Blind analysis results of the TWIST experiment

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Abstract. The TRIUMF Weak Interaction Symmetry Test (TWIST) experiment was designed to test the standard model at high precision in the purely leptonic decay of polarized muons. A general four-fermion interaction model is used to describe the muon decay. TWIST measures three of the four muon decay parameters of this model, ρ, δ and $P^{\pi}_{\mu}\xi$, from the shape of the momentum-angle spectrum. The results of this model independent approach are compared to the standard model predictions and used to constrain new physics.

Our collaboration has finalized the blind analysis of the final experimental data taken in 2006 and 2007. This analysis mostly reached our goal of a precision of an order of magnitude better than the pre-TWIST measurements.

1. Introduction

The discovery of new physics is expected at the high energies reached by the LHC. However low energy physics such as muon decay can also play a complementary role by providing limits and constraints on physics beyond the standard model.

Muon decay is a purely leptonic process ideal for testing the weak interaction at high precision. A model independent approach is possible due to the large mass of the W boson compared to the muon mass. The most general Lorentz-invariant, derivative-free, lepton-number-conserving matrix element M describing muon decay 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

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

[1] `http://twist.triumf.ca/`: R. Bayes, Yu.I. Davydov, W. Faszer, M.C. Fujiwara, A. Grossheim, D.R. Gill, P. Gumplinger, A. Hillairet, R.S. Henderson, J. Hu, G.M. Marshall, R.E. Mischke, K. Olchanski, A. Olin, R. Openshaw, J.-M. Poutissou, R. Poutissou, G. Sheffer, B. Shin (TRIUMF), A. Gaponenko, R.P. MacDonald (University of Alberta), J.F. Bueno, M.D. Hasinoff (University of British Columbia), P. Depommier (Université de Montréal), E.W. Mathie, R. Tacik (University of Regina), V. Selivanov (Russian Research Center, Kurchatov Institute), C.A. Gagliardi, R.E. Tribble, (Texas A&M), D.D. Koetke, T.D.S. Stanislaus (Valparaiso University).

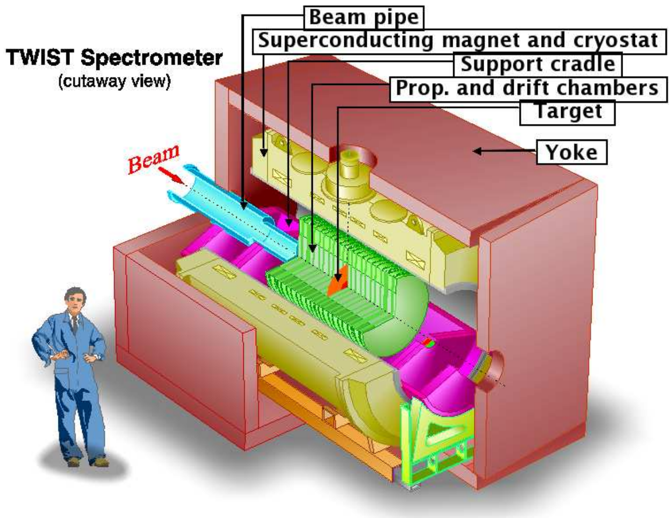

Figure 1. The TWIST spectrometer.

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

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

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

The R.C. terms are radiative corrections, which become more significant as x approaches one. x_0 is the dimensionless electron mass defined by $x_0 = m_e/E_{\text{max.}}$. The muon decay parameters ρ, δ, ξ and η are bilinear combinations of the weak coupling constants g_{ij}. The TWIST experiment measures ρ, δ and $P_\mu^\pi \xi$ to parts in 10^4 from the momentum-angle of the decay positron. P_μ^π is the polarization of the muon from pion decay. The standard model predicts that $\rho = \delta = 3/4$, $P_\mu^\pi = \xi = 1$, and $\eta = 0$; deviations from these predictions would indicate new physics.

2. Experiment

The experiment was sited at the M13 channel at TRIUMF in Vancouver, Canada. Positive pions decaying at rest at the surface of the production target produced highly polarized positive muons with a momentum of 29.792 MeV/c. The M13 channel momentum selection was set at 29.6 MeV/c with a resolution of 0.7% to select these muons and guide them to the spectrometer. A thin metal foil acted as a stopping target for the muons, and was placed at the center of a symmetric array of wire chambers within the bore of a solenoid that produced a highly uniform 2.0 T magnetic field known to three parts in 10^5 (see Fig. 1). The particle identification relied mostly on three modules of four proportional chambers (PCs) each. A module was installed at each end of the spectrometer. The third module used the stopping target as a cathode foil in the center of the four PCs and was installed in the center of the detector stack. Muons that stop in the target were selected using the PCs of this target module. The decay positron helices were tracked by 44 drift chambers, and their trajectories were later reconstructed to determine the positron's initial momentum and angle. The wire positions were known to five parts in 10^5 providing a high reconstruction resolution of 60 keV at a positron energy of 52 MeV. The wire chambers were low mass to reduce multiple scattering and to allow the muons to reach the target since it takes only about 1 mm of water equivalent to stop muons at 29 MeV/c. The decay positrons traverse a range of only 77 mg/cm^2. Further detail on the apparatus can be found elsewhere [2].

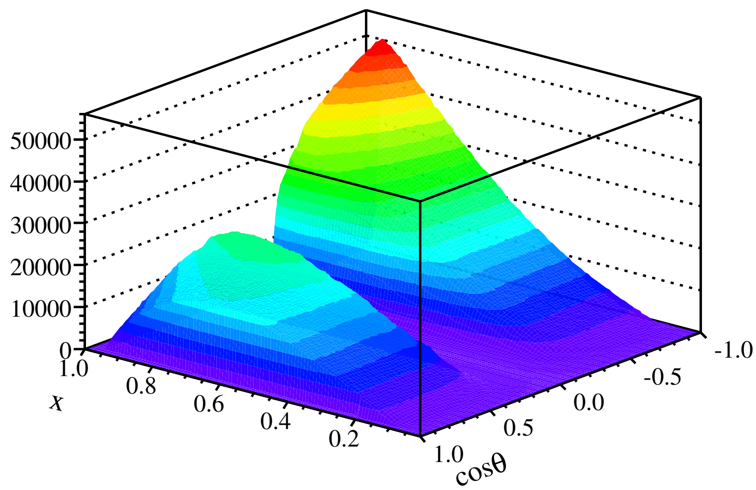

Figure 2. Experimental momentum-angle spectrum. The detector response is included in this spectrum.

The muon decay parameters were measured by comparing the positron momentum-angle spectra from the data and from a `GEANT3.21` simulation (see Fig. 2) that was subjected to the same analysis. In this way the detector response 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 provided a blind analysis by exploiting the spectrum's linearity in ρ, $P_\mu^\pi \xi$ and $P_\mu^\pi \xi \delta$ (see Eqs. (3),(4)).

Special data validated the positron physics in the simulation using muons stopped close to the entrance of the detector. In this configuration the decay positrons traversed the whole detector. The corresponding tracks were independently reconstructed in each half of the detector, before and after crossing the stopping target. The reconstruction efficiency was measured from this special data by counting the number of tracks reconstructed in one half of the detector but not the other.

3. Improvements for the final measurement

An initial and an intermediate measurement of the decay parameters were already performed by the TWIST collaboration on data taken in 2002 [3, 4] and 2004 [5, 6]. Final data were acquired in 2006 and 2007, with a higher quality muon beam and a threefold increase in statistics.

The space-time relationships (STRs) in the drift cells have been improved, by correcting them so that the fitting residuals of the positron track are minimized. These improved STRs also corrected reconstruction biases. 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 $\approx 1.0\,\text{cm}$. The beam was steered onto the symmetry axis of the solenoid, which reduced the uncertainty in simulating the depolarization of the muon. The long term stability of the beam was monitored using its average position measured by the wire chambers. Muons were stopped in both an Al and Ag target foil (previously only an Al foil was used) in two separate sets of data. This allow for the study and validation of the fast depolarization of the muons in the target material.

Table 1. Systematic uncertainties for each decay parameter in units of 10^{-4} from the blind analysis. The depolarization and background muons systematic uncertainties affect only the muon polarization P_μ.

	ρ	δ	$P_\mu^\pi \xi$
Depolarization in fringe field	-	-	$^{+15.8}_{-4.0}$
Depolarization in production target	-	-	3.2
Depolarization in stopping material	-	-	0.3
Background muons	-	-	1.0
Positron interactions	1.8	1.6	0.6
Chamber response	1.0	1.8	2.3
Momentum calibration	1.2	1.2	1.5
Resolution	0.6	0.7	1.5
Alignment	0.2	0.3	0.2
Beam stability	0.1	0.0	0.3
Radiative corrections	0.8	0.6	0.5
Uncertainty in η	1.0	0.1	1.0
Total	2.8	2.9	$^{+16.5}_{-6.2}$

4. Systematics uncertainties

The systematic uncertainties from the blind analysis of the final measurement are summarize for each decay parameter in the Table 1.

Most systematic uncertainties are evaluated by altering a component source of uncertainty in the simulation or in the analysis. The momentum-angle spectrum created by this modified simulation or analysis is fitted against the unaltered spectrum. The difference in decay parameters scaled to the uncertainty in the source of the systematic is used as a systematic uncertainty. The alteration is typically many times greater than the measured uncertainty on the modified component in order to increase the sensitivity. For example the Bremsstrahlung production rate uncertainty (dominant uncertainty in the group "positron interactions") was evaluated by generating a simulation with the Bremsstrahlung production rate multiplied by a factor of 3. The Bremsstrahlung rate was measured in the simulation and the experimental data using the topology of the events to identify events with a Bremsstrahlung being emitted. The simulation and the data Bremsstrahlung rates differ by 2.4%. Therefore the difference in decay parameters between the altered and the unaltered simulations was multiplied by (1.024-1)/(3-1) to provide the corresponding systematic uncertainty.

The dominant systematic uncertainty for the $P_\mu \xi$ parameter comes from the depolarization undergone by the muons as they enter the 2.0 T tracking magnetic field. A mismatch in the depolarization in the fringe field between the simulation and the data leads to a mismatch in the muon polarization P_μ at the time of decay. This creates a systematic bias in the determination of P_μ^π and in the measurement of $P_\mu^\pi \xi$. The accuracy of the simulation of the depolarization was evaluated by modifying the position or size of the experimental muon beam and verifying that the simulation could reproduce this change in polarization. This evaluation indicated that the simulation underestimates the depolarization which leads to an asymmetric uncertainty.

5. Results

The TWIST collaboration agreed on the list and values of the systematic uncertainties and corrections before revealing the hidden parameters of the blind analysis.

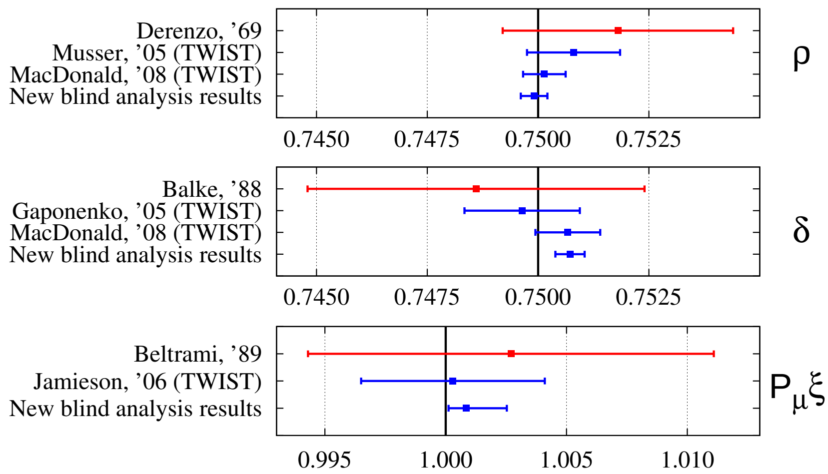

Figure 3. Experimental momentum-angle spectrum. The detector response is included in this spectrum.

The results of the blind analysis are

$$\rho = 0.74991 \pm 0.00009 \text{ (stat)} \pm 0.00028 \text{ (sys)}, \tag{5}$$
$$\delta = 0.75072 \pm 0.00016 \text{ (stat)} \pm 0.00029 \text{ (sys)}, \tag{6}$$
$$P_\mu^\pi \xi = 1.00083 \pm 0.00035 \text{ (stat)}^{+0.00165}_{-0.00063} \text{ (sys)}. \tag{7}$$

The parameter η is fixed to the world average value, which introduces an additional uncertainty through its correlation with ρ. The parameters ρ, δ and $P_\mu^\pi \xi$ are respectively 0.3, 2.2 and 1.2 standard deviations away from the predictions of the standard model. All the parameters are consistent with the previous measurements from TWIST and from experiments prior to TWIST [7, 8, 9] (see Fig. 3).

The spectrum asymmetry A_{EP} at the positron kinematic end point is given by

$$A_{EP} = \frac{P_\mu^\pi \xi \delta}{\rho}, \quad \text{therefore} \quad \frac{P_\mu^\pi \xi \delta}{\rho} \leq 1. \tag{8}$$

However the results from the blind analysis give:

$$\frac{P_\mu^\pi \xi \delta}{\rho} = 1.00192^{+0.00167}_{-0.00066} \tag{9}$$

which corresponds to 2.9 standard deviations above the physical limit of one of the four-fermion interaction model. At the present time we assume that there is a systematic uncertainty or correction that we haven't identified. For this reason the blind analysis results are not considered final and are subject to change.

6. Theoretical implications

The blind analysis results can be use to put stringent constraints on new physics. It is important to emphasize that these constraints like the blind analysis results are not to be considered final.

In Left-Right Symmetric (LRS) models the right-handed current is suppressed but not zero. An additional heavy right-handed W-boson (W_R) is introduced to restore parity conservation at high energies [10]. In these models, the left- and right-handed gauge boson fields are given by:

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta \tag{10}$$
$$W_R = e^{i\omega}(-W_1 \sin\zeta + W_2 \cos\zeta) \tag{11}$$

where ω is a CP violating phase. The TWIST result for ρ allow for model-independent constraints on the mixing angle (ζ) between the W_L and W_R and on the mass m_2 of the W_2 mass eigenstate. No assumptions on the left and right couplings, CKM matrices, or on the CP violation are made. The pre-TWIST limits from muon decay were $(g_R/g_L)|\zeta| < 0.06$ and $(g_R/g_L)m_2 > 400\mathrm{GeV/c}^2$. Our preliminary results improve these limites to $(g_R/g_L)|\zeta| < 0.02$ and $(g_R/g_L)m_2 > 680\mathrm{GeV/c}^2$.

7. Conclusions

The blind analysis of the final data from the TWIST spectrometer reached the original goal of a precision of a few 10^{-4} on the measurement of the decay parameters ρ, δ and $P_\mu\xi$. The product $P\mu\xi\delta/\rho$ is 2.9 standard deviations above the physical limit of one defined by the four-fermion interaction model used. The present results are therefore not final and the possibility of a missing systematic uncertainty or correction is being investigated.

8. Acknowledgments

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