Significance of the TRIUMF Weak Interaction Symmetry Test

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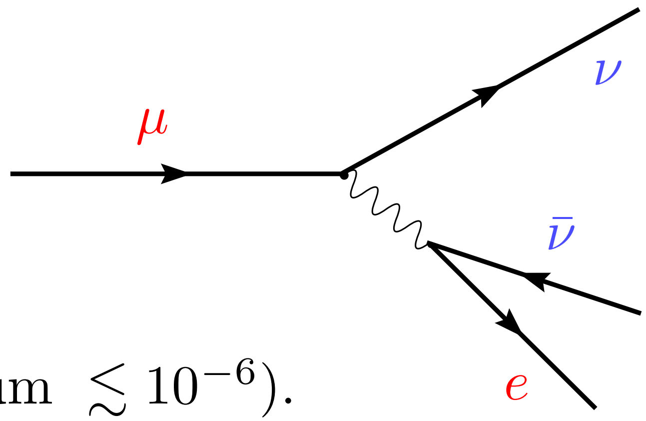
Outline

- Introduction to muon decay
- $\mathcal{TWIST}$ experiment
  - Overview
  - Blind analysis
  - Existing $\mathcal{TWIST}$ measurements and future prospects
- Current constraints on non-SM interactions from μ decay
  - Model-independent limits on right-handed interactions
  - $g^{\gamma}_{\epsilon\mu}$ from a global analysis
  - R-parity violating SUSY
  - Left-right symmetric models
- Summary

Why muon decay

Test of the space-time structure
of the weak interaction:



- Theoretically very "clean"
  (hadronic contribution to the spectrum $\lesssim 10^{-6}$).
- High experimental statistics is affordable.

$\Longrightarrow$ Model independent search for new physics.

- Constraints on models of new physics that are complementary to collider and nuclear beta decay measurements.

Some New Physics models affecting muon decay

Tree level effects in:

- Left-Right symmetric models
- R-parity violating SUSY
- Composite leptons
- Some extra dimensions models
- Nonlocal tensor interactions
- ...

Model-independent parametrization of muon decay

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

$$\Gamma^S = 1, \qquad \Gamma^V = \gamma^\alpha, \qquad \Gamma^T = \frac{i}{\sqrt{2}} \sigma^{\alpha\beta}.$$

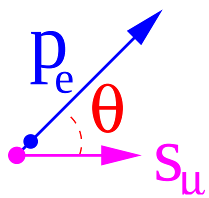
- Scalar, vector and tensor interactions.
- Left and right-handed particles.
- 10 complex coupling constants $\Longrightarrow$ 19 independent real parameters.
- The Standard Model: $g^V_{LL} = 1$, the rest are zero.

Muon decay spectrum

$$\frac{d^2\Gamma}{x^2\,dx\,d\cos(\theta)} \propto 1 - x + \frac{2}{9}\rho\,(4x-3)$$

$$+\frac{1}{3}P_\mu\xi\,\cos(\theta)\,\left[(1-x)+\frac{2}{3}\delta\,(4x-3)\right]$$

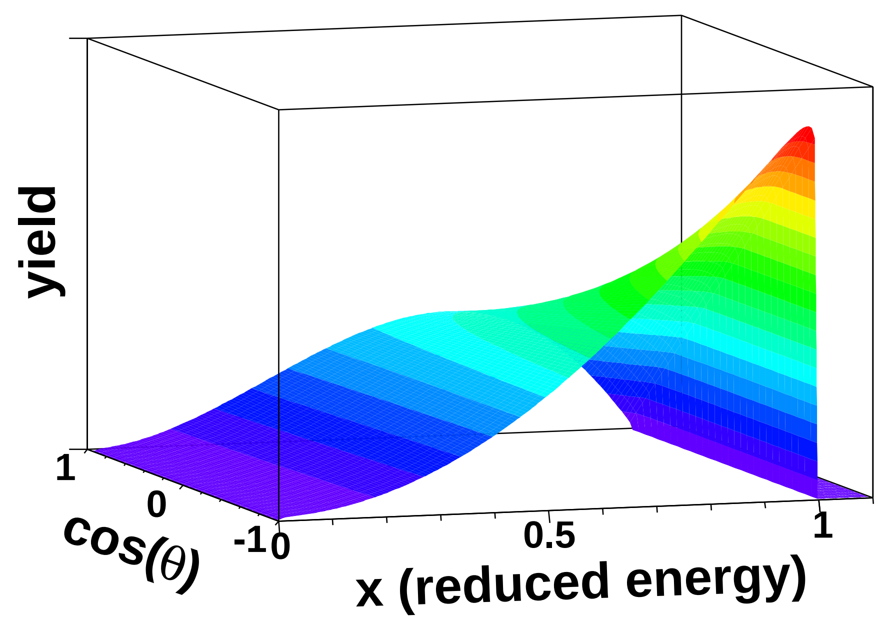
$$+\,\eta\,\mathcal{O}(m_e/m_\mu) + \text{Rad. Corrections}$$



$x = E_e/E_{\max}$

$\mathcal{TWIST}$ directly measures ρ, $P_\mu\xi$, δ.

Improves constraints on η via a global fit of muon decay measurements [C.A. Gagliardi *et al.*, PRD **72** (2005) 073002]



Michel parameters and the couplings

$$\rho = \frac{3}{4} - \frac{3}{4}\left[\left|g^V_{RL}\right|^2 + \left|g^V_{LR}\right|^2 + 2\left|g^T_{RL}\right|^2 + 2\left|g^T_{LR}\right|^2 + \mathrm{Re}\left(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR}\right)\right]$$

$$\eta = 0 + \frac{1}{2}\mathrm{Re}\left[g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})\right]$$

$$\xi = 1 - \frac{1}{2}\left|g^S_{LR}\right|^2 - \frac{1}{2}\left|g^S_{RR}\right|^2 - 4\left|g^V_{RL}\right|^2 + 2\left|g^V_{LR}\right|^2 - 2\left|g^V_{RR}\right|^2 + 2\left|g^T_{LR}\right|^2 - 8\left|g^T_{RL}\right|^2 + 4\,\mathrm{Re}(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

$$\xi\delta = \frac{3}{4} - \frac{3}{8}\left|g^S_{RR}\right|^2 - \frac{3}{8}\left|g^S_{LR}\right|^2 - \frac{3}{2}\left|g^V_{RR}\right|^2 - \frac{3}{4}\left|g^V_{RL}\right|^2 - \frac{3}{4}\left|g^V_{LR}\right|^2 - \frac{3}{2}\left|g^T_{RL}\right|^2 - 3\left|g^T_{LR}\right|^2 + \frac{3}{4}\mathrm{Re}(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

Physics with Michel parameters

- Standard Model: $\rho = \frac{3}{4}$, $\delta = \frac{3}{4}$, $\xi = 1$.

$\Longrightarrow$ Any deviation would mean New Physics.

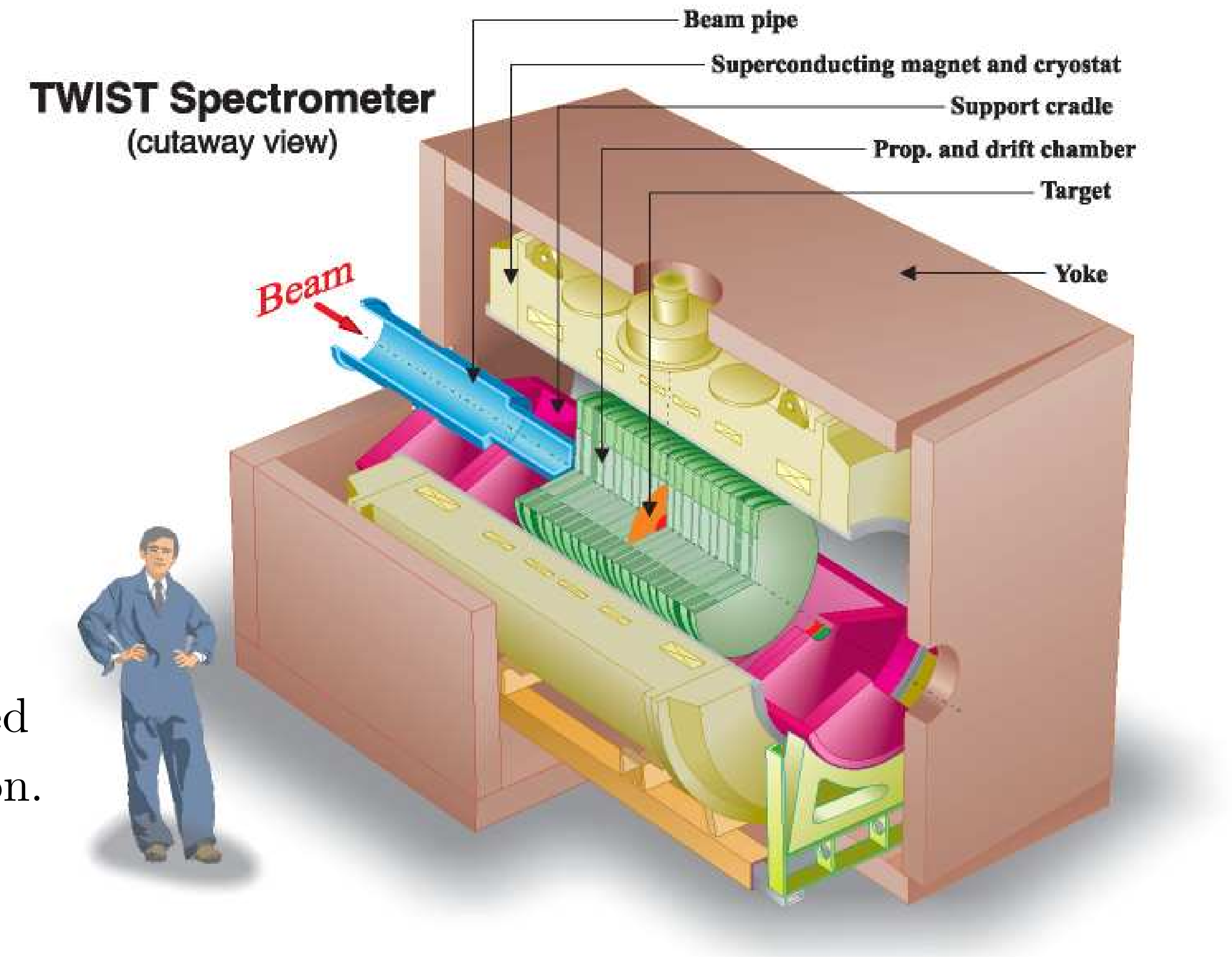
- Model independent search for right-handed interactions:

$$\begin{aligned} Q_R^\mu &= \frac{1}{2}\left\{1 + \frac{1}{3}\,\xi - \frac{16}{9}\,\xi\delta\right\} \\ &= \frac{1}{4}|g_{RR}^S|^2 + \frac{1}{4}|g_{LR}^S|^2 + |g_{RR}^V|^2 + |g_{LR}^V|^2 + 3|g_{LR}^T|^2 \\ &= 0\,? \end{aligned}$$

- Left-Right symmetric models: affect ρ and ξ.
- R-parity violating SUSY: changes η.

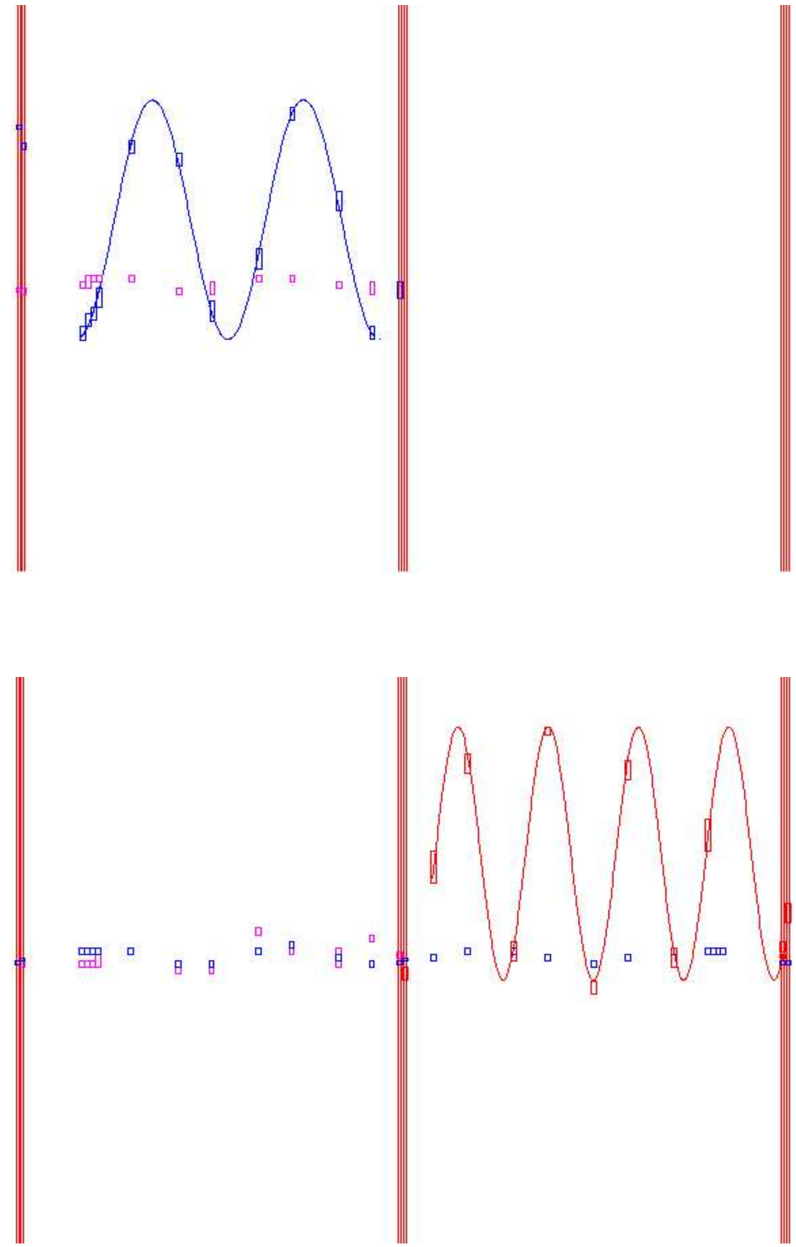
The TRIUMF Weak Interaction Symmetry Test

- Uses highly polarized μ^+ beam.
- Stops μ^+ in a very symmetric detector.
- Tracks e^+ through uniform, well-known field.
- Extracts decay parameters by comparison to detailed and verified simulation.

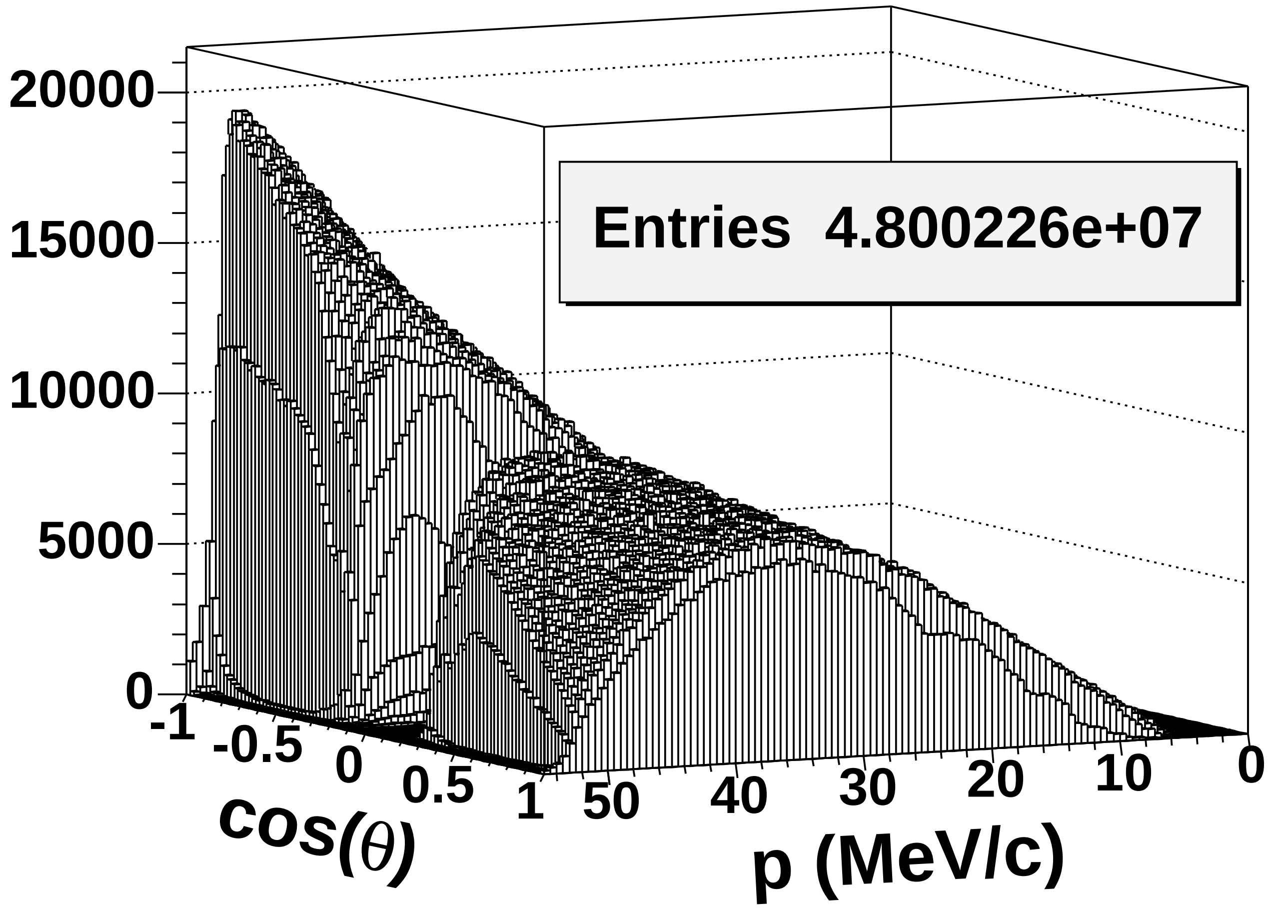


TWIST data events

- Triggers on muons entering detector—unbiased.
- Read out all activity in the detector from 6μs before to 10μs after the trigger. ($\tau_\mu = 2.2\mu$s.)
- Use pattern recognition (in time and position) to sort hits in tracks, then fit to helix.
- Must recognize beam positrons, delta tracks, backscattered tracks.



A data spectrum



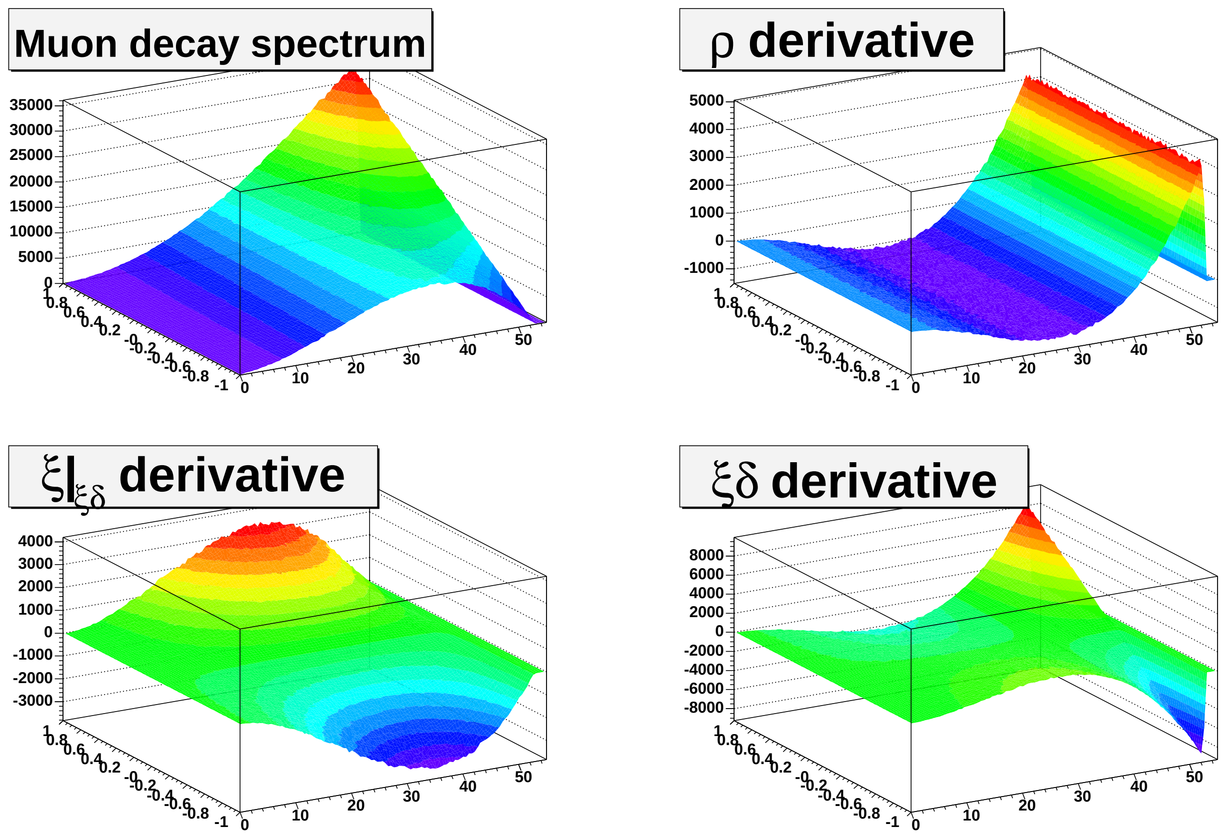
From kinematics $p_{\mathrm{max}} \approx 52.8$ MeV/c.

Use the sharp edge for energy loss calibration.

Fitting the data

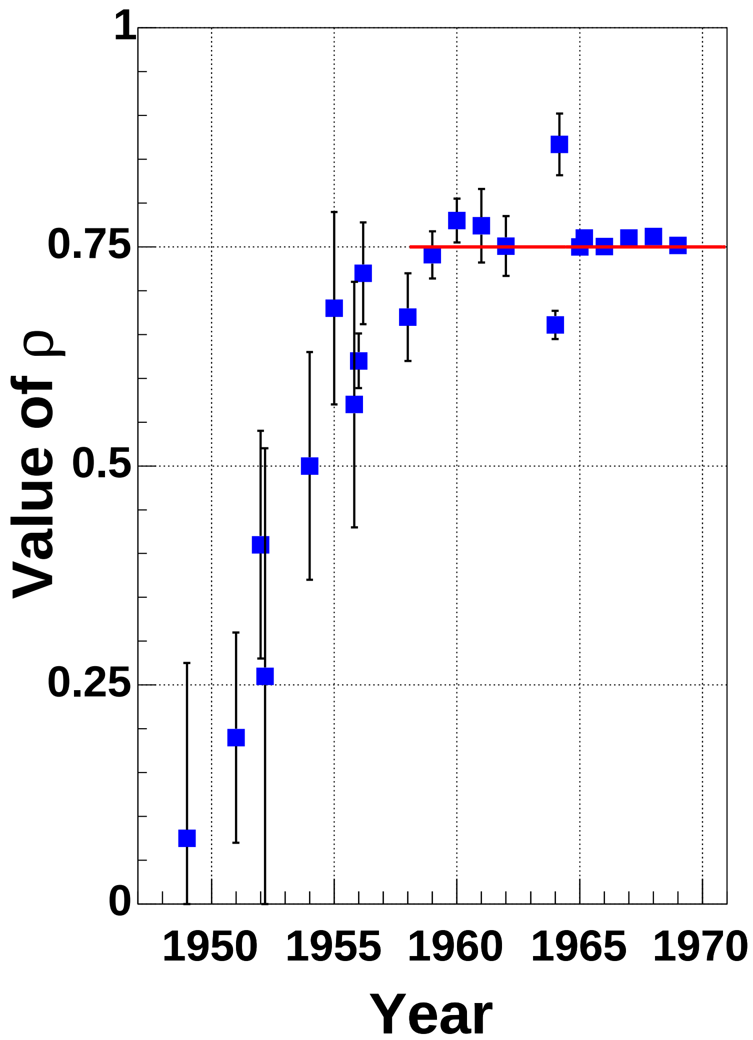
$$n_i(\lambda_{\text{Data}}) = n_i(\lambda_{\text{MC}}) + \frac{\partial n_i}{\partial \lambda}(\lambda_{\text{Data}} - \lambda_{\text{MC}})$$

- Fit data to a sum of a base MC distribution plus MC-generated derivative distributions.
- $\lambda = \{\rho, \eta, \xi, \xi\delta\}$ $\Longrightarrow$ linear expansion is exact.
- Data and MC reconstructed in the same way $\Longrightarrow$ many systematics cancel.



Blind analysis

- Motivation: to eliminate human systematics.
- Method: Keep the final result hidden until the measurement is done.
- The value of a measurement does not contain any information about its correctness!



$\mathcal{TWIST}$ implementation:

- $n_i(\lambda_{\text{Data}}) = n_i(\lambda_{\text{MC}}) + \frac{\partial n_i}{\partial \lambda}\,\Delta\lambda$
- Uses public key cryptography.

For examples see: P.F. Harrison, Advanced Statistical Techniques in Particle Physics, Durham, 18 - 22 March 2002. http://www.ippp.dur.ac.uk/Workshops/02/statistics/proceedings.shtml

Current *TWIST* results

- $\rho = 0.75080 \pm 0.00044(\text{stat}) \pm 0.00093(\text{sys}) \pm 0.00023(\eta)$
  - ▷ J.R. Musser *et al.*, PRL **94** 101805 (2005)
  - ▷ 2.5 times better precision than previous PDG value
- $\delta = 0.74964 \pm 0.00066(\text{stat}) \pm 0.00112(\text{sys})$
  - ▷ A. Gaponenko *et al.*, PRD **71** (2005) 071101
  - ▷ 2.9 times better precision than previous PDG value
- $P_\mu \xi = 1.0003 \pm 0.0006(\text{stat}) \pm 0.0038(\text{sys})$
  - ▷ B. Jamieson *et al.*, PRD **74** (2006) 072007
  - ▷ 2.2 times better precision than previous PDG value

Current $\mathcal{TWIST}$ results (continued)

- $0.9960 < P_\mu\xi \leq \xi < 1.0040$ (90% CL)
  - ▷ Indirect result from $\mathcal{TWIST}$ ρ, δ, and constraints on $P_\mu\xi\delta/\rho$ by
    - A. Jodidio *et al.*, PRD **34** (1986) 1967; **37** (1988) 237
    - D.P. Stoker *et al.*, PRL **54** (1985) 1887
  - ▷ More constraining than the best direct $P_\mu\xi$ measurement to date.

Systematics for ρ and δ

Effect	$\sigma_\rho \times 10^3$	$\sigma_\delta \times 10^3$
Chamber response(ave)	0.51	0.56
Stopping target thickness	0.49	0.37
Positron interactions	0.46	0.55
Spectrometer alignment	0.22	0.61
Momentum calibration(ave)	0.20	0.29
Theoretical radiative corrections	0.20	0.10
Muon beam stability(ave)	0.04	0.10
Upstream/Downstream efficiencies		0.04
Track selection algorithm	0.11	
Total in quadrature	0.93	1.12

Systematics for $P_\mu \xi$

Effect	$P_\mu \xi$ uncertainty $\times 10^3$
Depolarization in fringe field (ave)	3.4
Depolarization in muon stopping materials (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(ave)	0.2
Upstream-downstream efficiency	0.2
Background muon contamination (ave)	0.2
Beam intensity (ave)	0.2
Michel parameter η	0.1
Theoretical radiative corrections	0.1
Total in quadrature	3.8

Future precision goals ($\times 10^3$)

Parameter	stat	sys	total
ρ	0.10	0.24	0.26
δ	0.22	0.32	0.39
$P_\mu \xi$	0.30	0.30	0.43

Right-handed interactions in $\mathcal{TWIST}$: a model-independent test

Total muon right-handed coupling: decays of right-handed muon into right-handed and left-handed electrons.

$$
\begin{aligned}
Q_R^\mu &= Q_{RR}^\mu + Q_{LR}^\mu \\
&= \frac{1}{4}\left|g_{RR}^S\right|^2 + \frac{1}{4}\left|g_{LR}^S\right|^2 + \left|g_{RR}^V\right|^2 + \left|g_{LR}^V\right|^2 + 3\left|g_{LR}^T\right|^2 \\
&= \frac{1}{2}\left\{1 + \frac{1}{3}\,\xi - \frac{16}{9}\,\xi\delta\right\} \\
&\geq 0.
\end{aligned}
$$

Using $\mathcal{TWIST}$ δ and ρ, and existing constraints on $P_\mu \xi\delta/\rho$:

$$Q_R^\mu < 0.00184 \text{ (90\% CL)}.$$

Limits on the coupling constants

Model independent global analysis of μ decay: new(old)
[Gagliardi *et al.*, PRD **72** (2005)]

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

- Also gives new model-independent result $\eta = -0.0036 \pm 0.0069$.
- "New" uses $\mathcal{TWIST}$ and Dannenberg *et al.*, PRL **94** (2005), in addition to measurements used by "old".
- All inputs are important to constrain η.
- Note: naturalness considerations for neutrino mass imply LR,RL couplings are $< 10^{-7} \ldots 10^{-4}$. [R.J. Erwin *et al.*, hep-ph/0602240]

R-parity violating SUSY

Tree-level contribution to muon decay from $\tilde{\tau}_L$ exchange
[K. Cheung, R.-J. Zhang, Phys.Lett. **B427** (1998) 73]

$$g^S_{RR} = -\frac{\sqrt{2}}{4G_F}\,\frac{\lambda_{131}\lambda^*_{232}}{m^2_{\tilde{\tau}_L}}$$

$$\Longrightarrow \qquad |\lambda_{131}\lambda_{232}| < 0.022\left(\frac{m_{\tilde{\tau}_L}}{100\ GeV}\right)^2 \quad 90\%\ \mathrm{CL}$$

Another constraint is from

$$R_\tau = \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$$
$$= R^{\mathrm{SM}}_\tau\left[1 + \frac{1}{2\sqrt{2}G_F}\sum_{k=1}^{3}\left(\frac{|\lambda_{13k}|^2}{m^2_{\tilde{l}_{kR}}} - \frac{|\lambda_{23k}|^2}{m^2_{\tilde{l}_{kR}}}\right)\right]$$

Can get $|\lambda_{i3k}| < 0.076\frac{m_{\tilde{l}_{kR}}}{100\ \mathrm{GeV}}$ 90% CL for $i = 1, 2,\ k = 1, 2, 3$
assuming that only one λ at a time $\neq 0$.

The muon decay constraint does not go away when
$|\lambda_{131}|/m_{\tilde{e}_R} \approx |\lambda_{232}|/m_{\tilde{\mu}_R}$.

Left-Right symmetric models: $SU(2)_L \times SU(2)_R \times U(1)$

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

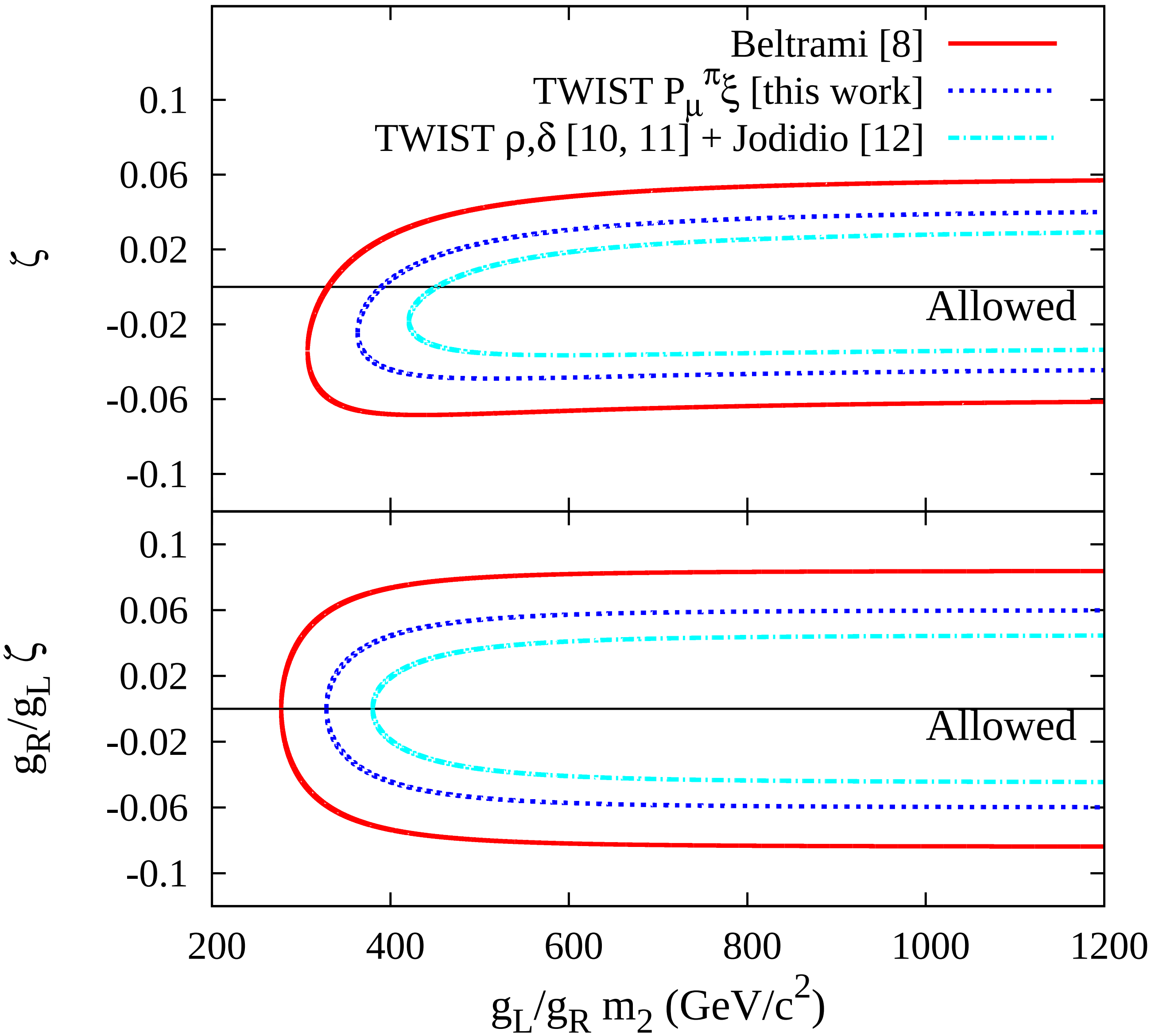
$$\rho = \frac{3}{4}\left(1 - 2{\zeta_g}^2\right)$$
$$\xi = 1 - 2\left(t^2 + {\zeta_g}^2\right)$$
$$P_\mu = 1 - 2{\zeta_g}^2 - 2t^2\,\frac{|V^R_{ud}|^2}{|V^L_{ud}|^2} - 4\zeta_g t\,\frac{|V^R_{ud}|}{|V^L_{ud}|}\cos(\alpha + \omega)$$

where $t = \dfrac{g_R^2\, M_1^2}{g_L^2\, M_2^2}$, $\quad \zeta_g = \dfrac{g_R}{g_L}\,\zeta.$ $\quad$ and $\quad \alpha = \arg V^R_{ud}.$

Limits on LRS parameters

Observable	M_2, GeV/c^2	$\|\zeta\|$	Pros	Cons
$m(K_L - K_S)$	> 1600		reach	(P)MRLS
Direct W_R searches	$> 720 \ldots 650$(D0) > 786(CDF)		clear signal	(P)MRLS decay model
CKM unitarity		$< 10^{-3}$	sensitivity	(P)MLRS, heavy ν_R
β decay	> 310	< 0.040	both parameters	(P)MLRS, light ν_R
μ decay *TWIST*	> 406 (> 420)	< 0.033 (< 0.030)	model independence	light ν_R

Muon decay LRS limits



Summary

- *TWIST* is a model independent search for new physics.
  - ▷ May set a scale for new physics, and provide hints what models are possible.
- Has improved limits on ρ, δ, $P_\mu\xi$ by factors of 2–3.
- Potential for further improvements.
- Implications
  - ▷ model-independent limits on muon right-handed couplings,
  - ▷ constraints on specific models complementary to other data.
- The first blind analysis measurement of muon decay.
- The first experiment to measure the muon decay spectrum over a broad range of positron energies and angles and extract 3 decay parameters from the same data.