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FERMILAB PROPOSAL P-772

STUDY of the NUCLEAR ANTIQUARK SEA via p+N → DIMUONS

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ABSTRACT

We propose a precise measurement of the A dependence of the Drell-Yan process for 900 GeV protons on targets of deuterium and calcium using the E605 spectrometer. Emphasis will be placed on the kinematic region $M > 4$ GeV and $x_F > 0.2$, where one is most sensitive to beam-valence-quark, target-antiquark annihilation. Such measurements will be very sensitive to the A dependence of the target sea quark distribution in the range $0.05 < x_2 < 0.3$, and hence provide important clues about the origin of the EMC (European Muon Collaboration) effect, and unique information on the general issue of quark distributions in nuclear systems. Only minor modifications (liquid deuterium target, and reduced-size beam dump) of the E605 spectrometer will be required.

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A. INTRODUCTION

The EMC effect[1] caught everyone by surprise. It was anticipated neither by particle physicists seeking the most convenient target material for tests of QCD nor by nuclear physicists searching for "smoking-gun" evidence of quark effects in nuclei. In spite of nearly three years of intense interest and debate, the only universally accepted fact is that deep inelastic lepton scattering from bound nucleons is not identical to that from free nucleons. As is seen in Figure 1, lower energy electron scattering from SLAC[2] and higher energy muon scattering from CERN[1,3] are in accord on the depletion of the valence quark momentum distribution in heavier nuclei. The rise of the A-corrected ratio of the F(2) structure functions approaching $x = 1$, presumably due to Fermi motion, is likewise seen. The positive "EMC" enhancement in the region $x < 0.3$ is still, however, the subject of continuing measurement and debate. Recent muon data from the BCDMS[3] group suggest that the trend of the data above a ratio of unity seen for $x < .2$ in the EMC data is not in error.

At present, deep-inelastic neutrino scattering experiments[4,5,6] do not shed much additional light on the EMC effect due to large errors in measured A dependences. Figure 2 shows the appropriate ratio of the F(2) structure functions from CDHS.[6] More complex analyses of F(3), considered later, have even larger associated errors.

B. MODELS OF THE EMC EFFECT

The past three years of theoretical publications on the origin of the EMC effect would fill a modest sized filing cabinet (see Refs. 7 and 8 for a compilation of references). They span the range from regarding the effect as profound to almost trivial. They can be crudely categorized as follows:

RESCALING - These models suggest that the EMC effect is the result of a slight swelling of the nucleon size when it is bound in nuclear matter.[9] No mechanism for the size increase is given.

QUARK CLUSTERS - Here the relatively high density of nuclear matter combined with the finite size of the nucleon is seen to imply a sizable probability of volume overlap - resulting in clusters of six or more quarks.[10]

QUARK CONDUCTIVITY - These ideas, although in the primitive model stage, envision some kind of non-color-singlet parton communication among nucleons.[11]

EXCESS PIONS - Several versions of this "classical nuclear physics" explanation have emerged.[12] The physics is simple in principle: A very modest enhancement of the pion-field occurs in dense nuclear matter (a weak remnant of pion-condensation, discussed extensively ten years ago) leading to a slight increase in the number of pions per nucleon. This manifests itself as an enhanced sea in deep inelastic scattering.

NUCLEAR BINDING - Taken in its simplest form this model[13] "explains" the EMC effect as a simple consequence of the nuclear binding energy. It is a kind of rescaling, but on the basis of mass rather than radius.

Roughly speaking, models in all of the above categories can "explain" the A-dependence of deep inelastic scattering, particularly the non-controversial valence quark momentum depletion. The manner in which the models achieve agreement, however, is far from being microscopically identical. Depending on the model, momentum is taken from the valence quarks and deposited in the sea or vice versa. Observable differences among the models for other experimental quantities therefore follow. This is where a precise experimental measurement of the A-dependence of the Drell-Yan (DY) process can have significant impact.

C. A-DEPENDANCE IN THE DRELL-YAN PROCESS

In the parton model the DY cross section has the familiar form

$$\frac{d^2\sigma}{dx_1 dx_2} = K \frac{4\pi\alpha^2}{9s} \frac{1}{x_1 x_2} \left[\sum_f e_f^2 [q_f(x_1)\bar{q}_f(x_2) + \bar{q}_f(x_1) q_f(x_2)]\right] \quad , \tag{1}$$

where x_1 and x_2 are respectively the beam and target quark momentum fractions, and K is a factor of order 2 whose magnitude is given by 2nd-order QCD corrections[14] (we suppress the Q^2 dependance of the structure functions for simplicity). Theoretical issues associated with A dependence in the DY process are summarized in Appendix 1. For the proton-induced DY process one can emphasize the first term, corresponding to beam valence-quark, target sea-antiquark annihilation by requiring $x_1 >$

x_2 ,ie. $x_F = x_1 - x_2$ greater than 0., (the forward hemisphere). Detailed discussions of many of the motivations for studying the A dependence of the DY process are found in Refs.7, 8, 15-17. Specifically for the purpose of event rate estimates presented later we choose $x_1 \gtrsim x_2 + .2$, or equivalently, $x_F \gtrsim 0.2$. With this condition the A dependent ratio of DY cross sections is roughly[7]

$$R_{DY} = \frac{\sigma^{pA}}{\sigma^{pN}} \approx \frac{\sum_f e_f^2 q_f^P(x_1) \bar{q}_f^A(x_2)}{\sum_f e_f^2 q_f^P(x_1) \bar{q}_f^N(x_2)} \quad , \qquad (2)$$

where N denotes deuterium, and A denotes Calcium in this experiment. Further simplification arises from the dominance of the charge of the u quark over that of the d quark. Indeed, in our proposed kinematic acceptance, more than 3/4 of the predicted cross section in Eq. 1 arises from the $u\bar{u}$ annihilation term (see Table 1),therefore:

$$R_{DY} \approx \frac{\bar{u}^A(x_2)}{\bar{u}^N(x_2)} \quad . \qquad (3)$$

Thus the A dependence of proton-induced DY at $x_F \gtrsim 0.2$ is sensitive to the change of the anti-u-quark distribution in going from free to bound nucleons. This is clearly complementary to deep-inelastic scattering where an incoherent sum of quark and antiquark (and hence valence and sea) effects is measured.

The impact of this proposal on "EMC" physics is clear from Fig.3, which shows the prediction of R(DY) for two models which reproduce the EMC effect along with statistical errors achievable with the E605 spectrometer with four months of running time. Also shown are the current data available for the quantity

$$[(\bar{u} + \bar{d})/2 + \bar{s}]^{Fe}/(\bar{d} + \bar{s})^{P} \qquad (4)$$

from neutrino and antineutrino reactions on Fe and hydrogen targets.

Clearly proton-induced DY can provide significant evidence about possible enhancement or depletion of the nuclear antiquark sea.

D. EXISTING STUDIES OF DRELL-YAN A-DEPENDANCE

There have been several studies of the A-dependence of the DY process induced by both protons[18] and pions.[19,20] With the exception of the NA3 data for antiprotons on hydrogen[19], these experiments have compared light and heavy metallic targets, with the A dependence parameterized as:

$$\sigma = \sigma_0 A^{\alpha} \quad . \qquad (5)$$

As is evident in Figs.4 and 5, the existing experimental errors are too large to address the existence of an EMC effect in DY. In both the proton data with $x_F = 0.$ and the pion data where both terms of Eq.1 enter with comparable size, the A dependence of the DY process should resemble the EMC effect (due to contributions by both quarks and antiquarks in the target).

E. EXPERIMENTAL DETAILS

The E605 configuration during the 1985 dimuon run is almost ideal for this measurement. Indeed, at the end of the 1985 running, we took a few hours of data in almost an identical setting to what we are now proposing. The lack of targets of different atomic mass prevented us from obtaining preliminary A-dependance measurements at that time. The data we did take have enabled us to make accurate estimates of our intensity capabilities as well as the size of the pion decay backgrounds which can contaminate dimuon measurements at lower masses.

In detail, we propose the following changes to the present E605 setup shown in Figure 6:

TARGET: - We request the reinstallation of the cryotarget refrigerator used in our 1984 hadron running. A larger 20 inch long by 4 inch diameter deuterium flask will be needed. We envision suspending a distributed calcium target from the deuterium flask thereby enabling easy alternation between the two nuclear targets and empty target running. (Note, the existing target mechanism has provision for remote vertical movement.) We plan on varying the target about once an hour.

DUMP: - The water cooled proton beam dump in the large analysing magnet SM12 is 12 inches thick vertically. Removal of the outside 2 inch thick pieces will yield an 8 inch thick dump and much improved acceptance for forward dimuons.

ABSORBER: - In 1985 our absorber consisted of a 4 foot thick lead wall located at the downstream end of SM12. In order to reduce the effect of pion decays, we will rebuild this absorber wall coincident with the downstream end of the proton beam dump (see Figure 6a.) and follow it with 6 feet of borated polyethylene to help suppress the neutron flux from the dump. Based on the observed yield of like sign dimuons in the 1985 test run we estimate a residual pion decay contamination of less than 10 percent. The simultaneous measurement of like-sign and unlike-sign dimuons then enables a subtraction of the remaining contamination.

SPECTROMETER: - Except for small changes in the trigger hardware and software, the spectrometer will remain the same. The test data taken in 1985 indicates that some improvements in the efficiency and rejection of the trigger are available. The most important consequence of this will be the reduction in the calendar and CPU time needed to analyse the results.

MAGNETS: - By running the first target magnet, SM0, in the opposite polarity to the main focussing magnet, SM12, forward dimuon pairs are bent around the dump enhancing the acceptance for $x_F > .2$ events. Running the third magnet, SM3 reversed then enhances the low mass, ie. low x_2, acceptance.

F. ESTIMATED RUNNING TIME

The test data taken in 1985 convince us that we can record dimuons comfortably at an intensity of 2.E12 protons per 20 second spill. The event yields indicated in Fig.3 and in Table 1 are based on an integrated exposure of 1.2E17 protons, half on deuterium and half on calcium. The yields are sufficient that in the x_2 bins below about .2 the deuterium/calcium ratio will be dominated by the systematics of intertarget normalization which we assume (based on past experience with the beam monitoring in MEast) we can keep to +/- 1 percent.

It was our experience in 1985 that during the second half of the run, ie. after the Tevatron had settled down, we averaged 1.E16 protons per week at an average intensity of 2.E12 per pulse. Therefore we request 12 weeks for data taking (at 2.E12 protons per pulse) and an additional 4 weeks to cover target out runs, trigger setup, spectrometer checkout, etc.

G. MANPOWER AND SUPPORT

It is apparent to the members of the 1985 E605 collaboration that many of the critical skills needed to operate our spectrometer would not be available in 1987. This is due to the usual movement to other projects of the talented young scientists that drive such a large device. The Los Alamos contingent of the present proposal has agreed to supply critically needed Electrical Engineering support to replace Columbia Univ. support of the E605 data acquisition electronics. Also, if this proposal is approved, a graduate student and a postdoctoral scientist will be added by the FNAL and Stony Brook contingent. The Los Alamos group has promised financial support for electronics, travel, analysis, etc., and the FNAL and Stony Brook collaborators expect support consistent with the operating levels needed in 1985 and 1986.

The FNAL support needed for the Deuterium target modifications is estimated to be $50,000. The mechanical modifications of the SM12 dump and absorber are estimated to cost less than $25,000.

We believe that the necessary modifications and routine maintenance needed to ready the E605 apparatus for this proposed measurement can be done by the beginning of the next fixed target run if preliminary approval is given by the Spring 1986 PAC.

Appendix 1 - THEORETICAL CONSIDERATIONS

The past few years have seen considerable theoretical effort applied to the DY process. Here we briefly summarize two aspects relevant to the present proposal: (1) studies of the basic theory of the process in QCD, and: (2) issues connected to the propagation of the incident hadron through the nuclear medium.

The first issue is summarized in a recent paper by Altarelli, Ellis, and Martinelli:[21]

> "We have recently made[22] a theoretical reevaluation of the QCD description of lepton pair production in hadron-hadron collisions. A full treatment of the complete transverse momentum, q_T, dependence was given including the large amount of theoretical information about this process which has been accumulating over the last few years. The resulting q_T and y distribution reproduces the correct perturbative behavior[23] at large q_T and contains the soft gluon exponentiation at leading[24] and next-to-leading[25,26] double logarithmic accuracy. Upon integration over q_T it reproduces the known perturbative results[27] for the total cross section and rapidity distribution dsigma/dy (including the terms of order alpha-strong which give rise to the "K-factor")."

For the purpose of the present proposal, detailed calculations indicate that the parton-model expression for the cross section is a reliable guide provided one employs appropriately evolved quark distribution functions $q(x) \to q(x,m^2)$. For small values of x_2 (Fig. 3) where cross sections are largest it will be feasible to use a binning in x_1 such that the Q^2 interval represented is not too large (recall $Q^2 = M^2$

$= x_1*x_2*s$). Thus scaling changes should be readily handled.

The second issue deals with the effect of the nuclear matter on the passage of the incident proton, and the validity of the factorized form of the DY process for heavy targets. Hard scattering processes such as DY pass this test beautifully. Bodwin et al.[28] and Collins[29] derive the condition for the applicability of factorization. Collins' version is:

$$M^2 > (1\ \mathrm{GeV}^2)x_2A^{1/3} \quad . \tag{6}$$

Since we require $M > 4$ GeV in order to be above the charmonium resonances, this requirement is met easily in this proposal. Bodwin et al. foresee some effect of initial state interactions on the transverse momentum distribution of the muon pair due to multiple elastic scattering (at the quark level). Although no evidence of this has been seen yet experimentally,[20] one needs only to integrate over q_T to eliminate the effect. Finally, the essentially linear A dependence of DY measured thus far[18] is a qualitative confirmation that the above ideas are correct.

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TABLE 1 :- Acceptance in the x_1-x_2 plane.
a) The mass of the dimuon pair produced.
b) The fraction of the cross section due to $u\bar{u}$ annihilation.
c) The number of events expected on each target.

x_1 ↓ \ x_2 →	.03–.07	.07–.11	.11–.15	.15–.19	.19–.23	.23–.27	.27–.31	.31–.35	.35–.39
.20–.25	a) b) c)								
.25–.30			7.8 0.75 6.5K	8.9 0.70 5.2K					
.30–.35		7.0 0.84 8K	8.4 0.81 12K	9.7 0.77 10K	10.7 0.72 4K				
.35–.40	5.6 0.89 10K	7.5 0.88 23K	9.1 0.85 16K	10.4 0.83 10K	11.5 0.79 4000	12.6 0.74 1600	13.5 0.68 150		
.40–.45	6.0 0.91 20K	8.0 0.90 26K	9.7 0.89 15K	11.0 0.87 5K	12.3 0.84 2500	13.4 0.81 900	14.4 0.76 350	15.4 0.71 75	
.45–.50	6.3 0.92 15K	8.5 0.92 18K	10.2 0.91 10K	11.7 0.90 4K	13.0 0.88 1800	14.2 0.86 600	15.3 0.83 220	16.3 0.79 110	17.2 0.74 16
.50–.55	6.7 0.94 6K	8.9 0.93 12K	10.7 0.93 5K	12.3 0.92 2K	13.6 0.91 1100	14.9 0.89 440	16.0 0.87 150	17.1 0.85 60	18.1 0.81 18
.55–.60	7.0 0.94 3K	9.3 0.94 5K	11.2 0.94 2.4K	12.8 0.93 1500	14.3 0.93 560	15.6 0.92 260	16.8 0.91 110	17.9 0.89 36	19.0 0.87 12
.60–.65	7.3 0.95 400	9.7 0.95 1800	11.7 0.95 1300	13.4 0.95 780	14.9 0.94 360	16.2 0.94 150	17.5 0.93 55	18.7 0.92 20	19.8 0.91 6
.65–.70	7.5 0.96 150	10.1 0.96 700	12.2 0.96 500	13.9 0.96 380	15.5 0.95 180	16.9 0.95 70	18.2 0.95 30	19.4 0.94 10	20.5 0.93 3

Figure Captions

Fig. 1. The ratio (A-corrected) of F_2 structure functions from deep inelastic charged-lepton scattering from iron and deuterium (Refs. 1-3).

Fig. 2. The ratio of F_2 structure functions from deep inelastic neutrino scattering from iron and hydrogen (Ref. 6). The curves are calculations of various models of the EMC effect discussed in the text (calculations described in detail in Ref. 8).

Fig. 3. The antiquark ratio of Eq. 2 (for iron and deuterium cross sections). The square points are the quantity described by Eq. 4 derived from ν and $\bar{\nu}$ measurements of the F_3 structure function (Ref. 6). The round points are the estimated errors obtainable for the present experiment. The calculations from Ref. 7 use two models which reproduce the EMC effect (dashed - pion excess model; solid - rescaling model).

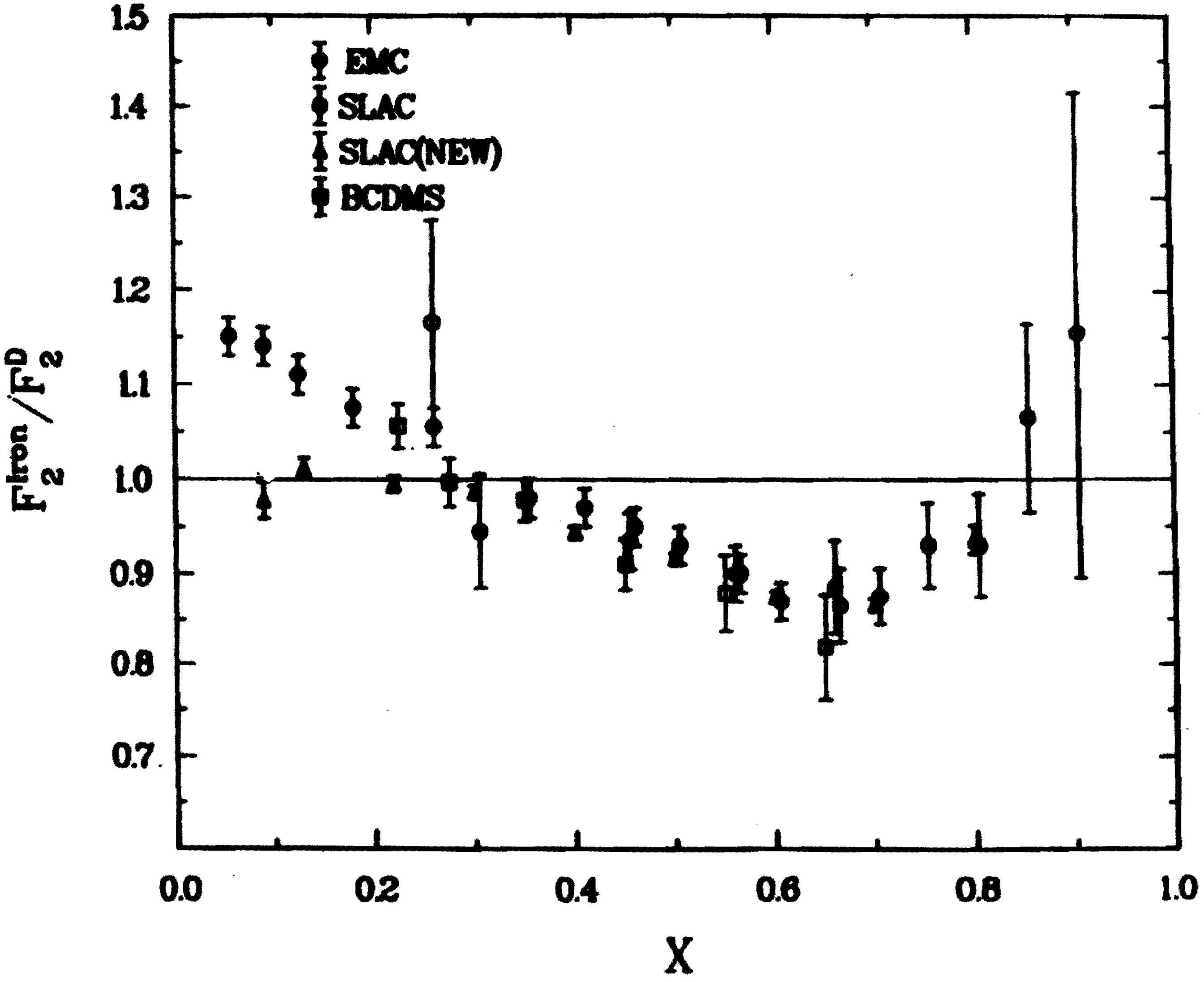
Fig. 4. The A dependence of the Drell-Yan process from 400 GeV proton-nucleus interactions (Ref. 18) plotted as a function of x_2 (target). The dashed line is the α corresponding to the original low-x EMC effect.

Fig. 5. The A dependence of the Drell-Yan process from 225 GeV π^--nucleus interactions (Ref. 20). The dashed line is the α corresponding to the original low-x EMC effect.

Fig. 6. Event display, 1985 test data, 5 GeV Drell-Yan dimuon pair:

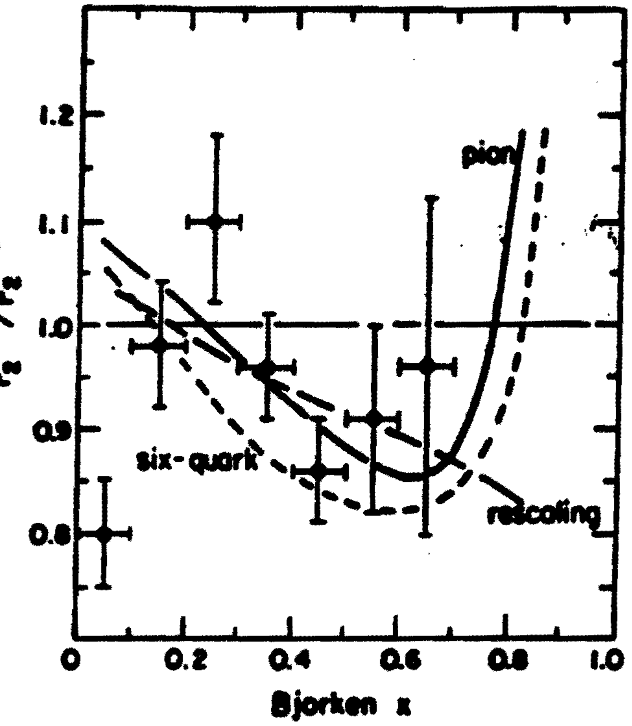
a). Elevation view, proposed location of the absorber is shown dotted.

b). Plan view, note transverse kick of the magnets, SMO deflects the forward going muons around the beam dump.



EMC
SLAC
SLAC(NEW)
BCDMS
F_2^{Iron}/F_2^D
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.0
0.2
0.4
0.6
0.8
1.0
X

Figure 1.



1.2
1.1
1.0
0.9
0.8
$F_2^{D^3He}/F_2^{D^2H}$
0
0.2
0.4
0.6
0.8
1.0
Bjorken x
pion
six-quark
rescaling

Figure 2.

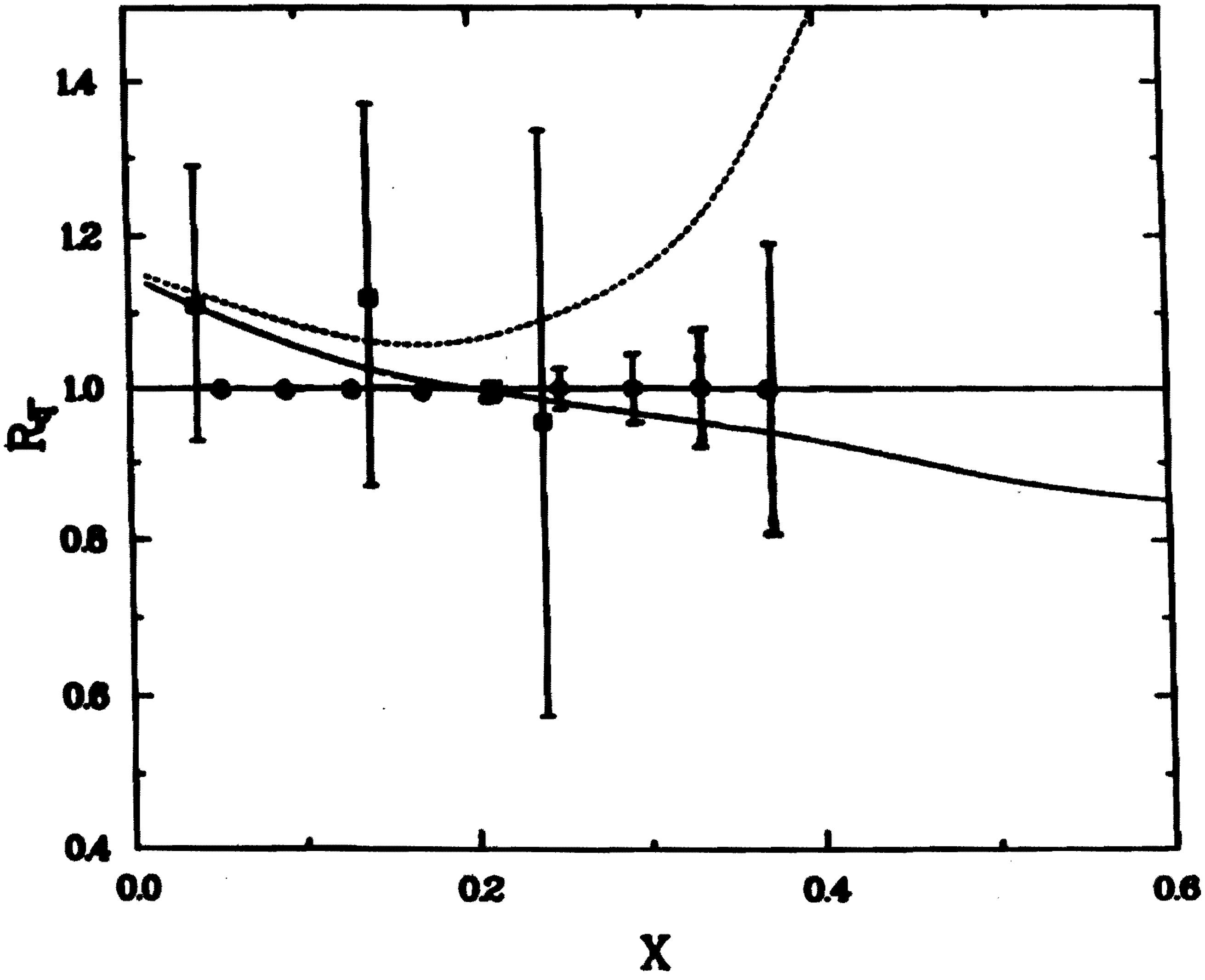


Figure 3.

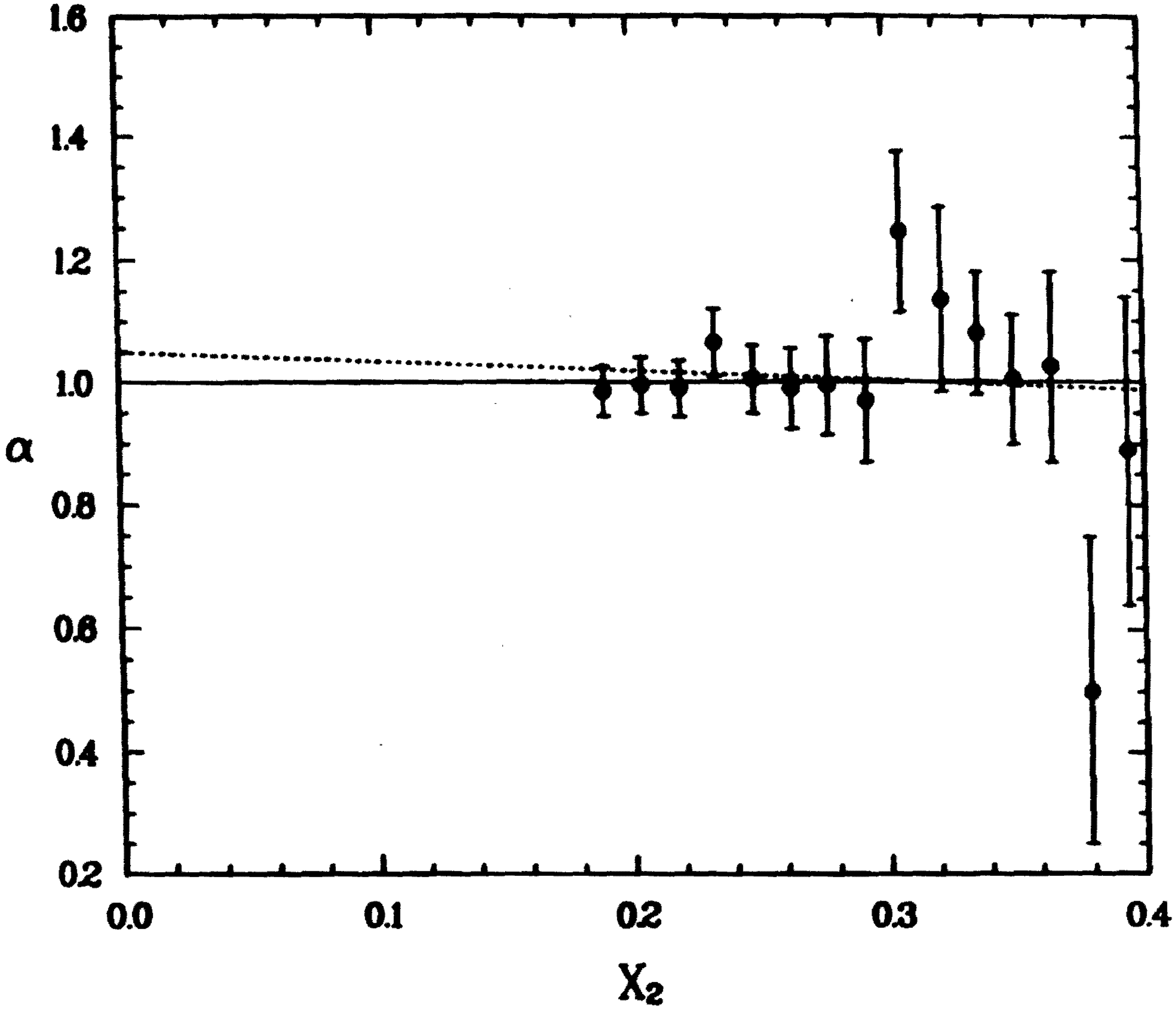


Figure 4.

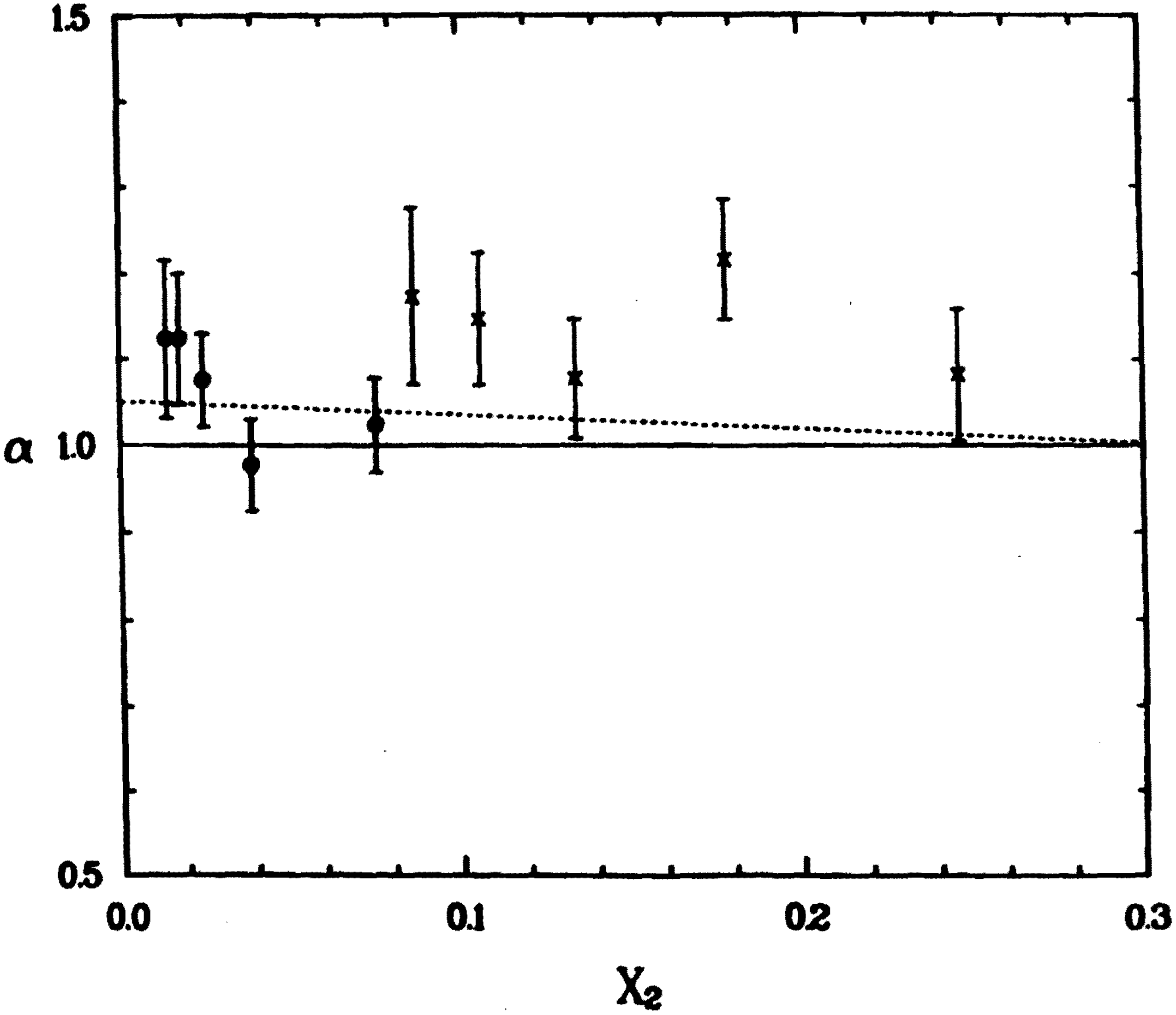
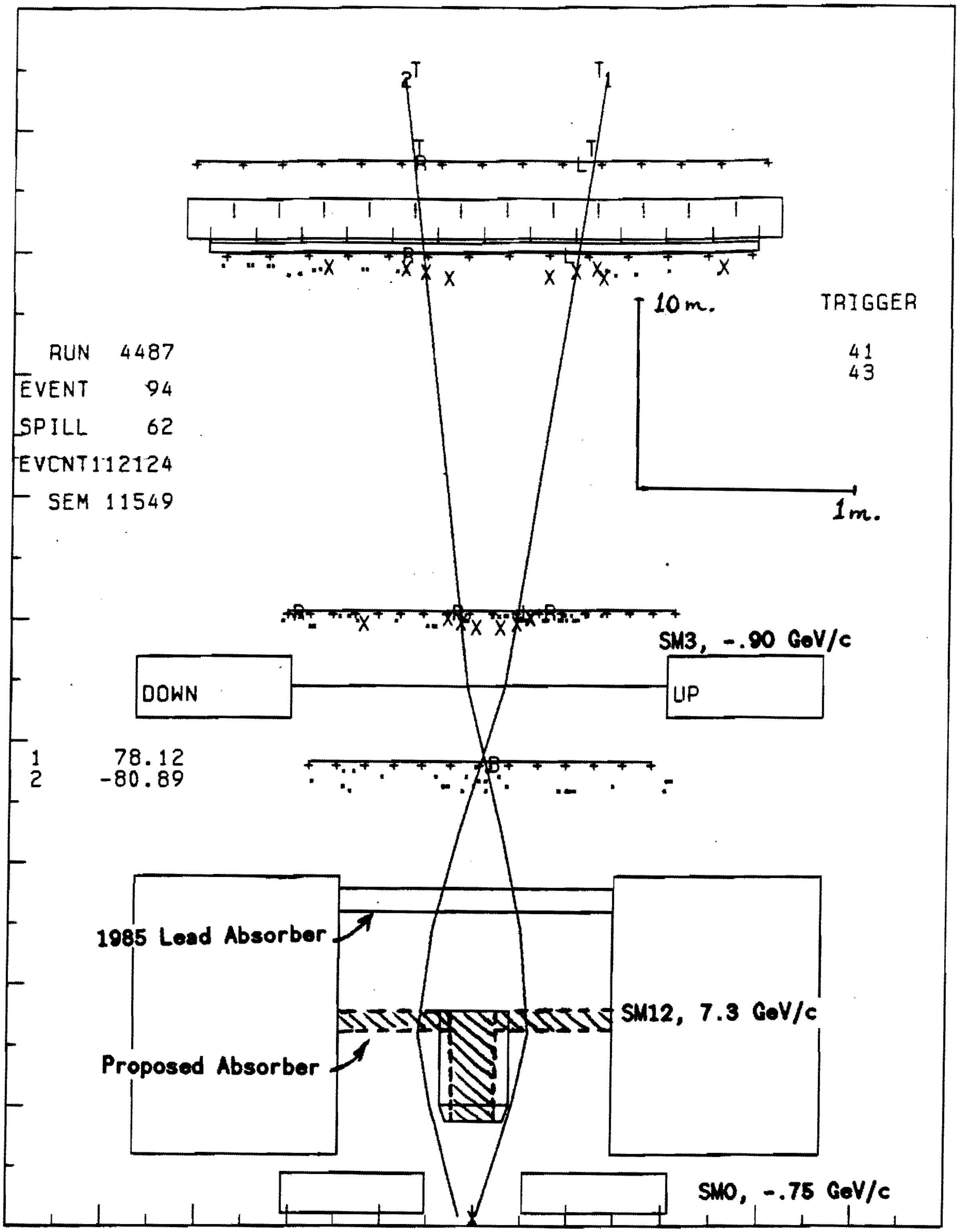


Figure 5.



T2
T1
TRIGGER
41
43
10m.
1m.
RUN 4487
EVENT 94
SPILL 62
EVCNT112124
SEM 11549
SM3, -.90 GeV/c
DOWN
UP
1 78.12
2 -80.89
1985 Lead Absorber
SM12, 7.3 GeV/c
Proposed Absorber
SM0, -.75 GeV/c

Figure 6a..

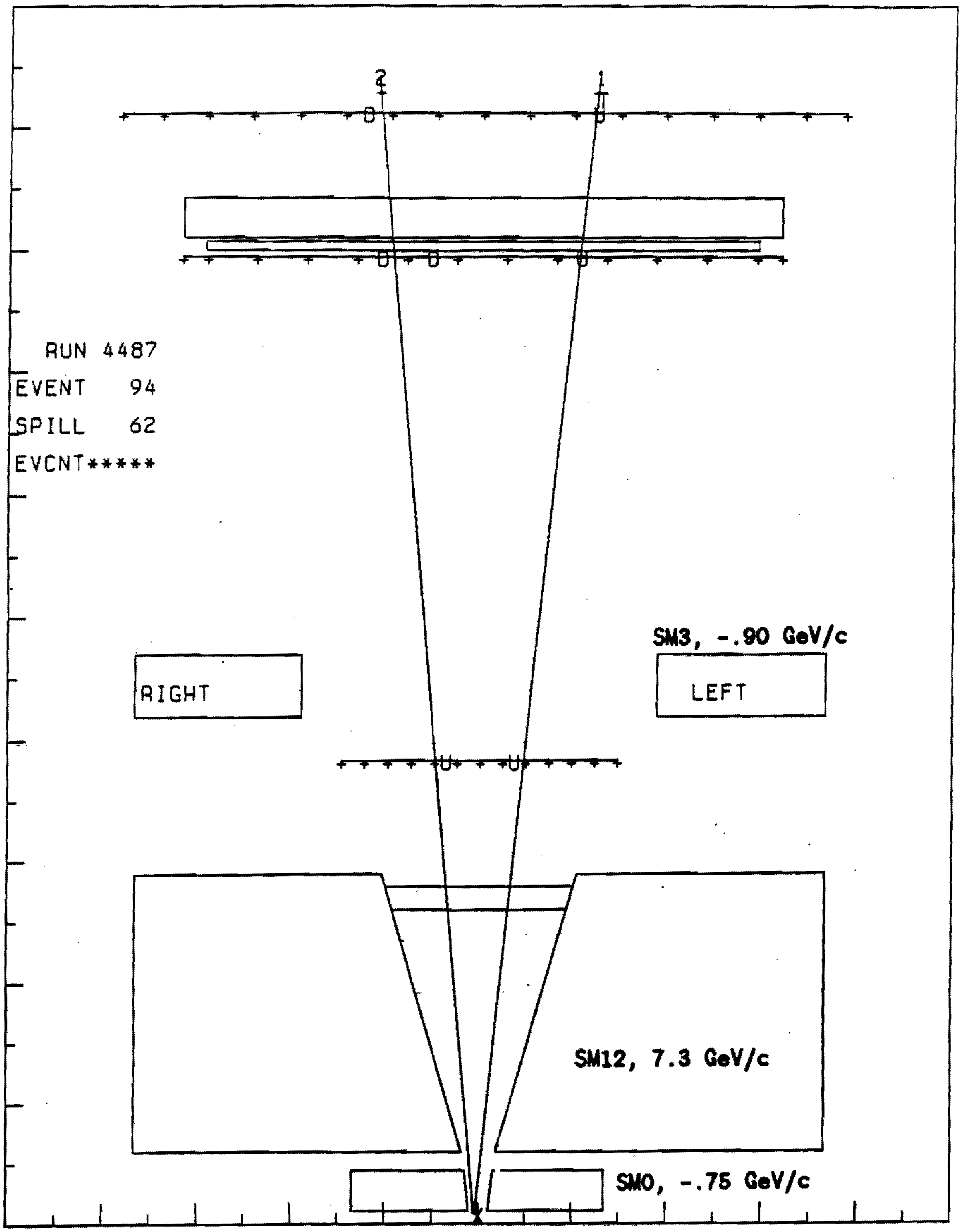

2
1
RUN 4487
EVENT 94
SPILL 62
EVCNT*****
SM3, -.90 GeV/c
RIGHT
LEFT
SM12, 7.3 GeV/c
SM0, -.75 GeV/c

Figure 6b.