Status of the *TWIST* Measurement of the Muon Decay Parameter $P_\mu\xi$

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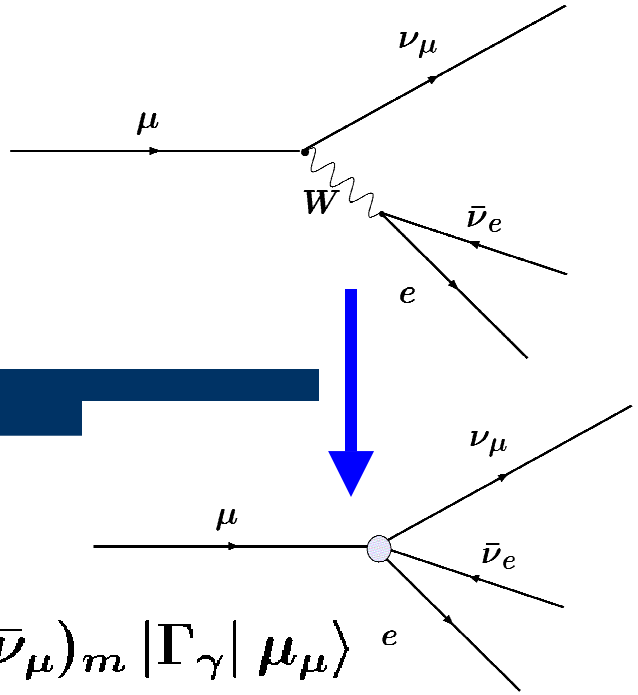
Outline

- Physics of muon decay
- The *TWIST* spectrometer
- Analysis method
- Status of $P_\mu \xi$ measurement

Muon decay



- Matrix Elements (see PDG):

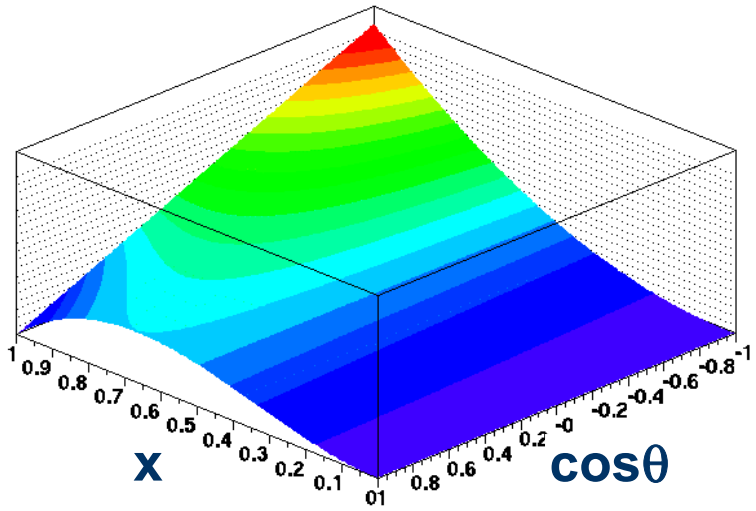
$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L}} g^{\gamma}_{\varepsilon\mu} \left\langle \bar{e}_\varepsilon \left| \Gamma^\gamma \right| (\nu_e)_n \right\rangle \left\langle (\bar{\nu}_\mu)_m \left| \Gamma_\gamma \right| \mu_\mu \right\rangle$$

- Probability for decay of μ–handed muon to ε–handed electron:

$$Q_{\varepsilon\mu} = \frac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1-\delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2$$

$$Q^\mu_R = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta]$$

Michel parameters



- Muon decay (Michel) parameters ρ, η, $P_\mu\xi$, δ:

  muon differential decay rate vs. energy and angle:

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

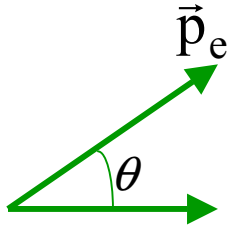
  where

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

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

  and

$$x = \frac{E_e}{E_e^{\max}} \qquad x_o = \frac{m_e}{E_e^{\max}}$$



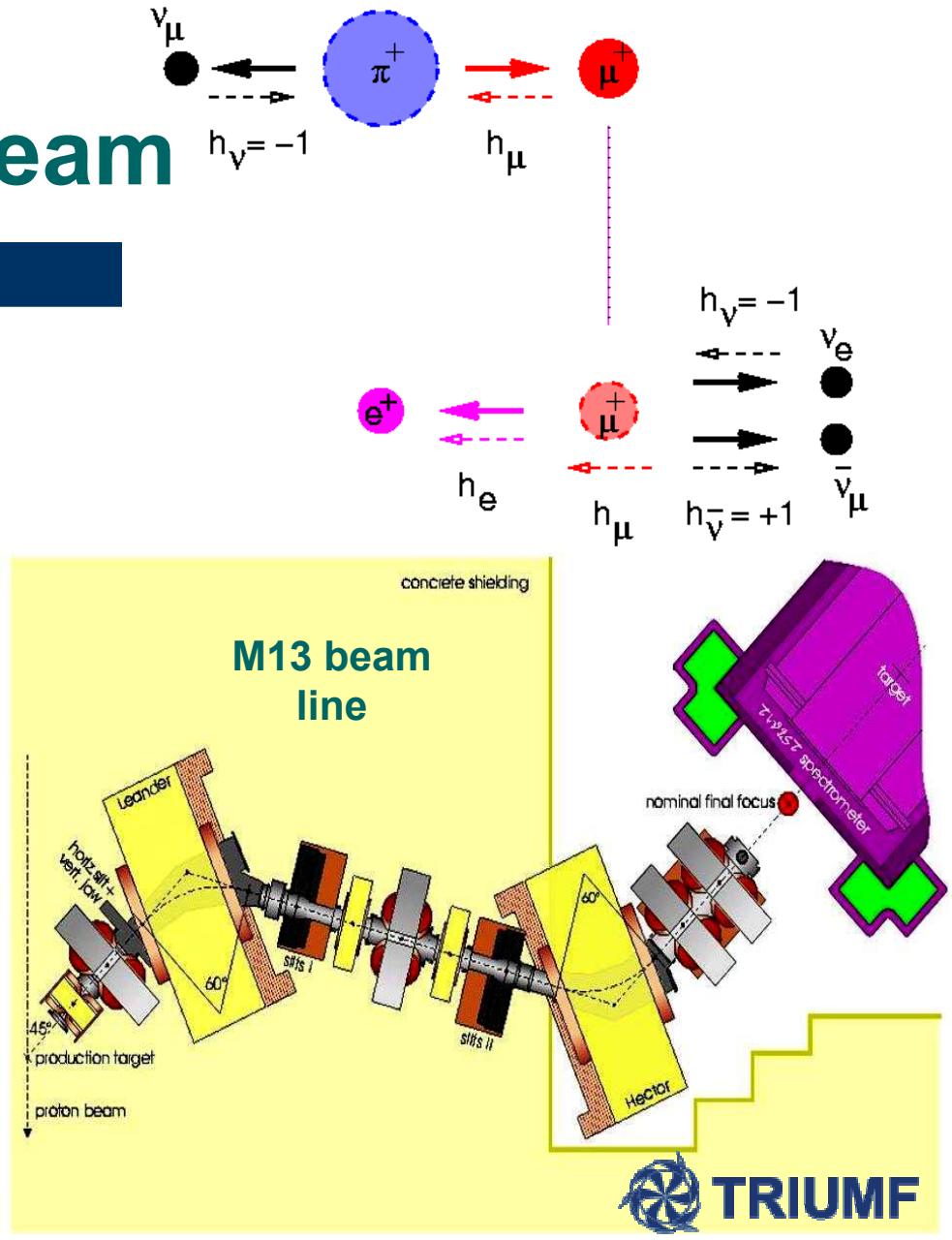
Goals of TWIST

Pre-TWIST (PDG)	Year	SM
η = -0.007 ± 0.013	1985	0
ρ = 0.7518 ± 0.0026	1969	3/4
δ = 0.7486 ± 0.0026 ± 0.0028	1988	3/4
$P_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030	1987	1
$P_\mu(\xi\delta/\rho)$ > 0.99682 (90% c.l.)	1986	1

- Search for new physics that may be revealed through measurements of the muon decay parameters **ρ**, **δ**, $P_\mu\xi$ to a **few parts in 10^4**.

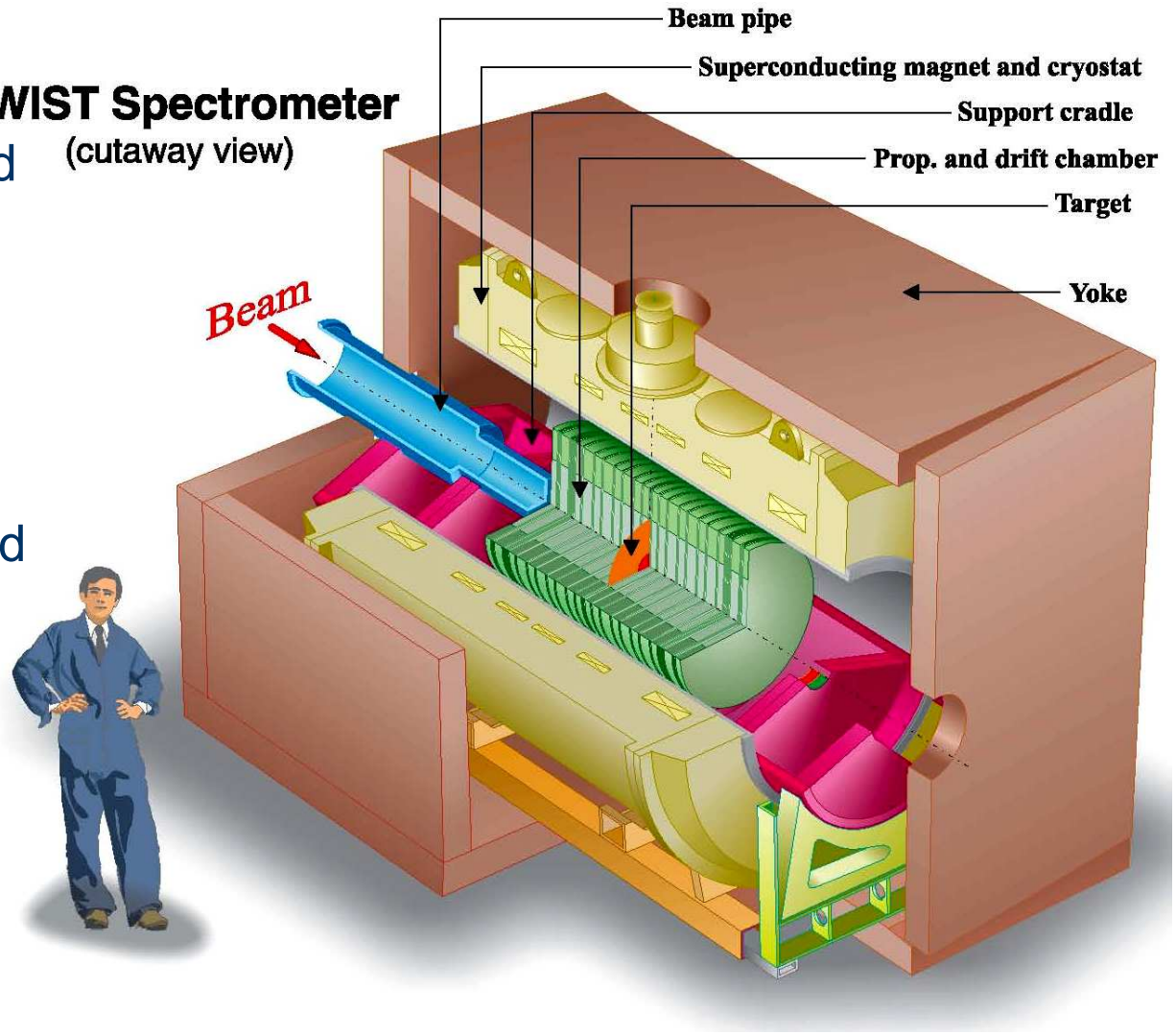
Surface muon beam

- Pions decaying at rest produce muon beams with $P_\mu \sim 1$.
- Depolarization must be controlled using small beams near kinematic edge, 29.8 MeV/c.
- Use ~2.5 x 10^3 μ^+/s.
- Muon total range ~150 mg/cm^2

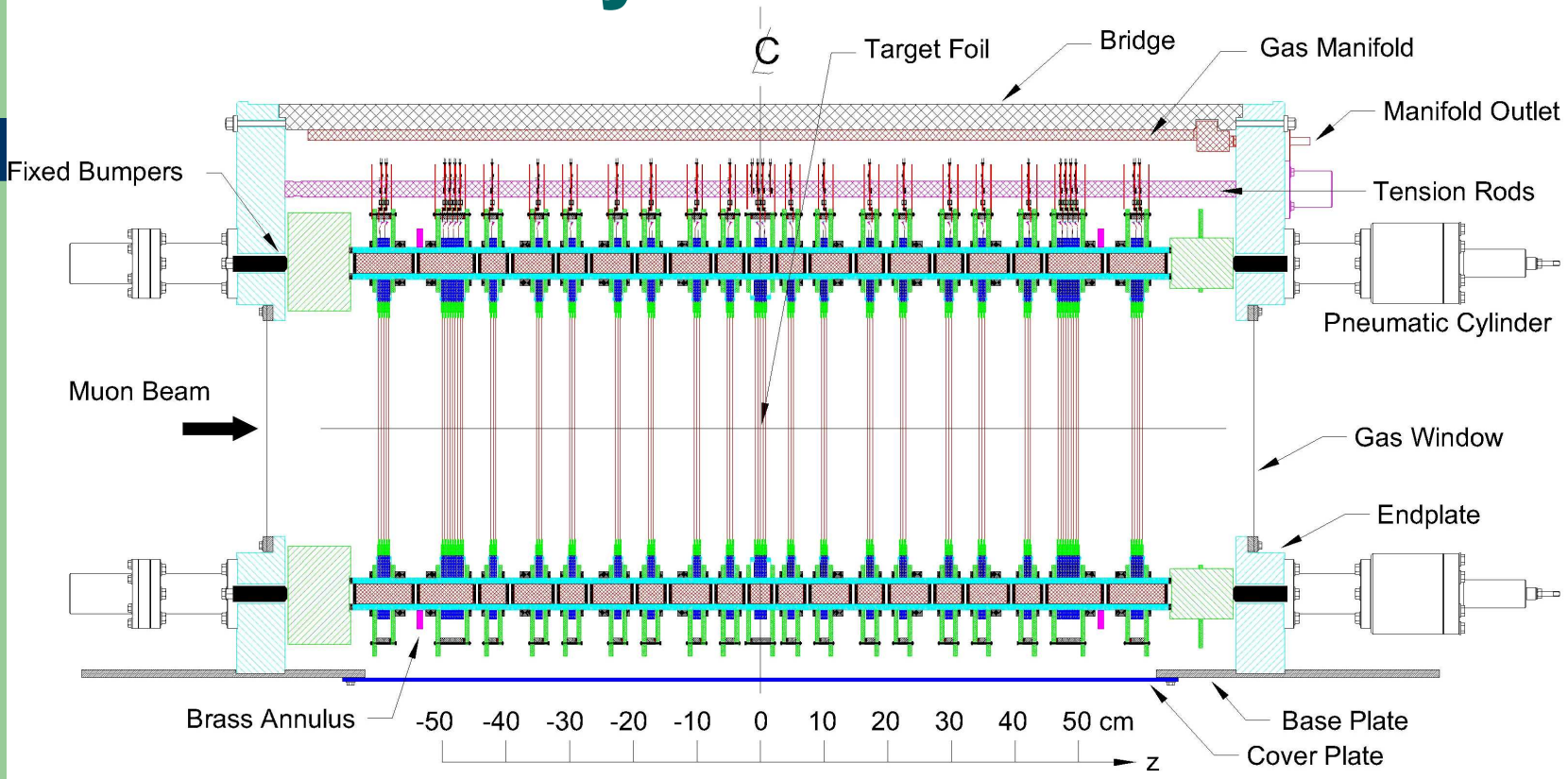


The *TWIST* Spectrometer

- Use highly polarized μ^+ beam.
- Stop them in a very symmetric detector.
- Decay e^+ are tracked through uniform, well-known field.



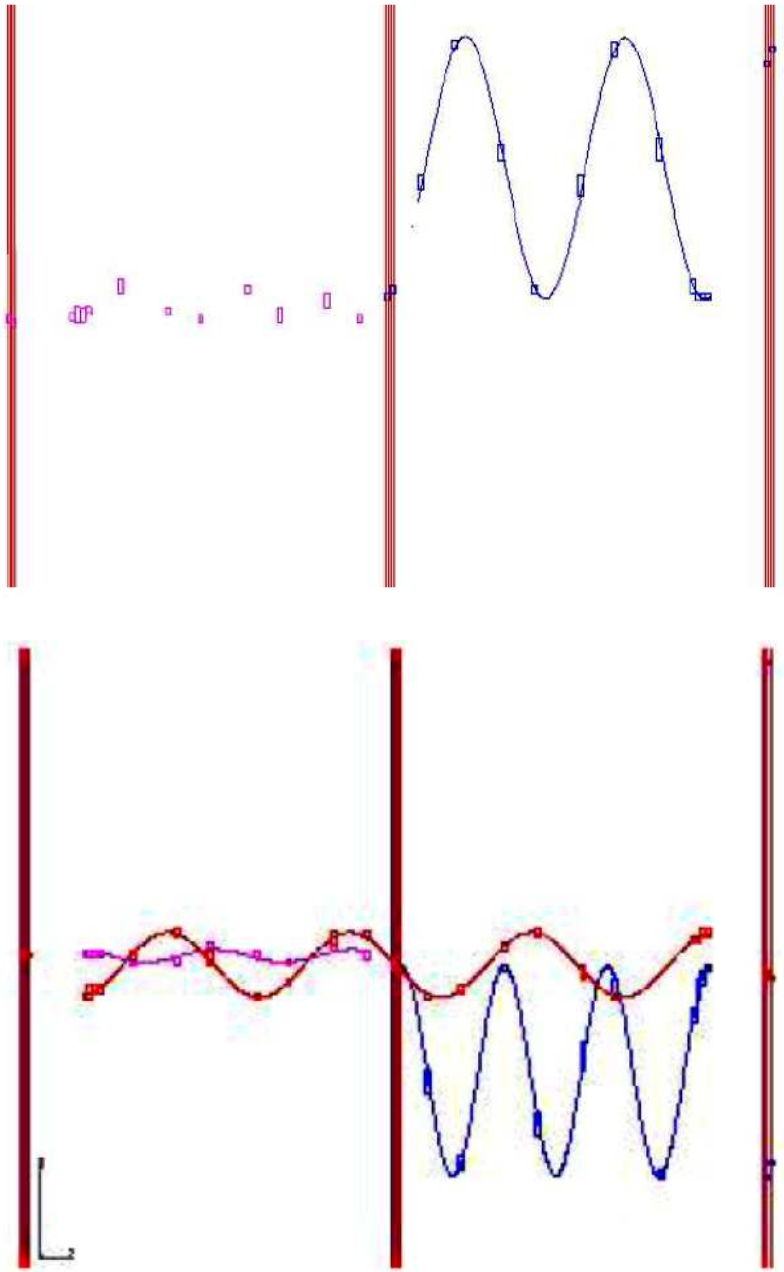
Detector array



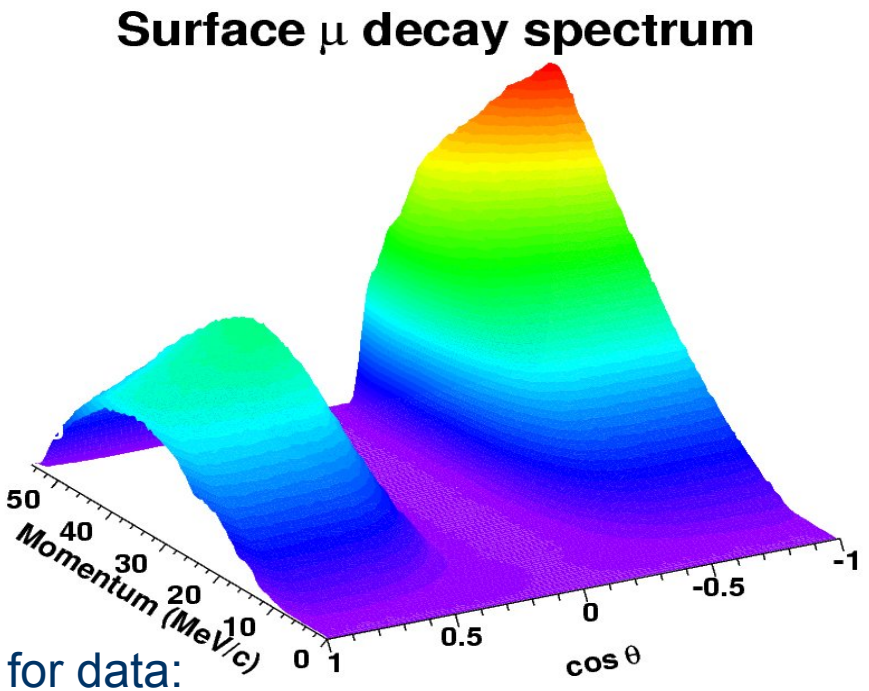
- 56 low-mass high-precision planar chambers symmetrically placed around thin target foil
- Measurement initiated by single thin scintillation counter at entrance to detector
- Beam stop position controlled by variable He/CO_2 gas degrader

Typical events

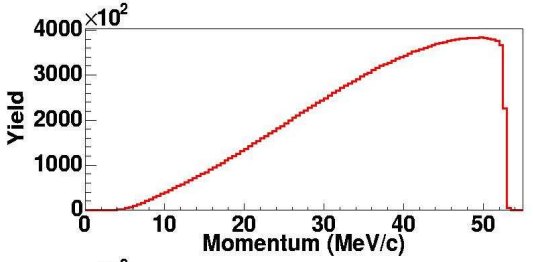
- Read out chamber hits in time interval [-6,+10] μs
- Use pattern recognition (in position and time) to sort hits into tracks, then fit to helix
- Write track parameters and other variables
- Must recognize beam positrons, delta tracks, backscattering tracks



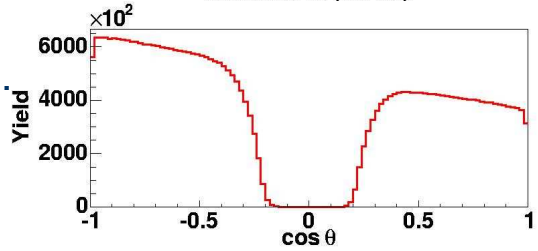
Analysis method



- Extract energy and angle distributions for data:
  - Apply (unbiased) cuts on muon variables.
  - Reject fast decays and backgrounds.
  - Calibrate e^+ energy to kinematic end point at 52.8 MeV.



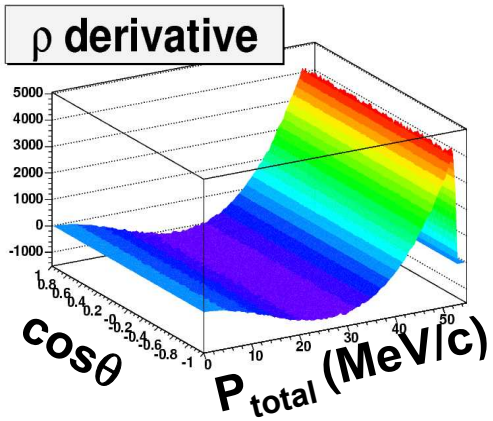
- Fit to identically derived distributions from simulation:
  - GEANT3 geometry has virtually all detector components.
  - Simulate chamber response in detail.
  - Realistic, measured beam profile and divergence.
  - Extra muon and beam positron contamination included.
  - Output in digitized format, identical to real data.
  - Fit to hidden variables with **blind analysis technique**.

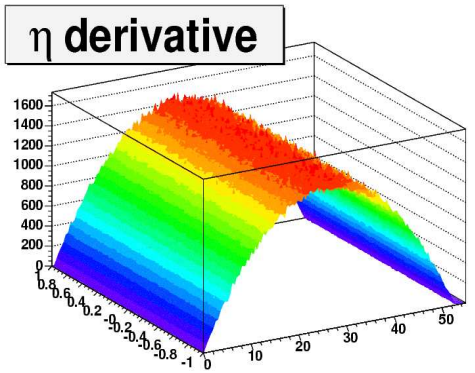


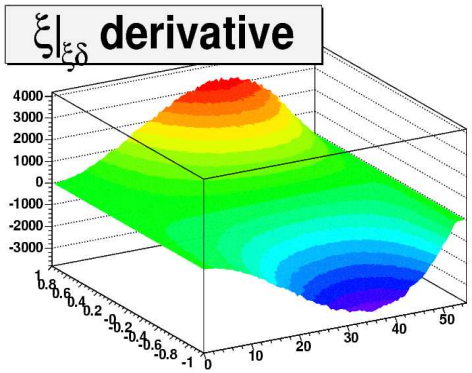
Fitting the data distributions

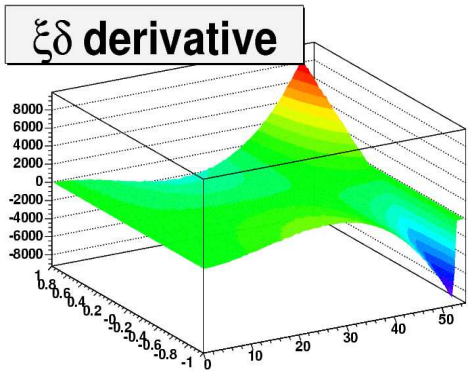
$$n_i(\alpha_{\rm data}) = n_i(\alpha_{\rm MC}) + \frac{\partial n_i}{\partial \alpha}\Delta\alpha,$$
$$\alpha = [\rho, \eta, \xi, \xi\delta]$$

- Michel distribution is linear in ρ, η, ξ, and $\xi\delta$, so a fit to first order expansion is exact.
- 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.
- Can also fit data to data or MC to MC for systematic tests.









TWIST ρ and δ -> Next Talk (J.R. Musser)
-PRL 94, 101805 (2005)
-PRD 71, 071101(R)(2005)

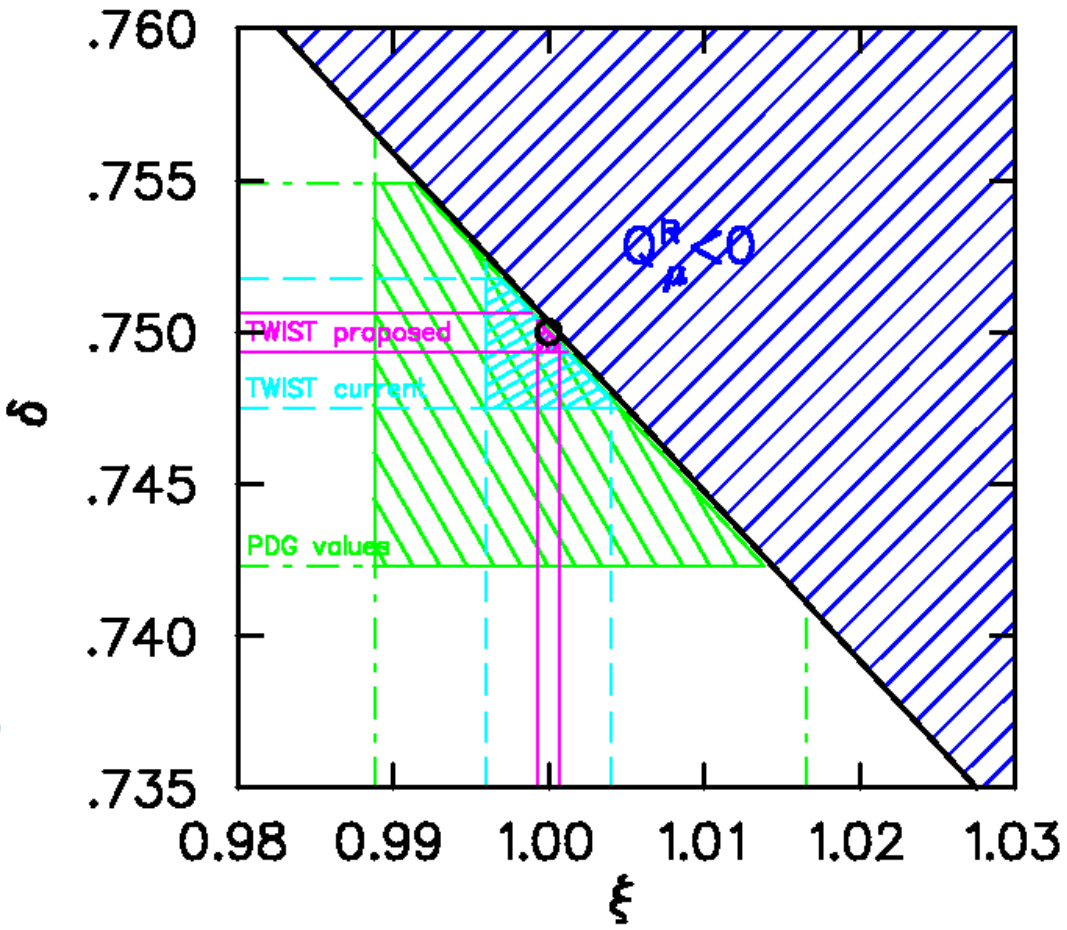
Handedness of the muon

- First *TWIST* ρ and δ with $P\mu(\xi\delta/\rho) > 0.99682$ (Jodidio,1986) and $Q\mu^R \geq 0$, we get the indirect limit (90% c.l.):

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

- Improves upon direct measurement (Beltrami, 1987):

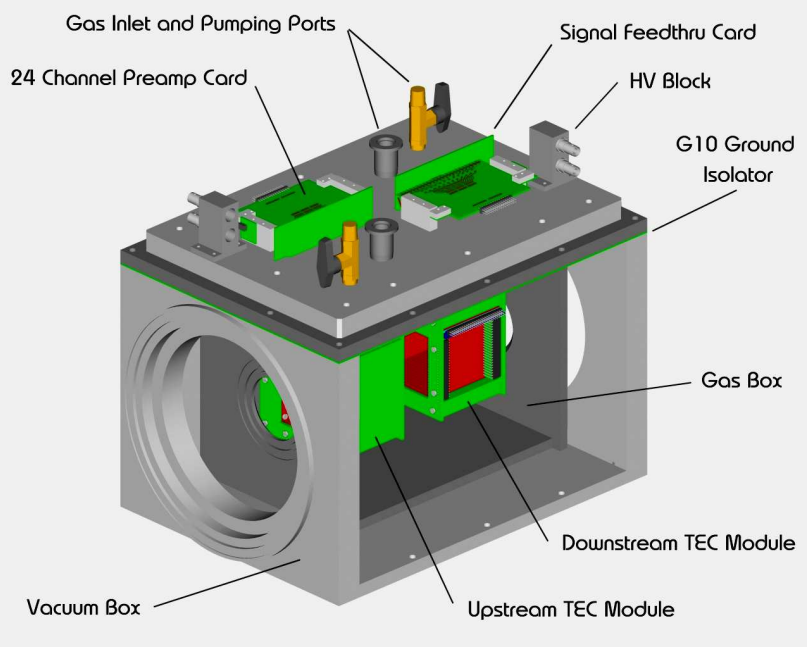
$P\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$



Status of *TWIST* $P_\mu\xi$ Measurement

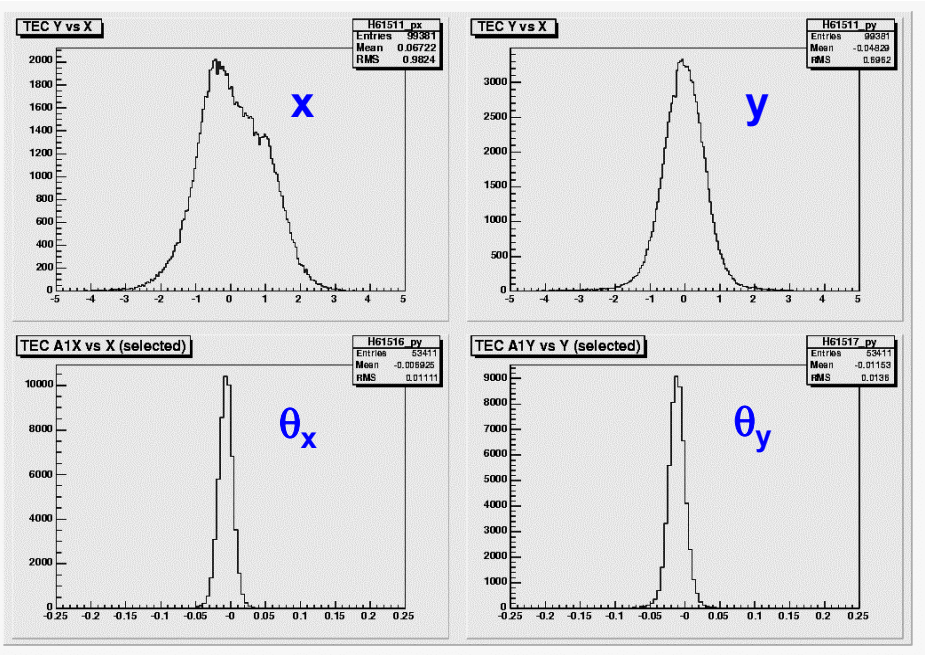
- Collected more than 10^8 muon decays in 2004 with improved apparatus and procedures:
  - 71 μm high-purity aluminum target (reduced muon depolarization, reduced target thickness uncertainty).
  - Better monitoring and control of muon beam with TEC (improved simulation input, reduced beam uncertainty).
  - Improved chamber drift cell geometry (control of chamber response).
  - Better online diagnostics of detectors and beam.
  - ... and others.
- Expect first direct measurement of $P_\mu\xi$ (~10^{-3}) and 2x better precision for ρ and δ **this fall**

The TEC



Time **E**xpansion **C**hamber:

- Low pressure transverse drift chamber
- 6 μm Mylar windows
- High precision measurement of muon beam



Summary

- *TWIST* has produced its first physics results.
- Has also successfully tested strategies and procedures for the next phase.
- Current data analysis for the first direct measurement of $P\mu\xi$. It will also lead to better precision for ρ and δ.
- In 2006-2007, *TWIST* will produce its final results, an overall reduction of uncertainty for ρ and δ by at least an order of magnitude, and twice that for $P\mu\xi$.

¤ Graduate student
† also Univ. of Victoria
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* also Saskatchewan
x deceased

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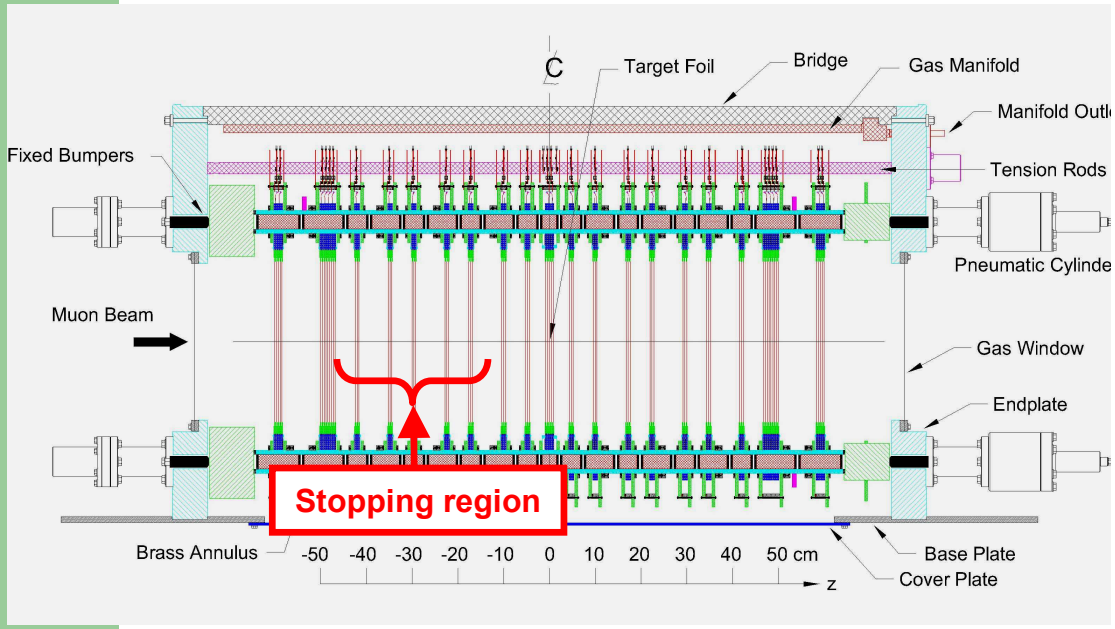
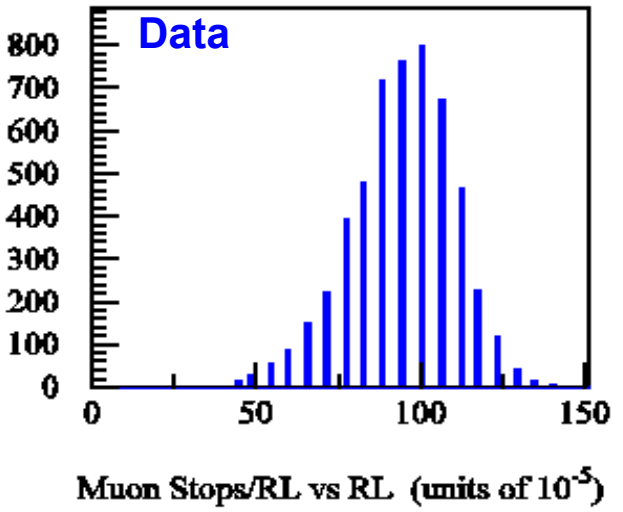
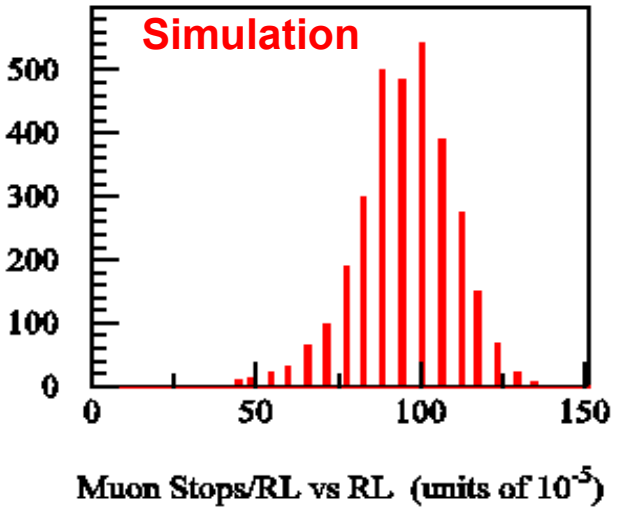
Simulation: muon interactions







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

Coupling constants

- Coupling constants $g^{\gamma}_{\varepsilon\mu}$ can be related to

$$Q_R^{\mu} \doteq Q_{RR} + Q_{LR}$$
$$= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2$$

- PDG limits on all couplins (90% c.l.):

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.550$	$\lvert g^V_{LL}\rvert > 0.960$	$\lvert g^T_{LL}\rvert \equiv 0$

Testing the Standard Model

- Model-independent muon handedness:

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

- Left-right symmetric models:

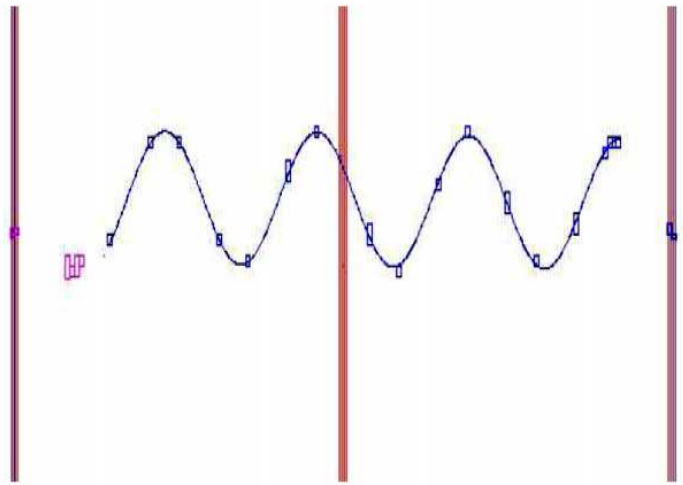
$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2, \qquad 1 - \mathcal{P}_\mu\xi = 4\{\zeta^2 + \frac{M_L^4}{M_R^4} + \zeta\frac{M_L^2}{M_R^2}\}$$

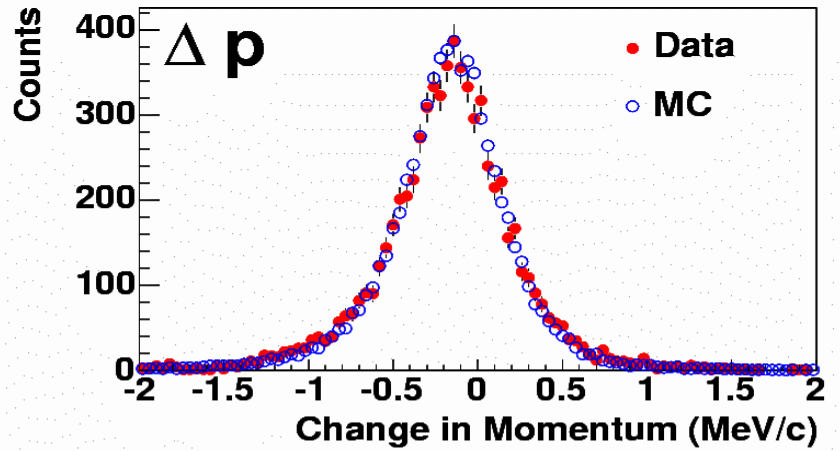
- Tensor interaction (M. Chizhov, hep-ph/0405073):

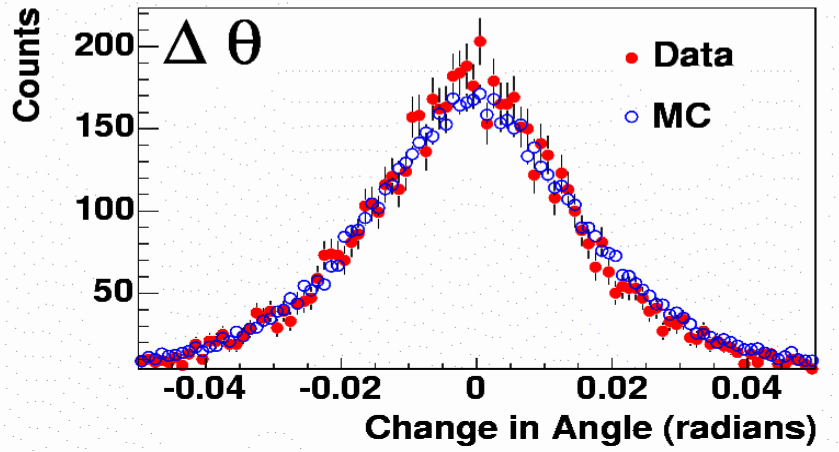
$$\delta = \frac{3}{4}(1 - 6|g_{RR}^T|^2)$$

Simulation: positron interactions

- GEANT simulation must be validated for e^+ energy loss and multiple scattering.
- Stop muons at one end of detector.
- Measure e^+ track on each side of target, before and after passage through it.

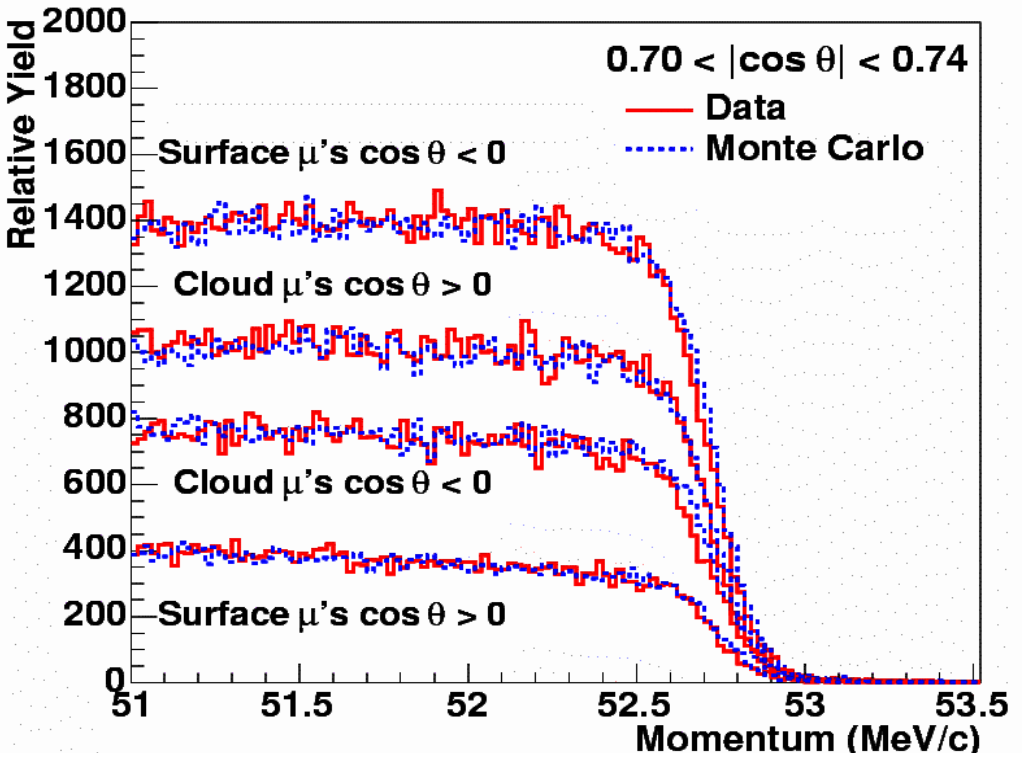


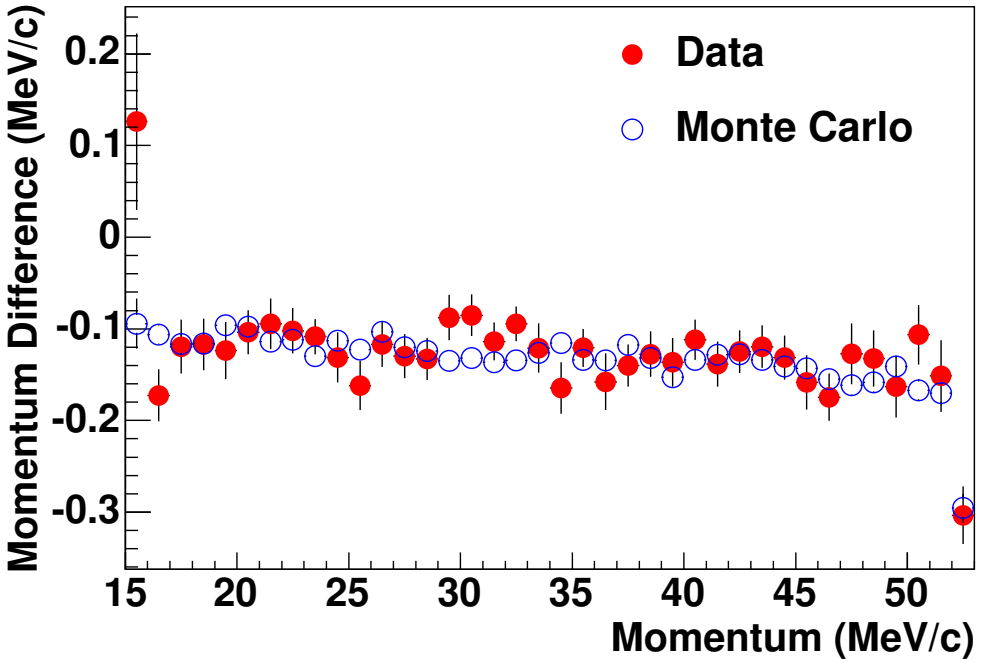




Energy Calibration

- Use only distinctive feature of distribution: the end point.
- Fit edge energy and width for narrow angle ranges.
- Edge energy: absolute and angle-dependent parameters β, α.
- With correct field, $\beta = 0$.
- α represents energy loss in stopping target and chamber planes.





Blind analysis

- The base set is generated using **unknown**, **hidden values** of (α_{MC}).
- All systematic uncertainties as well as offsets $\Delta\alpha$ are **determined prior to revealing** hidden values.
- Open box to reveal hidden values of $\Delta\alpha$.
- η was held fixed in the fit, but hidden; refit with η fixed to PDG value.
- Obtain final values of decay parameters.

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) that may cause error.
  - Measure effect by fitting, using correlated sets where practical.
  - Scale results according to variance in a data set.

List of systematics

- 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