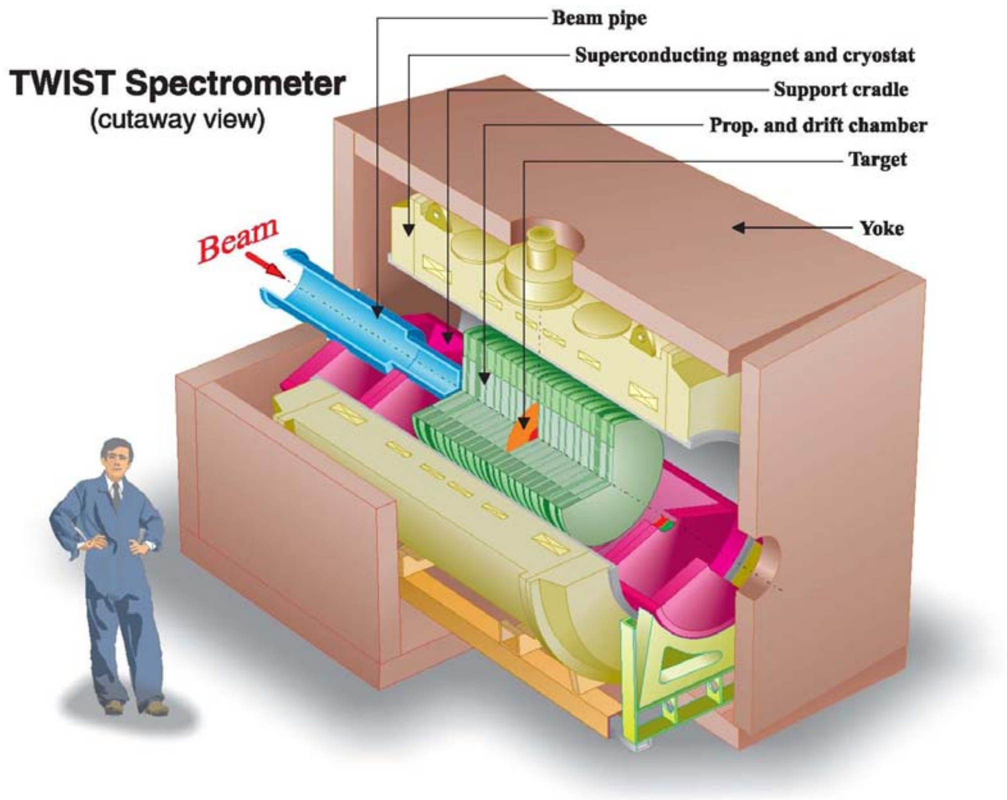
The *TWIST* Experiment: Testing the Standard Model with Muon Decay

Glen Marshall, for the *TWIST* Collaboration

μCF-07, Dubna, 18-21 June 2007

The TRIUMF Weak Interaction Symmetry Test

- Tests Standard Model predictions for muon decay.
- Uses highly polarized μ^+ beam (μ^- doesn't work!).
- Stops μ^+ in a very symmetric detector.
- Tracks e^+ through uniform, well-known field.
- Extracts decay parameters by comparison to detailed and verified simulation.



Michel parameter description

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

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

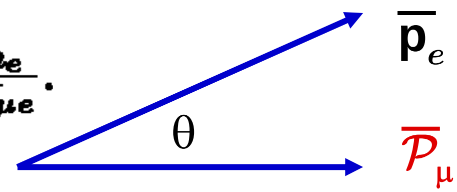
Louis Michel

  - where

$$\mathcal{F}_{IS}(x,\rho,\eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

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

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

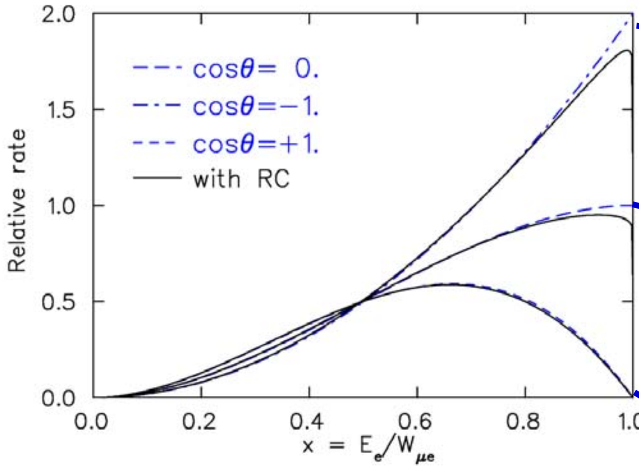


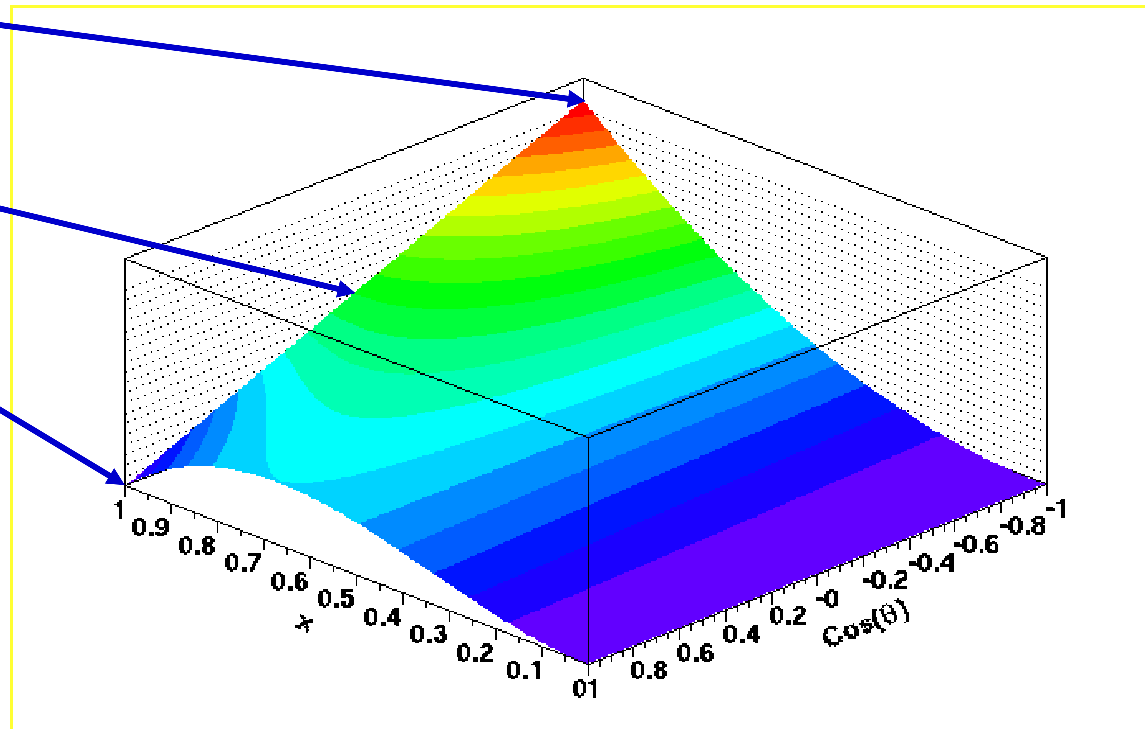
Pre-*TWIST* decay parameters

- 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
compared to prior experimental results.

Spectrum shape, graphically





- 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.

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

Anastasiou et al., hep-ph/0505069 to O(α^2) (not yet published, not implemented).

Michel parameters and coupling constants

- Fetscher and Gerber coupling constants (see PDG):

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

$$\begin{aligned}
\rho &= \frac{3}{4} - \frac{3}{4}[|g^V_{RL}|^2 + |g^V_{LR}|^2 + 2\,|g^T_{RL}|^2 + 2\,|g^T_{LR}|^2 \\
&\quad + \mathbb{R}e\,(g^S_{RL} g^{T*}_{RL} + g^S_{LR} g^{T*}_{LR})] \\
\eta &= \frac{1}{2}\mathbb{R}e[g^V_{RR} g^{S*}_{LL} + g^V_{LL} g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6 g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6 g^{T*}_{RL})] \\
\xi &= 1 - \frac{1}{2}\,|g^S_{LR}|^2 - \frac{1}{2}\,|g^S_{RR}|^2 - 4\,|g^V_{RL}|^2 + 2\,|g^V_{LR}|^2 - 2\,|g^V_{RR}|^2 \\
&\quad + 2\,|g^T_{LR}|^2 - 8\,|g^T_{RL}|^2 + 4\mathbb{R}e(g^S_{LR} g^{T*}_{LR} - g^S_{RL} g^{T*}_{RL}) \\
\xi\delta &= \frac{3}{4} - \frac{3}{8}\,|g^S_{RR}|^2 - \frac{3}{8}\,|g^S_{LR}|^2 - \frac{3}{2}\,|g^V_{RR}|^2 - \frac{3}{4}\,|g^V_{RL}|^2 - \frac{3}{4}\,|g^V_{LR}|^2 \\
&\quad - \frac{3}{2}\,|g^T_{RL}|^2 - 3\,|g^T_{LR}|^2 + \frac{3}{4}\mathbb{R}e(g^S_{LR} g^{T*}_{LR} - g^S_{RL} g^{T*}_{RL})
\end{aligned}$$

Coupling constants

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

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

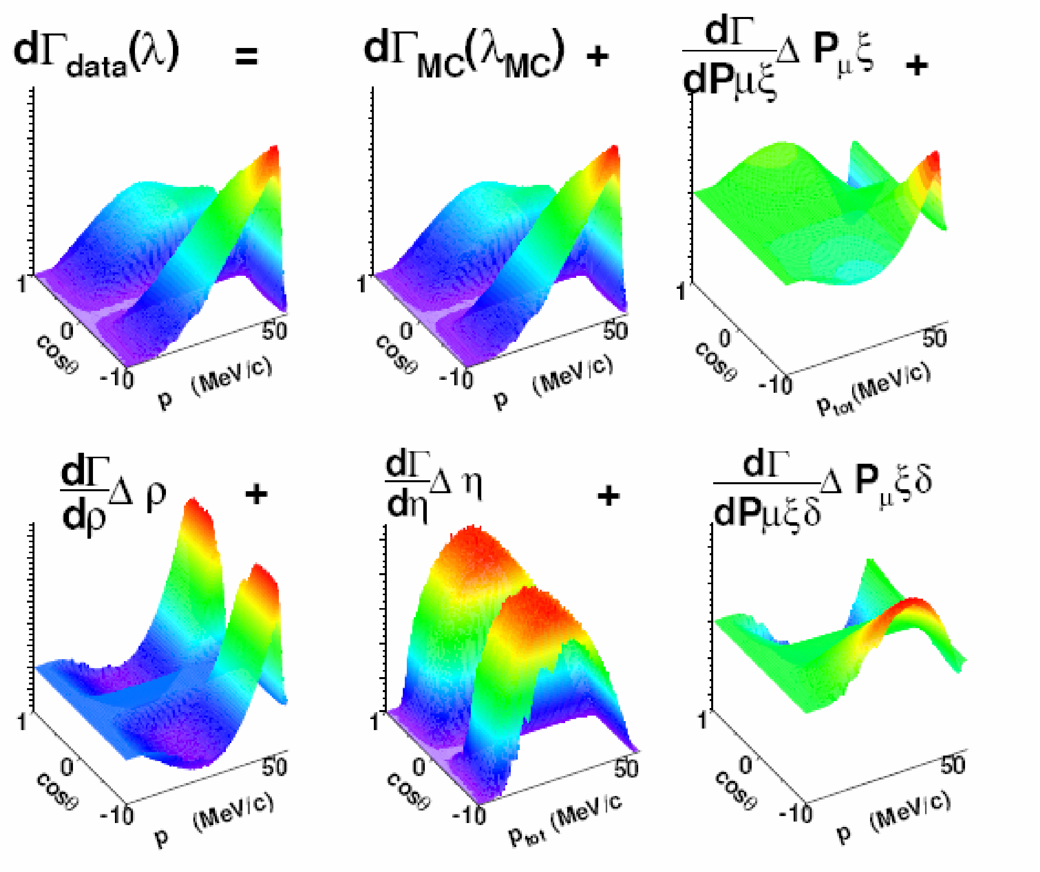
- Global analysis of μ decay (Gagliardi *et al.*, PRD **72** (2005) 073002)
  - no existing similar analysis for other weak decays.

$|g^S_{RR}| < 0.066(0.067)$	$|g^V_{RR}| < 0.033(0.034)$	$|g^T_{RR}| \equiv 0$
$|g^S_{LR}| < 0.125(0.088)$	$|g^V_{LR}| < 0.060(0.036)$	$|g^T_{LR}| < 0.036(0.025)$
$|g^S_{RL}| < 0.424(0.417)$	$|g^V_{RL}| < 0.110(0.104)$	$|g^T_{RL}| < 0.122(0.104)$
$|g^S_{LL}| < 0.550(0.550)$	$|g^V_{LL}| > 0.960(0.960)$	$|g^T_{LL}| \equiv 0$

- Neutrino mass implications at 10^{-7}-10^{-4} for LR/RL:
  - Erwin *et al.,* Phys. Rev. D **75** (2007) 033005 (hep-ph/0602240).

Fitting the data distributions

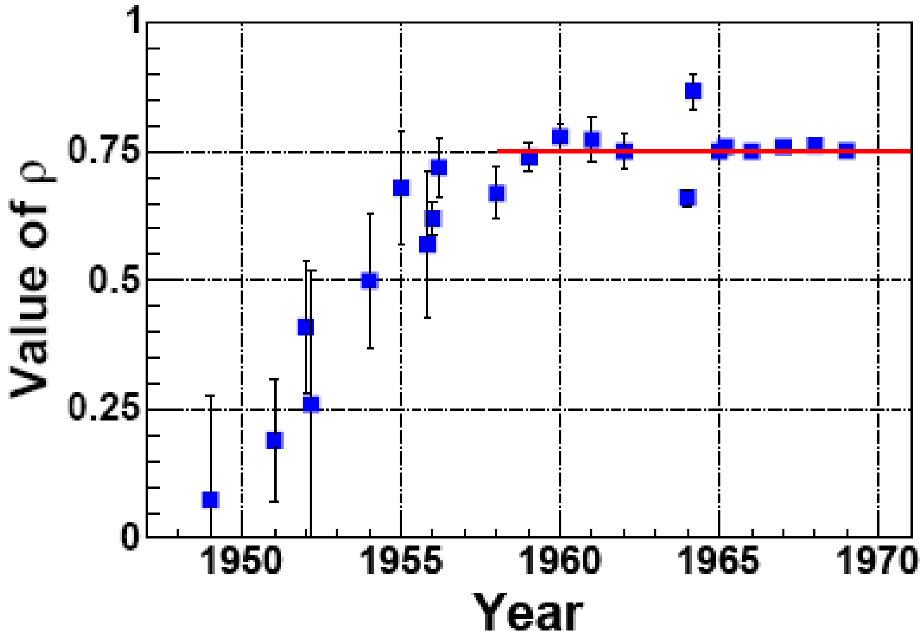
- Decay distribution is linear in ρ, η, $\mathcal{P}_\mu\xi$, and $\mathcal{P}_\mu\xi\delta$, so a fit to first order expansion is exact.
- Fit data to simulated (MC) base distribution with *hidden assumed parameters*,
  $\lambda_{MC} = (\rho, \eta, \mathcal{P}_\mu\xi_{|\mathcal{P}_\mu\xi\delta}, \mathcal{P}_\mu\xi\delta)$
  plus MC-generated distributions from analytic derivatives, times fitting parameters ($\Delta\lambda$) representing deviations from base MC.



(graphic thanks to Blair Jamieson)

Blind analysis motivation

- Reduce "human" systematics, *i.e.*, biases.
- Keep final result hidden until analysis is completed and systematic uncertainties evaluated.
- In fit procedure, the set of simulation parameters λ_{MC} is encrypted and unknown; results of fits are ***differences*** $\Delta\lambda$ from hidden values.



A. Gaponenko, Ph.D. thesis

Evaluation of Systematic Uncertainties

- *TWIST* relies on a fit to simulation:
  - Simulation must be verified.
  - Reconstruction systematics eliminated if simulation is perfect.

- General method:
  - exaggerate a condition (in data or MC) which may cause error.
  - measure effect by fitting, using correlated sets where practical.
  - scale results according to variance in a data set.
  - Linearity? Double counting?

- **Positron interactions:**
  - **Energy smearing**
  - **Multiple scattering**
  - **Hard interactions**
  - **Material in detector**
  - **Material outside**

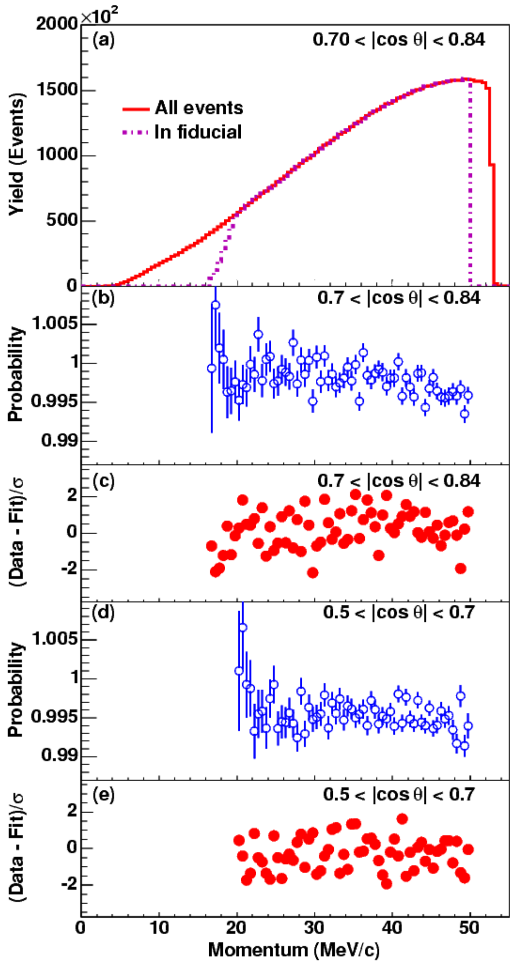
- **Chamber response:**
  - **DC and PC efficiencies**
  - **Dead zone**
  - **Long drift times**
  - **HV variations**
  - **Temperature, pressure**
  - **Chamber foil bulges**
  - **Crosstalk**
  - **Variation of t_0**

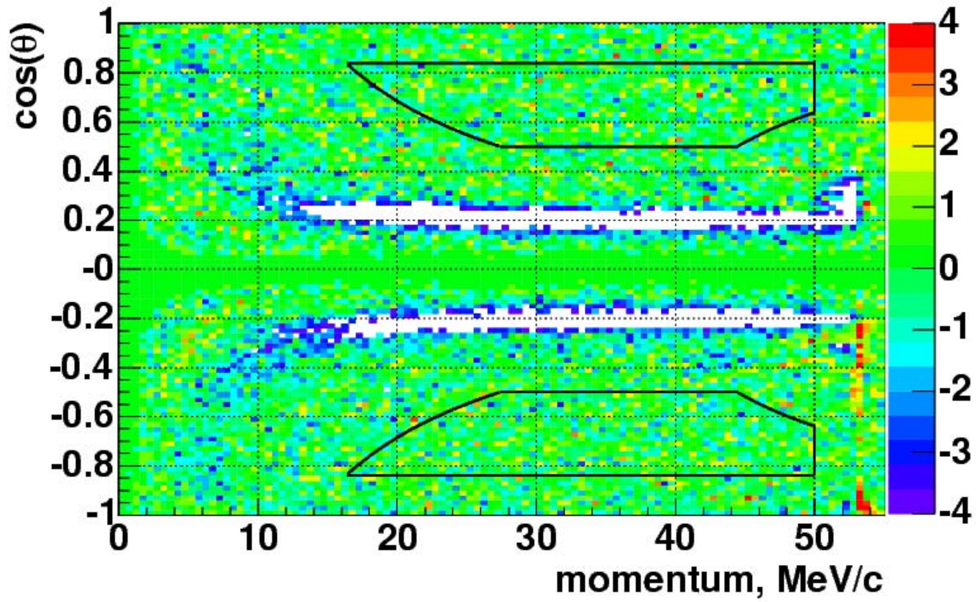
- **Momentum calibration:**
  - **End point fits**
  - **Field reproduction**

- **Muon beam stability:**
  - **Stopping location**
  - **Beam intensity**
  - **Magnet stability**

- **Spectrometer alignment:**
  - **Translations**
  - **Rotations**
  - **Longitudinal**
  - **Field to detector axis**

Fits to data distributions

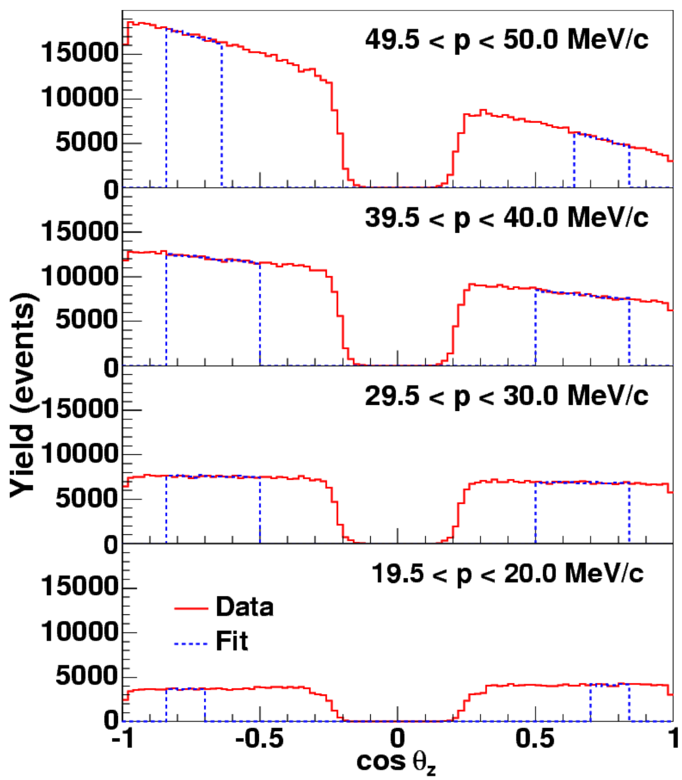




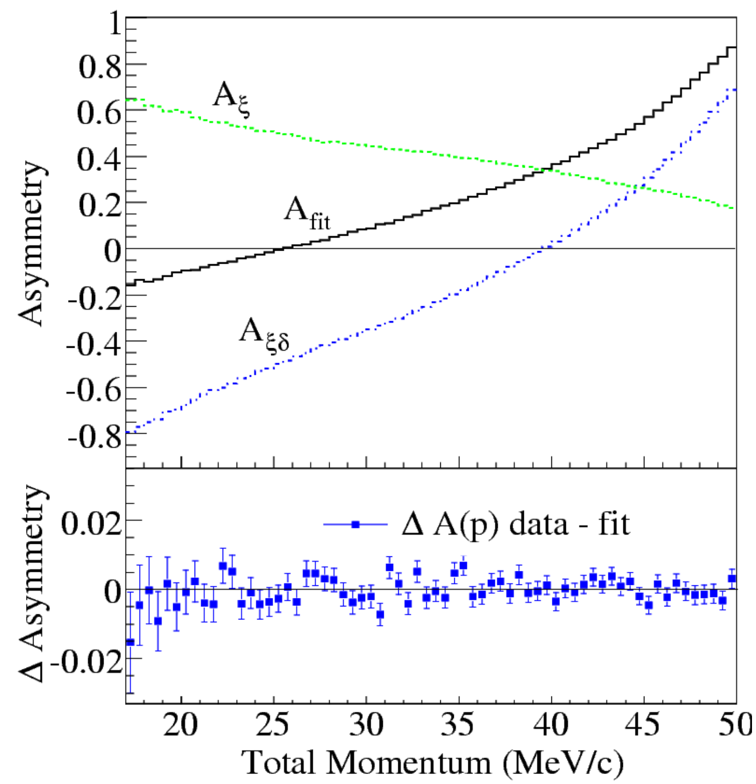
Above: normalized residuals of fit, and fiducial region used for fit: $p < 50$ MeV/c, $0.50 < |\cos\theta| < 0.84$, $|p_z| > 13.7$ MeV/c, $p_T < 38.5$ MeV/c.

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

Fits to data distributions (cont.)



Angular distributions for restricted momentum ranges. Dashed lines show fiducial region of two-dimensional fit.



Dependence of asymmetry on momentum, its two contributions, and comparison of data and fit (MC)distributions.

Summary of results: ρ and δ

- **ρ = 0.75080 $\pm$ 0.00044(stat) $\pm$ 0.00093(syst) $\pm$ 0.00023(η)**
  - 2.5 times better precision than PDG value.
  - Uncertainty scaled for χ^2/dof = 7.5/4 (CL=0.11) for different data sets.
  - J.R. Musser *et al.*, PRL **94** (2005) 101805, hep-ex/0409063.

- **δ = 0.74964 $\pm$ 0.00066(stat) $\pm$ 0.00112(syst)**
  - 2.9 times better precision than PDG value.
  - A. Gaponeko *et al.*, PRD **71** (2005) 071101(R), 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

  $0.9960 < \mathcal{P}_\mu\xi \leq \xi < 1.0040$ (90% c.l.)

  - improves upon $\mathcal{P}_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$.

Systematic uncertainties: ρ and δ

Systematic uncertainties	ρ ($\times 10^4$)		δ ($\times 10^4$)	
	published	current	published	current
Chamber response (ave)	5.1	3.2	5.6	5.2
Stopping target thickness	4.9	-	3.7	-
Positron interactions	4.6	3.8	5.5	2.4
Spectrometer alignment	2.2	0.3	6.1	-
Momentum calibration (ave)	2.0	1.1	2.9	2.2
Theoretical radiative correction	2.0	2.0	1.0	1.0
Muon beam stability (ave)	0.4	0.5	1.0	0.9
Track selection algorithm	1.1	-		
Asymmetric efficiencies			0.4	0.1
Total in quadrature	**9.3**	**5.5**	**11.2**	**6.3**

New data and analysis: thesis of R.P. MacDonald, in preparation.

Summary of results: $\mathcal{P}_\mu\xi$

- **$\mathcal{P}_\mu\xi$ = 1.0003 $\pm$ 0.0006(stat) $\pm$ 0.0038(syst)**
  - 2.2 times better precision than PDG value (Beltrami *et al.*).
  - still not as precise as TWIST indirect result from ρ and δ.
  - B. Jamieson *et al.*, PRD **74** (2006) 072007, hep-ex/0605100.

- Dominated by systematic uncertainty from spectrometer fringe field depolarization:
  - prospects for improvement are excellent.
  - data taken in 2004; new data with improved muon beam from data taken in 2006-07.

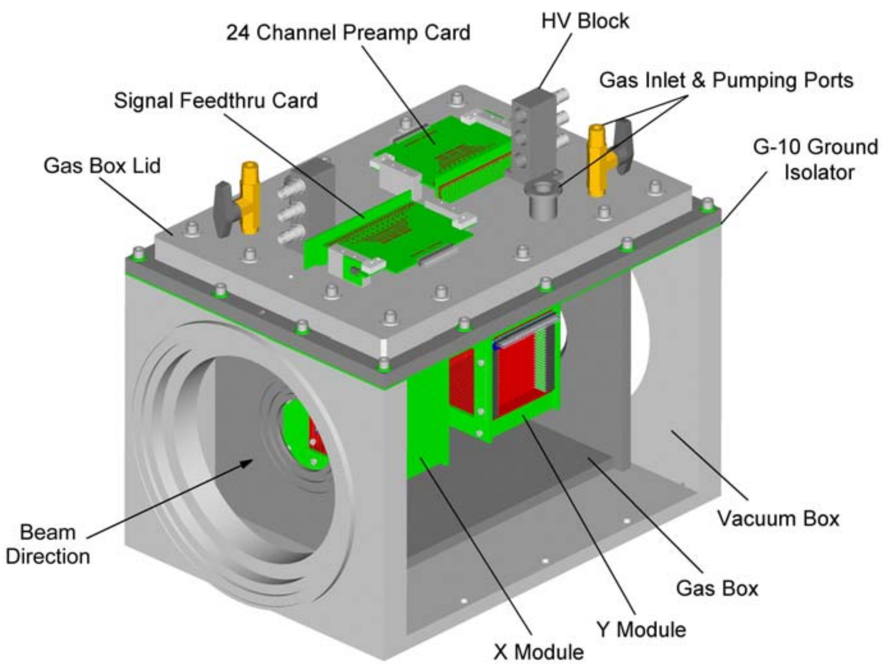
Systematic uncertainties: $\mathcal{P}_\mu\xi$

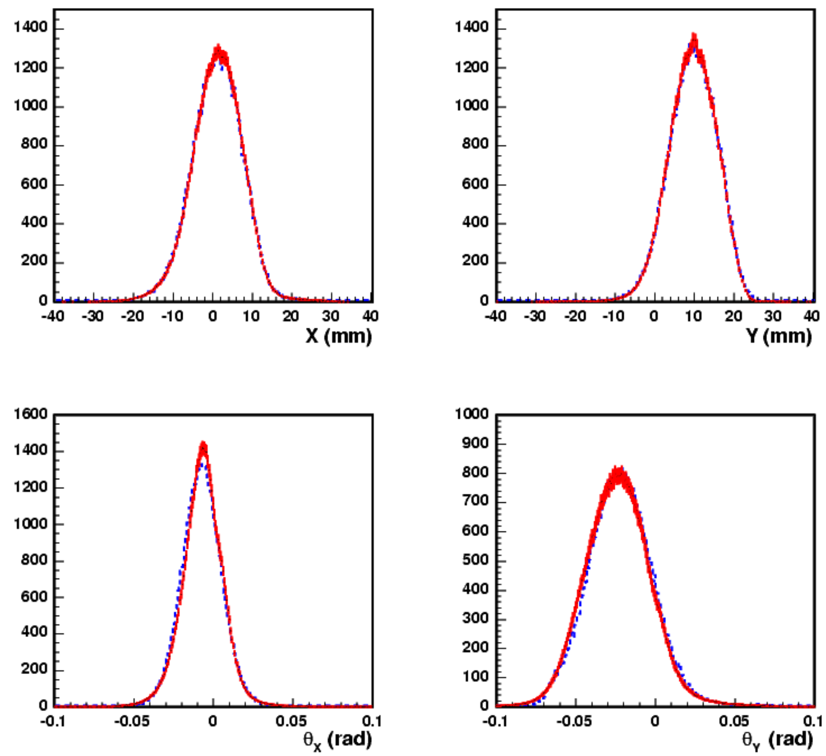
Systematic uncertainties	$\mathcal{P}_\mu\xi$ ($\times 10^3$)
Depolarization in fringe field (ave)	3.4
Depolarization in muon stopping material (ave)	1.2
Chamber response (ave)	1.0
Spectrometer alignment	0.3
Positron interactions (ave)	0.3
Depolarization in muon production target	0.2
Momentum calibration	0.2
Upstream-downstream efficiency	0.2
Background muon contamination (ave)	0.2
Beam intensity (ave)	0.2
Michel η parameter	0.1
Theoretical radiative correction	0.1
Total in quadrature	**3.8**

Improving the systematics

Systematic	Improvement
positron interactions	precision target geometry, improved chamber spacing, simulation tuning
momentum calibration	new techniques with reduced bias
chamber response	online monitoring, improved instrumentation, drift time measurements
fringe field depolarization	beam monitoring (TEC), beam alignment and steering
stopping target depolarization	aluminum and silver targets, depolarization studies with μSR.

Fringe field systematic improvement





The TECs (time expansion chambers) are transverse drift chambers operating at 0.08 bar, separated from beam vacuum by 6 μm Mylar windows. Two modules measure x and y.

Red lines show measurements of beam, dashed blue lines show resulting simulation.

Left-right symmetric models

- Weak eigenstates in terms of mass eigenstates and mixing angle:

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

- Assume possible differences in left and right couplings and CKM character. Use notation: $t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}$, $t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}$, $\zeta_g = \frac{g_R^2}{g_L^2}$
- Then, for muon decay, the Michel parameters are modified:

$$\rho = \frac{3}{4}(1 - 2\zeta_g^2), \qquad \xi = 1 - 2(t^2 + \zeta_g^2),$$

$$\mathcal{P}_\mu = 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g^2 \cos(\alpha + \omega)$$

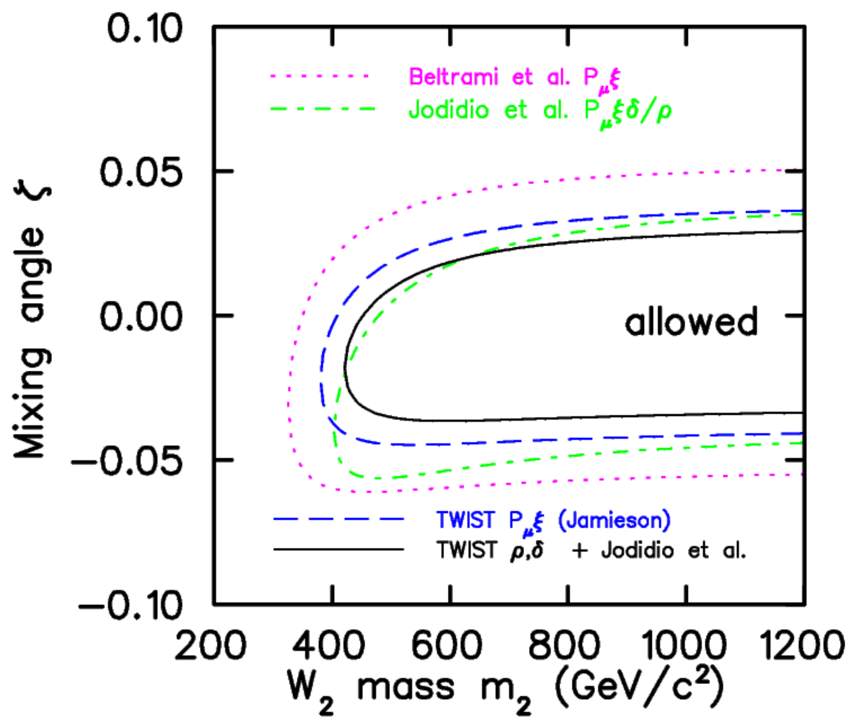
  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\omega = 0$ (no CP violation).
  - "pseudo-manifest" LRS allows CP violation ($\alpha \neq \mathbf{0}$), but $V^R = (V^L)^*$ and $g_R = g_L$.
  - RS "non-manifest" or generalized LRS makes no such assumptions.

- ***Most experiments must make assumptions about LRS models!***

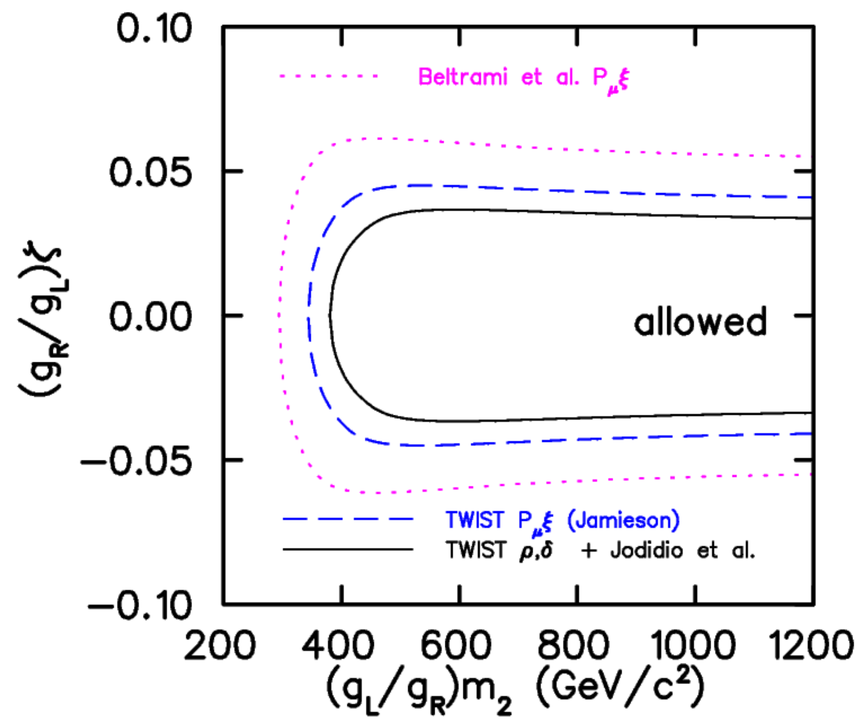
Limits on LRS parameters: PDG06

Observable	m_2 (GeV/c_2)	$\lvert\zeta\rvert$	+	-
m(K_L – K_S)	>1600		reach	(P)MLRS
Direct W_R searches	>800 (D0) >786 (CDF)		clear signal	(P)MLRS decay model
CKM unitarity		<10^{-3}	sensitivity	(P)MLRS heavy ν_R
β decay	>310	<0.040	both parameters	(P)MLRS light ν_R
μ decay (*TWIST*)	>406 (>420)	<0.033 (<0.030)	model independence	light ν_R

Muon decay LRS limits



Restricted ("manifest") LRS model



General LRS model

Exclusion (90% cl) plots for left-right symmetric model mixing angle and right partner boson W_2 mass m_2

Summary

- *TWIST* has produced its first direct measurement of $\mathcal{P}_\mu\xi$, to add to previous results for ρ and δ.

- Analysis underway for second measurements for ρ and δ, representing further improvements by $\sim$ 2.

- Reduction of depolarization systematics for $\mathcal{P}_\mu\xi$ seems achievable, but it is not yet known by how much.

- In 2006-2008, *TWIST* will produce its final results:
  the goal remains the reduction of uncertainty by an order of magnitude compared to previous muon decay parameter experiments.

TWIST Participants

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