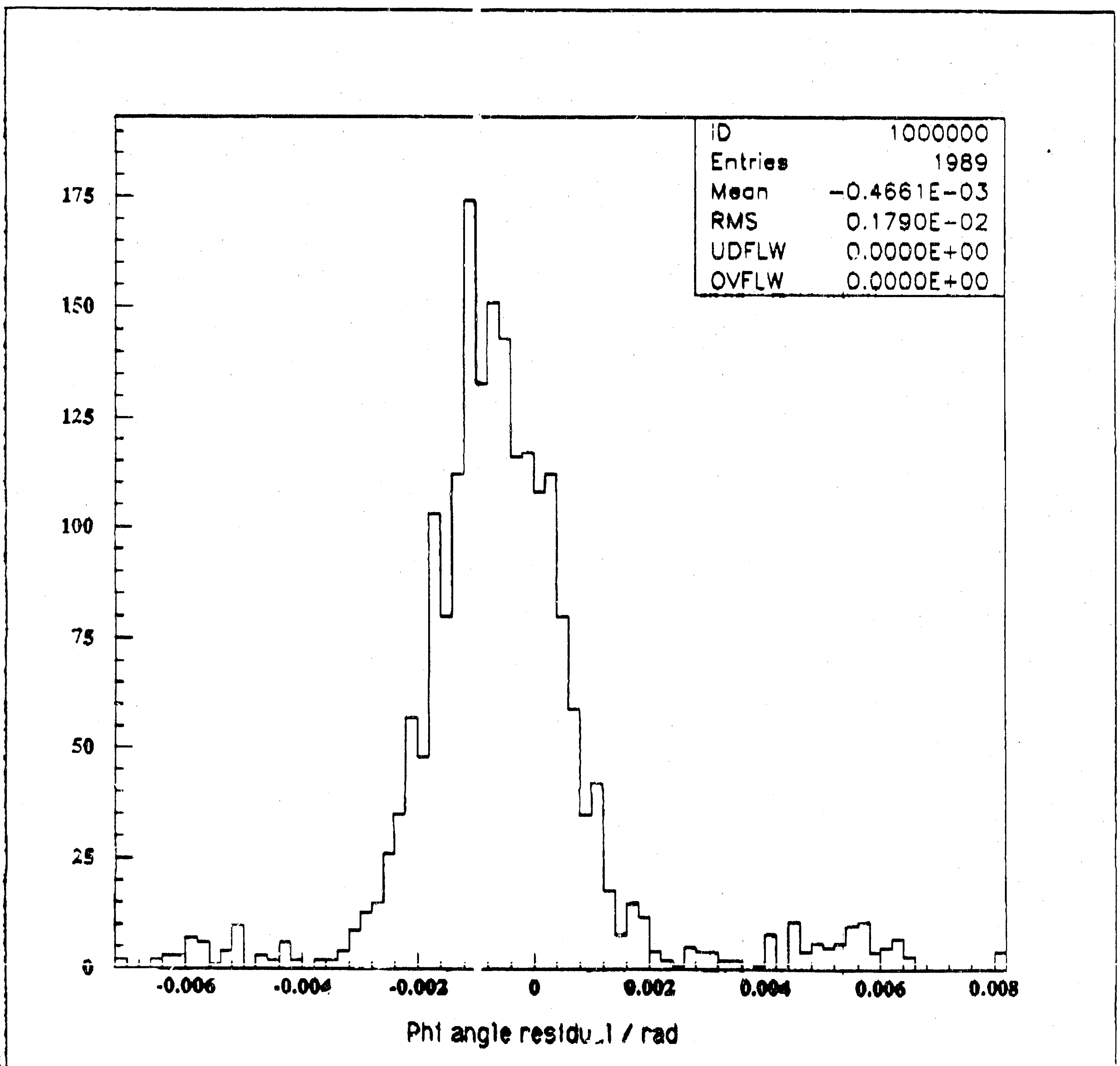
Fig 3 shows the distribution of the phi angle residual at the HCAL between muon segments found by the strip cluster algorithm and extrapolated tracks from muon pair events. The width of 3 mrad is compatible with the expected extrapolation and multiple-scattering errors. This width remained unchanged after opening and closing the various sections of the magnet yoke for maintenance. Thus, the initial survey and position calibration, based on nominal streamer cell positions within the iron, appears to be accurate and stable enough for present purposes.

e) Trigger

Although all components of the trigger system were available by April 1990, shortage of manpower prevented cabling and commissioning until late summer. The 92 trigger signals are 16-fold analog sums generated by the tower readout ADC's. These signals, each representing the energy deposited in a 4 $\times$ 4 tower element, are discriminated at 3 different thresholds by 18 comparator cards. Elements with energies above the lowest threshold are mapped onto the hadron layer of the OPAL trigger matrix by matching cards. Signals above the other 2 thresholds are used to generate coincidence triggers between the 18 different half-ring sections of the HCAL. Fig 4

FIG 3

Phi Residual At The Hadron Calorimeter Between Central Tracks And HCAL Muon Segments For Muon Pair Events



shows the correlation between set track trigger matrix elements and set HCAL matrix elements for muon pair events. There is perfect correlation with no noise. The HCAL threshold corresponds to an energy of about 700 MeV and the efficiency for triggering on a single muon pair track within the acceptance is about 85%.

f) Physics Applications

The HCAL plays a crucial role in the identification of inclusive muons. Most of the analysis has been directed towards the measurement of the $Z^{\circ} \rightarrow b\bar{b}$ branching ratio. Studies of muon pairs, real K°'s, and simulated multihadron events show that the HCAL alone can identify muons with an efficiency of 85% and a hadronic contamination of less than 1.5% per track. In some geometrical regions, this is the only muon identifier. Generally, however, there is overlap with the barrel and endcap muon detectors. Cross-checks between the HCAL and these detectors enable the efficiency of each to be determined. In addition, a coincidence requirement between loosely defined muon segments in the HCAL and the muon detectors provides the purest sample of muons, with a contamination probability of less than 0.5% per pion track.

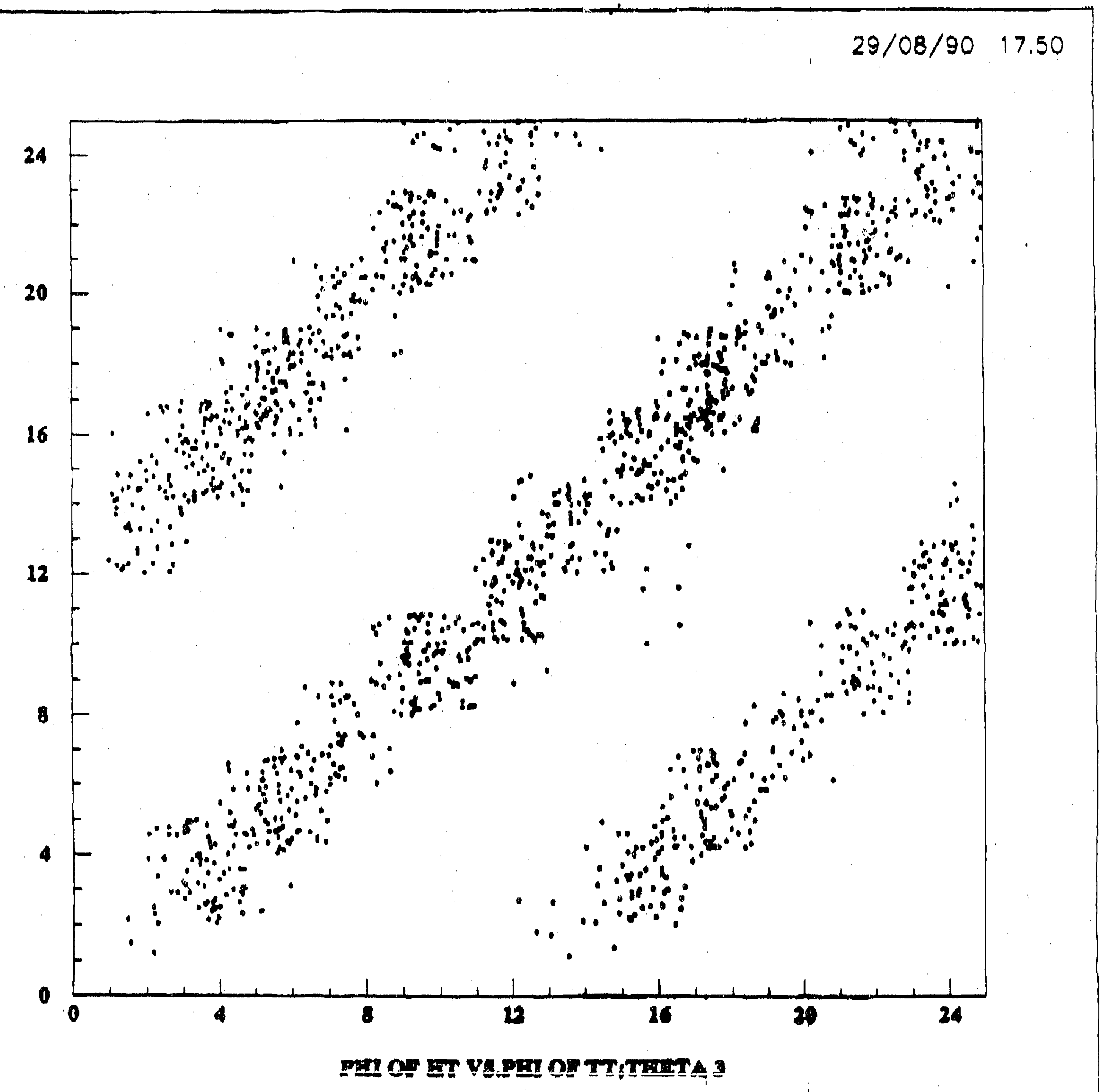
Higgs bosons, both in the standard and SUSY models, are likely to be produced by the Bjorken process $Z^{\circ} \rightarrow Z^{\circ}H^{\circ}$. The missing energy channel, where the virtual Z decays to a pair of neutrinos, offers the most promising search channel. It results in a distinctive signature of a pair of jets (probably b-jets) recoiling against invisible energy.

Initially, the search for this signature was conducted without using the HCAL. Events with missing energy recoiling against a pair of heavy jets were selected using cuts on thrust, acoplanarity, acolinearity, transverse

FIG 4

Scatter Plot of Set Track Trigger Elements vs Set HCAL Trigger Elements For Muon Pair Events

(the side-bands correspond to the opposite track of the pair)



momentum, and both the total mass and the separate masses in two hemispheres. (Only charged and electromagnetic energy were considered.)

Several events remain, of which Fig 5 is an example. The apparent "missing energy" is clearly due to one or more neutral hadrons, which deposit energy only in the HCAL. Identification and removal of these events increases the latest OPAL lower limit on the mass of the standard model Higgs boson from 31 GeV/c^2 to 39.4 GeV/c^2.

g) Future Upgrades

Besides the gas system improvements already mentioned, several other repairs and upgrades will be necessary during the long 1990-91 shutdown.

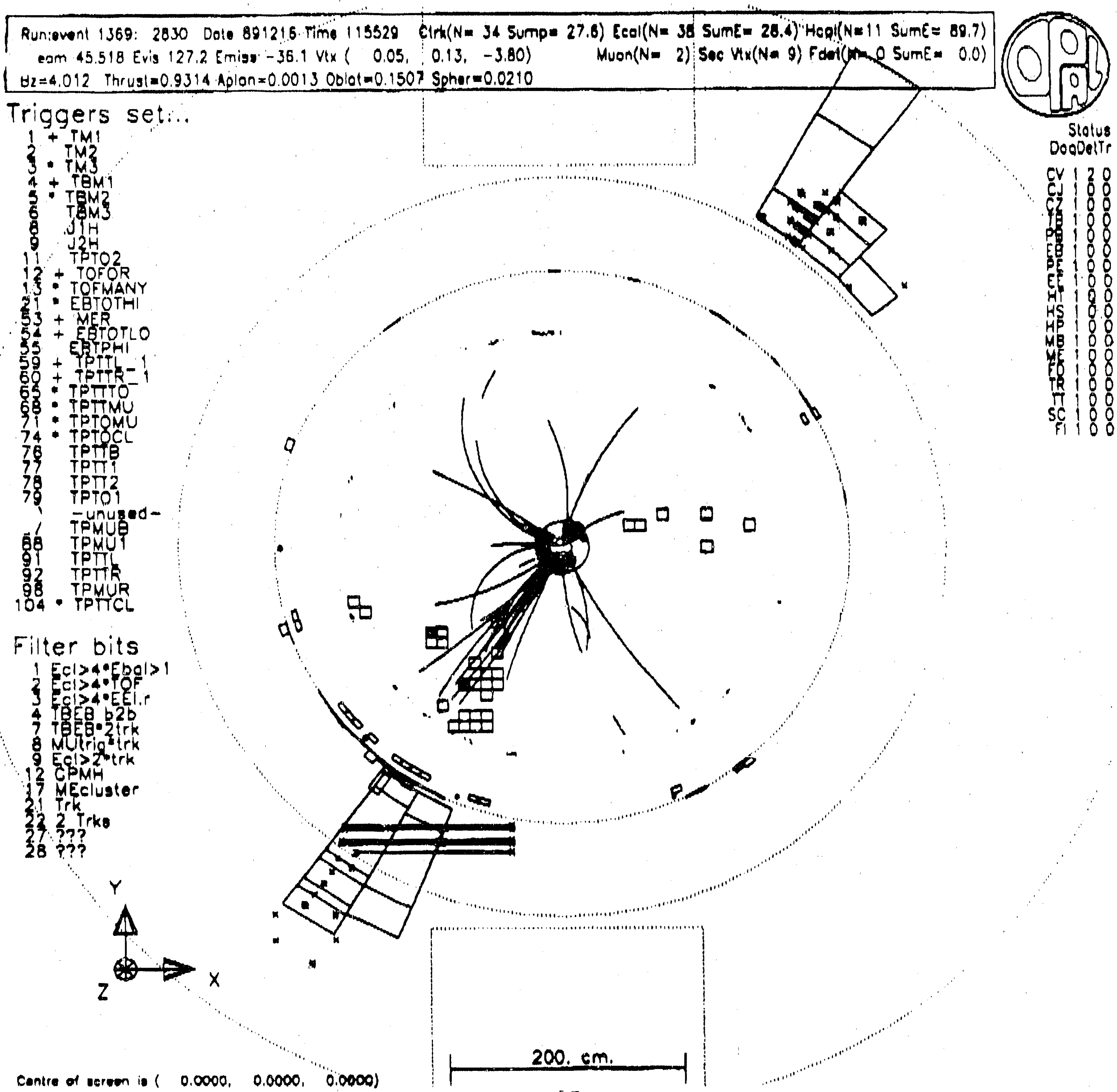
The monitor system, which measures the singles counting rates of groups of chambers, and incorporates a wire pulser, suffered front end damage apparently due to an accidental beam loss into the OPAL detector. This system is vital for the re-commissioning of the detector and about 20 of the 72 monitor cards will have to be removed from their on-board housings for repair.

Continued improvements in the LEP luminosity, and the longer term prospect of at least doubling the number of circulating bunches, demand reciprocal improvements in the OPAL trigger rate capability and deadtime. Targets of 10 ms readout time and 10 Hz rate capability have been set for 1990. The present HCAL readout time of about 15 ms is essentially limited by the 68020 c.p.u. in the master system crate where the 2 halves of the hadron calorimeter readout are merged and where most of the calibration, monitoring, and control tasks are performed. Replacement of this c.p.u. by a 68030 processor, combined with a major software upgrade, may be sufficient to meet the target. If this is not the case, the 2 branch CAMAC system will

FIG 5

Example Of A Candidate Event For $Z^0 \rightarrow Z^0 H^0$ In The Missing Energy Channel Where the Z^0 Decays to Neutrinos, & The H^0 to Heavy Quarks.

(The Event Is Rejected Only Because Of The Large Energy Deposit In The HCAL Along The Direction Of The Missing Charged & Electromagnetic Energy)



have to be reconfigured into 4 branches. This will require new VME-CAMAC interface hardware and software.

Some re-building of the trigger control logic will be necessary. To permit this, and to ease a perilous spares situation, more logic and gating units will be needed.

h) Manpower

Despite a reasonably reliable and successful first year of operation, shortage of manpower remains the most serious threat to the future performance of the HCAL.

Each sub-detector is required to have both hardware and data acquisition experts available around the clock. From the data-acquisition point of view, HCAL is 2 separate sub-detectors, HS (strips) and HT (towers). In addition, the performance of daily checklists, adjustment of constant gain and routine monitoring requires approximately one full-time physicist. (This task is rotated amongst the 3 collaborating institutes.) Detailed problem diagnosis, routine maintenance and repairs, gas supply logistics (bottle delivery, changing, etc.) and further hardware developments such as isobutane recuperation and underground gain monitoring required one full-time technician throughout 1990. The need for skilled and experienced technical support to maintain and improve such a large and complex device is self-evident. Although these requirements were met during 1990, the chronic understaffing is apparent from the delayed implementation of the trigger and the poor understanding of the individual layer efficiency (apparently only 75%, probably resulting from detailed survey and status uncertainties), and of the individual energy calibration and cross-talk for the towers.

i) Conclusion

The Hadron Calorimeter has performed well during its first year of operation. Hardware and data acquisition reliability have been good, with every prospect of continued stability during 1991. More manpower is clearly needed urgently, but nevertheless data from the detector have been crucial to several physics analyses.

C. Dϕ Experiment at the Tevatron Collider. (A Baden, N. J. Hadley, S. Kunori, K. Streets, T. M. L. Ren, D. Norman, Univ. of Md., in collaboration with the Univ. of Arizona, Brookhaven National Lab., Brown Univ., Univ. of Calif., Riverside, Columbia Univ., Fermilab, Florida State Univ., Univ. of Hawaii, Indiana Univ., Lawrence Berkeley Lab., Univ. of Michigan, Michigan State Univ., New York Univ., Northern Illinois Univ., Univ. of Rochester, CEN Saclay, Serpukov, SUNY Stony Brook, Texas A&M Univ. Yale Univ.)

1. Introduction

The Dϕ experiment, which is being built by a collaboration of more than 100 physicists from 22 institutions, is a large 4π detector facility designed to study proton-antiproton collisions at 2 TeV center of mass energy. Since Dϕ has no magnetic field, it is able to have compact, highly segmented, nearly hermetic calorimetry with excellent energy resolution. It also has excellent lepton identification for both electrons and muons. We hope to use the strengths of Dϕ to:

1. Study the physics of QCD, in particular that of jet production, at the highest energy accelerator in the world.

2. Search for phenomena that are predicted to exist by the Standard Model but have not yet been observed, most notably the top quark.

3. Search for phenomena that lie beyond the standard model, such as supersymmetry and technicolor.

The Dϕ experiment has been under construction during 1990 and large parts of the apparatus are installed at Fermilab. The central calorimeter modules are complete and have been installed in their cryostat. The internal cryostat cabling is complete and the central cryostat has been welded shut. All of the elements of the central detector, the Central Drift chamber, the Transition Radiation detector, the Forward Drift chambers, and the Vertex detector, are now complete and at Fermilab. See Fig. 1 for a drawing of the Dϕ calorimeters. The muon iron is complete and more than half of the muon chambers are installed in the detector. In addition to these efforts, Dϕ is

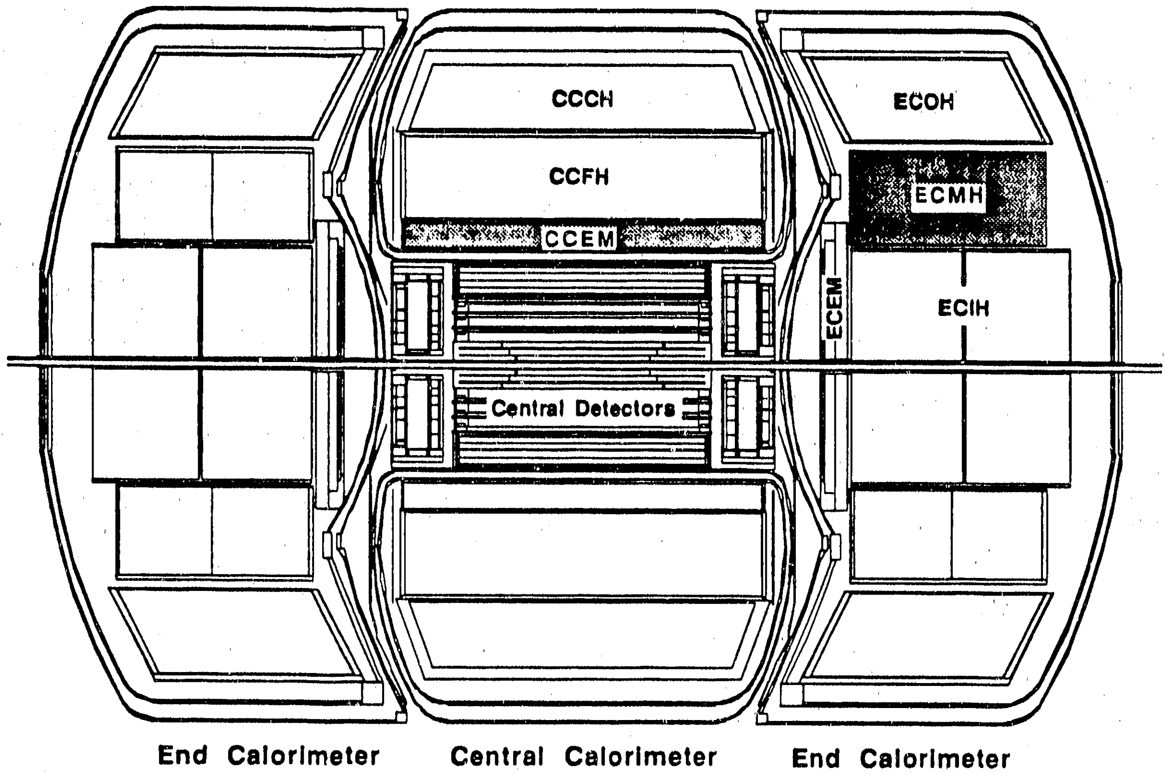

CCCH
CCFH
CCEM
ECOH
ECMH
ECEM
ECIH
Central Detectors
End Calorimeter
Central Calorimeter
End Calorimeter

Figure 1

testing both calorimeter modules and parts of the central detector in a Test Beam at Fermilab during the current fixed target run. The goal of all of these efforts is to be ready to take data during the next Fermilab collider run which is now scheduled for summer 1991.

The University of Maryland Dϕ group remained essentially the same size during 1990. We are now 4 Ph.D.'s (Prof. Baden, Prof. Hadley, Dr. Kunori, and Dr. Streets) and two full time graduate students (Mr. Norman and Ms. Ren). Dr. Baden was promoted to Assistant Professor in July 1990. In addition, we employed two graduate summer students during the summer of 1990. The Maryland group has hardware responsibilities for the construction of Dϕ high voltage fanout and current monitoring system. The group has software responsibilities for the development of muon analysis programs and for jet reconstruction algorithms. We have also been heavily involved with the calorimeter test beam effort and with the testing of calorimeter electronics. Prof. Hadley is the co-organizer with Paul Grannis, the spokesman for Dϕ, of the two D0 Upgrade workshops at Fermilab during the summer of 1990. He also organized the Dϕ session at Snowmass 1990.

2. **High Voltage Fanouts**

The Maryland group is responsible for building most of the Dϕ high voltage fanouts and for designing and building high voltage fanouts with current monitoring for the Dϕ calorimeters. We have built about 1700 channels of high voltage fanouts without current monitoring this year. Despite our only becoming involved with this project in June of 1989, we completed these fanouts in time for use in the test beam and for general debugging of various detectors in Dϕ this year. The fanouts met the specifications of less than 2 nanoamps of leakage current at 10,000 volts.

They were built and tested at Maryland by our group's electronics engineer and technicians, using the services of the Maryland Physics Department machine shop.

The design of the fanouts with current monitoring for the Dϕ calorimeters is now complete and a prototype has been successfully tested. The current monitors are computer controlled and are capable of reading from 100 nanoamps to 20 microamps at 4000 volts. The design and testing were again accomplished by the High Energy Physics group's electrical engineer (R. Bard) and technicians (W. Miller and J. Colmer) with the assistance of Prof. Baden and graduate student, M. L. Ren. We anticipate going into production of the fanouts with current monitoring in late August 1990. Current monitoring will only be implemented on about 521 out of a total of 2500 channels to reduce the cost. The fanouts are being built in such a way that current monitoring can be added later when more funds are available.

The work on the high voltage fanouts is funded by Dϕ equipment monies which are transferred to Maryland through Fermilab.

3. **Calorimeter Test Beam**

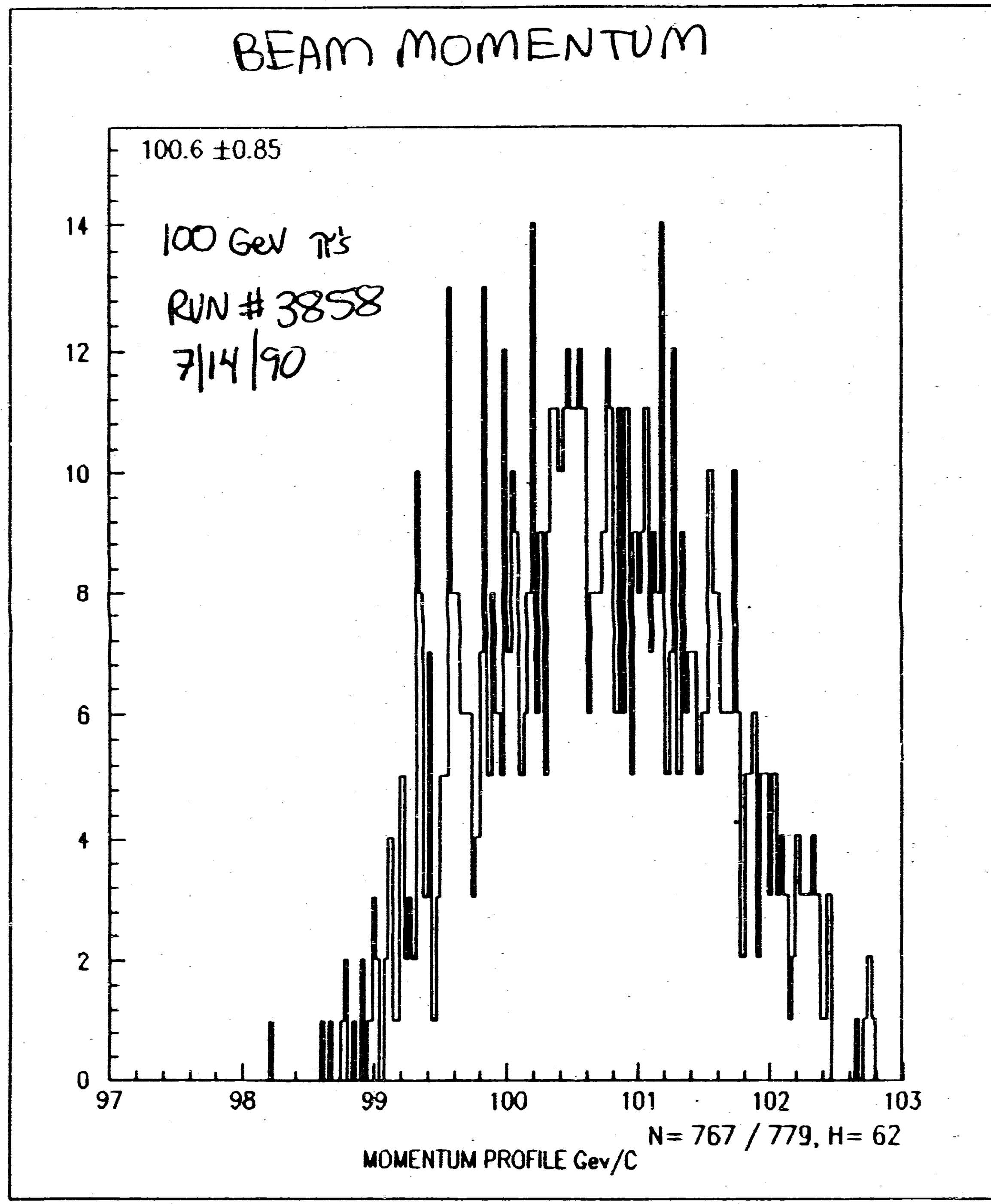
Dϕ has mounted a major effort in an FNAL test beam during the current fixed target run at Fermilab. During this run, we plan not only to test individual calorimeter modules, but also groups of modules and the cracks between them. Since Dϕ does not have a magnetic field, the test beam is the best place to obtain a thorough understanding of the detector. This test beam work is a large effort and involves most of the member institutions in the Dϕ collaboration.

D. Norman helped with the installation and testing of the calorimeter modules in the central cryostat in the Dϕ hall. He was then responsible for the preparation and checking of the cart and grid used to move and hold the modules in the cryostat. K. Streets from the Maryland group is in charge of commissioning and maintaining the calorimeter electronics for the test beam run. This continued her earlier work with the "5000 channel test" which was a test of one twelfth of the Dϕ calorimeter electronics. Work for the test beam has included installing, debugging and maintaining the electronics during the run. This, of course, has been a large effort. The Maryland group (principally K. Streets and D. Norman) has also written software for studies of pedestal stability, pulser stability, and pulser uniformity and linearity. It was necessary to optimize the choice of calorimeter channels that were instrumented in order to fully contain a hadronic shower, since there were not enough feedthroughs in the test beam cryostat to completely hook up all of the modules inside. This required ganging of some of the calorimeter signals and re-mapping them for their usual locations. This ganging and re-mapping was done in "Kluge Cards". K. Streets designed these "Kluge Cards" and oversaw their production and testing. There were a total of 41 "Kluge Cards" made of 19 different types. These cards were completed on time for the test beam run and are being used in the current data taking.

The Maryland group, of course, has been taking shifts during the test beam running and has been active in the data analysis, concentrating on this time on the electronics and on online data analysis including the measurement of the beam momentum. See Fig. 2. This followed up on our earlier work analyzing the 1987-1988 test beam data.

4. **Muon and Jet Software**

S. Kunori is currently working as coordinator of the muon reconstruction program and muon Monte Carlo simulation program. The initial version of the muon finding program was developed by D. Hedin of Northern Illinois



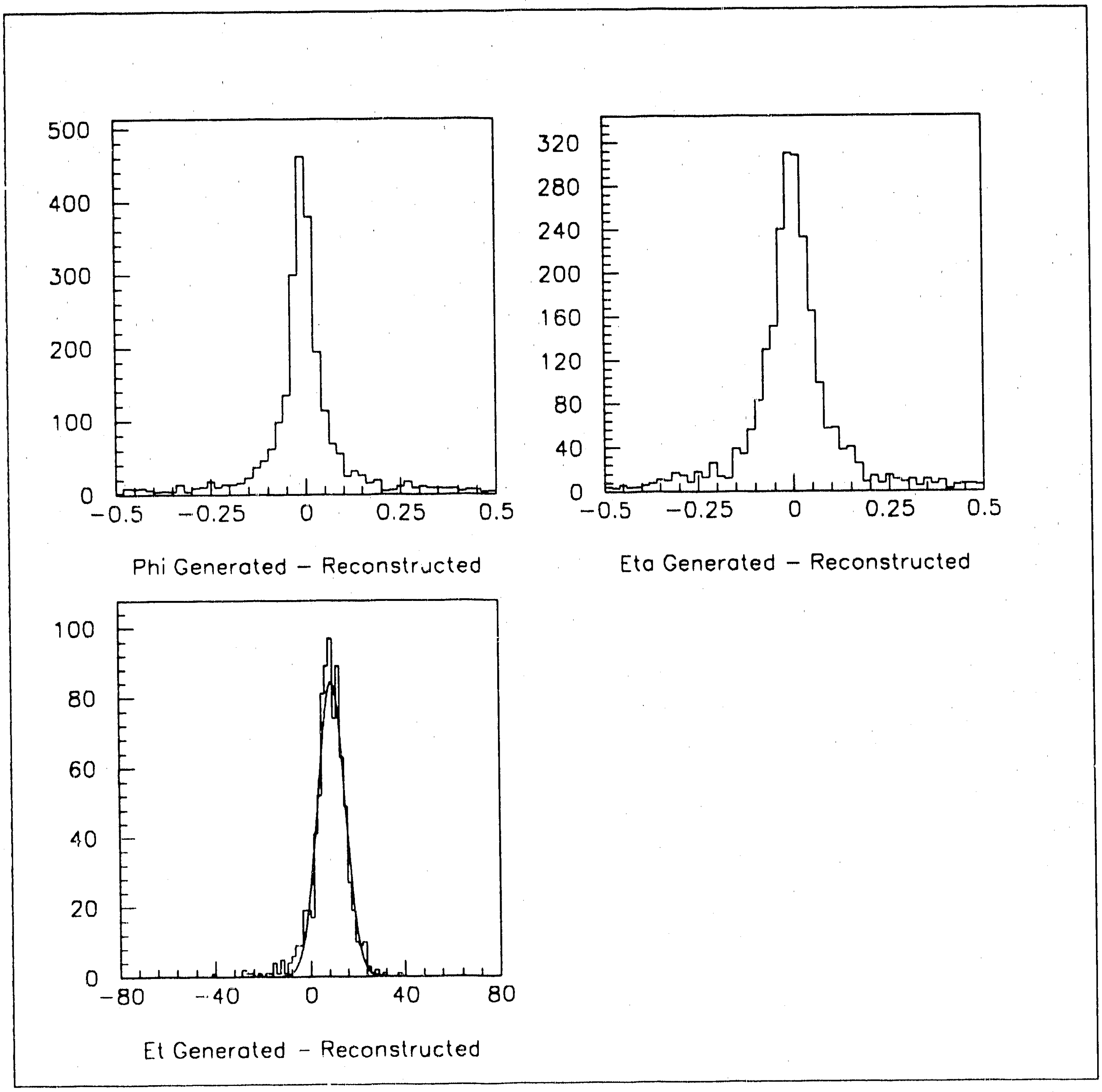
BEAM MOMENTUM

University. The program looks for muons locally in the muon chambers and does fitting using only the muon chamber hits. The muons that have been found are then matched to tracks found in the central detector to provide an improved momentum measurement. The first version of the matching program was written by S. Kunori along with S. Abachi from Fermilab and D. Zieminska from Indiana. These program packages are currently being tested and improved.

N. Hadley and B. Klima from FNAL are the co-leaders of the Dϕ Jets Algorithm gruop. This year we completed algorithms based on both a fixed cone on $\delta\eta$ $\delta\phi$ space including splitting of overlapping jets as well as a "nearest neighbor" algorithm that clusters adjacent towers. Both algorithms have been tested extensively on more than 10,000 Monte Carlo events. These algorithms have been used to detect a number of inconsistencies in the Dϕ geometry between the Monte Carlo and reconstruction programs. We present in Fig. 3 results for the expected Dϕ jet η, ϕ and energy resolution obtained by comparing the known parton energies and directions in the Monte Carlo with the reconstructed jets. We have started work studying cross sections expected as a function of the jet cone size to compare with QCD calculations.[1]

References

1. See, for example, F. Aversa, et al., Phys. Rev. Lett. 65, 401 (1990).


500
400
300
200
100
0
−0.5
−0.25
0
0.25
0.5
Phi Generated − Reconstructed
320
280
240
200
160
120
80
40
0
−0.5
−0.25
0
0.25
0.5
Eta Generated − Reconstructed
100
80
60
40
20
0
−80
−40
0
40
80
Et Generated − Reconstructed

5. Dϕ Upgrade

Although the Dϕ detector is not yet complete, we are, nevertheless, starting to prepare for an upgrade of Dϕ to best utilize the physics opportunities with the proposed new main injector at Fermilab. With the main injector, the luminosity at the collider is expected to rise from the present value of a few times 10^{30} to about 10^{32} after 1995. Prof. N. Hadley has been a co-organizer with P. Grannis, the Dϕ spokesman, of the Dϕ collaborations internal workshops on the Upgrade. He also led the Dϕ Upgrade group at the 1990 Snowmass workshop.

D. Deep Inelastic Muon Scattering of TeV II (E665 at Fermilab). (S. Aid, S. Kunori, S. O'Day, E. Ramberg, A. Skuja and G. A. Snow of the Univ. of Maryland in collaboration with physicists from Argonne National Lab., Univ. of California (San Diego), Cracow, Fermilab, Harvard, Illinois (Chicago Circle), Max Planck Institute (Munich), MIT, Washington, Wuppertal and Yale).

The Fermilab experiment, E665, took data in 1987-88 using 500 and 100 GeV/c muon beams on three targets, a high pressurized gaseous xenon, liquid hydrogen and liquid deuterium. All of 500 GeV/c data have been processed through reconstruction programs and data analyses are in progress. The collaboration reported its first preliminary result on a cross section ratio of xenon to deuterium at small x_{bj} at the DPF meeting at Rice in January 1990 and since then has been reporting preliminary results on structure functions and hadron production reactions at various conferences (table 1).

The experiment finished its second run in August 1990. 500 GeV/c muon beams were directed at three solid targets, carbon, calcium and lead, and two liquid targets, hydrogen and deuterium. With these targets, we are planning to study more details of the A-dependence of structure functions and hadron production in muon interactions relative to the study based on RUN87-88 which had only the gaseous Xe target and liquid deuter'um for such A dependence studies.

E665 has been approved for running in the next fixed target running period at Fermilab starting in December 1990. In that run the plan is to concentrate on taking data from light targets, liquid hydrogen and deuterium, with the 500 GeV/c muon beam.

In the following sections we describe: 1) some results from the first run (RUN87-88), 2) status of second run (RUN90) and 3) the next run (RUN91).

Table 1.

Contributed Papers to International Conferences (on E665 results)

Muon Interactions at 490 GeV: First Results from E665 (talk by M. Schmitt) 25th Recontres de Moriond: High Energy Hadronic Interactions, Les Arcs, France, Mar. 1990.

Nuclear Dependence of Hadron Production in Deep Inelastic Muon-Nucleon Scattering at 490 GeV/c, (Talk by J. Ryan), 12th International Conference on Particles and Nuclei (PANIC 90) MIT, Cambridge, MA, June, 1990.

Preliminary Results on Neutron-to-Proton Cross-Section Ratio at Low χ_{bj} From Deep Inelastic Muon Scattering at 490 GeV/c, M. Adams, et al., submitted to the 25th International Conference on High Energy Physics, Singapore, 1990 (Talk given by C. Halliwell).

Measurement of the Xenon/Deuterium Inelastic Scattering Cross Section Ratio Using 490 GeV/c Muon, S. Magill, et al., submitted to the 25th International Conference on High Energy Physics, Singapore, 1990 (Talk given by C. Halliwell).

Energy Flow and Transverse Momentum of Hadron Jets Produced in Deep Inelastic Scattering, M. Adams, et al., submitted to the 25th International Conference on High Energy Physics, Singapore, 1990 (Talk given by H. Lubatti).

Talks at APS Meetings (on E665 Results)

X_e/D_2 Cross-section Ratios at Low X_{Bj} from Muon Scattering at 490 GeV/c by S. Magill at 15th APS Division of Particles and Fields Meeting, Houston, TX, Jan. 1990, and at APS Meeting, Wash., D. C., Apr., 1990.

D_2/H_2 Cross-section Ratio at High Q^2 from Deep-Inelastic Muon Scattering, S. Aid at APS Meeting, Washington, D. C., Apr., 1990.

D_2/H_2 Cross-section Ratio at Low Q^2 from Deep-Inelastic Muon Scattering by A. Bhatti at APS Meeting, Washington, D. C. Apr., 1990.

Transverse Momentum and Energy Flow for Forward Charged Hadrons and Photons in Deep-inelastic Muon Scattering by D. Michael, at APS Meeting, Washington, D. C., Apr., 1990.

Transverse Momentum of Charged Hadrons Produced in Deep Inelastic Muon Scattering by D. Jansen, at APS Meeting, Washington, D. C., Apr., 1990.

Pi Zero Production in Deep Inelastic Muon Scattering at 490 GeV/c by E. Ramberg at APS Meeting, Washington, D. C., Apr., 1990.

Charged Hadron Multiplicities in Deep Inelastic Muon-Hydrogen and Muon-Deuterium Scattering by S. O'Day at APS Meeting, Washington, D. C., Apr., 1990,

[1] **Some results from RUN87-88**

The E665 detector in RUN87-88 has been described in previous progress reports and published elsewhere. (Nucl. Instr. and Meth. A291, 533 (1990)). Two triggers were employed as main physics triggers. The large angle trigger (LAT) covers the muon scattering angle down to 3 mrad. The small angle trigger (SAT) goes down to 1.0 mrad. It used 12% of the beam luminosity relative to that for the LAT. These triggers with the world's highest muon beam energy, 500 GeV, allow us to explore physics in a wide kinematical region; the Bjorken scaling variable (x_{bj}) ≈ 10^{-3} to 1, 4 momentum transfer (Q^2) ≈ 0.1 - 100 GeV^2 and the total hadronic energy (W) in the center of mass system up to 30 GeV.

(a) Nuclear Shadowing

Since the observation of A dependence effects in structure functions by EMC in 1983, the so-called EMC effect, many experiments have focused on this subject and many theoretical papers have been published. E665 also studied the effect, especially in the small x_{bj} region where shadowing becomes important.

Shown in Fig. 1 are ratios of cross sections for xenon and deuterium for the SAT data sample with $Q^2 > 0.1$ GeV^2 and y (= E_1-E_0)/E_0) < 0.75, where E_0 and E_1 are energy of the beam and scattered muon, respectively. Since the contribution of radiative processes to the total cross section becomes significant in the small x_{bj} region, we used three methods to obtain the ratio.

The stars in Fig. 1(a) are corrected by a calculation for the full radiative processes, i.e., internal loop, quasi-elastic and inelastic. A contribution of the internal loop process (so-called vertex correction) is the same for xenon and deuterium and cancels out in the ratio of the cross sections. The quasi-elastic process becomes significant at high y and small x_{bj}, typically about 50% of total cross section at y = 0.75. The inelastic process has almost constant contributions to the total cross section, roughly 10% in all of the y range and does not much change the slope of the ratio.

In order to exclude the biggest contribution due to the quasi-elastic radiative events, we used the electromagnetic calorimeter to identify such events. These are subtracted and the result is shown by triangles in Fig. 1(a). The result may still have a small residual contribution from the inelastic process.

Third method to avoid the problem due to the radiative processes is to exclude a kinematical region where we expect large contributions of the radiative processes. Open circles in Fig. 1(a) are for events with a tighter kinematical cut in y, $y < 0.5$.

All three methods agree with each other within our statistical error bars. The result shows clear shadowing effect in the small x_{bj} region. Fig. 1(b) shows comparison of the E665 result with the full radiative correction and EMC (NA28) result. Both show quite similar shadowing effects and the E665 shows the ratio continuously decreasing down to $x_{bj} \sim 10^{-3}$.

Shown in Fig. 2 are the cross section ratios of xenon to deuterium as a function of Q^2 with the results from NA28. The E665 data points cover a wider range of Q^2 than the NA28 data and show no strong Q^2 dependence both at small x_{bj} (0.001-0.025) and at larger x_{bj} (0.025-0.2). This result is inconsistent with the naive vector meson dominance model, whereas it is consistent with the gluon recombination model which predicts no strong Q^2 dependence.

(b) n/p ratio

We also studied the ratio of cross sections of neutron to proton using liquid hydrogen and deuteirum data. As shown in Fig. 3 the ratio is consistent with results from BCDMS and EMC at larger x_{bj} and approaches unity as x_{bj} decreases. The result is consistent with expectation from the standard QCD-quark parton model. This is a topic for S. Aid's thesis. He reported the results at the APS meeting at Washington and the structure function workshop at Fermilab in April, 1990.

We have been also studying hadron productions in the muon interactions.

(c) Exclusive ρ° production.

In the exclusive channel we studied ρ° production. The exclusive events are selected by a requirement of energy-momentum conservation for final state of μ^+, π^+ and π^-. A contamination due to e^+, e^- pair production from pure electromagnetic interactions are removed using the electromagnetic calorimeter. The resultant invariant mass distribution for π^+ and π^- (Fig. 4) shows a clear peak of ρ° production. The decay angular distributions of the ρ° candidates are shown in Fig. 5 for three Q^2 ranges. The decay angular distributions are fitted to a formula,

$$W(\cos(\theta)) = A[1-r+(3r-1)\cos^2\theta]$$

where A and r are free parameters. r = 0 for transverse polarized ρ°'s and r = 1 for longitudinally polarized ρ°'s. The parameter r is shown in Fig. 6 as a function of Q^2. The E665 data clearly show the transition of the ρ° polarization from transverse to longitudinal as Q^2 changes.

(d) High p_T jets and photon-gluon fusion

The single photon exchange diagram and the diagrams for the lowest order

QCD corrections in deep inelastic muon scattering are shown in Fig. 6. a) is the lowest order diagram. b) and c) are gluon bremsstrahlung diagrams and d) and e) are photon-gluon fusion diagrams. The diagrams b-e are called Hard QCD diagrams. The gluon bremmsstrahlung has been studied extensively in e^+e^- colliding experiments, while the photon-gluon fusion process is a channel unique to deep inelastic interaction experiments. It becomes a major contributor to the cross section at small x_{bj} where gluons dominate in the target nucleon. E665 has an advantage over previous deep inelastic experiments in studying this process because of its higher beam energy which allows a smaller x_{bj} to be reached.

The gluon bremsstrahlung and the photon-gluon fusion processes increase the transverse momentum of particles with respect to the virtual photon axis and create a two-jet like event structure in the forward hemisphere in the hadronic center of mass system. The transverse momentum distribution of forward charged particles is shown in Fig. 7 (stars). A LUND Monte Carlo curve with the hard QCD processes (dotted-dashed lines) agrees quite well with data, while that without the hard QCD processes (dotted line) is quite off from data.

The two jet like event structure is clearly seen in an energy flow diagram. (Fig. 8). In order to define jet like event structures we apply cuts on events as follows:

$$\text{Planarity:} \quad \frac{\Sigma(p_{T_{in}}^2 - p_{T_{out}}^2)}{\Sigma(p_{T_{in}}^2 + p_{T_{out}}^2)} > 0.5$$

$$\text{Dispersion:} \quad 4\,\Sigma(p_{ri}^2 - \langle p_T^2 \rangle)/(\text{no. of tracks})^{1/2} > 3$$

The LUND program with the hard QCD processes (solid curve) agrees well with data, while that without the hard QCD process does not reproduce the event shape.

(e) Charged Particle Multiplicities

The charged particle multiplicities are studied using streamer chamber data by S. O'Day of Maryland. He developed a program to link forward spectrometer tracks and streamer chamber tracks. Shown in Fig. 9 is the average multiplicities as a function of W^2 with the LUND prediction and EMC(NA9) data. E665 data is higher than the EMC results in the same W range. The LUND program reproduces well the E665 results with a newly calculated structure function by Wu-ki Tung and Morfin, but does not with the old Gluck, Reya and Hoffman structure functions which have fewer gluons at small x_{bj}. Our results indicate that the multiplicity distribution is sensitive to the contribution of the photon-gluon processes to the total cross section at small x_{bj}.

In addition to the above results E665 has been studying a wide range of hadron formation reactions in muon-nucleon and muon-nucleus interactions. For example we reported the A dependence of hadron production at the APS meeting in Washington, April 1990 and at the PANIC conference in June, 1990 and a paper on the Bose-Einstein correlation is in preparation.

The Maryland group has been playing a major role in the data analysis. The group contributed a lot in developing Monte Carlo codes and event reconstruction codes. Dr. Kunori has been leading efforts on data analyses in the collaboration. Dr. Ramberg finished his Ph.D. thesis last year on the neutral pion productions in the deep inelastic scattering. Some of his preliminary results were included in the previous progress report. S. Aid and S. O'Day are expected to finish their theses work on the cross section ratio of neutron to proton and on the charged particle multiplicities, respectively, this year.

Fig.1 Xe to D2 cross section ratio as a function of Xbj for Q2 > 0.1 GeV2, vu > 40 GeV and y < 0.75. a) by three differnt methods, b) comaprison with NA28.

Fig.2 Xe to D2 cross section ratio as a function of Q2.

Fig.3 neutron to proton cross section ratio as a function of Xbj for SAt and LAT data sample.

Fig.4 Invariant mass distibution for pi+pi- and K+K- for exclusive events,

Fig.5 Decay angular distributions of rho0.

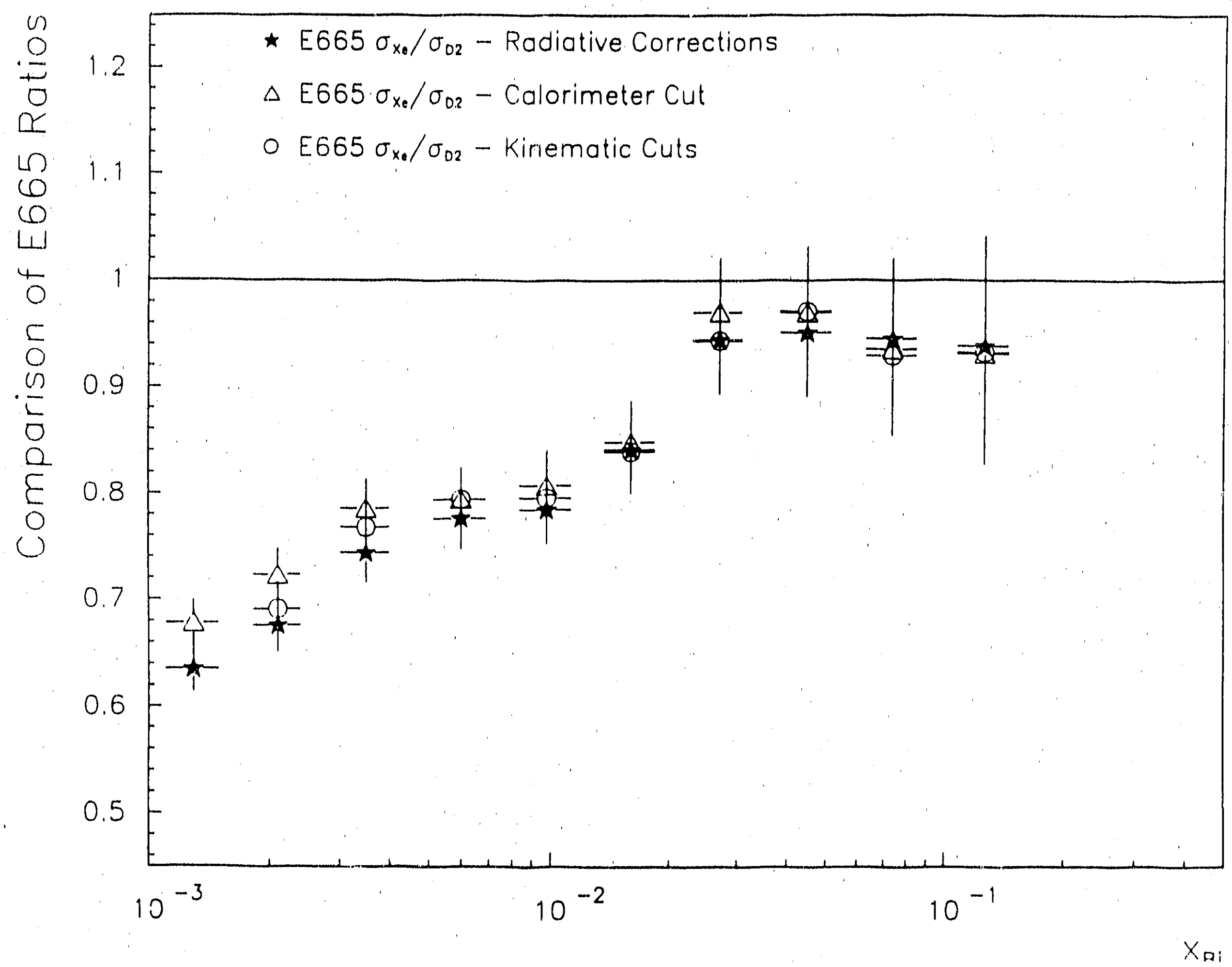
Fig.6 Rho0 decay parameter as a function of Q2.

Fig.7 diagrams for muon deep inelastic scattering. a) lowest order one photon exchange, b) gluon bremsstrahlung and c) photon-gluon fusion.

Fig.8 Transverse momentum distribution for charged hadrons with W2 > 300 GeV2.

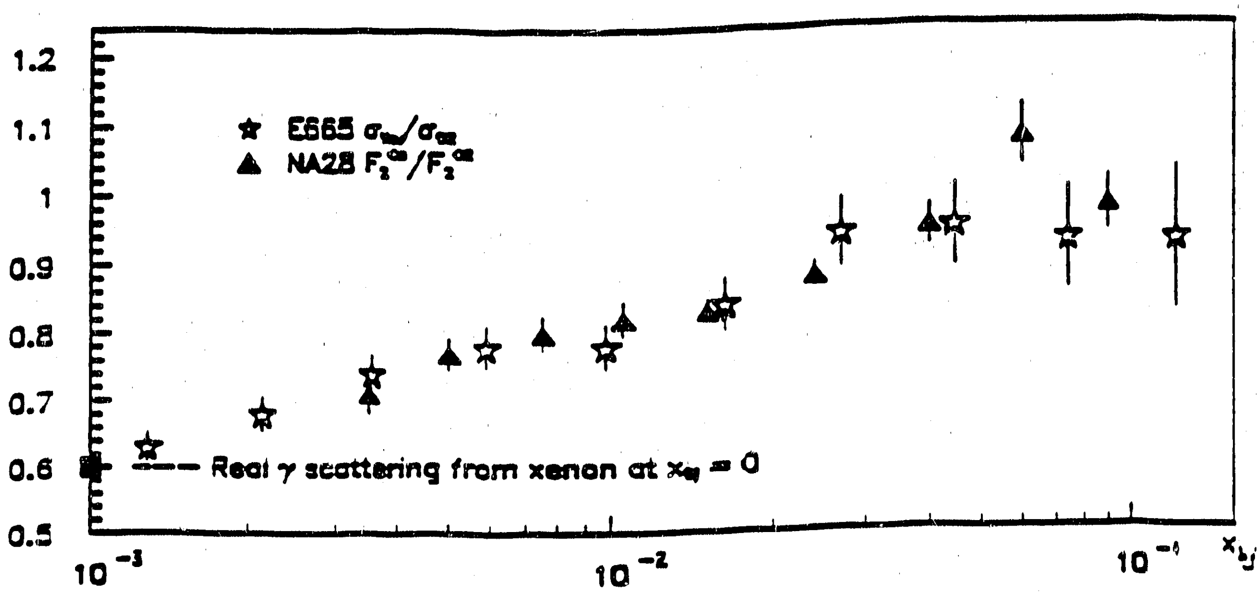
Fig.9 Energy flow distributions calculated using forward charged hadrons. a) comparison with LUND Monte Carlo with hard QCD and b) without hard QCD.

Fig.10 average charged hadron multiplicity as a function of W2.



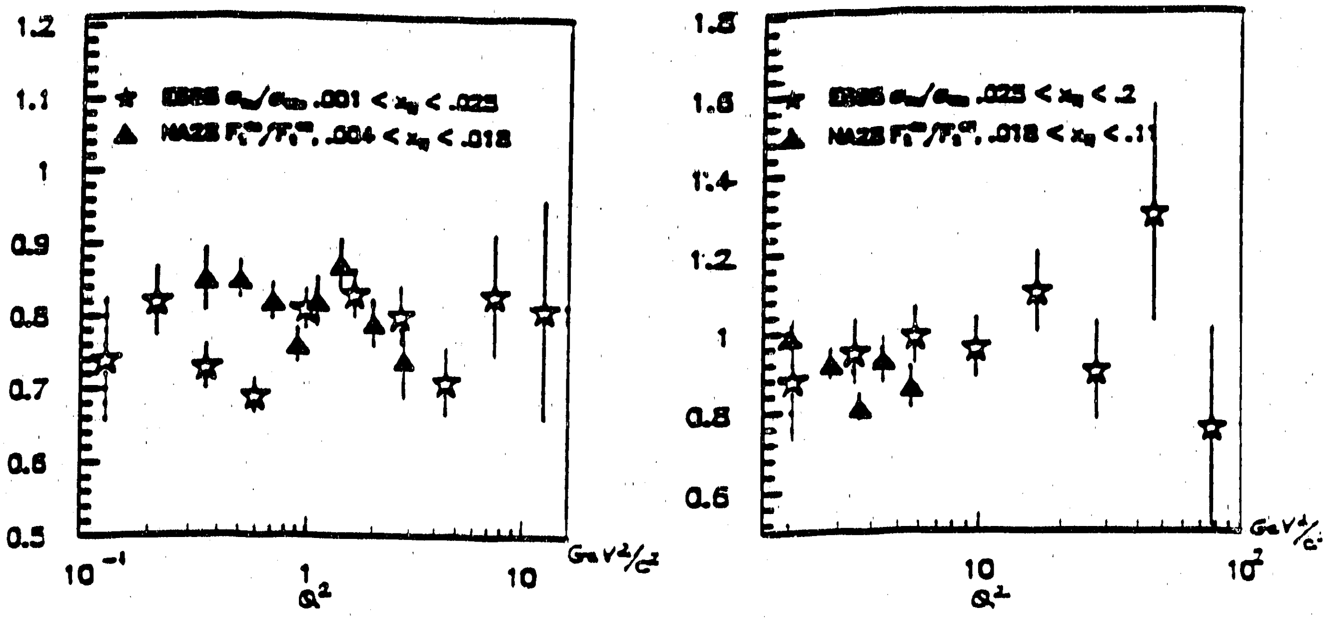
Comparison of E665 Ratios
E665 σ_{Xe}/σ_{D2} – Radiative Corrections
E665 σ_{Xe}/σ_{D2} – Calorimeter Cut
E665 σ_{Xe}/σ_{D2} – Kinematic Cuts
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
10^{-3}
10^{-2}
10^{-1}
x_{Bj}

Fig. 1(a).



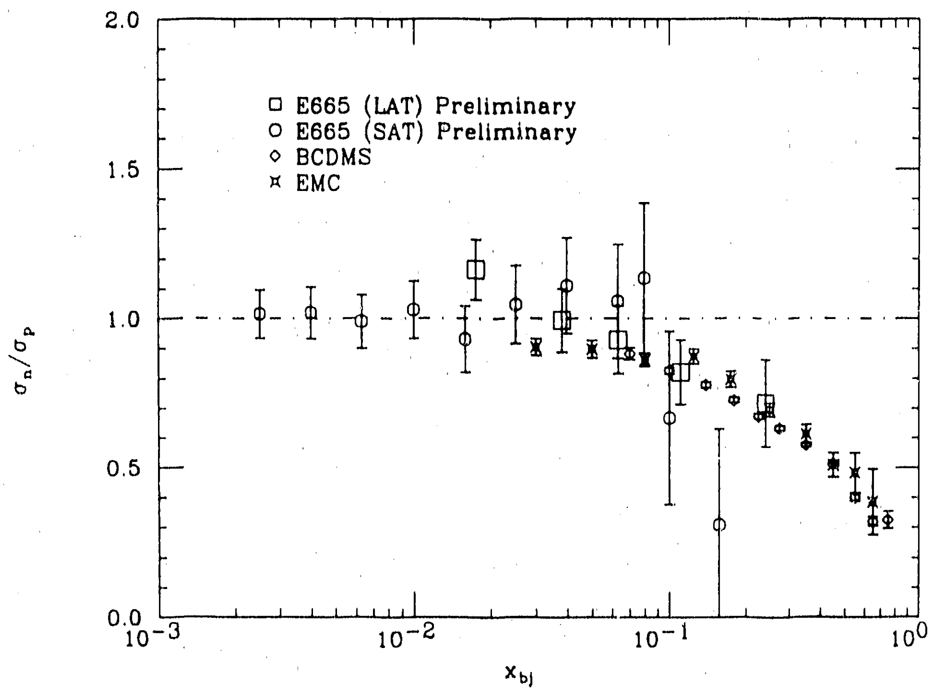
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
Real γ scattering from xenon at x_{bj} = 0
10^{-3}
10^{-2}
10^{-1}
x_{bj}

Fig. 1(b)



1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
10^{-1}
1
10
Q^2
GeV²/c²
1.8
1.6
1.4
1.2
1
0.8
0.6
10
10^2
Q^2
GeV²/c²

Fig. 2



E665 (LAT) Preliminary
E665 (SAT) Preliminary
BCDMS
EMC
2.0
1.5
1.0
0.5
0.0
σ_n/σ_p
10^{-3}
10^{-2}
10^{-1}
10^{0}
x_{bj}

Fig. 3

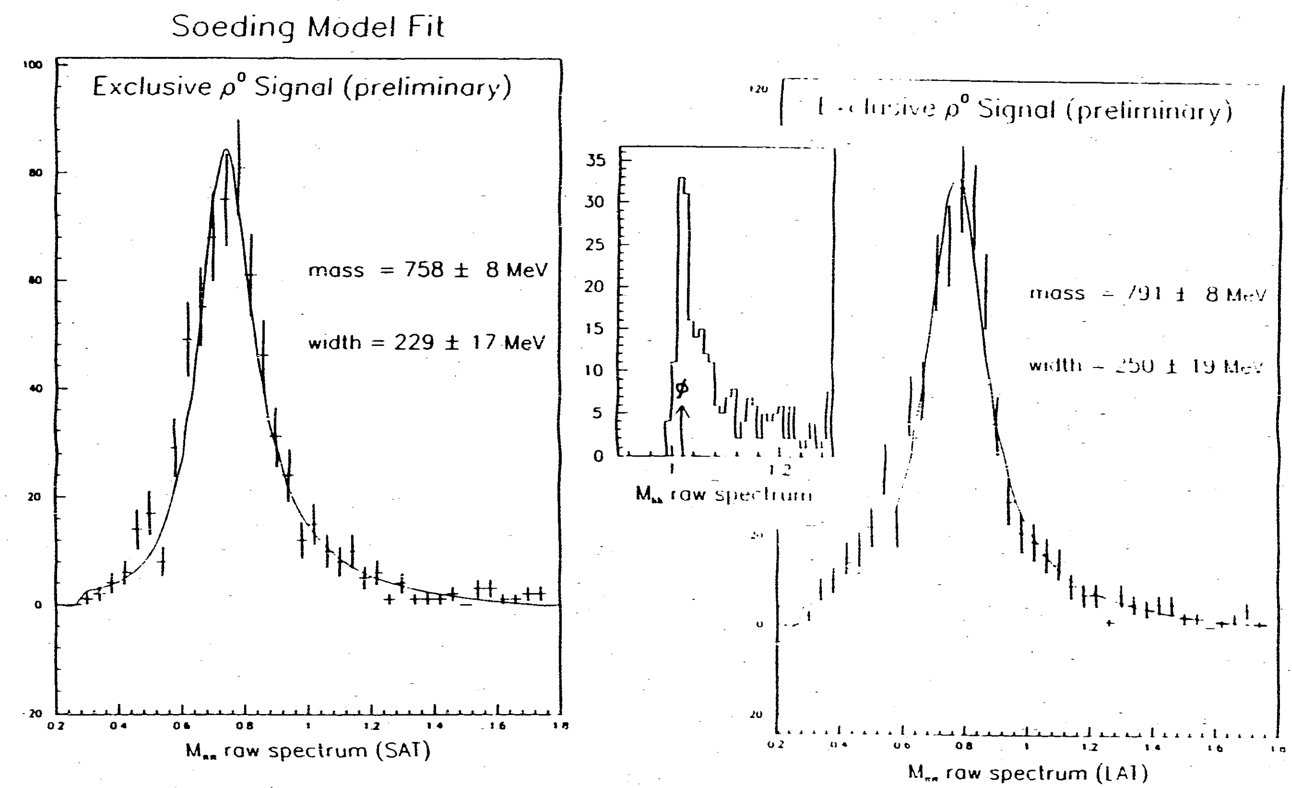
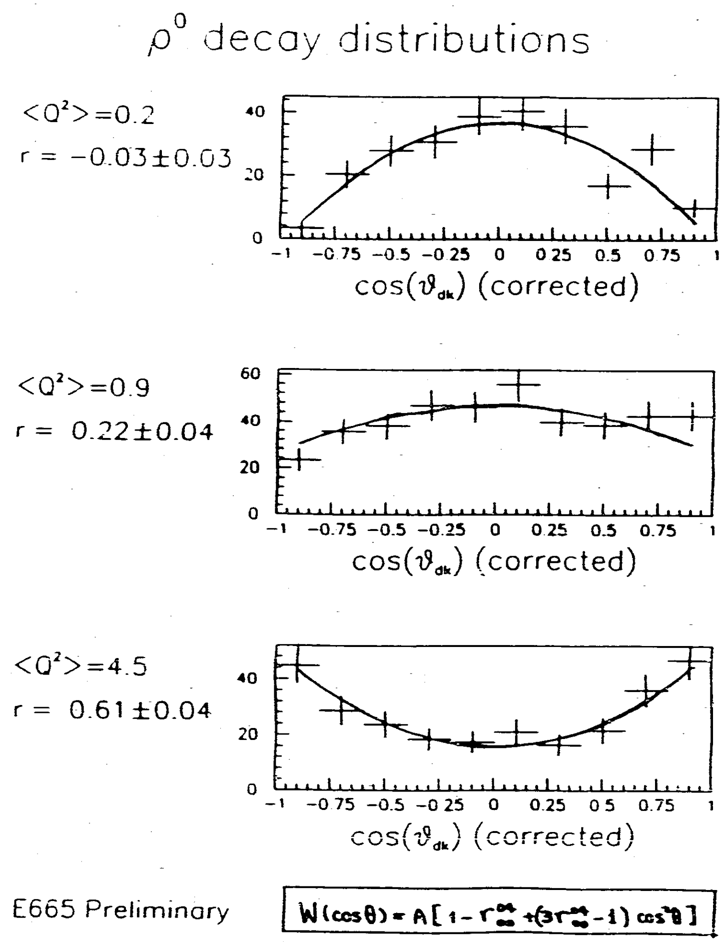
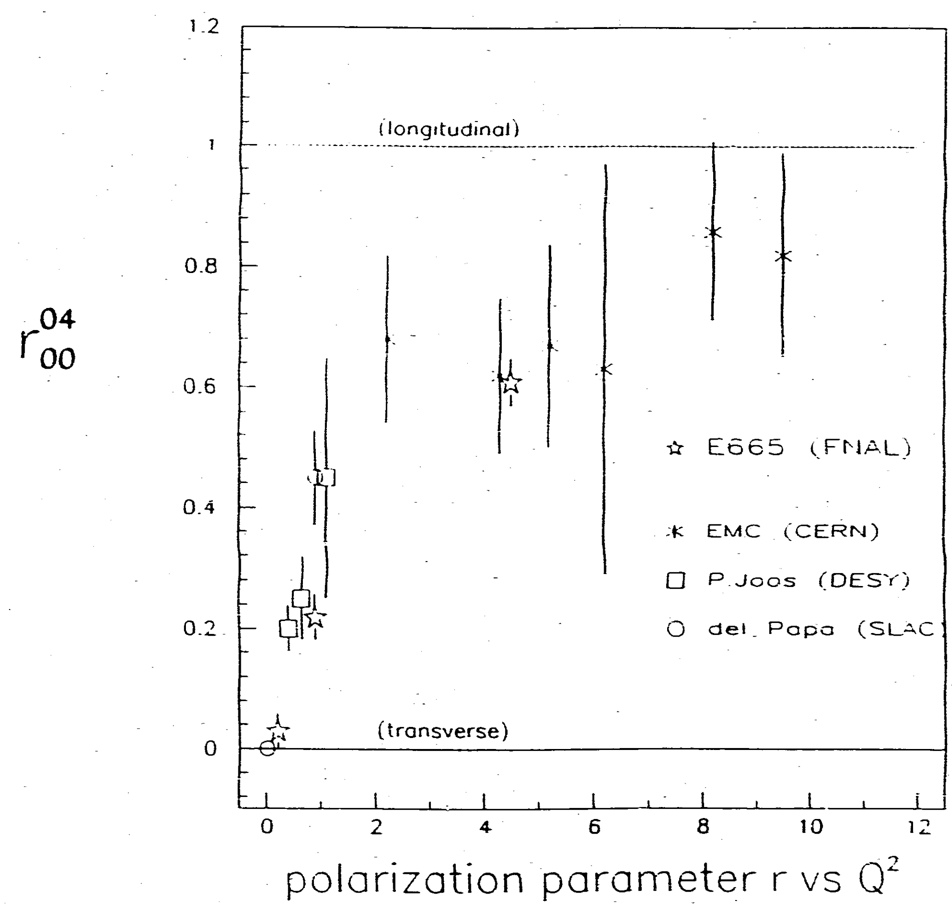

Soeding Model Fit
Exclusive ρ⁰ Signal (preliminary)
mass = 758 ± 8 MeV
width = 229 ± 17 MeV
M raw spectrum (SAT)
Exclusive ρ⁰ Signal (preliminary)
mass = 791 ± 8 MeV
width = 250 ± 19 MeV
M raw spectrum (LAT)
M raw spectrum
φ

Fig. 4



ρ^0 decay distributions
$<Q^2>=0.2$
$r = -0.03\pm0.03$
$<Q^2>=0.9$
$r = 0.22\pm0.04$
$<Q^2>=4.5$
$r = 0.61\pm0.04$
$\cos(\vartheta_{dk})$ (corrected)
E665 Preliminary
$W(\cos\theta) = A[1 - r^{04}_{00} + (3r^{04}_{00} - 1)\cos^2\theta]$

Fig. 5



r^{04}_{00}
(longitudinal)
(transverse)
E665 (FNAL)
EMC (CERN)
P. Joos (DESY)
del. Papa (SLAC)
polarization parameter r vs Q^2

Fig. 6

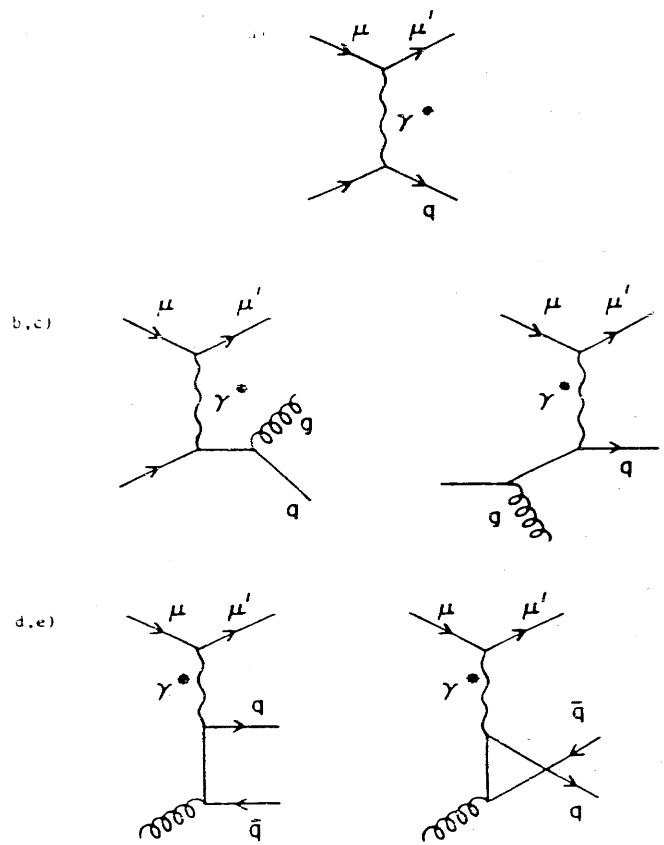

b,c)
d,e)
μ
μ'
γ*
q
g
q̄

Fig. 7

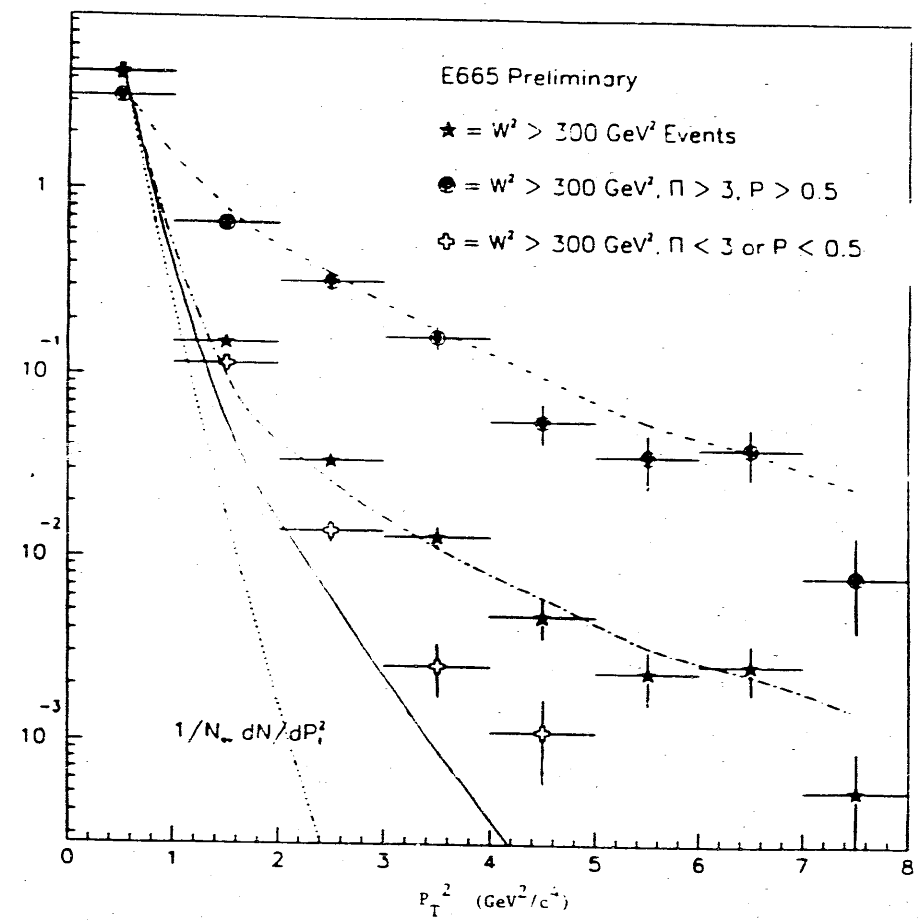
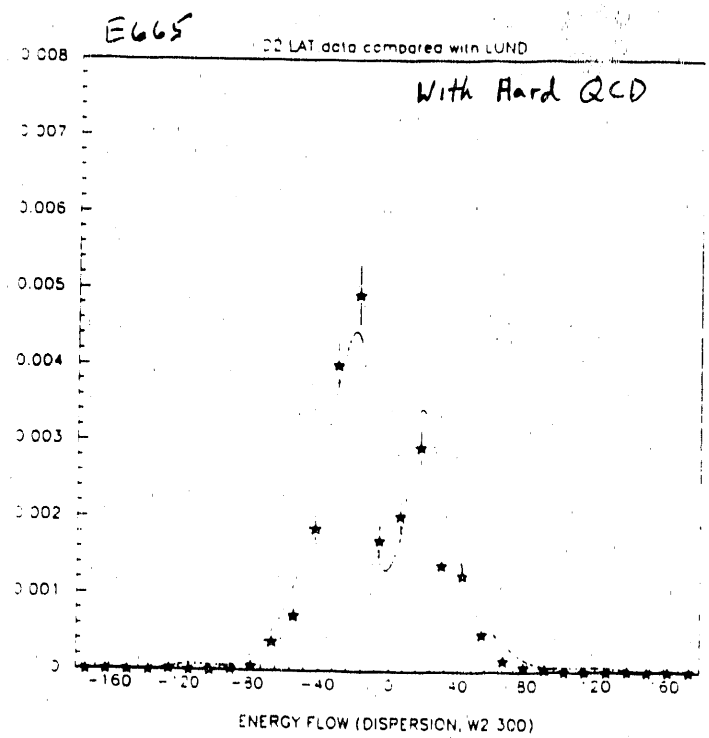

E665 Preliminary
★ = W² > 300 GeV² Events
● = W² > 300 GeV², Π > 3, P > 0.5
✧ = W² > 300 GeV², Π < 3 or P < 0.5
1/N dN/dP²
1
10⁻¹
10⁻²
10⁻³
0
1
2
3
4
5
6
7
8
P_T² (GeV²/c²)

Fig. 8


E665
D2 LAT data compared with LUND
With Hard QCD
ENERGY FLOW (DISPERSION, W2 300)

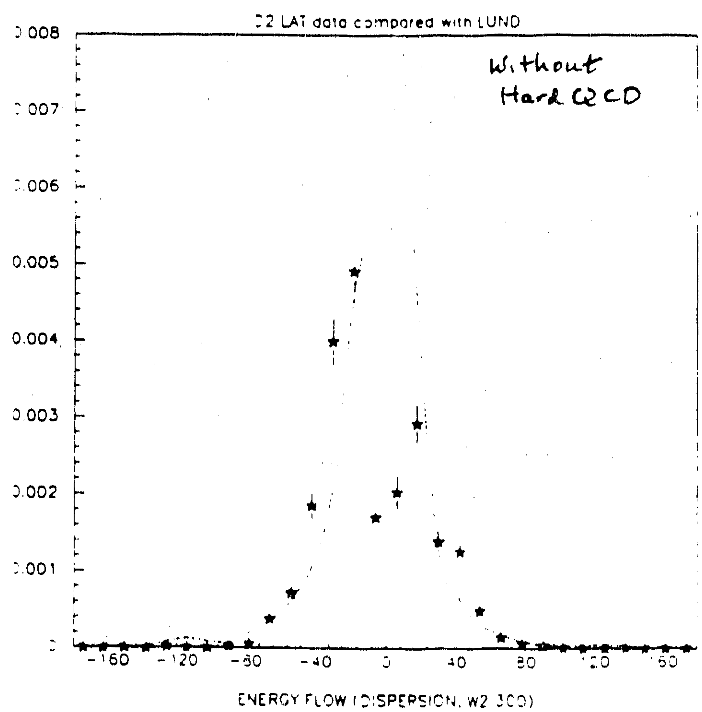

D2 LAT data compared with LUND
Without Hard QCD
ENERGY FLOW (DISPERSION, W2 300)

Fig. 9

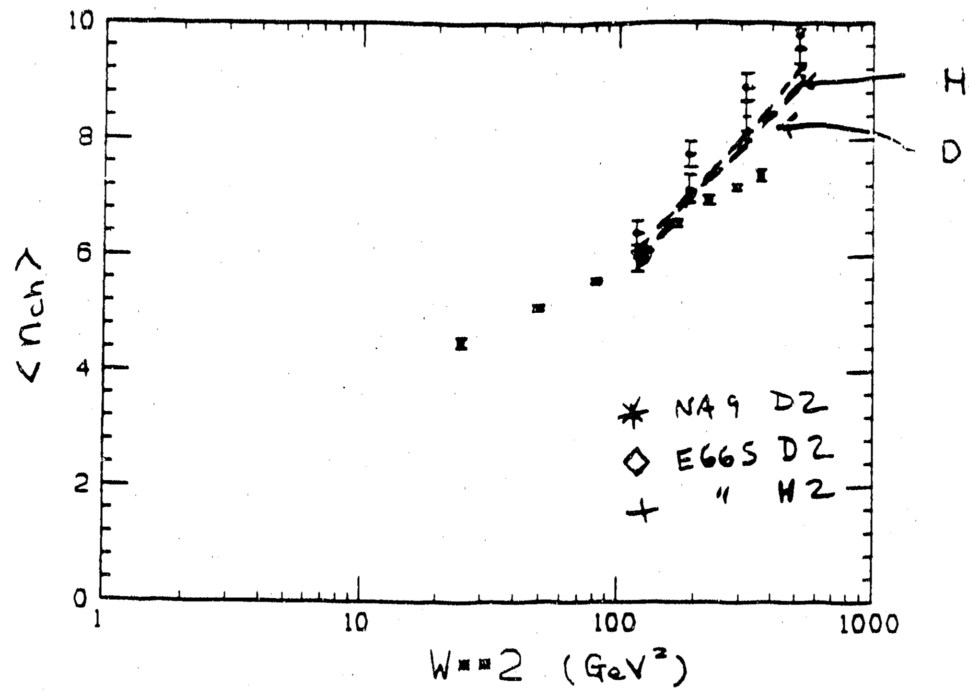


Fig. 10

[2] Status of the second run (RUN90)

A summary of statistics of RUN90 is shown in table 2.

Major modifications for RUN90 were i) new target system, (ii) new vertex drift chambers and iii) improvement of triggers.

In order to reduce time dependence effects in A-dependence studies, E665 built a new movable target system. The new system was placed in front of the vertex magnet (CVM) and held all targets on its movable table. It switched target from one to another during the 40 second periods between spills and cycled through all the targets during data taking.

New vertex drift chambers replaced the streamer chamber in order to improve statistics of slow tracks in the laboratory system. Also they will improve the resolution of scattering angles of muons which is crucial in the structure function analyses. 13 out of 16 modules were installed and were working during the run.

Triggers were also improved. The small angle trigger (SAT) used about 50% of beam luminosity instead of 12% in RUN87-88. For the large angle trigger (LAT) new scintillator walls were built in front of the electromagnetic calorimeter in order to reduce false triggers due to interactions in absorbers. Also LAT used a second level trigger based on muon roads in wire chambers (PTM) behind the absorbers for the first time. Dr. Skuja and Dr. Kunori helped to establish those triggers.

All data were written onto 8mm video cassette tapes. Alignment constants have been calculated for most of runs and a fraction of the data have been processed through the reconstruction program for the VDC tracks and the vertex fitting program has been modified to include them.

[3] Plan for the next run (RUN91)

The next major run is scheduled to start at the beginning of December, 1990. No major upgrade is planned for the run. We are planning to use only liquid hydrogen and deuterium targets and no heavy target. We hope to increase statistics at high W to study the hard QCD effects and other hadron processes on light targets.

E. Experiments at Los Alamos.

E1. CYGNUS Experiment. (C. Y. Chang, D. A. Krakauer (at ANL), R. Talaga (at ANL), U. of Maryland in collaboration with the Cosmic Ray Group at U. of Md., George Mason U., Los Alamos National Lab. and U. of California, Irvine.)

The purpose of this research is to identify the sources of ultra high energy (UHE) radiation and to study the nature of the interaction of this radiation with matter. Extensive air showers caused by primary cosmic rays above ≈ 50 TeV are detected by the CYGNUS array at Los Alamos. This array consists of 202 scintillation counters and several well shielded muon detectors. The direction of showers is obtained by reconstructing the nanosecond timing of the scintillation counters. This allows the array to search for directional and temporal excesses from the direction of suspected sources of UHE nuclei. When specific signals are detected the details of these showers can be studied to gain information about the nature of collisions between fundamental particles at energies above that available from earth-based accelerators.

The CYGNUS Experiment has continued taking data during the past year while undergoing a major expansion. The Air Shower Array has been expanded from 96 to 202 counters. The addition of these new counters has increased the area of the array from 20,000 m^2 to about 80,000 m^2. New muon counters have been installed in tunnels drilled under the expanded array. The array has recorded over 120 million showers.

The high resolution of the CYGNUS array and our vast data base have enabled us to check the resolution of an EAS array using celestial objects for the first time ever. Background cosmic ray triggers, which make up most (if not all) of our data set, are to first order isotropic in arrival direction. They are, however, blocked completely by the moon. The moon subtends a very small solid angle (0.2 square degrees) compared to our resolution of 0.8°. In addition, the $\cos^7\theta$ dependence of our trigger efficiency reduces our acceptance from the moon's direction. Nonetheless, we have used our new data set to see the shadow of the moon. Using the deficit in events and a maximum likelihood analysis we have shown that our resolution is what was predicted and most importantly, that our systematic errors are small. Using the same technique the "shadow" of the sun was also seen (above 10^{14} eV the magnetic field of the sun has little effect). This gives us renewed confidence in the quality of our array's performance. This result has been submitted to Phys. Rev. D Brief Reports. In addition, we have published our results on the observation of no signal from Cyg X-3 during the July 1989 radio burst.

We have recently installed a Local Area VAX Cluster with our online system. This allows access to the raw data as soon as a run is completed. Runs, which last about eight hours, are written directly to disk. At the completion of a run, which is timed to end when no potential sources are directly overhead, the data are copied to 8mm tape and simultaneously a processing run is started on a workstation. This workstation reconstructs all events and performs additional monitoring of the data. The processed output data are then copied to 8mm tape and compressed files are transferred via Decnet to Maryland. This allows us to study the data nearly in real time.

MILAGRO

We at Maryland (along with U.C. Irvine) have been spearheading a new proposal which has received significant attention in the non-accelerator community. It is called **MILAGRO** - Maryland Irvine Los Alamos Gamma Ray Observtory. The motivation behind this experiment is that air showers from primaries with energies below 50 TeV have previously only been studied with atmospheric Cherenkov techniques which can only observe one source at a time and are limited to viewing on dark moonless nights. Sources are visible only on moonless nights and for only half of the year. The time variability of sources can only be understood with near continuous observation. This new experiment proposes a completely new technique for studying small (> 1 TeV) air showers. It would allow for 24-hour open aperture operation. A large covered pond, 60m by 80m, located at Fenton Hill (8600′ elev.) near Los Alamos would be instrumented with two layers of a fast newly developed 10" phototube. The air shower electrons which reach the surface radiate Cherenkov light which is detected by the PMT's. The photons convert into electron-positron pairs which then radiate. The arrival direction is then determined, as in a conventional air shower array, by timing. A second layer deployed below 8m of water would be used to measure the muon content of air showers. The advantage of this technique is that by having a total sensitive detector which is capable of measuring the photonic component as well as the electronic component, the threshold can be lowered to ~ 1 TeV. This detector can bridge the gap between atmospheric Cherenkov and EAS techniques thus allowing us to study a completely unexplored energy interval.

We are currently conducting a test to study the response of this type of water Cherenkov system. An 8m diameter pool has been set up at Los Alamos near the center of the CYG-I array. The pool is 2.2 meters deep and is being covered by a light tight plastic. Ten IMB phototubes are being placed in the pool to study the light and timing response of this system under a variety of shower conditions. The next stage will be to use two new Burle 10" PMT's. Information from the CYGNUS array on pulse height and timing should allow the high precision measurements needed to understand the proposed detector.

E2. $\nu_e \bar{e}$ Elastic Scattering Experiment (E225). D. A. Krakauer(now at ANL) and R. Talaga (now at ANL), U. of Maryland in collaboration with U. of California-Irvine and Los Alamos National Laboratory.

The paper entitled "Measurement of Interference between W and Z Exchange in Electron-Neurino Electron Scattering" was published in Phys. Rev. Lett. 64, 1330 (1990), and was highlighted at the ν'90 Conference. Details of the experiment have been described in previous Annual Reports. The paper reports the observation of 234 ± 35 $\nu_e e^- \rightarrow \nu_e \bar{e}$ events using a beam-stop source of ν_e at LAMPF. The elastic cross section is found to be $\sigma(\nu_e e)$ = [9.9 ± 1.5 (stat) ± 1.0 (syst.)] x 10^{-12} cm^2 x [E_ν(GeV)]. This reaction is mediated by the exchange of W and Z bosons and is thus sensitive to the interference between them. This interference is measured to be -1.07 ± 0.17 (stat) ± 0.11 (syst.) consistent with the destructive interference (-1.08) predicted by the Standard Model.

This same experiment was used to measure the exclusive cross section $^{12}C(\nu_e, e^-)\ ^{12}N$(g.s.), as reported in Phys. Rev. Lett. 64, 1871 (1990). Using the 15-ton fine-grained tracking detector, this exclusive final state is identified by both an electron track and the positron decay of ^{12}N. From the observation of 181 ± 17 $^{12}C(\nu_e, e^-)\ ^{12}N$(g.s.) events with subsequent positron decays the flux-averaged cross section, equivalent to the cross section for 35.0 MeV neutrinos, is found to be [1.05 ± 0.10 (Stat) ± 0.10 (syst.)] x 10^{-41} cm^2. This result is in good greement with recent calculations.

A paper is being prepared on the determination of an upper limit for the ν_e magnetic moment using the data of this experiment.

F. Physics with the CLEO Detector at CESR. (A. Jawahery and C. Park, U. of Maryland with Carnegie Mellon U., Cornell U., Florida U., Harvard U., Ithaca Coll., Kansas U., Minnesota U., Ohio State U., Purdue U., Rochester U., SUNY at Albany, Syracuse U. and Vanderbilt U.)

The analysis of the $\Upsilon(5S)$ run with CLEO at CESR lead by A. Jawahery and C. Park is essentially complete. This will form the basis of Mr. Park's thesis that will be completed this year. The physics of this study was described in last year's Report so it is not repeated here. Several other analysis projects from the data taken by CLEO in 1987-88 have been completed. A few of these are described below. (Prof. Jawahery will not work on CLEO II since he is fully occupied with the OPAL program at LEP).

(1) Observation of B-Meson Semileptonic Decays to Noncharmed Final States, (R. Fulton, et al., Phys. Rev. Lett. 64, 16 (1990)).

The first evidence of charmless semileptonic decays of B mesons is reported in this letter. Leptons are found with momenta near and above the kinematic limit for $b \to cl\nu$ in $\Upsilon(4S) \to B\bar{B}$ decays. Since the contribution of $b \to cl\nu$ decays in this region is small, this excess is interpreted as evidence for $b \to ul\nu$ decays. The crucial experimental distribution is shown in Fig. 1. These events were selected from 244,000 $\Upsilon(4S)$ events (ON) recorded by the CLEO detector at CESR, corresponding to a luminosity of 212 pb^{-1}, with an additional sample of 101 pb^{-1} accumulated at total energies 60 MeV below the resonances (OFF). A detailed analysis of this data yields an excess of leptons attributed to $b \to ul\nu$ of $62.0 \pm 28.4 \pm 27.6$ in the momentum interval p_e = 2.2-2.4 GeV/c. Interpreting this excess in terms of the Kobayashi-Maskawa quark-mass-mixing matrix element V_{ub} is somewhat model dependent, but one can say that the value of $|V_{ub}/V_{cb}|$ obtained from the data is approximately 0.1, not zero.

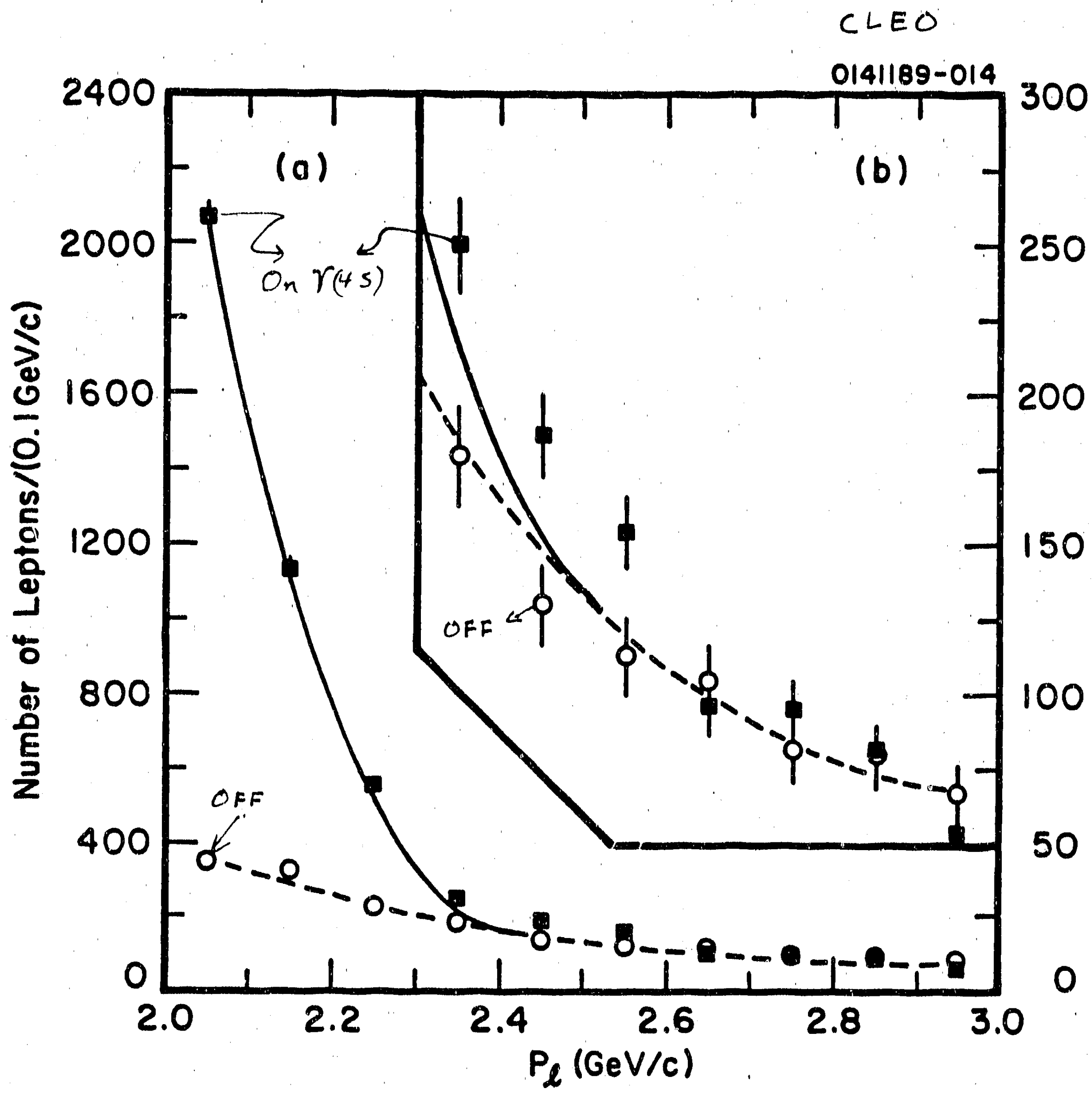


Fig. 1 Sum of the e and μ momentum spectra for ON data, scaled OFF data, the fit to the OFF data (- - -), and the fit to the OFF data plus $b \to c \ell \nu$ yield (—).

(2) Exclusive and Inclusive Decays of B mesons into D_s mesons (D. Bortoletto, et al., PRL 64, 2117 (1990)).

The sample of 242,000 $B\bar{B}$ events at the $\Upsilon(4S)$ corresponding to $L = 212\ pb^{-1}$, and a background sample of $L = 110\ pb^{-1}$, were examined for evidence of $D_s^- \rightarrow \phi\pi^-$ decay, where the $\phi \rightarrow K^+K^-$. A clear signal of 257 ± 41 D_s mesons from $B\bar{B}$ events was found. Assuming that the branching ratio of $D_s^- \rightarrow \phi\pi^-$ is 2%, one obtains $B(B \rightarrow D_sX) = (15.3 \pm 2.3)\%$. The observed momentum spectra of the D_s indicates that (56 ± 10%) are two body events, $B \rightarrow D_sD$, and the remainder mostly three body $B \rightarrow D_sD\pi$.

A detailed analysis of these events revealed a sample of exclusive events of the type $\bar{B}^\circ \rightarrow D^{*+}D_s^-$ and $D^+D_s^-$, and $B^- \rightarrow D^\circ D_s^-$. No examples were found of a $b \rightarrow u$ exclusive event such as $\bar{B}^\circ \rightarrow \pi^+D_s^-$ or $\bar{B}^\circ \rightarrow K^-D_s^+$. A summary of this set of exclusive events is given in Table I.

TABLE I. Branching ratios for two-body $B \rightarrow D_s$ decays. Here we have used $B(D_s^- \rightarrow \phi\pi^-) = 2\%$.

Decay mode	Efficiency (%)	Events	Branching ratio (%)	Theoretical prediction (%)
$\bar{B}^0 \rightarrow D^{*+}D_s^-$	0.05	3	2.4 ± 1.4	0.40–0.67
$\bar{B}^0 \rightarrow D^+D_s^-$	0.10	3	1.2 ± 0.7	0.90
$B^- \rightarrow D^0D_s^-$	0.07	5	2.9 ± 1.3	0.8–1.0
$\bar{B}^0 \rightarrow \pi^+D_s^-$	0.90	< 3	< 0.13 at 90% C.L.	$0.35\lvert V_{ub}/V_{cb}\rvert^2$
$\bar{B}^0 \rightarrow K^-D_s^+$	0.90	< 3	< 0.13 at 90% C.L.	...

The detection efficiency for double-charm decays is handicapped by the small branching ratios of the D_s and D mesons into easily detectable modes. For the two decay modes $\bar{B}^\circ \rightarrow D_s^- D^{*+}$ and $\bar{B}^\circ \rightarrow D_s^{*-}D^{*+}$, one can exploit the low momentum π^+ in $D_s^{*+} \rightarrow D^\circ\pi^+$ decays and not require explicit reconstruction of the D°. In this way a measurement $B(\bar{B}^\circ \rightarrow D_s^-D^{*+} + \bar{B}^\circ \rightarrow D_s^{*-}D^{*+}) = 7.5 \pm 2\%$ was obtained.

3. Observation of $\Upsilon(4S)$ Decays into non-$B\bar{B}$ Final States Containing ψ Mesons, (J. Alexander, et al., PRL 64, 2226 (1990)).

Using the same sample of $\Upsilon(4S)$ CLEO data described in (1) and (2) above plus a sample of 35,000 $\Upsilon(5S)$ decays, a search was made for $\psi \to e^+e^-$ or $\mu^+\mu$ secondaries. The maximum ψ momentum from a B decay ($B \to \psi\pi$) is 1.73 GeV/c in the B rest system, and 1.94 GeV/c in the laboratory system. A 2 GeV/c ψ would have a maximum x parameter $x_B = 0.378$ at the $\Upsilon(4S)$ where x is the momentum divided by the beam energy. A signal of 150 ± 14 ψ events is seen in the $x_c < x_B$ sample, but also $15.2^{+4.9}_{-4.5}$ events for $x > x_B$. No signal is seen in the continuum (OFF) sample. This implies after efficiency corrections that the branching ratio $B(\Upsilon(4S) \to \psi X) = (0.22 \pm .06 \pm .04)\%$ for $x > 0.378$.

No evidence for D^{*+} or ψ meson emission above the B decay kinematica limits were found.

G. Results from JADE at PETRA. (P. H. Hill (now at DESY), J.A.J. Skard, (now at ST Systems Corp.), G. T. Zorn, U. of Maryland, with DESY, Hamburg U., Heidelberg U., Lancaster U., Manchester U., Rutherford Lab. and Tokyo U.).

Analyses of JADE data at PETRA continue to be completed and published. Here we discuss three recent works not included in the 1989 Progress Report.

(i) Measurement of Resonance Production in the Reactions $\gamma\gamma \rightarrow \pi^{\circ}\pi^{\circ}$ and $\gamma\gamma \rightarrow \pi^{\circ}\eta$ (T. Oest et al., DESY 90-025).

The JADE detector had excellent photon detection capabilities down to photon energies of ~ 50 MeV with 4π angular coverage of high granularity. This has made possible the study of the exclusive channel $e^{+}e^{-} \rightarrow e^{+}e^{-}\gamma\gamma\gamma\gamma$ in the mass region up to ~3 GeV with reduced background from QED processes. The $\pi^{\circ}\pi^{\circ}$ mass distribution shows a large $f_2(1270)$ and a small shoulder at the $f_o(975)$. The $\pi^{\circ}\eta$ mass distribution is well fit with two Breit Wigner terms at the $a_o(980)$ and the $a_2(1320)$ plus a smooth background term. Information about the $\gamma\gamma$ widths of these resonants states are given in Table I.

Table 1

Measured $\gamma\gamma$ widths.

Resonance	Number of Events	$\Gamma_{\gamma\gamma}$ (keV)
$f_2(1270)$	2177 ± 47	$3.19 \pm 0.09 ^{+0.22}_{-0.38}$ (helicity 2)
$a_2(1320)$	85 ± 9	1.01 ± 0.14 ± 0.22 (helicity 2)
$a_o(980)$	44 ± 7	$0.28 \pm 0.04 \pm 0.10/BR(a_o(980)\rightarrow\pi^{\circ}\eta)$
$f_o(975)$	60 ± 8	< 0.6 (95% C.L.)
$f_4(2050)$	13 ± 4	< 1.1 (95% C.L.) (helicity 2)

Assuming that the spin 0 background under the $f_2(1270)$ is small, the $f_2(1270)$ was found to be produced exclusively in a helicity 2 state. The helicity 0 contribution is < 15% at 95% c.l.

The cross section for $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$ in the mass range 2.0 - 3.5 GeV/c^2 was measured for the first time. It is found to be ~ 1/2 as large as the $\gamma\gamma \rightarrow \pi^+\pi^-$ cross section measured in the same mass region by the TPC/2γ experiment. This implies that the $\pi\pi$ production cross section takes place predominantly in an isotopic spin I=0 state in this high mass region. The QCD calculation for direct $\pi^\circ\pi^\circ$ production is an order of magnitude below the measurements.

(ii) A Study of Photon Production in Hadronic Events from e^+e^- Annnihilation.
(D. D. Pitzl, et al., Zeits. fur Phys. C46, 1 (1990).

Photons in hadronic events from e^+e^- annihilation may be associated with two different types of processes. They can be decay products of mesons and baryons or be emitted as bremsstrahlung photons by the incoming leptons or final state quarks. The latter are called direct photons and a study of their properties may be used to test the current picture of hadron production in which fractionally charged quarks are created in e^+e^- annihilation and then fragment into hadrons. The majority of the observed photons are of hadronic origin and stem from π° and η decays. A reconstruction of the parent particles allows a comparison with the inclusive spectra of charged pions and kaons.

Results are presented on an investigation of photons produced in multi-hadronic final states from e^+e^- annihilations at 35 GeV and 44 GeV center of mass energies. Scaling violation between 14 and 44 GeV is observed in inclusive photon spectra. Comparing inclusive π° spectra with charged pion spectra it is found that the average π° multiplicity exceeds one half the charged pion multiplicity by (16 ± 5)% and (21 ± 7)% at 35 and 44 GeV respectively. The excess can be attributed to isospin violating decay of hadrons. The η multiplicity is found to be $\langle n_\eta \rangle = 0.64 \pm 0.09 \pm .06$ at 35 GeV.

A three standard deviation signal is observed for single photon emission via quark bremsstrahlung. The measured charge asymmetry in hadronic final states, due to the interference between initial and final state radiation, of $A = -0.141 \pm 0.041$ is in accord with QED expectations. An interference effect in the azimuth angle distribution of charged jets around the photon direction is observed for the first time.

(iii) Final Results on Mu and Tau Pair Production by the JADE Collaboration at PETRA, (S. Hegner, et al., DESY 89-178.)

Here we present the results of an analysis of data which were accumulated with the JADE detector in the last year of operation of e^+e^- storage ring PETRA. Data were taken at $\sqrt{s} = 35$ GeV and 4772 muon pairs corresponding to an integrated luminosity of 88.3 pb^{-1}, and 3238 tau pairs corresponding to 92.5 pb^{-1} were analyzed. In the muon pair analysis a renewed effort was made to understand the absolute normalization and thus the total cross-section. As a further test of the predictions of the standard model the angular asymmetry was studied as a function of acollinearity of the muon pairs. In the tau-pair analysis the main point of interest was an improved determination of background, in particular of any contamination by events from Bhabha scattering.

The cross sections $\sigma_{\mu\mu}(\sqrt{s} = 35 \text{ GeV}) = 69.79 \pm 1.35 \pm 1.40$ pb and $\sigma_{\tau\tau}(\sqrt{s} = 35 \text{ GeV}) = 71.72 \pm 1.48 \pm 1.61$ pb are in agreement with the QED α^2 prediction $\sigma = 70.9$ pb. The forward-backward charge asymmetries are found to be $A_\mu = (-9.9 \pm 1.5 \pm 0.5)\%$ and $A_\tau(-8.1 \pm 2.0 \pm 0.6)\%$ in agreement with

H. Rare Kaon Decay Experiments at the Brookhaven National Lab. (N. J. Hadley, A. M. Lee, IV, Univ. of Md., in collaboration with Brookhaven National Lab., the Paul Scherrer Institute (formerly SIN), the Univ. of Washington, and Yale University.)

Experiment 851 designed to study the decays $K^+ \rightarrow \pi^+ e^+ e^-$ and $\pi^\circ \rightarrow e^+ e^-$ at the Brookhaven AGS finished data taking in the spring of 1989. This experiment was a continuation of Brookhaven experiment 777 which searched for the decay $K^+ \rightarrow \pi^+ \mu^+ e^-$. The data on $K^+ \rightarrow \pi^+ \mu^+ e^-$ from experiment 777 have now been completely analyzed. No $K^+ \rightarrow \pi^+ \mu^+ e^-$ were seen, and an upper limit was set on the branching ratio of 2.1×10^{-10} at the 90% confidence level [1]. This is a factor of 20 improvement over the previous limit [2]. This same data was used to establish an upper limit of 1.6×10^{-8} (90% C.L.) for the decay $\pi^\circ \rightarrow e^\pm \mu^\mp$. Translating the $K^+ \rightarrow \pi^+ \mu^+ e^-$ branching ratio limit into a limit of new physics, is, of course, model dependent. However, as an example of sensitivity of the decay to new physics, we note that in the model of Cahn and Harari [3] where the decay is mediated by new horizontal gauge bosons, the above limit would imply that the mass of these new bosons would be greater than 39 TeV, assuming an interaction strength equal to the weak interaction. The analysis of the $K^+ \rightarrow \pi^+ e^+ e^-$ data from Experiment 851 is in progress and we expect to publish a value for the branching ratio of $K^+ \rightarrow \pi^+ e^+ e^-$ before the fall of 1990.

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each other and with the value -9.2% predicted by the standard model using M_Z = 91.0 GeV and $\sin^2\theta_W$ = 0.230.

I. Search for the Top Quark. Drew Baden, U. of Md., with the CDF Collaboration.

During the 1989-90 year, I have worked on the CDF experiment. My activities were concentrated in data analysis, after having spent the previous three years working on getting the experiment running.

My analysis contribution was in the field of heavy quarks. CDF has set a lower limit of 78 GeV on the mass of the heavy "top" quark using events with electrons and jets. We are now in the process of preparing a publication extending this limit above the mass of the W boson, to approximately 89 GeV. This result, to be published sometime around September 1990 is extremely important as it implies that all "top" quarks will "radiate" real (non-virtual) W particles, and the decays of real W's are theoretically well-predicted. There were several approaches undertaken in order to set such a limit.

1. Events with 2 leptons (e-e, e-μ, μ-μ) have a small rate due to the semi-leptonic branching ratio (approximately 1/9 per lepton) but have either non-existent or well-known backgrounds.
2. Events with an electron at high transverse energy and jets, which have large rates (branching ratio of approximately 20% at high energy) but have large backgrounds due to higher order QCD production of real W bosons.

For the latter events, there are many handles to extracting a heavy top limit. Two examples are:

1. Each top quark decays to a real W and a bottom quark, which can decay semi-leptonically. The background from QCD W decay will most likely not have any "extra" bottom quarks. By looking for events with a lepton from the W at high transverse energy and one from the bottom quark(s) at low

transverse energy, one can eliminate most of the QCD background.

2. For top production, there are 2 top quarks which decay into 2 real W's and 2 bottom quarks. For the QCD background, there is a single W and some recoil "jets". The global event measures for these two event types are expected to be different.

My analysis focused on the 2nd method for extending the mass limit in the electron+jets events. It is my belief that this method is potentially the most powerful, but requires significant Monte Carlo simulation. The 1st method, although also model dependent, was thought to be less sensitive to overall detector simulation. Both methods will be used in the forthcoming paper to some extent, although the final limit will depend on the dilepton analysis.

During the spring, the CDF group began to explore whether it is possible to make contributions in "bottom" physics at the Tevatron. I have spent some time familiarizing myself with these issues, and presented the recent CDF results at the SLAC Summer Institute.

J. SSC Major Subsystems and the Solenoidal Detector Collaboration at the SSC. (A. R. Baden, A. H. Ball, C. Y. Chang, D. G. Fong, N. J. Hadley, A. Jawahery, R. G. Kellogg, S. Kunori, A. Skuja, G. T. Zorn with collaborators from many institutions).

During 1989 the University of Maryland HEP group embarked on two major subsystem investigations (in collaboration with colleagues from many other institutions) for the SSC Laboratory - namely, Liquid Argon Calorimeter and Muon Detection for Solenoidal Detectors. We also became one of the (many) founding member institutions for the Solenoidal Detector Collaboration for the SSC.

1a. Liquid Argon Calorimetry Subsystem. (A. R. Baden, D. G. Fong, N. J. Hadley, A. Skuja).

We are members of the Liquid Argon Calorimeter Collaborations (LACC) for SSC Research and Development. This proposal was partially funded in FY 1990. Maryland's portion of the funding came partially from the DOE SSC equipment funds ($13,500) and partially from DOE HEP operating funds ($31,500). The LACC plans to build a prototype lead liquid argon calorimeter. We will measure the performance of this device at shaping times of 50, 100, and 150 nsec. These measurements will, of course, include the measurement of the ratio of the calorimeter's response to electrons and hadrons. The calorimeter will have lead plates given our belief that uranium, which has been successfully used by the Dϕ experiment at FNAL and by the Helios experiment at CERN, will be too expensive for use at the SSC. A unit cell of the calorimeter will consist of one 12 mm lead plate followed by a 2mm argon gap, followed by a 1.6 mm G10 printed circuit board and then another 2 mm argon gap. The calorimeter will be tested initially in a test beam at BNL. Details of the physics goals and motivation for these tests as well as other aspects of the LACC research program are given in the Memorandum of Understanding. In what follows we will concentrate on the University of Maryland's effort.

The Maryland members of the Liquid Argon Calorimeter Collaboration (LACC) include Professors Hadley, Skuja, Goodman, and Baden and Research Scientist Doug Fong plus one summer student (undergraduate). Maryland is responsible for providing instrumentation for the test beam. This instrumentation includes Cerenkov counters for particle identification as well as scintillator (or scintillating fiber) hodoscopes and veto counters for triggering and beam definition. We are also responsible for the data acquisition system and the setup of the trigger electronics and logic along with BNL and Iowa State. To date this year, we have acquired on loan one ancient Cerenkov counter which we are modifying and refurbishing for the needs of the LACC. We have designed an extension to the counter so that the length of the radiator will be three meters. We are currently engineering new beam exit and entrance windows for this counter. Within the next two months, we hope to borrow yet another counter and to start modifying it as well. We note that both counters must operate at reduced pressure in order to give wood good e/π separation at the higher (10 GeV) beam momenta. We have acquired samples of scintillating fibers and tested their light output and attenuation length. From our experience in similar test beams for the Dϕ experiment good beamline instrumentation is essential for understanding calorimeter performance.

We have acquired the necessary data acquisition software from Fermilab and are in the process of installing it on a microvax located at Maryland. We specified the computer needed for data acquisition and it has been ordered by Brookhaven National Laboratory. We have secured a loan of a Jorway branch driver from Professor Zeller's group at Yale University and it is now in transit to Maryland. We plan to bring up the DAQ system here on the microvax at Maryland and then to transfer it to the dedicated DAQ computer at

BNL late in the fall.

1b. Muon Detection for Solenoidal Detectors at the SSC. (A. H. Ball, N. J. Hadley, S. Kunori, A. Skuja, G. T. Zorn)

The SSC Subsystem for Muon Detection for Detectors with Solenoidal Magnets (and central trackers) is partially funded to investigate:

- Appropriate design of muon detectors (type of wire chambers, resolution, etc.) for the central ($|\eta| < 1.$), intermediate $|1. < |\eta| < 1.6$) as well as forward ($1.6 < |\eta| > 2.5$ regions.
- Appropriate triggering elements as well as electronics for single and multiple muons.
- The effect of neutrons on muon detection and triggering. These neutrons are produced by hadron scattering in the hadron calorimeter of the detector and many present severe difficulties if scintillator is used as the triggering element.
- The effect of knock-on electrons (or delta rays) on the muon wire detectors as well as on triggering elements. These electrons are produced near the surface of materials through which the muon has passed. In addition, this study includes the effect of high energy muon bremsstrahlung as the muon passes through material. This latter effect becomes more pronounced above 300 GeV and must be understood for SSC muon detectors.
- Simulation work to understand the resolution as well as the electron and neutron contamination of the muon trigger, of the identification process, as well as the muon momentum measurement.

The neutron production rate behind various materials of varying thickness is being investigated both experimentally as well as by simulation. Some beam tests took place this summer at Fermilab and more measurements will have to be made around CDF and Dϕ when they take data at the next collider at Fermilab.

Shuichi Kunori of Maryland is involved in modifying the GEANT code to incorporate neutron transport appropriately and reproduce such measurements using Monte Carlo techniques. The Maryland group will also build and test lucite trigger counters to see if we can trigger on the Cherenkov light of relativistic charged particles and simultaneously suppress the neutron-proton knock-on contribution to the counting rate.

Similarly, the effect of bremsstrahlung showers and delta rays has been simulated using GEANT by the Wisconsin group. Measurements behind E665 will take place during 1990-91 to verify the accuracy of these predictions. Such measurements will be particularly important to study whether muon detectors with open or closed geometry would be more appropriate for an SSC detector. The Maryland group (mainly S. Kunori and A. Skuja with Maryland technician assistance) will play a major role in the setup and measurement of these effects. Our participation in this measurement is a natural extension of our E665 commitments as well as our long involvement in muon experiments and detection generally. We will also assist in the simulation work necessary for the appropriate muon detector design.

The Maryland group is responsible for the layout and design of the forward muon system for the SD Collaboration. A. Skuja and H. Lubatti (Washington) are responsible for the forward muon detection and triggering. In conjunction with this responsibility, we will produce a detector design and layout for this region taking into account the results of the neutron, electron, and bremsstrahlung measurements as well as simulations.

2. <u>The Solenoidal Detector Collaboration for the SSC</u>

The SD Collaboration was formed late in 1989 and consists of about 320 physicists from U.S. universities and national laboratories, 90 physicists from KEK and Japanese universities, and 90 physicists from Bulgaria, Czechoslovakia, Italy, the Soviet Union, and the United Kingdom. The University of Maryland was one of the founding institutions of the collaboration.

The solenoidal detector contains powerful calorimetry, tracking, and muon detection. The solenoid and its associated tracking system provide all-important redundancy through measurements of charged particles and monitoring of the performance of the other detecting elements. Since the interactions of interest will represent an extremely small fraction of all interactions, this redundancy will play a vital role in establishing the credibility of any new observations. The detector will identify and measure electrons, muons, and particle jets with transverse momenta above a few GeV/c over a pseudorapidity range $|\eta| < 3$. To allow determination of missing transverse energy, calorimetry will be extended to pseudorapidities of about 5.

While the basic design concept of the detector is determined, a number of technologies are being considered for the individual components for calorimetry as well as tracking. Liquid Argon is one of the technologies under consideration for calorimetry, and the Maryland involvement in the LAR Subsystem investigation will help determine the viability of this technology for the calorimeter of choice.

The Maryland group's major involvement in the SDC is in the forward muon detection. We are responsible for preparing the layout and design of the forward muon system ($1.6 < |\eta| < 2.5$ to 3.0). We will also be involved in the design, construction and testing of the forward muon detector and trigger elements. At present, the detector of choice is a multi-cell drift chamber (closed geometry) operated in the proportional mode. But we will have to consider open geometry (jet chamber type) designs, as well. This work will be done by S. Kunori, N. Hadley and A. Skuja with assistance from F. Desrosier and his co-workers (Univ. of Maryland design engineers).

Because of our experience with streamer tube type detectors at OPAL, an alternative technology to the proportional mode drift chamber is a drift chamber operated in the streamer mode. Very good resolutions have been obtained with such devices (better than 200 microns per cell), but their multi-hit capabilities may not be adequate for SSC requirements. This investigation will be spear-headed by G. Zorn and A. Ball.

The Maryland group is also involved in specifying and designing the eventual computing system to be used by the SDC. Since the SDC involves an increase of almost an order of magnitude in both number of collaborators and event size over existing experiments, it is clear that present paradigms in computing for high energy physics have to be reconsidered. A. Baden is the U. S. university representative on the SDC technical board, and is charged (along with representatives from U. S. laboratories - L. Price, - and from Japan - K. Amako) with formulating a model for computing which encompasses both Offline and Online/DAQ. J. Goodman will be working with A. Baden on the committee. One example of the types of computing models consists of 3 layered systems, starting with a major computing center at the SSC Laboratory, followed by somewhat smaller (although still significant) satellite centers scattered throughout the U.S. with one in Europe and one in Japan, with heavy reliance on powerful workstations on the physicists' desk. Such a system warrants serious network considerations, and would employ as much as possible state-of-the-art computer science (e.g. object oriented programming, client/server software, computer aided software engineering, etc.)

The Maryland group sees the SD Collaboration at the SSC as its next major experimental program. The SSC program committee has reacted favorably to the SDC Letter of Interest and we are helping prepare the groundwork for a successful continuation of the experimental program.

K1. HEP Computer Developments (D. Fong).

Phase II of the HEP Computer Upgrade has been completed as planned.

(i) The VAX11/780 computer has been replaced by a VAX 6000 model 210. This improves the CPU power by a factor of 3. Its Ethernet interface has a throughput twice as great. This greatly improves the response time on the VAXcluster. Most of the peripherals have been reconnected, and all the functionalities are kept the same. An HSC device server is now used to handle the VAXcluster disks and tapes. The total cluster disk storage has been increased by 2.5 Gbytes to ~ 8 Gbytes.

(ii) Four additional VAXstation 3100's were installed as satellites in the cluster. A VAXstation II was replaced by another VAXstation 3100-38 which is more than three times as powerful.

(iii) Two VAXstation 3100's were purchased and sent to CERN to join the OPAL VAXcluster there. They are for the exclusive use of University of Maryland personnel.

(iv) Three exabyte tape drives and three Wren disks have been installed on three VAXstation 3200's as local devices. The exabyte units allow us to transfer large volumes of data from CERN and Fermilab.

(v) The communication tools using a local line to Fermilab with DECNET allowed us to copy samples of OPAL data from CERN to Maryland. At the start of LEP running in the Fall of 1989, we were actively involved in the scanning for mu-pair and tau-pair events, using the full set of OPAL programs and utilities, at Maryland. Results were reported back to CERN and helped to establish more automatic scanning criteria as the sample size increased. More recently programs were written to search for a number of different rare decay modes of the Z° and these search programs were run on subsamples of the OPAL hadronic data that had been transported to Maryland electronically.

K2. Electronics Support Group. (R. Bard)

This year our major effort has been to finish the OPAL trigger system and also to continue to complete other cable assemblies and small circuits for OPAL. To accomplish this task, John Colmer and I have kept Laura Shaffer, Caia Qing,, and Xiao Li working full time on electronics assembly.

The Trig comp cards were designed, prototyped, built and tested this year for use in the OPAL trigger system. These cards each take six CIA outputs and compare them to three computer selected energy thresholds. The outputs of the Trig comp card go to a theta match card which then feeds the OPAL theta phi matrix.

The Trig comp cards also feed an OR fan out which in turn feeds into an EOR circuit which can supply a fast trigger signal under programmable conditions.

The 18 Trig comp card circuits, six theta phi match circuits, one OR fan-out and three EOR circuits, two commuter drive boxes (trig comp drivers), their respective enclosures and spares, were all completed this year. Also, in order to test these complex devices special testers had to be designed and built. As usual, this system construction required a great effort to keep parts and construction flowing smoothly. The fine tuning of the trigger system will require some experimentation at OPAL before an optimum matrix of signals will be selected.

As in any experiment, OPAL required some lower level of support to keep existing apparatus functioning, or incrementally improving it. To that end various cables were built, one of a kind curcuits developed, and devices selected and procured. For example, OPAL needed a barometric pressure transducer which normally would cost $1,000 dollars and require four months to fabricate, but we found a similar device used for automobiles in stock for $150!

This year we have also started a large effort for Dϕ. This effort has kept our production facility going at full steam and will continue to do so into next year.

Dϕ requires the construction of a large system of High Voltage distribution boxes. The patch panels alone will require the construction of many thousand high voltage patch cords! This system has required a coordinated effort with the Mechanical Shop as well as a myriad of mechanical constructions all of which has been handled by Wyatt Miller.

We have had to develop high voltage pico ammeters and other special apparatus to enable us to test our HV distribution boxes to Dϕ specifications.

Some of these distribution boxes have active circuitry to monitor the current at high voltage. To this end we designed and prototyped a 16 channel High Voltage current monitoring board of which two can be used in a HV distribution box. We have also had to design and build a computer driver readout system for the "active current monitoring High voltage distribution boxes" (ACMOB). A PC based system has been developed for the design and testing of the ACMOB.

In other areas, some effort has been made this year in connection with the new phone system. As usual, there has been our continued low level support of the VAX system.

K3. Summer Course on Hadron Spectroscopy (D. C. Peaslee, Guest at U. of Md.)

The third Hadron Spectroscopy Course, organized by Dr. Peaslee, was held at the UMCP Physics Department from August 6th through August 10th. Excellent lectures were presented daily by the three guest lecturers: Prof. F. Binon of the Free Univ. of Brussels on "Neutral Particles from Multigamma Decay", Prof. O. D. Dalkarov, of the Lebedev Physical Institute on "Hadron Spectra from Low Energy $\bar{p}p$ and $\bar{p}d$ Interactions" and by Dr. Daniel M. Coffman of Cornell Univ. on "Heavy Quark Spectroscopy". The experimental results from GAMS, LEAR, Mark III and CLEO and many other programs were discussed together with a great deal of discussion of phenomenology and considerable amounts of theory. It was a good week.

L. Publications Since 1984

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2. MEASUREMENT OF THE TRANSVERSE MOMENTA IN e^+e^- ANNIHILATION AT PETRA, Ch. Berger, et al., (PLUTO Collaboration), Z. Phys. C22, 103 (1984).
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II. BUDGET REPORT

This report describes the monies spent or obligated in the current contract period March 1, 1990 to February 28, 1991. The salary items listed below are obligated through 2/28/91, the operating and capital expenses listed are expended through 5/31/90 and obligated through 8/2/90.

A. DOE CONTRIBUTION SUBJECT TO UNIVERSITY OVERHEAD

	ON CAMPUS	OFF CAMPUS	COMBINED
1. Salary Items			
a) Faculty	111,645	230,686*	342,331
b) Grad. Res. Asst.	31,514	74,039	105,553
c) Secretarial	31,031	0	31,031
d) Supporting Staff	61,751	19,042	80,793
e) Benefits	63,623	64,082	127,705
	299,564	387,849	687,413
*Includes estimated salary supplement related to low $/S.F.			
a) Expendable Supp	8,880	1,779	10,659
b) Comp.Sup./Serv.	3,426	0	3,426
c) Travel	54,314	9,462	63,776
d) Communications	5,677	0	5,677
e) Publications	1,323	0	1,323
	73,620	11,241	84,861
2. Total Direct Costs	373,184	399,090	772,274
3. Indirect Costs (25% Off Campus, 46% On Campus)	171,665	99,773	271,438
TOTAL PART A	544,849	498,863	1,043,712

B. DOE CONTRIBUTION FOR CAPITAL EQUIPMENT CONSTRUCTION AND ACQUISITION

4.	OPAL Equipment Acquisition	180,000	
5.	CERN Subcontract	75,726	
6.	Other Equipment	100,579	
	TOTAL PART B	356,305	
	TOTAL DOE (PARTS A AND B)		1,400,017

It will be extremely difficult if not impossible to complete this contract period with the operating money remaining; namely, $82,983.

C. UNIVERSITY OF MARYLAND CONTRIBUTION

1)	Salaries of Senior Faculty	161,432
2)	Fringe Benefits	39,551
3)	Indirect Costs	89,962
4)	Misc. Costs	10,000
5)	Univ. of Md. contribution to HEP Computer	70,000
	TOTAL PART C	370,945
	PART A	1,043,712
	PART B	356,305
	TOTAL DOE CONTRIBUTION*	1,400,017
	UNIV. OF MD. CONTRIBUTION	370,945
	TOTAL PROJECT COST*	1,770,962

*See applicable time period explained above.

III. INCIDENT REPORT

No incidents of the types described in Items 1, 2, 3 and 4 of Attachment A have occurred during this contract period.

END

DATE FILMED

11 / 15 / 90