A High Precision Measurement of Muon Decay Parameters

The Precision Frontier in Particle Physics

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TWIST Collaboration

TRIUMF/University of Alberta

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Canadian Association of Physicists

TWIST will test the standard model predictions for the weak interaction by measuring the energy and angular distribution of e+ from the decay of polarized μ+.
The TWIST collaboration

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§ Deceased
Muon decay rate

\[
\text{rate} \sim \sum_{\gamma=S,V,T} g_{ij}^\gamma \left< \bar{\psi}_{e_i} | \Gamma_\gamma \psi_{\nu_e} \right> \left< \bar{\psi}_{\nu_\mu} | \Gamma_\gamma \psi_{\mu_j} \right>
\]

- \( S,V,T = \) scalar, vector or tensor interactions
- \( R, L = \) right and left handed leptons

- **In the standard model only vector couplings of left-handed to left-handed fermions are allowed:**

\[
\begin{align*}
|g_{RR}^S| &= 0 \\
|g_{RR}^V| &= 0 \\
|g_{RR}^T| &\equiv 0 \\
|g_{LR}^S| &= 0 \\
|g_{LR}^V| &= 0 \\
|g_{LR}^T| &= 0 \\
|g_{RL}^S| &= 0 \\
|g_{RL}^V| &= 0 \\
|g_{RL}^T| &= 0 \\
|g_{LL}^S| &= 0 \\
|g_{LL}^V| &= 1 \\
|g_{LL}^T| &\equiv 0
\end{align*}
\]
Current limits on the coupling constants

\[
\begin{align*}
g_{RR}^S & < 0.066 & g_{RR}^V & < 0.033 & g_{RR}^T & = 0 \\
g_{LR}^S & < 0.125 & g_{LR}^V & < 0.060 & g_{LR}^T & < 0.036 \\
g_{RL}^S & < 0.424 & g_{RL}^V & < 0.110 & g_{RL}^T & < 0.122 \\
g_{LL}^S & < 0.55 & g_{LL}^V & > 0.96 & g_{LL}^T & = 0
\end{align*}
\]

Deviations from V-A structure are possible. Need more sensitive searches!

TWIST will improve the coupling constants precision by a factor of 3 - 10
The muon decay parameters & the coupling constants

\[ \rho = \frac{3}{4} - \frac{3}{4} \left[ |g_{LR}|^2 + |g_{RL}|^2 + 2 |g_{LR}|^2 + 2 |g_{RL}|^2 + \text{Re}(g_{RL}^* g_{RL} + g_{LR}^* g_{LR}) \right] \]

\[ \xi \delta = \frac{3}{4} - \frac{3}{4} \left[ |g_{LR}|^2 + |g_{RL}|^2 + 4 |g_{LR}|^2 + 2 |g_{RL}|^2 + 2 |g_{RR}|^2 \right. \\
\left. + \frac{1}{2} |g_{RR}|^2 + \frac{1}{2} |g_{LR}|^2 + \text{Re}(g_{RL}^* g_{RL} - g_{LR}^* g_{LR}) \right] \]

\[ \xi = 1 - \left[ \frac{1}{2} |g_{RR}|^2 + \frac{1}{2} |g_{LR}|^2 + 2 |g_{RR}|^2 + 4 |g_{RL}|^2 - 2 |g_{LR}|^2 \right. \\
\left. - 2 |g_{LR}|^2 + 8 |g_{RL}|^2 + 4 \text{Re}(g_{RL}^* g_{RL} - g_{LR}^* g_{LR}) \right] \]

\[ \eta = \frac{1}{2} \text{Re}[g_{LL}^* g_{RR} + g_{RL}^* (g_{LR}^* + 6 g_{LR}) + g_{LR}^* (g_{RL}^* + 6 g_{RL}) + g_{RR}^* g_{LL}] \]

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The muon decay parameters & the spectrum shape

rate \sim x^2 \left[ 3 - 3x + \frac{2}{3} \rho (4x - 3) + 3\eta x_o \frac{1-x}{x} + P_\mu \xi \cos \theta_e \left(1 - x + \frac{2}{3} \delta (4x - 3)\right) \right]

Spectral shape in \(x, \cos \theta_e\) is characterized in terms of four parameters -- \(\rho, \eta, \xi, \delta, P_\mu\) is the muon polarization

\(x \equiv \frac{E_e}{E_{e_{\max}}}\)

\(x_o \equiv \frac{m_e}{E_{e_{\max}}}\)

\(E_{e_{\max}} \equiv \frac{m_\mu^2 + m_e^2}{2 m_\mu}\)

\(\text{TWIST will measure} \ \rho, \ \xi, \ \delta \ \text{in two phases} \ 10^{-3} \ \text{in 2004} \ & \ \text{fewx} 10^{-4} \ \text{in 2005/6}\)
**Coupling to right-handed muons...**

\[
rate \sim \sum_{m,n=L,R} Q_{mn}
\]

\[
Q_{mR} = Q_{RR} + Q_{LR} = \frac{1}{4}|g_{RR}|^2 + |g_{RR}|^2 + \frac{1}{4}|g_{LR}|^2 + |g_{LR}|^2 + 3|g_{LR}|^2
\]

\[
\equiv 0 \quad \text{by the standard model}
\]

\(Q_{mR}\) describes decay of a *right-handed* \(\mu\) into a *right-handed* or *left-handed* \(e^+\)

\(Q_{mR}\) can be written in terms of \(\delta\) and \(\xi\)

\[
Q_{mR} = \frac{1}{2} \left( 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right)
\]

A determination of \(\delta\) and \(\xi\) gives a *model-independent test* for
the existence of *right-handed couplings to muons*, i.e., \(Q_{mR} \neq 0\)

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Anticipated TWIST sensitivity to right-handed currents

\[ Q^\mu_R = \frac{1}{2} \left( 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right) \]

- PDG
- TWIST preliminary
- TWIST final
- Existing limits - Discovery region

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Beyond the standard model

- In the SM there are two (weak) charged-current vector bosons

\[ W^\pm (W_L^\pm) \]

- In some extensions to the SM one has left-handed as well as right-handed vector bosons

\[ W_L^\pm \ & \ & W_R^\pm \]

- \( W_L \ & \ W_R \) mix to form the mass eigenstates \( W_1 \ & \ W_2 \)

\[
W_1 = W_L \cos \xi - W_R \sin \xi \\
W_2 = W_L \sin \xi + W_R \cos \xi
\]

- Mixing angle \( \xi \) is small
- \( W_2 > W_1 \) since left handed couplings are dominant at low energies.

\[
W_1 \approx W_L \ & \ & W_2 \approx W_R
\]
Anticipated TWIST sensitivity to left-right mixing
The beamline

- The TRIUMF beamline delivers highly polarized “surface muons”.
The spectrometer

- The TWIST detector is a set of high precision, low mass chambers sitting in a superconducting magnet.
The spectrometer
A typical decay event
TWIST statistics and systematics

- TWIST can accumulate $\sim 10^9$ muon decay events in two weeks.
- TWIST is systematics limited.
- In 2002-03, $\sim 6 \times 10^9$ muon decay events on tape.
- Need a lot of computer power (thanks to WestGrid –1008 CPUs)!
- Long list of systematic effects to investigate!

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Sample systematic studies (data &amp; MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber response</td>
<td>Change high voltage from standard.</td>
</tr>
<tr>
<td>Chamber alignment &amp; geometry</td>
<td>Randomize plane positions in MC.</td>
</tr>
<tr>
<td>Beam tune</td>
<td>Change beam tune from standard (data &amp; MC).</td>
</tr>
<tr>
<td>Solenoidal field effects</td>
<td>Change magnetic field from standard (data &amp; MC).</td>
</tr>
<tr>
<td>GEANT physics and stepping</td>
<td>MANY GEANT validation studies!</td>
</tr>
<tr>
<td>Polarization</td>
<td>Use non-surface (cloud) muons.</td>
</tr>
<tr>
<td>Muon stopping distribution</td>
<td>Stop muons off centre (data &amp; MC).</td>
</tr>
<tr>
<td>Code biases</td>
<td>MANY code validation studies!</td>
</tr>
</tbody>
</table>

Data sets acquired

<table>
<thead>
<tr>
<th>Data sets acquired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard data sets</td>
</tr>
<tr>
<td>$B = 1.96$ tesla</td>
</tr>
<tr>
<td>$B = 2.04$ tesla</td>
</tr>
<tr>
<td>DC HV lowered</td>
</tr>
<tr>
<td>PC HV lowered</td>
</tr>
<tr>
<td>Muon stopped slightly upstream</td>
</tr>
<tr>
<td>Muon stopped slightly downstream</td>
</tr>
<tr>
<td>Al slab inserted downstream</td>
</tr>
<tr>
<td>Plastic slab inserted downstream</td>
</tr>
<tr>
<td>Beam flux rate doubled</td>
</tr>
<tr>
<td>Beam flux rate cut in half</td>
</tr>
<tr>
<td>Bending magnet field increased by 10G</td>
</tr>
<tr>
<td>Bending magnet field decreased by 10G</td>
</tr>
<tr>
<td>Channel momentum tuned for non-surface (cloud) muons</td>
</tr>
</tbody>
</table>

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Evaluating systematic errors: data to data

- Event classification (31 types)
- Helix fit to events within fiducial volume
- Extract $e^+$ momentum and angle spectrum in bins of $x$ and $\cos\theta_e$

Δρ, Δη, Δδ, Δξ
Evaluating systematic errors: MC to MC

**Monte Carlo data**

- Event classification (31 types)
- Helix fit to events within fiducial volume
- Extract $e^+$ momentum and angle spectrum in bins of $x$ and $\cos\theta_e$

**Event Analysis**

**Base set**

- $\Delta \rho$, $\Delta \eta$, $\Delta \delta$, $\Delta \xi$

**Monte Carlo data Test set**

- One parameter changed

**Test set**

- $\Delta \rho$, $\Delta \eta$, $\Delta \delta$, $\Delta \xi$

**Base set spectrum**

- $\Delta \rho$, $\Delta \eta$, $\Delta \delta$, $\Delta \xi$

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Final result

- Event classification (31 types)
- Helix fit to events within fiducial volume
- Extract $e^+$ momentum and angle spectrum in bins of $x$ and $\cos \theta_e$

Accelerator data spectrum

Monte Carlo data are collected

Accelerator data are collected

Monte Carlo data are generated

Fit

$\Delta \rho$, $\Delta \eta$, $\Delta \delta$, $\Delta \xi$
• **2004 program:**
  
  • Publish measurement of $\rho, \delta$ at $10^{-3}$ in 2004.
    
  • Data in hand for measurement of $\rho, \delta$ to $10^{-3}$
  
  • Study of systematic errors for $10^{-3}$ nearly complete
  
  • Take data for measurement of $P_{\mu \xi}$ for $10^{-3}$ precision (publish 2004/05).

• **2005/06 program:**

  • Take data for measurement of $\rho, \eta, \xi, \delta$ to a precision of a few parts in $10^4$ ($\sim 10^3$ for $\eta$)