TWIST: Measuring the Space-Time Structure of Muon Decay

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Abstract. TWIST, the TRIUMF Weak Interaction Symmetry Test, is a precision measurement of the energy and angular distributions of the positrons emitted in polarized muon decay. The goal is to search for new physics that leads to deviations of the Michel parameters ρ, δ, and $P_\mu \xi$ from their Standard Model values. TWIST will determine these parameters to a few parts in 10^4, an improvement of at least an order of magnitude in each case. At this level, TWIST will confront several proposed extensions to the Standard Model.

PHYSICS OF TWIST

The energy and angular distributions of the positrons emitted in the decay of polarized muons may be written in a number of equivalent forms. One convenient form [1, 2] describes the distributions in terms of four parameters ρ, η, δ, and ξ, commonly referred to as the Michel parameters. Neglecting the electron and neutrino masses and radiative corrections, the differential decay rate for positive muon decay is given in terms of the decay parameters ρ, δ, and ξ by

$$\frac{d^2\Gamma}{x^2\,dx\,d(\cos\theta)} \propto 3 - 3x + \frac{2}{3}\rho(4x-3) + P_\mu \xi \cos\theta \left[(1-x) + \frac{2}{3}\delta(4x-3)\right], \qquad (1)$$

where P_μ is the polarization of the muon, x is the outgoing positron energy as a fraction of the maximum possible value, and θ is the angle between the muon polarization axis and the positron decay direction. The fourth decay parameter η contributes to the angle-independent part of the distribution if one includes the finite electron mass.

The decay parameters characterize the space-time structure of muon decay. Thus, within the Standard Model they take on precise values: $\rho = \frac{3}{4}$, $\eta = 0$, $\delta = \frac{3}{4}$, $\xi = 1$. Any deviations from these values would signify new physics. For example, in left-right symmetric models [3], deviations of ρ from $\frac{3}{4}$ imply mixing between the left- and right-handed W bosons, and deviations of ξ from 1 primarily measure the ratio of the squares of the two W boson masses. In more general extensions that include scalar and tensor interactions in addition to vector and axial vector currents, the linear combination

$$Q_R^\mu = \frac{1}{2}\left[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right] \qquad (2)$$

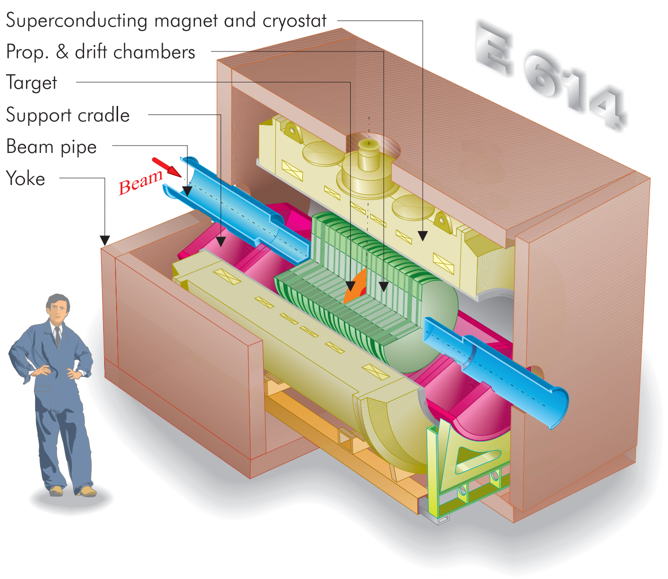

FIGURE 1. The TWIST spectrometer.

provides a model-independent measure of the total right-handed contributions to muon decay [4]. In Eq. (1), ξ appears only in the product $P_\mu \xi$. Conventionally, P_μ represents the polarization of the muons produced in pion decay. Thus, $P_\mu = 1$ in the Standard Model and any deviation would also provide a signature for new physics.

The best current measurements of the Michel parameters are [5]: $\rho = 0.7518 \pm 0.0026$, $\eta = -0.007 \pm 0.013$, $\delta = 0.7486 \pm 0.0026 \pm 0.0028$, $P_\mu \xi = 1.0027 \pm 0.0079 \pm 0.0030$, $P_\mu \xi \delta / \rho > 0.99682$. The ultimate goal of TWIST is to determine ρ, δ, and $P_\mu \xi$ to a few parts in 10^4, over an order of magnitude improvement in each case. At this level, TWIST will be sensitive to the existence of right-handed W bosons with masses up to 800 GeV/c^2, without needing to make assumptions about the form of the right-handed CKM matrix, and will be sensitive to mixing angles between left- and right-handed W bosons as small as 0.01.

EXPERIMENT

Figure 1 shows the TWIST spectrometer. It consists of an array of very thin, high precision planar wire chambers [6] located within a 2 T uniform magnetic field. The spectrometer includes 44 drift chambers and 12 MWPCs. The $\sim$5000 sense wires are positioned with 3 μm accuracy, and longitudinal and transverse dimensions are known to better than 5 parts in 10^5. A highly-polarized beam of surface muons from the M13 beam line at TRIUMF enters the spectrometer. The muons are tracked as they pass through the detector planes until they stop in a thin target in the center of the spectrometer. The decay positrons then follow helical trajectories through the detectors, permitting their energies and angles to be measured precisely.

Equation (1) shows that the differential decay rate is linear in the decay parameters.

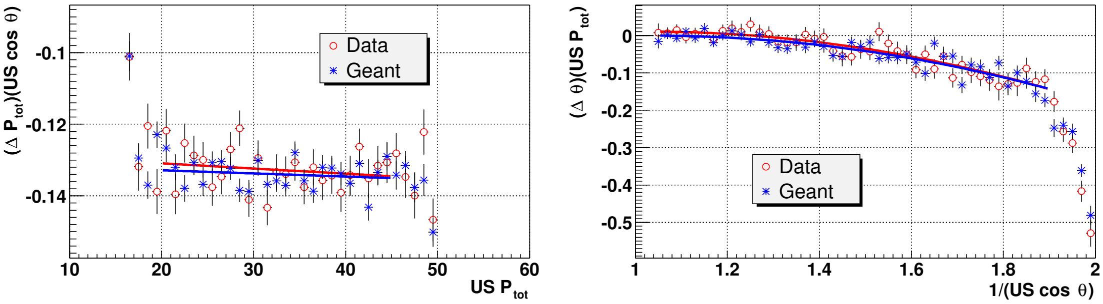

FIGURE 2. The energy loss in MeV as a function of energy (left) and the change in the polar angle in radians as a function of relative path length (right) when positrons pass through the stopping target and half of the detector planes. The energy loss is corrected event-by-event for the observed path length, yielding the typical energy loss for positrons moving parallel to the magnetic field. Similarly, the scattering is rescaled event-by-event according to the momentum of the positron, yielding the average scattering angle that would be experienced by a 1 MeV/c positron. Monte Carlo predictions are shown for comparison.

This provides the basis for the blind analysis scheme. The measured energy-angle spectrum will be compared to the sum of a Monte Carlo 'standard' spectrum produced with unknown Michel parameters, together with additional Monte Carlo distributions that describe the dependence on $\Delta\rho$, $\Delta\eta$, $\Delta\delta$, and $\Delta P_{\mu}\xi$. These Monte Carlo spectra are generated including the effects of the electron mass, plus first- and many second-order radiative corrections, in contrast to Eq. (1).

CURRENT STATUS

TWIST had its first physics run during Fall, 2002. The goal was to determine ρ and δ to 10^{-3}. TWIST is a systematics-dominated experiment. Thus, most of the running time was devoted to exploring the possible systematic effects by amplifying them as much as practical, then measuring their impact. 3×10^{8} muon decay events are sufficient to determine ρ and δ with a statistical precision of $\sim 6 \times 10^{-4}$, but a total of 6×10^{9} events were recorded to tape. Independent data sets were taken to explore the sensitivity to the beam properties (polarization, stopping distribution, steering, focus, intensity), the detector performance (efficiencies, gas pressure), the magnetic field, the upstream-downstream symmetry of the system, and the overall system stability. In addition, special runs were taken to provide additional data to validate the quality of our GEANT-based Monte Carlo simulation.

These data are now being analyzed, and the initial results are very encouraging. The Monte Carlo simulation has been shown to provide an excellent description of the muon stopping distribution. Special runs during which the muon beam was stopped near the upstream end of the detector have been used to study the overall detector response. For these runs, positrons which are emitted in the downstream direction pass through the upstream half of the detector, the stopping target, then the downstream half of the detector. Each half may be treated as an independent detector, permitting the two measurements of the helix parameters at different points along the trajectory to be

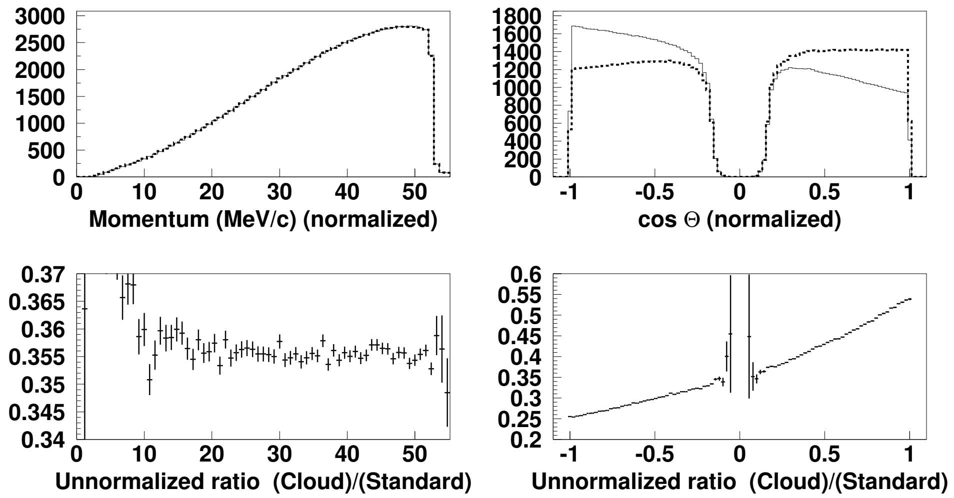

FIGURE 3. Comparison of momentum and angular distributions between surface muon (solid curves, $P_\mu \approx -1.0$) and cloud muon (dashed curves, $P_\mu \approx +0.3$) data sets. In each case, fiducial cuts have been applied to the other variable. The upper panels show the spectra normalized to the same total number of events. The lower panels show the ratio of the yields for cloud muons relative to surface muons.

compared. Figure 2 shows that the Monte Carlo simulates the positron energy loss and scattering very well.

The various independent data sets are also being analyzed. Figure 3 shows a comparison between spectra obtained with a surface muon beam under nominal conditions and with a cloud muon beam. The angular distributions are quite different, but the overall momentum distributions are very similar within the fiducial range, demonstrating the uniformity and upstream-downstream symmetry of the spectrometer. At present, work continues to optimize the pattern recognition and track fitting algorithms and to validate the Monte Carlo. The goal is to have the first physics results available near the end of 2003.

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