A High Precision Measurement of Muon Decay Parameters

The Precision Frontier in Particle Physics

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TWIST Collaboration

TRIUMF/University of Alberta

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Canadian Association of Physicists

TWIST will test the standard model predictions for the weak interaction by measuring the energy and angular distribution of e^+ from the decay of polarized μ^+.

The TWIST collaboration

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Muon decay rate

$$rate \sim \left| \sum_{\substack{\gamma = S,V,T \\ i,j = R,L}} g_{ij}^{\gamma} \left\langle \overline{\psi}_{e_i} \left| \Gamma^{\gamma} \right| \psi_{\nu_e} \right\rangle \left\langle \overline{\psi}_{\nu_\mu} \left| \Gamma_{\gamma} \right| \psi_{\mu_j} \right\rangle \right|^2$$

$$\Gamma^S = 1$$

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

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

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

- ***In the standard model only vector couplings of left-handed to left-handed fermions are allowed:***

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

Current limits on the coupling constants

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

Deviations from V-A structure are possible. Need more sensitive searches!

TWIST will improve the coupling constants precision by a factor of

3 - 10

The muon decay parameters & 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

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

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

$$\xi = 1$$

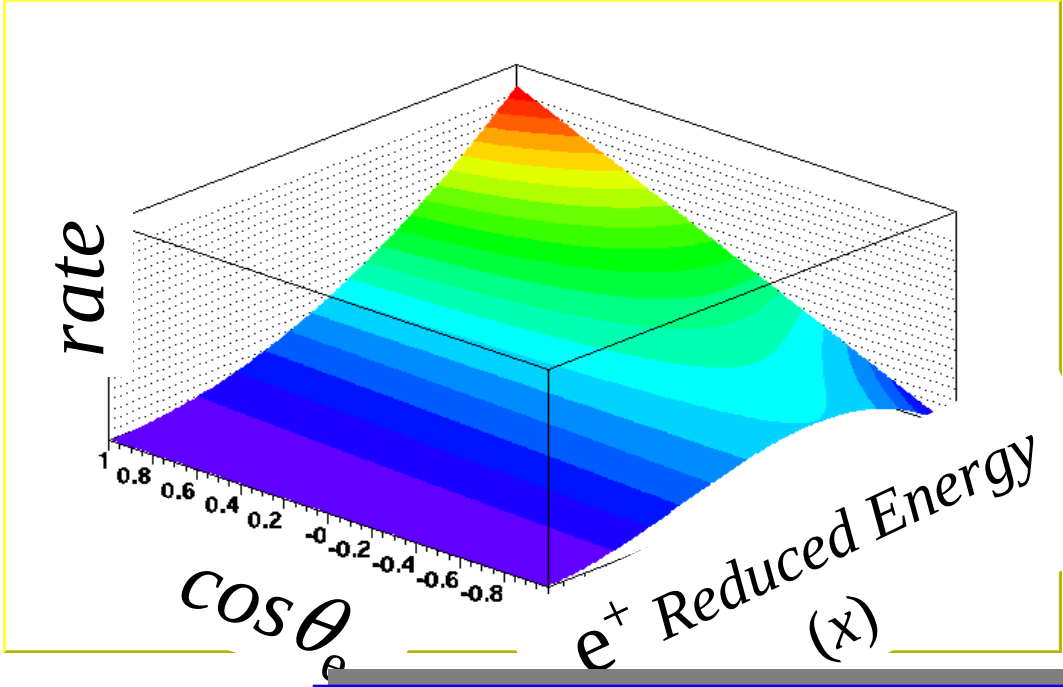
$$\eta = 0$$

The muon decay parameters & the spectrum shape

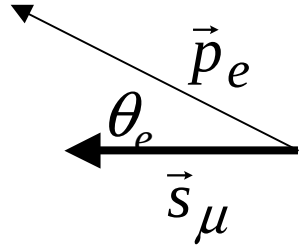
$$rate \sim x^2\left[3-3x+\frac{2}{3}\rho(4x-3)+3\eta x_o\left(\frac{1-x}{x}\right)+P_\mu\xi\cos\theta_e\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$

Spectral shape in x, $\cos\theta_e$ is characterized in terms of four parameters -- ρ, η, ξ, δ. P_μ is the muon polarization

$$x \equiv \frac{E_e}{E_e^{\max}}$$



(L. Michel, A. Sirlin)



$$x_o \equiv \frac{m_e}{E_e^{\max}}$$

$$E_e^{\max} \equiv \frac{m_\mu^2 + m_e^2}{2m_\mu}$$

TWIST will measure ρ, ξ, δ in two phases
10^{-3} in 2004 & fewx10^{-4} in 2005/6

Coupling to right-handed muons…

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

$$Q_{mR} = Q_{RR} + Q_{LR} = \frac{1}{4}\left|g^{S}_{RR}\right|^2 + \left|g^{V}_{RR}\right|^2 + \frac{1}{4}\left|g^{S}_{LR}\right|^2 + \left|g^{V}_{LR}\right|^2 + 3\left|g^{T}_{LR}\right|^2$$

$$\equiv 0 \quad \textit{by the standard model}$$

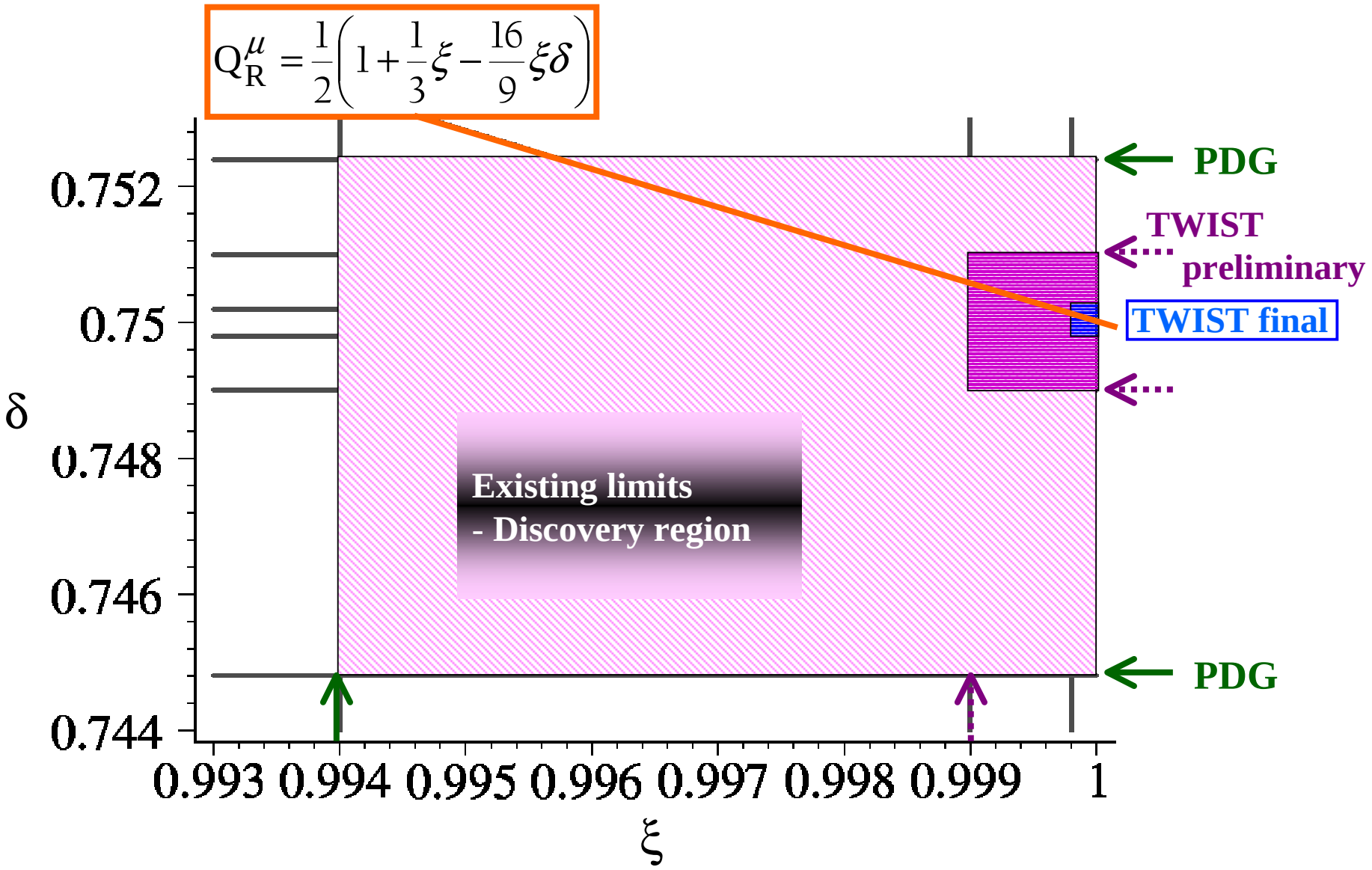
Q_{mR} describes decay of a *right-handed* μ into a *right-handed* or *left-handed* e^+

Q_{mR} can be written in terms of δ *and* ξ

$$Q_{mR} = \frac{1}{2}\left(1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right)$$

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

Anticipated TWIST sensitivity to right-handed currents



Beyond the standard model

- In the SM there are two (weak) charged-current vector bosons

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

- In some extensions to the SM one has left-handed as well as right-handed vector bosons

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

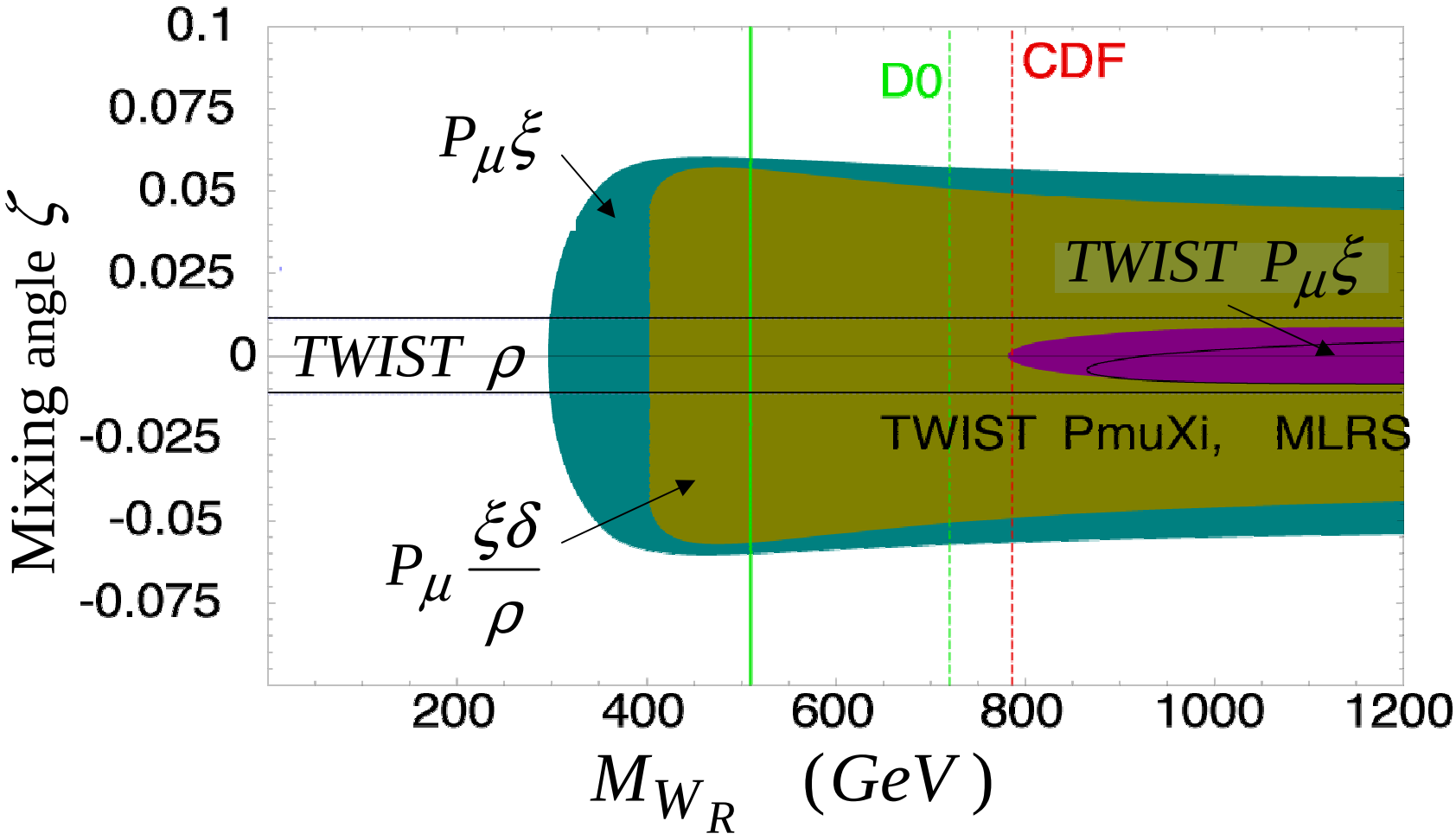
- W_L & W_R mix to form the mass eigenstates W_1 & W_2

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

  - Mixing angle ξ is small
  - $W_2 > W_1$ since left handed couplings are dominant at low energies.

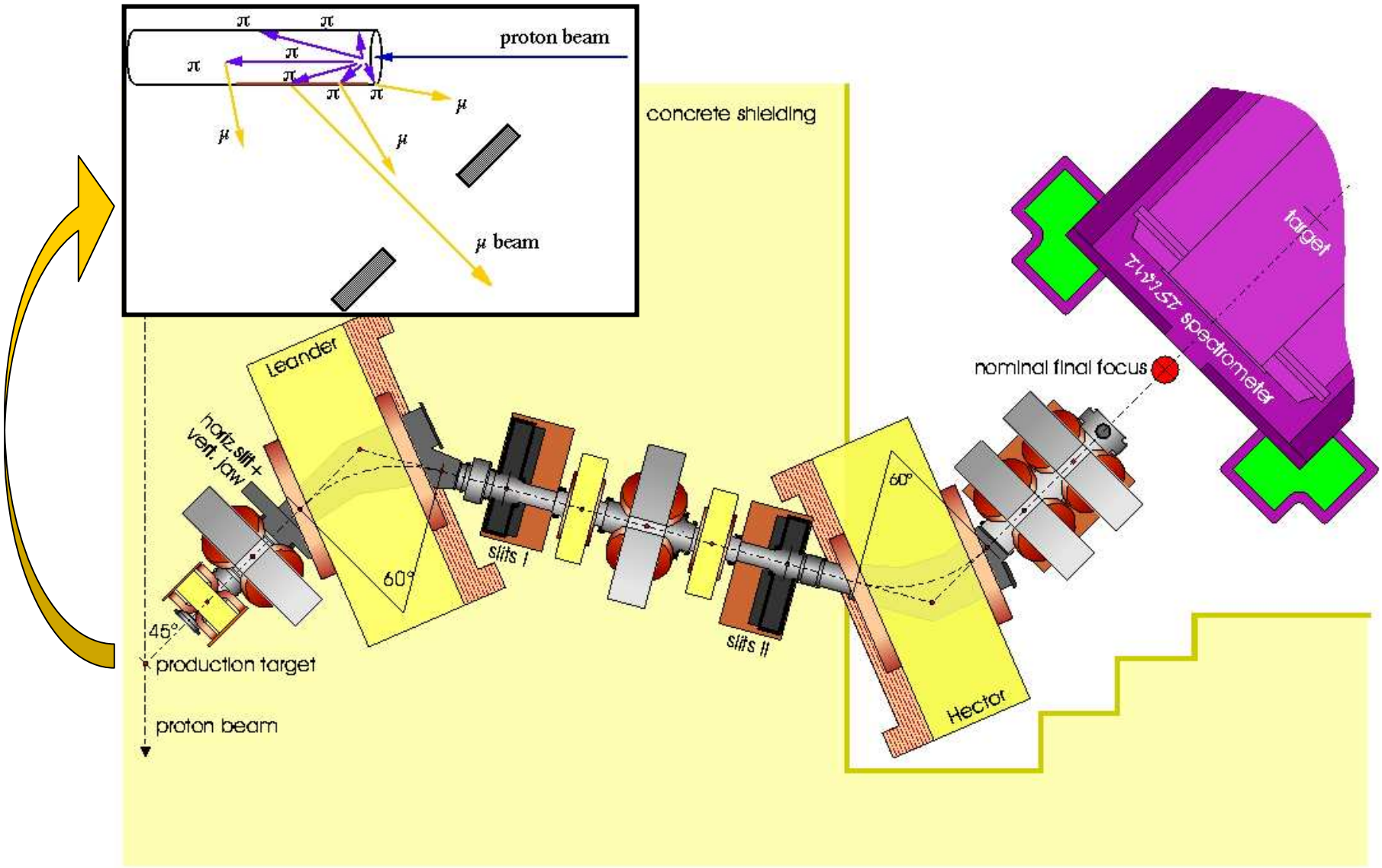
$$W_1 \approx W_L \quad \& \quad W_2 \approx W_R$$

Anticipated TWIST sensitivity to left-right mixing



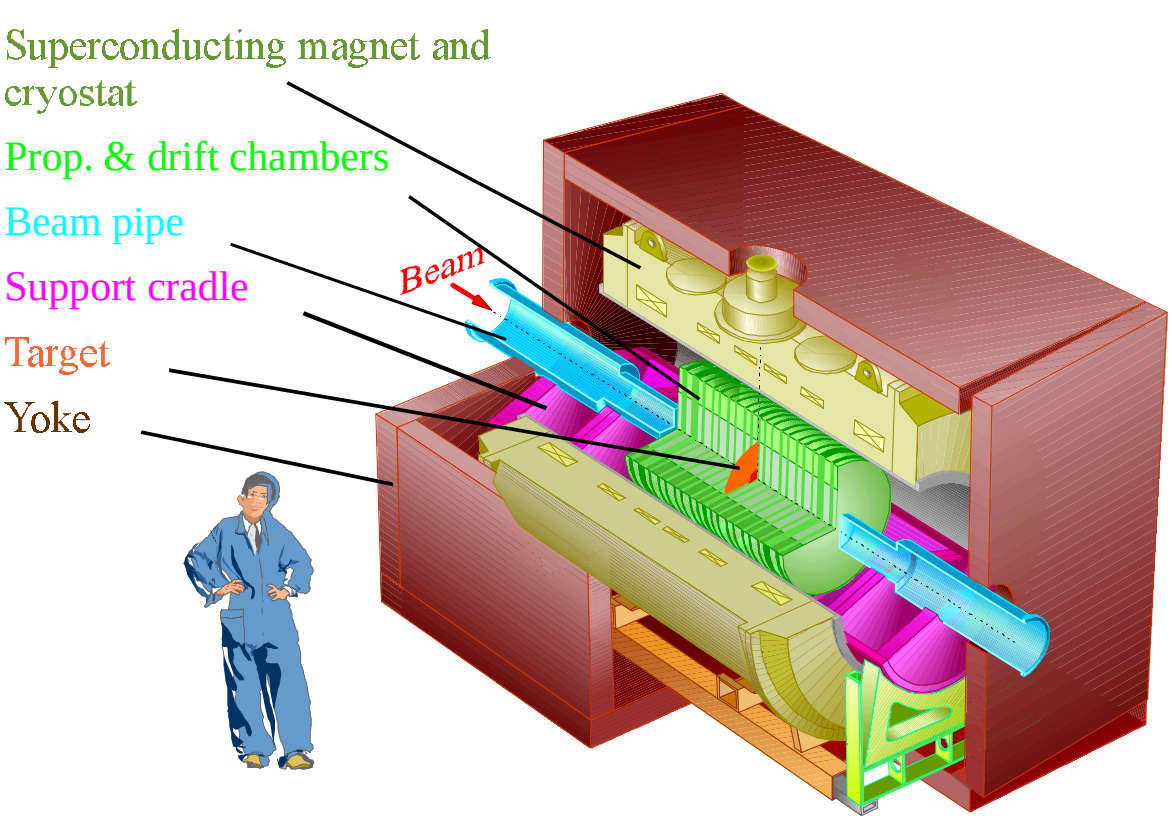
The beamline

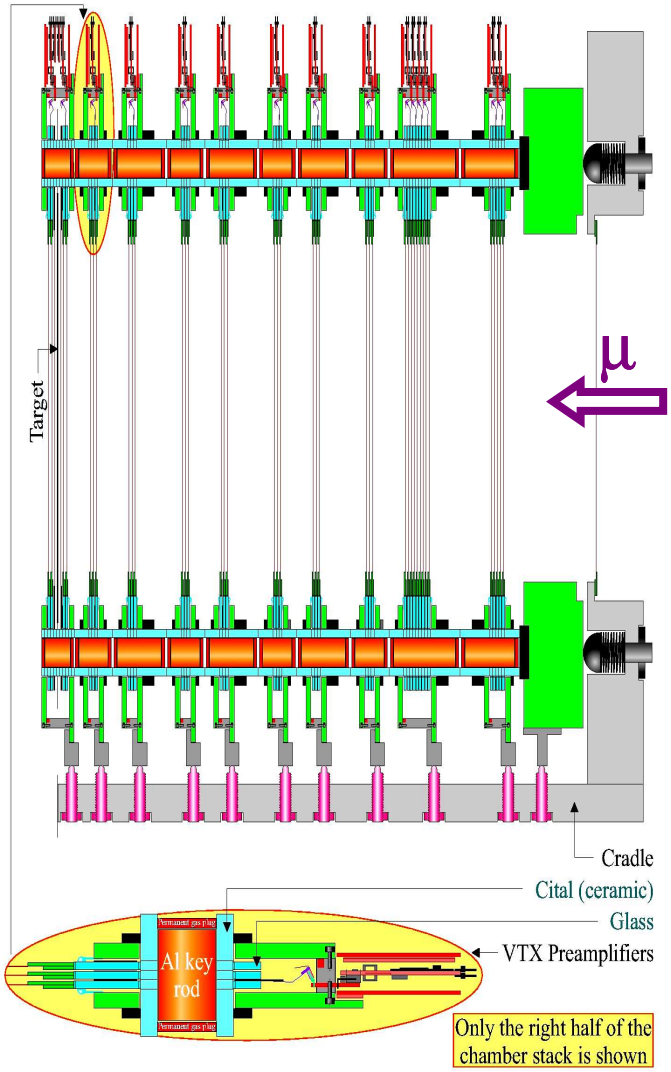
- ***The TRIUMF beamline delivers highly polarized "surface muons".***



The spectrometer

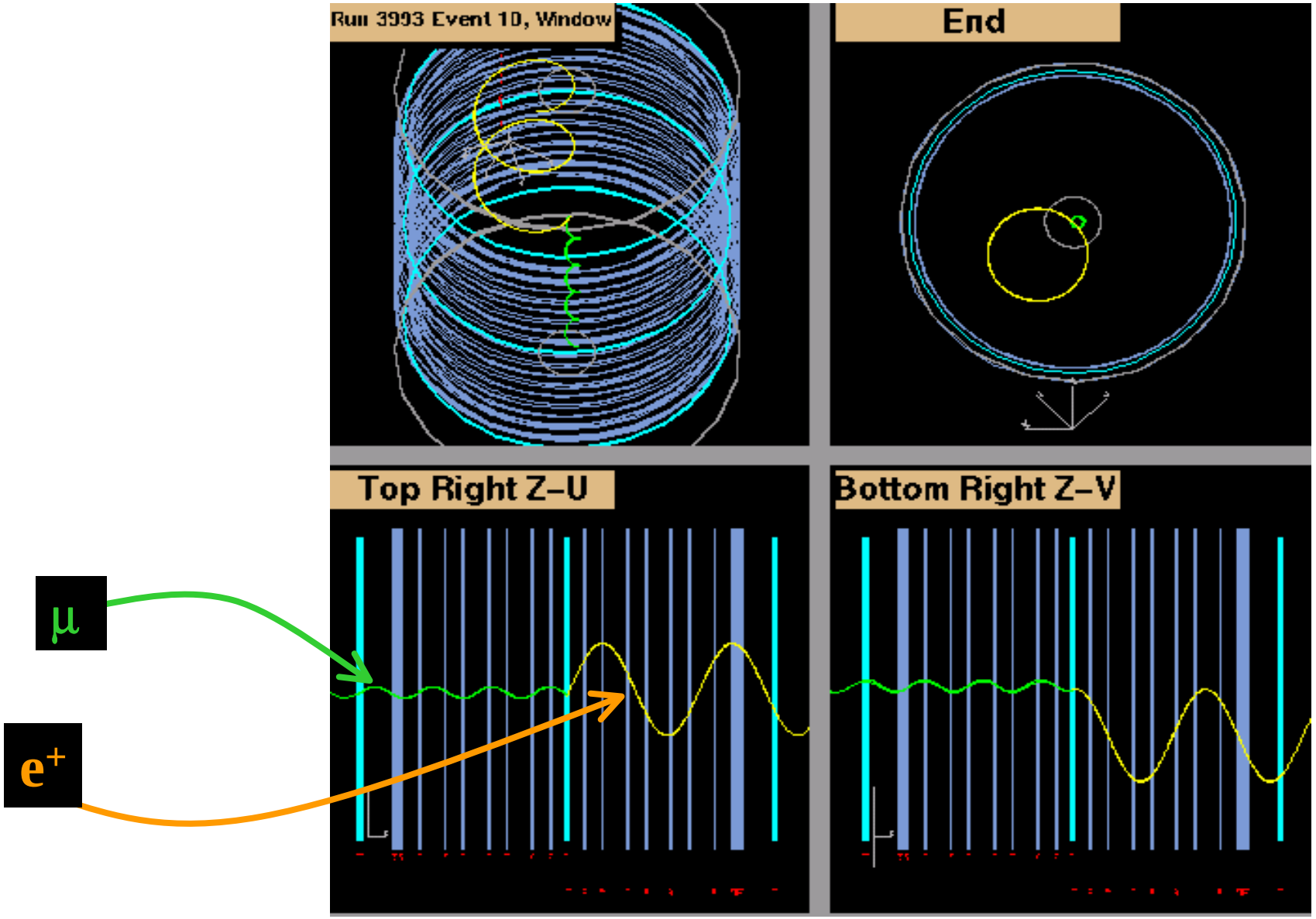
- ***The TWIST detector is a set of high precision, low mass chambers sitting in a superconducting magnet.***





The spectrometer

A typical decay event



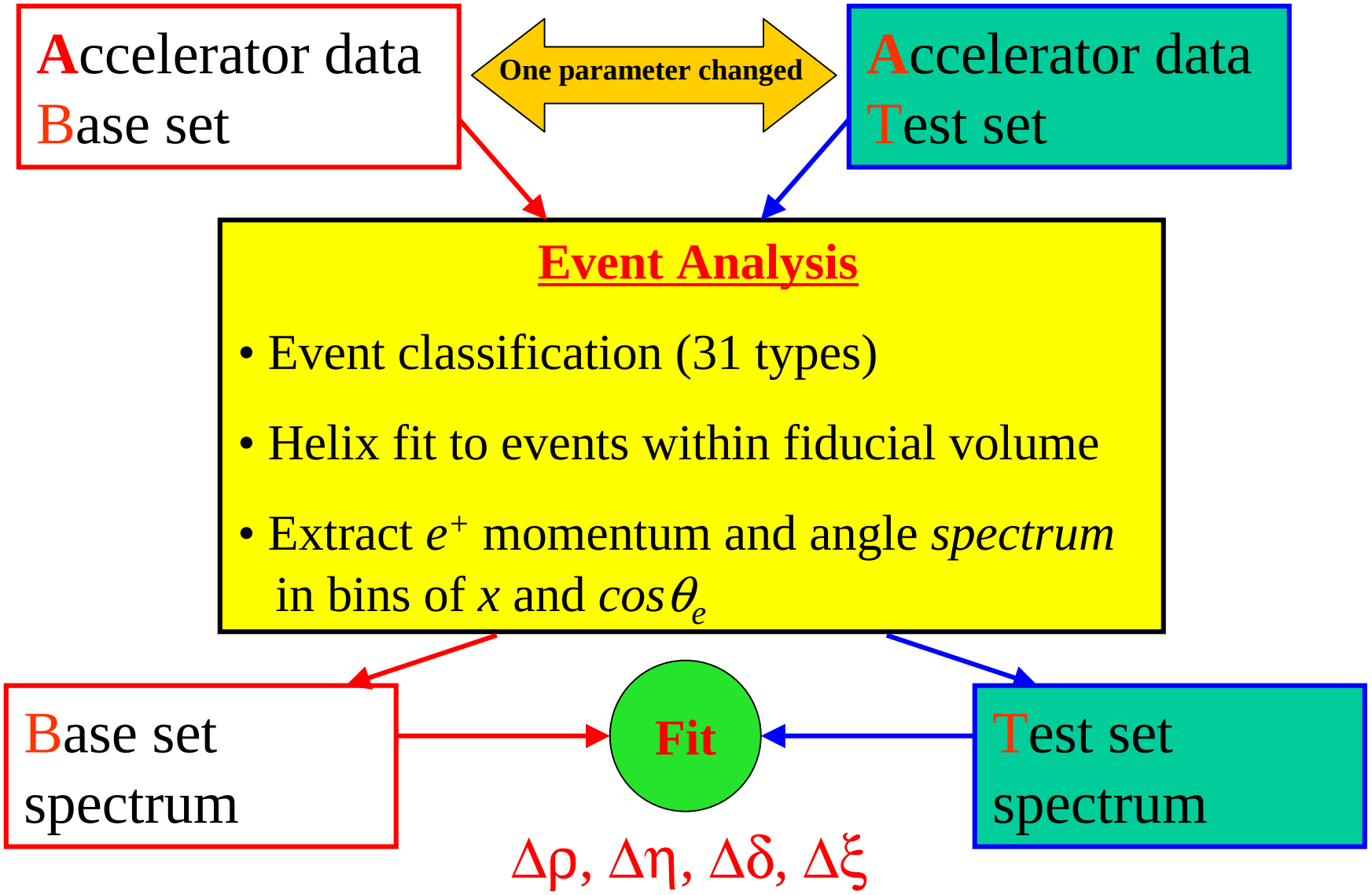
TWIST statistics and systematics

- *TWIST* can accumulate ~**10^9** muon decay events in *two weeks.*
- *TWIST* is *systematics* limited.
- In 2002-03, ~**6 x 10^9** muon decay events on tape.
- Need a lot of computer power (thanks to WestGrid –1008 CPUs)!
- Long list of systematic effects to investigate!

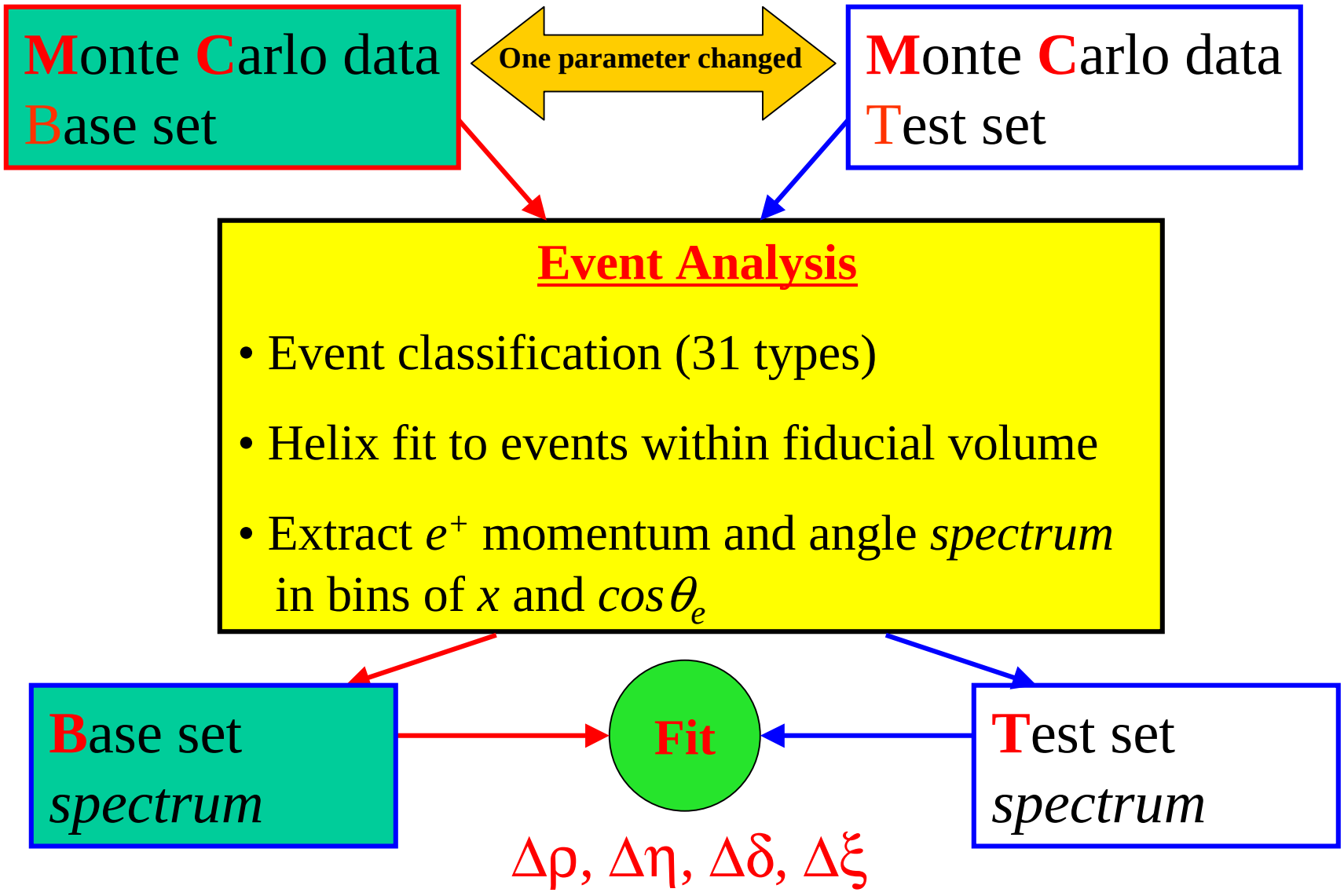
Systematic	Sample systematic studies (data & MC)
Chamber response	Change high voltage from standard.
Chamber alignment & geometry	Randomize plane positions in MC.
Beam tune	Change beam tune from standard (data & MC).
Solenoidal field effects	Change magnetic field from standard (data & MC).
GEANT physics and stepping	MANY GEANT validation studies!
Polarization	Use non-surface (cloud) muons.
Muon stopping distribution	Stop muons off centre (data & MC).
Code biases	MANY code validation studies!

Data sets acquired
Standard data sets
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

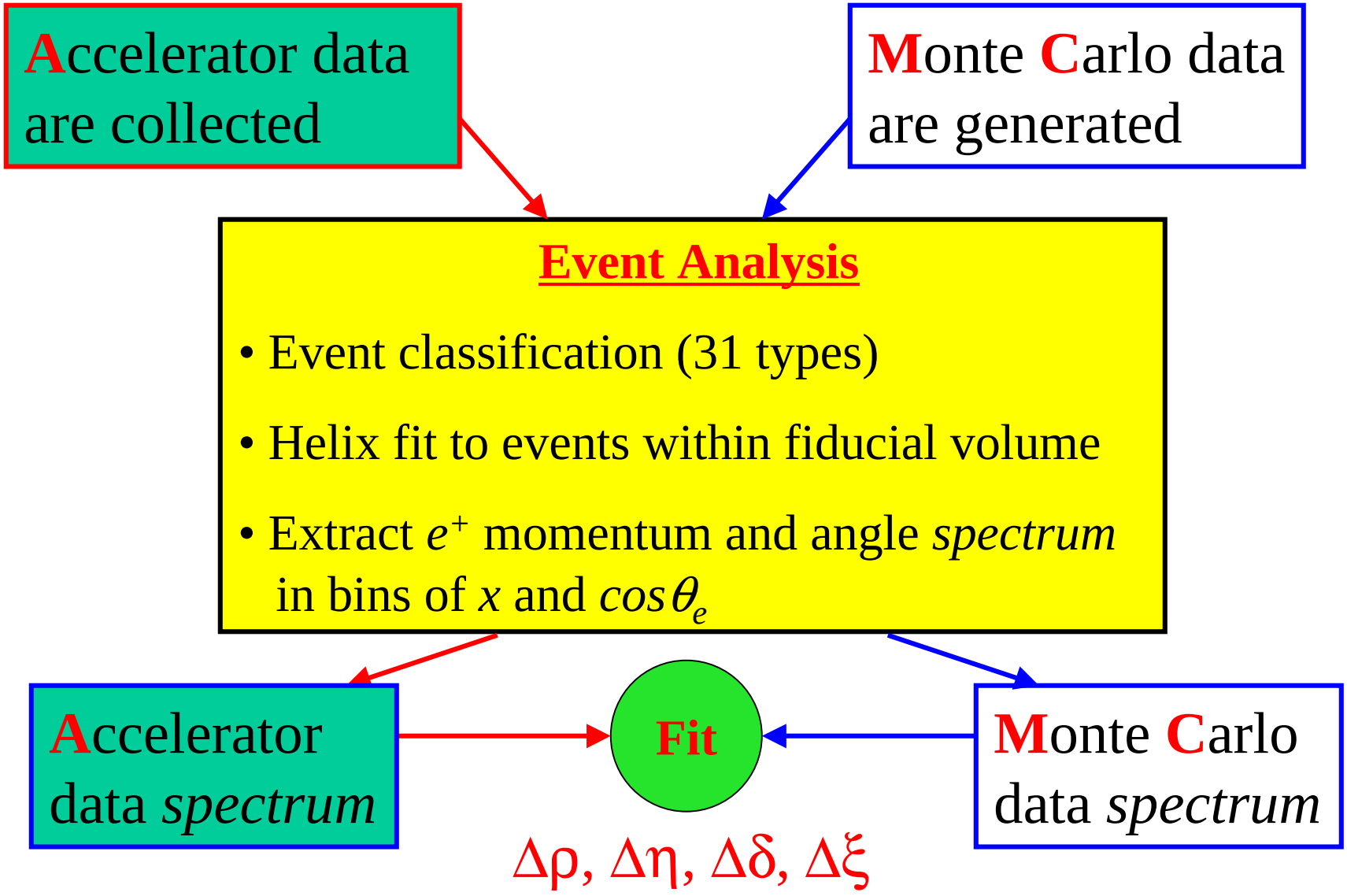
Evaluating systematic errors: data to data



Evaluating systematic errors: MC to MC



Final result



TWIST timeline

- ***2004 program:***
  - Publish measurement of ρ, δ at 10^{-3} in 2004.
    - Data in hand for measurement of ρ, δ to 10^{-3}
    - Study of systematic errors for 10^{-3} *nearly complete*
  - Take data for measurement of $P_\mu \xi$ for 10^{-3} precision (publish 2004/05).
- ***2005/06 program:***
  - Take data for measurement of ρ, η , ξ, δ to a precision of a *few parts in* 10^4 *(~*10^3 *for* η*)*