TWIST Results

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Abstract.
The TRIUMF Weak Interaction Symmetry Test (TWIST) has now completed its data collection period. These data represent the world's most precise measurement of the muon decay spectrum. The experiment expects to meet its ambitious goals of an order of magnitude improvement over pre-TWIST results for the muon decay parameters ρ, δ and $P_\mu^\pi \xi$.
Our most recent published results are presented. The measures that have been taken to reduce the systematic uncertainties for the upcoming final result are described.

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INTRODUCTION

Muon decay is a purely leptonic process. The matrix element for the most general Lorentz-invariant, derivative-free, lepton-number-conserving matrix element M can be written in terms of helicity-preserving amplitudes as [1]

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{i=L,R \\ j=L,R \\ \kappa=S,V,T}} g^\kappa_{ij} \langle \bar{\psi}_{e_i} | \Gamma^\kappa | \psi_{\nu_e} \rangle \langle \bar{\psi}_{\nu_\mu} | \Gamma_\kappa | \psi_{\mu_j} \rangle, \tag{1}$$

where g^κ_{ij} are the complex weak coupling constants and Γ^κ are the possible interactions (scalar, vector, tensor). In this notation, the Standard Model (SM) postulates that $g^V_{LL} = 1$, and $g^\kappa_{ij} = 0$ otherwise. If the polarization of the decay positron is undetected, then the differential decay rate can be expressed as

$$\frac{d^2\Gamma}{dx\, d\cos\theta} \propto F_{IS}(x) + P_\mu \cos\theta\, F_{AS}(x), \tag{2}$$

where $x = E_e/E_{\mathrm{max.}}$, θ is the angle between the muon polarization and the positron momentum, $P_\mu = |\vec{P}_\mu|$ (the degree of muon polarization), and

$$F_{IS}(x) = x(1-x) + \frac{2}{9}\rho\left(4x^2 - 3x - x_0^2\right) + \eta x_0(1-x) + R.C., \tag{3}$$

$$F_{AS}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 3 + \left(\sqrt{1-x_0^2} - 1\right)\right)\right] + R.C. \tag{4}$$

The R.C. terms are radiative corrections, which become more significant as x approaches one. The muon decay parameters ρ, δ, $P_\mu\xi$ and η are bilinear combinations of the

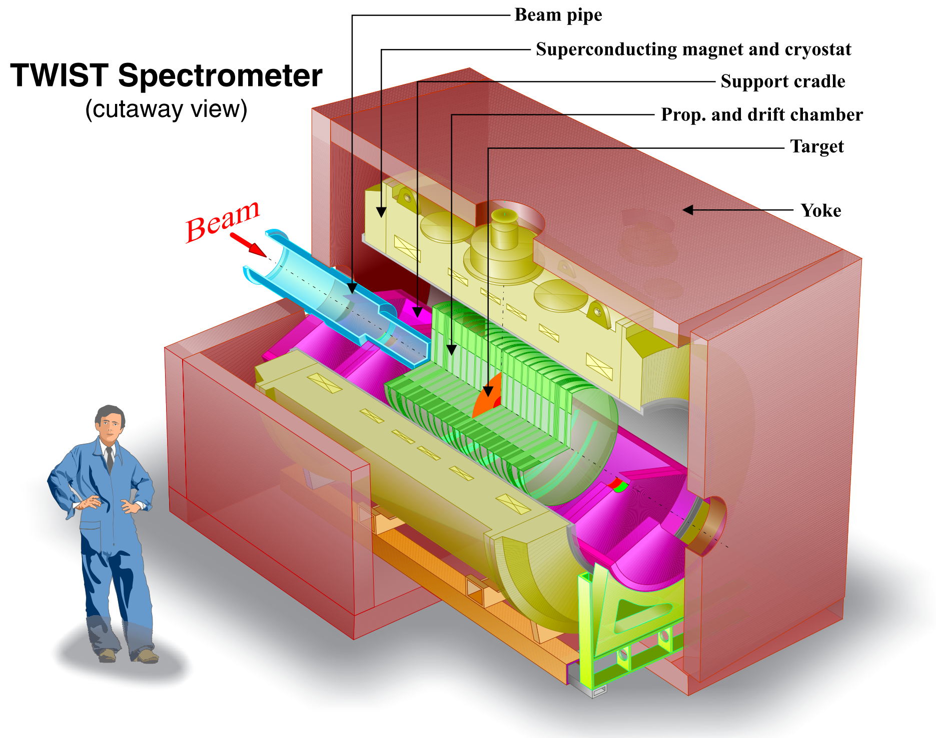

FIGURE 1. The TWIST spectrometer.

weak coupling constants. The TWIST experiment measures ρ, δ and $P_\mu^\pi \xi$ to parts in 10^4, where P_μ^π is the polarization of the muon from pion decay. The SM predicts that $\rho = \delta = 3/4$, $P_\mu^\pi = \xi = 1$, and $\eta = 0$; deviations from these predictions would indicate new physics.

EXPERIMENT

Highly polarized positive muons were stopped in a thin metal foil at the center of a symmetric array of planar drift chambers (see Fig. 1), within the bore of a solenoid that produced a uniform 2.0 T magnetic field. The decay positron helices were tracked by the drift chambers, and their trajectories were later reconstructed to determine the positron's initial energy and angle. Further detail on the apparatus can be found elsewhere [2].

The muon beam's position and emittance were measured before the 2.0 T field using a pair of low mass time expansion chambers (TECs) [3]. These were removed while accumulating nominal data since their multiple scattering depolarized the muons significantly. The measured beam from the TECs was used to initiate the muons in a `GEANT3` simulation that transported the muons to the metal target in order to determine their decay polarization.

The muon decay parameters were measured by comparing the positron spectrum from the data to a `GEANT3` simulation that was subjected to the same analysis. In this way

TABLE 1. Confidence limits (90%) on the weak coupling constants, from a global analysis of muon data.

	Pre-TWIST	**Gagliardi** *et al.*	**MacDonald** *et al.*
$\lvert g^S_{LR}\rvert$	< 0.125	< 0.088	$<$ **0.074**
$\lvert g^V_{LR}\rvert$	< 0.060	< 0.036	$<$ **0.025**
$\lvert g^T_{LR}\rvert$	< 0.036	< 0.025	$<$ **0.021**

the inefficiencies and reconstruction biases were accounted for within the simulation. Hidden values of ρ, δ and ξ were used in the simulation, and these were not revealed until corrections and systematic uncertainties had been evaluated on the *difference* in decay parameters between the data and simulation spectra; this technique exploited the spectrum's linearity in ρ, $P^{\pi}_{\mu}\xi$ and $P^{\pi}_{\mu}\xi\delta$ (see Eqs. (3),(4)).

Special data validated the positron physics in the simulation: muons were stopped close to the entrance of the detector, and the decay positrons were independently reconstructed in each half of the detector. The differences in energy and angle between these two trajectories were in excellent agreement for data and simulation [4].

RESULTS

Our most precise results for the muon decay parameters are [4, 5]

$$\rho = 0.75014 \pm 0.00017\,(\text{stat.}) \pm 0.00046\,(\text{syst.}) \pm 0.00011\,(\eta), \tag{5}$$

$$\delta = 0.75068 \pm 0.00030\,(\text{stat.}) \pm 0.00067\,(\text{syst.}), \tag{6}$$

$$P^{\pi}_{\mu}\xi = 1.0003 \pm 0.0006\,(\text{stat.}) \pm 0.0038\,(\text{syst.}). \tag{7}$$

The parameter η is fixed to the world average value, which introduces an additional uncertainty through its correlation with ρ. The results are consistent with the SM, and represent more than a factor of five improvement over the pre-TWIST ρ and δ measurements [6, 7], and are a factor of two more precise than the previous direct $P^{\pi}_{\mu}\xi$ result [8]. The ρ and δ results were limited in precision by uncertainties in the drift chamber response, and the P^{π}_{μ} result was limited by the accuracy of simulating the depolarization.

A global analysis of muon decay data that included the latest TWIST results [9] has improved the limits on the weak coupling constants (g^{κ}_{ij} in Eq. (1)). The three coupling constants that are most sensitive to TWIST results are shown in Table 1. The coupling constants can be used to establish a limit on the probability for the decay of a right-handed muon into a left- or right-handed positron. Prior to TWIST this was 1.4% (90% C.L.), and our latest results reduce the limit to 0.23%.

In left-right symmetric models, an additional heavy right-handed W-boson (W_R) is introduced to restore parity conservation at high energies [10]. The TWIST result for ρ, combined with a previous measurement of $P_{\mu}\xi\delta/\rho$ [11], allows model-independent limits on the the mixing angle (ζ) between the W_L and W_R. The pre-TWIST limit from muon decay was $|\zeta| < 0.066$, and this is now reduced to $|\zeta| < 0.022$.

IMPROVEMENTS FOR THE FINAL MEASUREMENT

Final data were acquired in 2006 and 2007, with a higher quality muon beam and a threefold increase in statistics. The analysis of this data is nearing completion.

The space-time relationships (STRs) in the drift cells have been improved, by correcting them so that the fitting residuals are minimized. Each drift chamber was corrected independently; this accounted for small differences in construction and response.

The beam line was upgraded to correct an undesirable muon beam vertical deflection of ≈ 1.0 cm. The beam was steered onto the symmetry axis of the solenoid, which reduced the uncertainty in simulating the depolarization. Beam measurements using the TECs were carried out more frequently, and the long term stability of the beam was monitored using its average position within the detector.

Muons were stopped in both an Al and Ag foil (previously only an Al foil was used). The statistical uncertainty of the polarization's relaxation rate was reduced by a factor of three. A subsidiary μ^+SR experiment measured relaxation in the same foils, and provided confirmation that a single exponential form was appropriate and sufficient for the depolarization down to 10 ns. The target foil was also the cathode foil for a proportional chamber; for the final measurement, the pulse width in this chamber was used to remove muons that stopped and depolarized in the chamber gas.

CONCLUSIONS

The experiment is on course to achieve an order of magnitude improvement over the pre-TWIST results for ρ, δ and $P_\mu^\pi \xi$. The dominant systematic uncertainties have been reduced, and the final results are expected in early 2010.

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