TWIST
A Precision Measurement
of
Muon Decay at TRIUMF

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TWIST Collaboration

• Physics of TWIST
• Introduction to the Experiment
• Current Status
TRIUMF WEAK INTERACTION SYMMETRY TEST

- Uses intense “Surface Muon” beam of polarised muons from pions decaying at rest on surface of production target
- Incoming muon is tracked and stopped in thin, planar target
- Decay positron is tracked through 2T uniform field with a symmetric stack of high precision, low mass, planar drift chambers
Muon Decay in a Model-Independent Form

The muon decay matrix element can be written as:

$$\frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,T} g^\gamma \langle \bar{e}_\epsilon | \Gamma^\gamma | \nu_e \rangle \langle \bar{\nu}_\mu | \Gamma^\gamma | \mu_\mu \rangle$$

with 19 real-valued parameters and one overall phase. In the Standard Model, $g^V_{LL} = 1$ and all others are zero.

The right-handed coupling of the muon can be written in terms of these parameters as:

$$Q^\mu_R = \frac{1}{4} |g^S_{LR}|^2 + \frac{1}{4} |g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2$$
Muon Decay and the Michel Parameters

The muon decay rate can also be written in terms of the Michel parameters. If you neglect the electron mass and radiative corrections, you obtain:

\[
\frac{d^2 \Gamma}{x^2 \, dx \, d(\cos \theta)} \propto 3 - 3x + \frac{2}{3} \rho (4x - 3) + P_\mu \xi \cos \theta \left[ (1 - x) + \frac{2}{3} \delta (4x - 3) \right]
\]

with:

\[
\begin{align*}
\rho &= 0.7518 \pm 0.0026 \\
\eta &= -0.007 \pm 0.013 \\
\delta &= 0.7486 \pm 0.0026 \pm 0.0028 \\
P_\mu \xi &= 1.0027 \pm 0.0079 \pm 0.0030 \\
P_\mu \frac{\xi \delta}{\rho} &> 0.99682 ~ (90\% \, C.L.)
\end{align*}
\]
Goals of TWIST

- Search for new physics through measurements of $\rho$, $\delta$, and $P_{\mu \xi}$ to a few parts in $10^4$.
- Model-independent limit on right-handed muon coupling:

$$Q_R^\mu = \frac{1}{2} \left[ 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right]$$

- In left-right symmetric models:
M13 Secondary Beamline at TRIUMF

π Production Target

Proton Beam

Jaws

Q1

Q2

B1

First Focus

SL1

Q3

Q4

Q5

SL2

Second Focus

B2

Q6

Q7

Final Focus

1 meter

Momentum Resolution Δp/p = 1%

Superconducting magnet and cryostat
Support cradle
Prop. & drift chambers
Target
Beam pipe
Yoke
TWIST Wire Chamber Modules

- **DCs:**
  - 80 wires/plane
  - DME

- **MWPCs:**
  - 160 wires/plane
  - CF$_4$  iso-C$_4$H$_{10}$

- All wires 15 µm W(Au)
- 2, 4 or 8 planes per module
TWIST Wire Chambers

- 44 drift chambers and 12 MWPCs
- Very thin -- only $\sim 5 \times 10^{-5} X_0$ per chamber
- $\sim 5000$ wires positioned with $\sim 3 \, \mu m$ accuracy
- Longitudinal and transverse distances known to $< 5$ parts in $10^5$
Analysis Strategy

If the decay rate is written as a function of:

\[ \rho = \rho_0 + \Delta \rho \]
\[ \eta = \eta_0 + \Delta \eta \]
\[ P_{\mu \xi} = P_{\mu \xi_0} + \Delta P_{\mu \xi} \]
\[ \delta = \delta_0 + \Delta \delta \]

It can be made linear in \( \Delta \rho, \Delta \eta, \Delta P_{\mu \xi}, \) and \( \Delta \delta. \)

This provides the basis for our blind analysis scheme. We will fit our measured spectrum to a sum of a GEANT “standard” spectrum, produced with unknown \( \rho_0, \eta_0, P_{\mu \xi_0}, \) and \( \delta_0, \) together with GEANT distributions thrown according to:

\[ d\Gamma/d(\Delta \rho), \ d\Gamma/d(\Delta \eta), \ d\Gamma/d(\Delta P_{\mu \xi}), \) and \( d\Gamma/d(\Delta \delta). \]
First Physics Run: Sept-Dec, ‘02

- **Goal:** Determine $\rho$ and $\delta$ to $10^{-3}$.
- Recorded $\sim 6 \times 10^9$ events to tape. Note that $3 \times 10^8$ events suffice to measure $\rho$ and $\delta$ with a statistical precision of $\sim 6 \times 10^{-4}$.
- Basic philosophy: If we might be sensitive to a particular systematic effect, can we take data in a configuration that will make it “really big”?
- Recorded many separate $3 \times 10^8$ event data sets under various experimental conditions to investigate:
  - Varying beam polarization - (“Surface” vs “cloud” muon beams)
  - Beam line and detector performance (Vary beam line,detector, time)
  - Upstream-downstream symmetry (Vary stopping point, material)
  - Momentum scale (Vary solenoid field)
  - Analysis codes (Vary trigger rate)
  - GEANT simulation quality (vary muon stop location, beam positron data)
Validating the Muon Stopping Distribution in GEANT

- Began with muons stopping in the center of the target in both experiment and Monte Carlo

- Inserted an upstream mylar degrader with the same known thickness in both

- Measured the new stopping distribution in the upstream half of the detector stack
Validating the Positron Interactions in GEANT

Energy loss

Multiple scattering

- Stop muons near the upstream end of the system
- **Track** decay positrons *independently* before and after the target
- Compare the two reconstructions
- Measures energy loss and multiple scattering in data and GEANT
Classifying Events: What Really Happened?

Do MC analysis and history match? Do MC and data match?

Same Monte Carlo analysis
Surface Muon Data Set taken under “Standard” Conditions

Standard Set A

Momentum (MeV/c)

cos Θ vs. Momentum (MeV/c)
Comparing **Cloud Muons** to **Surface Muons**

**Cloud vs. Standard A**

Events in Standard A data set 16112307
Events in Cloud data set 5730232

**Unnormalized ratio (Cloud)/(Standard A)**

**Cloud vs. Standard A**

Events in Standard A data set 30534801
Events in Cloud data set 10832352

**Unnormalized ratio (Cloud)/(Standard A)**

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Comparing Cloud Muons to Surface Muons

Cloud vs. Standard A

Events in Standard A data set 16112307
Events in Cloud data set 5730232

Events in Standard A data set 30534801
Events in Cloud data set 10832352
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More Cloud Muons vs. Surface Muons

Cloud vs. Standard A

Events in Standard A data set 9579373
Events in Cloud data set 2686038

Cloud vs. Standard A

Events in Standard A data set 6214309
Events in Cloud data set 2865119
More **Cloud Muons** vs. **Surface Muons**

**Cloud vs. Standard A**

- **Unnormalized ratio (Cloud)/(Standard A)**
  - Events in Standard A data set 30534801
  - Events in Cloud data set 10832352
DCHV 1850V vs. Standard A

Normalized overlay of Momentum (MeV/c), Upstream

Unnormalized ratio of histograms, (DCHV 1850V)/(Standard A)

Events in Standard A data set 1481827
Events in DCHV 1850V data set 5472748
DCHV 1850V vs. Standard A

Normalized overlay of ABS(cos(\theta))

Unnormalized ratio of histograms, (DCHV 1850V)/(Standard A)

Events in Standard A data set 3957969
Events in DCHV 1850V data set 14454754
Atmospheric Pressure and Muon Stopping Location

High Density vs. Low

Momentum (MeV/c) (normalized)

High Density vs. Low

cos θ (normalized)

Unnormalized ratio (High Density)/(Low)

Events in Low data set 2324119
Events in High Density data set 3200343

Events in Low data set 4401366
Events in High Density data set 6064934
Additional Material Downstream of the Detector

**DnStr Al vs. Standard A**

- Momentum (MeV/c) (normalized)

**DnStr Al vs. Standard A**

- $\cos \Theta$ (normalized)

**Unnormalized ratio \((DnStr Al)/(Standard A)\)**

- Events in Standard A data set 16112307
- Events in DnStr Al data set 8779997

- Events in Standard A data set 30534801
- Events in DnStr Al data set 16499435
Endpoint Fits for Momentum Calibration Check

Ptot for 136.5°<θ<135° deg (1/c = -1.39641)

MC

Data

Endpoint vs 1/cos(θ)

MC

Data
Conclusions

- TWIST is the first experiment ever to measure the full muon decay energy-angle spectrum simultaneously.

- The ultimate goal of TWIST is to improve our knowledge of $\rho$, $\delta$, and $P_{\mu,\xi}$ by over an order of magnitude in each case. We may also improve our knowledge of $\eta$. This will give us model-independent sensitivity to right-handed vector bosons with masses up to 800 GeV in left-right symmetric theories, plus sensitivity to right-handed muon coupling through scalar or tensor interactions.

- The data in hand should provide measurements of $\rho$ and $\delta$ to $\sim 10^{-3}$.

- We hope to have the existing data analyzed by the end of this year.