TWIST

The TRIUMF Weak Interaction Symmetry Test

Goal: A high precision measurement of the positron (T_e) and ($\cos\theta_e$) spectrum from μ-decay to test the SM predictions for the weak interaction

Outline

- Physics motivation
- Discovery potential for ***TWIST***
- Experimental method
- Analysis approach
- Systematics studies
- Timeline

The *TWIST* Collaboration

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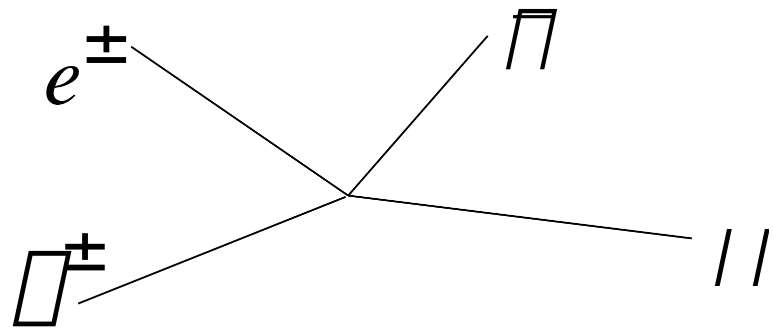
TWIST physics motivation -- test the Standard Model for μ-decay

… Most general interaction does not presuppose the W



$$rate \sim \left| \sum_{\substack{\gamma=S,V,T \\ i,j=R,L}} g_{ij}^{\gamma} \left\langle \bar{e}_i \middle| \Gamma^{\gamma} \middle| \nu_e \right\rangle \left\langle \bar{\nu}_{\mu} \middle| \Gamma_{\gamma} \middle| \mu_j \right\rangle \right|^2$$

- ***S,V,T*** **= scalar, vector or tensor interactions**
- ***R, L*** **= right and left handed leptons (*e*, μ, or τ)**

Couplings in the present Standard Model

$$rate \sim \left| \sum_{\substack{\gamma = S,V,T \\ i,j = R,L}} g_{ij}^{\gamma} \left\langle \bar{e}_i \middle| \Gamma^{\gamma} \middle| (\nu_e)_n \right\rangle \left\langle (\bar{\nu}_\mu)_m \middle| \Gamma_\gamma \middle| \mu_j \right\rangle \right|^2$$

$\lvert g_{RR}^{S} \rvert = 0$	$\lvert g_{RR}^{V} \rvert = 0$	$\lvert g_{RR}^{T} \rvert \equiv 0$
$\lvert g_{LR}^{S} \rvert = 0$	$\lvert g_{LR}^{V} \rvert = 0$	$\lvert g_{LR}^{T} \rvert = 0$
$\lvert g_{RL}^{S} \rvert = 0$	$\lvert g_{RL}^{V} \rvert = 0$	$\lvert g_{RL}^{T} \rvert = 0$
$\lvert g_{LL}^{S} \rvert = 0$	$\lvert g_{LL}^{V} \rvert = 1$	$\lvert g_{LL}^{T} \rvert \equiv 0$

Current measured couplings --

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

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

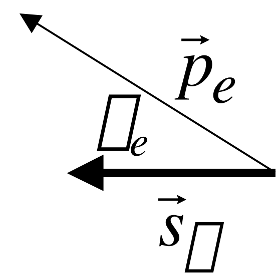
e^+ spectrum in x, $\cos\theta_e$

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

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

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

P_μ is the muon polarization



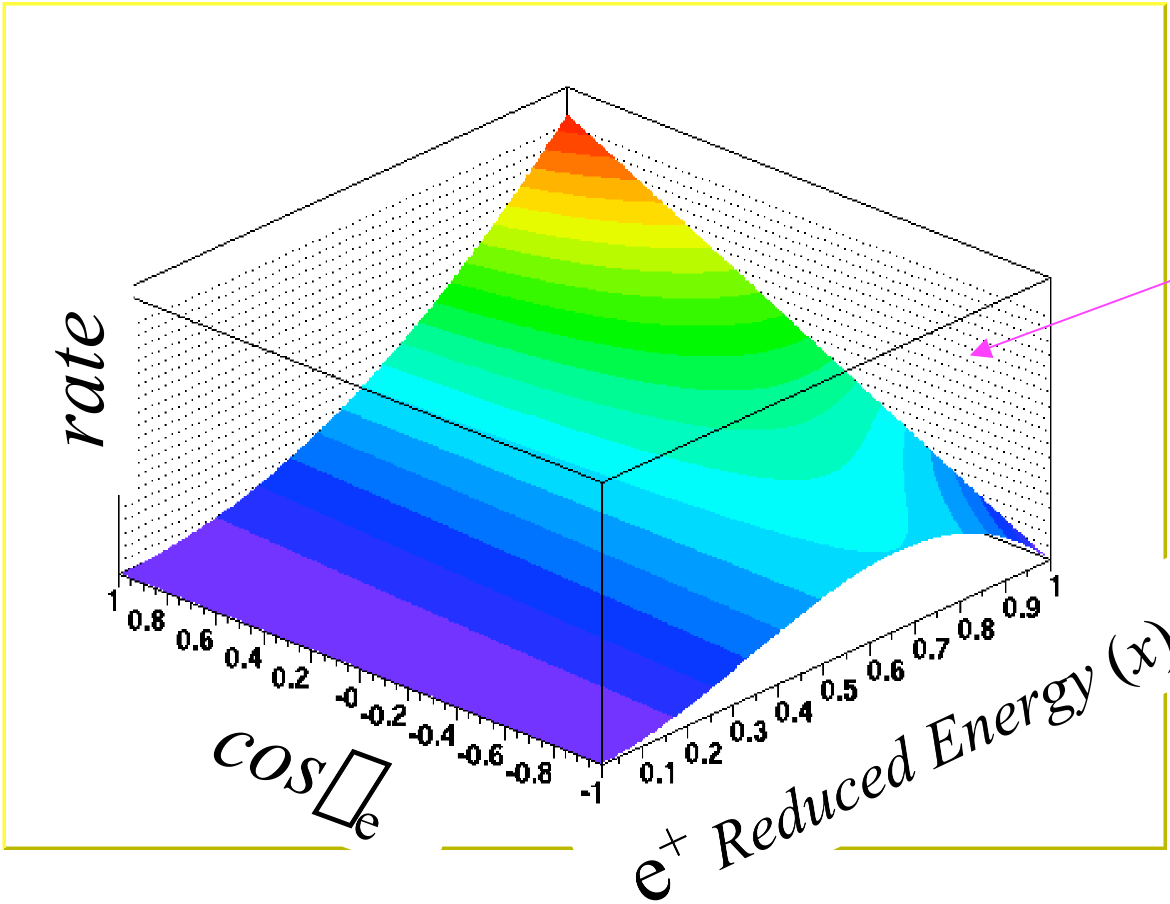
$$x_o \equiv \frac{m_e}{E_e^{\max}}$$

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

(L. Michel, A. Sirlin)

e^+ spectrum in x, $\cos\theta_e$

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



TWIST --

- *will measure the e^+ spectral shape to very high precision*

⇓

- *will extract ρ, δ, ξ to a few parts in 10^4*

- *η is being measured at PSI*

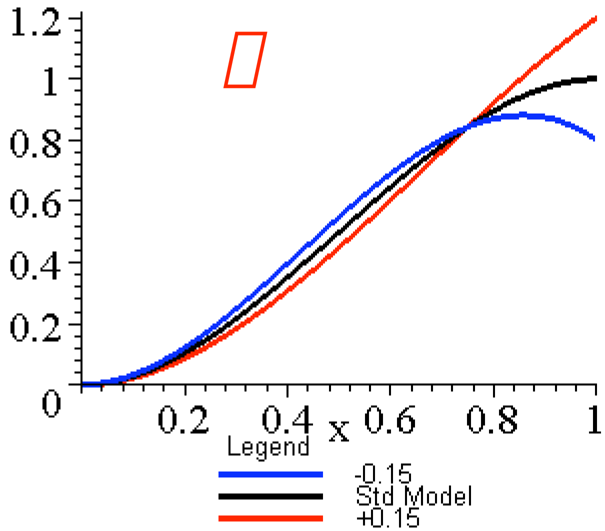
Current status --

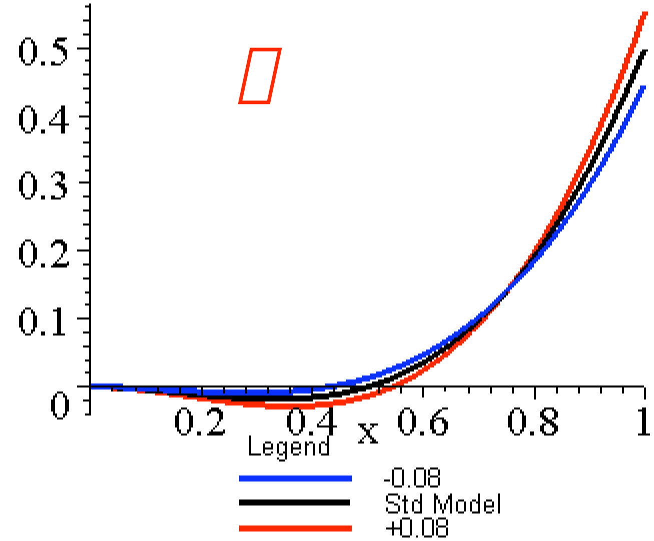
	SM		PDG	
□	3/4	=	0.7518 ± 0.0026	1969
□	3/4	=	0.7486 ± 0.0026 ± 0.0028	1988
□	1.0	=	1.0027 ± 0.0026	1987
□	0.0	=	□0.007 ± 0.013	1985
$P_{□}\frac{□□}{□}$	1.0	>	0.99682, CL = 90%	1986

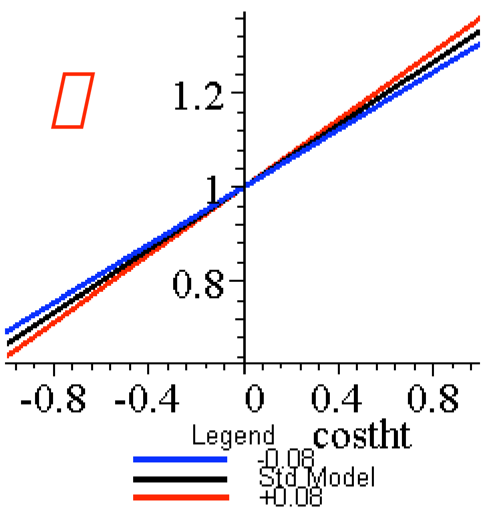
TWIST will measure □, □, □ in two steps --
10^{-3} in 2004; ~3×10^{-4} in 2005/6

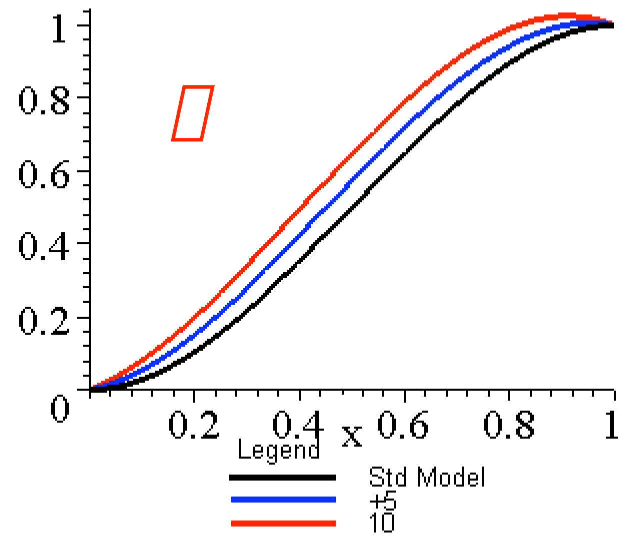
Spectral effects with changes in □, □, □, □

~500 times
TWIST sensitivity









Search for deviations from SM --

$$\rho \equiv \frac{3}{4}\left[\left|g^V_{LL}\right|^2 + \left|g^V_{RR}\right|^2 + \left|g^T_{LR}\right|^2 + \left|g^T_{RL}\right|^2 \right]$$

$$+ \frac{3}{16}\left[\left|g^S_{LL}\right|^2 + \left|g^S_{RR}\right|^2 + \left|g^S_{LR}\right|^2 + \left|g^S_{RL}\right|^2 \right]$$

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

$\rho = \frac{3}{4}$ *with* $g^V_{LL} = 1$ *and all other couplings* $= 0$

$\rho \neq \frac{3}{4}$ *implies non-standard model couplings*

Search for deviations from SM --

$$\square\square 1 \equiv \square\frac{1}{2}\left(\left|g^{S}_{RR}\right|^{2}+\left|g^{S}_{LR}\right|^{2}\right)\square 2\left(\left|g^{V}_{RR}\right|^{2}+2\left|g^{V}_{RL}\right|^{2}\square\left|g^{V}_{LR}\right|^{2}\right)\square 2\left(4\left|g^{T}_{RL}\right|^{2}\square\left|g^{T}_{LR}\right|^{2}\right.$$

$$\square\frac{1}{2}\mathrm{Re}\left[\left(g^{S*}_{RL}g^{T}_{RL}\right)+\left(g^{S}_{RL}g^{T*}_{RL}\right)\square\left(g^{S*}_{LR}g^{T}_{LR}\right)\square\left(g^{S}_{LR}g^{T*}_{LR}\right)\right]$$

$$\square\square\square\frac{3}{4}\equiv\square\frac{3}{4}\left(\left|g^{S}_{RR}\right|^{2}+\left|g^{S}_{LR}\right|^{2}+2\left|g^{V}_{RR}\right|^{2}+\left|g^{V}_{RL}\right|^{2}+\left|g^{V}_{LR}\right|^{2}\right)$$

$$+2\left(\left|g^{T}_{RL}\right|^{2}+2\left|g^{T}_{LR}\right|^{2}\right)$$

$$\square\mathrm{Re}\left[\left(g^{S*}_{RL}g^{T}_{RL}\right)+\left(g^{S}_{RL}g^{T*}_{RL}\right)\square\left(g^{S*}_{LR}g^{T}_{LR}\right)\square\left(g^{S}_{LR}g^{T*}_{LR}\right)\right]$$

… and also for $\square$

Chirality of the muon decay…

$$rate \sim \left| \sum_{\substack{\gamma=S,V,T \\ i,j=R,L}} g^{\gamma}_{ij} \left\langle \bar{e}_i \middle| \Gamma^{\gamma} \middle| \nu_e \right\rangle \left\langle \bar{\nu}_{\mu} \middle| \Gamma_{\gamma} \middle| \mu_j \right\rangle \right|^2$$

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

Q_{mn} describes decay of
n-handed μ into an
m-handed e^+

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

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

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

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

Coupling to right-handed muons…

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

$Q_{mR} = 0$ by SM

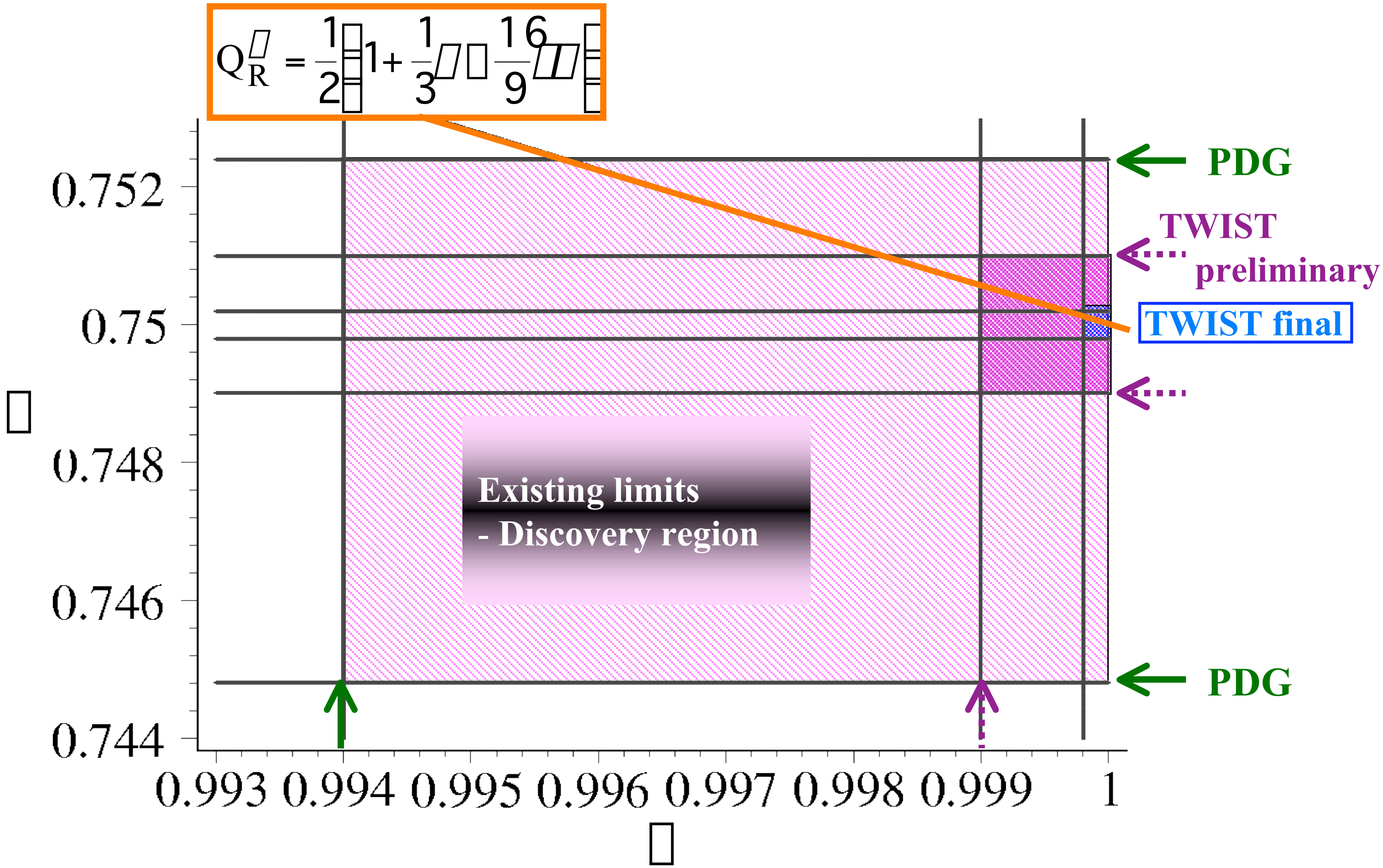
$$Q_{mR} = Q_{RR} + Q_{LR} = \frac{1}{4}\left|g^S_{RR}\right|^2 + \left|g^V_{RR}\right|^2 + \frac{1}{4}\left|g^S_{LR}\right|^2 + \left|g^V_{LR}\right|^2 + 3\left|g^T_{LR}\right|^2$$

which can be shown to be equivalent to to the following combination of □□--

$$Q_{mR} = \frac{1}{2}\square 1 + \frac{1}{3}\square\square\frac{16}{9}\square\square\square$$

A determination of □ and □ 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 in muon decay



Left/Right Symmetric Model

Two weak bosons with mass eigenstates M_1 and M_2

$$M_{W_L} = M_1 \cos\square \square M_2 \sin\square$$

$$M_{W_R} = e^{i\square}\left(M_1 \sin\square + M_2 \cos\square\right)$$

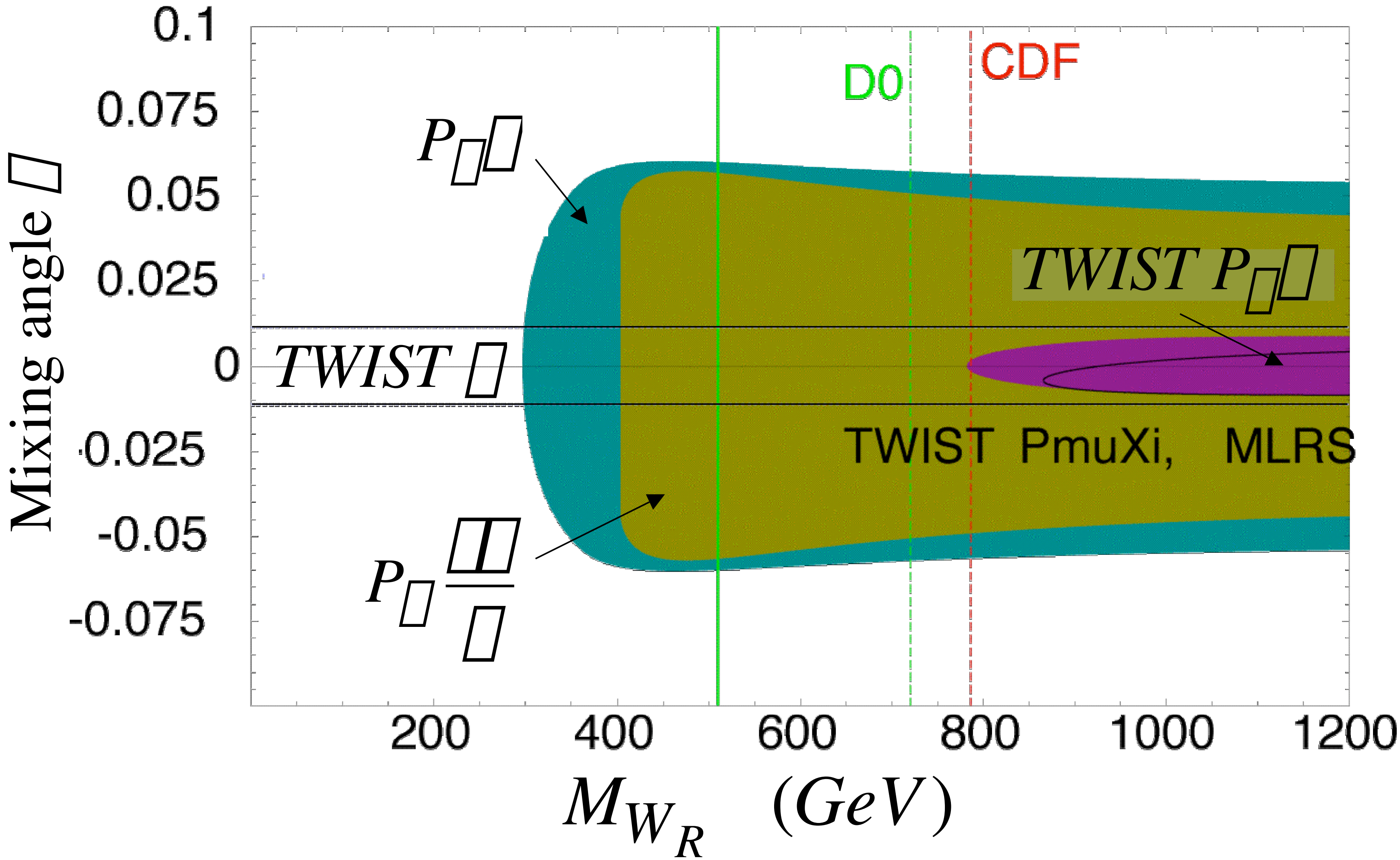
$$M_{W_{SM}} \square M_{W_L}$$

$$\square = \frac{M_1^2}{M_2^2} << 1$$

$\square$ Left/Right mixing angle;

$$\square = \sqrt{\frac{1}{2}\square\frac{2}{3}\square} \qquad \square = \sqrt{\frac{2}{3}\square\square\frac{1}{2}\square}$$

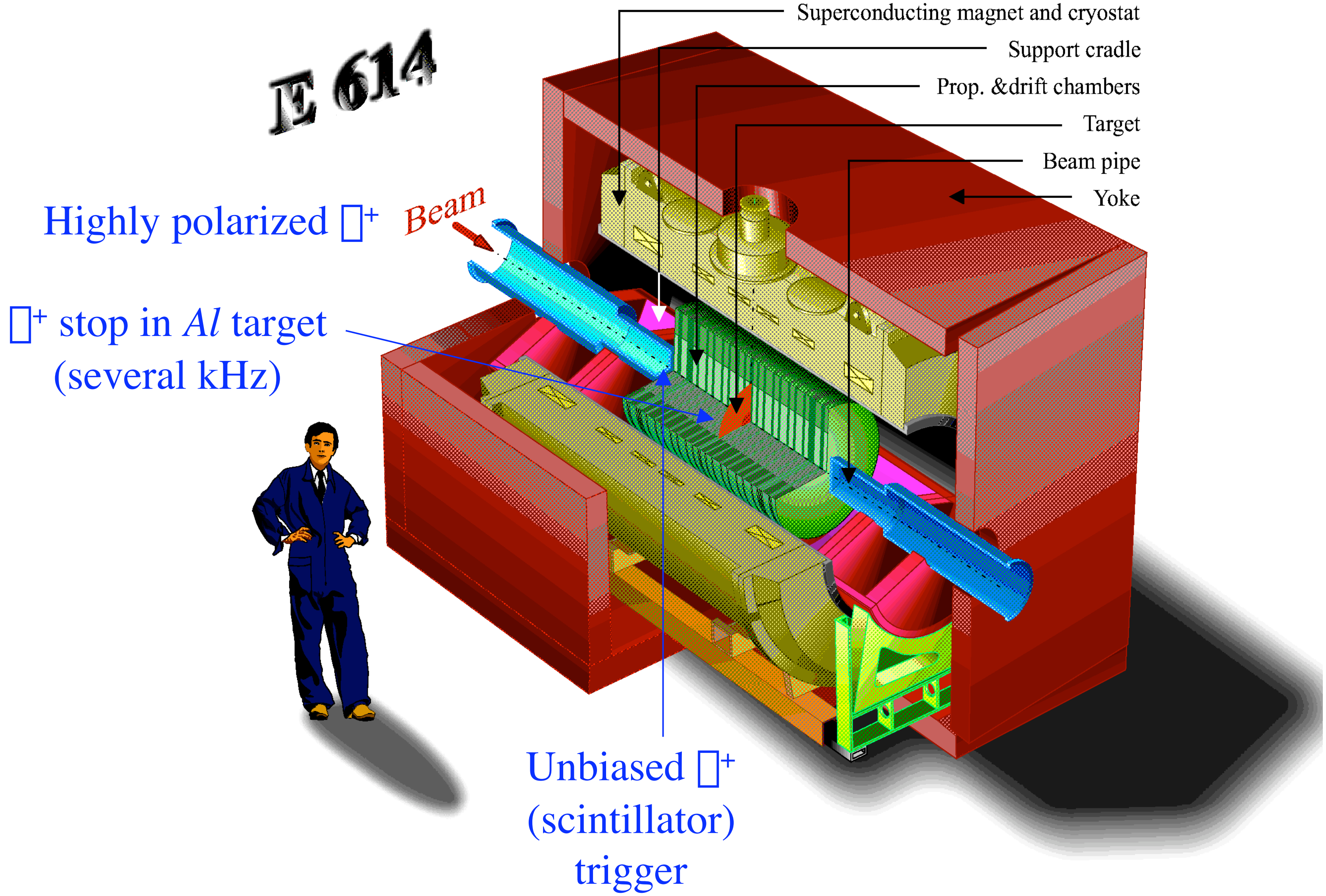
Left/Right Mixing constraints – Anticipated *TWIST* Sensitivity



The ***TWIST*** *program*:

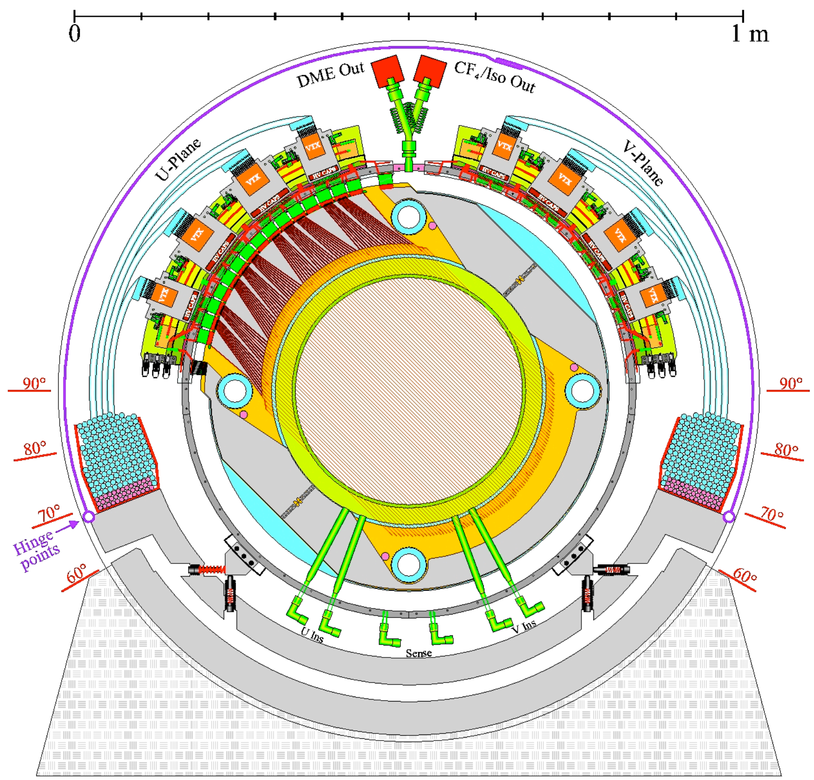
- Collect *high precision data* to obtain the e^+ spectrum from □-decay as a function of x and $cos□_e$
- Detailed *study of systematic* errors in ***TWIST***
- Extract the *best values* of the spectral parameters □, □ , □, □ *simultaneously* (the first time this has been done)
- Obtain a precision in □, □, □ (a) of 10^{-3} and (b) a *few parts in* 10^4 *(~*10^{-3} *precision for* □*)*
- Compare □, □ , □, □ from our fit with Standard Model values

Obtain *high precision data* on the e^+ spectrum

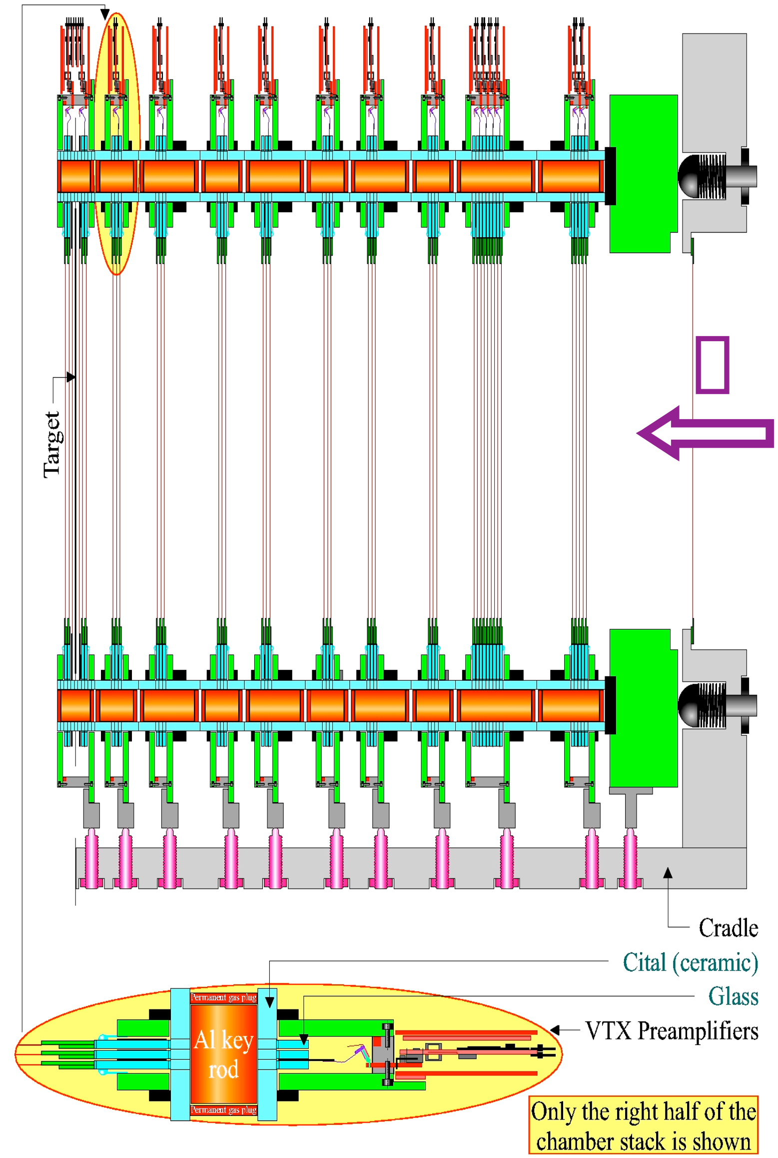


Chambers & half detector

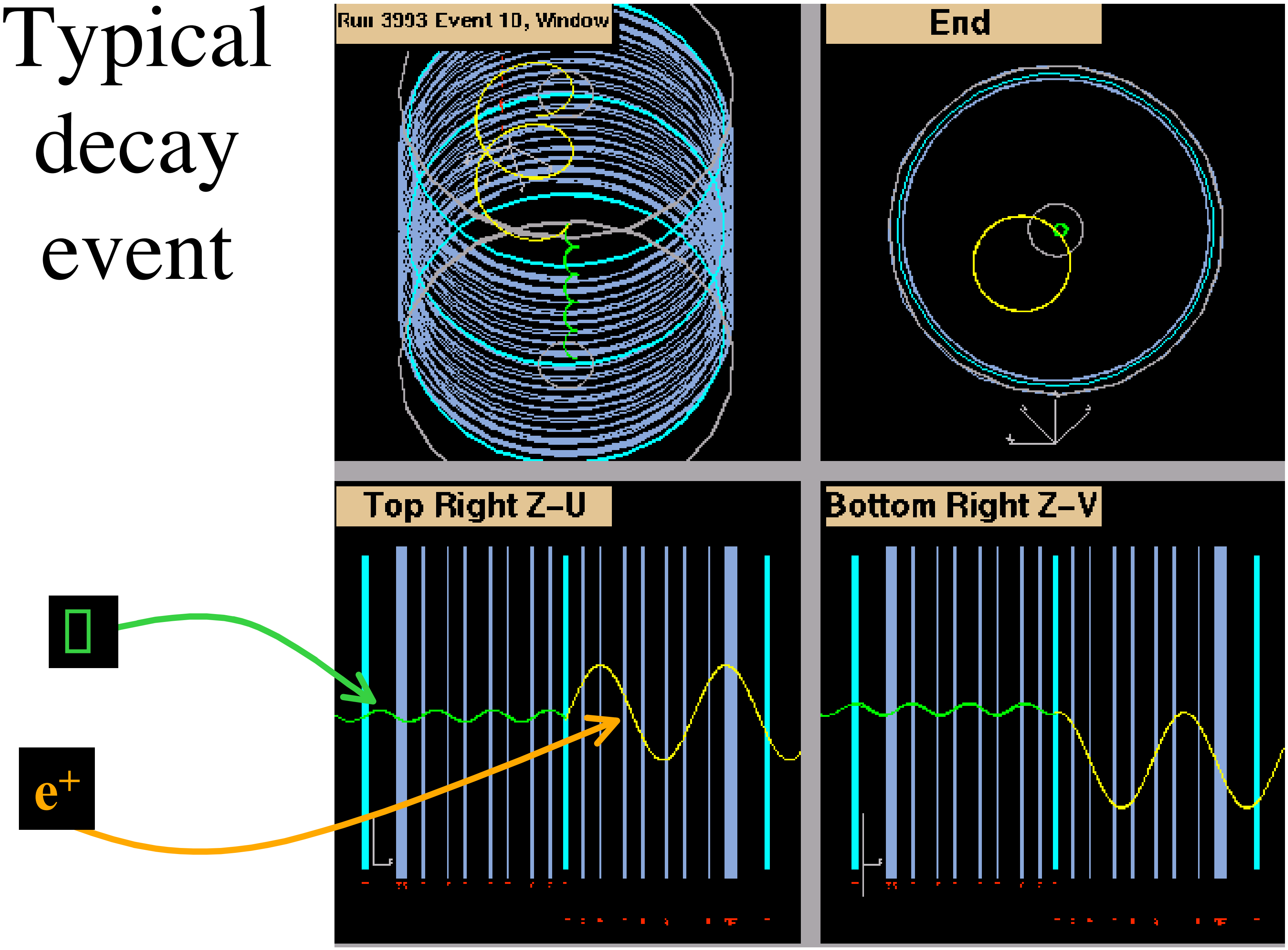
Planar drift chambers sample positron track



Use 44 drift planes, and 12 PC planes



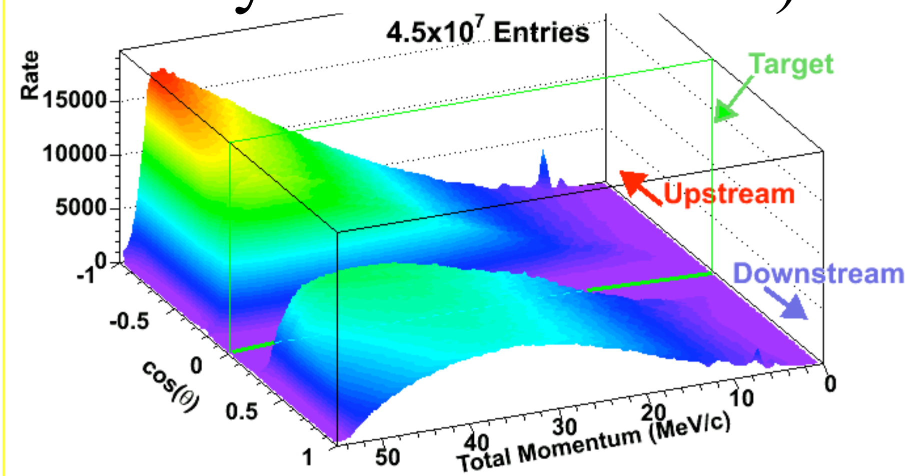
Typical decay event



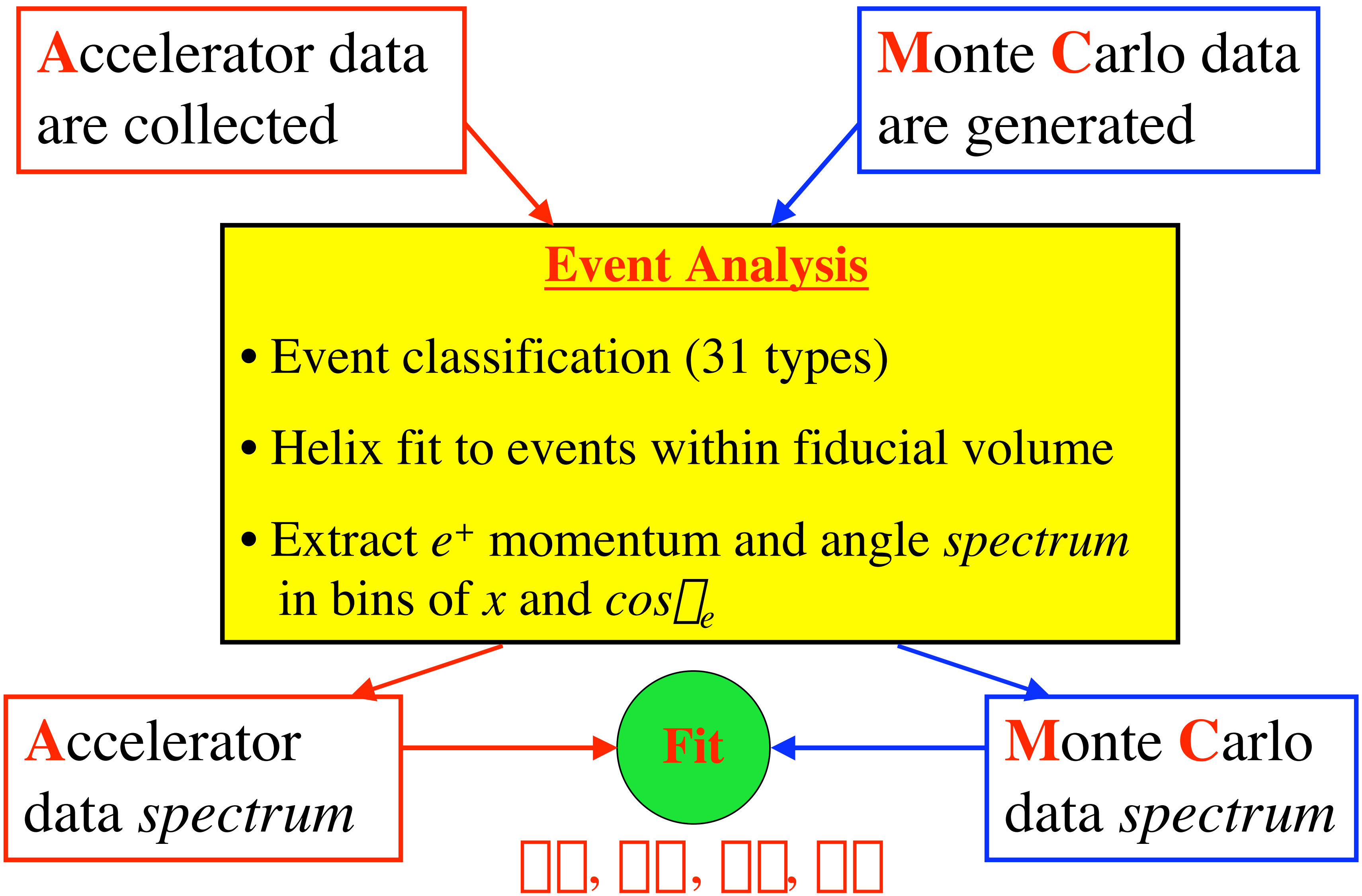
TWIST Data

- High data rates (few kHz) → Data sets of **10^9** muon decay events in ~ *two weeks*
- ***TWIST*** is *systematics* limited. (High data rates and computational resources are essential for studying systematic effects.)
- In 2002-03, ~**6×10^9** muon decay events on tape.
- Standard data set ~ **300M triggers → ~58M useful events** (smaller samples for some systematics studies)

Reconstructed muon decay spectrum



Determination of □, □, □, □



Determination of ρ, η, ξ, δ

Data *spectrum* is fit to Monte Carlo *spectrum* --

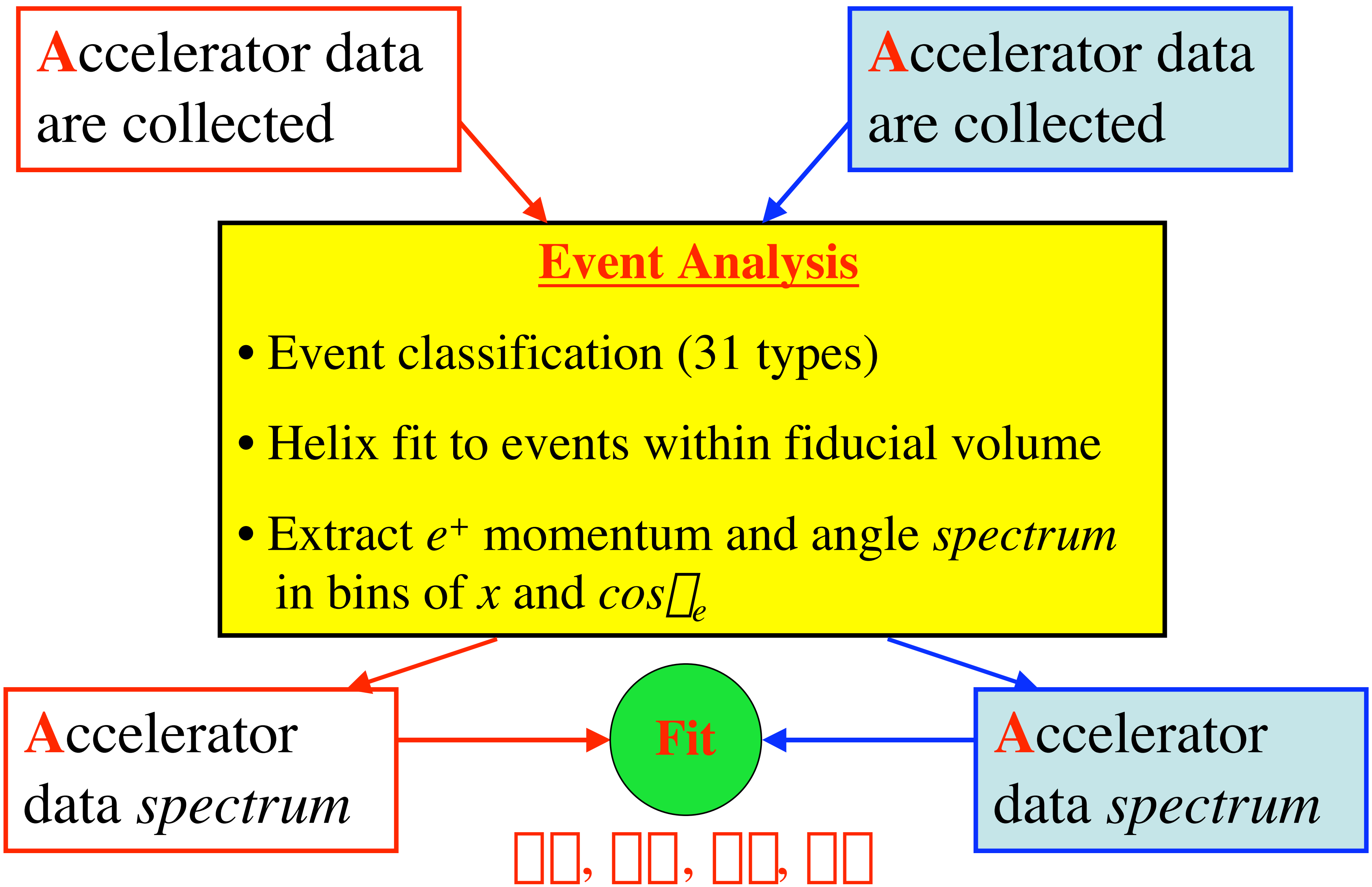
$$\left(\frac{d^2N}{dx\, d(\cos\theta_e)}\right)_{Data} = N_o \left(\frac{d^2N}{dx\, d(\cos\theta_e)}\right)_{(\rho_o,\eta_o,\xi_o,\delta_o)}$$

$$+ N_o \sum_{\lambda=\rho,\eta,\xi,\delta} \left[\frac{\partial}{\partial\lambda}\left(\frac{d^2N}{dx\, d(\cos\theta_e)}\right)_{(\rho_o,\eta_o,\xi_o,\delta_o)} \Delta\lambda \right]$$

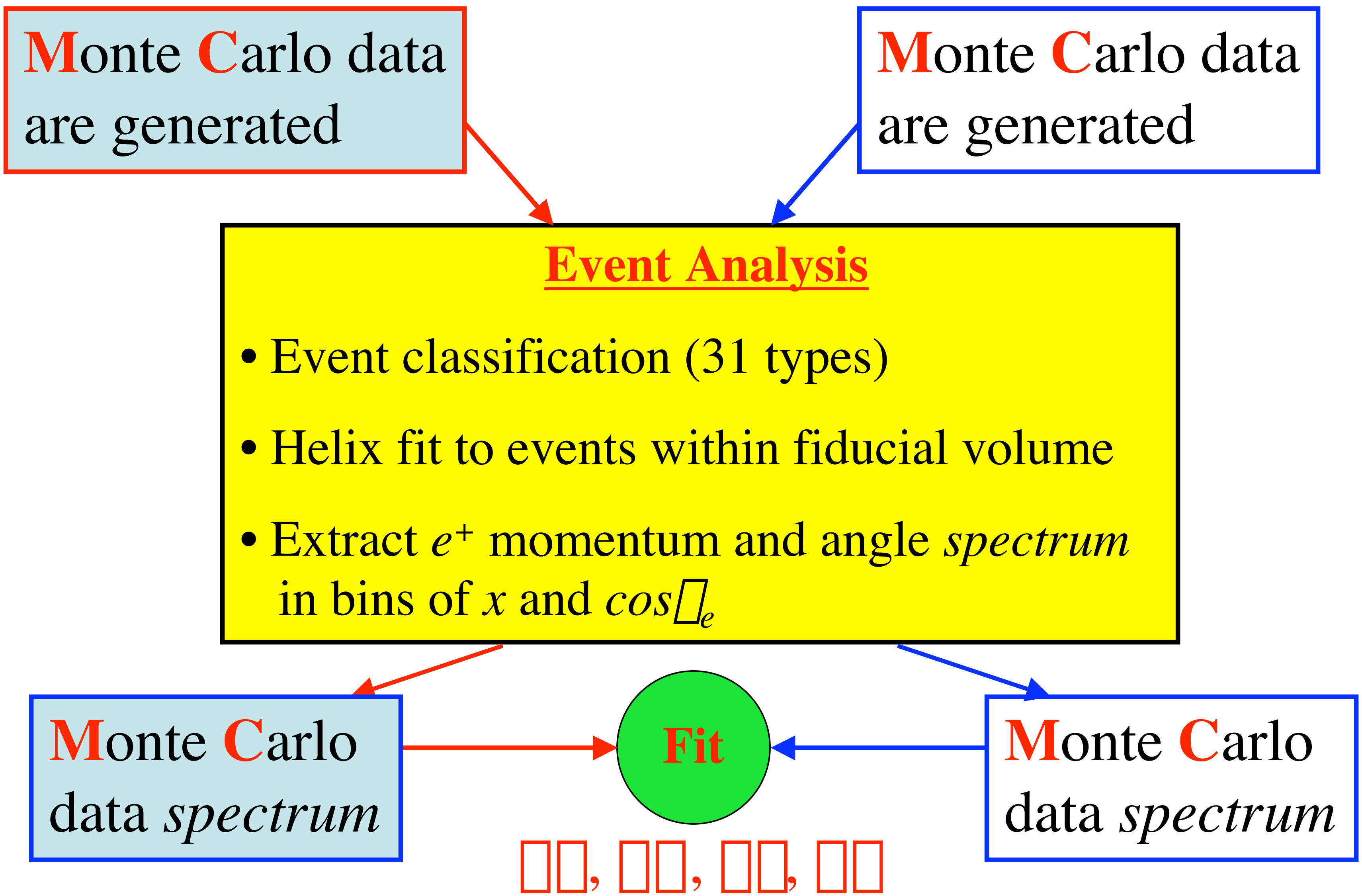
From the fit $\Delta\rho$, $\Delta\eta$, $\Delta\xi$, $\Delta\delta$ are determined.

Blind Analysis: ρ_o, η_o, ξ_o, δ_o are generated randomly (*once*) and remain ***hidden*** until the end of the experiment.

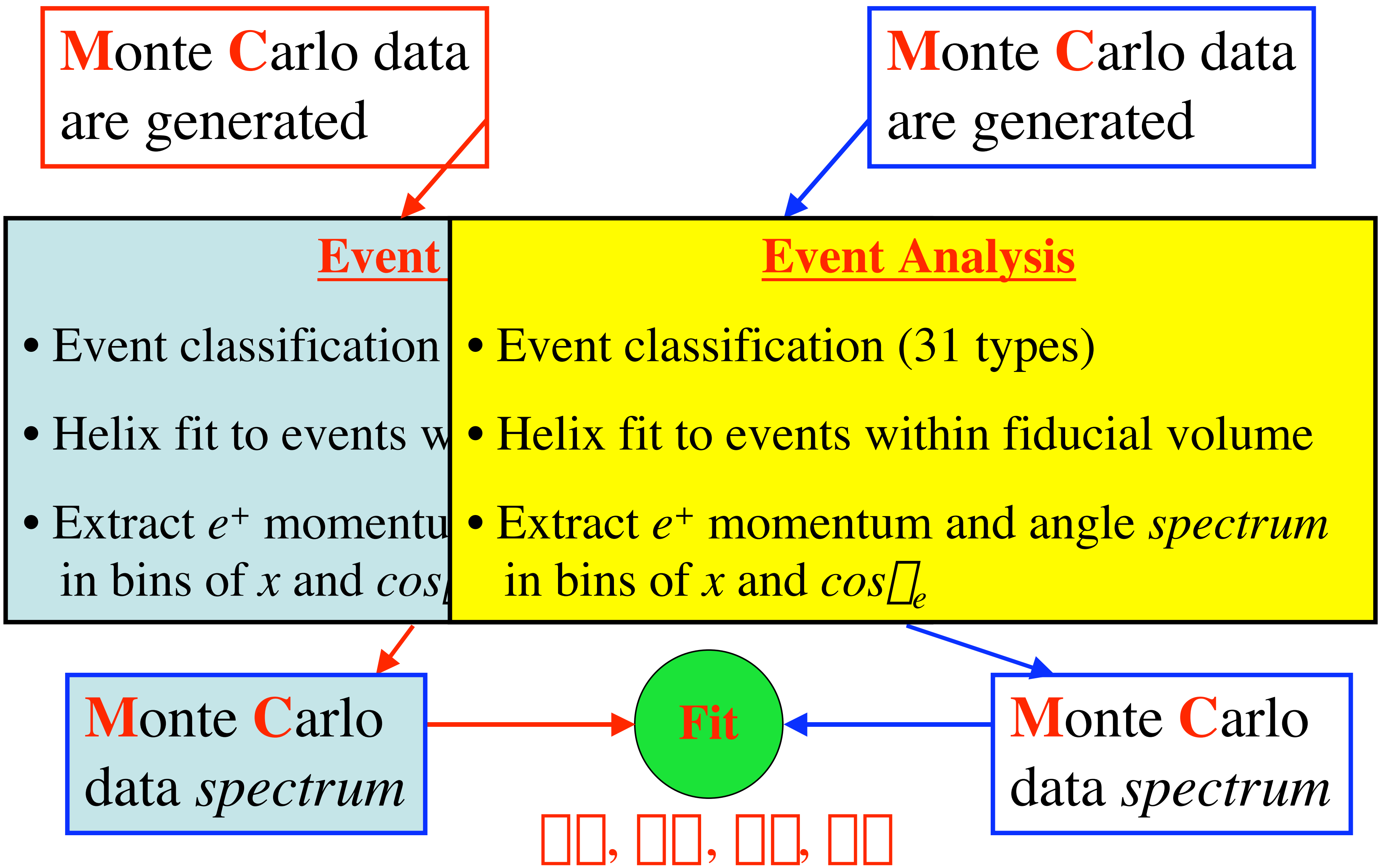
Evaluating Systematic Errors



Evaluating Systematic Errors



Evaluating Systematic Errors



Evaluating Systematic Errors

Methodology:

- Exaggerate possible sources of systematic error -
  - Take accelerator data sets under a different conditions
  - Generate Monte Carlo runs with different settings
  - Analyze same data with different calibrations

  (Use full (or nearly full) data set for each test)

- Fit two data sets; measure the effect on □□, □□, □□, □□
- Scale the effect by the exaggeration factor

Evaluating Systematic Errors

Examples

- Chamber gas density: muon stopping distribution
- Different magnetic field: energy calibration
- Magnetic field shape
- Alignments
- Beam properties
- Detector response:
  - STR: HV, drift cell geometry
  - Efficiency, fiducial region
  - Resolution
  - Cross talk
- TWIST simulation (GEANT)

…and more…

Evaluating Systematic Errors

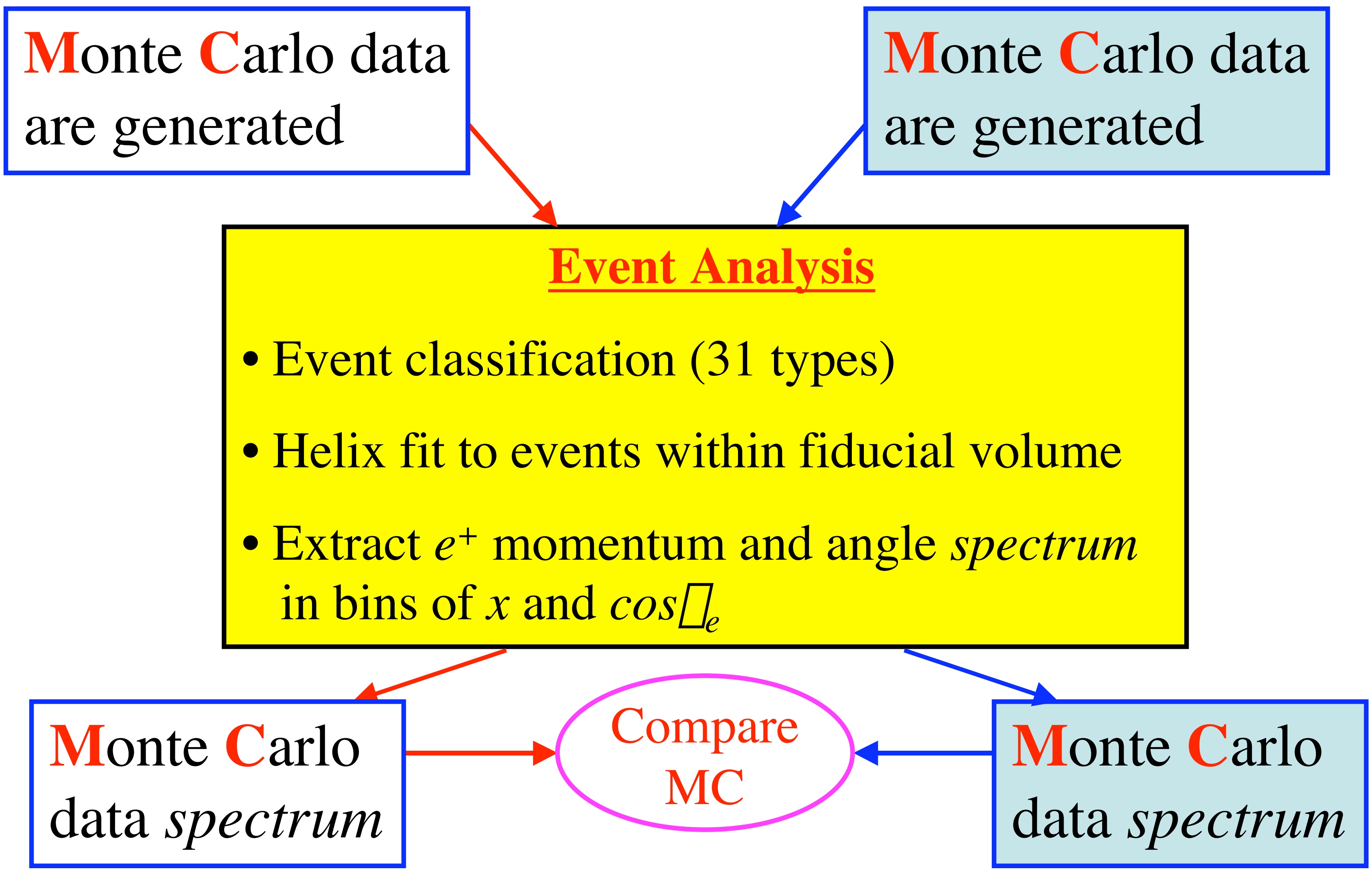
Present Status

	10^{-3}	□	□	□	□
Alignment	**Translation**	**0.10**	**0.08**	**0.13**	**7.8**
	Rotation	**0.07**	**0.05**	**0.23**	**3.9**
Chamber	**HV**	**0.05**	**0.03**	**0.06**	**2.6**
	Cell Geometry	**0.28**	**0.21**	**0.36**	**16.**
	Gas Density	**0.15**	**0.11**	**0.20**	**8.5**
Calibration	**Trigger time**	**0.13**	**0.09**	**0.16**	**7.0**

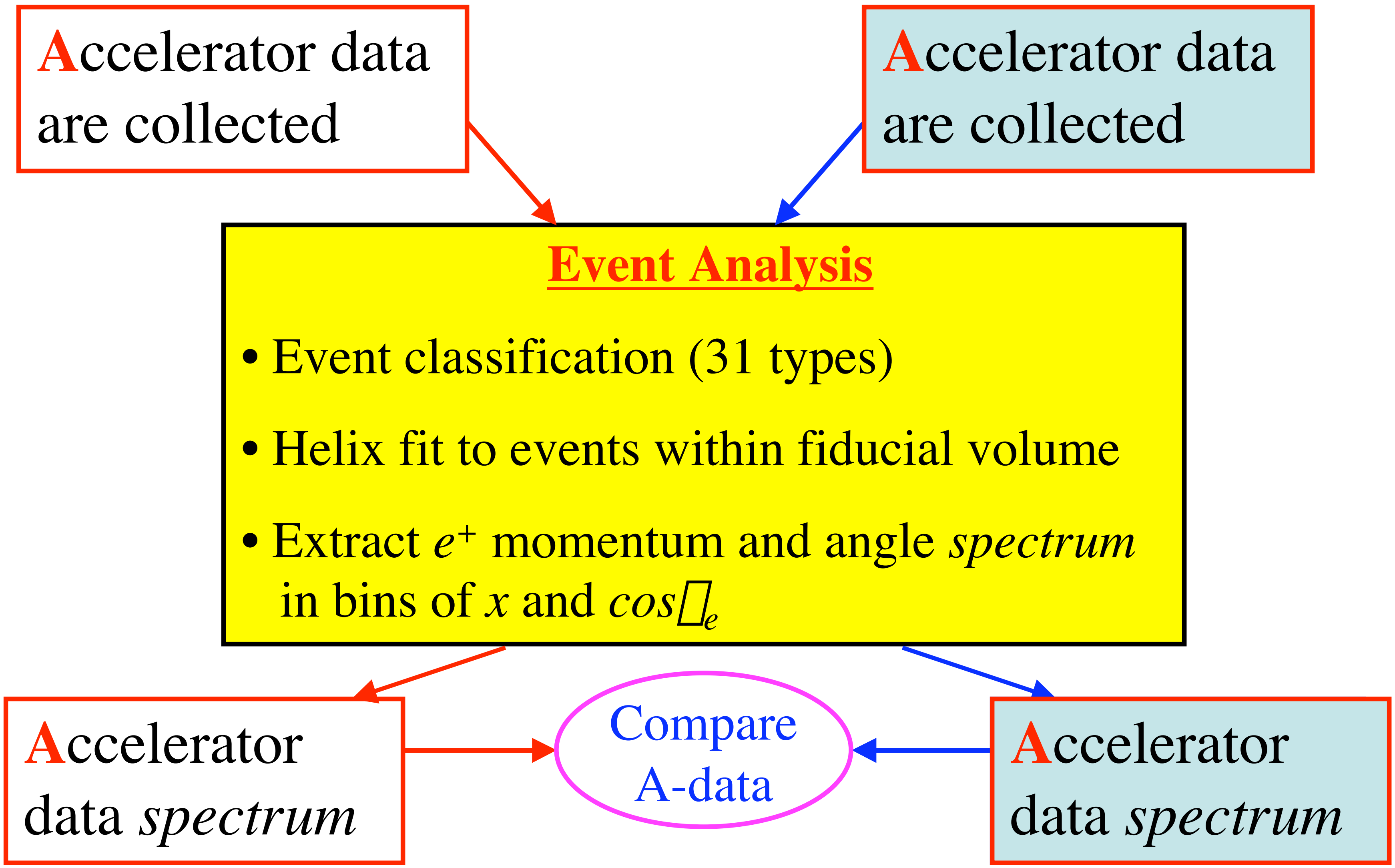
… and many more at this level…

No show-stoppers!

TWIST Simulation Validation

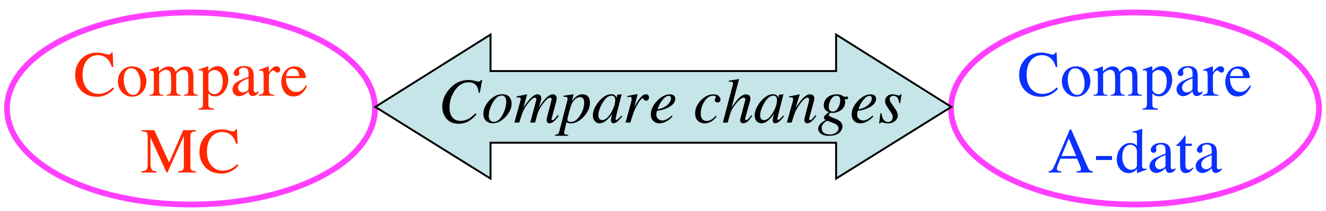


TWIST Simulation Validation



TWIST Simulation Validation

- Test the simulation independently of □, □, □, □
    - Take accelerator data sets under a different conditions
    - Generate Monte Carlo data sets with same conditions
    - Analyze data sets with the same analysis package
    - Compare the differences --



- Determine the sensitivity for each physics/detector effect in □□, □□, □□, □□

TWIST Simulation Validation

Examples

- Chamber gas density: muon stopping distribution
- Different magnetic field: energy calibration
- p_{max} vs θ_e
- χ^2 and confidence level distributions
- hits per plane
- muon stopping distribution
- delta production cross-section
- energy loss
- multiple scattering
- …and more…

Compute power - WestGrid

- At University of British Columbia
- 504 dual-3Ghz Xeon nodes
- 10 TB global disk storage
- Robot tape archiving system
- Many tens of 10^8 events analyzed
- Many tens of 10^8 events simulated & analyzed
  - ~70 ms/event (simulation)
  - ~30 ms/event (reconstruction)
  - >5000 CPU days used
- (www.westgrid.ca)

Funded by the Canada Foundation for Innovation, Alberta Innovation and Science, BC Advanced Education, and the participating research institutions.

*The **TWIST** timeline:*

- ***2004***
  - Data in hand for measurement of □, □ to 10^{-3}
  - Study of systematic errors (for 10^{-3}) *nearly complete*
  - Publish measurement of □, □ at 10^{-3} in 2004.
  - Take data for measurement of *$P_{□}$*□ - for precison of 10^{-3} - publish 2004/05

- ***2005/06***
  - Take data for measurement of □, □ , □, □ to a precision of a *few parts in* 10^4 *(~10^{-3} precision for □)*

BOTTOM LINE: Compare □, □ , □, □ from our fit with Standard Model values □ *New Physics?*