Final results from the TWIST Experiment

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Lake Louise Winter Institute 2010

Outline

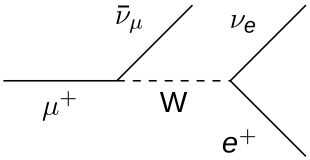
Muon decay to probe the weak interaction

Muon decay is ideal to study the weak nuclear interaction at low energy.

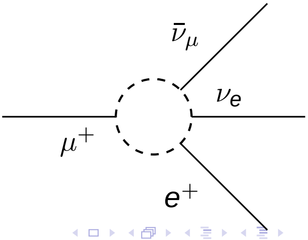
- Only weak interaction involved
- Muons are easy to produce
- One decay mode dominates ($\approx$ 100%)

One can study muon decay at low energy in a model independent way.

Standard Model



4-fermion interaction



The interaction can be described as a derivative-free, Lorentz-invariant and lepton-number conserving matrix[1]:

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

$$\begin{aligned} \gamma &= \text{S(calar), V(ector), T(ensor)} \\ \epsilon, \mu &= \text{R(ight-handed), L(eft-handed)} \end{aligned}$$

[1] W. Fetscher, H. J. Gerber, and K.F. Johnson, *Phys. Lett.* **B173** (1986) 102

4-fermion formalism

The interaction can be described as a derivative-free, Lorentz-invariant and lepton-number conserving matrix[1]:

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

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

Standard Model, V-A interaction

$$g^V_{LL} = 1$$

$\Longrightarrow$ 19 real and independent parameters

[1]W. Fetscher, H. J. Gerber, and K.F. Johnson, *Phys. Lett.* **B173** (1986) 102

The muon decay parametrization

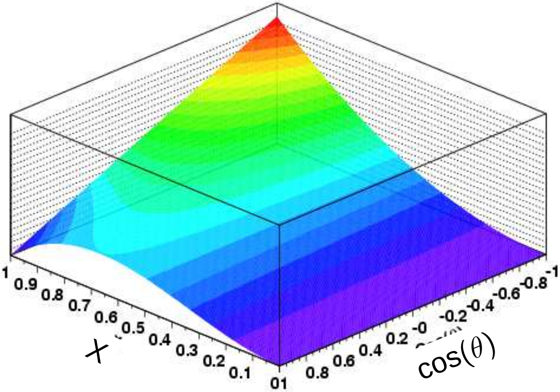
The differential decay rate can be written:

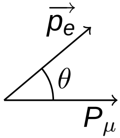
$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2}\left(F_{IS}(x) + P_\mu \cos\theta F_{AS}(x)\right) + \text{R.C.}$$

$$W_{e\mu} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$$

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

$$x_0 = \frac{m_e}{W_{e\mu}}$$





The muon decay parametrization

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The isotropic and anisotropic parts are:

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

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

Standard Model predictions

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

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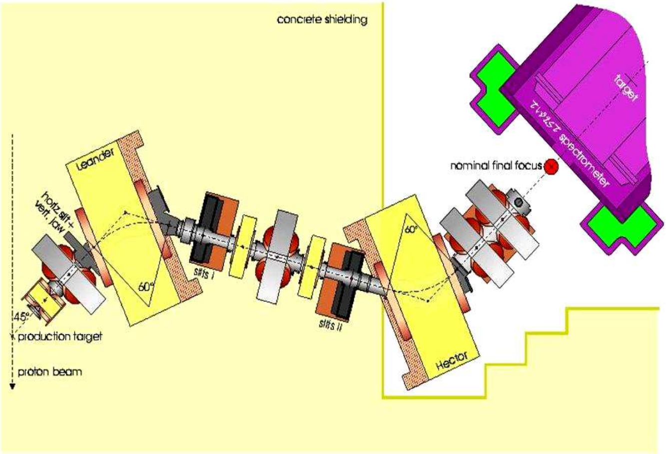
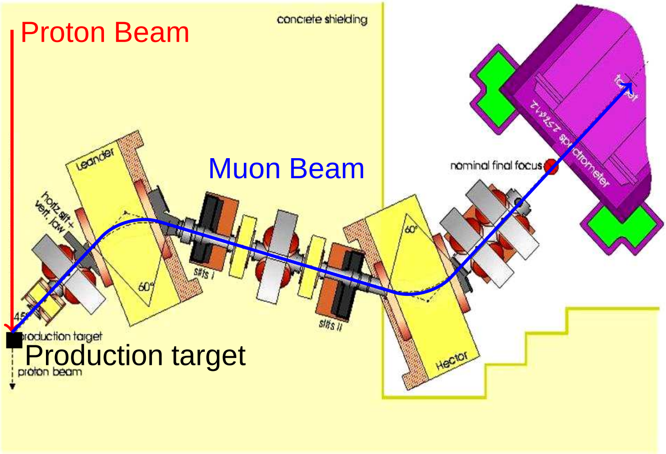
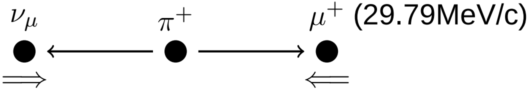
The TWIST experiment

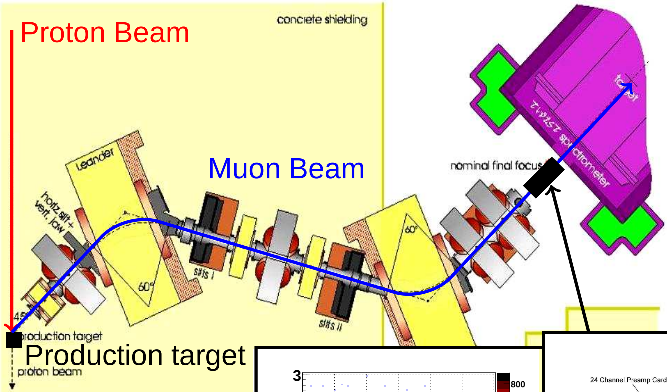




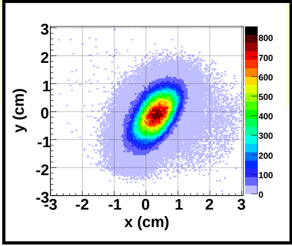


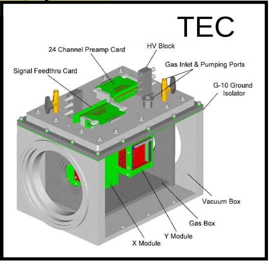
Highly polarized muon beam

The TWIST experiment

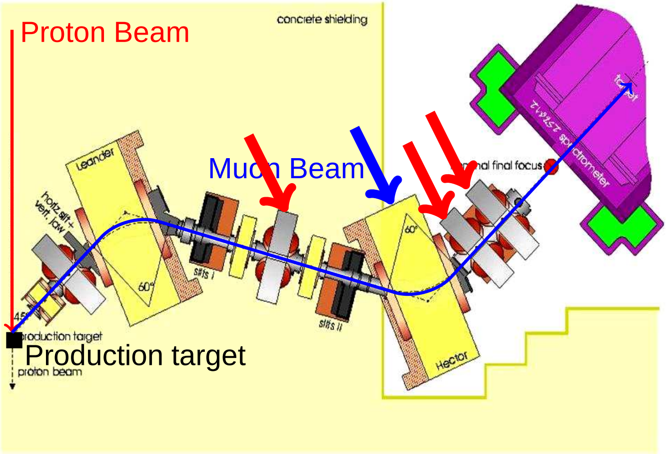


Beam profile measurement



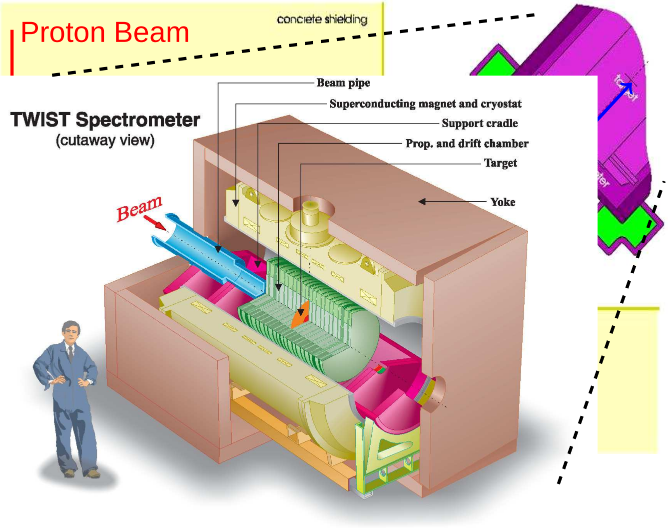


The TWIST experiment



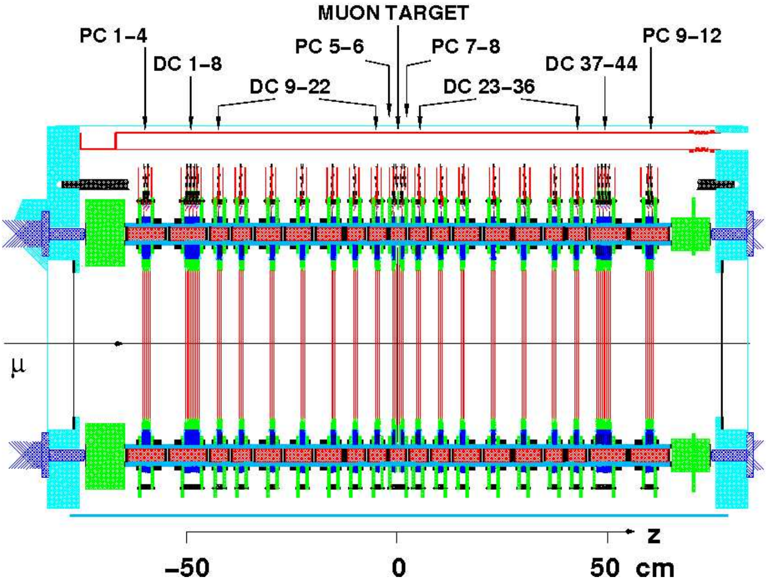
Upgrade: Control of the beam position and angle
by using asymmetric currents in quadrupoles.

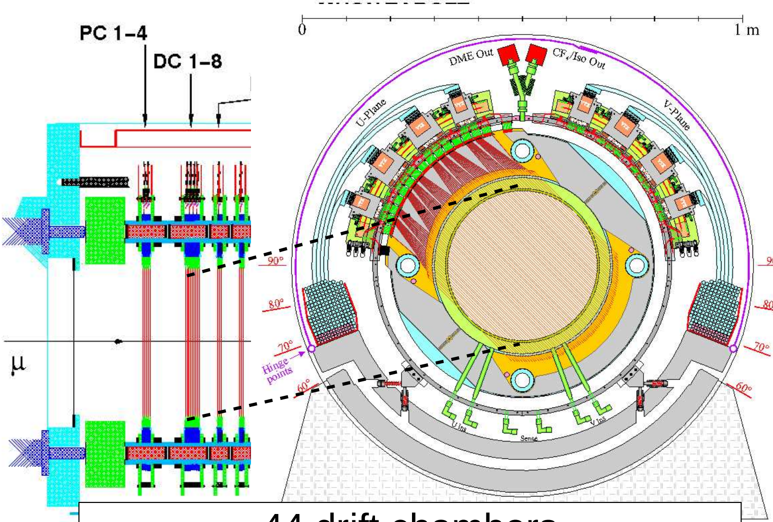
The TWIST experiment



TWIST = TRIUMF Weak Interaction Symmetry Test

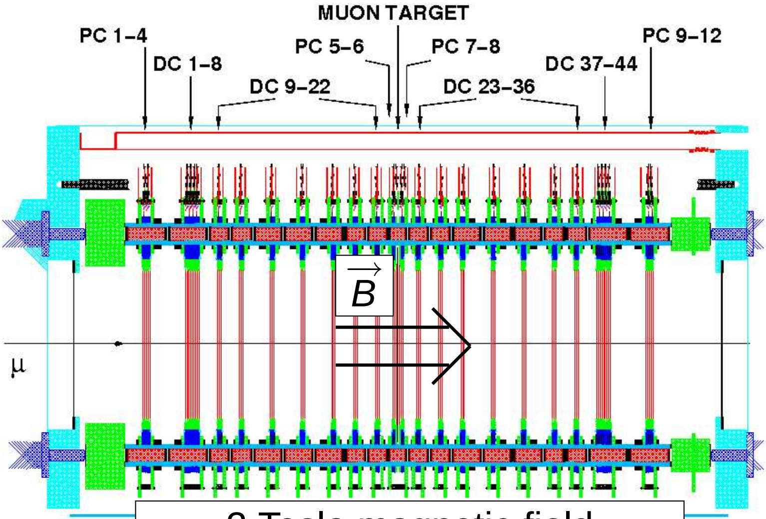
Typical event





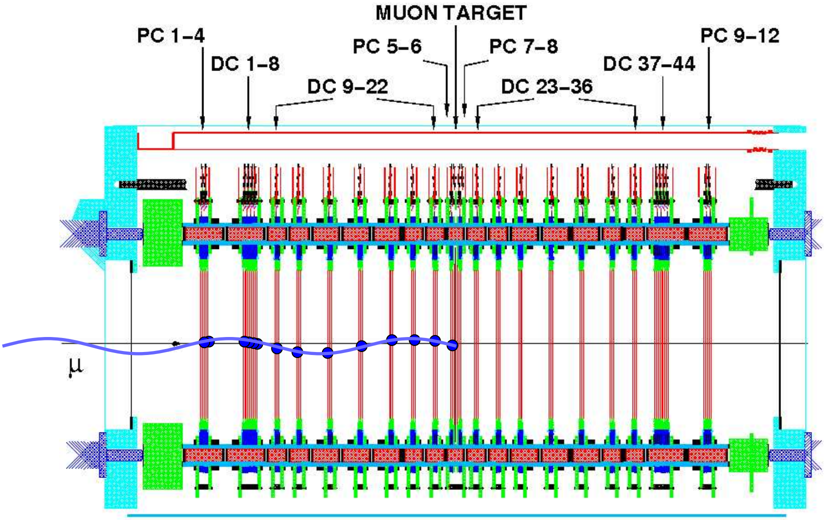
44 drift chambers
Wire position known to 5 parts in 10^5

Typical event



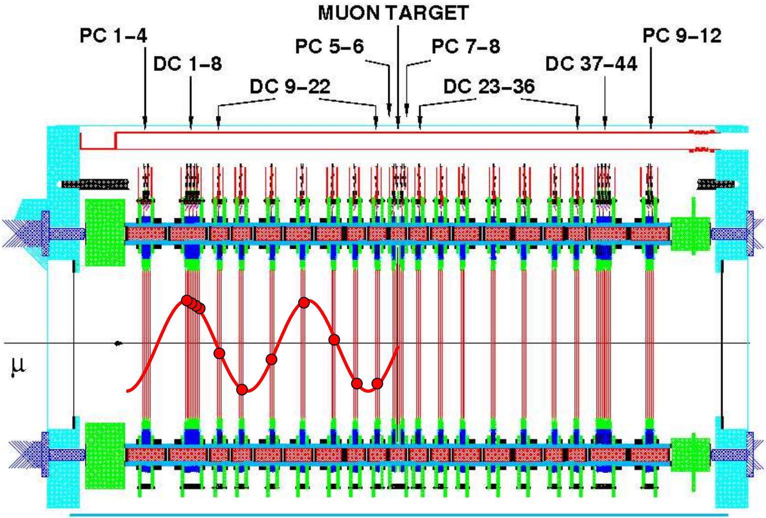
2 Tesla magnetic field known to 3 parts in 10^5

Typical event



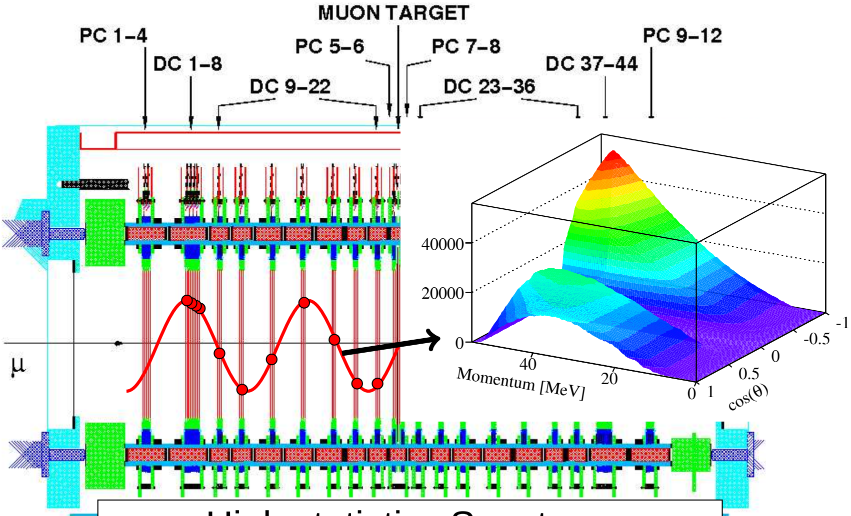
Muon rate $\leq$ 5000Hz

Typical event



Decay positron track reconstruction

Typical event

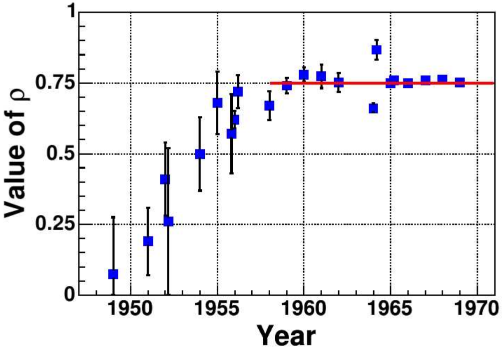


High statistics Spectrum
Total of 5.5×10^8 decays selected

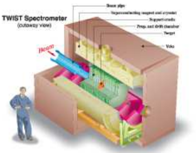
Trust no one.

The analysis in TWIST is blind to avoid any human bias:

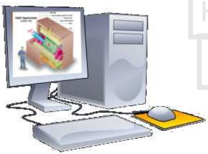
- Choices of data samples
- Looking for errors if disagreement with expectations
- Systematic error evaluation influenced by final result



Analysis



Experimental data



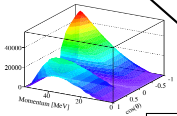
Hidden parameters

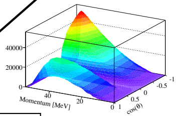
range: SM $\pm 10^{-2}$

$\xi_{MC}, \rho_{MC}, \delta_{MC}$

Monte Carlo data

Reconstruction Software

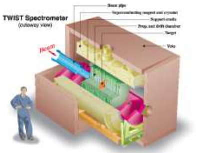




Spectrum Fit

$\Delta\xi, \Delta\rho, \Delta\delta$

ξ, ρ, δ



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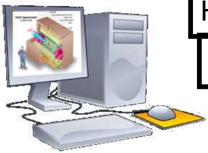

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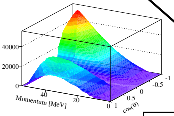

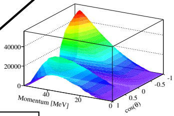

Spectrum Fit

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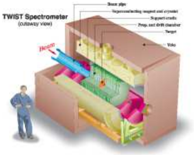
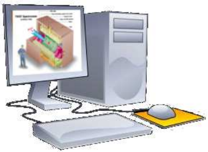
Evaluation of systematic uncertainties

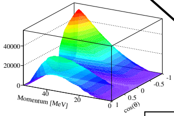


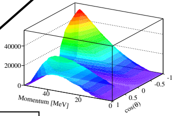


Experimental data

Monte Carlo data

Reconstruction Software

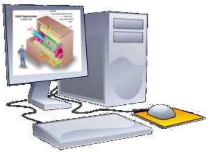


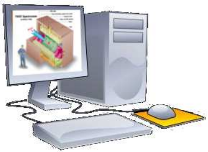


Spectrum Fit

$\Delta\xi, \Delta\rho, \Delta\delta$

Evaluation of systematic uncertainties



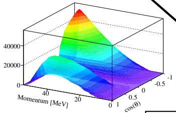


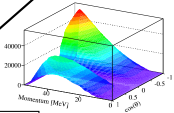
Exaggeration

Example: Bremsstrahlung rate

Monte Carlo data → Reconstruction Software

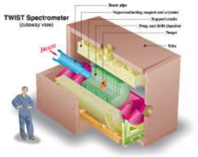
Monte Carlo data (exaggerated) → Reconstruction Software

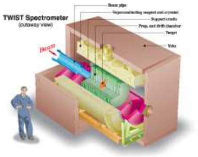




Spectrum Fit

$\Delta\xi, \Delta\rho, \Delta\delta$





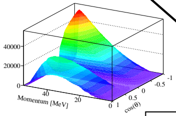
Exaggeration

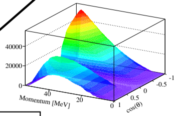
Example:
Magnetic field map

Experimental data

Experimental data

Reconstruction Software

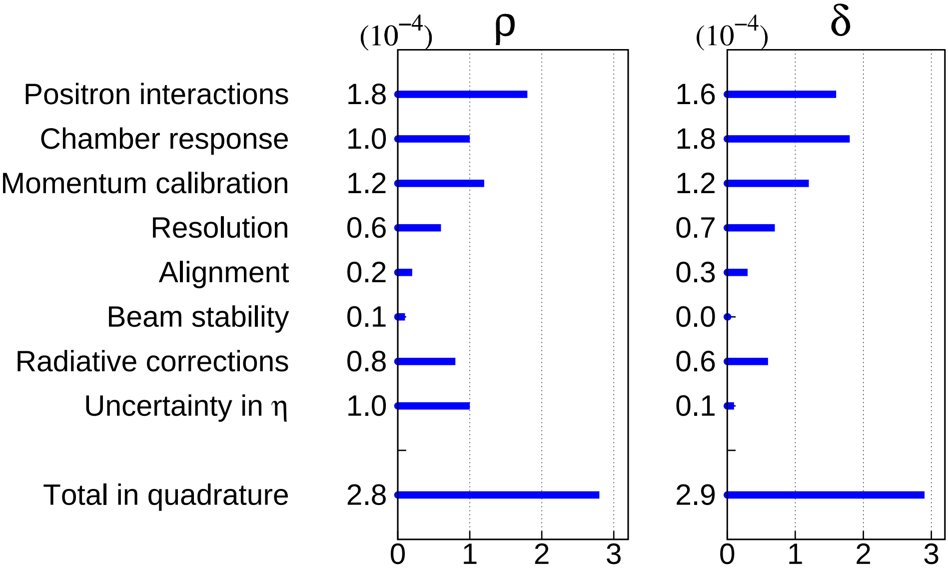


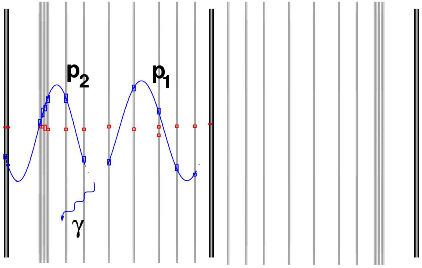


Spectrum Fit

$\Delta\xi, \Delta\rho, \Delta\delta$

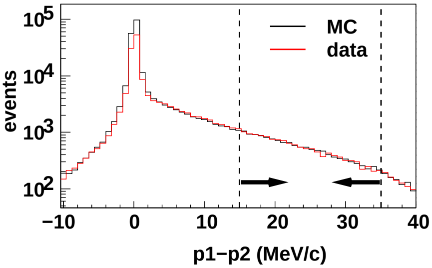
Systematic uncertainties for ρ, δ



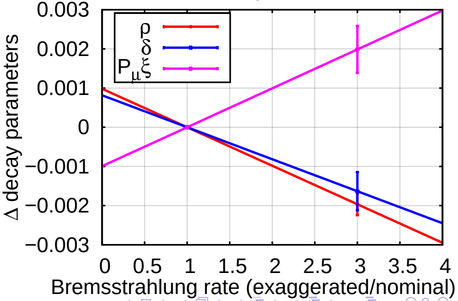


1. Event topology of brem.
   ⟹ "broken" positron track
2. Select momentum difference
3. Scale down sensitivity

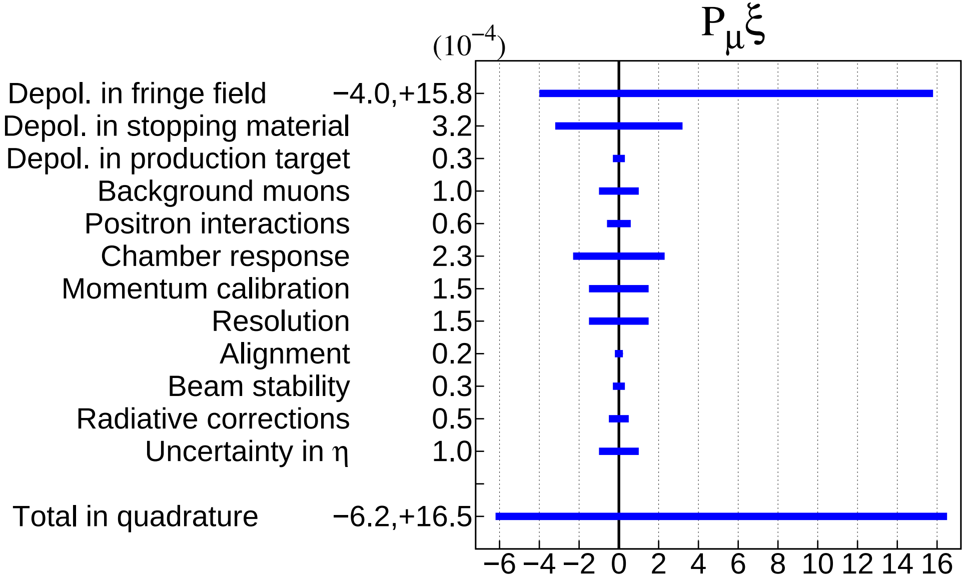
Brem: data/sim differ by 2.4%



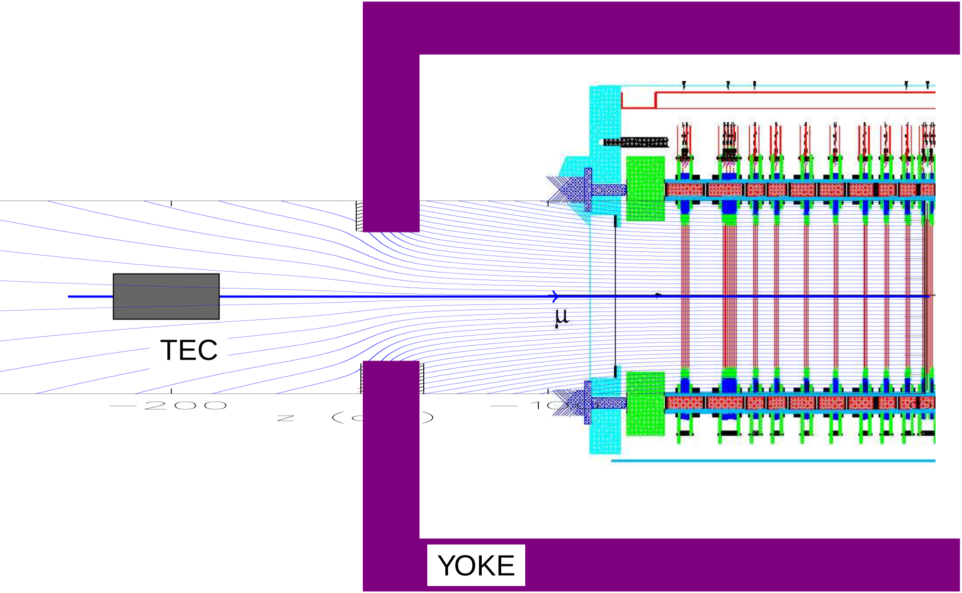
Decay parameters sensitivity to brem.



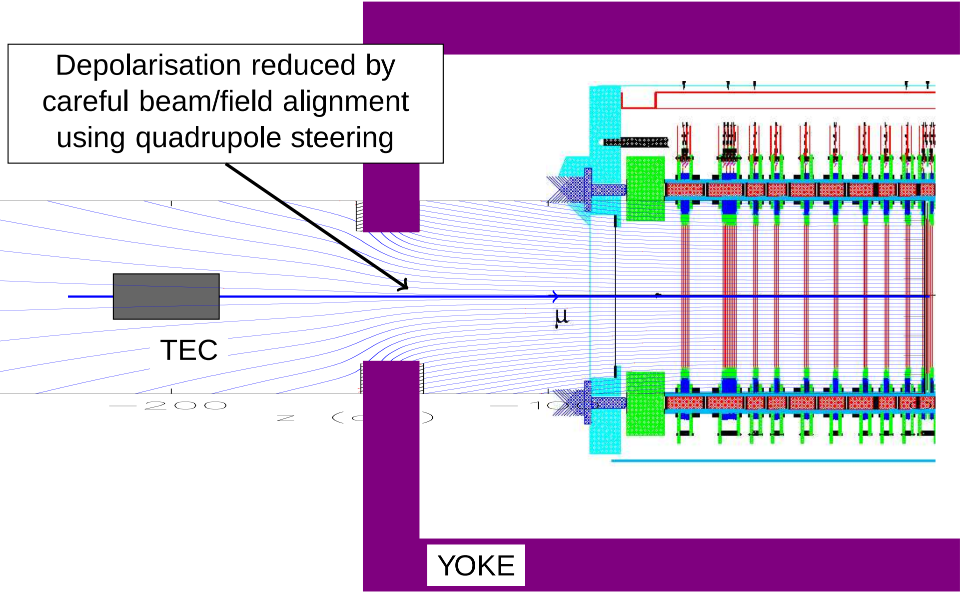
Systematics uncertainties for $P_\mu \xi$



Fringe field depolarization

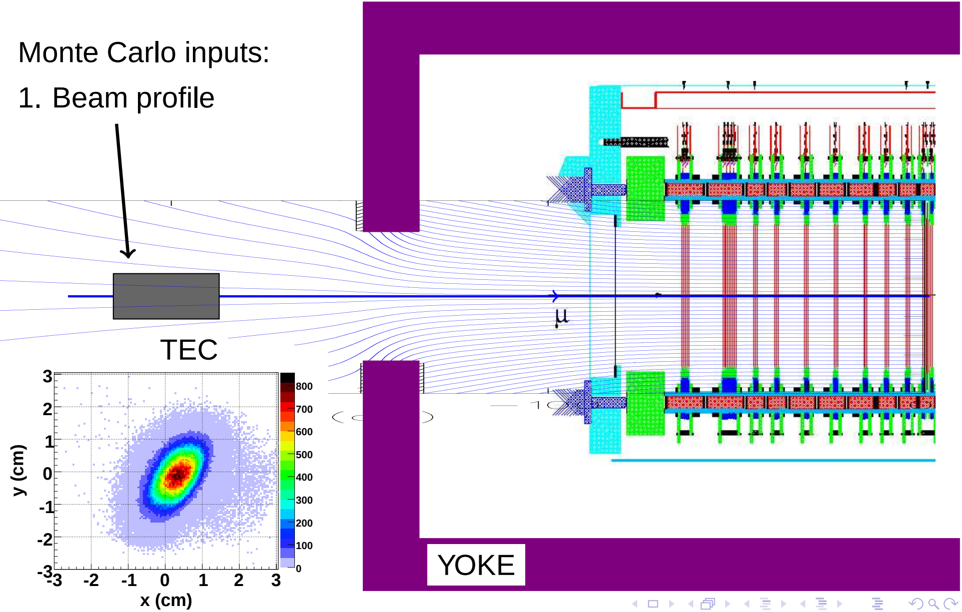


Fringe field depolarization



Monte Carlo inputs:

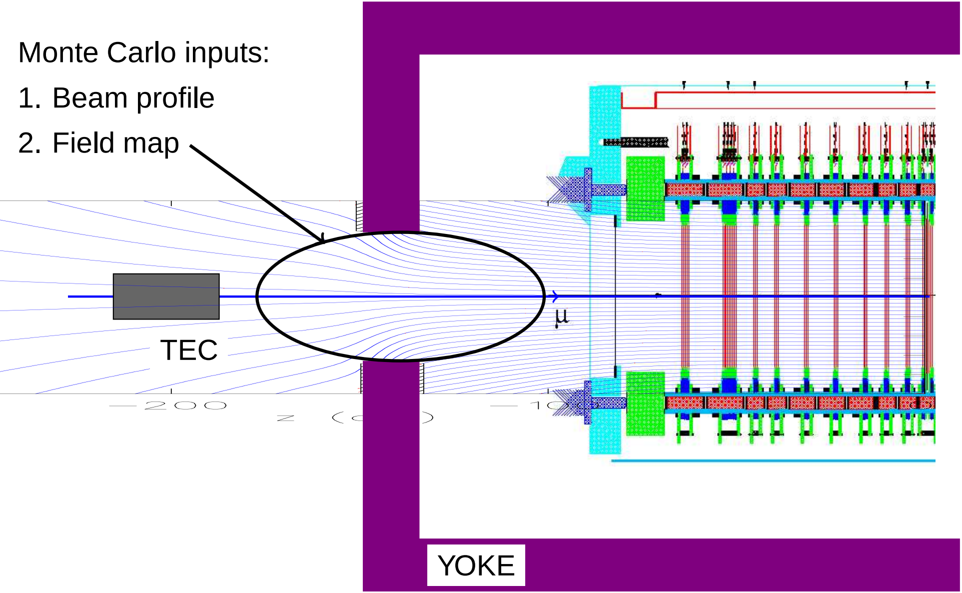
1. Beam profile



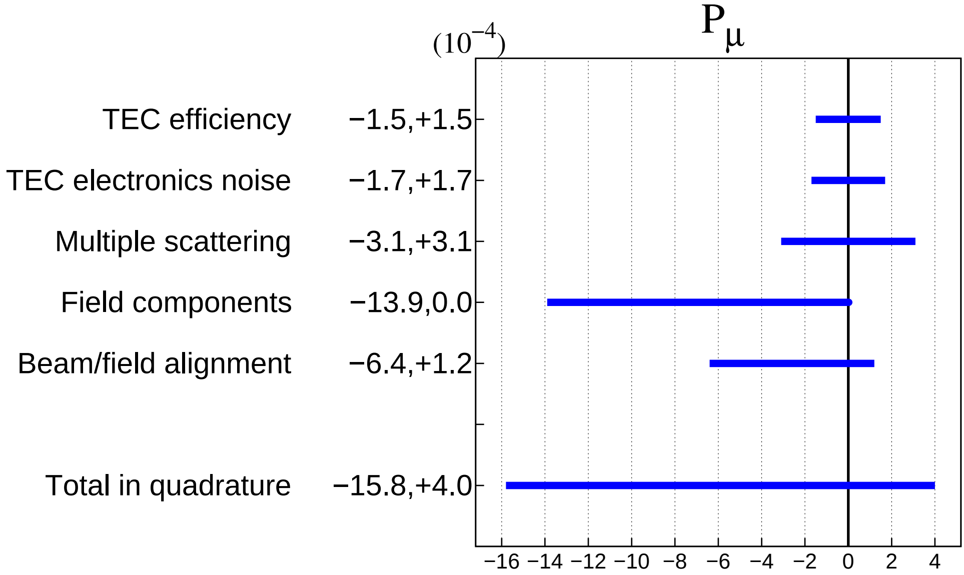
Fringe field depolarization

Monte Carlo inputs:

1. Beam profile
2. Field map



Fringe field systematic uncertainties

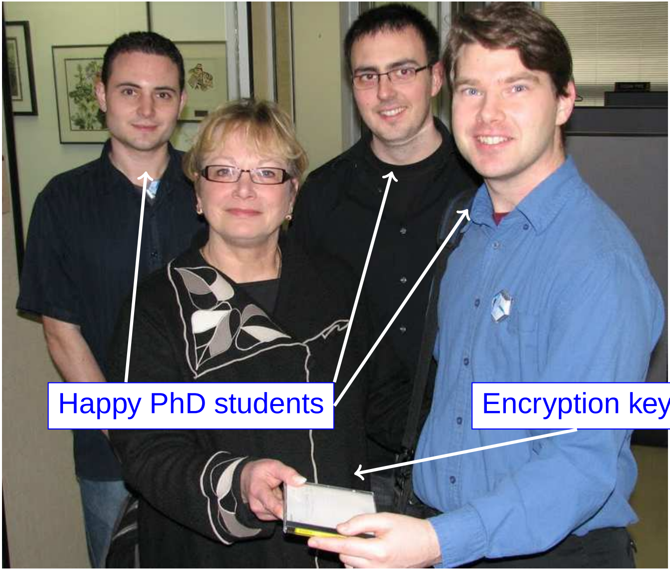


Conditions required to reveal the results

Prior to unblinding the results, the collaboration agreed on:

- Data sets to include.
- Systematics uncertainties and corrections.
- Level of required consistency with previous results.
- New measurement supersedes previous TWIST measurements.
- Publish even if inconsistent with Standard Model.

Hidden parameters revealed, 29th January 2010



Final TWIST measurement

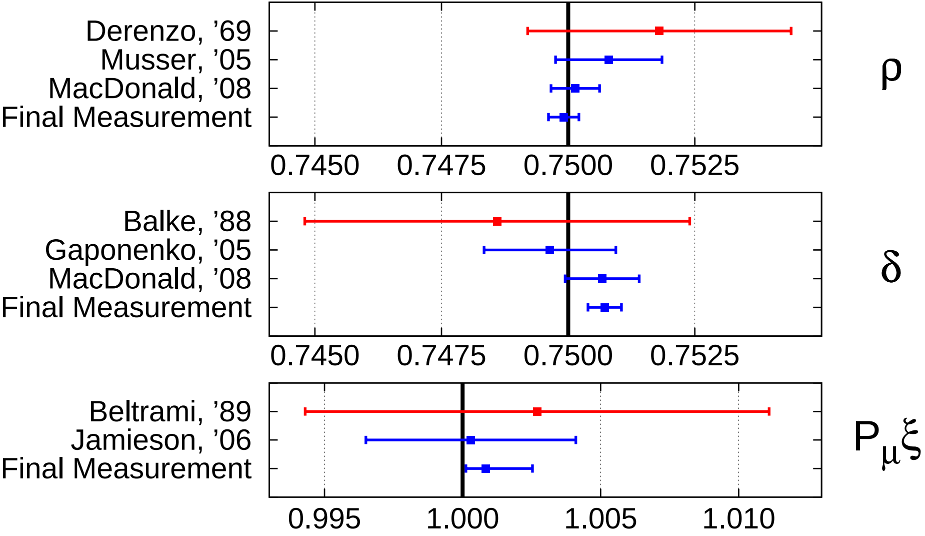
$$\rho = 0.74991 \pm 0.00009 \text{ (stat)} \pm 0.00028 \text{ (sys)}$$

$$\delta = 0.75072 \pm 0.00016 \text{ (stat)} \pm 0.00029 \text{ (sys)}$$

$$P_\mu \xi = 1.00083 \pm 0.00035 \text{ (stat)}^{+0.00165}_{-0.00063} \text{ (sys)}$$

Results

Consistency with previous measurements



Pre-TWIST **TWIST**

Results

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$$P_\mu \xi = 1.00083 \pm 0.00035 \text{ (stat)}^{+0.00165}_{-0.00063} \text{ (sys)}$$

	Improvement over pre-TWIST	Deviation from SM
ρ	$\times$ 8.7	0.3 σ
δ	$\times$ 11.5	2.2 σ
$P_\mu \xi$	$\times$ 11.7 and $\times$ 5.0	1.2 σ

Results

Differential decay rate at the kinematic end point and in the direction opposite to the muon polarization:

$$\frac{d^2\Gamma}{dx\ d\cos\theta} \approx \left(1 - \frac{P_\mu \xi \delta}{\rho}\right)$$

Therefore $\frac{P_\mu \xi \delta}{\rho} \leq 1$.

TWIST measurement

$$\frac{P_\mu \xi \delta}{\rho} = 1.00192^{+0.00167}_{-0.00066}$$

The measurement is 2.9 σ above 1.

Under investigation

Results

Differential decay rate at the kinematic end point and in the direction opposite to the muon polarization:

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TWIST measurement

$$\frac{P_\mu \xi \delta}{\rho} = 1.00192^{+0.00167}_{-0.00066}$$

The measurement is 2.9 σ above 1.

Under investigation

Left Right Symmetry Test

In left-right symmetric models the (V+A) current is suppressed, but not exactly zero[2].

The left- and right-handed gauge boson fields are given by:

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

$$W_R = e^{i\omega}(-W_1 \sin\zeta + W_2 \cos\zeta)$$

The following notations assume possible differences in left and right coupling and CKM character:

$$t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \qquad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}, \qquad \zeta_g^2 = \frac{g_R^2}{g_L^2}\zeta^2$$

[2] Herczeg, P.,Phys. Rev. D, 34, 3449–3456, 1986

Relation to the muon decay parameters:

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

$$P_\mu = 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g \cos(\alpha + \omega)$$

with α a CP-violating phase from the CKM matrix.

In manifest model

$g_R = g_L$, $\omega = 0$, $V_{ud}^R = V_{ud}^L$. In consequence $\alpha = 0$.

In nonmanifest model

No assumptions on couplings, CKM matrices or CP violation.

Left Right Symmetry Test

Relation to the muon decay parameters:

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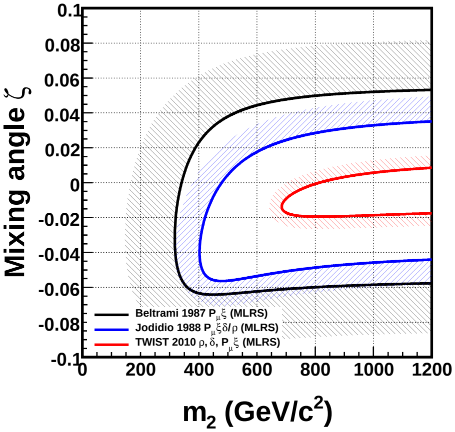
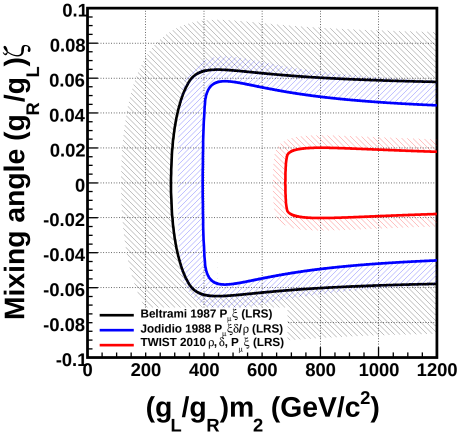
No assumptions on couplings, CKM matrices or CP violation.

Left Right Symmetry Test

Manifest



Nonmanifest



90% confidence level

Global analysis of muon decay

The global analysis uses a Monte Carlo integration techniques to extract the couplings $g^{\gamma}_{\epsilon\mu}$ from the 11 (not all independent) observables of muon decay:

- the four muon decay parameters ρ, η, $P_\mu\xi$ and δ
- the measurement of $P_\mu\xi\delta/\rho$
- the parameters ξ' and ξ'' from the longitudinal polarisation of the outgoing electrons
- the parameters η'', α, β, α' and β' from the transverse polarisation of the outgoing electrons
- the parameter $\bar{\eta}$ from the radiative muon decay

Gagliardi and al. (Phys. Rev. D 72, 073002) used the initial TWIST results (2005).

Model-Independent search for right-handed interactions

Model-independent measure of the right-handed muon decay probability:

$$Q_R^\mu = Q_{RR} + Q_{LR}$$

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

Results from the global analysis at a 90% confidence level:

- **Pre-TWIST:** $Q_R^\mu < 0.0051$
- **Gagliardi:** $Q_R^\mu < 0.0031$
- **New preliminary limit:** $Q_R^\mu < 0.00058$

The new limit is a factor 9 smaller than pre-TWIST.

Limits on the coupling constants

Weak Coupling	pre-TWIST	Gagliardi	Preliminary results
$\|g^S_{RR}\|$	< 0.066	< 0.067	< 0.031 ($\times$2.1)
$\|g^S_{LR}\|$	< 0.125	< 0.088	< 0.041 ($\times$3.0)
$\|g^V_{RR}\|$	< 0.033	< 0.034	< 0.015 ($\times$2.2)
$\|g^V_{LR}\|$	< 0.066	< 0.036	< 0.018 ($\times$3.7)
$\|g^T_{LR}\|$	< 0.036	< 0.025	< 0.012 ($\times$3.0)

90% confidence level

Summary

- Final TWIST measurement completed
- Results to be published soon
- New results consistent with previous measurements
- More stringent limits on Left-Right Symmetric models
- More stringent limits on coupling constants

	Improvement over pre-TWIST	Deviation from SM
ρ	$\times$ 8.7	0.3 σ
δ	$\times$ 11.5	2.2 σ
$P_\mu \xi$	$\times$ 11.7 and $\times$ 5.0	1.2 σ

The TWIST Collaboration

TRIUMF		Alberta
Ryan Bayes†	Glen Marshall	Andrei Gaponenko◇
Yuri Davydov	Dick Mischke	Robert MacDonald◇
Wayne Faszer	Konstantin Olchanski	
Makoto Fujiwara	Art Olin	
David Gill	Robert Openshaw	**British Columbia**
Alexander Grossheim	Jean-Michel Poutissou	James Bueno†
Peter Gumplinger	Renée Poutissou	Mike Hasinoff
Anthony Hillairet†	Grant Sheffer	
Robert Henderson	Bill Shin	**Texas A&M**
Jingliang Hu		Carl Gagliardi
	Montréal	Bob Tribble
Regina	Pierre Depommier	
Ted Mathie		**Valparaiso**
Roman Tacik	**Kurchatov Institute**	Don Koetke
	Vladimir Selivanov	Shirvel Stanislaus

◇ Graduated

† Graduate student

Supported under grants from NSERC and US DOE.
Additional support from TRIUMF, WestGrid, NRC, and the Russian Ministry of Science.

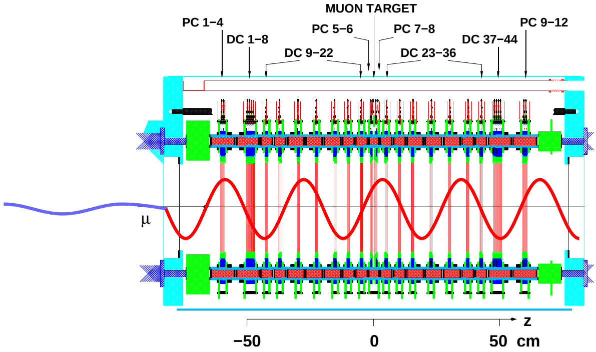
EXTRA SLIDES

Upstream stops data

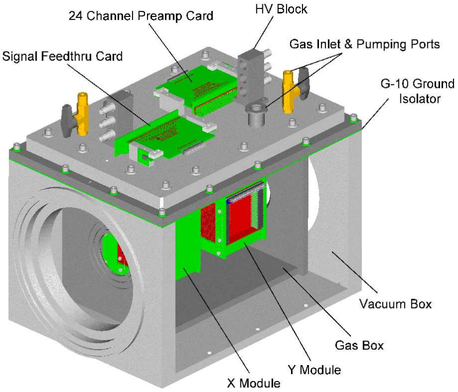
A special set of data was taken with the muons stopping at the far upstream end of the detector.

This data gives us information on the physics and the response of the detector:

- Test of the detector asymmetry
- Measure of the positron interaction with the target



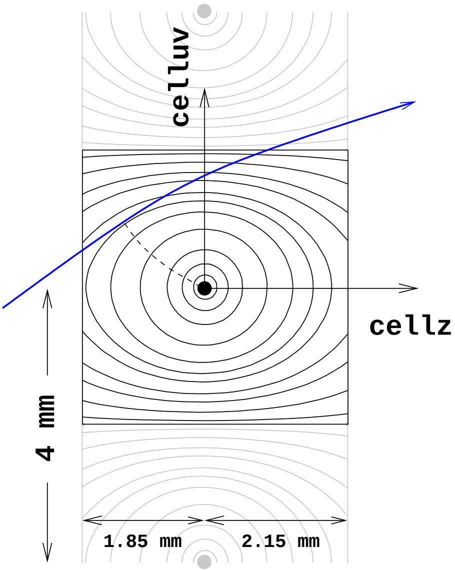
The Time Expansion Chamber (TEC)



The TEC:

- is low mass
- operates in the beamline vacuum
- is removed during data taking

Chamber response, Space Time Relations (STRs)

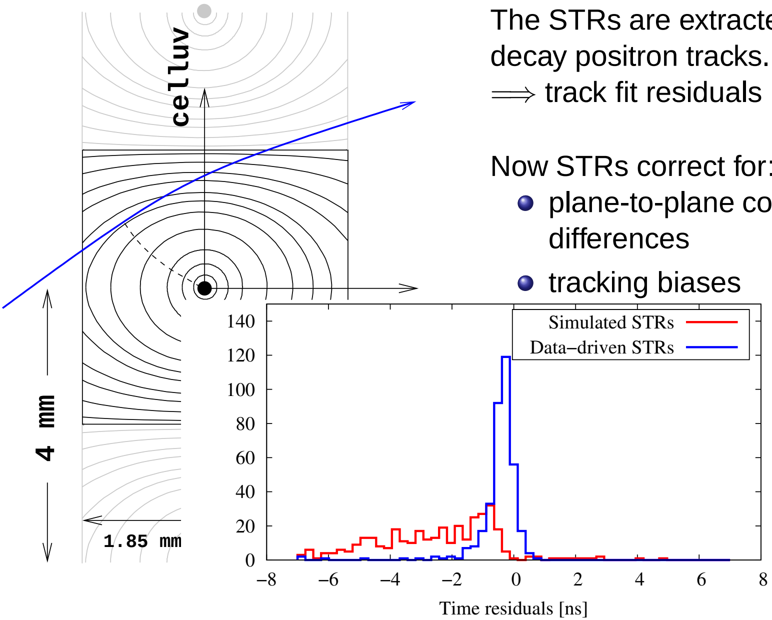


The STRs are extracted from the decay positron tracks.
⟹ track fit residuals minimized

Now STRs correct for:

- plane-to-plane constructions differences
- tracking biases

Chamber response, Space Time Relations (STRs)



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$\Longrightarrow$ track fit residuals minimized

Now STRs correct for:

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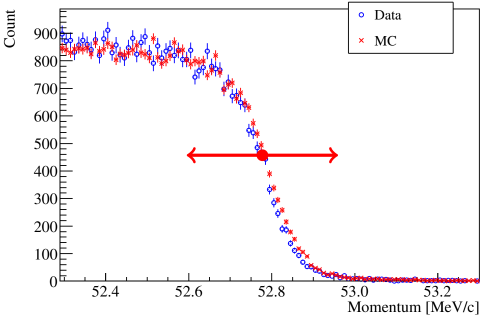
- tracking biases

Momentum calibration

The kinematic end-point of the decay is used to correct the mismatch in detector response between data and MC. ($p_{max} \approx 52.83$ MeV/c).



- MC edge shifted versus data edge
- χ^2 calculated and minimized
- Typical mismatch $\approx$ 10 keV/c

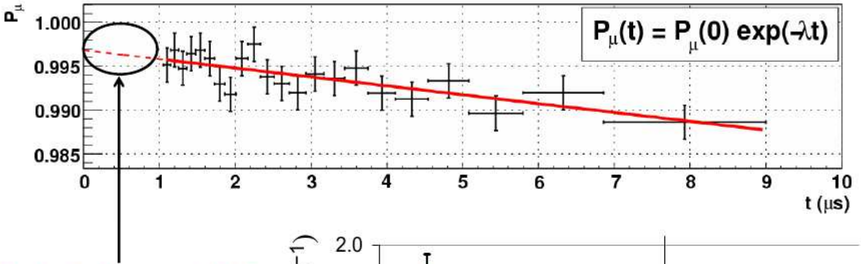
The model to propagate the mismatch to the rest of spectrum is unkown.

Systematic uncertainty evaluated using the extreme cases:

- mismatch 100% constant or 100% momentum dependent.

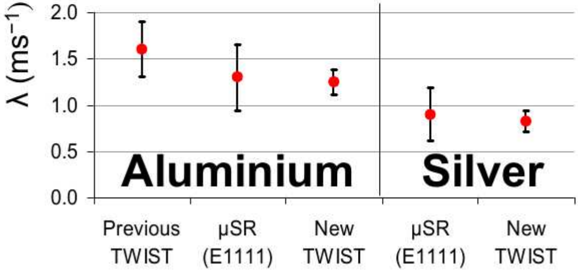
Target depolarization

Targets are high purity (>99.999% purity) Al and Ag.

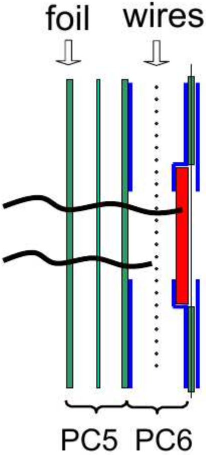


Subsidiary μ⁺SR experiment:

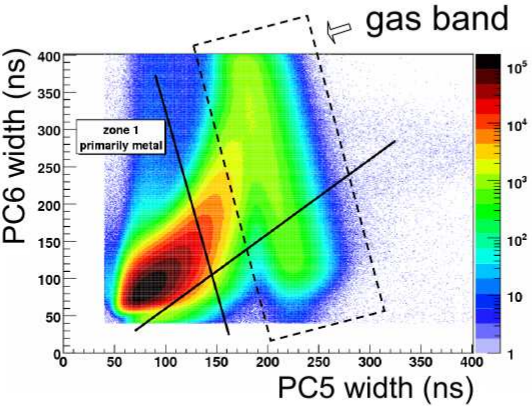
no "fast depolarisation" down to 5 ns



Selecting muons in stopping in the target

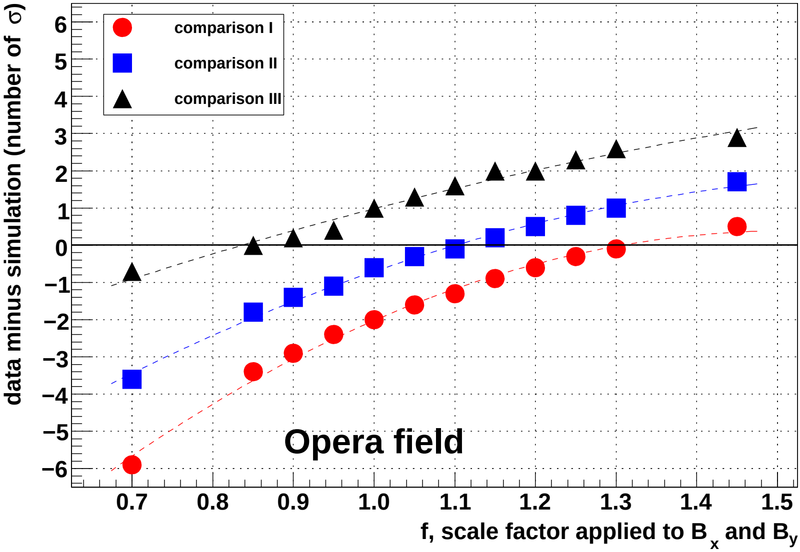


(PC = proportional chamber)



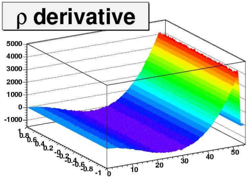
Cut placed so that < 0.5% of the gas distribution contaminates “zone 1”.

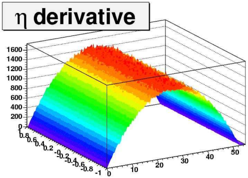
Fringe field depolarization uncertainty

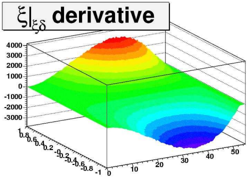


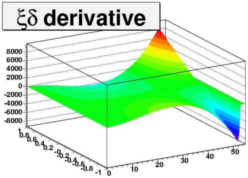
Muon decay parameters derivatives

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

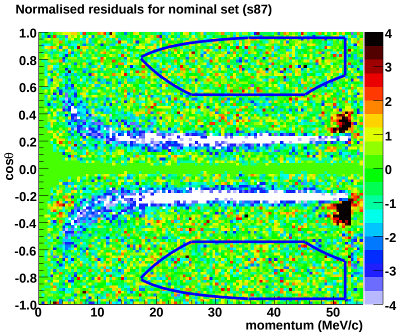


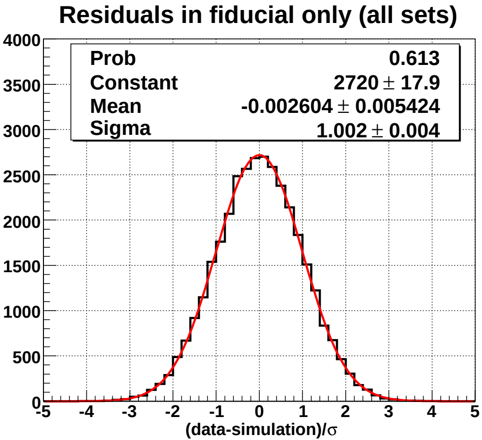






Fit residuals





Excellent fit quality over kinematic fiducial

Global analysis

The following parametrization is used:

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

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

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

$$B_{LR} = \frac{1}{16}|g^S_{LR} + g^T_{LR}|^2 + |g^V_{LR}|^2$$

$$B_{RL} = \frac{1}{16}|g^S_{RL} + g^T_{RL}|^2 + |g^V_{RL}|^2$$

$$I_\alpha = \frac{1}{4}[g^V_{LR}(g^S_{RL} + 6g^T_{RL})^* + (g^V_{RL})^*(g^S_{LR} + 6g^T_{LR})]$$

$$I_\beta = \frac{1}{2}[g^V_{LL}(g^S_{RR})^* + (g^V_{RR})^* g^S_{LL}]$$

Global analysis

In this parametrization:

- The $Q_{\epsilon\mu}$ are total probabilities of a μ-handed muon decays into a ϵ-handed electron. Example:

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

  The corresponding normalization condition is used to eliminate Q_{LL} from the analysis:

$$Q_{RR} + Q_{LR} + Q_{RL} + Q_{LL} = 1$$

- There are useful constraints:

$$\begin{aligned} 0 \leq Q_{\epsilon\mu} \leq 1, & \qquad \text{where } \epsilon, \mu = R, L \\ 0 \leq B_{\epsilon\mu} \leq Q_{\epsilon\mu}, & \qquad \text{where } \epsilon\mu = RL, LR \\ |I_\alpha|^2 \leq B_{LR}B_{RL}, & \qquad |I_\beta|^2 \leq Q_{LL}Q_{RR} \end{aligned}$$