Probing the Weak Interaction Spacetime Structure with Muon Decay

Art Olin, for the TWIST Collaboration

INPC 2007
Muon Decay Parameters

- Muon decay parameters $\rho$, $\eta$, $P_{\mu}\xi$, $\delta$: (Michel, Kinoshita and Sirlin)
  - Polarized muon differential decay rate vs. energy and angle:

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

- Where
  $$\mathcal{F}_{IS}(x, \rho, \eta) = x(1 - x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1 - x)$$
  $$\mathcal{F}_{AS}(x, \xi, \delta) = \frac{1}{3}\xi \sqrt{x^2 - x_0^2} \left[ 1 - x + \frac{2}{3} \delta \left( 4x - 3 + \sqrt{1 - x_0^2} - 1 \right) \right]$$

- $W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$, $x = \frac{E_e}{W_{\mu e}}$, $x_0 = \frac{m_e}{W_{\mu e}}$

- $\rho = 3/4$, $\eta = 0$, $P_{\mu}\xi = 1$, $\delta = 3/4$ in SM.
On the Range of the Electrons in Meson Decay

J. Steinberger*

The Institute for Nuclear Study, University of Chicago, Chicago, Illinois
(Received January 10, 1949)

An experiment has been carried out both at Chicago and on Mt. Evans, Colorado, to determine the absorption of the electrons emitted in the decay of cosmic-ray mesons. Approximately 8000 counts have been obtained, using a hydrocarbon as the absorbing material. These data are used to deduce some features of the energy spectrum of the decay electrons. The resolution of the apparatus is calculated, taking the geometry, scattering, and radiation into account. The results indicate that the spectrum is either continuous, from 0 to about 55 Mev with an average energy $\sim$ 32 Mev or consists of three or more discrete energies. No variation of the lifetime with the thickness of the absorber is observed. The experiment, therefore, offers some evidence in favor of the hypothesis that the $\mu$-meson disintegrates into 3 light particles.

Fig. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.
Other $\mu$ decay measurements

- From the Review of Particle Physics (SM values in parentheses):
  - $\rho = 0.7518 \pm 0.0026$ (Derenzo, 1969) (0.75)
  - $\eta = -0.002 \pm 0.007$ (Dannenberg et al., 2005) (0.00)
  - $\delta = 0.7486 \pm 0.0026 \pm 0.0028$ (Balke et al., 1988) (0.75)
  - $P_{\mu \xi} = 1.0027 \pm 0.0079 \pm 0.0030$ (Beltrami et al., 1987) (1.00)
  - $P_{\mu} (\xi \delta / \rho) > 0.99682$ (Jodidio et al., 1986) (1.00)

**TWIST's** goal is to explore or constrain physics beyond the SM by improving the precision of each of $\rho$, $\delta$, and $P_{\mu \xi}$ by an order of magnitude.
Surface muon beam

- Pions decaying at rest produce muon beams with $P_{\mu \pi} = 100\%$. (SM).
- Depolarization must be controlled using small emittance beams near kinematic edge, 29.8 MeV/c.
- Use $\approx 3 \times 10^3 \mu^+ \, \text{s}^{-1}$.
- Muon total range at density $\approx 1$ only about 1.5 mm!

Low Pressure Time Expansion Chamber

Art Olin, INPC 2007, Tokyo

Probing the Spacetime Structure of the Weak Interaction
Low-mass high-precision planar chambers symmetrically placed around thin target foil which stops nearly all of surface muon beam. Z precision $5 \times 10^{-5}$, wire position $15\mu$. 44 drift chambers (DME), 12 proportional chambers ($\text{CF}_4$-isobutane), He gaps.

Measurement initiated by single thin scintillation counter at entrance to detector.

Beam stop position controlled by variable He/CO$_2$ gas degrader.
Data Analysis Methodology

Fit data to identically derived distributions from simulation:

- Muon decay spectrum includes radiative corrections to $O(\alpha^2)$.
- GEANT3 geometry contains virtually all detector components.
- Simulate detector response in detail.
- Realistic, measured beam profile and divergence.
- Fit to hidden muon decay parameters with blind analysis method.
- Determine consistency of data and sensitivity of analysis to model uncertainties before hidden parameters are revealed.

GEANT simulation must be validated for $e^+$ energy loss and multiple scattering.

Stop muons at one end of detector.

Measure $e^+$ track on each side of target, before and after passage through it.

Compare differences, with data and MC.
Summary of results: $\rho$ and $\delta$

2002 Data Mylar target

- $\rho = 0.75080 \pm 0.00044{}^{(\text{stat})} \pm 0.00093{}^{(\text{syst})} \pm 0.00023{}^{(\eta)}$
  - 2.5 times better precision than PDG value.
  - Uncertainty scaled for $\chi^2/\text{dof} = 7.5/4$ (CL=0.11) for different data sets.

- $\delta = 0.74964 \pm 0.00066{}^{(\text{stat})} \pm 0.00112{}^{(\text{syst})}$
  - 2.9 times better precision than PDG value.

- Using the above values of $\rho$ and $\delta$, together with $P_{\mu}(\xi\delta/\rho) > 0.99682$ (PDG) and $Q_{R\mu} > 0$
  - $0.9960 < P_{\mu} \xi \leq \xi < 1.0040$ (90% c.l.)
  - $P_{\mu} \xi = 1.0027 \pm 0.0079 \pm 0.0030$.

- Leading systematics: chamber response, graphite, positron interactions, alignment
Coupling constants

- Coupling constants $g^\gamma_{\mu\mu}$ can be related to handedness, e.g., total muon right-handed coupling:

$$Q^\mu_R = \frac{1}{4} |g^S_{LR}|^2 + \frac{1}{4} |g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3 |g^T_{LR}|^2 = \frac{1}{2} \left[ 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right]$$

- Global analysis of $\mu$ decay (Gagliardi et al., PRD 72 2005)
  - no existing similar analysis for other weak decays.
  
  $|g^S_{RR}| < 0.066(0.067)$  
  $|g^S_{LR}| < 0.125(0.088)$  
  $|g^S_{RL}| < 0.424(0.417)$  
  $|g^S_{LL}| < 0.550(0.550)$  

  $|g^V_{RR}| < 0.033(0.034)$  
  $|g^V_{LR}| < 0.060(0.036)$  
  $|g^V_{RL}| < 0.110(0.104)$  
  $|g^V_{LL}| > 0.960(0.960)$

  $|g^T_{RR}| \equiv 0$  
  $|g^T_{LR}| < 0.036(0.025)$  
  $|g^T_{RL}| < 0.122(0.104)$  
  $|g^T_{LL}| \equiv 0$

- Neutrino mass implications at $10^{-7}$-$10^{-4}$ for vector LR/RL: Erwin et al. PRD75,33005 (2007).
Summary of results: $P_{\mu\xi}$

2004 Data  pure Al target

- Improvements to target, chamber stability.
- Beam monitoring with TEC.
- Full instrumentation of outer drift chambers.

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

- 2.2 times better precision than PDG value (Beltrami et al.).
- still not as precise as TWIST indirect result from $\rho$ and $\delta$.

- Dominated by muon beam uncertainties which control the polarization at the target.

- Improved $\rho$ and $\delta$ results are expected soon. Polarization not an issue, so improvements above are significant, and increase the usable fiducial region.
## Systematic uncertainties: $\rho$ and $\delta$

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>$\rho \times 10^4$ (published)</th>
<th>$\rho \times 10^4$ (current)</th>
<th>$\delta \times 10^4$ (published)</th>
<th>$\delta \times 10^4$ (current)</th>
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<td><strong>11.2</strong></td>
<td><strong>7.2</strong></td>
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</table>

2006/2007: Final Data

- **Beam characterization improvements:**
  - Significant improvement to TEC. Beam characterizations start and end of each dataset.
  - Online monitoring of beam conditions.
  - Steering added to M13 beamline.

- **Chamber improvements:**
  - Rearrangement of chamber spacing.
  - Measurement of stops in PC gas.

- **Analysis improvements:**
  - Chamber response
  - Calibrations
  - Depolarization measured independently.

- **Increased statistics especially in simulations.**
TWIST has produced its first physics results, which are in agreement with the Standard model.

We have almost completed the 2\textsuperscript{nd} phase analysis of $\rho$ and $\delta$.

Current data taking through 2007 will take us to our systematic limits which represents an order of magnitude improvement.