TWIST Muon Decay Asymmetry Measurement

Blair Jamieson
University of British Columbia
TRIUMF AGM, Dec. 7, 2005

OUTLINE

• Physics of $\mu$ decay asymmetry
• Brief review of previous measurements
• Description of detector
• Analysis overview
• Systematic error estimates
• Data Sets, fits, and final results
Muon Decay $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

General derivative free interaction matrix element:

$$M = 4 \frac{G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} \sum_{\epsilon,\mu=L,R} g_{\epsilon\mu}^\gamma < \bar{e}_\epsilon | \Gamma^\gamma | \nu_e > < \bar{\nu}_\mu | \Gamma^\gamma | \mu_\mu >$$

(1)

- $g_{\epsilon\mu}^\gamma$ are the decay coupling constants
- $\gamma = S, V, T$ are the scalar, vector, and tensor interactions
- $\epsilon, \mu = L, R$ are the chirality of the electron or muon
- SM: all zero coupling constants, except $g_{LL}^V = 1$
Physics of $\mu$ decay asymmetry

- $P_\mu$ is the polarization of the muon, $\xi$ is the asymmetry in angle of the decay positrons from normal $\mu$ decay
- Standard Model (V-A) predicts $\xi = 1$ and $P_\mu = -1$

$$\frac{d^2\Gamma}{dx d\cos \theta} \propto F_{IS}(x, \rho, \eta) + P_\mu \xi \cos \theta F_{AS}(x, \delta) \quad (2)$$

$$x = \frac{E_e}{W_{e\mu}}$$

$$W_{e\mu} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$$

$$x_0 = \frac{m_e}{W_{e\mu}}$$
Measurements and Motivation for $P_\mu \xi$

- **Direct Measurements:**
  - $P_\mu \xi = 1.0027 \pm 0.0079 \pm 0.0030$ (Beltrami et al, PL B194 1987)
  - $P_\mu \xi \delta/\rho > 0.99682$, 90% conf. level (Jodidio et al, PR D34, PR D37 1986)

- **Indirect Measurement** ($\text{TWIST} \: \rho/\delta$ PRL 94, 101805 + PRD 71, 071101(R) (2005)):
  
  \[ 0.9960 < P_\mu \xi \leq \xi < 1.0040 \text{ at 90\% conf. level} \]

- **$\xi$ and $\delta$ limit the probability of a right-handed muon decaying into any handed positron:**
  
  \[ Q^\mu_R = \frac{1}{2} \left( 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right) \]  \( (3) \)

- **In Left-Right Symmetric Models**, $P_\mu \xi$ sets limit on $W_L/W_R$ mass ($\epsilon = \left( \frac{g_R M_1}{g_L M_2} \right)^2$) and LR mixing parameter ($\zeta_g = \frac{g_R}{g_L} \zeta$): (Herczeg, PR D34)

  \[ P_\mu \xi \approx 1 - 2\epsilon^2 - 4\zeta_g^2 - 2\epsilon^2 \left( \frac{\cos \theta_1^R}{\cos \theta_1^L} \right)^2 - 4\epsilon \zeta_g \frac{\cos \theta_1^R}{\cos \theta_1^L} \cos(\alpha + \omega) \]  \( (4) \)
Left-Right Symmetric Model Limits

- Pseudomannifest Left-Right Symmetry
Locations of Muon Depolarization

Production Target

Fringe Field

Stopping Material
Spectrum Fits \[ \lambda = (\rho, \eta, P_\mu \xi | P_\mu \xi \delta, P_\mu \xi \delta) \]

\[ \begin{align*}
\frac{d\Gamma_{\text{data}}(\lambda)}{d\rho} &= \frac{d\Gamma_{\text{MC}}(\lambda_{\text{MC}})}{d\rho} + \frac{d\Gamma_{\Delta \rho}}{d\rho} + \frac{d\Gamma_{\Delta \eta}}{d\eta} + \frac{d\Gamma_{\Delta P_\mu \xi \delta}}{dP_\mu \xi \delta} \\
\frac{d\Gamma_{\text{data}}(\lambda)}{d\eta} &= \frac{d\Gamma_{\text{MC}}(\lambda_{\text{MC}})}{d\eta} + \frac{d\Gamma_{\Delta \rho}}{d\rho} + \frac{d\Gamma_{\Delta \eta}}{d\eta} + \frac{d\Gamma_{\Delta P_\mu \xi \delta}}{dP_\mu \xi \delta} \\
\frac{d\Gamma_{\text{data}}(\lambda)}{dP_\mu \xi} &= \frac{d\Gamma_{\text{MC}}(\lambda_{\text{MC}})}{dP_\mu \xi} + \frac{d\Gamma_{\Delta \rho}}{d\rho} + \frac{d\Gamma_{\Delta \eta}}{d\eta} + \frac{d\Gamma_{\Delta P_\mu \xi \delta}}{dP_\mu \xi \delta} \\
\end{align*} \]
Estimating Systematic Uncertainty

- Total systematic uncertainty is:

\[ \epsilon_{\text{tot sys}} = \sqrt{\sum_i \frac{\sigma_i^2}{R_i^2} S_i^2} \]  

(5)

- sensitivity measurement \( S_i \)
- scale factor \( R_i/\sigma_i \)
- exaggerated change introduced \( R_i \)
- RMS change in data \( \sigma_i \)
Example: $t_0$ Systematic Uncertainty

- Sensitivity from fit of spectra from data analyzed with different calibration files:
  - $t_0$ before data collection
  - $t_0$ before with offsets of $10 \times (t_0^{\text{begin}} - t_0^{\text{end}})$
- Find $S_i = (8.9 \pm 2.3) \times 10^{-3}$
- Scale factor $R_i/\sigma_i$ of 10
- Systematic uncertainty in $P_\mu \xi$: $0.89 \times 10^{-3}$
- Also tried with scale factor of 5 to confirm linearity
## Systematics for $TWIST \, P_{\mu \xi}$

<table>
<thead>
<tr>
<th>Systematic Effect</th>
<th>Uncertainty ($\times 10^3$)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muon Beam and Polarization</strong></td>
<td></td>
<td>3.69</td>
</tr>
<tr>
<td>fringe field (ave)</td>
<td>3.40</td>
<td></td>
</tr>
<tr>
<td>stopping target (ave)</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td>production target</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td><strong>Chamber Response</strong></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>$t_0$ variations (ave)</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>foil bulges (ave)</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>cell asymmetry</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>up-down efficiency</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>density (ave)</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td><strong>Spectrometer Alignment</strong></td>
<td></td>
<td>0.31</td>
</tr>
<tr>
<td>rotations</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>z position</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>B field to axis</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td><strong>Positron Interactions</strong></td>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td>hard interactions (ave)</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>multiple scattering</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>outside material</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td><strong>Momentum Calibration</strong></td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>end point fits</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>B field uniformity</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td><strong>Radiative Corrections</strong></td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Total Systematic Uncertainty</strong></td>
<td></td>
<td>3.8</td>
</tr>
</tbody>
</table>
Fringe field depolarization

- Muons depolarized in fringe field of the solenoid
- Estimated three ways:
  - muon beam size + divergence from TEC alignment
  - variation in $P_\mu$ from TEC characterizations of “same settings”
  - variation in $P_\mu$ from TEC characterizations of nominal runs
• Uncertainty in TEC position of $\pm 2$ mm and $\pm 5$ mrad

• Systematic uncertainty in $P_\mu \xi$ of $1.5$ to $3.5 \times 10^{-3}$
$P_\mu$ from TEC runs of “same settings”

- Large difference in $<dy>$
- Systematic uncertainty in $P_\mu \xi$ of $3.3 \times 10^{-3}$

<table>
<thead>
<tr>
<th>B2 (Gauss)</th>
<th>$&lt;x&gt;$ (cm)</th>
<th>$&lt;dx&gt;$ (mrad)</th>
<th>$&lt;y&gt;$ (cm)</th>
<th>$&lt;dy&gt;$ (mrad)</th>
<th>$P_\mu^{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>949</td>
<td>0.85</td>
<td>-1.1</td>
<td>0.87</td>
<td>-5.0</td>
<td>0.9955</td>
</tr>
<tr>
<td>946.5</td>
<td>0.45</td>
<td>-3.4</td>
<td>0.92</td>
<td>1.8</td>
<td>0.9952</td>
</tr>
<tr>
<td>944</td>
<td>0.07</td>
<td>-5.9</td>
<td>0.97</td>
<td>7.0</td>
<td>0.9929</td>
</tr>
<tr>
<td>941.5</td>
<td>-0.29</td>
<td>-8.3</td>
<td>1.03</td>
<td>10.0</td>
<td>0.9897</td>
</tr>
<tr>
<td>949</td>
<td>0.94</td>
<td>-1.5</td>
<td>0.64</td>
<td>-19.2</td>
<td>0.9922</td>
</tr>
<tr>
<td>944</td>
<td>0.06</td>
<td>-6.7</td>
<td>0.73</td>
<td>-11.2</td>
<td>0.9941</td>
</tr>
</tbody>
</table>
Material Dependent Muon Depolarization

- Partly from 2.5 to 5% gas stops (unkn. form), rest from Al (exponential)
- Gaussian or exponential extrapolation?
- Systematic uncertainty in $P_{\mu}\xi$ is $\pm\sqrt{2}(0.00099) = \pm1.4 \times 10^{-3}$
2002 Data: Large Change in $P_{\mu}$ (Top)

2005 Data: No Change in $P_{\mu}$ (Bottom)

2002 Solenoid Field Change $P_{\mu}(t)$ from Asymmetry

Solenoid Field Change Data to Data Spectrum Fits

$\lambda = \rho$

$\lambda = \delta$

$\lambda = P_{\mu}\xi$
<table>
<thead>
<tr>
<th>Set #</th>
<th># Runs (2 GB)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>60</td>
<td>B2=949G, z cent, M1 Trigger</td>
</tr>
<tr>
<td>31</td>
<td>265</td>
<td>B2=949G, z cent, M Trigger</td>
</tr>
<tr>
<td>32</td>
<td>120</td>
<td>B2=944G, PC5 Stops</td>
</tr>
<tr>
<td>33</td>
<td>91</td>
<td>Far Upstream Stops</td>
</tr>
<tr>
<td>34</td>
<td>11</td>
<td>Far Downstream Stops</td>
</tr>
<tr>
<td>35</td>
<td>368</td>
<td>2004 Nominal Stops centered</td>
</tr>
<tr>
<td>36</td>
<td>390</td>
<td>2004 Stops at 3/4 position</td>
</tr>
<tr>
<td>37</td>
<td>281</td>
<td>High Rate</td>
</tr>
<tr>
<td>38</td>
<td>303</td>
<td>Aperture In</td>
</tr>
<tr>
<td>39</td>
<td>211</td>
<td>2004 Stops at 3/4 position</td>
</tr>
<tr>
<td></td>
<td>Total 2100 (4.2 TB)</td>
<td>1998 Nominal Runs</td>
</tr>
</tbody>
</table>

Data Set Summary for TWIST $P_{\mu \xi}$
Data Set Consistency

- Consistency check (difference from value hidden in simulation)

\[ \Delta P_\mu \xi \text{ Corrected} \]

\[ \Delta P_\mu \xi = -0.0065 \pm 0.0006 \text{ (stat)} \]

\[ \chi^2/\text{NDOF} = 3.0/6 \]
$P_{\mu \xi}$ Refit with Black Box Open

- $P_{\mu \xi} = 1.0003 \pm 0.0006\text{(stat)} \pm 0.00038\text{(syst)}$

$P_{\mu \xi}$ from Refit with Blackbox Open

$P_{\mu \xi} = 1.0003 \pm 0.0006 \text{ (stat)}$

$\chi^2/NDOF = 3.0/6$
Spectrum Fit Residuals

- Data to simulation spectrum fit residuals look reasonable
- Residual from all fits look similar
Model Independent Muon Handedness

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

- \textit{TWIST} has measured, consistent with standard model:

\[
P_{\mu \xi} = 1.0003 \pm 0.0006 \text{ (stat)} \pm 0.0038 \text{ (syst)}
\]

- Result reduces uncertainty in PDG value by a factor of about 2. Current PDG value = 1.0027 \pm 0.0079 \pm 0.0030.

- Largest systematic error is due to fringe field depolarization

\textit{TWIST} is funded by NSERC, DOE, Russian Ministry of Finance. Special thanks to Westgrid computing resources and to the \textit{TWIST} collaboration.
TWIST Collaboration

TRIUMF
Ryan Bayes*\textsuperscript{v}
Yuri Davydov
Jaap Doornbos
Wayne Faszer
Makoto Fujiwara
David Gill
Peter Gumplinger
Robert Henderson
Anthony Hillairet*\textsuperscript{v}
Jingliang Hu
John A. Macdonald\textsuperscript{d}
Glen Marshall
Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin\textsuperscript{v}

TRIUMF
Robert Openshaw
Tracy Porcelli*\textsuperscript{u}
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin\textsuperscript{s}

Alberta
Andrei Gaponenko*
Peter Kitching
Robert MacDonald*
Maher Quraan
Nate Rodning\textsuperscript{d}
John Schaapman
Glen Stinson

Kurchatov Institute
Vladimir Selivanov
Vladimir Torokhov

Texas A&M
Carl Gagliardi
Jim Musser*
Bob Tribble
Maxim Vasiliev

British Columbia
James Bueno*
Mike Hasinoff
Blair Jamieson*

Montréal
Pierre Depommier

Valparaiso
Don Koetke
Paul Nord

Regina
Ted Mathie
Roman Tacik

Key:
* graduate student
\textsuperscript{v} also UVic
\textsuperscript{d} deceased
\textsuperscript{u} also UNBC
\textsuperscript{s} also Saskatchewan

- Previous collaborators:
  Peter Green, Arkadi Khruchinsky, Michael Kroupa, Farhana Sobratee, Sun-Chong Wang, Dennis Wright.

- Professional and technical support:
  Daniel Allen, Pierre Amaudruz, Willy Andersson, Curtis Ballard, Michael Barnes, Brian Evans, Marielle Goyette, Doug Maas, Jan Soukup, Len Wampler, and many undergraduate student research assistants.
Extra Slides
Energy Calibration Correlations

$\alpha_{\text{sum}}$ vs $\beta$

Data vs MC

12 keV/c
GEANT Validation

- From fits to two halves of decay positrons from far upstream stops
- Discrepancy in tails in momentum of $4\%$, and in $\theta$ of $8\%$
- Overall $5\%$ discrepancy in hard interactions

Upstream muon stops positron $\Delta p \cos\theta$

![Graph showing entries (unscaled) with data and simulation points](image1)

![Graph showing change in angle (rad) with data and simulation points](image2)
Upstream-Downstream Efficiency

- Difference of 0.18 NDOF between downstream MC and Data
- MC with 5% downstream inefficiency had 1.8 fewer NDOF
- Fit of normal MC to ineffic. MC change in $P_{\mu \xi}$ of $(1.9 \pm 0.9) \times 10^{-3}$
- Systematic unc. due to US/DS Inefficiency is $0.2 \times 10^{-3}$
Contents

1  Muon Decay $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$  2

2  Physics of $\mu$ decay asymmetry  3

3  Measurements and Motivation for $P_{\mu \xi}$  4

4  Left-Right Symmetric Model Limits  5

5  Locations of Muon Depolarization  6

6  TWIST Detector  7

7  Analysis Strategy  8

8  Spectrum Fits $\lambda = (\rho, \eta, P_{\mu \xi} \vert_{P_{\mu \xi \delta}}, P_{\mu \xi \delta})$  9
9 Estimating Systematic Uncertainty

10 Example: \( t_0 \) Systematic Uncertainty

11 Systematics for \( TWIST \ P_\mu \xi \)

12 Fringe field depolarization

13 Time Expansion Chamber - Muon Beam

14 \( P_\mu \) from TEC runs of “same settings”

15 Material Dependent Muon Depolarization

16 2002 Data: Large Change in \( P_\mu \) (Top)
   2005 Data: No Change in \( P_\mu \) (Bottom)

17 Data Set Summary for \( TWIST \ P_\mu \xi \)
27 Upstream-Downstream Efficiency