First Results on Muon Decay from TWIST

The Precision Frontier in Particle Physics

Maher Quraan

TWIST Collaboration

TRIUMF/University of Alberta

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Canadian Association of Physicists Congress

TWIST is testing the standard model predictions for the weak interaction by measuring the energy and angular distribution of $\boldsymbol{e}^{+}$ *from the decay of polarized* μ^{+}.

The collaboration

TRIUMF

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

Alberta

- **Andrei Gaponenko**
- **Peter Kitching**
- **Rob MacDonald**
- **Maher Quraan**
- ***Nathan Rodning §***
- **John Schaapman**
- **Glen Stinson**

British Columbia

- **Blair Jamieson**
- **Mike Hasinoff**

Montreal

- **Pierre Depommier**

Regina

- **Ted Mathie**
- **Roman Tacik**

Kurchatov Institute

- **Vladimir Selivanov**
- **Vladimir Torokhov**

Texas A&M

- **Carl Gagliardi**
- **Jim Musser**
- **Robert Tribble**
- **Maxim Vasiliev**

Valparaiso

- **Don Koetke**
- **Paul Nord**
- **Shirvel Stanislaus**

Graduate Students
† also UVic
‡‡ also Saskatchewan
‡ also UNBC
†† also LANL
§ Deceased

The collaboration

I. Motivation

Muon decay matrix element

- In the SM only vector couplings of left handed to left handed fermions are allowed.
- To search for new physics start with a general interaction matrix
  - Local.
  - Derivative free.
  - Lorentz-invariant.
  - Lepton number conserving.

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

Fetscher, Gerber and Johnson. Phys Rev B 173 (102), 1986.

- S,V,T = scalar, vector or tensor interactions
- R, L = right and left handed leptons

$$\Gamma^S = 1$$

$$\Gamma^V = \gamma^{\mu}$$

$$\Gamma^T = \frac{1}{\sqrt{2}} \sigma^{\mu\nu} \equiv \frac{i}{2\sqrt{2}} (\gamma^{\mu}\gamma^{\nu} - \gamma^{\nu}\gamma^{\mu})$$

The coupling constants

- In the SM only vector couplings of left handed to left handed fermions are allowed.

$\left\|g^{S}_{RR}\right\| = 0$	$\left\|g^{V}_{RR}\right\| = 0$	$\left\|g^{T}_{RR}\right\| \equiv 0$
$\left\|g^{S}_{LR}\right\| = 0$	$\left\|g^{V}_{LR}\right\| = 0$	$\left\|g^{T}_{LR}\right\| = 0$
$\left\|g^{S}_{RL}\right\| = 0$	$\left\|g^{V}_{RL}\right\| = 0$	$\left\|g^{T}_{RL}\right\| = 0$
$\left\|g^{S}_{LL}\right\| = 0$	$\boxed{\left\|g^{V}_{LL}\right\| = 1}$	$\left\|g^{T}_{LL}\right\| \equiv 0$

- PDG limits on the coupling constants.

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

Differential decay rate

- Calculate the muon decay rate differential in energy and angle
  - Start with the general form.
  - Parametrize using the Michel parameters.

isotropic

anisotropic

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

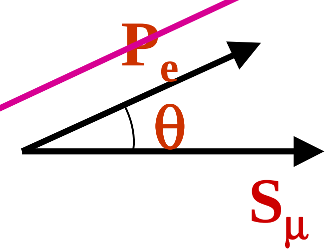
$$F_{IS}(x) = x(1-x) + \frac{2}{9}\rho\,(4x^2 - 3x - x_o^2) + \eta\, x_o(1-x) + F_{IS}^{RC}(x)$$

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

$$W_{e\mu} = \frac{\left(m_\mu^2 + m_e^2\right)}{2\,m_\mu}$$

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

$$x_o = m_e / W_{e\mu}$$



Radiative corrections

The MPs & the coupling constants

$$\rho = \frac{3}{4} - \frac{3}{4}\left[\left|g_{LR}^{V}\right|^2 + \left|g_{RL}^{V}\right|^2 + 2\left|g_{LR}^{T}\right|^2 + 2\left|g_{RL}^{T}\right|^2 + \mathrm{Re}\left(g_{RL}^{S} g_{RL}^{T*} + g_{LR}^{S} g_{LR}^{T*}\right)\right]$$

$$\xi\delta = \frac{3}{4} - \frac{3}{4}\left[\left|g_{LR}^{V}\right|^2 + \left|g_{RL}^{V}\right|^2 + 4\left|g_{LR}^{T}\right|^2 + 2\left|g_{RL}^{T}\right|^2 + 2\left|g_{RR}^{V}\right|^2 + \frac{1}{2}\left|g_{RR}^{S}\right|^2 + \frac{1}{2}\left|g_{LR}^{S}\right|^2 + \mathrm{Re}\left(g_{RL}^{S} g_{RL}^{T*} - g_{LR}^{S} g_{LR}^{T*}\right)\right]$$

$$\xi = 1 - \left[\frac{1}{2}\left|g_{RR}^{S}\right|^2 + \frac{1}{2}\left|g_{LR}^{S}\right|^2 + 2\left|g_{RR}^{V}\right|^2 + 4\left|g_{RL}^{V}\right|^2 - 2\left|g_{LR}^{V}\right|^2 - 2\left|g_{LR}^{T}\right|^2 + 8\left|g_{RL}^{T}\right|^2 + 4\mathrm{Re}\left(g_{RL}^{S} g_{RL}^{T*} - g_{LR}^{S} g_{LR}^{T*}\right)\right]$$

$$\eta = \frac{1}{2}\mathrm{Re}\left[g_{LL}^{V} g_{RR}^{S*} + g_{RL}^{V}\left(g_{LR}^{S*} + 6 g_{LR}^{T*}\right) + g_{LR}^{V}\left(g_{RL}^{S*} + 6 g_{RL}^{T*}\right) + g_{RR}^{V} g_{LL}^{S*}\right]$$

SM

$$\rho = \frac{3}{4}$$

$$\delta = \frac{3}{4}$$

$$\xi = 1$$

$$\eta = 0$$

Model-independent physics

- Define decay probabilities according to handedness

$$rate \sim \sum_{m,n=L,R} Q_{mn}$$

Fetscher, Gerber and Johnson,
Phys Rev Lett B 173 (102), 1986.

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

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

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

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

- Decay of a ***right-handed*** μ into a ***right-handed*** or ***left-handed*** e^+
- Can be written in terms of δ and ξ

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

$$\equiv 0$$

by the standard model

A determination of δ and ξ gives a *model-independent test* for the existence of *right-handed couplings to muons,* i.e. $Q^\mu_R \neq 0$

Left-right symmetric models

TRIUMF

Standard Model

$$W^{\pm}\left(W_L^{\pm}\right)$$

Left-right symmetric models

$$W_L^{\pm} \& W_R^{\pm}$$

- W_L & W_R mix to form the mass eigenstates W_1 & W_2
  - Mixing angle ζ is small.
  - **$M_2 > M_1$** since left handed couplings are dominant at low energies.

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

$$W_1 \approx W_L \& W_2 \approx W_R$$

- The mass and mixing angles are sensitive to ρ and ξ

$$\rho = \frac{3}{4}\left(1-2\zeta_g^2\right) \xrightarrow{MLRS} \frac{3}{4}\left(1-2\zeta^2\right)$$

$$\xi = 1-2\left(t^2+\zeta_g^2\right) \xrightarrow{MLRS} 1-2\left(\frac{M_1^2}{M_2^2}+\zeta^2\right)$$

$$\zeta_g = \frac{g_R}{g_L}\zeta$$

$$t = \frac{g_R^2}{g_L^2}\frac{M_1^2}{M_2^2}$$

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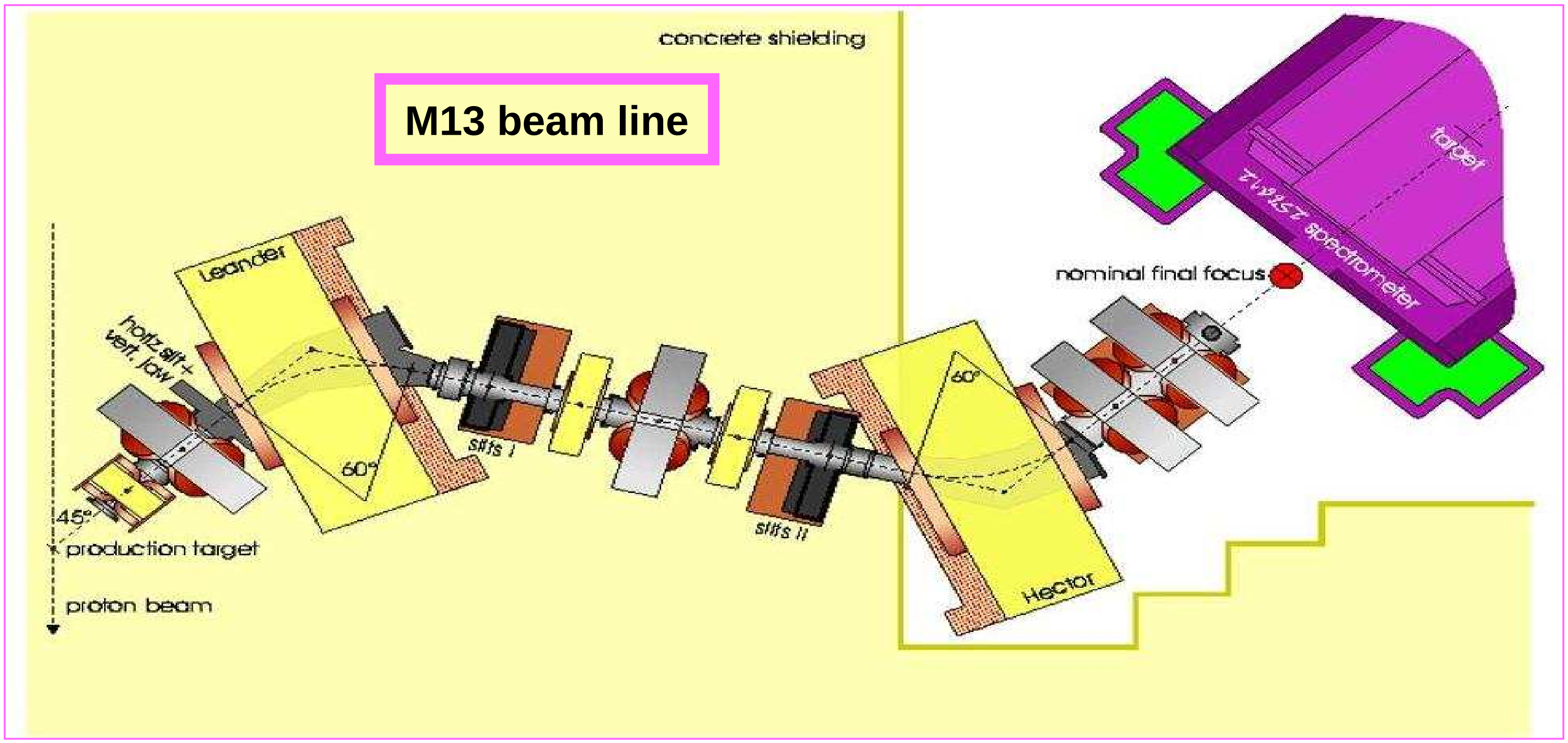
II. The Experiment

The beamline

- Surface μ^+ beam
  - Mono-energetic (P=29.7 MeV/c).
  - Highly polarized.

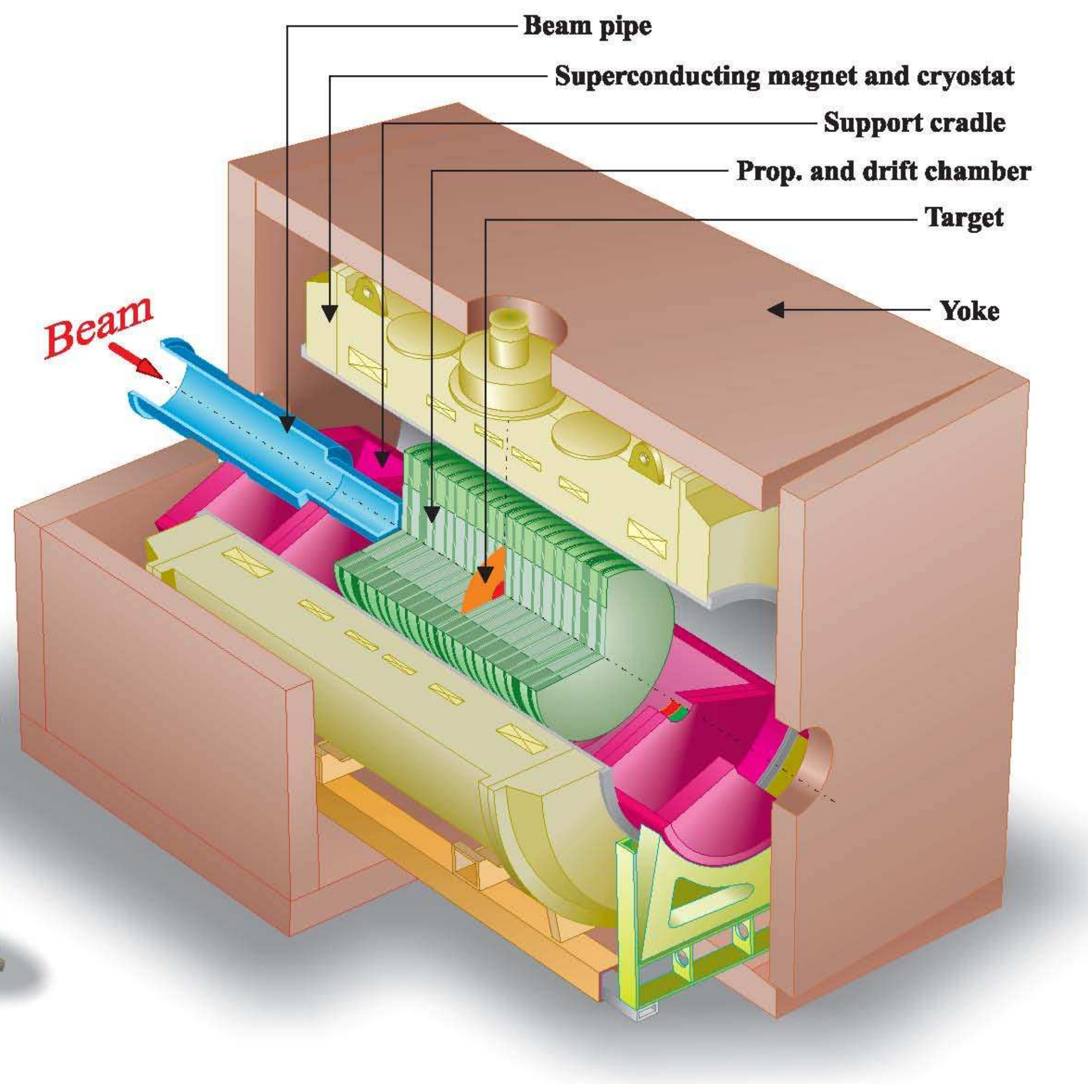
ν_μ $\pi+$ $\mu+$

h_ν=-1 h_μ



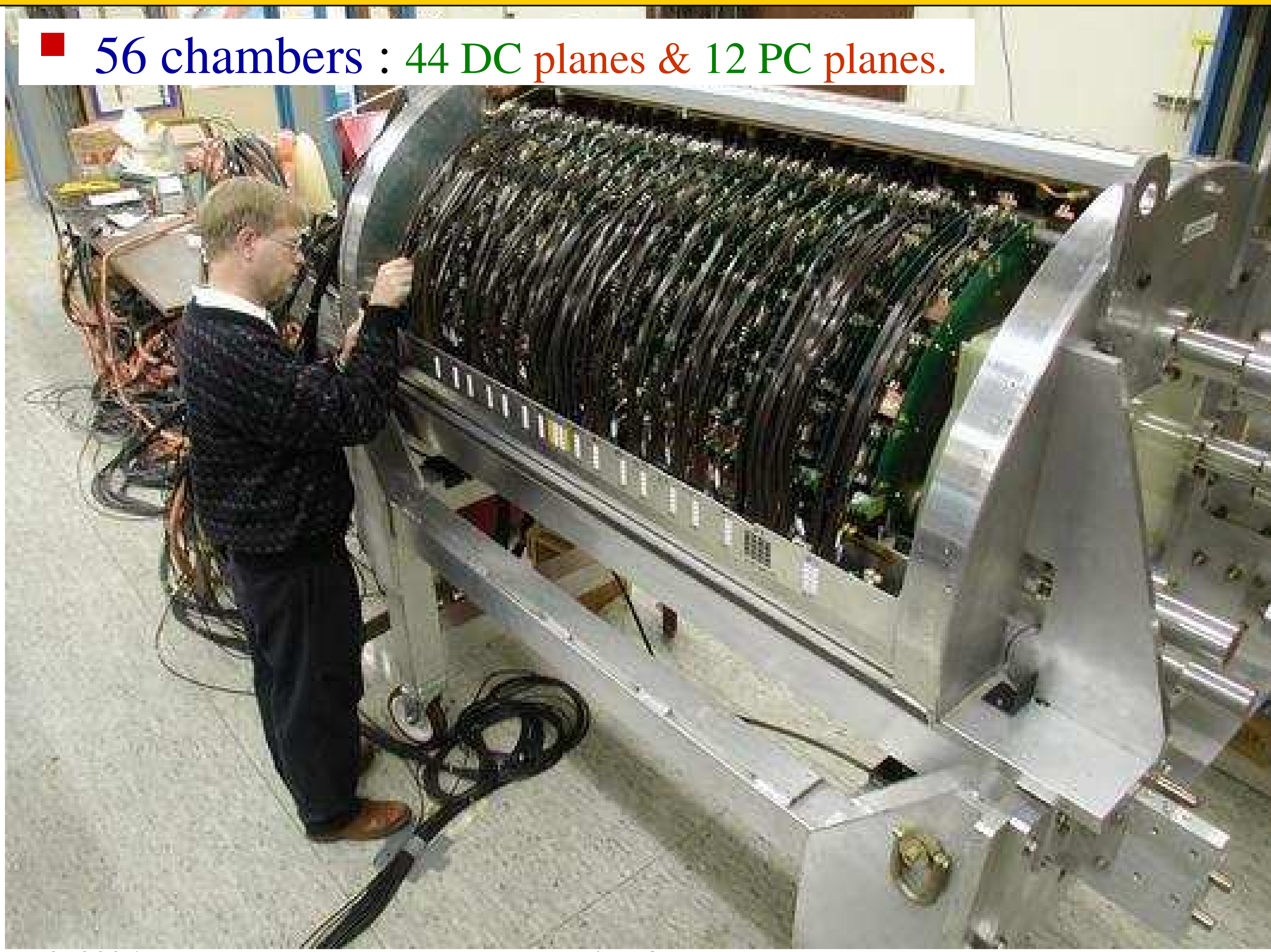
The detector

- μ^+ beam stops at the centre.
- Detector is highly symmetric.
- Chambers sit inside a highly uniform MRI magnet.
- Drift chambers used to track decay e^+.
- Trigger provided by a thin upstream scintillator.
- Beam stopping position fine-tuned using a variable CO_2:He gas degrader.
- The 2 tesla field is uniform to 4×10^{-3}, mapped to precision of 5×10^{-5}.



The detector

- 56 chambers : 44 DC planes & 12 PC planes.



Chamber performance

- High precision
  - Longitudinal plane positions accurate to **5×10^{-5}** by engineering.
  - Measured wire positions yield **σ=3.3μm**
  - Transverse positions calculated to an accuracy of 5 μm using 120 MeV/c pions.
- High resolution
  - High alignment precision.
  - Choice of gas
    - **DME: slow gas, high ionization density, low Lorentz angle.**
- High efficiency.
  - No hot or dead wires throughout 2002 data taking!
  - Efficiency >99.9% at 1900V.

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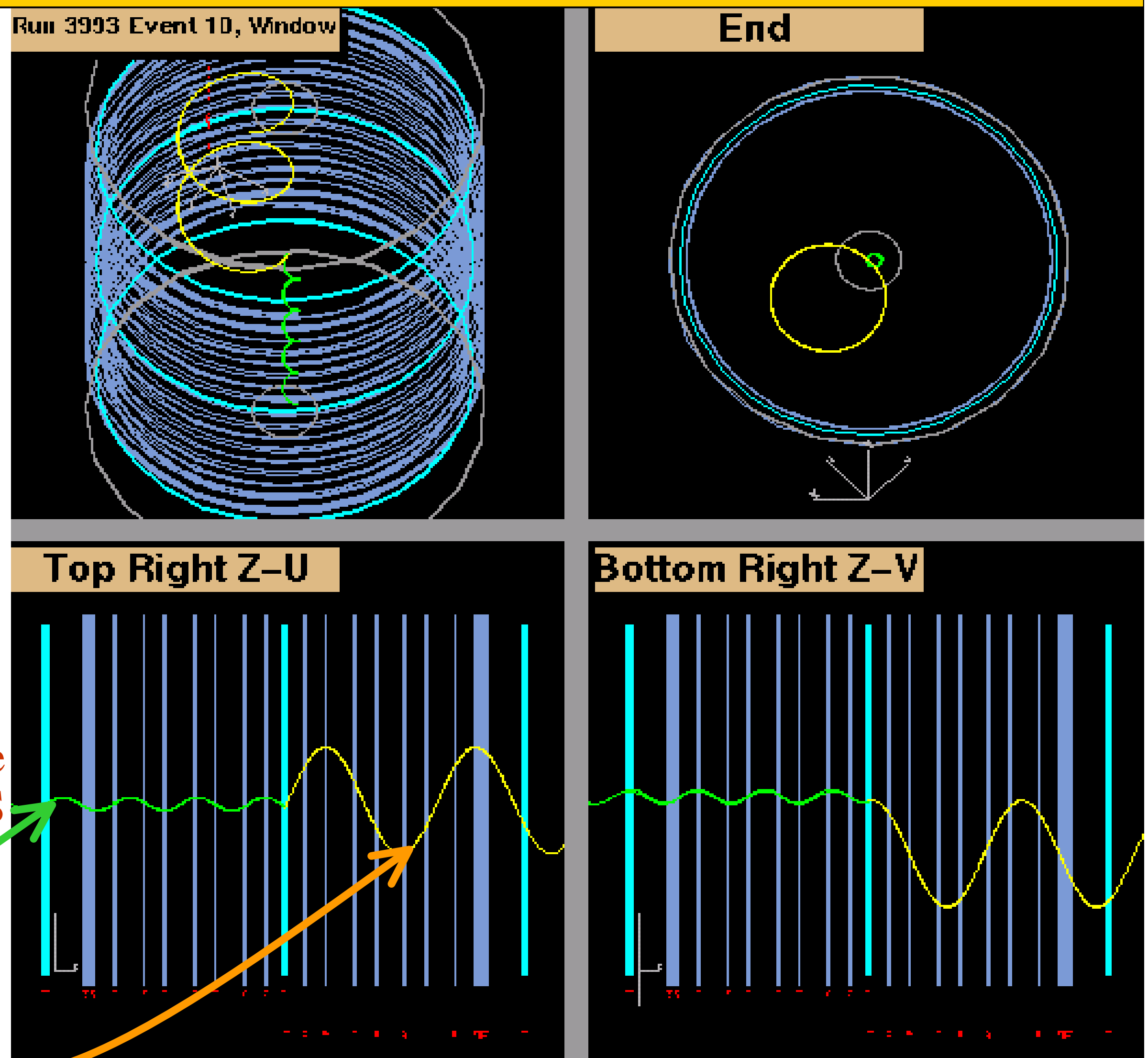
III. The analysis

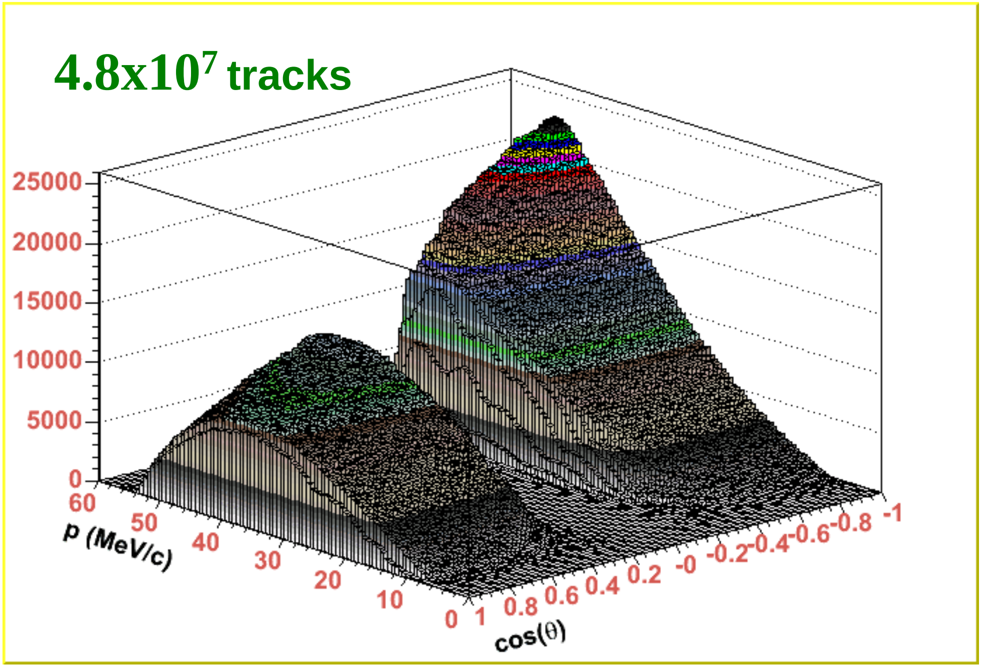
Track reconstruction

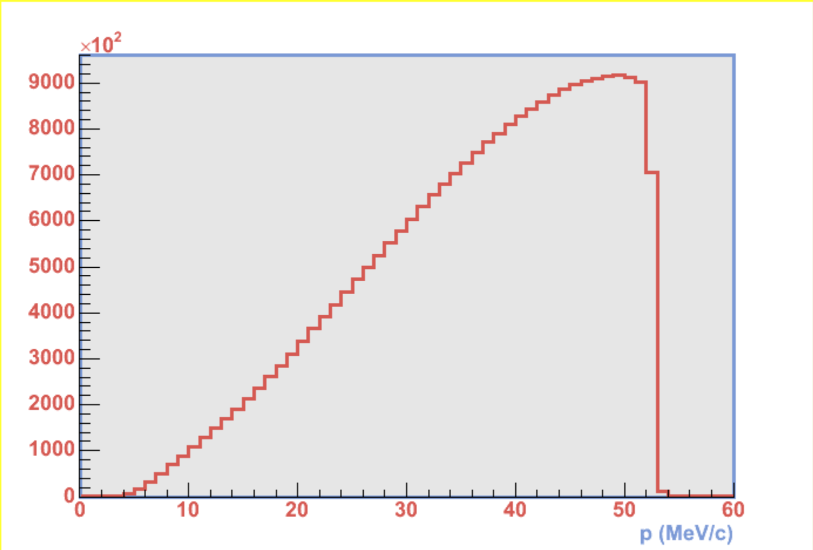
- Pattern recognition
  - Group hits in time using PC timing info.
  - Classify tracks according to hit patterns.
  - Must recognize beam positron tracks, delta tracks, backscattering, etc.
- Track fitting
  - Perform a crude fit using wire centres,
  - Refine fit using drift time and take into account MS field non-uniformities.

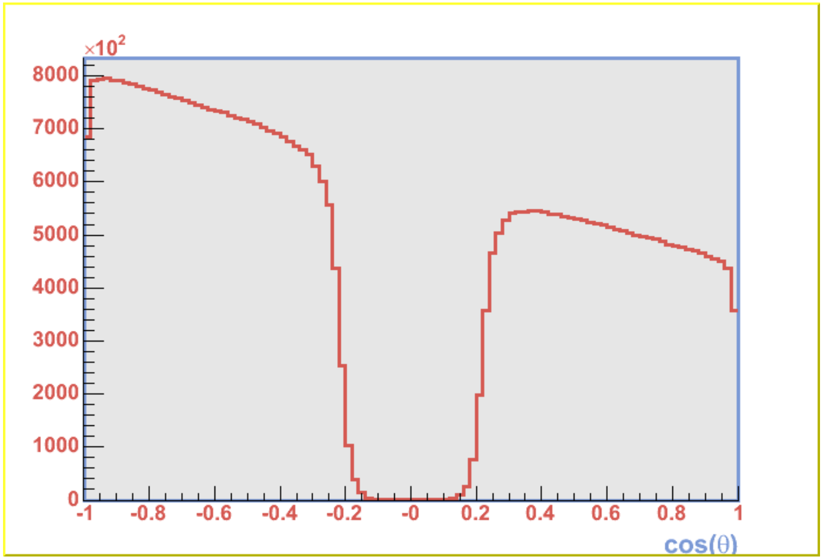


Spectrum reconstruction

- Reconstruct decay positron energy and angle
  - Apply (unbiased) cuts on muon variables.
  - Reject fast decays and backgrounds.
  - Calibrate positron momentum spectrum at the endpoint (~52.8 MeV/c).







The TWIST Monte Carlo

- TWIST relies on GEANT3 to simulate detector acceptance
  - Data spectrum fitted to MC spectrum.
- Monte Carlo includes elaborate details
  - GEANT3 geometry contains virtually all detector components.
  - Simulate detector response in detail (ionization clusters).
  - Realistic, measured beam profile and divergence.
  - Extra muon and beam positron contamination included.
  - Output into digitized format, identical to real data.
- Monte Carlo verified using real data
  - See contributed talk by Robert MacDonald on **Wednesday, 12:00pm (CEME 1202).**

"**Evaluation and simulation of the response function in the TWIST experiment**"

Energy calibrations

- For a planar detector energy loss is linear in $1/\cos(\theta)$.

$$p_{edge}(\vartheta) = \left(1 + \frac{\beta}{p_o}\right)\left(p_o - \frac{\alpha}{|\cos(\vartheta)|}\right)$$

$P_o = 52.828$ MeV/c α, β are fitting parameters

- α corrects for energy loss.
- β corrects for a possible magnetic field shift.
  - $\beta=0$ if field is known accurately.

Extracting the Michel parameters

TRIUMF

- The decay spectrum is linear in ρ, η, ξ, $\xi\delta$.
  - First order expansion is exact.

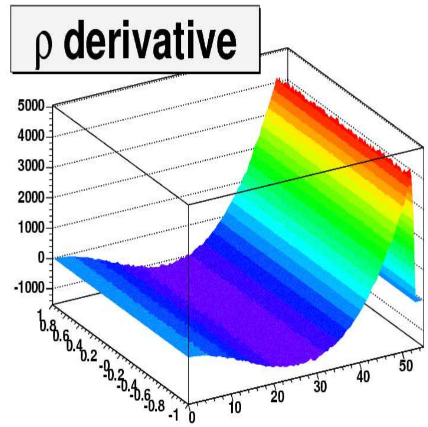
$$n_i(\lambda_{data}) = n_i(\lambda_{mc}) + \frac{\partial n_i}{\partial \lambda}\Delta\lambda$$

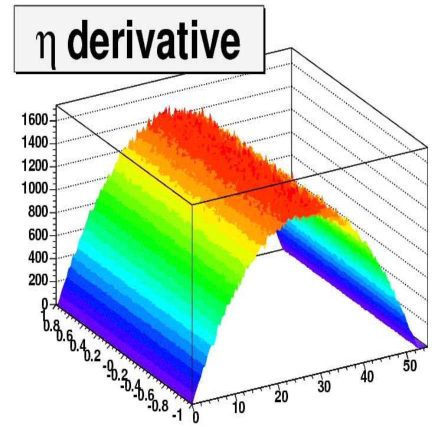
$$\text{where}$$

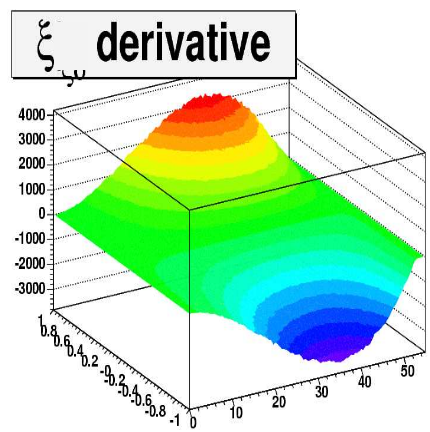
$$\lambda = [\rho, \eta, \xi, \xi\delta]$$

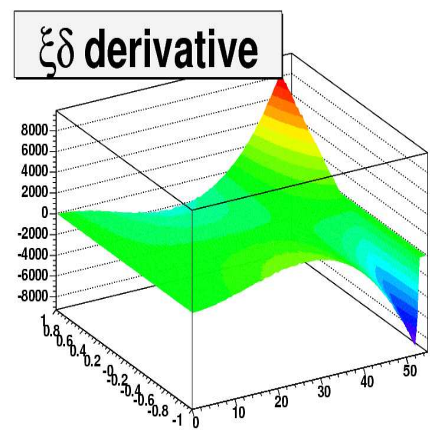
$\Delta\lambda$ are the fitting parameters

- Use standard model values (λ_{mc}) to generate the MC spectrum.
  - $\lambda_{mc} = \lambda_{SM}$.
  - $\Delta\lambda$ are the deviations from the SM.



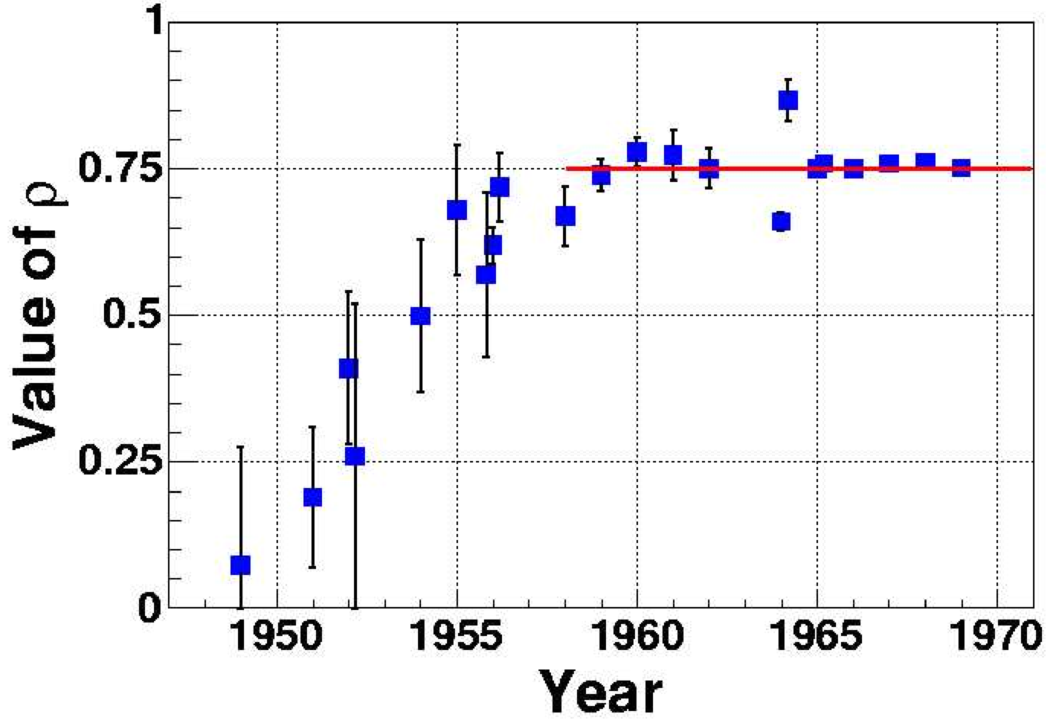






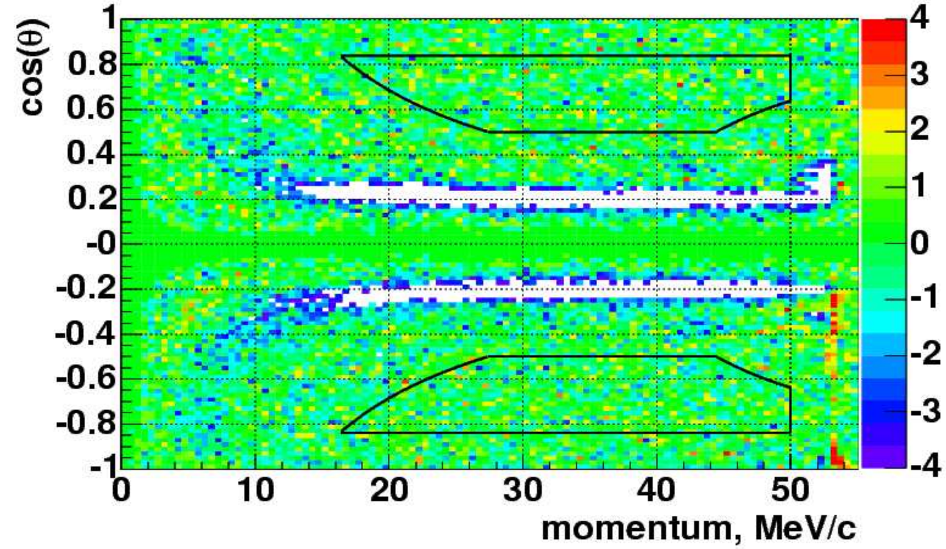
The blind analysis

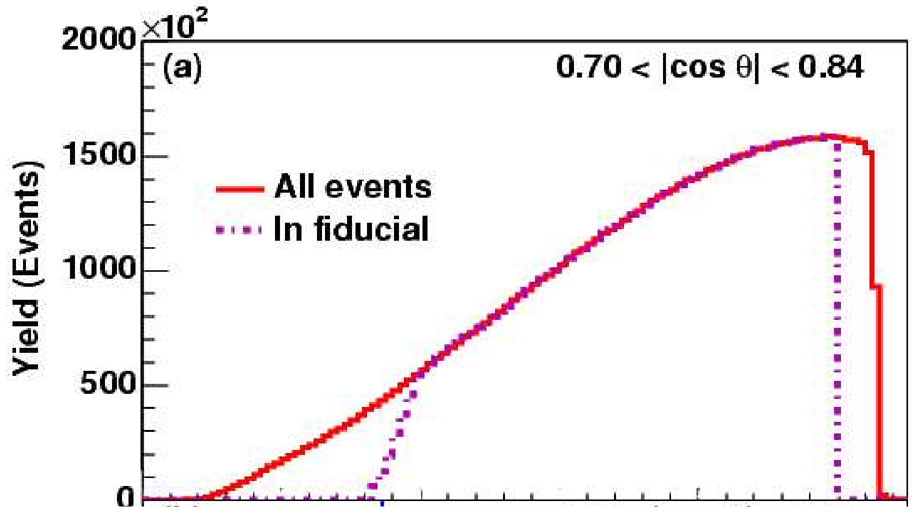
- Use hidden values (λ_{mc}) to generate the MC spectrum
  - $\Delta\lambda$ are the deviations from hidden values.
- Complete data analysis and fit before opening the box.
- Complete systematic evaluations before opening the box.



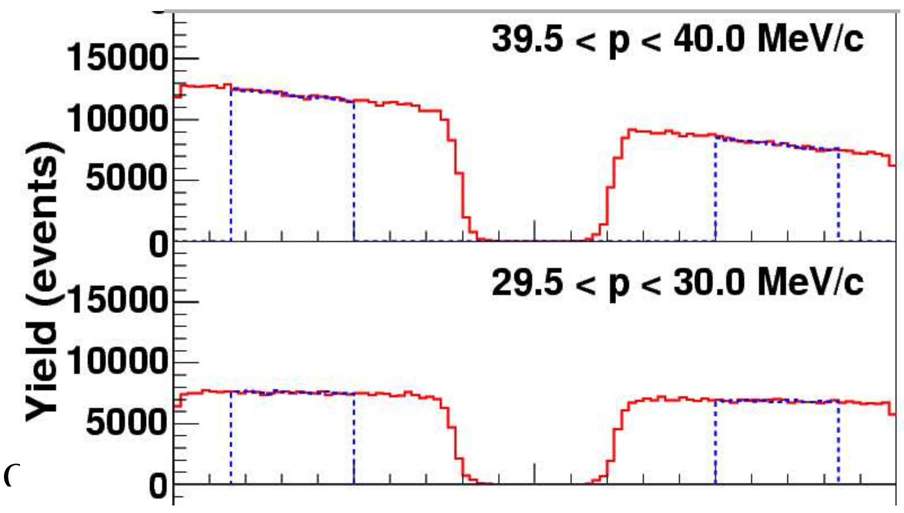
Fit quality and fiducial region

- High fit quality.
  - Normalized residuals ~1.
- Conservative fiducial region.
  - **$p < 50$ MeV/c.**
  - **$0.50 < |\cos\theta| < 0.84$.**
  - **$|p_z| > 13.7$ MeV/c.**
  - **$p_T < 38.5$ MeV/c.**





Momentum, MeV/c



cos(θ)

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IV. The systematics

Evaluating the systematics

- Fit data to data and MC to MC to evaluate systematic effects

$$n_i(\lambda_{mc}) = n_i(\lambda'_{mc}) + \frac{\partial n_i}{\partial \lambda}\Delta\lambda$$

$$n_i(\lambda_{data}) = n_i(\lambda'_{data}) + \frac{\partial n_i}{\partial \lambda}\Delta\lambda$$

Data sets acquired for systematic evaluations
B = 1.96 tesla
B = 2.04 tesla
DC HV lowered
PC HV lowered
Muon stopped slightly upstream
Muon stopped slightly downstream
Al slab inserted downstream
Plastic slab inserted downstream
Beam flux rate doubled
Beam flux rate cut in half
Bending magnet field increased by 10G
Bending magnet field decreased by 10G
Channel momentum tuned for non-surface (cloud) muons

Summary of the systematics

TRIUMF

ρ systematics

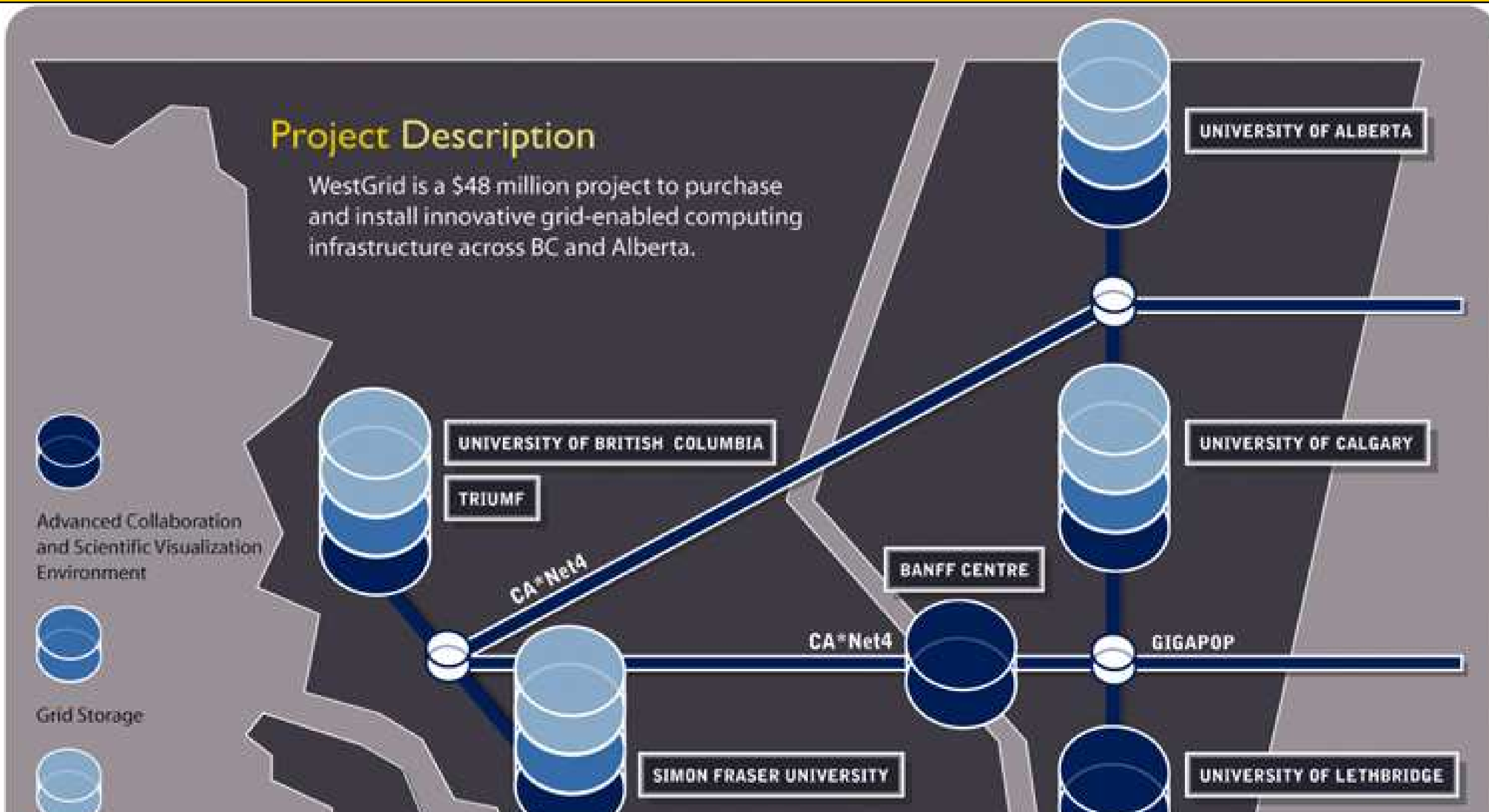
Systematic effect	Uncertainty ($\times 10^{-3}$)
Chamber response (ave)	0.51
Stopping target thickness	0.49
Positron interactions	0.46
Spectrometer alignment	0.22
Momentum calibration (ave)	0.20
Theoretical radiative corrections	0.20
Track selection algorithm	0.11
Muon beam stability (ave)	0.04

δ systematics

Systematic effect	Uncertainty ($\times 10^{-3}$)
Spectrometer alignment	0.61
Chamber response (ave)	0.56
Positron interactions	0.55
Stopping target thickness	0.37
Momentum calibration (ave)	0.29
Muon beam stability	0.10
Theoretical radiative corrections	0.10
Up & down efficiencies	0.04

Thanks to WestGrid!

Western Canada Research Grid



- During 2002 data processing WestGrid had ~1000 CPUs @ 3GHz.
- TWIST used ~30,000 CPU days to process 2002 data.

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V. The Results

TWIST results for ρ and δ

- TWIST results for ρ
  - A factor of 2.5 improvement over PDG value.

$$\rho = 0.75080 \pm 0.00032(\text{stat}) \pm 0.00097(\text{syst}) \pm 0.00023(\eta)$$

Musser et. al. Phys. Rev. Lett. 94, 101805 (2005)

- TWIST results for δ
  - A factor of 2.9 improvement over PDG value.

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

Gaponenko et. al.,Phys. Rev. D 71, 071101(R) (2005)

Results in agreement with the Standard Model

Right-handed currents

- Right handed currents

$$Q_R^\mu \le \frac{1}{2}\left(1 - P_\mu \xi\left(\frac{16}{9}\delta - \frac{1}{3}\right)\right)$$
$$= \frac{1}{2}\left[1 - P_\mu(\xi\delta/\rho)\rho\left(\frac{16}{9} - \frac{1}{3\delta}\right)\right]$$

TWIST $Q_R^\mu < 0.00184$

Pre-TWIST	TWIST
$\lvert g_{LR}^S \rvert < 0.125$	$\lvert g_{LR}^S \rvert < 0.086$
$\lvert g_{LR}^V \rvert < 0.060$	$\lvert g_{LR}^V \rvert < 0.043$
$\lvert g_{LR}^T \rvert < 0.036$	$\lvert g_{LR}^T \rvert < 0.025$

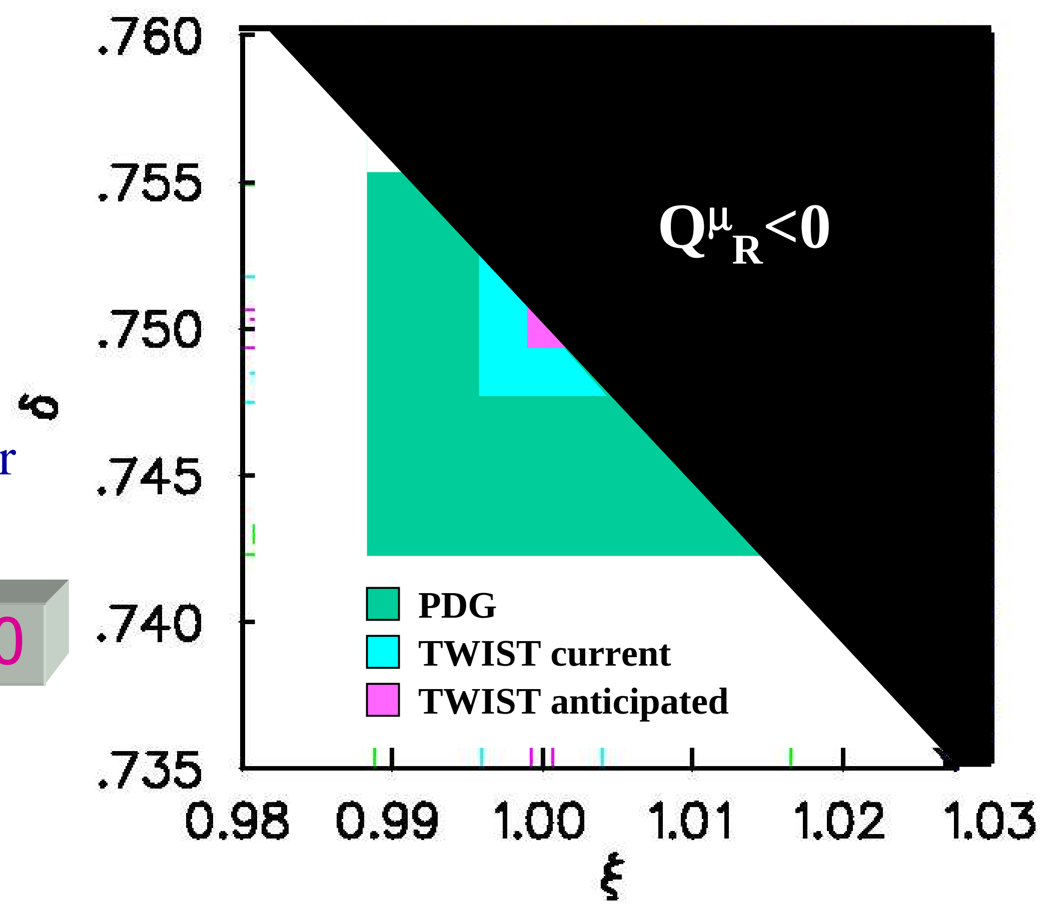
- Use:
  - TWIST ρ, δ.
  - $P_\mu(\xi\delta/\rho) > 0.99787$.

Model-independent result

TWIST results for ξ

- Indirect results for ξ.
- Use:
  - TWIST ρ, δ.
  - $P_\mu(\xi\delta/\rho) > 0.99787$.
  - $Q^\mu_R > 0$.
- A factor of >3 improvement over previous result

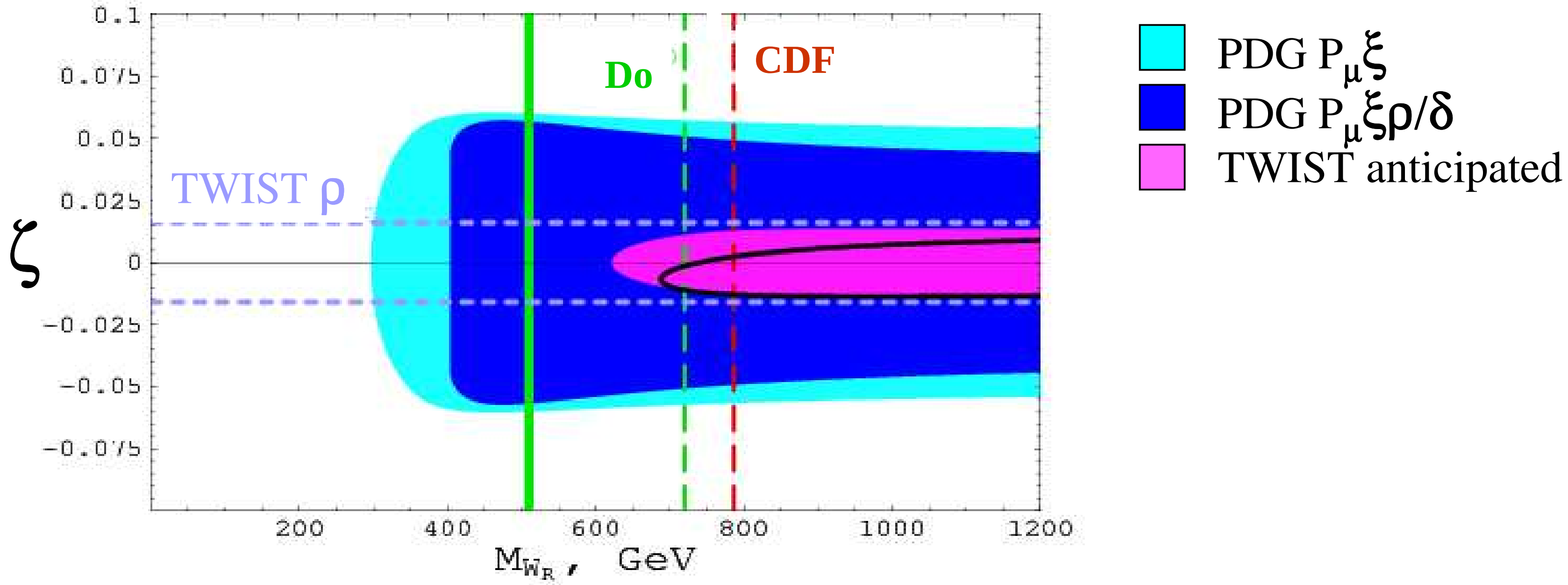
$$0.9960 < P_\mu\xi \leq \xi < 1.0040$$



- Direct measurement of **Pμξ.**
  - See contributed talk by Blair Jamieson on Monday, 3:00pm (CEME 1202).

"Status of the TWIST Measurement of the muon decay asymmetry"

Limits on left-right symmetric models



- Limits are from high precision muon decay experiments, nuclear β decay, and high energy experiments
  - Different types of experiments are complementary.
  - β decay experiments subject to theoretical uncertainties.
  - High energy experiments place limits only on W_R mass.
  - Muon decay offers a clean system with limits on mass and mixing angle.

Exotic particle searches

Monday, 7:00pm poster & beer session: Ryan Bayes
"A Search for Rare Decays in the TWIST Muon Decay Spectrum"

Summary & conclusions

- TWIST has been able to improve substantially on the measurement of the Michel parameters ρ and δ.
  - First successful improvement on ρ in over 30 years.
  - First successful improvement on δ in over 20 years.

- Several factors allowed this improvement to happen.
  - A highly polarized high flux stable beam from TRIUMF.
  - A high precision, high efficiency, low mass detector.
  - A planar detector geometry allowing precise energy calibrations.
  - The availability of ***WestGrid*** allowing evaluation of the systematics.

- All results are in agreement with the standard model predictions.
  - The values of ρ and δ agree with the Standard Model values.
  - No evidence for right handed currents.
  - Improved limits on mass and mixing angle of W_R compared to muon decay experiments.

- The TWIST results are particularly important due to the use of blind analysis.