TWIST – the TRIUMF Weak Interaction Symmetry Test

A precision study of the \( \mu^+ \) decay spectrum

- Designed to achieve \( \sim 0.01\% \) in the \textit{shape} of the \( \mu \) decay spectrum
- Several data sets of \( 10^9 \) events each
- A precision test of the weak interaction in the Standard Model

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Outline

- Motivation
- Overview of the experiment
- Analysis status
- Timeline
The **TWIST** Collaboration

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**Graduate Students**
- † also UVic
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- ‡‡ also Saskatchewan
- † † also LANL

*§ Deceased*
**TWIST** Motivation – testing the Standard Model

... Most general interaction does not presuppose the $W$

\[
\text{rate} \sim \left| \sum_{\gamma = S, V, T} g_{ij}^{\gamma} \langle \overline{\psi}_{ei}^{\gamma} | \Gamma^{\gamma} | \psi_{e} \rangle \langle \overline{\psi}_{\nu_{\mu}}^{\gamma} | \Gamma^{\gamma} | \psi_{\mu} \rangle \right|^2
\]

- $S, V, T =$ scalar, vector or tensor interactions
- $R, L =$ right and left handed leptons ($e, \mu, or \tau$)
Expanded in terms what have become known as the Michel parameters

\[ \text{rate} \sim x^2 \left[ 3 - 3x + \frac{2}{3} \rho(4x - 3) + 3\eta x_0 \frac{1-x}{x} + P_\mu \xi \cos(\theta) \left( 1 - x + \frac{2}{3} \delta(4x - 3) \right) \right] \]

These shape parameters of the spectrum are what TWIST is studying!

Modified by radiative corrections. Now several calculations to 2nd order exist.

See Arbuzov JHEP0303:063,2003
{hep-ph/0206036}
The Michel Parameter - $\rho$

The parameter $\rho$ largely determines the shape of the positron energy spectrum

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

$$+ \frac{3}{4} \left[ \text{Re}(g_{LR}^S g_{LR}^{T*}) + \text{Re}(g_{LR}^{S*} g_{LR}^T) + \text{Re}(g_{RL}^S g_{RL}^{T*}) + \text{Re}(g_{RL}^{S*} g_{RL}^T) \right]$$

- positive definite terms
  → fewer required experiments
- can conspire so $\rho = \frac{3}{4}$
  → measure parameters simultaneously

The effect of large deviations in $\rho$ on the shape of the energy spectrum. The effect shown is roughly $500$ times the TWIST sensitivity.
Anticipated TWIST sensitivity to R-H currents in muon decay

\[
Q^\mu_R = Q_{RR} + Q_{LR} = \frac{1}{4} |g^S_{LR}|^2 + |g^V_{LR}|^2 + 3 |g^T_{LR}|^2 + \frac{1}{4} |g^S_{RR}|^2 + |g^V_{RR}|^2
\]

\[
Q^\mu_R = \frac{1}{2} \left( 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right)
\]
Left/Right **Symmetric Extensions of the Standard Model**

Two weak bosons with mass eigenstates $M_1$ and $M_2$

\[
M_{WL} = M_1 \cos(\zeta) - M_2 \sin(\zeta)
\]
\[
M_{WR} = e^{i\omega} (M_1 \cos(\zeta) + M_2 \sin(\zeta))
\]

Parity violation at low energy is presumably due to

\[
\frac{m_{WR}}{m_{WL}} \gg 1
\]

In general, the models may include a CP violating phase ($\omega$), and a left/right mixing parameter $\zeta$
For Left/Right Symmetric extensions

For \( g_{LR}^V = g_{RL}^V \approx \xi \ll 1 \quad \text{and} \quad g_{RR}^V \approx \left( \frac{m_L}{m_R} \right)^2 \)

\[
\begin{align*}
\rho & \approx \frac{3}{4} \left( 1 - 2\xi^2 \right) \\
\xi & \approx 1 - 2 \left( \frac{m_L}{m_R} \right)^4 - 2\xi^2 \\
& \approx \frac{4}{3} \rho - 2 \left( \frac{m_L}{m_R} \right)^4 \\
\delta & \approx \frac{3}{4} \\
\eta & \approx 0
\end{align*}
\]

- \( \rho \) is sensitive to the Left/Right mixing
- \( \xi \) to the mixing and to the \( W_R \) mass
- \( \delta \) and \( \eta \) are unchanged by Left/Right extensions with manifest symmetry

A measurement of \( \rho \) and \( \xi \) determines the \( W_R \) mass and its mixing
Left/Right Mixing constraints – Anticipated TWIST Sensitivity

Anticipated TWIST sensitivity due only to the $P_\mu \xi$ measurement

(D0 & CDF with various assumptions re CKM$_R$

Manifest l/r symmetry

Anticipated TWIST $\rho$ result

Discovery potential

$W_R$ Mass (GeV)
Complementary

$\beta$ decay

$$\left( \frac{g_R}{g_L} \right)^4 \left( \frac{V_{ud}^R}{V_{ud}^L} \right)^2 \left( \frac{M_L}{M_R} \right)^4$$

p pbar collider

$$\left( \frac{g_R}{g_L} \right)^2 \left( \frac{V_{ud}^R}{V_{ud}^L} \right)^2 \text{ function} \left( \frac{M_L}{M_R} \right)$$

$\mu$ decay

$$\left( \frac{g_R}{g_L} \right)^4 \left[ 1 + \left( \frac{V_{ud}^R}{V_{ud}^L} \right)^2 \right] \left( \frac{M_L}{M_R} \right)^4$$

β decay

p pbar collider

μ decay
The Experiment

- Highly polarized muons enter the spectrometer one at a time
- Unbiased trigger on muon entering system
- Data sets of $10^9$ muon decay events in roughly two weeks (modern computing)
- The experiment is **systematics limited**. The high data rate is a must for systematics studies.

The large acceptance makes possible measurements of Michel parameters under differing conditions – therefore improving the reliability of the result.
Chambers & half detector

Planar drift chambers sample positron track

Use 44 drift planes, and 12 PC planes
Typical decay event
Analysis Concept

Fit real data to Monte Carlo generated data

• many effects of reconstruction cancel
• MC must reproduce the detector response well

TWIST detector thin so effects small

Useful for systematics search/study

• systematics comparisons can be done directly

fit data to data or MC to MC

Hide values of ρ, δ, ξ and η used in MC generation

• can be done in straightforward way
• avoids human bias in analysis of systematics
Spectrum is linear in $\rho$, $\eta$, $\xi$ and $\xi\delta$ so fit

$$N_i(\lambda_{\text{data}}) = N_i(\lambda_{\text{MC}}) + \frac{\partial N_i}{\partial \lambda}(\lambda_{\text{data}} - \lambda_{\text{MC}})$$

where $\lambda_{\text{data}} - \lambda_{\text{MC}} = \Delta \lambda$ is the fit parameter

$N_i$ - number in momentum/angle bin $i$

Generate $\mu$ beam, track to stop, get $e^+$ kinematics from box, track $e^+$ through detector

Fit data to this spectrum

Determine $\Delta \rho$, $\Delta \delta$, $\Delta \xi$ and $\Delta \eta$
Use in systematics studies

**Type 1**
(Monte Carlo or data)
Analysis 1

Fit mc to mc or data to data

**Type 2**
(Monte Carlo or data)
Analysis 1

Fit uncorrelated samples
Detect & evaluate systematic

**Type 1**
(Monte Carlo or data)
Analysis 1

Fit correlated samples
Enhance & evaluate systematic
## Systematics study status

### Sample from correlated data to data fits

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Long list at this level – **No showstopper found**

session J11
\(\rho\) – (Musser)
\(\delta\) – (Gaponenko)
Timeline

- 6x10^9 muon decay events are in hand
  - complete 10^{-3} analysis this summer!
  - publish determination of \( \rho \) and \( \delta \)
- 2004 data run
  - data on \( P_\mu \xi \) at 10^{-3} (and \( \eta \)?) this summer/fall
- at least 3 PhD’s granted by 2005
- Final parts in 10^{-4} data & publications: 2005/2006
- Need More Graduate Students Now
Summary

- The TWIST experiment is near end of phase 1
  - Anticipate preliminary measurements at \( \sim 0.1\% \) of:
    - \( \rho \) and \( \delta \) (this summer)
    - \( P_{\mu \xi} \) (Data during the summer/fall of 2004)
    - Final precision on \( \rho \) and \( \delta \) and \( P_{\mu \xi} \) at \( \sim \pm 0.02\% \)

- TWIST is exploring significant new space where evidence may be found to challenge the standard model

- For left/right symmetric models, TWIST has a mass reach which is comparable to - and which complements \( \beta \) decay experiments and direct searches at the Tevatron