CERN SPSC 90-19

SPSC / M450

MEMORANDUM TO THE SPSC

FUTURE CERN COLLIDER PROGRAM WITH THE UPGRADED UA1 DETECTOR

H. Faissner (Aachen), A. Norton (CERN), J.P. Revol (CERN/MIT),
J. Tuominiemi (Helsinki), D. Dau (Kiel), A. Ferrando (Madrid), D.Cline (UCLA),
A.P. Vorobiev (Serpukhov).

[on behalf of interested parties]

Contact Person: J.P. Revol.

May 17th, 1990

Enclosures:

(1) Physics with the upgraded UA1 detector at the CERN $p\bar{p}$ collider.

(2) Status of construction of the Uranium–TMP calorimeter and test beam results.

1. INTRODUCTION

As part of a new collaboration, we are prepared to present a proposal for a physics program with the upgraded UA1 detector over the years 1990-1992. It is our assumption that the central Uranium–TMP calorimeter will be completed soon and that the CERN $p\bar{p}$ collider will continue to operate over the next few years. However, we have been informed recently by P. Darriulat and W. Hoogland, in a memorandum to A. Norton [1], that severe financial constraints may prohibit approval of any new collider experiment. We hope this situation will improve quickly. Therefore we wish to bring to your attention:

- the highly successful status of construction of new calorimeter modules and their impressive performance at the SPS test beam.
- an update in our physics interest where new ideas have emerged.

We are encouraged by the positive statements in ref. [1] that the collider is likely to run again, that the UA1 detector should be kept available and that the first supergondola should be completed as soon as possible. However, we deeply regret the lack of resources to continue rapidly with a second supergondola and to carry out a test run at LSS5 in 1990.

Finally we wish to point out the value of an adiabatic transition from $p\bar{p}$ collider running to LHC research and development over the next few years. Indeed this front-end collider activity could be used as a test bench for new components of future LHC detectors. In this context we consider it very important to fully commission and exploit the first warm liquid calorimeter.

2. PHYSICS WITH THE UPGRADED UA1 DETECTOR.

A comprehensive physics program with the upgraded UA1 detector has already been presented in Ref [2]. In this document we concentrate on specific topics where new data or new theoretical understanding provide a strong competitive case for exploitation of the Uranium–TMP calorimeter. Other objectives remain, in particular measurement of the mass difference, $M_Z - M_W$. This is a fundamental quantity which should be measured as precisely as possible by several experiments, with strong emphasis on good understanding of systematic errors. From existing test beam results we can assert that the Uranium–TMP calorimeter will provide unprecedented stability and control of calibration. Detailed Monte Carlo studies show that 20 pb^{-1} of data with the supergondolas should give a mass error below 350 MeV, dominated by systematics. Fine tuning of the Monte Carlo simulation, based on the present test beam program, may well lead to smaller systematic errors. The expected performance should be confirmed as early as possible with a low statistics test run in LSS5.

New considerations of physics at the CERN collider concern mainly two domains :

- **Jet physics,** where the inclusive cross section can be measured with much better precision than in other experiments, providing a very significant new test of QCD. In addition the gluon structure function g(x) can be measured at low values of x relevant to Higgs and $t\bar{t}$ production at LHC.

- **b-quark physics,** where the analysis of present UA1 data indicates a rich physics program involving exclusive studies of B meson decays and mixing of the neutral B mesons. $20pb^{-1}$ of data with the upgraded UA1 would provide better precision and high statistics for both e and μ channels, along with the power of the new calorimeter to study the associated jet and decay structures at a new level of detail.

A more detailed discussion is given in the attached document (1).

3. STATUS OF THE NEW CALORIMETER AND TEST BEAM RESULTS

Since the SPSC meeting at Cogne [3], tremendous progress has been made on the construction of the Uranium-TMP calorimeter. The main technical problem, concerning high voltage, has been fully understood and modules are now operating routinely at 2000V while the desired operating voltage is only between 1000 and 1500 Volts. The conclusions of the studies of high voltage behaviour are of considerable general interest for any calorimeter involving liquids.

As of today four modules have been filled with the modified procedures and are all working very well, while three further modules are ready to receive the TMP. The entire production chain is working smoothly.

One module, produced with the improved construction techniques, has already been tested extensively at the test beam at 1500 V and has shown better characteristics than expected. In particular the signal to noise ratio for muons is 4.4 times the standard deviation of the noise, the linearity of the energy response for electrons is better than 0.25 % reaching the limit of the momentum determination of the beam itself, the electron energy resolution is $12\%/\sqrt{E}$, the single hadron energy resolution is $58\%/\sqrt{E}$, the first measurement of compensation indicates that the e/π ratio is very close to 1. This ratio is about to be measured more precisely in an assembly of five uranium-TMP modules in order to completely contain the hadronic showers.

A more detailed discussion is given in the attached document (2).

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[3] Memoranda to the SPSC, The UA1 Collaboration, SPSC/M448 and addendum.

Physics with the upgraded UA1 detector at the CERN $p\bar{p}$ Collider.

a) THE INCLUSIVE JET CROSS SECTION

A precise measurement of the inclusive jet cross section would provide a very significant quantitative test of QCD. This is clearly important in the search for a breakdown of the standard model due, for example, to the possible composite structure of particles now thought to be elementary.

Furthermore, a precise measurement of low E_T jets would allow determination of the gluon structure function g(x), in a range relevant to Higgs and $t\bar{t}$ production at LHC and SSC energies. At LHC, the range of x values relevant for the Higgs mass range considered (0.1 to 1 TeV) is approximately: 0.01 to 0.15.

Fig. 1 shows that the existing data are rather poor.

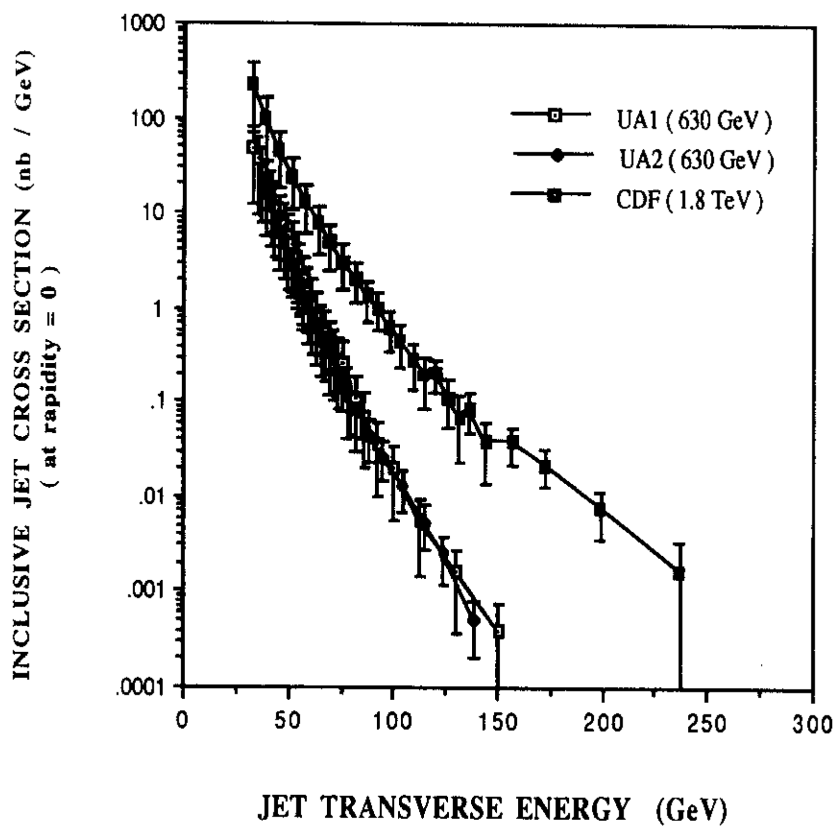

Figure 1.
Measurements of the inclusive jet cross section at $p\bar{p}$ Colliders.
The errors shown combine systematic and statistical errors in quadrature.

There exists two types of limitation to the precision with which a test of QCD can be made:

- the experimental uncertainty in the measurement of the jet energy,
- the theoretical uncertainties in the parton distribution functions, the higher-order effects, the choice of the QCD scale parameter μ, and the value of $\Lambda_{\overline{MS}}$.

Recently, the next to leading order (α_s^3) inclusive jet cross section [1] has been calculated including both quarks and gluons, resulting in a much reduced theoretical error ($\leq 25\%$ for jets with $E_t \geq 40$ GeV). This new calculation takes into account the finite cone size of the jet algorithm and therefore allows a more detailed comparison with experiment. On the experimental side the Uranium-TMP calorimeter will provide a superior accuracy for the measurement of the inclusive jet cross section.

The improvement comes mainly from:

- better jet energy resolution. Due to compensation ($e/\pi \sim 1$) $\Delta E^{jet} / E^{jet} \leq 0.5 / \sqrt{E^{jet}}$,
- better jet definition due to the excellent granularity of the detector,
- an energy scale precision of the order of 1% .

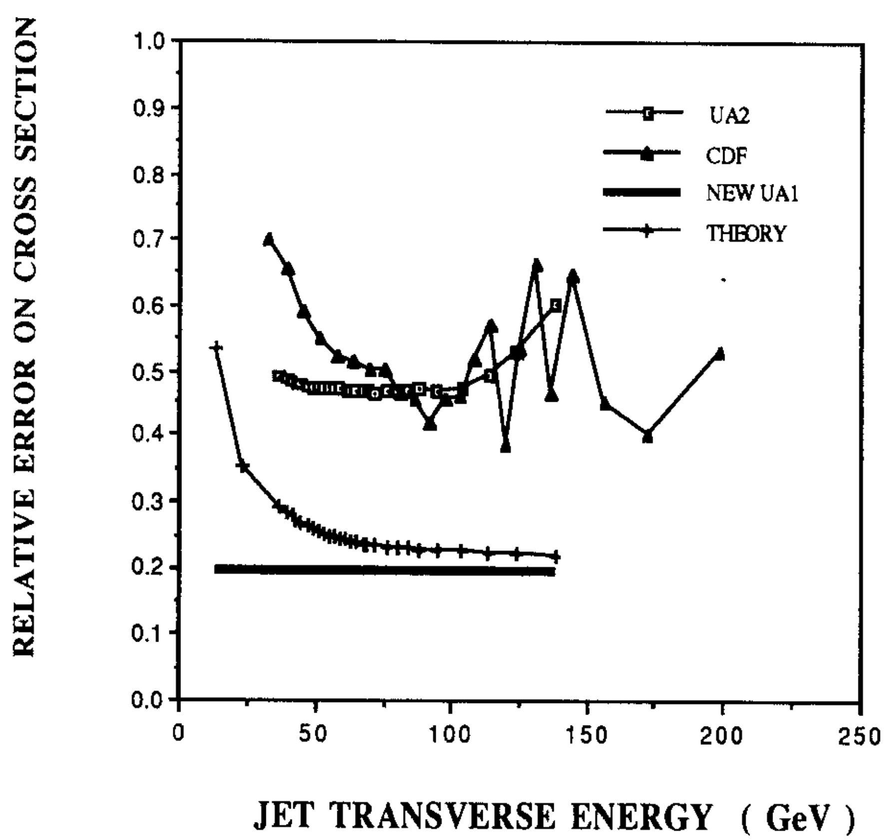

Figure 2.
Precision on the measurement of the inclusive jet cross section.
Statistical and systematic errors are combined in quadrature.

The precision reached so far in the measurement of the inclusive jet production cross section by UA2 [2] and CDF [3] is at best 50% as shown in Fig. 2.

A Monte Carlo simulation of the Uranium–TMP calorimeter [4] with full detector simulation has shown that the jet energy resolution has little dependence on the jet transverse energy, for a given jet energy. The jet energy resolution for the upgraded UA1 is $50\%/\sqrt{E}$. Response fluctuations are small and therefore an individual jet acceptance correction is meaningful. Finally the systematic error on the jet energy scale should be around 1% using both test beam calibration and $p\bar{p}$ collisions [i.e. W data ($W \rightarrow$ jet-jet and $W \rightarrow \tau\nu$) and transverse energy balance of events with a hard photon].

Conservative estimation of the various systematic errors on the inclusive jet cross section gives:

– Integrated luminosity :	8%
– Energy scale (1%) :	6%
– Uniformity of calibration :	6%
– Geometrical acceptance :	5%
– Jet acceptance and jet finding efficiency :	15%

Combining them in quadrature gives a total systematic error of 19.6% , as shown in Fig 2. Note that, if the energy scale error is taken to be 2%, the corresponding error on the cross section is 22.2 %. This level of precision is not only better than any existing measurements but is also better than the current error on the theory.

One of the attractive features of this type of process is the very large cross section, such that the outcome does not critically depends on how long the $Sp\bar{p}S$ Collider can run. Fig. 3 shows that, with only two adjacent supergondolas (placed on the same side of the beam line in order to contain jets) and for a relatively modest integrated luminosity, a significant measurement of the inclusive jet cross section can already be made up to jet transverse energies of about 100 GeV.

Finally we stress again the importance of jet spectroscopy which was mentioned in our previous memorandum to this Committee [5] and which constitutes a unique feature of this new detector to explore a different domain of physics at the Collider.

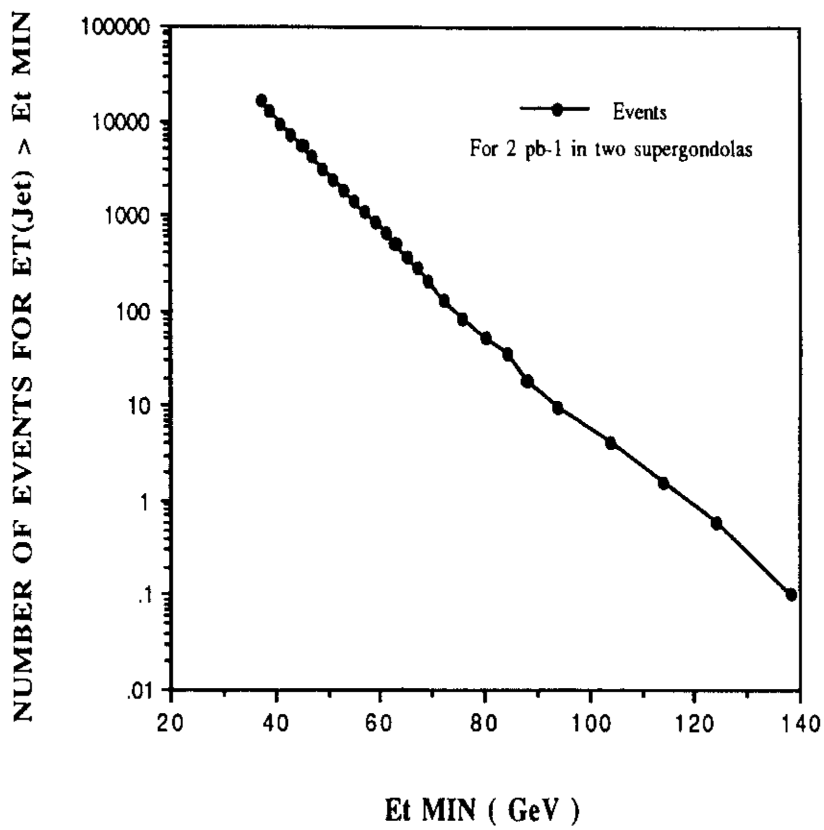

Figure 3.
Number of events collected in two adjacent supergondolas for $2pb^{-1}$

b) PHOTON PHYSICS:

Rare W decays.

UA1 has recently searched for $W^{\pm} \to \pi^{\pm}\gamma$, and obtained an upper limit on:

$$\Gamma(W^{\pm} \to \pi^{\pm}\gamma) / \Gamma(W^{\pm} \to e^{\pm}\nu) \text{ of } 5.8*10^{-2} \text{ (95\% C.L.) [6]}$$

which rules out some new theoretical predictions [7]. The issue of this particular rare decay mode of the W is still entirely open.

The presence of a position detector with an very fine granularity greatly increases the photon detection efficiency with the new Uranium-TMP calorimeter. Specific tests of the Standard Model, such as in radiative decays $W^{\pm} \to \gamma q\bar{q}$, could be made. Even though the branching ratios involved are usually considered to be very small (up to 3.10^{-4} in Ref. [8] for instance), this study would provide the first information on the $WW\gamma$ coupling. One can expect of the order of 40,000 $W^{\pm} \to q\bar{q}$ events per year of running at the Collider (assuming $10.pb^{-1}$ / year).

By comparison, for standard radiative processes [9], 350 $W^{\pm} \rightarrow \gamma e \nu$ and 180 $W^{\pm} \rightarrow \gamma \mu \nu$ events would be produced per year with a photon of energy larger than 8 GeV.

Photon production in W decays provides a tool for searching for rare decays and for testing the electroweak theory in a new domain.

Direct photon production:

The importance of tests of QCD with prompt photon production has already been pointed out in a previous memorandum [5] to this Committee. Early measurements made by UA1 [10] have shown the feasibility of such studies.

With an integrated luminosity of 20 pb^{-1}, we can collect several hundred two-photon events with $E_t^{\gamma} > 10$ GeV. A study of these 2γ events would provide not only a test of QCD but also the first high statistics search for C=+1 states produced in proton-antiproton collisions. The two photon mass resolution is $\Delta m/m \sim 0.01$ at a mass of 100 GeV/c^2.

A measurement and understanding of two-photon production may also be important for the future, as a background to detection of an intermediate mass neutral Higgs through its 2γ decay mode.

c) B–QUARK PHYSICS:

Proton - antiproton colliders represent by far the most copious source of beauty particles presently existing. Out of the $2 * 10^8$ beauty pairs produced in 20 pb^{-1}, 10^7 have a transverse momentum above 10 GeV/c and can be detected via their semileptonic decays into electrons or muons. However, the best way to identify beauty mesons is via their decays into J/ψ (B.R.=1.1%) and ψ' (B.R.= 0.4%), which are low multiplicity decays with typically an additional K, K^*or ϕ. The latter decay is of particular interest since ψ' cannot stem from higher mass χ states. Thus 1/3 of all J/ψ and more than 2/3 of all ψ' are decay products from beauty mesons.

Fig. 4(a) shows the dimuon mass distribution from the UA1 1988/89 data. The background underneath the J/ψ is negligible and also the ψ' can be clearly seen. The ψ' can as well be tagged via its decay into $J/\psi\ \pi^+ \pi^-$ (Fig. 4(b)). For future collider runs with electron and muon detection capability and improved triggers we expect about 15000 J/ψ and 1000 ψ' into the two leptonic decay channels. These numbers take account of the expected detector acceptance and efficiency. In comparison, at LEP, to obtain similar statistics, 10^7 Z^0's are needed which corresponds to several years of running (assuming 100% detection efficiency in both the muon and the electron channels).

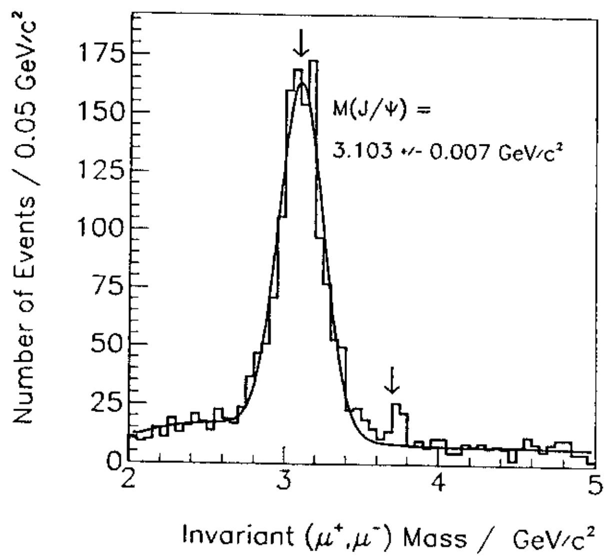

Figure. 4a

Dimuon invariant mass spectrum.

The histogram represents the data and the solid line is the result of a fit including the expected background from $b\bar{b}$ and $c\bar{c}$ processes. Clear J/ψ and ψ' signals (indicated by arrows) can be decerned from the background.

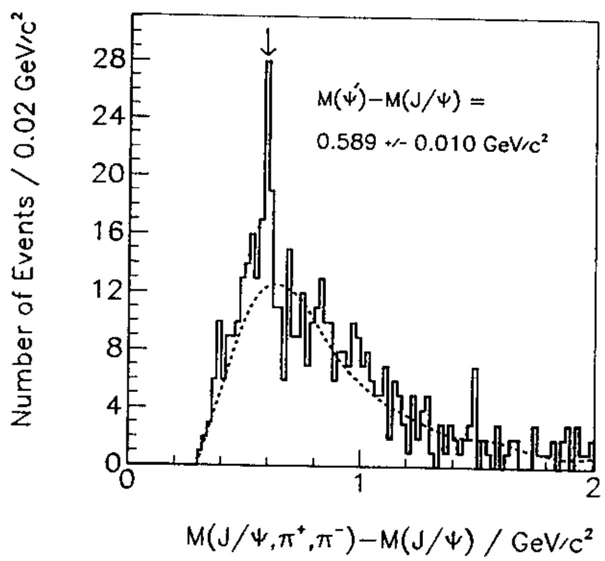

Fig. 4b

Mass difference between the [J/ψ ππ] system and the J/ψ.

The histogram represents the data, the solid line is the result of a simulation of the background from $b\bar{b}$ and $c\bar{c}$ production. We observe a clear ψ' signal from the decay at the expected mass-difference.

Presently only a few B decays have been fully reconstructed, the $B^o{}_s$ has yet to be detected. The large statistics will permit us to reconstruct several decay channels and to determine the relative branching ratios. Already in our 1988/89 data we observe convincing evidence for K^{o*} (Fig. 5(a)) and ϕ (Fig. 5(b)) production in a cone around the J/ψ. The invariant mass of the total system, including the J/ψ, is consistent with the expectation from B decays. Furthermore, the capability of the new calorimeter to reconstruct neutral pions will improve the K^* identification and will reduce the background underneath the ϕ by a better rejection of gamma conversions. We also observed in our 1988/89 data a clear D meson signal in conjunction with a large p_t single muon (Fig. 5c). Larger statistics will allow harsher cuts to improve the signal to background ratio.

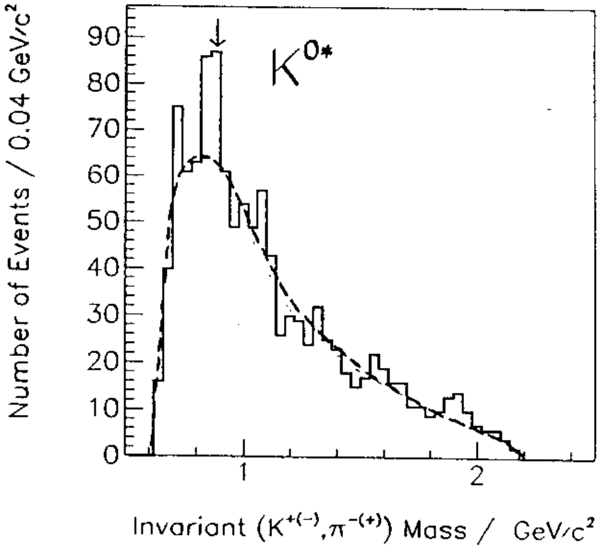

Figure. 5a
Invariant Kπ mass spectrum for charged tracks close to the J/ψ.
A clear peak at the K* mass (indicated by an arrow) is visible.

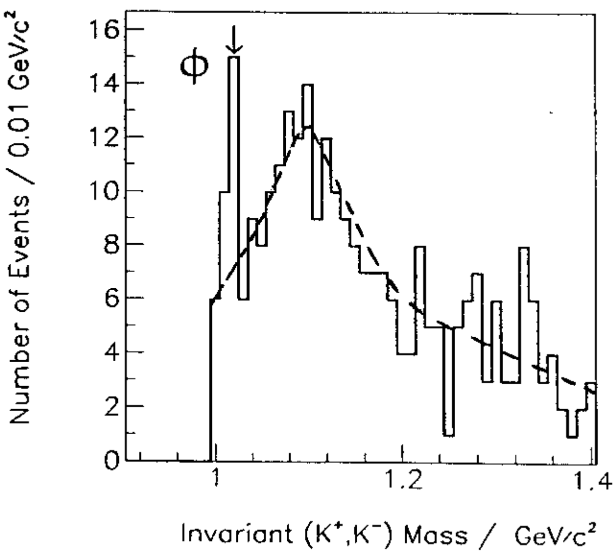

Figure 5b
Invariant KK mass spectrum for charged tracks close to the J/ψ.
A clear peak at the φ mass (indicated by an arrow) is visible.

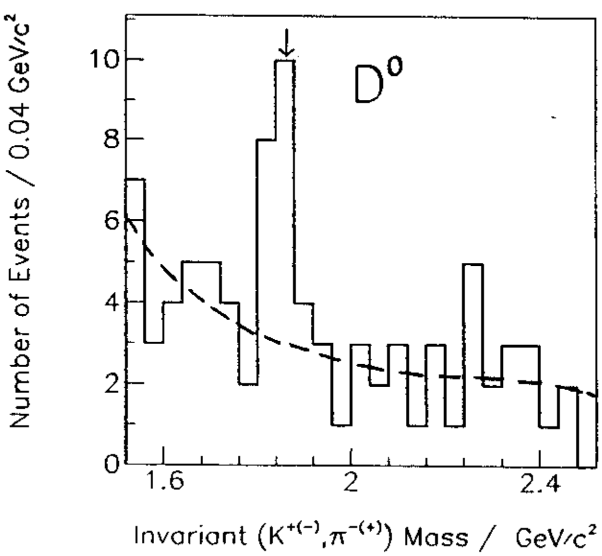

Figure 5c
D signal in the Kπ mass distribution.

Our detector is also well suited for the search for very rare B decays with clear signatures, such as $B^o \rightarrow \mu^+\mu^-$ or $B^o \rightarrow \mu^+\mu^- X$, where the dimuon mass is outside the J/ψ and the ψ' mass windows. In the standard model of electroweak interactions, flavor-changing neutral current processes are forbidden at the tree level but will occur in higher orders. Such decays of neutral B mesons into lepton pairs exclusively are expected with a probability of 10^{-9}. Decay rates for all B mesons into lepton pairs plus some hadronic final states particles are predicted to be as high as 10^{-5}. These decays proceed through so-called penguin diagrams and are sensitive to the top quark mass [11].

Currently UA1 is carrying out searches for these very rare decay modes. We find an upper limit on the branching ratios of 1.3×10^{-5} (90% C.L.) and 6×10^{-5} (90% C.L.) for the decays $B^o \rightarrow \mu^+\mu^-$ and $B^o \rightarrow \mu^+\mu^- X$ respectively (X is any hadronic final state). Finally, for the exclusive decay mode $B^o{}_d \rightarrow \mu^+\mu^- K^{o*}$, the UA1 upper limit is 1.7×10^{-5} (90% C.L.). Each of these limits is an improvement on current world limits. The last two results imply an upper limit on the top quark mass on the order of 400 GeV/c^2. With the upgraded UA1 detector and the larger statistics the above limits can be improved by an order of magnitude.

Finally, and most exciting, the upgraded UA1 detector should be able to reconstruct between 10 and 100 $B^o \rightarrow \ell^+\ell^- K^{o*}$ decays outside the J/ψ and the ψ' mass windows. Similar numbers of events can be obtained for the decays $B^+ \rightarrow \ell^+\ell^- K^{+*}$ and $B_s \rightarrow \ell^+\ell^- \Phi$. These branching ratios are sensitive to the top quark mass and offer the possibility of measuring the top quark mass in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV.

UA1 found the first evidence for beauty oscillations [12]. The ratio R of like-sign to unlike-sign dilepton events was used to determine the $B^o\bar{B}^o$ mixing parameter χ, where χ is a weighted average of the mixing parameters χ_d and χ_s of the $B^o{}_d$ and $B^o{}_s$ mesons. We expect to be able to use not only μ pairs, but also e-μ and e-e events. In addition to the increased statistics, there are two qualitative advantages over the previous analysis:

- the e-μ channel is free from Drell-Yan and Υ decay background and can thus be analyzed without any isolation cuts.
- the technical backgrounds to the electron and muon signatures are of different nature, which allows a cross-check of the systematic errors.

We estimate that we can determine χ with a relative error of 10% or less. Together with the measurements of χ_d (by Argus and Cleo), χ_s can be inferred (Fig.6) and consistency with the bound coming from the unitarity of the CKM [13] matrix can be checked. Furthermore, χ_s can be measured directly, if events with identified $B^o{}_s$ mesons accompanied by leptons can be identified Ref. [14].

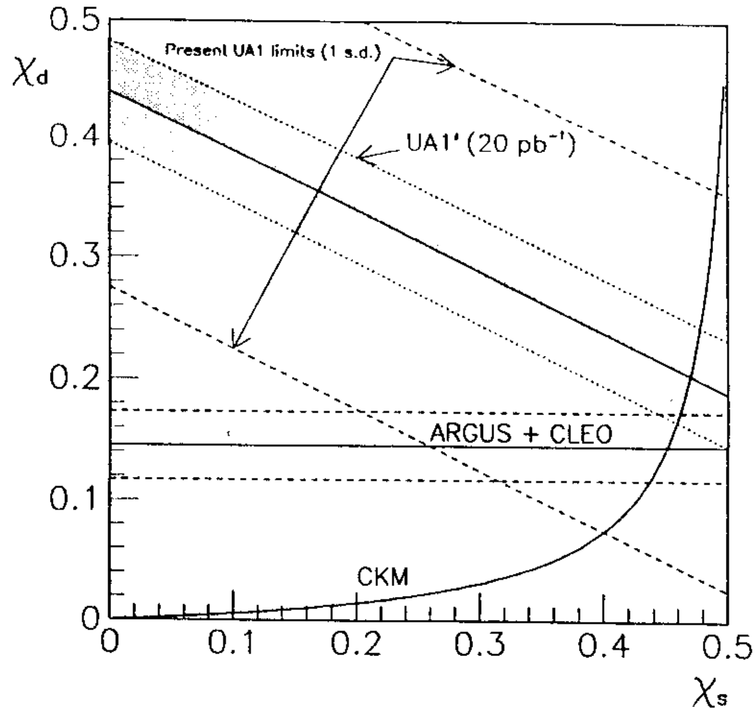

Figure 6

χ_s vs. χ_d for $B^0\bar{B}^0$ mixing with the expected improvement for 20 pb^{-1} and using electrons in addition to muons. Also shown is the Argus and Cleo measurement of χ_d and the bound from the unitarity of the CKM matrix (the allowed region is to the right and below the curve).

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Status of the Uranium-TMP Calorimeter construction and test beam results.

This document contains a brief status report on the construction of the Uranium-TMP calorimeter and a description of the main test beam results. In a previous status report on the Uranium-TMP calorimeter [1], dated December 15th 1989, a possible scenario was presented for 1990, namely:

"— successful completion of four modules, including beam testing.
— continued assembly and testing of modules."

A: STATUS OF THE CALORIMETER CONSTRUCTION.

(prepared by G. Maurin / CERN on behalf of the calorimeter project team).

1) Module assembly:

The cleaning procedure of stacks has been radically improved by multiple wash and rinse cycles. After drying with Argon a full HV test is performed with Nitrogen. The bake out procedure is unchanged. A total of 21 stacks have been through the new procedure and their leak rate is better than 10^{-8} mbar$*$liter/sec. The improvement is mainly due to the fact that all feedthroughs are now protected by Vac-seal before bake out. Two bake out tanks are operational allowing a bake out of 8 modules every 12 days.

After bake out, the stacks are assembled into Uranium modules. Geometrical problems are minimised by better controls and by careful selection of Uranium plates.

For the TMP filling, a filter has been added on the filling lines, and an additional pressuring device transmits the TMP hydrostatic pressure through the filter with topping up of the pressure to 1.3 bar. Using two filling tanks, modules can be filled with TMP at a rate of 3 per 12 days. It is important that the preparation of position detectors and the TMP cleaning remain in phase with the module preparation.

2) Cabling and electronics of modules :

Four modules have been successfully cabled. With present manpower, and assuming continued availability of components, cabling operations are not a limiting factor in the production schedule .

3) Schedule:

In order to prepare two super gondolas, 32 modules should be assembled. Based on the present manpower (already reduced due to budget constraints) and recent assembly experience the following production rate could be achieved (n.b. two stacks per module):

- assembly of 4 stacks per week (including HV tests under Nitrogen)
- bake out of 8 stacks per 12 days using two tanks,
- assembly of 2 to 3 modules with Uranium plates per week,
- filling of 3 modules with TMP every 12 days.

These numbers would allow preparation of 16 modules by mid July and 32 by end August.

3) Assembly of Supergondolas:

Assuming availability of modules, assembly of the first Supergondola could start early in June. For this first structure we expect that the first half would be fully mounted and cabled by the end of July and the second half would be completed during August. By mid-September the first supergondola could be available. Given sufficient resources, the assembly of the second Supergondola could start in parallel from mid-July and should be completed by October.

4) Beam testing of modules

Since the beginning of 1990, 4 modules have been successfully filled with TMP, fully cabled and equipped with electronics. The first module of this series has already been thoroughly beam tested at 1500 volts both for position detectors and calorimeter boxes.

During the first half of May, a sub-element of the Gondola structure with 3 modules has been assembled and is now installed in the beam test facility for further studies, in particular a more precise measurement of compensation.

B: PERFORMANCE OF URANIUM–TMP MODULES

(prepared by M. Mohammadi / UCLA on behalf of the test beam team).

The performance of Uranium-TMP calorimeter modules has been measured in PS and SPS test beams at CERN. Three Supergondola modules have been operated in electron, pion and muon beams with momenta between 3 and 70 GeV/c. Measurements have been done with the applied high voltage ranging from 200 to 1500 volts, corresponding to gap fields of 1.6 to 12 kV/cm. The calorimeter modules perform well and in good agreement with our expectations. In the following, a number of figures showing the main results of test beam measurements are presented.

Fig. 1 shows the distribution of the charge collected in the six samplings of a tower exposed to 70 GeV/c muons. The shaded area shows the pedestal noise distribution. The applied voltage is 1500 volts. From this distribution we obtain a signal to noise ratio of:

$$S / N = (\textit{muon peak} - \textit{pedestal mean}) / \textit{pedestal sigma} = 4.4,$$

which gives a muon signal loss of only 6% if a cut at 3 sigma is applied to completely suppress the pedestal noise. Similarly, the response to muons are measured with the position detector strips, which have their own independent readout electronics. For 70 GeV/c muons and HV=1500 volts, a signal to noise ratio of 2.2 is obtained, in a TMP gap of only 2.5 mm.

In **Figs. 2(a)** and **2(b)** we show the energy resolution measured for a supergondola module operated at 1000 volts and exposed to electrons and pions of various energies. After subtracting the pedestal noise, a fit to these data gives:

Electron resolution: $(\sigma/\mu)^2 = (0.12 / \sqrt{E})^2 + (0.009)^2$,

Hadron resolution: $(\sigma/\mu)^2 = (0.58 / \sqrt{E})^2 + (0.068)^2$.

For hadron resolution, the constant term is relatively large because measurements are done using a supergondola module and a C-module (old UA1 hadron calorimeter). Unlike electron showers, hadron showers are not fully contained in a supergondola module. The longitudinal leakage is measured using the C-module, which is a non-compensating hadron calorimeter with a resolution of about 100%/√E. A more complete measurement of the single hadron resolution, using five Uranium-TMP modules, is underway.

Fig. 3 shows the ratio of the electron response to the pion response as a function of the incident particle energy. The measurements were taken with the supergondola at 1000 Volts.The **e/π ratio** is close to 1 and varies between 1.08 to 1.02 for energies larger than 7 GeV. Again it should be noted that a more precise measurement is underway at the SPS test beam.

In **Fig. 4**, we plot the distribution of the mean collected charge when each tower is exposed to 70 GeV/c electrons, with the supergondola module operated at 1500 volts. The mean charge of all 16 towers is 2641.5 fC with an rms variation of 18.9 fC, or 0.7%, indicating the excellent **uniformity** of the calorimeter modules.

The performance of the **position detector** as a device for measuring shower positions has been studied with stand-alone boxes [2] as well as in supergondola modules. A spatial resolution of better than 2 mm has been measured for electron showers in excess of 7 GeV/c. For muons, a resolution of about 5 mm can be obtained with a reconstruction efficiency of about 50%.

Other types of Uranium-TMP calorimeter modules have also been sucessfully tested in PS and SPS beams, in particular, semi-octogonal modules for the forward part of the UA1 calorimeter [3].

C: CONCLUSION.

The present status shows that we are following the scenario outlined in our December 15th, 1989 report. The test beam results are extremely good and encouraging.

The construction of the full Uranium-TMP calorimeter is possible on a reasonable time scale.

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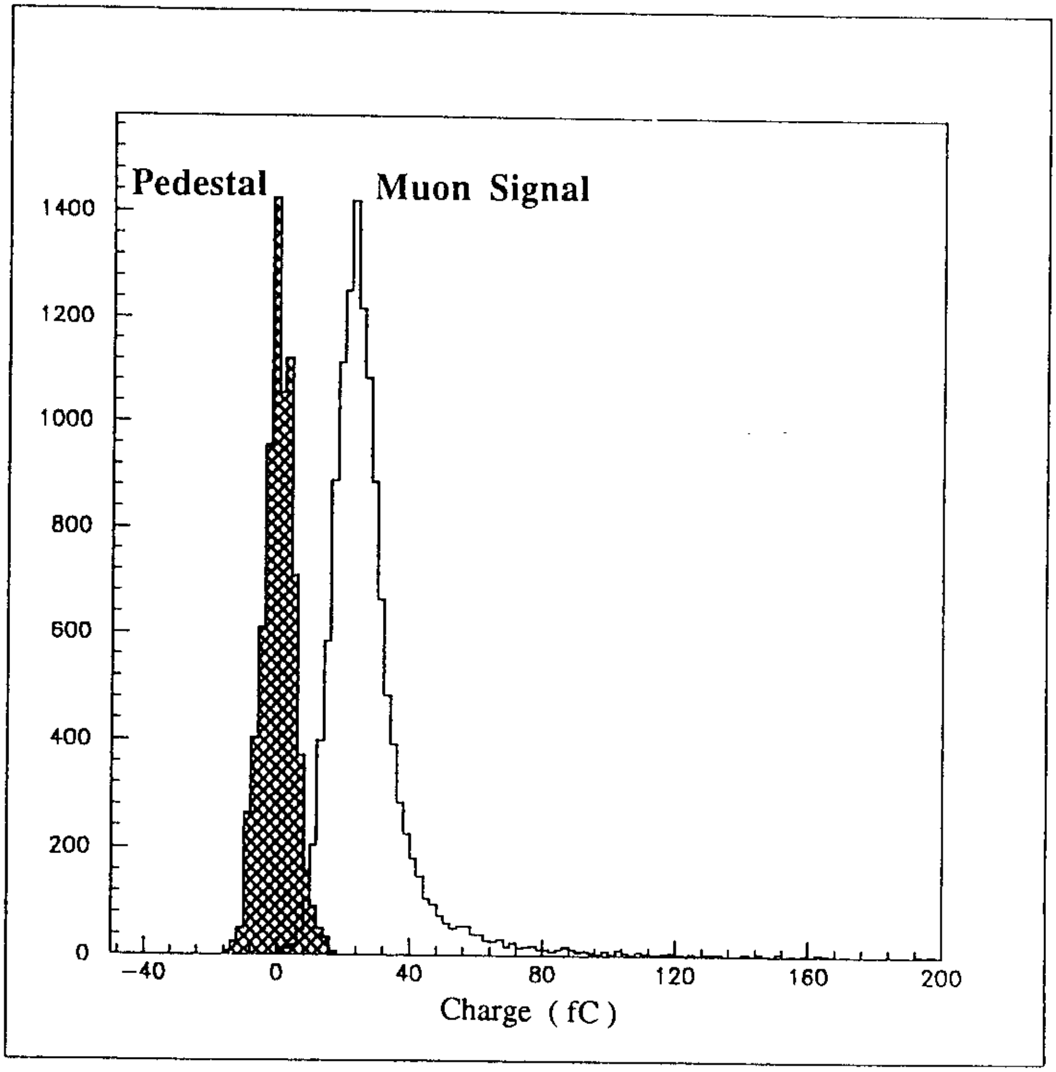
Pedestal
Muon Signal
1400
1200
1000
800
600
400
200
0
-40
0
40
80
120
160
200
Charge (fC)

Figure 1

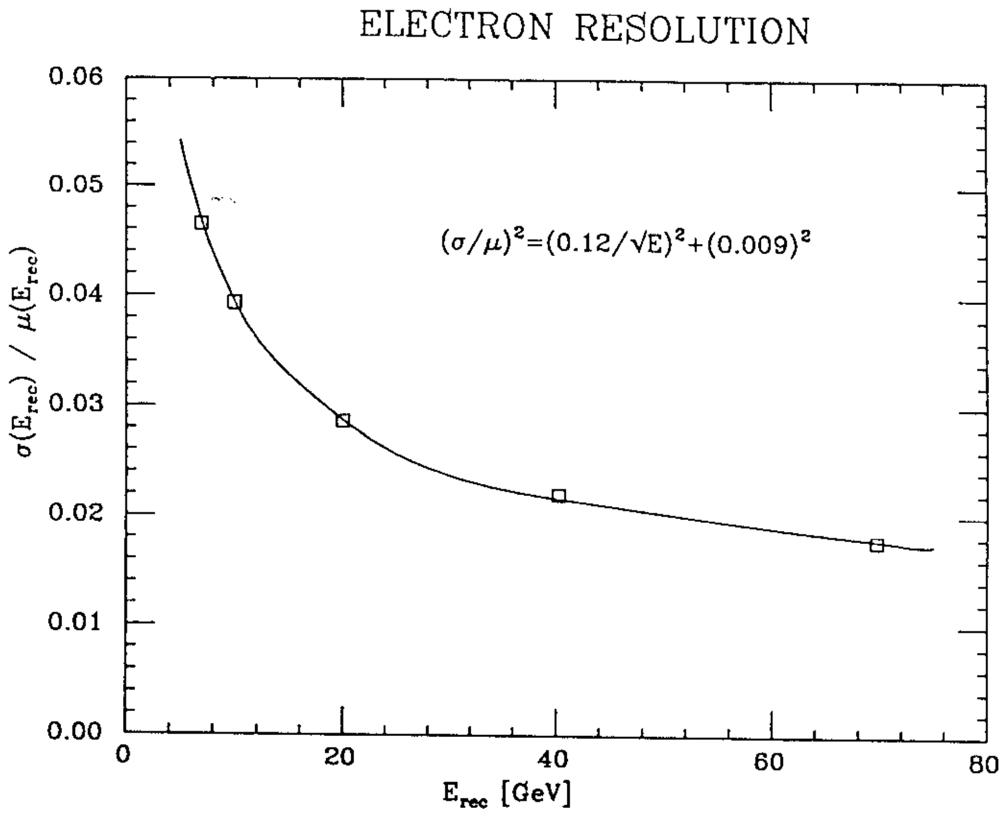

Figure 2 (a)

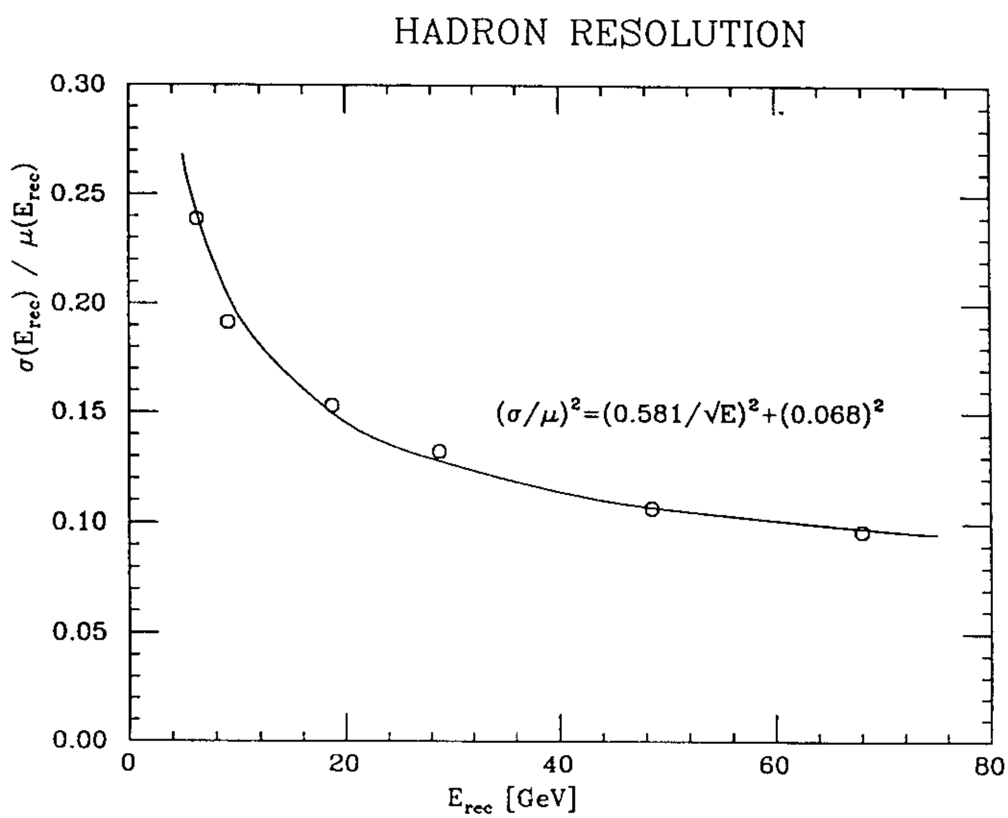

Figure 2 (b)

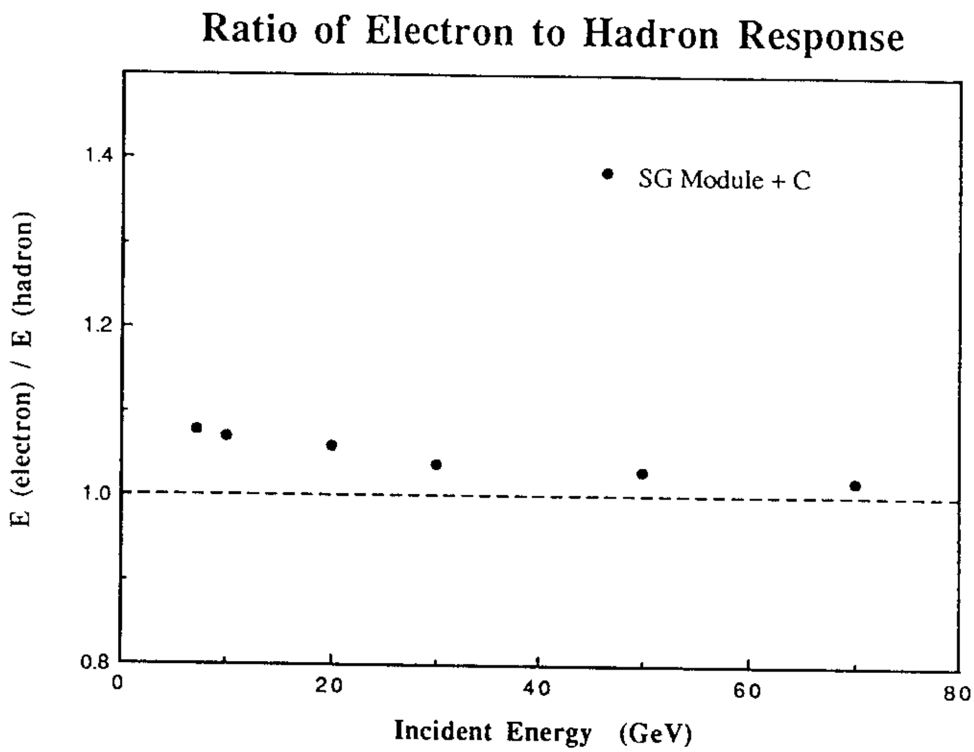

Figure 3

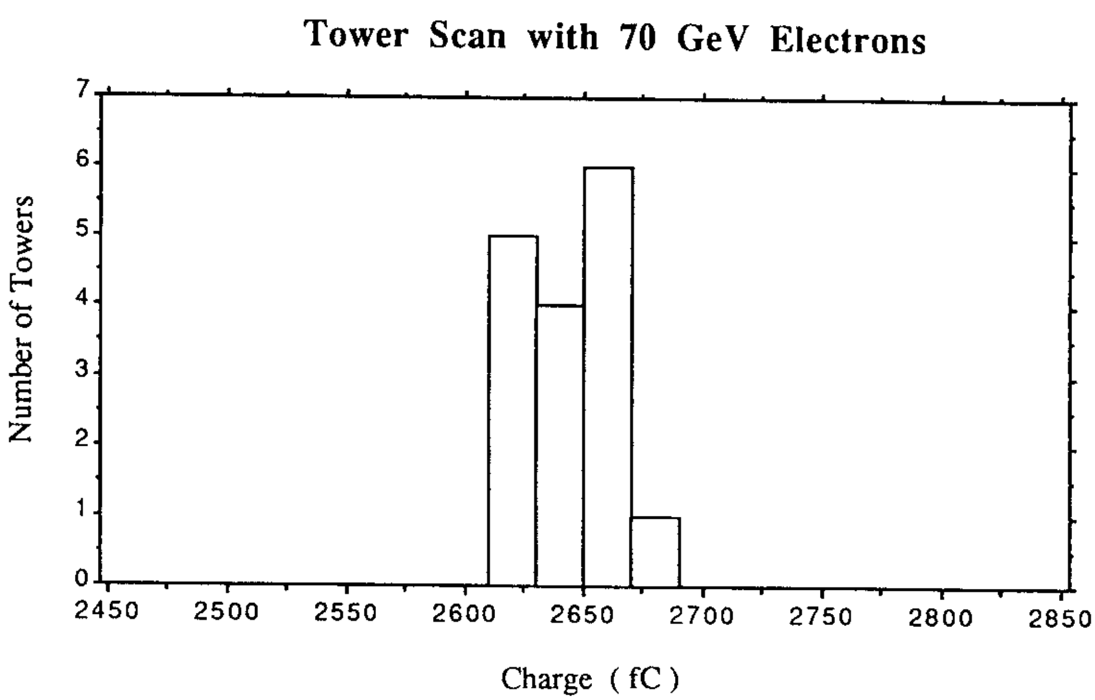

Figure 4