Tests of the Standard Model with the TWIST experiment

Yuri Davydov
JINR Dubna
For the TWIST collaboration

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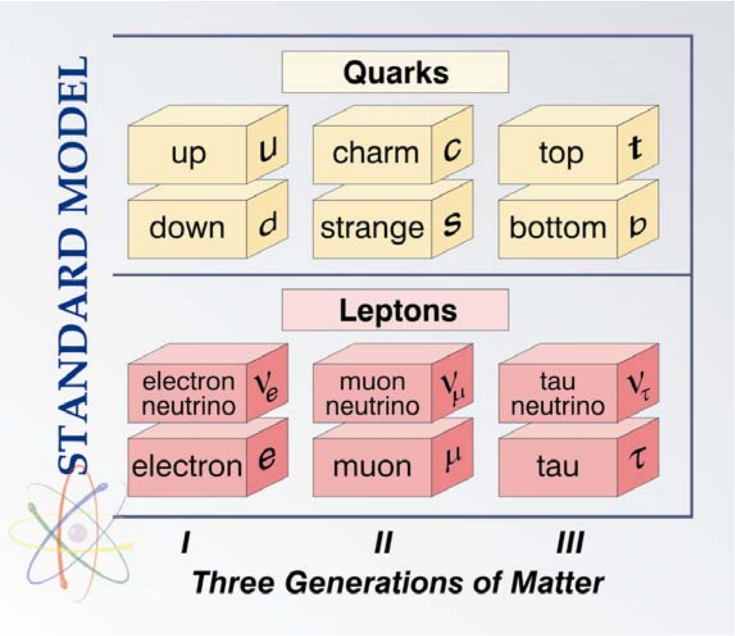
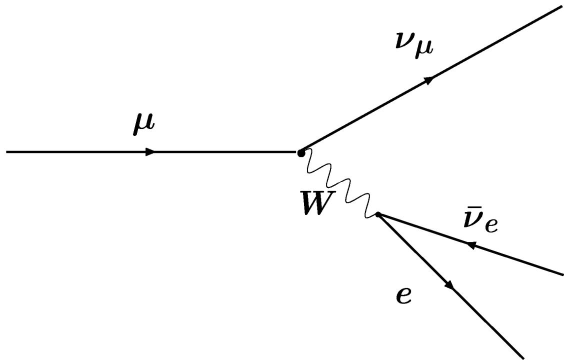
Properties of muons

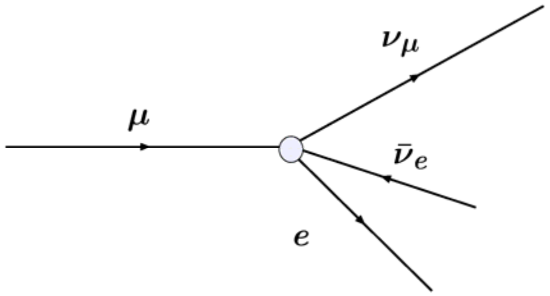
- **Muons (μ-, μ+):**
  - **are second generation leptons**
  - **are not affected by strong interaction (hadronic contribution to the spectrum ≤10^{-6})**



- **Mass:**
  - **105.7 MeV/c^2 (200 ×m_e, 1/9 ×m_p)**
- **Lifetime:**
  - **2.19703 μs**
- **Spin:**
  - **1/2**
  - **easily produced with high polarization**
- **Decay:**
  - **99% to** $\mu \longrightarrow e\bar{\nu}_e\nu_\mu\,,$ **E_e^{max}= 52.8 MeV**

Muon decay diagram





- Assume a four-fermion interaction that is:
  - local
  - derivative-free
  - lepton-number-conserving
- Allows scalar, vector, or tensor; left or right; or combinations.

Muon decay (Michel) parameters

- Muon decay (Michel) parameters ρ, η, $\mathcal{P}_\mu\xi$, δ
  - muon differential decay rate *vs.* energy and angle:

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

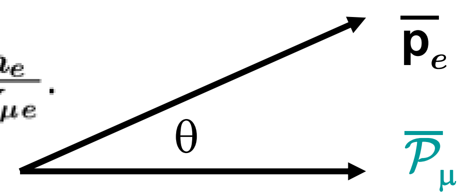
Louis Michel

  - where

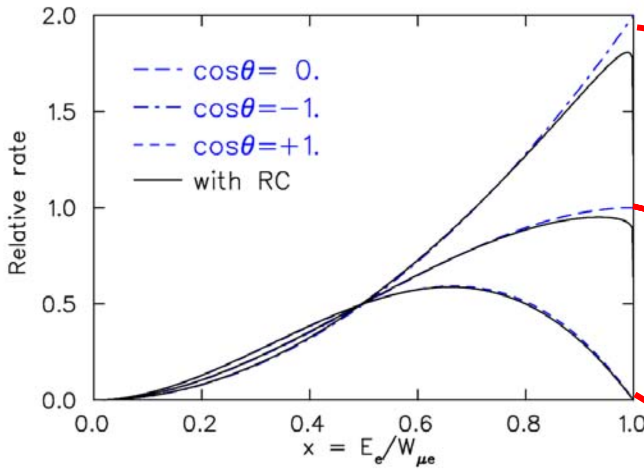
$$\mathcal{F}_{IS}(x,\rho,\eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0 (1-x)$$

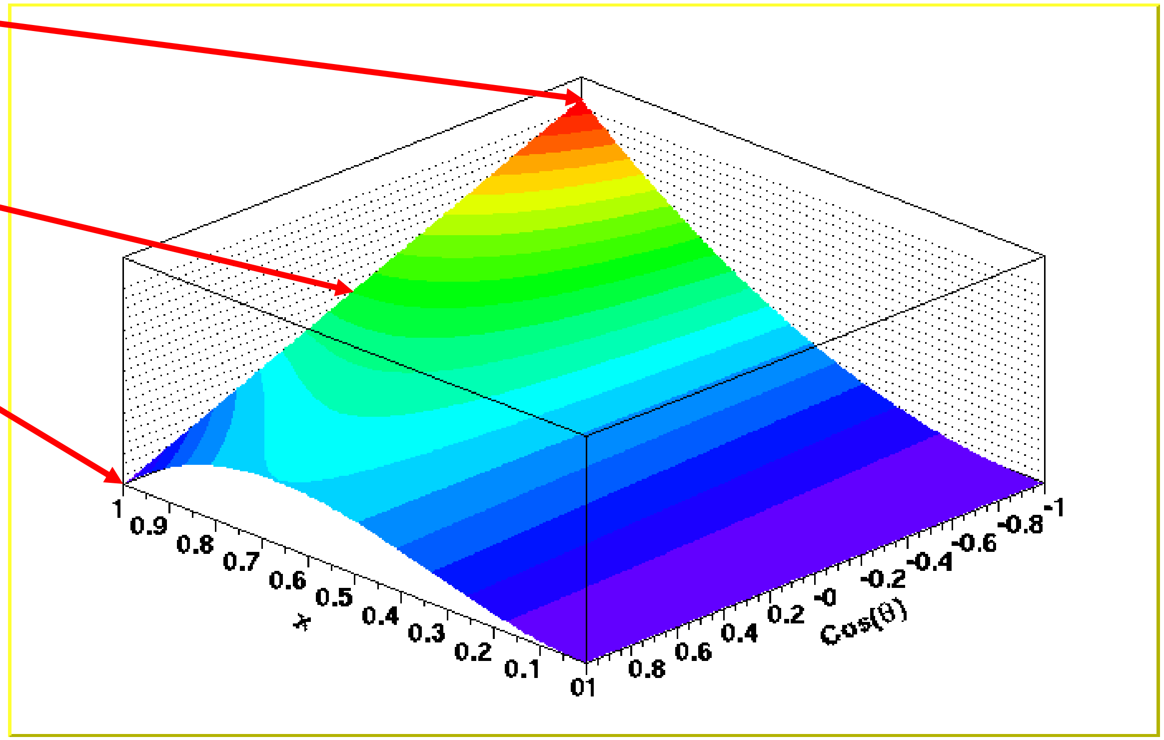
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\sqrt{x^2 - x_0^2}\left[\xi\{1-x\} + \frac{2}{3}\xi\delta\left\{4x - 3 + \left(\sqrt{1-x_0^2} - 1\right)\right\}\right]$$

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



Muon decay spectrum shape





- 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.

Arbuzov et al., Phys. Rev. D66 (2002) 93003.
Arbuzov et al., Phys. Rev. D65 (2002) 113006.
Anastasiou et al., hep-ph/0505069 to O(α^2).

Pre-TWIST decay parameters

- From the Review of Particle Physics — SM values

		SM values
ρ	$= 0.7518 \pm 0.0026$ (Derenzo, 1969)	0.75
η	$= -0.007 \pm 0.013$ (Burkard *et al.*, 1985)	0.00
δ	$= 0.7486 \pm 0.0026 \pm 0.0028$ (Balke *et al.*, 1988)	0.75
$\mathcal{P}_\mu \xi$	$= 1.0027 \pm 0.0079 \pm 0.0030$ (Beltrami *et al.*, 1987)	1.00
$\mathcal{P}_\mu(\xi\delta/\rho)$	> 0.99682 (Jodidio *et al.*, 1986)	1.00

Michel parameters and coupling constants

- Fetscher and Gerber coupling constants (see PDG):

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

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

Coupling constants

- Coupling constants $g^{\gamma}_{\varepsilon\mu}$ can be related to handedness, *e.g.*, total muon right-handed coupling:

$$\begin{aligned} Q_R^\mu &\equiv Q_{RR} + Q_{LR} \\ &= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \end{aligned}$$

- In the Standard Model, g^V_{LL} **= 1**, all others are zero
- Pre-TWIST global fit results (all 90% c.l.):

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

The TWIST experiment

TWIST – **T**RIUMF **W**eak **I**nteraction **S**ymmetry **T**est

The goal of **TWIST** is to find any new physics which may become apparent by improving the precision of each of ρ, δ, and $P_\mu\xi$ by at least one order of magnitude compared to prior experimental results

- TRIUMF, Vancouver, Canada
- University of Alberta, Edmonton, Canada
- University of British Columbia, Vancouver, Canada
- University of Montreal, Montreal, Canada
- University of Regina, Regina, Canada
- RRC "Kurchatov Institute", Moscow, Russia
- Texas A&M University, College Station, TX, USA
- Valparaiso University, Valparaiso, IN, USA

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TWIST Participants

TRIUMF

Ryan Bayes ∗†
Yuri Davydov
Jaap Doornbos
Wayne Faszer
Makoto Fujiwara
David Gill
Alex Grossheim
Peter Gumplinger
Anthony Hillairet ∗†
Robert Henderson
Jingliang Hu
John A. Macdonald §
Glen Marshall
Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin †
Robert Openshaw
Tracy Porcelli ‡
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin ‡‡

Alberta

Andrei Gaponenko ∗∗
Peter Kitching
Robert MacDonald ∗
Maher Quraan†
Nate Rodning §
John Schaapman
Glen Stinson

British Columbia

James Bueno ∗
Mike Hasinoff
Blair Jamieson ∗∗

Montréal

Pierre Depommier

Regina

Ted Mathie
Roman Tacik

Kurchatov Institute

Vladimir Selivanov
Vladimir Torokhov

Texas A&M

Carl Gagliardi
Jim Musser ∗∗
Bob Tribble
Maxim Vasiliev

Valparaiso

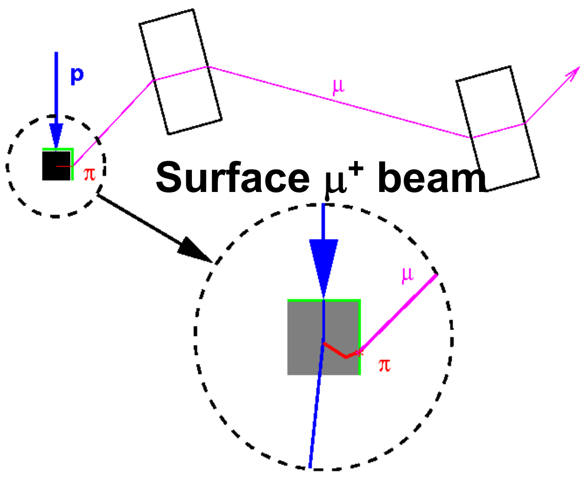
Don Koetke
Paul Nord
Shirvel Stanislaus

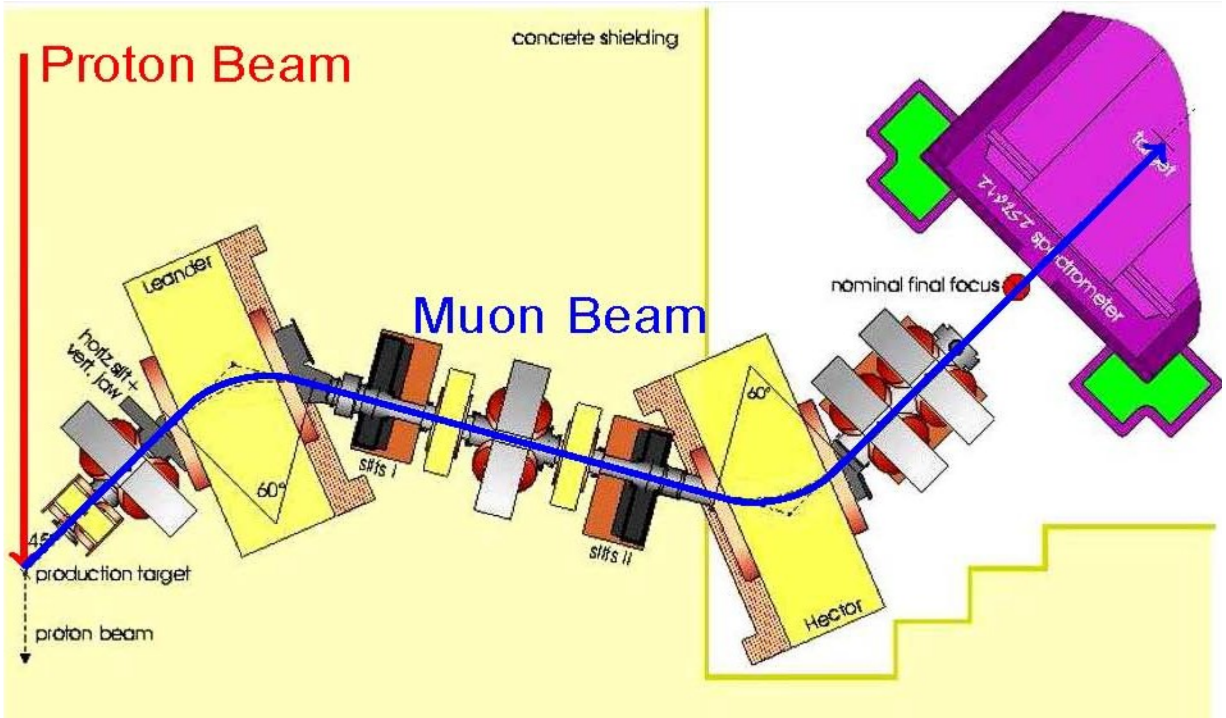
∗ Graduate student
∗∗ Graduated
† also U Vic
‡ also Manitoba
‡‡ also Saskatchewan
§ deceased

http://twist.triumf.ca

Surface muon beam

M13 beam channel

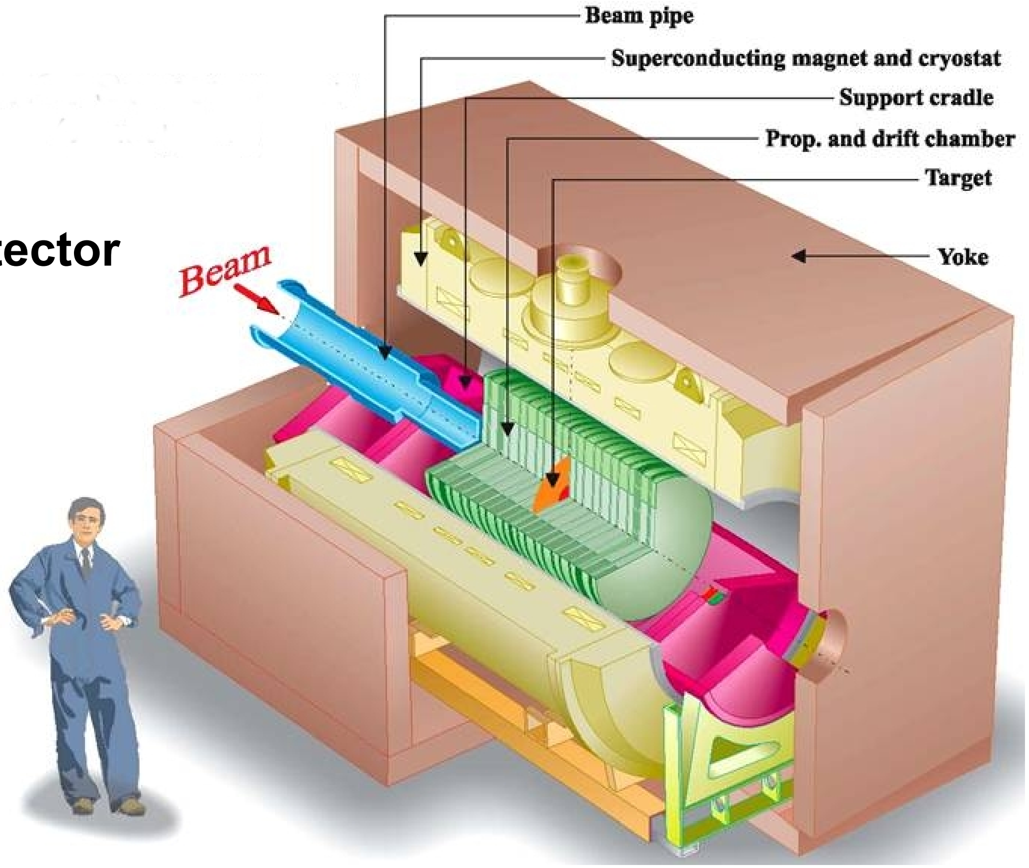




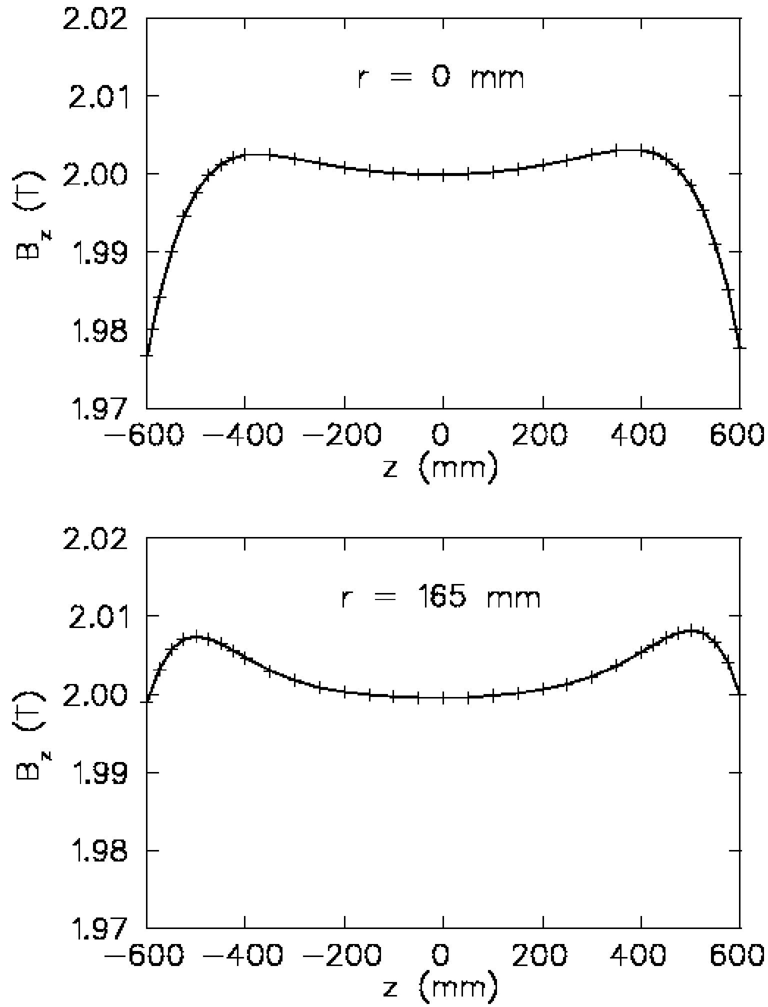
- Pions decaying at rest produce muon beams with P_μ > 99%
- Depolarization must be controlled using beams near kinematic edge, 29.8 MeV/c
- M13 channel: momentum resolution $\Delta p/p$=1%
- Use ~$2.5 \bullet 10^3$ μ+ s^{-1}
- Muon total range at density ~1 only about 1.5 mm!

The TWIST spectrometer

- Tests Standard Model predictions for muon decay
- Uses highly polarized μ^+ beam
- Stops μ^+ in a very symmetric detector
- Tracks e^+ through uniform field
- Extracts decay parameters by comparison to detailed and verified simulation



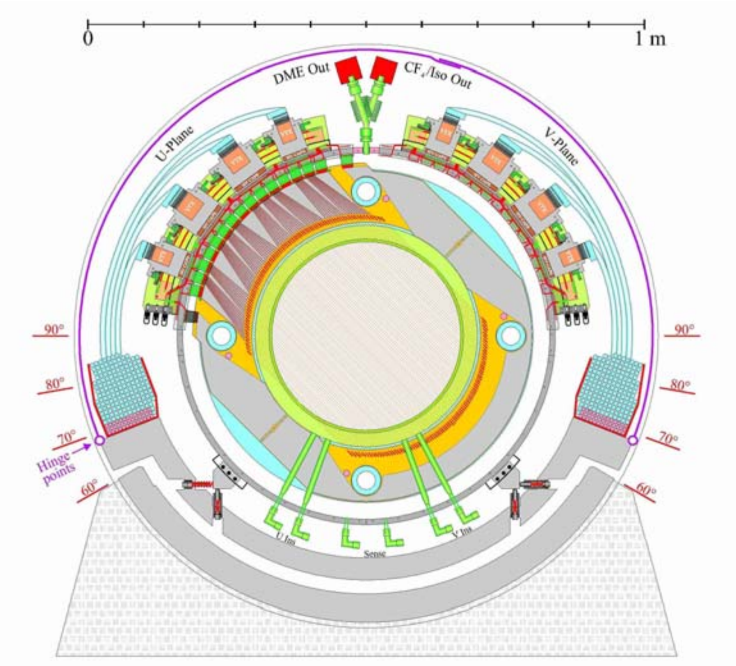
Solenoid field

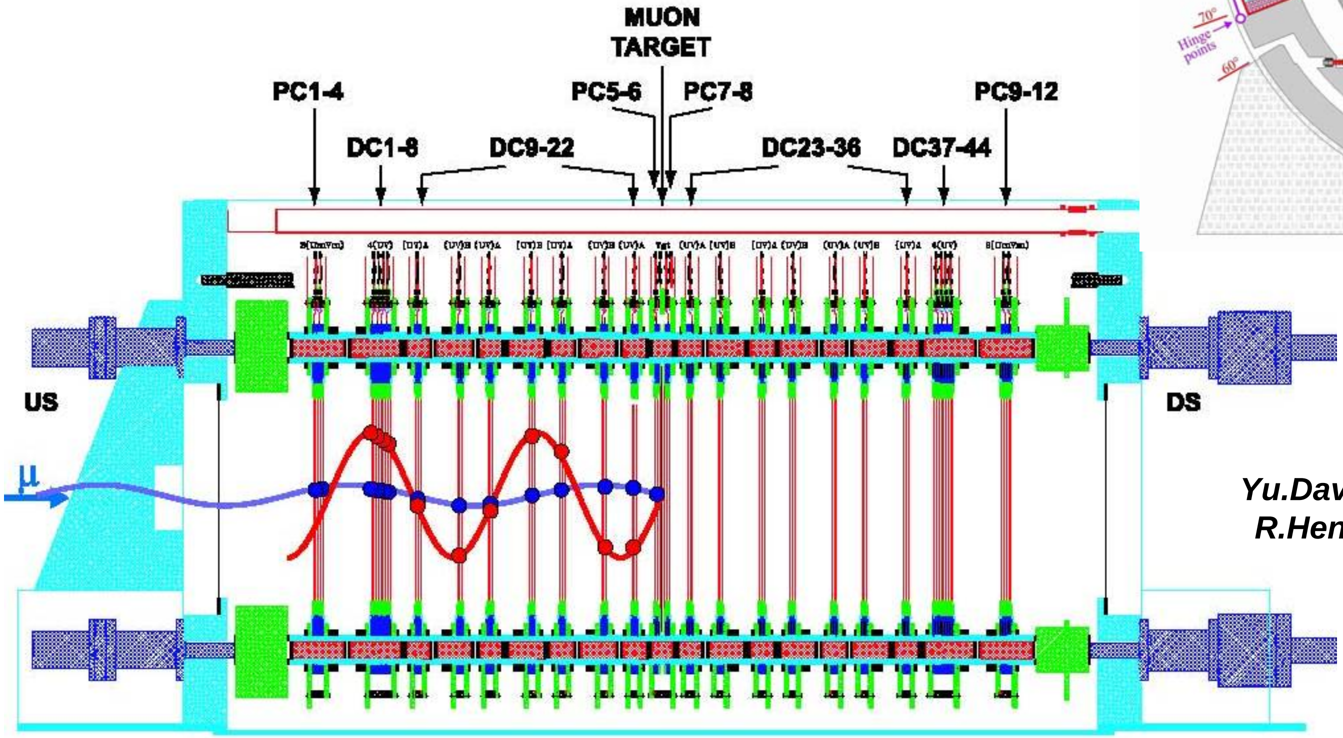


- 20 year old ex-MRI superconducting solenoid provides 2 T field.
- Steel yoke improves uniformity, reduces stray fields.
- Uniform to 4×10^{-3}, mapped to precision of 5×10^{-5}.

Detector array

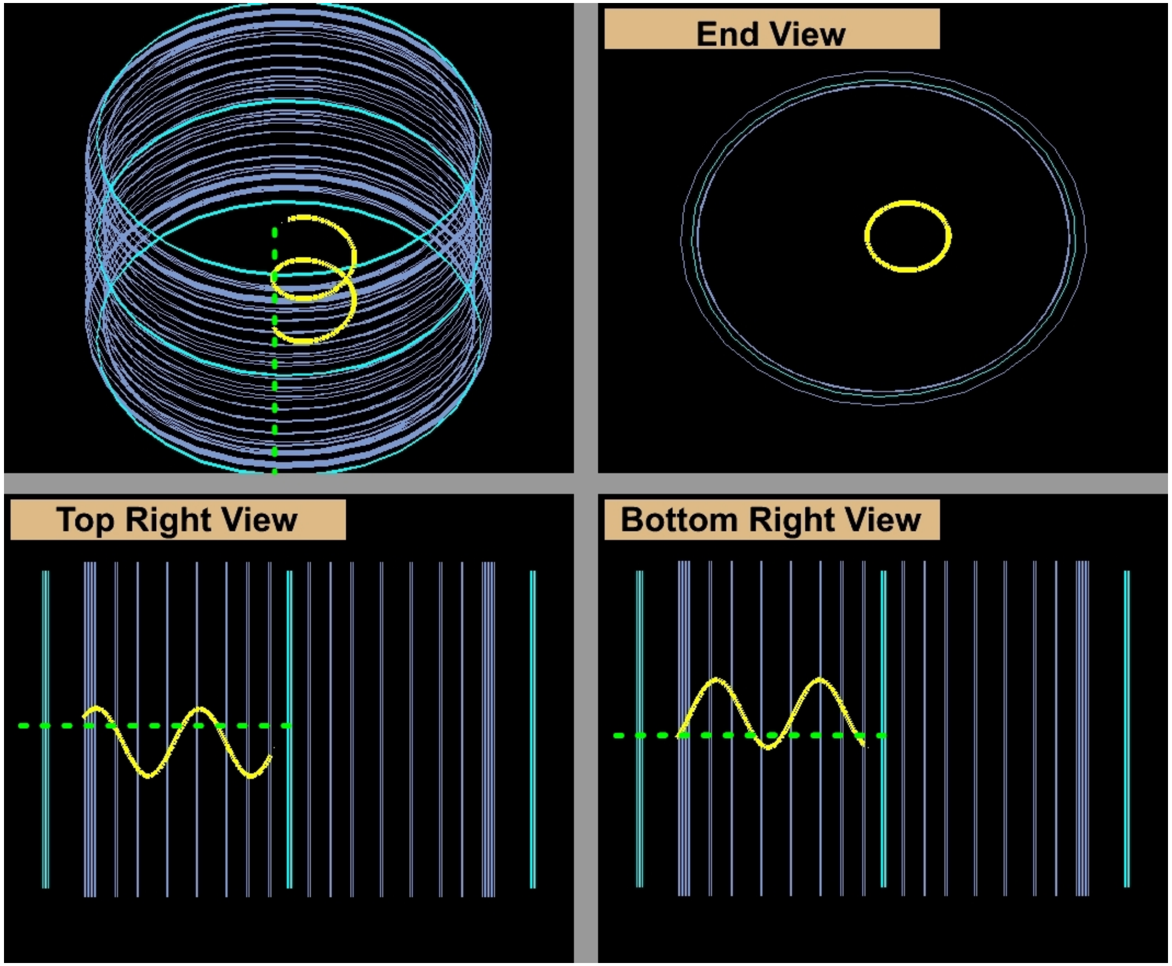
- 56 low-mass high-precision planar chambers symmetrically placed around thin target foil
- Measurement initiated by single thin scintillation counter at entrance to detector
- Beam stop position controlled by variable He/CO2 gas degrader





Yu.Davydov et al. NIM A461(2001)68
R.Henderson et al. NIM A548(2005)306

Typical event



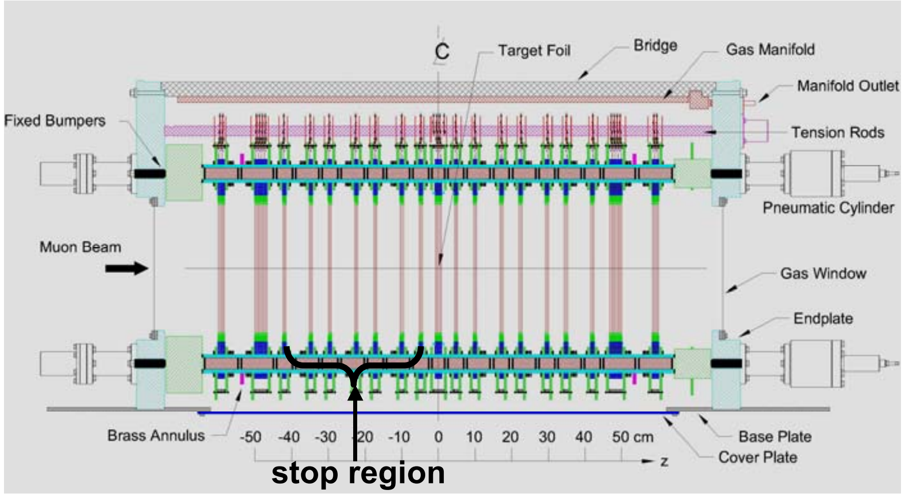
- Read out chamber hits in time interval [-6,+10] μs.
- Use pattern recognition (in position and time) to sort hits into tracks, then fit to helix.
- Write track parameters and other variables.
- Must recognize beam positrons, delta tracks, backscattering tracks.

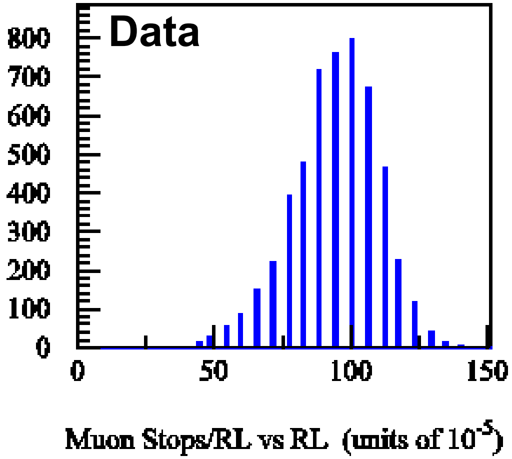
Analysis Method

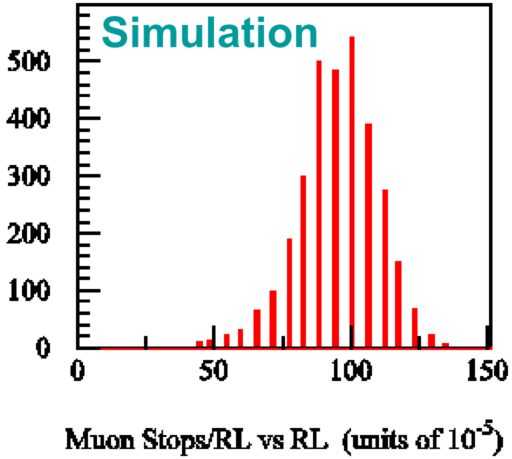
- Extract energy and angle distributions for data:
  - apply (unbiased) cuts on muon variables.
  - reject fast decays and backgrounds.
  - calibrate e^+ energy to kinematic end point at 52.8 MeV.

- Fit to identically derived distributions from simulation:
  - GEANT3 geometry contains virtually all detector components.
  - simulate detector response in detail (clusters of ionization).
  - realistic, measured beam profile and divergence.
  - extra muon and beam positron contamination included.
  - output into digitized format, identical to real data.
  - fit to hidden variables with blind analysis method.

Simulation: muon interactions



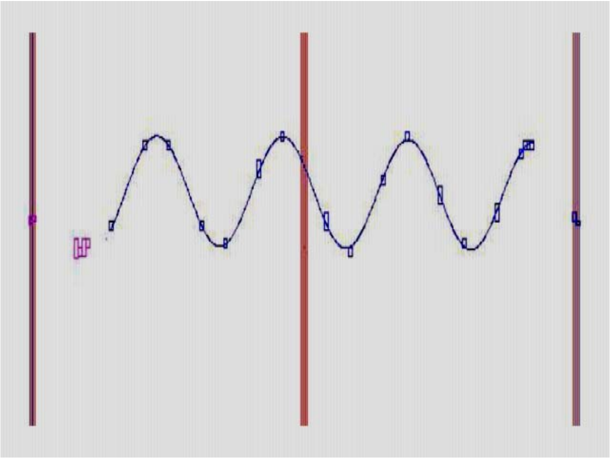


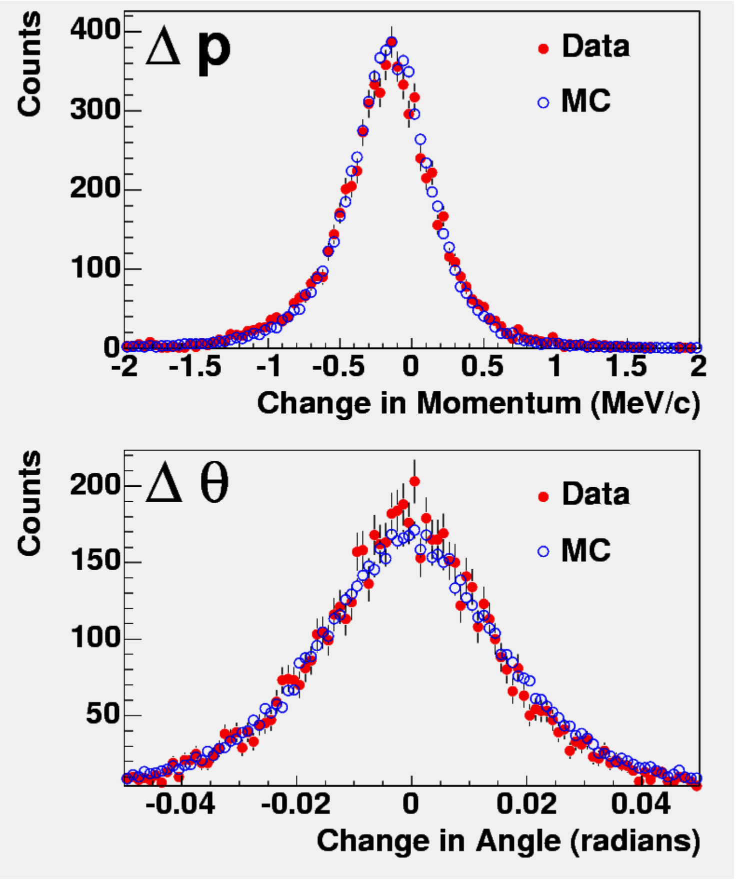


- Simulation must reliably predict muon stopping distributions.
- Verify by comparison in low-mass detector region.

Simulation: positron interactions

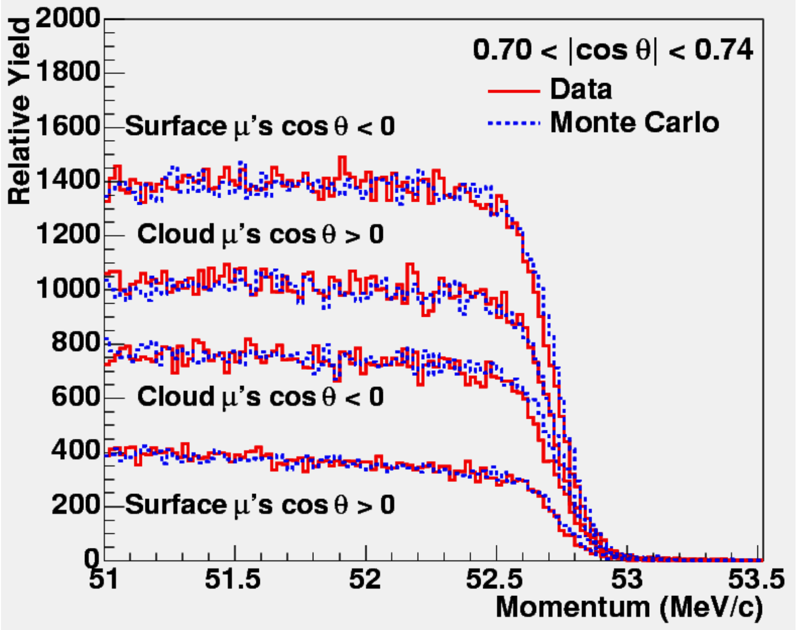
- GEANT simulation must be validated for e^{+} energy loss and multiple scattering.
- Stop muons at one end of detector.
- Measure e^{+} track on each side of target, before and after passage through it.
- Compare differences, with data and MC.





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, β = 0.
- α represents energy loss, mostly in muon stopping target.



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

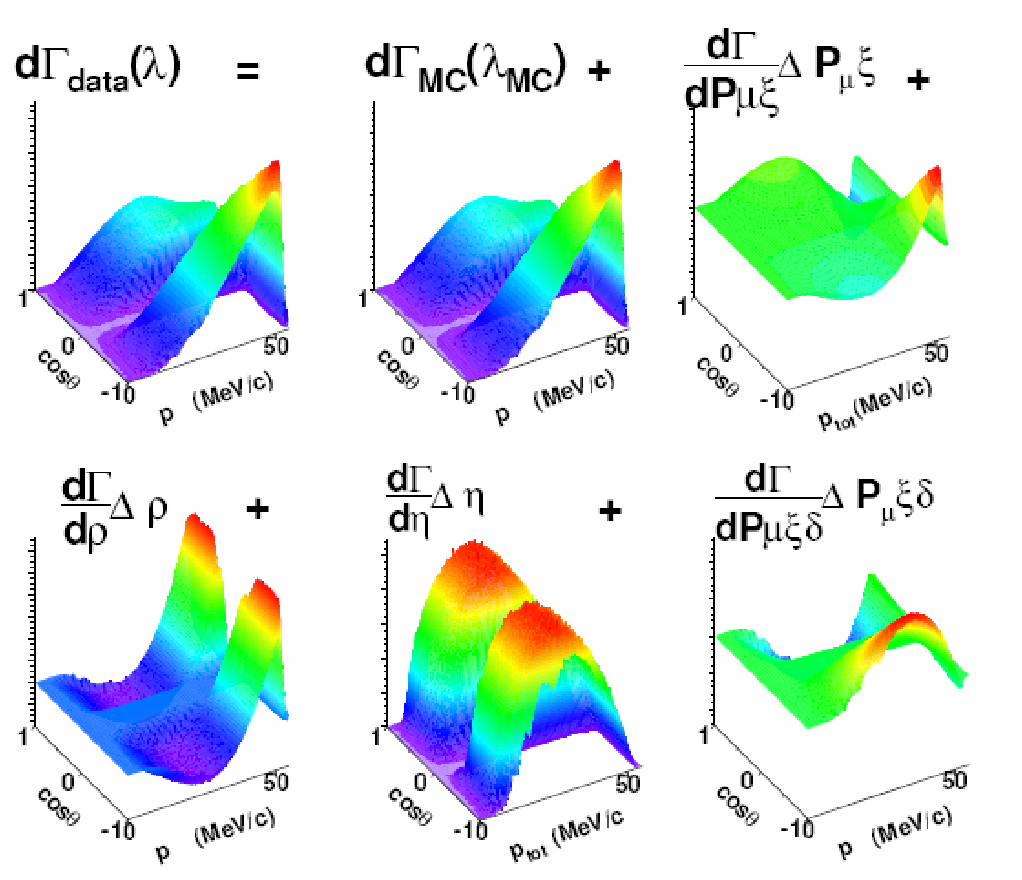
Fitting the data distributions

- Michel distribution is linear in ρ, η, $\mathcal{P}_\mu\xi$, and $\mathcal{P}_\mu\xi\delta$, so a fit to 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 ($\Delta\lambda$) representing deviations from base MC.



(graphic thanks to Blair Jamieson)

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) which may cause error.
  - measure effect by fitting, using correlated sets where practical.
  - scale results according to 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 reproduction**

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

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

Summary of results: ρ and δ

- **ρ = 0.75080 $\pm$ 0.00032(stat) $\pm$ 0.00097(syst) $\pm$ 0.00023(η)**
  - 2.5 times better precision than PDG value.
  - Uncertainty scaled for χ^2/dof = 7.5/4 (CL=0.11) for different data sets.
  - PRL **94**, 101805 (2005), hep-ex/0409063.

- **δ = 0.74964 $\pm$ 0.00066(stat) $\pm$ 0.00112(syst)**
  - 2.9 times better precision than PDG value.
  - PRD **71**, 071101(R) (2005), hep-ex/0410045.

- 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

  0.9960 < $\mathcal{P}_\mu\xi \leq \xi$ < 1.0040
  - improves upon $\mathcal{P}_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$.

Systematic uncertainties: ρ and δ

Systematic uncertainties	ρ $(\leq 10^{4})$		δ $(\leq 10^{4})$	
	published	current	published	current
Chamber response (ave)	5.1	3.2	5.6	5.2
Stopping target thickness	4.9	-	3.7	-
Positron interactions	4.6	3.8	5.5	2.4
Spectrometer alignment	2.2	0.3	6.1	-
Momentum calibration (ave)	2.0	1.1	2.9	2.2
Theoretical radiative correction	2.0	2.0	1.0	1.0
Muon beam stability (ave)	0.4	0.5	1.0	0.9
Track selection algorithm	1.1	-		
Asymmetric efficiencies			0.4	0.1
Total in quadrature	**9.3**	**5.5**	**11.2**	**6.3**

preliminary

preliminary

Summary of results: $\mathcal{P}_\mu \xi$

- $\mathcal{P}_\mu \xi$ **= 1.0003 ± 0.0006(stat) ± 0.0038(syst)**
  - 2.2 times better precision than PDG value (Beltrami *et al.*).
  - still not as precise as TWIST indirect result from ρ and δ.
  - B. Jamieson *et al.*, PRD **74** (2006) 072007, hep-ex/0605100.

- Dominated by systematic uncertainty from spectrometer fringe field depolarization:
  - prospects for improvement are excellent.
  - data was taken in 2004; new data with improved muon beam from data taken in 2006-07.

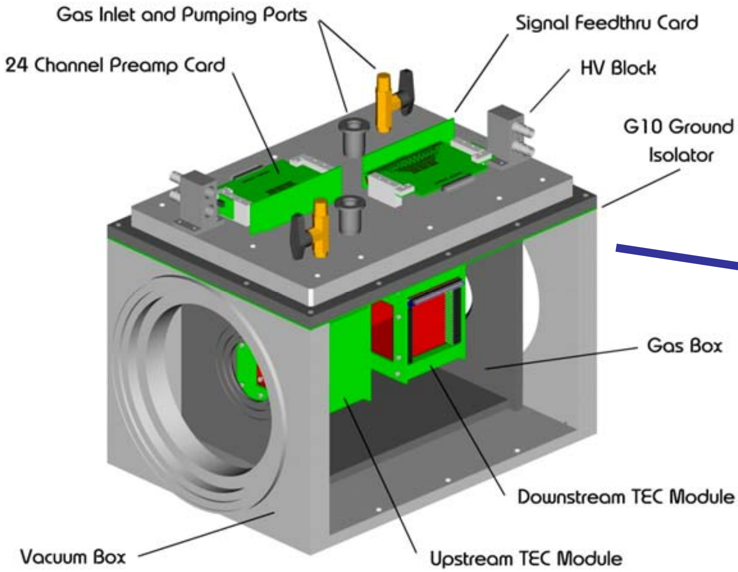
Systematic uncertainties: $\mathcal{P}_\mu\xi$

Systematic uncertainties	$\mathcal{P}_\mu\xi$ ($\times 10^3$)
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**

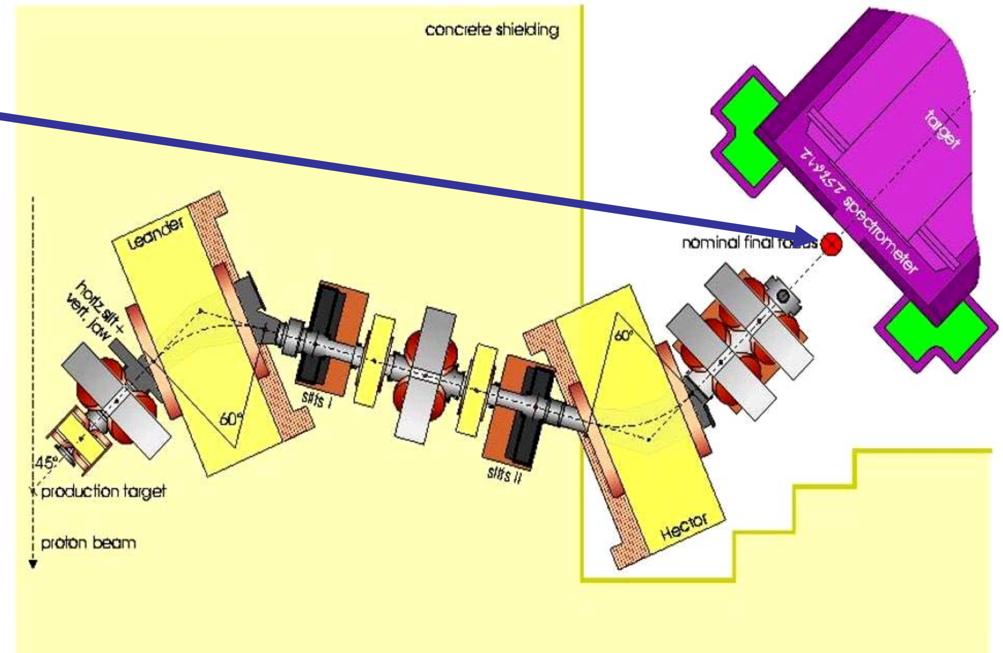
Improving the systematics

Systematic	Improvement
positron interactions	precision target geometry, improved chamber spacing, simulation tuning
momentum calibration	new techniques with reduced bias
chamber response	online monitoring, improved instrumentation, drift time measurements
fringe field depolarization	beam monitoring (TEC), beam alignment and steering
stopping target depolarization	aluminum and silver targets, depolarization studies with μSR.

Muon depolarization across the fringe field

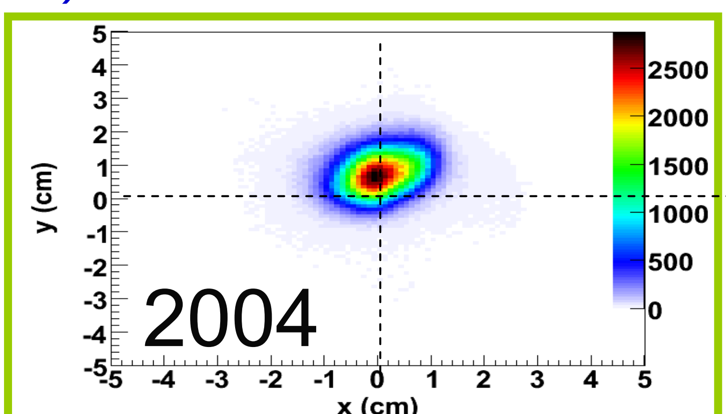


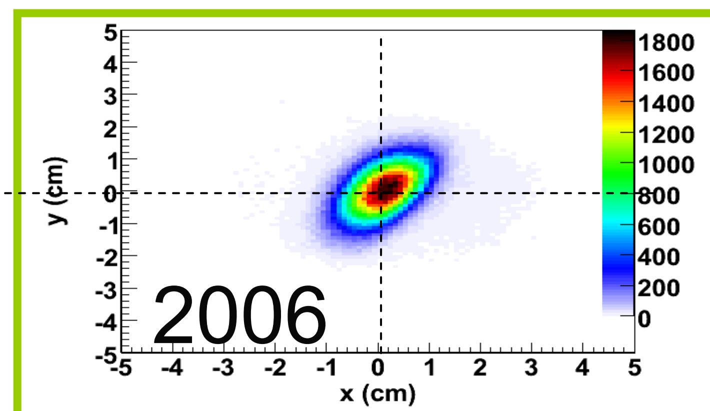
Use Time Expansion Chamber (TEC) to measure and **optimize** the muon beam



- First installed for 2004 run
- Found vertical beam offset – corrected
- Now take frequent beam characterizations

J.Hu et al. NIM A566(2006)563

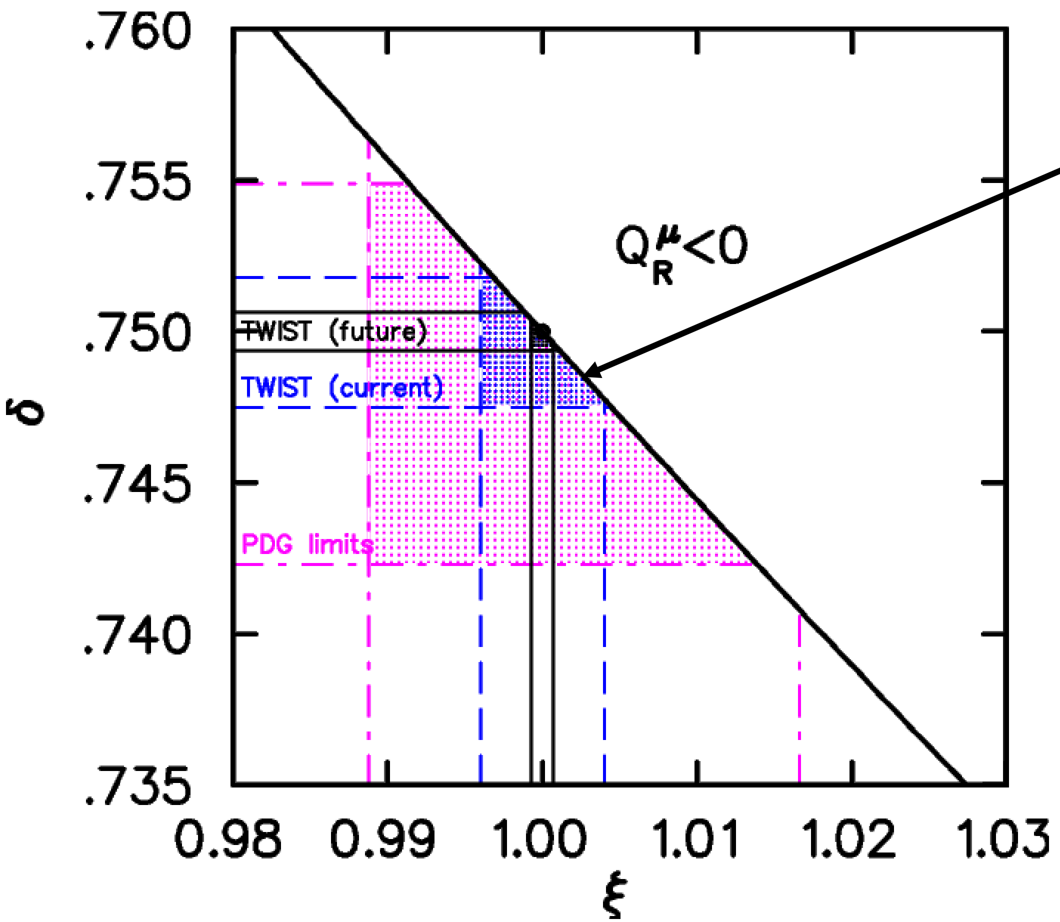




2006/2007: Final data taking

- **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:**
  - Chamber response
  - Calibrations
- **Depolarization in target:**
  - Al and Ag targets

Handedness of the muon



Diagonal represents exactly left-handed muon decay.

Shaded regions represent comparison of current (indirect) and proposed (direct) *TWIST* limits, compared to previous PDG limits.

$$Q^{\mu}_{R} = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta]$$
$$\geq 0$$
$$< 0.00184(90\%CL)$$

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:

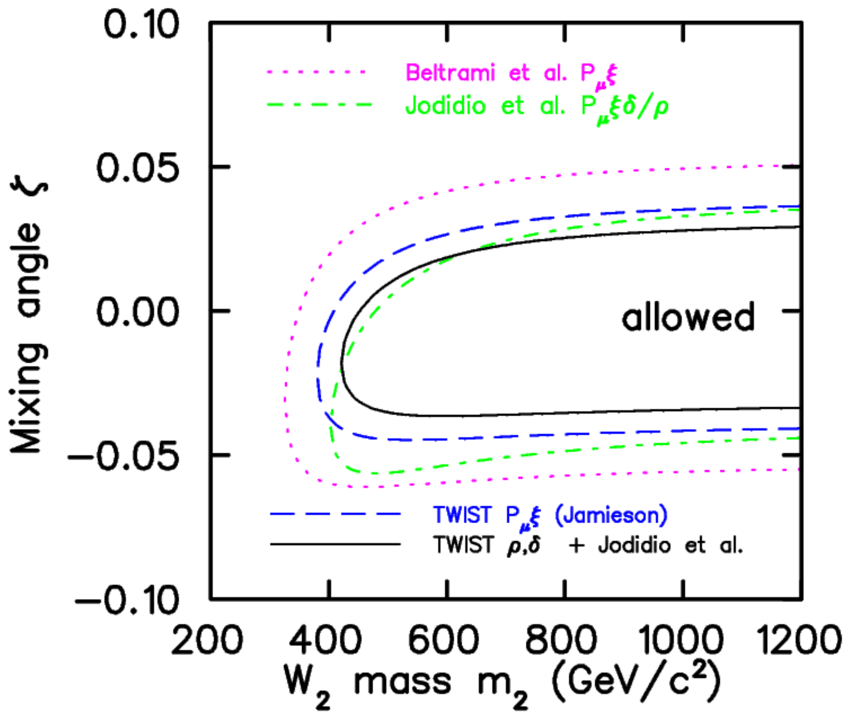
$$\rho = \frac{3}{4}(1 - 2\zeta_g^2), \qquad \xi = 1 - 2(t^2 + \zeta_g^2),$$

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

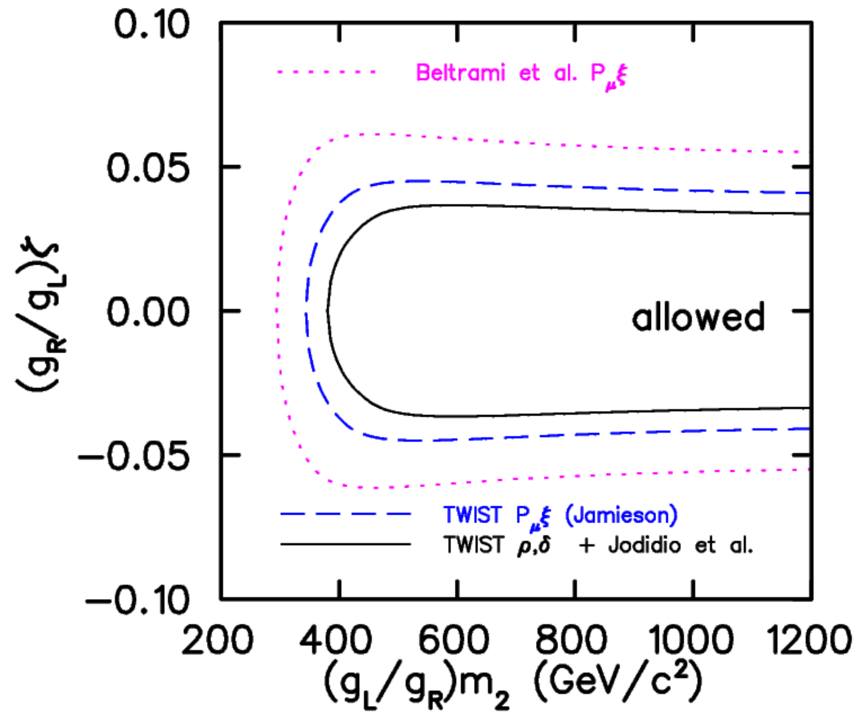
  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\omega = 0$ (no CP violation).
  - "pseudo-manifest" LRS allows CP violation, but $V^R = (V^L)^*$ and $g_R = g_L$.
  - RS "non-manifest" or generalized LRS makes no such assumptions.

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

Muon decay LRS limits



Restricted (“manifest”) LRS model



General LRS model

Initial **TWIST** measurements already provide significant new limits

Recent muon decay global analysis

	Ref. [8]	Present work
$\lvert g^S_{RR}\rvert$	<0.066	<0.067
$\lvert g^V_{RR}\rvert$	<0.033	<0.034
$\lvert g^S_{LR}\rvert$	<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
$\lvert g^S_{LR} + 6g^T_{LR}\rvert$		<0.143
$\lvert g^S_{LR} + 2g^T_{LR}\rvert$		<0.108
$\lvert g^S_{LR} - 2g^T_{LR}\rvert$		<0.070
$\lvert g^S_{RL} + 6g^T_{RL}\rvert$		<0.418
$\lvert g^S_{RL} + 2g^T_{RL}\rvert$		<0.417
$\lvert g^S_{RL} - 2g^T_{RL}\rvert$		<0.418

These improvements arise from the **TWIST** ρ and δ measurements.

C. Gagliardi et al. PRD 72, 073002

- Fit also finds η = -0.0036 ± 0.0069, a factor of ~2 more precise than the previously accepted value, -0.007 ± 0.013.
- Significant improvement in η comes from new measurements of the transverse polarization of the e^+ in muon decay (PRL 94, 021802), but the **TWIST** ρ and δ measurements also play an important part.

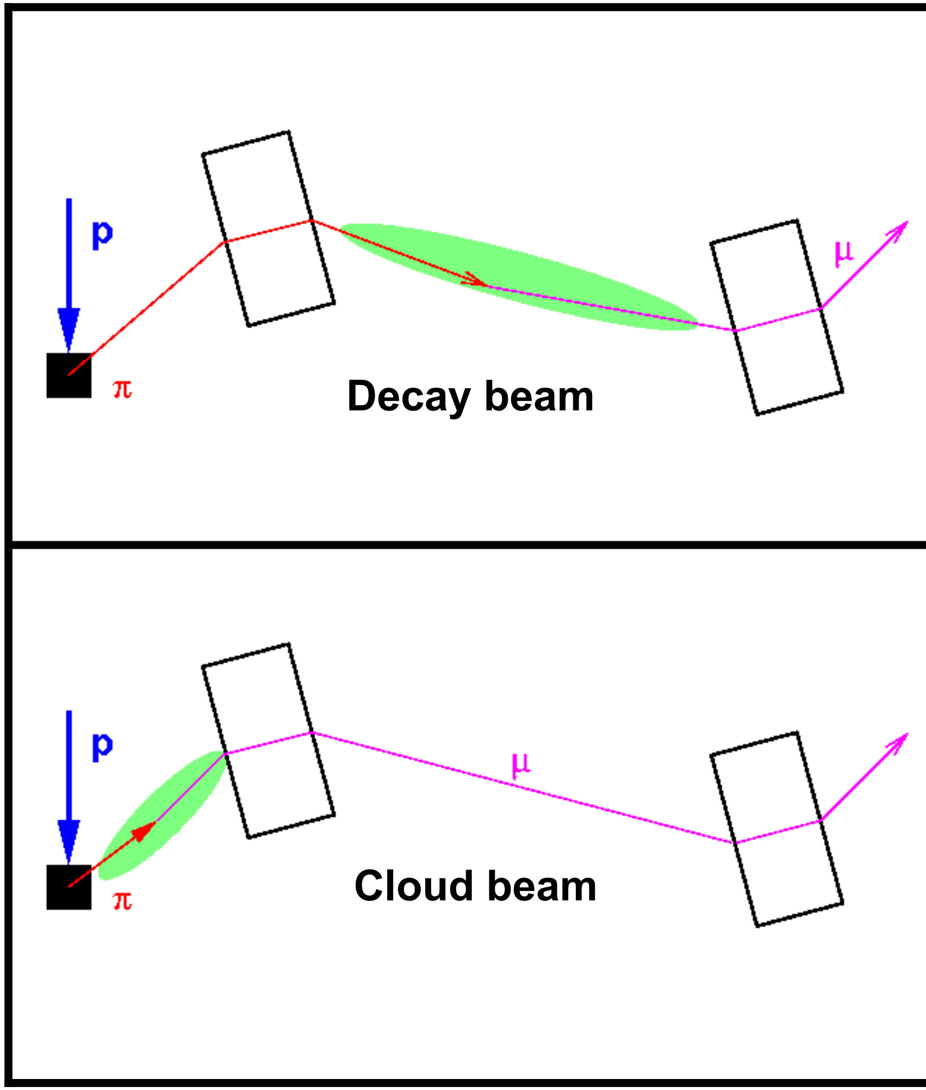
CONCLUSION

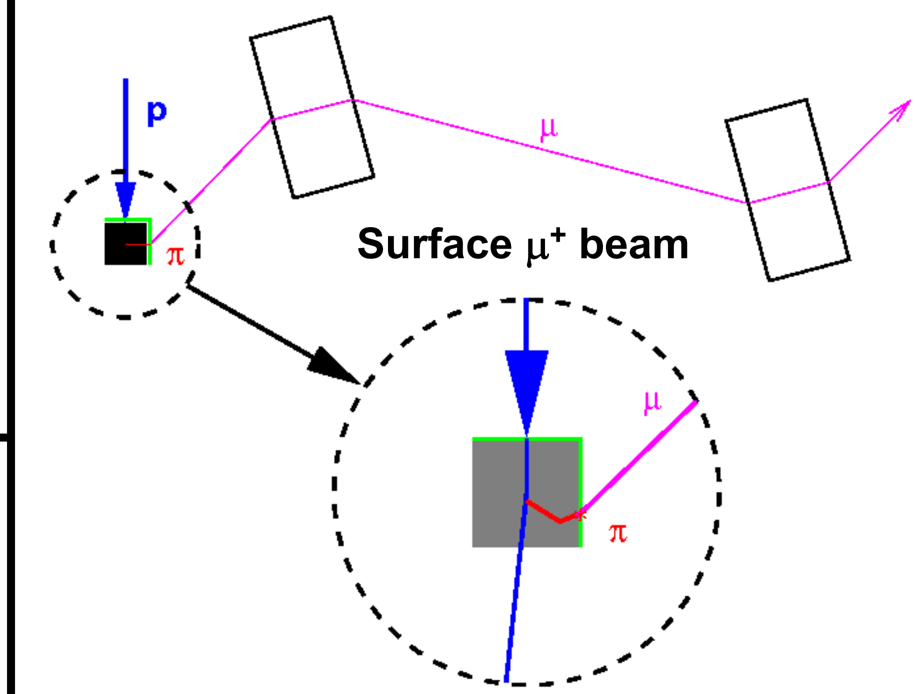
- TWIST measured the Michel parameters ρ, δ and $\mathbf{P}_{\mu}\xi$ with 2-3 times better precision than PDG values.
- New data were taken in 2006-2007
- Analysis underway for second measurements for muon decay parameters.
- In 2008-2009, TWIST will produce its final results. Improvements by additional factors 3-5 are anticipated.

TWIST Participants

Extra slides

Types of muon beams

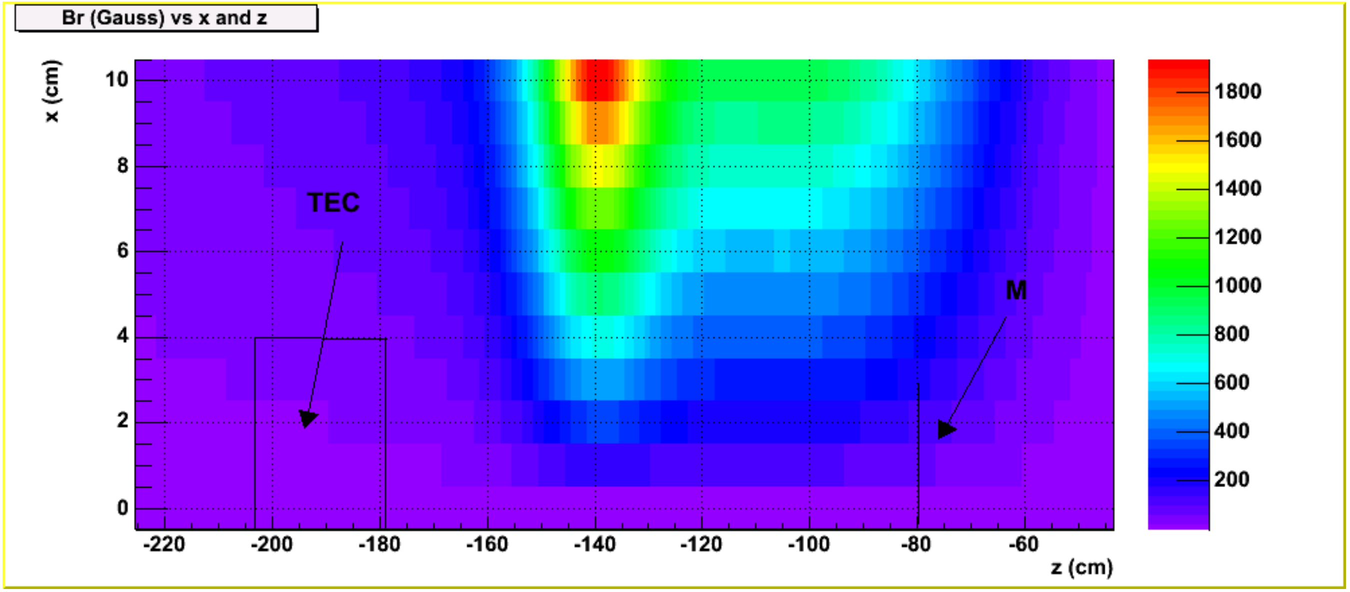




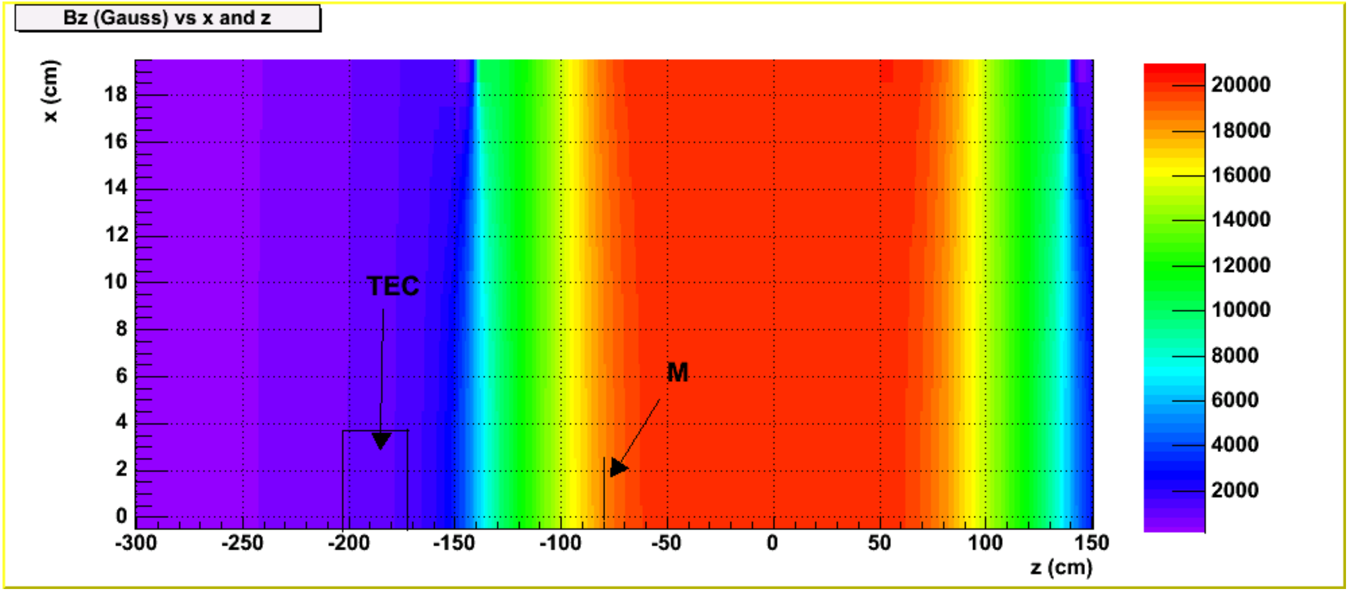
Surface muons have high polarization (in the direction of muon momentum) and high luminosity at low momentum (<29.79 MeV/c, or 4.1 MeV).

B field

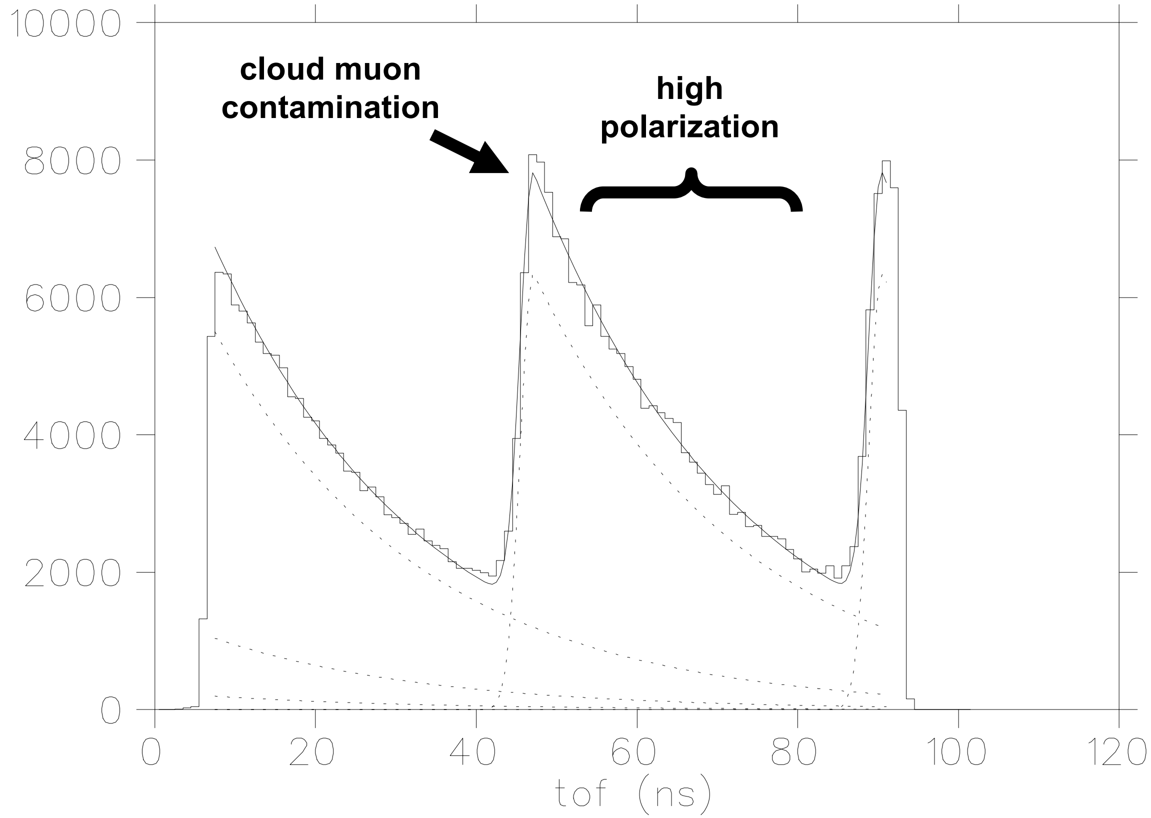
B_r vs x and z



B_z vs x and z



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 surface muon arrival time, while low polarization cloud muons are at the leading edge of surface muon time distribution.

Testing the Standard Model

- Model independent muon handedness:

- The relative probability for a right-handed muon to decay into an electron:

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

- in terms of Michel parameters:

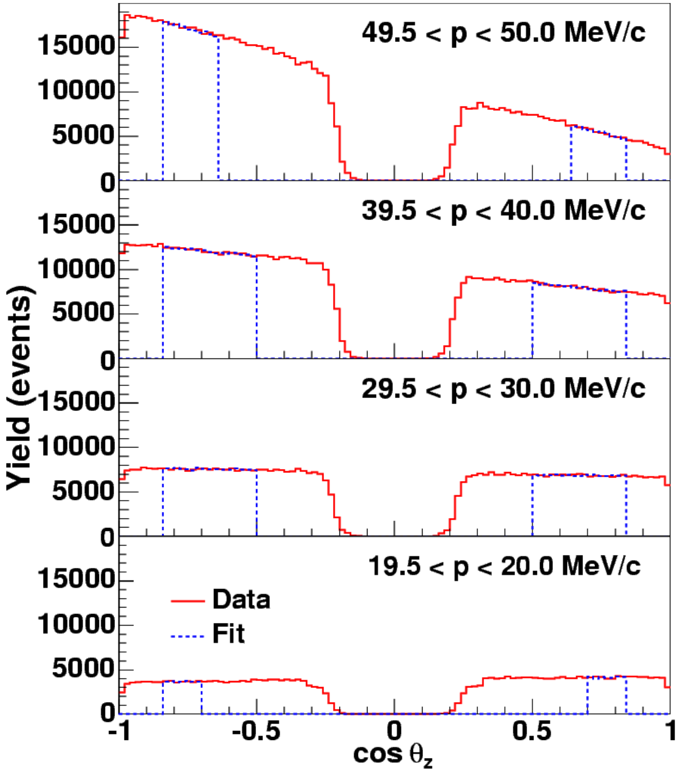
$$Q_R^\mu = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta]$$

- Left-right symmetric models:

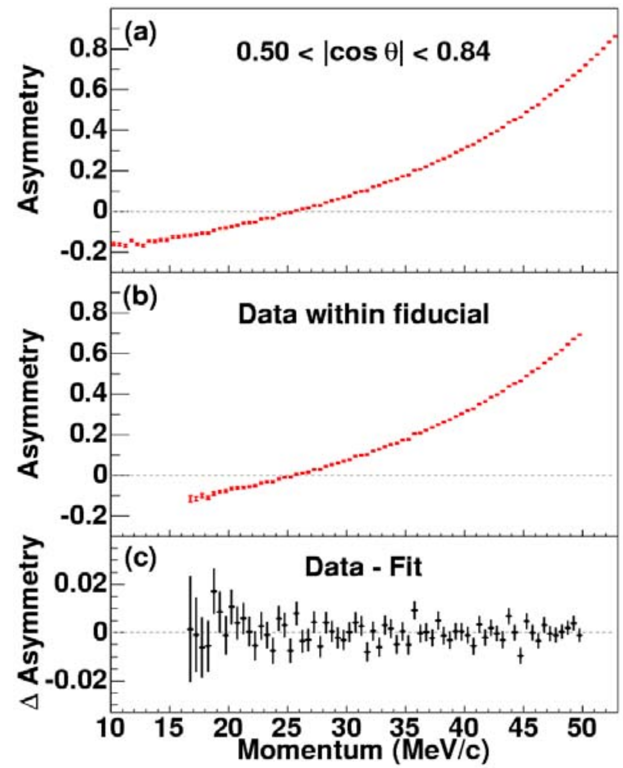
$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2, \qquad 1 - \mathcal{P}_\mu\xi = 4\{\zeta^2 + \frac{M_L^4}{M_R^4} + \zeta\frac{M_L^2}{M_R^2}\}$$

- …..

Fits to data distributions

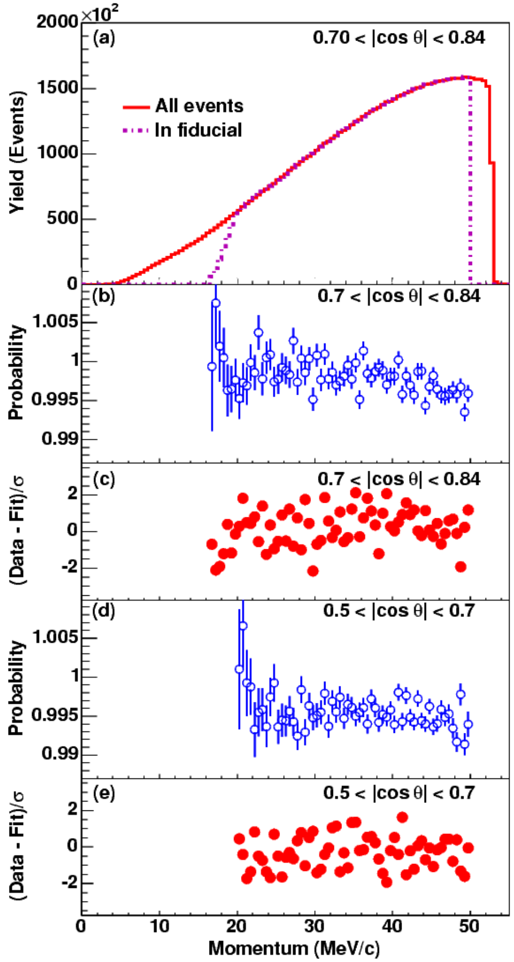


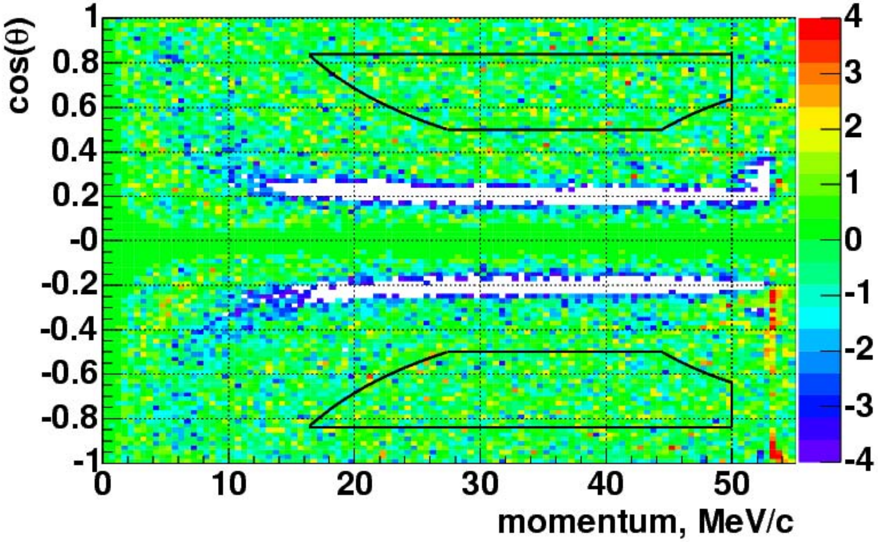
Angular distributions for restricted momentum ranges. Dashed lines show fiducial region of two-dimensional fit.



Dependence of asymmetry on momentum, and comparison of data and fit (MC) distributions.

Fits to data distributions: ρ

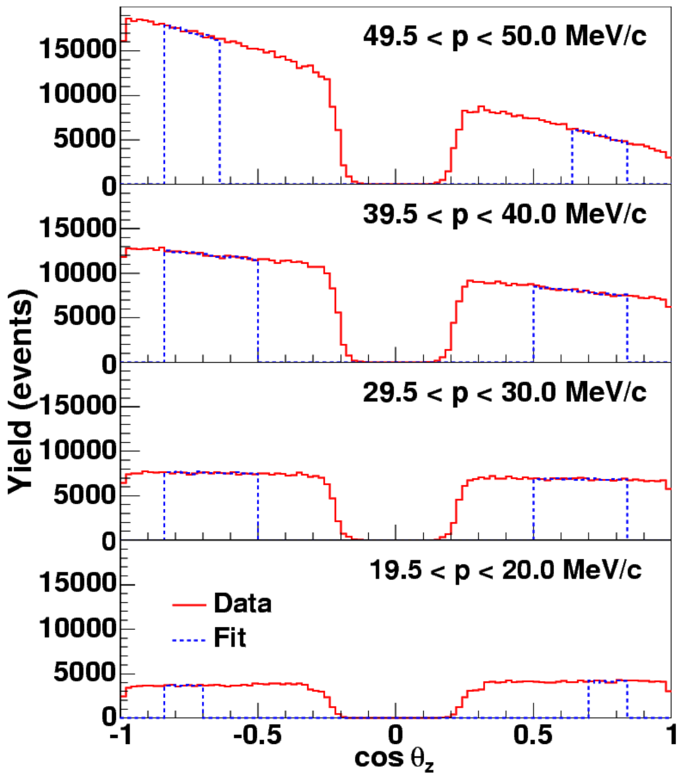




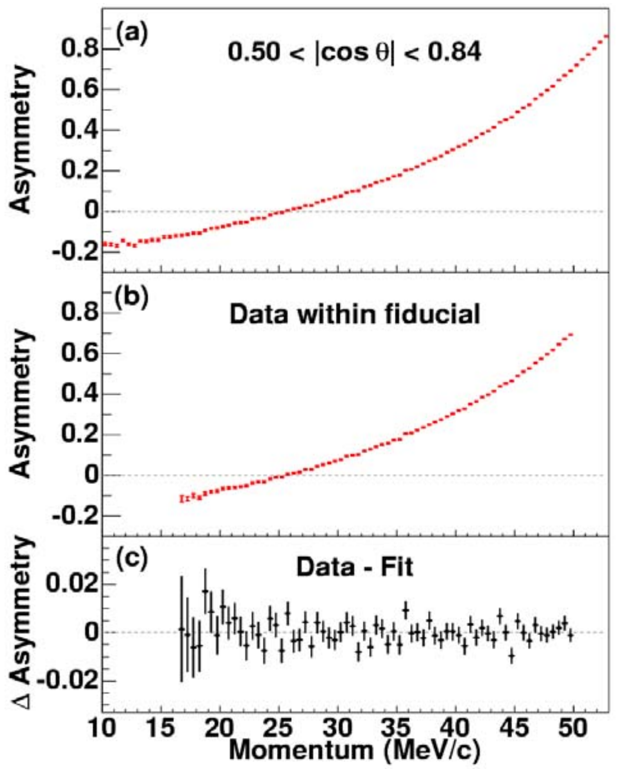
Above: normalized residuals of fit, and fiducial region used for fit: $p < 50$ MeV/c, $0.50 < |\cos\theta| < 0.84$, $|p_z| > 13.7$ MeV/c, $p_T < 38.5$ MeV/c.

Left: comparison of data to fit (MC) *vs.* momentum, also showing (MC reconstructed)/(MC thrown) comparisons and normalized residuals.

Fits to data distributions: δ



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



Dependence of asymmetry on momentum, and comparison of data and fit (MC) distributions.