A Muon Decay Spectrum Measurement from *TWIST*

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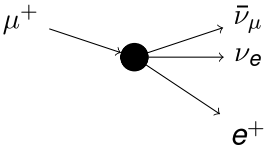
Muon Decay: A Constraint on the Weak Interaction

- General Lorentz invariant, derivative-free, interaction described by

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

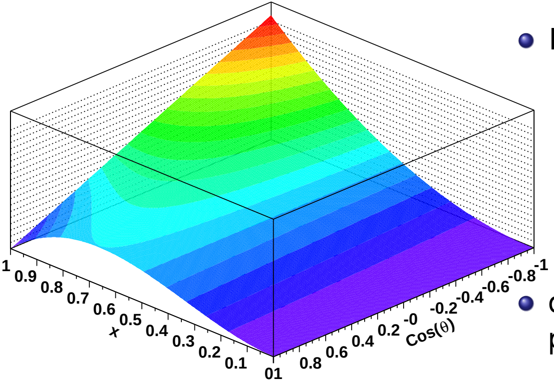
- In the standard model (V - A) interaction $g^{V}_{LL} = 1$
- all other contributions are zero



Positron Spectrum of Muon Decay

- Given in momentum and angle as

$$\frac{\partial\Gamma}{\partial x \partial \cos\theta} = F(x;\rho,\eta) + P_\mu \cos\theta G(x;\xi,\delta), \qquad x = \frac{E_e}{E_{max}}$$



- In the Standard Model

$$\begin{aligned} \rho &= 0.75 \\ \eta &= 0 \\ \delta &= 0.75 \\ P_\mu^\pi \xi &= 1 \end{aligned}$$

- deviations represent new physics

Tests for New Physics

Right Handed Decays

- Probability given by

$$Q_R^\mu = \frac{1}{4}(|g^S_{LR}|^2 + |g^S_{RR}|^2) + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 = \frac{1}{2}\left(1 + \frac{\xi}{3} + \frac{16\xi\delta}{9}\right)$$

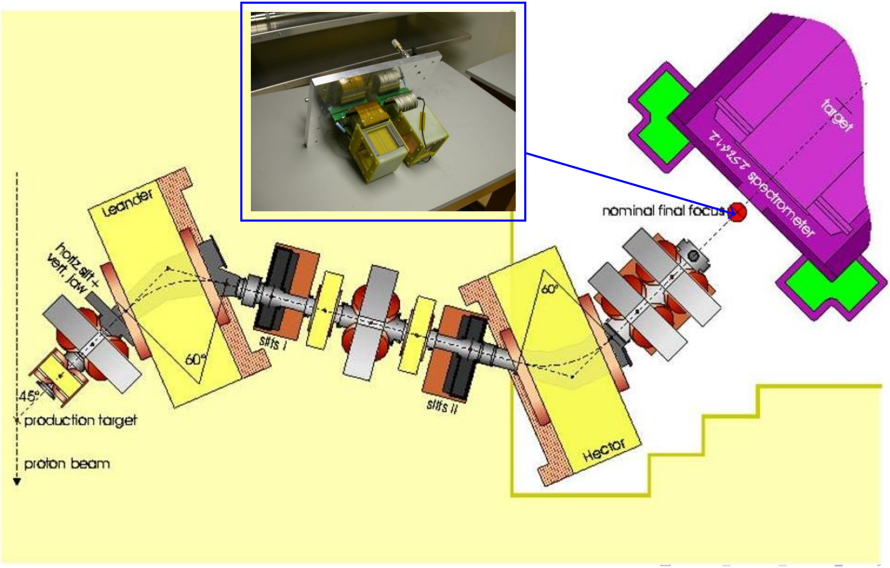
Left - Right Symmetric Models

$$W_L = \cos\zeta W_1 + \sin\zeta W_2$$
$$W_R = e^{i\omega}(-\sin\zeta W_1 + \cos\zeta W_2)$$

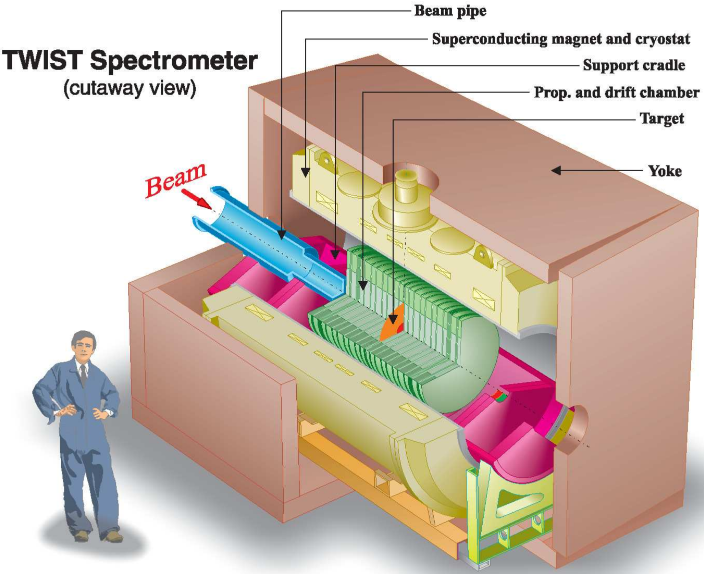
where

$$\zeta = \left|\frac{g_L}{g_R}\right|\sqrt{\frac{1}{2}\left(1 - \frac{4}{3}\rho\right)}$$

M13: Surface Muon Source



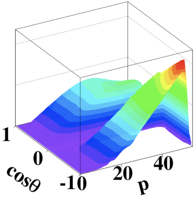
TWIST detector



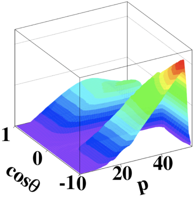
TWIST Analysis

Experimental Data

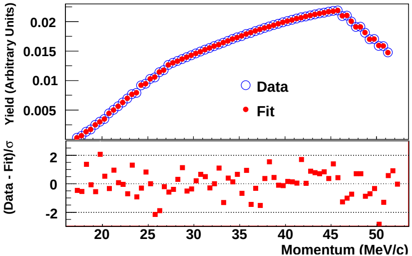
$\rho_h, P_\mu^\pi \xi_h, \delta_h \longrightarrow$ Geant 3 Simulation



→ Spectrum Fit ←



$\Delta\rho, \Delta P_\mu \xi, \Delta\delta$



Systematics Measurement

General Systematics Determination

Verify strength and uncertainty of effect.

↓

Exaggerate the effect in data or simulation.

↓

Measure the sensitivity of the decay parameters.

↓

Scale the final sensitivities.

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General Systematics Determination

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↓

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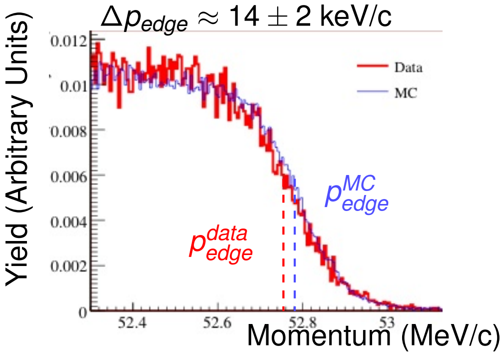
↓

Scale the final sensitivities.

Example: Endpoint Calibration

- Corrects differences between simulation and data at endpoint



Sensitivity: $\frac{\Delta\rho}{\Delta p_{edge}} \approx \frac{(-1.72\pm0.37)\times10^{-3}}{100keV/c}$

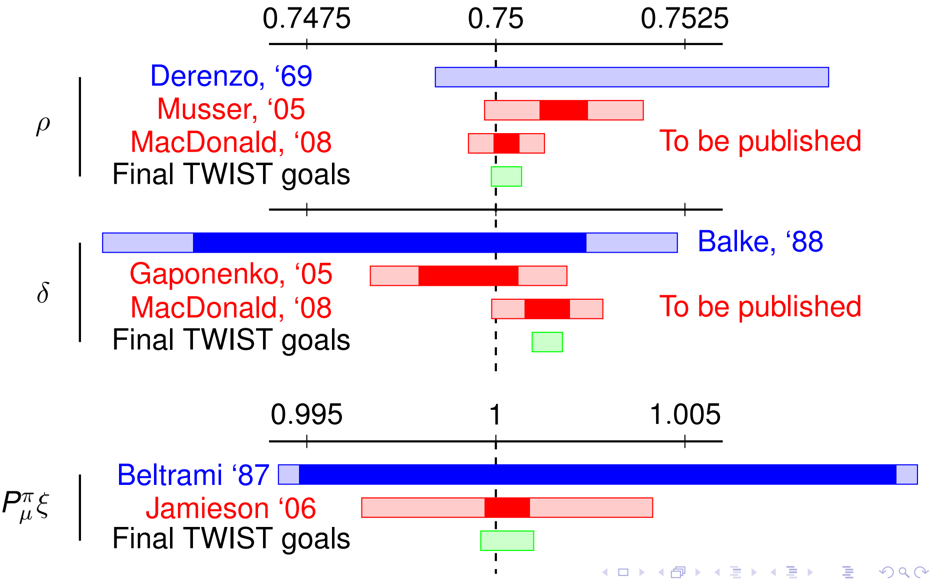
Systematic Effects on $\mathcal{TWIST}$ Measurements

Current State of Leading Systematic Uncertainties

Effect	$\Delta\rho \times 10^4$	$\Delta\delta \times 10^4$	$\Delta P^{\pi}_{\mu}\xi \times 10^4$
Fringe Field Depol.	NA	NA	34
Stopping Material Depol.	NA	NA	12
Chamber Response	2.9	5.2	10
Energy Scale	2.9	4.1	2
Positron Interactions	1.6	0.9	3
Resolution	1.2	1.4	NA
η correlations	1.1	0.1	0.1

- R. MacDonald, PhD Thesis, University of Alberta
- B. Jamieson, Phys. Rev. 74D, 72007 (2006)

Latest TWIST Results

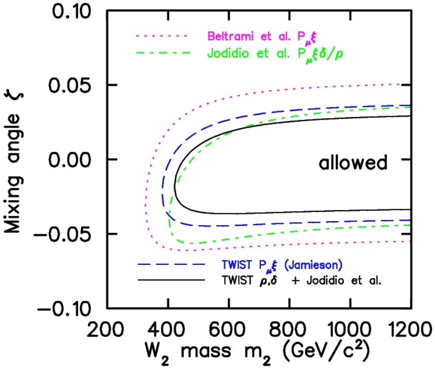


Limits on New Physics

Right Handed Muon Decays

- $Q_R^\mu < 0.014$: 90% limit before 2004
- $Q_R^\mu < 0.0024$: 90% limit from current results

- Improved Limits on Left-Right-Symmetric Models



Approaching Final analysis

- Ultimate goal of an order of magnitude improvement in sight

Improvements in Statistical Uncertainties

- Experiment collected 8×10^9 events during 2006 and 2007
  - physics data set nearly 6 times larger than previous

Reduction of Systematic Uncertainties

Better Beamline Monitoring	$\Longrightarrow$	Fringe Field Depol.
Better Chamber Modelling	$\Longrightarrow$	Chamber Response
Large Sample Through Going e^+	$\Longrightarrow$	Positron Interactions

Summary

Consistency with the Standard Model

$$\begin{aligned}\rho &= 0.75014 \pm 0.00017(\textit{stat}) \pm 0.00046(\textit{sys}) \pm \\ &\quad 0.00011(\eta) \\ \delta &= 0.75068 \pm 0.00030(\textit{stat}) \pm 0.00067(\textit{sys}) \\ P_\mu^\pi \xi &= 1.0003 \pm 0.0006(\textit{stat}) \pm 0.0038(\textit{sys})\end{aligned}$$

- Preliminary results improve precision on ρ and δ by a factor of 5.
- Improved precision on $P_\mu^\pi \xi$ by a factor of 2 .
- Precision goal of an order of magnitude improvement in decay parameters coming soon.

The *TWIST* Collaboration

TRIUMF
Ryan Bayes ♣★
Yuri Davydov
Wayne Faszer
Makoto Fujiwara
David Gll
Alex Grossheim
Peter Gumplinger
Anthony Hillairet ♣★
Robert Henderson
Jingliang Hu
John A. MacDonald ♦
Glen Marshall
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Mina Nozar
Konstantin Olchanski
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Vladimir Selivanov

Texas A&M
Carl Galiardi
Jim Musser ⊛
Bob Tribble

Valpariso
Don Koetke
Shirvel Stanislaus

★ graduate student
⊛ graduated
♣ also UVic
♦ deceased

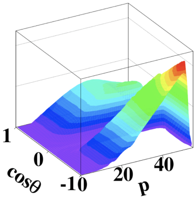
- Funding Support from NSERC and US DOE
- Additional support from TRIUMF and NRC
- Computing resources provided by Westgrid

Full Muon Decay Spectrum

$$\begin{aligned}
\frac{\partial^2\Gamma}{\partial x \partial \cos\theta} &= F(x;\rho,\eta) + P_\mu \cos\theta \, G(x;\xi,\delta) \\
F(x;\rho,\eta) &= x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0 (1-x) \\
G(x;\xi,\delta) &= \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 3 + \left(\sqrt{1-x_0^2} - 1\right)\right)\right]
\end{aligned}$$

Spectrum Fits

$$\left.\frac{\partial^2\Gamma}{\partial x \partial \cos\theta}\right|_{fit} = \left.\frac{\partial^2\Gamma}{\partial x \partial \cos\theta}\right|_{base} + \Delta\rho \frac{\partial}{\partial\rho}\frac{\partial^2\Gamma}{\partial x \partial \cos\theta} + \dots$$



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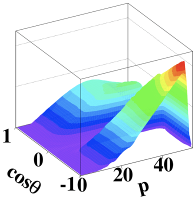
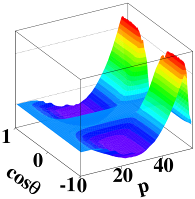
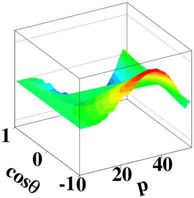


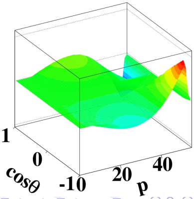
$+\Delta\rho$



$+\Delta\xi$



$+\Delta\xi\delta$



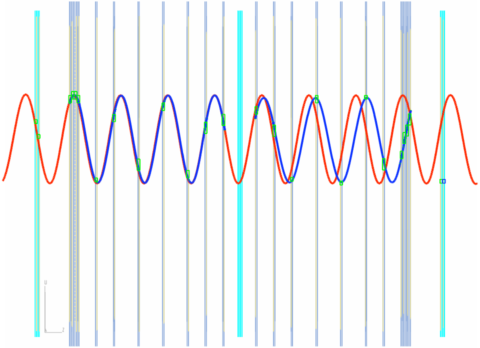
Testing Positron Interactions: Far Upstream Stops

A specialised type of data set

- muons stopped in the far upstream end of the detector
- downstream decaying positrons pass through entire detector stack

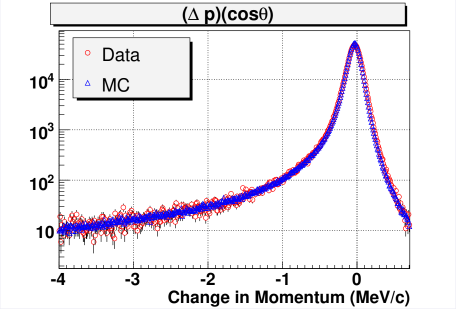
Uses for these data

- check efficiency of reconstruction
- measure reconstruction resolution
- directly measure target thickness

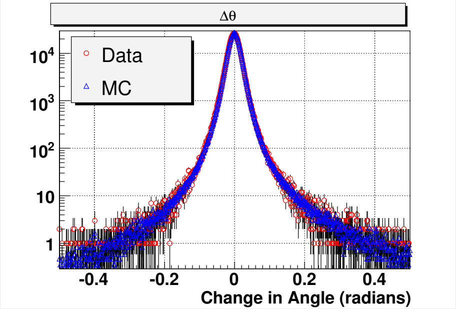


Response Function

Momentum Response



Angle Response



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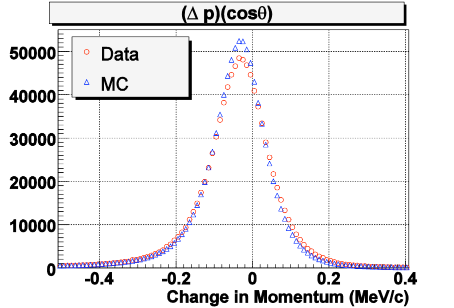

Angle Response