Cost estimates for the coming five years are:

2001	$450,000	Operating
2002	$485,000	Operating
2002	$200,000	Equipment (computing)
2003	$499,000	Operating
2004	$515,000	Operating
2005	$530,000	Operating

Priorities for partial funding

Fixed costs include:

Graduate and summer or Co-op students	$88,000
Liquid Helium and Chamber gas	$83,000 or more
Research Associates	$145,000
Data tapes	$40,000
Subtotal:	$356,000 or more

Savings on cryogenic costs are difficult to achieve, since the cost of warming and the subsequent cooling of the magnet is approximately $15,000. It is probably most cost effective to leave the magnet cold for the duration of the experiment. We have also been warned that the price of liquid helium can be expected to be higher in 2002.

Discretionary spending includes computing, development (related primarily to $P_\mu \xi$), field trips, and conferences.

If funding is reduced below the requested amount, those items itemized above (students, research associates, consumables, and data tapes) will not be adjusted, with the possible exception of the expenditure on data tapes. This could, however, result in the requirement of additional time to complete the program. Discretionary items that would be delayed include all development costs which do not relate directly to the measurements of ρ, δ, and η. A reduction of $25k per year would probably jeopardize our ability to achieve a measurement of $P_\mu \xi$.

Our projected budget is already minimal when compared with other projects.

Budget time-scale preferences

We prefer a three year budget, but if we do not receive the full amount requested we would prefer a one year award. A one-year award would be less efficient for both the collaboration and for NSERC, but a budget of less than about 95% of the requested level would jeopardize the success of the experiment.

1) Give the size and groups of the non-Canadian part of the collaboration, responsibilities and funding situation.

The American Group comprises nine individuals plus technical staff from two institutions. Operating funds come from the DOE through grants to each institution. Funding is on a three-year cycle, with the present funding in place through November, 2002. Capital funding of $300k ($US) was used to purchase TDC's, chips for the production of analogue readout units to be used in conjunction with the TDC's, lamels for the wire chamber construction, and the fabrication of miscellaneous parts for use in the wire chambers.

Texas A&M

Bob Tribble, Professor
Physics analysis co-coordinator
Carl Gagliardi, Professor
WC response group coordinator
John Hardy, Professor
Physics analyses and WC response
Maxim Vasiliev, Research Associate
GEANT MC
Jim Musser, PhD Student
Preliminary determination of ρ, WC fabrication, tracking

Valporaiso University

Donald Koetke, Professor
Alignments coordinator
Shirvel Stanislaus, Professor
Alignments group
Paul Nord, Systems Programmer
Software, calibrations
Danny Allen, Technical Staff
WC fabrication

The Russian Group (KIAE) provided the glass frames on which the chambers are strung, and the precision ground glass-ceramic citals that form the backbone of the detector. Funding is presently approximately $25k per year. We use NSERC funds to help with visits to TRIUMF.

Vladimir Selivanov, Research Scientist
Systematics
Vladimir Torkhov, Research Scientist
WC fabrication
Arkadi Krchinsky, Research Scientist
Response studies

2) Provide an update on the construction status.

Recent Milestones achieved:

Yoke delivery:	8 December 2000
Yoke assembly completed:	22 December 2000
Yoke alignment:	mid January 2001
Solenoid alignment:	mid January 2001
Solenoid commissioning: magnet cool down	beginning 5 February 2001
38 DC and 4 PC wire planes strung (of 56)	as of the end of January
Final post-amps completed and delivered	January, 2001
Initial batch of 120	October, 2000
100 preamps completed and delivered	January, 2001
Cradle fabrication completed	February, 2001
First cosmic ray events in six plane stack	November, 2000
First cosmic ray events in dense stack (8 planes)	January, 2001

2a) What are the risks involved with using DME? What would be the loss in performance in using a CO2 based gas?

DME RISKS

The attached table compares some of the risks associated with DME to isobutane and CO2.

FLAMMABILITY

The dangers posed by DME are quite similar to those of the more commonly used isobutane. Safety protocols developed for isobutane gas mixtures are adequate, and will be employed for DME usage in wire chambers.

TOXICITY

DME, isobutane and CO2 can all cause unconsciousness and death if a person is exposed to high concentrations for a sufficient length of time. Isobutane and DME are more insidious in that they both depress the central nervous system and can lead to a sense of euphoria and a loss of judgment before rendering the victim unconscious. Enclosed spaces where there exists the potential for venting large quantities of these gasses should be actively ventilated with air.

MATERIALS COMPATIBILITY

There are some contradictions between various sources listing the compatibility of DME and isobutane with various materials. However there is general consensus that DME attacks many elastomers and is absorbed into some plastics. Isobutane is less aggressive than DME, but it also attacks some elastomers and is absorbed into some plastics. Buna-N is recommended as the common elastomer most resistant to both DME and isobutane.

Materials exposed to gas in the TWIST wire chambers include glass, G-10, various epoxies, brass, gold, aluminum, tin-lead solder, Mylar, Buna-N and latex. In the gas system materials exposed include stainless steel, copper, brass, nickel, gold, glass, silicon, silicon nitride, aluminum oxide, Buna-N, Kalrez, polyethylene, Teflon, natural rubber, epoxy and polyetherimide.

All materials used in the wire chambers and the gas system have been tested in DME for periods ranging from 2 or 3 months up to 2 years. Observations of performance during exposure, and visual inspection after exposure have not revealed any serious problems with these materials. We are currently testing a complete prototype chamber in DME, and will continue this test for several more months.

Although some sources list natural rubber as unsuitable for use with both DME and isobutane, it has been used in line regulators in isobutane gas systems at TRIUMF for 20 years, and continuously in a DME gas system for more than 2 years with no obvious loss in performance of either the line regulators or the wire chambers supplied by the gas systems.

AGEING

We have conducted extensive ageing tests with DME. Single-wire wire chambers (SWC) were exposed to a strong source yielding ionization current densities ranging from 200 nA/cm-wire down to 10 nA/cm-wire. To test exposure to the various materials used in our chambers and gas system, the DME was passed through a device containing the material to be tested, located at the gas input of the SWC. The SWC's were periodically scanned with a 55Fe x-ray source to measure any degradation of gain in the area of the wire exposed to the source. Ageing damage is expressed as the percentage change in gain per ionization charge per centimeter of wire (%/C/cm-wire). The attached table shows some of the results.

Some of the materials (RTV, urethane, Kapton tape, ultraviolet cured epoxy) exhibited significant damage and were dismissed from consideration for use in the chambers or gas system. All of the materials which will be exposed to gas in the chambers and gas systems caused damage rates of less than 100%/C/cm-wire. The "worst case" estimate of total deposited charge to the central area of a TWIST chamber during the lifetime of the experiment is ~ 0.1 C/cm-wire. Thus a linear extrapolation of our worst case ageing damage would indicate ~ 10% reduction in pulse height at the end of the experiment.

We have not tested isobutane or CO2 gas mixtures. However, several years ago, using the same apparatus and techniques we conducted extensive tests of argon/ethane gas mixtures. We observed that the current density employed during ageing of the chambers dramatically affected the damage rate. Test at high currents (>800 nA/cm-wire) would produce almost no permanent gain reduction, while tests at low currents (<100 nA/cm-wire) would produce damage rates > 100%/C/cm-wiire. With argon/ethane at currents of 50 nA/cm we observed damage rates up to 1200%/C/cm-wire, significantly greater than the 6%/C/cm-wire and 100%/C/cm-wire observed in 2 separate tests with DME at 10 nA/cm-wire. The other entries marked with a * in the attached table have been summarized (J.Kadyk, NIM A300(1991) 436-479), and generally involved using high ageing currents > 500 nA/cm.

From the tests we have done, we would conclude that DME is likely to be more resistant to ageing damage than many of the more common gas mixtures currently in use in wire chambers.

CO2 PERFORMANCE CONSIDERATIONS

The gas used in the TWIST drift chambers must provide excellent resolution in the 2 Tesla magnetic field and excellent efficiency in the thin (4 mm) planar drift chambers. DME with its low drift velocity, small Lorentz angle, reasonably low Z, high primary ionization, low longitudinal diffusion and excellent quenching ability is admirably suited to the task. The requirement of low Z rules out argon based CO2 mixtures, and neon based mixtures would be too expensive. We suspect that helium/CO2 mixtures would be insufficiently quenched, and the low primary ionization could lead to efficiency problems. We have been conducting some tests with helium/isobutane 70:30, and intend to do some trial runs with the TWIST apparatus in the 2 Tesla field to compare the resolution and efficiency obtained to that obtained with DME. There may also be some possibilities of using helium/isobutane/CO2 or helium/DME mixtures. More complete data on all the relevant characteristics of these gas mixtures would first need to be obtained.

DME RISKS

FLAMMABILITY

	DME	ISOBUTANE	CO2
LEL	3.4%	1.8%	Non Flammable
UEL	27.0%	8.4%	
AUTOIGNITION	350 °C	480 °C	
SPECIFIC GRAVITY	1.59	2.00	1.52

TOXICITY

	DME	ISOBUTANE	CO2
TLV	N/A inflammation ocular membranes powerful narcotic unconsciousness, suffocation	N/A (500 PPM?) narcotic unconsciousness, suffocation	5000 PPM 3 - 5% headaches 8 - 15% nausea, unconsciousness > 15% coma, death cerebral vasodilator

MATERIALS COMPATIBILITY

DME	ISOBUTANE	CO2
many elastomers attacked absorbs into some plastics OK all metals	some elastomers attacked absorbs into some plastics OK all metals	OK most elastomers OK all metals (if dry)

AGEING (%/C/cm-wire)

	DME	ISOBUTANE	CO2
		?	?
Pure Gas	3 - 6, 100	pure Ar/Et 11 - 1200	Ar/CO2/CH4 mixtures 2 - 200 *
epoxies	4 - 20		
RTV	380 -1250	Ar/Et 100 *	
Buna-N	14		
Latex	5 - 7		
neoprene	4		
LDPE	7 - 18		
urethane	70 -290		
Kapton Tape	11 - 450		
UV glue	> 6000		

2b) What is the status of the magnet yoke machining?

The machining of the yoke was completed, and the yoke was delivered to TRIUMF on December 8, 2000. TRIUMF personnel supervised the assembly of the yoke at the fabricator, and the yoke was reassembled at TRIUMF before Christmas with the Solenoid inside. Alignment of the solenoid and the yoke was completed by mid January.

2c) Will the magnet power supply feedback be on the currents or the magnetic field?

It is anticipated that the power supply regulation on the current, as determined from very stable and reproducible DC current transformers that are now being installed on the M13 power supplies, will be adequate. However, we will install temperature-compensated Hall effect devices in all magnets (dipole and quadrupole) to complement the existing NMR devices in the dipoles (field uniformity is not adequate to use NMR devices in the quadrupoles). The fields thus determined will be monitored for stability and reproducibility, to learn whether current control alone will provide fields within the tolerance range. If it does not, the communication envisaged between the slow monitoring system and the muon beam line control system does allow software feedback to maintain Hall or NMR device readings, and in any case these will be recorded into the data stream, with alarms to notify us of any excursions beyond a very restricted range of values. One problem that may occur is the degradation of the Hall device characteristics with radiation. While we are designing the system to avoid this as much as possible, the first quadrupoles in the M13 beam line are in a high radiation field and their Hall devices may have a limited lifetime in beam. For this reason, we hope to learn by recipe how to control the quadrupole field to the required precision via current control only, characterizing and understanding any instability, non-reproducibility, or hysteresis effects, before exposing the Hall devices to beam radiation.

The spectrometer's superconducting coil was designed as a medical MRI device. It must be operated in persistent mode with the power supply leads removed in order to avoid excessive helium boil off. (The boil-off rate increases more than an order of magnitude with the power leads connected.) As such there is no question of power supply ripple or regulation during the muon decay measurement. However, the field does slowly decay due to imperfections in the superconducting coil. During acceptance tests our coil showed a short-term (~ 12 h) decay rate of 0.6 ppm/h. It is expected that this rate should decrease over a few days as the current flow equilibrates. We anticipate that the current will be "topped up" every 15 -- 20 days corresponding to a field decay of approximately 2 parts in 10^4.

The field will be set and the decay followed using an NMR probe and calibrated Hall probes. The Hall probes can be calibrated to about 1 gauss and the NMR is of course one or two orders more precise. Field data will be recorded along with spectrometer event data.

It should be understood that this operation is a legacy of the coil's MRI history, and somewhat atypical of SC spectrometer magnets which tend to have active cooling plants in order to retain the extra flexibility of having the current easily adjustable. Of course then one is subject to PS stability issues and capital and operation costs of the cooling plant.

2d) Can TRIUMF provide a smaller 1AT1 target and are any other target modifications needed (you mention tailoring the shape)?

We believe that TRIUMF can provide a smaller 1AT1 target, and with some development, can provide a shape of target that is more advantageous for some parts of the TWIST program. While the present target is well suited to the measurements of ρ, δ, and η, a modified target would be desireable for the $P_\mu\xi$ measurement.

In the past, TRIUMF routinely provided graphite targets of up to 10 mm thickness at 1AT1. Graphite is preferred for TWIST because it is not encased in a water-cooling jacket as the beryllium targets are. For surface muons, the lack of enclosure leads to increased muon rate (typically at least 30% higher, depending on proton beam characteristics). The graphite targets are edge-cooled, i.e., they are bonded on one edge to a water-cooled heat sink. Targets that are thinner in the beam direction are usually easier because radiation cooling is more effective, and the demands of thermal transfer for edge cooling are not as great.

The muon source size must be kept small in order that the beam emittance from the channel is small. This makes muon beam injection into the solenoidal field easier, especially where maintaining polarization across the fringe field is critical, as in the $P_\mu\xi$ measurement. Making a smaller target is one ingredient to reducing the source size, but there is another. With the existing target shape, surface muons from both the upstream face (where the proton beam enters) and the side are visible in the direction of M13, at 135 degrees to the proton beam direction. By constructing a graphite target of prismatic shape, where only the side of the target is visible from the direction of M13, the effective source size is reduced. This shape would also reduce or eliminate the effects of horizontal movement of the proton beam on the target.

Providing a smaller production target is not difficult. The pyrolytic graphite used for these targets cleaves easily along planes perpendicular to the proton beam direction. Graphite is preferred for TWIST because it is not encased in a water cooling jacket as the beryllium targets are. For surface muons, the lack of enclosure leads to increased muon rate (typically at least 30% higher, depending on proton beam characteristics) simply from solid angle considerations. Thin (approx. 2 mm thick) targets have been used in the past both for the original muon decay experiment at TRIUMF and for tuning of the QQD spectrometer. Any thickness of graphite can easily be provided. With some development, a different shape of target could also be provided. A conceptual design of a target which presents only one face to the M13 channel exists, but detailed heat flow calculations have not been carried out. The existing graphite targets are edge-cooled, i.e., they are bonded on one edge to a water-cooled heat sink, and it is necessary to ensure this cooling will be adequate for the modified shape.

3) Funding:

3a) Estimate funding requirements beyond 2003.

We anticipate the possibility of running the experiment through 2005, so funding requirements will be approximately $500k per year in years 2004 and 2005. Increases in consumable costs (such as cryogens and gasses) may increase this amount to $600k per year.

3b) Explain the funding for 1999-2000 and 2000-2001 comparing the amount awarded and the amounts spent.

The amounts expended and the distribution of funds is explained in Table 1 of the grant request under budget detail. The total amount spent from NSERC funds is $678,374. The award amounts were $280k (1999-2000), $358k (2000-2001), and $40k in NSERC funding used for TWIST from a University of Alberta NSERC team grant. We were asked by the previous GSC to transfer that funding from the team request to the project request.

4) What are the expected yearly running times?

We anticipate using approximately 12 weeks of beam during 2001, with the goal of obtaining preliminary data suitable for studies of ρ and δ at the level of parts in 1,000 by the end of the year.

We anticipate using approximately nine months of beam during 2002 and 2003. Our goals during 2002 will be primarily related to refining our studies of systematic effects and beam optics. In 2003 we will have improved data for ρ and δ at the level of parts in 10,000, and we will be prepared for a measurement of $P_\mu\xi$.

During 2001, we have the following goals for the use of beam:

1) Study raw rates and multiplicities
2) Look at individual channels, looking for
   - verification of the channel map
   - dead wires
   - hot wires
3) Online data quality monitors
4) Online tracking (cell level only, no drift times)
5) Tune for high momentum pions, field off
   - Look for WC timing variations
   - Study chamber alignment
6) Stop muons throughout chambers, track positrons
7) Study muon stopping distribution
8) With field on, check that positrons spiral relative to B without bias
9) Obtain a Michel distribution which can be used for
   - determining energy calibrations
   - making preliminary measurements of ρ and δ.

Effort will be directed according to the following table of systematic uncertainties with the indicated approximate start dates:

Non-surface muon contamination **2000**

cloud muon flux: 9%

cloud muon polarization: 0.3 (opposite that of surface muons)

no systematic uncertainties introduced on the ρ, δ, or η measurement. +/- 0.5 x 10^{-4} on $P_\mu\xi$ Indeed the cloud muon flux will be used to produce an unpolarized beam which will be a useful tool in performing calibrations and in obtaining a cross check on ρ.

Proton beam shift on the existing production target **2000**

monitor under development. Beam is stable to within 2 mm at present. No effect on ρ, δ, or η measurement, +/- 0.5 x 10^{-4} on $P_\mu\xi$

Instability of current in the M13 magnets **2000**

monitoring done in 2000 led to upgrades in the readback for power supplies. No effect on ρ, δ, or η measurement, +/- 0.1 x 10^{-4} on $P_\mu\xi$

Positron backgrounds **2000**

measured during beam studies in 2000. Anticipate effect of much less than 0.1 X 10^{-4}

Muon decay in flight (within the spectrometer) **2001**

Muons decaying within the spectrometer must decay very near the stopping target, or else they will be rejected. Furthermore, muon decay times will be restricted to greater than 500 ns. The effect is expected to contribute less than 0.1 X 10^{-4}.

Deviation of average distances in PDC assembly **2001**

The average wire spacing in the PDC assembly must be known to within 2 microns to avoid distortions of the spectrum. Expected uncertainty is a few parts in 10^{-5} for all Michel parameters.

Random errors in sense wire positions **2001**

Random errors do not appreciably distort the Michel distribution.

Magnetic field mapping **2001**

Field uniformity of one part in 10^4 results in negligible distortions in the Michel distribution.

Drift chamber time-zero **2001**

Jitter of 1 ns will result in an uncertainty of 0.5 X 10^{-4} in the Michel parameters.

Non-uniformity of detector acceptance **2001**

The acceptance from $0.3 < x < 1$ and for $0.34 < |\cos(\theta)| < 1$ is expected to be unity within one part in 10^4. The effect on the Michel parameters is < 0.1 X 10^{-4}.

Positron energy calibration **2001**

The energy scale is calibrated by fitting the endpoint of the Michel distribution. This can be done by using a roughly unpolarized beam of cloud muons mixed with surface muons. This beam will produce a distinct endpoint independent of decay angle, which can be fit to considerably better than 10 keV, resulting in a systematic uncertainty in the Michel parameters of less than 0.5 X 10^{-4}.

Effect of incident muon trajectory **2002**

The principle tool for study of the incident muon trajectories will be the TEC. This will be of importance for the $P_\mu\xi$ measurement.

Misalignment of B with respect to the beam 2002

Supplementary detectors will be used to take MuSR data in the solenoidal field to determine the component of the beam polarization transverse to the field.

Coulomb scattering of muons inside the production target 2003

Coulomb scattering results in depolarization in the production target. This depolarization is linear in the depth in the target. By taking data at increasing depth, we can confirm the calculations and limit depolarization to ~ 1 X 10^{-4}. Again, knowledge of the polarization at this level is of concern only for the measurement of $P_\mu\xi$.

Depolarization of thermal muon in metal at 2T 2003

High purity Al will be used for the final target (Fe, Co, Ni at less then 10 ppm). Sensitivity to target will be tested by using various targets and purities. As well, data can be binned by muon decay time to test for depolarization. This is of importance only for $P_\mu\xi$.

5) Upgrades:

5a) Compare anticipated TWIST precision with and w/o the hardware upgrades.

The hardware upgrades which we plan are related to the determination of the parameter $P_\mu\xi$. We will be able to achieve the quoted systematic uncertainties for ρ and δ (1 X 10^{-4}) without undertaking upgrades, though these upgrades will be initiated now so that the effects can be studied as we obtain data for ρ and δ.

These upgrades include the implementation of –

- the TEC for studying the beam, a realignment of the beamline to avoid quadrupole steering,
- a smaller production target, and
- a recycling system for DME.

What is the expected competition from other experiments?

While electroweak tests will be done at hadronic machines, such as pp colliders, and at lepton machines such as LEP and BaBar, muon decay will continue to play a special role because there are only a few purely leptonic decay modes and because muon beams can be produced with very high quality and/or intensity allowing high precision experiments and the most sensitive searches for “forbidden” decays.

The main decay mode into 3 particles, is rather complex from the theoretical point of view, since in the most general case it involves 19 coupling constants (10 complex matrix elements with one arbitrary phase) of the form

$$g^{g}_{mn},$$

where γ can be scalar, vector or tensor and μν refers to the two helicity states of the muon and decay positron, respectively. There are a large number of observables such as spectrum shapes, angular dependencies of positron emission versus muon spin and positron polarizations versus its emission direction that can be used to constrain the coupling constants. In many cases, muon decay provides the most precise values of standard model parameters and the most stringent limits for physics beyond the standard model.

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Muon decay experiments traditionally have been performed at all “meson factories”. For the foreseeable future there are only two places where these experiments are being done: TRIUMF and PSI in Switzerland (exceptions include the (g-2) and MECO experiments at BNL and possible new experiments at the recently approved Japanese Hadron Facility). The following muon decay experiments are going on or are in the design stage at PSI:

1. Muon lifetime measured with the μLan (Muon Lifetime analysis) detector at PSI. The lifetime will be measured to 1 ppm (absolute 2 ps, or 20 time improvement over world average), yielding a precision in the Fermi coupling constant of 0.5 ppm. A pulsed (chopped) beam, a depolarizing sulphur stopping target in a dephasing 75 G transversal magnetic field, and a 20*9 module icosahedral 4π scintillation detector equipped with 500 MHz digitizers will be used to collect the 10^{12} necessary events.

2. Muon lifetime measurement using the FAST (Fiber Active Scintillator Target) detector aiming at the same accuracy as μLan. A 170 MeV/c DC pion beam (to avoid effects from muon polarization) is stopped in a 20*20*20 cm^3 target made of scintillating plastic fibers viewed by position sensitive photomultipliers. Correlations between decay positrons and decay muons from pion decay are established by vertex detection. Both experiments have been approved at PSI because of their complementarity of the methods used and hence of their systematic errors. Both experiments cost in the order of 1 MCHF.

3. Measurement of the transverse polarization of positrons from the decay of polarized muons at PSI. The two transverse polarizations P_{T1} and P_{T2} of positrons within and perpendicular, respectively, to the plane spanned by the muon spin and positron emission, will be measured with an accuracy of $3*10^{-3}$, i.e. an order of magnitude improvement over the previous experiment by the same group. A value for η will be derived from the high energy dependence of P_{T1} with a precision of 0.005 or 0.03, depending on whether or not P_{T2} is set identical to zero. P_{T2} is zero, if time reversal invariance is true, it may also be zero due to cancellations. Another constant called η'' is correlated with η in this experiment. The error in the Fermi coupling constant traditionally is evaluated under the assumption that $\eta \equiv 0$, and would be 50 times larger if today’s experimental error for η (0.085) is allowed for. TWIST too will measure η with comparable accuracy by observing the positron spectrum shape at low energy. The two experiments are extremely complementary and call for each other in order to yield reliable systematic errors for both of them.

4. Measurement of the Michel parameter ξ'' in Polarized Muon Decay. This parameter enters the energy and angular dependence of the longitudinal polarization P_L of the decay positron and is only known with large uncertainty (0.65 ± 0.36). The experiment will measure the combination ($\xi'' / \xi \, \xi'$ - 1) at backward angles where it is enhanced by a factor of about 6. An improvement of a factor of 8 compared to the previous experiment (± 0.005 for the above combination) is aimed at, constraining in particular the scalar and tensor couplings g^S_{RL} and g^T_{RL}.

5b) Describe the role of the TEC and the envisaged schedule.
The TEC will allow us to optimize the beam tune to reduce the effective depolarization due to muons entering the spectrometer off-axis, or with off axis momenta. Studies show that a correlation exists between the trajectory of the entering muon and the effective polarization at the target. A cut placed on the trajectory will enable us to select a sample of muons with an effective depolarization of less than 2 X 10^{-4} with a rate of approximately 1/8 of the total beam rate. Data will be taken both with and without the TEC in place. The TEC will be built during 2001, and will be in place late in 2002.

6) Can the extremely small errors on the muon decay parameters be defended? In particular, could the systematic errors associated to detector efficiency and measurement bias be explained? Points to cover are:
6a) Momentum calibration in all directions in the spectrometer.
The momentum calibration will be obtained by fitting the edge of the Michel distribution at x = 1. This will be done with unpolarized beam, obtained by taking a mixture of cloud muons (Pol = 0.3) and surface muons (Pol = -1). This beam will have a sharp edge at 52.8 MeV independent of angle. The isotropy of the detector means that a single calibration energy is sufficient (though the calibration must be done for all angles), and Monte Carlo studies indicate that we will be able to calibrate to approximately 2 keV. A calibration of better than 10 keV is required.

The TWIST energy calibration can be verified using an idea suggested by Martin Cooper. It utilizes the fact that the ratio

$$M = \frac{\frac{\partial}{\partial x}(d^2N(x=0.5, P_m x = 0)}{d^2N(x=0.75, P_m x = 0)} = \frac{16}{9}$$

is practically independent of the parameters ρ, η, $P_\mu\xi$ and δ . Here d^2N represents the differential muon decay rate spectrum $d^2N/dxdcosq$. While the above ratio is exactly correct for unpolarized muons a simple estimate shows that for example if $P_\mu\xi = 0.01$ the errors on the present experimental values of ρ, η, $P_\mu\xi$ and δ change this ratio by less than 10^{-7}, 1.7×10^{-5}, 10^{-7}, and 10^{-7} respectively. An energy calibration error Δ results in

$$M = \frac{16}{9}(1 - \frac{\Delta}{E_{\max}}).$$

To check the ratio is 16/9 with a precision $\sigma(\Delta) < 3keV$ will require about 10^8 muon decay events, i.e. about 3 days at a muon rate of 1kHz.

6b) Energy loss in material in different directions.
Energy loss and multiple scattering in the detector have been studied extensively. Energy loss in each PDC is roughly 10 keV/cos(theta). The small size of the energy loss is helpful in avoiding large systematic uncertainties in the energy calibrations. The positron energy loss is linear in 1/cos(θ), which provides a powerful check on the angular independence of the calibrations.

As well, we have an extremely powerful monitor of the stopping distribution of the muons in the target, so we are able to ensure that the stopping distribution is symmetrical to the order of 1 micron. The positron energy loss in 1 micron of aluminum is the order of 1 keV, so the variation in the energy loss due to asymmetries in the stopping distribution is negligible.

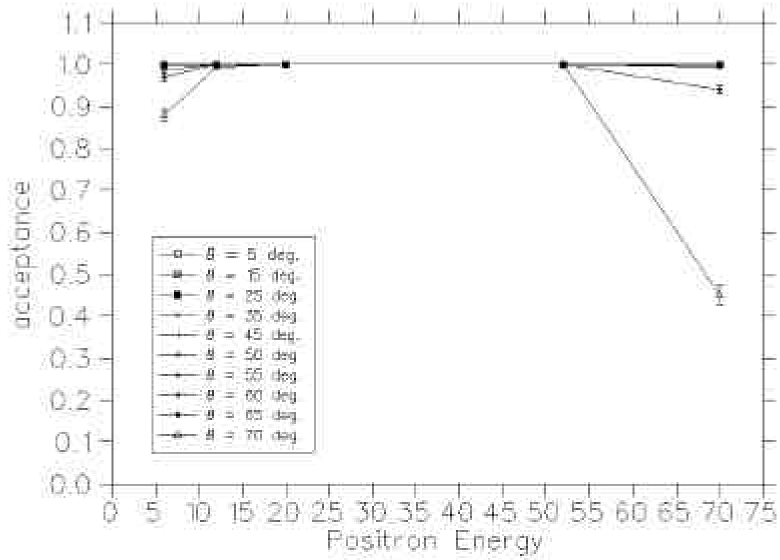
6c) Final state radiation.

Inner radiative corrections can significantly affect the spectrum of the positron. The dominant effect is due to positron emitting a collinear photon. This can be followed by the photon conversion into a collinear electron-positron pair or by the positron emitting another collinear photon. Both processes induce corrections characterized by $((\alpha/\pi)*\ln(m_\mu/m_e))^2$ in the energy spectrum. These effects have very recently been evaluated by Arbuzov and Czarnecki (unpublished) and we intend to include their results in the TWIST Monte Carlo programs.

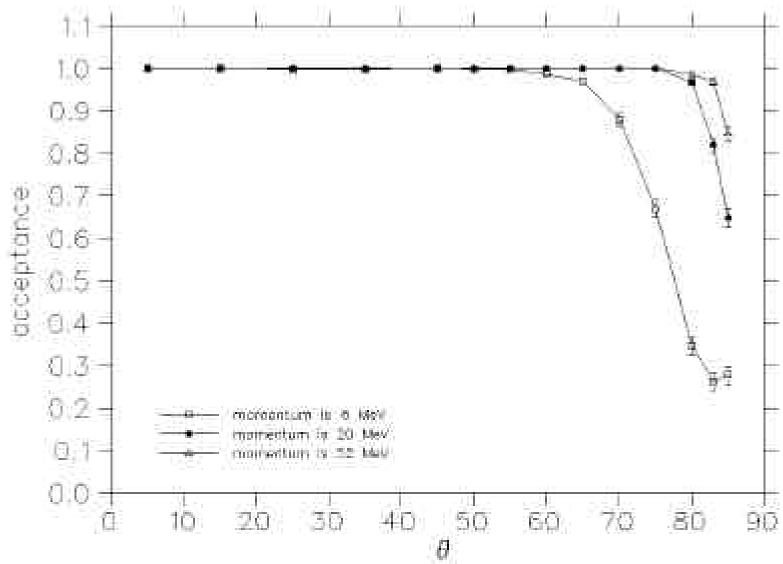
While the double-collinear effects are dominant, the theoretical prediction is now being studied also for the semi-collinear effects. The remaining corrections of order $(\alpha/\pi)^2$ are estimated to be of relative order 10^{-5} and, therefore, negligible for TWIST.
(diagrams to be included)

6d) Efficiency as a function of angle and momentum.

The efficiency of the spectrometer will be mapped by using positrons from muons tuned to stop in windows throughout the detector. In this way, we can obtain rather complete illumination of the spectrometer with Michel positrons. The efficiency predicted by Monte Carlo studies is as shown below.



Spectrometer Acceptance vs. Energy



Spectrometer Acceptance vs. Angle

6e) Give a comparison with existing measurements to explain how TWIST can do better.
Many Monte Carlo and experimental studies have been made in the past few years to estimate the accuracy with which the proposed apparatus will determine the Michel parameters. These studies have provided estimates of the influence of possible imperfections of parts of the experimental apparatus from the muon production target, through the M13 beam line, to the TWIST detector. It is clear from these studies that the experiment could be done in a short period of time if there were no imperfections. While some of the problems can be corrected others will require studies using extensive periods of beam time. These concerns are discussed below beginning with the $\mathbf{P_\mu}$x measurement for which most of the upgrades are required.

$\mathbf{P_\mu}$x parameter:
M13 beam line quality:

1) The M13 surface muon beam does not necessarily have a small emittance. For rays that cross the spectrometer fringe field at large radial distance the muon polarization at the TWIST stopping target is significantly reduced.

The horizontal and vertical slits/jaws at the front end of the channel will be used to limit the emittance in order to reduce this effect. In order to increase the effectiveness of the vertical jaw for this purpose it has been necessary to develop a new tune for the channel. This tune was tested during the November 2000 beam tests and found to perform as expected. In order to assure that the beam emittance meets the requirements to provide a systematic error $< 10^{-4}$ an upgrade we have called a Time Expansion Chamber (TEC) has been designed to measure the emittance of this beam. GEANT studies indicate that the proposed TEC positioned at the point where the muon beam enters the spectrometer will register each muon trajectory with the needed accuracy to allow a calculation of the muon spin direction in the stopping target. The TEC will also provide a monitor of the muon beam emittance during a run.

2) Any shift of the proton beam position on the 1AT1 production target in the horizontal plane will shift the position of the surface muon beam at the momentum slit hence shifting the accepted muon momentum. This will consequently change the muon distribution at the fringe field crossing as well as the Z position in stopping target. The first effect will produce an apparent change in the beam emittance. The latter effect will change the positron energy calibration of the spectrometer and contribute a systematic error to all Michel parameters. A rotation of the 1AT1 target by 45° in the horizontal plane will make motion of the proton beam invisible to the M13 channel thus removing both of the influences just described. The new 1AT1 target design will also provide a smaller beam emittance in horizontal plane. In addition, the TEC counter will register each muon trajectory and hence exclude any influence of possible shifts in the proton beam vertical position.

3) Magnetic field instabilities in the M13 beam line elements (especially the bending magnets) change both the momentum and the emittance of the beam, and contribute an additional systematic error. Improved current stabilization of the M13 elements is needed, together with TEC monitoring, to hold this error to a minimum.

In summary, our studies indicate that **without** the above upgrades (new production target, M13 magnet stability and TEC) we will only be able to measure Pμx with an accuracy of 10^{-3}. Note that this compares well with the present world value for the error, 8.5×10^{-3} from Beltrami et al. [Phys. Lett. B194 326(1987)]. The upgrades will provide the proposed accuracy of Pμx ~ 2×10^{-4}.

r, d and h parameters:

In contrast to Pμx, the accuracy achievable for ρ, δ, and η does not depend nearly as significantly on the quality of the muon beam. The results for these parameters will be defined primarily by the TWIST detector quality and alignment. As a consequence

TWIST will concentrate its efforts in the first year(s) of beam in understanding the detector systematics with the aim of publishing results of ρ, δ, and η early. At the same time development work will proceed on the upgrades described above, in particular the low pressure TEC which will be used to measure each muon track trajectory in a manner similar to that employed by Jodidio et al., Phys. Rev. D34, 1967(1986) where the measurement was made using PCs with normal gas pressure. In that work this measurement introduced a systematic error of 5×10^{-4} in the $P_\mu\xi\delta/\rho$ determination. The proposed TEC will contribute by contrast, according to GEANT calculations an error of < 10^{-4}.

6f) Explain clearly the argument that one global experiment can do better than the previous experiments which focused on particular parameters with a particular detector and technique.

The advantage of doing a global experiment as opposed to a more focused experiment is that the global approach allows us to do multiple experiments which give independent tests of systematic uncertainties and which break correlations between parameters.

For example, we can make a measurement of ρ using polarized muons. By summing the forward and the backward distributions, we obtain data that is independent of ξ and δ. The same data set can be used to determine δ by taking the difference between the forward and backward data sets to produce a distribution which is independent of ρ and η, and which is only sensitive to $P_\mu\xi$ as an overall normalization.

We can take the same data and produce a nearly unpolarized beam sample by applying an RF TOF cut which mixes surface and cloud muons. That data sample should give a consistent result for ρ. Indeed, we can take a large data set and take slices of the data in cos(θ). Each of these data samples should give consistent results for ρ, thereby testing for systematic uncertainties in our energy calibrations or distance scales.

The tracking will be robust with respect to variations in wire efficiency, given the redundancy in the number of tracks, and the high efficiency of the individual planes. The use of the unpolarized distributions, which are independent of theta, will be a powerful test of problems with variations in efficiency.

6f-i) What is the correlation between the Michel parameters when they are extracted by a global fit and how do systematic errors affect the correlation?

The correlations between the Michel parameters in the global distribution are significant. These correlations would make an unconstrained global fit prohibitively difficult.

	r	d	h	$P_m x$
r	1	0.22	0.97	0.83
d		1	0.18	−0.29
h			1	0.83
$P_m x$				1

As pointed out above, however, these correlations can be largely eliminated by taking combinations of the data. In practice, we will test for consistency by taking various combinations of the data, such as (forward + backward) and (forward - backward).
In this way, the ρ-δ, ρ-$P_\mu\xi$, δ-η, δ-$P_\mu\xi$ and the η-$P_\mu\xi$ correlations can be essentially eliminated.