# NEW PHYSICS OPPORTUNITIES WORKING GROUP †

S. Errede and K.-B. Luk
Co-Leaders representing the New Physics Opportunities Group

## Abstract

The participants in the New Physics Opportunities Working Group at the Workshop on Fermilab Physics In The 1990's at Breckenridge, Colorado consisted of a group of physicists with very broad interests. Topics covered ranged from fairly conventional approaches to various physics topics associated with fixed target and collider experiments, to highly exotic, novel types of experiments and physics facilities.

†V. Bharadwaj[g], D. Carlsmith[p], V.A. Chaloupka[o], S. Cihangir[g], J. Cumalat[e], D. Dimitroyannis[i], S. Errede[h], G. Fanourakis[m], T. Ferbel[m], N. Giokaris[n], J. Green[l], H.R. Gustafson[j], U. Joshi[g], I. Kourbanis[k], L.M. Lederman[d,g], K.-B. Luk[c], A. Malensek[g], F.A. Nezrick[g], J. Rutherfoord[b], M. Shupe[b], A. Sinanidis[k], D. Underwood[a], N. Varelas[m], V. Višnjić[g], J. Volk[g], W.D. Walker[f] and M. Zielinski[m] [a]*Argonne National Laboratory, Argonne, IL 60439* [b]*The University of Arizona, Tucson, AZ 85721* [c]*The University of California, Berkeley, CA 94720* [d]*The University of Chicago, Chicago, IL 60637* [e]*The University of Colorado, Boulder, CO 80309* [f]*Duke University, Durham, NC 27706* [g]*Fermi National Accelerator Laboratory, Batavia, IL 60510* [h]*The University of Illinois, Urbana, IL 61801* [i]*University of Maryland, College Park, MD 20742* [j]*The University of Michigan, Ann Arbor, MI 48109* [k]*Northeastern University, Boston, MA 02115* [l]*Northern Illinois University, De Kalb, IL 60115* [m]*University of Rochester, Rochester, NY 14627* [n]*The Rockefeller University, New York, NY 10021* [o]*The University of Washington, Seattle, WA 98195* [p]*The University of Wisconsin, Madison, WI 53706*

# 1 INTRODUCTION

N. Giokaris et al., reviewed the experimental and theoretical limits on the neutrino magnetic moment and examined the feasibility of carrying out a muon neutrino magnetic moment search experiment with detection sensitivity at the $10^{-10}$ to $10^{-11}$ Bohr magneton level using the Fermilab Booster. This group considered a possible secondary beam from the Booster and outlined a detector configuration for such an experiment.

D. Carlsmith et al., studied the feasibility of a new generation of fixed target experiments to study the Primakoff effect. This program would improve upon the results of previous experiments by several orders of magnitude, and search with high sensitivity for production of hybrid mesons in the Coulomb field of heavy nuclei.

L.M. Lederman designed an "ultimate" rare decay mode experiment with an intense, high-rate neutral beam to search for rare decays of neutral hyperons and neutral K-meson with *e.g.* $e^{\pm}\ \mu^{\mp}$ pairs in the final state. With a quality, high-rate capability experiment, sensitivity to rare decays with branching ratios in the range $10^{-13} - 10^{-14}$ is achievable.

S. Errede and H.R. Gustafson studied the feasibility of a Tevatron "collider" experiment to search for evidence of weakly or pseudo-weakly interacting gravitationally bound dark matter. If terrestrial dark matter is present at sufficient density, and can interact with normal matter via weak or pseudo-weak interactions, use of a coasting beam in the Tevatron may be able detect dark matter by proton (or pbar)-dark matter collisions. A possible experiment is outlined, with search sensitivity in number density fraction $\times$ cross section on the order of $10^{-44}$.

F. Nezrick studied the impact of recent improvements in various technologies which makes it feasible to consider new tests of relativistic gravitation with significantly enhanced sensitivity. By improvements in detector design and use of new technology, improved displacement sensitivites of $\Delta x \sim 4 \times 10^{-21}$ cm could be achieved. However, this is still a factor of $6 \times 10^{4}$ too insensitive to measure the predicted effect of relativistic Newtonian gravity. Nevertheless, this detector *is* capable of ruling out higher-than-spin 3 gravity theories and the existence of long or intermediate-range weak interactions $10^{28}$ times weaker than the conventional weak interaction.

D. Underwood studied potential applications of polarized beams. The apparent ease with which polarized beam could be accelerated in the Main Injector opens up a wide range of new physics opportunities. The issue of the spin content of the proton could be addressed with fixed target experiments using beams from the Injector and the Tevatron. Experiments requiring energy and intensity beyond that available with upgrades of the existing Fermilab polarized beam could be done. Searches for evidence of supersymmetry could be greatly enhanced with polarized colliding beams.

J. Rutherfoord and M. Shupe studied the feasibility of detecting an intermediate mass Higgs boson at the Tevatron collider, concluding that conventional methods for Higgs detection would be extremely difficult.

W.D. Walker outlined potential physics uses of a muon storage beam at Fermilab, such as precision determination of structure functions, and as a vector meson factory.

# 2 SEARCH FOR THE MUON NEUTRINO MAGNETIC MOMENT AT THE FERMILAB BOOSTER†

## 2.1 Cross Sections

We review the experimental and theoretical limits on the neutrino magnetic moments and examine the possibility of doing a muon neutrino magnetic moment search down to $10^{-10}$ to $10^{-11}$ Bohr magneton level using the Booster accelerator at Fermilab. A possible secondary beam and detector configuration is outlined.

The interaction of the neutrino magnetic moment $\mu$ and the electromagnetic field $F_{\mu\nu}$ is described by the following Lagrangian term[1]:

$$\mathcal{L}_{int} = \frac{1}{2}\overline{\nu}_R \sigma_{\mu\nu} \nu_L F_{\mu\nu} + h.c.. \tag{1}$$

In the standard $SU(2)_L \times U(1)$ theory the neutrino has a magnetic moment induced by radiative corrections and proportional to the neutrino mass $m_\nu$ [2,3]:

$$\mu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu = \frac{3m_e G_F}{4\sqrt{2}\pi^2}\mu_B m_\nu \sim 2.7 \times 10^{-10}\mu_B \frac{m_\nu}{m_N}, \tag{2}$$

where $G_F$ is the Fermi constant, $\mu_B$ is the Bohr magneton ($\mu_B = e\hbar/2m_e c$) and $m_N$ is the nucleon mass. The magnetic moment described by the above formula is very small. For example, a neutrino with mass $m_\nu = 30$ eV has a magnetic moment $\mu \sim 10^{-17}\mu_B$.

We will now review the limits on $\mu$ that follow from reactor experiments and astrophysical estimates. The interaction (1) produces an additional contribution to the neutrino-electron scattering cross section described by the Feynman diagram of Fig. 1.

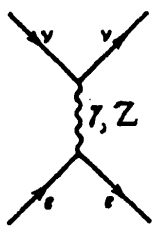


Figure 1. Feynman diagram for neutrino-electron scattering, due to the exchange of a $Z$ (weak neutral current) or a photon (electromagnetic part due to the neutrino magnetic moment).

The differential cross section for $\nu - e$ scattering due to the neutrino magnetic moment is given by [4]:

$$\frac{d\sigma_{em}}{dT} = \frac{\mu^2}{\mu_B^2}\frac{\pi\alpha^2}{m_e{}^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right), \tag{3}$$

where $E_\nu$ is the energy of the incident neutrino and $T$ is the kinetic energy of the recoil electron. This is to be compared with the following expression for the differential cross

†N. Giokaris, V. Višnjić, V. Bharadwaj, S. Cihangir, D. Dimitroyannis, G. Fanourakis, J. Green, U. Joshi, I. Kourbanis, A. Malensek, A. Sinanidis and N. Varelas

section due to the weak neutral current [5]:

$$\frac{d\sigma_W}{dT} = \frac{G_F^2\, m_e}{2\pi}\left[(1-\frac{T}{E_u})^2(1+2\sin^2\theta_W)^2 + 4\sin^4\theta_W - (1+2\sin^2\theta_W)\frac{m_e T}{E_\nu^2}\right], \quad (4)$$

where $\theta_W$ is the electroweak mixing angle. The electromagnetic and weak amplitudes do not interfere, because the final states are different for the two cases (the final state neutrino helicities are opposite). Hence, the total cross section is the sum of the expression given by (3) and (4). When $T \ll E_\nu$, the cross section given by (4) becomes constant, while that in (3) behaves as $T^{-1}$ and for $\sin^2\theta_W = 0.22$ and $\mu \sim 10^{-10}\mu_B$ it becomes comparable with the weak cross section at $T = 0.3$ MeV. The experimental data reported in Ref. (6) have been used to show that the electron neutrino $\mu \leq 2\times 10^{-10}\mu_B$. Astrophysical limits on $\mu$ have been obtained (see Ref. 1 and references therein) by considering the cooling of young white dwarfs due to the decay of plasmons to $\nu\bar{\nu}$ pairs. Analysis of astrophysical data gives $\mu \leq 0.7\times 10^{-10}\mu_B$.

The possibility that the electron neutrino could have a magnetic moment around $10^{-10}\mu_B$ was enhanced by the new information provided by the solar neutrino experiment [7]. It is well-known that the average neutrino capture rate is almost three times smaller than the value predicted in the standard solar model [8]. Even more interesting is that the solar-neutrino data indicate an anticorrelation between the neutrino capture rate and the sun-spot number [9]. An explanation has been proposed in Ref. 1. It is suggested that this anticorrelation could be explained if the electron neutrino had a magnetic moment of the order of $10^{-10}\mu_B$. The $B\cdot L$ required to turn the spin through an angle of the order of unity is given by

$$B\cdot L \sim \mu^{-1} \sim 3\times 10^{13}\,\mathrm{G\,cm}. \quad (5)$$

Since the thickness of the convective zone of the sun is $L \approx 2\times 10^{10}$cm, from Eq. (5), the magnetic field needed is $B \approx 1.5\times 10^3$G. This value is consistent with what is believed to be the strength of the magnetic field in the sun's convective zone. We pointed out earlier that the Standard Model prediction for the magnetic moment of a neutrino with mass 30 eV is $\sim 10^{-17}\mu_B$ (see Eq.(2)). A value of $10^{-10}\mu_B$, as suggested by the solar neutrino experiment, could be explained by the introduction of right handed currents [1] or by simple extensions [10,11,12] of the Standard Model which lead to a large transition magnetic moment of the electron neutrino while keeping the neutrino mass naturally small. This model can provide a solution to the solar neutrino puzzle while at the same time avoiding the SN1987A bound on the neutrino magnetic moment.

Irrespective of theoretical prejudices we think that the data of the solar neutrino experiment provide a strong hint that the magnetic moment of the electron neutrino could be $10^{-10}\mu_B$. If the anticorrelation between the number of solar spots and the number of neutrino interactions is observed again during the next solar activity maximum (expected to take place during the next year), the significance of the earlier observation will be greatly enhanced. Since the discovery of a neutrino magnetic moment would strongly suggest that the neutrino also has mass, with further consequences for both particle physics and cosmology, we feel that an accelerator search is justifiable. The most suitable accelerators for this purpose are those that can provide high intensity, low energy neutrino beams. In the following section we examine the feasibility of doing a muon neutrino magnetic moment search at Fermilab's Booster accelerator.

## 2.2 Muon Neutrino Magnetic Moment Search at the Fermilab Booster

The best experimental limit on the muon neutrino magnetic moment comes from Brookhaven experiment E734, a study of $\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$. It gives a limit[13] of $0.85 \times 10^{-9} \mu_B$. The astrophysical limit[14] (for $m_{\nu_\mu} < 10$ keV) is $8.5 \times 10^{-11} \mu_B$.

In order to examine the feasibility of doing a muon neutrino magnetic moment search at the Fermilab Booster (to at least one order of magnitude higher level than Brookhaven E734) we have run the NUADA[15] program with the pion production spectrum of Ref. 16. Taking the incident proton energy to be 8 GeV using a single MORI-type horn, a pion decay length of $\sim$ 15 meters, the muon neutrino flux 5 meters behind a 7 meter concrete dump is found to be $2 \times 10^{10}$ per $10^{13}$ protons over a 4m$^2$ area detector (2m×2m). Since, after the Linac upgrade[17,18], the Booster will be able to provide $3 \times 10^{13}$ protons/sec this means that a total neutrino flux of $6 \times 10^{10}$/sec over a detector of 2 m×2 m could be achieved. This is to be compared with $10^{10}$ neutrinos/sec at BNL E734. We further take our detector to be a 2 m×2 m (area), two 5 m long water tanks with complete photomultiplier coverage on their back surface. Such a detector contains $3.2 \times 10^{26}$ target electrons/cm$^2$. Since the electron threshold energy in water is 0.26 MeV we have integrated Eq. (3) from a $T_{min}$ of 1 MeV to $T_{max} = 100$ MeV to get a total $\sigma_{EM} = 1.24 \times 10^{-44}$ cm$^2$ (for a muon neutrino magnetic moment of $10^{-10} \mu_B$). Putting all the numbers together we get an electromagnetic rate of $\sim$ 8 per year. We conclude that a search for a muon neutrino magnetic moment down to $10^{-10} \mu_B$ is possible. A search to the $10^{-11} \mu_B$ level could be feasible if the Booster intensity could be increased by a factor of 5. This, for example, might be achieved if the Booster cycles at the nominal 15 Hz and if its intensity could be pushed to its space charge limit.

Work is at present underway on the following subjects:
*i*) Setting up a Monte Carlo for simulation of both background and signals of physics of interest, and
*ii*) Using the NUADA program to optimize (as far as signal *vs.* background is concerned) the incident proton energy.

At the same time we are anxiously awaiting the coming of the next solar activity maximum!

# 3 SEARCH FOR PRIMAKOFF PRODUCTION OF HYBRID MESONS†

The availability of high energy intense beams at Fermilab, as well as the development of new detectors and data acquisition techniques, provide motivation for a new generation of Primakoff experiments. The physics goals are to improve on previous experiments by several orders of magnitude, and, in particular, to search with high sensitivity for production of hybrid mesons in the Coulomb field of heavy nuclei.

In the past, the one-photon exchange mechanism ('Coulomb' or 'Primakoff' production) has been used in meson spectroscopy mainly for measurements of radiative and two-photon widths of known mesons ( $\pi^0, \eta, \rho, A_2$ etc.); this is the 'Primakoff effect'[19]. The production mechanism, being electromagnetic (see Fig. 2), is characterized by ex-

†D. Carlsmith, V. Chaloupka, T. Ferbel and M. Zielinski

tremely low values of momentum transfer: $|t| < m^4/p^2$ where $m$ is the mass of the produced meson, and $p$ is the laboratory beam momentum.

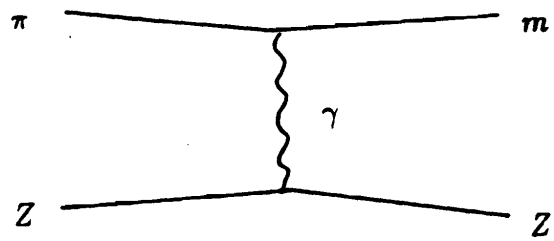


Figure 2. One Photon Exchange Graph

This means that after an appropriate cut, the data sample will contain very small contamination from other processes, and this purity (see examples on Fig. 3) improves with increasing beam momentum. At the same time, the total Coulomb production of a given state increases logarithmically with $p$. These features, together with

- the availability of intense high energy beams at Fermilab
- the development of silicon detectors with high position resolution
- the development of modern data acquisition and data-processing techniques

make it possible to design a new generation of experiments which would result in a significant improvement over previous Primakoff studies. Rather than continuing exploration of 'classical' issues such as verifying the Z-dependence and $p$-dependence of the effect, or measuring the radiative widths of known mesons with better precision, we intend to perform a high sensitivity study of meson states with masses up to 3 GeV. Through an appropriate trigger, we will exclude the bulk of large cross section processes such as the Coulomb production of $\rho$ and $A_1$.

Of particular interest is a search for Primakoff production of hybrid mesons. As a specific example, we will discuss the search[20] for an isovector $J^{PC} = 1^{-+}$ meson $\tilde{\rho}$. The quantum numbers of this state are exotic in the sense of the traditional $q\bar{q}$ quark model. States of this kind are expected to exist in the hadron spectrum of the elementary particles, especially in the form of a system composed of a gluon and a $(q\bar{q})$ color octet. Such hybrid mesons have been discussed on the basis of a variety of QCD-inspired models[21]. Although there is uncertainty concerning the widths and specific decay channels for hybrids, most models predict these mesons to have masses in the range of 1.5–2.0 GeV. There is general consensus that $\tilde{\rho}$ will have a branching width into $\rho\pi$ that is of the order of 1–10 MeV, and a substantially larger rate into more complex channels[22] such as $b_1(1235)\pi$ or $f_1(1285)\pi$. The presence of a 1–10 MeV width into the $\rho\pi$ channel assures, through vector-dominance arguments, a width of $\tilde{\rho}$ into $\pi\gamma$ at a level of 3–30 keV. This means that such a state could be observed in a Primakoff experiment[23].

Previous searches conducted for objects such as $\tilde{\rho}$ have met with mixed success. The results of Alde et al, although very interesting are somewhat controversial[24] and have yet to be confirmed. Earlier studies published by Fermilab experiment E272[25] were limited in scope because E272 was designed for low-mass spectroscopy. Therefore the sensitivity to masses in excess of 1.5 GeV was rather poor. The data in the $\eta\pi$ and $\rho\pi$

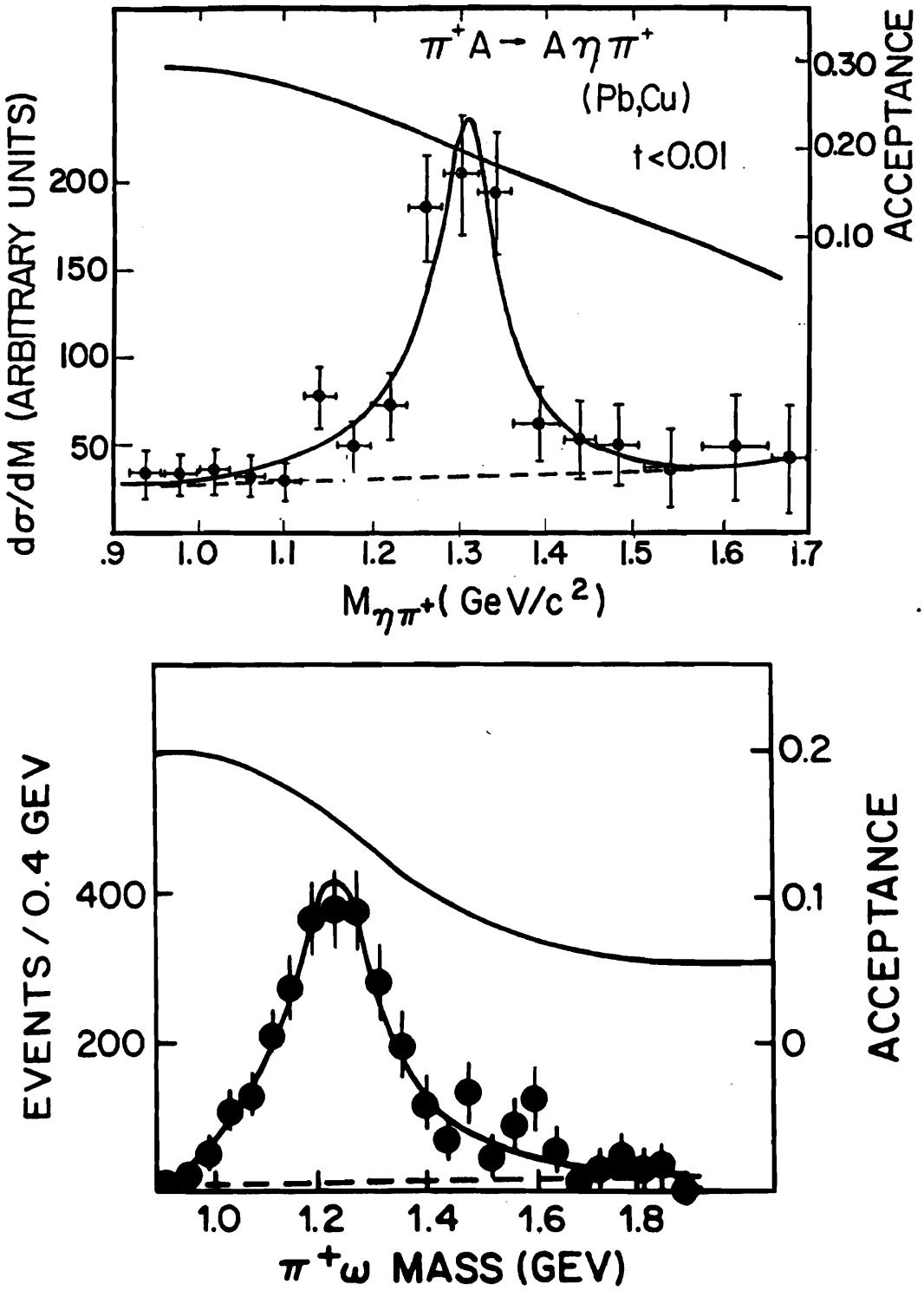


Figure 3 . Examples of Primakoff production of $a_2(1320)$ and $b_1(1235)$ from E272[7].

modes did not yield any effect, and could only be used to set upper limits on the branching rate of the hybrid meson into the $\pi\gamma$ mode[26]. This result is not surprising because the width of the vector hybrid into the above channels is expected to be rather small (several percent of the total width). These upper limits were not very restrictive for masses beyond 1.5 GeV. The only decay mode to which E272 could be anticipated to be sensitive was the $f_1(1285)\pi$ channel. In fact, the data[27] show a tantalizing enhancement at $\sim$ 1.6 GeV in this state (see Fig. 4). The limited statistics and acceptance did not allow any definite conclusion.

In addition to a search for hybrid mesons, the experiment will yield valuable data on "ordinary" meson spectrocopy. Obviously, not all possible hybrid, multiquark or glue states are expected to have manifestly exotic quantum numbers. The 'crypto-exotic' states will have to be disentangled from the $q\bar{q}$ mesons by the systematic observation and classification of different production and decay modes. As a specific example of an issue opened by the previous Primakoff experiment, we note the discrepancy in the mass and width values of the $b_1(1235)$ meson:

- $M = 1233 \pm 10\,\mathrm{MeV/c^2}$, $\Gamma = 150 \pm 10$ MeV (world average)[28]
- $M = 1271 \pm 11\,\mathrm{MeV/c^2}$, $\Gamma = 232 \pm 29$ MeV (E272)[25]

This may indicate the observation of more than one state in strong or Primakoff production or both. The new data will enable a detailed Partial Wave Analysis which should settle this question. Another important by-product of our experiment will be a remeasurement of the pion polarizability (by analyzing the reaction $\pi Z \rightarrow \pi\gamma Z$ in terms of a Compton effect on a pion). The urgent need for this has been stressed in a recent analysis of chiral perturbation theory in QCD[29].

The experiment will be state-of-the-art, but relatively straightforward. It will involve:

- an intense (about $5\times10^6$ per sec) $\pi^-$ beam at the highest possible energy ($\sim$ 600 GeV/c), with a thin ($\sim$ 1% interaction length) Pb target.
- a magnetic spectrometer with $dP_T$ of about 1.5 GeV/c providing precise measurement of charged particles (for beam and fast secondaries, we will use Silicon Strip Detectors).
- adequate measurement of high energy photons from $\pi^0$ and $\eta$ decays (e.g. using a Liquid Argon Calorimeter).

Instead of building a dedicated spectrometer, an economical way to perform the experiment would be in conjunction with an existing or approved FNAL experiment. A good possibility appears to be experiment E781, a large-x spectrometer designed for the study of charmed hyperons. It could be adapted to our purpose by:

- upgrading the beam Si system to enable faster readout.
- enclosing the target in a veto-box to reject any incoherent interactions.

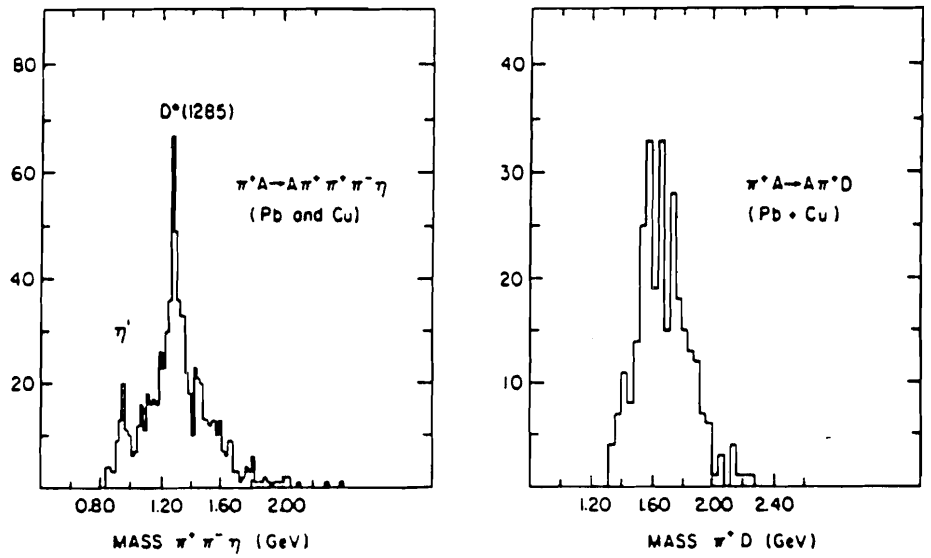


Figure 4 Distributions in $\pi^+\pi^-\eta$ and $\pi^+$D mass for coherent production of $\pi^+\pi^+\pi^-\eta$ systems on Pb and Cu targets in $\pi^+ A$ collisions at 200 GeV/c.

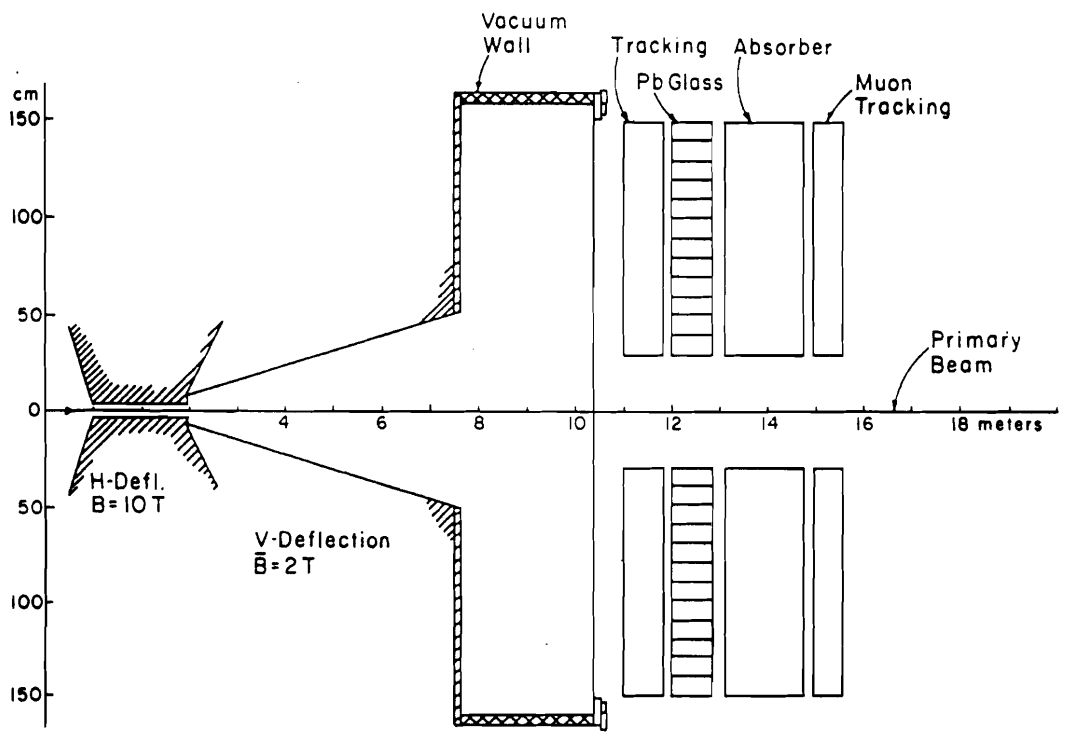


Figure 5: Set-up for Rare Decay Mode experiment

- using the E781 counters and computer hardware to develop an appropriate hardware and software trigger for the Primakoff experiment.

We have studied the acceptance and the angular and energy resolution of the E781 spectrometer, and have found them suitable for the Primakoff experiment. We have also discussed this possibility with E781 principals, and did not find any reason why this approach should not be feasible. The upgrading of the readout can be used by both experiments. The last two changes imply the necessity of separate runs. Note that running in one mode can be used for de-bugging of the other. Our running requirements are relatively modest. We estimate that 2 weeks of good data taking would represent an improvement over E272 by more than two orders of magnitude for $m < 1.5$ GeV, and an even more dramatic improvement in the higher mass region where the E272 acceptance was poor. As an example, we would obtain several thousand events in a specific final state such as $\pi^+\pi^+\pi^-\gamma\gamma$ for a meson with $m = 1.6$ GeV, $\Gamma_{\pi\gamma} = 10$ keV, and branching ratio into $f_1(1285)\pi$ of 0.4. The desirability of more data would depend on the results obtained.

# 4 RARE DECAY MODES REVISITED†

This is an attempt to see if an "ultimate" rare decay mode experiment can be carried out at the TEVATRON. The philosophy is to make an intense neutral beam which will be dominated by hyperons which decay, neutrons which don't, photons which scatter and $K^0$'s some of which decay. One sweeps charged decay products out of the neutral beam into two detector boxes in which e's and $\mu$'s are identified and the momenta and origin point are determined precisely. A rare decay mode is an $e^\pm \mu^\mp$ pair which are cotemperal (1 bucket), copunctual (0.1 mm), show plausible lifetime for the parent, etc. The physics of the data, which will also be registered, on $e^+e^-$, $e^-e^-$, $e^+e^+$ and ditto for muons clearly depends on the physics backgrounds in this constrained study. So we look at *e.g.*

$$\begin{aligned} \Lambda^0 &\rightarrow n\, e^\pm \mu^\mp \\ \Xi^0 &\rightarrow \Lambda^0,\ \Sigma^0\, e^\pm \mu^\mp \\ \Sigma^0 &\rightarrow \Lambda^0\, e^\pm \mu^\mp \\ K^0_s &\rightarrow \mu^+\mu^-,\ e^\pm\mu^\mp,\ \textit{etc.} \end{aligned} \tag{6}$$

With an incident 900 GeV/c proton beam, particle momenta of 100-200 GeV/c are prominent and the mfp for decay of 3-6 meters allow for creating an intense neutral beam. Since the entire downstream is in vacuum, the detectors see only charged particles of less than about 50 GeV that are produced in the vacuum region. Of course there will be a burden of ambient singles rates due to the intense beam-on-target. If we can successfully "disappear" the primary proton beam, the sensitivity of the experiment will be limited by the rate of $\Lambda^0 \rightarrow p\,\pi^-$. Assuming the detector can handle a burden of $10^7$ charged particles/sec, this amounts to observing $\sim 10^{14}$ $\Lambda^0$'s with detected decays in an eight month run. Thus branching ratios of the order $10^{-13}$ can be detected. This requires about $10^{10}$ proton interactions per second. (It is nice to know that there is another factor of 100 to be gained.)

†L. M. Lederman

The arrangement starts with a 20% target at the entrance to a very powerful sweeping magnet. A schematic layout is shown in Figure 5. We assume we can use iron-assisted superconducting coils, adequately shielded from the target to produce a 2m long 10T horizontal bend. Uninteracted primary protons would be deflected horizontally by 7mr and emerge from the next stage, a 5m vertical plane bending magnet, deflected by 10cm. All lower momentum charged particles will be "buried" in the side walls of the long magnet.

At this stage of experimental design, we now assume a neutral beam with an "effective divergence" of $\pm$ 10mr and a mean momentum of 150 GeV/c produced by 900 GeV/c protons. This implies a gap in the apparatus positioned 4m downstream of the 5m-long magnet of $\pm$ 30cm.

The effective mass of $e^{\pm}\mu^{\mp}$ events in the hyperon decays is $\leq$ 200 MeV which gives the $e^{\pm}\mu^{\mp}$ pair an energy of 20 GeV and hence an opening angle of

$$\theta_{op} \sim \frac{200\,\mathrm{MeV}}{20\,\mathrm{GeV}} \leq 0.010 \tag{7}$$

The vertical deflection magnet produces a displacement:

$$y = y_o + 0.3H\left(\frac{x^2}{2p}\right) + \left(\theta_o + \frac{0.3Hx}{p}\right)\cdot(4\mathrm{m}) \tag{8}$$

where H is $\sim$ 1T and x varies from 5m to 0m. Most of the hyperons and $K_s^0$'s decay in the early part of the 5m flight path.

The kinematics of hyperon decay leads to a strong peaking of leptons at momenta <u>below</u> 30 GeV/c. The $K_s^0$'s products tail out to something like 80 GeV/c but if we have a cut off of 30 GeV/c, we still have a good collection efficiency.

Back of the envelope calculations indicate that the overall efficiency for detecting the pair of leptons in hyperon decay is $\sim$ 0.3 and this includes decay probability. Assuming the rate is limited by $\Lambda^0 \rightarrow p\pi^-$ decay, a branching ratio of $10^{-12}$ yields about 10 detected events, enough to confirm that the parent is hyperon-like in lifetime and kinematics.

The tracking, which locates the decay point in non-bend plane <u>and</u> measures the momenta, <u>must</u> be fast i.e. scintillating fibers. This is also true of the EM calorimeter which identifies electrons (pion rejection needs to be $\sim 10^5$), presumably some exotic and fast material e.g. BaF. If these work very well and if the shielding, vacuum, beam dump, etc., are well controlled there may be another factor of 10 available, i.e. good observations at $10^{-13}$, limits at $10^{-14}$.

Accidental $\pi$'s in each arm, misidentified as muons and/or electrons are the major sources of background. At $10^7$/sec, the accidental rate is $10^5$/sec. Simultaneous misidentifications reduces this to 1 per 1000 seconds and accidental copunctuality reduces this by another factor of $10^4$ with 100$\mu$m resolution in the decay point. This yields a few events per run. The accidental rate can be simultaneously monitored during the experiment. A large number of combination decays, e.g. $\Lambda^0 \rightarrow n\pi^0$; $\pi^0 \rightarrow e^+e^-\gamma$ combined with a charged $\pi$ decay-in-flight from another hyperon, all point to the need for excellent space resolution. One bucket time resolution is straightforward. A serious simulation is needed to confirm these guesstimates. Useful but insufficient conversations with experts Bill Luk and Bruce Winstein are acknowledged.

# 5 SEARCHING FOR TERRESTRIAL DARK MATTER WITH THE TEVATRON†

We ask; is there a large amount of gravitationally bound dark matter (with $M_D \sim 10\,GeV/c^2$, weakly or pseudo-weakly interacting)? We then outline a scheme for its detection using the Fermilab Tevatron.

Searching for direct evidence of dark matter has now become a growth industry. Indirect evidence for the existence of dark matter has been inferred from evolutionary kinematics associated with galaxy formation in the primordial universe and from observational data - e.g., galactic rotation curves, and velocity distributions in clusters and superclusters[30]. On aesthetic grounds, dark matter is also "wished for" in order to close the universe. It has lately been realized that dark matter within the mass range $5 \leq M_D \leq 10\,GeV/c^2$ and an interaction cross section with normal matter on the order of $\sigma_D \sim 10^{-36}\,cm^2$ could cool the sun sufficiently to "solve" the solar neutrino problem[31]. We have asked[32,33]: Why is there not dark matter trapped here on the earth and indeed present at/on the surface of the earth? The dark matter particle mass is limited on the one hand by evaporation in the lifetime of the local solar system ($M_D \geq 8\,GeV/c^2$) and by the need to have a finite but not dominating fraction of the mass of the earth ($M_D \leq 10\,GeV/c^2$). Recent claims[34] of radial deviations from Newton's inverse-square law of gravity can be alternatively interpreted as an indication of the presence of a local over-density of dark matter $\rho_D(r)$, rather than due to non-Newtonian "fifth-force" interactions. Such matter would be present as a dilute, weakly-interacting, all-pervasive "gas", co-existing with the normal matter on our own planet, very occasionally interacting (via $Z^0$ exchange) with normal matter at presumably an average thermal energy of $\sim$ 5-6000 K, otherwise only participating in the gravitational life of the earth. We propose that such matter could be detected by smashing particle beams into this "gas" of dark matter, presuming it to have a weak (or pseudo-weak) interaction (see Fig. 6). This report sketches such a scheme, and outlines some of the considerations and expectations.

We propose the use of a high energy beam of particles, such as the 1 TeV proton (or anti-proton) beam(s) in the Tevatron, in coasting mode. The use of coasting single $p$or $\bar{p}$beams has the distinct advantage of enhanced physics capability from consideration of the overall detector live time/data-taking in a continuous, rather than pulsed-mode operation (*e.g.* using an extracted beam to a fixed target experimental area). Conceptually, the circulating proton (or anti-proton) beam would pass through an ultra-high vacuum region in one of the straight sections of the Tevatron, instrumented as a $\sim$ 10 m long "active" region, in which the "target" is a "gas" of dark matter particles. The resulting collision products from proton-dark matter (and/or beam-gas) interactions would be detected in a $\sim 4\pi$ vertex-detection tracking system surrounding the beam pipe along its active length, and extending into the forward/backward regions in order to detect particles emitted at large rapidities. The capabilities of the vertex chambers must be sufficient to establish that the interaction vertex was indeed beam-induced. Immediately outside the vertex chamber system, a fine-grained, dense EM/hadron calorimeter (*e.g.* tungsten-scintillating fiber sandwich) instrumented with tracking could be used for the multiple tasks of $e/\pi$ separation, muon identification, measurment of the kinetic energies of charged and neutral

†S. Errede (Alfred P. Sloan Research Fellow, 1985-89) and H.R. Gustafson

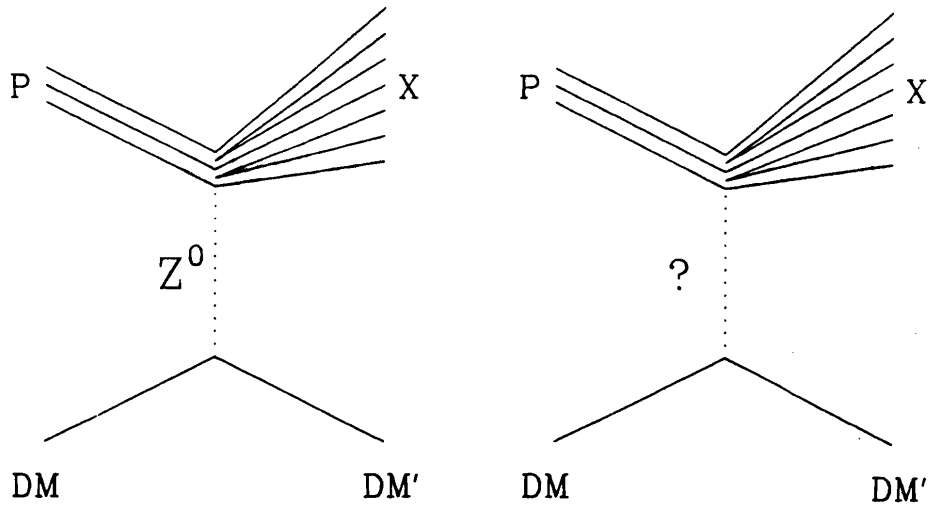


Figure 6. Dark-Matter - Normal-Matter Interactions

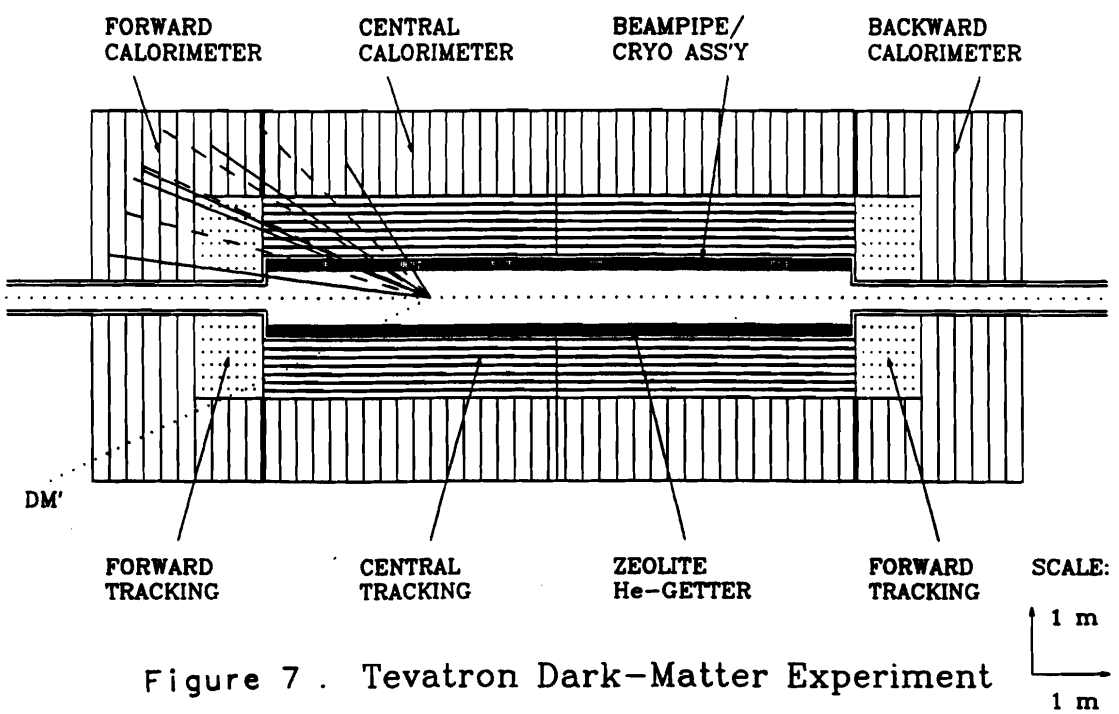


Figure 7. Tevatron Dark-Matter Experiment

collision products for individual particle measurement and overall measurement of $\not{E}_T$ (see Fig. 7). Use of a solenoidal magnetic field for track momentum analysis may also help to distinquish the signal from the background.

The principal limitations to this experiment are the local vacuum in the experimental region and the beam intensity. The local section of vacuum pipe could possibly be cooled to $1-2\,^{\circ}$K to improve the vacuum. A series of baffles define transition regions, which are ion- and cryo-pumped in the up- and down-stream beam pipes. These separate the main detection chamber from the relatively crude vacuum of the rest of the accelerator. Zeolite pumping for He gas removal is in each stage. Finally the whole internal system is designed for baking at 3-500 °C. We plan/hope to achieve effective number densities at the $10^{-15}$ to $10^{-20}$ atmosphere level.

In principle, this experiment is such that it *could* be run in collider mode with simultaneously counter-circulating $p$ and $\bar{p}$ beams. This experiment *is* compatible with operation of the conventional collider experiments, provided the $p$ and $\bar{p}$ beams passing through the straight-section DM interaction/detection region are well-separated from each other. Note that the use of electrostatic separators at the Tevatron in future runs will also be beneficial in this regard for the DM experiment. However, in practice, for optimum sensitivity for DM detection it is likely better to have a dedicated run with a series of single-beam proton-only stores in which *all* RF buckets (19 ns spacing) are filled. Single-beam stores of this nature could have several $10^{13}$ circulating protons with a resulting 1/10 amp of stored beam (i.e. $10^{18}$ protons/sec), provided that the beam losses in the Tevatron at this beam intensity are not large enough to cause the superconducting magnets to quench. For a good vacuum at the $10^{-15}$ atmosphere level, this implies beam-gas event rates of order a few per hour. We envisage initially using the proton (and/or antiproton) beam(s) in the Tevatron as a pressure gauge, then steadily and successively improving the local vacuum, thereby reducing the beam-gas background to a negligible rate.

A physics cross section on the order of $10^{-44} \leq \sigma_D \leq 10^{-36}\text{cm}^2$ is expected. This is $10^{-11}$ to $10^{-19}$ of the cross section for the strong interactions (*e.g.* beam-gas). Thus, the DM experiment has search-sensitivity in number density fraction x cross section on the order of $\sim 10^{-44}$. This corresponds to an event rate of a few per hour for a dark matter number density equal to that for normal matter at STP, *i.e.* about $2 \times 10^{19}$ particles/cm$^3$. The larger the dark-matter – normal-matter interaction cross section, the smaller the DM number density (and vice-versa) for a constant physics event rate .

# 6 STUDY OF THE GRAVITATIONAL FORCE PRODUCED BY RELATIVISTIC PARTICLES†

Recent improvements in technology have made it feasible to consider testing relativistic gravity using pure laboratory experiments, i.e. a laboratory gravitional source and a laboratory detector. Two bodies, moving with a relative relativistic velocity $\beta c$, impart a transverse gravitational impulse which increases with energy as $\gamma = 1/\sqrt{1-\beta^2}$ if gravity is a classical spin-two field as described by general relativity. For a general field with a propagator of spin s, the energy dependence goes as $\gamma^{s-1}$. Recalling that the impulse resulting from the electromagnetic interaction is independent of $\gamma$ lead the pioneers in this field[35,36] to consider, as a gravitational source, proton bunches in a

†Frank A. Nezrick

circular accelerator. The advantage of using an accelerator beam is that $\gamma$ can be varied to allow separating the electromagnetic and gravitational effects and by using circular accelerators, cyclic impulses can be integrated and powerful phase locking techniques can be utilized for signal detection. To date the only experiment of this style to be performed was Fermilab Experiment E-723 led by A. Melissinos[37,38]. This brief study follows the path of E-723 to explore what improved sensitivity might be expected from the improved properties of the Tevatron stored beam resulting from the new Main Injector and from possible detector improvements.

A source of mass m passing an observer of mass M with relative velocity $\beta c$ and impact parameter b produces on the observer a gravitational impulse[35,39]

$$\int_{-\infty}^{+\infty} \left(\frac{F}{M}\right) dt = \frac{2G_N m}{\gamma\beta c b} \cdot \left(1 + 2\gamma^2\beta^2\right) \tag{9}$$

For a circular accelerator, with N protons stored and a circulation time of $\tau$, giving a current $I = Ne/\tau$, and m being the proton mass, the time averaged acceleration of the observer is

$$\langle\frac{F}{M}\rangle = \frac{1}{\tau}\int_0^{\tau} \left(\frac{F}{M}\right) dt = \frac{2G_N I}{\gamma\beta c b} \cdot \frac{m}{e} \cdot \left(1 + 2\gamma^2\beta^2\right) \tag{10}$$

In the limit of large $\gamma$ :

$$\langle\frac{F}{M}\rangle \simeq 4\frac{m\gamma c}{b} \cdot \left(\frac{G_N}{2}\right) \cdot \left(\frac{I}{e}\right). \tag{11}$$

What average acceleration is expected using the Tevatron Collider with the new Main Injector? Assuming a six-bunch on six-bunch operation at 1 TeV and a proton and antiproton single bunch intensity of $6 \times 10^{10}$, the (observer) detector located in a collision straight section 1 cm from the beam will receive at a frequency of 286 kHz average accelerations of[40]

$$\langle\frac{F}{M}\rangle \simeq 5.8 \times 10^{-22}\ \mathrm{cm/sec^2} \tag{12}$$

Can these infinitesimal accelerations be detected? The detector used by E-723 was a microwave parametric converter[41], which operated at 10 GHz. The converter consisted of two coupled superconducting cavities[42]. The cavity coupling was designed[43] so that the difference between the frequencies of the two electromagnetic converter modes was equal to the cavity mechanical resonance frequency and also equal to the frequency (or one of its harmonics) with which the proton bunches produce gravitational impulses to the endwall of the cavity. If the cavities have a mechanical quality factor $Q_m$, the endwall has a mass M and is a distance b from the beam, and the desired impulse frequency is $\omega$ then the endwall maximum harmonic displacement is

$$\Delta x = \langle\frac{F}{M}\rangle \cdot \frac{Q_m}{\omega^2} = 7 \times 10^{-26}\ \mathrm{cm} \tag{13}$$

for $\omega = 286$ kHz, $Q_m = 10^7$, and the value from Eq. (12). This displacement is reached after time $\Delta t = Q_m/\omega = 35$ sec.

Can the displacement of Eq. (13) be detected? E-723 measured a displacement of $3 \times 10^{-17}$ cm with $\omega = 1.137$ MHz (26th harmonic) and $Q_m \simeq 1000$. Assuming

this displacement sensitivity, the shortfall in observing the relativistic gravitational effect from Eq. (13) expressed as a ratio of coupling limit to gravitational constant is

$$\frac{G_{limit}}{G_N} < \frac{3 \times 10^{-17}\,\mathrm{cm}}{7 \times 10^{-26}\,\mathrm{cm}} = 4 \times 10^{8} \tag{14}$$

What improvements can be made in the experimentally measured displacement? The cavity electrical quality factor can be increased from $7 \times 10^8$ to $5 \times 10^{10}$ giving $\times 70$. The microwave energy stored in the lower converter mode can be increased to the maximum allowed for a Type II superconductor giving $\times 10$. Improving the front end microwave hardware and use of a low noise cryogenic GaAs FET amplifier gives $\times 10$. These overall improvements could give a displacement sensitivity of $\Delta x \simeq 3 \times 10^{-17}\,\mathrm{cm}/7000 = 4 \times 10^{-21}\,\mathrm{cm}$, resulting in

$$\frac{G_{limit}}{G_N} < 6 \times 10^{4} \tag{15}$$

Can such a sensitive measurement be realized? The most serious fundamental[44)] background appears to be thermal excitation of the mechanical resonator of the parametric converter. Since the excitation (beam) frequency is fixed, the thermal noise contribution of the converter can be reduced by decreasing the detection frequency band width. This increases the measuring time t since the band width is proportional to $1/t$. If the detector is at temperature T then the effective displacement of the converter endwall by thermal excitation is

$$\Delta x_T = \langle \frac{F}{M} \rangle_T \cdot \frac{Q_m}{\omega^2} = \left[ \frac{8kT}{M} \cdot \frac{Q_m}{\omega^3} \cdot \frac{1}{t} \right]^{1/2} \mathrm{cm} \tag{16}$$

Using the above described detector operating at 0.1 °K, with $M = 1$ kg, phase summing runs totaling $t = 2 \times 10^6$ sec gives $\Delta x_T = 5 \times 10^{-18}$ cm. The thermal excitation therefore overshadows the improved displacement sensitivity of $4 \times 10^{-21}$ cm. Using Eqs. (11), (13), and (16), the relativistic Newtonian signal to thermal background displacement ratio is:

$$\frac{\Delta x_N}{\Delta x_T} \propto \frac{I}{b} \left[ \frac{M}{T} \cdot \frac{Q_m}{\omega} \cdot t \right]^{1/2} \tag{17}$$

Further improvement factors, although quite difficult, could be from I($\times 4$), b($\times 2$), M($\times 4$), T($\times 20$), $Q_m$($\times 200$ using sapphire crystal), and $\omega$($\times 6$ going to the Tevatron fundamental frequency). The total super–optimistic, super–difficult improvement factor could be $4.3 \times 10^3$, giving a thermal noise displacement of $1.2 \times 10^{-21}$ cm. This nicely matches the displacement sensitivity of the improved detector described above; however, it is still 60,000 times too insensitive to measure the effect of relativistic Newtonian gravity. Nevertheless theories of gravitation with field propagators of spin greater than three can be ruled out (or detected) and long range weak interactions can be ruled out for interactions $10^{28}$ times weaker than the conventional weak interaction.

# 7 INTERMEDIATE MASS HIGGS PRODUCTION AT THE UPGRADED TEVATRON†

We report on predictions for Higgs production at the Tevatron Collider at upgraded luminosities of order $5 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$ in the mass range above about 50 GeV, out of range of decays of the $Z^o$, but below the $2W$ mass threshold. We also assume the top quark mass is above the $Z^o$ mass, so that a Higgs in this mass range won't decay to $t\bar{t}$. This is a difficult mass range because the dominant Higgs decay modes are hard to identify and the backgrounds are very large. In this study we considered two decay modes, the two gamma decay which is of order $10^{-3}$ branching ratio at best and the $2\tau$ decay which is somewhat larger. Fig. 8 shows branching ratios[45)] under the above stated assumptions. Backgrounds to the two gamma mode are large. Those considered are the continuum production of gamma pairs[46)] and single and double quark bremsstrahlung[47)]. Misidentification of $\pi^o$'s depends on details of the detector and must be simulated. Backgrounds to the $2\tau$ decay mode are much smaller. Fig. 9 shows the Drell-Yan continuum of $\tau$ pairs[48)]. A Higgs near the $Z^o$ mass, however, will be hard to see in this decay mode. It is difficult to reconstruct $\tau$'s in hadronic final states due to missing neutrinos. Techniques suggested for the SSC[49)] were investigated to see if they might work better at lower energies. One first selects narrow jets hoping to separate $\tau$'s from the jet background. The narrow jet allows one to accurately determine the $\tau$ direction. Thus, given the direction of each of two $\tau$'s and the vector sum of the $p_T$ of the rest of the event, the momenta of the two $\tau$'s can be determined and thus the $\tau\bar{\tau}$ invariant mass. We hoped that for a given Higgs mass the experimental resolution might be better than at the SSC because less $p_T$ from the rest of the event will be lost down the beam holes. Still the resolution is quite poor. Selecting $\tau$ decays with $\geq 3\pi$'s, to give an estimate of the $\tau$ momentum[49)], leads to an overconstrained $\tau\bar{\tau}$ invariant mass estimate, but the experimental mass resolution is only marginally better.

Diagrams leading to the Higgs production cross section in $p\bar{p}$ collisions for Higgs masses under consideration here are shown in Fig. 10. There is a tricky double counting between the diagrams which must be subtracted out, but a reasonably accurate estimate is obtained by considering the $2 \rightarrow 1$ two gluon diagram alone[50)]. Fig. 11 shows the Higgs production cross section at 2 TeV under a range of assumptions. At a luminosity of $5 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$, the number of produced Higgs in a nominal year-long run ($10^7$ sec) (assuming $\sigma = 1$ pb) is 100. So there will be about 0.1 two gamma decays (on a large background) and around 4 (at best) di-$\tau$ decays, on a non-negligible background. Hence, it appears that the event rate is too low to discover a Higgs in this mass range via these decay modes at an upgraded Tevatron.

# 8 NEW PHYSICS OPPORTUNITIES WITH POLARIZED BEAM IN THE MAIN INJECTOR†

The apparent ease with which polarized beam could be accelerated in the Main Injector opens up a range of Physics opportunities. The issue of the spin content of the proton could be addressed with fixed target experiments using beams from the Injector

†J. Rutherfoord and M. Shupe

†David Underwood

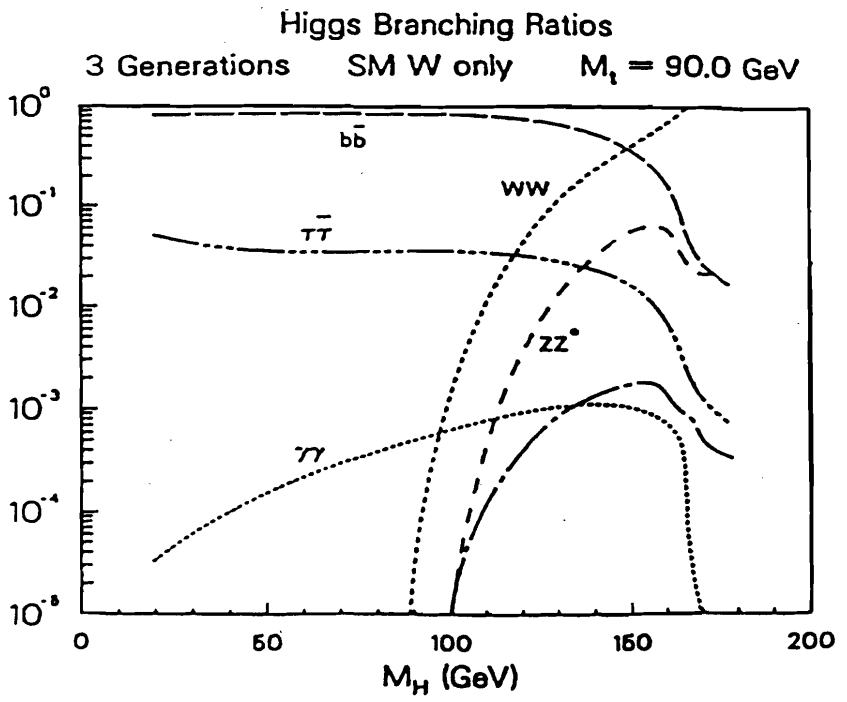


Fig. 8. Decay branching ratios for a standard model minimal Higgs as a function of the unknown Higgs mass. From Ref. (1)

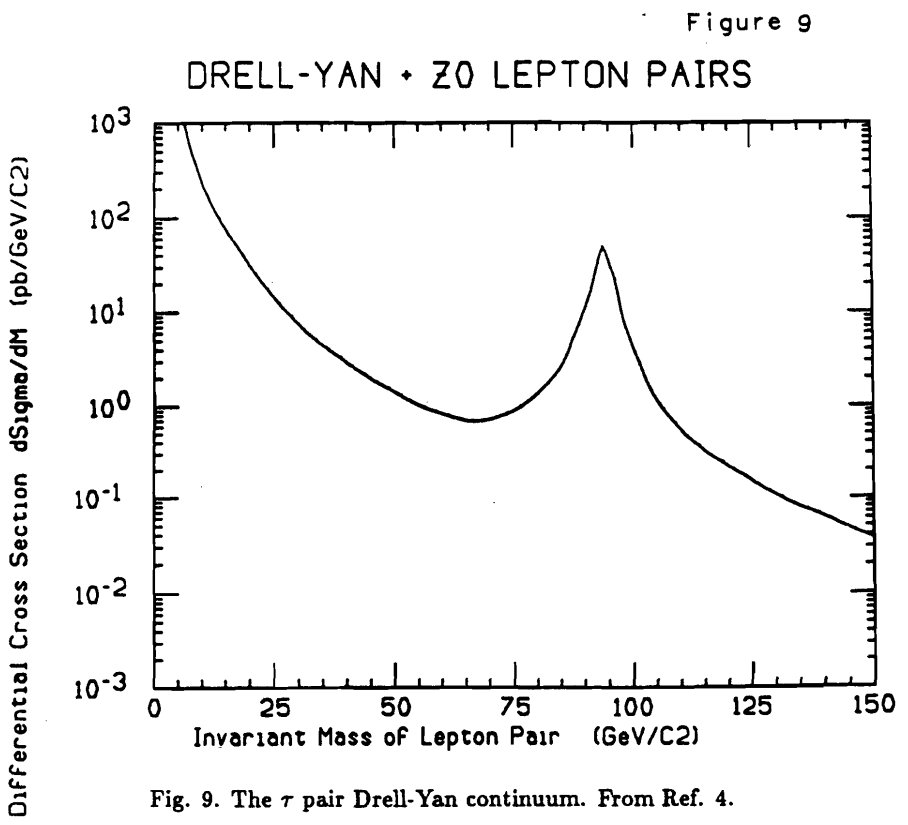


Fig. 9. The $\tau$ pair Drell-Yan continuum. From Ref. 4.

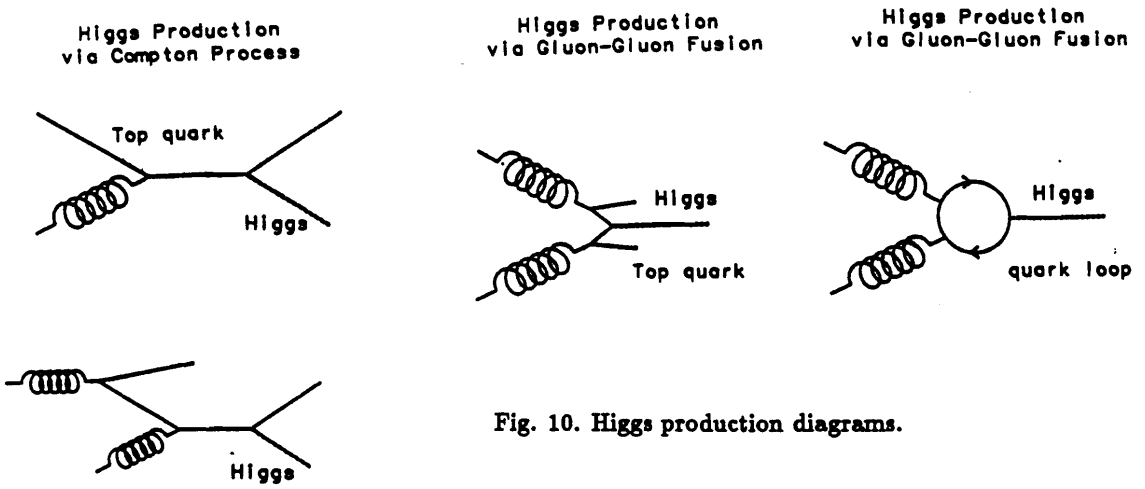


Fig. 10. Higgs production diagrams.

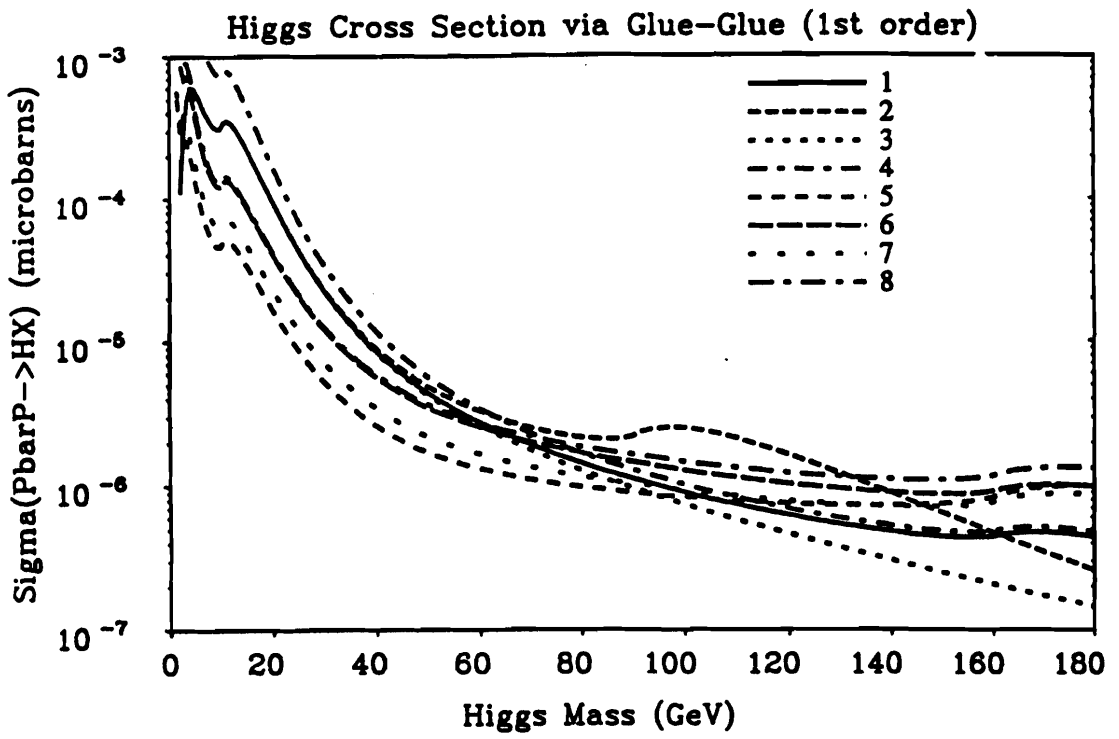


Fig. 11. Higgs production cross section in 2 TeV $p\bar{p}$ collisions.
The curves all have slightly different assumptions:

1.) Duke-Owens SF Set 1 (DO1), $m_t = 80\,GeV$, $\Lambda = 0.2\,GeV$.
2.) Same as 1 but $m_t = 45\,GeV$.
3.) Same as 1 but $m_t = 200\,GeV$.
4.) Same as 1 but DO2.
5.) Same as 1 but $xG(x) = 3(1-x)^5$.
6.) Same as 1 but $xG(x) = 5.5(1-x)^{10}$.
7.) Same as 1 but $xG(x) = 4.5(1-x)^8$ and $\Lambda = 0.1\,GeV$.
8.) Same as 7 but $\Lambda = 0.4$ GeV.

and the Tevatron. Experiments requiring energy and intensity even beyond that available with upgrades of the existing Fermilab polarized beam could be done. Also, the search for supersymmetric partners could be greatly enhanced with polarized colliding beams.

There are experiments with polarized protons which can address the issues of the gluon and anti-quark contributions to the spin of the proton much more directly than deep inelastic scattering with leptons[51,52,53]. The Drell-Yan and direct photon experiments were discussed extensively in the QCD section at this Workshop[54,55]. These experiments require both polarized beam and polarized target. It appears that the energy and intensity directly from the Injector are a good match to the kinematics and cross section for Drell-Yan. The energy of the Tevatron is a good match to the Direct Photon experiment. Also, there may be single spin experiments which can address the relationship between intrinsic $k_t$ and orbital angular momentum[56,57].

The straight sections in the proposed Main Injector open up the possibility of using spin precession snakes which are needed to accelerate polarized beam to 120 GeV[58,59,60]. Acceleration of polarized beams in the Tevatron has been the subject of several studies and also looks quite feasible if portions of two straight sections are available for snakes[58,59,60]. The polarized source has been used at ZGS, AGS, KEK, LAMPF, SATURNE, etc. In designing new transfer lines from Linac to Booster, Booster to Main Injector, Injector to Tevatron, etc., consideration should be given NOW to insuring that transmission of polarization is not precluded. Some more details are given in a report from the Fermilab Injector Workshop[61].

There is a paper[62] which points out that all 2-to-2 processes involving supersymmetric partners have the opposite two-spin asymmetry of the usual 2-to-2 processes. In the low squark, gluino, etc. mass limit most of these asymmetries are -1. Even at masses large on the scale of present colliders, the effects appear to be easily observable at low rapidity. This could be a major motivation for the upgrade of the collider to proton-proton collisions if no efficient way is found to obtain polarized anti-protons. This would be an exciting experiment.

There is also mention in the literature of ways to investigate electroweak interactions (left and right handed) and compositeness (parity violating at sub-quark level) with one polarized beam and one unpolarized beam[51,60].

While certain experiments can be done to some level of accuracy by using an unpolarized beam on a polarized target, there are two major advantages to a polarized beam. For single spin measurements the unpolarized background to polarized target materials is eliminated. Two spin measurements can only be done with both the beam and target (or other beam) polarized. The major advantage of accelerating polarized beam for fixed target experiments is to get higher beam intensity than is possible with upgrades of the present Fermilab polarized beam.

The straight sections in the proposed Main Injector open up the possibility of using spin precession snakes which are needed to accelerate polarized beam to high energy. At 120 GeV one can do the Drell-Yan experiment with polarized beam and target and gain experience with snakes for the Tevatron, HERA, SSC, etc. Polarized beam from the Tevatron would be good for a direct gamma experiment and various existing experiments at Fermilab. A good way to look for supersymmetry in a large background would be to exploit the opposite sign of the two spin asymmetry relative to ordinary processes in a

collider experiment.

# 9 THE CASE FOR A MUON STORAGE RING†

The $\mu$ lepton is in most respects a heavy electron. Whether it is more than that must be the subject of future studies. We explore here the feasibility of constructing a storage ring for muons.

The Tevatron produces beams of $\pi$'s that could be injected into a storage ring. Depending on the average dipole field in the ring, it is possible to achieve much higher integrated luminosities than with a single-pass beam.

Consider the following example. A negative beam of 500 GeV/c $\pi$ is injected into a ring with an average dipole field of 4T, which corresponds to a ring radius of 417 meters. The mean life of a 500 GeV/c $\pi$ is 500 $\mu$s. The $\pi$'s will on average go around the ring 10 times before decaying. If the acceptance of the ring, $\Delta P/P$, is of order 10% then about 15% of the decay $\mu$'s will be captured in the ring. This means if we start with $2 \times 10^9$ we might end up with $3 \times 10^8$ $\mu$'s in the ring. The mean life of a 500 GeV/c $\mu$ is 10 ms so that a $\mu$ will on average go around 1146 times before it decays. Thus a target in the ring can be traversed on order 1000 times per beam load. If our target has a thickness of 50 g/cm$^2$, then each muon will traverse $5 \times 10^4$ g/cm$^2$ of material unless it scatters out of the beam. The ionization energy loss would be about 50 GeV for a light target material. With a beam of a few x $10^8$ $\mu$'s a large interaction rate could be achieved with relatively thin targets. After a few turns around the ring the beam would be an equal mixture of $\mu_L$ and $\mu_R$ so far as the helicity of $\mu$'s is concerned. This means that one might expect roughly 20 charge-changing weak interactions per storage ring load.

The number of ring traversals depends on the average dipole field, B, according to the relation:

$$N = \frac{0.3\, c\, \tau_o\, B}{2\, \pi\, m_o} \tag{18}$$

where B is in Tesla, $\tau_o$ is the lifetime of the particle, and $m_o$ is its mass in GeV/c$^2$.

A 500 GeV/c $\mu$ beam incident on a thin fixed target inserted into the storage ring could be used to an advantage for a number of measurements. The main interaction rate would come through the coupling to the electromagnetic field. The resulting beams could be used for precision determination of structure functions, or one could utilize the beam, through vector meson dominance effects, to generate large numbers of particles such as $\rho^o$, $\omega^o$, $\phi^o$, and $J/\psi$.

The useful target thickness would be determined by the effective mean free path of the $\mu$ in the material. In carbon, for example, a $\mu$ would have a mean free path for nuclear interaction of $5 \times 10^5$ g/cm$^2$. A 50 g/cm$^2$ target would result in about 10% of the $\mu$'s interacting with the nuclear matter of the target. A 50 g/cm$^2$ lead target would degrade the energy of the $\mu$'s by a factor of $\sim$ 2x after 400-500 traversals, mainly as a result of bremsstrahlung. The multiple coulomb scattering in the target would also be quite devastating.

A storage ring for $\mu$'s seems to be technically feasible and quite useful. However, because of its size, it would be quite expensive. It is also not obvious how one might cool the beam in a thousand turns. A diffuse beam would be useful for fixed target experiments

†W. D. Walker

at $\sqrt{s} = 32$ GeV. At that energy, one would have a beam of particles that interacted primarily through the medium of the electromagnetic field. It would thus be competitive with something like a tagged photon beam. The intensities would be higher, but the physics done would be similar. The advantage of studying $e - p$ or $\mu - p$ collisions is that there is relatively little hadronic spray in the direction of the incoming lepton. The chances of finding something startling in a fixed target mode, such as an excited state of the $\mu$, would seem to be quite small in view of the g-2 results.

Exercising the option of building something like this ring depends on some kind of technical breakthrough like the capability of building 20T magnets or putting the ring in a modest-size sewer pipe.

I wish to acknowledge several useful conversations with Fred Mills, Vernon Barger and Alan Martin.

## References

1. M.B. Voloshin *et al.*, *Zh. Eksp. Teor. Fiz.* **91** (1 986) 754.
2. B.W. Lee and R.E. Shrock, *Phys. Rev.* **D16** (1977) 1444.
3. K. Fujikawa and R.E. Shrock, *Phys. Rev. Lett.* **55** (1980 ) 963.
4. G.V. Domogatskii *et al.*, *Sov. J. Nucl. Phys.* **12** (1971) 678.
5. L.B. Okun, *Leptons and Quarks*, North-Holland, 1982.
6. F. Reines *et al.*, *Phys Rev. Lett.* **37** (1976) 315.
7. R. Davis, Jr. *et al.*, *Phys. Rev. Lett.* **20** (1968) 1205.
8. J.N. Bahcall *et al.*, *Rev. Mod. Phys.* **54** (1982) 7 67.
9. R. Davis, Jr., in *Proceedings of the Seventh Workshop on Grand Unification*, Toyama, Japan, 1986 (p.237-276).
10. M. Fukugita *et al.*, *Phys. Rev. Lett.* **58** (1987) 1 807.
11. K.S. Bahu *et al.*, *Phys. Rev. Lett.* **63** (1989) 228 .
12. M. Leurer, M. Golden, *FERMILAB-PUB 89/175-T.*
13. M.V. Diwan, *A study of the Weak Neutral Current and the Electromagnetic Properties of the Muon Neutrino*, Ph.D. thesis, Brown University (1988).
14. P. Sutherland *et al.*, *Phys. Rev.* **D13** (1976) 2700 .
15. D.C. Carey and V.A. White, *FNAL internal report, NUADA*, June 1975.
16. A. Malensek, *Fermilab Internal memo FN-341*, July 15, 1982.
17. Linac Upgrade, *Fermilab, July 1989.*
18. V. Bharadwaj and S. Holmes, *private communication.*
19. H. Primakoff, Phys. Rev. 81, 899 (1951).
20. D. Alde, et al., Phys. Lett. B205, 397 (1988); F. Iddir, et al., Phys. Lett. B205, 564 (1988); S.F. Tuan, T. Ferbel, R.H. Dalitz, Phys. Lett. B213, 537 (1988); H.J. Lipkin, Phys. Lett. B219, 99 (1989); F.E. Close, H.J. Lipkin, Phys. Lett. B196, 245 (1987); Proc. of Brookhaven Workshop on Glueballs, Hybrids, and Exotic Hadrons, AIP Conf. Proc. 185, S.U. Chung, ed. (1988).

21. F. deViron, J. Govaerts, Phys. Rev. Lett. 53, 2207 (1984); J. Govaerts et al, Nucl. Phys. B248, 1 (1984); J. Latorre et al., Phys. Lett. B147, 171 (1984); T. Barnes, F. Close, F. deViron, Nucl. Phys. B224, 241 (1983); N. Isgur, R. Kokoski, J. Paton, Phys. Rev. Lett. 54, 869 (1985); J.M. Cornwall, S.F. Tuan, Phys. lett. B136, 110 (1984); J.I. Balitsky, D.I. Diakonov, A.V. Yung, Phys. B112, 71 (1982); M. Chanowitz, S. Sharpe, Nucl. Phys. B222, 221 (1983); M. Tanimoto, Phys. Rev. D27, 2648 (1983).
22. T. Barnes, Proc. XVIII Moriond Conf. on Gluons and Heavy Flavors (La Plagne, 1983), P. 525; Reviews by F.E. Close, by S. Godfrey and by N. Isgur in Proc. of BNL Workshop (1988), loc. cit.
23. M. Zielinski, in *Glueballs, hybrids and exotic hadrons* (see ref.2).
24. S.F. Tuan et al., PL B 213, 537 (1988)
25. D. Berg et al., PL 98B, 119 (1981), S. Cihangir et al., PL 117B, 119 (1982), B. Collick et al., PRL 53, 2374 (1984), T. Jensen et al., PR D27, 26 (1983), J. Huston et al., PR D12, 1129 (1986),
26. M.Zielinski et al., Z.Phys.C. 31, 545 (1986)
27. D.Berg et al., Proc. XVI Recontre de Moriond on New Flavors and Hadron Spectroscopy, p. 373 (1981), T.V. Tran, ed.
28. Review of Particle properties, Particle Data Group, PL B204, 1 (19 88)
29. J.F. Donoghue and B.R. Holstein, PR D40, 2378 (1989)
30. For review articles on dark matter, see *e.g.* J. Rich, D. Lloyd Owen and M. Spiro, Phys. Rep. **151**, 239 (1987); and B. Sadoulet, in the Proceedings of the SLAC Summer School, 277 (1987).
31. D.N. Spergel and W.H. Press, Ap. J. **294**, 663 (1985); G. Steigman, C.L. Sarazin, H. Quintana and J. Faukner A. J. **83**, 1050 (1978); W.H. Press and D.N. Spergel, Ap. J. **296**, 679 (1985); and R.L. Gilliland, J. Faulkner, W.H. Press and D.N. Spergel, Ap. J. **306**, 703 (1986).
32. H.R. Gustafson, University of Michigan internal memo UM-89-32.
33. S. Errede, University of Illinois internal memo UI-89-4.
34. D.H. Eckhardt *et al.*, Phys. Rev. Lett. **60**, 2567 (1988); M.E. Ander, *et al.*, Phys. Rev. Lett. **62**, 985 (1989); F.D. Stacey, *et al.*, Rev. Mod. Phys. **59**, 157, 1987; S.C. Holding, F.D. Stacey and G.J. Tuck, Phys. Rev. **D33**, 3487 (1986); F.D. Stacey, G.J. Tuck and G.I. Moore, Phys. Rev. **D36**, 2374 (1987); and F.D. Stacey, G.J. Tuck and G.I. Moore, J. G. R. **93**, 10, 575 (1988).
35. V. Braginsky, C. Caves, and K. Thorne, Phys. Rev., 15D, 2047 (1 977).
36. A. C. Melissinos, Il Nuovo Cimento, 62B, 190 (1981).
37. A. C. Melissinos, et al., "Test of a Gravitational Detector at th e Tevatron Collider," October 1982.
38. Reiner, P. et al., Phys. Lett. 176B, 233 (1986).
39. It will be assumed that gravity is a tensor classical field (s=2) as described by general relativity.
40. Using $I/e = N/\tau$ where N is the proton plus antiproton intensity per bunch, $\tau$ being 1/6 of the proton circuit time, and $G_N/c^2 = 0.7 \times 10^{-28}$ cm/gm.
41. Reece, C., Reiner, P., and Melissinos, A. C., Phys. Lett., 104A, 3 81 (1984).
42. Bethe, H. A., Phys. Rev., 66, 163 (1944).

43. Reece, C. E., Ph.D. Thesis, U. of Rochester Report UR-867 (1983), (unpublished).
44. The electromagnetic interaction between beam and detector is not considered fundamental.
45. J.F. Gunion *et al.*, Nucl. Phys. **B299**, 231 (1988).
46. See Ref. 1 and D. Dicus and S. Willenbrock, Phys. Rev. **D37**, 1801 (1988) and references therein.
47. H. Baer and J.F. Owens, Phys. Lett. **B205**, 377 (1988).
48. S. Errede, CDF Internal Memo CDF/MUON/PHYS/PUBLIC/524 July 1987.
49. D.M. Atwood *et al.*, "Intermediate Mass Higgs Boson(s)", in Experiments, Detectors, and Experimental Areas for the Supercollider, Ed. R. Donaldson and M.G.D. Gilcriese, p 728, Berkeley, 1987.
50. J.F. Gunion *et al.*, Nucl. Phys. **B294**, 621 (1987).
51. N.S. Craigie et al., Phys. Rep. 99, (1983).
52. Proc. of the Symp. on Future Polarization Physics at Fermilab, (June, 1988).
53. Proc. of VIII Int. Symp. on High Energy Spin Physics, AIP Conf. Proc. 187, Particles and Fields 37, (1989).
54. See Summary of QCD/Electroweak Section by M.Corcoran, these proceedings.
55. See introductory talk by E. Berger, these proceedings.
56. E. Berger and J. Qiu, ANL-HEP-PR-88-64 (1988).
57. D. Sivers, ANL-HEP-PR-89-32 (1989).
58. L. Teng, FNAL-TM-1559-Revised (1988).
59. Workshop on Snakes and Accelerated Polarized Beams, AIP Conf. Proc. 187, Particles and Fields 37, (1989).
60. Polarized Beams at SSC, AIP Conf. Proc. 145, Particles and Fields 34, (1985).
61. Report from the Polarization Group of the Fermilab Main Injector Workshop, (July 1989).
62. N.S. Craigie, K. Hidaka, P. Ratcliffe, Phys. Lett., 129B, 310, (1983).