Measurement of the muon decay parameters with the TRIUMF Weak Interaction Symmetry Test (TWIST) Experiment

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The muon decay is very interesting

- Only weak interaction involved
- Muons are easy to produce
- One decay mode dominant
  \( \approx 100\% \)
  \[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]
4-fermion formalism

To study the muon decay we describe it by using a very general formalism.

The interaction is described as a derivative-free, Lorentz-invariant and lepton-number conserving matrix:

\[ M = 4 \frac{G_F}{\sqrt{2}} \sum_{\gamma = S, V, T} \epsilon, \mu = R, L \]

\[ g_{\epsilon\mu}^\gamma < \bar{e}_\epsilon | \Gamma^\gamma | \nu_e > < \bar{\nu}_\mu | \Gamma^\gamma | \mu_\mu > \]

- \( g_{RR}^T \equiv g_{LL}^T \equiv 0 \)
- A common phase doesn’t matter

\[ \Rightarrow \text{19 real and independent parameters} \]

Standard Model, V-A interaction

\( g_{LL}^V \) is the only non zero coupling

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The differential decay rate can be written using the Michel parametrization:

\[
\frac{d^2\Gamma}{dx d \cos \theta} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} (F_{IS}(x) + P_\mu \cos \theta F_{AS}(x)) + RC.
\]
The Michel parametrization

The isotropic and anisotropic parts of the Michel parameters are:

\[ F_{IS}(x) = x(1 - x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1 - x) \]

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

Standard Model predictions

\[ \rho = \frac{3}{4}, \quad \eta = 0, \quad P_\mu \xi = 1, \quad \delta = \frac{3}{4} \]
The isotropic and anisotropic parts of the Michel parameters are:

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**Standard Model predictions**

\[ \rho = \frac{3}{4}, \quad \eta = 0, \quad P_\mu \xi = 1, \quad \delta = \frac{3}{4} \]
The TWIST spectrometer

TWIST Spectrometer (cutaway view)

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

Measurement of the muon decay parameters with the TWIST experiment.
The spectrometer in the M13 beamline

Production Target
Fringe Field
Stopping Material
Measurement of the muon decay parameters with the TWIST experiment.
Typical event

Measurement of the muon decay parameters with the TWIST experiment.
A Blind Analysis

The TWIST analysis is blind to avoid any human bias:
- Choices of data samples
- Looking for errors if disagreement with expectations
- Systematic error evaluation influenced by final result

![Graph showing the value of \( \rho \) over time from 1950 to 1970.](image-url)
The software analysis

**Experimental data**

MOFIA

Monte Carlo data

Energy calibration

Michel Spectrum Fit

$\Delta \xi, \Delta \rho, \Delta \delta$

$\xi, \rho, \delta$

Black Box

$\xi_{MC}, \rho_{MC}, \delta_{MC}$

Measurement of the muon decay parameters with the TWIST experiment.
The software analysis

Experimental data

MOFIA

Monte Carlo data

Black Box

Energy calibration

Michel Spectrum Fit

$\Delta \xi, \Delta \rho, \Delta \delta$

$\xi, \rho, \delta$

Measurement of the muon decay parameters with the TWIST experiment.
The software analysis

Experimental data → MOFIA → Energy calibration

Monte Carlo data

Black Box $\xi_{MC}, \rho_{MC}, \delta_{MC}$

Michel Spectrum Fit

$\Delta\xi, \Delta\rho, \Delta\delta$

$\xi, \rho, \delta$
The software analysis

Experimental data

MOFIA

Energy calibration

Michel Spectrum Fit

Black Box

\( \xi_{MC}, \rho_{MC}, \delta_{MC} \)

\[ \Delta \xi, \Delta \rho, \Delta \delta \]

\[ \xi, \rho, \delta \]
The software analysis

Experimental data

Monte Carlo data

MOFIA

Energy calibration

Michel Spectrum Fit

$\Delta \xi, \Delta \rho, \Delta \delta$

$\xi, \rho, \delta$

Black Box

$\xi_{MC}, \rho_{MC}, \delta_{MC}$
Measurement of the muon decay parameters with the TWIST experiment.
The software analysis

- Detector response included in MC
- Reconstruction biases reduced because $\Delta\xi$, $\Delta\rho$, $\Delta\delta$ are small
- Most systematics are from the difference between the MC simulation and the reality

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Measurement of the muon decay parameters with the TWIST experiment.
The TWIST Results

### Published results

\[ \rho = 0.75080 \pm 0.00044 \text{ (stat)} \pm 0.00093 \text{ (sys)} \pm 0.00023 (\eta) \]

\[ \delta = 0.74964 \pm 0.00066 \text{ (stat)} \pm 0.00112 \text{ (sys)} \]

\[ P_\mu \xi = 1.0003 \pm 0.00006 \text{ (stat)} \pm 0.0038 \text{ (sys)} \]

<table>
<thead>
<tr>
<th></th>
<th>Published Statistics</th>
<th>Published Systematics</th>
<th>Final Goal Statistics</th>
<th>Final Goal Systematics</th>
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<tbody>
<tr>
<td>\rho</td>
<td>4.4</td>
<td>9.3</td>
<td>1.3</td>
<td>2.4</td>
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<tr>
<td>\delta</td>
<td>6.6</td>
<td>11.2</td>
<td>2.3</td>
<td>2.2</td>
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<tr>
<td>(P_\mu \xi)</td>
<td>6.0</td>
<td>38</td>
<td>2.8</td>
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</table>
## The TWIST Collaboration

### TRIUMF
- Ryan Bayes†
- Yuri Davydov
- Jaap Doornbos
- Wayne Faszer
- Makoto Fujiwara
- David Gill
- Alex Grosshein
- Peter Gumplinger
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- Robert Henderson
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- Art Olin
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- Renée Poutissou
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- Bill Shin

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- Yuri Davydov
- Dick Mischke
- Mina Nozar
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- Robert Openshaw
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- Renée Poutissou
- Grant Sheffer
- Bill Shin

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- Mike Hasinoff
- Blair Jamieson

### Texas A&M
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- Jim Musser
- Bob Tribble
- Maxim Vasiliev

<table>
<thead>
<tr>
<th>Kurchatov Institute</th>
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<tbody>
<tr>
<td>Vladimir Selivanov</td>
</tr>
<tr>
<td>Vladimir Torokhov</td>
</tr>
<tr>
<td>Don Koetke</td>
</tr>
<tr>
<td>Paul Nord</td>
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<td>Shirvel Stanislaus</td>
</tr>
</tbody>
</table>

- ◊ Graduated
- † Graduate student
Model-Independent search for right-handed interactions

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

- Right-handed interaction contribution in the muon decay:
  \[Q_R^\mu = Q_{RR} + Q_{LR}\]
- Also defined as:
  \[Q_R^\mu = \frac{1}{2} \left( 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right)\]

Standard Model, V-A interaction

\[Q_R^\mu = 0\]
\[ \frac{d^2 \Gamma}{dx d(\cos \theta)} \bigg|_{\rho_{MC}, \delta_{MC}, \xi_{MC}} \ + \ \sum_{\alpha = \rho, \xi, \xi\delta} \frac{\partial}{\partial \alpha} \left[ \frac{d^2 \Gamma}{dx d(\cos \theta)} \right] \Delta \alpha \]

MC spectrum

Derivatives fitted
TABLE II. Contributions to the systematic uncertainty in ρ. Average values are given for those denoted (av), which are considered set dependent when performing the weighted average of the data sets.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Uncertainty</th>
</tr>
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<tbody>
<tr>
<td>Chamber response (av)</td>
<td>±0.000 51</td>
</tr>
<tr>
<td>Stopping target thickness</td>
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<tr>
<td>Positron interactions</td>
<td>±0.000 46</td>
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<tr>
<td>Spectrometer alignment</td>
<td>±0.000 22</td>
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<tr>
<td>Momentum calibration (av)</td>
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<tr>
<td>Theoretical radiative corrections [12]</td>
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<td>Track selection algorithm</td>
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<tr>
<td>Muon beam stability (av)</td>
<td>±0.000 04</td>
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<tr>
<td>Total in quadrature</td>
<td>±0.000 93</td>
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<tr>
<td>Scaled total</td>
<td>±0.000 97</td>
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TABLE III. Contributions to the systematic uncertainty for $P^\pi_\gamma$.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depolarization in fringe field (ave)</td>
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</tr>
<tr>
<td>Depolarization in stopping material (ave)</td>
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<td>Chamber response (ave)</td>
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<tr>
<td>Positron interactions</td>
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<tr>
<td>Depolarization in production target</td>
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<td>Momentum calibration</td>
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<td>Upstream-downstream efficiency</td>
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<td>Background muon contamination (ave)</td>
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<tr>
<td>Beam intensity (ave)</td>
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<td>Michel parameter η</td>
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<tr>
<td>Theoretical radiative corrections</td>
<td>0.0001</td>
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