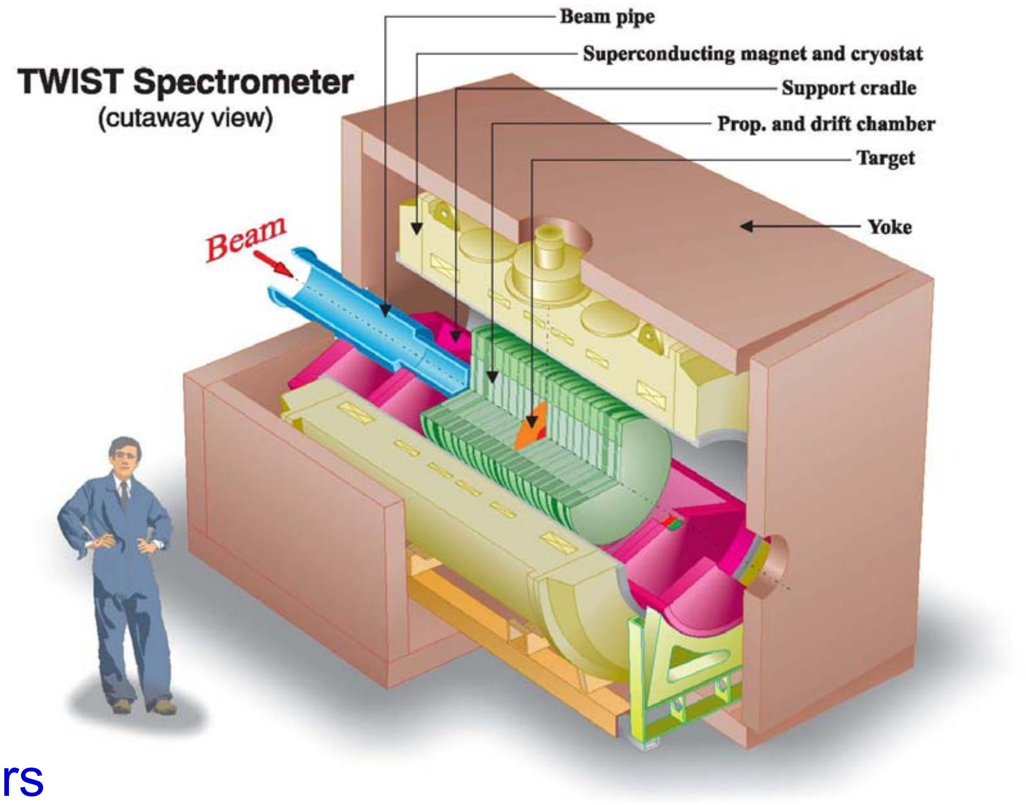
The *TWIST* Experiment -- Testing the Standard Model with Muon Decay

Mike Hasinoff, for the *TWIST* Collaboration

KEK seminar, 6 Nov 2007

The TRIUMF Weak Interaction Symmetry Test -- TWIST

- Tests the Standard Model predictions for muon decay.
- Uses a highly polarized μ^+ beam (μ^- don't work!).
- Stops the μ^+ in a very symmetric detector.
- Tracks the e^+ through a very uniform B field.
- Extracts the decay parameters by comparison to a detailed and verified MC simulation.



Michel parameter description

- Muon decay (Michel) parameters $\rho, \eta, \delta, \mathcal{P}_\mu \xi$
  - e^+ differential rate *vs.* energy and angle

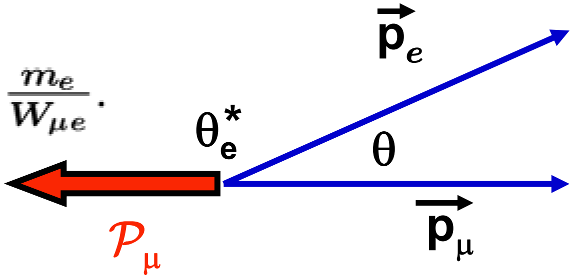
$$\frac{d^2\Gamma}{dx\, d\cos\theta_e^*} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot$$
$$\{\mathcal{F}_{IS}(x,\rho,\eta) + \mathcal{P}_\mu \cos\theta_e^* \cdot \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

Louis Michel

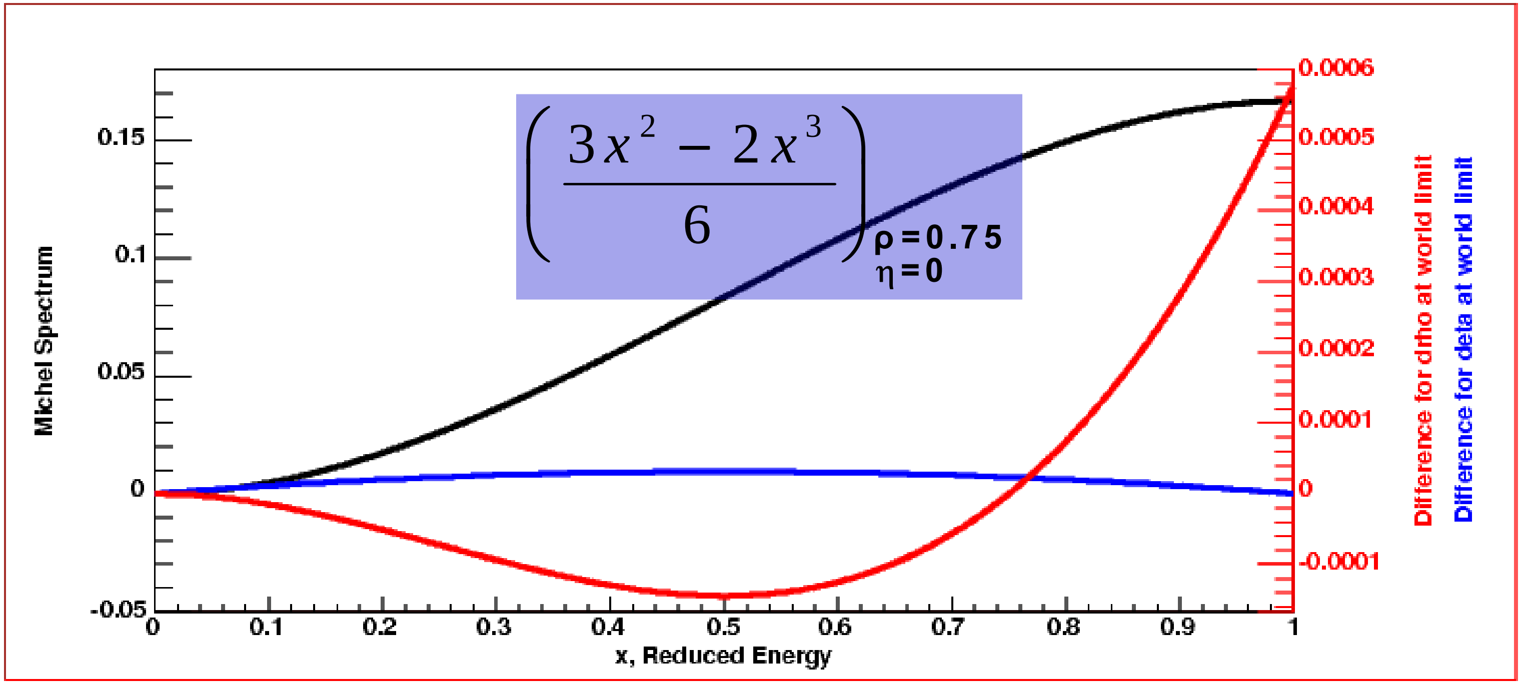
  - where

$$\mathcal{F}_{IS}(x,\rho,\eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\sqrt{x^2 - x_0^2}\left[\xi\,\{1-x\} + \frac{2}{3}\xi\delta\left\{4x - 3 + \left(\sqrt{1-x_0^2} - 1\right)\right\}\right]$$

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



Energy dependence of $(x\mathcal{F}_{IS}(x,\rho,\eta))$



Momentum dependence of isotropic term in the muon decay spectrum (black), compared with magnified (300x) excess contributions of ρ (red) and η (blue) at PDG limits.

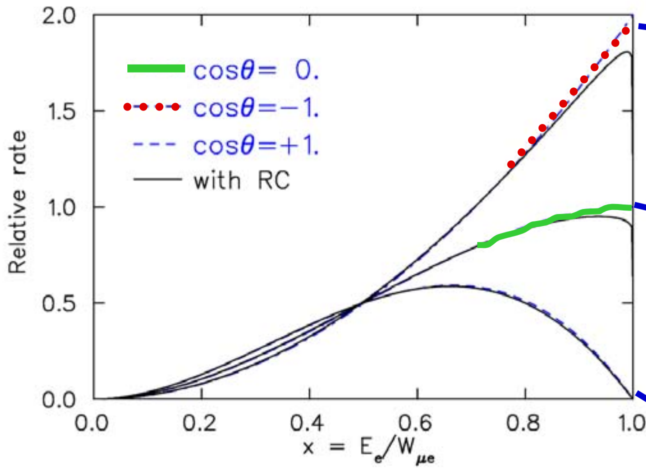
Pre-*TWIST* decay parameters

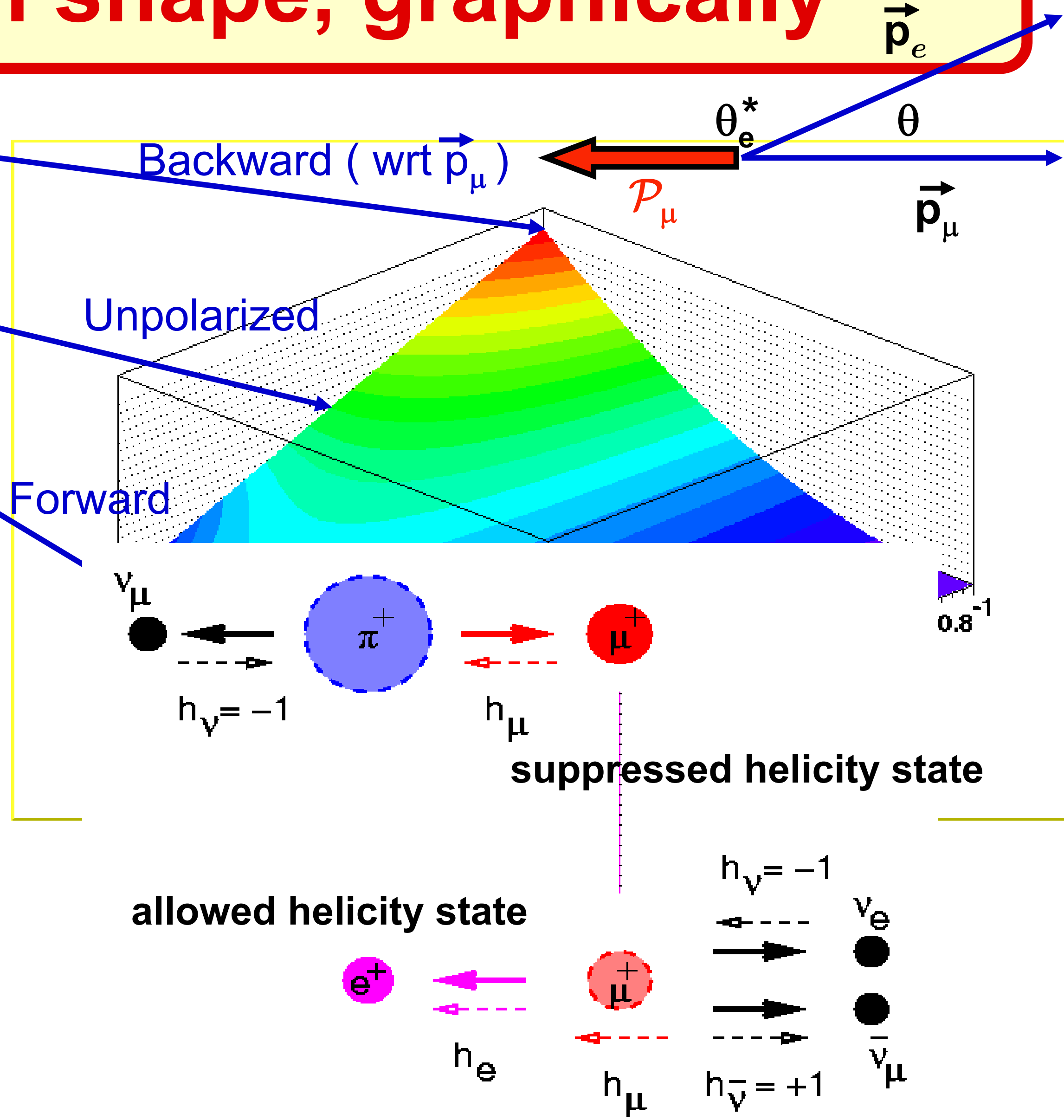
- From the Review of Particle Physics (SM values in parentheses) :

▪	$\rho = 0.7518 \pm 0.0026$	(Derenzo, 1969)	(0.75)
▪	$\eta = -0.0070 \pm 0.0130$	(Burkard *et al.*, 1985)	(0.00)
▪	$\delta = 0.7486 \pm 0.0026 \pm 0.0028$	(Balke *et al.*, 1988)	(0.75)
▪	$\mathcal{P}_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$	(Beltrami *et al.* , 1987)	(1.00)
▪	$\mathcal{P}_\mu\xi = 0.9996 \pm 0.0030 \pm 0.0048$	(Aoki *et al.*, 1994)**	(1.00)
▪	$\mathcal{P}_\mu(\xi\delta/\rho) > 0.99682$	(Jodidio *et al.*, 1986)	(1.00)

TWIST is searching for non Standard Model physics which might become apparent by improving the precision of each of the muon decay parameters -- ρ, δ, and $\mathcal{P}_\mu\xi$ by at least one order of magnitude compared to the existing experimental results.

Spectrum shape, graphically





- **O(α) -- Full radiative corrections with the exact electron mass dependence.**
- **O(α²) -- Leading order (LO) and NLO logarithmic terms.**
- **O(α³) -- LO logarithmic terms.**
- **Corrections for soft pairs, virtual pairs and an ad-hoc exponentiation.**

Michel parameters and coupling constants

- Fetscher and Gerber coupling constants (see PDG):

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

Local, derivative free, Lorentz-invariant theory

$$\begin{aligned}
\rho &= \frac{3}{4} - \frac{3}{4}[|g^V_{RL}|^2 + |g^V_{LR}|^2 + 2|g^T_{RL}|^2 + 2|g^T_{LR}|^2 \\
&\quad + \mathbb{R}e\,(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR})] \\
\eta &= \frac{1}{2}\mathbb{R}e[g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})] \\
\xi &= 1 - \frac{1}{2}|g^S_{LR}|^2 - \frac{1}{2}|g^S_{RR}|^2 - 4|g^V_{RL}|^2 + 2|g^V_{LR}|^2 - 2|g^V_{RR}|^2 \\
&\quad + 2|g^T_{LR}|^2 - 8|g^T_{RL}|^2 + 4\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL}) \\
\xi\delta &= \frac{3}{4} - \frac{3}{8}|g^S_{RR}|^2 - \frac{3}{8}|g^S_{LR}|^2 - \frac{3}{2}|g^V_{RR}|^2 - \frac{3}{4}|g^V_{RL}|^2 - \frac{3}{4}|g^V_{LR}|^2 \\
&\quad - \frac{3}{2}|g^T_{RL}|^2 - 3|g^T_{LR}|^2 + \frac{3}{4}\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})
\end{aligned}$$

$$\mathbf{g^V_{LL}} = 1$$

Limits on coupling constants

- Coupling constants $g^{\gamma}_{\varepsilon\mu}$ can be related to handedness, *e.g.*, total muon right-handed coupling:-- (ie μ^+ coupling to both RH and LH e^+)

$$Q^{\mu}_{R} \equiv Q_{RR} + Q_{LR} = \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \geq 0$$

- Global analysis of μ decay -- Gagliardi *et al.*, Phys. Rev. **D72** (2005)
  - no existing similar analysis for other weak decays.

$\lvert g^S_{RR}\rvert < 0.066(0.067)$	$\lvert g^V_{RR}\rvert < 0.033(0.034)$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125(0.088)$	$\lvert g^V_{LR}\rvert < 0.060(0.036)$	$\lvert g^T_{LR}\rvert < 0.036(0.025)$
$\lvert g^S_{RL}\rvert < 0.424(0.417)$	$\lvert g^V_{RL}\rvert < 0.110(0.104)$	$\lvert g^T_{RL}\rvert < 0.122(0.104)$
$\lvert g^S_{LL}\rvert < 0.550(0.550)$	$\lvert g^V_{LL}\rvert > 0.960(0.960)$	$\lvert g^T_{LL}\rvert \equiv 0$

New calculations -- m_ν masses

Erwin et al., Phys. Rev. **D75** (2007) 033005 (hep-ph/0602240).

Coupling Constant	Global Analysis	from ν mass limits*
$\lvert g^V_{LR} \rvert$	< 0.036	8×10^{-7}
$\lvert g^S_{LR} \rvert$	< 0.088	4×10^{-7}
$\lvert g^T_{LR} \rvert$	< 0.025	2×10^{-7}
$\lvert g^V_{RL} \rvert$	< 0.104	2×10^{-4}
$\lvert g^S_{RL} \rvert$	< 0.417	8×10^{-5}
$\lvert g^T_{LR} \rvert$	< 0.104	4×10^{-5}

- Effective Operator Field Theory
- consider only operators that contribute to both processes (no LL, RR)
- $g^{S,T}_{RL}$, $g^{S,T}_{LR}$ ~ 4 fermions
- g^V_{RL}, g^V_{LR} ~ 2 fermions + 2 Higgs
- one loop ~ 10^{-2} x two loop effects
- only Dirac neutrinos
- *Units $\left(\frac{\mathbf{v}}{\Lambda}\right)^2 \mathbf{m}_\nu$

Testing the Standard Model

- Model independent muon handedness:

$$Q_R^\mu = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \geq 0$$

- Left-right symmetric models (simplified!):

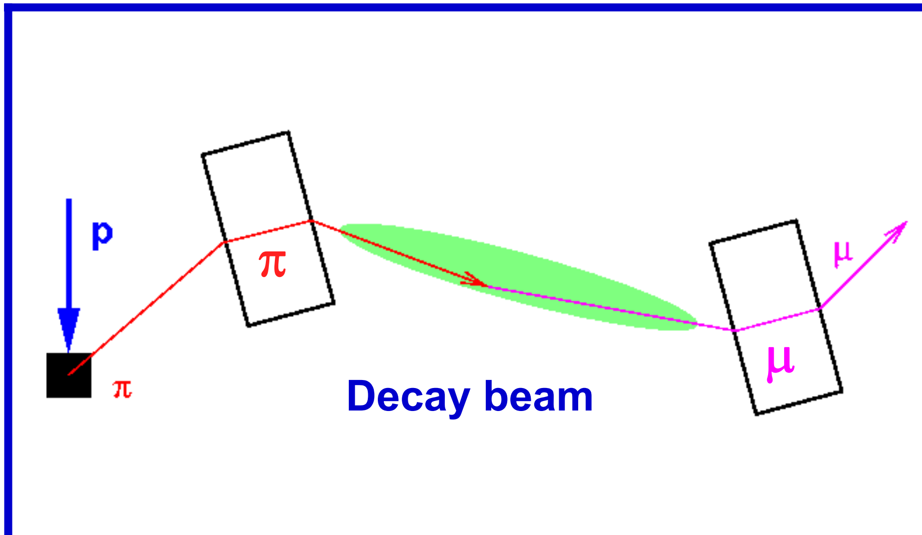
$$W_L = W_1 \cos\zeta + W_2 \sin\zeta, \qquad W_R = -W_1 \sin\zeta + W_2 \cos\zeta$$

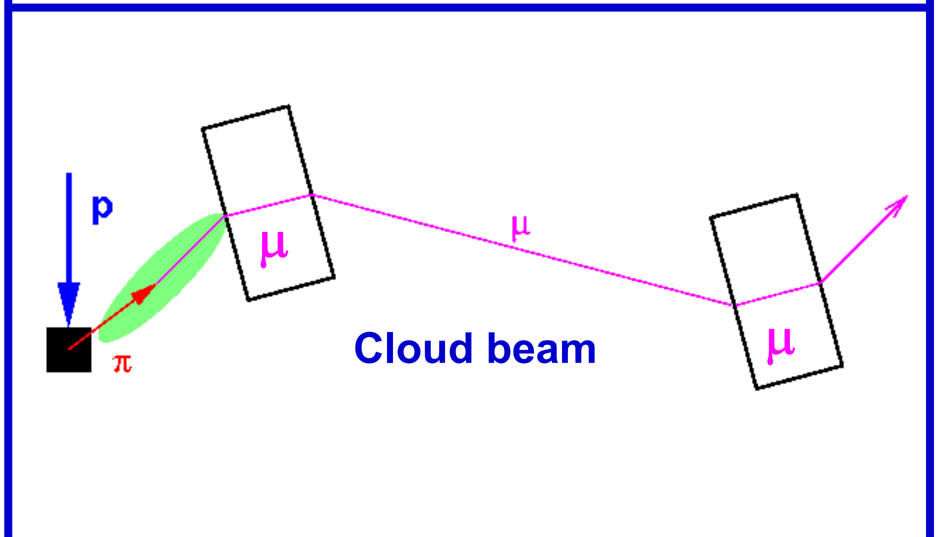
$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2, \qquad 1 - \mathcal{P}_\mu \xi = 4\{\zeta^2 + \frac{m_1^4}{m_2^4} + \zeta\frac{m_1^2}{m_2^2}\}$$

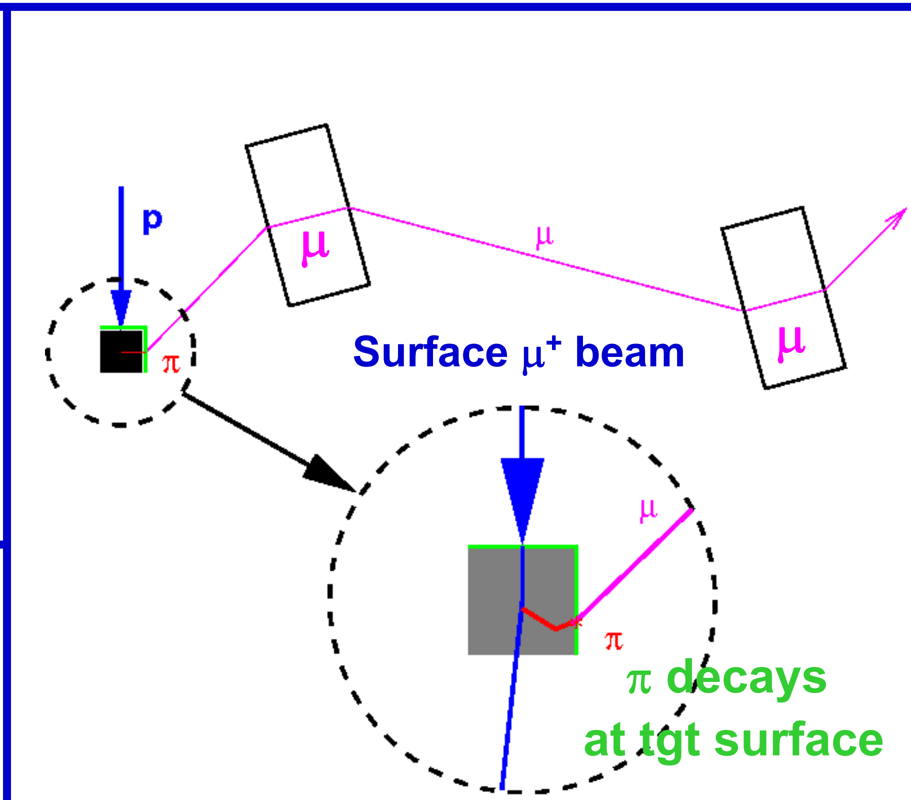
- Tensor interaction (M. Chizhov, hep-ph/0405073):

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

Types of muon beams



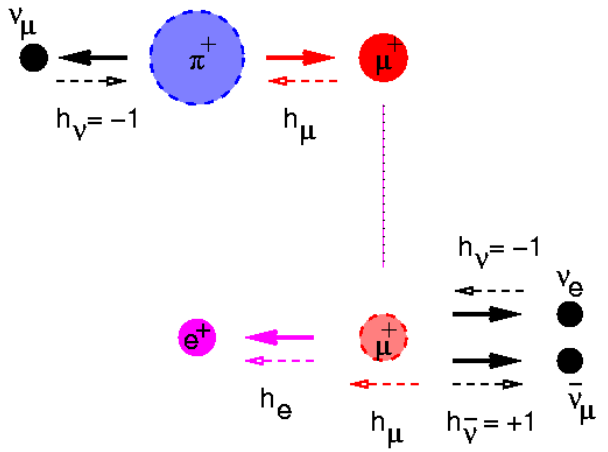


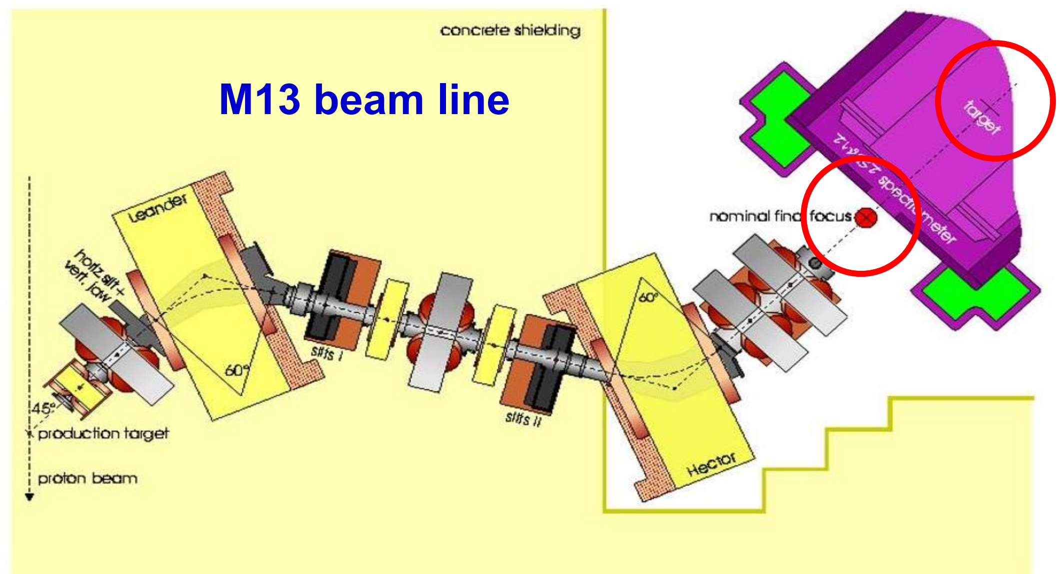


Surface muons have high polarization (in the direction of muon momentum) and very high luminosity at low momentum (29.79 MeV/c, or 4.1 MeV).

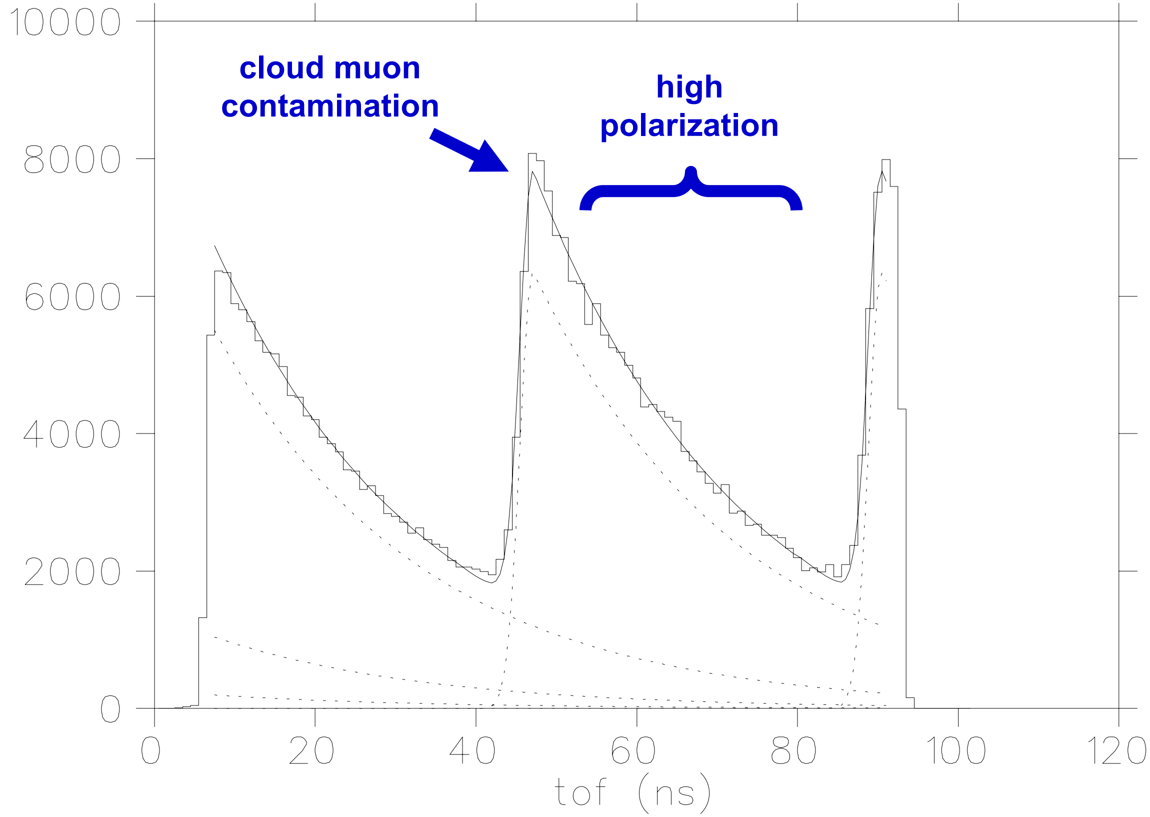
Surface muon beam

- Pions decaying at rest produce muon beams with $\mathcal{P}_\mu > 99\%$.
- Depolarization must be controlled using narrow beam near kinematic edge, 29.8 MeV/c.
- Use $\sim 2.5\times10^{3}$ μ^{+} /s.
- Muon total range for density $\sim$1 is only about 1.5 mm!





Muon TOF and polarization

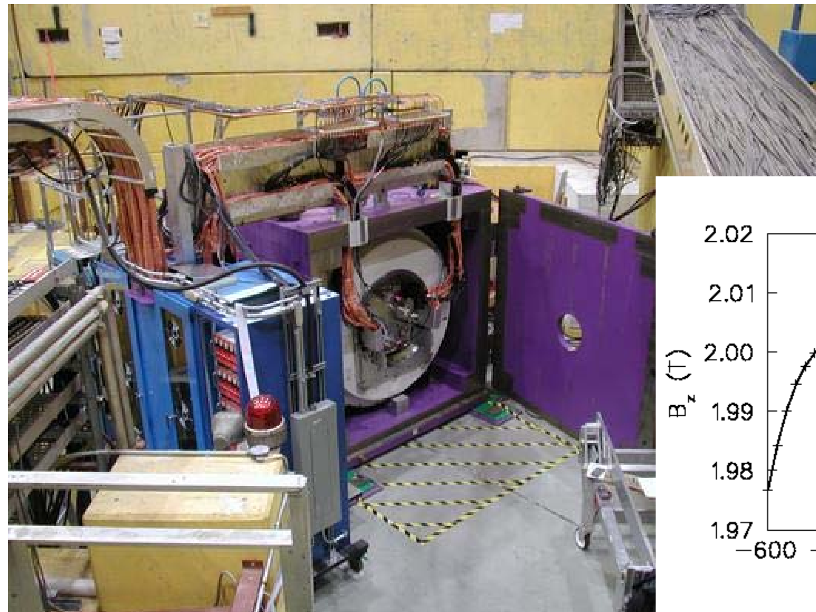


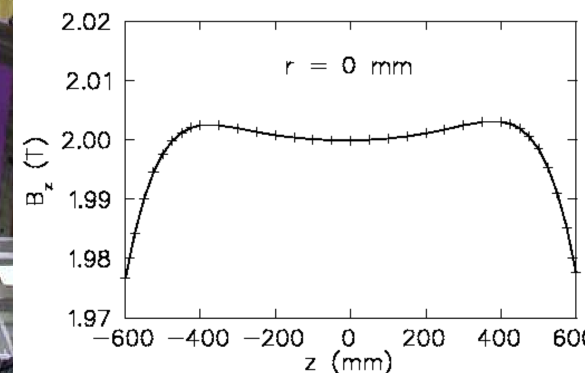
-- Time of flight with respect to accelerator RF (43 ns period).

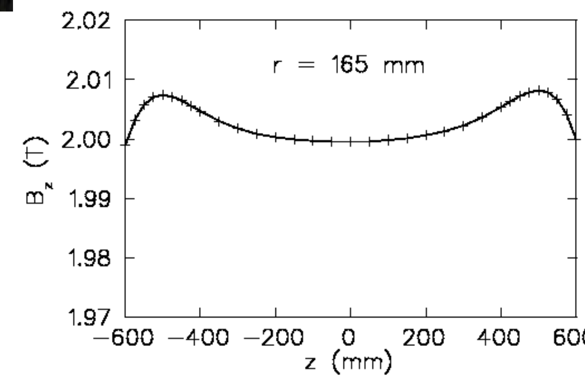
-- Pion decay at rest leads to 26 ns exponential for the surface muon arrival time, while the low polarization cloud muons are at the leading edge of the muon time distribution.

TWIST Solenoid field

- 20 year old ex-MRI superconducting solenoid magnet provides 2T field.
- Steel yoke improves uniformity, reduces stray fields.
- Uniform to 4×10^{-3}; mapped to precision of 5×10^{-5}.

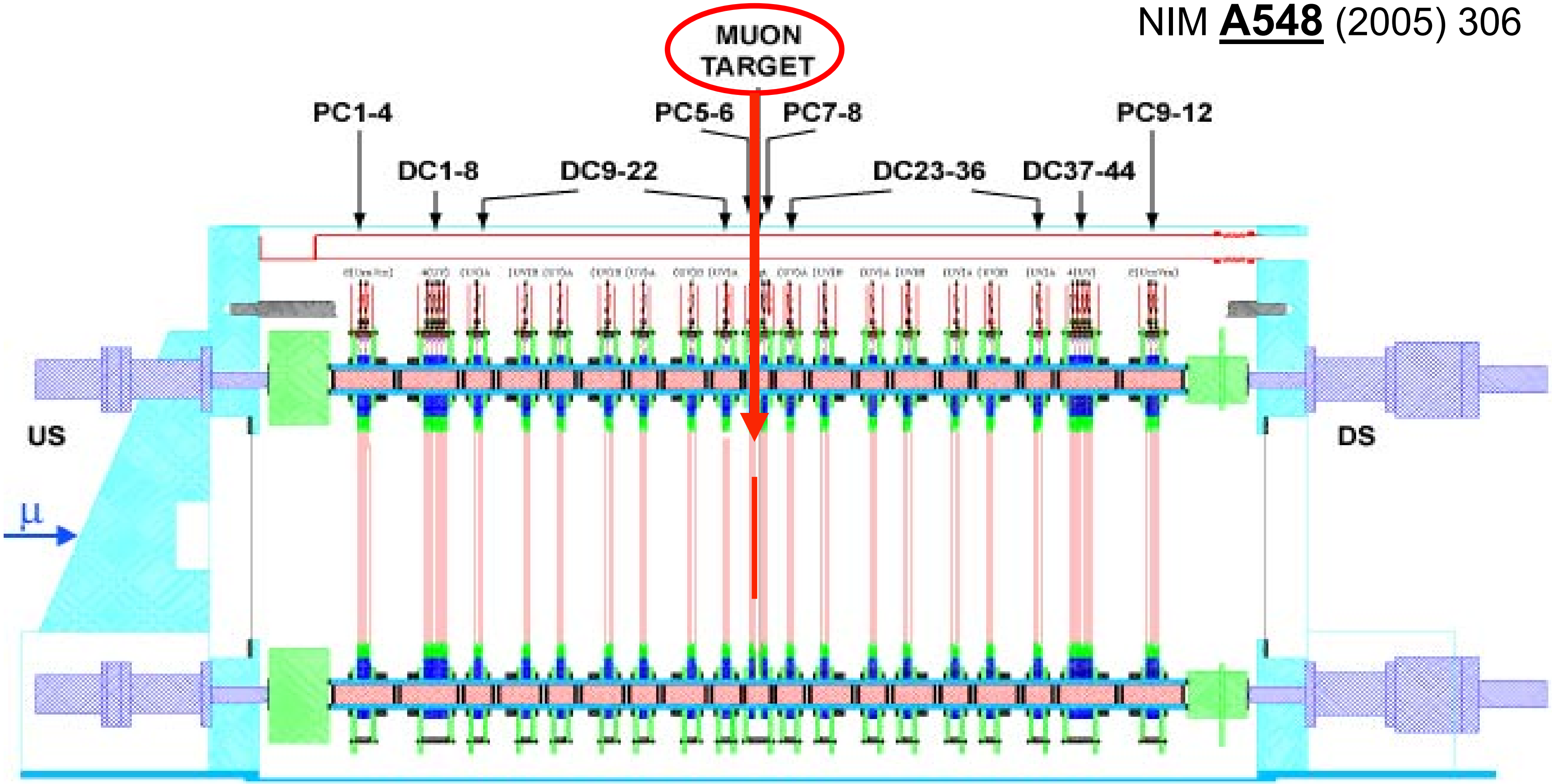






TWIST Detector array

NIM **A548** (2005) 306



- 56 low-mass high-precision planar chambers symmetrically placed around a thin target foil which stops nearly all of the surface muon beam. (44 DC + 12 PC).
- Measurement started by a single thin scintillation counter at the entrance to detector.
- μ^+ Beam stopping position is controlled by a variable He/CO_2 gas degrader.

TWIST Detector Cradle

-- Use glass frames – wire positions ~3 μm

$$\frac{\delta L}{L} = 5 \times 10^{-6}\,\Delta T$$

-- Use ceramic spacers– optical quality – flat & parallel ~0.5 μm

$$\frac{\delta L}{L} = 1 \times 10^{-7}\,\Delta T$$

DCs — use DME gas

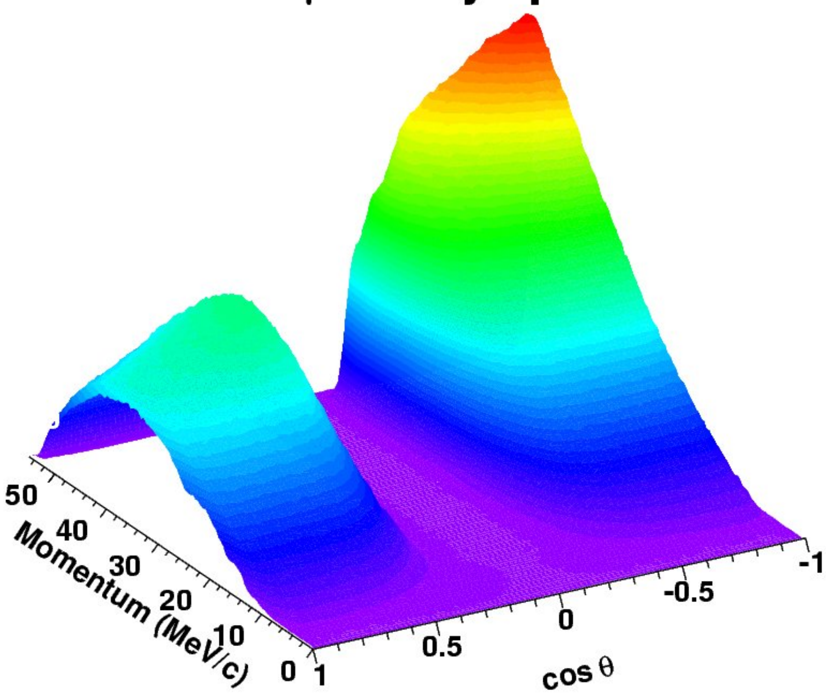
PCs — use CF4/isobutane

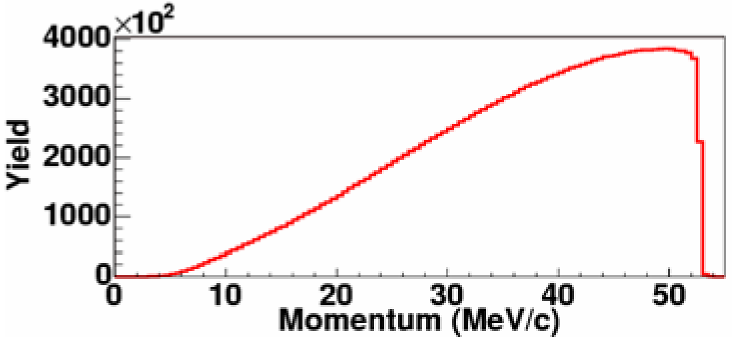
Cradle –- He/N (97:3)

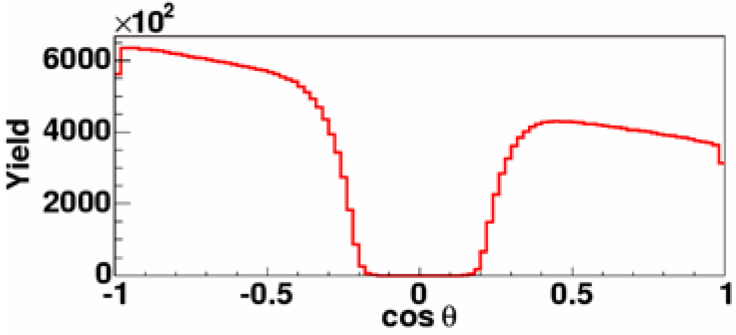
Array of 56 detector planes in the support cradle

Measured Data distributions

Surface μ decay spectrum







Acceptance of TWIST spectrometer → 0 at 90 deg

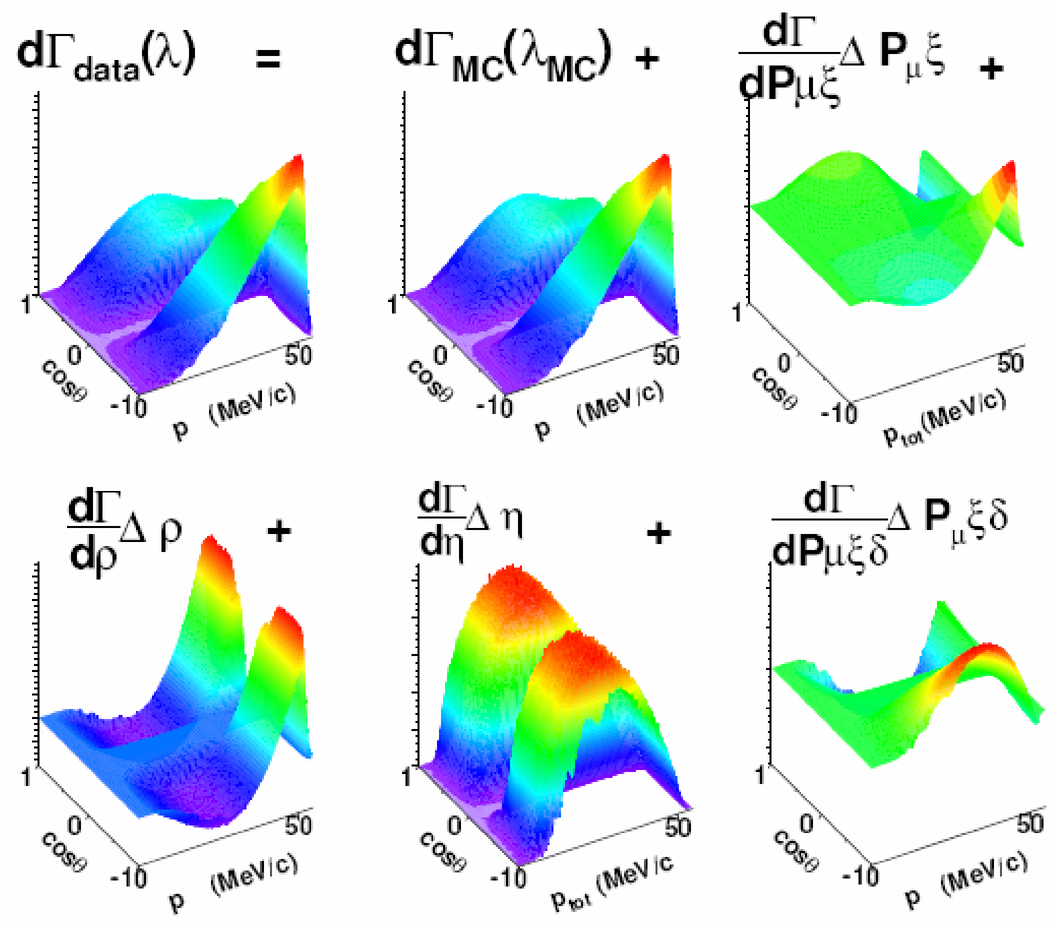
Fitting the data distributions

- Decay distribution is linear in ρ, η, $\mathcal{P}_\mu\xi$, and $(\mathcal{P}_\mu\xi\delta)$; hence a fit to a first order expansion is exact.

- Fit data to simulated (MC) base distribution with ***hidden assumed parameters***,

  $\lambda_{MC} = (\rho, \eta, \mathcal{P}_\mu\xi_{|\mathcal{P}_\mu\xi\delta}, \mathcal{P}_\mu\xi\delta)$

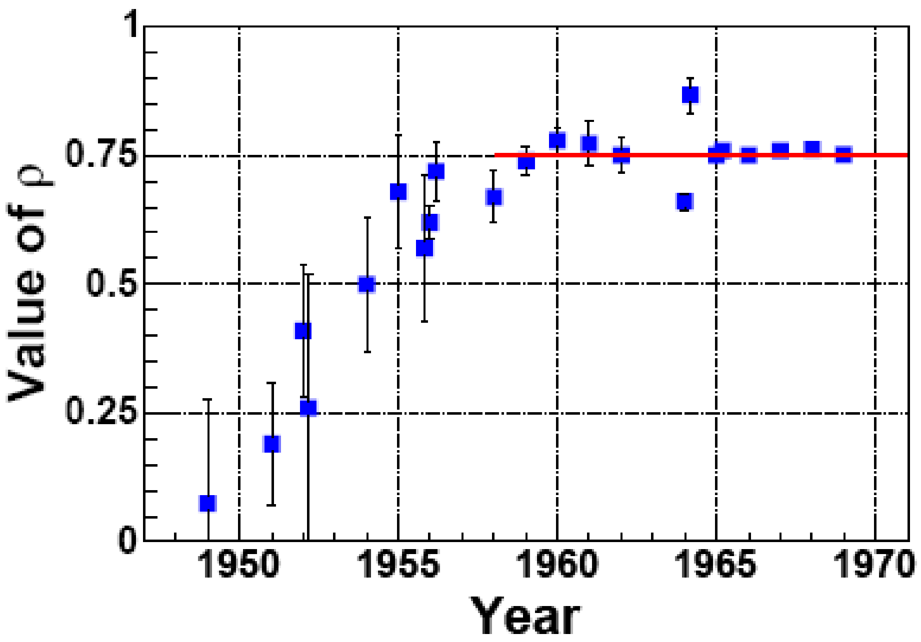
  plus MC-generated distributions from analytic derivatives, times fitting parameters ($\Delta\lambda$), which represent the deviations from the base MC.



(graphics thanks to Blair Jamieson)

Blind analysis -- motivation

- Reduce "human" systematics, *i.e.*, biases towards the "expected" result.
- Keep final result hidden until the analysis is finished and the systematic uncertainties are completely evaluated.
- In the fit procedure, the set of simulation parameters λ_{MC} is encrypted and unknown; the results of the fits are just the ***differences*** $\Delta\lambda$ from the hidden values.



A. Gaponenko, Ph.D. thesis

First *TWIST* analysis

- Data taken in Fall 2002: -- mylar/graphite target
  - 6×10^{9} muon decay events in data sets of about 3×10^{8} events (2-3 days) each.
  - Five (ρ) or four (δ) sets were analyzed and fit to extract results.
  - Remainder were used for systematic tests.

- Analysis relied on the WestGrid installation at UBC:
  - 1040 ($\rightarrow$ 1680) Intel 3 GHz processors in total.
  - became available in Fall 2003; operating well in early 2004.
  - *TWIST* used $\sim$31,000 processor days in 2004 to analyze the data and to generate & analyze the MC simulations.

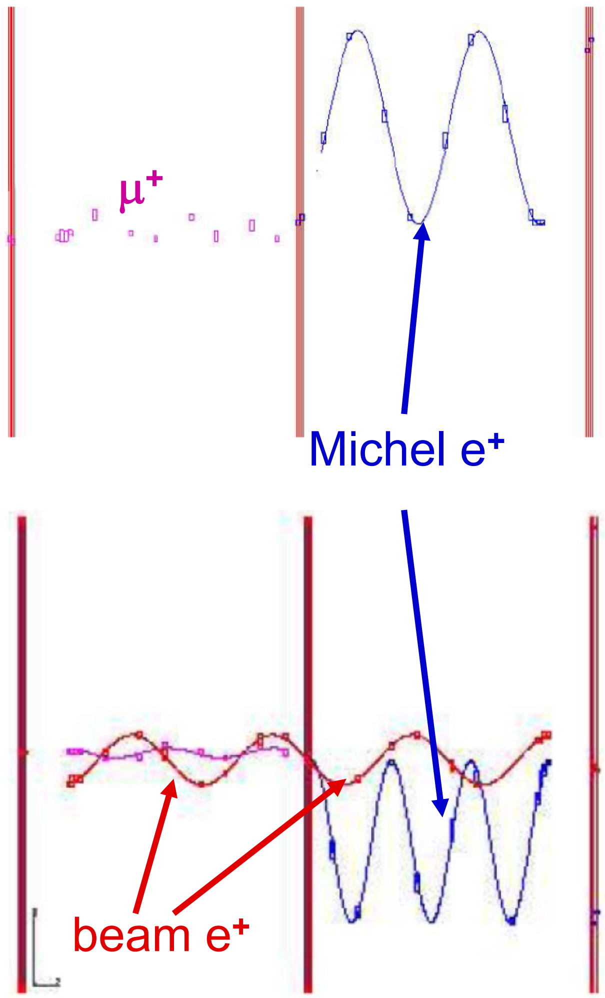
Analysis Method

- Extract energy and angle distributions for data:
  - apply (unbiased) cuts on muon variables.
  - reject fast decays and complicated background events.
  - calibrate e^+ energy using the kinematic end point at 52.8 MeV.
- Fit to identically derived distributions from MC simulation:
  - GEANT3 geometry contains virtually all detector components.
  - simulate detector response in detail (eg. ionization clusters).
  - use realistic, measured beam profile and divergence.
  - include extra muon and beam positron contamination.
  - output MC in digitized format, identical to real data.
  - fit to hidden variables using the blind analysis method.

Track Fitting

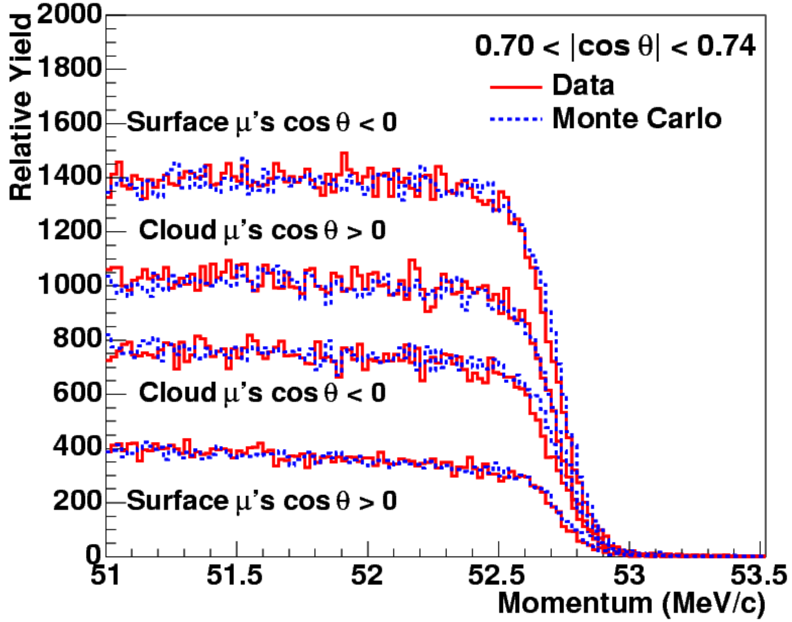
- Read out chamber hits in time interval (-6, +10) μs.
- Use pattern recognition (in position and time) to sort hits into tracks, then fit to helix.

  -- good e^+ t_e = (1.05, 9.0) μs.
- Write out track parameters and other variables for each event.
- Must recognize beam positrons, delta tracks, backscattering tracks.



Energy calibration

- Use the only distinctive feature of the distribution: the end point.
- Fit the edge energy and width for different narrow angular ranges.
- Edge energy: absolute and angle-dependent parameters β, α.
- With correct B field, β = 0.
- α represents energy loss, mostly in the muon stopping target.



$$E_{\rm edge} = (1+\beta)\left(E_{\rm max} - \frac{\alpha}{|\cos\theta|}\right)$$

Evaluation of Systematic Uncertainties

- *TWIST* relies on a fit to the MC simulation:
  - Simulation must be verified.
  - Reconstruction systematics are eliminated if the MC simulation is perfect.
- General method:
  - exaggerate a condition (in data or MC) which may cause an error.
  - measure the effect by fitting, using correlated sets where practical.
  - scale the results according to the variance in a data set.
  - Linearity? Double counting?

•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 reproducability**

•Muon beam stability:
- **•Stopping location**
- **•Beam intensity**
- **•Magnet stability**

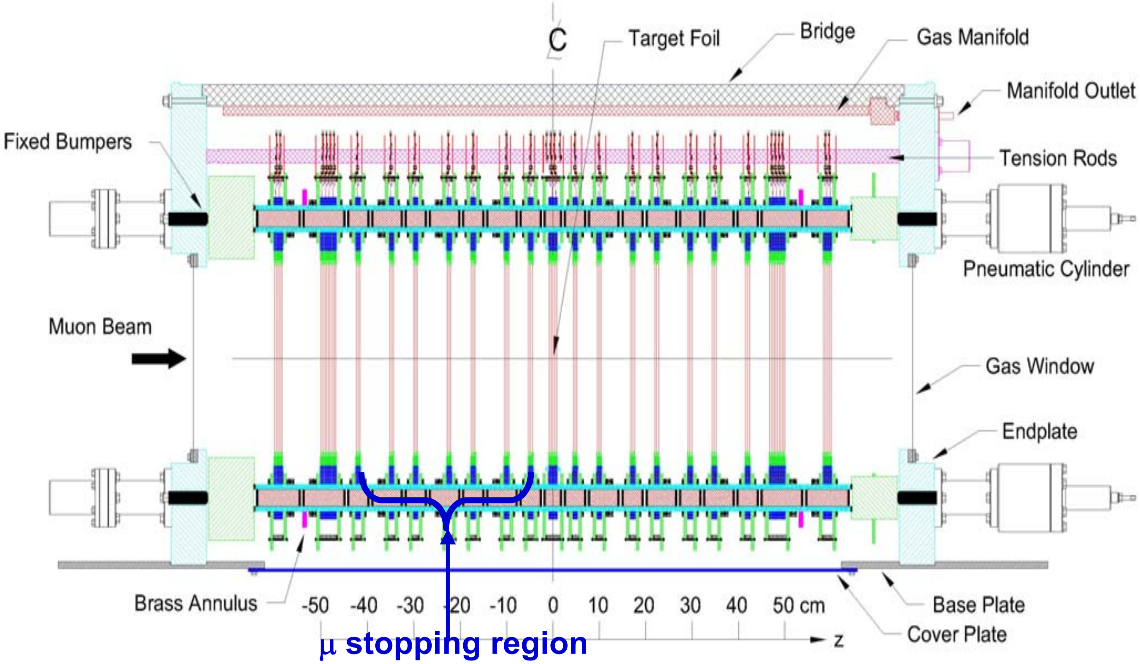
•Spectrometer alignment:
- **•Translations**
- **•Rotations**
- **•Longitudinal**
- **•B Field relative to the detector axis**

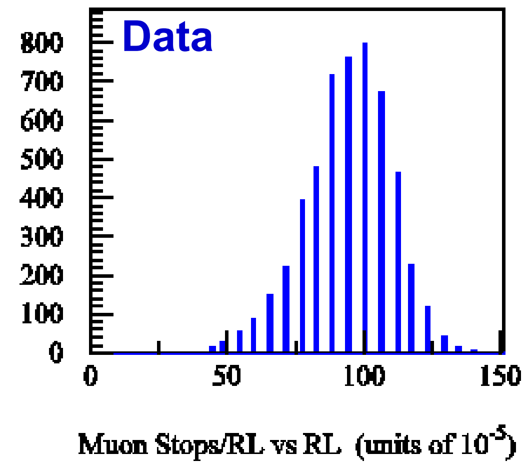
Systematics-- general method

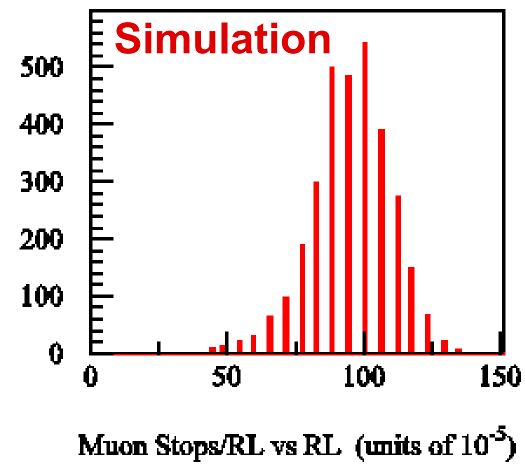
- Muon stopping target was 125 μm Mylar, coated with 10$\pm$10 μm graphite for conductivity. What is the uncertainty in the Michel parameters due to the thickness uncertainty ?
  - simulate with 30 μm graphite thickness (3$\times$ exaggeration).
  - fit to simulation (correlated) with nominal thickness:
    - shift for $\rho = -\,0.98 \times 10^{-3}$ and $\delta = -\,0.73 \times 10^{-3}$.
  - divide shift by exaggeration factor (3).

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

Simulation-- muon interactions



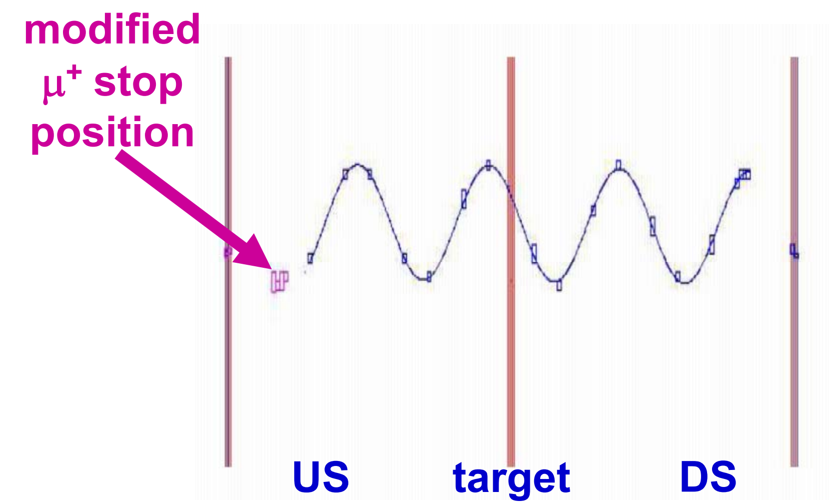


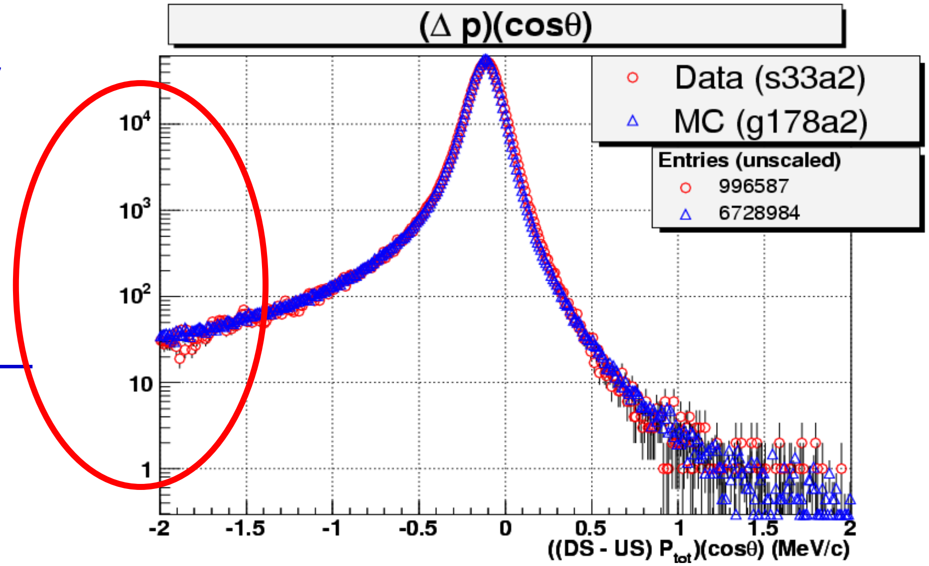


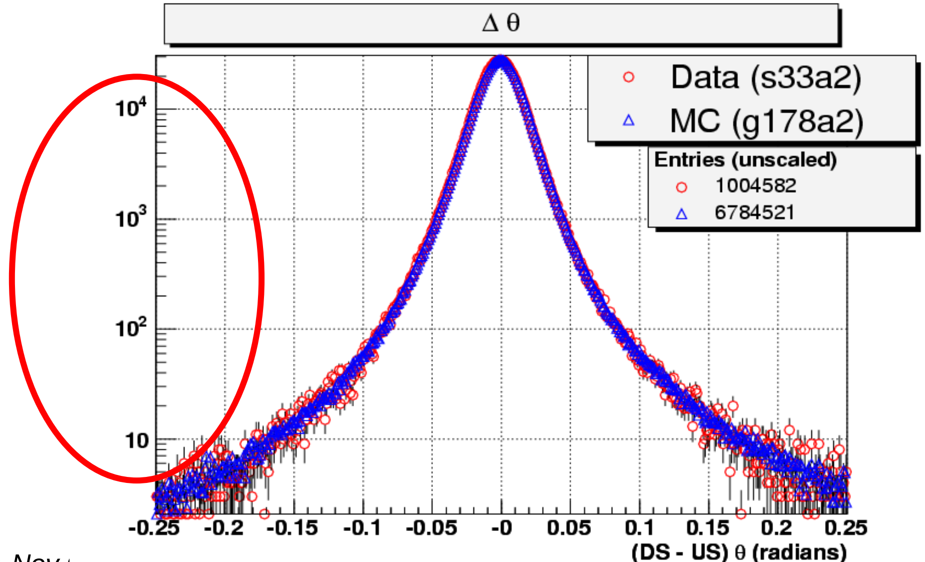
- Simulation must reliably predict the muon stopping distributions.
- Verify by comparison in a low-mass detector region.

Simulation-- positron interactions

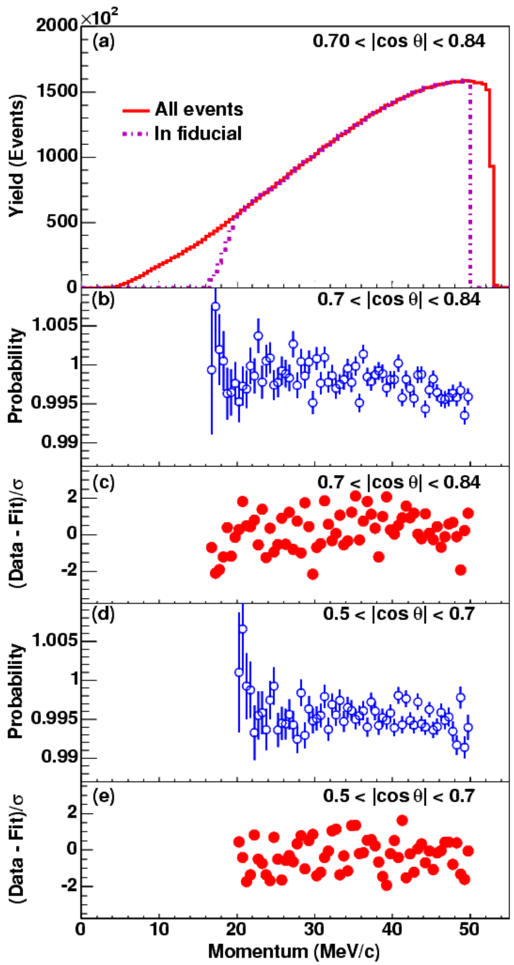
- GEANT simulation must be validated for e^+ energy loss and multiple scattering.
- Stop muons at one end of detector.
- Measure e^+ track on each side of target—before and after passing through target.
- Compare differences, for data and MC.

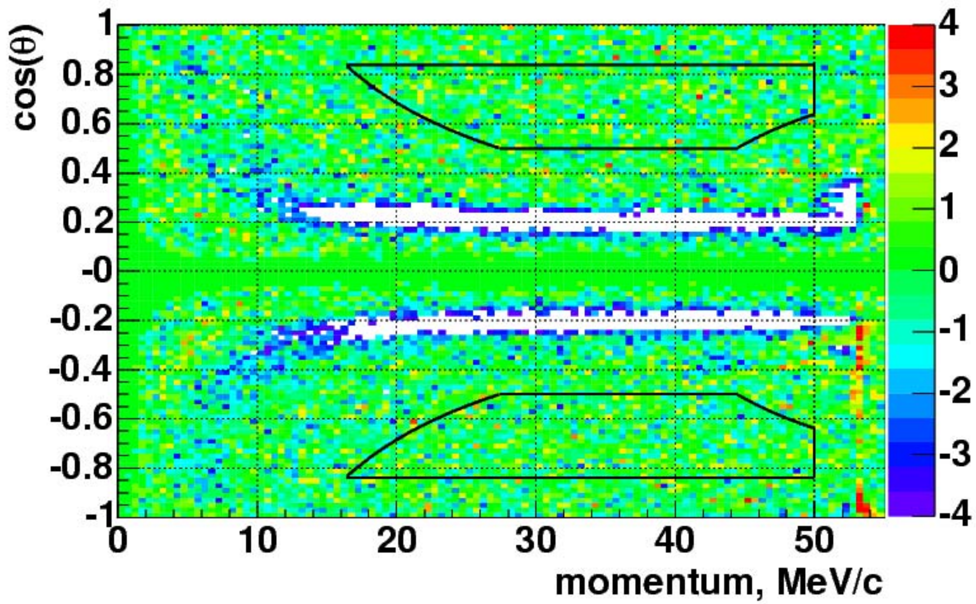






Fits to data distributions-- Fiducial Region

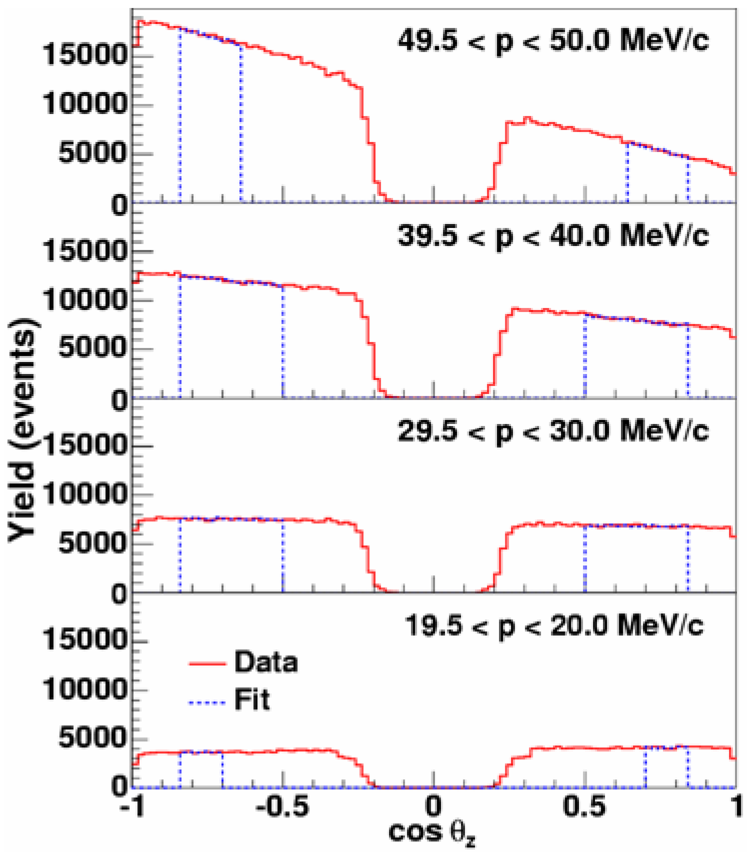




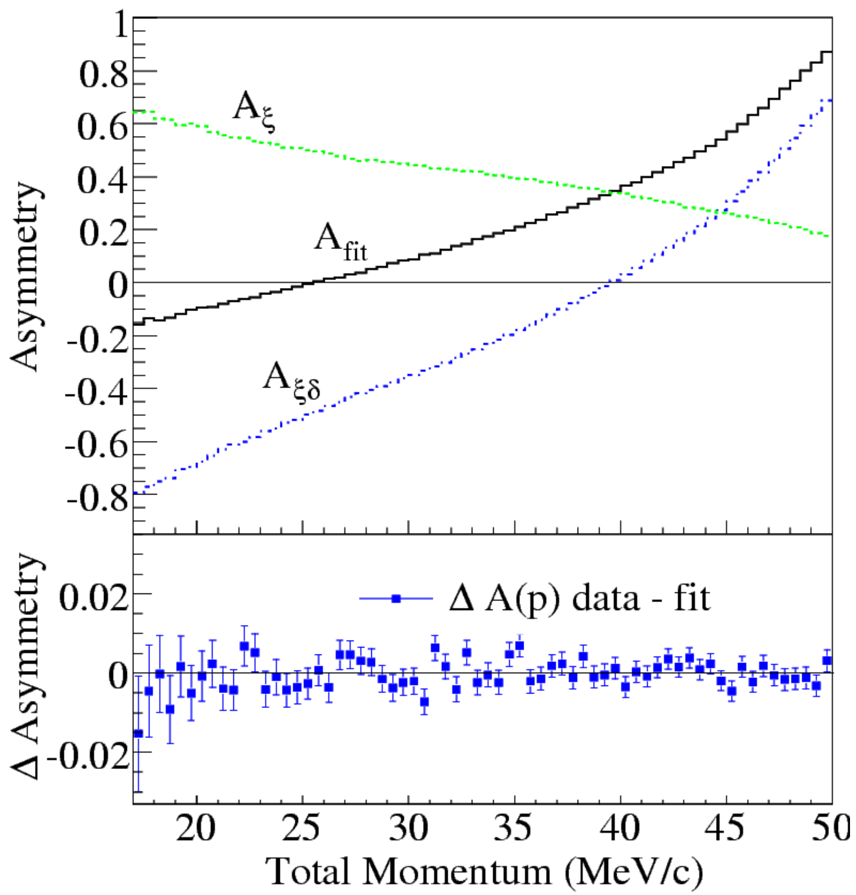
Above: normalized residuals of fit, and fiducial region used for fit: $p < 50$ MeV/c, $0.50 < |\cos\theta| < 0.84$, $|p_z| > 13.7$ MeV/c, $p_T < 38.5$ MeV/c.

Left: comparison of data to fit (MC) *vs.* momentum, also showing R = (MC reconstructed)/(MC thrown) comparisons and normalized residuals for two different angular regions.

Fits to data distributions (cont.)



Angular distributions for 4 restricted momentum ranges. Dashed lines show fiducial region of the two-dimensional fit.



Dependence of the asymmetry on momentum-- its two separate contributions, and the difference of the data and the fit (MC) distributions.

2002 -- Summary of results: ρ and δ

- ρ = **0.750 80 $\pm$ 0.000 44(stat) $\pm$ 0.000 93(syst) $\pm$ 0.000 23(η)**
  - 2.5 times better precision than PDG value.
  - Uncertainty scaled for χ^2/dof = 7.5/4 (C.L.= 0.11) for different data sets.
  - J.R. Musser *et al.*, PRL **94** (2005) 101805.

- δ **= 0.749 64 $\pm$ 0.000 66(stat) $\pm$ 0.001 12(syst)**
  - 2.9 times better precision than PDG value.
  - A. Gaponeko *et al.*, Phys. Rev. **D71** (2005) 071101(R).

- Using the above values of ρ and δ, with $\mathcal{P}_\mu(\xi\delta/\rho)$ > 0.99682 (PDG) and $Q_R^\mu \geq 0$, we get

  $$\mathbf{0.9960 < \mathcal{P}_\mu\xi \leq \xi < 1.0040\ (90\%\ C.L.)}$$

  - improves upon $\mathcal{P}_\mu\xi$ = 0.9996 $\pm$ 0.0030 $\pm$ 0.0048 (KEK)
    > 0.990 (90% C.L.) (KEK)

2002 -- Systematic uncertainties: ρ and δ

Systematic uncertainties	ρ ($\times 10^4$)		δ ($\times 10^4$)	
	published	current	published	current
Chamber response (ave)*	5.1	2.9	5.6	5.2
Stopping target thickness	4.9	-	3.7	-
Positron interactions*	4.6	1.6	5.5	1.0
Spectrometer alignment	2.2	0.3	6.1	0.3
Momentum calibration (ave)*	2.0	2.8	2.9	4.0
Theoretical radiative correction	2.0	2.0	1.0	1.0
Muon beam stability (ave)	0.4	0.1	1.0	0.2
Track selection algorithm	1.1	-		
Asymmetric efficiencies			0.4	0.1
Resolution		1.2		1.4
Total in quadrature	**9.3**	**5.1**	**11.2**	**6.9**

New data (2004) and analysis: thesis of R.P. MacDonald, in preparation.

2004 -- New *Al* target result: $\mathcal{P}_\mu\xi$

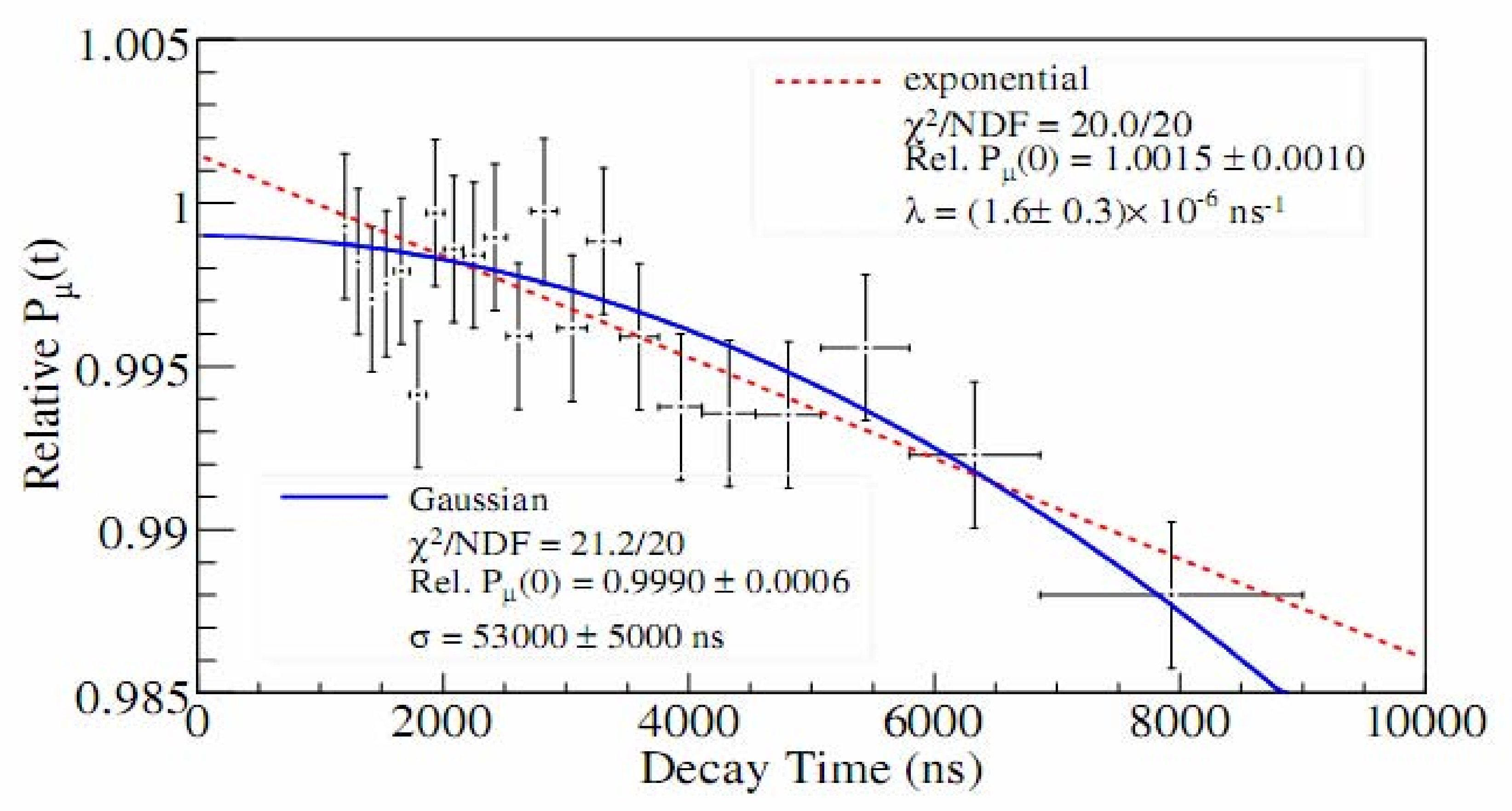
- $\mathcal{P}_\mu\xi$ = **1.000 3 $\pm$ 0.000 6(stat) $\pm$ 0.00 38(syst)**
  - 2.2 times better precision than PDG value (Beltrami *et al.*).
  - 1.5 " " " than KEK value (Aoki el al.).
  - no better than TWIST indirect result using ρ and δ.
  - B. Jamieson *et al.*, Phys. Rev. **D74** (2006) 072007.

- Dominated by systematic uncertainty from the spectrometer fringe field depolarization of the incident μ^+ beam:
  - prospects for significant improvement are excellent.
  - published data were taken in 2004; new data with an improved muon beam (and monitoring) have been collected in 2006-07.

2004 -- Systematic uncertainties: $\mathcal{P}_\mu\xi$

Systematic uncertainties (2004)	$\mathcal{P}_\mu\xi$ ($\times 10^3$)
Depolarization in fringe field (ave)	**3.4**
Depolarization in muon stopping material (ave)	**1.2**
Chamber response (ave)	1.0
Spectrometer alignment	0.3
Positron interactions (ave)	0.3
Depolarization in muon production target	0.2
Momentum calibration	0.2
Upstream-downstream efficiency	0.2
Background muon contamination (ave)	0.2
Beam intensity (ave)	0.2
Michel η parameter	0.1
Theoretical radiative correction	0.1
Total in quadrature	**3.8**

Al Target Depolarization

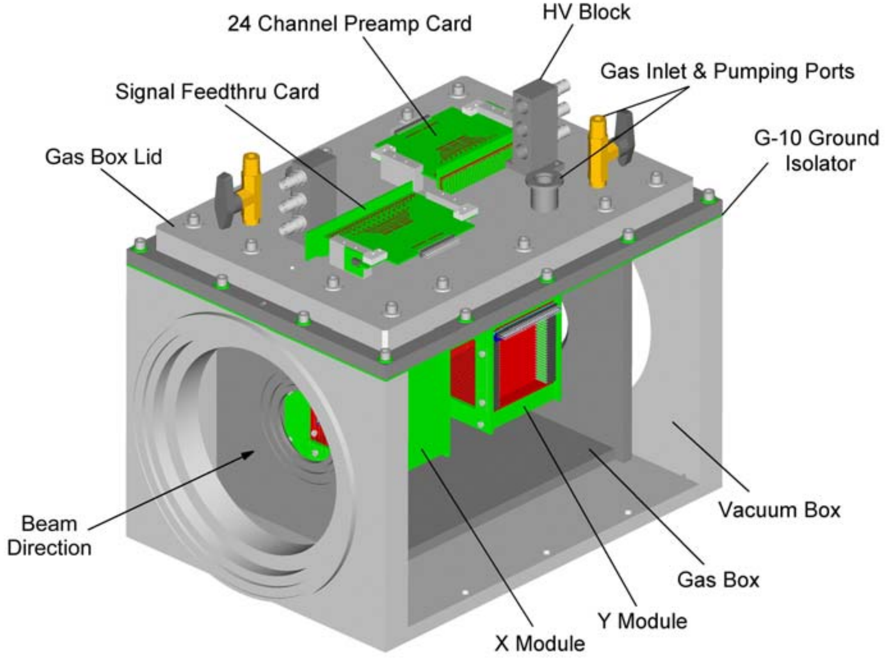


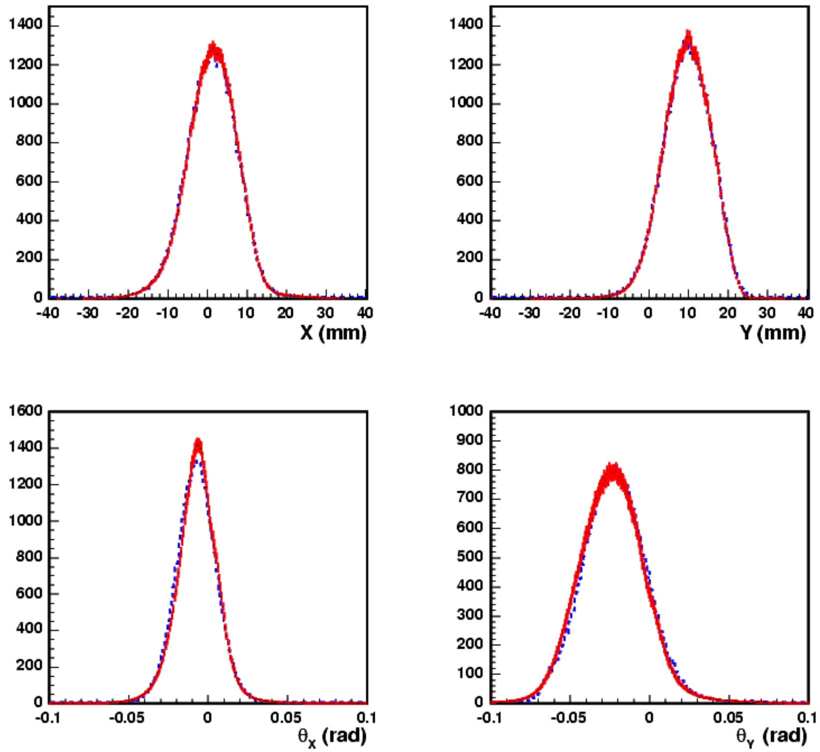
Absolute difference in $\mathcal{P}_\mu(0) = 2.4 \times 10^{-3}$

Improving the systematics

Systematic	Improvement
positron interactions	better target geometry, improved chamber spacing, improved MC simulation
momentum calibration	new techniques with reduced bias
chamber response	online monitoring & pressure control, drift time measurements (use asymmetric or data-determined STRs), E-loss (e^+ helix)
fringe field depolarization	beam monitoring (TEC), beam alignment by additional quad steering
stopping target depolarization	use both aluminum and silver targets, dedicated depolarization expt. using μSR, lower HV on PC5/6 to identify stops in gas

Fringe field systematic improvement





NIM **A566** (2006) 563

The TECs (time expansion chambers) are transverse drift chambers operating at 0.08 bar, separated from the beam vacuum by 6 μm Mylar windows. Two separate modules measure x and y independently.

Depolarisation in fringe field

Beam angle changed between monitoring runs

B2 (mT)	$\bar{x}$ (cm)	$\bar{\theta}_x$ (mrad)	$\bar{y}$ (cm)	$\bar{\theta}_y$ (mrad)	P_μ^{sim}
94.4	0.07	−5.9	0.97	7.0	0.9929
94.4	0.06	−6.7	0.73	−11.2	0.9941
94.9	0.85	−1.1	0.87	−5.0	0.9955
94.9	0.94	−1.5	0.64	−19.2	0.9922

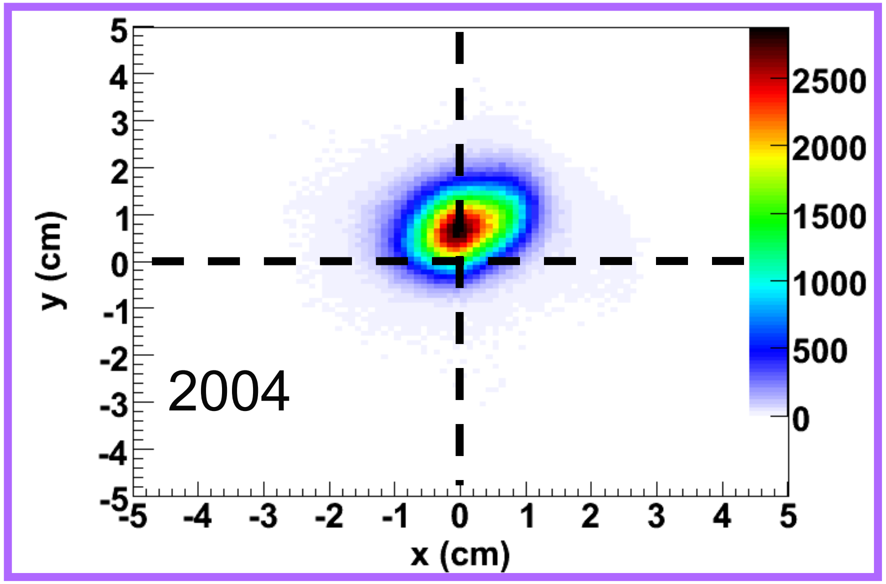
2004: uncertainty of 0.0033 in $\mathcal{P}_\mu \xi$

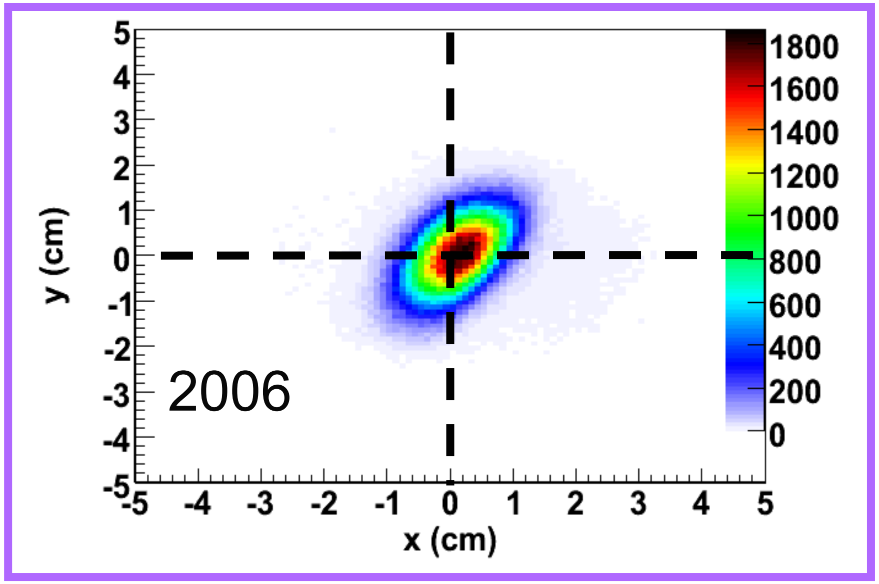
For 2006/7:

- Monitored the beam at beginning and end of every data set.
- Monitored the proton beamline and beam spot on production target.
- Collected entire data sets with the beam monitor 'in' to look for changes.
- Efficiency of beam monitor was very closely monitored.
- Improved the beam monitor calibration and alignment to detector.

James Bueno, WNPPC'07, 18 February 2007

Depolarisation in fringe field





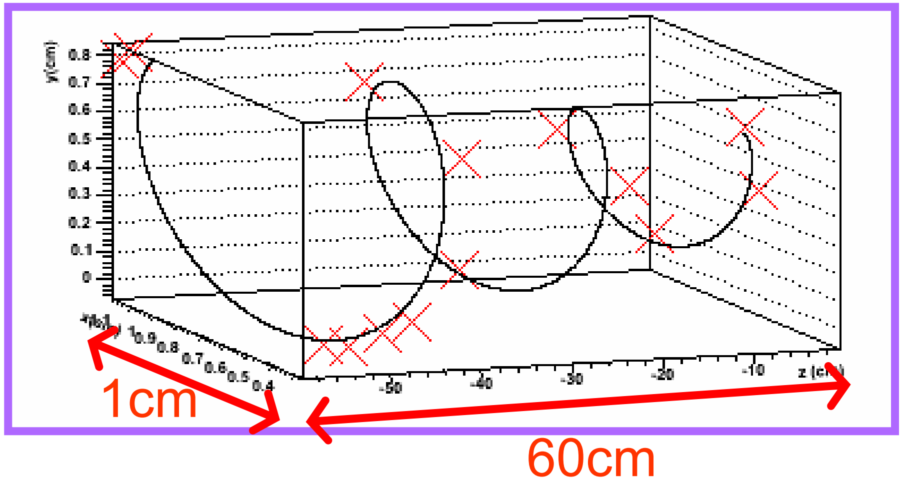
$\langle x\rangle,\langle y\rangle = (0.05\ ,\ 0.74)$ cm
$\langle \theta_x\rangle,\langle \theta_y\rangle = (-6.7\ ,\ -11.2)$ mrad

$\langle x\rangle,\langle y\rangle = (0.13\ ,\ 0.02)$ cm
$\langle \theta_x\rangle,\langle \theta_y\rangle = (-4.9\ ,\ -1.0)$ mrad

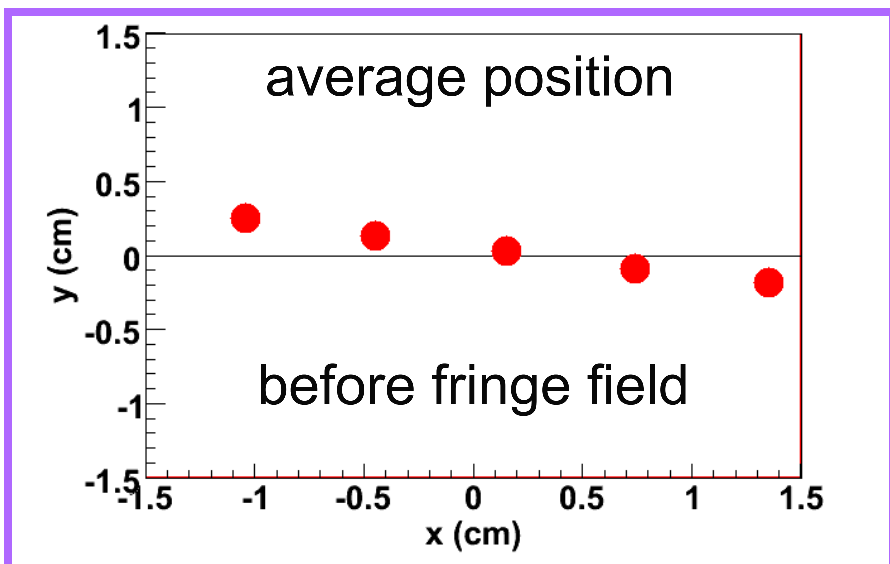
also: 3 data sets were taken in 2006 with deliberate mis-steering to validate the MC simulation of $\mathcal{P}_\mu$

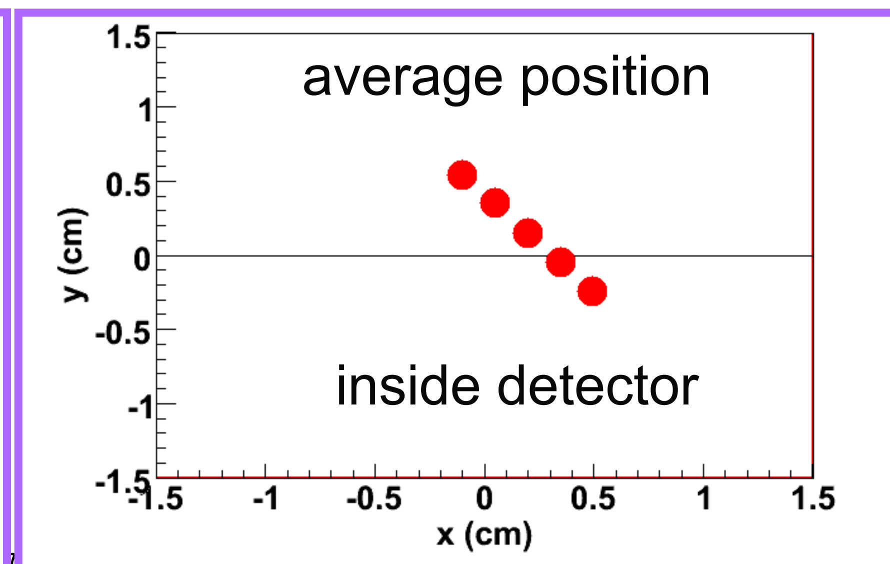
James Bueno, WNPPC'07, 18 February 2007

Muon Beam stability



Discovered that the internal muon beam is sensitive to angle changes < 2mrad and position changes < 2mm.



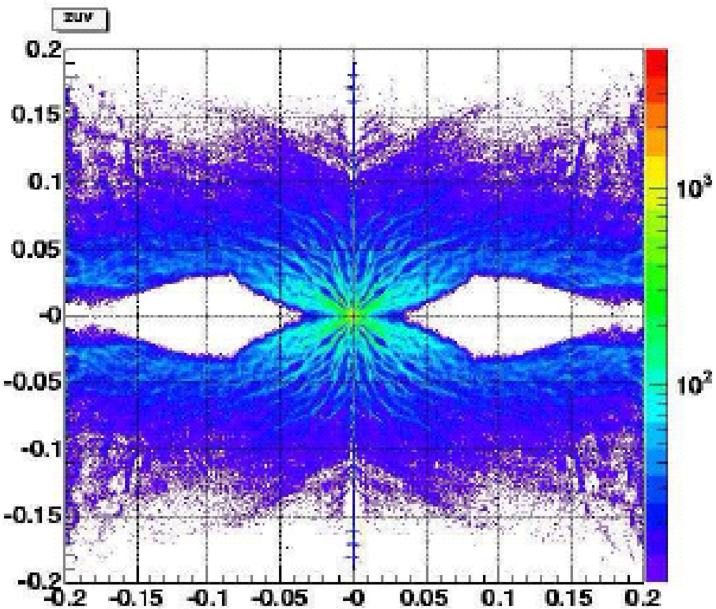


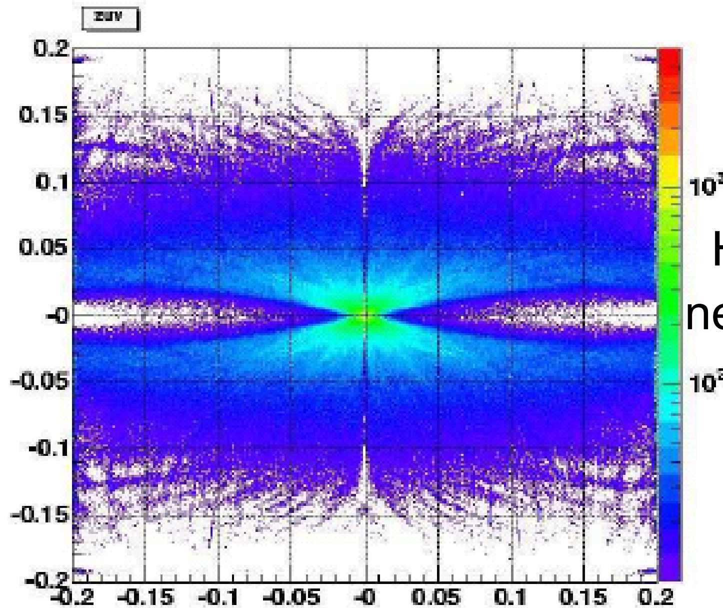
TWIST Final Uncertainty Goals

Michel Parameter	Published Values stat. ± syst.	Estimated **Final** Uncertainties stat. ± syst. (total)	Pre TWIST values
ρ	3.2 ± 9.7	1.3 ± 2.4 (2.8)	26
δ	6.6 ± 11.2	2.3 ± 2.2 (3.4)	38
$\mathcal{P}_\mu\xi$	6.0 ± 38	2.8 ± 7.5 (8.5)	85 56*

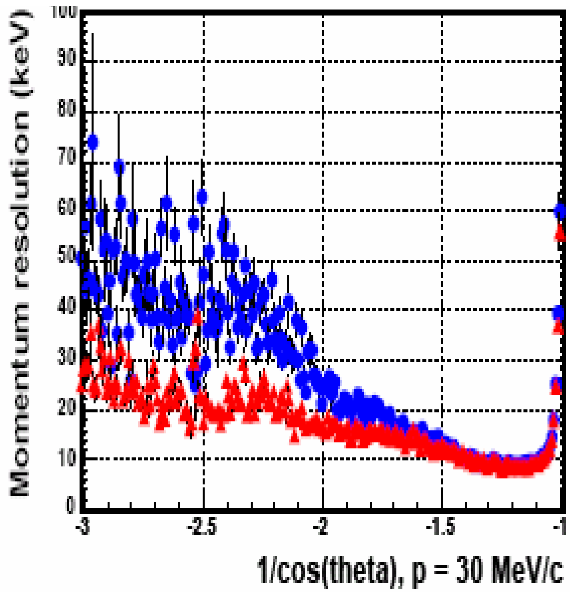
all values in units of 10^{-4}

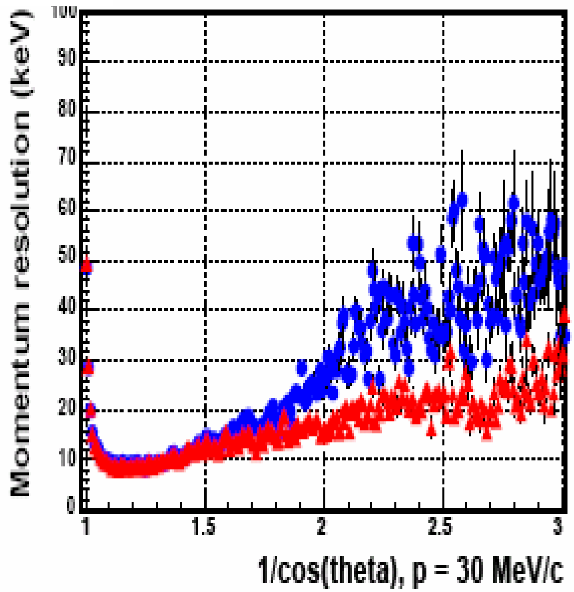
Improved Tracking





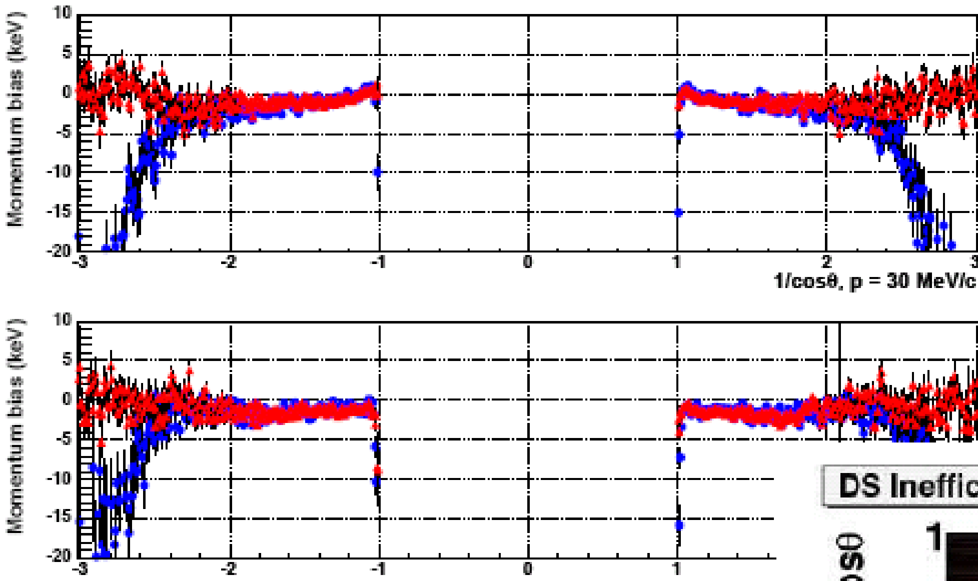
Hit Occupancies--
new tangent method



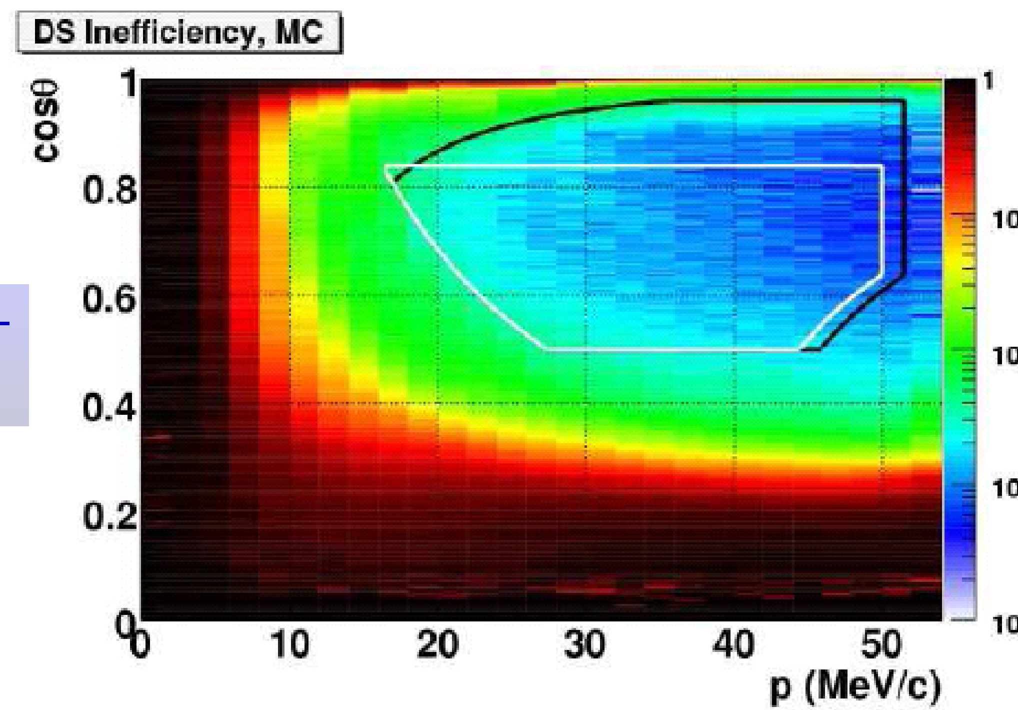


Momentum Resolution
--symmetric STRs
--asymmetric STRs

Improved Tracking (con't)



Track reconstruction momentum bias at p = 30, 50 MeV/c



Track reconstruction inefficiency—old & new fiducial regions

Left-right symmetric models

- Weak eigenstates in terms of mass eigenstates and mixing angle:

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta, \quad W_R = e^{i\omega}(-W_1 \sin\zeta + W_2 \cos\zeta)$$

- Assume possible differences in left and right couplings and CKM character. Use notation:

$$t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \qquad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}, \qquad \zeta_g = \frac{g_R^2}{g_L^2}$$

- Then, for muon decay, the Michel parameters are modified:

$$\rho = \frac{3}{4}(1 - 2\zeta_g^2), \qquad \xi = 1 - 2(t^2 + \zeta_g^2),$$

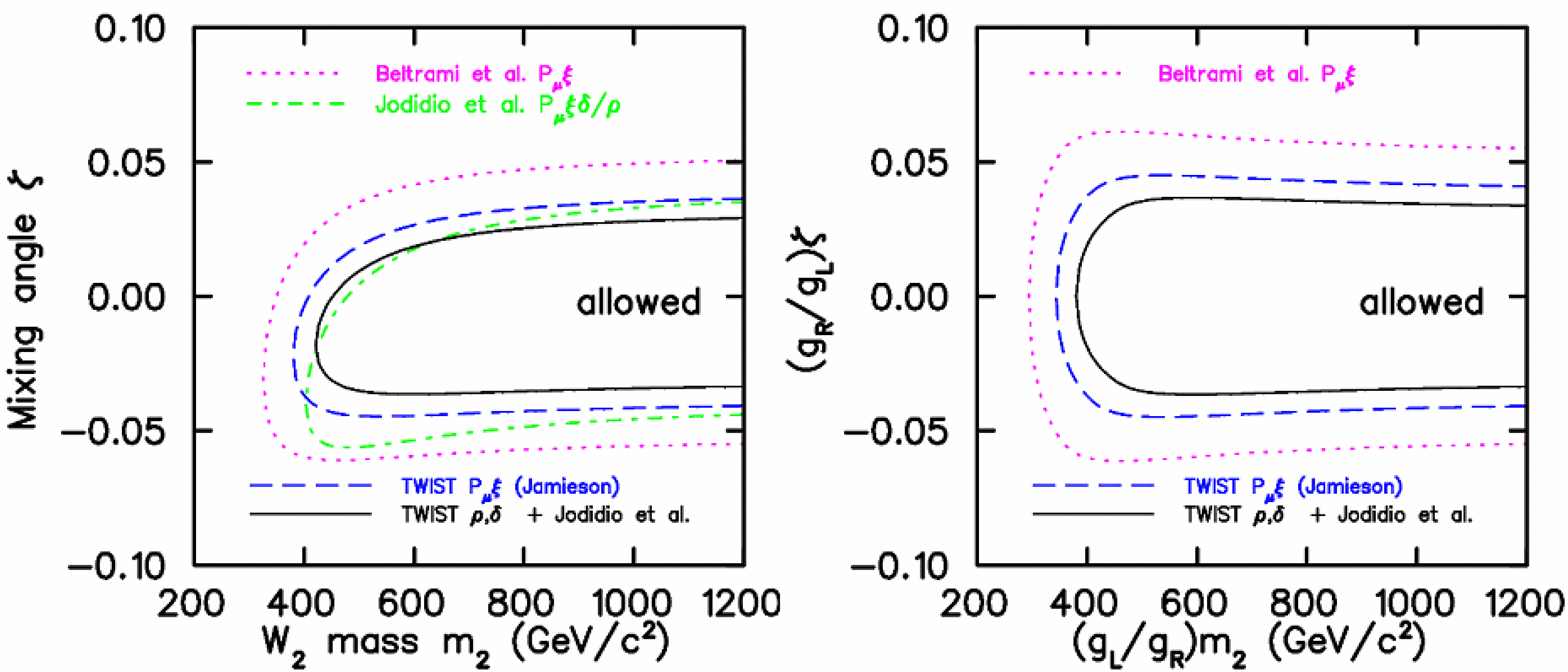
$$\mathcal{P}_\mu = 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g^2 \cos(\alpha + \omega)$$

  - "manifest" LRS models assume $g_R = g_L$, $V^R = V^L$, $\omega = 0$ (no CP violation).
  - "pseudo-manifest" LRS models allow CP violation, but have $V^R = (V^L)^*$ and $g_R = g_L$.
  - "non-manifest" or "generalized" LRS models make no such assumptions.

- ***Most experiments must make assumptions about LRS models !***

Implications for LRS models

Restricted ("manifest") LRS model — General LRS model



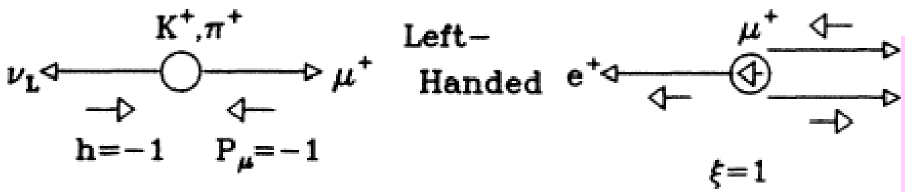
Exclusion plots (90% C.L.) for LRS models:

mixing angle -- ζ vs. W_2 mass -- m_2

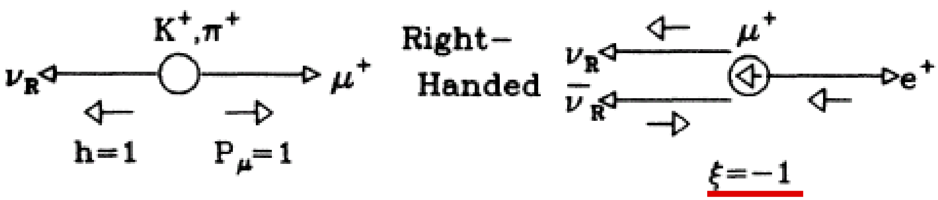
Limits on LRS parameters: PDG06

Observable	m_2 (GeV/c^2)	$\lvert \zeta \rvert$	+	-
$m(K_L - K_S)$	>1600		reach	(P)MLRS
Direct W_R searches	>800 (D0) >786 (CDF)		clear signal	(P)MLRS decay model
CKM unitarity		$<10^{-3}$	sensitivity	(P)MLRS heavy ν_R
β decay	>310	<0.040	both parameters	(P)MLRS light ν_R
μ decay (*TWIST*)	>406 (>420)	<0.033 (<0.030)	model independence	light ν_R

K→μν versus π→μν decay



KEK experiments—
Phys Rev **D34**(1986)85 Yamakada et al
Phys Rev **D50**(1994)69 Aoki et al

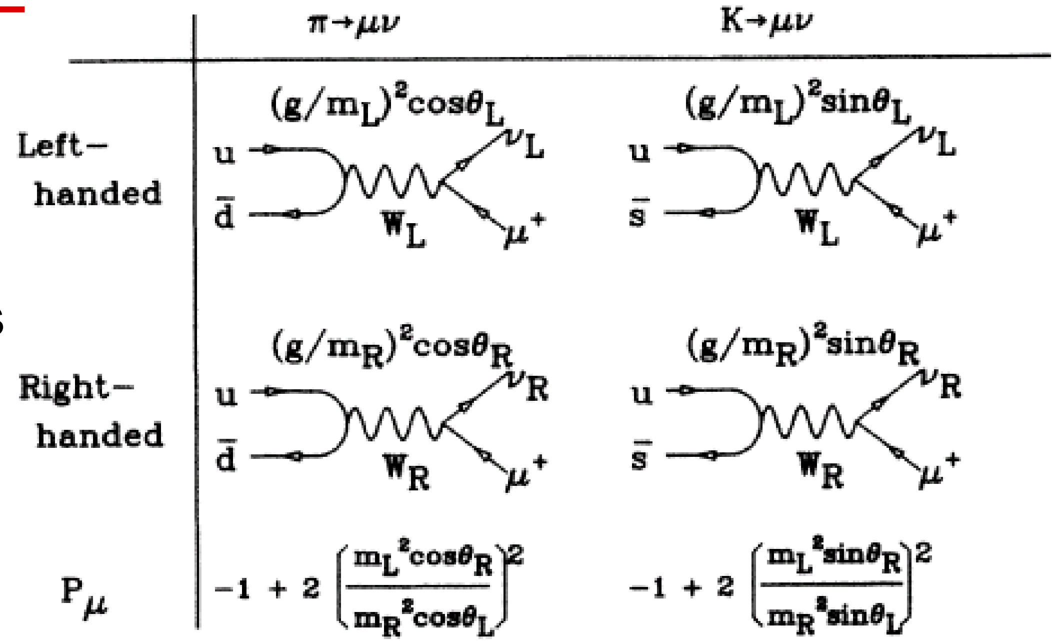


$$\pi_{\mu 2} \propto \left(\frac{\cos\theta_R}{\cos\theta_L}\right)^2$$

$$K_{\mu 2} \propto \left(\frac{\sin\theta_R}{\sin\theta_L}\right)^2$$

Theory—
PRL **50**(1983)1423--Oka
PRev **34**(1986)3449--Herczeg

ΔS=0, ΔS=1 semi-leptonic decays



K→μν versus π→μν decay

$$K_{\mu 2} \propto \left(\frac{\sin\theta_R}{\sin\theta_L}\right)^2$$

$$\pi_{\mu 2} \propto \left(\frac{\cos\theta_R}{\cos\theta_L}\right)^2$$

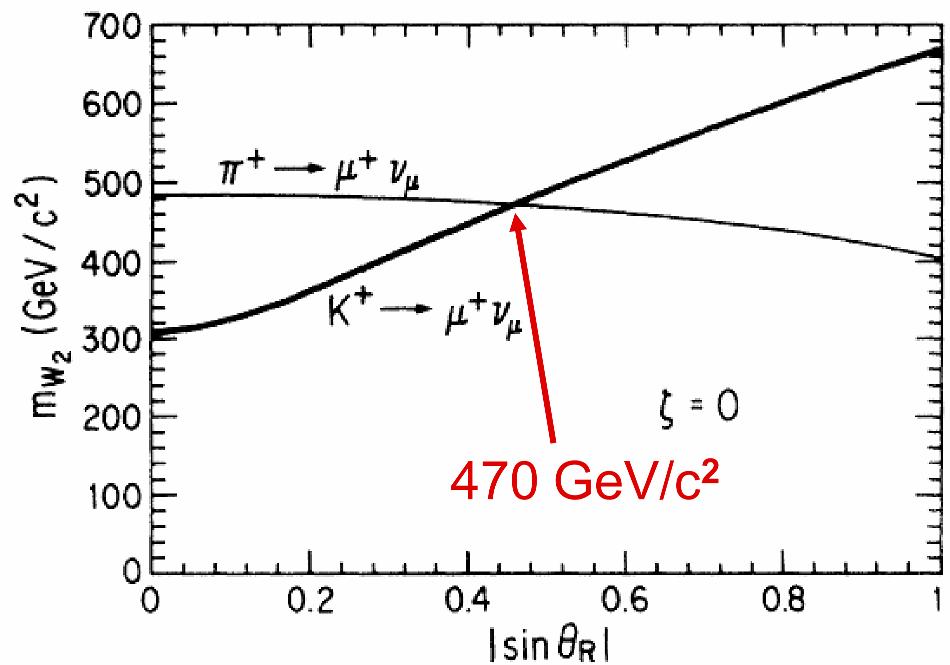
$$1-|\xi P_\mu| \simeq 2\left(\epsilon\frac{\sin\theta_R}{\sin\theta_L}+\zeta\right)^2+2(\epsilon^2+\zeta^2) \qquad (1.1$$

for $K_{\mu 2}$ decay and

$$1-|\xi P_\mu| \simeq 2\left(\epsilon\frac{\cos\theta_R}{\cos\theta_L}+\zeta\right)^2+2(\epsilon^2+\zeta^2) \qquad (1.2,$$

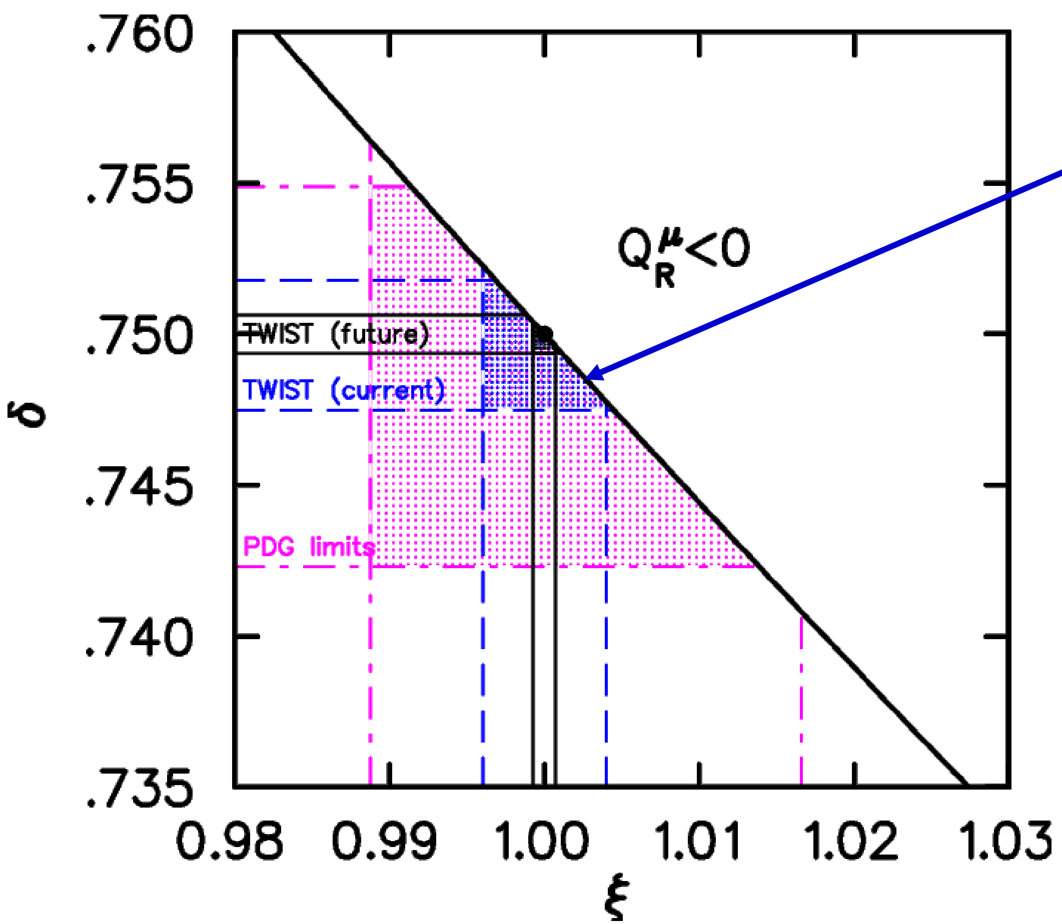
for $\pi_{\mu 2}$ decay[1] [25,26]. This difference makes kaon decay much more sensitive to m_{W_2} than pion decay if $|\sin\theta_R|$

Aoki et al--Phys Rev **D50**(1994)69



300 GeV/c² < M_{W2} < 650 GeV/c²

Improved limits on ξ and δ



Diagonal represents exactly left-handed muon decay.

Shaded regions represent a comparison of current (indirect or direct) limits & the proposed (final) *TWIST* limits, compared to the previous PDG limits.

$$
\begin{aligned}
Q_R^\mu &= \frac{1}{2}\left[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right] \\
&\geq 0 \\
&< 0.00184(90\%CL)
\end{aligned}
$$

Are there derivative couplings ??

- π radiative decay experiments see a small anomaly which might be explained by a tensor interaction.

  E. Friez et al., (PiBeta collab) Phys. Rev. Lett. **93** (2004)181804

- Chizhov (hep-ph/0405073) calculates:
  - $(\delta - 0.750)_{\mathbf{theory}} = 1 - 6|g^{T}_{RR}|^2 \approx 0.0010$
  - deviation from Standard Model value is slightly less than the current *TWIST* precision

    $(\delta - 0.750)_{\mathbf{exp}} = (\ 3.6 \pm 6.6 \pm 11.2\ ) \times 10^{-4}$

Summary

- *TWIST* has published its first direct measurement of $\mathcal{P}_\mu\xi$, to add to our previous results for ρ and δ.
- Analysis is underway for 2nd(3rd) measurements for ρ and δ, representing further improvements by ~2(2007) & ~4(2008).
- Reduction of depolarization systematics for $\mathcal{P}_\mu\xi$ also seems achievable, but it is not yet certain by how much.
- In 2007-2008, *TWIST* will produce its final results:
  - goal remains the reduction of the uncertainties by an order of magnitude compared to previous muon decay experiments.
  - new ρ and δ results will be released on Nov 15

TWIST Participants

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‡ also Manitoba
# also Saskatchewan
§ deceased

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Computing facilities of WestGrid are gratefully acknowledged.

Arigato Gozaimasu

Extra Slides

Energy Loss

Material	Thickness (mg/cm^2)
Degrader and vacuum foils	11.91
He/CO_2 degrader	1.95 to 42.80
Air gap (2.82 cm)	3.65
Muon scintillator	20.12
Scintillator wrap	3.03
Cradle window	0.88
PC module	9.46
Dense stack	13.41
Seven UV modules	27.80
He/N_2 (63.8 cm)	12.25
Half target module before target	4.31
Half of 71 μm Al target	9.59
Total to center of Al target	118.36 to 159.21

2002 -- Results of different data sets

Data set	ρ (stat)(syst)	χ^2 dof=1887	δ (stat)(syst)	χ^2 dof=1887
Set A	0.75134(83)(53)	1814	0.75087(156)(73)	1924
Set B	0.74937(66)(53)	1965	0.74979(124)(55)	1880
1.96 T	0.75027(65)(55)	1951	0.74918(124)(69)	1987
2.04 T	0.75248(70)(60)	1804	0.74908(132)(65)	1947
Cloud μ^+	0.75157(76)(53)	1993	-	-

Oka -- PRL 50 (1983) 1423

ΔS=0, ΔS=1 semi-leptonic decays

$$H_{\Delta S=0} = (g_L^2/8m_L^2)\cos\theta_1^L[(\bar{u}\Gamma_L d)(\bar{l}\Gamma_L \nu_l) + a\lambda(\bar{u}\Gamma_R$$

$$H_{\Delta S=1} = (g_L^2/8m_L^2)\sin\theta_1^L\cos\theta_3^L[(\bar{u}\Gamma_L s)(\bar{l}\Gamma_L \nu_l) +$$