TWIST – the TRIUMF Weak Interaction Symmetry Test

A precision study of the μ^+ decay spectrum

- Designed to achieve ~ 0.01% in the shape of the decay spectrum
- Several data sets of 10^9 events each
- A precision test of the weak interaction in the Standard Model

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Outline

- Motivation
- Overview of the experiment
- Status and plans

TWIST - Personnel

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- Don Koetke
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- Vladimir Selivanov
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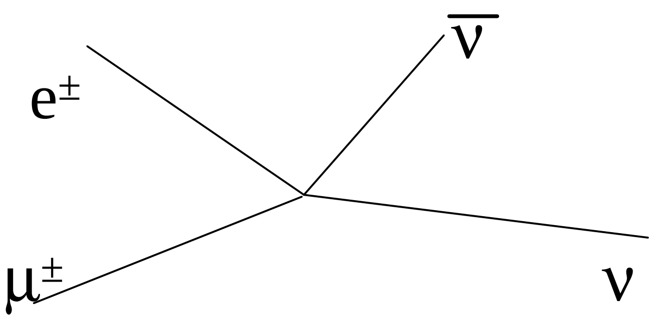
◈ Presently at SLAC

Students (red names)
Professional Staff (blue names)

TWIST Motivation – testing the Standard Model

$$\text{rate} \sim \Big| \sum_{\substack{g=S,V,T \\ i,j=R,L}} g^{g}_{ij} \langle \bar{y}_{ei} | \Gamma^{g} | y_{n_e} \rangle \langle \bar{y}_{n_m} | \Gamma_{g} | y_{m\,j} \rangle \Big|^2$$

… The most general interaction, which does not presuppose the W



Allows for possible

- scalar
- vector
- tensor

Scalar	$\bar{y}\, y$
Vector	$\bar{y}\, g^{m} y$
Tensor	$\bar{y}\, s^{mn} y$
Axial Vector	$\bar{y}\, g^{5} g^{m} y$
Pseudoscal ar	$\bar{y}\, g^{5} y$

interactions of right-handed and left-handed leptons

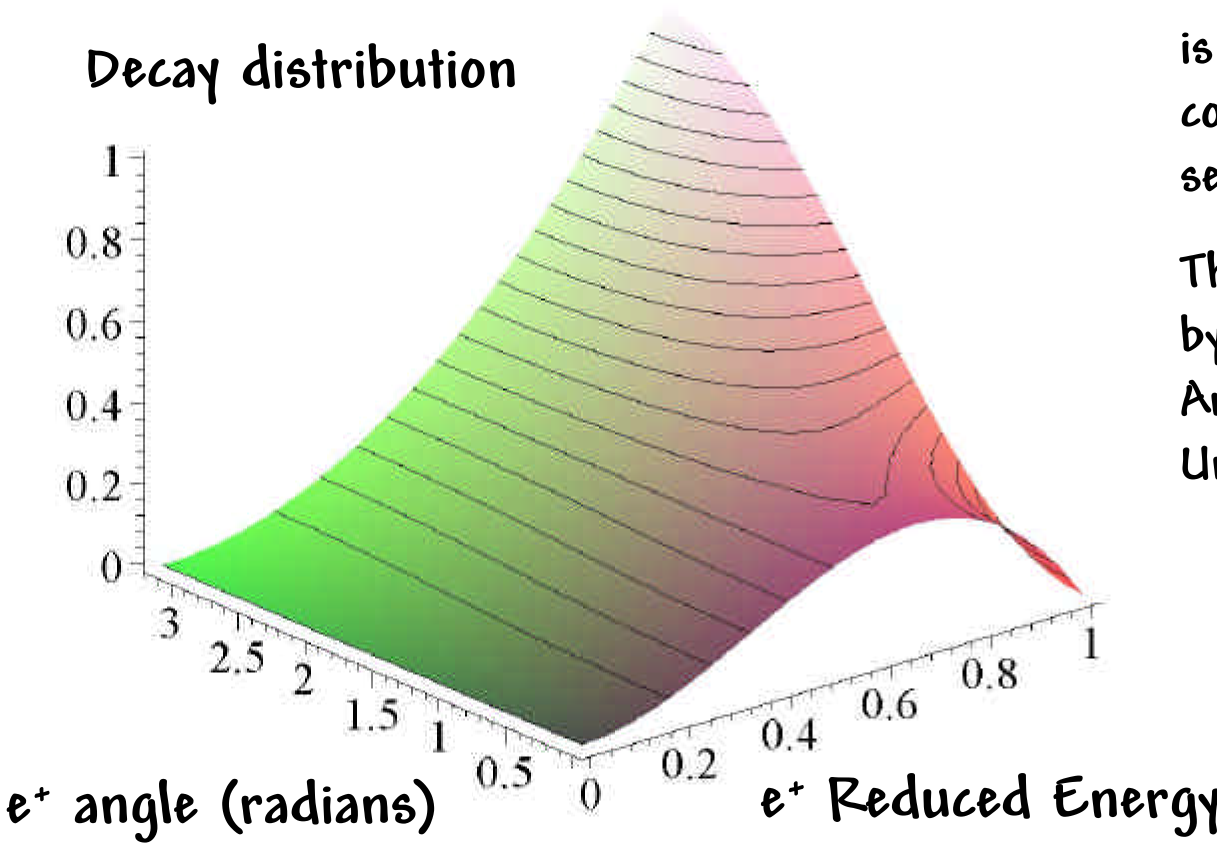
Actual knowledge of couplings-

Plenty of room for a surprise

$\lvert g^{S}_{RR} \rvert < 0.066$	$\lvert g^{V}_{RR} \rvert < 0.033$	$\lvert g^{T}_{RR} \rvert \equiv 0$
$\lvert g^{S}_{LR} \rvert < 0.125$	$\lvert g^{V}_{LR} \rvert < 0.060$	$\lvert g^{T}_{LR} \rvert < 0.036$
$\lvert g^{S}_{RL} \rvert < 0.424$	$\lvert g^{V}_{RL} \rvert < 0.110$	$\lvert g^{T}_{RL} \rvert < 0.122$
$\lvert g^{S}_{LL} \rvert < 0.55$	$\lvert g^{V}_{LL} \rvert > 0.96$	$\lvert g^{T}_{LL} \rvert \equiv 0$

The general interaction can be expanded in terms of the Michel parameters

$$\text{rate} \sim x^2\left[3-3x+\frac{2}{3}r\,(4x-3)+3hx_0\,\frac{1-x}{x}+P_m x\cos(q)\left(1-x+\frac{2}{3}d\,(4x-3)\right)\right]$$



The above decay distribution is modified by radiative corrections, required to second order

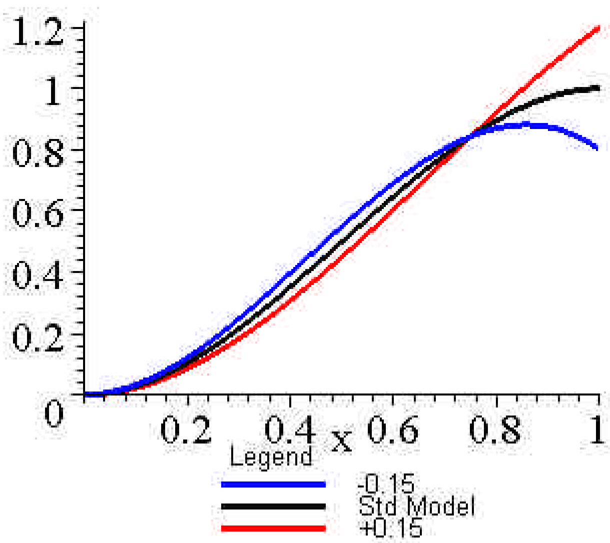
These are being calculated by Andrzej Czarnecki and Andrej Arbuzov, at the University of Alberta

The Michel Parameters - ρ

The parameter ρ largely determines the shape of the positron energy spectrum

$$r - \frac{3}{4} \equiv \frac{3}{4}\left[-|g^V_{LR}|^2 - |g^V_{RL}|^2 - 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right)\right]$$

$$+ \frac{3}{4}\left[\mathrm{Re}\left(g^S_{LR}g^{T*}_{LR}\right) + \mathrm{Re}\left(g^{S*}_{LR}g^T_{LR}\right) + \mathrm{Re}\left(g^S_{RL}g^{T*}_{RL}\right) + \mathrm{Re}\left(g^{S*}_{RL}g^T_{RL}\right)\right]$$

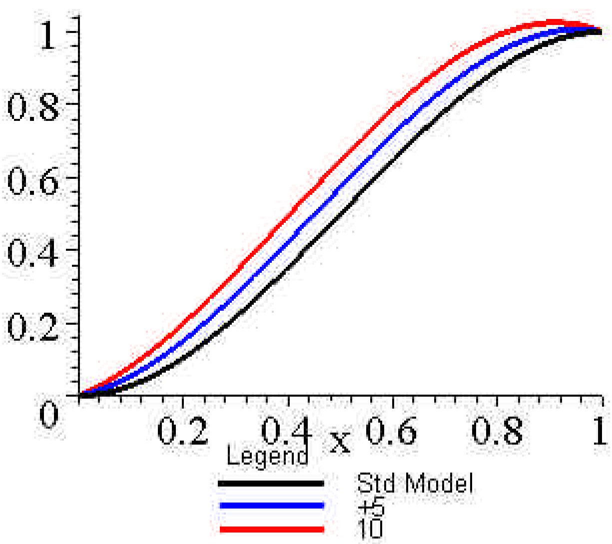


The effect of large deviations in ρ on the shape of the energy spectrum. The effect shown is roughly 500 times the TWIST sensitivity

The Michel Parameters - η

The parameter η makes a subtle correction to the shape of the positron energy spectrum

$$h \equiv \frac{1}{2}\mathrm{Re}\left[g^{V}_{LL}g^{S*}_{RR} + g^{V}_{RR}g^{S*}_{LL} + g^{V}_{RL}\left(g^{S*}_{LR} + 6g^{T*}_{LR}\right) + g^{V}_{LR}\left(g^{S*}_{RL} + 6g^{T*}_{RL}\right)\right]$$



The effect of large deviations in η on the shape of the energy spectrum. The effect shown is roughly 500 times the TWIST sensitivity

As well, the Fermi coupling constant has a significant dependence on η

$$G_F^2 = \frac{1}{t}\frac{192p^3}{m_m^5}\frac{1}{1+4h(m_e/m_m)}$$

$$\left.\frac{\Delta G_F}{G_F}\right|_{h=0} = -\frac{\Delta h}{5} \approx 0.00025$$

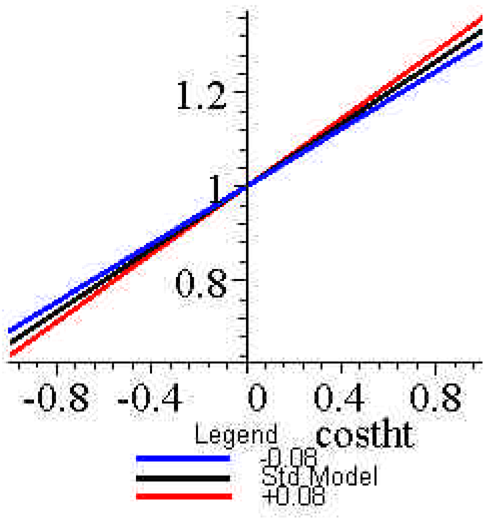
Which is roughly 25x larger than the total quoted uncertainty in G_F

The Michel Parameters - ξ

The parameter ξ determines the asymmetry in the energy-integrated spectrum.

$$x - 1 \equiv -\frac{1}{2}|g^S_{RR}|^2 - \frac{1}{2}|g^S_{LR}|^2 - 2|g^V_{RR}|^2 - 4|g^V_{RL}|^2 + 2|g^V_{LR}|^2 - 8|g^T_{RL}|^2 + 2|g^T_{LR}|^2$$

$$-\frac{1}{2}\mathrm{Re}\left[g^{S*}_{RL}g^{T}_{RL} + g^{S}_{RL}g^{T*}_{RL} - g^{S*}_{LR}g^{T}_{LR} - g^{S}_{LR}g^{T*}_{LR}\right]$$

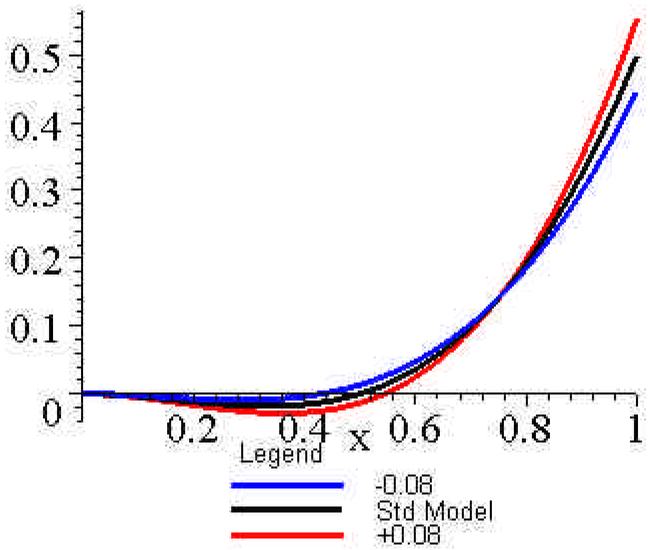


The effect of large deviations in ξ on the energy-integrated angular distribution. The effect shown is roughly 500 times the TWIST sensitivity

The Michel Parameters - δ

The parameter δ determines the energy dependence of the asymmetry in the spectrum.

$$x\delta - \frac{3}{4} \equiv -\frac{3}{4}\Big[|g^S_{RR}|^2 + |g^S_{LR}|^2 + 2|g^V_{RR}|^2 + |g^V_{RL}|^2 + |g^V_{LR}|^2$$
$$+ 2|g^T_{RL}|^2 + 4|g^T_{LR}|^2 - \mathrm{Re}\left[g^{S*}_{RL} g^T_{RL} + g^S_{RL} g^{T*}_{RL} - g^{S*}_{LR} g^T_{LR} - g^S_{LR} g^{T*}_{LR}\right]\Big]$$



The effect of large deviations in δ on the coefficient of the cos(θ) dependent term. The effect shown is roughly 500 times the TWIST sensitivity

TWIST Precision on the Michel Parameters

	Std Model	Accepted Value	TWIST precision
ρ	0.75	0.7518 + 0.0026	0.00031
η	0.0	-0.007 + 0.013	~ 0.01
δ	0.75	0.7486 + 0.0026 + 0.0028	0.00015
$P_{\mu}\xi$	1.0	1.0027 + 0.0079 + 0.0030	0.00017

Note: the TWIST precision quoted here includes uncertainties stemming from calculations of second-order radiative corrections in the leading log approximation. The uncertainty in the calculations should be smaller when the next-to-leading second order calculations are completed.

A test of (V-A)

Because the coupling constants often enter as sums of positive definite terms, it is possible to test (V-A) with far fewer than the 19 experiments one might expect for the determination of the 19 free parameters.

It has been shown, for example, that a rigorous test of the (V-A) postulate can be made by measuring:

- The muon lifetime
- The Michel parameter δ
- The Michel parameter ξ
- The outgoing positron polarization
- The rate of absorption of ν_e from muon decay

TWIST will contribute two of these five required measurements

Dependence of the decay on Chirality

For example, a measurement of ξ and δ provides a model independent test of five coupling constants set to zero in the standard model

- The muon decay rate can be written as $$\Gamma = \sum_{\substack{m=L,R \\ e=L,R}} Q_{em}$$

Where $Q_{\varepsilon\mu}$ describes the decay of a left- or right-handed muon into a left- or right-handed positron

$$Q_{LL} = \frac{1}{4}|g^S_{LL}|^2 + |g^V_{LL}|^2$$

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

$$Q_{RL} = \frac{1}{4}|g^S_{RL}|^2 + |g^V_{RL}|^2 + 3|g^T_{RL}|^2$$

$$Q_{RR} = \frac{1}{4}|g^S_{RR}|^2 + |g^V_{RR}|^2$$

Coupling to right-handed muons

- The decay rate of right-handed muons into either right- or left-handed electrons is given by the sum

$$Q_R^m = Q_{RR} + Q_{LR} = \frac{1}{4}|g_{LR}^S|^2 + |g_{LR}^V|^2 + 3|g_{LR}^T|^2 + \frac{1}{4}|g_{RR}^S|^2 + |g_{RR}^V|^2$$

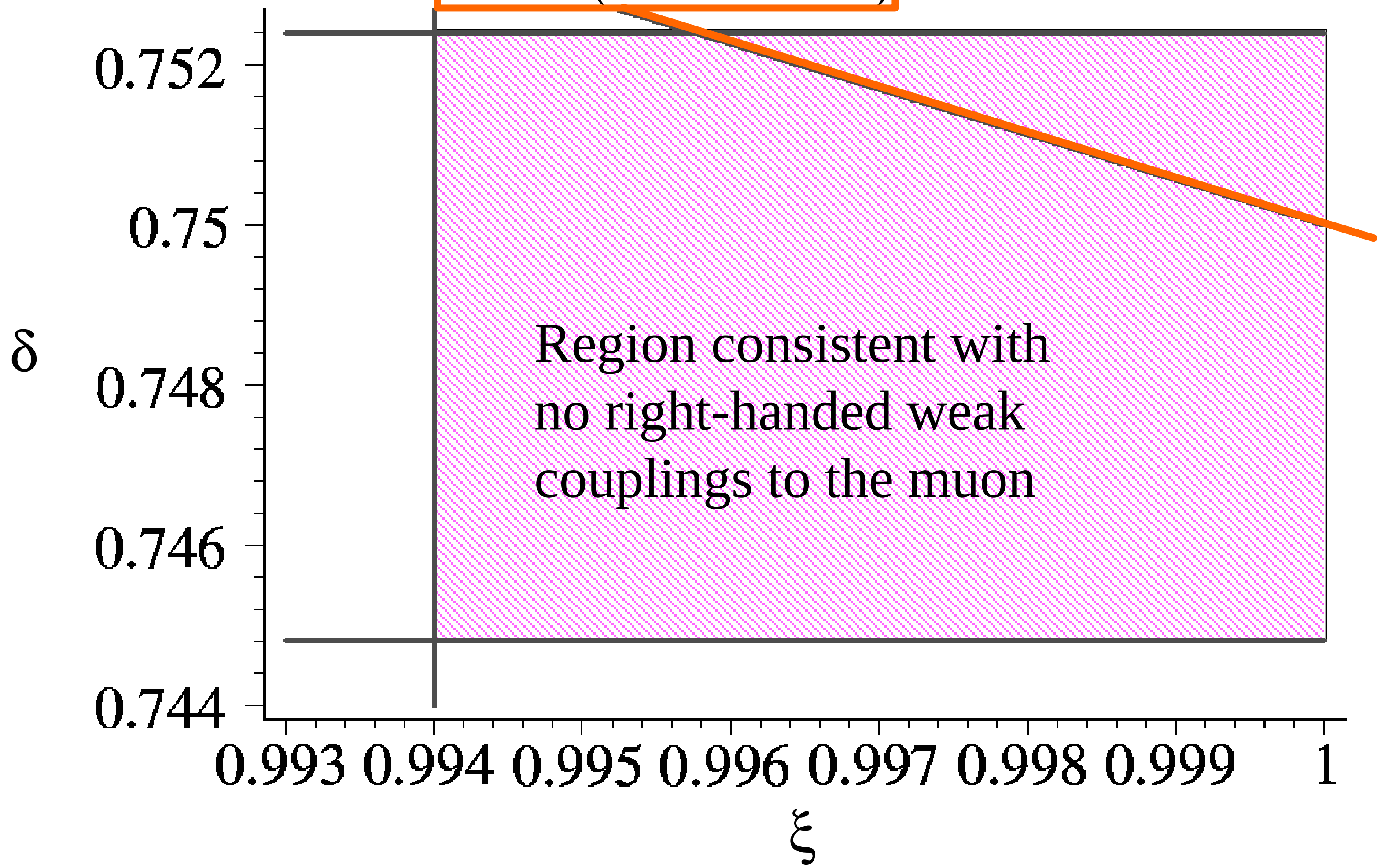
This combination of couplings happens to be equal to a combination of Michel parameters, so that

$$Q_R^m = \frac{1}{2}\left(1 + \frac{1}{3}x - \frac{16}{9}xd\right)$$

- A determination of ξ and δ provides a model-independent test for the existence of right-handed weak couplings to muons.
  - $Q \neq 0$ indicates a violation of the Standard Model, and the existence of right-handed couplings for muons
  - $Q = 0$ indicates that right-handed couplings to the muon do not exist

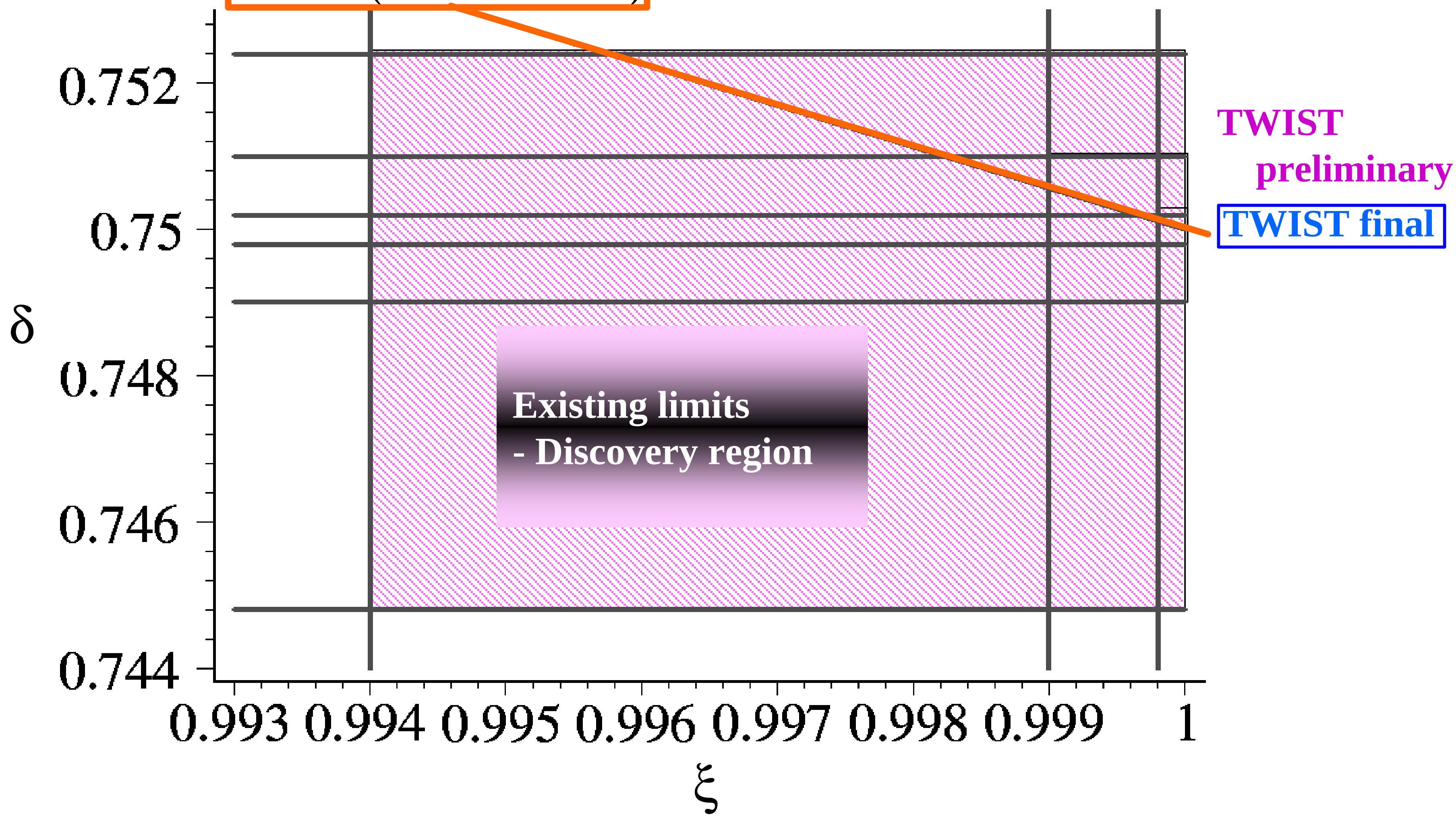
Existing limits on right-handed currents in muon decay

$$Q_R^m = \frac{1}{2}\left(1+\frac{1}{3}x-\frac{16}{9}xd\right)$$



Anticipated TWIST sensitivity to right-handed currents in muon decay

$$Q_R^m = \frac{1}{2}\left(1 + \frac{1}{3}x - \frac{16}{9}xd\right)$$



Consider Left/Right Symmetric extensions to the Standard Model

Consider a model with two weak bosons with the mass eigenstates M_1 and M_2

$$M_{W_L} = M_1 \cos(z) - M_2 \sin(z)$$

$$M_{W_R} = e^{iw}\left(M_1 \cos(z) + M_2 \sin(z)\right)$$

Parity violation at low energy is presumably due to $\frac{m_{W_R}}{m_{W_L}} >> 1$

In general, the models may include a CP violating phase (ω), and a left/right mixing parameter ζ

Left/Right Symmetric extensions to the Standard Model

Expect a non zero g_{RR} and g_{LR}

$$g^V_{LR} = g^V_{RL} \approx z << 1 \qquad g^V_{RR} \approx \left({m_L}/{m_R} \right)^2$$

If tensor and scaler couplings are excluded (as unnecessary) from these extensions, then-

$$r = \frac{3}{4}\left[| g^V_{LL} |^2 - 2 | g^V_{LR} |^2 \right] \qquad xd = \frac{3}{4}\left[| g^V_{LL} |^2 - 2\left(| g^V_{LR} |^2 + | g^V_{RR} |^2 \right) \right]$$

$$x = | g^V_{LL} |^2 - 2\left[\left| g^V_{RR} \right|^2 + \left| g^V_{LR} \right|^2 \right] \qquad h = 0$$

For Left/Right Symmetric extensions

For $g^V_{LR} = g^V_{RL} \approx z << 1$ $\quad g^V_{RR} \approx \left({m_L}/{m_R} \right)^2$

$$r \approx \frac{3}{4}\left(1 - 2z^2\right)$$

$$x \approx 1 - 2\left(\frac{m_L}{m_R}\right)^4 - 2z^2$$

$$\approx \frac{4}{3} r - 2\left(\frac{m_L}{m_R}\right)^4$$

$$d \approx \frac{3}{4}$$

$$h \approx 0$$

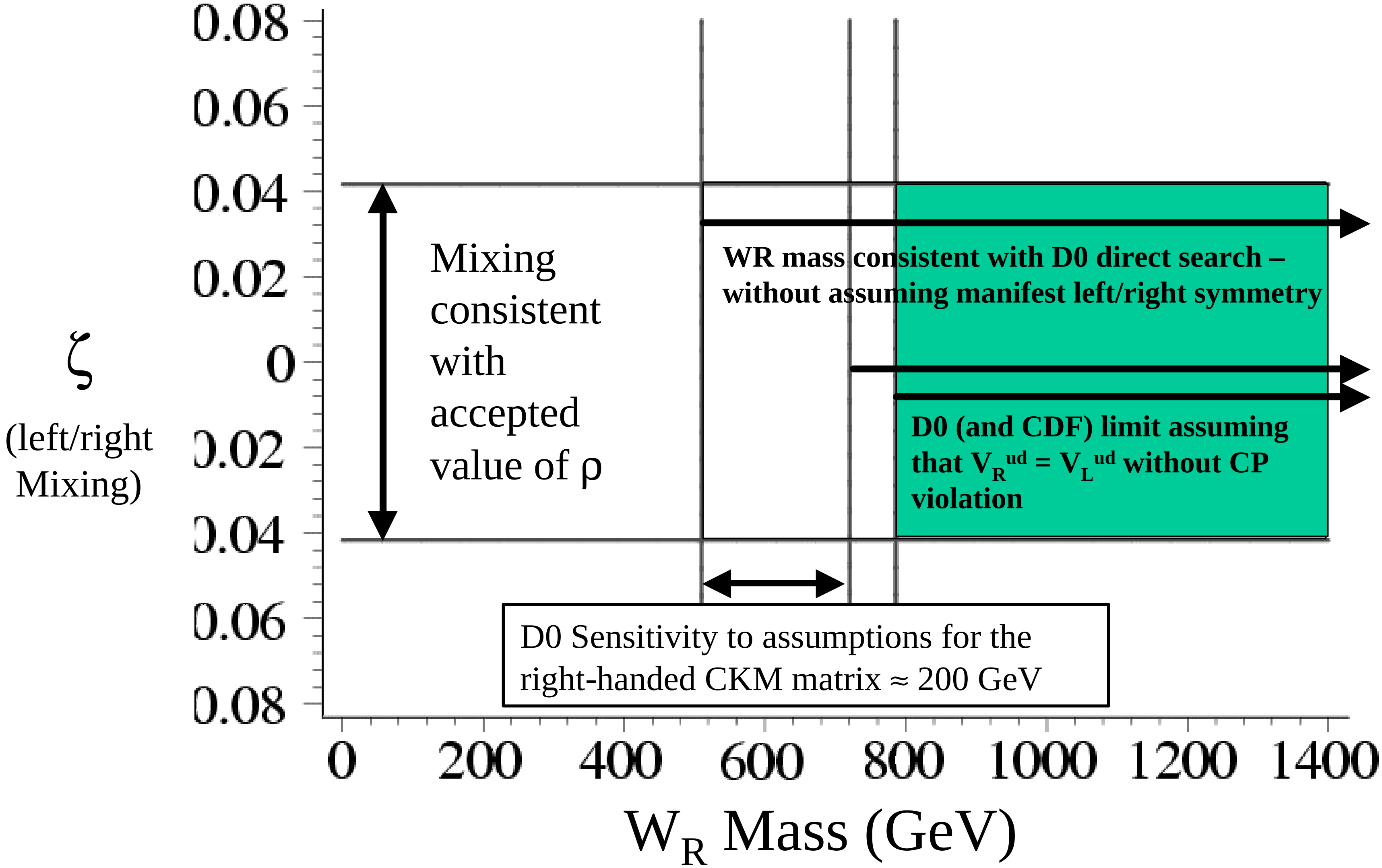
ρ is sensitive to the Left/Right mixing

ξ to the mixing and to the W_R mass

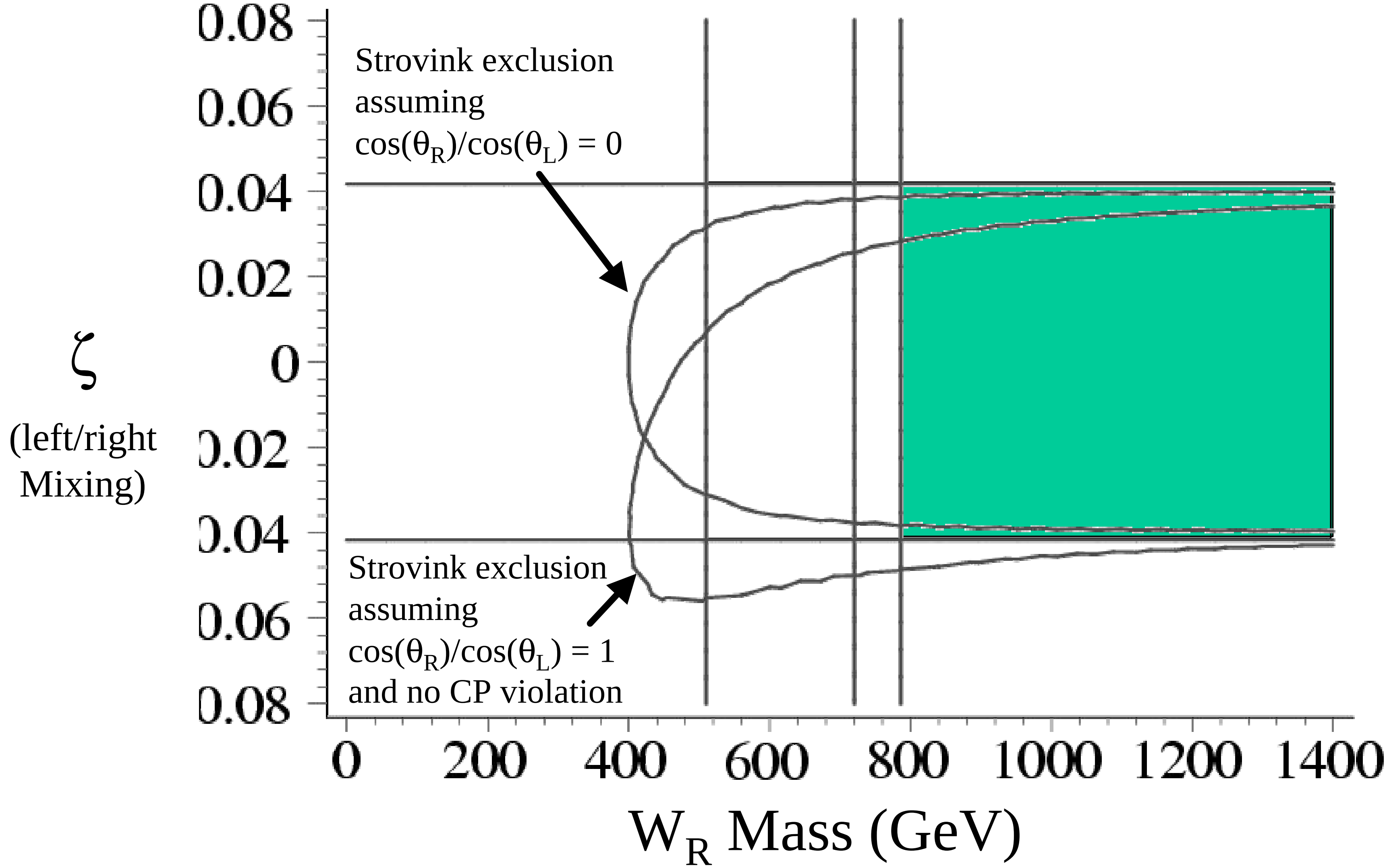
δ and η are unchanged by Left/Right extensions with manifest symmetry

A measurement of ρ and ξ determines the W_R mass and its mixing

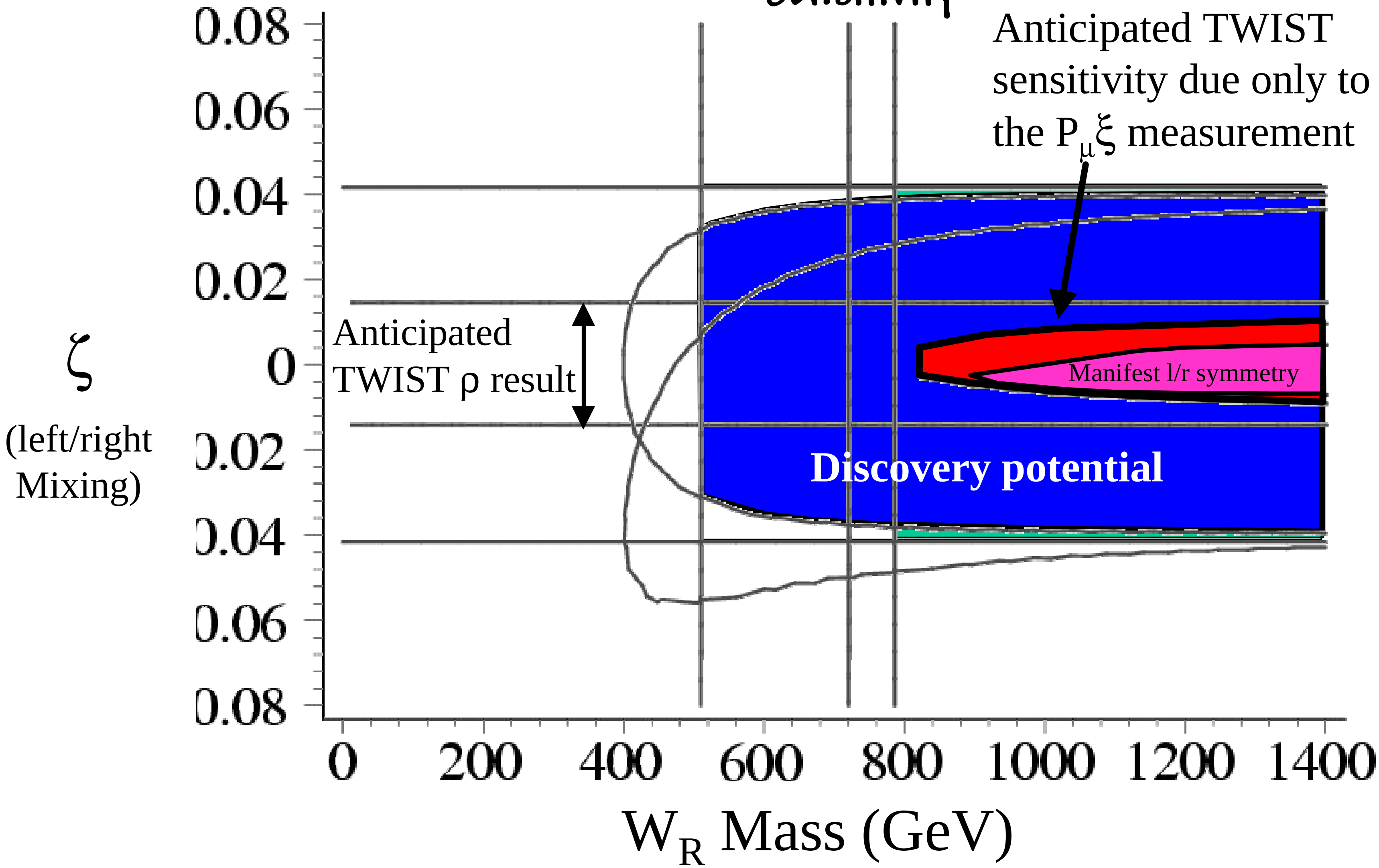
Left/Right Mixing constraints - Existing limits



Left/Right Mixing constraints - Existing limits



Left/Right Mixing constraints - Anticipated TWIST Sensitivity



Testing SUSY

- R-parity violating SUSY leads to the following deviations in the parameters at tree level

$$\Delta r = \frac{3e^2}{16} \qquad \Delta d = 0$$

$$\Delta h = \frac{e}{2} \qquad \Delta x = -\frac{e^2}{4}$$

where

$$e = \frac{l_{311} l_{322}}{4\sqrt{2} G_F \tilde{m}^2}$$

So that

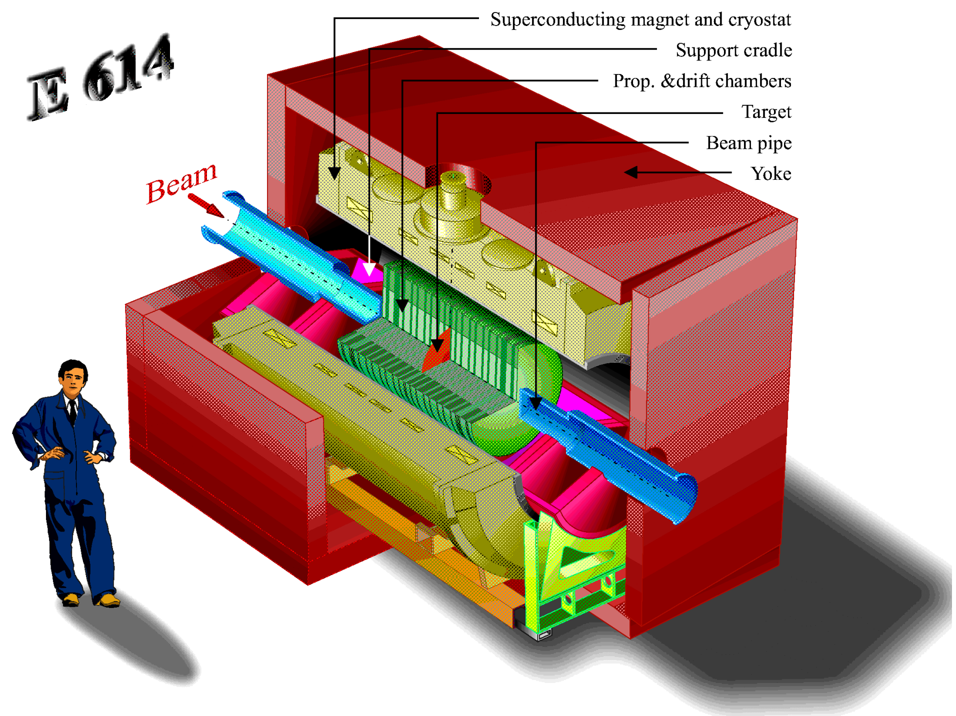
$$\Delta r = \frac{3}{4} \Delta h^2$$

$$\Delta x = -\Delta h^2$$

Deviations in h bigger than 1% would show up with deviations in r and x bigger than 0.01% - with d unchanged. Speculative, but a rather specific prediction.

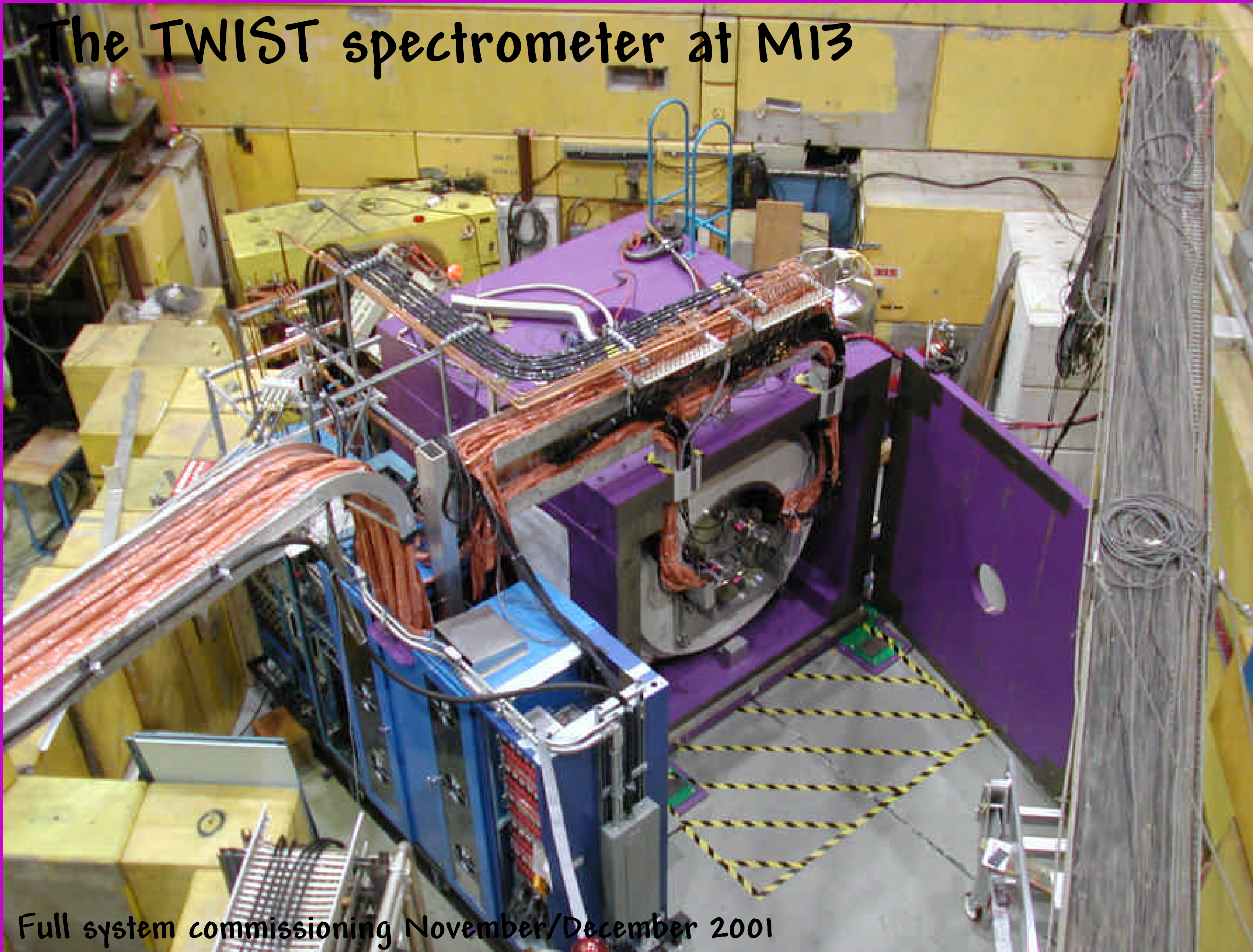
The Experiment

- Highly polarized muons enter the spectrometer one at a time
- Unbiased trigger on muon entering system
- Data sets of 10^9 muon decay events are obtained in roughly two weeks
- The experiment is systematics limited. The high data rate is essential for systematics studies



The large acceptance of the device makes it possible essentially to make measurements of the Michel parameters under differing conditions – therefore improving the reliability of the result.

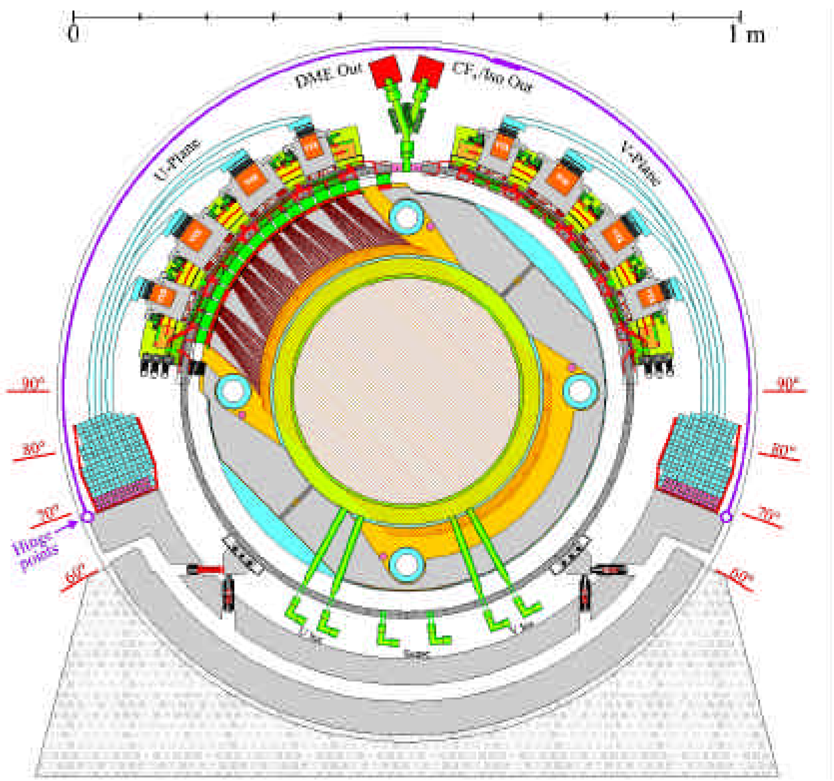
The TWIST spectrometer at M13



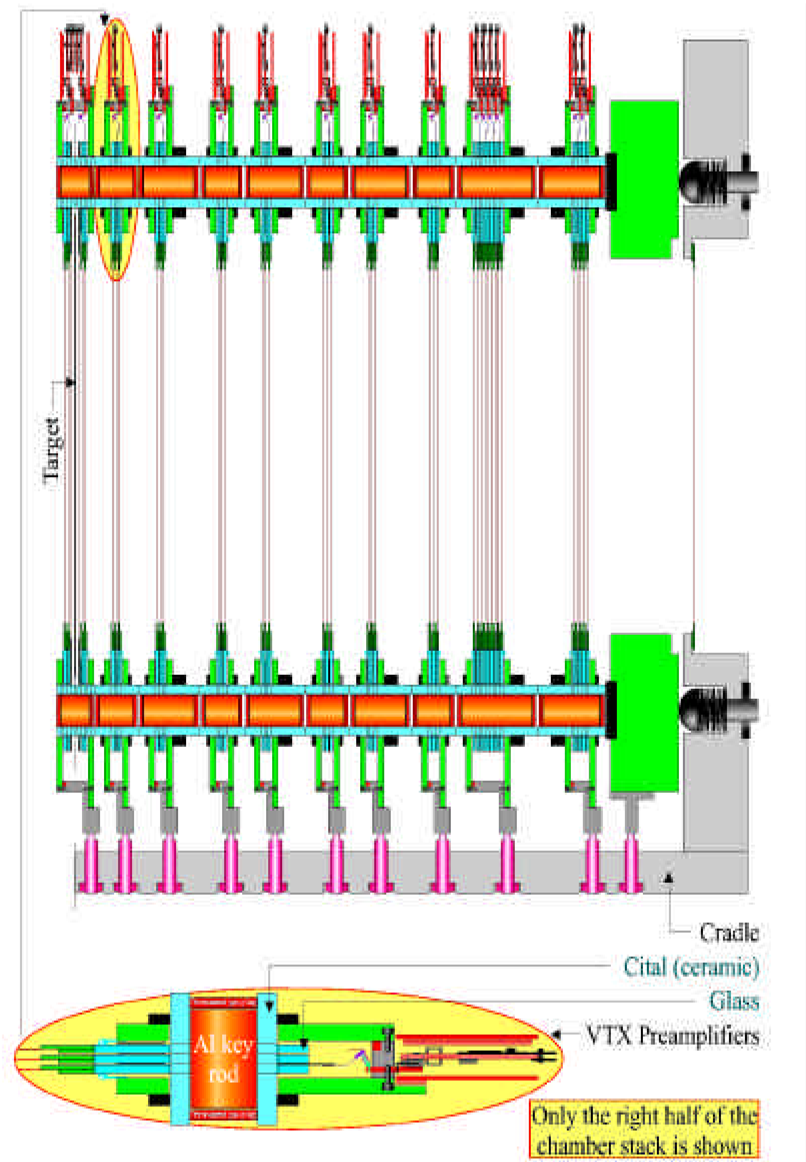
Full system commissioning November/December 2001

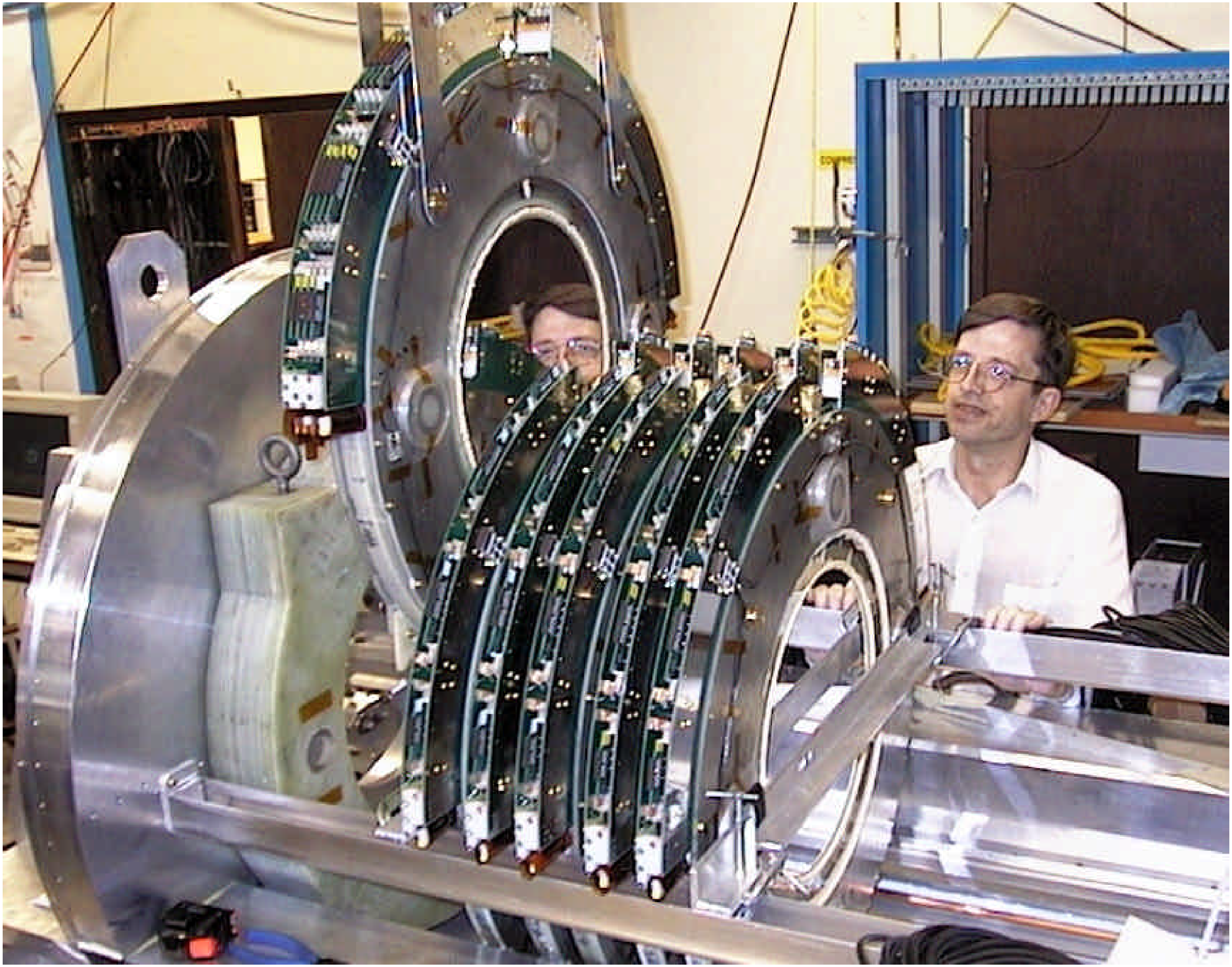
Chambers & half detector

Planar drift chambers sample positron track

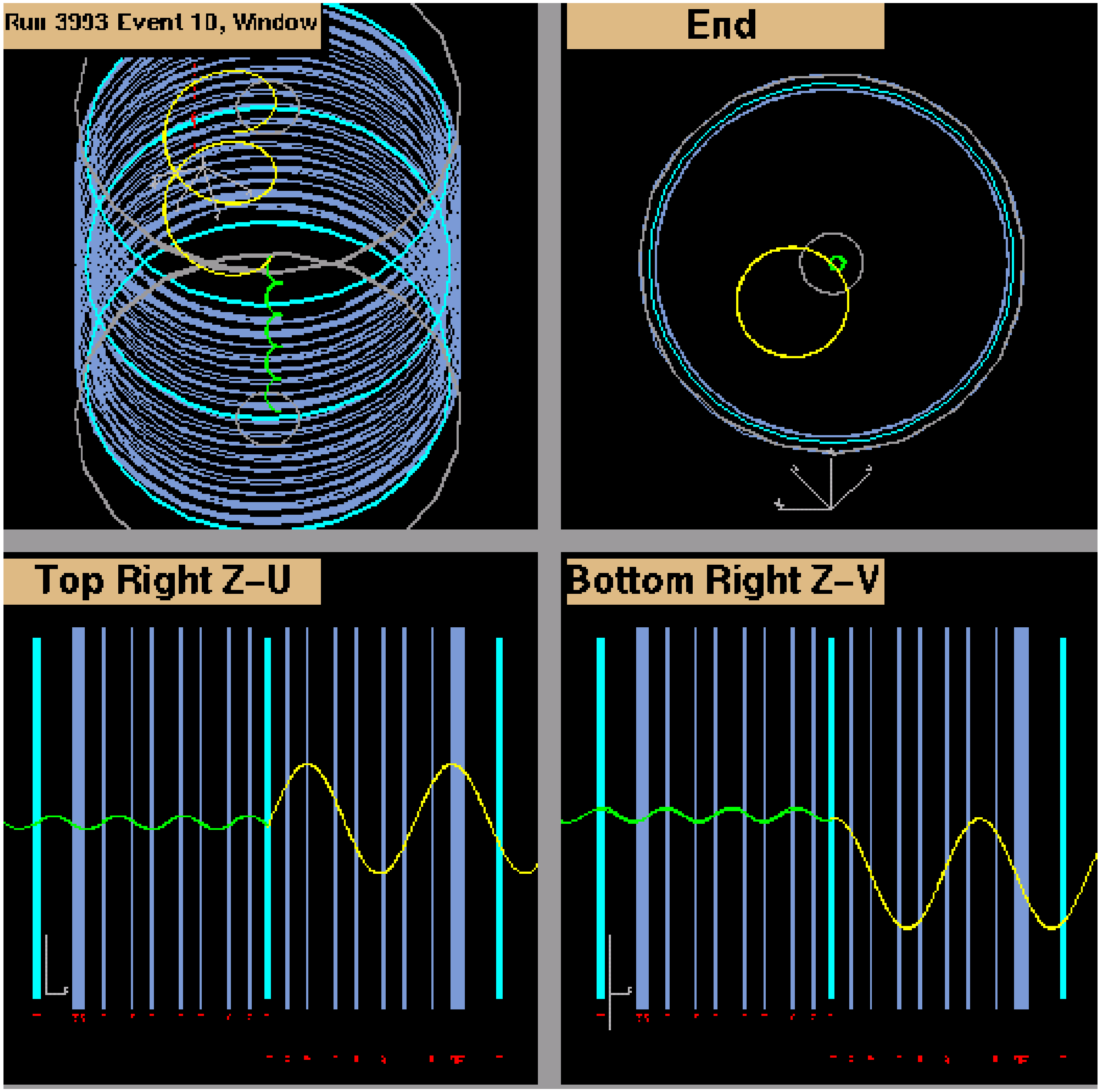


Use 44 drift planes, and 12 PC planes



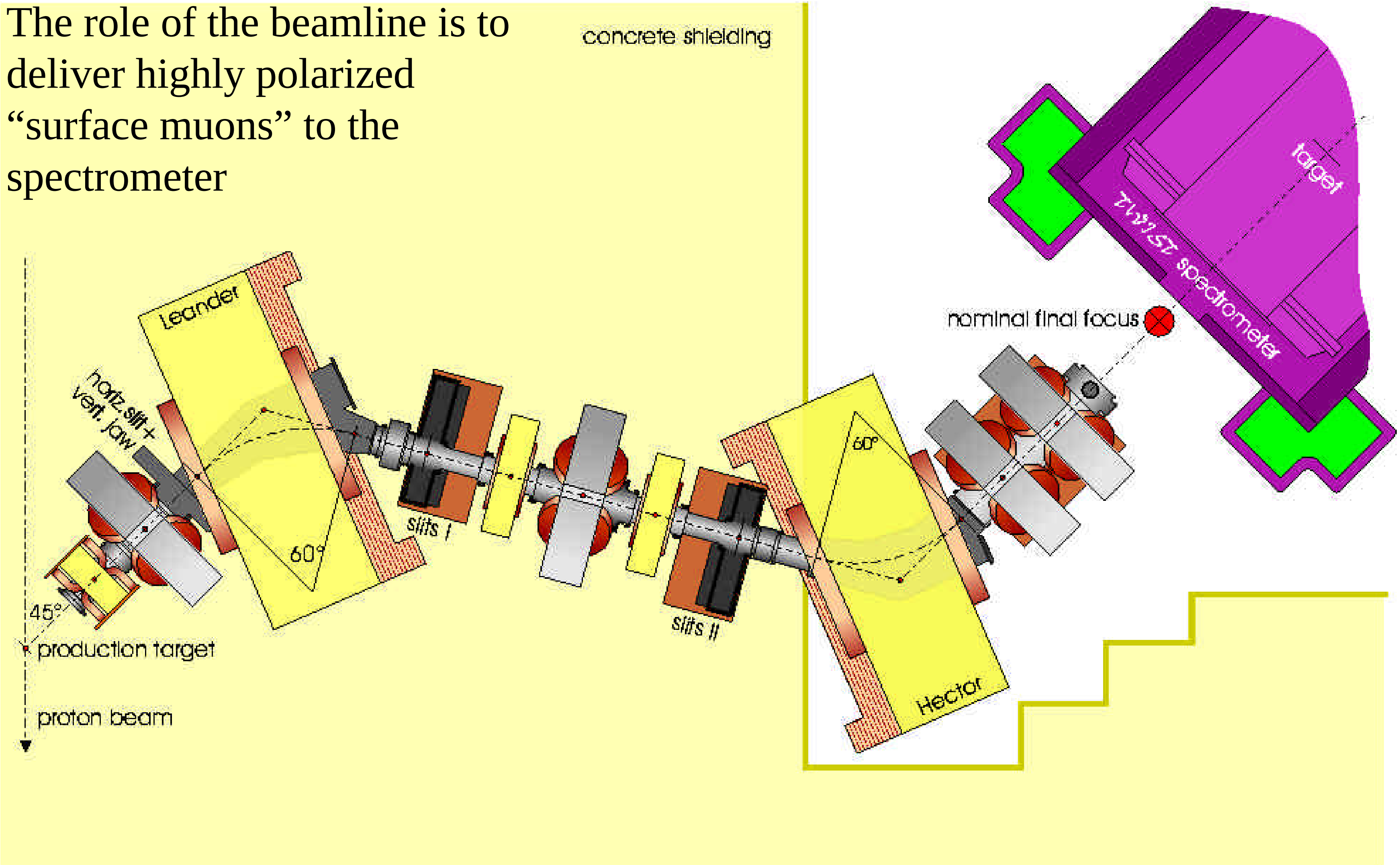


Typical decay event



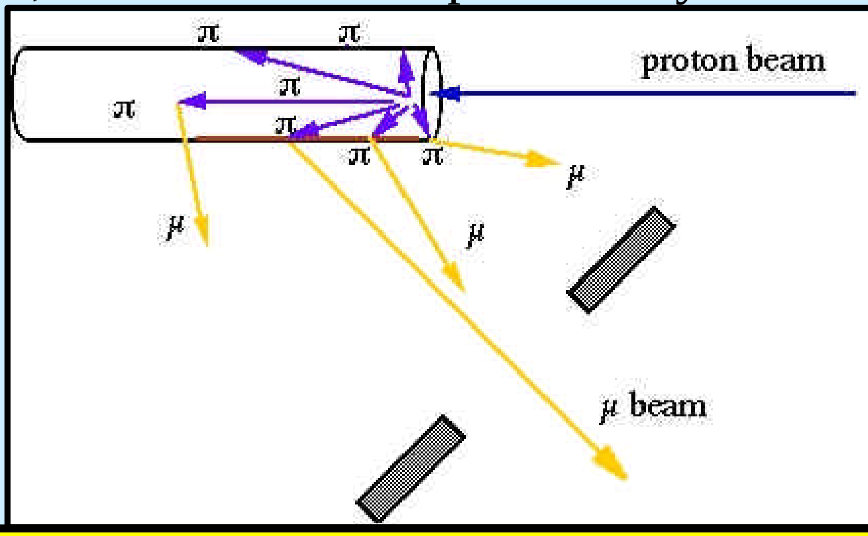
TWIST - Beamline

The role of the beamline is to deliver highly polarized "surface muons" to the spectrometer

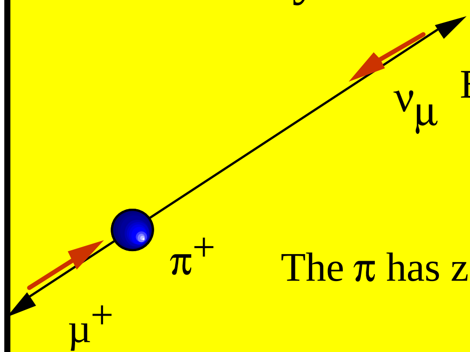


Polarized Muon Source

Protons incident on graphite produce numerous pions, some of which stop and decay into muons



Pion decay at rest produces polarized muons



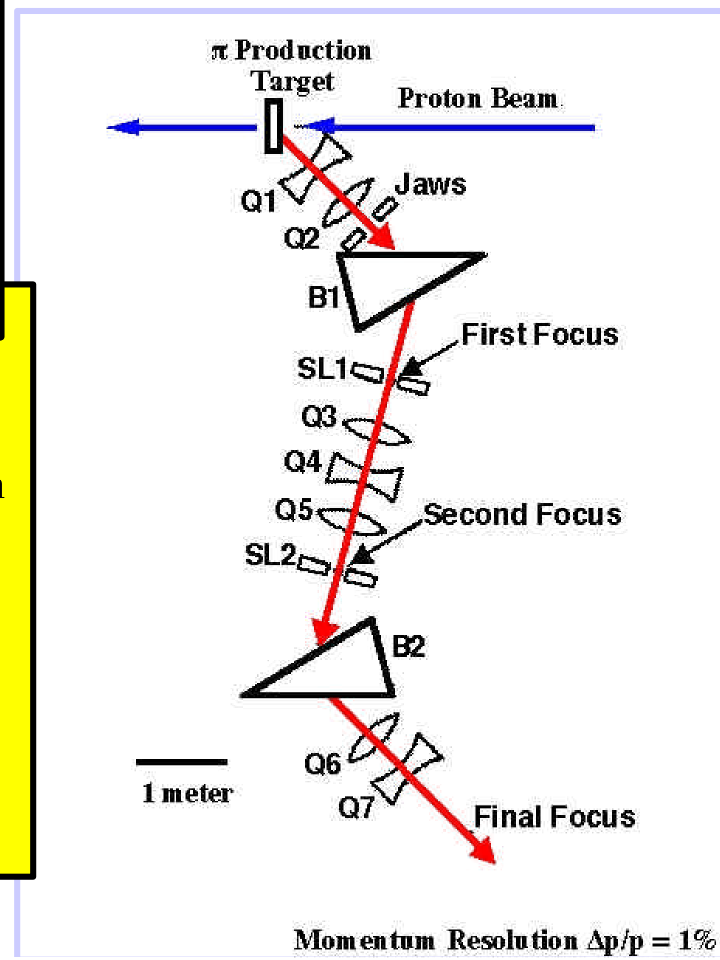
Back to back to conserve linear momentum

The π has zero angular momentum

=> no angular momentum in the final system

TWIST channel resolution allows for the selection of muons produced within 25 microns of the surface of the production target

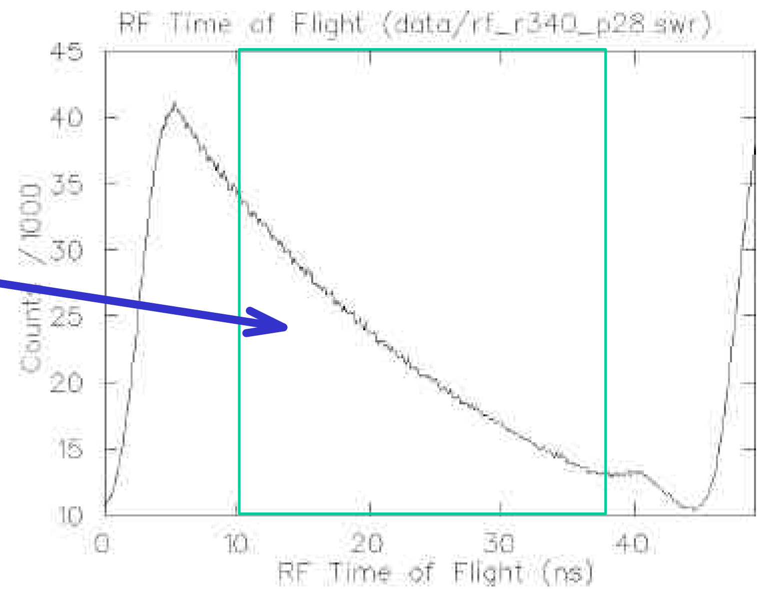
Depolarization: 0.0002 per 25 microns of target material



TWIST - RF Cuts

Flight time through beamline

- Flight time through the channel show the time that pions are stopped in the pion production target prior to their decay
- RF period ~ 1.5 pion lifetimes makes the TRIUMF beam perfect for TWIST

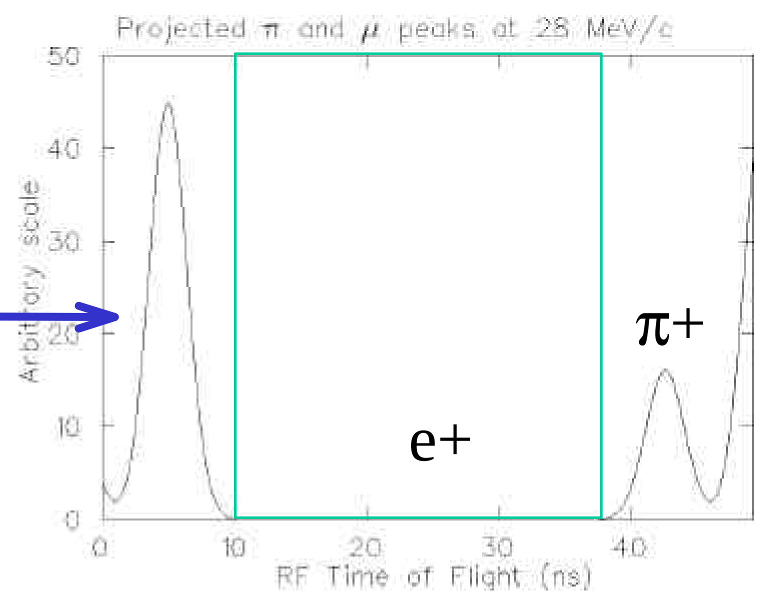


Backgrounds (extrapolated from higher momentum)

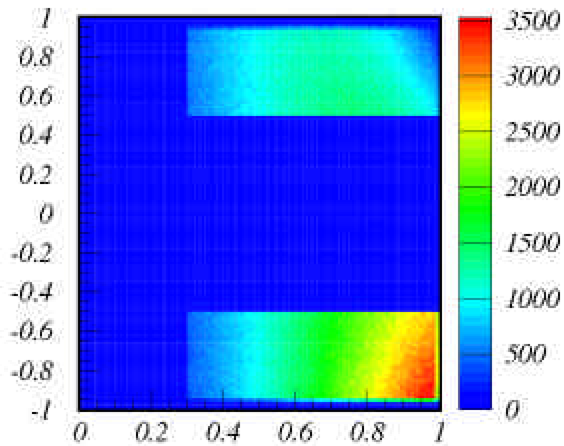
Cloud Muons

polarization ~ -0.3

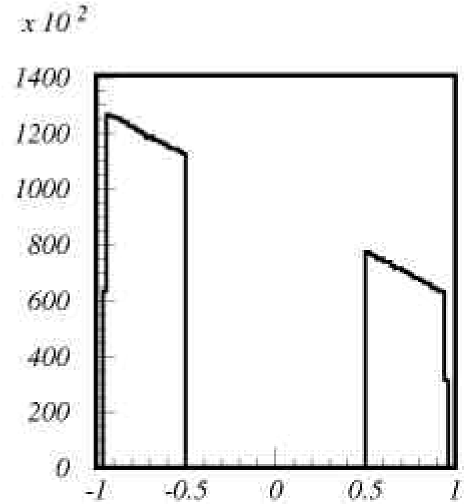
flux ~ 1%



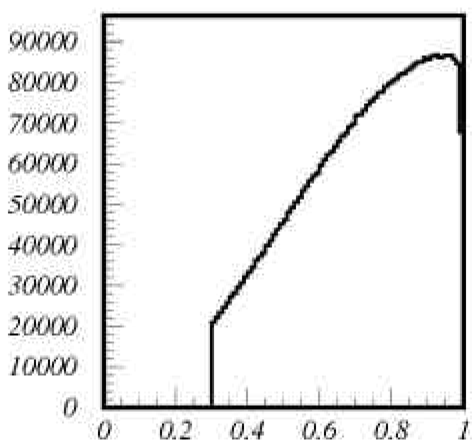
Anticipated Michel Spectrum in TWIST



Michel Spectrum in TWIST



Angular Distribution



Energy Distribution

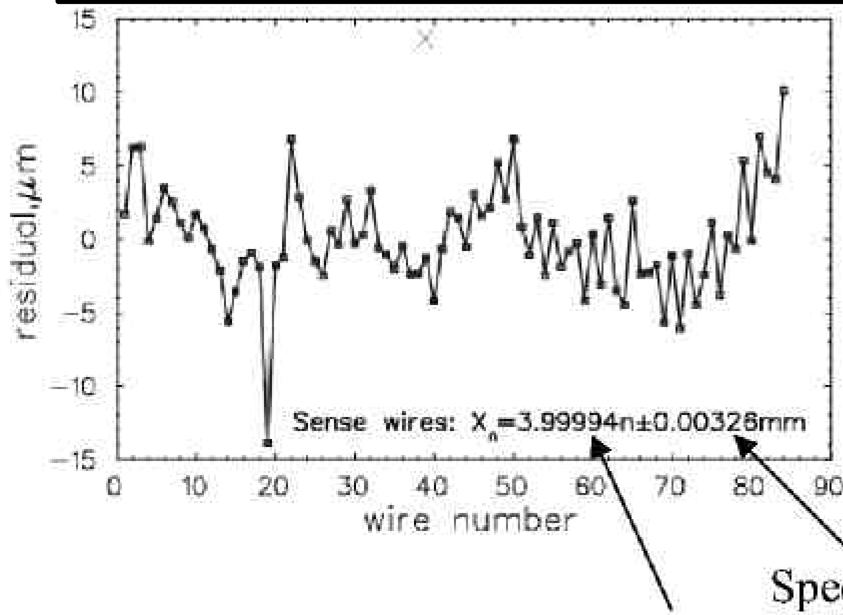
Distributions in cos(q) and reduced energy (x). The fiducial volume will be cut at roughly

$x > 0.3$

$0.5 < |\cos(q)| < 0.95$

Drift Plane Geometry

- The chambers are built to high precision
  - Wires are placed to within about three microns of their nominal position
  - Average deviation in wire position much less than three microns



Spec: 0.020 mm

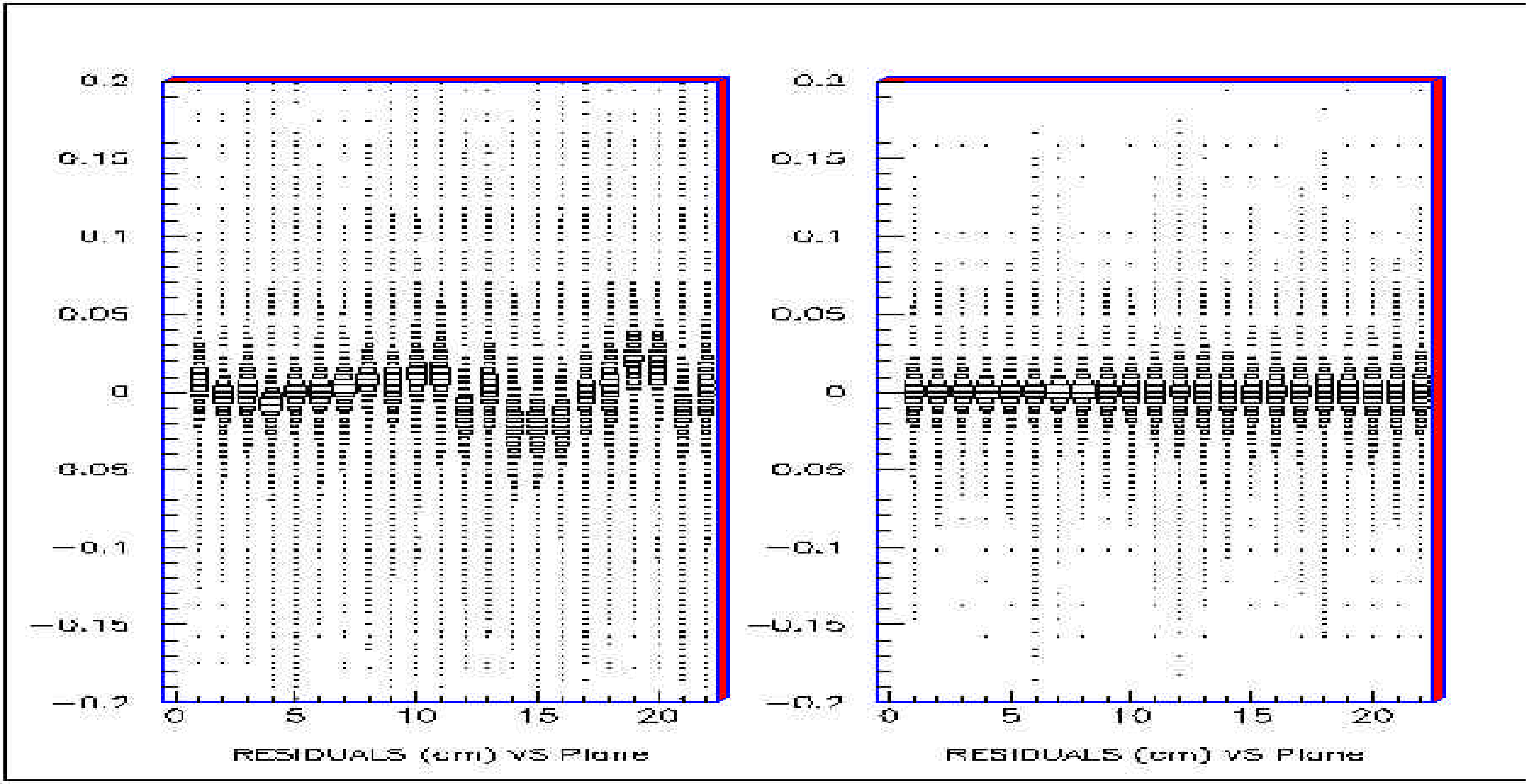
Spec: 4.000+/-0.002 mm

Specification on the average wire spacing is exceeded by a factor of 30. Average deviation in wire positions is ± 2m

Scatter in the individual wire placements is ~ 20 microns, a factor of 7 better than specification.

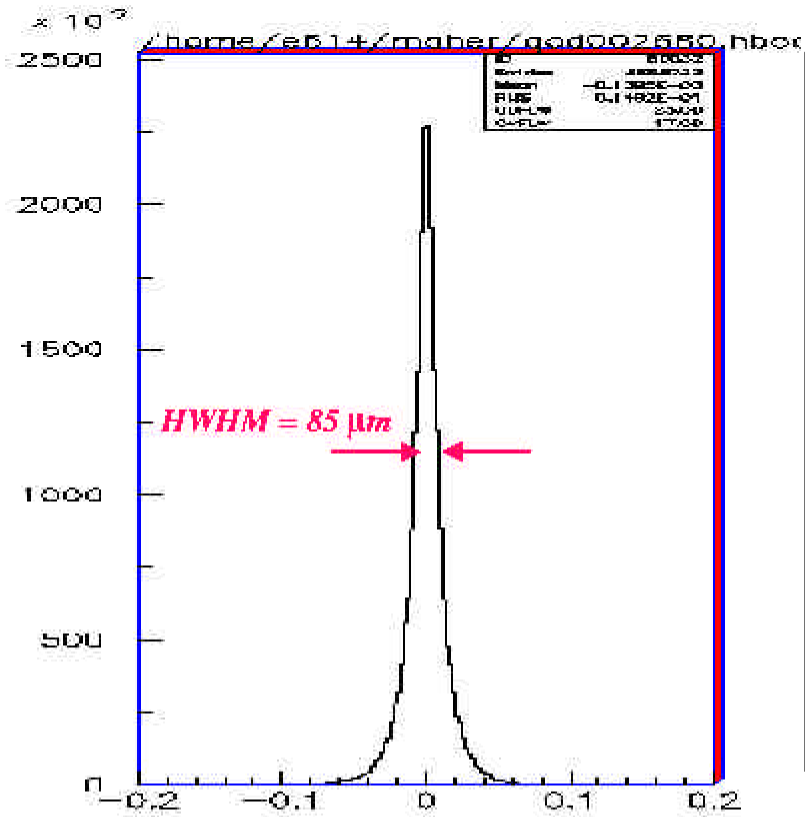
Plane-to-plane Alignments

Before plane alignment ***After plane alignment***

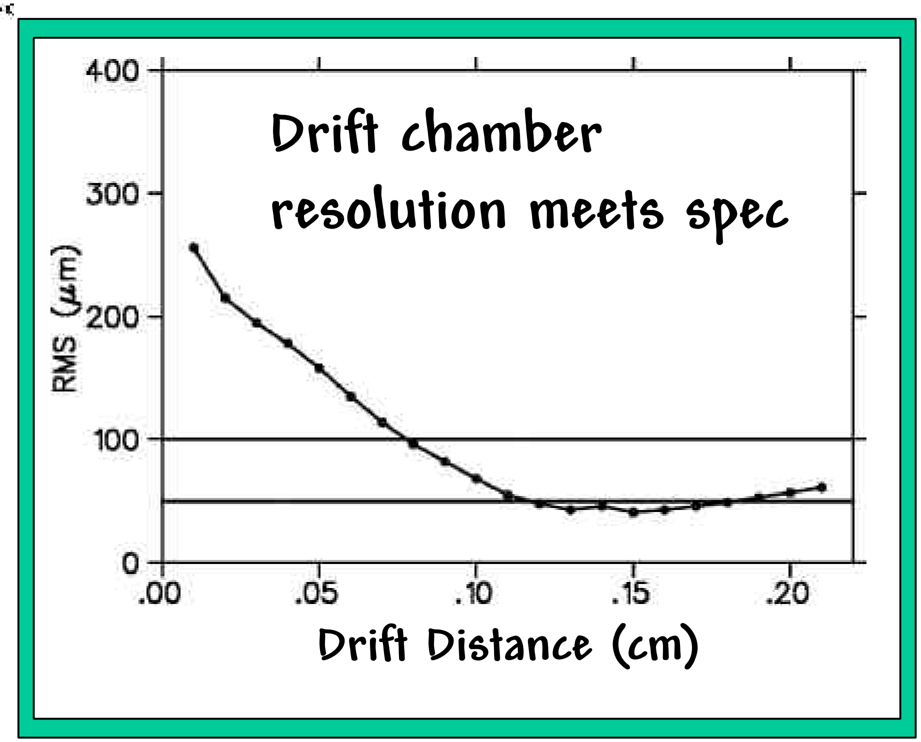


Tracking Residuals

Results to date; further improvements in alignments and T-zero are underway.

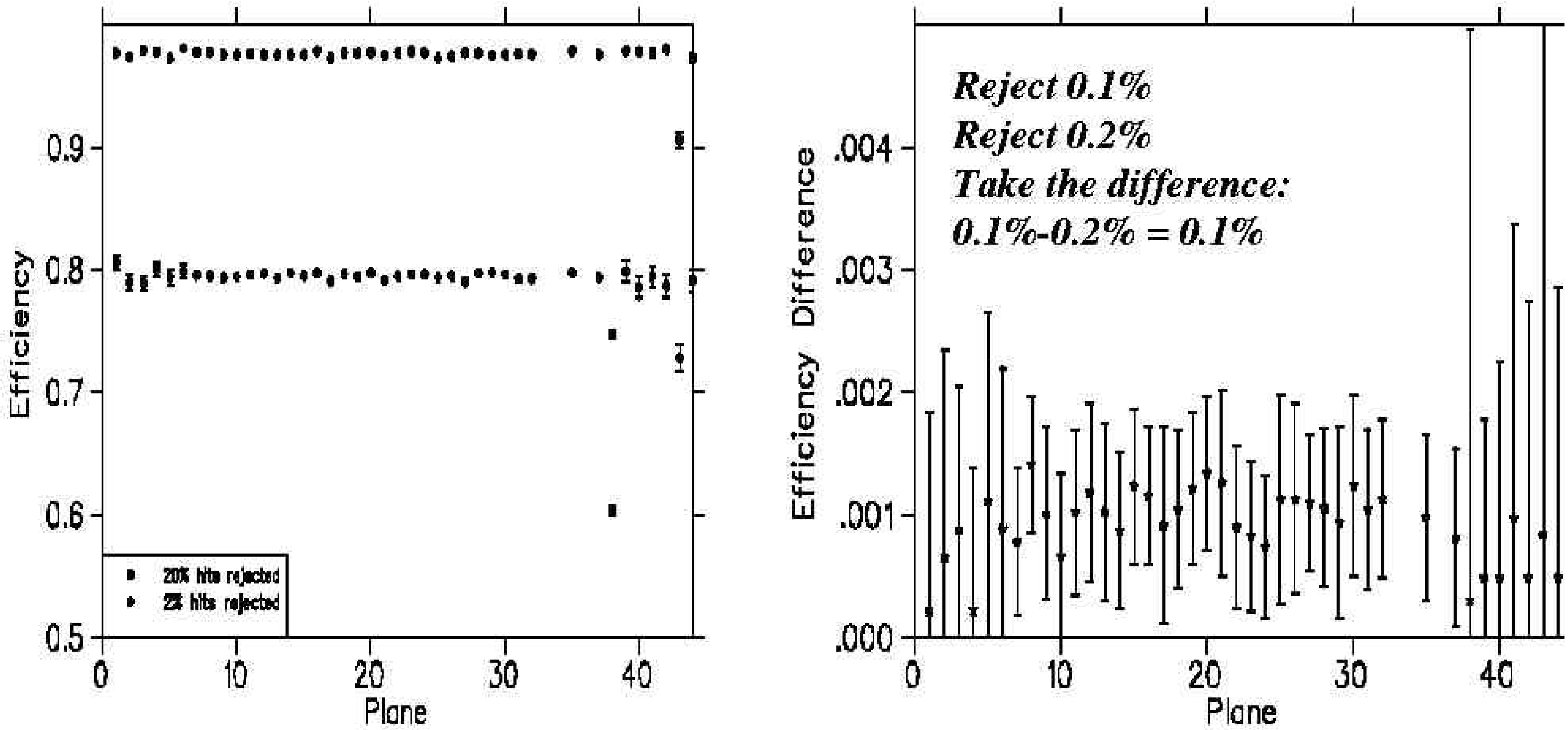


Distribution of tracking residuals



RMS tracking residuals as a function of drift distance in wire cells.

Efficiency - artificial random hit losses accurately identified as inefficiencies by tracking



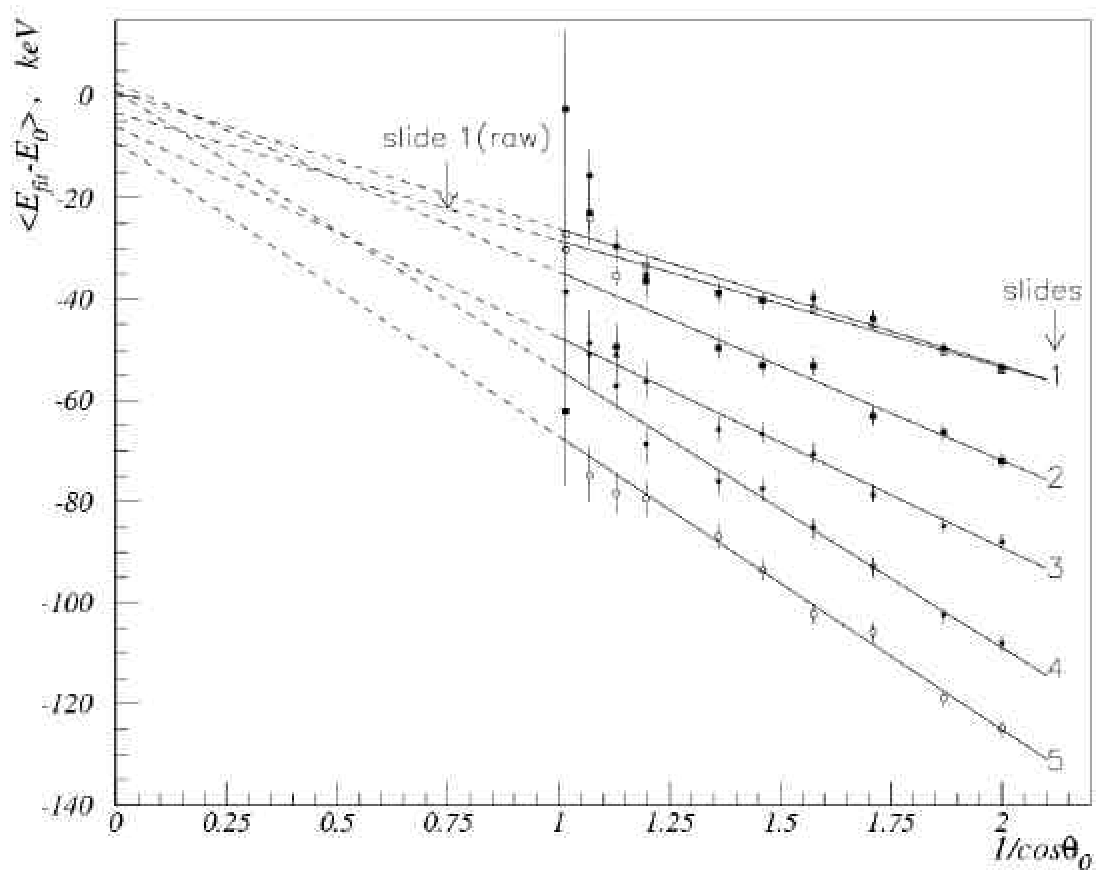
TDC hits were rejected at random at the event unpacking stage to mimic an inefficiency. The inefficiency is accurately identified by the track reconstruction code. Efficiency differences of ~ 0.1% are accurately identified. Plane efficiencies are ~99.8%.

Planar Drift Chambers

- All material seen by the outgoing positrons is in a planar geometry
  - Effects of interactions with the detector are proportional to 1/cos(θ)
    - Energy loss, Multiple scattering, Hard scattering (kinks)
      - including wire scatters

Energy lost along positron track in the TWIST spectrometer vs. 1/cos(q). The curves are for successive sets of detector planes. The slope is proportional to the amount of material in the path of the positron prior to the reconstruction.

The intercept is related to our ability to calibrate the energy scale.

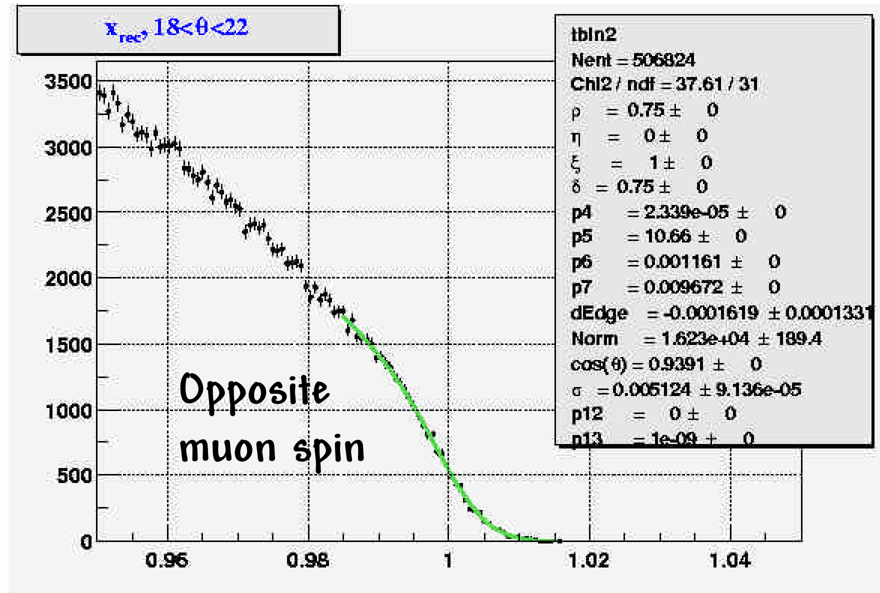


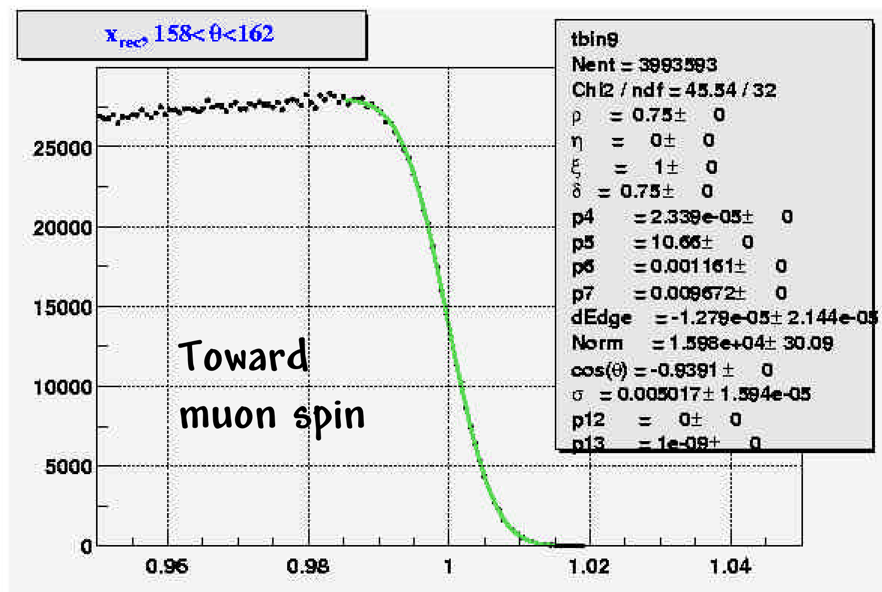
Calibration of the energy scale through End-Point Fits

The energy calibration is obtained from the data itself. The endpoint of the spectrum has a "sharp edge" at 52.83 MeV.

The edge is rounded by finite resolution and by radiative corrections. As well, the edge is reduced at forward angles (opposite the muon spin).

The forward and backward data can be calibrated to approximately 3.8 and 1.3 keV, respectively. The resultant contribution to the uncertainty in the extracted Michel parameters is typically on the order of 1 part in 10,000.





Upcoming schedule

- 10^7 muon decay events are in hand
  - "practice" analysis during January-April 2002
- Field mapping: April 2002
- First physics beam: Summer 2002
  - Preliminary measurement of ρ and δ
- Beamline and depolarization studies: 2002/2003
  - Preliminary data on $P_\mu \xi$
- Final publications: 2005/2006

Conclusions

- The TWIST experiment is underway
  - Anticipate preliminary measurements at ~0.1% of:
    - ρ and δ (Data this summer)
    - $P_\mu\xi$ (Data during the summer of 2003)
  - Final precision on ρ and δ and $P_\mu\xi$ at ~ $\pm$0.02%

- TWIST will explore significant new space where evidence may be found for physics beyond the standard model

- For left/right symmetric models, TWIST has a mass reach which is comparable to - and which complements - that of the Tevatron