Probing the Weak Interaction Spacetime Structure with Muon Decay

Art Olin, for the TWIST Collaboration

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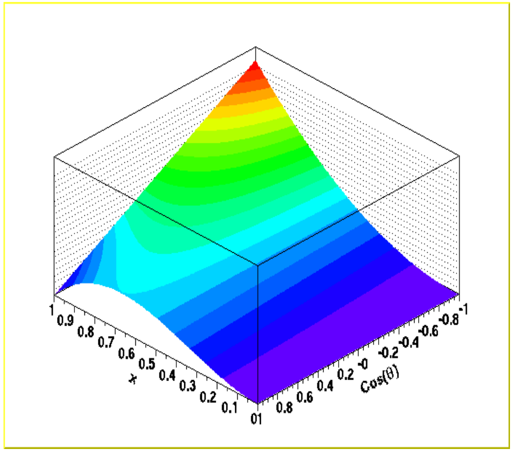
Muon Decay Parameters

- Muon decay parameters ρ, η, $P_\mu\xi$, δ: (Michel, Kinoshita and Sirlin)
  - Polarized muon differential decay rate *vs.* energy and angle:

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



  - where

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

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

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

- $\rho=3/4$, $\eta=0$,, $P_\mu\xi=1$,, $\delta=3/4$ in SM.

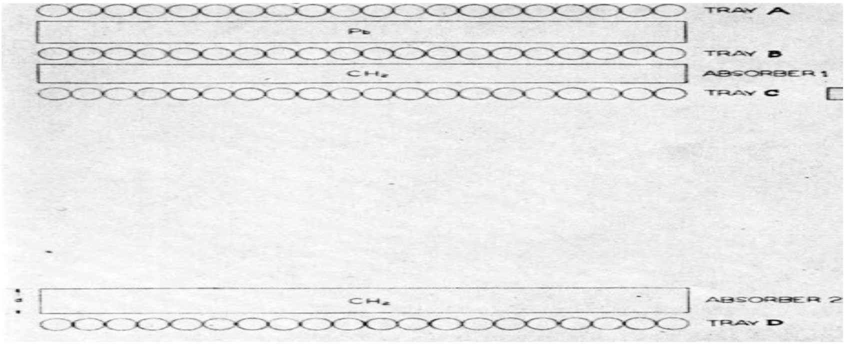
Early Measurements

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Range of the Electrons in Meson Decay

J. STEINBERGER*
The Institute for Nuclear Study, University of Chicago, Chicago, Illinois
(Received January 10, 1949)

An experiment has been carried out both at Chicago and on Mt. Evans, Colorado, to determine the absorption of the electrons emitted in the decay of cosmic-ray mesons. Approximately 8000 counts have been obtained, using a hydrocarbon as the absorbing material. These data are used to deduce some features of the energy spectrum of the decay electrons. The resolution of the apparatus is calculated, taking the geometry, scattering, and radiation into account. The results indicate that the spectrum is either continuous, from 0 to about 55 Mev with an average energy ~32 Mev or consists of three or more discrete energies. No variation of the lifetime with the thickness of the absorber is observed. The experiment, therefore, offers some evidence in favor of the hypothesis that the μ-meson disintegrates into 3 light particles.



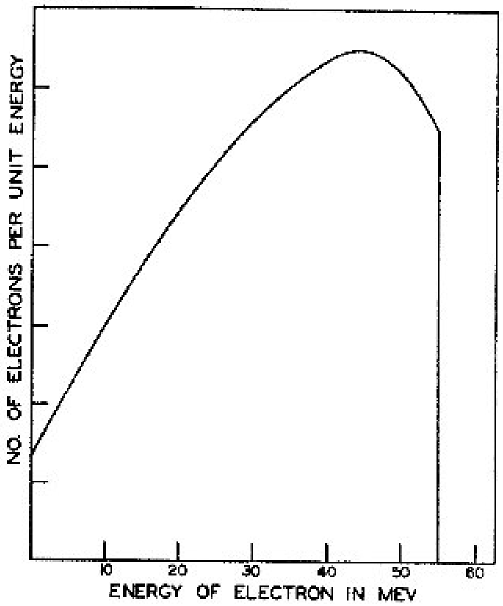


FIG. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.

Other μ decay measurements

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

  ρ = 0.7518 ± 0.0026 (Derenzo, 1969) (0.75)

  η = -0.002 ± 0.007 (Dannenberg *et al.* , 2005) (0.00)

  δ = 0.7486 ± 0.0026 ± 0.0028 (Balke *et al.* , 1988) (0.75)

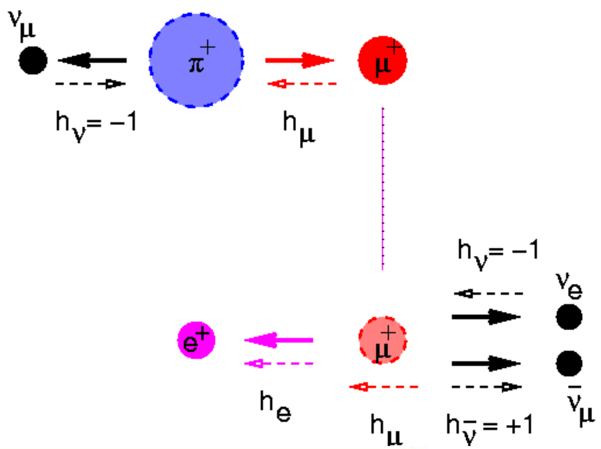
  $P_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (Beltrami *et al.* , 1987) (1.00)

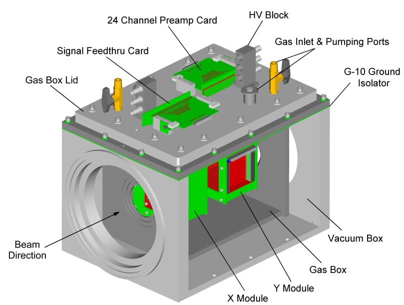
  $P_\mu(\xi\delta/\rho)$ > 0.99682 (Jodidio *et al.* , 1986) (1.00)

TWIST's goal is to explore or constrain physics beyond the SM by improving the precision of each of ρ, δ, and $P_\mu\xi$ by an order of magnitude.

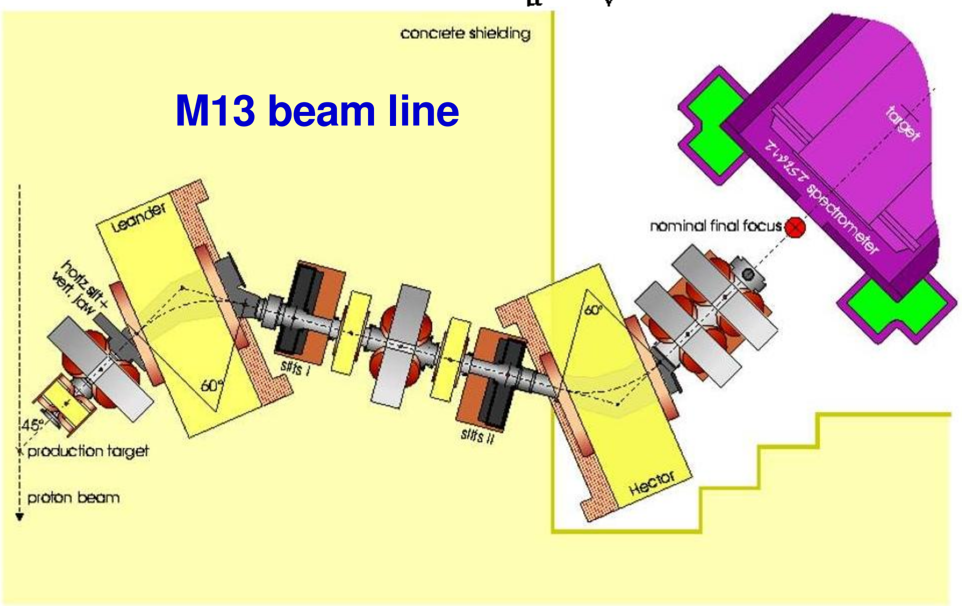
Surface muon beam

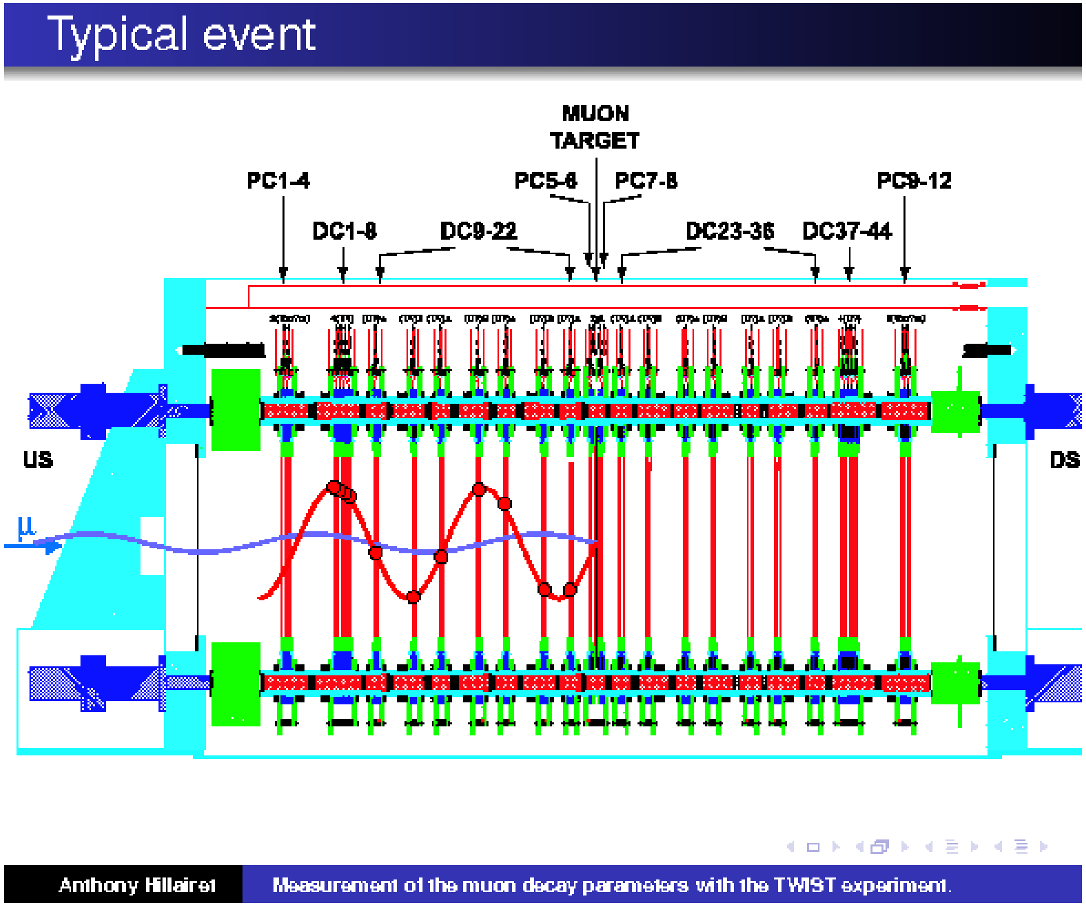
- Pions decaying at rest produce muon beams with P_{μ}^{π} =100%. (SM).
- Depolarization must be controlled using small emittance beams near kinematic edge, 29.8 MeV/c.
- Use $\approx 3\ \ 10^{3}\ \mu^{+}\ s^{-1}$.
- Muon total range at density $\approx$1 only about 1.5 mm!





Low Pressure Time Expansion Chamber



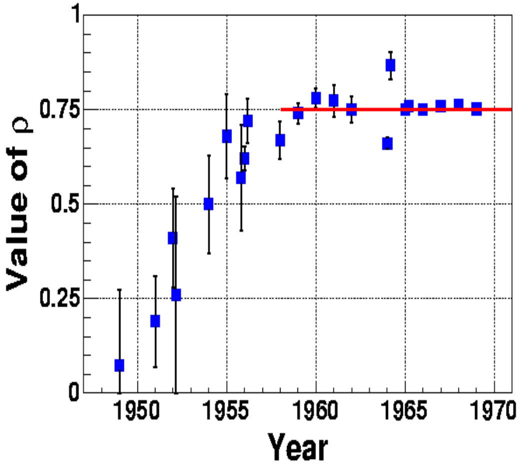


- Low-mass high-precision planar chambers symmetrically placed around thin target foil which stops nearly all of surface muon beam. Z precision 5 10^{-5}, wire position 15μ. 44 drift chambers (DME), 12 proportional chambers (CF_4-isobutane), He gaps.
- Measurement initiated by single thin scintillation counter at entrance to detector.
- Beam stop position controlled by variable He/CO_2 gas degrader.

Data Analysis Methodology

Fit data to identically derived distributions from simulation:

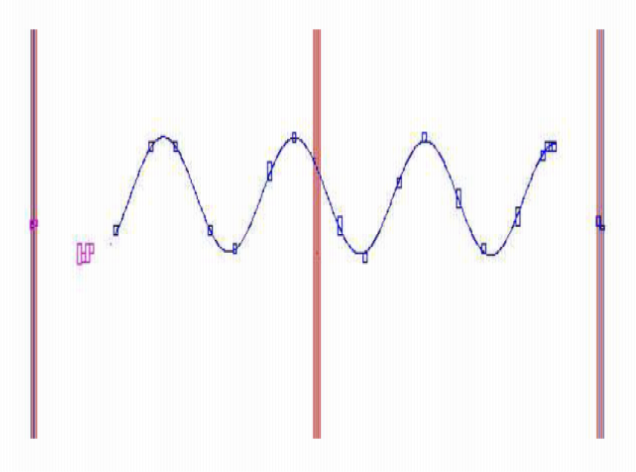
- Muon decay spectrum includes radiative corrections to $O(\alpha^2)$.
- GEANT3 geometry contains virtually all detector components.
- simulate detector response in detail.
- realistic, measured beam profile and divergence.
- fit to hidden muon decay parameters with blind analysis method.
- Determine consistency of data and sensitivity of analysis to model uncertainties before hidden parameters are revealed.

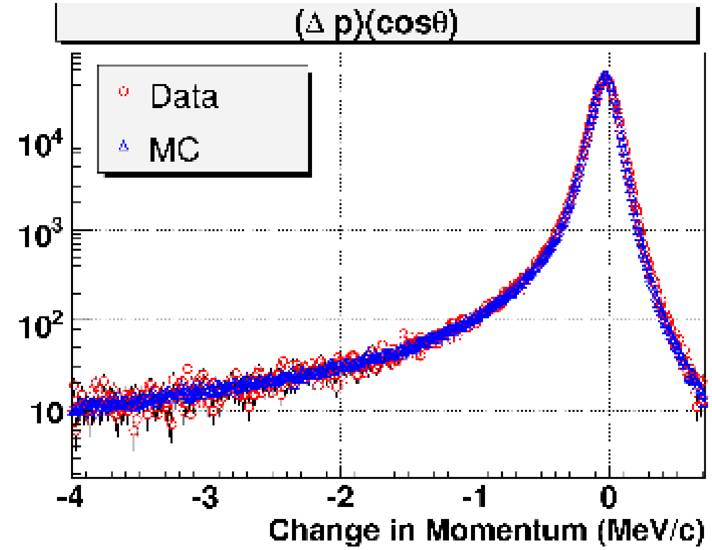


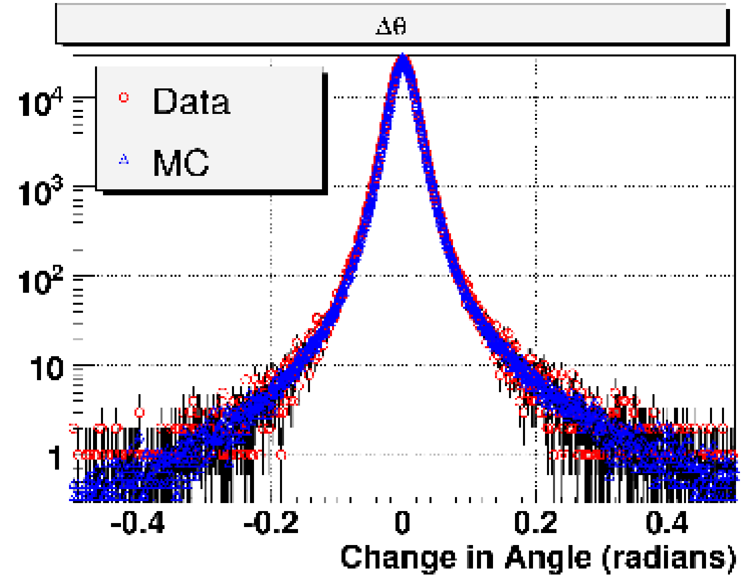
Greiner *et al.*, Gauge Theory of Weak Interactions, Springer (1996).

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.

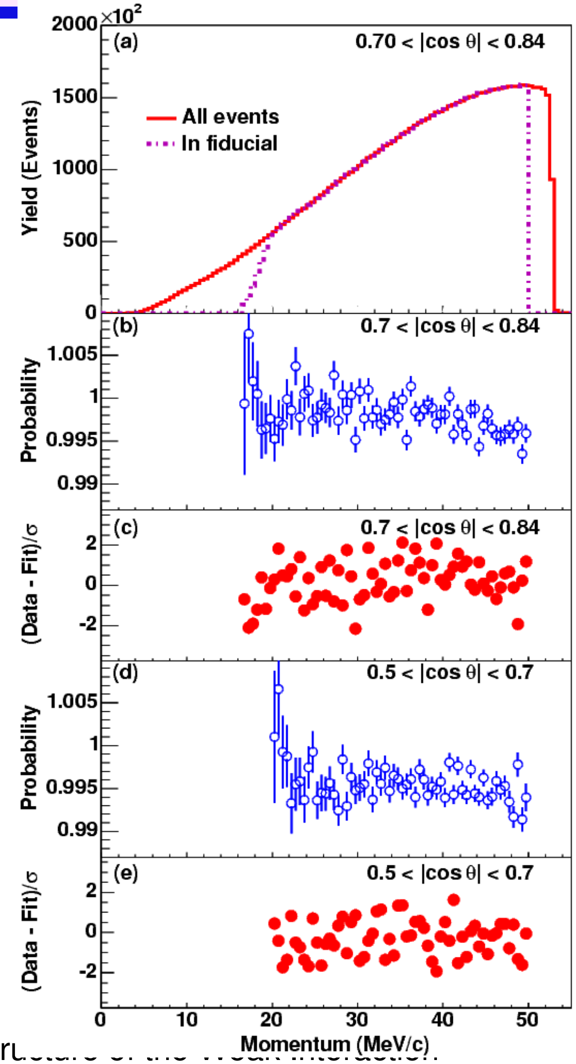






Summary of results: ρ and δ
2002 Data Mylar target

- ρ = **0.75080 ± 0.00044(stat) ± 0.00093(syst) ±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.
  - J.R. Musser *et al.*, PRL **94**, 101805 (2005).
- δ = **0.74964 ± 0.00066(stat) ± 0.00112(syst)**
  - 2.9 times better precision than PDG value.
  - A. Gaponeko *et al.*, PRD **71**, 071101(R) (2005).
- Using the above values of ρ and δ, together with $P_\mu(\xi\delta/\rho) > 0.99682$ (PDG) and $Q_R^\mu > 0$
  - **$0.9960 < P_\mu\xi \leq \xi < 1.0040$ (90% c.l.)**
  - $P_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$.
- Leading systematics: chamber response, graphite, positron interactions, alignment



Coupling constants

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

$$Q_R^{\mu} = \frac{1}{4}\left|g_{LR}^{S}\right|^2 + \frac{1}{4}\left|g_{RR}^{S}\right|^2 + \left|g_{LR}^{V}\right|^2 + \left|g_{RR}^{V}\right|^2 + 3\left|g_{LR}^{T}\right|^2 = \frac{1}{2}\left[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right]$$

- Global analysis of μ decay (Gagliardi *et al.*, PRD **72** 2005)
  - no existing similar analysis for other weak decays.

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

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

Summary of results: $P_\mu \xi$
2004 Data pure Al target

- Improvements to target, chamber stability.
- Beam monitoring with TEC.
- Full instrumentation of outer drift chambers.
- **$P_\mu \xi$ = 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 74,72007(2006) .
- Dominated by muon beam uncertainties which control the polarization at the target.
- Improved ρ and δ results are expected soon. Polarization not an issue, so improvements above are significant, and increase the usable fiducial region.

Systematic uncertainties: ρ and δ

Systematic uncertainties	ρ (x10[4])		δ (x10[4])	
	published	current	published	current
Chamber response (ave)	5.1	0.5	5.6	0.2
Stopping target thickness	4.9	0	3.7	0-
Positron interactions	4.6	2.0	5.5	1.6
Spectrometer alignment	2.2	0.3	6.1	0.3
Momentum calibration (ave)	2.0	1.1	2.9	1.5
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		1.1	0.4	0.1
Total in quadrature	**9.3**	**4.3**	**11.2**	**7.2**

preliminary preliminary

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

2006/2007: Final Data

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

Summary

- **TWIST** has produced its first physics results, which are in agreement with the Standard model.
- We have almost completed the 2nd phase analysis of ρ and δ.
- Current data taking through 2007 will take us to our systematic limits which represents an order of magnitude improvement.

TWIST Participants

TRIUMF

Ryan Bayes y
Yuri Davydov
Jaap Doornbos
Wayne Faszer
Makoto Fujiwara
David Gill
Alex Grossheim
Anthony Hillairet y
Robert Henderson
Jingliang Hu
Glen Marshall
Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin y
Robert Openshaw
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin zz

Alberta

Andrei Gaponenko
Peter Kitching
Robert MacDonald
Maher Quraan

British Columbia

James Bueno
Mike Hasinoff
Blair Jamieson

Montréal

Pierre Depommier

Regina

Ted Mathie
Roman Tacik

Kurchatov Institute

Vladimir Selivanov

Texas A&M

Carl Gagliardi
Jim Musser
Bob Tribble

Valparaiso

Don Koetke
Shirvel Stanislaus

Graduate student
Graduated student
y also U Vic
zz also Saskatchewan

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