Precision Measurement of Muon Decay

Art Olin, for the $\mathcal{TWIST}$ collaboration

- The physics of muon decay
- The detector
- Tracking
- Analysis techniques
- Status/conclusions

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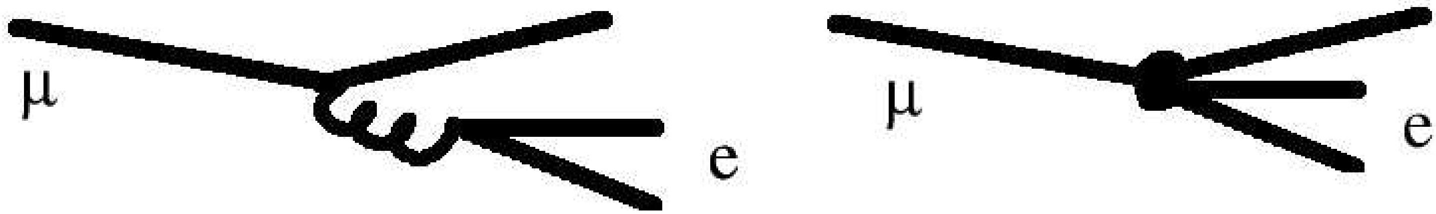
Spacetime Structure of the Weak Interaction



The general matrix element:

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

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

- 10 complex coupling constants $\Longrightarrow$ 19 independent real parameters.
- The Standard Model: $g^V_{LL} = 1$, the rest are zero.
- V - A maximal parity violating.
- Broken symetries??

Muon decay

Michel spectrum: (L. Michel, A. Sirlin)

$$\frac{d^2\Gamma}{dx\,d\cos(\theta)} \propto F_{\text{IS}}(x) + P_\mu \cos(\theta)\, F_{\text{AS}}(x)$$

where $x = E_e/E_e^{\text{max}}$, and

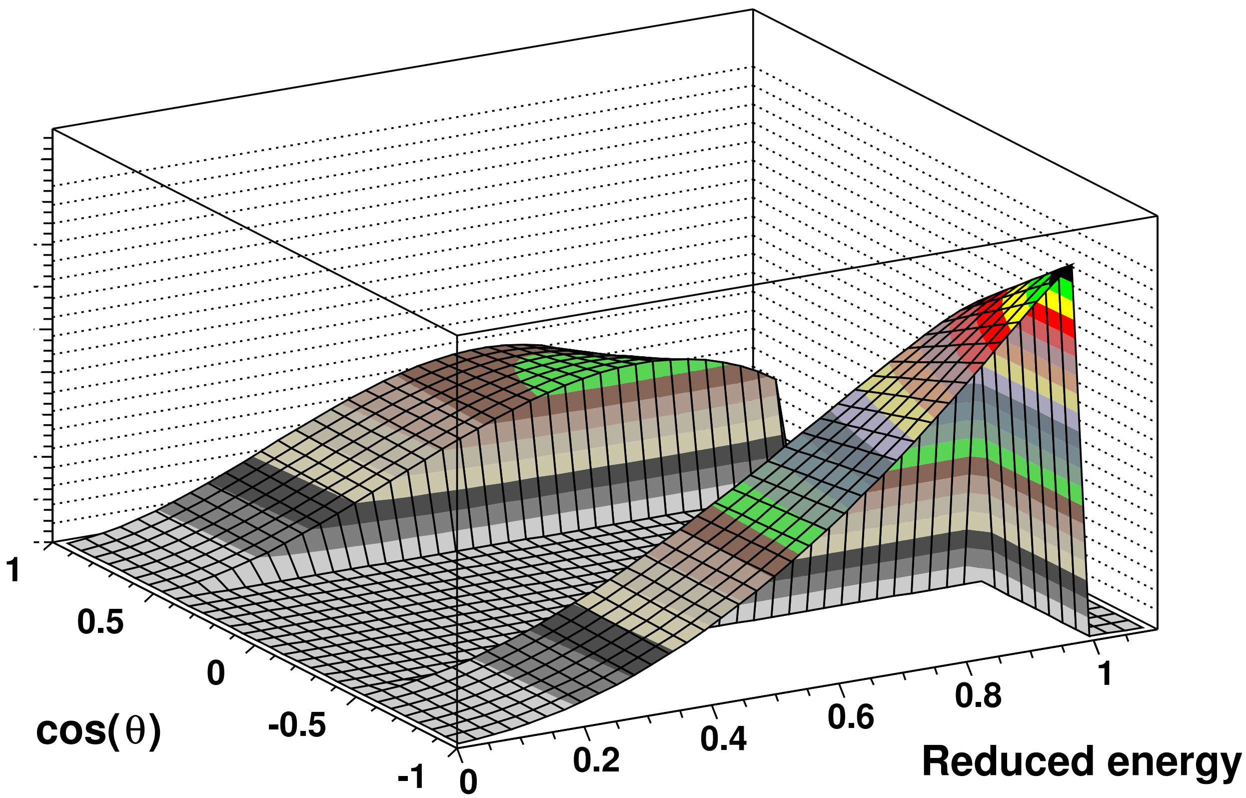
$$F_{\text{IS}} = x^2(1-x) + \frac{2}{9}\rho\,(4x^3 - 3x^2) + \eta\,\frac{m_e}{E_e^{\text{max}}}\,x(1-x)$$

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

- *TWIST* will measure the shape of a large part of the 2D spectrum to high precision $\Longrightarrow$ *Simultaneous measurement* of 3 (or 4) Michel parameters for the first time .

Michel spectrum

Shown is the approximate TWIST fiducial region.



Current best measurements

From the Review of Particle Physics

ρ	$=$	0.7518 ± 0.0026	(Derenzo, 1969)
η	$=$	-0.007 ± 0.013	(Burkard *et al.*, 1985)
δ	$=$	$0.7486 \pm 0.0026 \pm 0.0028$	(Balke *et al.*, 1988)
$P_\mu \xi$	$=$	$1.0027 \pm 0.0079 \pm 0.0030$	(Beltrami *et al.*, 1987)
$P_\mu \frac{\xi\delta}{\rho}$	$>$	$0.99682,\ CL = 90\%$	(Jodidio *et al.*, 1986)

Left-Right symmetric models—I

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

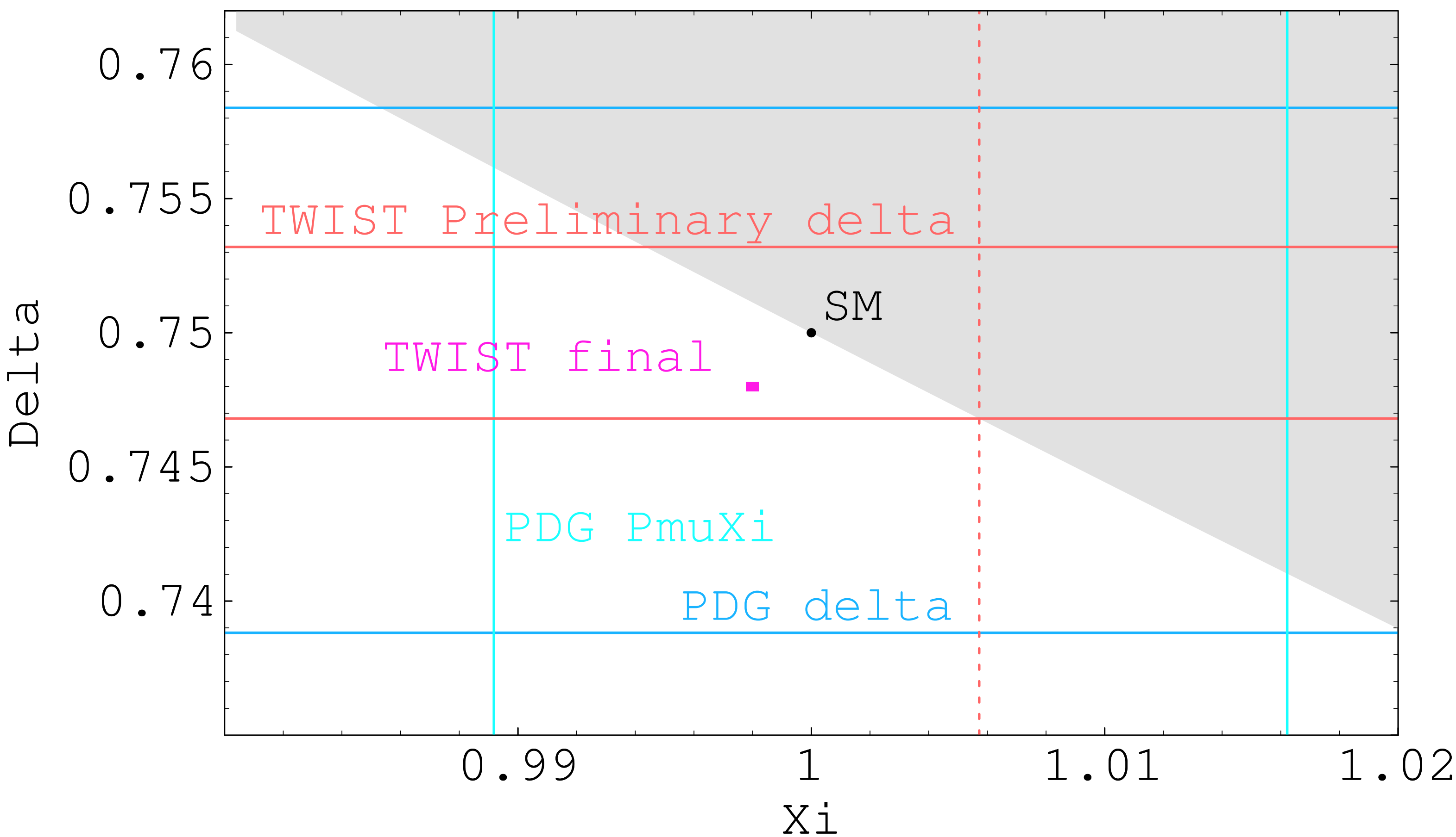
$$W_R = -\sin\zeta\, W_1 + \cos\zeta\, W_2$$

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

$$\xi = 1 - 2\left(t^2 + \zeta^2\right)$$

$$P_\mu = 1 - 2\zeta^2 - 2t^2\,\frac{|V_{ud}^R|^2}{|V_{ud}^L|^2} - 4\zeta t\,\frac{|V_{ud}^R|}{|V_{ud}^L|}$$

where $t = M_1^2/M_2^2$.



TWIST data on this plot show anticipated precision, the central values are arbitrary.

Some other models affecting Michel parameters

- SUSY with R-parity violation:

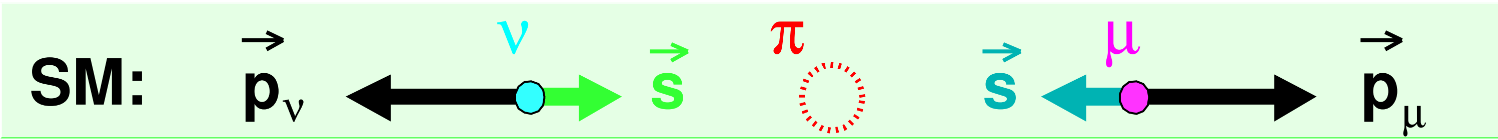
$$\Delta\rho = \frac{3\varepsilon^2}{16}, \quad \Delta\eta = \frac{\varepsilon}{2}, \quad \Delta\xi = -\frac{\varepsilon^2}{4}, \quad \Delta\delta = 0.$$

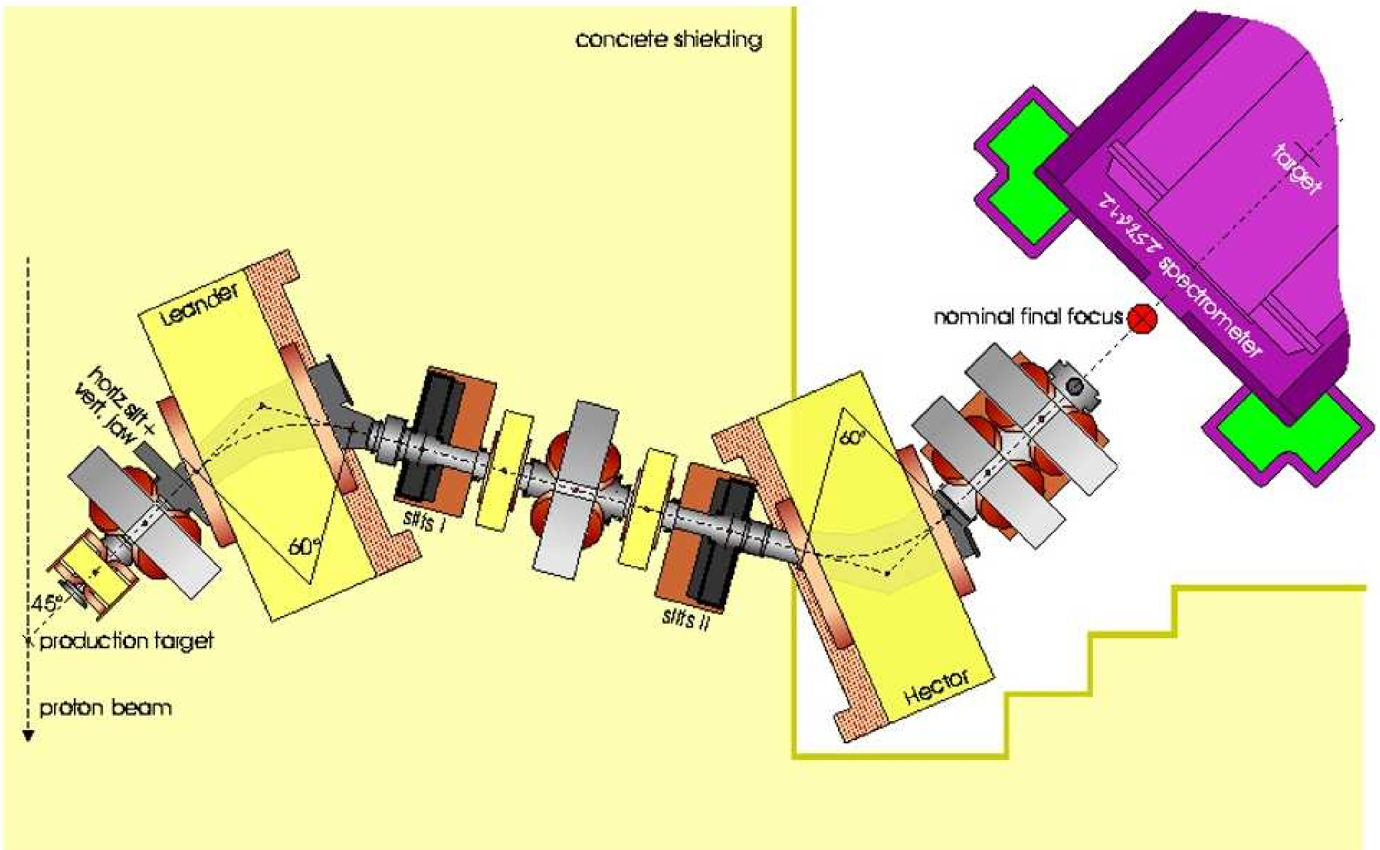
- K.S. Babu and Sandip Pakvasa (hep-ph/0204236, April 2002). To accomodate the LSND result:

$$\Delta\rho \approx -0.0015, \quad \Delta\eta = 0, \quad \Delta\xi \approx -0.0026, \quad \Delta\delta \approx -0.0015.$$

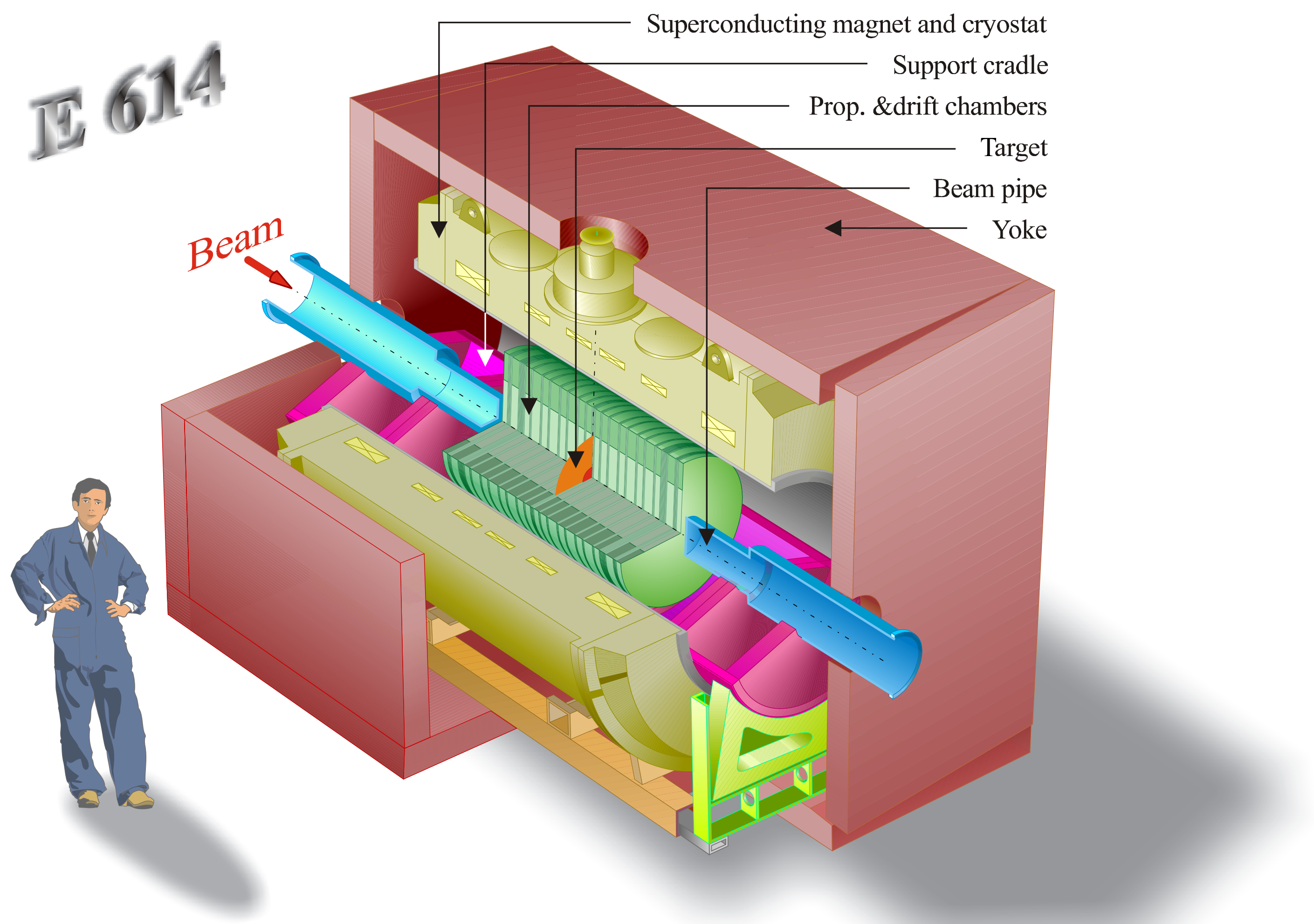
- Extra dimensions?
  - ▷ Split fermions: $\eta \neq 0$.

The experiment: beamline

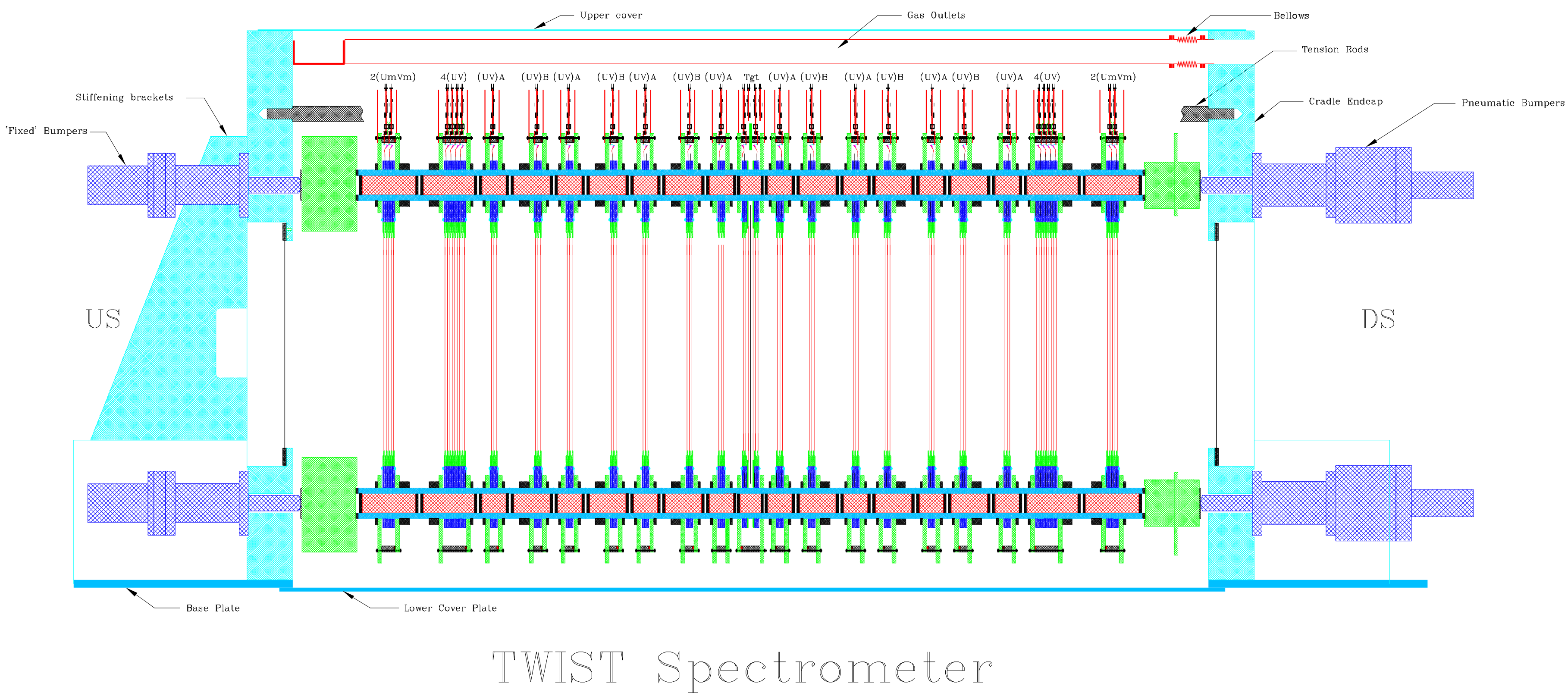




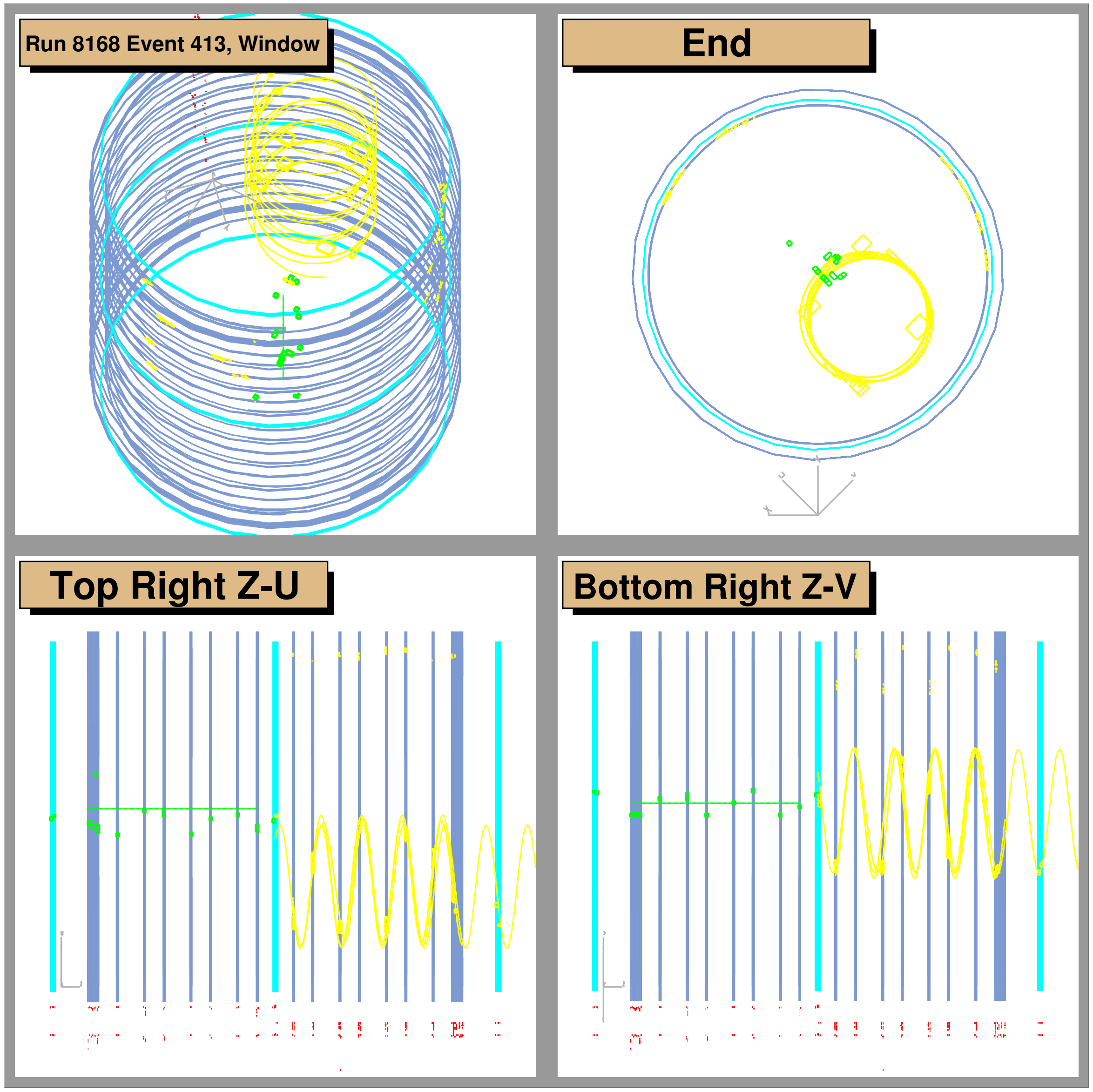
The experiment: *TWIST* detector—I



The experiment: *TWIST* detector—II



Typical Event

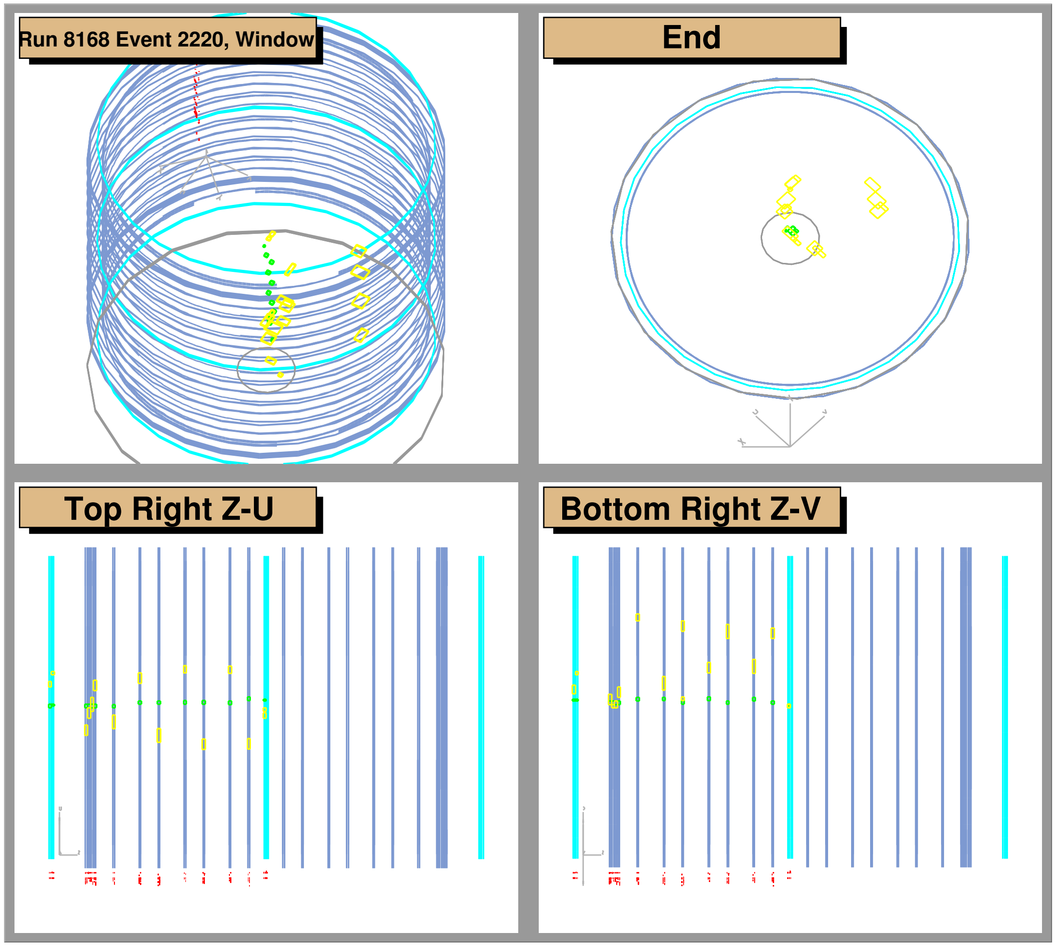


Tracking in *TWIST*

Track reconstruction should have minimum bias in angle and momentum. This is best achieved by high reconstruction efficiency.

- Associate clusters of hits with a track using circle fit and then sine fit.
- Fit hit wire centers to helix using least squares technique with kink constraints to model multiple scattering.
- Fit hit times using kinks for most accurate p,cos(θ).
- Reconstruction efficiency currently $\sim 99\%$.

Detector Granularity



Some events will not accurately reconstruct a circle, reducing the efficiency for certain p, $\cos(\theta)$.

$\mathcal{TWIST}$ Response Function

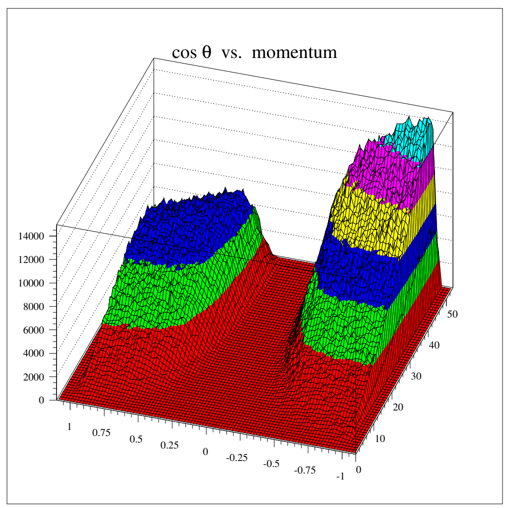
TWIST measures $\frac{d^2\Gamma^{Measured}(p,\cos(\theta))}{dp\,d\cos(\theta)} =$

$\int_0^\infty \int_{-1}^{1} \frac{d^2\Gamma(p',\cos(\theta');\rho,\eta,\delta,\xi)}{dp'\,d\cos(\theta')} G(p,p',\cos(\theta),\cos(\theta'))dp'\,d\cos(\theta')$

- The response function G is calculated by GEANT and histogrammed in bins of $|\vec{p}|$ and $\cos(\theta)$.
- Derivatives are calculated by using eg $\frac{\partial}{\partial\rho}d^2\Gamma(p',\cos(\theta'))$ in the simulation.
- Validation of this response function is the subject to Rob Macdonald's talk.

Michel Parameter Determination

Resulting 2D histogram is fitted to the simulation code 2D distribution analyzed by the same reconstruction program. Radiative corrections are included in the simulation to the leading log level. Next to leading log terms have been calculated and will be required for 10^{-4} precision.



Fitting $\Delta\rho, \Delta\eta, \Delta\delta, \Delta\xi$

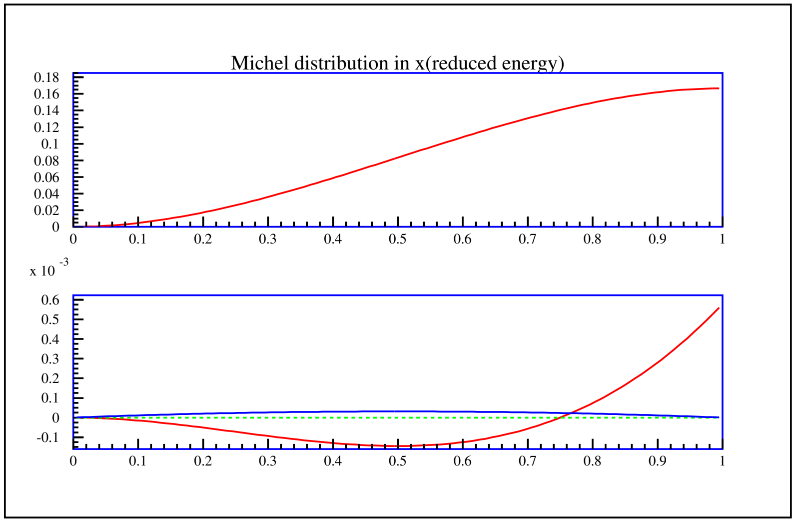
$$\left[\frac{d\Gamma}{dx}\right]_{Data} = \left[\frac{d\Gamma}{dx}\right]_{Std}$$

$$+\frac{\partial}{\partial\rho}\left[\frac{d\Gamma}{dx}\right]_{Std}\Delta\rho + \frac{\partial}{\partial\eta}\left[\frac{d\Gamma}{dx}\right]_{Std}\Delta\eta + \frac{\partial}{\partial\xi}\left[\frac{d\Gamma}{dx}\right]_{Std}\Delta\xi + \frac{\partial}{\partial\xi\delta}\left[\frac{d\Gamma}{dx}\right]_{Std}\Delta\xi\delta$$

Because the decay rate is linear in the Michel parameters, these derivatives are independent of them.

Derivative Distributions

Derivative distributions are also produced from the simulation code. The Michel parameters are determined from the combination of distributions that best fit the data.



Standard Model(top), $\Delta\rho$ (bottom, red)$\Delta\eta$(bottom, green)

Fitting $\rho\eta$ with a blind analysis

(Ignoring $\cos\theta$ term)

Replace Std Model ρ, η with values ρ_0, η_0 thrown randomly at event generator initialization. These parameters are encrypted and will be revealed to the group after the analysis is completed.

$$\rho = \rho_{Std} + \Delta\rho \quad \rightarrow \quad \rho = \rho_o + \Delta\rho'$$

$$\eta = \eta_{Std} + \Delta\eta \quad \rightarrow \quad \eta = \eta_o + \Delta\eta'$$

Fitting $\Delta\rho'$ and $\Delta\eta'$

$$\left[\frac{d\Gamma}{dx}\right]_{Data} = \left[\frac{d\Gamma}{dx}\right]_{\rho_o,\eta_o} + \frac{\partial}{\partial\rho}\left[\frac{d\Gamma}{dx}\right]_{\rho_o,\eta_o}\Delta\rho' + \frac{\partial}{\partial\eta}\left[\frac{d\Gamma}{dx}\right]_{\rho_o,\eta_o}\Delta\eta'$$

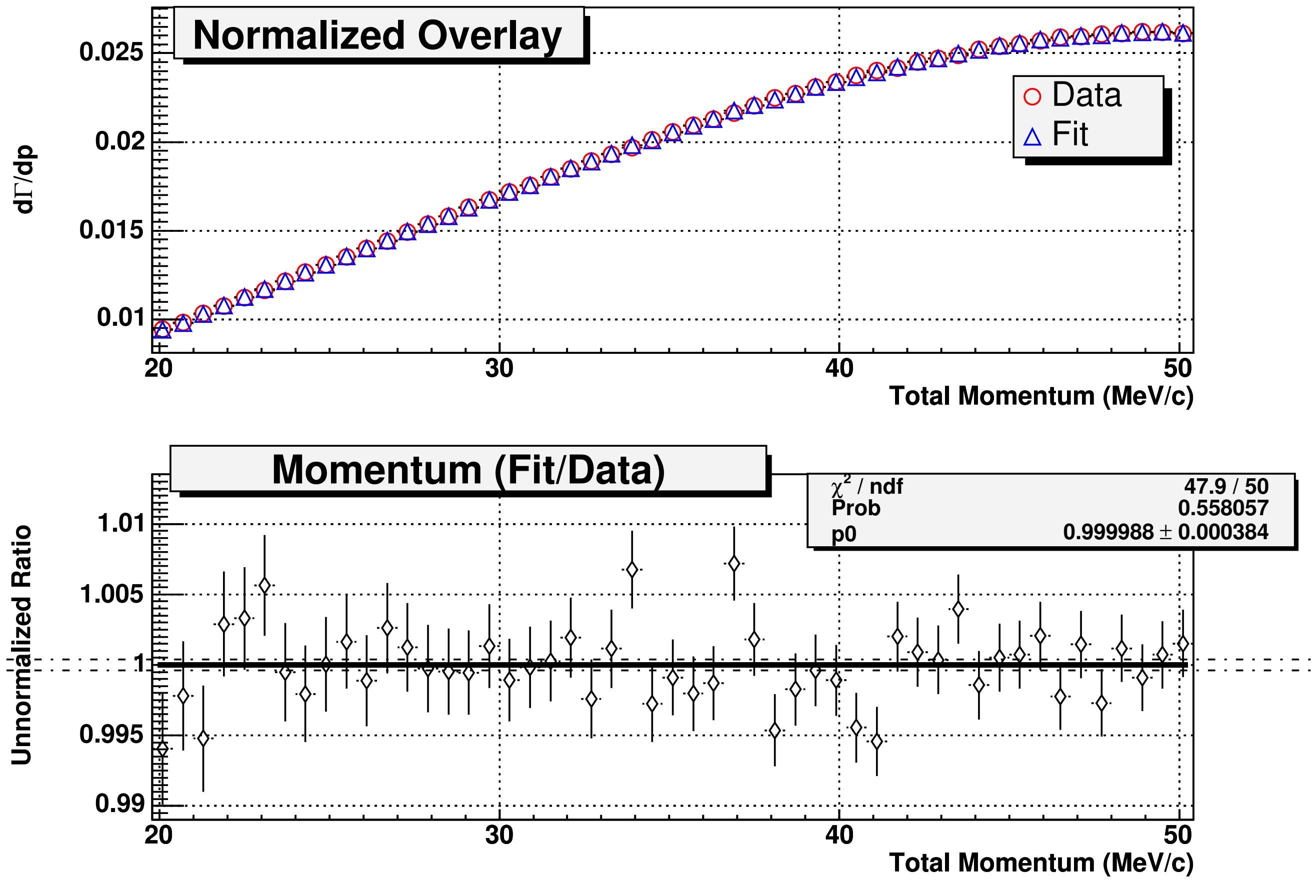
Westgrid

- Compute nodes: 3.06Ghz Xeon blades, 2GB memory and 80GB disk/blade, 14 blades/crate, 4 x 1GB ethernet channels/crate = 1008 CPUs.
- 10 TB global disk storage.
- Tape archiving system with robot good for > 30TB.
- *TWIST* has been a major beta-tester and breaker of Westgrid.
- Still problems with file system stability and archiving. IBM crisis team at work.

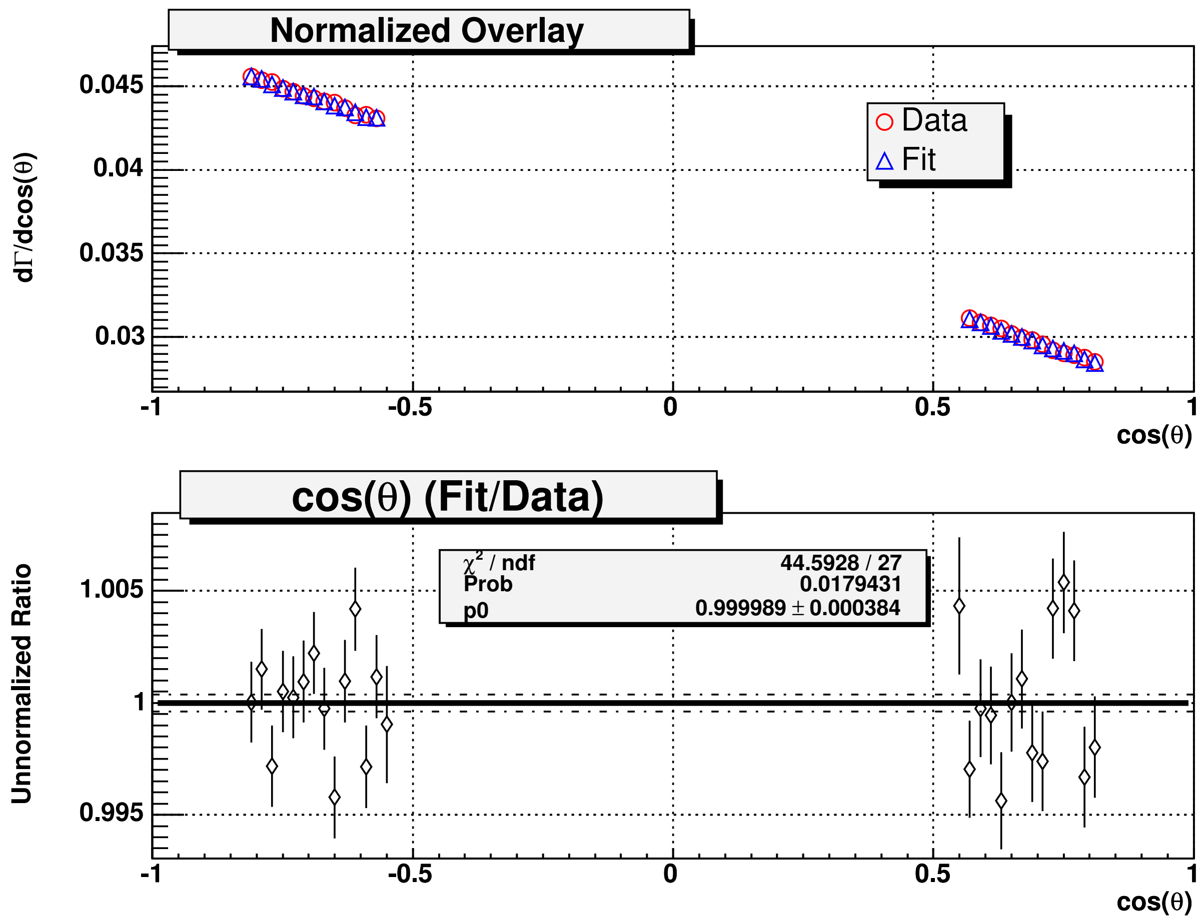
TWIST 2 months on Westgrid

- 50×10^8 events simulated. Processing time 70ms/event=4051 CPU days.
- Raw data transferred: 30×10^8 events.
- 32 analyses of raw data and analyses of all simulated data. Processing time 25 ms/event. 3182 CPU days.
- Data archived so far: 5.7TB simulated data, 6.7TB raw data, 2.5TB root trees - 15TB total.
- Very powerful resource even when it is limping!
- We appreciate the excellent support and cooperation from the Westgrid team.

Fit Quality: Momentum Projection



Fit Quality: Angle Projection



$\Delta\rho(10^{-3}) = -10.6 \pm 2.3$; $\Delta\eta = 0.12 \pm 0.12$; $\Delta\delta(10^{-3}) = -10.8 \pm 1.9$; $\Delta P_\mu \xi = -140.5 \pm 1.9$.

Systematic errors

TWIST is a systematics - limited experiment and the evaluation of biases and systematic errors is of paramount importance. This will be discussed in Blair Jamieson's talk.

Status

- The $\mathcal{TWIST}$ detector is operational. We have recorded several data sets of 10^8 events with mylar and aluminum targets and are investigating the major expected sources of systematics.
- $\mathcal{TWIST}$ makes extensive use of GEANT simulation to understand the experiment, and to help extract physics.
- The reconstruction program is being refined to minimize biases in the analysis.
- Techniques have been developed to validate GEANT without having to perfectly simulate beam properties, and without having a monoenergetic source.
- First results at 10^{-3} precision for ρ and δ are expected next fall.
- Data accumulated this year will focus on the polarization -dependent parameters δ and $P_\mu\xi$.