A Muon Decay Spectrum Measurement from *TWIST*

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Motivation

Apparatus

Analysis

Systematics

Results
Motivation

Muon Decay: A Constraint on the Weak Interaction

- General Lorentz invariant, derivative-free, interaction described by

\[ \mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} g_{\epsilon\mu}^\gamma \langle \bar{e}_\epsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma^\gamma | \mu_\mu \rangle. \]

- In the standard model (V - A) interaction \( g_{LL}^V = 1 \)
- all other contributions are zero

\[ \begin{array}{c}
\mu^+ \\
\bar{\nu}_\mu \\
\nu_e \\
e^+
\end{array} \]
Motivation

Positron Spectrum of Muon Decay

Given in momentum and angle as

\[ \frac{\partial \Gamma}{\partial x \partial \cos \theta} = F(x; \rho, \eta) + P_\mu \cos \theta G(x; \xi, \delta), \quad x = \frac{E_e}{E_{\text{max}}} \]

In the Standard Model

\[ \rho = 0.75 \]

\[ \eta = 0 \]

\[ \delta = 0.75 \]

\[ P_\mu^\pi \xi = 1 \]

deviations represent new physics
Motivation

Tests for New Physics

Right Handed Decays

- Probability given by

\[
Q^\mu_R = \frac{1}{4} (|g^S_{LR}|^2 + |g^S_{RR}|^2) + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2
\]

\[
= \frac{1}{2} \left( 1 + \frac{\zeta}{3} + \frac{16\zeta \delta}{9} \right)
\]

Left - Right Symmetric Models

\[
W_L = \cos \zeta W_1 + \sin \zeta W_2
\]

\[
W_R = e^{i\omega} (-\sin \zeta W_1 + \cos \zeta W_2)
\]

where

\[
\zeta = \left| \frac{g_L}{g_R} \right| \sqrt{\frac{1}{2} \left( 1 - \frac{4}{3} \rho \right)}
\]
M13: Surface Muon Source
TWIST detector

TWIST Spectrometer
(cutaway view)

Beam pipe
Superconducting magnet and cryostat
Support cradle
Prop. and drift chamber
Target
Yoke
TWIST Analysis

Experimental Data

$\rho_h, P^\pi_\mu \xi_h, \delta_h$

Geant 3 Simulation

$\Delta \rho, \Delta P^\pi_\mu \xi, \Delta \delta$

Spectrum Fit

Yield (Arbitrary Units)

Momentum (MeV/c)

$\sigma (Data - Fit) / \sigma$

Data
Fit

R. Bayes (UVIC, TRIUMF)
General Systematics Determination

- Verify strength and uncertainty of effect.
- Exaggerate the effect in data or simulation.
- Measure the sensitivity of the decay parameters.
- Scale the final sensitivities.

Example: Endpoint Calibration
Corrects differences between simulation and data at endpoint

\[ p_{\text{data}} - p_{\text{MC}} \approx 14 \pm 2 \text{ keV/c} \]

Sensitivity:

\[ \Delta \rho \Delta p_{\text{edge}} \approx (-1.72 \pm 0.37) \times 10^{-3} \times 100 \text{ keV/c} \]
**General Systematics Determination**

- Verify strength and uncertainty of effect.
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**Example: Endpoint Calibration**

Corrects differences between simulation and data at endpoint

\[ \Delta p_{\text{edge}} \approx 14 \pm 2 \text{ keV/c} \]

Yield (Arbitrary Units)

<table>
<thead>
<tr>
<th>Momentum (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.4</td>
</tr>
<tr>
<td>Data</td>
</tr>
</tbody>
</table>

Sensitivity:

\[ \frac{\Delta \rho}{\Delta p_{\text{edge}}} \approx \frac{(-1.72 \pm 0.37) \times 10^{-3}}{100 \text{ keV/c}} \]
# Systematic Effects on TWIST Measurements

## Current State of Leading Systematic Uncertainties

<table>
<thead>
<tr>
<th>Effect</th>
<th>$\Delta \rho \times 10^4$</th>
<th>$\Delta \delta \times 10^4$</th>
<th>$\Delta P^\pi_\mu \xi \times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fringe Field Depol.</td>
<td>NA</td>
<td>NA</td>
<td>34</td>
</tr>
<tr>
<td>Stopping Material Depol.</td>
<td>NA</td>
<td>NA</td>
<td>12</td>
</tr>
<tr>
<td>Chamber Response</td>
<td>2.9</td>
<td>5.2</td>
<td>10</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>2.9</td>
<td>4.1</td>
<td>2</td>
</tr>
<tr>
<td>Positron Interactions</td>
<td>1.6</td>
<td>0.9</td>
<td>3</td>
</tr>
<tr>
<td>Resolution</td>
<td>1.2</td>
<td>1.4</td>
<td>NA</td>
</tr>
<tr>
<td>$\eta$ correlations</td>
<td>1.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- R. MacDonald, PhD Thesis, University of Alberta
Latest TWIST Results

\[ \rho \]
- Derenzo, ‘69
- Musser, ‘05
- MacDonald, ‘08

Final TWIST goals

\[ \delta \]
- Balke, ‘88
- Gaponenko, ‘05
- MacDonald, ‘08

Final TWIST goals

\[ P^{\pi \xi} \]
- Beltrami ‘87
- Jamieson ‘06

Final TWIST goals

To be published
Limits on New Physics

Right Handed Muon Decays

- $Q^\mu_R < 0.014$: 90% limit before 2004
- $Q^\mu_R < 0.0024$: 90% limit from current results

Improved Limits on Left-Right-Symmetric Models
Approaching Final analysis

- Ultimate goal of an order of magnitude improvement in sight

### Improvements in Statistical Uncertainties

- Experiment collected $8 \times 10^9$ events during 2006 and 2007
- Physics data set nearly 6 times larger than previous

### Reduction of Systematic Uncertainties

- Better Beamline Monitoring $\implies$ Fringe Field Depol.
- Better Chamber Modelling $\implies$ Chamber Response
- Large Sample Through Going $e^+$ $\implies$ Positron Interactions
Conclusion

Summary

Consistency with the Standard Model

\[
\rho = 0.75014 \pm 0.00017 \text{(stat)} \pm 0.00046 \text{(sys)} \pm 0.00011 \text{(η)}
\]

\[
\delta = 0.75068 \pm 0.00030 \text{(stat)} \pm 0.00067 \text{(sys)}
\]

\[
P^{\pi}_{\mu} \xi = 1.0003 \pm 0.0006 \text{(stat)} \pm 0.0038 \text{(sys)}
\]

- Preliminary results improve precision on $\rho$ and $\delta$ by a factor of 5.
- Improved precision on $P^{\pi}_{\mu} \xi$ by a factor of 2.
- Precision goal of an order of magnitude improvement in decay parameters coming soon.
The **TWIST** Collaboration

**TRIUMF**
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Yuri Davydov
Wayne Faszer
Makoto Fujiwara
David Gill
Alex Grossheim
Peter Gumplinger
Anthony Hillairet ♣★
Robert Henderson
Jingliang Hu
John A. MacDonald ♦
Glen Marshall
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Mina Nozar
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**Texas A&M**
Carl Galiardi
Jim Musser ★
Bob Tribble

**Valpariso**
Don Koetke
Shirvel Stanislaus

★ graduate student
★ graduated
♣ also UVic
♦ deceased

- Funding Support from NSERC and US DOE
- Additional support from TRIUMF and NRC
- Computing resources provided by Westgrid
\[
\frac{\partial^2 \Gamma}{\partial x \partial \cos \theta} = F(x; \rho, \eta) + P_\mu \cos \theta G(x; \xi, \delta)
\]
\[
F(x; \rho, \eta) = x(1-x) + \frac{2}{9} \rho (4x^2 - 3x - x_0^2) + \eta x_0 (1-x)
\]
\[
G(x; \xi, \delta) = \frac{1}{3} \xi \sqrt{x^2 - x_0^2} \left[ 1 - x + \frac{2}{3} \delta \left( 4x - 3 + \left( \sqrt{1 - x_0^2} - 1 \right) \right) \right]
\]
Spectrum Fits

\[
\frac{\partial^2 \Gamma}{\partial x \partial \cos \theta} \bigg|_{fit} = \frac{\partial^2 \Gamma}{\partial x \partial \cos \theta} \bigg|_{base} + \Delta \rho \frac{\partial}{\partial \rho} \frac{\partial^2 \Gamma}{\partial x \partial \cos \theta} + \ldots
\]
Testing Positron Interactions: Far Upstream Stops

A specialised type of data set
- muons stopped in the far upstream end of the detector
- downstream decaying positrons pass through entire detector stack

Uses for these data
- check efficiency of reconstruction
- measure reconstruction resolution
- directly measure target thickness
Response Function

Momentum Response

\[ (\Delta p)(\cos\theta) \]

- Change in Momentum (MeV/c)
- Data
- MC

Angle Response

\[ \Delta\theta \]

- Change in Angle (radians)
- Data
- MC
Response Function

Momentum Response

\[ (\Delta p)(\cos\theta) \]

![Momentum Response Graph]

Angle Response

\[ \Delta \theta \]

![Angle Response Graph]