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

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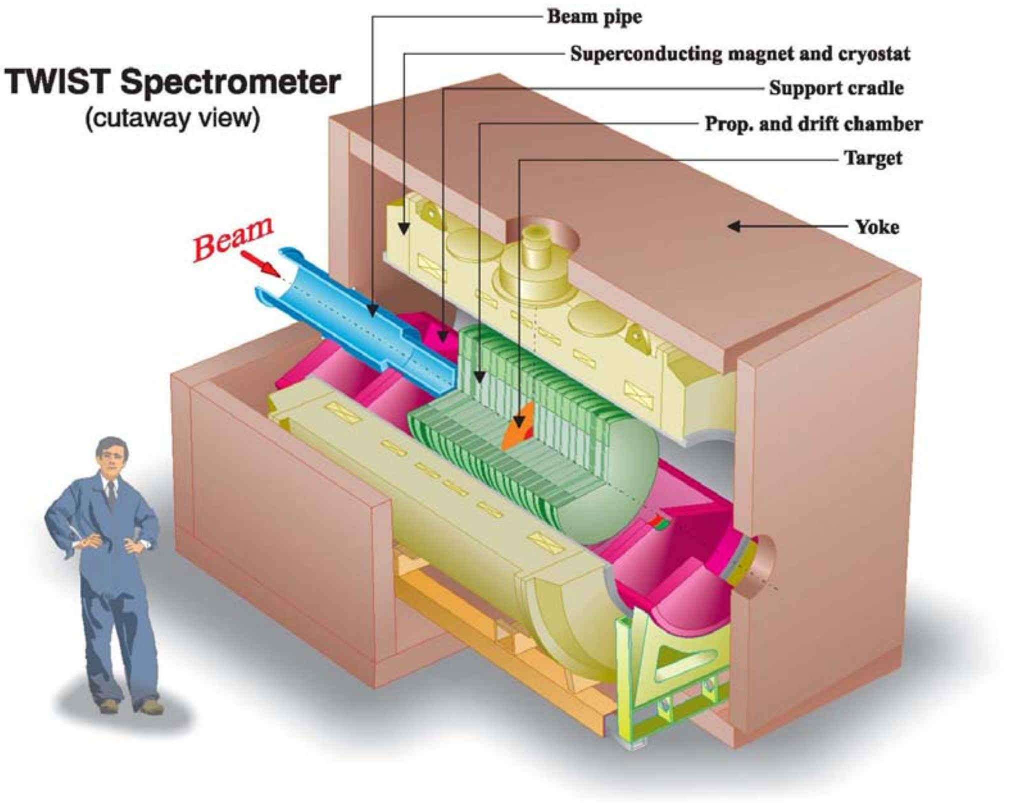
# The $\mathcal{T}$RIUMF $\mathcal{W}$eak $\mathcal{I}$nteraction $\mathcal{S}$ymmetry $\mathcal{T}$est

- Tests Standard Model predictions for muon decay.
- Uses highly polarized $\mu^+$ beam ($\mu^-$ don't work!).
- Stops $\mu^+$ 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

Louis Michel

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

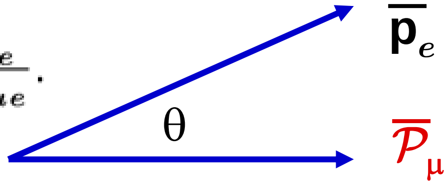
$$\frac{d^2\Gamma}{dx\; d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot \{\mathcal{F}_{IS}(x,\rho,\eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

  - where

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

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

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

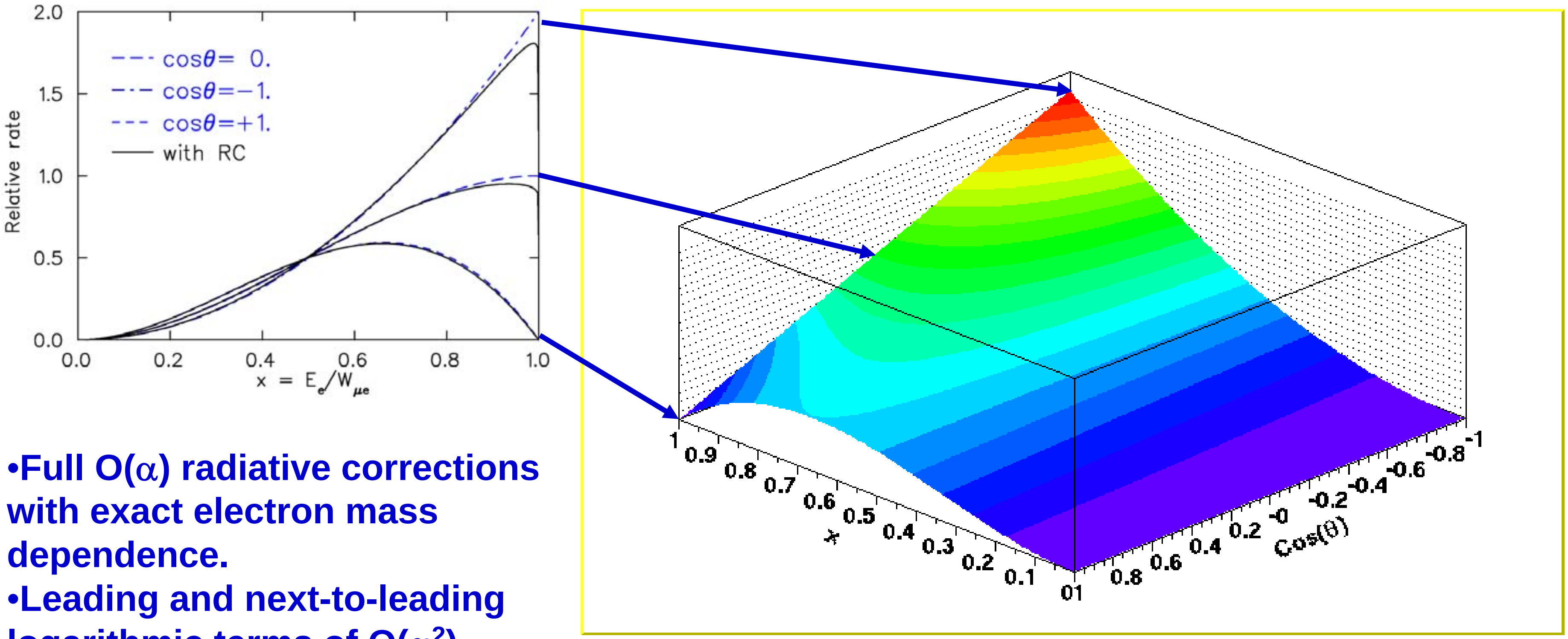


# Pre-*TWIST* decay parameters

- From the Review of Particle Physics (SM values in parentheses) :
  - $\rho$ = 0.7518 $\pm$ 0.0026 (Derenzo, 1969) (0.75)
  - $\eta$ = -0.007 $\pm$ 0.013 (Burkard *et al.*, 1985) (0.00)
  - $\delta$ = 0.7486 $\pm$ 0.0026 $\pm$ 0.0028 (Balke *et al.*, 1988) (0.75)
  - $\mathcal{P}_\mu\xi$ = 1.0027 $\pm$ 0.0079 $\pm$ 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
$\rho$, $\delta$, 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 $O(\alpha^2)$.
- Leading logarithmic terms of $O(\alpha^3)$.
- 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 $O(\alpha^2)$.

# Michel parameters and coupling constants

- Fetscher and Gerber coupling constants (see PDG):

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

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

# 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)
  - no existing similar analysis for other weak decays.

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

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

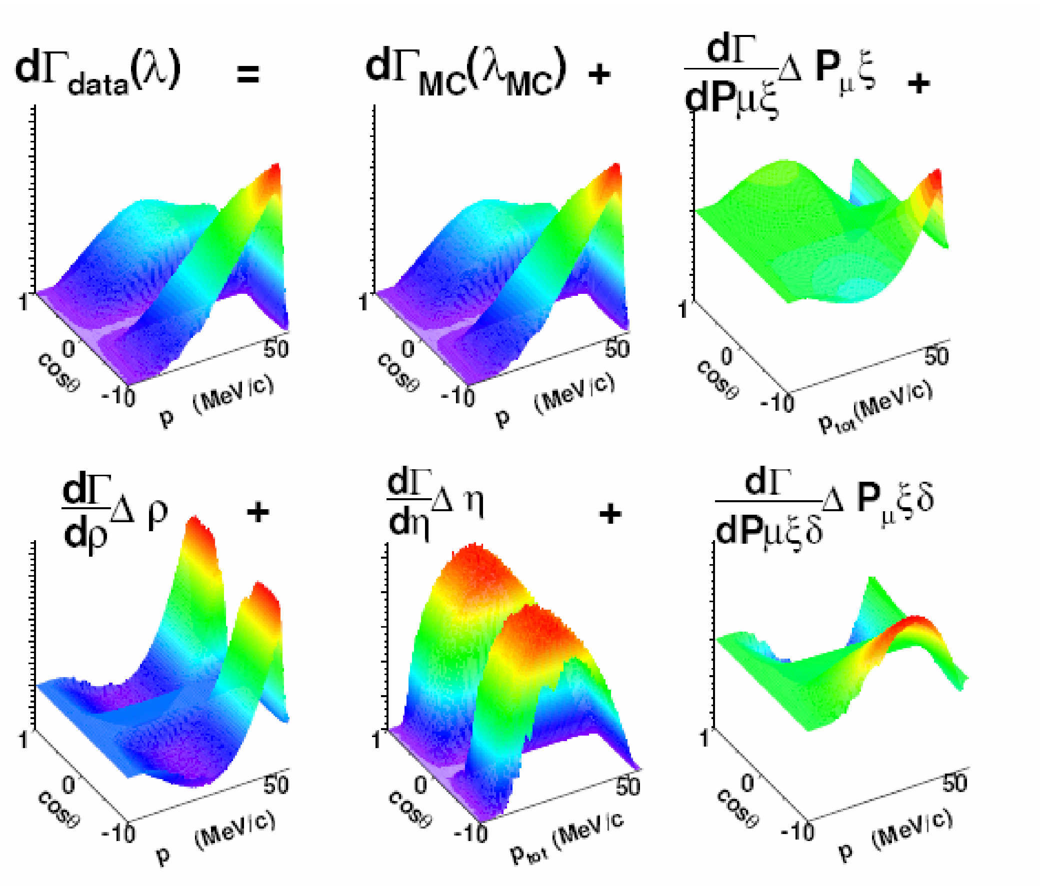
# Fitting the data distributions

- Decay distribution is linear in $\rho$, $\eta$, $\mathcal{P}_\mu\xi$, 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)

# 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**

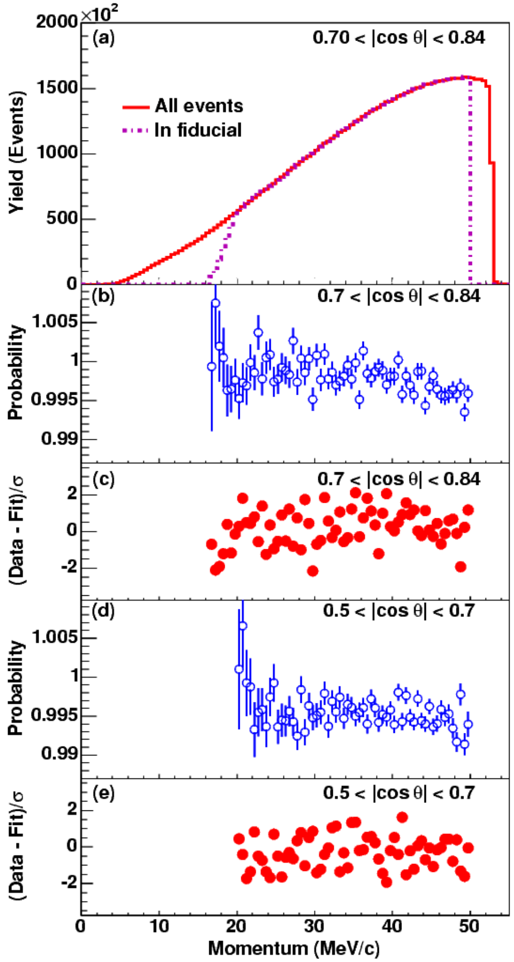
**•Chamber response:**
- **•DC and PC efficiencies**
- **•Dead zone**
- **•Long drift times**
- **•HV variations**
- **•Temperature, pressure**
- **•Chamber foil bulges**
- **•Crosstalk**
- **•Variation of $t_0$**

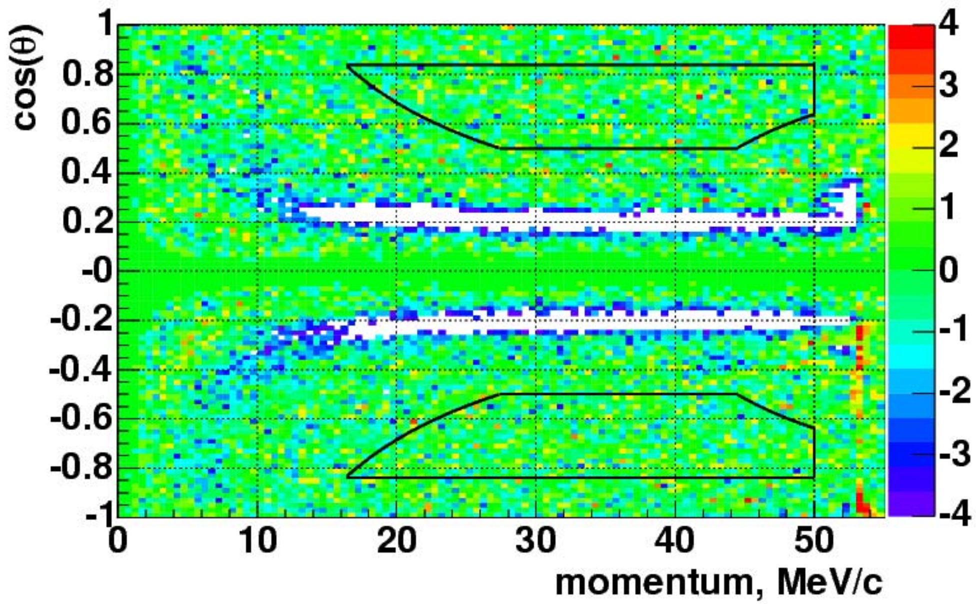
**•Momentum calibration:**
- **•End point fits**
- **•Field reproduction**

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

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

# Fits to data distributions

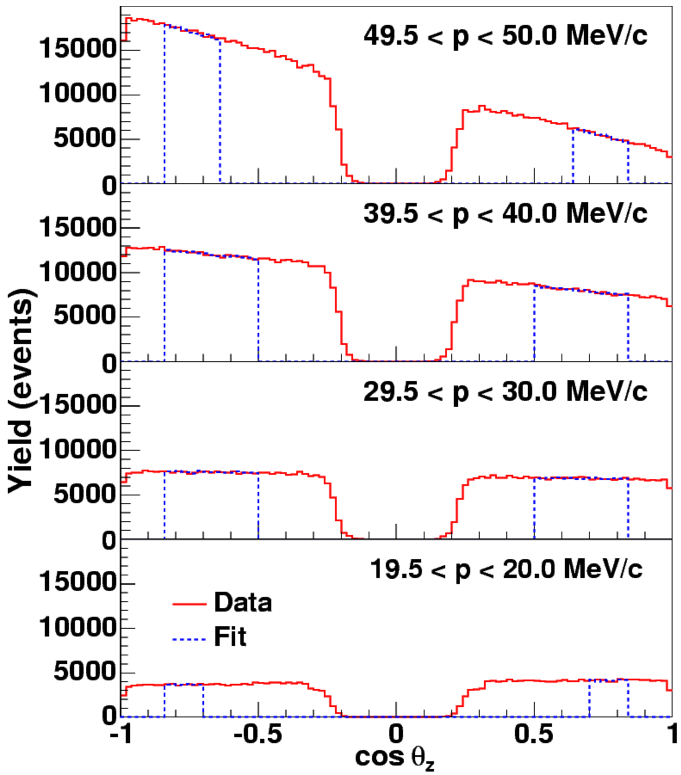


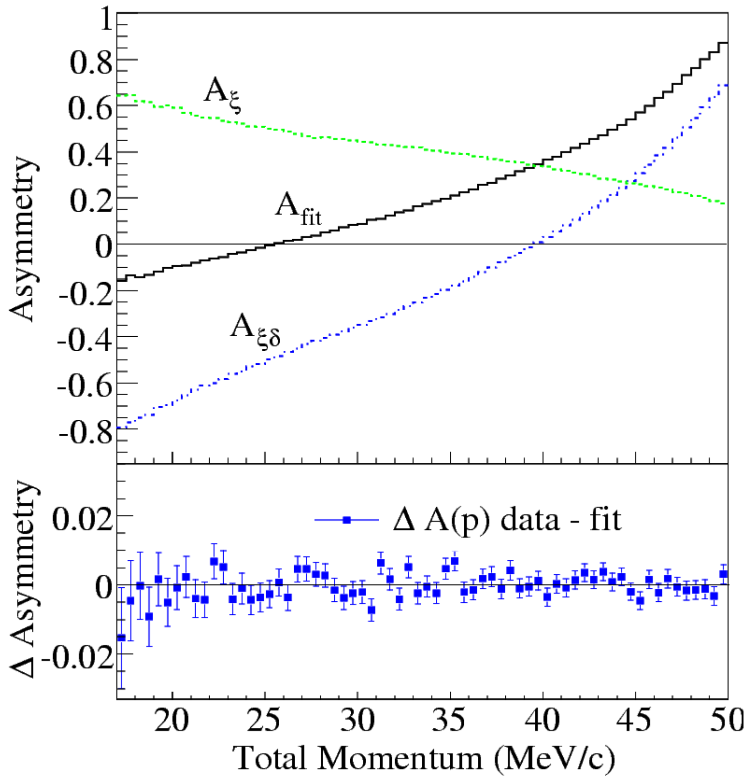

**Above: normalized residuals of fit, and fiducial region used for fit: $p < 50$ MeV/c, $0.50 < |\cos$ □ $| < 0.84$, $|p_z| > 13.7$ MeV/c, $p_T < 38.5$ MeV/c.**

**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: $\rho$ and $\delta$

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

- **$\delta$ = 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 $\rho$ and $\delta$ , 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: $\rho$ and $\delta$

| Systematic uncertainties | $\rho$ ($\leq 10^4$) | | $\delta$ ($\leq 10^4$) | |
|---|---|---|---|---|
| | 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 $\rho$ and $\delta$.
  - 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 was taken in 2004; new data with improved muon beam from data taken in 2006-07.

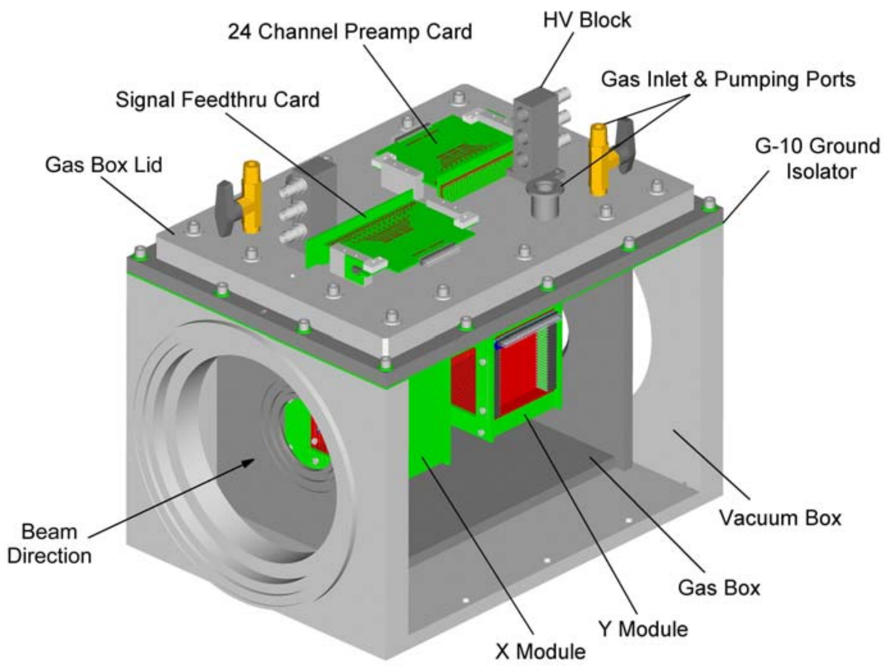
# Systematic uncertainties: $\mathcal{P}_\mu \xi$

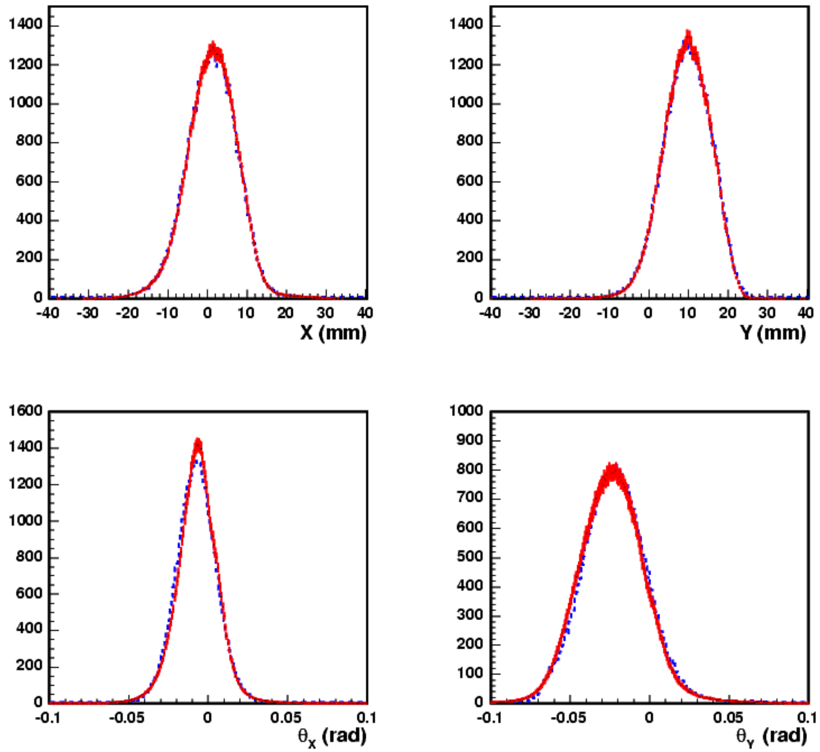
| Systematic uncertainties | $\mathcal{P}_\mu \xi$ ($\times 10^3$) |
|---|---|
| Depolarization in fringe field (ave) | 3.4 |
| Depolarization in muon stopping material (ave) | 1.2 |
| Chamber response (ave) | 1.0 |
| Spectrometer alignment | 0.3 |
| Positron interactions (ave) | 0.3 |
| Depolarization 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 $\eta$ 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 $\mu$SR. |

# 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.**

# 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:

$$t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \qquad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}, \qquad \zeta_g = \frac{g_R^2}{g_L^2}$$

- Then, for muon decay, the Michel parameters are modified:

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

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

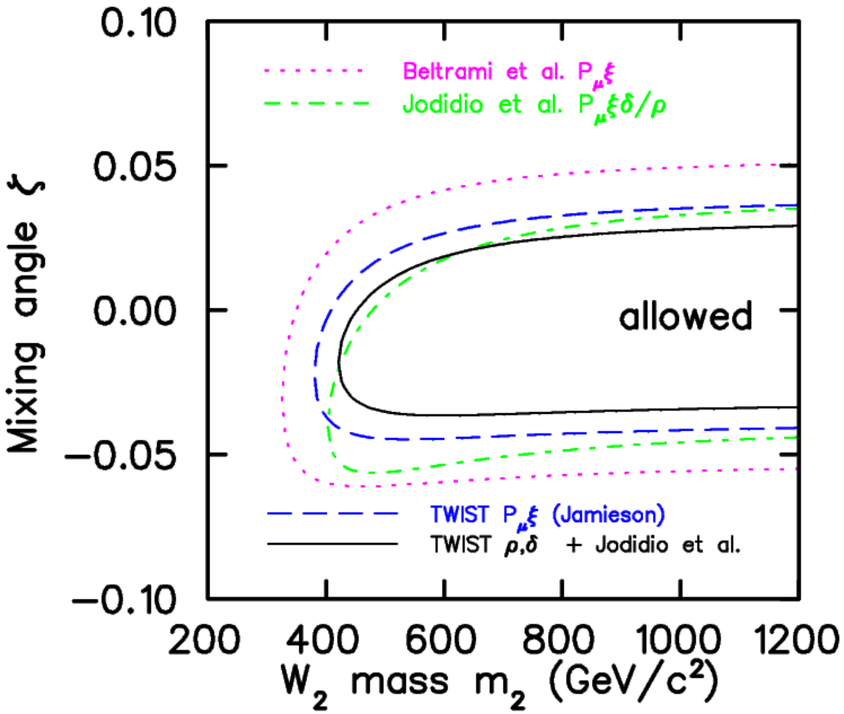
  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\omega = 0$ (no CP violation).
  - "pseudo-manifest" LRS allows CP violation, but $V^R = (V^L)^*$ and $g_R = g_L$.
  - RS "non-manifest" or generalized LRS makes no such assumptions.

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

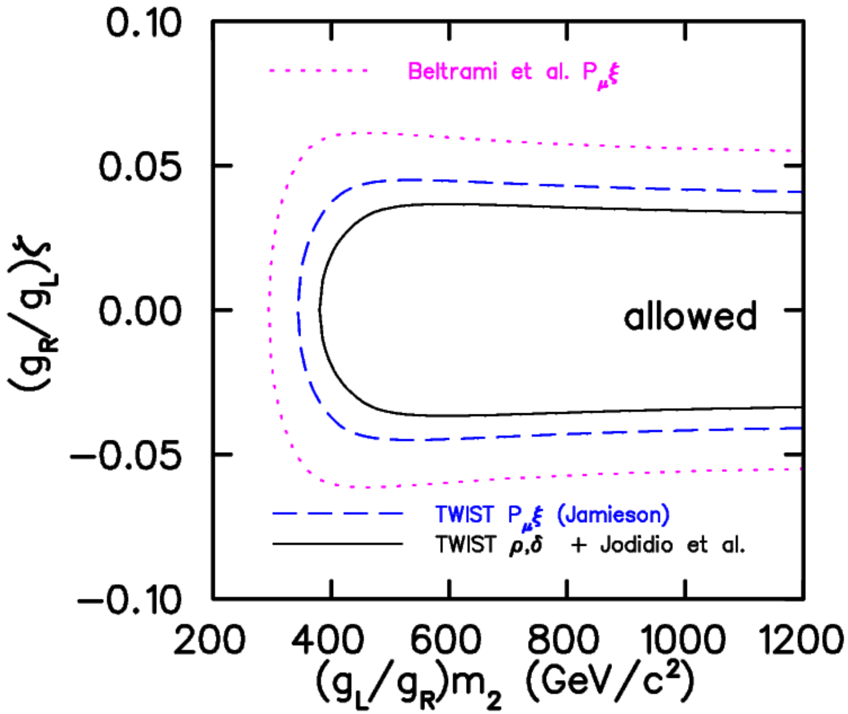
# Limits on LRS parameters: PDG06

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

# 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 $\rho$ and $\delta$.

- Analysis underway for second measurements for $\rho$ and $\delta$, 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:
  - goal remains the reduction of uncertainty by an order of magnitude compared to previous muon decay parameter experiments.

# *TWIST* Participants

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