Precision Measurement of the Muon Decay Spectrum

Robert MacDonald
for the TWIST Collaboration

- Physics of Muon Decay
- The TWIST Detector
- TWIST Analysis Techniques
- Simulation verification
- Status of TWIST
- Conclusion

The TWIST Collaboration

TRIUMF
Ryan Bayes*†
Yuri Davydov
Jaap Doornbos
Wayne Faszer
Makoto Fujiwara
David Gill
Robert Henderson
Jingliang Hu
John A. Macdonald§
Glen Marshall
Dick Mischke††
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
§ deceased

† also UVic
†† also LANL
‡ also UNBC
‡‡ also Saskatchewan

Professional and technical support:

Daniel Allen, Pierre Amaudruz, Willy Andersson, Curtis Ballard, Michael Barnes, Brian Evans, Marielle Goyette, Peter Gumplinger, Doug Maas, Jan Soukup, Len Wampler, and many undergraduate student research assistants.

Model-Independent Description of Muon Decay

- Matrix element for four-fermion derivative-free interaction can be written as:

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

- In Standard Model:

$$g^{V}_{LL} = 1; \;\; g^{\gamma}_{\epsilon\mu} = 0 \text{ otherwise.}$$

- Right-Handed Coupling of Muon:

$$Q^{\mu}_{R} = \frac{1}{4}|g^{S}_{LR}|^2 + \frac{1}{4}|g^{S}_{RR}|^2 + |g^{V}_{LR}|^2 + |g^{V}_{RR}|^2 + 3|g^{T}_{LR}|^2$$

Muon Decay Distribution

$$\frac{d^2 N}{dx\, d(\cos\theta)} \propto \sqrt{x^2 - x_0^2}\left[F_{IS}(x, \rho, \eta) + P_\mu \cos\theta\, F_{AS}(x, \xi, \delta) \right]$$

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

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

$$x = \frac{E_e}{E_{max}}, \quad x_0 = m_e / E_{max}, \quad E_{max} = \frac{m_\mu^2 + m_e^2}{2 m_\mu}$$

Values of Decay Parameters

$$\rho = \frac{3}{4} - \frac{3}{4}|g^{V}_{LR}|^2 - \frac{3}{4}|g^{V}_{RL}|^2 - \frac{3}{2}|g^{T}_{LR}|^2|g^{T}_{RL}|^2 - \frac{3}{4}\Re\left[g^{S}_{LR}g^{T*}_{LR} + g^{S}_{RL}g^{T}_{RL}\right]$$

Parameter	Standard Model	World Average	(Year)
ρ	0.75	0.7518 ± 0.0026	(1969)
η	0	-0.007 ± 0.013	(1985)
ξ	1	1.0027 ± 0.0079 ± 0.0030	(1987)
δ	0.75	0.7486 ± 0.0026 ± 0.0028	(1988)

Extensions to the Standard Model

Example: Left-Right Symmetric Models

$$W_L = W_1 \cos\zeta - W_2 \sin\zeta$$

$$W_R = e^{i\epsilon}\left(W_1 \sin\zeta + W_2 \cos\zeta\right)$$

$$\left(W_{SM} \approx W_L\right)$$

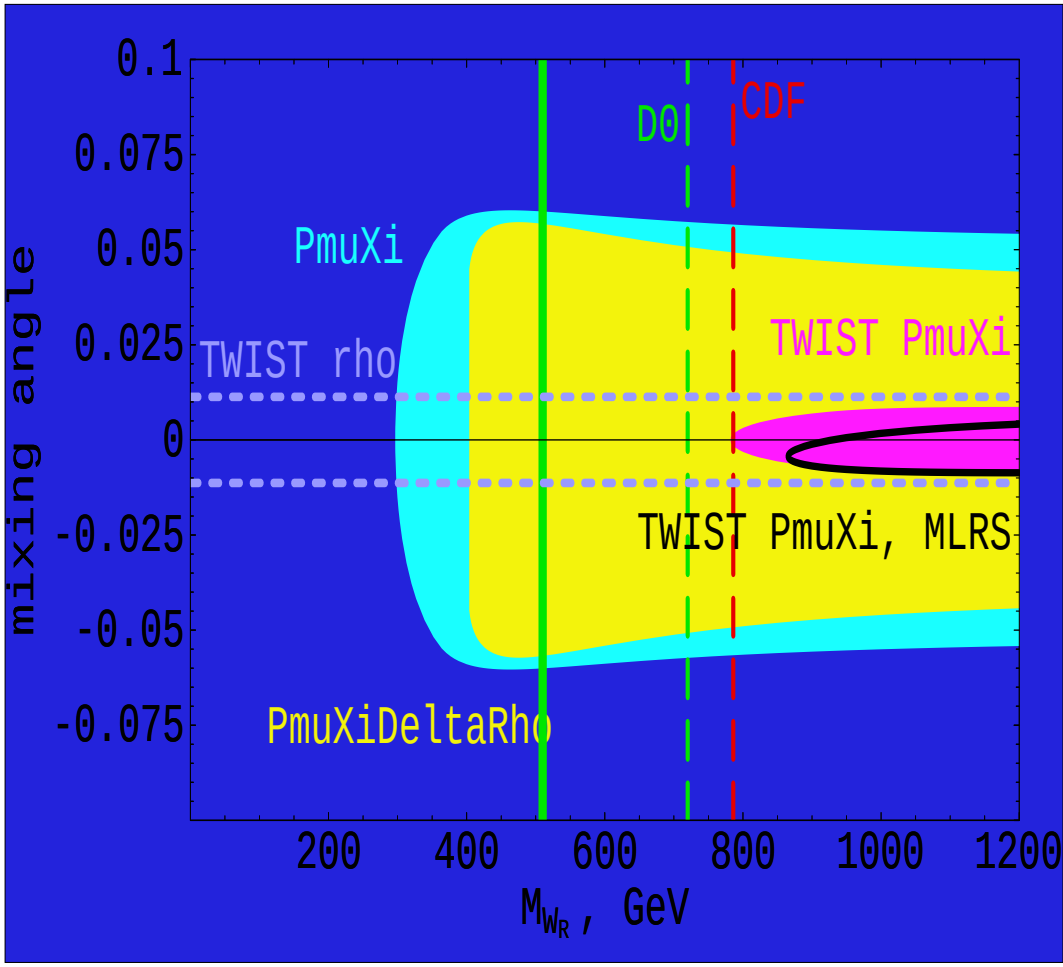
$$\epsilon = \frac{M_1^2}{M_2^2} < 1$$

$$\zeta = \sqrt{\frac{1}{2} - \frac{2}{3}\rho} \qquad \epsilon = \sqrt{\frac{2}{3}\rho - \frac{1}{2}\xi}$$

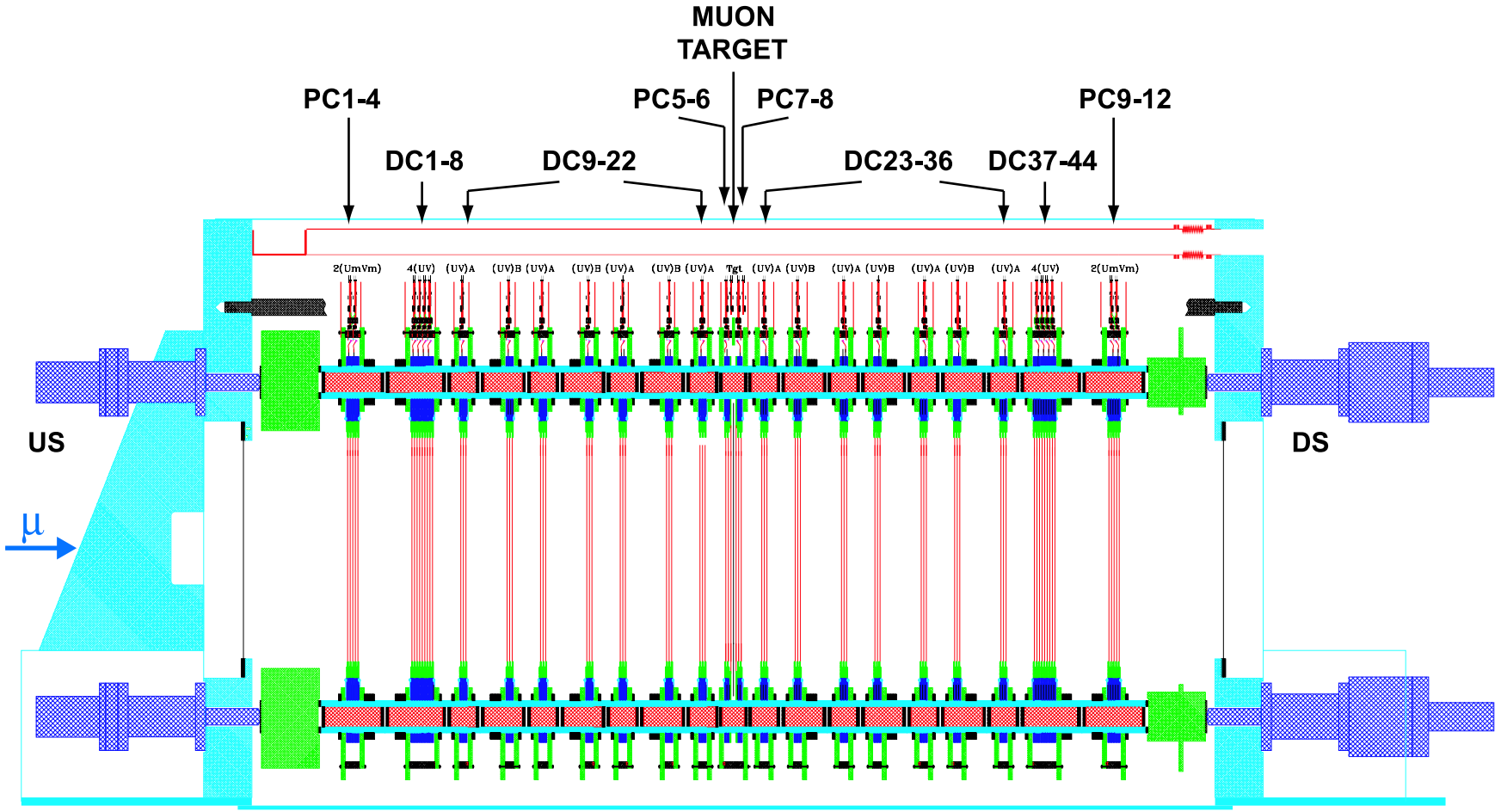
Goals of TWIST

- Search for new physics through measurement of ρ, δ, and $P_\mu \xi$ at parts in 10000.
- e.g. Right-Handed Muon Coupling:

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

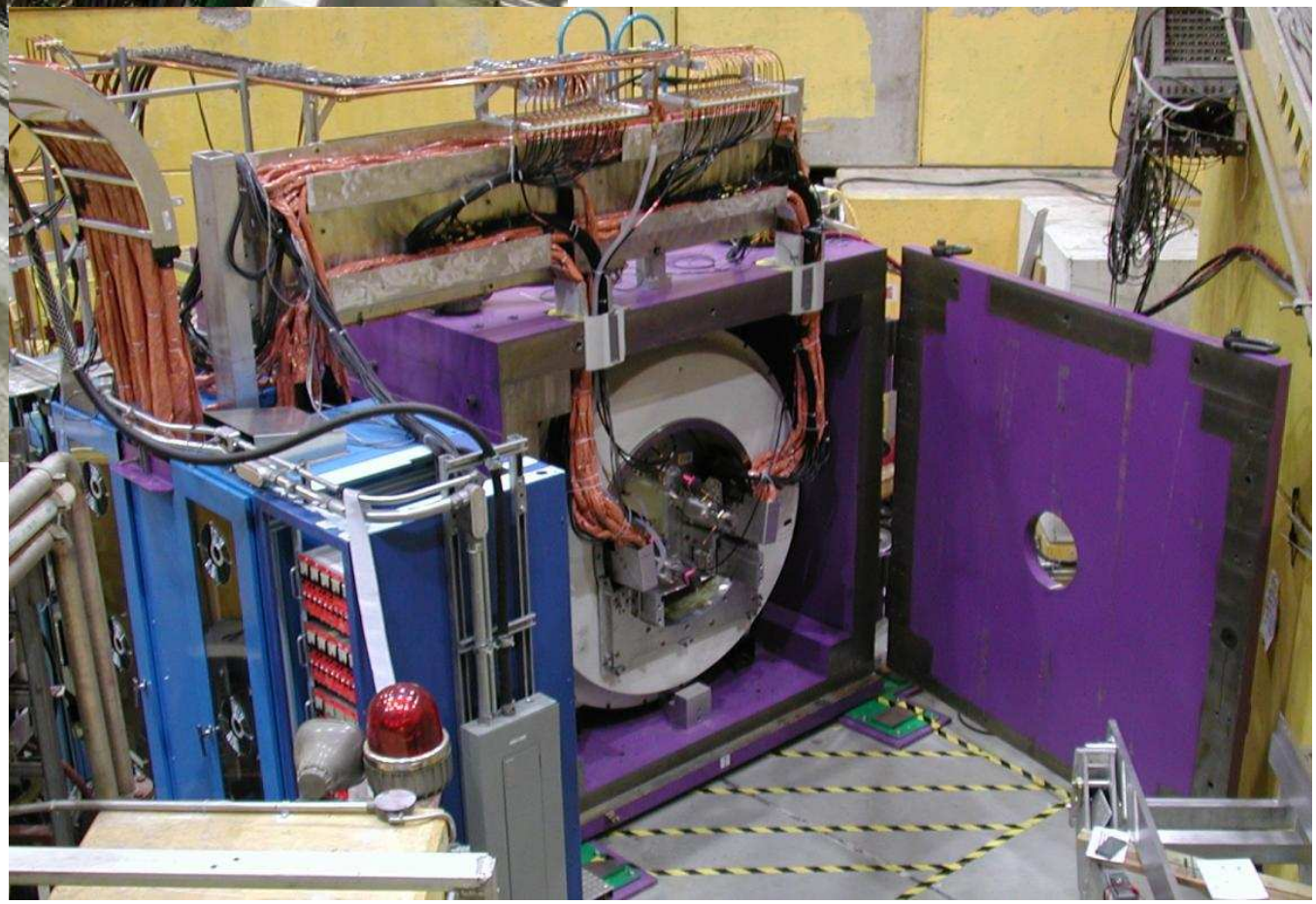


The TWIST Detector



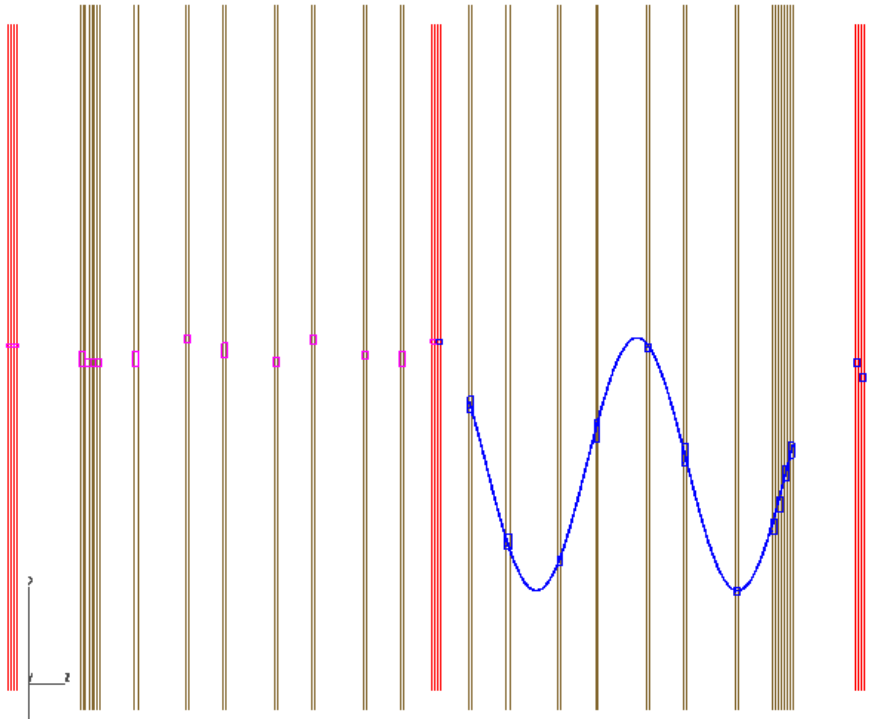
- ~5000 wires positioned with ~3 micron accuracy.
- Longitudinal and transverse distances known to <5 parts in 10^5.

The TWIST Detector

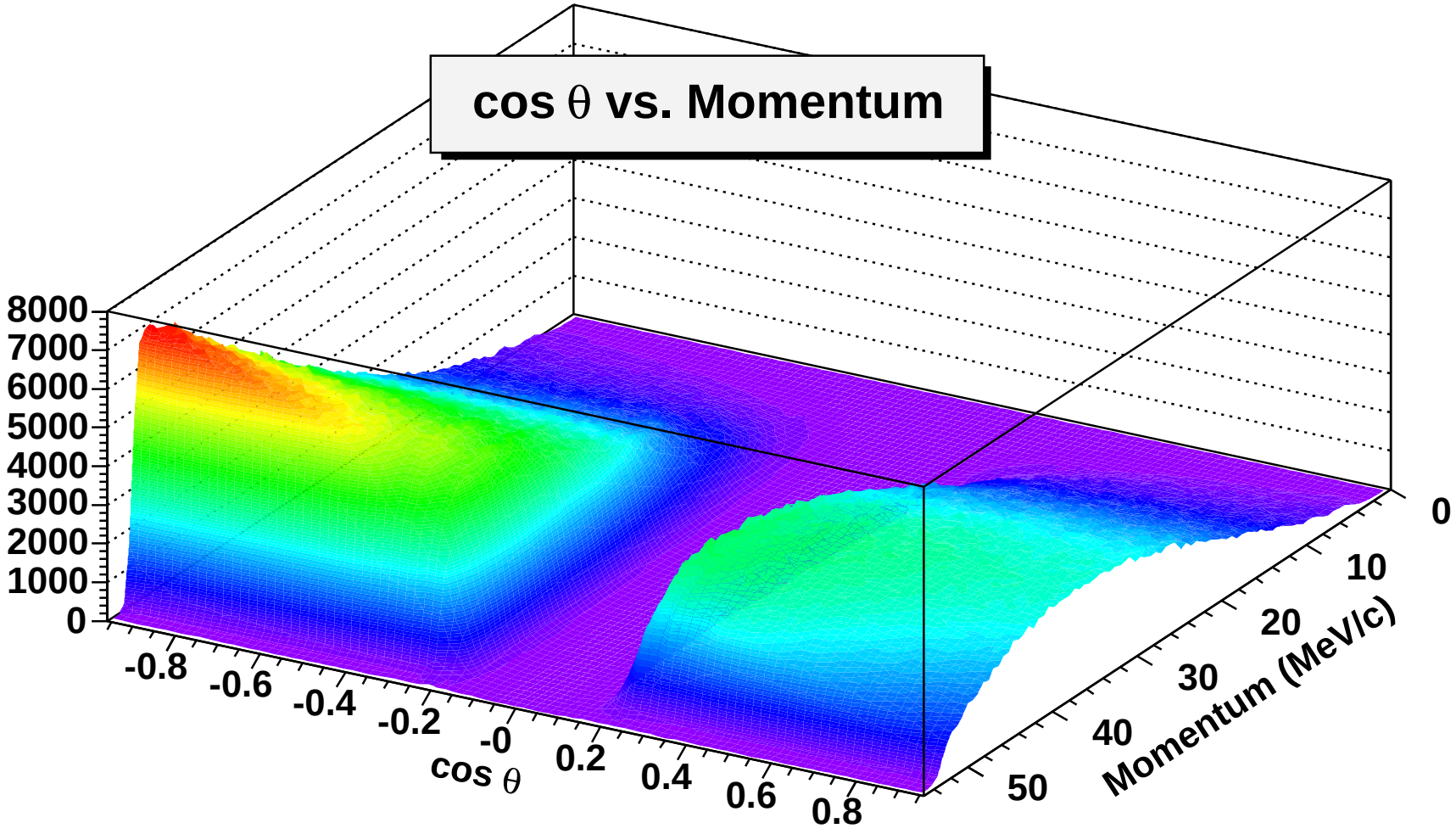


TWIST Features

- Reconstruct trajectories of decay positrons to measure energy and angle.
- Few kHz event rate means systematics limits TWIST.
- Measure large region of spectrum simultaneously.



Muon Decay Spectrum



TWIST Analysis

- Data will be fit to Monte Carlo generated spectra.

$$\left[\frac{d^2N}{dx\,d(\cos\theta)}\right]_{Data} = N_0\left[\frac{d^2N}{dx\,d(\cos\theta)}\right]_{(\rho_0,\eta_0,\delta_0,\xi_0)} + N_0\sum_{\alpha\in\{\rho,\eta,\delta,\xi\}}\left(\frac{\partial}{\partial\alpha}\left[\frac{d^2N}{dx\,d(\cos\theta)}\right]_{(\rho_0,\eta_0,\delta_0,\xi_0)}\Delta\alpha\right)$$

- Accounts for detector response function.
- Facilitates blind analysis: hide parameters used to generate Monte Carlo spectra.

Evaluating Systematic Errors

- Methodology: Exaggerate possible sources of error and measure the effect on the fit of the decay parameters.
  - Full or nearly full data set for each test.
  - Fit one test set to another.
- "Systematics" data sets include:
  - Different chamber gas density: muon stopping position
  - Different magnetic field: energy calibration
  - Additional downstream material: effect of scintillator package
  - ...and many more...

Verifying TWIST Simulation

- Need to know that errors in our simulation are not introducing biases in reconstruction of decay parameters.
- Must verify accuracy of simulation by comparison to data in ways independent of decay parameters.
- Method:
  - Produce real and simulated data under modified conditions.
  - Analyze both with identical software.
  - Check that results show the same change from both data and simulation.

Verification Studies

- Studies include:
  - Material outside the detector
  - p_{max} vs angle
  - chi^2 and confidence level distributions
  - hits per plane
  - energy loss
  - multiple scattering
  - ...and more...

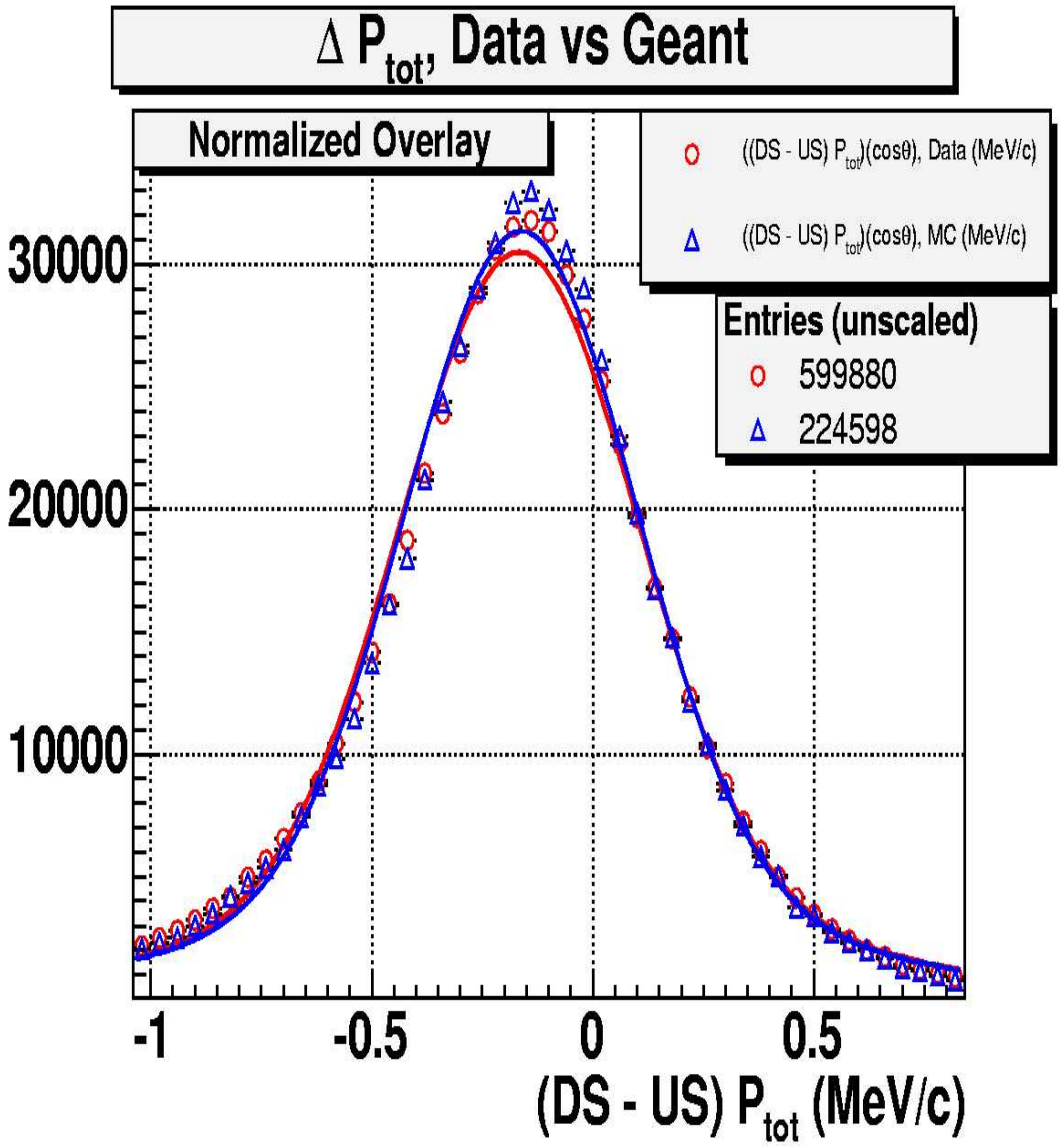
TWIST Experiment Status

- Data in hand for first ρ and δ measurements.
- Each data set has about 6 x 10^8 events within the fiducial volume.
  - Statistical precision better than a part in 1000.
- Sets include multiple "standard" sets to test reproducibility, and many "systematics" sets under various exaggerated conditions.

Conclusion

- TWIST is the first experiment ever to measure the full energy-angle spectrum of muon decay simultaneously.
- Ultimate goal: improve our knowledge of ρ, δ, and $P\mu\xi$ by over an order or magnitude.
  - High-precision search for new physics.
- Data in hand for ρ and δ at parts in 10^3.
- We hope to complete analysis of existing data by mid 2004.

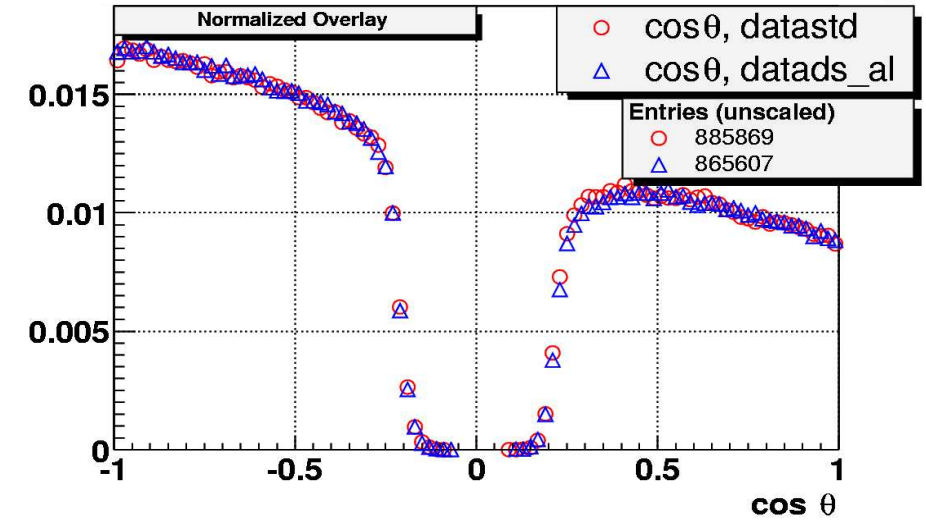
Energy Loss

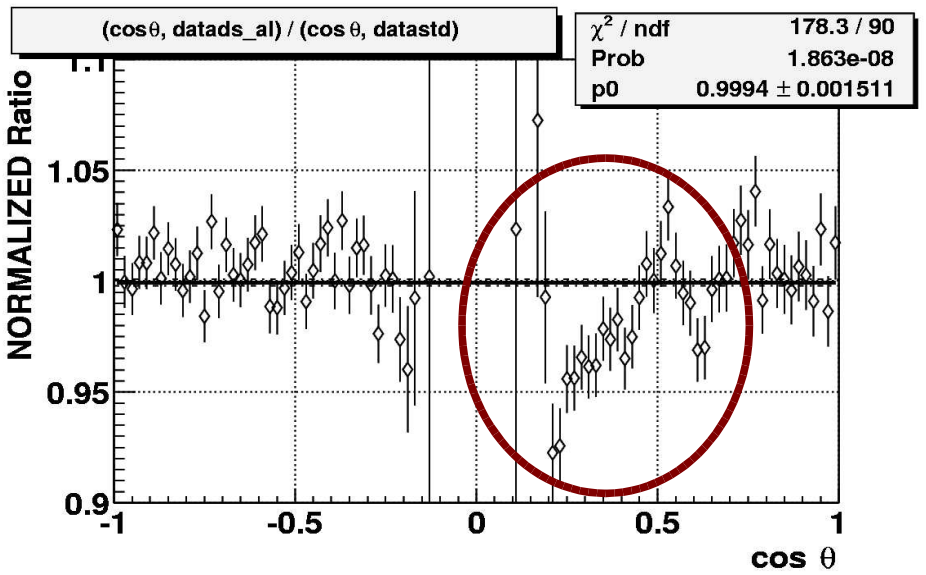


- Mean:
  Geant: -161.9±0.7 keV
  Data: -161.4±0.5 keV
  Diff: 0.5±0.9 keV
- Weighted Width:
  Geant: 306±2 keV
  Data: 314±2 keV
  Diff: 8±3 keV

Effect of Downstream Aluminum

Data





Geant