First results from *TWIST*

Glen Marshall, for the *TWIST* Collaboration
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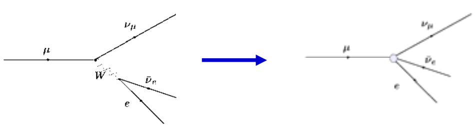
Outline

- Muon Decay and Standard Model Tests
- The *TWIST* Spectrometer
- Analysis Methods
- Evaluation of Systematic Uncertainties
- New Results
- The Future of *TWIST*

Muon decay made simple



- Assume four-fermion interaction which is:
  - local
  - derivative-free
  - lepton-number-conserving
- Allows scalar, vector, or tensor; left or right; or combinations.

Matrix elements

- Description of Fetscher and Gerber (see PDG):

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L}} g^{\gamma}_{\varepsilon\mu} \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_\gamma | \mu_\mu \rangle$$

- Includes includes scalar, vector, and tensor (Γ^S,Γ^V,Γ^T) interactions among left- and right-handed μ, e.
- Probability for decay of μ–handed muon to ε–handed electron:

$$Q_{\varepsilon\mu} = \frac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1-\delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2$$

Coupling constants

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

$$\begin{aligned} Q^{\mu}_{R} &\equiv Q_{RR} + Q_{LR} \\ &= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \end{aligned}$$

- PDG limits on all couplings:

$\|g^S_{RR}\| < 0.066$	$\|g^V_{RR}\| < 0.033$	$\|g^T_{RR}\| \equiv 0$
$\|g^S_{LR}\| < 0.125$	$\|g^V_{LR}\| < 0.060$	$\|g^T_{LR}\| < 0.036$
$\|g^S_{RL}\| < 0.424$	$\|g^V_{RL}\| < 0.110$	$\|g^T_{RL}\| < 0.122$
$\|g^S_{LL}\| < 0.550$	$\|g^V_{LL}\| > 0.960$	$\|g^T_{LL}\| \equiv 0$

Michel parameter description

- Muon decay (Michel) parameters ρ, η, $\mathcal{P}_\mu\xi$, δ:
  - muon differential decay rate *vs.* energy and angle:

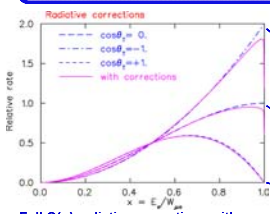
$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \frac{1}{4} m_\mu W^4_{\mu e} G^2_F \sqrt{x^2 - x_0^2}\, \{\mathcal{F}_{IS}(x,\rho,\eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

  - where

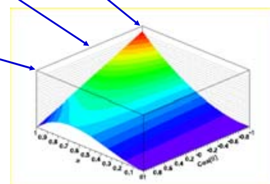
$$\begin{aligned} \mathcal{F}_{IS}(x,\rho,\eta) &= x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x) \\ \mathcal{F}_{AS}(x,\xi,\delta) &= \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right] \end{aligned}$$

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

Decay distribution and radiative corrections



Arbuzov et al., Phys. Rev. D66 (2002) 93003.
Arbuzov et al., Phys. Rev. D65 (2002) 113006.



- Full O(α) radiative corrections with exact electron mass dependence.
- Leading and next-to-leading logarithmic terms of O(α^2).
- Leading logarithmic terms of O(α^3).
- Corrections for soft pairs, virtual pairs, and an ad-hoc exponentiation.

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Testing the Standard Model

- Model independent muon handedness:

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

- Left-right symmetric models:

$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2, \quad 1 - \mathcal{P}_\mu\xi = 4\{\zeta^2 + \frac{M_L^4}{M_R^4} + \zeta\frac{M_L^2}{M_R^2}\}$$

- Tensor interaction (M. Chizhov, hep-ph/0405073):

$$\delta = \frac{3}{4}(1 - 6|g_{RR}^T|^2)$$

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Pre-*TWIST* decay parameters

- From the Review of Particle Physics (SM values in parentheses) :
  - ρ = 0.7518 ± 0.0026 (Derenzo, 1969) (0.75)
  - η = -0.007 ± 0.013 (Burkard *et al.* , 1985) (0.00)
  - δ = 0.7486 ± 0.0026 ± 0.0028 (Balke *et al.* , 1988) (0.75)
  - $\mathcal{P}_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (Beltrami *et al.* , 1987) (1.00)
  - $\mathcal{P}_\mu(\xi\delta/\rho)$ > 0.99682 (Jodidio *et al.* , 1986) (1.00)

The goal of *TWIST* is to find any new physics which may become apparent by improving the precision of each of ρ, δ, and $\mathcal{P}_\mu\xi$ by at least one order of magnitude.

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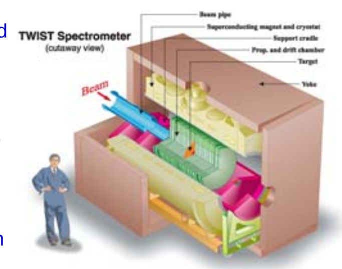
The *TWIST* Spectrometer

- Use highly polarized μ^+ beam.
- Stop them in a very symmetric detector.
- Decay e^+ are tracked through uniform, well-known field.



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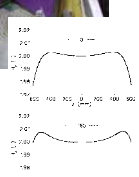
Solenoid field

- 20 year old ex-MRI superconducting solenoid provides 2 T field.
- Steel yoke improves uniformity, reduces stray fields.
- Uniform to 4×10^{-3}, mapped to precision of 5×10^{-5}.



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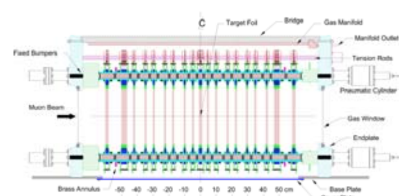
Detector array



- 56 low-mass high-precision planar chambers symmetrically placed around thin target foil which stops nearly all of surface muon beam.
- Measurement initiated by single thin scintillation counter at entrance to detector.
- Beam stop position controlled by variable He/CO_2 gas degrader.

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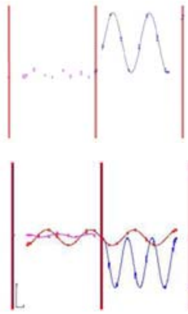
Analysis of data and simulation

- Read out chamber hits in time interval [-6,+10] μs.
- Use pattern recognition (in position and time) to sort hits into tracks, then fit to helix.
- Write track parameters and other variables.
- Must recognize beam positrons, delta tracks, backscattering tracks.



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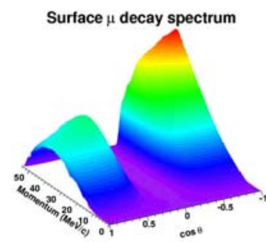
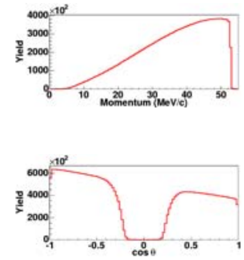
Data distributions





Acceptance of *TWIST* spectrometer

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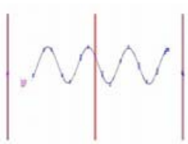
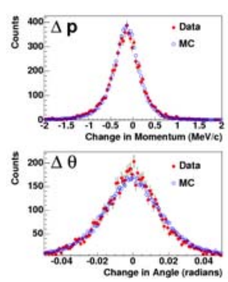
Simulation: positron interactions

- 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.





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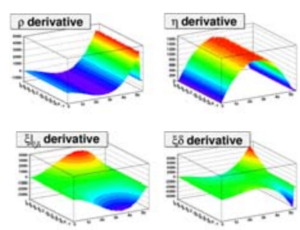
Fitting the data distributions

- Michel distribution is linear in ρ, η, ξ, and ξδ, so a fit to first order expansion is exact.

$$n_i(\alpha_{\rm data}) = n_i(\alpha_{\rm MC}) + \frac{\partial n_i}{\partial \alpha}\Delta\alpha,$$
$$\alpha = [\rho, \eta, \xi, \xi\delta]$$

- Fit data (α_{data}) to sum of a base MC distribution (α_{MC}) plus MC-generated derivative distributions times fitting parameters ($\Delta\alpha$) representing deviations from base MC.
- Can also fit data to data and MC to MC for systematic tests.



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Systematics: two examples

- Muon stopping target was 125 μm Mylar, coated with 10±10 μm graphite for conductivity. What is uncertainty in decay parameters due to the thickness uncertainty?
  - simulate with 30 μm graphite thickness (2× exaggeration).
  - fit to simulation (correlated!) with nominal thickness:
    - shift for ρ of -0.98 × 10⁻³ and δ of -0.73 × 10⁻³.
  - divide shift by exaggeration factor.
- HV was maintained to accuracy of ± 5 V. What is uncertainty in decay parameters due to HV variation?
  - take data set with HV lowered by 100 V (20× exaggeration).
  - fit to nominal (uncorrelated) data set:
    - shift for ρ of -0.70 × 10⁻³ and δ of +0.08 × 10⁻³.
  - divide shift by exaggeration factor.

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Summary of systematic uncertainties

Systematic effect	Uncertainty in ρ (×10⁴)
Chamber response (ave)	5.1
Stopping target thickness	4.9
Positron interactions	4.6
Spectrometer alignment	2.2
Momentum calibration (ave)	2.0
Theoretical radiative correction	2.0
Track selection algorithm	1.1
Muon beam stability (ave)	0.4

Systematics for ρ

Systematic effect	Uncertainty in δ (×10⁴)
Spectrometer alignment	6.1
Chamber response (ave)	5.6
Positron interactions	5.5
Stopping target thickness	3.7
Momentum calibration (ave)	2.9
Muon beam stability (ave)	1.0
Theoretical radiative correction	1.0
Up and downstream efficiencies	0.4

Systematics for δ

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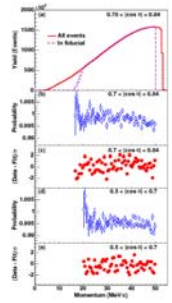
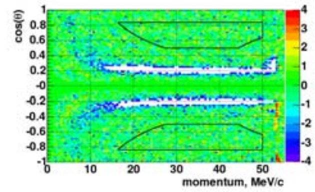
New Results

- Data taken in Fall 2002:
  - 6×10^9 muon decay events in data sets of about 3×10^8 events (2-3 days) each.
  - Five (ρ) or four (δ) sets were analyzed and fit to extract results.
  - Remainder were for systematic tests.
- Analysis relied on WestGrid installation at UBC:
  - 1008 Intel 3 GHz processors in total.
  - Available in late 2003; operating well in early 2004.
  - *TWIST* used ~31,000 processor days in 2004 to analyze data and simulations.

Fits to data distributions: ρ





Above: normalized residuals of fit, and fiducial region used for fit: $p < 50$ MeV/c, $0.50 < |\cos\theta| < 0.84$, $|p_z| > 13.7$ MeV/c, $p_T < 38.5$ MeV/c.

Left: comparison of data to fit (MC) *vs.* momentum, also showing (MC reconstructed)/(MC thrown) comparisons and normalized residuals.

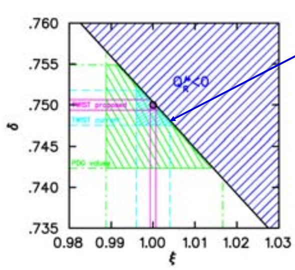
Results of different data sets

Data set	ρ (stat)(syst)	χ^2 dof=1887	δ (stat)(syst)	χ^2 dof=1887
Set A	0.75134(83)(53)	1814	0.75087(156)(73)	1924
Set B	0.74937(66)(53)	1965	0.74979(124)(55)	1880
1.96 T	0.75027(65)(55)	1951	0.74918(124)(69)	1987
2.04 T	0.75248(70)(60)	1804	0.74908(132)(65)	1947
Cloud μ^+	0.75157(76)(53)	1993	-	-

Summary of results

- **ρ = 0.75080 ± 0.00044(stat) ± 0.00093(syst) ± 0.00023(η)**
  - 2.5 times better than PDG value.
  - Uncertainty scaled to account for χ^2/dof = 7.5/4 for different data sets.
  - hep-ex/0409063
- **δ = 0.74964 ± 0.00066(stat) ± 0.00112(syst)**
  - 2.9 times better than PDG value.
  - hep-ex/0410045
- Using the above values of ρ and δ, with $\mathcal{P}_\mu(\xi\delta/\rho) > 0.99682$ (PDG) and $Q^R_\mu \geq 0$, we get
  $0.99288 < \mathcal{P}_\mu\xi \leq \xi < 1.01078$
  - improves upon $\mathcal{P}_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$.

Handedness of the muon

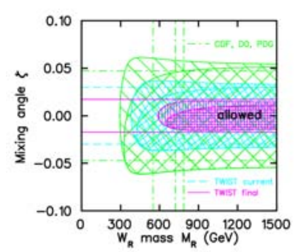


Diagonal represents exactly left-handed coupling of the muon.

Shaded regions represent comparison of current (indirect) and proposed (direct) *TWIST* limits, compared to previous PDG limits.

$$Q^\mu_R = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \geq 0$$

Implications for L-R symmetric model



Exclusion plot for L-R symmetric model mixing angle and right-coupling partner boson W_R mass.

The plot compares current and proposed *TWIST* limits with previous limits from muon decay and direct particle searches.

$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2, \qquad 1 - \mathcal{P}_\mu\xi = 4\{\zeta^2 + \frac{M_L^4}{M_R^4} + \zeta\frac{M_L^2}{M_R^2}\}$$

Are there derivative couplings?

- π β-decay experiments see a small anomaly which might be explained by a tensor interaction.
  (hep-ex/0312029, recently published in Phys. Rev. Lett.)
- Chizhov (hep-ph/0405073) calculates:
  - $\delta = \frac{3}{4}(1 - 6|g^T_{RR}|^2) \approx 0.74924$
  - deviation from Standard Model value is ~2× less than current *TWIST* precision.

The next phase of *TWIST*

- Analysis of new data underway, from an improved apparatus and revised analysis procedures:
  - 71 μm high-purity aluminum target (reduced muon depolarization, reduced target thickness uncertainty).
  - better monitoring and control of muon beam with TEC (improved simulation input, reduced beam uncertainty).
  - improved chamber drift cell geometry (control of chamber response).
  - better online diagnostics of detectors and beam.
  - ... and others.
- Expect first direct measurement of $\mathcal{P}_\mu\xi$ (~10^{-3})and 2× better precision for ρ and δ, from 2004-05 data.

Summary

- *TWIST* has produced its first physics results.
- Strategies and procedures for the next phase have been tested and implemented.
- Analysis underway for the first direct measurement of $\mathcal{P}_\mu\xi$, improving it by at least a factor of 5 and leading to further gains in precision for ρ and δ.
- In 2006-2008, *TWIST* will produce its final results, an overall reduction of uncertainty by at least an order of magnitude (twice that for $\mathcal{P}_\mu\xi$) compared to previous muon decay parameter experiments.

TWIST Participants

TRIUMF
Ryan Bayes ∗†
Yuri Davydov
Jaap Doornbos
Wayne Faszer
Makoto Fujiwara
David Gill
Peter Gumplinger
Robert Henderson
Jingliang Hu
John A. Macdonald §
Glen Marshall
Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin †
Robert Openshaw
Tracy Porcelli ‡
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin ‡‡

Alberta
Andrei Gaponenko ∗
Peter Kitching
Robert MacDonald ∗
Maher Quraan†
Nate Rodning §
John Schaapman
Glen Stinson

British Columbia
Mike Hasinoff
Blair Jamieson ∗

Montréal
Pierre Depommier

Regina
Ted Mathie
Roman Tacik

Kurchatov Institute
Vladimir Selivanov
Vladimir Torokhov

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

Valparaiso
Don Koetke
Paul Nord
Shirvel Stanislaus

∗ Graduate student
† also U Vic
‡ also Manitoba
‡‡ also Saskatchewan
§ deceased