New Results from TWIST: Probing The Weak Interaction with Muon Decay

Art Olin, for the TWIST Collaboration

Generalized Muon Decay

Lorentz invariant, local 4 fermion interaction

$$M = \frac{4G_F}{\sqrt{2}} \sum g^{\gamma}_{\epsilon\mu} \langle \overline{e_\epsilon} \Gamma^\gamma \nu_e \rangle \langle \overline{\nu_\mu} \Gamma_\gamma \mu_\mu \rangle$$

Fetscher-Gerber formalism

- Includes scalar, vector, and tensor (Γ^S,Γ^V,Γ^T) interactions among left- and right-handed leptons. 19 real parameters.
- SM postulate: $g^V_{LL}=1$, all others 0.
- Muon decay purely leptonic process, testing this assumption.

Muon Decay Parameters

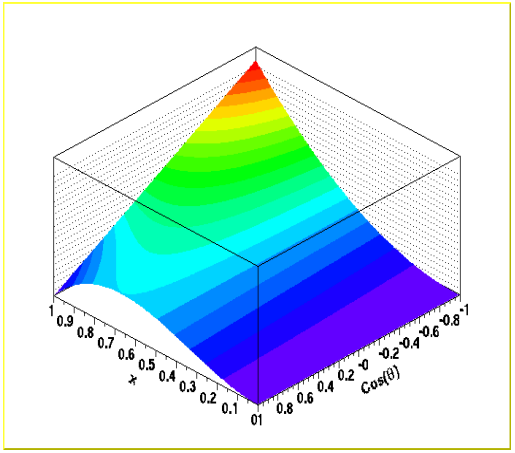
Polarized muon differential decay rate *vs.* energy and angle:

$$\frac{d^2\Gamma}{dx\ d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2}\ \{\mathcal{F}_{IS}(x,\rho,\eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

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

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

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

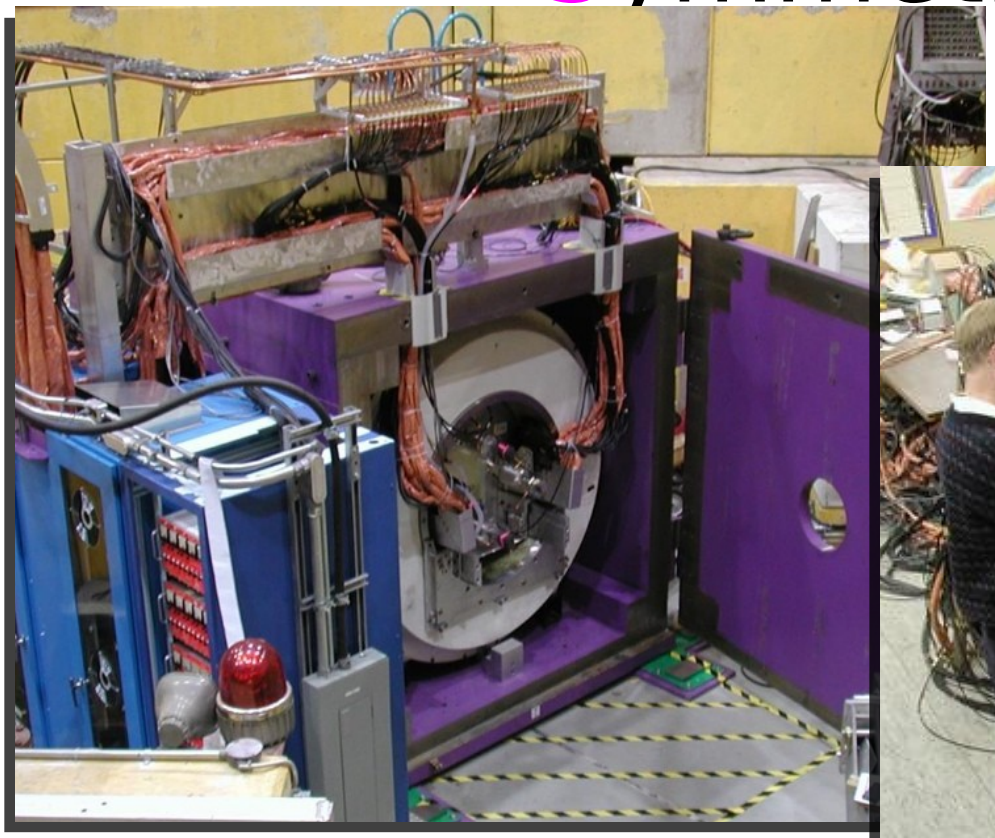


Muon decay parameters ρ, η, ξ, δ bilinear products of $g^{\gamma}_{\varepsilon\mu}$: (Michel, Kinoshita and Sirlin)

Measurement of positron polarization yields additional parameters

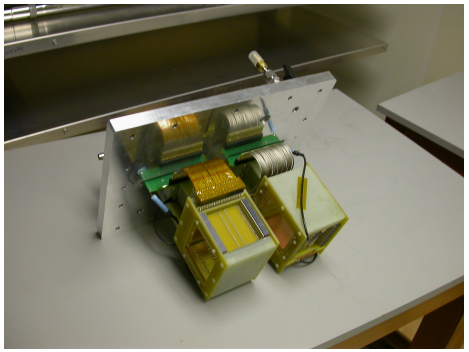
The *TWIST* Experiment

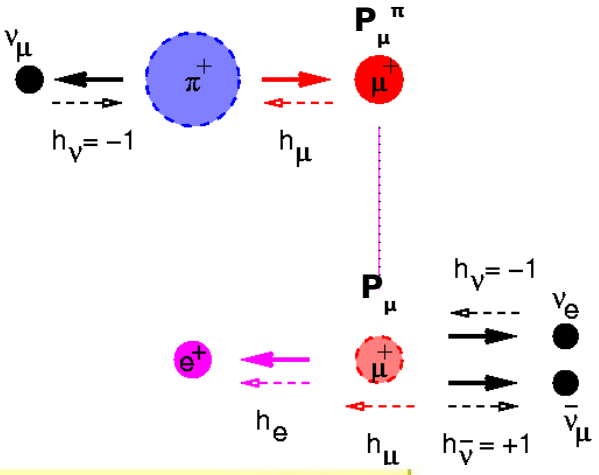
TRIUMF Weak Interaction Symmetry Test

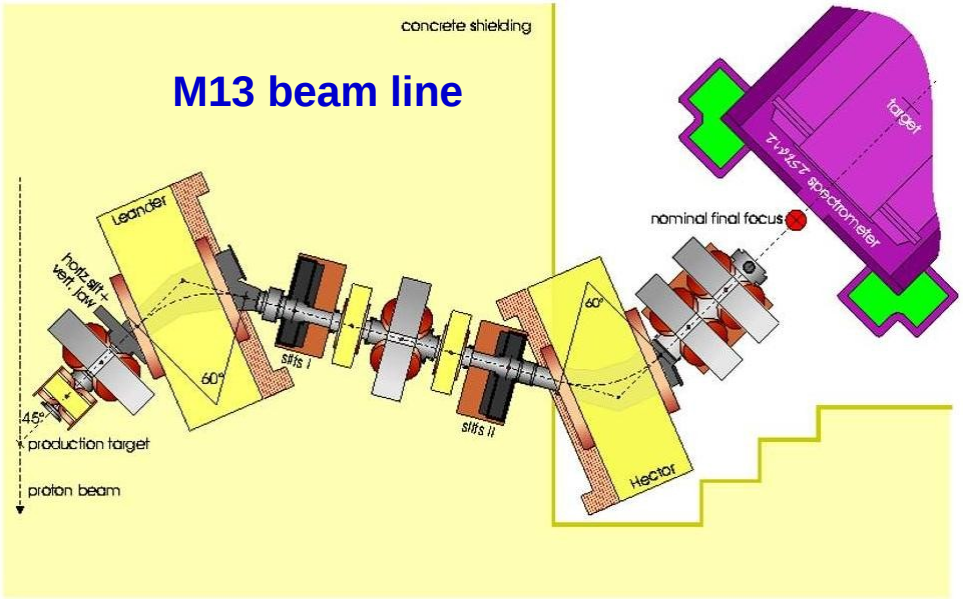


Polarized Muon Production and Transport

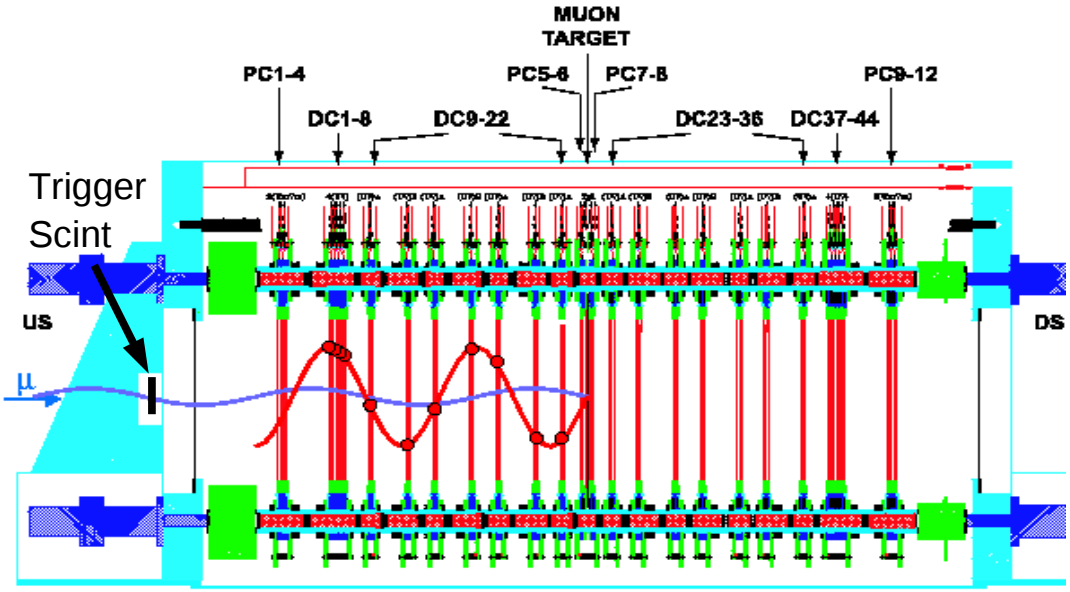
- Pions decaying at rest produce muon beams with $\mathcal{P}_\mu^\pi$ =100%. (SM).
- Depolarization must be controlled using small emittance beams near kinematic edge, 29.8 MeV/c.
- Use ≈3 10^3 μ^+ s^{-1}.
- Muon total range at density ≈1 only about 1.5 mm!
- Measure beam emittance at entrance to solenoid.







Typical event



Low-mass high-precision planar chambers symmetrically placed around thin target foil which stops nearly all of surface muon beam. Z precision 5 10^{-5}, wire position 5μ. 44 drift chambers (DME), 12 proportional chambers (CF_4-isobutane), He gaps.

Measurement initiated by single thin scintillation counter at entrance to detector.

Beam stop position controlled by variable He/CO_2 gas degrader. NIM A548(2005)206

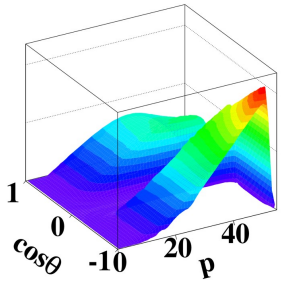
Momentum and angle of the decay positron are determined from the drift chamber hits.

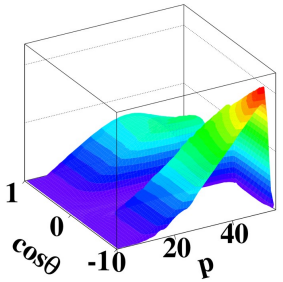
Michel Parameter Analysis

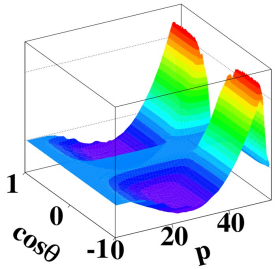
Decay spectrum linear in ρ, η, $P_\mu\xi$, $P_\mu\xi\delta$. Fix η to expt.

Fit experimental spectrum to blinded simulation.

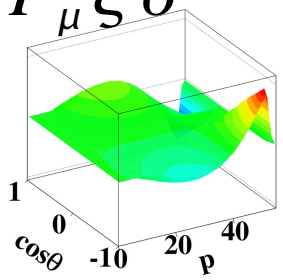
$$N(Data) = N(\mathrm{Sim}) + \frac{\partial N}{\partial \rho}\Delta\rho$$

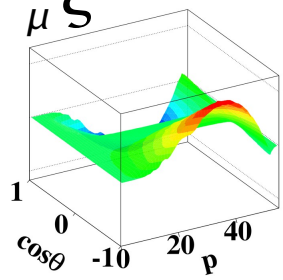






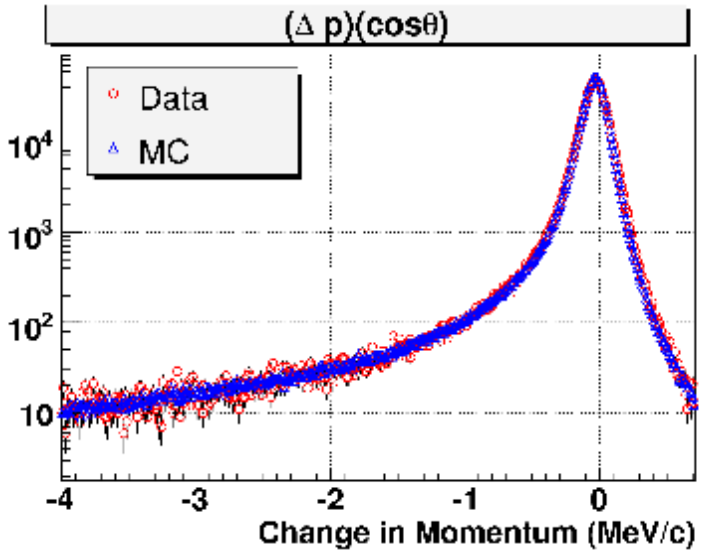
$$+ \frac{\partial N}{\partial P_\mu\xi\delta}\Delta P_\mu\xi\delta + \frac{\partial N}{\partial P_\mu\xi}\Delta P_\mu\xi$$



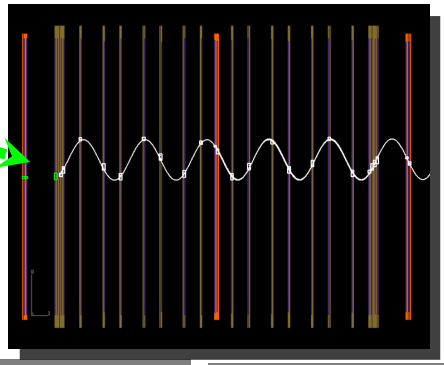


Simulation: positron interactions

- 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.
- Compare differences in 2004 data and simulation.

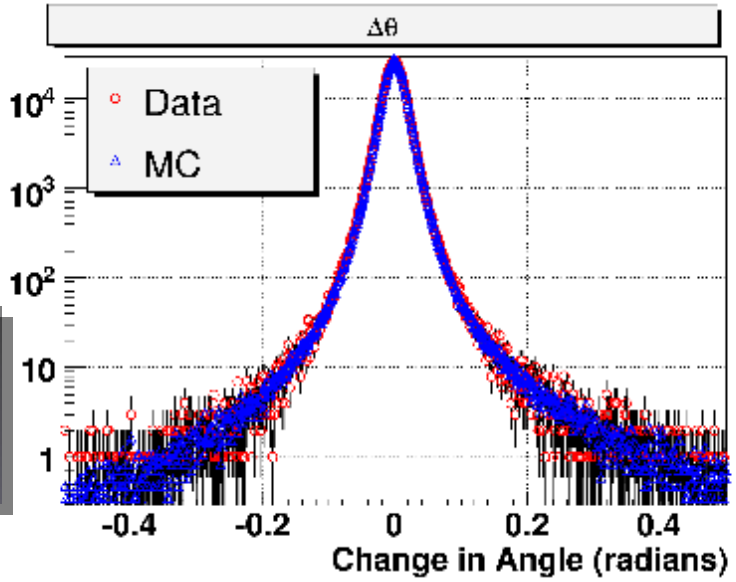


Muon stops here



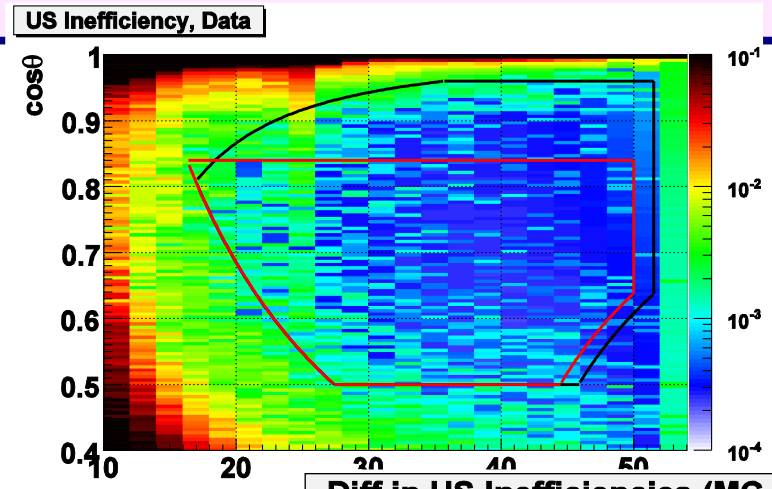
fit track upstream

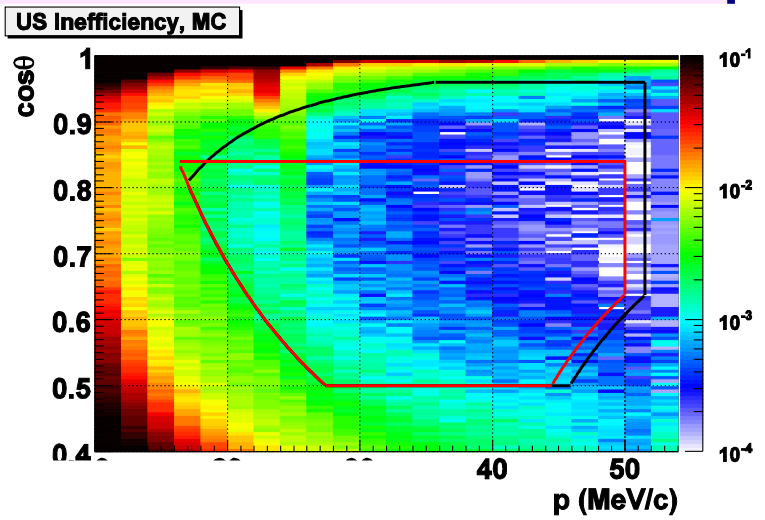
fit track downstream

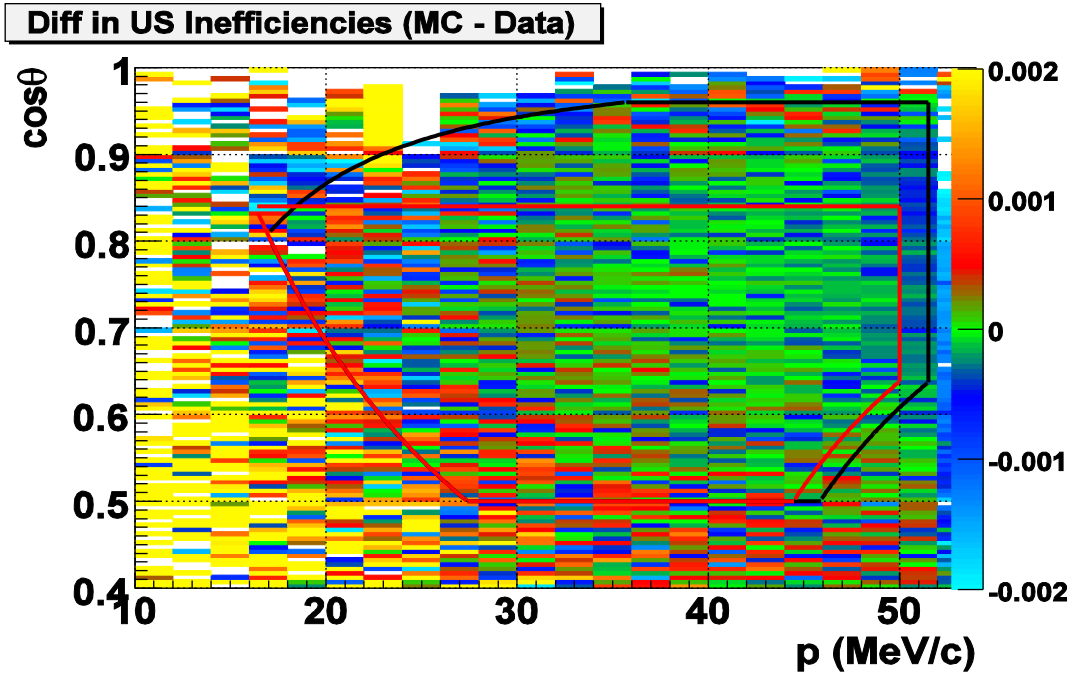


A Precision

Tracking (in)efficiency

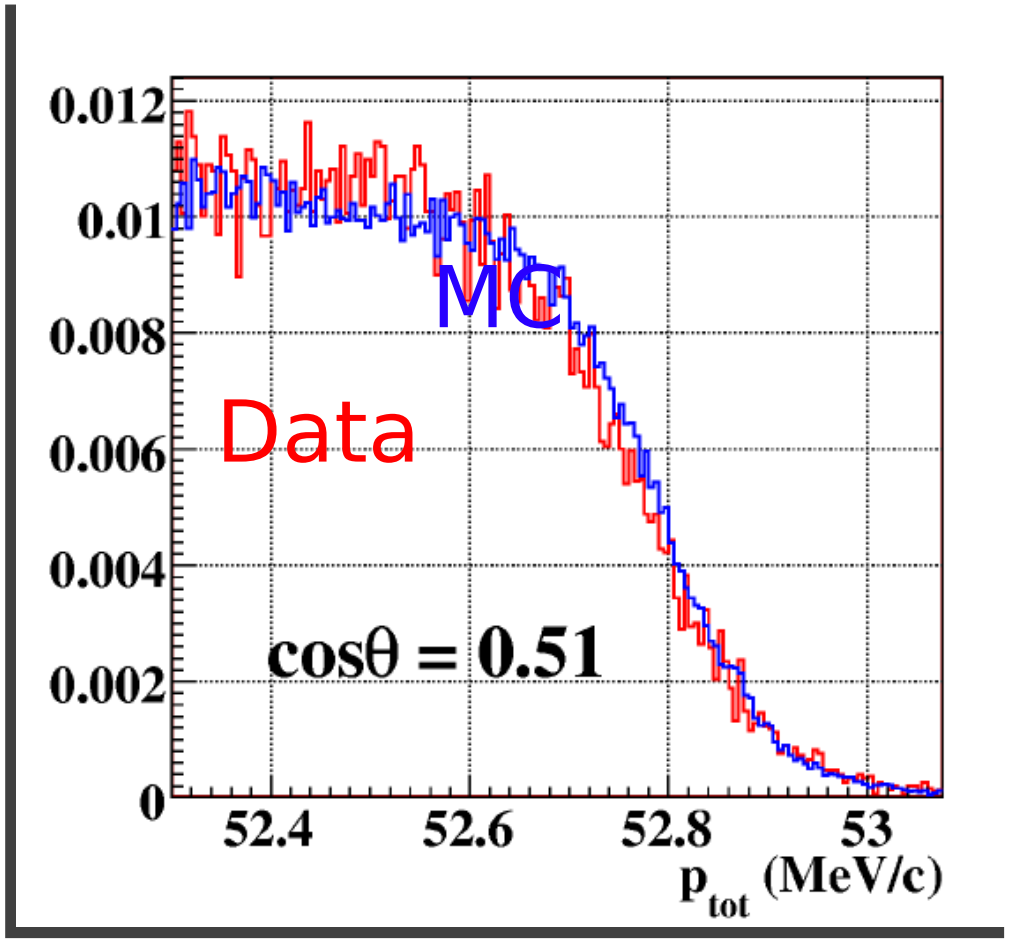






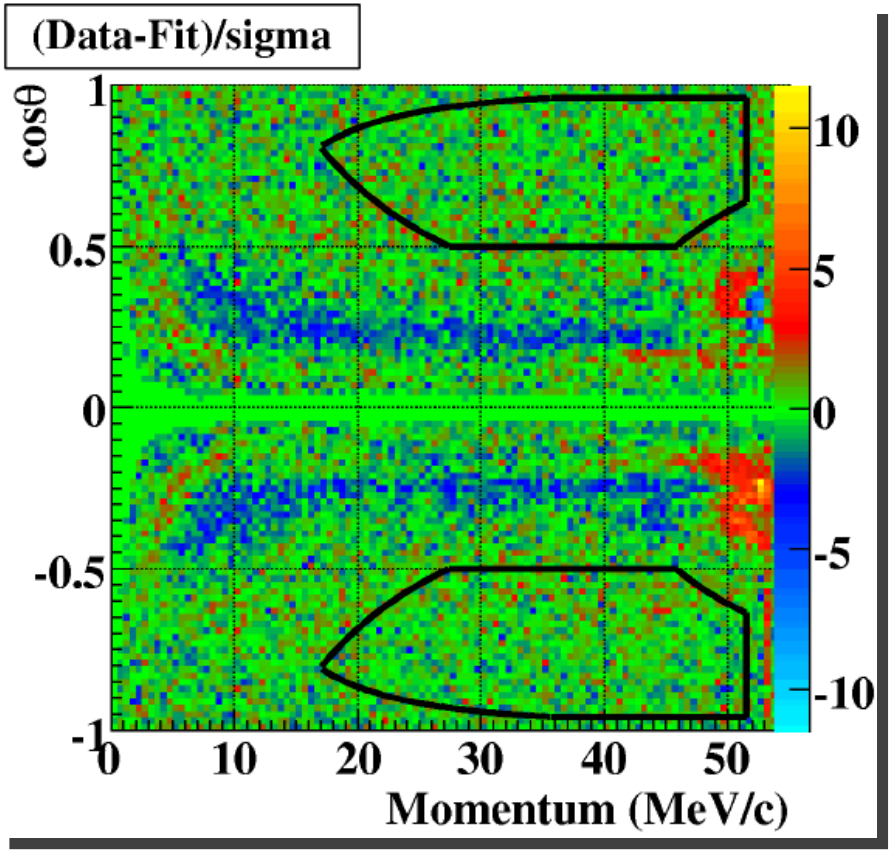
Note the scale!

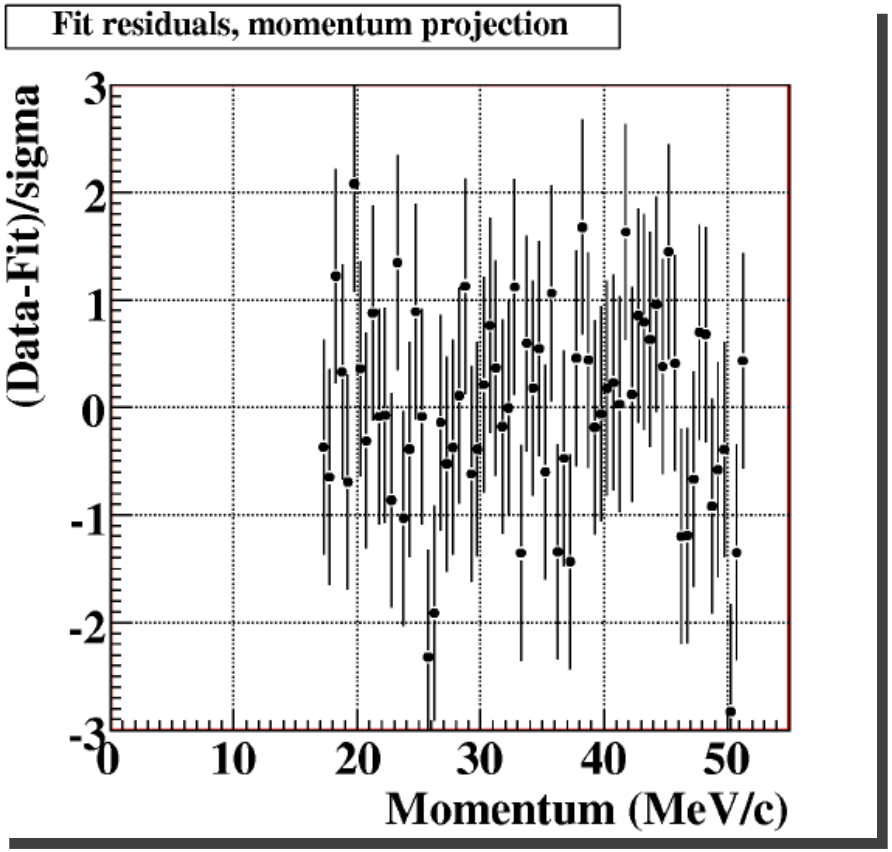
Energy Calibration



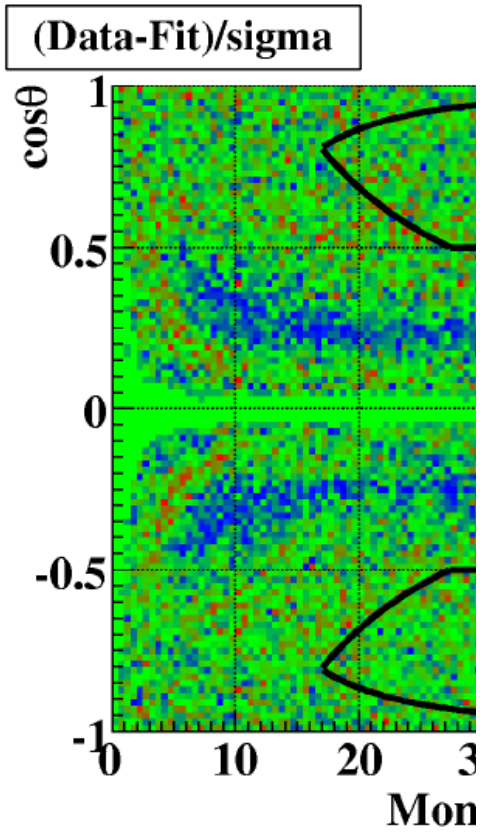
Data Resolution ~70 KeV/c
MC Resolution ~65 KeV/c
Relative Shift ~5 KeV/c
Geometry Error ~5 KeV/c
Adjusts for energy loss in target
Account for resolution difference

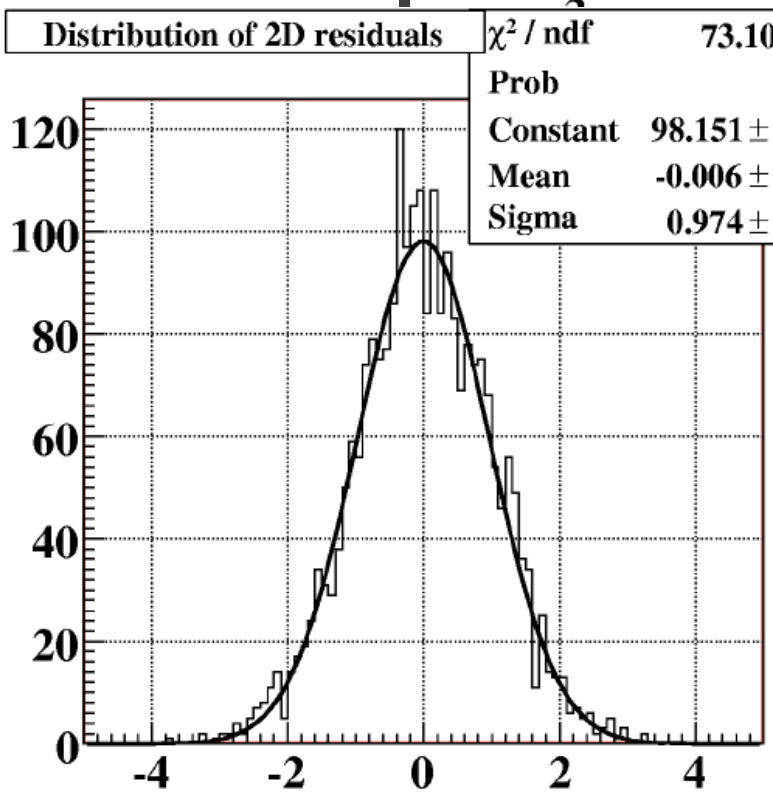
Spectrum Fit Quality

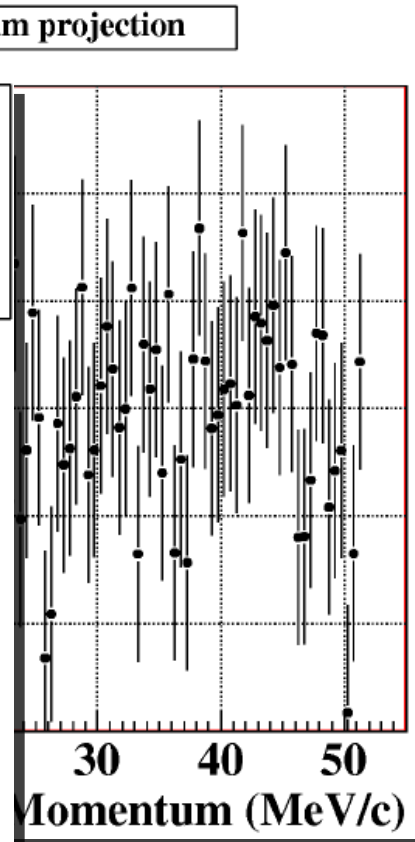




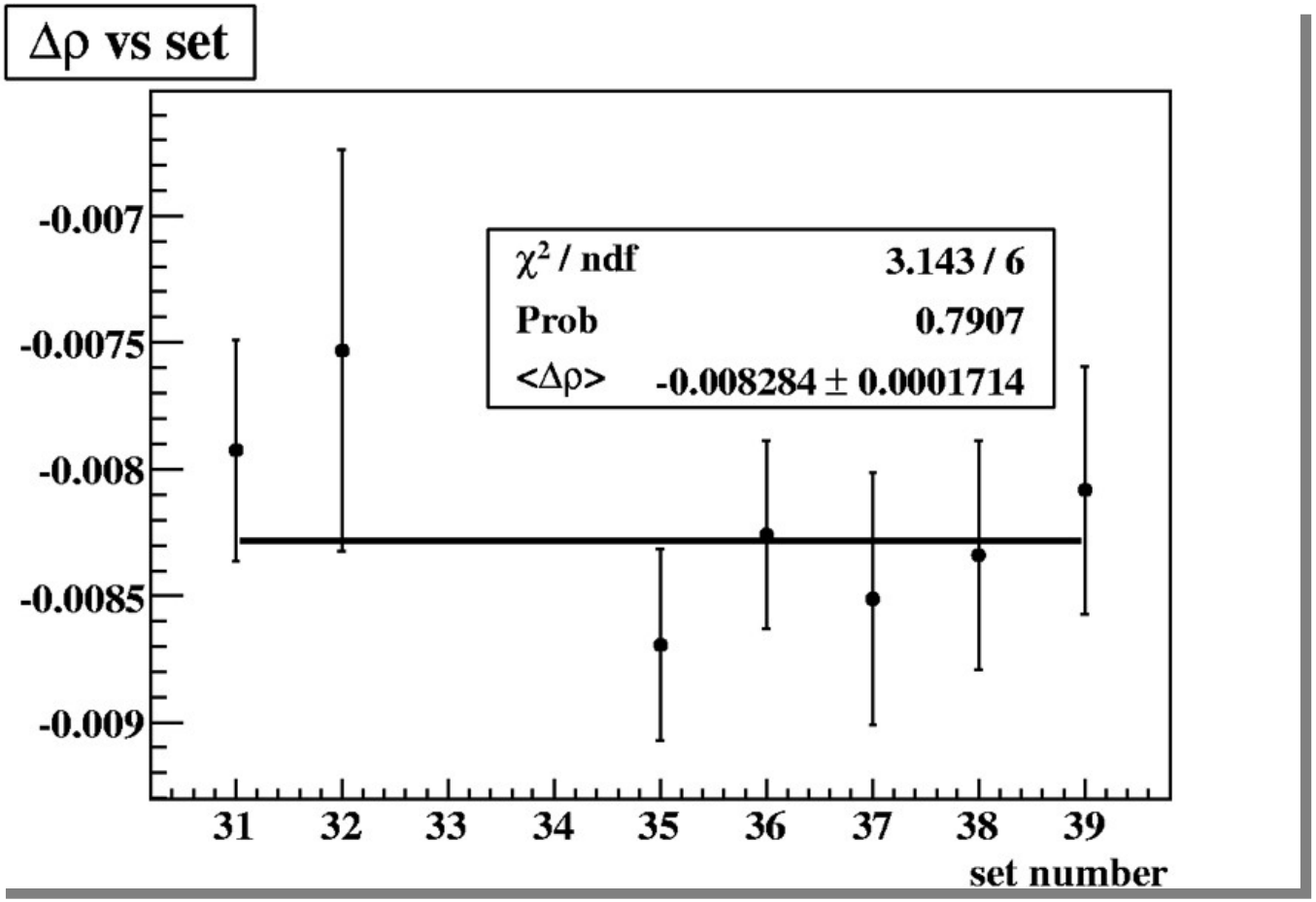
Spectrum Fit Quality







Consistency of Fits



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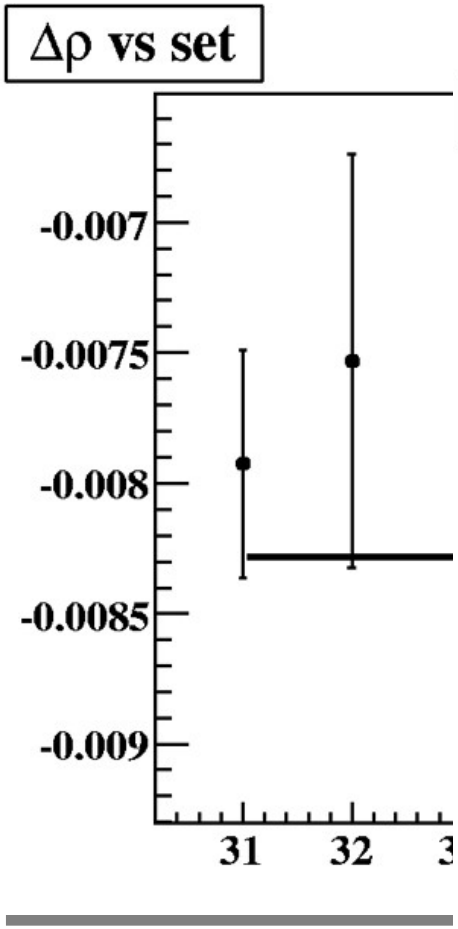

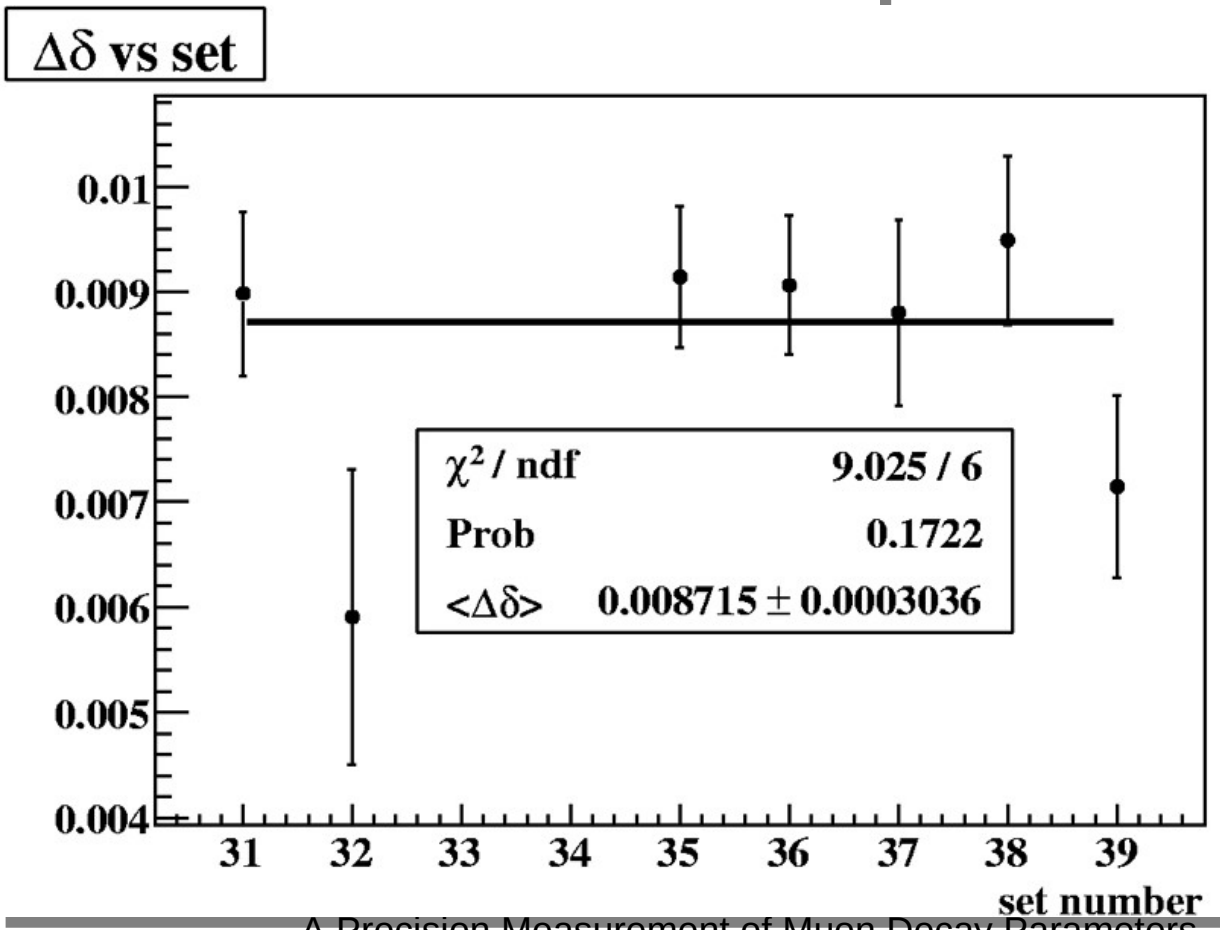

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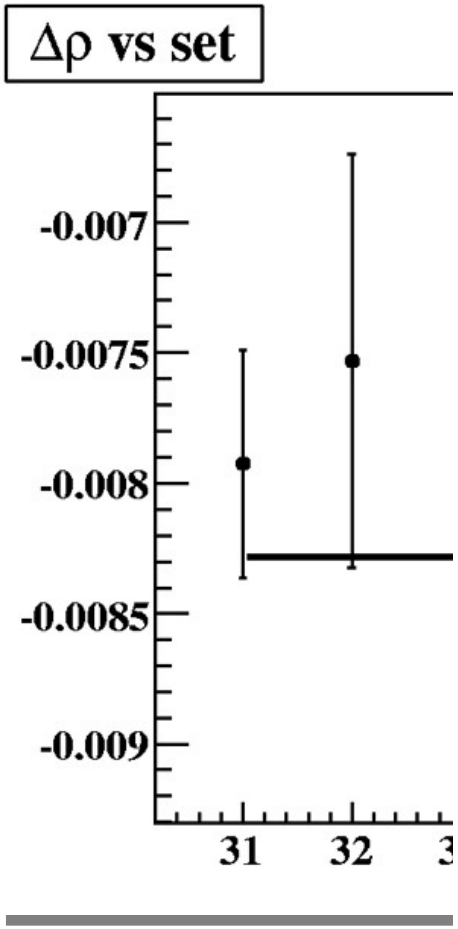
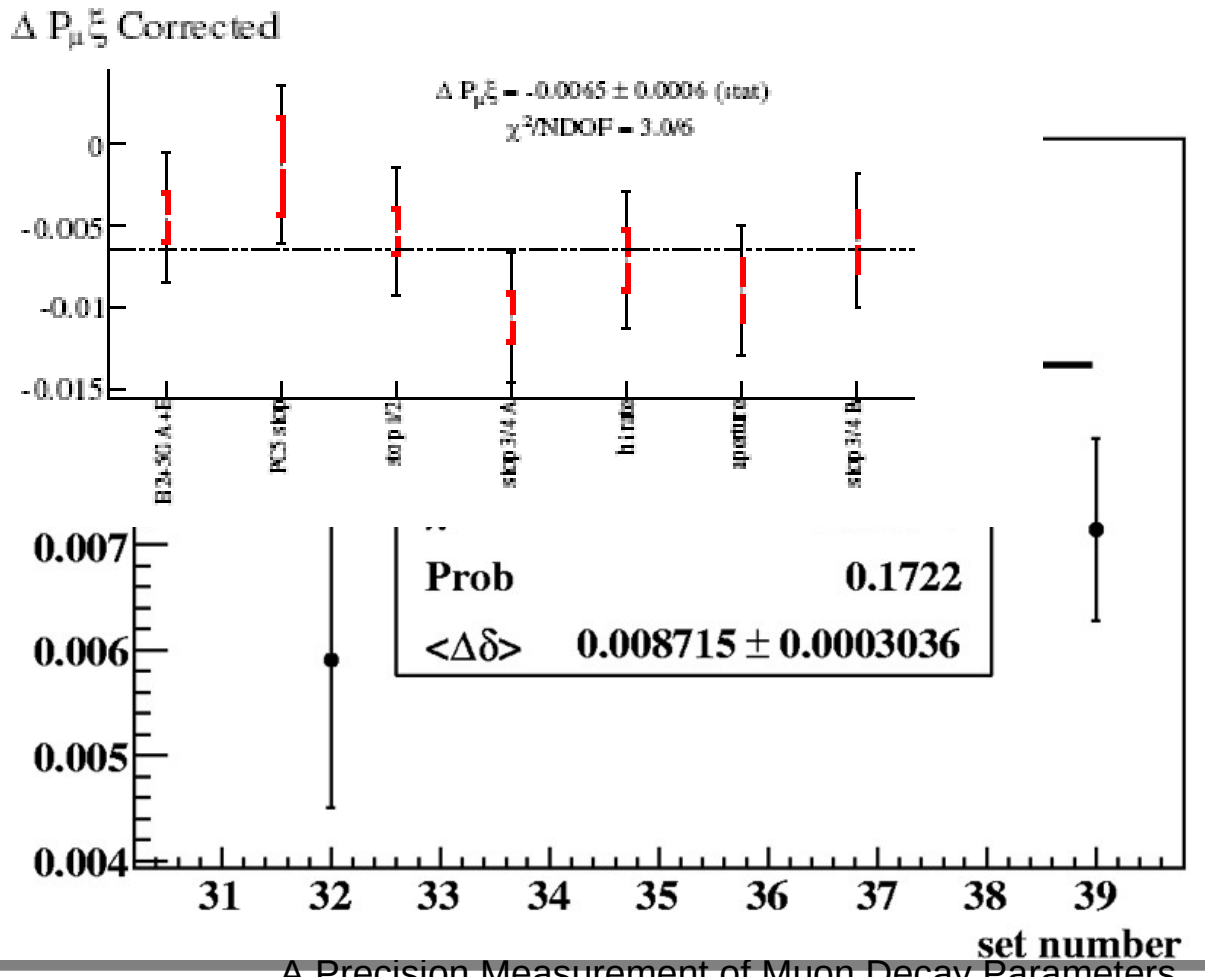
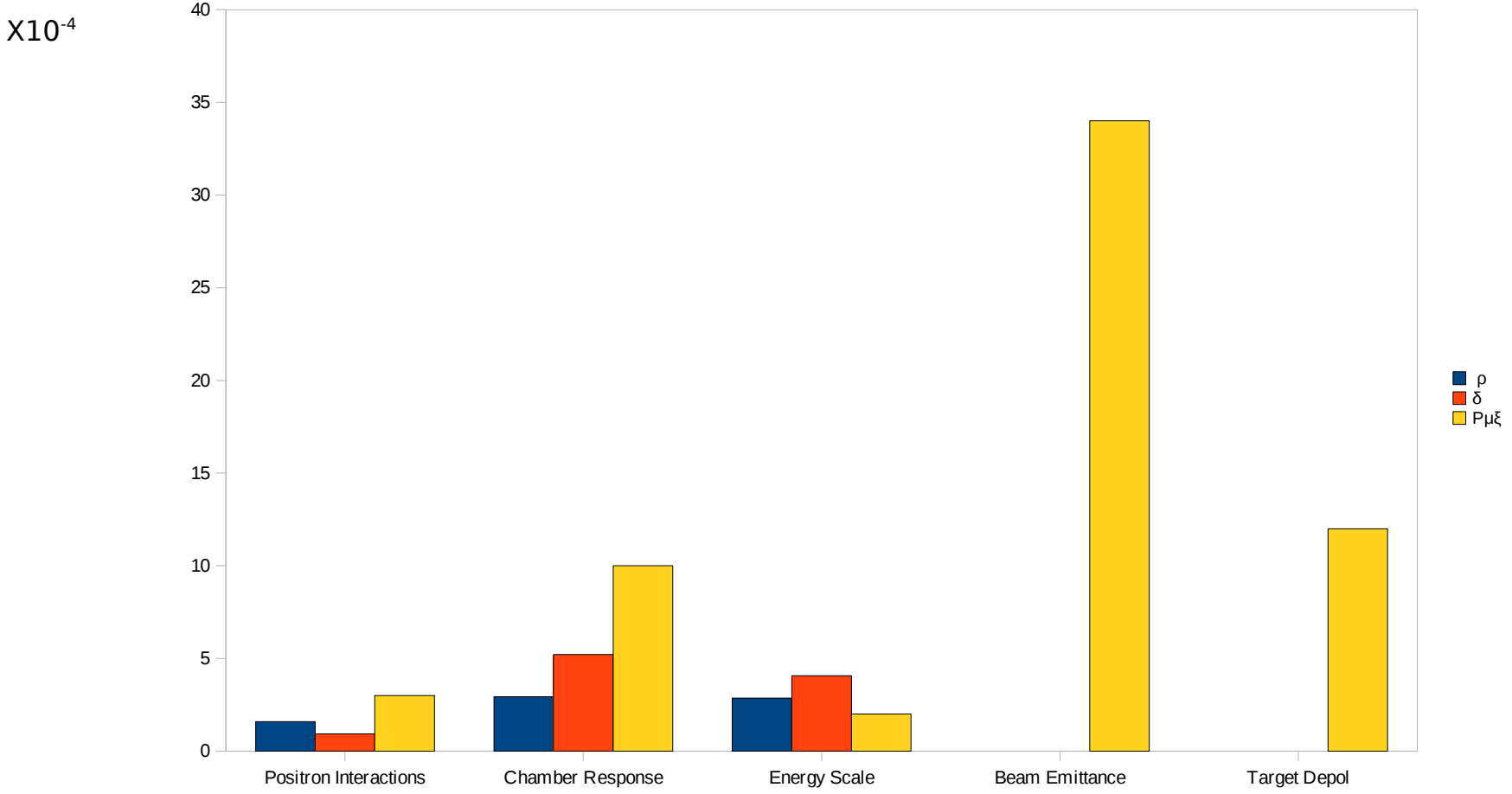
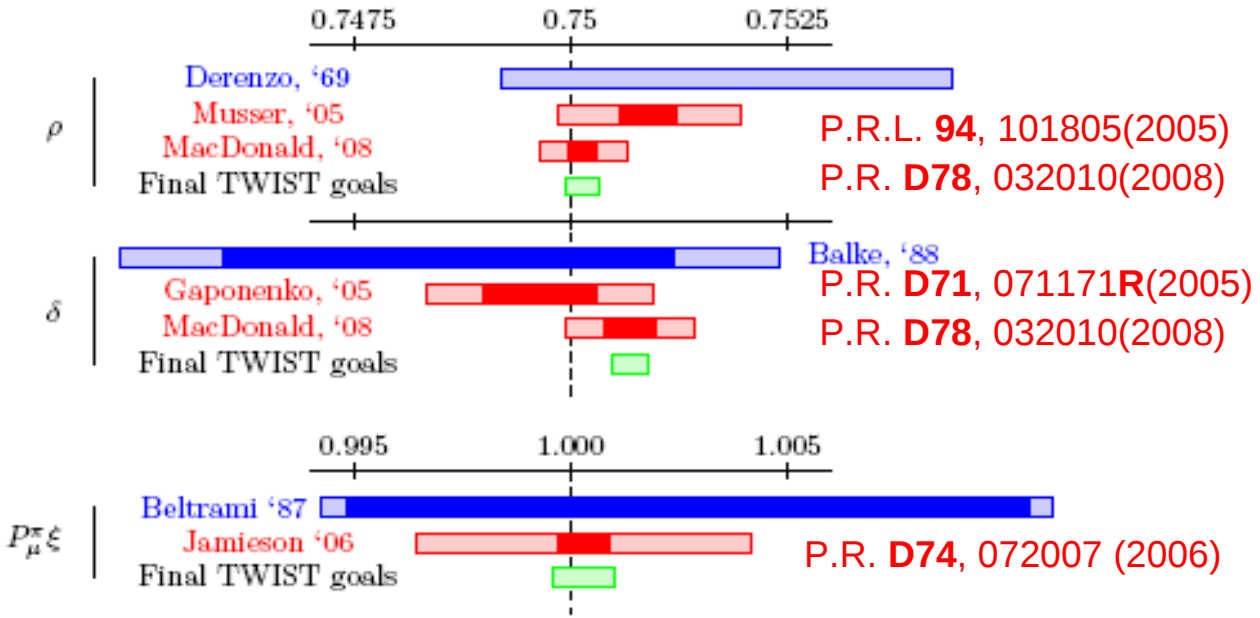




Leading Systematic Uncertainties



Current Status; Final Goals



Inner bars show statistical uncertainties only. Outer bars are full uncertainties.

Global Analysis of Muon Decay Data

μ decay parameters can be expressed as bilinear combinations of $g^{\gamma}_{\varepsilon\mu}$: $Q_{\varepsilon\mu}$, $B_{\varepsilon\mu}$, I_{α}, I_{β}

$$\rho = \frac{3}{4} + \frac{1}{4}(Q_{\mathrm{LL}} + Q_{RR}) - (B_{LR} + B_{RR})$$

$$\xi = 1 - Q_{RR} - \frac{10}{3}Q_{LR} + \frac{4}{3}Q_{RL} + \frac{16}{3}(B_{LR} - B_{RL})$$

$$\xi\delta = \frac{3}{4} - \frac{3}{2}Q_{RR} - \frac{7}{4}Q_{LR} + \frac{1}{4}Q_{RL} + (B_{LR} - B_{RL})$$

$$Therefore\ Q^{\mu}_{R} = Q_{LR} + Q_{RR} = \frac{1}{2}\left(1 + \frac{\xi}{3} + \frac{16}{9}\xi\delta\right)$$

more positron polarization parameters ...

Allowed ranges of these coupling constants are then obtained by computing the joint probability density function from the experimental measurements.
Gagliardi et al, Phys Rev 72(2005)73002.

Limits on Right-Handed Muon Decay

$$Q_R^{\mu} = \frac{1}{4}\left(\left|g_{LR}^{S}\right|^2 + \left|g_{RR}^{S}\right|^2\right) + \left|g_{LR}^{V}\right|^2 + \left|g_{RR}^{V}\right|^2 + 3\left|g_{LR}^{T}\right|^2$$

Pre-*TWIST*: $Q^{\mu}_{R} < 0.014$

Gagliardi: $Q^{\mu}_{R} < 0.007$

Current: $Q^{\mu}_{R} < 0.006$

Indirect $P_\mu\xi$ Limit

Jodidio $P_\mu\xi\delta/\rho > 0.9968$
combined with $Q_\mu^R \geq 0$:

$P_\mu\xi = 0.9973 \pm 0.0013$

TWIST Direct : $P_\mu\xi = 1.0003 \pm 0.0006 \pm 0.0038$

2006/2007: Final Data

- **Beam characterization improvements:**
  - Significant improvement to TEC. Beam characterizations start and end of each dataset.
  - Online monitoring of beam conditions.
  - Steering added to M13 beamline.
- **Chamber improvements:**
  - Rearrangement of chamber spacing.
  - Measurement of stops in PC gas.
- **Analysis improvements:**
  - Measured chamber response for each plane
  - Calibrations
  - Depolarization measured independently.
- **Increased statistics especially in simulations.**
- **Code is frozen and analysis is underway.**
- **Completion 2009-2010**

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New Coupling Constant Limits

Coupling	Fetcher	TWIST
$\lvert g^{S}_{RR}\rvert$	<0.066	<0.063
$\lvert g^{V}_{LR}\rvert$	<0.033	<0.032
$\lvert g^{S}_{LR}\rvert$	<0.125	<0.076
$\lvert g^{V}_{LR}\rvert$	<0.060	<0.027
$\lvert g^{T}_{LR}\rvert$	<0.036	<0.022
$\lvert g^{S}_{RL}\rvert$	<0.424	<0.415
$\lvert g^{V}_{RL}\rvert$	<0.110	<0.105
$\lvert g^{T}_{RL}\rvert$	<0.122	<0.104
$\lvert g^{S}_{LL}\rvert$	<0.550	<0.550
$\lvert g^{V}_{LL}\rvert$	>0.960	>0.960

Neutrino mass implications at 10^{-7}-10^{-4} for vector LR/RL: Erwin *et al.* PRD75,33005 (2007).