TWIST muon decay analysis: recent progress

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NuFact09
11th International Workshop on Neutrino Factories, Superbeams and Beta Beams

Illinois Institute of Technology
Chicago, July 2009
Outline

- Muon decay description
  - parametrizations and summary of measurements
  - Standard Model tests

- TWIST experiment – detectors, beam, and analysis

- Reduction of systematic uncertainties
  - for $\rho$ and $\delta$
  - for $P_{\mu}^\xi$ - depolarization
  - expectations for final analysis

- Electron energy spectrum from $\mu^*\text{Al}$

- Summary
Muon decay parameters

Muon decay parameters $\rho$, $\eta$, $\mathcal{P}_\mu \xi$, $\delta$

Muon differential decay rate vs. energy and angle:

$$\frac{d^2 \Gamma}{dx \; d \cos \theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot$$

$$\{ \mathcal{F}_{IS}(x, \rho, \eta) + \cos \theta \cdot \mathcal{P}_\mu \mathcal{F}_{AS}(x, \xi, \delta) \} + R.C.$$

\[d^2\Gamma \]

\[dx \; d\cos\theta\]

\[\cos\theta\]

\[x = E_e/E_{\text{max}}\]
Published results

\[
\rho = 0.75014 \pm 0.00017 \text{(stat)} \pm 0.00046 \text{(syst)} \pm 0.00011 \text{ (\eta)} \\
\delta = 0.75068 \pm 0.00030 \text{(stat)} \pm 0.00067 \text{(syst)} \\
\mathcal{P}_{\mu \xi} = 1.0003 \pm 0.0006 \text{(stat)} \pm 0.0038 \text{(syst)} \\
\]

Also \( \mathcal{P}_{\mu \xi \delta}/\rho > 0.99682 \) from Jodidio et al, 1986
Decay parameters and coupling constants

Fetscher and Gerber coupling constants (see PDG):

\[ M = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T}^{\varepsilon,\mu=R,L} g_{\varepsilon\mu}^{\gamma} \langle \bar{\varepsilon}_s | \Gamma^{\gamma} | \nu_{\varepsilon} \rangle_n \langle (\bar{\nu}_\mu) m | \Gamma_{\gamma} | \mu_\mu \rangle \]

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

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

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

\[ \xi \delta = \frac{3}{4} - \frac{3}{8} |g_{RR}^S|^2 - \frac{3}{8} |g_{LR}^S|^2 - \frac{3}{2} |g_{RR}^V|^2 - \frac{3}{4} |g_{RL}^V|^2 - \frac{3}{4} |g_{LR}^V|^2 \\
- \frac{3}{2} |g_{RL}^T|^2 - 3 |g_{LR}^T|^2 + \frac{3}{4} \Re (g_{LR}^S g_{LR}^{T*} - g_{RL}^S g_{RL}^{T*}) \]
Global analysis results

Standard model:
\[ g_{VLL} = 1, \text{ all others zero} \]

Global analysis:
\[ |g_{VLL}| > 0.96 \ (90\%CL) \]

Muon RH coupling:
\[ Q_{\mu}^R = \frac{1}{2} \left[ 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right] \geq 0 \]
\[ < 0.0024 \ (90\%CL) \]

(previously 0.014)
Weak eigenstates in terms of mass eigenstates and mixing angle:
\[ W_L = W_1 \cos \zeta + W_2 \sin \zeta, \quad W_R = e^{i\omega}(-W_1 \sin \zeta + W_2 \cos \zeta) \]

Assume possible differences in left and right couplings and CKM character.
Use notation:
\[ t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \quad t_\theta = t \frac{|V_{ud}^R|}{|V_{ud}^L|}, \quad \zeta_g^2 = \frac{g_R^2}{g_L^2} \zeta^2 \]

Then, for muon decay, the Michel parameters are modified:
\[ \rho = \frac{3}{4} (1 - 2 \zeta_g^2), \quad \xi = 1 - 2 (t^2 + \zeta_g^2), \]
\[ \mathcal{P}_\mu = 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta \zeta_g^2 \cos(\alpha + \omega) \]

“manifest” LRS assumes \( g_R = g_L, V^R = V^L, \omega = 0 \) (no CP violation).
“pseudo-manifest” LRS allows CP violation, but \( V^R = (V^L)^* \) and \( g_R = g_L \).
LRS “non-manifest” or generalized LRS makes no such assumptions.

Many experiments must make assumptions about LRS models!
Muon decay LRS limits

- Exclusion (90% cl) plots for left-right symmetric model mixing angle $\zeta$ and $W_2$ mass $m_2$.
- "Generalized LRS" model; no assumptions on RH CKM matrix elements.
- Complementary to other experiments: e.g., DΦ and CDF for $m_2$, $K^0_L - K^0_S$ mass difference for $\zeta$.
TWIST spectrometer

- Uses highly polarized $\mu^+$ beam ($P_\mu \sim -1$ w.r.t beam)
- Stops $\mu^+$ in a very symmetric detector.
- Tracks $e^+$ through uniform, well-known field.
- Extracts decay parameters by comparison to detailed and verified simulation.

Muon production and transport

500 MeV proton beam

Muon production

muon decay detector

fringe field region

elements used for additional beam steering

NuFact09 Workshop WG-4, July 2009
Need to know x, y, \( \theta_x \), \( \theta_y \), and correlations, for incident muon beam.

- Measure in two modules of low pressure (80 mbar) time expansion chambers (TEC).
- “Correct” for multiple scattering (\( \sim 20 \) mrad rms).
- Simulate by sampling corrected distributions.
- Decay parameters measured with TEC removed; multiple scattering reduces polarization.

J. Hu et al., NIM A566 (2006) 563-574
Positron tracking

Variable density gas degrader

PC1-4
DC1-8
DC9-22
PC5-6
PC7-8
DC23-36
DC37-44
PC9-12

NuFact09 Workshop WG-4, July 2009
G.M. Marshall, TWIST muon decay analysis
Analysis: fit to simulation

- fit data to GEANT3 simulation with hidden parameters
- distribution is linear in $P_\mu \xi$, $P_\mu \xi \delta$, $\rho$, $\eta$
- fits to data or MC with systematically changed conditions show decay parameter dependence on systematics
- Use measured $\eta$, rather than fit it
### Systematics for $\rho$ and $\delta$

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>$\rho \times 10^{-4}$</th>
<th>$\delta \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber response</td>
<td>2.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Energy scale</td>
<td>2.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Positron interactions</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Alignment and lengths</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Beam intensity (ave)</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Correlations with $\eta$</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Theoretical radiative correction</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total in quadrature</strong></td>
<td><strong>4.6</strong></td>
<td><strong>6.7</strong></td>
</tr>
</tbody>
</table>

Chamber response

- Improvements benefit all three parameters, $\rho$, $\delta$, and $P_{\mu}\xi$.
- Detector position response:
  - use drift chamber Space Time Relationships as determined from data tracks for data analysis, as well as from simulated tracks for simulation analysis (common biases).
  - accounts for geometry variations, drift model dependence, tracking biases

Drift time isochrones for data, before (GARFIELD) and after correction from track residual analysis (developed by A. Grossheim)
Wire time offsets extracted from simulation (initial values all zero) before (left) and after (right) improvements in the procedure (developed by A. Olin)

- time offsets \( t_0 \)'s of >3000 wires required
- fit decay \( e^+ \) time distributions vs. scintillator signals
  - careful event selection, careful time-of-flight corrections
  - realistic function (Gaussian-exponential convolution)
- tested for simulation and also for data with beam \( e^+ \)
Correct for small differences between data and simulation:
- magnetic field shape and magnitude
- muon stopping position in foil target
- target thickness
- dE/dx differences

Compare kinematic edge at 52.8 MeV for small angular range:
- \( p_i = B_i + A_i / \cos \theta \), for \( i \in [\text{US,DS}] \), from planar geometry
- fit data and simulation to find relative difference, then correct
- 1-point calibration: propagation of correction to lower energy must be otherwise determined
Positron interactions

- Test GEANT3 energy loss and scattering – “upstream stops”

Stopping target for decay data

- Test GEANT3 δ-ray and bremsstrahlung – broken tracks

- Check agreement of data and simulation
  - δ’s: 3 tracks (2+, 1-, e⁻ from 6 to 16 MeV/c) from primary positron
  - brem: 2 tracks (2+, Δp from 15 to 35 MeV/c)
  - compare with simulation with δ, brem increase (x3).
Systematics for $P_{\mu\xi}$

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>$P_{\mu\xi} \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depolarization in fringe field (ave)</td>
<td>34</td>
</tr>
<tr>
<td>Depolarization in muon stopping material (ave)</td>
<td>12</td>
</tr>
<tr>
<td>Chamber response (ave)</td>
<td>10</td>
</tr>
<tr>
<td>Spectrometer alignment</td>
<td>3</td>
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<tr>
<td>Positron interactions (ave)</td>
<td>3</td>
</tr>
<tr>
<td>Depolarization in muon production target</td>
<td>2</td>
</tr>
<tr>
<td>Momentum calibration</td>
<td>2</td>
</tr>
<tr>
<td>Upstream-downstream efficiency</td>
<td>2</td>
</tr>
<tr>
<td>Background muon contamination (ave)</td>
<td>2</td>
</tr>
<tr>
<td>Beam intensity (ave)</td>
<td>2</td>
</tr>
<tr>
<td>Decay $\eta$ parameter</td>
<td>1</td>
</tr>
<tr>
<td>Theoretical radiative correction</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total in quadrature</strong></td>
<td><strong>38</strong></td>
</tr>
</tbody>
</table>

The central field is 2 T, with a strong gradient near the solenoid yoke entrance. Muon tracks are measured by the TEC, to establish incident beam parameters. Muons are also tracked in the upstream part of the decay detector.
Measured average muon positions

- Each point represents the average muon beam position at a detector plane.
- Simulated data can be analyzed in the same way.
- Fit both to “shrinking helix”.
- Comparison of fits of data and simulation is a powerful way to verify the simulation, e.g., influence of fringe field on muon beam, detector-field alignment.

→ Use “internal beam” to test fringe field depolarization limitations.
  
  (developed by J. Bueno)
**Systematic correction for relaxation**

- **TWIST** detector is a very powerful $\mu$SR device:
  - uniform field, excellent background rejection.
  - $e^+$ momentum available for weighting the asymmetry.
  - ... but not very versatile...
- Observed relaxation rate is included in the simulation:
  - accounts realistically for relaxation.
  - statistical uncertainty in $\lambda$ is a source of target depolarization systematic uncertainty in $P_{\pi \xi \mu}$. 

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Weighted asymmetry ($457.0 < t \text{ (ns) } < 9000.0$)

**Ag**

$\lambda^{Ag} = 0.73(7) \times 10^{-3} \text{ s}^{-1}$

**Al**

$\lambda^{Al} = 1.18(7) \times 10^{-3} \text{ s}^{-1}$
### Preliminary estimated total uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Published (x10^4)</th>
<th>Improvement factor vs pre-TWIST</th>
<th>Final, estimated (x10^4)</th>
<th>Improvement factor vs pre-TWIST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistical</td>
<td>Systematic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.7</td>
<td>4.4</td>
<td>$\times 5$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\delta$</td>
<td>3.0</td>
<td>6.7</td>
<td>$\times 5$</td>
<td>1.9</td>
</tr>
<tr>
<td>$\mathcal{P}_{\mu \xi}$</td>
<td>6.0</td>
<td>38</td>
<td>$\times 2$</td>
<td>2.4</td>
</tr>
</tbody>
</table>

* Some challenges remain for final systematic uncertainty for $\mathcal{P}_{\mu \xi}$.
Electron spectrum from $\mu^-\text{Al}$

- One week of data with $\mu^-$ beam
- Precise measure of muonic aluminum ($\mu^-\text{Al}$) decay in orbit (DIO)
  - changes phase space, initial KE
  - competes with nuclear muon capture
- comparison with calculation
  - consistency above 53 MeV, but limited to $p<75$ MeV (below $\mu e$ conversion signal)
  - mismatch near peak and excess events at lower energies
  - higher order corrections required?

Preliminary only!

A. Grossheim et al., in preparation
Summary

- TWIST has completed data taking; analysis well underway.
  - Systematic and statistical precision roughly as expected
  - The polarization measurement has unique challenges
    - depolarization systematics especially

- Final results expected by NuFact10
Thank you to:
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- our support agencies: NSERC, DOE, TRIUMF
- WestGrid, for lots of CPU power
- the audience, for your attention
- the TWIST collaboration
**TWIST** Participants

**TRIUMF**
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- Wayne Faszer
- Makoto Fujiwara
- David Gill
- Alex Grossheim
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- Jingliang Hu
- Glen Marshall
- Dick Mischke
- Konstantin Olchanski
- Art Olin 
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**Texas A&M**
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- Bob Tribble

**Valparaiso**
- Don Koetke
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* Graduate student
** Graduated
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‡‡ also Saskatchewan
§ deceased

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Muon decay parameters

Muon decay parameters $\rho$, $\eta$, $P_\mu \xi$, $\delta$

Muon differential decay rate vs. energy and angle:

$$\frac{d^2\Gamma}{dx \, d\cos \theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot \left\{ \mathcal{F}_{IS}(x, \rho, \eta) + \cos \theta \cdot P_\mu \mathcal{F}_{AS}(x, \xi, \delta) \right\} + R.C.$$  

where

$$\mathcal{F}_{IS}(x, \rho, \eta) = x(1 - x) + \frac{2}{9} \rho (4x^2 - 3x - x_0^2) + \eta x_0 (1 - x)$$

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

and

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

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

$$x_0 = \frac{m_e}{W_{\mu e}}.$$
## Limits on LRS parameters: PDG08

| Observable                  | $m_2$ (GeV/c²) | $|\zeta|$ | **| ** |
|-----------------------------|---------------|---------|-------|-------|
| $m(K_L^0)-m(K_S^0)$         | >700          |         | reach | (P)MLRS |
| Direct $W_R$ searches       | >1000 (D0)    | <0.013  | fit   | (P)MLRS |
|                            | >788 (CDF)    |         |       | (P)MLRS decay model |
| Electro-weak fit            |               |         |       | (P)MLRS |
| $\beta$ decay              | >310          | <0.040  | both parameters | (P)MLRS light $\nu_R$ |
| $\mu$ decay*, $TWIST$      | >475 (530)    | <0.021  | model independence | light $\nu_R$ |

* in generalized LRS model; to be interpreted as $m_2(g_L/g_R)$, $\geq(g_R/g_L)$.

NuFact09 Workshop WG-4, July 2009
Simulating the muon beam

Comparison of TEC data and corresponding simulation of beam profiles

NuFact09 Workshop WG-4, July 2009
Muon paths in fringe field

- Nominal beam and mis-steered beam comparison for single track and average of many tracks.

- Plots showing muon position in the fringe field with axes labeled as x and y.

- Text: "single track" and "average of many tracks" are mentioned in the diagrams.

- Diagrams show fluctuations in muon position with z (cm) as the vertical axis.

- Notes: "NuFact09 Workshop WG-4, July 2009" and "G.M. Marshall, TWIST muon decay analysis".
Depolarization in stopping target

- “$\mu$SR” effect -- minimize by use of high-purity metal targets:
  - main mechanism at room temperature is via interaction with conduction electrons (Korringa relaxation), studied in $\mu$SR experiments.
  - asymmetry is a function of time: $P_\mu(t) = P_\mu^0 \exp(-\lambda t)$.
  - different targets, Al (76 $\mu$m) and Ag (28 $\mu$m) provide test of possible systematic bias.

- Stopping target forms anode of adjacent MWPC detectors:
  - energy loss (ionization charge) information discriminates against muons stopping in other detector materials, to reduce depolarization from
    - $(\mu^+ e^-)$ formation (e.g. in MWPC gas, He), which depolarizes muons (depolarization also reduced by high longitudinal field).
    - chemical reactions (analogous to hydrogen atom).