Direct Measurement of $P_{\mu \xi}$ at TWIST

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What is $P_\mu \xi$?

- $P_\mu$ is the polarization of the muon, and $\xi$ is the asymmetry in angle of decay positrons from normal muon decay.

$$\frac{d^2 \Gamma}{dxd\cos \theta} \propto F_{LS}(x, \rho, \eta) \pm P_\mu \xi \cos \theta F_{AS}(x, \delta)$$

Standard Model: $\xi = 1$, $P_\mu = -1$
Motivation

- $\xi$ and $\delta$ limit the probability of a right-handed muon decaying into any handed positron:

$$Q_R^\mu = \frac{1}{2} \left( 1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right)$$

- $P_\mu \xi$ sets limit on mass and mixing parameter in Left-Right Symmetric Models:

$$1 - P_\mu \xi = 4 \left\{ \zeta^2 + \frac{M_1^4}{M_2^4} + \zeta \frac{M_1^2}{M_2^2} \right\}$$

$$\frac{3}{4} - \rho = \frac{3}{2} \zeta^2$$
Status of $P_{\mu \xi}$ Measurement

- **Direct measurements:**
  - $P_{\mu \xi} = 1.0027 \pm 0.0079 \pm 0.0030$
    
    *Beltrami et al, PL B194 (1987)*
  
  - $P_{\mu \xi} \delta/\rho > 0.99682$ (90% c.l.)
    
    *Jodidio et al, PR D34, PR D37 (1986)*

- **Indirect measurement:**
  - $0.9960 < P_{\mu \xi} < \xi < 1.0040$ (90% c.l.)
    
    *TWIST, PRL 94, 101805 + PRD 71, 071101(R)*
Experimental Setup

Production Target

Fringe Field

Stopping Material
Muon Beam Characterization: Time Expansion Chamber

- 2 modules measure $\mu$ beam positions & divergences in X & Y directions.
- Uncertainty in tracking: $\Delta x = 270.0 \mu m$, $\Delta \theta = 3.0 \text{ mrad}$
- Uncertainty in TEC position: $\Delta x = 2 \text{ mm}$, $\Delta \theta = 5.0 \text{ mrad}$
**Evaluation of Systematic Uncertainties**

**Methodology**

- Take data set or generate Monte Carlo runs under a condition that exaggerates possible sources of systematic error.
- Measure the effect on $(\rho, \eta, \xi, \xi_\delta)$ by fitting two correlated data sets.
- Scale the effect by exaggeration factor.

**Example**

- Drift chamber time zero $(t_0)$ might change during the data taking. What is the uncertainty in $\mathcal{P}_\mu \xi$ due to the $t_0$ variation?
  - analyze a data set with $t_0$ before the data collection ($t_0^{\text{begin}}$).
  - analyze the same data with $t_0^{\text{begin}} + 10x(t_0^{\text{end}} - t_0^{\text{begin}})$ (10x exaggeration).
  - fit to each other: $\Delta \mathcal{P}_\mu \xi = 8.9 \times 10^{-3}$
  - divide the shift by exaggeration factor.
## Summary of Systematic Uncertainties

<table>
<thead>
<tr>
<th>Category</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon Beam &amp; Polarization</td>
<td>3.69</td>
</tr>
<tr>
<td>Fringe field</td>
<td>3.40</td>
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<tr>
<td>Stopping target</td>
<td>1.40</td>
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<tr>
<td>Production target</td>
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<tr>
<td>Chamber Response</td>
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<tr>
<td>$t_0$ variations</td>
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<tr>
<td>Foil bulges</td>
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<tr>
<td>Cell asymmetry</td>
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<tr>
<td>Up-down efficiency</td>
<td>0.19</td>
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<tr>
<td>Density</td>
<td>0.17</td>
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<tr>
<td>Spectrometer Alignment</td>
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<tr>
<td>Rotations</td>
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</tr>
<tr>
<td>Z position</td>
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<tr>
<td>B field to axis</td>
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<tr>
<td>Positron Interactions</td>
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<tr>
<td>Hard interactions</td>
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<tr>
<td>Multiple scattering</td>
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<tr>
<td>Outside material</td>
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<tr>
<td>Momentum Calibration</td>
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<tr>
<td>Endpoint fits</td>
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<tr>
<td>B field uniformity</td>
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<tr>
<td>Radiative Corrections</td>
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</tr>
</tbody>
</table>

### Total Systematic Uncertainty:

$$3.80 \times 10^{-3}$$
Why is the Contribution from Fringe Field Big?

- Beam measurement by the TEC is not precise
  - TEC efficiency is low, which causes a big uncertainty in the angle measurement and a bias in the position measurement.
  - TEC calibration is not prefect.
  - TEC alignment to the drift chamber is not monitored.

- Beam characterization runs are not consistent
  - runs with “same settings” see a large difference in $\theta_y$.

<table>
<thead>
<tr>
<th>Run</th>
<th>B2(G)</th>
<th>$\bar{x}$(cm)</th>
<th>$\bar{y}$(cm)</th>
<th>$\bar{\theta}_x$ (mrad)</th>
<th>$\bar{\theta}_y$ (mrad)</th>
<th>$P^MC_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18820</td>
<td>949</td>
<td>0.85</td>
<td>-1.1</td>
<td>0.87</td>
<td>-5.0</td>
<td>0.9955</td>
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<td>18825</td>
<td>944</td>
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<td>-5.9</td>
<td>0.97</td>
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<td>-6.7</td>
<td>0.73</td>
<td>-11.2</td>
<td>0.9941</td>
</tr>
</tbody>
</table>
Result and Its Implication

\[ P_\mu \xi = 1.0003 \pm 0.0006 \text{ (stat)} \pm 0.0038 \text{ (syst)} \]

- Consistent with the Standard Model prediction of 1. Reduces the uncertainty by about a factor of two on the current PDG value = 1.0027 \pm 0.0079 \pm 0.0030.
- Set new limits on muon handedness:

\[ Q_R^\mu = \frac{1}{2} \left(1 + \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right) \]
Summary and Outlook

- TWIST has completed its first direct measurement of $P_{\mu \xi}$ with 2004 data. The result reduces the uncertainty by a factor of \(~2\) on the PDG value.

- Largest systematic error is due to fringe field depolarization. Main reason is understood now. Improvements to the detector and beam line systems were made in 2005 data.
  - better calibration procedure
  - TEC alignment was carefully monitored and well determined

- Anticipation to improve $P_{\mu \xi}$ measurement by another factor of 2 in the future should be reasonable.

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Extra Slides
Analysis Strategy

- Measure energy and angular distribution of decay positron
  - Reconstruct $e^+$ track with helix fit and take into account multiple scattering and field non-uniformity.
  - Calibrate $e^+$ energy to kinematic end point.

- Simulate detector acceptance with GEANT3
  - GEANT3 geometry contains virtually all detector components.
  - Simulate detector response in detail (match TDC shape).
  - Realistic, measured beam profile and divergence.
  - Muon pileup and beam $e^+$ contamination.

- Extract Michel Parameters with blind analysis technique
  - Monte Carlo data are generated using unknown, hidden values of ($\rho$, $\eta$, $\xi$, $\xi\delta$).
  - Final result kept hidden until the analysis is completed and systematic uncertainties evaluated.
Detector Array

- 56 chambers (44 DC+12 PC planes) symmetrically placed around the target.
- All planes precisely aligned rotationally and translationally.
- Beam stopping position carefully controlled by variable CO$_2$/He gas degrader.
• Full $O(\alpha)$ 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.

Data Distribution

Surface $\mu$ decay spectrum

Acceptance of TWIST spectrometer
Extract the Michel Parameters

- Michel distribution is linear in $\rho$, $\eta$, $\xi$, and $\xi \delta$, so a fit to first order expansion is exact.

- Fit data ($\alpha_{\text{data}}$) to sum of a base MC distribution ($\alpha_{\text{MC}}$) 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.

\[ n_i(\alpha_{\text{data}}) = n_i(\alpha_{\text{MC}}) + \frac{\partial n_i}{\partial \alpha} \Delta \alpha, \]

\[ \alpha = [\rho, \eta, \xi, \xi \delta] \]