First Results on Muon Decay from TWIST
The Precision Frontier in Particle Physics

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TWIST Collaboration
TRIUMF/University of Alberta
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TWIST is testing the standard model predictions for the weak interaction by measuring the energy and angular distribution of $e^+$ from the decay of polarized $\mu^+$. 
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The collaboration
I. Motivation
In the SM only vector couplings of left handed to left handed fermions are allowed.

To search for new physics start with a general interaction matrix

- Local.
- Derivative free.
- Lorentz-invariant.
- Lepton number conserving.

\[
M = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} g_{\epsilon\mu}^\gamma \left\langle \bar{e}_\epsilon \Gamma^\gamma \left( \nu e \right)_n \left| \left( \bar{\nu}_\mu \right)_m \Gamma_\gamma \left| \bar{\mu}_\mu \right\rangle \right. \\
\left. \gamma=0,1,2 \right\}\nonumber
\]


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

\[
\Gamma^S = 1 \\
\Gamma^V = \gamma^\mu \\
\Gamma^T = \frac{1}{\sqrt{2}} \sigma^{\mu\nu} \equiv \frac{i}{2\sqrt{2}} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu)
\]
In the SM only vector couplings of left handed to left handed fermions are allowed.

\[
\begin{align*}
|g^S_{RR}| &= 0, & |g^V_{RR}| &= 0, & |g^T_{RR}| &= 0 \\
|g^S_{LR}| &= 0, & |g^V_{LR}| &= 0, & |g^T_{LR}| &= 0 \\
|g^S_{RL}| &= 0, & |g^V_{RL}| &= 0, & |g^T_{RL}| &= 0 \\
|g^S_{LL}| &= 0, & |g^V_{LL}| &= 1, & |g^T_{LL}| &= 0
\end{align*}
\]

PDG limits on the coupling constants.

\[
\begin{align*}
|g^S_{RR}| &< 0.066, & |g^V_{RR}| &< 0.033, & |g^T_{RR}| &\equiv 0 \\
|g^S_{LR}| &< 0.125, & |g^V_{LR}| &< 0.060, & |g^T_{LR}| &< 0.036 \\
|g^S_{RL}| &< 0.424, & |g^V_{RL}| &< 0.110, & |g^T_{RL}| &< 0.122 \\
|g^S_{LL}| &< 0.55, & |g^V_{LL}| &> 0.96, & |g^T_{LL}| &\equiv 0
\end{align*}
\]
Differential decay rate

- Calculate the muon decay rate differential in energy and angle
  - Start with the general form.
  - Parametrize using the Michel parameters.

\[
\frac{d^2 \Gamma}{dx d \cos \vartheta} = \frac{m_\mu}{4 \pi} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} \left\{ F_{IS}(x) + P_\mu \cos \vartheta \right\} F_{AS}(x)
\]

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

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

\[
W_{e\mu} = \frac{(m_\mu^2 + m_e^2)}{2 m_\mu}
\]

\[
x = E_e / W_{e\mu}
\]

\[
x_0 = m_e / W_{e\mu}
\]

Radiative corrections
The MPs & the coupling constants

\[
\rho = \frac{3}{4} - \frac{3}{4} \left[ \frac{1}{2} \left| g_{LR}^S \right|^2 + \frac{1}{2} \left| g_{LR}^S \right|^2 + 2 \left| g_{RL}^V \right|^2 + 2 \left| g_{RR}^T \right|^2 + 2 \left| g_{LR}^T \right|^2 + \text{Re} \left( g_{RL}^S g_{RL}^T + g_{LR}^S g_{LR}^T \right) \right]
\]

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

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

\[
\eta = \frac{1}{2} \text{Re} \left[ g_{LL}^V g_{RR}^S + g_{RL}^V \left( g_{LR}^S + 6 g_{LR}^T \right) + g_{LR}^V \left( g_{RL}^S + 6 g_{RL}^T \right) + g_{RR}^V g_{LL}^S \right]
\]
Model-independent physics

- Define decay probabilities according to handedness

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


- Decay of a right-handed \( \mu \) into a right-handed or left-handed \( e^+ \)

- Can be written in terms of \( \delta \) and \( \xi \)

\[ Q_R^\mu = Q_{RR} + Q_{LR} = \frac{1}{2} \left( 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right) \]

\( \equiv 0 \)

by the standard model

A determination of \( \delta \) and \( \xi \) gives a model-independent test for the existence of right-handed couplings to muons, i.e. \( Q_R^\mu \neq 0 \)
**Left-right symmetric models**

- **Standard Model**
  \[ W^\pm(W_L^\pm) \]

- **W_L & W_R mix to form the mass eigenstates W_1 & W_2**
  - Mixing angle \( \zeta \) is small.
  - \( M_2 > M_1 \) since left handed couplings are dominant at low energies.

- **Left-right symmetric models**
  \[ W_1 = W_L \cos \zeta - W_R \sin \zeta \]
  \[ W_2 = W_L \sin \zeta + W_R \cos \zeta \]
  \[ W_1 \approx W_L & W_2 \approx W_R \]

- The mass and mixing angles are sensitive to \( \rho \) and \( \xi \)

\[ \rho = \frac{3}{4} \left( 1 - 2 \zeta^2 \right) \]
\[ \xi = 1 - 2 \left( \frac{t^2 + \zeta^2}{g} \right) \]
\[ t = \frac{g_R}{g_L} \]
\[ \zeta = \frac{g_R}{g_L} \zeta \]
The beamline

- **Surface $\mu^+$ beam**
  - Mono-energetic ($P=29.7$ MeV/c).
  - Highly polarized.

$h_\nu = -1$

$h_\mu$

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The detector

- $\mu^+$ beam stops at the centre.
- Detector is highly symmetric.
- Chambers sit inside a highly uniform MRI magnet.
- Drift chambers used to track decay $e^+$.
- Trigger provided by a thin upstream scintillator.
- Beam stopping position fine-tuned using a variable CO$_2$:He gas degrader.
- The 2 tesla field is uniform to $4 \times 10^{-3}$, mapped to precision of $5 \times 10^{-5}$.

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The detector

- 56 chambers: 44 DC planes & 12 PC planes.
High precision

- Longitudinal plane positions accurate to $5 \times 10^{-5}$ by engineering.
- Measured wire positions yield $\sigma = 3.3 \mu m$
- Transverse positions calculated to an accuracy of 5 $\mu m$ using 120 MeV/c pions.

High resolution

- High alignment precision.
- Choice of gas
  - DME: slow gas, high ionization density, low Lorentz angle.

High efficiency.

- No hot or dead wires throughout 2002 data taking!
- Efficiency $> 99.9\%$ at 1900V.
III. The analysis
**Track reconstruction**

- **Pattern recognition**
  - Group hits in time using PC timing info.
  - Classify tracks according to hit patterns.
  - Must recognize beam positron tracks, delta tracks, backscattering, etc.

- **Track fitting**
  - Perform a crude fit using wire centres,
  - Refine fit using drift time and take into account MS field non-uniformities.
Reconstruct decay positron energy and angle
- Apply (unbiased) cuts on muon variables.
- Reject fast decays and backgrounds.
- Calibrate positron momentum spectrum at the endpoint (~52.8 MeV/c).

4.8x10^7 tracks
TWIST relies on GEANT3 to simulate detector acceptance
- Data spectrum fitted to MC spectrum.

Monte Carlo includes elaborate details
- GEANT3 geometry contains virtually all detector components.
- Simulate detector response in detail (ionization clusters).
- Realistic, measured beam profile and divergence.
- Extra muon and beam positron contamination included.
- Output into digitized format, identical to real data.

Monte Carlo verified using real data
- See contributed talk by Robert MacDonald on Wednesday, 12:00pm (CEME 1202).
  "Evaluation and simulation of the response function in the TWIST experiment"
Energy calibrations

- For a planar detector energy loss is linear in $1/\cos(\theta)$.

\[
p_{\text{edge}}(\nu) = \left(1 + \frac{\beta}{p_o}\right)\left(p_o - \frac{\alpha}{|\cos(\nu)|}\right)
\]

$P_o = 52.828$ MeV/c  $\alpha, \beta$ are fitting parameters

- $\alpha$ corrects for energy loss.

- $\beta$ corrects for a possible magnetic field shift.
  - $\beta=0$ if field is known accurately.
Extracting the Michel parameters

- The decay spectrum is linear in $\rho$, $\eta$, $\xi$, $\xi\delta$.
  - First order expansion is exact.

\[ n_i(\lambda_{data}) = n_i(\lambda_{mc}) + \frac{\partial n_i}{\partial \lambda} \Delta \lambda \]

where
\[ \lambda = [\rho, \eta, \xi, \xi\delta] \]

$\Delta \lambda$ are the fitting parameters

- Use standard model values ($\lambda_{mc}$) to generate the MC spectrum.
  - $\lambda_{mc} = \lambda_{SM}$.
  - $\Delta \lambda$ are the deviations from the SM.
Use hidden values ($\lambda_{mc}$) to generate the MC spectrum

$\Delta\lambda$ are the deviations from hidden values.

Complete data analysis and fit before opening the box.

Complete systematic evaluations before opening the box.
Fit quality and fiducial region

- High fit quality.
  - Normalized residuals ~1.

- Conservative fiducial region.
  - \( p < 50 \text{ MeV}/c \).
  - \( 0.50 < |\cos \theta| < 0.84 \).
  - \( |p_z| > 13.7 \text{ MeV}/c \).
  - \( p_T < 38.5 \text{ MeV}/c \).
IV. The systematics
Fit data to data and MC to MC to evaluate systematic effects

\[ n_i(\lambda_{mc}) = n_i(\lambda'_{mc}) + \frac{\partial n_i}{\partial \lambda} \Delta \lambda \]

\[ n_i(\lambda_{data}) = n_i(\lambda'_{data}) + \frac{\partial n_i}{\partial \lambda} \Delta \lambda \]

Data sets acquired for systematic evaluations

- \( B = 1.96 \text{ tesla} \)
- \( B = 2.04 \text{ tesla} \)
- DC HV lowered
- PC HV lowered
- Muon stopped slightly upstream
- Muon stopped slightly downstream
- Al slab inserted downstream
- Plastic slab inserted downstream
- Beam flux rate doubled
- Beam flux rate cut in half
- Bending magnet field increased by 10G
- Bending magnet field decreased by 10G
- Channel momentum tuned for non-surface (cloud) muons

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### Summary of the systematics

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Uncertainty (x10⁻³)</th>
<th>Systematic effect</th>
<th>Uncertainty (x10⁻³)</th>
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</thead>
<tbody>
<tr>
<td>Chamber response (ave)</td>
<td>0.51</td>
<td>Spectrometer alignment</td>
<td>0.61</td>
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<td>Stopping target thickness</td>
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<td>Chamber response (ave)</td>
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<td>Positron interactions</td>
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<td>Positron interactions</td>
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<tr>
<td>Spectrometer alignment</td>
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<td>Stopping target thickness</td>
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<td>Momentum calibration (ave)</td>
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<td>Momentum calibration (ave)</td>
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<tr>
<td>Theoretical radiative corrections</td>
<td>0.20</td>
<td>Muon beam stability</td>
<td>0.10</td>
</tr>
<tr>
<td>Track selection algorithm</td>
<td>0.11</td>
<td>Theoretical radiative corrections</td>
<td>0.10</td>
</tr>
<tr>
<td>Muon beam stability (ave)</td>
<td>0.04</td>
<td>Up &amp; down efficiencies</td>
<td>0.04</td>
</tr>
</tbody>
</table>
During 2002 data processing WestGrid had ~1000 CPUs @ 3GHz.

TWIST used ~30,000 CPU days to process 2002 data.
V. The Results
TWIST results for $\rho$ and $\delta$

- **TWIST results for $\rho$**
  - A factor of 2.5 improvement over PDG value.

  $$\rho = 0.75080 \pm 0.00032\text{(stat)} \pm 0.00097\text{(syst)} \pm 0.00023(\eta)$$


- **TWIST results for $\delta$**
  - A factor of 2.9 improvement over PDG value.

  $$\delta = 0.74964 \pm 0.00066\text{(stat)} \pm 0.00112\text{(syst)}$$


Results in agreement with the Standard Model
**Right-handed currents**

- Right handed currents

\[
Q_R^\mu \leq \frac{1}{2} \left( 1 - P_\mu \xi \left( \frac{16}{9} \delta - \frac{1}{3} \right) \right) = \frac{1}{2} \left[ 1 - P_\mu (\xi \delta / \rho) \rho \left( \frac{16}{9} - \frac{1}{3\delta} \right) \right]
\]

- Use:
  - TWIST \( \rho, \delta \).
  - \( P_\mu (\xi \delta / \rho) > 0.99787 \).

**Model-independent result**

- Pre-TWIST
  - \( g_{LR}^S < 0.125 \)
  - \( g_{LR}^V < 0.060 \)
  - \( g_{LR}^T < 0.036 \)

- TWIST
  - \( g_{LR}^S < 0.086 \)
  - \( g_{LR}^V < 0.043 \)
  - \( g_{LR}^T < 0.025 \)

\( Q_R^\mu < 0.00184 \)
Indirect results for $\xi$.

Use:
- TWIST $\rho$, $\delta$.
- $P_\mu(\xi\delta/\rho) > 0.99787$.
- $Q_R^\mu > 0$.

A factor of $>3$ improvement over previous result

$0.9960 < P_\mu \xi \leq \xi < 1.0040$

Direct measurement of $P_\mu \xi$.

- See contributed talk by Blair Jamieson on Monday, 3:00pm (CEME 1202).

“Status of the TWIST Measurement of the muon decay asymmetry”
Limits on left-right symmetric models

- Limits are from high precision muon decay experiments, nuclear $\beta$ decay, and high energy experiments.
  - Different types of experiments are complementary.
  - $\beta$ decay experiments subject to theoretical uncertainties.
  - High energy experiments place limits only on $W_R$ mass.
  - Muon decay offers a clean system with limits on mass and mixing angle.
Monday, 7:00pm poster & beer session: Ryan Bayes
"A Search for Rare Decays in the TWIST Muon Decay Spectrum"
TWIST has been able to improve substantially on the measurement of the Michel parameters $\rho$ and $\delta$.
- First successful improvement on $\rho$ in over 30 years.
- First successful improvement on $\delta$ in over 20 years.

Several factors allowed this improvement to happen.
- A highly polarized high flux stable beam from TRIUMF.
- A high precision, high efficiency, low mass detector.
- A planar detector geometry allowing precise energy calibrations.
- The availability of WestGrid allowing evaluation of the systematics.

All results are in agreement with the standard model predictions.
- The values of $\rho$ and $\delta$ agree with the Standard Model values.
- No evidence for right handed currents.
- Improved limits on mass and mixing angle of $W_R$ compared to muon decay experiments.

The TWIST results are particularly important due to the use of blind analysis.