High Precision Measurements of Muon Decay at TWIST

PANIC, October 25, 2005

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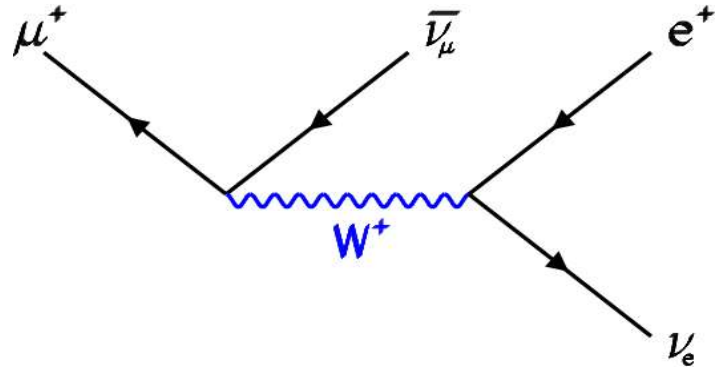
Why Is Muon Decay Interesting?



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

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

Muon Decay Parameters

- 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

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

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

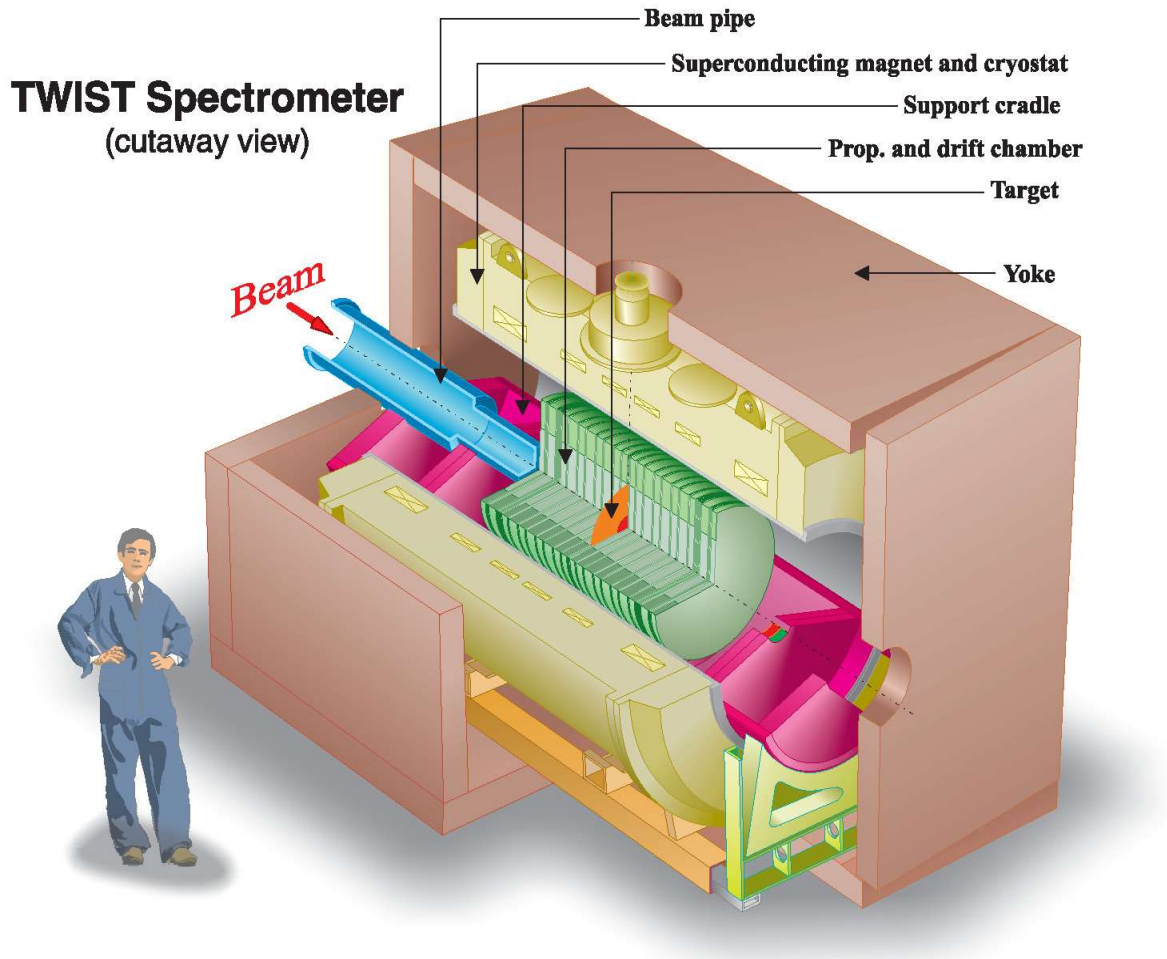
and

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

Standard Model 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 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 (ρ, η, ξ, $\xi\delta$).
  - Final result kept hidden until the analysis is completed and systematic uncertainties evaluated.

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

- Drift chamber HV was maintained to accuracy of ±5 V. What is the uncertainty in Michel parameters due to the HV variation?
  - take a data set with HV lowered by 100 V (20x exaggeration).
  - fit to the data set with nominal HV: $\Delta\rho = -0.70 \times 10^{-3}$, $\Delta\delta = +0.08 \times 10^{-3}$
  - divide the shift by exaggeration factor.

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

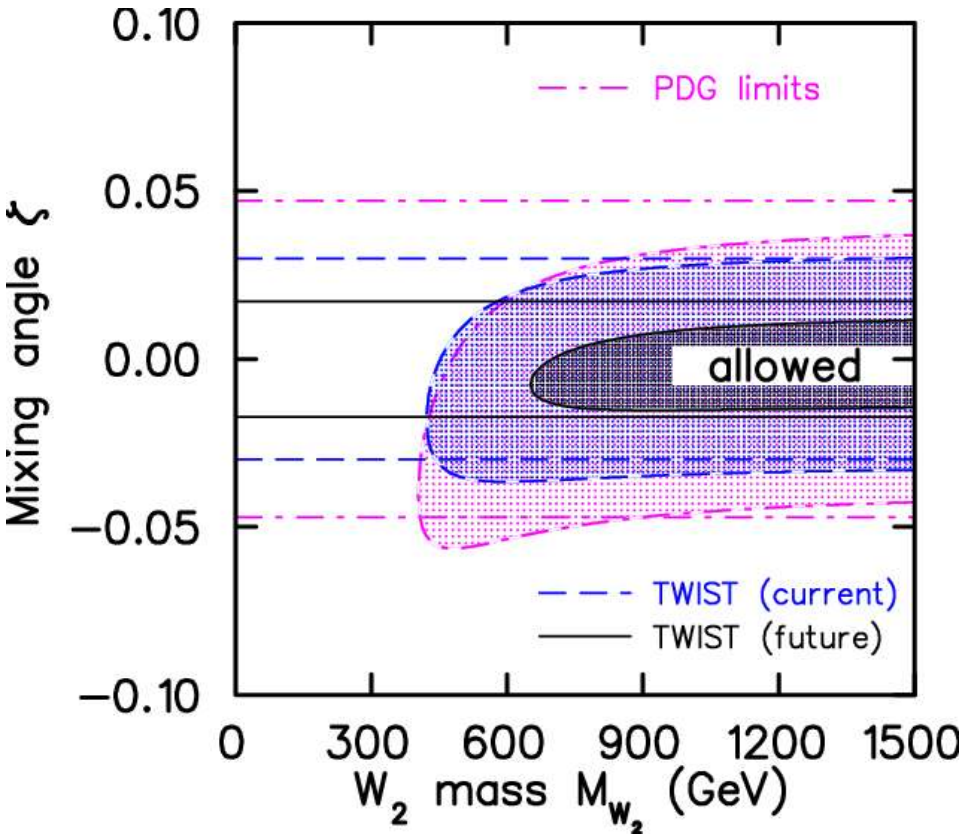
Results for ρ and δ

- $\rho = 0.75080 \pm 0.00032\ (\text{stat}) \pm 0.00097\ (\text{syst}) \pm 0.00023\ (\eta)$
  - 2.5x better precision than the PDG value.
  - Phys. Rev. Lett. 94, 101805 (2005), hep-ex/0409063.
- $\delta = 0.74964 \pm 0.00066\ (\text{stat}) \pm 0.00112\ (\text{syst})$
  - 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)
  - $Q^\mu_R \geq 0$ $(Q^\mu_R = ½[1 + \xi/3 - 16\xi\delta/9])$

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

improves upon $P_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$.

Impact on Left-Right Symmetric Model



- Muon decay offers a clean system to set limits on the L-R symmetric model mixing angle and right-handed coupling partner boson W_2 mass.

$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2$$

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

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 monitoring and control of muon beam.
  - improved online diagnostics of detectors (control of chamber response)

- Analysis of new data is in progress
  - first direct measurement of $P_\mu\xi$ with 04 data is about to be completed. See Dr. Blair Jamieson's poster

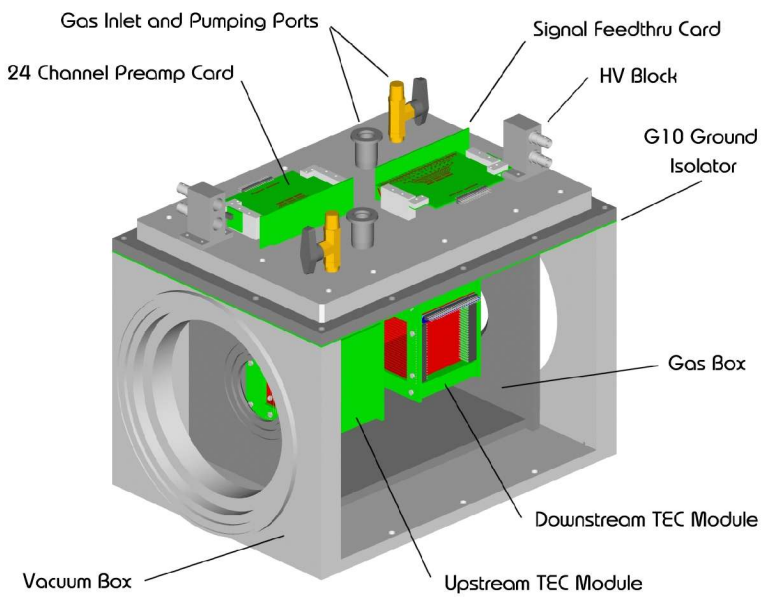
    Precision Measurement of the Muon Decay Parameter $P_\mu\xi$

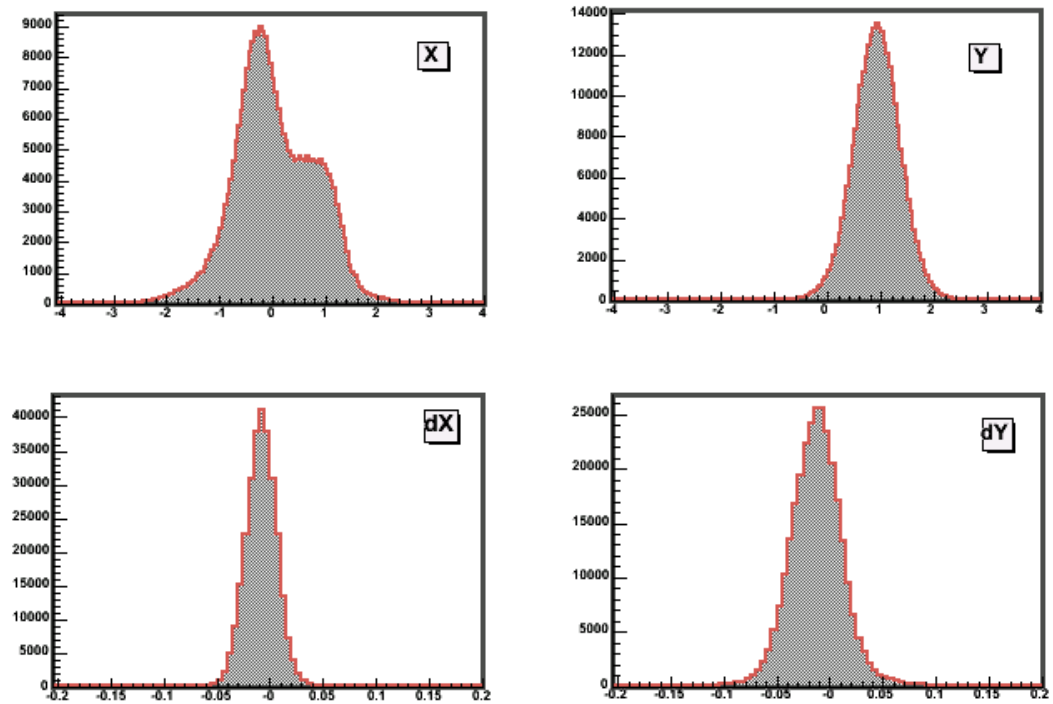
    (Tuesday, Oct. 25, 4:00pm - 6:30pm, Anasazi Ballroom, Eldorado Hotel)
  - expect to finish 2x better precision measurement for ρ and δ from 04-05 data in Spring of 2006.

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 Time Expansion Chamber.
  - more accurate chamber drift cell geometry.
  - improved dead zone simulation.
- Better validation of GEANT3 simulation of positron interactions in materials.

The Time Expansion Chamber



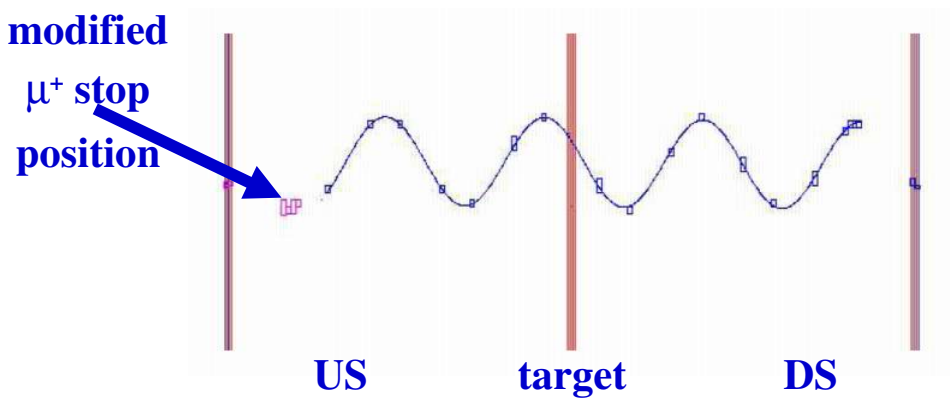


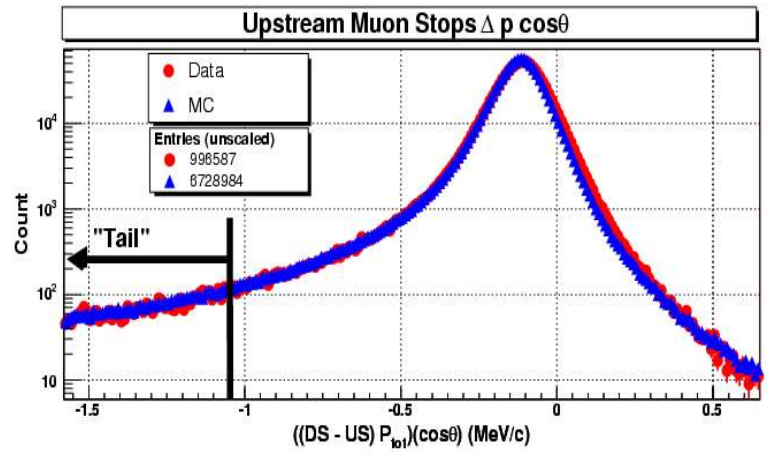
- Two modules measure beam positions and divergences in X and Y directions.
- Tracking resolution: Δx = 300.0 μm, $\Delta\theta$ = 5.0 mrad.

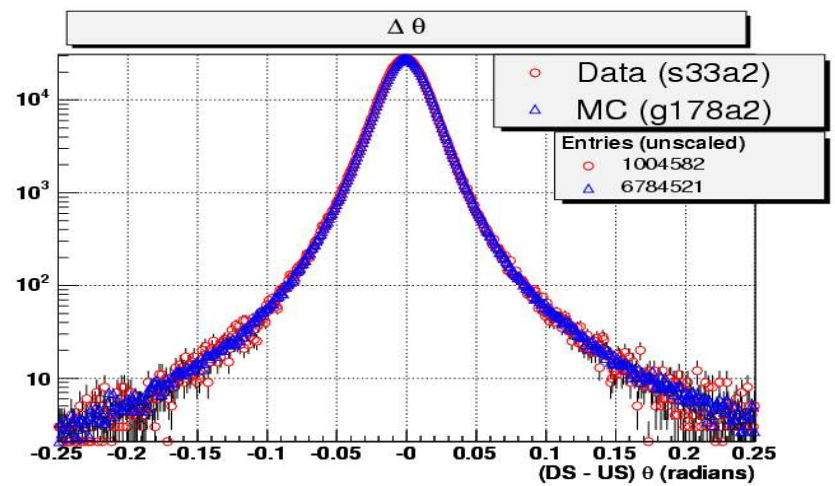
Validation of e^+ Interaction In Monte Carlo

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.







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 higher precision measurements.
- 2x improvement has been anticipated in first direct measurement of $P_\mu\xi$.
- Analysis of ρ and δ is underway. 2x better precision is expected.
- In 2006-2008, TWIST will produce its final results, an overall reduction of uncertainty by at least an order of magnitude.

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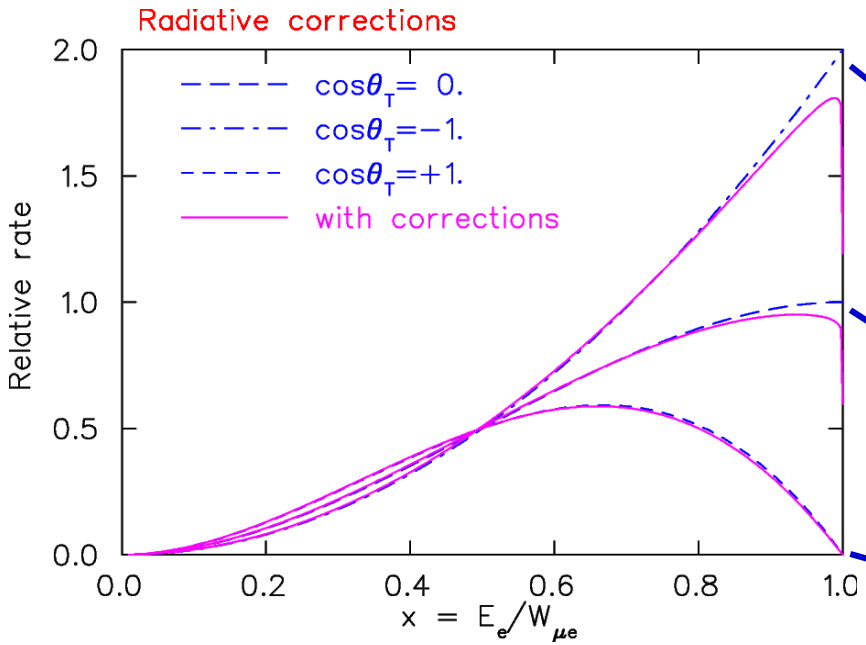
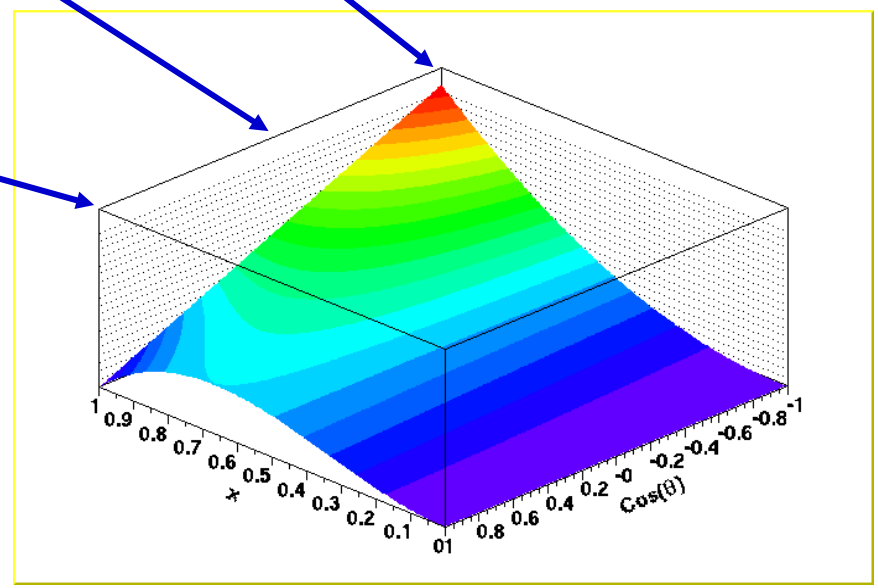
Special thanks to Western Canada Research Grid (Westgrid).

Extra Slides

Radiative Corrections



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

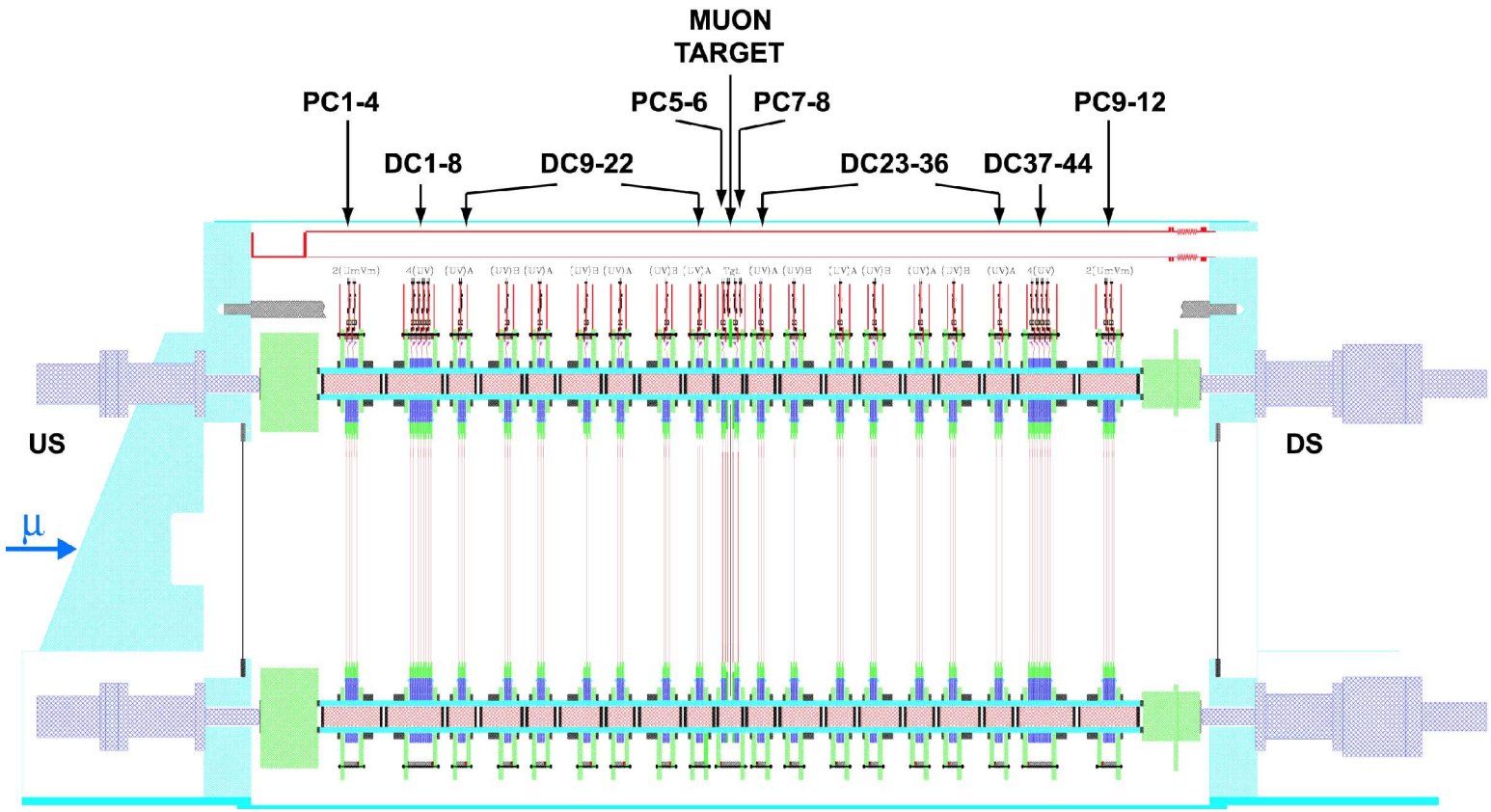


- Full O(α) radiative corrections with exact electron mass dependence.
- Leading and next-to-leading logarithmic terms of O(α^2).
- Leading logarithmic terms of O(α^3).
- Corrections for soft pairs, virtual pairs, and an ad-hoc exponentiation.

Pre-TWIST Michel Parameters

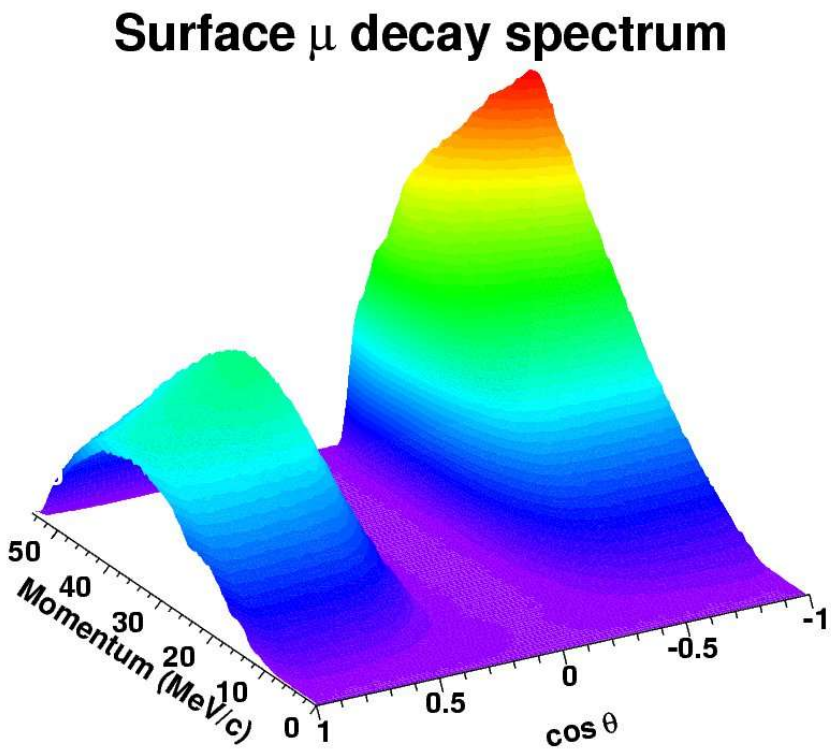
- From the Review of Particle Physics (SM values in parentheses) :
  - ρ = 0.7518 ± 0.0026 (Derenzo, 1969) (0.75)
  - η = -0.007 ± 0.013 (Burkard *et al.* , 1985) (0.00)
  - δ = 0.7486 ± 0.0026 ± 0.0028 (Balke *et al.* , 1988) (0.75)
  - $\mathbf{P}_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (Beltrami *et al.*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

Detector Array

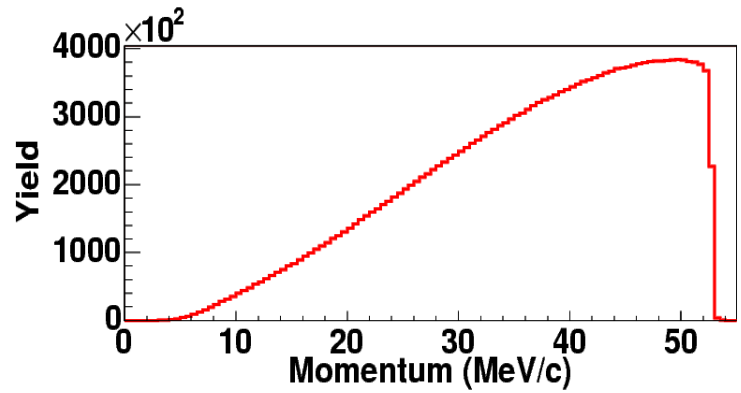


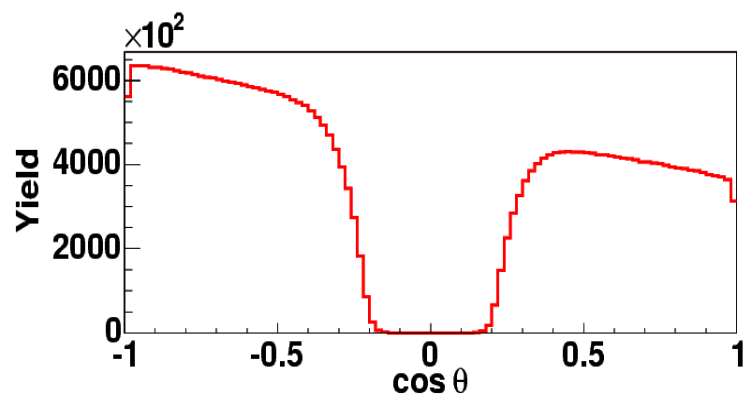
- 56 chambers (44 DC+12 PC planes) symmetrically placed around the target.
- All planes precisely aligned rotationally and translationally.
- Beam stopping position carefully controlled by variable CO_2/He gas degrader.

Data Distribution



Acceptance of TWIST spectrometer





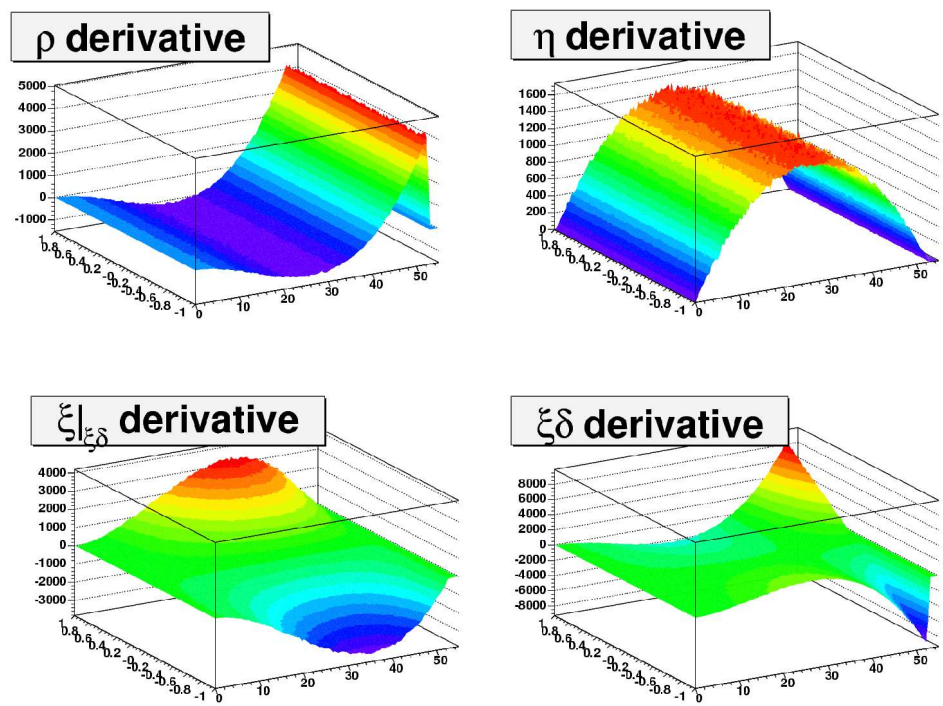
Extract the Michel Parameters

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

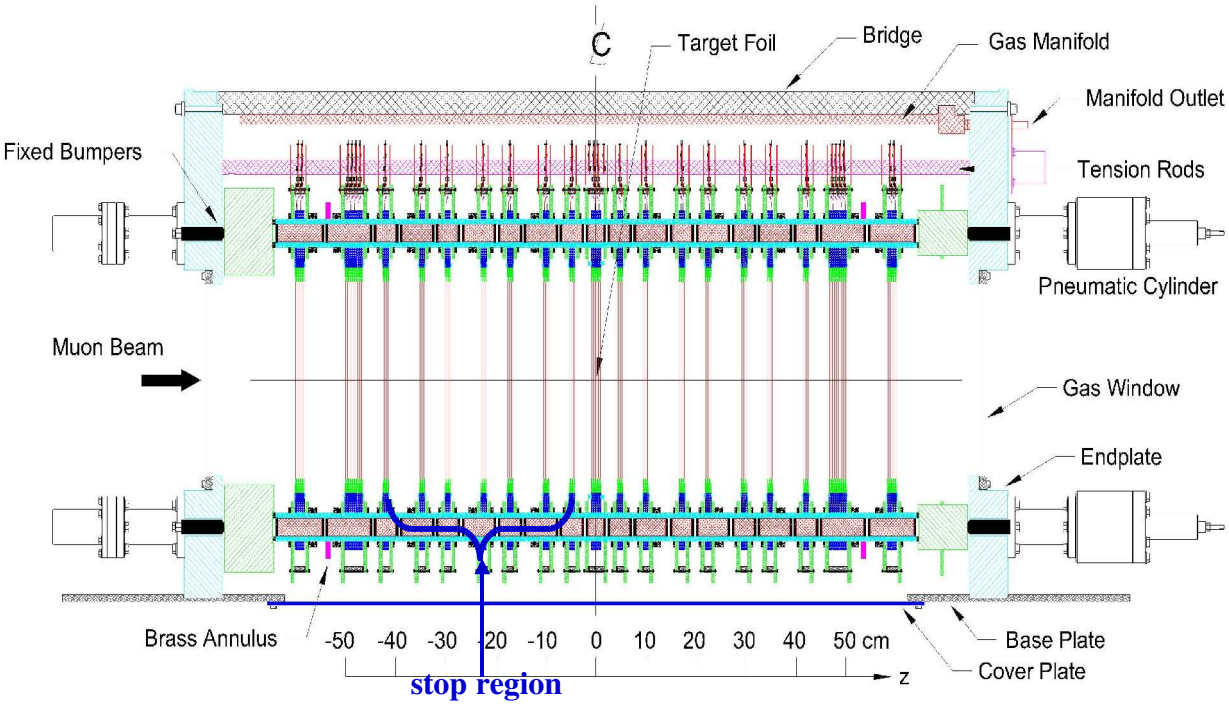
$$n_i(\alpha_{\rm data}) = n_i(\alpha_{\rm MC}) + \frac{\partial n_i}{\partial \alpha}\Delta\alpha,$$
$$\alpha = [\rho, \eta, \xi, \xi\delta]$$

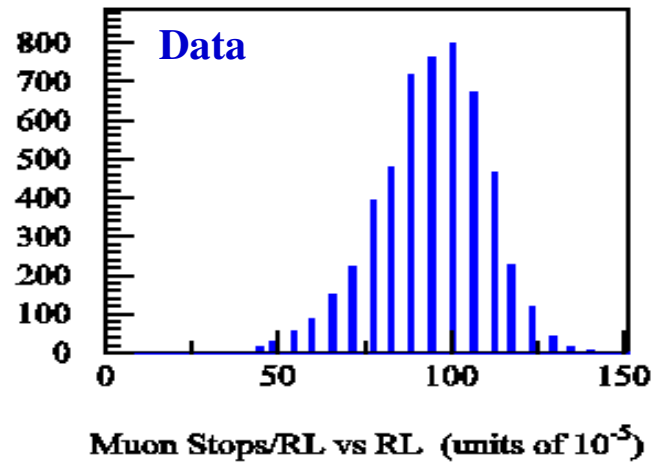
- Fit data ($\alpha_{\rm data}$) to sum of a base MC distribution ($\alpha_{\rm MC}$) plus MC-generated derivative distributions times fitting parameters ($\Delta\alpha$) representing deviations from base MC.

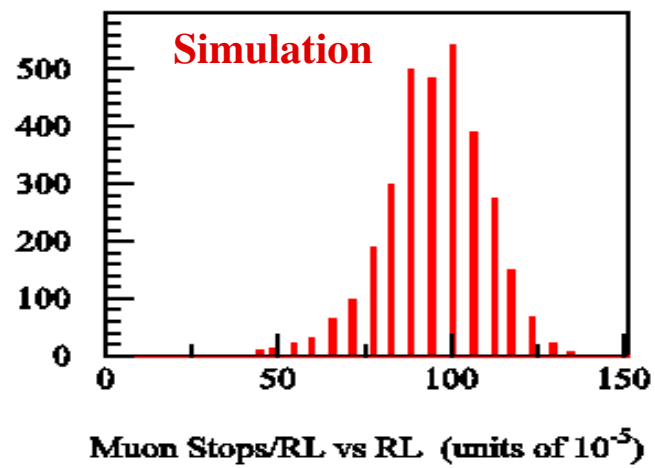
- Can also fit data to data and MC to MC for systematic tests.



Verification of Monte Carlo Simulation







- Simulation must reliably predict muon stopping distributions.
- Verify by comparison in low-mass detector region.