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High Luminosity Muon Scattering at FNAL*

K. Bazizi[1], J. Conrad[2], M. Erdmann[3], G. Fang[2], D. Geesaman[4], C. Guyot[5], H. Holmgren[6], H. Jackson[4], A. Malensek[7], H. Melanson[7], J. Morfin[7], R. Nickerson[8], H. Schellman[7], M. Virchaux[5]

[1]*University of California at Riverside, Riverside, California 92521*
[2]*Harvard University, Cambridge, Massachusetts 02138*
[3]*University of Freiburg i.Br., D-7800 Freiburg, Germany*
[4]*Argonne National Laboratory, Argonne, Illinois 60439*
[5]*Centre d'Etudes Nucleaires, Saclay, F-91191, Gif-sur-Yvette, France*
[6]*University of Maryland, College Park, Maryland 00742*
[7]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510*
[8]*Oxford University and Queen's College, Oxford, England*

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High Luminosity Muon Scattering at FNAL

Report of the Study Group on Future Muon Scattering Experiments

at the Workshop on Physics at Fermilab in the 1990's

Breckenridge, Colorado • August 15-24, 1989

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ABSTRACT

The charge of this group was to evaluate the physics that can be done with a high luminosity μ scattering experiment at FNAL using the upgraded Tevatron muon beam, and consider the apparatus required. In this report,

- The physics that can be accomplished with a high luminosity μ scattering experiment is evaluated.
- The CERN and FNAL μ beams are compared in the context of such an experiment. The expected muon flux with the upgraded machine is estimated.
- Two possible detectors are compared: the air-core toroid experiment proposed by Guyot *et al.* (1), and an upgraded version of the E665 double-dipole apparatus now in place at FNAL (2). The relative costs of the detectors are considered.
- A list of detailed questions that need to be answered regarding the double-dipole experiment has been compiled.

[1] University of California at Riverside
[2] Harvard University
[3] University of Freiburg i.Br.
[4] Argonne National Laboratory
[5] DPhPE, CEN Saclay
[6] University of Maryland
[7] Fermi National Accelerator Laboratory
[8] Oxford University and Queen's College, Oxford

I. SUMMARY OF THE RESULTS

This section is a summary of the more detailed discussions in the following pages.

PHYSICS

There are two basic motivations for doing a high precision, high luminosity μ scattering experiment. The first is to enable precision tests of QCD. The predicted running of α_s with Q^2 can be observed and disentangled from higher-twist terms within a single experiment. Λ_{QCD} can be measured to $\sim$ 10 MeV using scaling violations. In addition Λ_{QCD} can be measured using the pure non-singlet $F_2^p - F_2^n$ state. The QCD predictions for the variation of R with x_{Bj} can be tested at high Q^2 (> 20 GeV^2).

The second motivation is "community service measurements." F_2 can be measured with high precision. The F_2^n/F_2^p ratio can be remeasured with reduced systematic errors and the difference between neutrino and muon data addressed. Gluon distributions can be extracted using longitudinal structure function measurements, J/ψ production, and the traditional singlet fits to F_2. Multimuon capability will also allow a measurement of the mass of the charmed quark.

BEAM

The FNAL beam is well suited to the experiment under consideration. The final restriction on beam intensities comes from systematic problems in the detectors. The FNAL beam has three advantages over the CERN beam. It can achieve higher beam energies (up to 600 GeV vs. 300 GeV); it can deliver 2.5 times as many muons per unit time at a given beam energy when the instantaneous muon flux is limited by the detector; the machine RF is 53 MHz making the bucket structure easier to utilize (compared with 100 MHz at CERN after the upgrade). It is clear that FNAL is the best place to do a high precision, high luminosity μ experiment.

DETECTOR

Two basic detector configurations are considered: an air-core toroid (Figure 1) and a double-dipole (Figure 2). The prime consideration is the difference in systematic effects in the two possible detectors. Many systematic problems are common to both designs, the following are identified as significantly different:

- For a given beam energy the acceptance of the toroidal arrangement remains flat over more than twice the Q^2 range of the double-dipole. The dipole experiment would have to utilize data where the experiment has reduced acceptance to have a comparable Q^2 range to the toroid. Furthermore, the acceptance of the double-dipole varies with the position of the vertex within the target. The toroid has flat acceptance for all scattering positions within the target.

- Pattern recognition in the toroidal apparatus is helped by the fact that opposite sign hadrons are swept out, and the detector is intrinsically "phi" symmetric. It is believed that pattern recognition with very high efficiency is possible in the double-dipole experiment, provided that sufficient redundancy in chambers is implemented. Data exists which should allow the pattern recognition problems in the dipole to be understood.

- The air-core toroid has no magnetic material, which allows precise computation of the magnetic field to complement the measured field map. In the dipole experiment the fields, including the fringe fields, must be measured with no corroborating calculations possible. The required accuracy of the measurement of the dipole field is 1 part in 10^4.

- In the major part of the useful acceptance of the dipole apparatus there is no material. The coils of the toroid are in the acceptance of the experiment, restricting the maximum acceptance to 60%. The effect of this has been extensively studied and is not considered a problem.

In the case of the double-dipole experiment the trigger is relatively straightforward. Data exists which will allow a detailed understanding of how it will perform. A conceptual design for an efficient trigger in the toroidal experiment has also been proposed, but background rates are not yet completely understood and a detailed design remains to be completed.

CONCLUSIONS

A high luminosity, precision, μ scattering experiment should be done at FNAL in the 1990s. Such an experiment will allow precision tests of QCD. It would also contribute significantly to the accuracy with which F_2 is known and to understanding parton distributions.

The target length in the double-dipole experiment is restricted to 10 m. With a 10 m target, 500 GeV beam and using the entire target length, the acceptance remains flat at 100 % over the Q^2 range of 4 GeV^2 to 100 GeV^2 and x_{Bj} from 0.01 to 1.0. Questions relating to systematic effects in pattern recognition remain, and will be addressed using existing E665 data. The multimuon physics (J/ψ production, charm quark mass) can only be done with the double-dipole geometry. An estimate of the cost of the apparatus, an upgrade to E665, is $4M.

The air-core toroid apparatus can use a 25 m target. With a 25 m target and a beam energy of 500 GeV, the acceptance is flat at 60% over a Q^2 range of 60 GeV^2 to 500 GeV^2 and an x_{Bj} range of 0.1 to 1.0. With an upstream target of reduced length, the Q^2 range is 10 GeV^2 to 100 GeV^2 and the x_{Bj} range 0.01 to 1.0. Magnetic sweeping and phi-symmetric segmentation simplifies event geometry and helps with pattern recognition. With a heavy target, hadron absorption in the field-free region helps pattern recognition, but further study is needed in the case of light targets. The trigger also needs further study. A cost estimate for the air-core toroid is $15M, a large fraction of which could be borne by European labs. In addition $10M in new detectors would be needed.

The design of the air-core toroid also has applicability to neutrino experiments currently under consideration, and resembles one configuration being considered for forward muon detection at the SSC.

With the exception of J/ψ, charm mass, and perhaps low x_{Bj} physics, it is the conclusion of this working group that the air-core toroid is clearly the superior apparatus and this is the experiment that is recommended to address the physics in question. The primary restriction in the case of the double-dipole is acceptance at high Q^2. Several potential systematic problems in the dipole experiment remain to be studied in more detail. In order to do the experiment with a double-dipole, longer running time would be required and heavy targets might be necessary for some physics topics. Detailed Monte Carlo studies are needed to ascertain the feasibility of the dipole experiment.

II. PHYSICS OBJECTIVES OF THE EXPERIMENT

This section describes the physics objectives of a high luminosity, high precision experiment and required statitistics to attain these goals. The following physics items are considered as the priority objectives for a future μ scattering experiment:

1. $\alpha_s(Q^2)$, precise measurement of $\Lambda_{\overline{MS}}$, higher twist
2. F_2, F_2^p, $F_2^p - F_2^n$, F_2^n/F_2^p
3. $G(x_{Bj}, Q^2)$, $R = \frac{\sigma_L}{\sigma_T}$, charm mass.

The physics outcomes refer to a 9-month run at FNAL with the muon beam running mostly at 500 GeV energy with a rate of $\sim$ 25 MHz with 50% efficiency. This corresponds to $\sim \times 10^{14}$ muons on target. The following numbers assume a 25 m long target.

As a comparison, the highest statistics collected up to now on an H_2 target (25 m long target of BCDMS) corresponds to $\sim 2.5 \times 10^{13}$ μ (at 300 GeV). Given a slight increase of 20% of the cross section at a given (x_{Bj},Q^2) when going from 300 GeV to 500 GeV, it results in an increase by a factor $\sim$ 5 of the statistics compared to BCDMS H_2 data, i.e. $\sim 1 \times 10^7$ events ($x_{Bj} > 0.05$, $Q^2 > 10$ GeV^2) or $\sim 3.5 \times 10^6$ events ($x_{Bj} > 0.25$, $Q^2 > 10$ GeV^2).

PRECISE MEASUREMENT OF F_2 YIELDING α_s AND $\Lambda_{\overline{MS}}$

Given the present experimental errors and theoretical uncertainties, no single experiment has measured the variation of α_s with Q^2. Such a measurement, as well as a precise determination of $\Lambda_{\overline{MS}}$ would be of great importance when considering predictions from Grand Unified Theories. References (1) and (3) provide an overview of the present evidence for the running of α_s. This evidence comes from the combined data of various e^+e^- experiments. One aim of a new deep inelastic μ scattering experiment should be the observation of the Q^2-variation of α_s within a single experiment and the precise measurement of $\Lambda_{\overline{MS}}$.

Following reference (1), a 1-month run at FNAL using a carbon target would provide $\sim 20 \times 10^6$ events ($x_{Bj} > 0.25$) i.e. $\sim 6 \times 10^6$ events ($x_{Bj} > 0.05$) leading to the measurements of F_2 shown on figures 3a and b (only 2 high x_{Bj} bins are shown).

Assuming no higher twist above $Q^2 = 20$ GeV^2, a non-singlet analysis of these data for $x_{Bj} > 0.25$ would demonstrate the running of α_s with a significance of 8σ using a singlet analysis of the data. Assuming a glue behaving like $(1 - x_{Bj})^7$ at large x_{Bj} does not appreciably change this result. Figure 4 shows the approximate statistical errors one expects from running for two months to at Fermilab with a 20 m carbon target. The significance of measuring α_s using this method is discussed in more detail in the appendix.

The same significance without assuming the absence of twist-4 terms would be obtained with additional runs at low muon energy down to $Q^2 = 5$ GeV. This would allow at the same time a measurement of the twist-4 term for each x_{Bj} bin.

These analyses would lead to a determination of $\Lambda_{\overline{MS}}$ with a 3 MeV statistical error and a total error < 10 MeV (for $\Lambda_{\overline{MS}} = 200$ MeV).

Assuming 1×10^{14} μ on a H_2/D_2 target, one loses a factor 5 in statistics over the previously discussed measurement on carbon. Still, the running of α_s could be demonstrated with a 4σ significance and $\Lambda_{\overline{MS}}$ could be measured with a statistical accuracy of 7 MeV.

MEASUREMENT OF F_2^p, F_2^n, $F_2^p - F_2^n$

Currently, there is disagreement among measurements of the u and d quark distributions from lepton scattering experiments (4). In order to make any predictions for physics at future hadron colliders, these quantities must be well known, particularly at low x. Measurement of $F_2^p - F_2^n$, a non-singlet structure function, provides another method of measuring $\Lambda_{\overline{MS}}$ which is entirely independent of the gluon distribution.

Compared to the single measurement of F_2^p, there is a loss in the statistical error by a factor 10 to 3 for $x_{Bj} = 0.2$ to 0.8. However, in principle, one could include the low x data in the fit, since the gluon distribution does not contribute. A non-singlet fit analysis of $F_2^p - F_2^n$, assuming 1×10^{14} μ on the H_2 and D_2 targets, would give a determination of $\Lambda_{\overline{MS}}$ with a statistical error of $\sim$ 40 MeV. The systematic error would depend on how well the two data sets can be normalized and on the knowledge of the deuterium density.

DETERMINING $R = \frac{\sigma_L}{\sigma_T}$, $G(x_{Bj}, Q^2)$ AND THE CHARM QUARK MASS

$R = \frac{\sigma_L}{\sigma_T}$, $G(x_{Bj}, Q^2)$ and m_C are fundamental measurements which are interesting at low x_{Bj}. The most recent measurement of R by Experiment 140 at SLAC (5) is consistent with the prediction of QCD if target mass corrections are included, but not conclusive. R must be measured in the region of $x_{Bj} < 0.2$, where the variation is largest. Measuring R at low x_{Bj} allows one to directly measure $G(x_{Bj}, Q^2)$ as described in reference (6). This gives a measure of the three-gluon coupling.

The traditional method of obtaining $G(x_{Bj}, Q^2)$ in deep inelastic scattering, using the Altarelli-Parisi equations to fix Λ at high x_{Bj} has large systematic errors and poorly constrains the fit (4). However, extracting $\Lambda_{\overline{MS}}$ from the pure non-singlet structure function, $F_2^p - F_2^n$, eliminates this error.

A study of dimuons and J/ψ production could give another contribution to the determination of the glue if it is assumed to proceed via photon-gluon fusion. This could also provide valuable information on the knowledge of the charm quark mass. The measurement requires a calorameter target.

The ratio R can be determined accurately by comparing the cross sections at the same (x_{Bj},Q^2) for different beam energies. For reduced systematics on this measurement, a very good control of the normalization of the data sets at different energies (at a level of $\sim$ 0.1%) is required together with a calibration of the magnetic spectrometer at a level of 10^4 [see reference (1)].

The determination of the gluon distribution function for $x_{Bj} > 0.05$ would make use of the combination of a singlet analysis of F_2^p and F_2^n (or F_2 carbon), a non-singlet analysis of $F_2^p - F_2^n$ and the value of R. A gain by a factor 5 on the size of the errors compared to the existing determinations (4) of the $G(x_{Bj}, Q^2)$ could be obtained. The high statistics and the low systematics at large x_{Bj} (non-singlet region) greatly reduce the correlation between the fitted value of $\Lambda_{\overline{MS}}$ and the glue.

III. COMPARISON OF MUON BEAMS AT FNAL AND CERN

The following discusses the μ beam requirements for obtaining the physics goals described in the previous section. A comparison is made between the CERN and FNAL beams. The yields of muons at FNAL are presented with and without the main injector upgrade. It is assumed that the existing beamlines at FNAL and CERN would be used. The number of protons needed to achieve optimum running is estimated.

Figure 5 shows a comparison of the FNAL and CERN μ/p ratios as a function of muon beam energy, in the case of FNAL both 800 GeV and 900 GeV proton curves are given.

The CERN rep. rate is 14.4s and the spill length is 2.2 s. The corresponding numbers for FNAL are 54 s and 20 s. The resulting duty factors are 15.3% for CERN and 37% for FNAL.

The mean number of muons that each beam can deliver per unit time, for a given number of protons per pulse (ppp), is determined by the μ/p ratio and the rep. rate. For example, at 300 GeV:

$$\text{CERN } \mu/\text{p} = 5 \times 10^{-6}$$
$$\text{FNAL } \mu/\text{p} = 1.5 \times 10^{-4}$$

The μ/p ratios are a factor of 30 different, and the CERN rep. rate is 3.75 times faster. Thus FNAL delivers 8 times more muons per second at 300 GeV than CERN. Similarly, at 220 GeV the rates are comparable and at 150 GeV the CERN rate is 4 times that of FNAL.

If the limitation on beam flux is the instantaneous rate, then the FNAL machine can deliver 2.5 times as many muons per second as CERN since its duty cycle is 2.5 times better. This is true at any energy at which the FNAL beam can reach the maximum flux rate. 1×10^{13} ppp yields an instantaneous rate of 32 MHz at 100 GeV at the FNAL beam. For a maximum instantaneous rate of 25 MHz, the rate at which muons can be delivered is therefore 2.5 times higher an FNAL for $E_\mu > 100$ GeV.

The length of runs can be the same at FNAL and CERN. A reasonable total number of used protons at FNAL is 3×10^{18} for a 9-month run with the machine upgrades. At CERN 10^{19} protons could be obtained in this length of run (but fewer muons, except at low muon beam energy and a high, >90 MHz, instantaneous rate).

Table 1 lists some possible integrated μ fluxes.

The FNAL beam preserves the RF structure of the Tevatron, which helps reduce the systematic errors from counting the number of useful muons. E665 experience shows that reconstruction efficiency for muons in singly occupied RF buckets is greater than 99.9%. There seems to be no "in principle" problem with reconstruction in doubly occupied RF buckets, so instantaneous rates of order 25 MHz are probably reasonable for the FNAL beam.

IV. COMPARISON OF THE AIR-CORE TOROID TO THE DOUBLE-DIPOLE APPARATUS

Two possible detectors have been considered. A superconducting air-core toroid apparatus, figure 1, and a double-dipole open geometry configuration, figure 2. The air-core toroid is a new detector based on the BCDMS apparatus and specifically optimized for the experiments in question. The double-dipole apparatus is based on the E665 apparatus currently installed in the NM beamline at the Tevatron. E665 was designed to study final state hadrons and was not optimized for structure function measurements. A new experiment would utilize much of the equipment from E665.

This section is divided into the following topics:

- Description of the air-core toroid
- Description of the double-dipole
- Comparison of acceptance
- Discussion of triggers for the experiments
- Comparisons of costs and manpower

THE AIR-CORE TOROID APPARATUS

The air-core toroid experiment is described in detail in reference (1). Figure 1 shows the layout of the experiment. It consists of several modules, each of which has eight superconducting coils arranged as shown in the figure. The magnetic field is then approximately toroidal. The scattered muon (and hadrons) are tracked through the coils using planes of 2 mm wire spacing proportional chambers. The total length of the coils is 30 to 40 m. The momentum resolution of the spectrometer is 0.5%, independent of energy. The target is placed on the axis of the toroid, in the field free region. Hadrons of opposite sign to the muon are quickly bent out of the acceptance of the experiment and same sign hadrons are frequently absorbed in the case of a dense target. Triggering is based on detection of muons behind a steel absorber located at the end of the experiment.

THE DOUBLE-DIPOLE APPARATUS

The dipole apparatus would be closely related to the existing apparatus in E665, described in reference (2). Figure 2 shows the detector arrangement. Reference 6 describes the existing equipment. The exact arrangement of chambers in the dipole remains to be determined via detailed Monte-Carlo study, the following is a possible configuration.

All of the Cherenkov counters from E665 would be removed. This is especially important in the case of the RICH counter which is a substantial fraction of a radiation length. The target is located upstream of the first dipole magnet and is five 2 m long targets. Between each target are 1 mm MWPCs in the beam region and a jet chamber system at larger angles. Inside the first dipole magnet is a 50 plane jet chamber. Between the two dipoles are the existing 12 planes of 3 mm wire spacing MWPCs and 10 new planes of 2 mm pitch MWPCs. Fifteen existing planes of 2 mm pitch chambers are located in the upstream part of the second dipole aperture and 10 new planes with larger aperture are added in the downstream part of magnetic field and at wide angles in the bend view of the magnetic field. The existing 16 planes of drift chambers are left in place, with an increased hole size in the central region. This hole is covered with 10 new planes of 1 mm pitch MWPCs. Between the two banks of existing drift chambers, 15 new planes are added.

The large increase in chamber plane redundancy is expected to enable very efficient pattern recognition. The new chamber planes may be constructed with some form of azimuthal symmetry, similar to that proposed for the air-core experiment.

In the experiment with the double dipole spectrometer, it will be necessary to map the spectrometer fields including fringe field regions to about 1 part in 10^4. Field maps in open magnet geometries over large volumes, if not routine, are state of the art at a precision and stability of a part in 10^4 with position resolution no poorer than 0.0025 cm. Multi-meter volumes of non-uniform field are frequently mapped with Hall probes calibrated against NMR to a precision of 10^{-4} at a position resolution of 0.00125 cm. For measurements with many mesh points requiring an extensive measurement schedule, search coils can be used in place of Hall probes. Data can be accumulated more rapidly with equivalent precision, and the added advantage of sensitivity to the multipole composition of the field. For the E665 spectrometer the effort required to obtain the requisite field map will be determined by the configuration and step size of the measurement mesh required to insure that the field integral on particle trajectories is determined with the required precision, *i.e.* in the range $10^{-3} - 10^{-4}$.

The trigger for the dipole experiment would closely resemble the E665 trigger, although the target-pointing trigger logic would have to be replaced. In addition, finer segmentation of the trigger counters and removal of the waveshifter bars would be desirable. The primary change would be to enlarge the hole in the middle of the trigger wall. Data exists which will accurately predict the efficacy of the trigger.

COMPARISON OF THE ACCEPTANCES

Figures 6a and b show the Q^2 acceptances of the proposed superconducting toroid and for the existing double-dipole experiment, E665 at FNAL, for different beam energies at $x_{Bj} = 0.15$ and $x_{Bj} = 0.65$. For each x_{Bj}, the acceptance is shown for two different sections of the 10 m target. For the E665 case, the acceptance was calculated for interactions 2.5 m and 7.5 m from the upstream end of the target. For the toroid case, the acceptance is shown averaged over the first 5 m target section (upstream of the magnet) and the second 5 m section (in the magnet). The overall level of 60% for the toroid is limited by the size of the coils. Away from the coils, the acceptance is flat at 100%. Acceptances shown in Figure 6 for E665 were calculated using the proportional chambers (PCF) located within the second dipole (CCM) magnet as the limiting verticle aperture (see figure 2 and table 2). The acceptance for the Double Dipole Experiment is limited by the vertical gap of the the CCM, which is larger than the PCF chambers. The acceptance will improved if this magnet is replaced. It is 100% until the scattering angle becomes larger than this limiting aperture. Relevant parameters for the E665 experiment are given in Table 2.

Figure 7 illustrates the dependence in the E665 configuration of the maximum Q^2 accessible at 100% acceptance for a given beam energy, depending on the position of the interaction in the target. This dependence of the acceptance on the interaction position will place requirements on the longitudinal resolution of the vertex reconstruction. This point needs further investigation.

It is clear that, for a given beam energy, the acceptance of the toroid experiment is much better than the dipole configuration, and that a toroid at FNAL would have a very large Q^2 range. Another conclusion is that acceptance of the dipole experiment at FNAL (with its higher beam energy) is comparable to the toroid at CERN.

One issue with the dipole experiment is whether the kinematic region where the acceptance is not 100% (scattering angles greater than the limiting vertical CCM gap size) can be used in a precision structure function experiment. If possible, this would extend the Q^2 range of the dipole experiment. The question is whether one can know the (geometrical) acceptance to the required precision ($\approx 10^{-3}$). This is an outstanding issue that needs further attention.

POSSIBLE TRIGGERS

A Trigger for the Double Dipole Experiment

The trigger for a long target muon experiment should have the following features:

1) Triggers should come only from muons scattering in the target.

2) Triggers should be simply related to Q^2.

3) Triggers should allow more than one muon per bucket.

A "target-pointing trigger" satisfies these requirements for a muon double-dipole experiment. In such a trigger, one defines good "roads" along which a scattered muon from the target will travel. The roads are defined narrowly so that muons scattering from somewhere other than the target, such as the absorber, will not travel within the road. Hence only good events will be selected. It is difficult to develop a target pointing trigger which depends only on Q^2, but it is straightforward to trigger on scattering angle, θ, where:

$$\sin^2(\frac{\theta}{2}) = \frac{Q^2}{4E^2(1-y)}$$

If there is no magnetic field, then the radial distance from the axis for a scattered muon is $d \times \tan\theta$, where d is the distance traveled along the beam axis. With two dipole magnets, one can arrange for a "focussing condition" which maintains this relation between radial distance and scattering angle, see figure 8. Because this is not a veto trigger, it is possible to trigger on good scatters which have another muon in the same bucket and it has the added advantage of not having biases due to suicides.

E665 is building a trigger of this type for use in the Fermilab 1990 Fixed Target Run (7). It will use a hodoscope in front of the steel absorber and hodoscopes and proportional chambers located behind the absorber. It consists of a fast (<19 ns) Level 1 trigger using the hodoscopes in 3/4 coincidence and a Level 2 trigger with finally segmented roads, which uses the proportional chambers. The problems associated with such a trigger have been studied using the 1987-88 data and have been found to be understandable and solvable. A similar design could be used for a long target experiment.

A Trigger for the Toroid Experiment

The identification of DIS events proceeds via the detection of the scattered muon after an absorber thick enough ($\sim$ 2.5 m iron or $\sim$ 5 m concrete) to absorb all particles from the hadron shower. The main problem consists in rejecting the very large number of uninteresting interactions at very low Q^2 for which the scattering angle is very small.

The trigger logic would use the correlation between the angle of the muon track and its distance (e.g. in the first hodoscope plane) to the beam axis. The limitation in the Q^2 acceptance is given by the minimal angle that can be accepted for a track passing close to the beam axis. In the toroid experiment, the scattered muon track after the absorber would be sampled by 4 large planes of hodoscopes (about 6 m in diameter) separated by 2 m of concrete shielding in order to avoid contamination by low energy background tracks. A fine granularity would be needed near the beam axis (e.g. 10 cm at less than 0.5 m from the axis). both the absorber and the hodoscopes would have a hole (about 10 cm radius, slightly larger for the hodoscope) around the beam axis.

Following the experience gained with EMC and E665 experiments, a problem may arise from background particles created around the absorber hole by muons from low Q^2 interactions and scraping the counters at low radius. In order to reduce this background while keeping low angle scattered muons, $\sim$ 4 additional fine grained hodoscopes (about 1 m in diameter) would have to be added to increase the lever arm for identifying low angle muons. Over a 14 m path, muons at an angle above 25 mrad could be detected with little background, leading to a Q^2 cut of $\sim$ 40 GeV^2 for E_μ = 300 GeV and $\sim$ 4 GeV^2 for E_μ = 100 GeV. Figure 9 shows a possible set-up of the hodoscope planes after the dump.

A first level trigger would result from the following requirements:

- A beam signal corresponding to one and only one muon in an RF bucket (seen by the beam momentum station and a beam hodoscope in front of the target), in anti-coincidence with signals from the counters of the anti-halo wall.

- A coincidence of several hodoscopes counters (strobed by the beam signal) located above a certain distance from the beam axis (e.g. at least 3 counters hit at more than 20 cm from the beam axis).

In a second level trigger, a decision could be made based on the pattern of hodoscope hits, in order to reduce further the background from very low Q^2 events.

DETECTOR COSTS

The following section lists cost estimates for the two detectors. Those estimates marked "real" have been investigated in detail, those which are unmarked are considered reasonable estimates, those which are marked as "guesses" need further investigation.

Estimated Cost of the Double Dipole Experiment

The double-dipole experiment requires that the beamline be altered.

Upstream enclosure	\$ 50K (real)
Move beam spectrometer magnet	50K (guess)
Beamline silicon 12 planes	900K (real)
Remove Cherenkovs	10K
New chambers:	
(use \$20/channel MWPC)	
(use \$150/channel DCs)	
1 mm 128 wires 30 planes	80K
2 mm 1000 wires 60 planes	1.2M
2 cm DC 300 wires 15 planes	680K
2 cm JET 1000 wires	200K (real)
Gas handling, readout,...	1M (guess)
TOTAL ESTIMATE	**\$ 4M**

Estimated Cost of the Superconducting Air – core Toroid

The costs of the magnet and the chambers are listed separately. A large fraction of the cost of the magnet may be borne by European labs.

TOTAL EST. FOR MAGNET	**$ 15M**
Chambers (use $12/channel MWPC)	
2mm, 1000 wires, 1000 channels, 8 x 30 planes	
2mm, 1000 wires, 500 channels, 16 x 30 planes	$ 5.8M
2mm, 1000 channels, 8 x 4 planes	
2mm, 500 channels, 8 x 8 planes	0.8M
Hodoscopes	
beam hodoscopes, halo wall	0.8M
6 m x 6 m trigger hodoscope, 4 planes	
1 m x 1 m trigger hodoscope, 4 planes (1500 tubes)	1.0M
Gas system, readout, monitoring...	1.6M
Miscelaneous	0.6
TOTAL EST. FOR DETECTOR	**$ 10M**

APPENDIX: MEASUREMENT OF F_2 AS A CONSISITENCY TEST OF α_s RUNNING

The Q^2 scale dependence of the strong coupling constant α_s and of the F_2 structure function are both described by the Renormalization Group Equation (RGE):

$$\frac{d\alpha_s}{dt} = \beta(\alpha_s)$$

$$\frac{dF_2}{dt} = \gamma(F_2, G, \alpha_s)$$

Here G is the gluon distribution and $dt \equiv dln(Q^2/\Lambda^2)$. The second equation is usually referred to as the "Altarelli-Parisi Equation". The α_s in the list of arguments of the F_2 equation is the same as the one in the first equation. For a consistent theory — QCD in connection with the RGE — the α_s in the F_2 equation must run. *One needs to be aware of the fact that the measurement of a running α_s with the F_2 Altarelli-Parisi evolution equation is a consistency test for the theory, but not a stand-alone confirmation for a running strong coupling.*

Off course, a zero-th order measurement of a running α_s would be to show that a constant coupling is excluded. One would artificially assume in the second equation that α_s = constant. The predicted dominant behavior in a gluon suppressed region, that is at large $x_{Bj} > 0.3$ (or more: see WA70 results, this conference), is then linear in $logF_2$ vs. $logQ^2$.

For a positive test of a running coupling an experiment has to show that the data follow a dominant $logF_2$ vs. $loglogQ^2$ line. An exact analysis of the experimental data similar to the BCDMS analysis done on hydrogen or carbon would be needed.

Double logarithm and single logarithm are almost linear relative to each other in the high $Q^2 > 10$ GeV^2 region (see Figure 10). Very small errors on F_2 in this region will be needed to discriminate constant and running coupling. At small $Q^2 < 10$ GeV^2 the ratio of the double to the single logarithm becomes strongly non-linear. Unfortunately this is the Q^2 region where higher twist effects become large. The higher twist effects are supposed to follow a $1/Q^2$ series and vanish at about 15 GeV^2 for the accuracy of current experiments (see reference (4)).

An experiment to measure α_s running must simultaneously obtain data in the high Q^2 region, with small statistical and systematical errors, and in the low Q^2 region where higher twist effects are expected to be important. In this way, the contribution due to higher twist effects may be unfolded.

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TABLE 1

Estimated yields of muons at FNAL for different muon beam energies

The following assumptions have been made:

1. Maximum number of spills in a 9-month run = 4.1×10^5.
2. Number of protons per pulse, without Main Injector = 2.0×10^{13}. With Main Injector = 6.0×10^{13}.
3. Overall efficiency of accelerator and experiment = e = 0.50 for a "Typical Run."
4. Fraction of protons available to muon experiment = f = 0.75 for a "Typical Run."

Case I. FNAL, E_{proton} = 900 GeV, 2×10^{13} (*no Main Injector*), 20 sec spill.

E_μ (GeV)	μ/p x 10^6	Instan. Rate (MHz)	Integral μ x 10^{14}	Example for a " Typical Run"		Example for μ rate of 25 MHz	
				Rate for f = 0.75	μ x 10^{14} (e x f = 0.375)	Limit on f if μ rate is 25 MHz	μ x 10^{14} 25 MHz
100	46	46f	3.8ef	35	1.4	0.54	2.0e
300	140	140f	11.5ef	105	4.3	0.18	2.0e
400	60	60f	4.9ef	45	1.8	0.42	2.0e
500	17	17f	1.4ef	13	0.5	–	0.5
530	11	11f	0.9ef	8	0.3	–	0.3
600	3	3f	0.2ef	2	0.08	–	0.08

Case II. FNAL, E_{proton} = 900 GeV, 6×10^{13} (*Main Injector*), 20 sec. spill.

E_μ (GeV)	μ/p x 10^6	Instan. Rate (MHz)	Integral μ x 10^{14}	Example for a " Typical Run"		Example for μ rate of 25 MHz	
				Rate for f = 0.75	μ x 10^{14} (e x f = 0.375)	Limit on f if μ rate is 25 MHz	μ x 10^{14} 25 MHz
100	46	138f	11.3ef	104	4.2	0.18	2.0e
300	140	420f	34.5ef	315	12.9	0.06	2.0e
400	60	180f	14.7ef	135	5.5	0.14	2.0e
500	17	51f	4.2ef	38	1.6	0.49	2.0e
530	11	33f	2.7ef	25	1.0	0.75	2.0e
600	3	9f	0.6ef	7	0.2	–	0.2

TABLE 2

E665 Acceptance Parameters

Item	Position Along Beam	Half Height
Upstream face of target	-21.5 m	-
Downstream face of target	-11.5 m	-
CCM: Second dipole magnet	2.0 m	0.6 m
PCF5: Most downstream prop chamber in CCM	0.0 m	0.5 m
DCB: Most downstream drift chamber	13.0 m	1.0 m
PTM4: Last plane of muon detector	23.5 m	1.9 m

Figure 1: The Superconducting Air-core Toroid Apparatus as proposed in Reference (1).

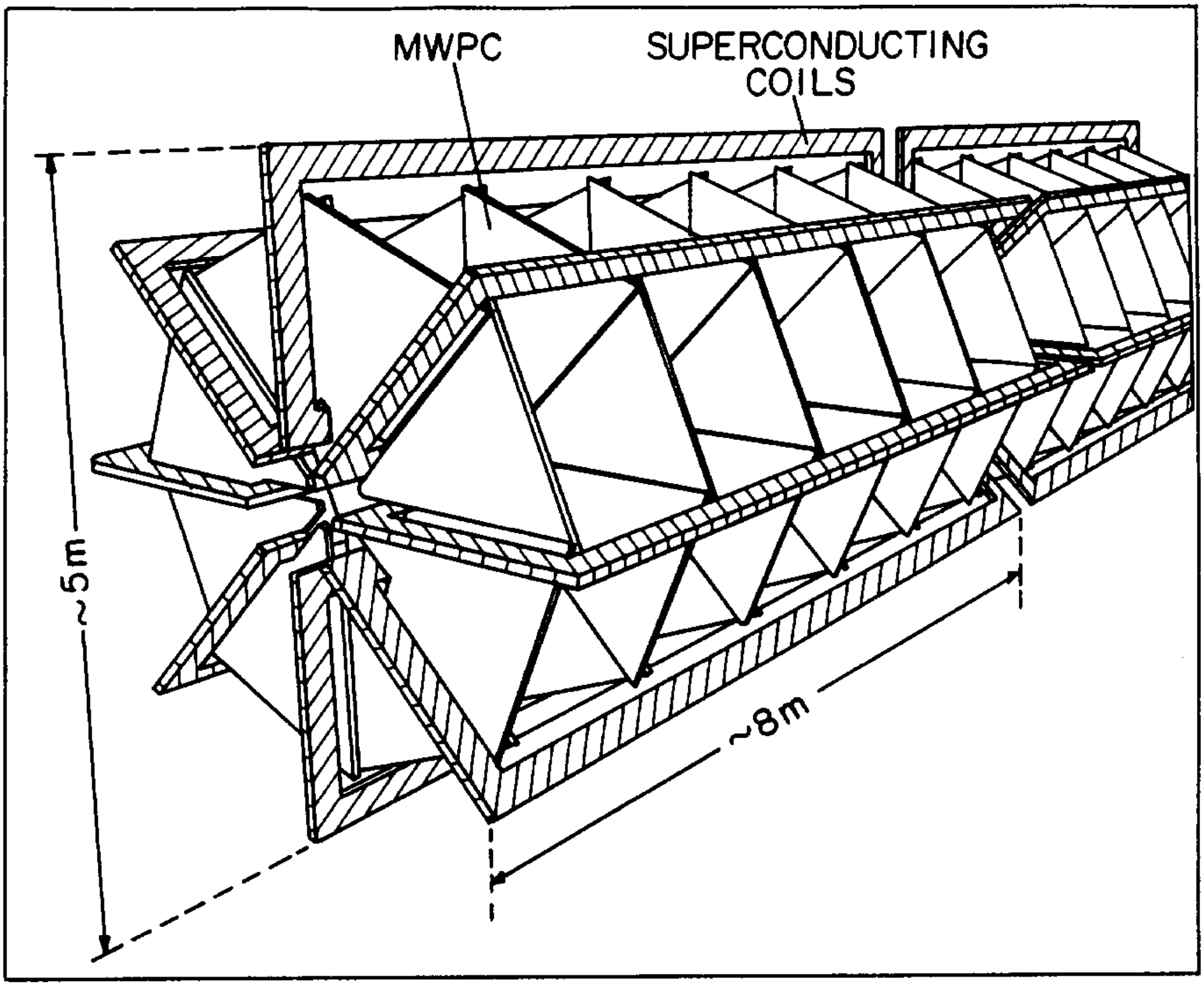

Figure 2: The Double-Dipole Apparatus, an upgrade to the E665 Apparatus described in Reference (2).

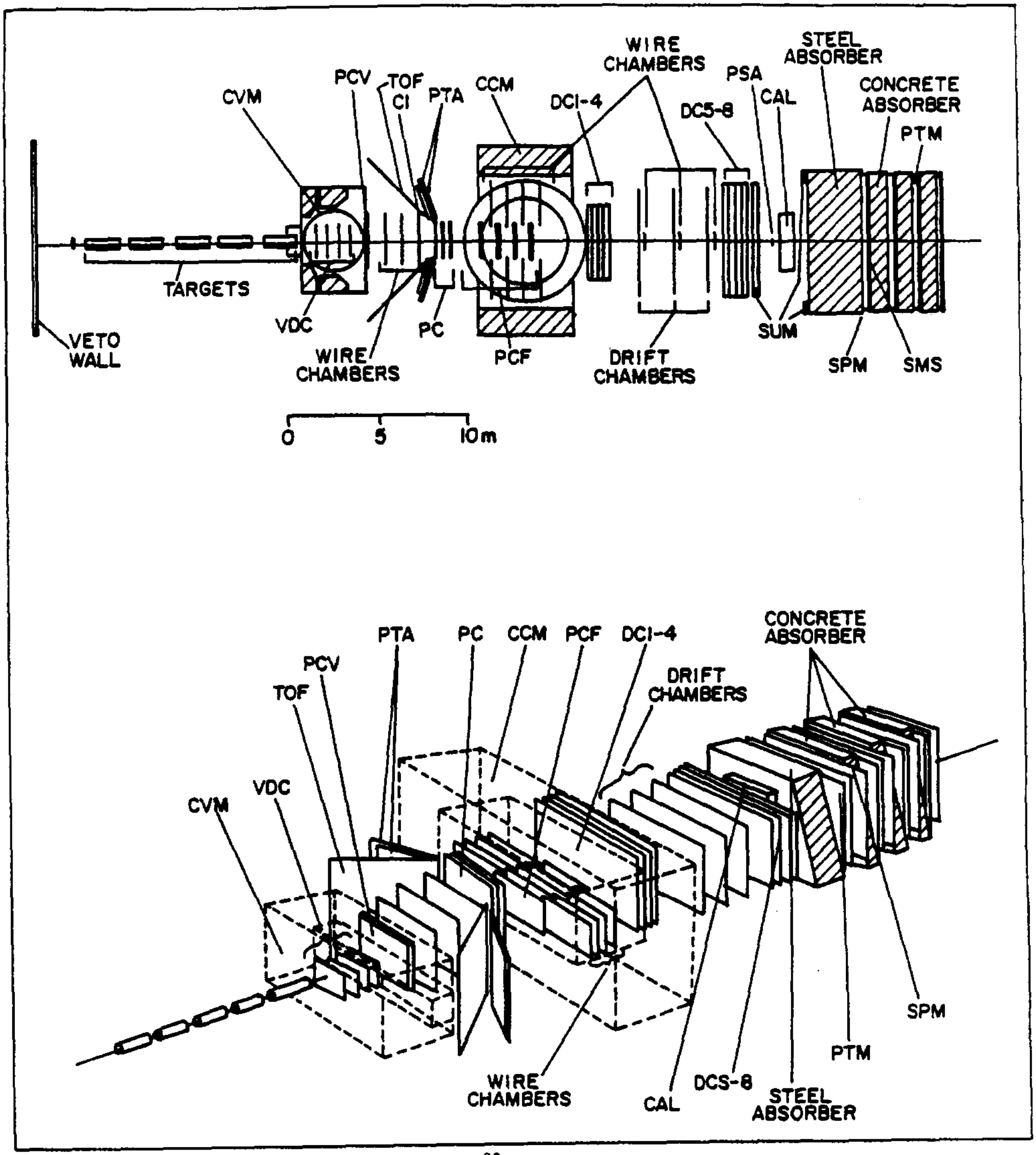

Figure 3a: Expected statistical error on F_2 for a 1 month run at FNAL, carbon target, $x_{Bj} = 0.55$

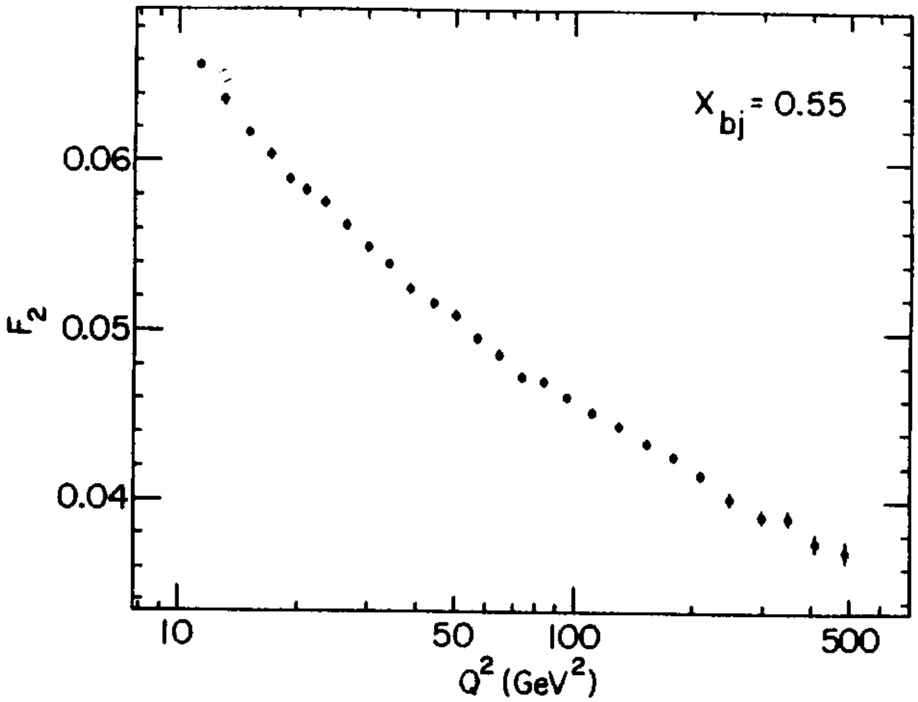

Figure 3b: Expected statistical error on F_2 for $x_{Bj} = 0.75$

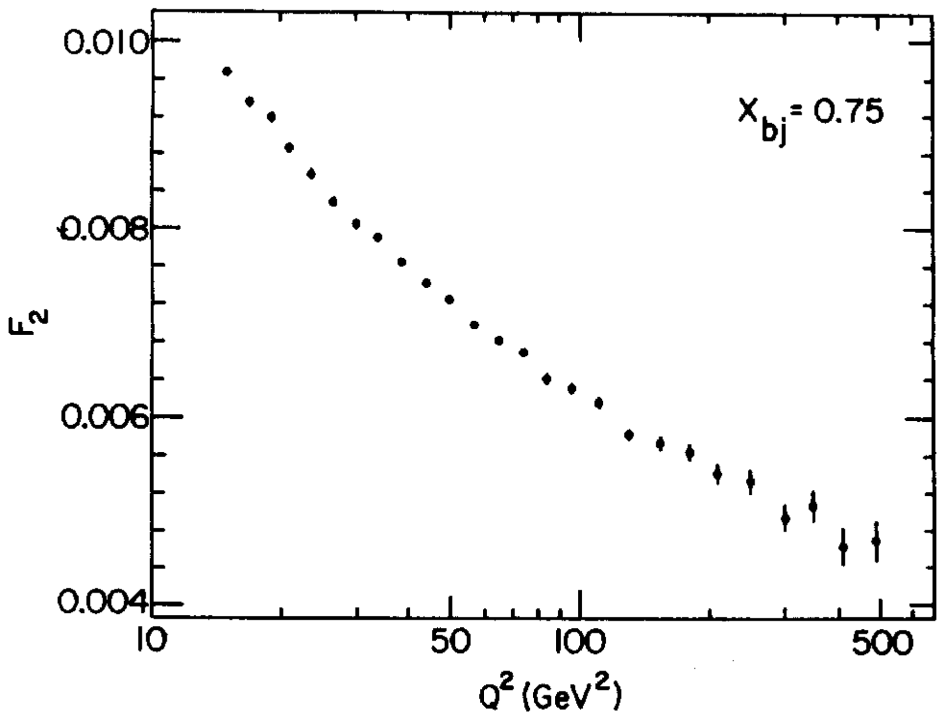

Figure 4: Expected statistical error for measurements of α_s at four Q^2 points given a 2 month run at FNAL, using a carbon target.

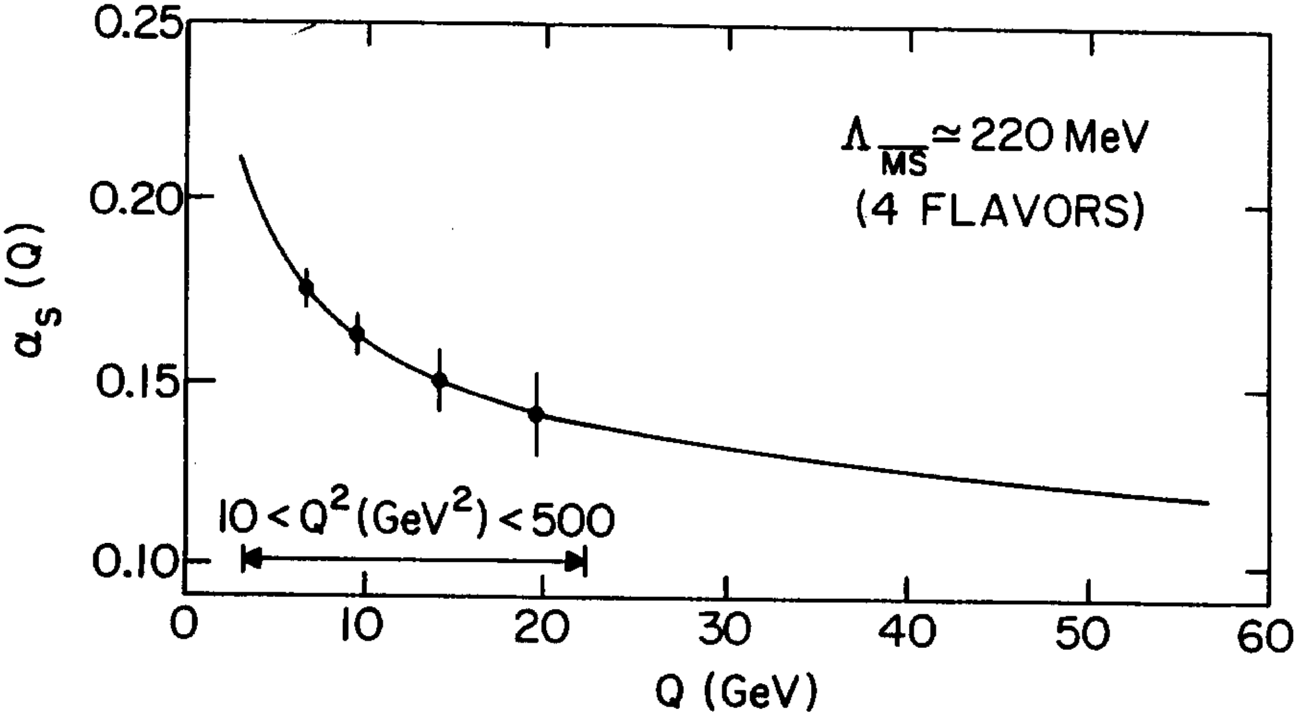

Figure 5: Comparison of FNAL and CERN μ/p as a function of μ beam energy. Curves are shown for 800 and 900 GeV protons at FNAL.

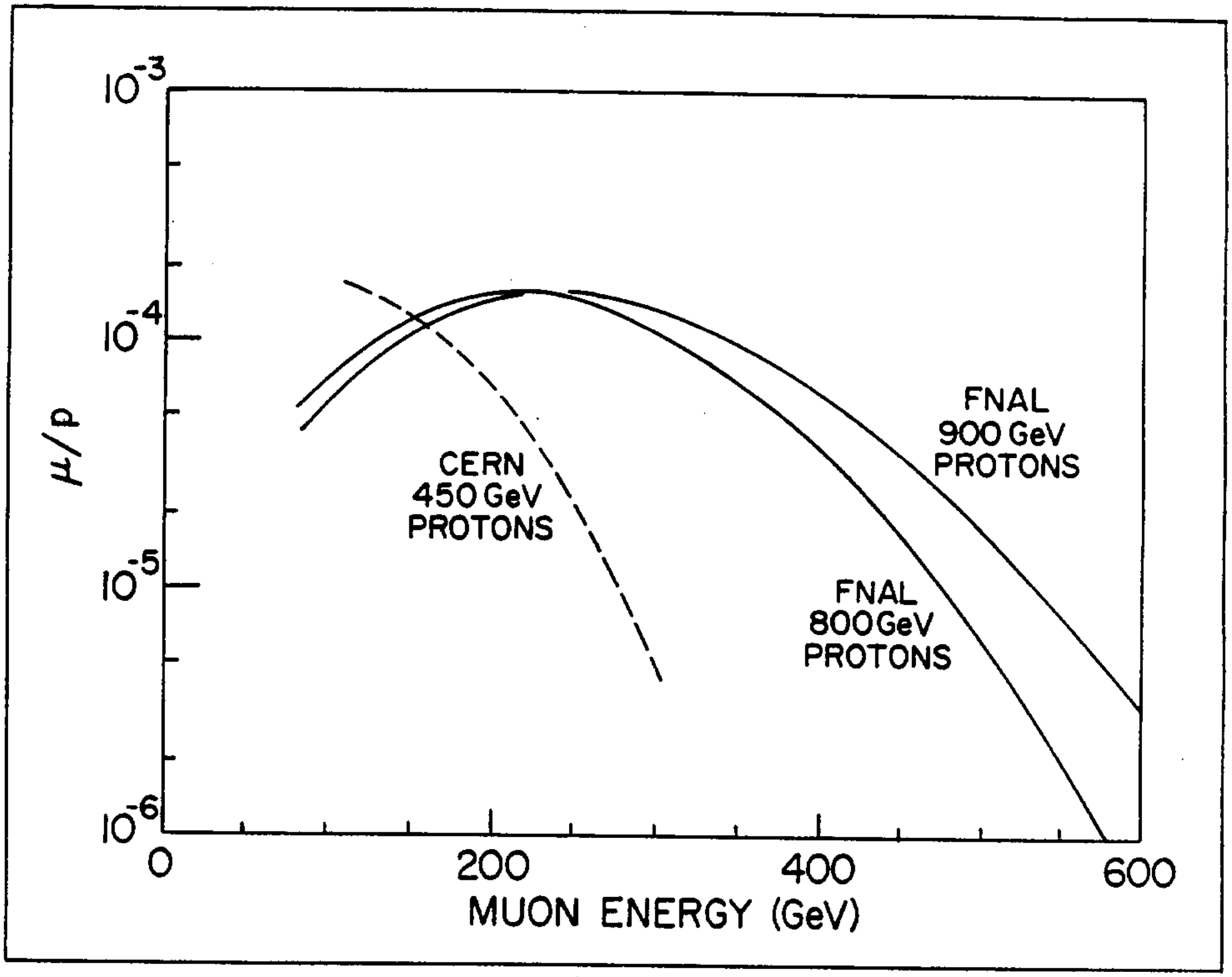

Figure 6a: Acceptance of E665 and the proposed Toroid at $x_{Bj} = 0.15$. The limiting aperture for E665 is the PCF chamber in the CCM magnet (see Figure 2 and table 2). Without replacing the CCM, the limiting aperture of the Dipole experiment would be the CCM apperture.

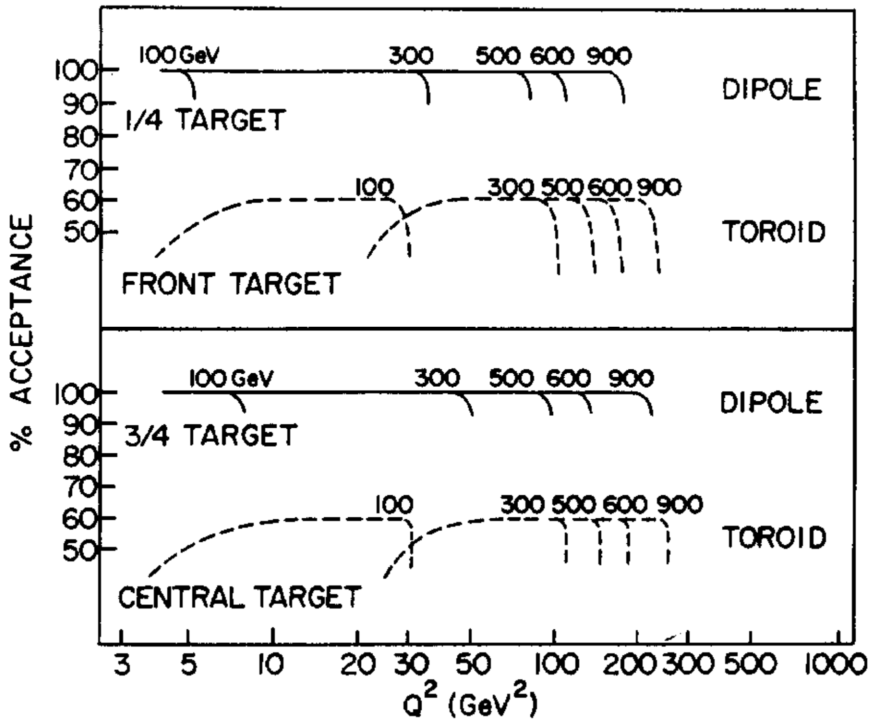

Figure 6b: Acceptance of E665 and the Toroid at $x_{Bj} = 0.65$.

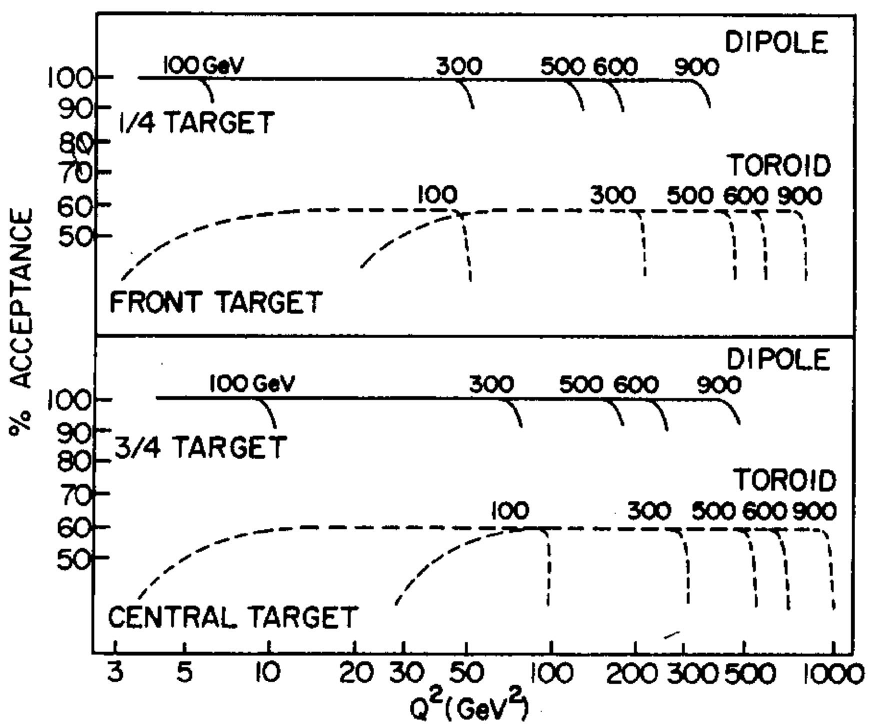

Figure 7: Curves of 100% acceptance for the Double Dipole Experiment as a function of maximum Q^2 and beam energy. Curves for 100% acceptance for upstream 1/4 and downstream 1/4 of a 10 m target are shown.

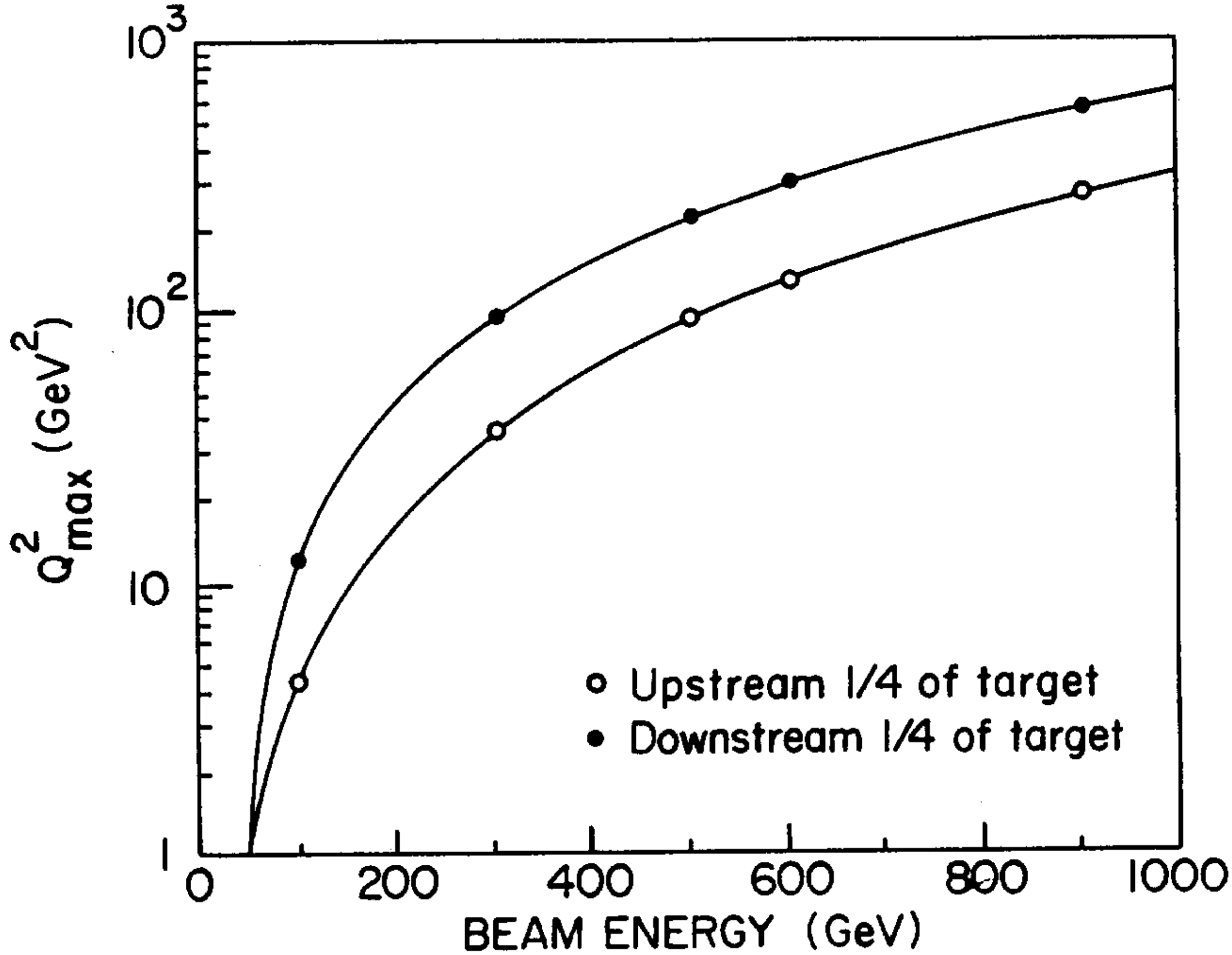

Figure 8: Schematic of the focussing condition used in the proposed Dipole Experiment Trigger.

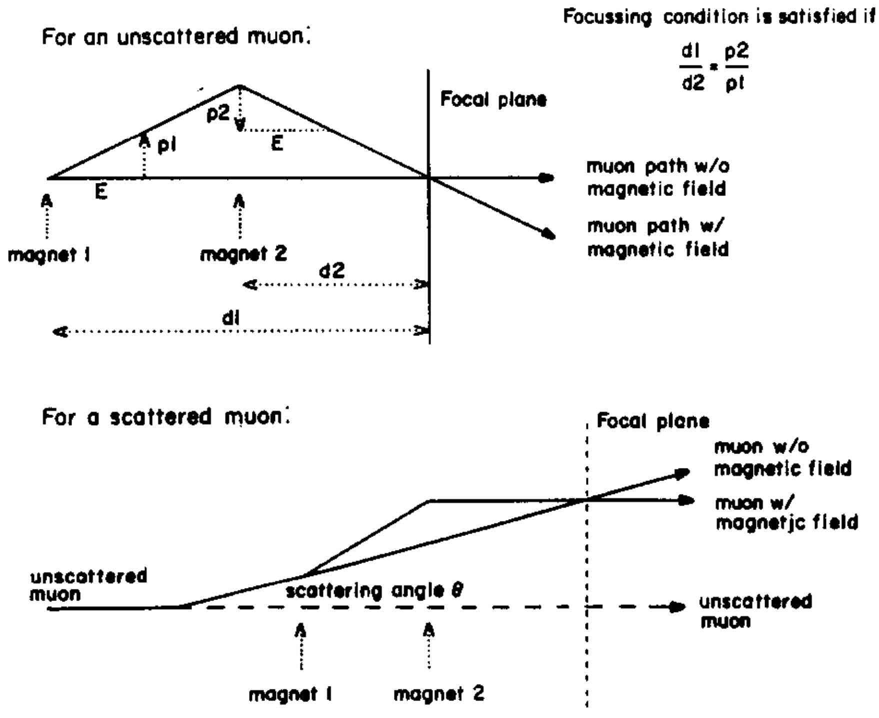

Figure 9: Possible configuration of hodoscopes for trigger of the Toroid Experiment.

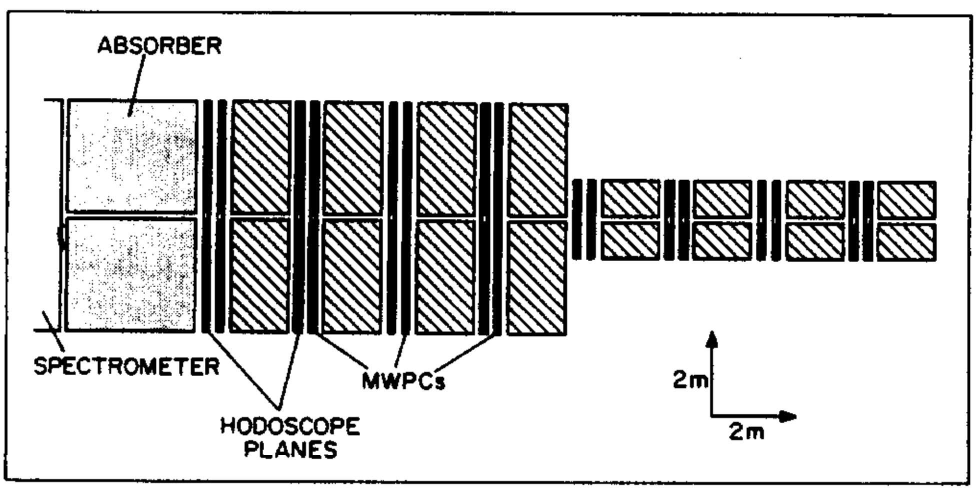

Figure 10: $Log Log Q^2$ vs. $Log Q^2$ plot showing data from SLAC and BCDMS.