

HIGH ENERGY PHOTOPRODUCTION
OF STATES CONTAINING HEAVY QUARKS
AND OTHER RARE PHENOMENA

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PROPOSAL SUMMARY

We propose to study the photoproduction of states containing heavy quarks, charm and beauty, using a multiparticle spectrometer. The apparatus is similar to that used in E87 and E401, but is upgraded to have a much larger acceptance, better γ and π^0 reconstruction capabilities, and a prompt decay vertex detector. To achieve high sensitivity to low cross sections, the experiment must run in a wide band photon beam, preferably the new beam proposed for the Proton East area.

The experiment has two phases:

1. A 500 hour run with a thick target (1 interaction length) and a beam dump. This phase will produce a large sample of dimuon decays of T 's and J/ψ 's with energies up to 450 GeV and will measure the size of beauty photoproduction through the detection of multimuon final states.
2. A 1500 hour run with an open geometry and a 10% interaction length target. We will collect very large samples ($> 10^6$) of charmed particle events and will search for specific B-meson and B-baryon final states.

The power of the spectrometer and the flexibility of the trigger scheme we employ enables us to do sensitive searches for completely new phenomena with less bias than other experiments.

This proposal is a logical extension of experiments carried out by members of this group over the past 6 years. In particular, the new spectrometer is designed so that we can take advantage of the powerful and efficient techniques we have used to reconstruct complicated multiparticle final states.

INTRODUCTION

Photons are known to couple to heavy quarks (charm, beauty, etc.) and other new phenomena. In order to take maximum advantage of the Tevatron capability to explore new regions of physics, it is vital to have a versatile multi-particle high rate spectrometer, with quick analysis capability, placed in a high intensity, high energy photon beam.

We propose the construction of such a spectrometer, capable of detailed characterization of the complex final states that will be produced by the interaction of high energy photons and hadrons available at the Tevatron. We would use this spectrometer initially to study photoproduction reactions at energies from 200 to 500 GeV. This energy and intensity regime, which is crucial to our proposed program, is available only in broad band photon beams.

Our basic strategy is to subject a large number of events to very detailed on-line analysis before deciding to record them. This approach allows us to achieve very high cross section sensitivity with smaller biases than other experiments.

This proposal is a logical extension of experiments conducted by members of the group over the last six years. These experiments successfully observed and studied three aspects of charmed photoproduction: J/ψ ¹, D-meson² and charmed baryon production³ (fig. 1). The program is continuing through 1982 with a study of charm production by neutrons, E400.⁴ Many of the techniques used in the present detector and the data analysis will be carried over to the proposed detector.

The physics objectives, which are discussed in detail in Section I, are to study the production of states containing c and b quarks and to look for new phenomena.

The initial phase of the experiment will use a thick segmented target and a beam dump. This phase will be directed at the measurement of final states containing muon pairs or at least one muon of high transverse momentum ($p_{\perp}$) ~ 1 GeV/c:

$$\begin{aligned} \gamma + \text{nucleus} &\rightarrow \mu^+ \mu^- + x \\ \mu^{\pm} (p_{\perp} > 1 \text{ GeV/c}) &+ x \end{aligned} \tag{1}$$

This will yield large samples of ψ , T and multilepton final states from beauty production. These give us an initial indication of the level of the beauty cross section and indications of the presence of new phenomena.

Subsequent phases will use a thin target in an open geometry to search for specific examples of charmed and beauty decays. We will continue to trigger on lepton pairs (muons and electrons) and large $p_{\perp}$ single leptons as well as using the full power of the spectrometer and vertex detector to implement a variety of other triggers.

Section II discusses details of the spectrometer, trigger, and analysis techniques. The spectrometer has two analyzing magnets and the following complement of detectors:

1. high resolution tracking system optimally configured to simplify the problem of track reconstruction and to achieve excellent momentum resolution,
2. charged particle identification using highly segmented threshold Cerenkov counters,
3. photon-electron identifier,
4. hadron calorimeter for triggering, neutral hadron identification, and lepton-hadron separation,

5. muon identifier,
6. a sophisticated triggering scheme and data acquisition system based on hardware which has already been used in experiments by a subset of this group,
7. a prompt decay vertex detector which is being developed for E400.

Section III describes the properties of the beam we require for this experiment. It has been our experience that the techniques that succeed in the study of photoproduction reactions can be extended (sometimes with some difficulty) to the study of hadro-production. We therefore would like this detector to be located in a beam line which can supply either photons or incident hadrons. The new beam proposed for Proton East⁵ seems to have ideal properties.

Section IV summarizes the event rates for some of the states we intend to study. For example, the total yield of $\psi(\ell\bar{\ell})$, $T(\ell\bar{\ell})$, like sign dimuons, and trimuons (from beauty) detected in this experiment will be 2.0×10^5 , 250, 5100 and 1200, respectively.

Section V discusses the cost of the experiment, the time scale for construction, the division of responsibilities, and the manpower.

I. PHYSICS MOTIVATION

The physics of the b and c quarks - both their production dynamics and their spectroscopy and decays - are clearly important topics that will need to be investigated at the Tevatron. Fig. 2 shows the predictions of the γ -gluon fusion model for beauty production by photons.⁶ All standard models predict an increase of a factor of ~ 10 as the average photon energy increases from 150GeV (typical of existing beams) to 400GeV (typical of broad band beams at the Tevatron). It is crucial to be able to realize the advantages of this rise, since the production rate, even from 400GeV photons is very small.

With this in mind, the specific physics objectives of this proposal are:

1. study of high mass vector meson photoproduction (ψ , T),
2. establishment of the beauty photoproduction cross section,
3. detailed measurement of charm: spectroscopy and decay modes,
4. investigation of specific beauty decay modes,
5. search for new phenomena.

$\psi, -\psi'$ photoproduction

ψ -photoproduction is a basic process which can be calculated in several models. Measurements using photons of energies up to 250GeV (fig. 3) show a large rise in the inclusive ψ cross section. The origin of this rise is still not completely understood and is certainly not predicted by the simplest and most popular models, such as the γ -gluon fusion model. The collection of more than 100,000 events at energies up to 500GeV will clearly help to clarify the issues raised by the data we have so far. The measurement must be unbiased with respect to production mechanisms so that non-diffractive production can also be studied. Moreover,

the experiment must provide a sufficiently detailed characterization of the events to allow the separation of elastic and inelastic production. The most natural way to accomplish these goals is to measure the reactions

$$\gamma + p \rightarrow \psi + x$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad \mu^+ \mu^-$$

and

$$\gamma + p \rightarrow \psi + x$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad e^+ e^-.$$

These two decay modes constitute 14% of all ψ -decays and are easy to trigger on. Part of this measurement should be done using a liquid hydrogen target. A simple recoil spectrometer, such as used in E401, capable of measuring the azimuthal and polar angle is sufficient to decide on the elastic or inelastic nature of the event at the target vertex. The elastic events can be used to find the total ψ -nucleon cross section by measuring $d\sigma/dt$ ($t = 0$) and using the optical theorem. Finally, the ψ signal provides an excellent calibration for a new spectrometer.

The photo-production of the ψ' has been barely observed at low energy. The higher yields that we can achieve should allow us to observe several hundred examples of $\psi' \rightarrow \mu^+ \mu^-$, $e^+ e^-$, $\psi \pi^+ \pi^-$. Detailed comparisons of the ψ and ψ' cross sections will be quite interesting.

T-production

T-production confronts the same physics as ψ -production except that the mass and charge of the constituent quark are now different. Even though the cross section is very small, by running at the high intensities and energies available in a wide band beam a few hundred examples of $T \rightarrow \mu^+ \mu^-$, $e^+ e^-$ can be obtained. This sample is roughly the size of the earliest ψ -photoproduction samples at Fermilab from which much was learned. In particular, the order of the cross section would provide a check of production models of

beauty and information on the T-nucleon cross section would be obtained. To achieve this yield of T, some fraction of the experiment would use a segmented target followed by a small dump. This would allow us to convert nearly all the photons. We have used this technique to enhance the photoproduced ψ signal in our previous experiments.

Level of Beauty photoproduction

Experience at CESR proves that the observation of individual B-meson or B-baryon decay modes is a formidable challenge. The minimum goal of this experiment will be to establish the level of B-photoproduction by indirect means. Inclusive measurements that would allow one to learn this are the detection of multimuon final states:

$$\begin{aligned}\gamma + \text{nucleus} &\rightarrow \mu^+\mu^+ + X \\ &\mu^-\mu^- + X \\ &\mu^+\mu^-\mu^- + X \\ &\mu^+\mu^+\mu^- + X \\ &\mu^+\mu^+\mu^-\mu^- + X.\end{aligned}$$

The semileptonic branching fractions of the B particles are known from CESR.⁷ This allows us to extract the b-photoproduction cross section from the measured yields of multimuon events. Expected rates, based on gluon-fusion predictions of the cross section ($2\frac{1}{2}\text{nb}$), are 5100 like-signed dimuons, 1200 trimuons, and 30 quadrimuons. These large yields are sufficient to reveal the energy dependence.

Charm production

Much has been learned about charm from measurements at e^+e^- machines, in photon beams and in hadron beams. Several powerful detectors, including Mark III and the Fermilab Tagged Photon Lab spectrometer, will have results before this experiment will run. Nevertheless, information on charm has been extracted only slowly. It is our thesis that the study of charm is a much easier task than the study of beauty and is therefore worth doing carefully. Given the complexity of beauty spectroscopy, we may well have to rely on our knowledge of charm to learn how heavy quarks behave. We present here a partial list of open questions which could be answered by the large accumulation of charmed events - of the order of several million - that we can achieve. We are confident that many of the answers will still be unknown at the time we begin this experiment and that new questions will arise as new results come in. A list of topics which this experiment could investigate are:

F-decay modes (including those involving τ 's)

Decay modes of charmed baryons Λ_c , Σ_c , and Σ_c^*

Masses and decay modes of baryons bearing both charm and strangeness

Lifetime measurements

Cabibbo suppressed hadronic decays

Cabibbo suppressed semi-leptonic decays

Better limits on possible violations of the "standard theory" of weak decays of charmed particles

Details of production mechanisms

Rare decays

Exotic four-quark charmed mesons

This program requires both a powerful forward spectrometer and a detector capable of resolving the weak D decays from the main event vertex. The separation of charmed vertices from the primary vertex will provide a large collection of tagged charmed events in which at least one charmed particle is completely reconstructed. We expect to learn much from our construction of a prompt decay vertex detector for E400.

Investigation of specific Beauty decay modes

This spectrometer has been designed to have very large acceptance, efficient particle identification, and good photon detection. These features will allow us to make further measurements of the properties of the B particle beyond the exploratory measurements of the dump phase of the experiment. First we will study events which contain downstream decays observed in the vertex detector together with a high transverse momentum lepton, reconstructed charmed particles together with a high transverse momentum lepton, or ψ 's observed to decay downstream. We expect to observe thousands of events in each of these categories. This will yield valuable information on the detailed structure of photo-produced B events which will allow us to search for individual B decay modes. Samples of some 100-500 events may be expected in particular final states such as

$$B \rightarrow \psi K \pi$$

$$B \rightarrow D + n\pi \quad n = 1, 2, 3, 4, \dots$$

New Phenomena

Because of our basic strategy of examining large numbers of events in considerable detail, we will be able to accumulate flexibly large samples of interesting topologies which can be investigated

for new physics. We will be sensitive to a wide variety of new phenomena in an unbiased fashion, avoiding dependence on any specific production mechanism.

II. SPECTROMETER

The layout of the apparatus is shown in fig. 4 and Table I. The spectrometer has two dipoles, M1 and M2, which deflect particles in the vertical plane.

The aperture of M1 is chosen to subtend an angle of $\pm 120\text{mr}$ in the horizontal (non-bend) plane from the center of a thin target located 36" upstream. The 36" of free space between the target and the magnet accommodates the prompt decay vertex detector described below. M1 is required to have a $p_{\perp}$ kick of between .750 GeV/c and 1 GeV/c. The 234" between M1 and M2 contains multi-wire proportional chambers for track reconstruction, three gas Cerenkov counters for charged particle identification, and a highly segmented electromagnetic shower detector for electron, γ , and π^0 reconstruction. The momentum resolution for tracks which are analyzed only by M1 is

$$\sigma(p)/p = 0.015\% p \text{ [GeV/c]}$$

The M2 magnet has two functions:

- 1) to allow the reconstruction of V^0 's which decay downstream of M1 and to aid in the reconstruction of V^0 's decaying inside M1.
- 2) to channel the highest momentum particles through the inner part of the spectrometer where additional chambers allow us to improve the momentum resolution and an added Cerenkov counter extends the particle identification to higher momenta.

The aperture of M2 is chosen to subtend $\pm 45\text{mr}$ from the center of the target in the non-bend view. A $p_{\perp}$ kick of up to 1 GeV/c is required. The downstream face of M2 is covered with scintillation counters and proportional tubes which provide muon identification for the outer part of the spectrometer.

Downstream of M2 are located additional Cerenkov counters, proportional chambers, an electromagnetic calorimeter, a hadrometer, and a muon detector. These are described in more detail below.

There are two separate phases of this experiment. The first uses a thick, segmented target and a beam dump. The physics objectives of this part of the experiment are prompt dimuon and multimuon production. The target and dump arrangement is shown in fig. 5. The second phase is an open geometry experiment with a 10% interaction length target. For this phase, we would use a thin beryllium target. Finally, we will have available the liquid hydrogen target used in E401 to make a brief measurement of ψ production on protons since we feel that the topic of elastic ψ -photoproduction needs additional investigation.

Tracking system

The tracking system is based on 5 sets of multiwire proportional chambers, P0-P4, which measure tracks which are not swept out by M1. Pattern recognition will be done using the wire hit information only, with drift time being used to provide higher resolution in track fitting. Two additional upstream sets of chambers, P-2 and P-1, will extend the acceptance down to particles of momentum 1GeV/c. Details on the sizes, wire spacings, and numbers of wires in the chamber system are given in Table II. (Additional tracking information will come from the prompt decay vertex detector described below.)

The first chamber, P-2 will be located directly upstream of M1. This chamber will have 3 planes, x, v, and u. The next chamber, P-1, will be placed inside of M1. It also will have 3 planes, x, v, and u. These planes will measure the non-bend view (x) and $\pm 11^\circ$

away from the bend view (v and u). These chambers will cover $\pm 120\text{mr}$.

The next three chambers, P0, P1, and P2, will be located between the magnets, M1 and M2, and are designed to cover $\pm 150\text{mr}$ in the non-bend view and $\pm 200\text{mr}$ in the bend view. Each of the chambers will have 4 planes, s, t, u, and v, measuring $\pm 11^\circ$ from the non-bend plane and $\pm 11^\circ$ from the bend plane. The time of arrival of hits on each wire, relative to a reference pulse will be measured. This "minidrift" scheme was developed by Columbia University for E87 and gave a position resolution of approximately 250 microns. The addition of the fourth plane allows the left/right hit ambiguity to be removed. The fourth plane will also increase our track reconstruction efficiency. Our expected position resolution with this 4 plane per chamber system is 200 microns.

Finally, two chambers, P3 and P4, will be placed after M2. These chambers will have 4 planes, s, t, u, and v, and will cover $\pm 45\text{mr}$. These chambers will redetermine the momentum of the highest energy tracks and will measure the momentum of particles coming from V's which decay upstream of P1.

One of the most important features of this experiment (and of our previous work on complicated multiparticle states) is the ability to examine extremely large numbers of events rapidly and to select those of greatest interest in an efficient manner. This requires a set of analysis algorithms which are both well optimized for off-line use and adaptable for use in our M7 on-line processor.⁸ In fact, the detector needs to be designed from the start in such a manner as to make the use of efficient algorithms possible. This is especially true of the wire chamber system and tracking algorithms, which are the basic analysis program which processes every event.

For our previous experiments, (E87, E401, and E400) we have developed such a set of tracking routines which work very well in conjunction with our present chamber system. We can routinely reconstruct a hundred complex events per second on the Cyber 175, and have also adapted these routines for use in the M7. The program is based on using only the hit information for pattern recognition (i.e., using the chambers as proportional chambers); higher precision is obtained by incorporating drift time information at a later stage after the tracks have been identified. The routines find projections in each of three different views, and then match up the projections to find tracks. They move sequentially through different categories of tracks, (tracks going all the way through the spectrometer, tracks going through the first magnet only, etc.) eliminating the hits on the found tracks at each stage.

The proposed experiment will use extensions of these same techniques. We will still use the chambers as proportional chambers to do the pattern recognition, and have adjusted the wire spacings in the various planes accordingly. However, we expect to obtain even better drift information than we have in the past and thus achieve resolutions of $200\mu\text{m}$ or better when we fit the tracks. Moreover, the addition of a fourth view will provide an additional constraint on the tracks, and will allow us to deal with higher multiplicities. Finally, the information from the small chamber near the target will provide a powerful constraint in the later stages of the pattern recognition.

Charged Particle Identification

Charged particle identification using gas Cerenkov counters and the reconstruction of neutral vees (K_S^0 , Λ^0 , and $\bar{\Lambda}^0$) are the only means we have of knowing the strangeness and baryon content of the final state. The charged hadron identification system consists of four highly segmented gas threshold Cerenkov counters. Three of these counters are upstream of the magnet M2 so that they can cover the whole angular range of particles passing through M1. The fourth one is placed downstream of M2 and provides additional information about the higher energy particles passing through that part of the system. Table III gives the radiator material, length, particle threshold momenta, expected photo-electron yields, and number of segments of each counter. All counters operate at a pressure of 1 atmosphere. High multiplicity (~ 10 tracks) photon events from our existing data are being analyzed to optimize the geometry of the cells. Cell sizes are chosen so that each sees significantly less than an average of one track per event, except at the center of the system, where the large track density makes this impossible. The cells which have low density each have one mirror viewed by one 2" or 5" photomultiplier, depending on the geometric size of the cell. Each region of high track density is viewed by an array of 3/4" photo-tubes placed in the focal plane of a single mirror. Each tube ends in a simple light funnel with a square cross section and the funnels are packed together to form a square array (fig. 6). These arrays provide a very crude imaging capability and should effectively eliminate confusion.

The optics of the counters, C0, C1, and C2, will be based on using low mass planar mirrors to bounce the light out of the aperture and spherical mirrors to focus it onto the photo-multipliers. The thin

mirrors present very little material to the particles passing through the spectrometer. C3 is a counter that has been used in E87 and E401, and is being upgraded for E400. It uses spherical mirrors to reflect light directly onto photomultiplier tubes.

This system allows complete particle identification for momenta from 10 to 40 GeV/c. Between 4 and 10 GeV/c, one can separate pions from Kaons and protons. Identification of protons extends up to 75 GeV/c. For some phases of the program, it might be useful to extend the particle identification to even higher momenta. One way to accomplish this would be to fill C3 with pure helium. The resulting threshold momenta would be 18, 63, 110 GeV/c for π , K, and p, respectively.

Photon-Electron identifier

Two electromagnetic shower counters are required to identify photons, π^0 's and electrons. The acceptance of the neutral detector is matched to the acceptance for the charged particles. One shower counter will be immediately downstream of P2 and upstream of M2, and the second shower counter will be placed behind P4.

In order to cover the entire charged particle acceptance, the shower counters must be able to withstand megacycles of 100 GeV electrons. Presently, we plan lead-scintillator sandwich shower counters with high spatial resolution. The expected energy resolution is $15\%/\sqrt{E}$. The $\frac{1}{4}$ " thick scintillator strips will be placed after each radiation length of lead and will be read out by wave shifter bars. Two wave bars will be used for each set of strips to longitudinally divide the counter and to aid in the identification of electrons. A position resolution of 4mm is obtained by measuring the energy deposited in $2\frac{1}{2}$ cm scintillator strips. The strips are

configured to run in both horizontal and vertical directions and to give independent measurements of the energy shower.

The upstream shower counter, S1, is 60" x 90" with a 36" square hole for the inner detector. The shower counter is 20 radiation lengths with the energy deposition in the first 5 radiation lengths and the last 15 radiation lengths being measured separately.

The downstream shower counter, S2, is also 60" x 90", but it only has a 4" square hole through which the non-interacting photon beam will pass. The counter will be 30 radiation lengths long. The energy deposition in the first 5 radiation lengths and the last 25 radiation lengths will be measured. To identify neutrals, this counter needs only to be square, matching the hole in M2, however the counter is designed to be rectangular in order to maintain good electron identification in the charged particle acceptance. A schematic diagram of this counter is presented in fig. 7.

About 3/4 of the lead which is needed for these two shower counters already exists in the old shower detectors constructed for E87. We would use all of these pieces.

Hadrometer

The hadrometer designed for this experiment will be placed immediately downstream of shower counter S2, and will be 70" x 90" with a 6" square hole in the center. The 7 interaction length detector consists of a stack of 25 2" thick steel plates. This is the same size as the calorimeter which was used in E87. All the cut and machined steel plates used in that experiment will be used for this hadrometer.

In E87, the calorimeter was used in making a hadronic trigger, but was too coarse in the transverse dimension to be effective as

a neutron or K_L^0 identifier. However, the calorimeter was still quite useful in electron and muon identification. For this Tevatron experiment we want the additional capability of identifying neutral hadrons. To accomplish this goal, the detector must be more finely divided.

The new detector's configuration will have 5" wide strips, horizontal and vertical. Parallel strips at the same level, but different layers, will be read together by wave shifter bars. The hadrometer will be divided in two longitudinally to observe shower development. A diagram is shown in figure 8.

Alternatively, the calorimeter currently being used by E609 might be reconfigured to match our required dimensions.

Muon detection

As with the electromagnetic detectors, there are two separate regions of muon detection, depending on whether the muon passes through the aperture of M2 or not.

Muons passing through the aperture of M2 ($\pm 45\text{mr}$) are identified by their ability to penetrate the electromagnetic detector, the hadrometer, and two blocks of iron at the end of the spectrometer. There is one block of 6' x 8' x 2', followed by a 2' gap, then a 6' x 8' x 6' block. The gap between the blocks contains an array of scintillation counters and two planes of proportional tubes, one with horizontal wires and one with vertical wires. After the last block, there is another set of X-Y proportional planes and a scintillation hodoscope. The proportional tubes give a $\frac{1}{2}$ " cell size (1" half-lapped square tubes). Their purpose is to permit the reconstruction of muon trajectories for the higher level triggers. The scintillation counters are used in the lower level triggers.

The remainder of the aperture is covered by an array of scintillation counters and vertical and horizontal proportional tubes mounted on the downstream face of M2. The iron yoke of M2 serves as the muon filter. The proportional tube cell size is $\frac{1}{2}$ ".

This arrangement with only scintillation counters has been used successfully to detect muons in our previous photoproduction experiments, E87 and E401. The existing steel blocks and scintillation counters can be used in this experiment. The proportional tubes are a new feature. Since both muon detectors are preceded by calorimetry, hadron punch through is readily identified and rejected.

Data acquisition system and triggering scheme

The trigger and data acquisition systems of the experiment will be a logical extension of the systems we have been using for several years. The two are closely tied in a multi-level decision-making scheme.

Data acquisition

In our experimental program, both completed and on-going, we have successfully used the philosophy of examining a tremendous quantity of data, rapidly and efficiently analyzing each event to the stage of being able to pass judgement intelligently. A crucial aspect of this approach is a high band width data acquisition system. Our goal has been to keep the experiment deadtime due to the read-out down to about 5% while recording hundreds of complicated events per spill.

We have constructed and used a stand-alone data acquisition system which fills a large, solid state buffer memory during the spill without computer intervention. We pipeline the look-up of the crate-module addresses, the reading of the modules, and the writing to the buffer memory. With a cycle time of about $1.0\mu\text{s}$, we fill our 64 kilo word

buffer during a spill with a deadtime of about 6%. This system has run smoothly through two experiments, E87 and E401. The data is leisurely copied through the on-line computer to magnetic tape between spills.

For E400 we are rearranging the system to cut the cycle time to 500ns. By running four systems in parallel we will gain a factor of four in speed. This will allow us to increase the buffer size by a factor of eight to half a megaword without increasing our deadtime.

In the Tevatron era, with a 10-second spill, we will be able to continue this approach. The only change we need to make is in the on-line computer software. By treating the memory as a ring buffer, we can copy the data to magnetic disk during the spill without increasing the deadtime. The inter-spill period is also longer, though not by the same factor of ten. At 1600bpi, 45 inch per second tape speed, and 45% loss to inter-record gaps, we wrote our 64K words to tape in about 4 seconds. Using a 6250bpi drive and increasing the record length (to decrease the fraction of tape lost to inter-record gaps), but leaving the tape speed the same, would allow us to read 0.5Mwords in 5.4 sec in E400, or 5.Mw in 54 sec at the Tevatron. Thus, we could record the entire data set on tape if we wanted to. A faster tape drive would ease the crunch a bit. However, at 5.Mw per minute and about 60Mw per tape we would be changing tapes every 12 minutes. We have no intention of writing five tapes per hour, although the data acquisition system could handle the rate with a readout deadtime of only 6% during the spill.

That tape load would impose an excessive strain on the experimenters' physical comfort, the stockroom budget, and the central computing facility's resources. The latter include tape drives, operators, and CPU time.

As described below, we will continue to develop the techniques we have been using for on-line data processing. Already in E401 we have done very preliminary track reconstruction at the trigger level to reject spurious triggers. In E400 we are making that process more sophisticated.

Also, in E400 we are applying on-line the event reconstruction algorithms (through the first momentum fit) which we have developed for off-line analysis of our earlier experiments. We expect to reject 75% of the events which reach this stage based on such criteria as multiplicity, identified particles, and minimum invariant masses. For those events which pass, we will write the raw data on tape with merely a brief note of the results of the calculations. In this proposed experiment we expect to improve this rejection rate by eliminating the myriad of high-cross section electromagnetic interactions which can overwhelm the measurement of the low cross section processes which we will study. Additionally, with increased computing power on-line we will be condensing information somewhat, thus reducing the number of tapes to be written and the analysis load on the central computing facility.

Our current data acquisition system can handle the data rates we need to make Tevatron measurements. We are, of course, closely following the development of instrumentation for the Collider Detector Facility and at Nevis Laboratory. We anticipate greatly increased capabilities in distributed processing to be available by the time of this experiment and will incorporate any appropriate devices in our system.

Triggering scheme

The power of our triggering scheme lies in its essentially unlimited flexibility, which gives us tremendous latitude in adjusting the acceptance criteria. Any knowledge gained from our experience or from other experiments can be directly incorporated in the trigger. Early stages of the trigger apply very loose cuts, while later stages, in which the full processing power of the M7⁸ is brought to bear on large numbers of events, permit us to apply in the trigger many of the cuts which are usually applied to the data off-line.

The primary trigger will be a simple cabled trigger, sensitive to much of the total cross section. We will run with MHz rate at this level. Second level triggers allow us to impose somewhat more detailed criteria. For example, we will be able to ask for a muon, signaled by a detector deep in some steel; a heavy particle, signalled by a scintillator firing without corresponding Cerenkov light; or an electron, signalled by energy in an electromagnetic shower counter. Additional cuts at this level can include rough multiplicity requirements.

The tertiary trigger decisions will be made by the M7 trigger processor. The M7 is a stored program computer which will have access to a subset of the event record directly through interfaces to the experiment. We have demonstrated in E401 and through simulation of E400 that a 50 μ sec calculation in the M7 can refine the straight hardware triggers of the lower levels. Simple pattern recognition is the most probable application. We can crudely match bend angles with Cerenkov cells to improve the heavy particle triggers. We can calculate dimuon masses or single muon transverse momenta to select more exciting events of those categories. Strike-shower correlations can help distinguish electron and photon showers.

Events which pass this third level trigger are written to the buffers and thence to disk.

The final decision to record the event is made during the tape-writing phase between spills. The M7 accepts events from the on-line computer, performs some rather extensive calculations, and returns the results to the on-line computer. In E400 the M7 will be doing the complete track finding program that we have run off-line on the data of our previous experiments. Given the geometric track parameters we can quickly calculate momenta and then invariant masses using the floating-point hardware in the on-line computer. Detailed particle identification is also possible. Alternatively, we may build a separate processor to handle these chores.

It is well known that photoproduction experiments are plagued with fake triggers from electromagnetic showers. In E87, a photoproduction experiment which required strikes in the proportional wire chambers consistent with a minimum of four particles, typically 50% of the events on tape had fewer than four tracks. At this level we can make our multiplicity cuts, mass cuts, particle identification cuts, and so on. These will clearly be applied very loosely, both in terms of the limits on each quantity, and on the total sample reduction. On the other hand, the low mass lepton pair spectrum, for example, can be suppressed very effectively. (We will, of course, sample the low mass pair spectrum.)

We can handle 5Mwords/10 seconds or .5Mw/sec., through the data acquisition system. If a typical event is 1000 words (we expect 2/3 that in E400), we can record 500 events/second with a dead time of 6%. Assuming a 75% rejection rate by the M7 during the spill, we can handle 2000 events/second at that level. At 50 μ sec/event we get a 10% deadtime. By starting the read out at the same time we

start the M7, then aborting the read out if the M7 vetos the event, we can save the calculation time on accepted events, reducing the dead-time to 7½%. The next lower level requires about a microsecond per trigger handled. Claiming a factor of five rejection we learn that we can handle 10,000 events/second with a deadtime of 1%. Our lowest trigger, the one which responds to a significant fraction of the total hadronic cross section, will generate a deadtime of some 50ns. We expect that the crudest selection methods will suppress this by an order of magnitude. The deadtime is negligible. We can thus stand a luminosity of $\sigma_T = 100,000$ events/second of spill, or 50M/hour.

High Resolution Vertex Chamber

A very small high resolution multi-wire proportional chamber system is presently being built for E-400. It will consist of 9 planes of wires, each with ½mm spacing. The active area of the chamber will be circular with a 60mm diameter. It will have 3 x planes (vertical wires) and 3 u planes and 3 v planes (30° wires with respect to the horizontal plane). Each 3-plane package will have x, v, and u wires. With this arrangement all nine planes can be identically machined. It will have an overall length of 100mm and would be located 100mm downstream of the center of the extended beryllium target. The beryllium target will be segmented along the beam direction into 3 pieces and will be placed in a vacuum. With our expected 1mm Z resolution and the 25mm separation between target pieces, we can demand that the decays of interest occur in the vacuum. Secondary interactions of particles should not be a problem. The gas in the chamber will be pressurized to four atmospheres. A schematic layout of the chamber and target is shown in fig. 9.

The typical minimum projected angle between tracks which will be detected in the spectrometer is greater than 10mr. These tracks will usually be separated by more than four wires when they reach the first plane of the high resolution detector. With the help of the downstream chambers P0, P1, and P2, which can resolve projected angles as small as 2mr, we believe we can resolve tracks with projected angles as small as 4mr in the high resolution chamber.

A vertex detector can be made to separate the primary production vertex from a decay vertex if the transverse measurement, L , of these vertices is less than speed of light, c , times the mean lifetime, τ , of the decaying particle, that is $L \lesssim c\tau$. The $c\tau$ values of interest are $D^0 = 30\mu\text{m}$, $F^+ \approx 60\mu\text{m}$, $\tau^- = 60\mu\text{m}$, $\Lambda^+ = 60-90\mu\text{m}$, and $D^+ = 300\mu\text{m}$. The transverse location of the primary production vertex or the decay vertex will be measured to $60\mu\text{m}$ in our detector. Such a measurement is quite adequate to distinguish the D^+ decays from the "tagged" charm events. But, the measurement is marginal for the F^+ , Λ^+ , and τ^- , and not sufficient for the D^0 .

During E-400 we will gain experience in using these chambers. Following E-400 we will evaluate the performance and consider possible upgrades. It does seem possible to improve the resolution by a factor of (2-4) by using the minidrift system we presently use for our downstream MWPC and by adding 1% Xenon to the chamber to lengthen the drift time. These upgrades would allow a separation of the D^0 , F^+ , Λ^+ , or τ^- decay vertex from the primary vertex and would provide additional sensitivity for the observation of beauty decays. Another possible use of the chamber would be to incorporate it into the trigger. Our M7 trigger processor could read out the wire information and search for events in which there were two vertices. This scheme would provide a unique way of separating charm and beauty decays from the background at the on-line trigger level.

III. BEAM REQUIREMENTS

The photon beam required for this experiment must have the following properties:

- 1) High intensity, high energy: The beam must be able to provide $\gtrsim 5 \times 10^7$ photons of energy greater than 200 GeV.
- 2) Low hadron contamination: The beam must be free of neutral hadrons (K^0 , n). We require a contamination of less than 0.01%.
- 3) Low muon halo: The muon flux in the detector hall should be less than 10^5 muons/m²-sec over the full area of the detector.

These requirements will not be satisfied by the two existing photon beams, even with 1 TeV protons incident on their production targets. The tagged beam, even operating at its maximum electron momentum of 300 GeV/c, does not meet the intensity requirements. In addition, the b-quark production cross section is rising with energy and it is important to have photons of energy greater than 300 GeV. The existing broad band beam can meet the energy and intensity requirements, but the hadron contamination is too high ($\sim 0.5\%$). Backgrounds from neutral hadrons have complicated the extraction of charm signals and might obscure the b-particle signals, as well. Muon fluxes in the present enclosure are expected to be intolerably high. If a new experimental area, farther away from the production target, could be constructed, part of the proposed program could be successfully done in this type of beam.

The wide band photon beam, proposed for Proton East, does meet all of the requirements listed above. The properties of this beam are described in a preliminary design report.⁵ The beam has several other advantages for this experiment. It has its own target station so that it can run simultaneously with the tagged photon beam. It is possible to make an excellent high intensity π^- beam with only a

small demand on proton intensity ($\ll 10^{12}$ protons/pulse). It should be possible to debug the detector using negative pions. Finally, the spectrometer we propose is very powerful and it makes sense to locate it in an area where it can be used in several different kinds of incident particles. (The proposed beam can be operated as a π^- , p, n, γ or e^- beam.)

IV. RATES AND BACKGROUNDS

To accomplish the goals outlined in Section I, we require 500 hours of running in the dump configuration and 1500 hours of data in the "open geometry" mode, of which 100 hours use a liquid target. In addition, it will take of order eight weeks to commission this complicated detector.

The 500 hours spent in the dump mode will produce a clear signal for T and multimuons from beauty. The large number of ψ 's produced in this time will be a stringent test of the spectrometer resolution. The multimuon events will confirm the level of the beauty cross section and will, in addition, provide some information about the event topologies, since the dump does not close off the entire aperture. This information will be used to guide the "open geometry" run.

The 1500 hour open geometry run will provide the primary data of the experiment. This will permit us to make the detailed measurements of charm particle properties and beauty photoproduction discussed in Section I.

Tables IV and V give the event rates for ψ , T, inclusive D^0 , inclusive Λ_c , multi-muon production from beauty, and B-meson production for each phase of the experiment. The acceptances and mass resolutions are also given.

In calculating these rates, we made the following assumptions about the Tevatron properties:

Total machine intensity:	2.4×10^{13}
Proton intensity on production target:	6×10^{12}
Repetition rate:	1 pulse/minute
Spill length:	10-15 sec.

For the photon beam intensity, we used the number given in the beam design report:

$$\# \text{ of photons of energy } E_\gamma > 200 \text{ GeV} = 4.5 \times 10^7 / \text{pulse}.$$

The acceptances were calculated by assuming that the b and c quarks are excited by a gluon-fusion or diffractive-like mechanism (fig. 2). The essential characteristic of this kind of production is the creation of a fast-forward pair of heavy-quark-bearing particles that have essentially the total energy of the incident photon. The invariant mass of the pair is strongly peaked toward the production threshold. These properties are characteristic of the charm events observed in E87.

The acceptances quoted in Tables IV and V are based on the requirement that the track reach the proportional chamber station P2. In fact, we expect that it will be possible to reconstruct tracks that are swept out of the acceptance before they reach P2, but pass through P-2, P-1, and P0. This lowers the momentum cut-off of the spectrometer to $\sim 1 \text{ GeV}/c$ and increases all acceptances to virtually 100%.

The rates projected in Tables IV and V clearly demonstrate that large samples of ψ 's, D's and Λ_c 's will be obtained. Thousands of events will be observed in any decay mode whose branching fraction is $\gtrsim 0.1\%$. Experiment 87 was able to observe significant signals (fig. 1) despite the presence of large backgrounds from hadron contamination in the old broad band beam. The absence of this contamination in the new beam will result in extremely favorable signal to background ratios. Similarly, the event yield calculations show that large samples of T and multilepton events will be obtained to study the general characteristics of b-quark excitation.

The hardest task for the experiment is the detection of individual B-meson or B-baryon decay modes. In the open geometry run, we expect to produce $\sim 50\text{K}$ B- bearing events at the target. We suppose that 60% of these will result in the lowest lying B-mesons. One way to search for these is to sum over all possible completely reconstructible D-decay modes and then to look for states like $D + n\pi$.

We expect 10-15% of all D decays to be potentially reconstructible. We don't have any hard information about branching fractions but any D+x decay mode with a branching fraction of 1-5% will give 30-150 events.

Whether we can distinguish the ~ 100 events from the background will depend on the details of charm and B-particle production. Although the ratio of direct charm to indirect charm (from B-particle decays) is $\sim 100/1$, we know that the event invariant mass and the track multiplicity will be significantly lower for direct charm. Invariant mass and multiplicity cuts may allow us to reduce the background by a factor of between 10 and 50. Other clues, like the presence of prompt leptons or ψ 's, may also help us whittle away the background.

The key to detecting charm production in E87 was the ability to see the D^*-D^0 cascade decay. The B^*-B^0 mass difference is likely to be too small to permit a charged pion cascade decay. The decay would then take place through the emission of a very soft γ which would have an energy of $\sim 1-2$ GeV in the Lab. We certainly are going to try to detect low energy gammas to exploit this rather striking correlation to eliminate the background. Finally, we have tried to produce a detector that gives excellent mass resolution to keep the background under the cascade D and the B to a minimum.

If it turns out that the B-lifetime is $\sim 2 \times 10^{-13}$ then our chances of directly observing the sequential decays in the prompt vertex detector are excellent and this should allow us to overcome even the most severe backgrounds. If any decay mode with a particularly striking signature, for example the much discussed $\psi K\pi$ mode, is substantial this would also improve our chances.

V. TIME SCHEDULES AND RELATION TO ONGOING PROGRAMS

We assume that an experimental hall will be available for occupancy in late 1983 and that this experiment could be installed and ready for an initial run 6 months later in the spring of 1984. The two major new projects for the experimenters will be the construction of the chamber system and the electromagnetic calorimetry. We would begin the design and the construction of prototypes beginning in 1982. We would expect to begin serious production by the summer of 1982 and to be finished in 1-1½ years.

It is important to understand the close relation between this proposal and the experiment E400 which is scheduled to run in late 1981. In that experiment we will use, for the first time, some of the equipment that is needed for the new proposal: the prompt decay vertex detector, the new triggering and data acquisition hardware, and part of the proportional tube system for the muon detector. Moreover, the average interaction rate and event topologies we will encounter in E400 will be similar to those we expect in the proposed photon experiment, so that we will gain valuable experience in applying our sophisticated triggering scheme. We see the new proposal as a logical extension of E400 and our completed photoproduction experiments, E87 and E401.

Division of responsibilities

Fermilab would provide:

- 1) the two magnets, power supplies, shield plates, stands,
- 2) muon steel (all of which can come from the present setup),
- 3) calorimeter steel (existing hadrometer steel can be used),
- 4) liquid hydrogen target and refrigerator (existing E401 target),
- 5) on-line computer,
- 6) some PREP electronics in addition to PREP electronics already assigned to E400.
- 7) some support structures for the electromagnetic calorimeters,
- 8) calibration dipole (AN421) from existing experiment.

The experimenters will provide all detectors described in Section II of this proposal together with support electronics and cabling. The experimenters will provide all special computer interfacing and memory extensions external to the online computer system.

Costs

The costs of the various detectors are summarized in Table VI. As can be seen, extensive use will be made of existing equipment developed in our previous and current experiments. The major expenditures are for the new multi-wire proportional chamber system and for the new shower counters.

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- 3 J. Russell et al., Photoproduction of Charmed Baryons, submitted to Phys. Rev. Lett.
- 4 M. Binkley et al., E400 Revised Objectives.
- 5 J. Butler et al., Design of a new wide band neutral beam for the Tevatron, Fermilab Technical Memo TM-963 (1980).
- 6 L. M. Jones and M. W. Wyld, Jr., Production of bound quark-antiquark systems, Phys. Rev. D, 17, 2332 (1978), and J. P. Leveille (private communication).
- 7 K. Chadwick et al., Decay of b-flavored Hadrons to single muon dimuon final states, Phys. Rev. Lett. 46, 88 (1981).
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TABLE I: DETECTOR GEOMETRY

<u>Device</u>	<u>Z position</u>	<u>Transverse dimension</u>
Target	0	
P-2	24"	4" x 4"
Front M1	36"	24" x 48"
P-1	66"	16" x 40"
Back M1	96"	
P0	116"	30" x 60"
P1	186"	40" x 60"
P2	266"	60" x 90"
Front M2	330"	36" x 36"
Back M2	402"	
P3	420"	40" x 60"
P4	600"	60" x 90"

P_⊥ M1 = 1.0 GeV

P_⊥ M2 = 0.5 GeV

TABLE II: CHAMBER PARAMETERS

<u>Chamber</u>	<u>Size</u>	<u>Planes (Spacing)</u>	<u>No. of Wires</u>				<u>Total</u>
P-2	4"x4"	x, v, u (1mm)	96,	96,	96	=	288
P-1	16"x40"	x, v, u (2mm)	224,	480,	480	=	1184
PØ	30"x60"	s, t, u, v (2mm)	384,	384,	768, 768	=	2304
P1	40"x60"	s, t, u, v (3mm)	352,	352,	512, 512	=	1728
P2	60"x90"	s, t, u, v (4mm)	384,	384,	576, 576	=	1920
P3	40"x60"	s, t, u, v (5mm)	192,	192,	288, 288	=	960
P4	60"x90"	s, t, u, v (6mm)	256,	256,	384, 384	=	1280

9,664 Wires

TABLE III: CERENKOV PROPERTIES

<u>Counter</u>	<u>Radiator material</u>	<u>Length</u>	<u>Threshold momenta $\pi/K/p$</u>	<u>Photo-electron yield (B = 1)</u>	<u>Number of cells</u>
C0	Isobutane	10"	2.5/9.0/17.0	8.8	30*
C1	N ₂	60"	5.75/21/39	9.6	30*
C2	20%N ₂ + 80%He	80"	10.8/38.7/73.4	4.0	30*
C3	20%N ₂ + 80%He	170"	10.8/38.7/73.4	8.5	30
C3**	He	170"	16.5/59/112	3.6	

* 1 or 2 cells may consist of densely packed clusters of 3/4" PMT's as shown in fig. 6.

** Alternative use for high momentum tracks.

TABLE IV

EVENT YIELD (Dump Phase)

Final State	Cross Section/ Nucleon	Total Event Rate/Pulse	Total Event Yield (500 hours)	Acceptance *
Total hadronic final state	120 μ b	2×10^5	6×10^9	--
Total $\psi \rightarrow \mu^+ \mu^-$	2.2nb	3.5	1.0×10^5	95%
Total like sign	70pb	1.2×10^{-1}	3500	85%
Total trimuons from B's	16.8pb	2.8×10^{-2}	840	80%
Total quadrimuons from B's	0.46pb	0.7×10^{-3}	20	50%
Total $\tau \rightarrow \mu^+ \mu^-$	2.5pb	4.0×10^{-3}	120	70%

* Lower limit. Does not include classes of tracks which are reconstructed in less than 5 chambers.

TABLE V

EVENT YIELD (Open Geometry Phase)

Final State	Cross Section/ Nucleon	Total Event Rate/Pulse	Total Event Yield (1500 hours)	Acceptance*
Total hadronic final states	120 μ b	3×10^4	2.7×10^9	--
Total charm	1 μ b	250	2.25×10^7	90% (3-4 trk)
Total charmed mesons	670nb	170	1.5×10^7	90% (3-4 trk)
Charmed baryons	330nb	80	0.75×10^7	90% (3-4 trk)
Total ψ	30nb	7.5	6.75×10^5	--
$\psi \rightarrow e^+e^-$	4.2/nb	1.0	9.0×10^4	95%
Total B	2.5nb	0.63	5.6×10^4	66% (6 trk)
Total T	70pb	0.017	1600	--
$T \rightarrow e^+e^-$ **	5pb	0.00119	110	70%
Total trimuons from B's	16.8pb	0.0042	375	80%
Total quadrimuons	0.46pb	0.0001	10	50%
Total like-sign dimuons	70pb	0.017	1600	85%

* Lower limit. Does not include classes of tracks which are reconstructed in less than 5 chambers.

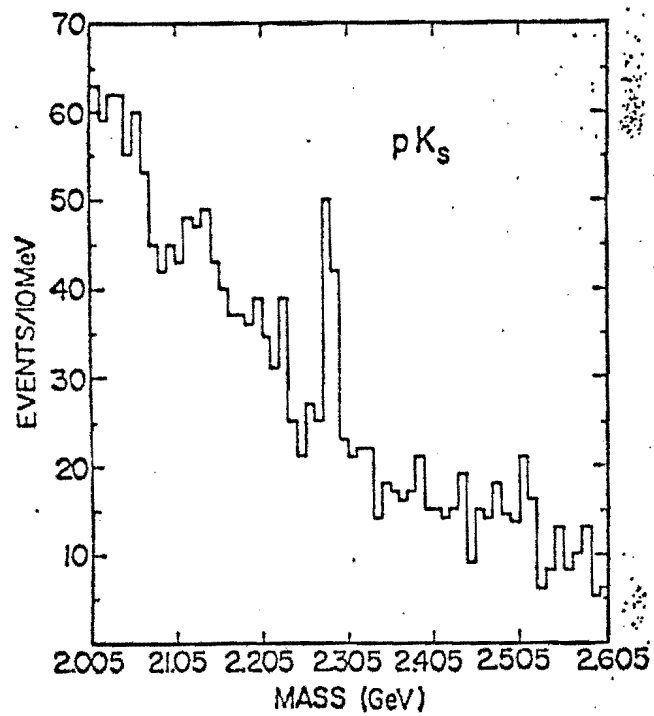
** Integrated mass resolution on the T is 70 Mev (σ).

TABLE VI: EXPERIMENTAL EQUIPMENT

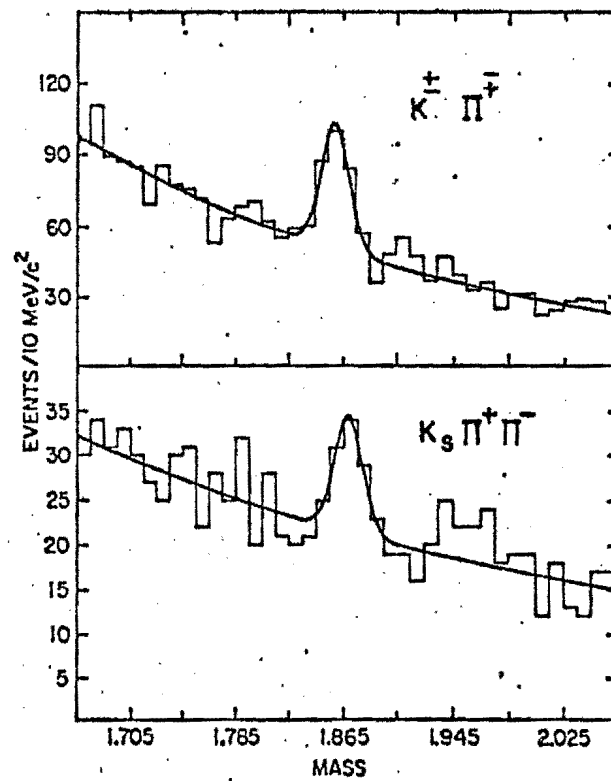
<u>Item</u>	<u>Existing Equipment</u>	<u>New Expenditures</u>
Prompt decay vertex detector	\$120K	-0-
Chamber system	200	\$750K
E+M shower counters	75	380
Hadrometer	50	40
Cerenkov counters	100	60
Muon detector	30	40
Fast electronics	100	-0-
M7	150	-0-
Data acquisition system	200	-0-
	<u>\$1025K</u>	<u>\$1270K</u>

FIGURE CAPTIONS

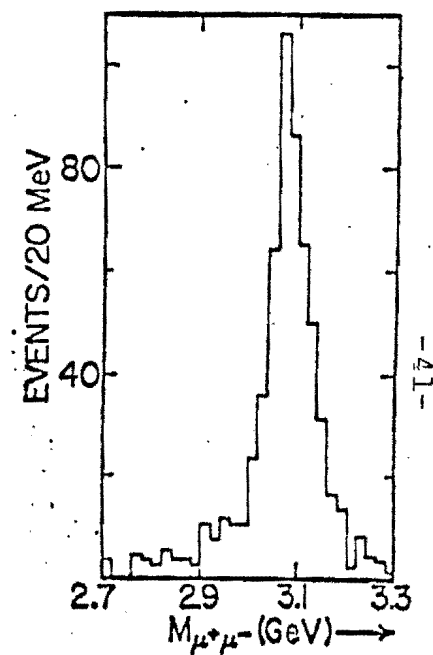
1. Representative results on charm particle production by photons from E87 and E401.
 - a. Charmed Baryon production
 - b. D-meson production
 - c. J/ψ production
2. Gluon fusion model production for bare beauty and upsilon production as a function of photon energy.
3. Preliminary results on the energy dependence of J/ψ photoproduction from E401.
4. Layout of proposed experiment (open geometry configuration).
5. Layout of target region for dump configuration.
6. Cerenkov counter cell arrangement to be used in regions of highest track density.
7. Electromagnetic shower counter.
8. Hadrometer.
9. Prompt decay vertex detector.
10. Photon spectrum of proposed wide band beam.



(a)



(b)



(c)

FIGURE 1

FIGURE 2a
GLUON FUSION MODEL PREDICTION FOR BEAUTY PRODUCTION

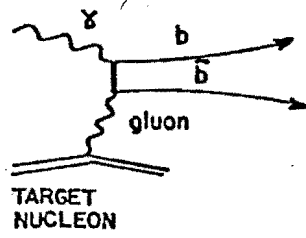
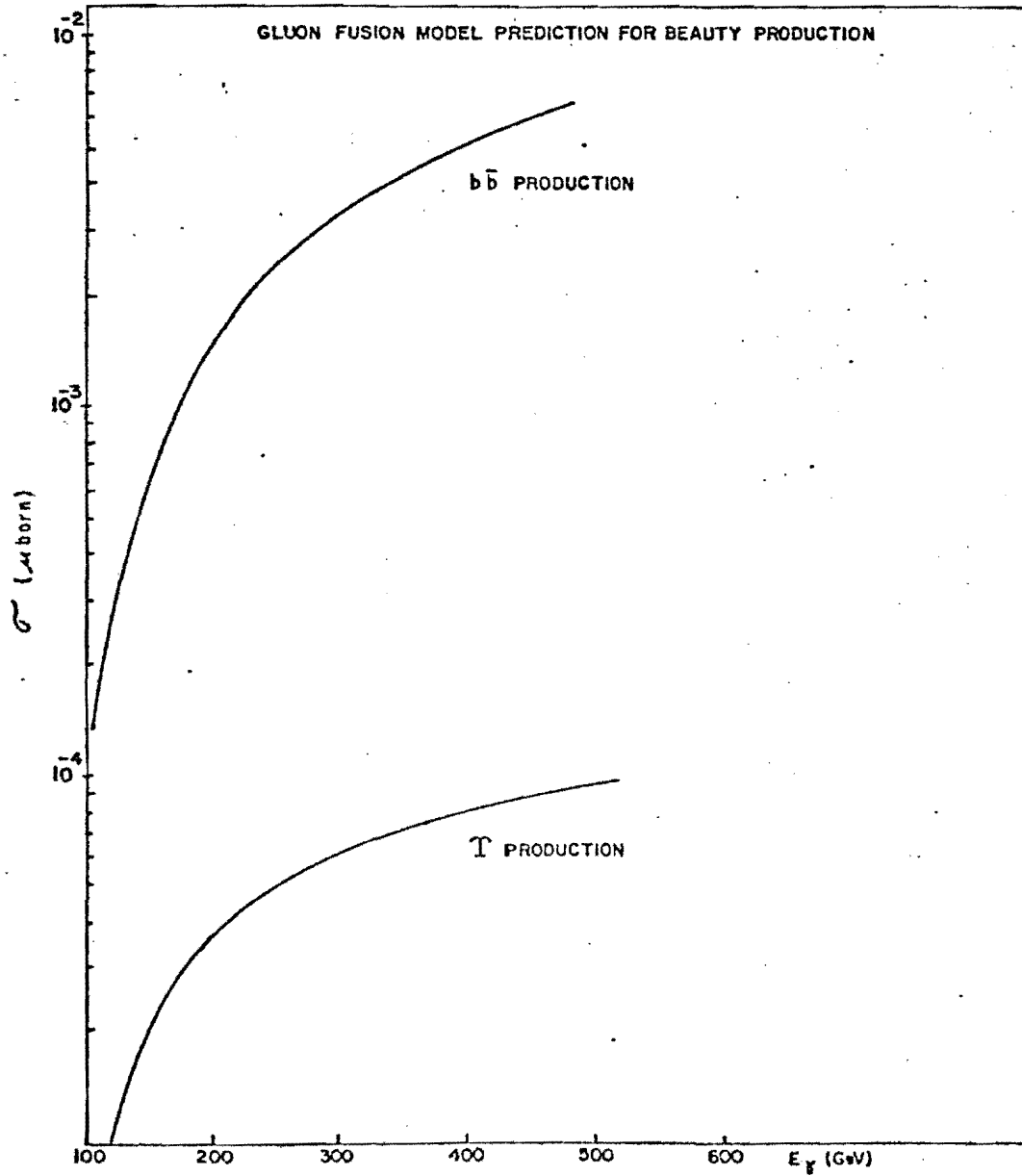


FIGURE 2b



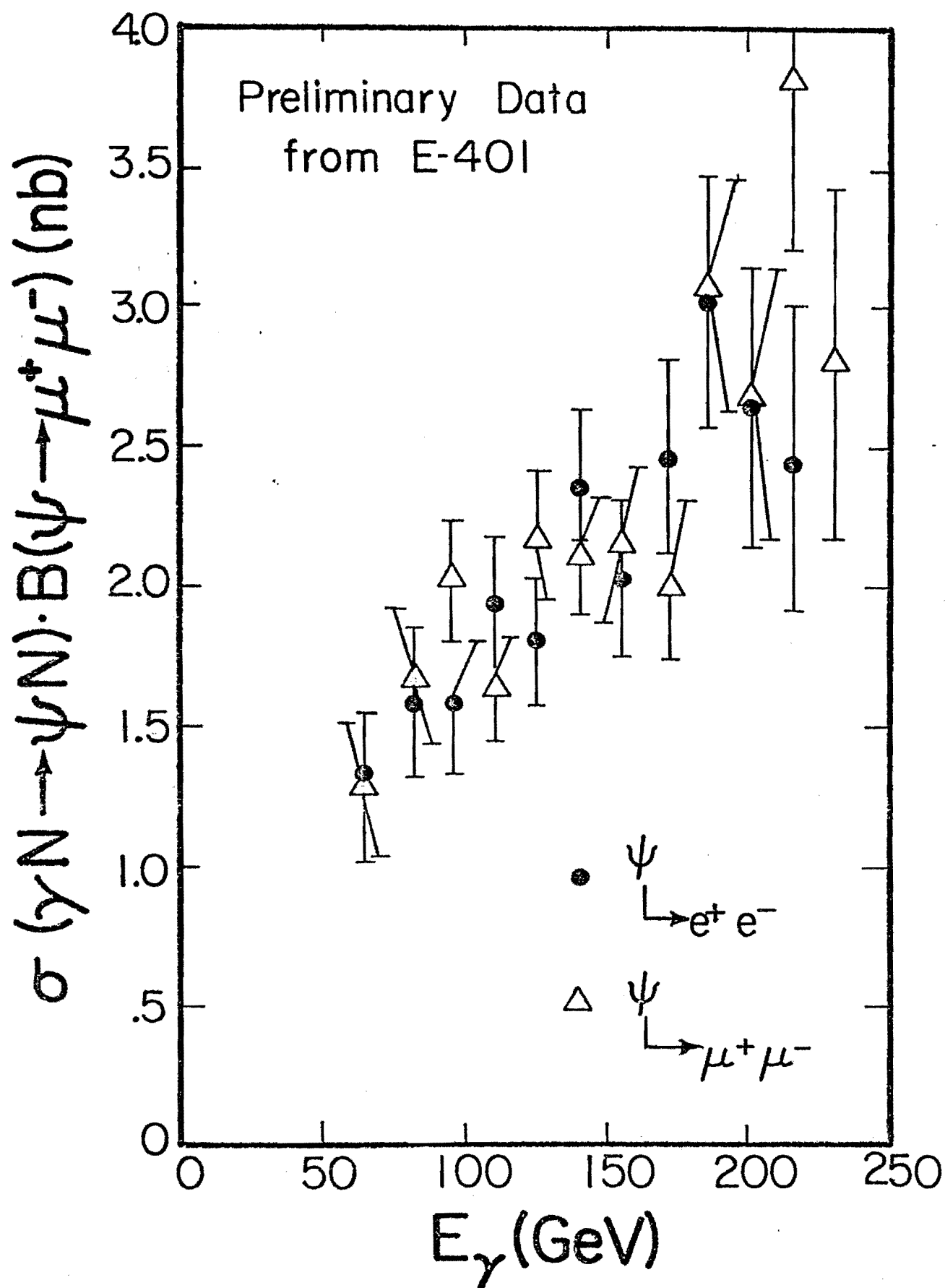


FIGURE 3

FIGURE 4

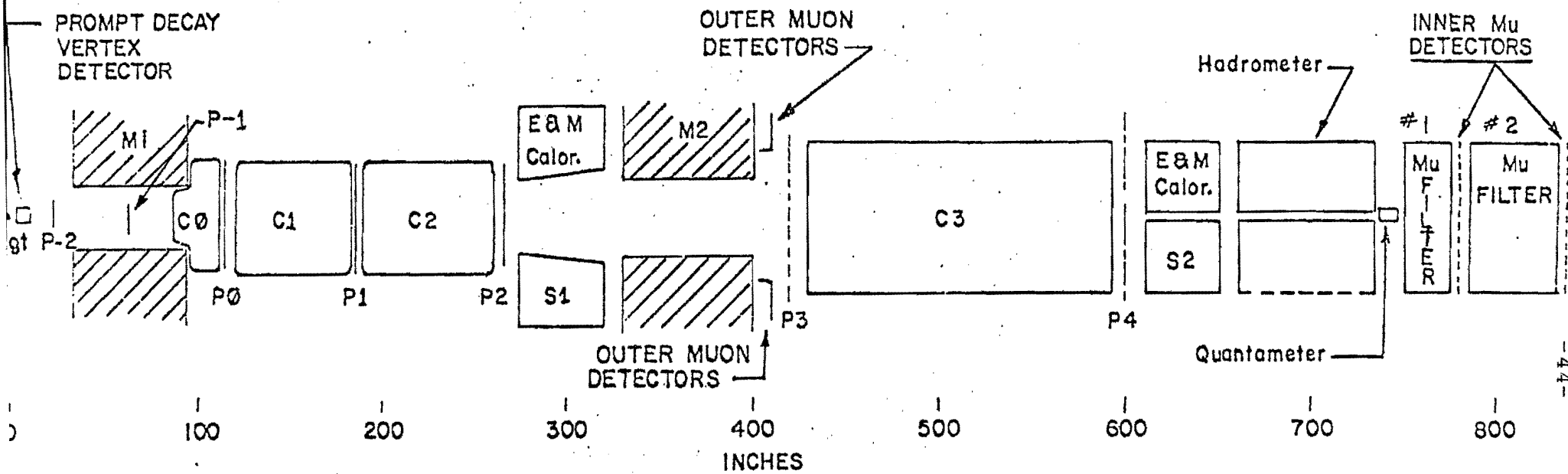
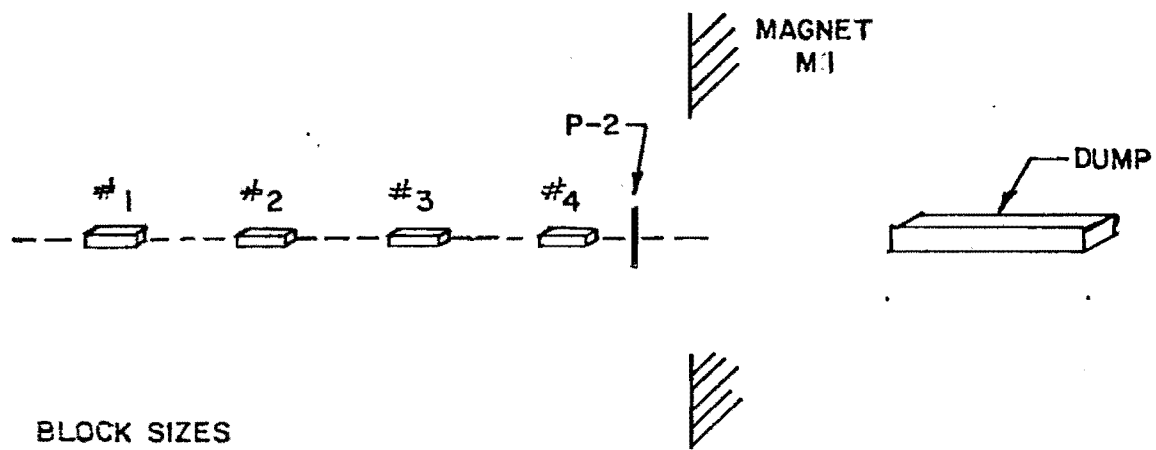


FIGURE 5

DUMP PHASE TARGET GEOMETRY



BLOCK SIZES

1"x1"x4"

Scale: 1/8" = 2"

FIGURE 6

CERENKOV COUNTER CELL LAYOUT
FOR HIGHEST DENSITY REGION

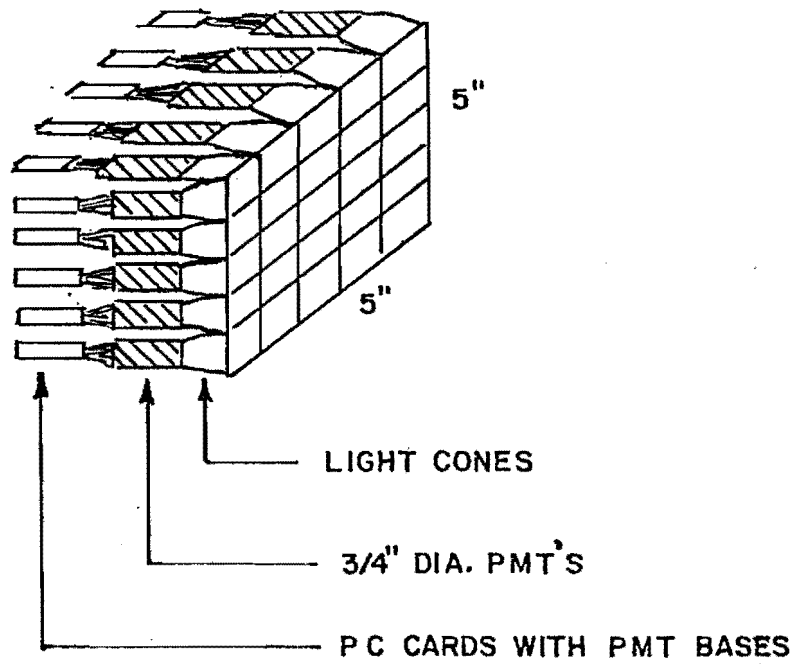


FIGURE 7

PHOTON-ELECTRON IDENTIFIER

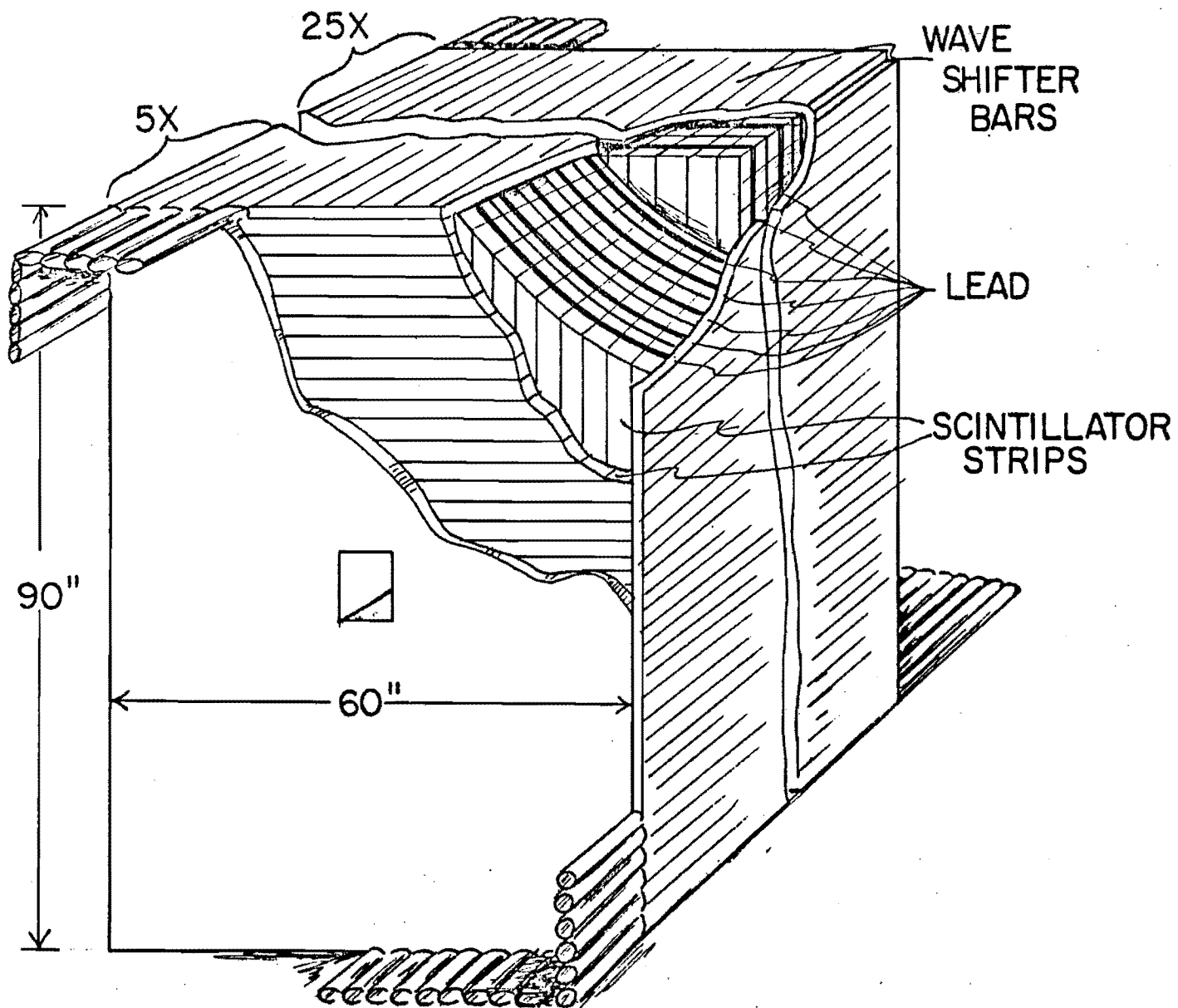
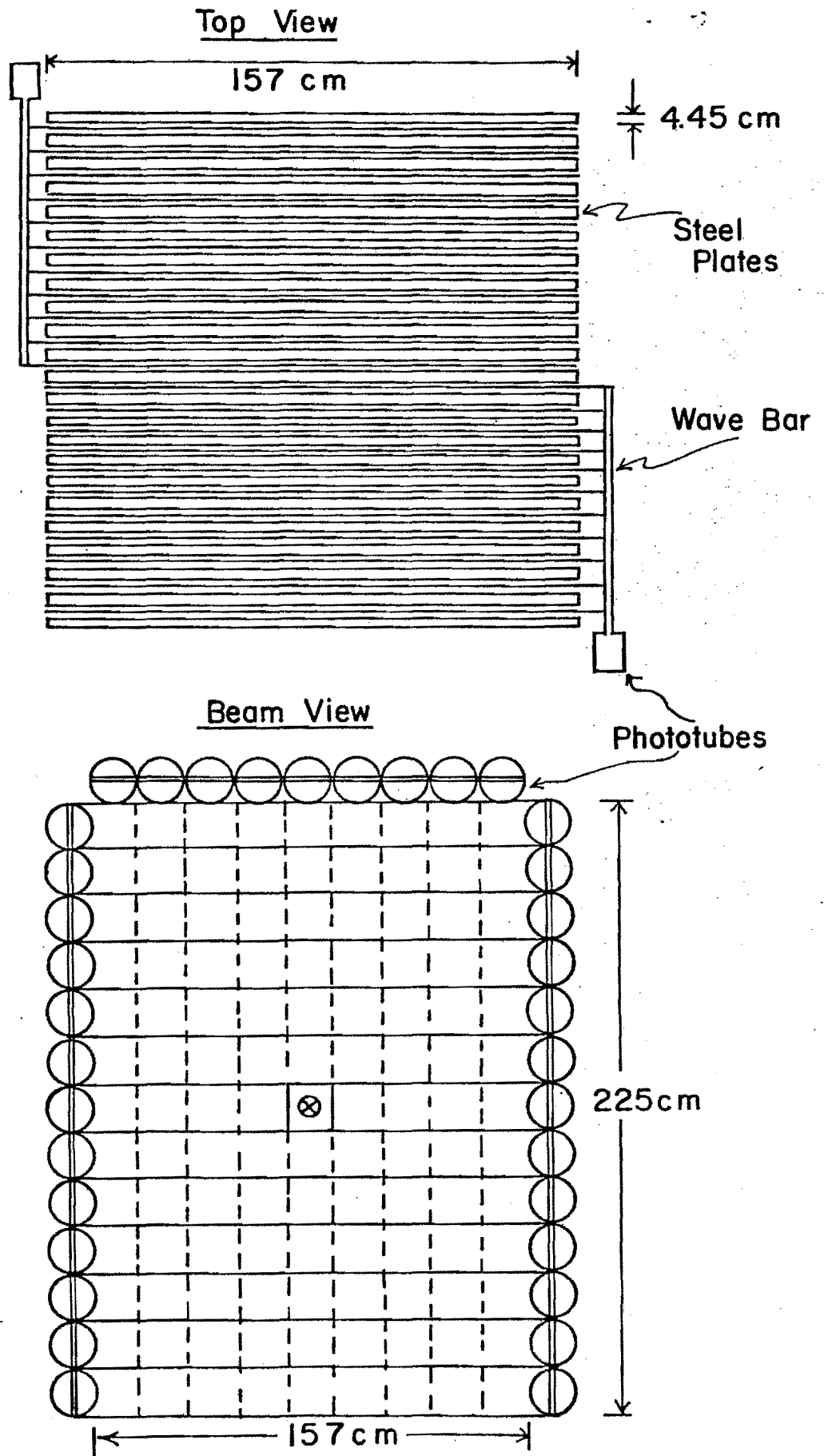


FIGURE 8

HADRON CALORIMETER



Target and Vertex Detector

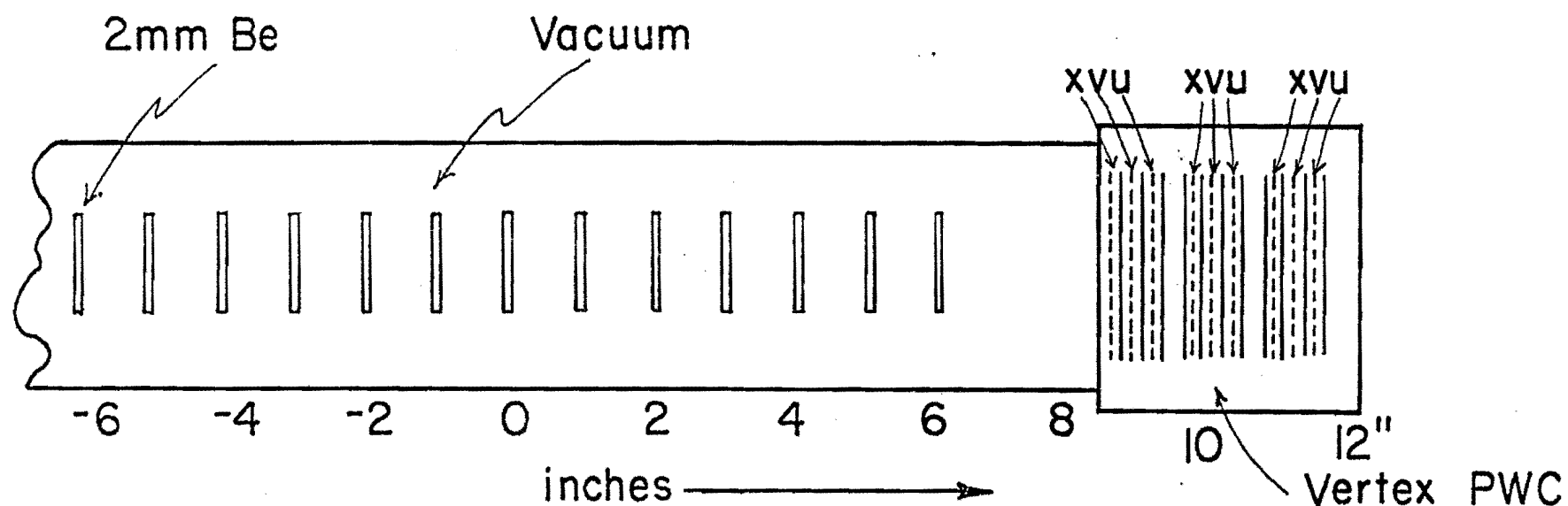


FIGURE 9

FIGURE 10

PHOTON FLUX:

NEW BROAD BAND BREMSTRAHLUNG BEAM
(30% RADIATOR)

$DN_{\gamma} / DE_{\gamma}$ (PHOTONS / GeV / INCIDENT 1 TeV PROTON)

