In 2005, the Division of Nuclear Physics (DNP) created a PhD Thesis Prize competition for best thesis in Experimental or Theoretical Nuclear Physics by any student receiving their PhD degree from a Canadian University in the current or prior calendar year. The DNP is pleased to announce that the recipient of the 2008-09 DNP Thesis Prize is Robert MacDonald. Dr. MacDonald was awarded his PhD by the University of Alberta in November 2008 for the work "A Precision Measurement of the Muon Decay Parameters Rho and Delta". A summary of Dr. MacDonald's thesis work appears below.

A PRECISION MEASUREMENT OF THE MUON DECAY PARAMETERS ρ AND δ

BY ROBERT PAUL MACDONALD

The Standard Model of particle physics is an amazingly successful model of the way matter and energy interact at the quantum mechanical level, passing nearly any experimental tests we care to throw at it. SNO, the Sudbury Neutrino Observatory, has shown that neutrinos have mass, contrary to the Standard Model. But this is one of the only tests the model hasn't passed. That said, it has some quirks. The most basic peculiarity is that there are nineteen free parameters, such as the mass of the electron or the strength of the weak force; these values could be anything in the Standard Model, and must simply be measured. Many of the details of the model are curious, as well. For example, there are six quarks, and six leptons; why are they the same number? And why not eight, or four?

Through challenging experiments, we're steadily improving our understanding of the Standard Model's quirks, moving towards a more complete explanation of what's going on "underneath". The TWIST experiment [1] (the TRIUMF Weak Interaction Symmetry Test) is studying one of the quirks of the weak interaction. It turns out that particles come in "left-handed" and "right-handed" varieties — related to their tendency to prefer spinning one way more than the other — but the weak interaction has been seen to affect only left-handed particles or right-handed antiparticles. The TWIST experiment is a high-precision study of the weak interaction, to see if this is universally true.

SUMMARY

The TWIST experiment is a high-precision study of the weak interaction, examining billions of muon decays to look for evidence for interactions not predicted by the Standard Model of particle physics. The spectrum of muon decays can be described by a set of decay parameters whose values depend on the fundamental nature of the weak interaction. This work presents TWIST's intermediate measurements of the decay parameters ρ and δ, which strengthened the Standard Model's predictions and significantly tightened the constraints these parameters place on competing theories.

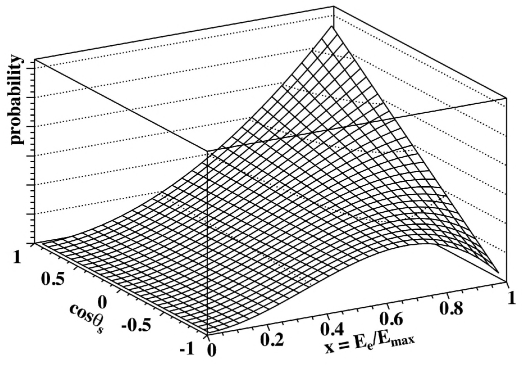

Fig. 1 Theoretical muon decay spectrum. θ_s is the direction of the emitted positron; $\cos\theta_s = 1$ is the direction of muon spin. $x = E_e/E_{max}$ represents the positron energy. The vertical axis is proportional to the probability that a positron will have the given x and $\cos\theta_s$. The TWIST experiment measures a large portion of this spectrum simultaneously; the measured region is not rectangular, but the range approximately covers $0.5 < |\cos\theta_s| < 1$ and $0.4 < x < 1$.

Specifically, TWIST is studying the decay of the positive muon into a positron and two neutrinos, $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$. Since there are no quarks involved, the strong interaction is entirely absent, leaving only the weak and electromagnetic interactions; the latter is very well understood and can be very precisely accounted. This makes muon decay an excellent choice for studying the weak interaction.
The distribution of energies and angles is called the decay spectrum, and its shape depends on the details of the weak interaction. The theoretical decay spectrum, shown in Fig. 1, is given by

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$$P(x,\cos\theta)\;\alpha\;x\left(x(1-x)+\rho\left(4x^2-3x\right)\right.$$
$$\left.+P_\mu\xi\frac{1}{3}x\left[1-x+\frac{2}{3}\delta(4x-3)\right]\cos\theta_s\right) \tag{1}$$

where $x = E_e / E_{max}$ represents the positron energy, and P_μ is the degree of polarization of the muons — that is, the degree to which the muon spins are aligned. Here the dependence on the electron mass and the radiative corrections have been left out for simplicity. The parameters ρ, δ, and ξ govern the shape of the decay spectrum; each depends on the details of the weak interaction and the handedness of the particles involved. There are other parameters as well, which can be determined by measurements involving e.g. the polarization of the decay electron. TWIST is designed to measure the positron energies and angles over a large portion of the decay spectrum, which allows it to measure ρ, δ, and ξ simultaneously to high precision: ρ controls the overall momentum dependence of the spectrum, δ controls how the angular asymmetry depends on momentum, and ξ controls the overall asymmetry. (The parameter ρ, and the parameter η related to the electron mass, are often called the Michel parameters.) The muon polarization will obviously affect the measured decay asymmetry as well, and $P_\mu\xi$ can only be measured as a product. Prior to the TWIST experiment's measurements, the uncertainty on ρ was ~3 x 10^{-3}, the uncertainty on δ was ~4 x 10^{-3}, and the uncertainty on $P_\mu\xi$ was ~9 x 10^{-3} [2]. This work in particular is focused on an intermediate measurement of ρ and δ [1] which reduced the uncertainties on these two parameters by about half, putting significantly tighter limits on right-handed muon decay. The final TWIST measurements, using later data, are to be published this year!

EXPERIMENT

The TRIUMF muon beam used by TWIST supplies us with about 2500 muons per second; a beam of protons strikes a carbon target, which produces pions, and some of these stop at the target surface. The muons are produced when the pions decay. The kinematics of pion decay mean that the muons created are essentially 100% polarized.

The heart of TWIST is a stack of high-precision tracking chambers [3], shown schematically in Fig. 2. The muons slow down as they pass through the detectors, stopping in a 71 μm thick foil of high-purity aluminum (>99.999%) at the centre of the spectrometer. Decay positrons are then tracked to determine their energy and direction. The stack of chambers sits inside a large solenoidal magnet — a surplus MRI magnet — contained within a 3 m purple cube-shaped steel yoke; the strong 2 Tesla magnetic field focusses the incoming beam, maintains the polarization of the stopped muons, and allows the reconstruction of the momenta of decay positrons.

The spectrometer consists of 44 drift chambers (DCs) and 12 multiwire proportional chambers (PCs), arranged symmetrically about the aluminum stopping target. (The wires — over 4000 of them — were all positioned with a precision of a few microns, by hand.) The PCs, which have very short reaction times (typically less than 20 ns), are used mainly for timing; the DCs, which have much longer reaction times (hundreds of nanoseconds), are used for high-precision tracking.

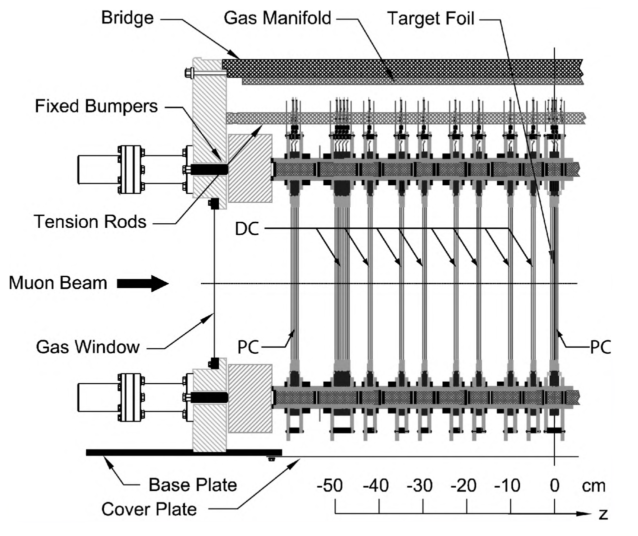

Fig. 2 Schematic drawing of the upstream half of the TWIST spectrometer, showing the arrangement of the drift chambers (DCs) and multi-wire proportional chambers (PCs). Muons enter from the left in the figure, slow down in the chambers, and stop in the aluminum target foil at the centre. The detector is symmetric about the target foil.

Data are taken around the clock, which means having TWIST personnel on site around the clock; for some reason, a large portion of the graveyard shifts are taken by graduate students. A variety of conditions were used — deliberately reduced polarization, increased muon rate, even detector temperature — in order to test for sensitivities to the experimental conditions. Obtaining consistent measurements of the muon decay parameters under these and other conditions provides useful confirmation of the simulation and analysis.

DATA ANALYSIS

One of the benefits of working on a relatively small experiment — TWIST involves just over 30 scientists — is that everybody is involved in every part of the project. For example, rather than working with a single aspect of the simulation or a particular analysis step, I was able to work on the entire analysis chain (and one of the things I learned from wading through that much C++ and Fortran programming is the value of good comments!)

The TWIST analysis software fits a helix to the positron tracking information from each muon decay event; the size and pitch of the helix depend on the momentum and direction of the decay positron. A matching simulation is run for each data set using the GEANT software from CERN; this simulation includes every detail of the TWIST spectrometer, down to pieces of tape. The decay spectra from data and simulation are then calibrated against each other for consistent momentum reconstruction.

The shapes of the calibrated decay spectra are then compared using a "spectrum fitter". This determines the differences ($\Delta\rho$, $\Delta\delta$, $\Delta P_\mu\xi$) in the muon decay parameters between data and simulation. If we know the values of the decay parameters used in the simulation, this tells us what the parameters are in the real world: $\rho_{data} = \Delta\rho + \rho_{sim}$, etc. In TWIST we hide the simulation's muon decay parameters until all analysis is complete — performing a *blind* analysis. A blind analysis is important to prevent "human bias," where the analysis is tuned and adjusted to bring the results more in line with what the experimenter is expecting — or hoping for! — or the experimenter stops looking for possible errors only when the results agree with expectations.

SIMULATION VALIDATION

Since TWIST determines the muon decay parameters by comparing the shape of a measured decay spectrum to the shape of a simulated spectrum, validation of the simulation is vital — in a high precision experiment, you can trust nothing.

The interactions between the decay positrons and the detector materials will influence track reconstruction, potentially affecting the decay spectrum. In particular, when a muon decays in the target, the tracking only begins after the positron has left the target, so it is especially important that the simulation correctly reproduce spectrum-distorting effects such as scattering and energy loss in the target region.

One of the studies used to validate the simulation uses a specialized data set and its corresponding simulation. The beam momentum is lowered, so that most muons are stopped in material just before ("upstream" of) the spectrometer. A decay positron produced in the downstream direction then passes through the entire length of the detector. The first data of this type were taken accidentally — somebody left something in the path of the beam after some other tests — but it was so useful that several more sets of this type of data have been taken since. The "upstream" and "downstream" halves of the positron's path are reconstructed separately, and their momentum and track angle compared. Energy loss, scattering, track fitting biases, and reconstruction resolution can all result in differences in the properties of the two tracks. Distributions of momentum differences, track angle differences, etc. then allow the direct examination of positron interactions in the detector — and hence the comparison of the positron interactions in the simulation to those in the real detector — independent of the shape of the muon decay spectrum. Figure 3 shows an example comparing the measured energy loss between data and simulation. There is a slight shift in the average energy loss, and a slight difference in resolution, both of which have to be accounted for, but otherwise the shape of the simulated distribution agrees with data across more than three orders of magnitude.

SYSTEMATIC UNCERTAINTIES

The precision of the TWIST experiment is limited by its systematic uncertainties rather than by statistics, and many sources of error other experiments would consider "negligible" had to be carefully examined for TWIST. The improvements we made over the first TWIST ρ and δ measurements [4,5] are in reducing these systematic uncertainties in a number of ways, and in better determining them.

Once a possible source of error is identified and its uncertainty determined, its impact on the decay parameter measurement can be assessed using the spectrum fitter, the same mechanism

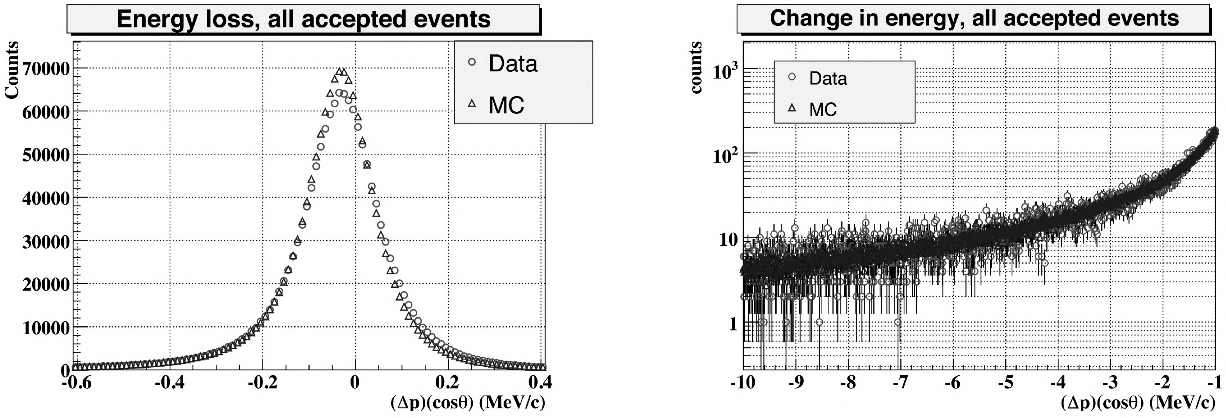

Fig. 3 Normalized distributions of reconstructed momentum loss from validation data and simulation. Momentum loss is multiplied by cosθ to account for angle dependence of energy loss. The left plot shows the peak energy loss region; the right plot shows the distribution for large energy loss events.

by which the decay parameters themselves are determined. The source of error is exaggerated in some way, usually by modifying the simulation or making some change to the analysis. A decay spectrum is produced under this exaggerated condition, and is compared to a standard data set or simulation to determine how the exaggeration affected the decay parameters. This is used to translate the original source of error into a systematic uncertainty in the decay parameters.

RESULTS AND CONCLUSIONS

After all systematic uncertainties are evaluated, the hidden values of the muon decay parameters used in the simulation are revealed and the measured decay parameters are determined. We find [1] $\rho = 0.75014 \pm 0.00017$ (stat) $\pm$ 0.00044 (syst) $\pm$ 0.00011 (η), where the last uncertainty is due to the uncertainty in the decay parameter η, and $\delta = 0.75067 \pm 0.00030$ (stat) $\pm$ 0.00067 (syst). Both results are consistent with the Standard Model values of 3/4. These represent factor of two improvements over the previous TWIST measurements [4,5]. Any modifications to the Standard Model will have to work within these tighter limits; for example, these measurements significantly reduce the possibility that the weak interaction affects right-handed particles at all.

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REFERENCE

1. R.P. MacDonald *et al*. (TWIST Collaboration), *Phys. Rev.* **D 78**, 032010 (2008).
2. W. Fetscher and H.-J. Gerber, in P. Langacker, editor, *Precision Tests of the Standard Electroweak Model*, World Scientific, Singapore, 1995.
3. R. Henderson *et al*., *Nucl. Instrum. Methods* **A 548**, 306 (2005).
4. J. Musser *et al*. (TWIST Collaboration), *Phys. Rev. Lett.* **94**, 101805 (2005).
5. A. Gaponenko *et al*. (TWIST Collaboration), *Phys. Rev.* **D 71**, 071101 (2005).