High Precision Measurements of Muon Decay at TWIST

PANIC, October 25, 2005

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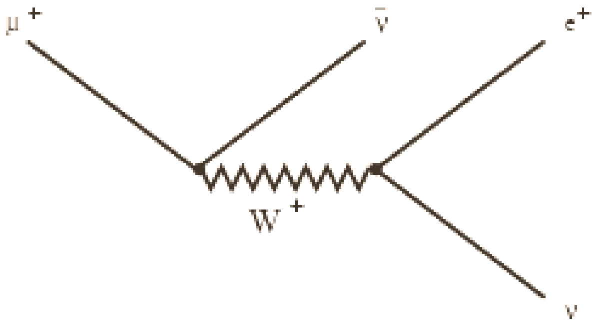
Why Is Muon Decay Interesting?



- A purely leptonic process, which can be calculated unambiguously with high accuracy (hadronic contribution $\leq 10^{-6}$).
- Experimentally, muons are easy to be produced in a large quantities by an accelerator, and high statistics is affordable.

Muon decay provides an ideal place to study the space-time structure of the weak interactions.

Muon Decay Parameters

- can be described by Michel parameters ρ, η, $P_\mu\xi$, δ.

$$\frac{d^2\Gamma}{dx\,d\cos\theta} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2}\{\mathcal{F}_{\mathcal{IS}}(x,\rho,\eta) \pm \mathcal{P}_\mu \cos\theta\, \mathcal{F}_{\mathcal{AS}}(x,\xi,\delta)\} + R.C.$$

where

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

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

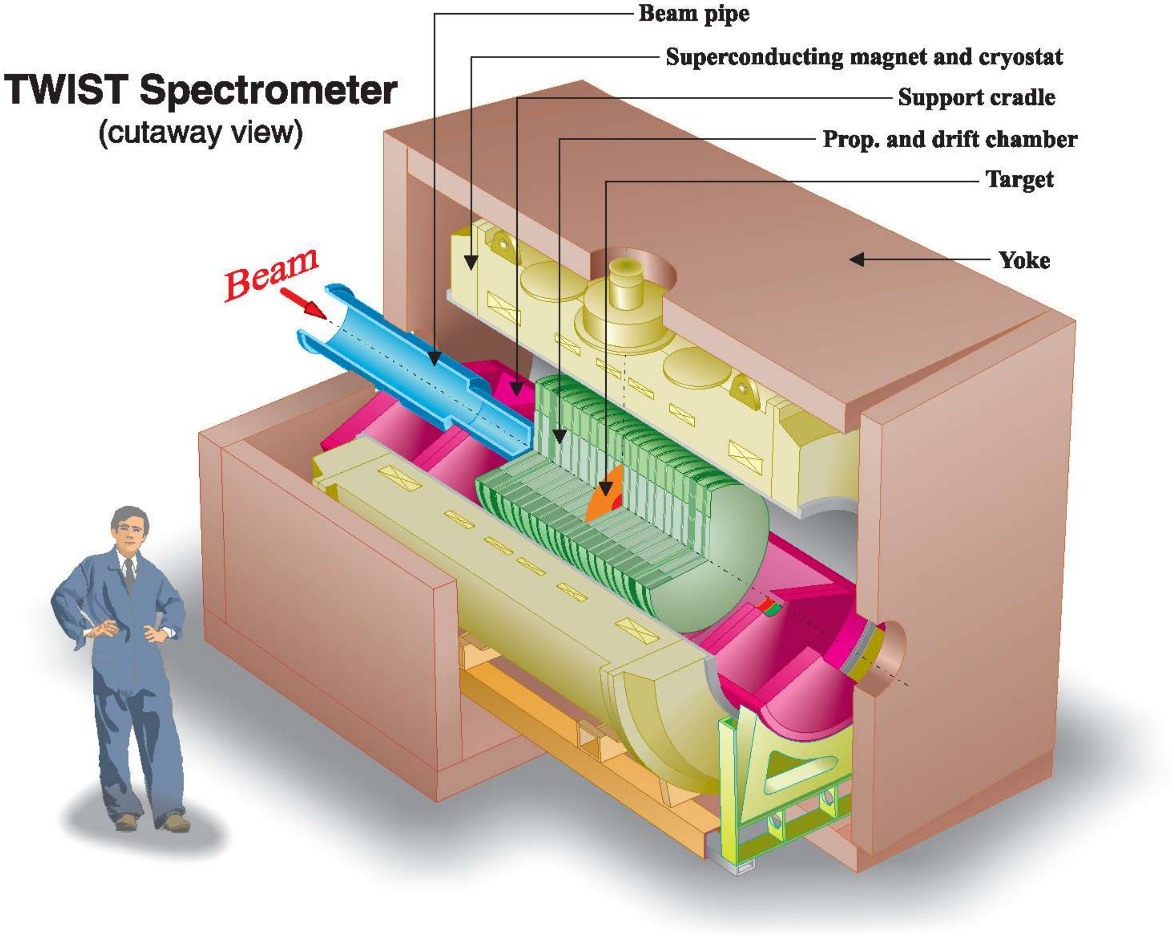
and

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

Theoretical prediction: $\rho = 3/4,\ \delta = 3/4,\ \xi = 1,\ \eta = 0$

The TWIST Detector

- Detector is very symmetric
- A thin upstream scintillator provides trigger.
- Highly polarized μ^+ beam stops at the center.
- Decay e^+ are tracked by Drift Chamber through a highly uniform 2T field.



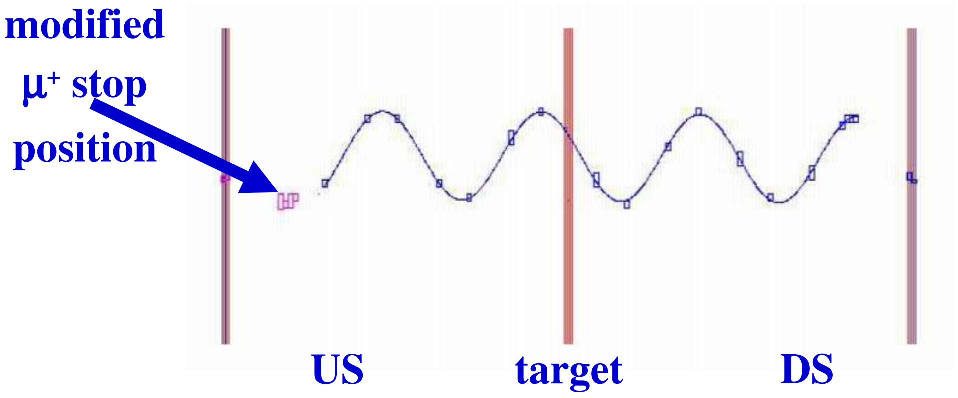
Analysis Strategy

- Measure energy and angular distribution of decay positron
  - Reconstruct e^+ track with helix fit and take into account TOF, Multiple scattering, energy loss 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.
  - include muon pileup and beam e^+ contamination.
- Extract Michel Parameter with blind analysis technique
  - Monte Carlo data is generated using unknown, hidden values of (ρ, η, ξ, $\xi\delta$).
  - Final result kept hidden until the analysis is completed and systematic uncertainties evaluated.

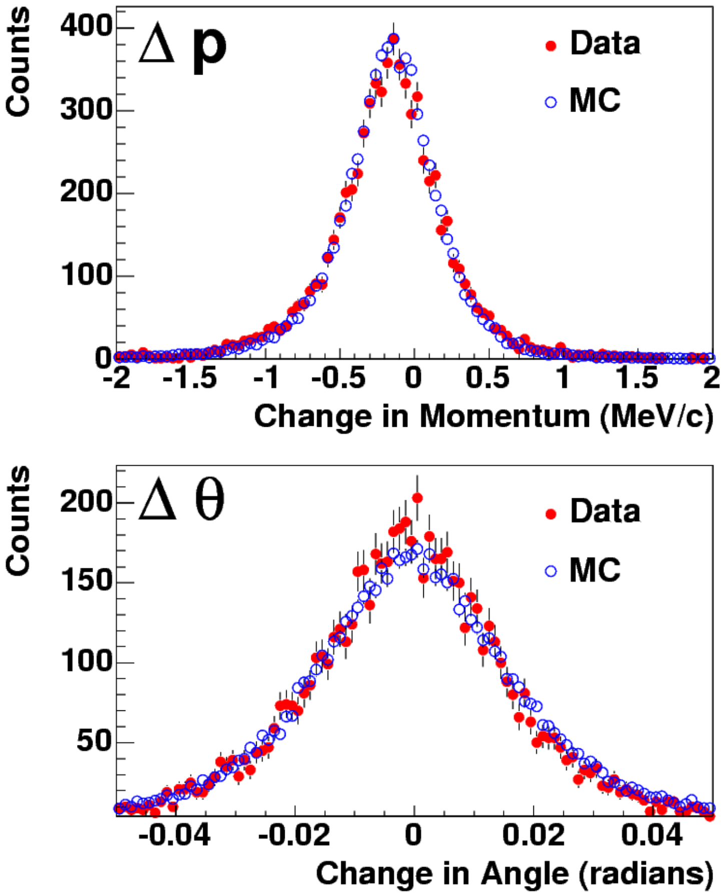
Verification of Monte Carlo Simulation

Upstream decay data were taken to validate GEANT3 simulation of e^+ energy loss and multiple scattering.

- Stop muons at one end of detector.
- Measure e^+ track on each side of target
- Compare differences in momentum and angle, with data and Monte Carlo.



Downstream minus Upstream



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 (ρ, η, ξ, $\xi\delta$) by fitting two correlated data sets.
- Scale the effect by exaggeration factor.

Example

- DC cathode foil position was maintained to accuracy of 250 μm. What is the uncertainty in Michel parameters due to the foil bulge?
  - generate MC with the foil displaced by 500 μm (2x exaggeration).
  - fit to nominal data set: $\Delta\rho = -1.4\times10^{-3}$, $\Delta\delta = -1.3\times10^{-3}$
  - divide by exaggeration factor.

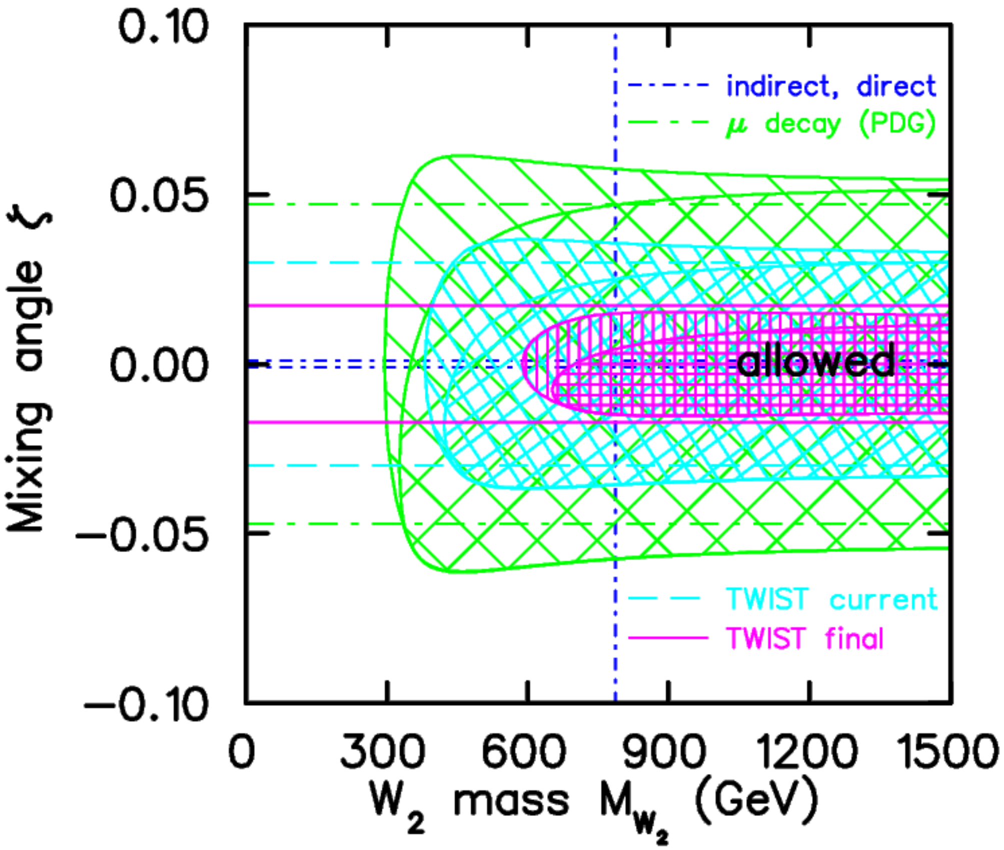
Results for ρ and δ

- $\rho = 0.75080 \pm 0.00032$ (stat) ± 0.00097 (syst) ± 0.00023 (η)
  - 2.5x better precision than the PDG value.
  - Phys. Rev. Lett. 94, 101805 (2005), hep-ex/0409063.
- $\delta = 0.74964 \pm 0.00066$ (stat) ± 0.00112 (syst)
  - 2.9x better precision than the PDG value
  - Phys. Rev. D 71, 071101(R) (2005), hep-ex/0410045.
- Indirect measurement of ξ
  - **ρ, δ** (TWIST) and $P_\mu(\xi\delta/\rho) > 0.99682$ (PDG)
  - $Q^m{}_R \geq 0$

3.0x better precision than previous value:

$$0.9960 < P_\mu\xi \leq \xi < 1.0040$$

Impact on L-R Symmetric Model



- Muon decay offers a clean system to set limits on the L-R symmetric model mixing angle and right-coupling partner boson W_2 mass.
- The plot compares current and proposed TWIST limits with previous limits from muon decay and direct particle searches.

$$\frac{3}{4}-\rho=\frac{3}{2}\zeta^2, \qquad 1-\mathcal{P}_\mu\xi=4\{\zeta^2+\frac{M_1^4}{M_2^4}+\zeta\frac{M_1^2}{M_2^2}\}$$

Current Status for TWIST

- 04 data were taken with improved apparatus and procedures
  - high-purity aluminum target (reduced muon depolarization, reduced target thickness uncertainty).
  - better control of muon beam with TEC (improved MC input, reduced beam uncertainty).
  - better online diagnostics of detectors and beam.

- Analysis of new data is in progress
  - first direct measurement of $P_\mu\xi$ is completed with 04 data.

    See Dr. Blair Jamieson's poster (Tuesday, Oct. 25, 4:00-6:30pm, Anasazi Ballroom, Eldorado Hotel)

    Precision Measurement of the Muon Decay Parameter $P_\mu\xi$
  - expect to finish 2x better precision measurement for ρ and δ from 04-05 data in Spring of 2006.

Improvement for ρ and δ Measurements

- Better data quality
  - more consistent between runs because of the muon beam stopping position regulator and DC foil bulge monitoring.
- Improved tracking procedure
  - energy loss taken into account.
  - better understanding of the chamber response.
- Refined Monte Carlo simulation
  - realistic beam input measured by a Time Expansion Chamber (TEC).
  - improved chamber drift cell geometry.
- Reduced uncertainty due to e+ hard interaction
  - better understanding of how well the e+ hard interaction in simulation.

Summary

- TWIST has produced its first physics results, improving substantially the measurement of muon decay parameters ρ and δ.
- Strategies and procedures have been tested and validated for the higher precision measurements.
- At least a factor of 5 improvement has been achieved in the first direct measurement of $P_\mu\xi$.
- Analysis of ρ and δ is underway. 2x better precision is expected
- In 2006-2007, TWIST will produce its final results, an overall reduction of uncertainty by at least an order of magnitude.

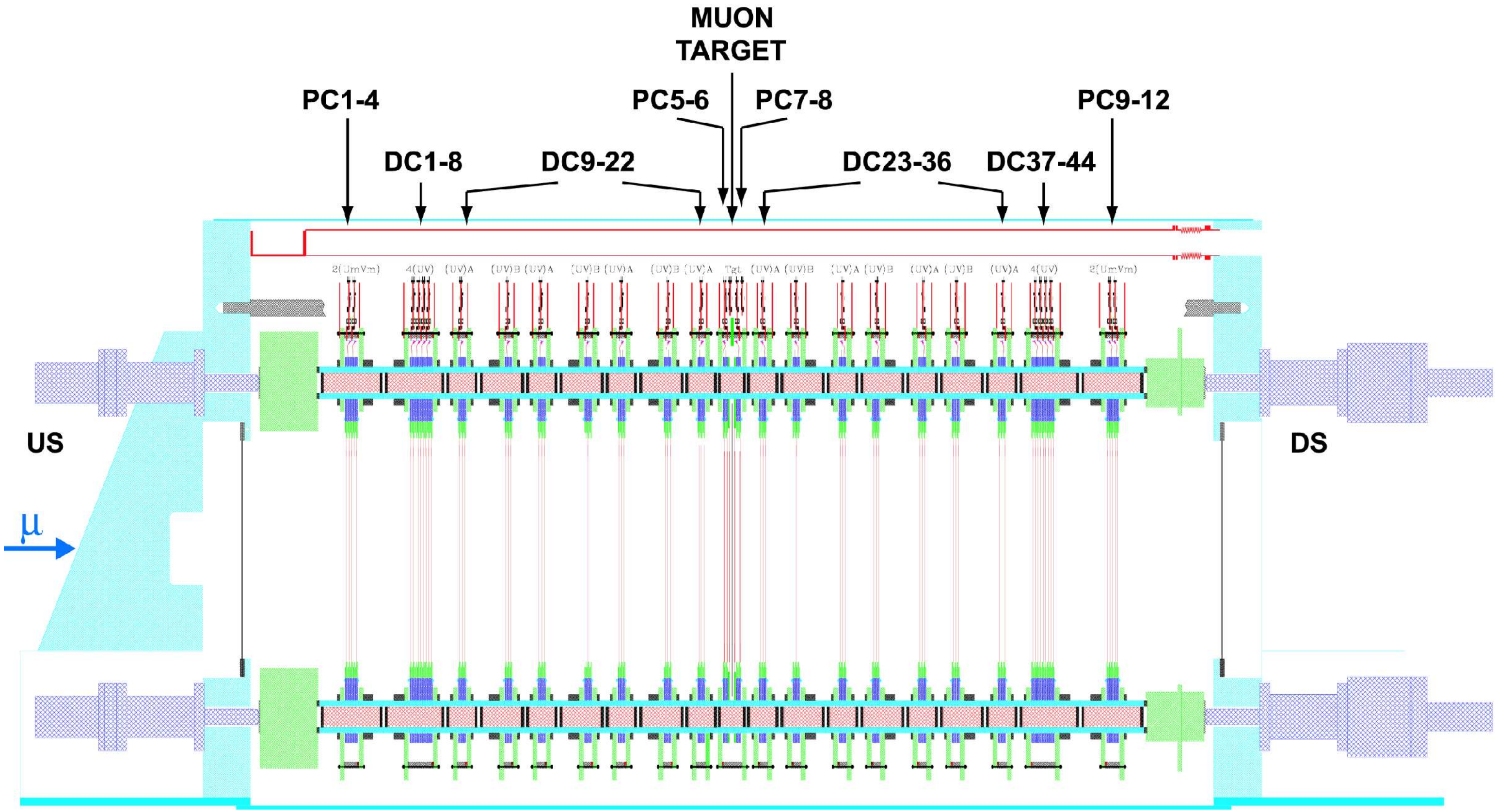
Thanks to NSERC, Western Canada Research Grid(Westgrid) and DOE.

Extra Slides

Pre-TWIST Michel Parameters

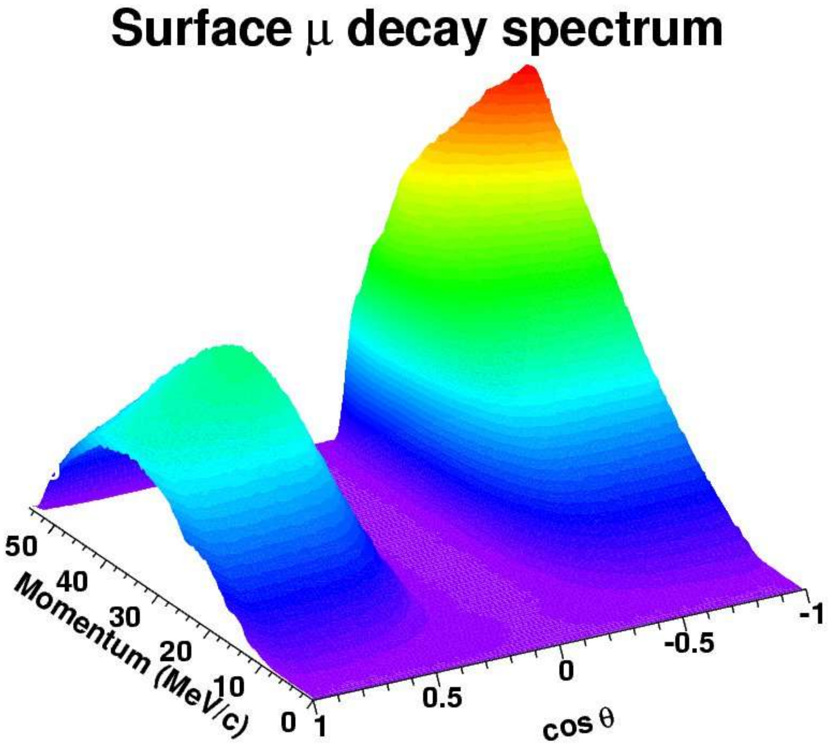
- From the Review of Particle Physics (SM values in parentheses) :
  - ρ = 0.7518 ± 0.0026 (Derenzo, 1969) (0.75)
  - η = -0.007 ± 0.013 (Burkard *et al.* , 1985) (0.00)
  - δ = 0.7486 ± 0.0026 ± 0.0028 (Balke *et al.* , 1988) (0.75)
  - $P_\mu \xi$ = 1.0027 ± 0.0079 ± 0.0030 (Beltrami *et al.* , 1987) (1.00)
  - $P_\mu (\xi\delta/\rho) > 0.99682$ (Jodidio *et al.* , 1986) (1.00)

Detector Array

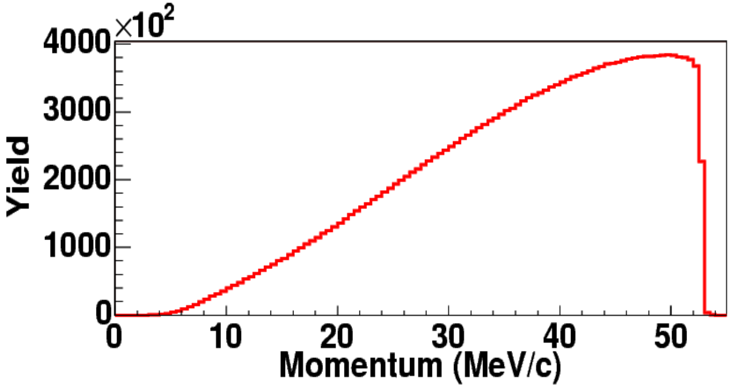


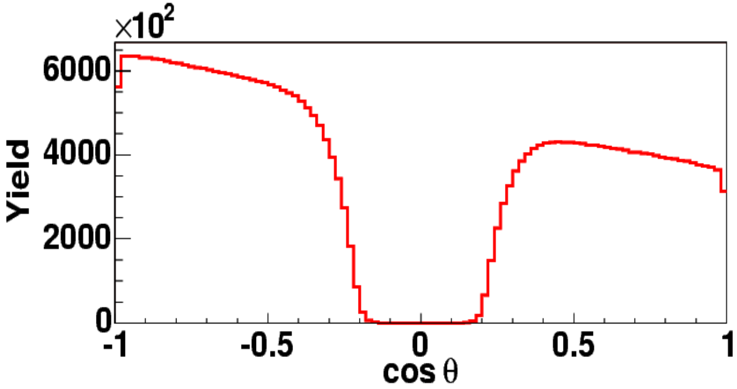
- 56 chambers (44 DC+12 PC planes) symmetrically placed around the target.
- All planes precisely aligned rotationally and translationally.
- Beam stopping position carefully controlled by variable CO_2/He gas degrader.

Data Distribution



Acceptance of **TWIST** spectrometer



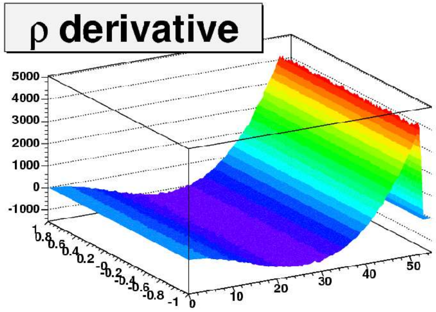


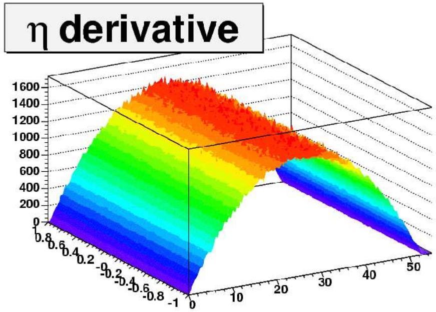
Extract the Michel Parameters

- Michel distribution is linear in ρ, η, ξ, and ξδ, so a fit to first order expansion is exact.

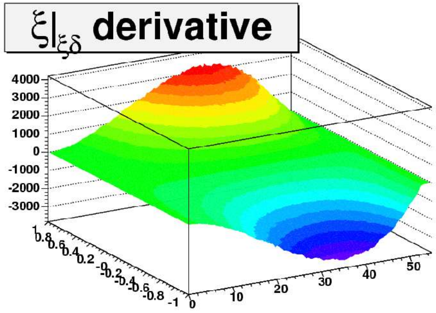
$$
\begin{aligned}
n_i(\alpha_{\mathrm{data}}) &= n_i(\alpha_{\mathrm{MC}}) + \frac{\partial n_i}{\partial \alpha}\Delta\alpha, \\
\alpha &= [\rho, \eta, \xi, \xi\delta]
\end{aligned}
$$

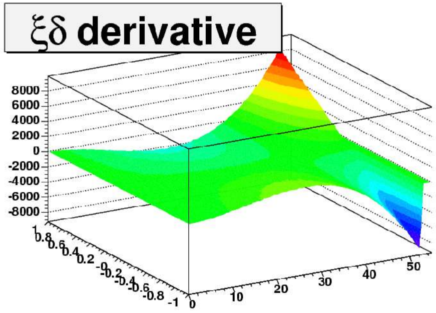
- Fit data (α_{data}) to sum of a base MC distribution (α_{MC}) plus MC-generated derivative distributions times fitting parameters ($\Delta\alpha$) representing deviations from base MC.


ρ derivative


η derivative

- Can also fit data to data and MC to MC for systematic tests.


$\xi|_{\xi\delta}$ derivative


ξδ derivative

Summary of Systematic Uncertainties

Systematic effect	Uncertainty in ρ (x10^4)
▪ Chamber response (ave)	5.1
Stopping target thickness	4.9
Positron interactions	4.6
Spectrometer alignment	2.2
Momentum calibration (ave)	2.0
Theoretical radiative correction	2.0
Track selection algorithm	1.1
Muon beam stability (ave)	0.4

Systematic effect	Uncertainty in δ (x10^4)
Spectrometer alignment	6.1
Chamber response (ave)	5.6
Positron interactions	5.5
Stopping target thickness	3.7
Momentum calibration (ave)	2.9
Muon beam stability (ave)	1.0
Theoretical radiative correction	1.0
Up and downstream efficiencies	0.4