Measurement of the muon decay parameters with the TRIUMF Weak Interaction Symmetry Test (TWIST) Experiment

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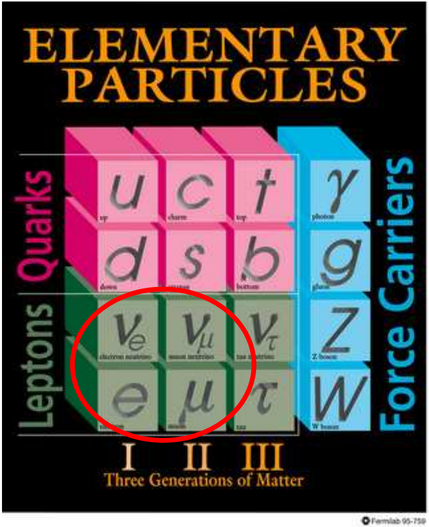


The muon decay is very interesting

- Only weak interaction involved
- Muons are easy to produce
- One decay mode dominant ($\approx$ 100%)

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$$

4-fermion formalism

To study the muon decay we describe it by using a very general formalism.
The interaction is described as a derivative-free, Lorentz-invariant and lepton-number conserving matrix:

$$M = 4\frac{G_F}{\sqrt{2}} \sum_{\substack{\gamma = S,V,T \\ \epsilon,\mu = R,L}} g^{\gamma}_{\epsilon\mu} < \bar{e}_{\epsilon}|\Gamma^{\gamma}|\nu_e >< \bar{\nu}_{\mu}|\Gamma_{\gamma}|\mu_{\mu} >$$

- $g^T_{RR} \equiv g^T_{LL} \equiv 0$
- A common phase doesn't matter

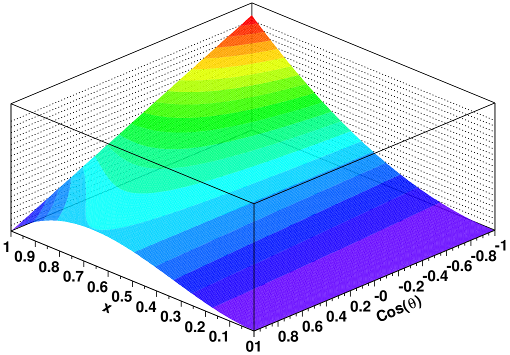
Standard Model, V-A interaction

g^V_{LL} is the only non zero coupling

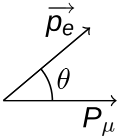
$\Longrightarrow$ 19 real and independent parameters

The differential decay rate can be written using the Michel parametrization:

$$\frac{d^2\Gamma}{dx\,d\cos\theta} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2}\,\left(F_{IS}(x) + P_\mu \cos\theta F_{AS}(x)\right) + \mathrm{RC}.$$



$$x = \frac{E_e}{W_{e\mu}}$$



The Michel parametrization

The isotropic and anisotropic parts of the Michel parameters are:

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

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

Standard Model predictions

$$\rho = \frac{3}{4}, \qquad \eta = 0, \qquad P_\mu\xi = 1, \qquad \delta = \frac{3}{4}$$

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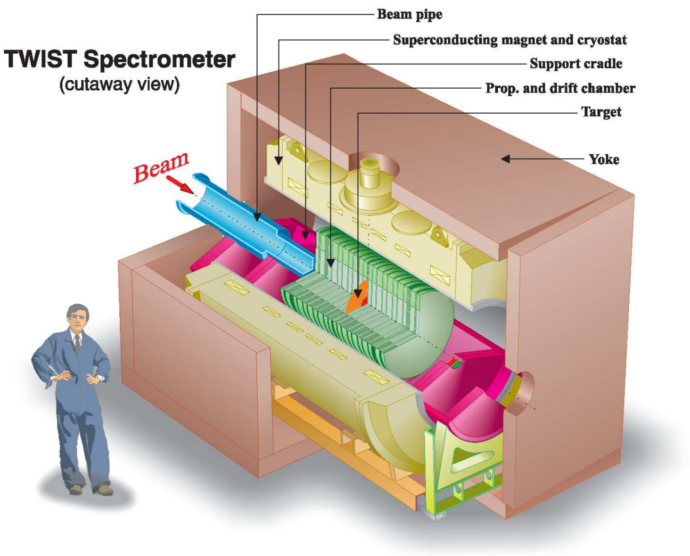
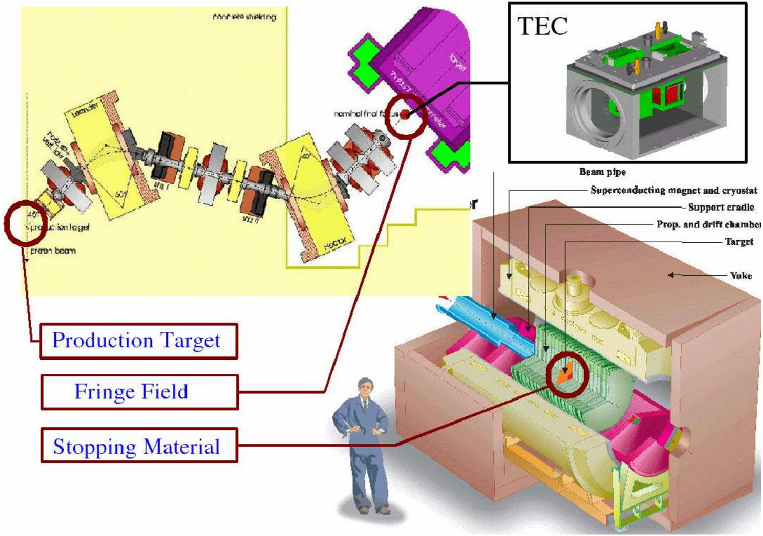
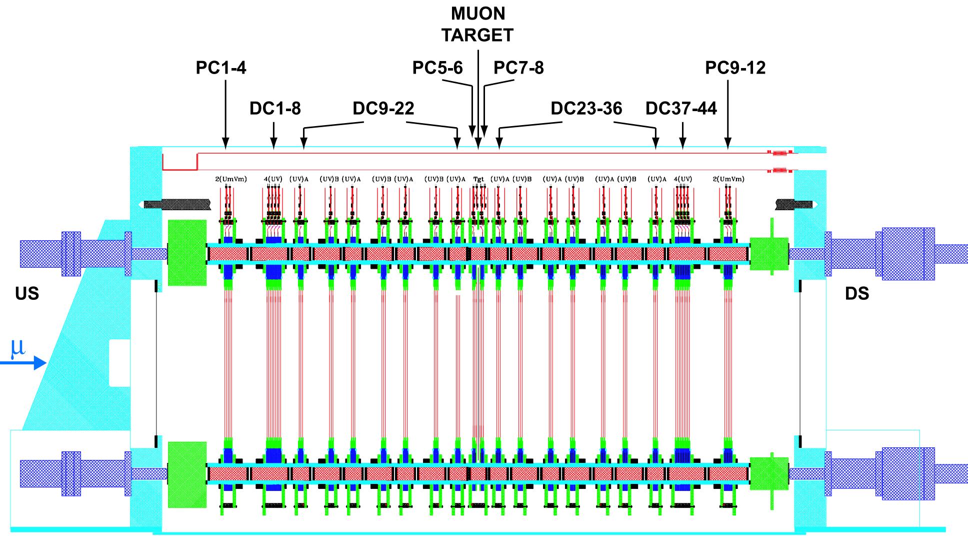
The TWIST spectrometer



The spectrometer in the M13 beamline




MUON
TARGET
PC1-4
PC5-6
PC7-8
PC9-12
DC1-8
DC9-22
DC23-36
DC37-44
2(UmVm)
4(UV)
(UV)A
(UV)B (UV)A
(UV)B (UV)A
(UV)B (UV)A
Tgt
(UV)A (UV)B
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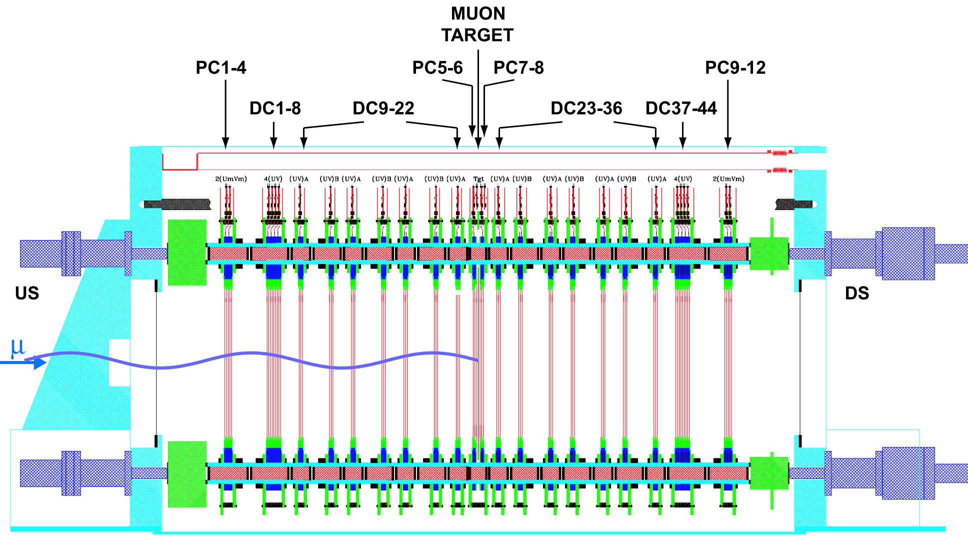
(UV)A
4(UV)
2(UmVm)
US
DS
μ


MUON
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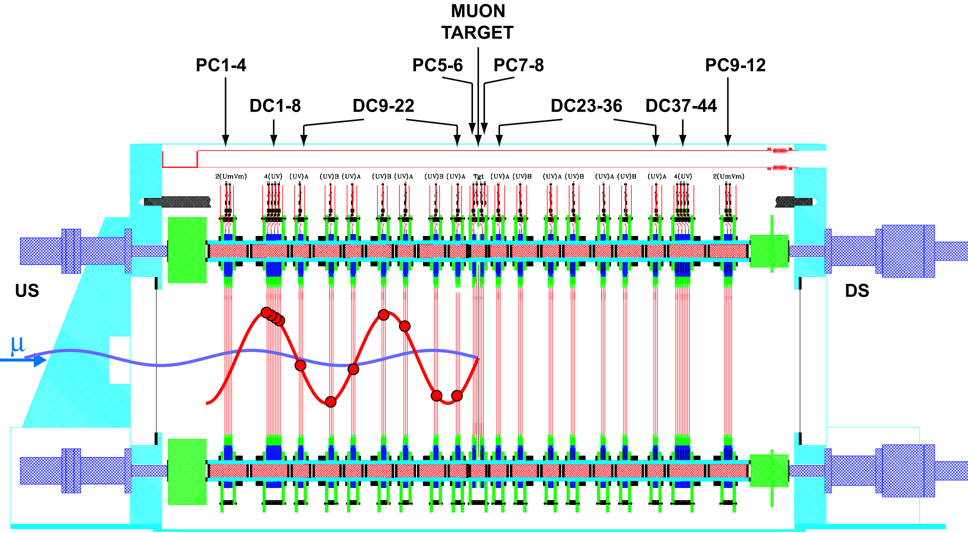
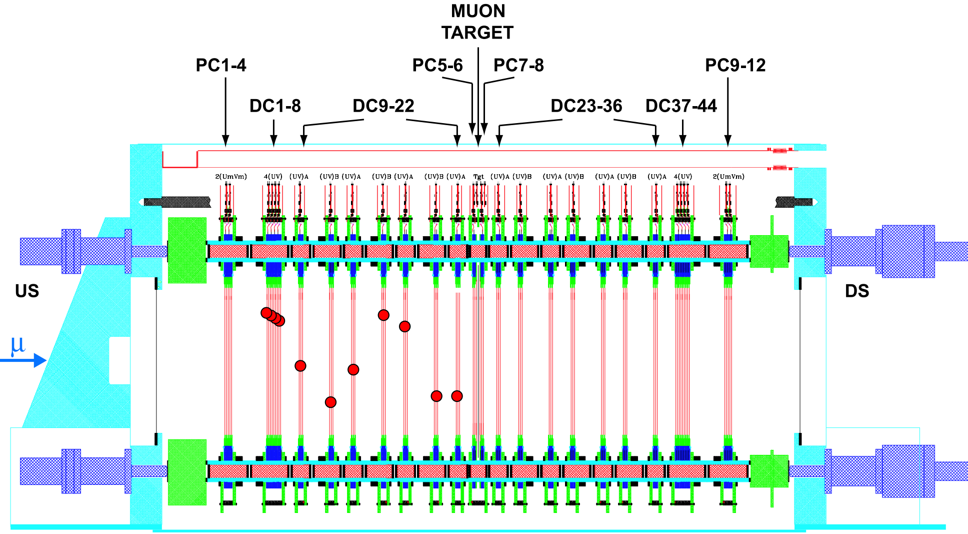
μ

Typical event



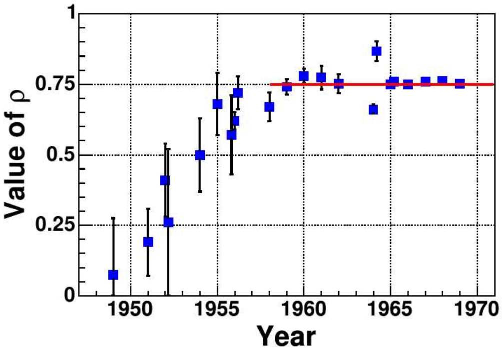
Typical event



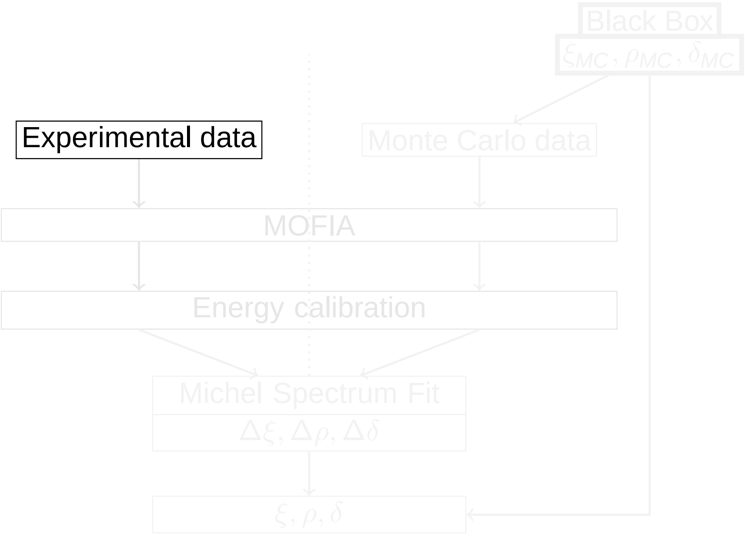
A Blind Analysis

The TWIST analysis is blind to avoid any human bias:

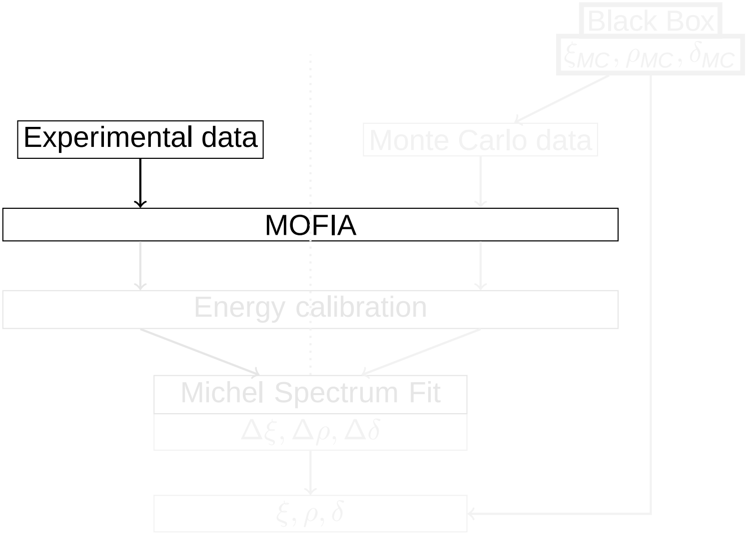
- Choices of data samples
- Looking for errors if disagreement with expectations
- Systematic error evaluation influenced by final result



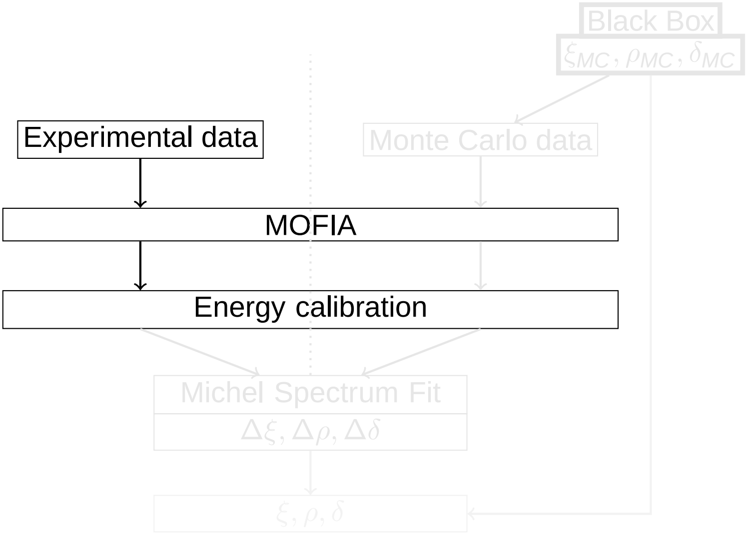
The software analysis

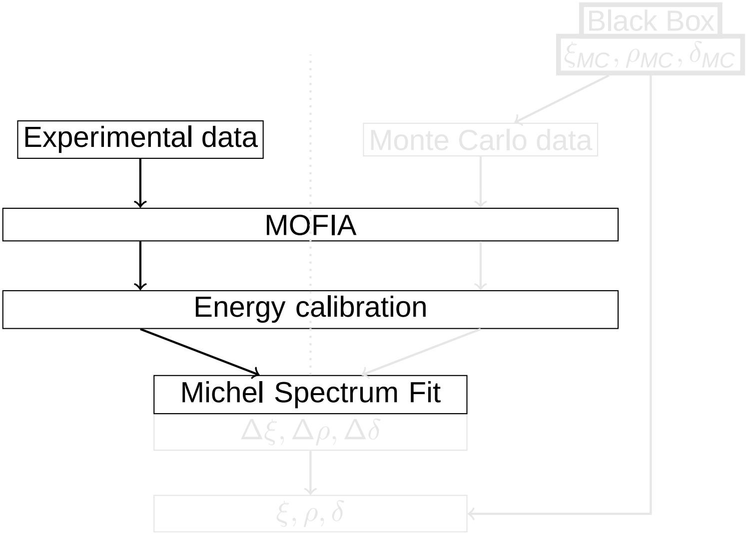


The software analysis



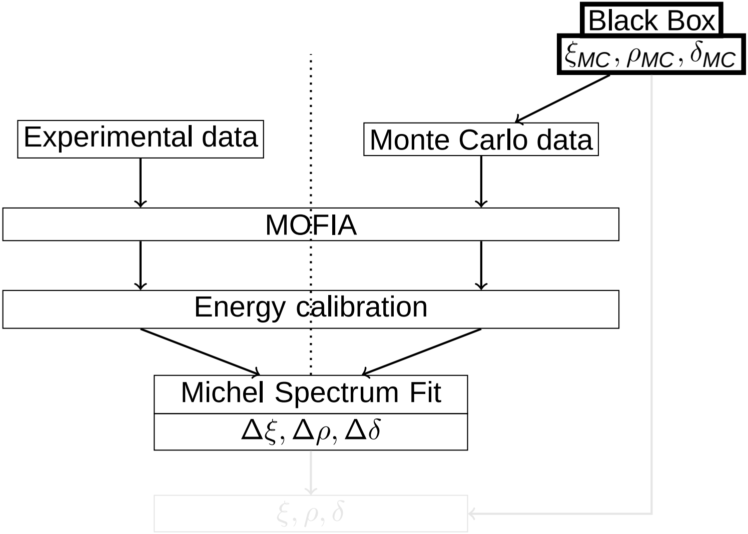
The software analysis





Black Box
$\xi_{MC}, \rho_{MC}, \delta_{MC}$
Experimental data
Monte Carlo data
MOFIA
Energy calibration
Michel Spectrum Fit
$\Delta\xi, \Delta\rho, \Delta\delta$
ξ, ρ, δ

The software analysis



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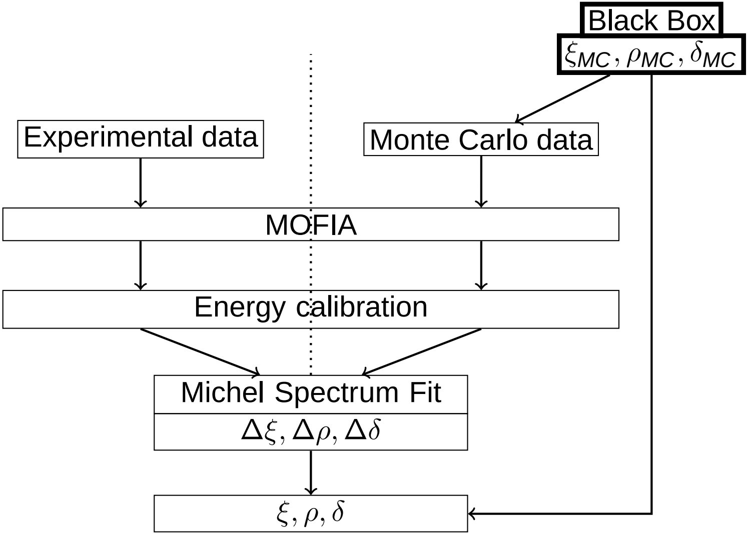
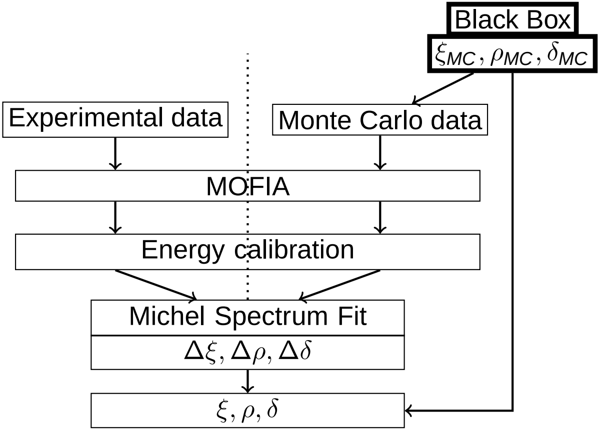


The software analysis



- Detector response included in MC
- Reconstruction biases reduced because $\Delta\xi, \Delta\rho, \Delta\delta$ are small
- Most systematics are from the difference between the MC simulation and the reality

The TWIST Results

Published results

$$\rho = 0.75080 \pm 0.00044\ \text{(stat)} \pm 0.00093\ \text{(sys)} \pm 0.00023\ (\eta)$$

$$\delta = 0.74964 \pm 0.00066\ \text{(stat)} \pm 0.00112\ \text{(sys)}$$

$$P_\mu \xi = 1.0003 \pm 0.00006\ \text{(stat)} \pm 0.0038\ \text{(sys)}$$

	Published		Final Goal	
	Statistics	Systematics	Statistics	Systematics
ρ	4.4	9.3	1.3	2.4
δ	6.6	11.2	2.3	2.2
$P_\mu \xi$	6.0	38	2.8	7.5

The TWIST Collaboration

TRIUMF		Alberta
Ryan Bayes†	Glen Marshall	Andrei Gaponenko◇
Yuri Davydov	Dick Mischke	Peter Kitching
Jaap Doornbos	Mina Nozar	Robert MacDonald†
Wayne Faszer	Konstantin Olchanski	Maher Quraan
Makoto Fujiwara	Art Olin	Nate Rodning
David Gill	Robert Openshaw	John Schaapman
Alex Grossheim	Tracy Porcelli	Glen Stinson
Peter Gumplinger	Jean-Michel Poutissou	
Anthony Hillairet†	Renée Poutissou	**British Columbia**
Robert Henderson	Grant Sheffer	James Bueno†
Jingliang Hu	Bill Shin	Mike Hasinoff
John A. Macdonald		Blair Jamieson◇
Regina	**Montréal**	**Texas A&M**
Ted Mathie	Pierre Depommier	Carl Gagliardi
Roman Tacik	**Valparaiso**	Jim Musser◇
Kurchatov Institute	Don Koetke	Bob Tribble
Vladimir Selivanov	Paul Nord	Maxim Vasiliev
Vladimir Torokhov	Shirvel Stanislaus	

◇ Graduated

† Graduate student

EXTRA SLIDES

Model-Independent search for right-handed interactions

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

- Right-handed interaction contribution in the muon decay :

$$Q^\mu_R = Q_{RR} + Q_{LR}$$

- Also defined as :

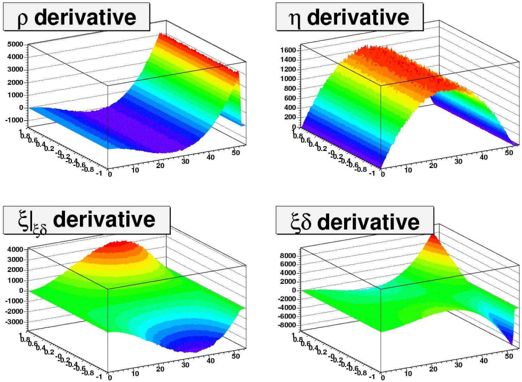
$$Q^\mu_R = \frac{1}{2}\left(1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right)$$

Standard Model, V-A interaction

$$Q^\mu_R = 0$$

Michel Parameters Derivatives

$$\underbrace{\left.\frac{d^2\Gamma}{dxd(\cos\theta)}\right|_{\rho_{MC},\delta_{MC},\xi_{MC}}}_{\text{MC spectrum}} + \underbrace{\sum_{\alpha=\rho,\xi,\xi\delta} \frac{\partial}{\partial\alpha}\left[\frac{d^2\Gamma}{dxd(\cos\theta)}\right]\Delta\alpha}_{\text{Derivatives fitted}}$$



Systematics in the previous measurement

TABLE II. Contributions to the systematic uncertainty in ρ. Average values are given for those denoted (av), which are considered set dependent when performing the weighted average of the data sets.

Effect	Uncertainty
Chamber response (av)	± 0.00051
Stopping target thickness	± 0.00049
Positron interactions	± 0.00046
Spectrometer alignment	± 0.00022
Momentum calibration (av)	± 0.00020
Theoretical radiative corrections [12]	± 0.00020
Track selection algorithm	± 0.00011
Muon beam stability (av)	± 0.00004
Total in quadrature	± 0.00093
Scaled total	± 0.00097

TABLE II. Contributions to the systematic uncertainty for δ. Average values are denoted by (ave), which are considered set-dependent when performing the weighted average of data sets.

Effect	Uncertainty
Spectrometer alignment	± 0.00061
Chamber response(ave)	± 0.00056
Positron interactions	± 0.00055
Stopping target thickness	± 0.00037
Momentum calibration(ave)	± 0.00029
Muon beam stability(ave)	± 0.00010
Theoretical radiative corrections[9]	± 0.00010
Upstream/downstream efficiencies	± 0.00004

TABLE III. Contributions to the systematic uncertainty for $P_\mu^\pi \xi$.

Effect	Uncertainty
Depolarization in fringe field (ave)	0.0034
Depolarization in stopping material (ave)	0.0012
Chamber response (ave)	0.0010
Spectrometer alignment	0.0003
Positron interactions (ave)	0.0003
Depolarization in production target	0.0002
Momentum calibration	0.0002
Upstream-downstream efficiency	0.0002
Background muon contamination (ave)	0.0002
Beam intensity (ave)	0.0002
Michel parameter η	0.0001
Theoretical radiative corrections	0.0001