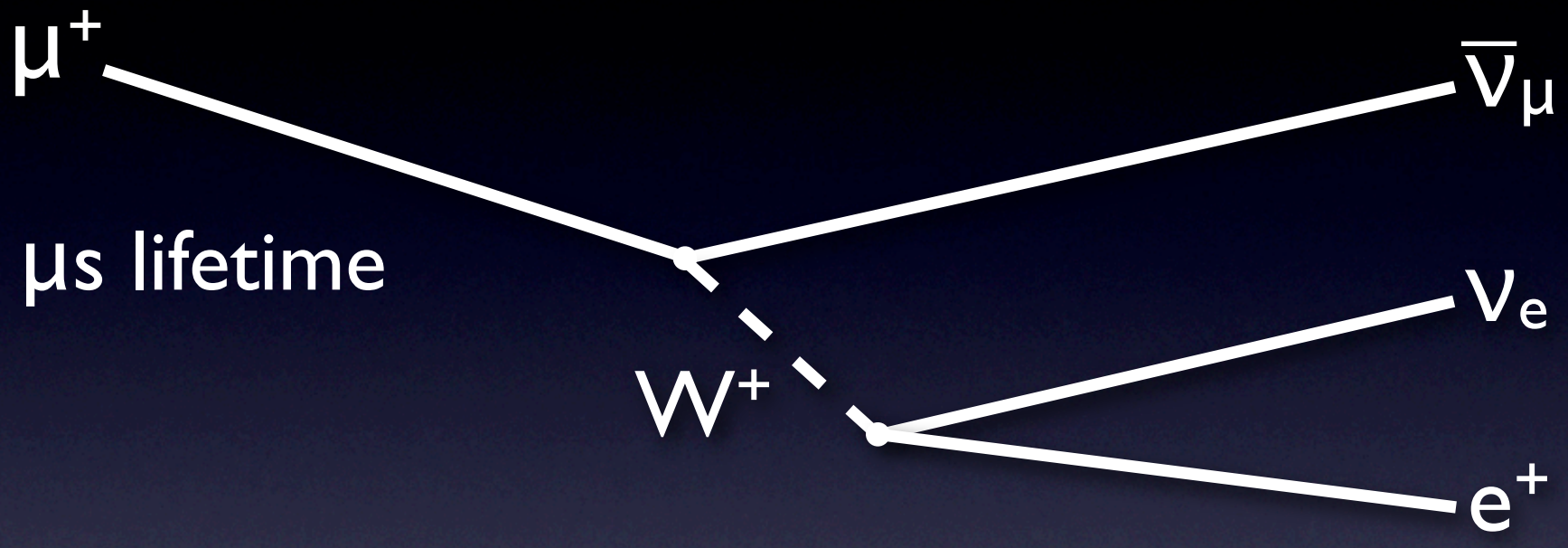
Results of a new muon decay measurement by *TWIST*

Robert MacDonald, University of Alberta
for the *TWIST* collaboration

- Muon Decay and the Weak Interaction
- *TWIST* experiment
- New *TWIST* Results
- Implications

Winter Nuclear and Particle Physics Conference, Banff, AB, 15 Feb 2008

Muon Decay

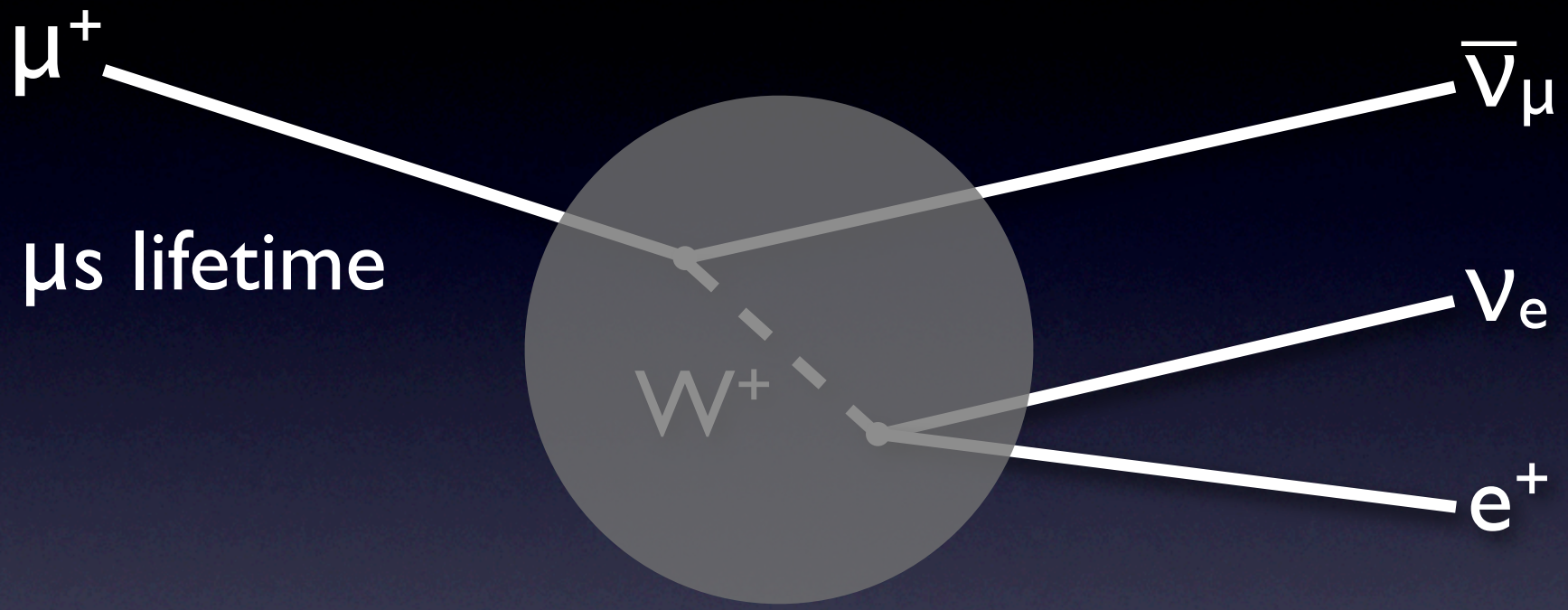


2 μs lifetime

EM radiative corrections calculable

Strong interactions are at < 1e-6 level

Muon Decay



2 μs lifetime

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Weak Matrix Element

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\epsilon=L,R \\ m=L,R \\ \kappa=S,V,T}} g^{\kappa}_{\epsilon m} \left\langle \psi_{e_\epsilon} \middle| \Gamma^{\kappa} \middle| \psi_{\nu_e} \right\rangle \left\langle \psi_{\nu_\mu} \middle| \Gamma_{\kappa} \middle| \psi_{\mu_m} \right\rangle$$

Weak Matrix Element

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Weak Matrix Element

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Weak Matrix Element

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In Standard Model ("V-A"):

$$g^{V}_{LL} = 1$$

$$g^{\kappa}_{\epsilon m} = 0 \quad \text{otherwise}$$

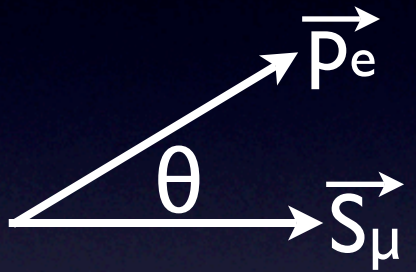
$g^{\kappa}_{\epsilon m}$ constrained by muon decay, inverse decay, etc.

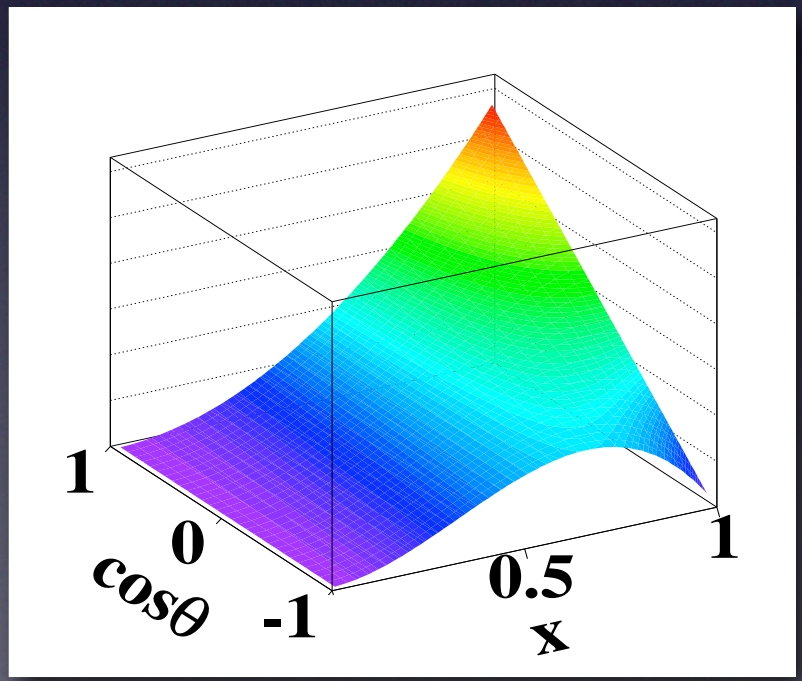
Decay ("Michel") Spectrum

Michel, Kinoshita & Sirlin

$$\frac{d^2\Gamma}{dx\, d(\cos\theta)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\delta) P_\mu \xi \cos\theta$$

$$x = \frac{E}{E_{\max}}$$





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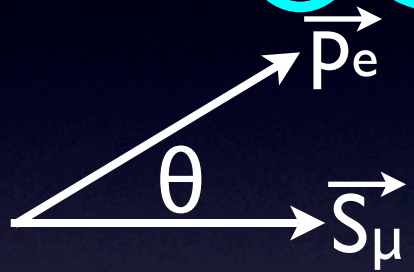
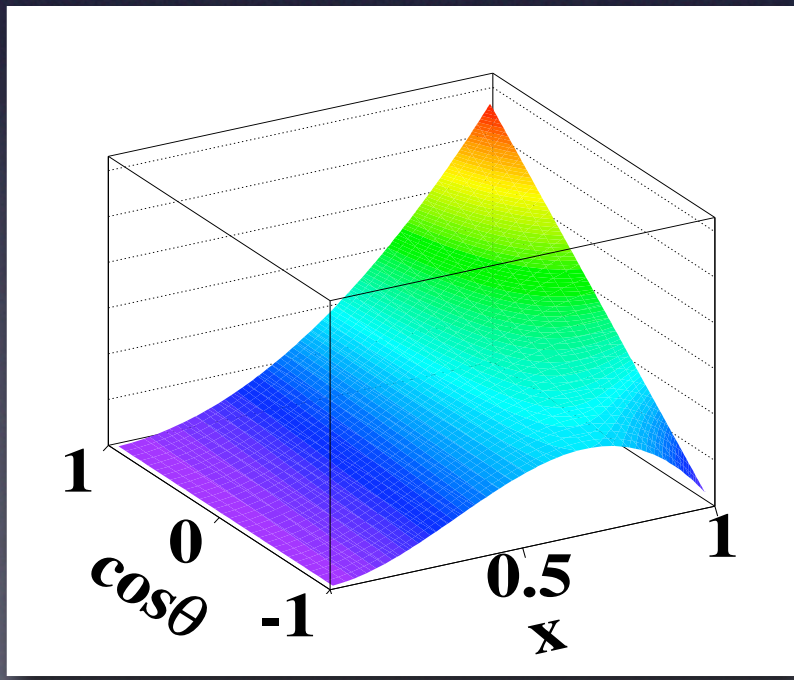


ρ, δ, ξ *are bilinear combinations of* $g^{K}_{\epsilon m}$

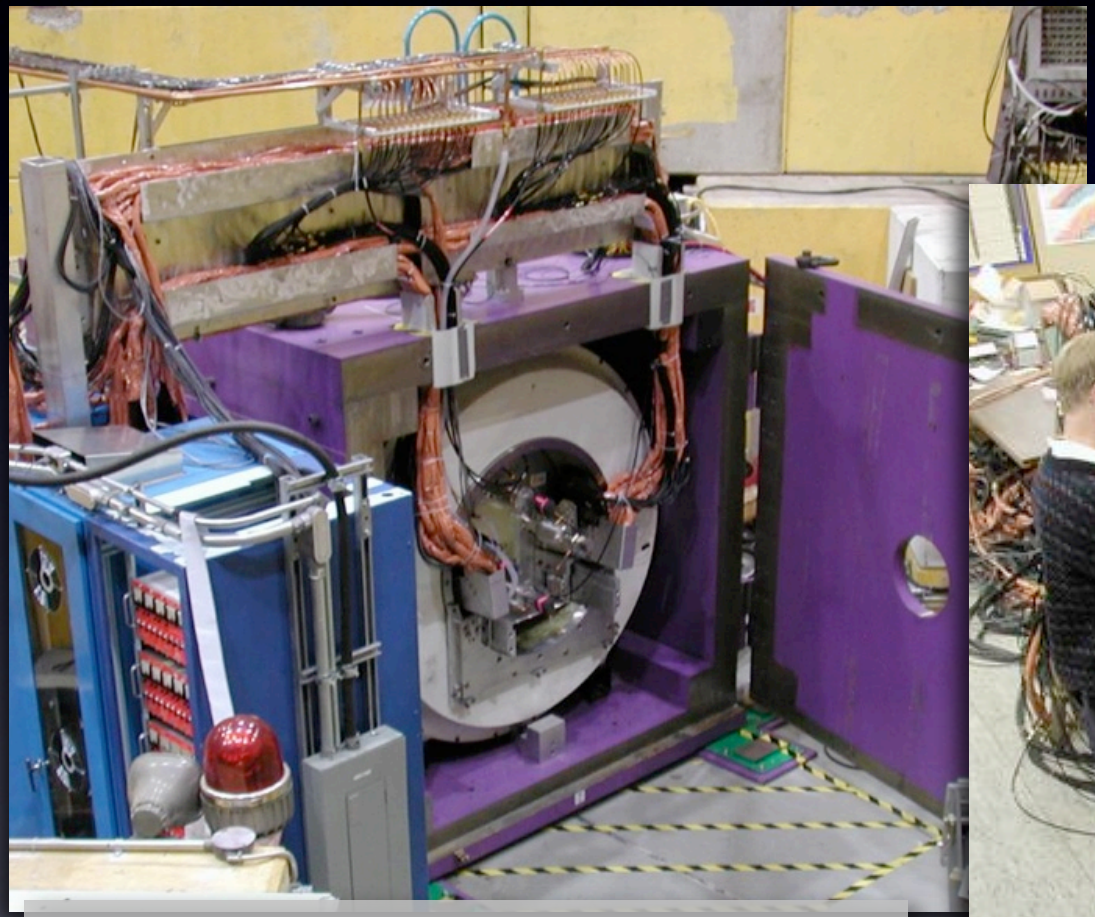
	Pre-TWIST	SM
ρ	0.7518 ± 0.0026	0.75
η	-0.007 ± 0.013	0
$P_\mu\xi$	1.0027 ± 0.0085	1
δ	0.7486 ± 0.0038	0.75



Today's results: new ρ and δ

The *TWIST* Experiment

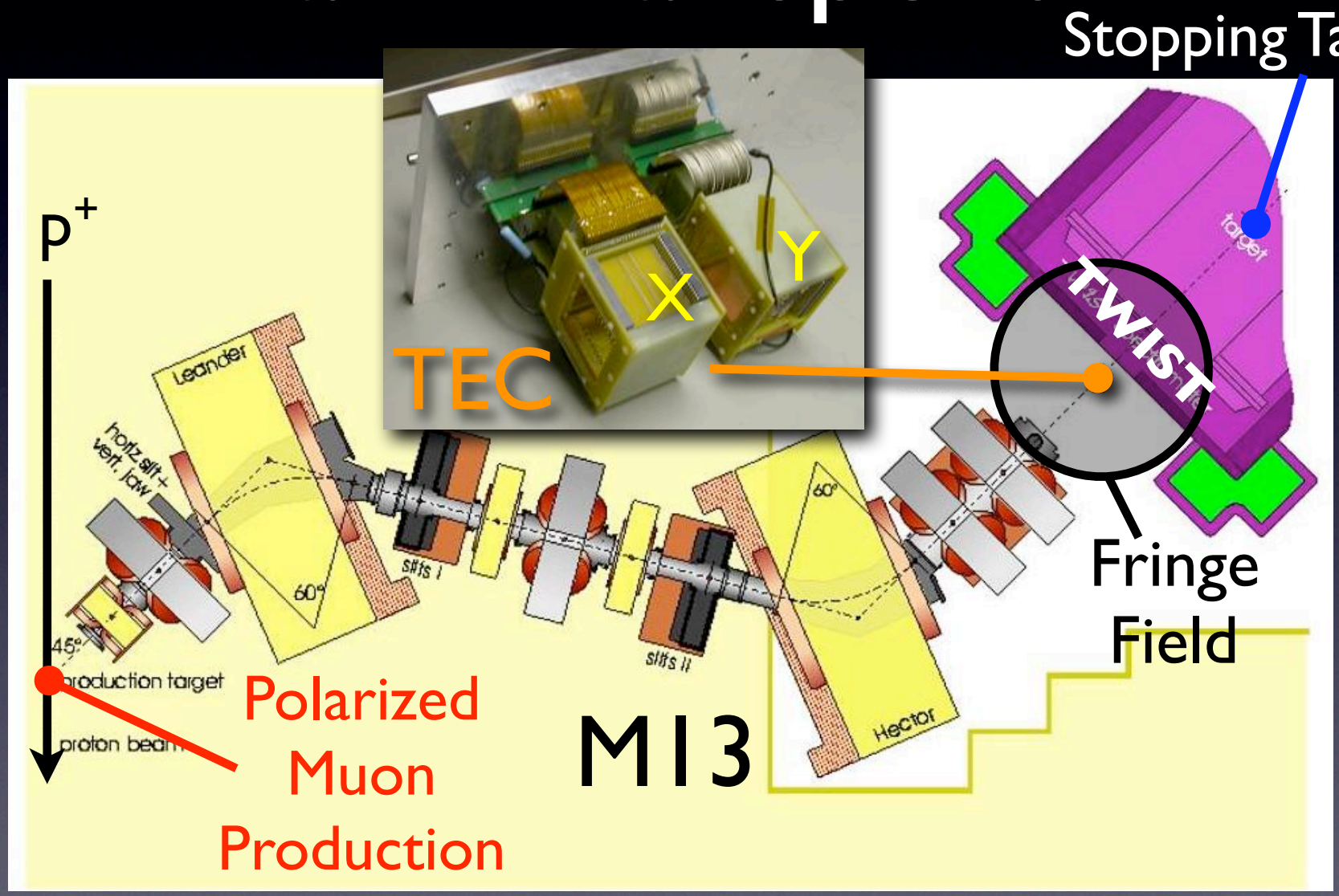
TRIUMF Weak Interaction Symmetry Test



2 Tesla Magnetic Field

Planar Drift Chambers

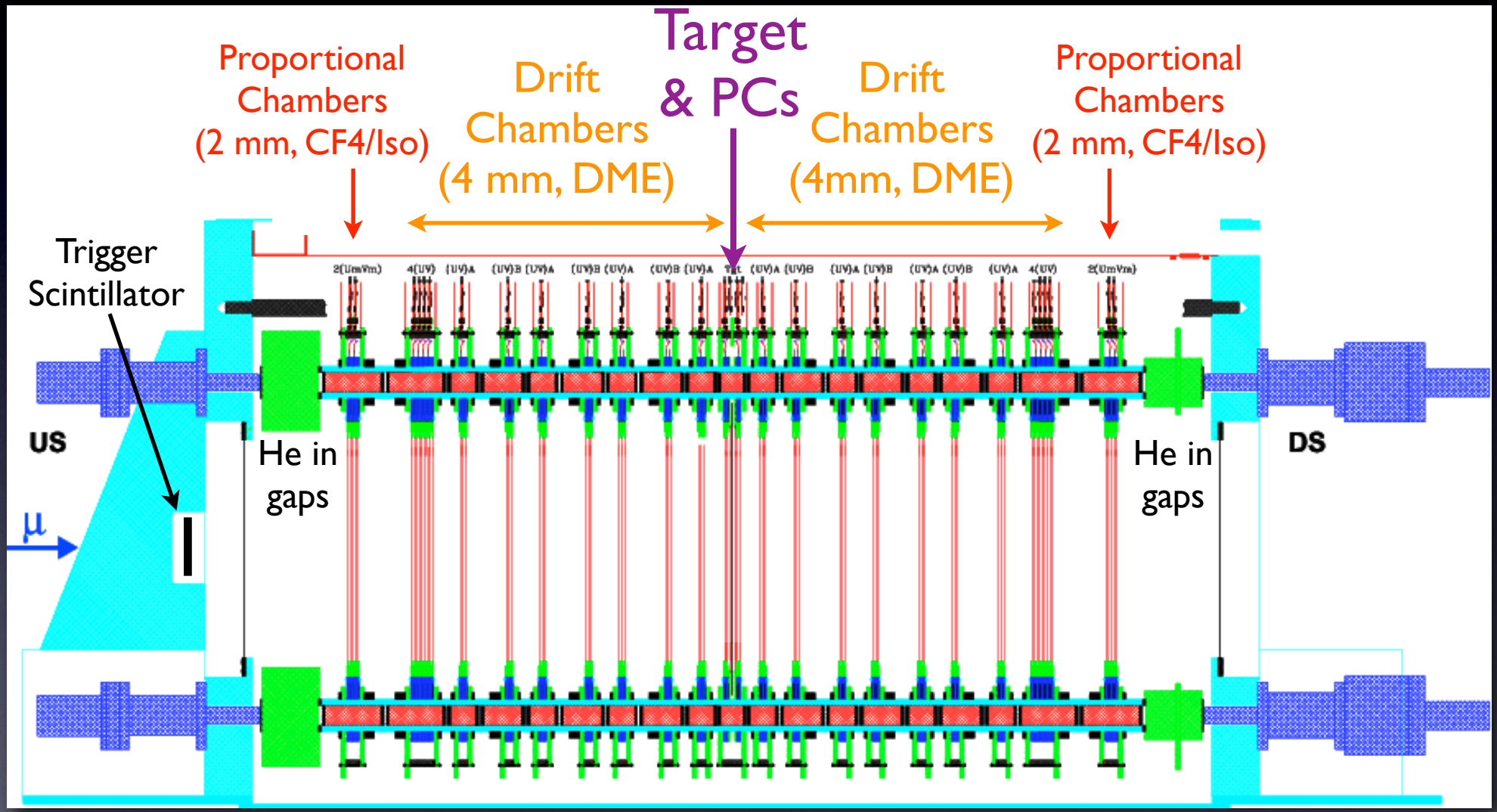
Muon Production and Transport



TEC: NIM A566 (2006), 563

The *TWIST* Detector

Low mass, symmetric, high-precision construction

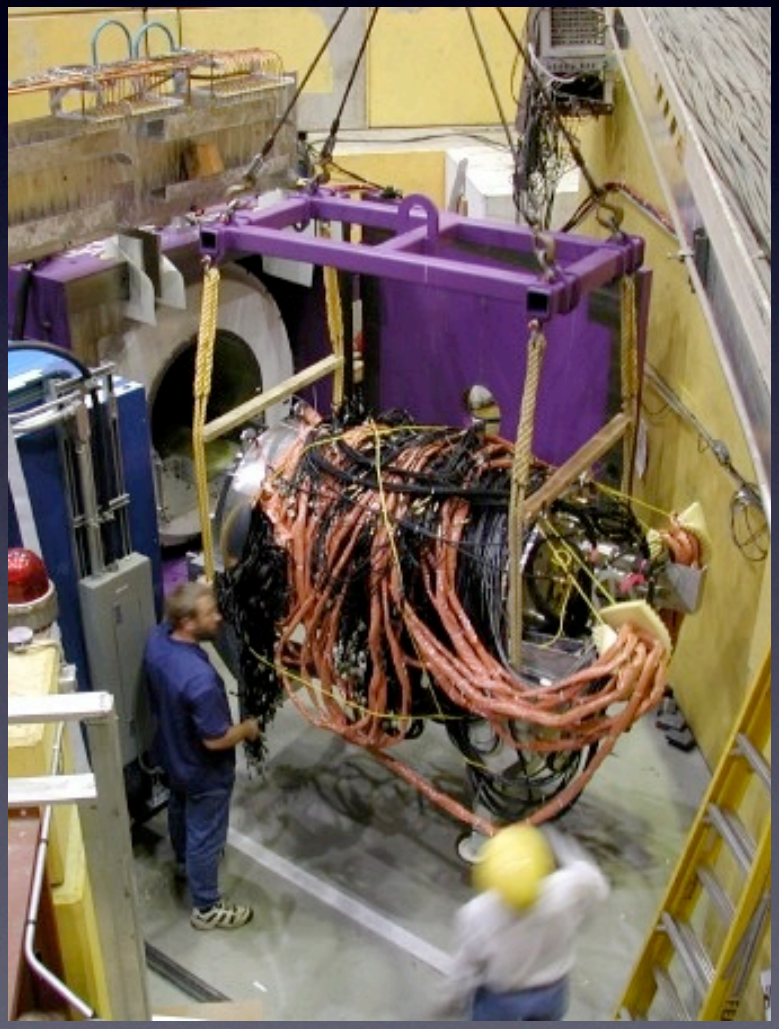


Assembled by hand at TRIUMF

NIM **A548** (2005) 206

TWIST Data Taking is Complete!

15 November, 2001



2 November, 2007

TWIST Data Taking is Complete!

15 November, 2001

2 November, 2007

Many thanks to TRIUMF support staff!

TWIST ρ and δ publications (2005) used 2002 data.

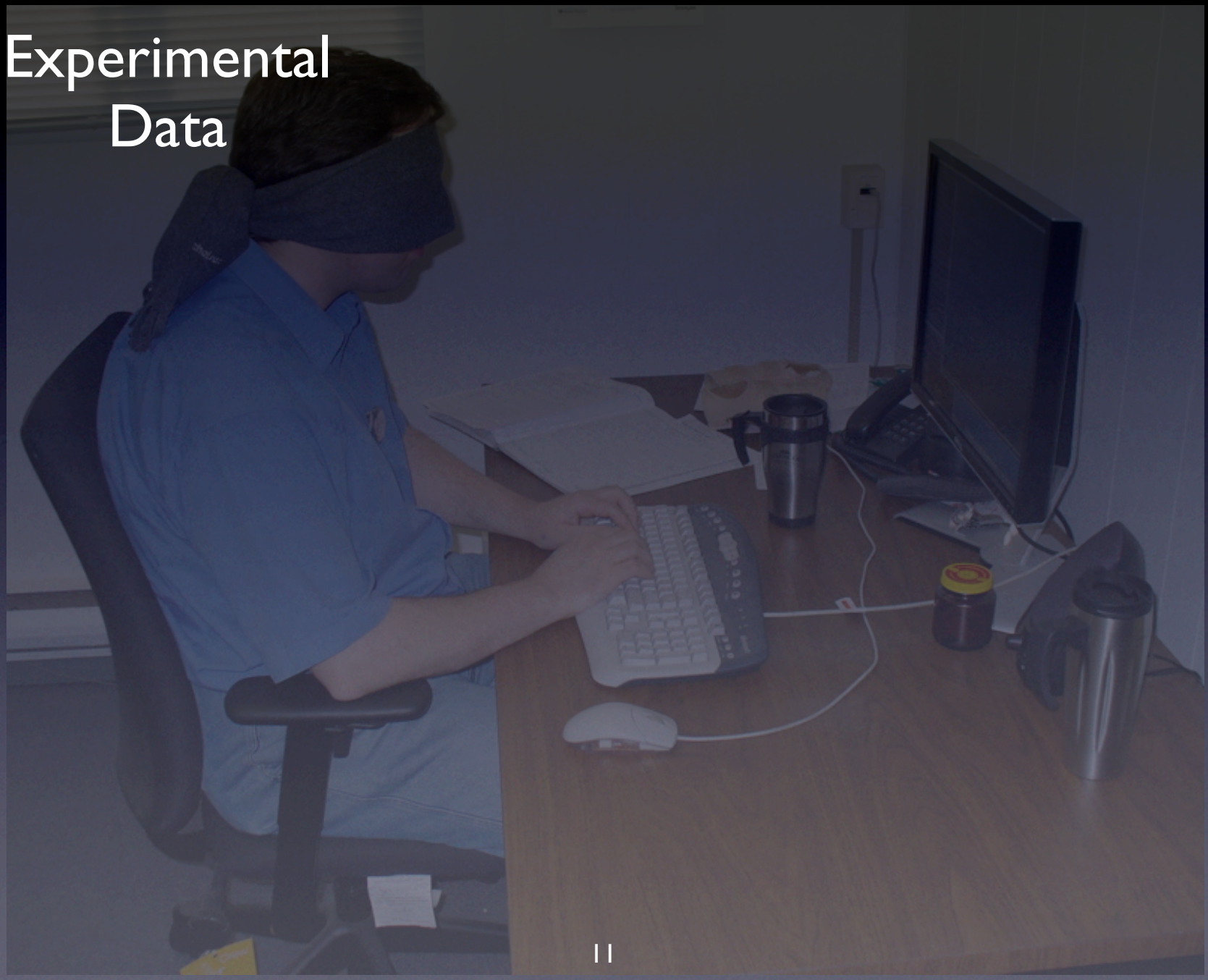
TWIST $P_\mu\xi$ publication (2006) used 2004 data.

Today's ρ and δ measurements
use the same 2004 data.

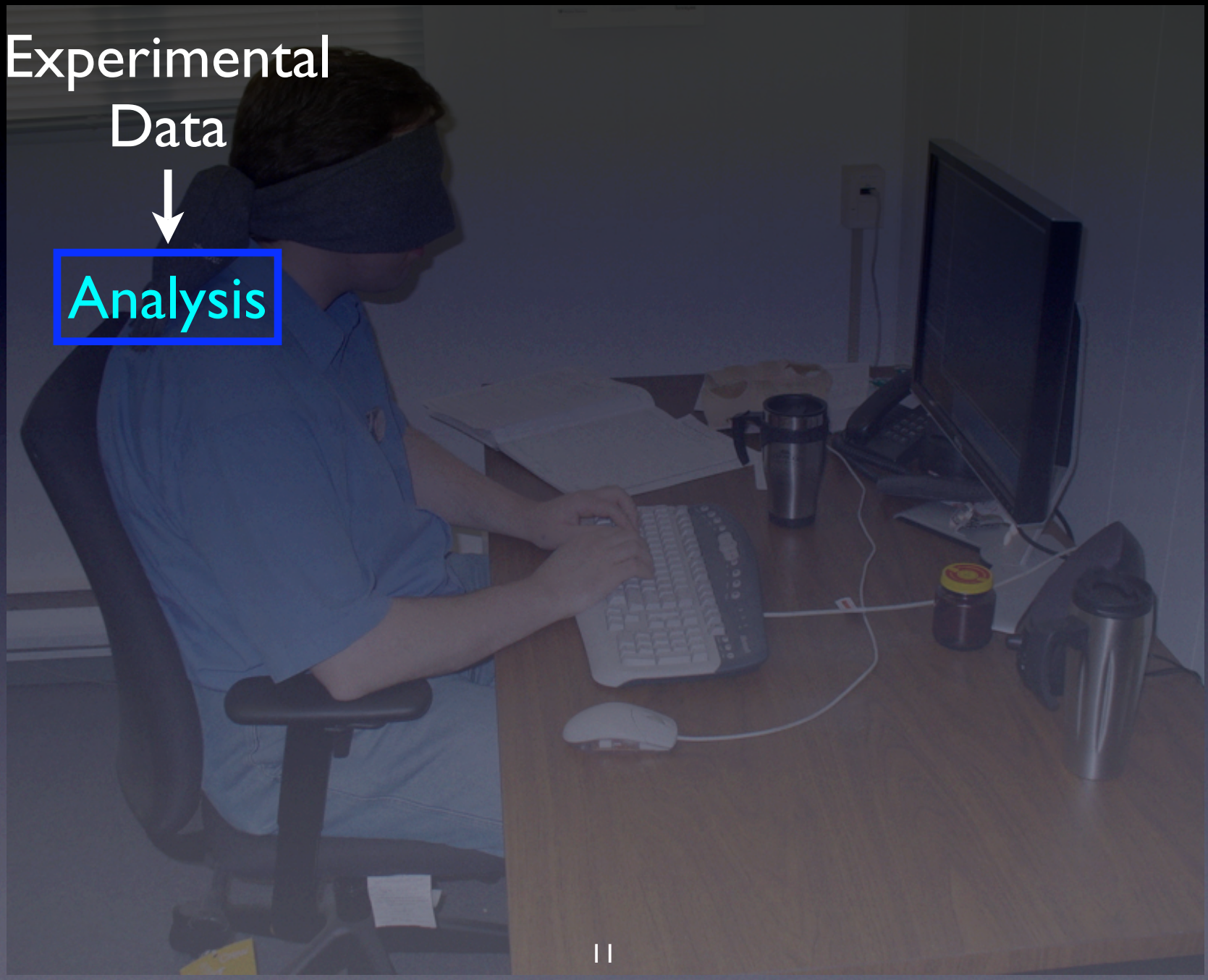
Measurements from 2006/2007 data still to come!
(See talk by James Bueno.)

Blind Analysis

Blind Analysis



Blind Analysis



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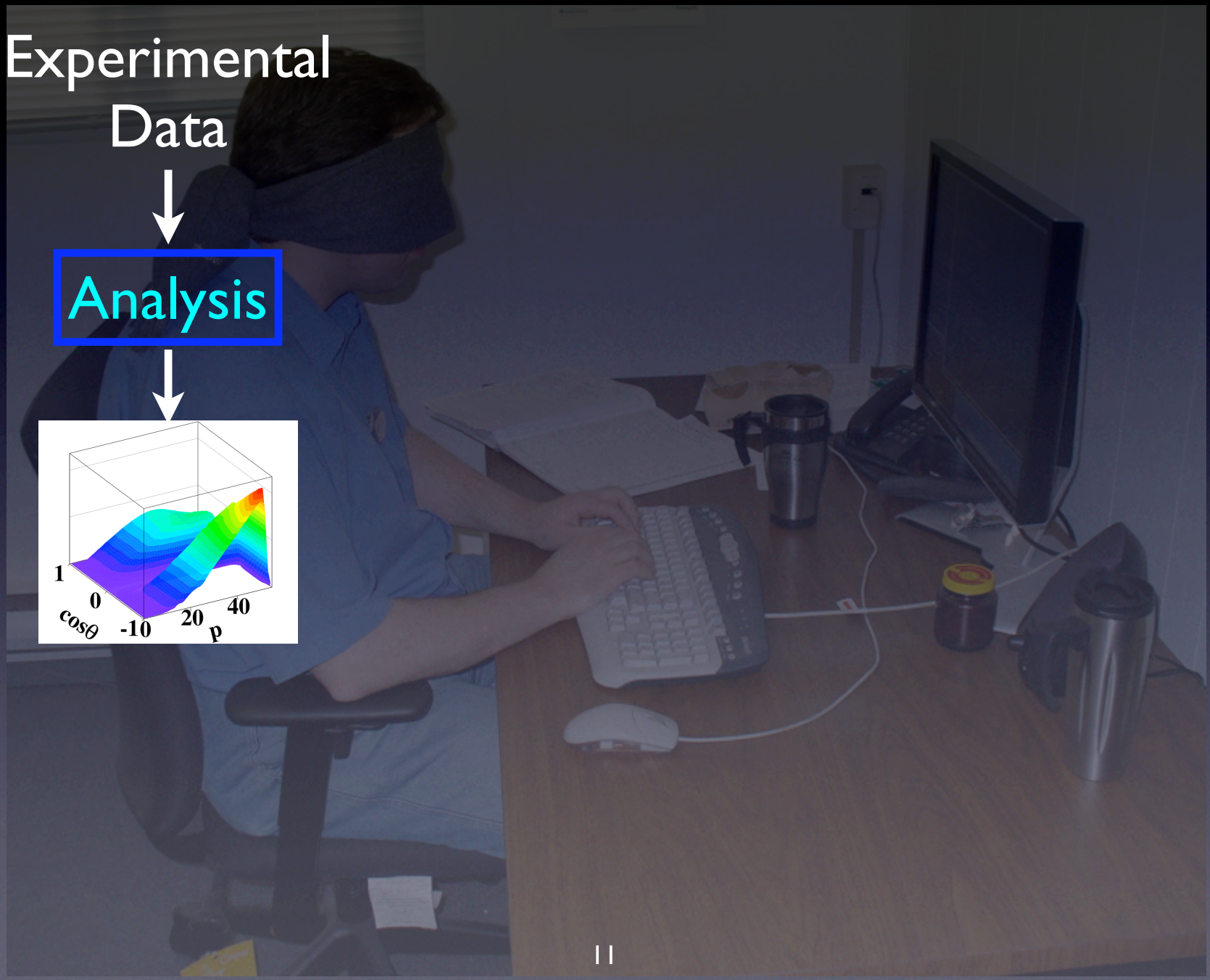
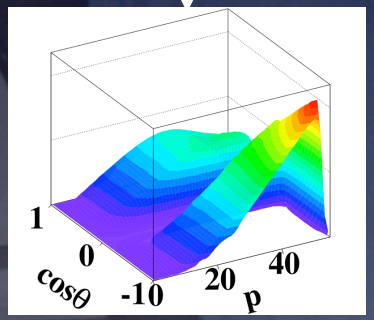


Blind Analysis

Experimental Data

Analysis

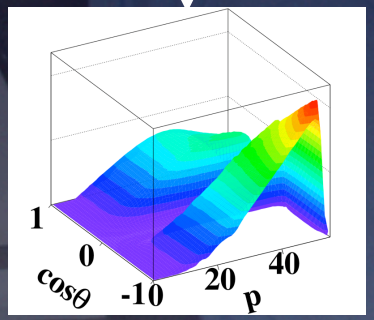


Geant3 Simulation

Blind Analysis

Experimental Data

Analysis



hidden
ρ_{MC}, δ_{MC}, ξ_{MC}

Geant3 Simulation

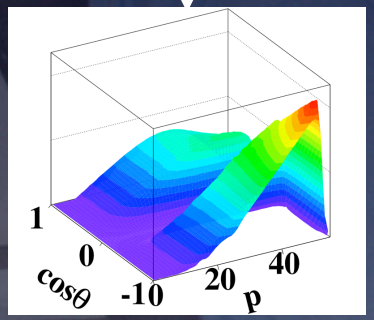
Blind Analysis

Experimental Data

↓

Analysis

↓



hidden
ρ_{MC}, δ_{MC}, ξ_{MC}

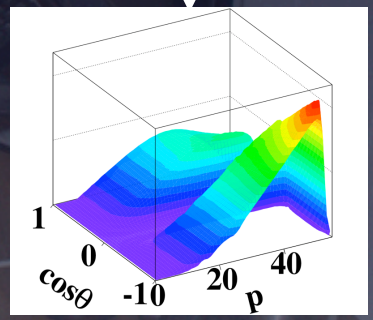
→

Geant3 Simulation

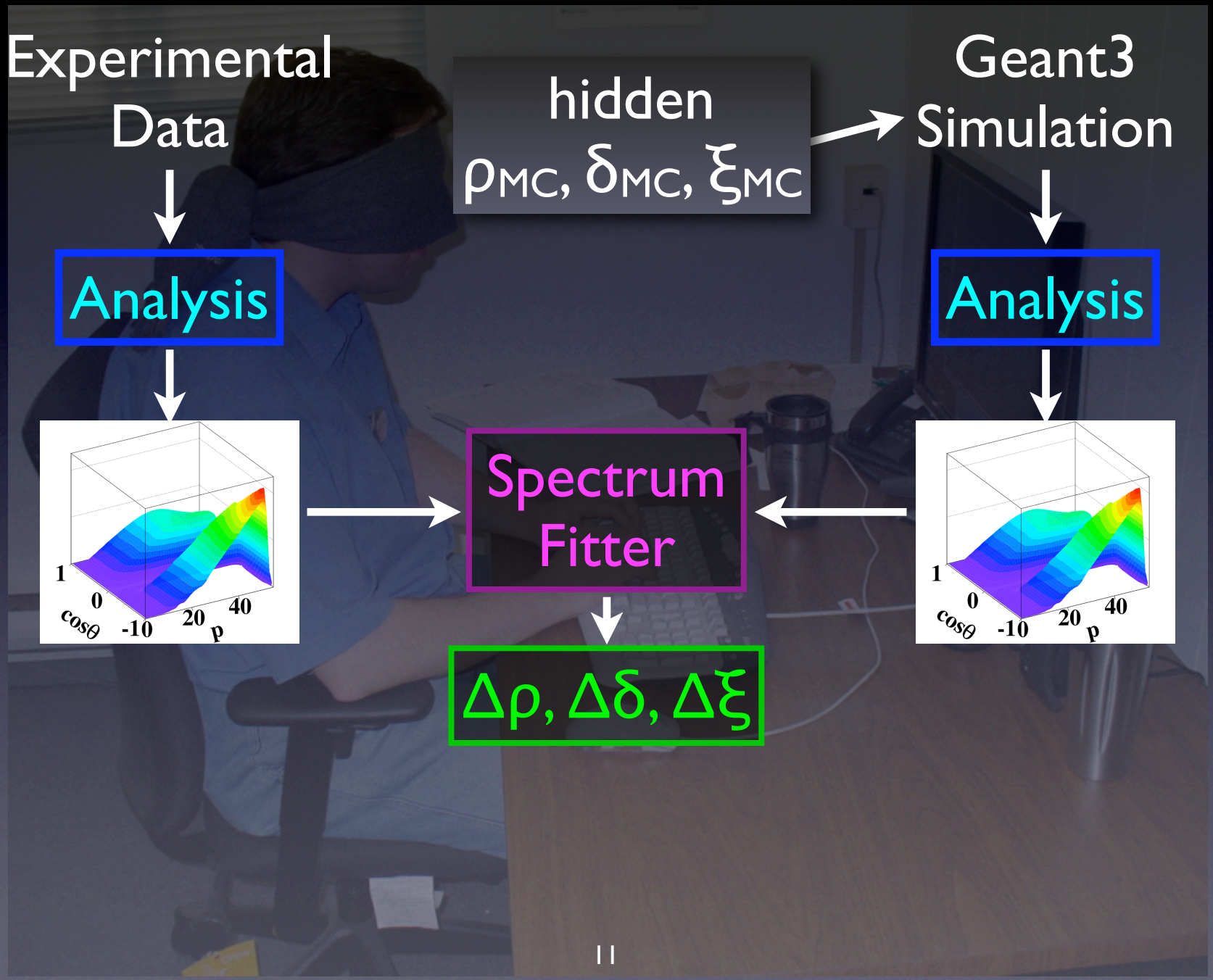
↓

Analysis

↓



Blind Analysis



Blind Analysis

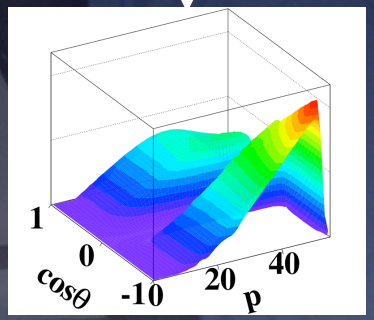
Experimental Data

hidden ρ_{MC}, δ_{MC}, ξ_{MC}

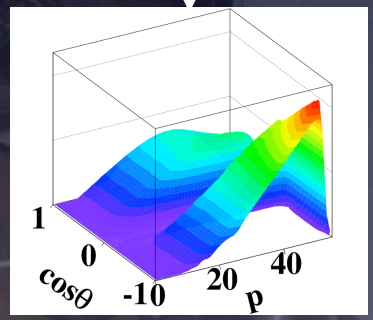
Geant3 Simulation

Analysis

Analysis



Spectrum Fitter



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

revealed ρ_{MC}, δ_{MC}, ξ_{MC}

ρ, δ, ξ

Blind Analysis

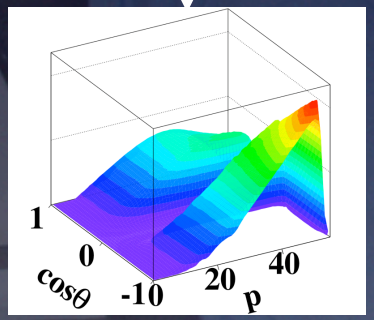
Experimental Data

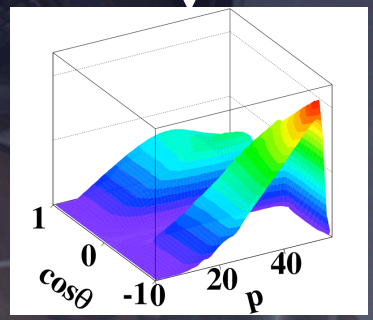
hidden ρ_{MC}, δ_{MC}, ξ_{MC}

Geant3 Simulation

Analysis

Analysis





Spectrum Fitter

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

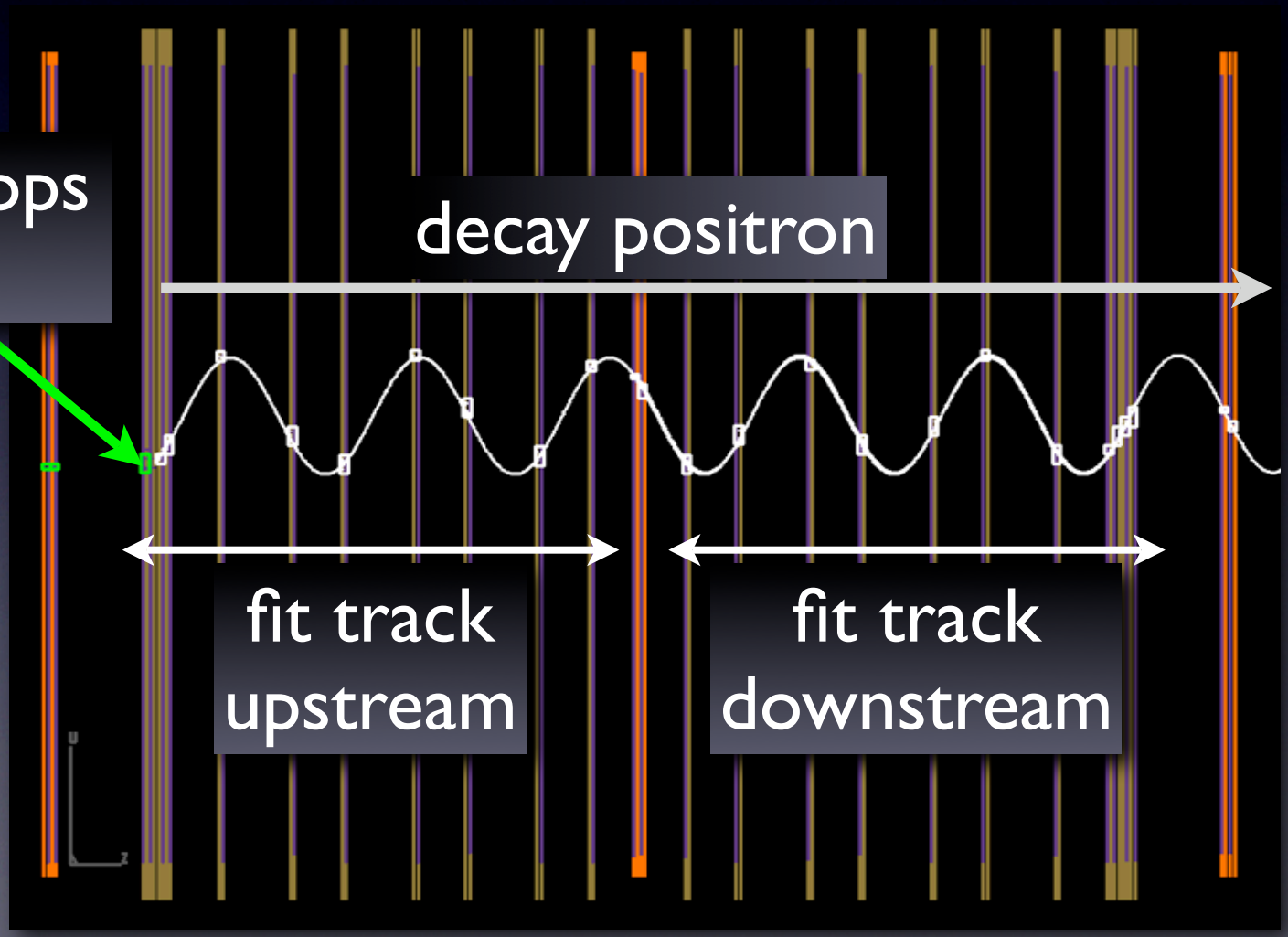
revealed ρ_{MC}, δ_{MC}, ξ_{MC}

ρ, δ, ξ

Analysis made possible by ***WestGrid***

Verifying our Simulation

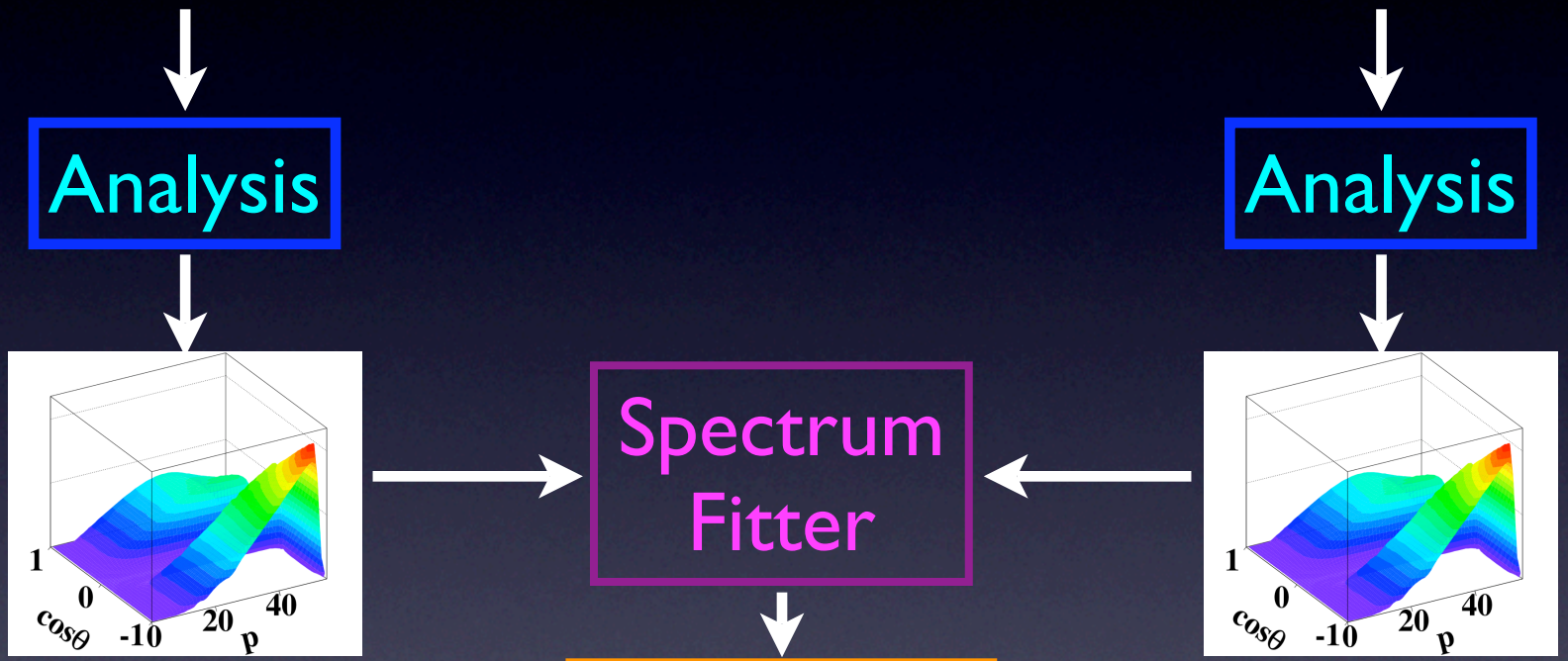
Specialized data, reproduced in simulation
➡ independent of Michel parameters



Determining Systematics

Exaggerated Simulation

Geant3 Simulation

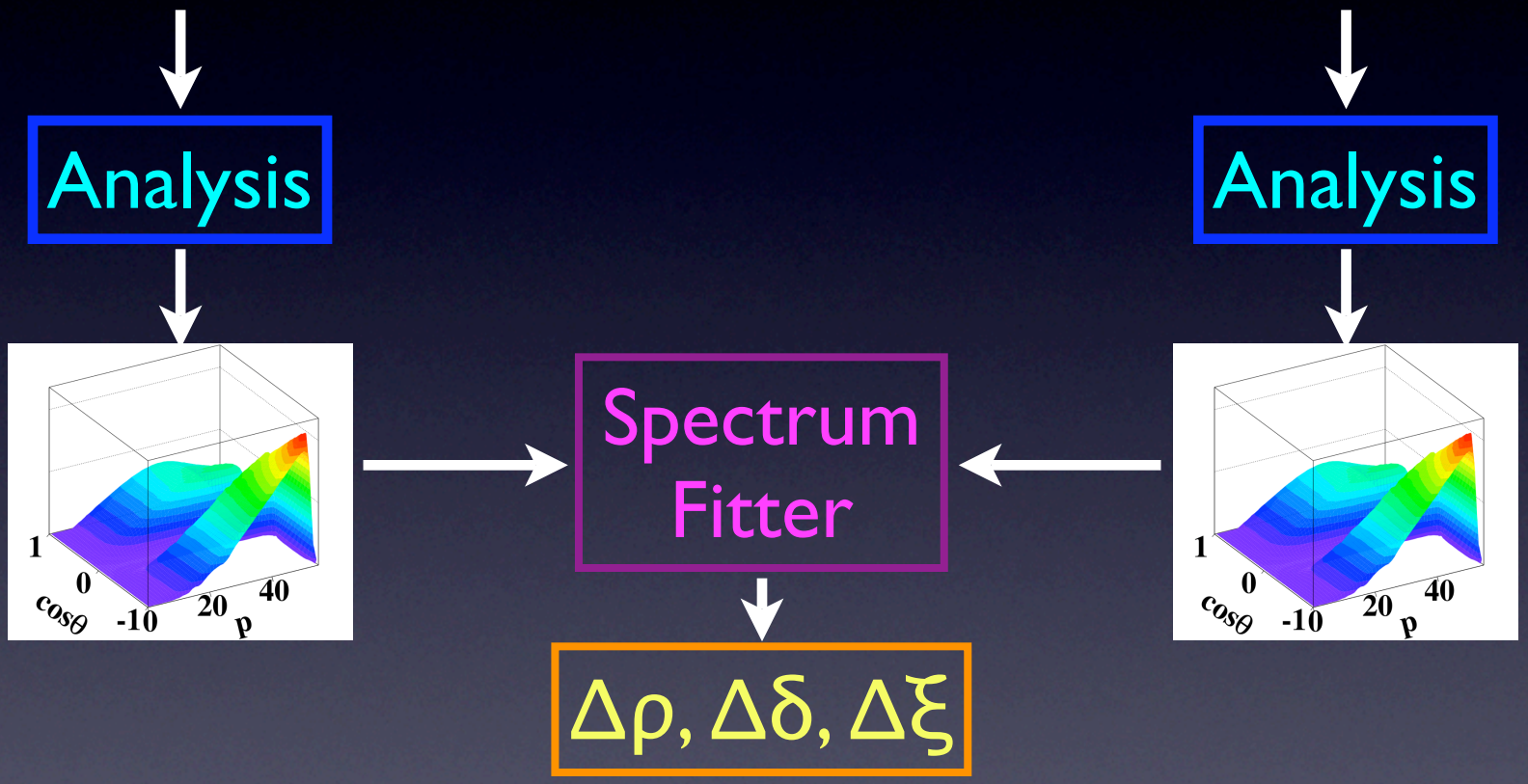


Determining Systematics

Exaggerated Simulation

- Bremsstrahlung
- Chamber geometry
- …

Geant3 Simulation



Determining Systematics

Exaggerated Simulation

- Bremsstrahlung
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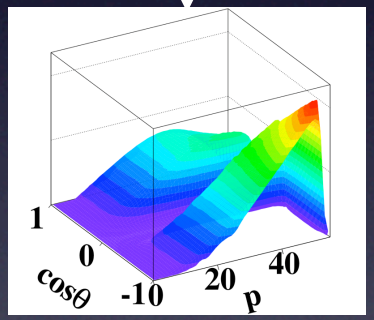
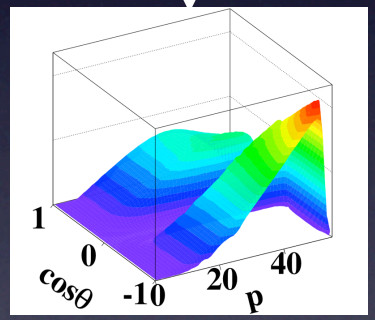
- …

Geant3 Simulation

Analysis



Spectrum Fitter



Analysis

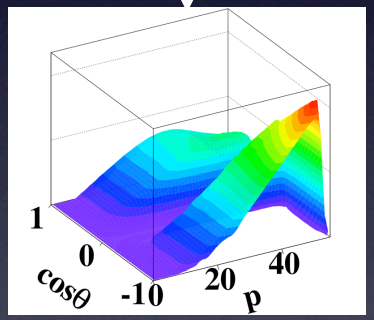
$\Delta\rho, \Delta\delta, \Delta\xi$

$$\text{Systematic Uncertainty} = \frac{(\Delta\rho, \Delta\delta, \Delta\xi)}{\text{Exaggeration}}$$

Determining Systematics

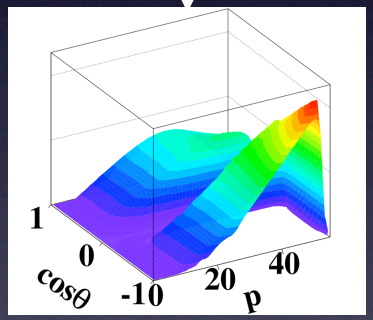
Geant3 Simulation

Exaggerated Analysis



Geant3 Simulation

Analysis



Spectrum Fitter

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

$$\text{Systematic Uncertainty} = \frac{(\Delta\rho, \Delta\delta, \Delta\xi)}{\text{Exaggeration}}$$

Determining Systematics

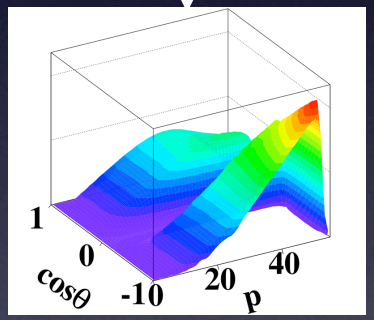
Geant3 Simulation

Exaggerated Analysis

- Magnetic field
- Chamber alignment
- …

Geant3 Simulation

Analysis



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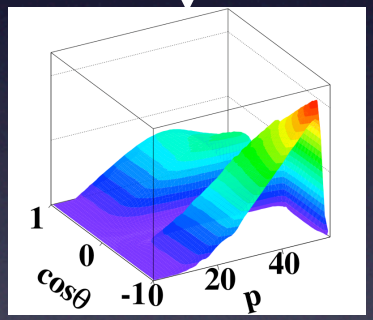


$\Delta\rho, \Delta\delta, \Delta\xi$

$$\text{Systematic Uncertainty} = \frac{(\Delta\rho, \Delta\delta, \Delta\xi)}{\text{Exaggeration}}$$

Units of 0.0001	Published ρ	New ρ	Published δ	New δ
Chamber response	5.1	2.9	6.1	5.2
Target thickness	4.9	< 0.1	3.7	< 0.1
Positron interactions	4.6	1.6	5.5	0.9
Alignment	2.2	0.3	6.1	0.3
Momentum calibration	2.0	2.9	2.9	4.1
Radiative corrections	2.0	< 0.1	1.0	< 0.1
Other	1.2	1.1	1.1	0.4
Total	**9.2**	**4.6**	**11.3**	**6.7**

ρ: *Phys. Rev. Lett.* ***94****, 101805 (2005)* δ: *Phys. Rev. D* ***71****, 071101(R) (2005)*

Highlights of Improvements

Chamber response	online monitoring, increased instrumentation
Target thickness	precision target geometry
Positron interactions	improved upstream stops data
Momentum calibration	New calibration technique; uncertainty is statistical

New Measurements

Pre-*TWIST*: 0.7518 ± 0.0026

TWIST published: 0.75080± 0.00032(stat)± 0.00097(sys)

NEW (preliminary): 0.75014± 0.00017(stat)± 0.00046(sys)
± 0.00011(η)

Pre-*TWIST*: 0.7468 ± 0.0026(stat) ± 0.0028(sys)

TWIST published: 0.74964± 0.00066(stat)± 0.00112(sys)

NEW (preliminary): 0.75068± 0.00030(stat)± 0.00067(sys)

Weak Coupling	pre-*TWIST*	Gagliardi*	Current
$\lvert g^{S}_{RR}\rvert$	< 0.066	< 0.067	< 0.063
$\lvert g^{S}_{LR}\rvert$	**< 0.125**	**< 0.088**	**< 0.076**
$\lvert g^{S}_{RL}\rvert$	< 0.424	< 0.417	< 0.415
$\lvert g^{S}_{LL}\rvert$	< 0.550	< 0.550	< 0.550
$\lvert g^{V}_{RR}\rvert$	< 0.033	< 0.034	< 0.032
$\lvert g^{V}_{LR}\rvert$	**< 0.066**	**< 0.036**	**< 0.027**
$\lvert g^{V}_{RL}\rvert$	< 0.110	< 0.104	< 0.105
$\lvert g^{V}_{LL}\rvert$	> 0.960	> 0.960	> 0.960
$\lvert g^{T}_{LL}\rvert$	$\equiv 0$	$\equiv 0$	$\equiv 0$
$\lvert g^{T}_{LR}\rvert$	**< 0.036**	**< 0.025**	**< 0.022**
$\lvert g^{T}_{RL}\rvert$	< 0.112	< 0.104	< 0.104
$\lvert g^{T}_{RR}\rvert$	$\equiv 0$	$\equiv 0$	$\equiv 0$

90% Confidence Limits

*Phys. Rev. D **72**, 073002 (2005)

The *TWIST* Experiment

New high-precision measurement!

$\rho = 0.75014 \pm 0.00017(\text{stat}) \pm 0.00046(\text{sys})$
$\pm 0.00011(\eta)$

$\delta = 0.75068 \pm 0.00030(\text{stat}) \pm 0.00067(\text{sys})$

Systematics well understood

Significant improvements in Weak limits

On course for order of magnitude improvement

The *TWIST* Collaboration

TRIUMF
Ryan Bayes ✪ ✻
Yuri Davydov
Wayne Faszer
Makoto Fujiwara
David Gill
Alexander Grossheim
Peter Gumplinger
Anthony Hillairet ✪ ✻
Robert Henderson
Jingliang Hu
John A. Macdonald ✾
Glen Marshall
Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin ✻
Robert Openshaw
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin ✧

Alberta
Andrei Gaponenko ★
Peter Kitching
Robert MacDonald ✪
Nate Rodning ✾
Maher Quraan

British Columbia
James Bueno ✪
Mike Hasinoff
Blair Jamieson ★

Montréal
Pierre Depommier

Regina
Ted Mathie
Roman Tacik

Kurchatov Institute
Vladimir Selivanov

Texas A&M
Carl Gagliardi
Jim Musser ★
Bob Tribble

Valparaiso
Don Koetke
Shirvel Stanislaus

✪ graduate student
★ graduated
✻ also U Vic
✧ also Saskatchewan
✾ deceased

http://twist.triumf.ca

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

Decay Parameters and Coupling Constants

$$
\begin{aligned}
\rho &= \frac{3}{4} - \frac{3}{4}[|g^V_{RL}|^2 + |g^V_{LR}|^2 + 2|g^T_{RL}|^2 + 2|g^T_{LR}|^2 \\
&\quad + \mathbb{R}e\,(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR})] \\
\eta &= \frac{1}{2}\mathbb{R}e[g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})] \\
\xi &= 1 - \frac{1}{2}|g^S_{LR}|^2 - \frac{1}{2}|g^S_{RR}|^2 - 4|g^V_{RL}|^2 + 2|g^V_{LR}|^2 - 2|g^V_{RR}|^2 \\
&\quad + 2|g^T_{LR}|^2 - 8|g^T_{RL}|^2 + 4\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL}) \\
\xi\delta &= \frac{3}{4} - \frac{3}{8}|g^S_{RR}|^2 - \frac{3}{8}|g^S_{LR}|^2 - \frac{3}{2}|g^V_{RR}|^2 - \frac{3}{4}|g^V_{RL}|^2 - \frac{3}{4}|g^V_{LR}|^2 \\
&\quad - \frac{3}{2}|g^T_{RL}|^2 - 3|g^T_{LR}|^2 + \frac{3}{4}\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})
\end{aligned}
$$

Spectrum Fitter

$$\frac{d^2\Gamma}{dx\, d(\cos\theta_s)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\delta) P_\mu \xi \cos\theta$$

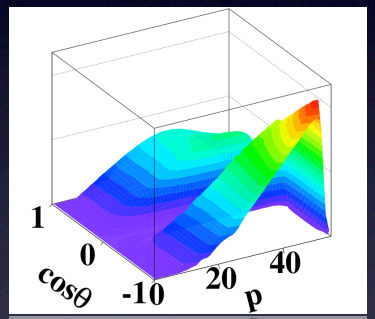
Spectrum Fitter

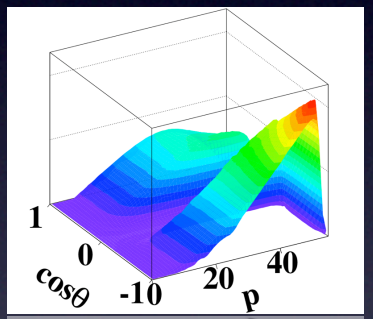
$$\frac{d^2\Gamma}{dx\, d(\cos\theta_s)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\xi,\xi\delta) P_\mu \cos\theta$$

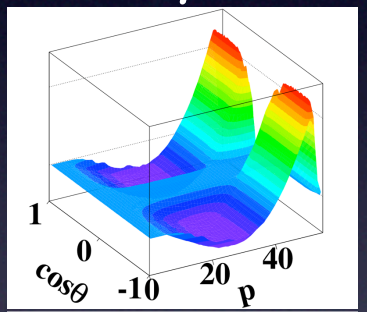
Spectrum Fitter

$$\frac{d^2\Gamma}{dx\, d(\cos\theta_s)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\xi,\xi\delta) P_\mu \cos\theta$$

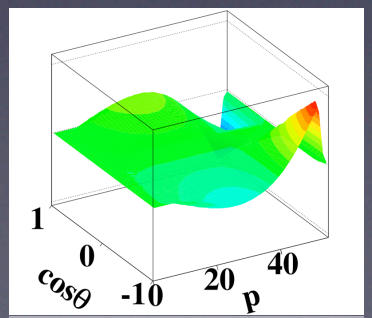
$$N(\alpha_{\mathrm{Data}}) = N(\alpha_{\mathrm{MC}}) + \frac{\partial N}{\partial \rho}\Delta\rho$$

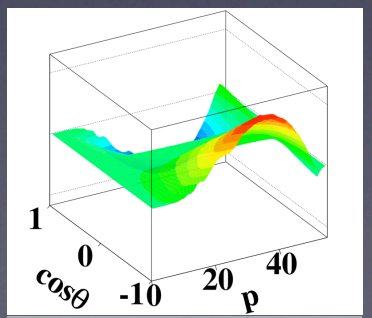






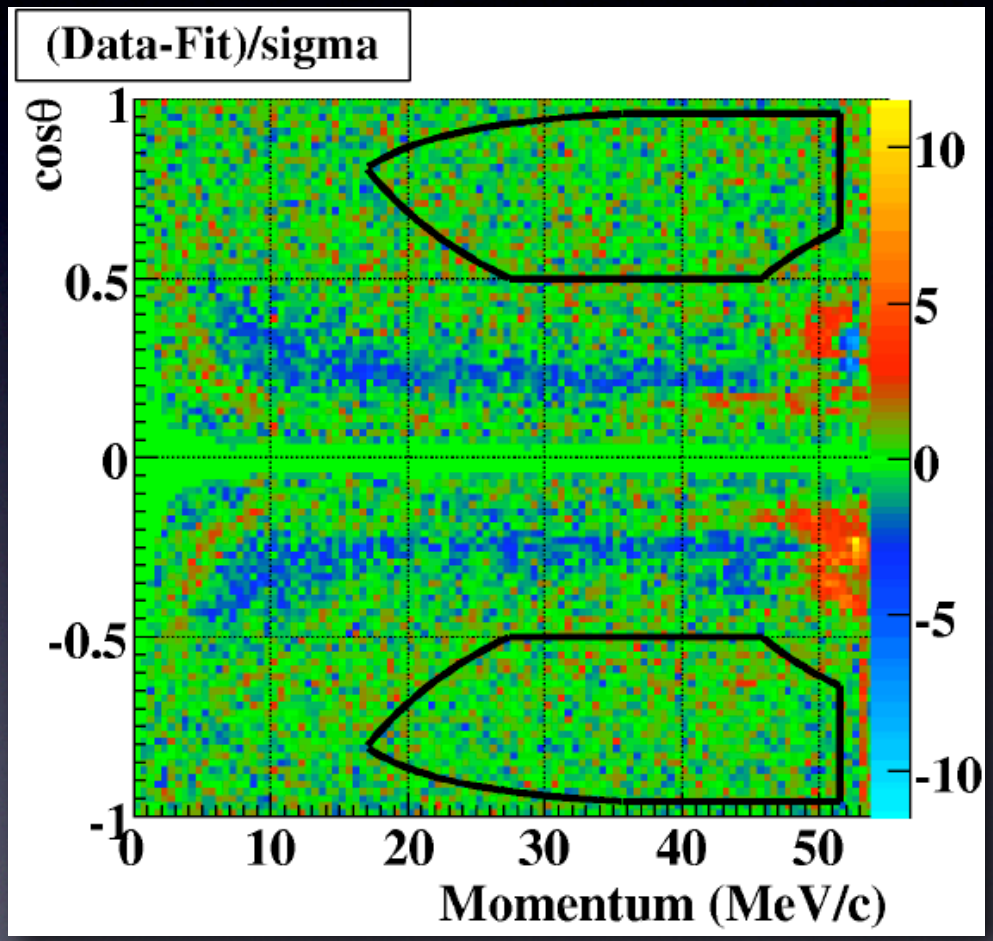
$$+ \frac{\partial N}{\partial \xi\delta}\Delta P_\mu \xi\delta + \frac{\partial N}{\partial \xi}\Delta P_\mu \xi$$

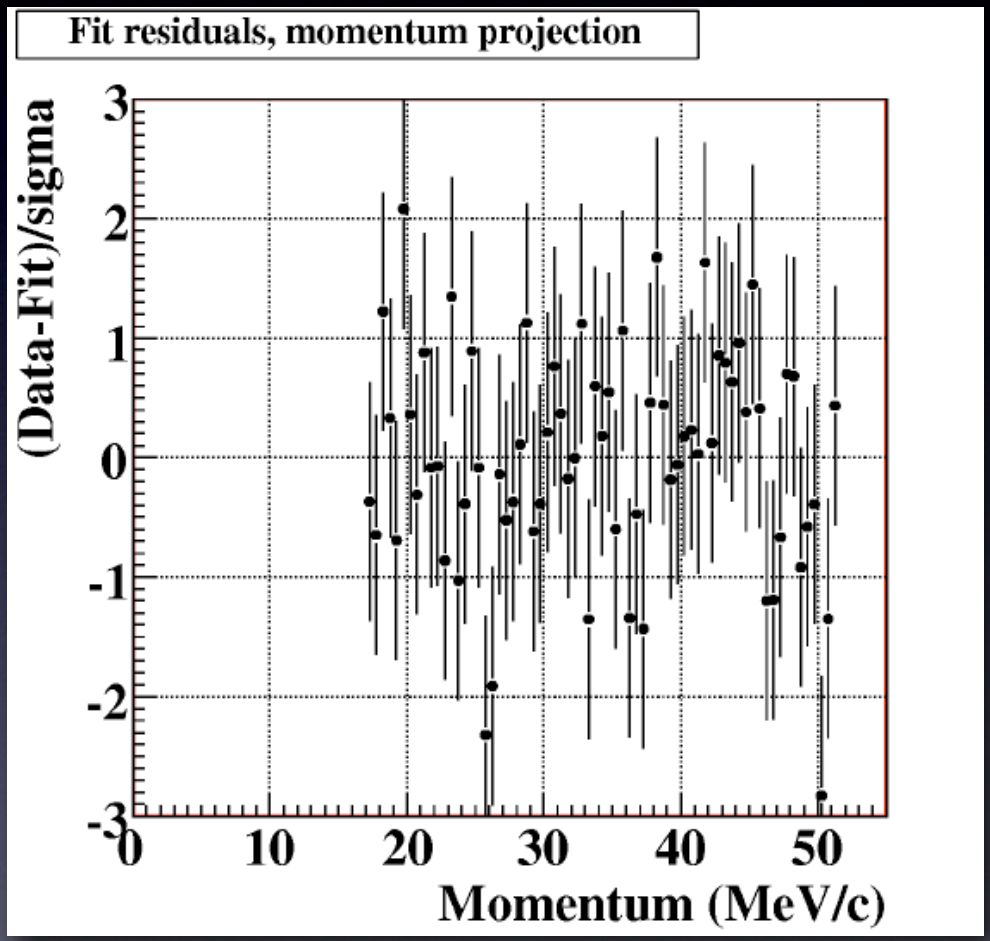




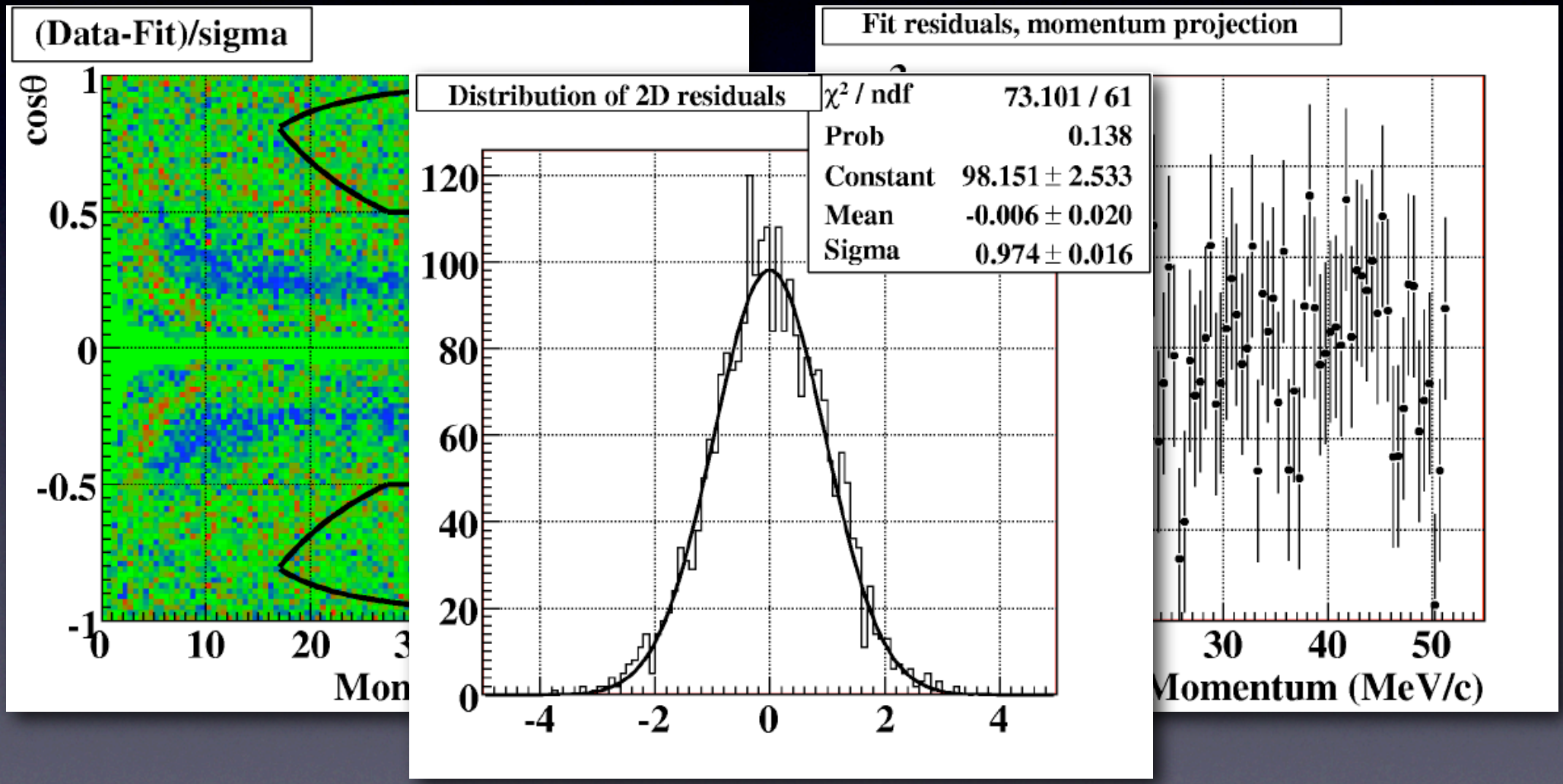
$\alpha = \{\rho, \delta, \xi\}$

Spectrum Fit Quality

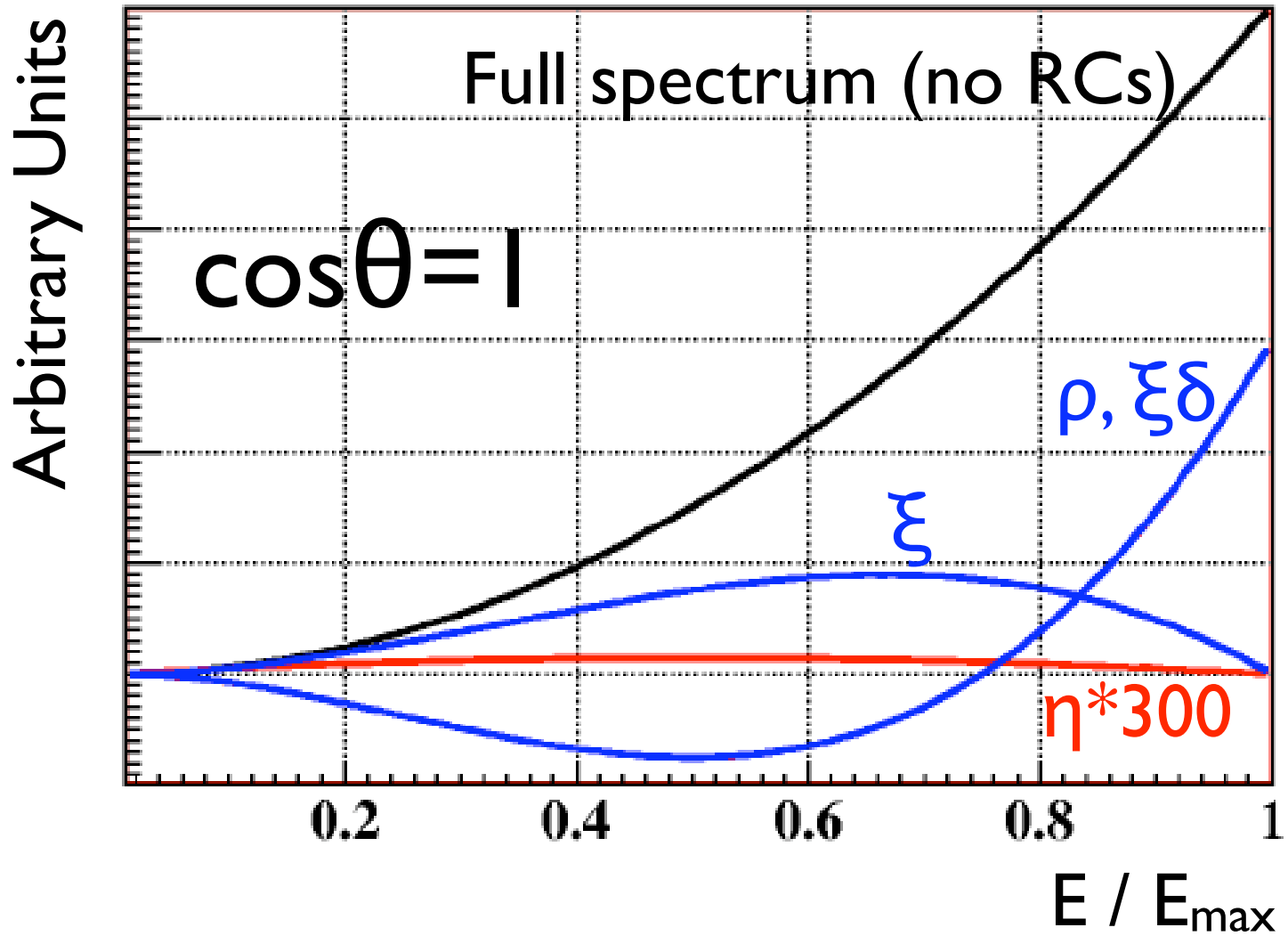


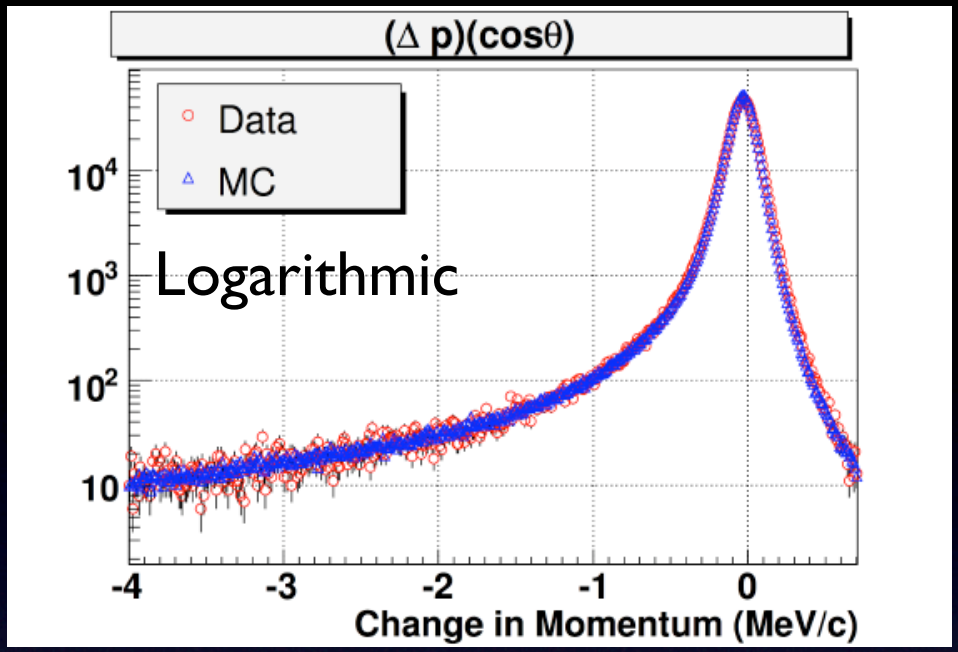


Spectrum Fit Quality

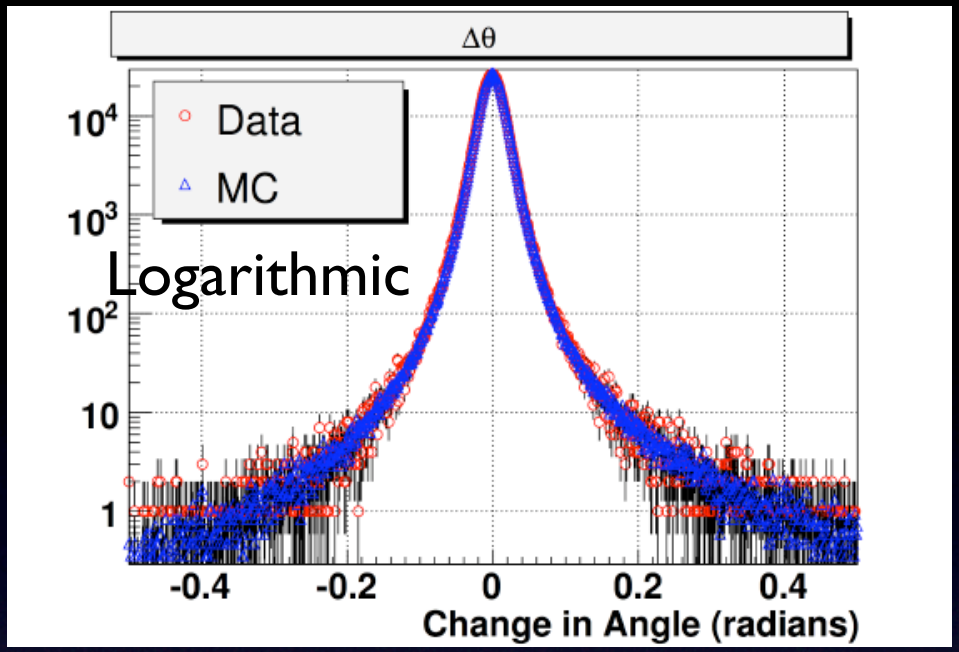


Parameter Sensitivity

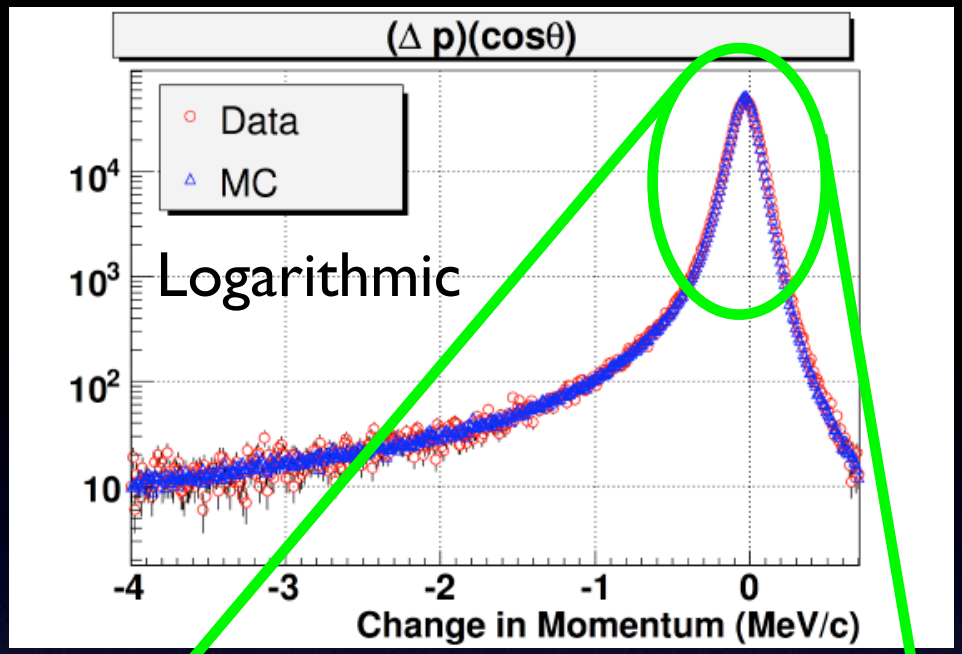


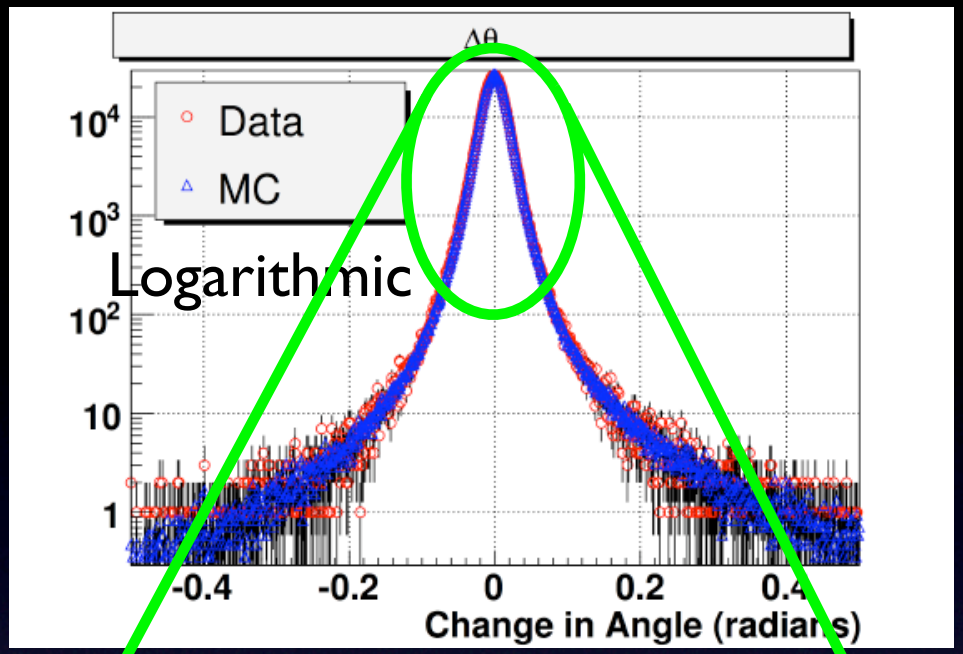


Energy Loss



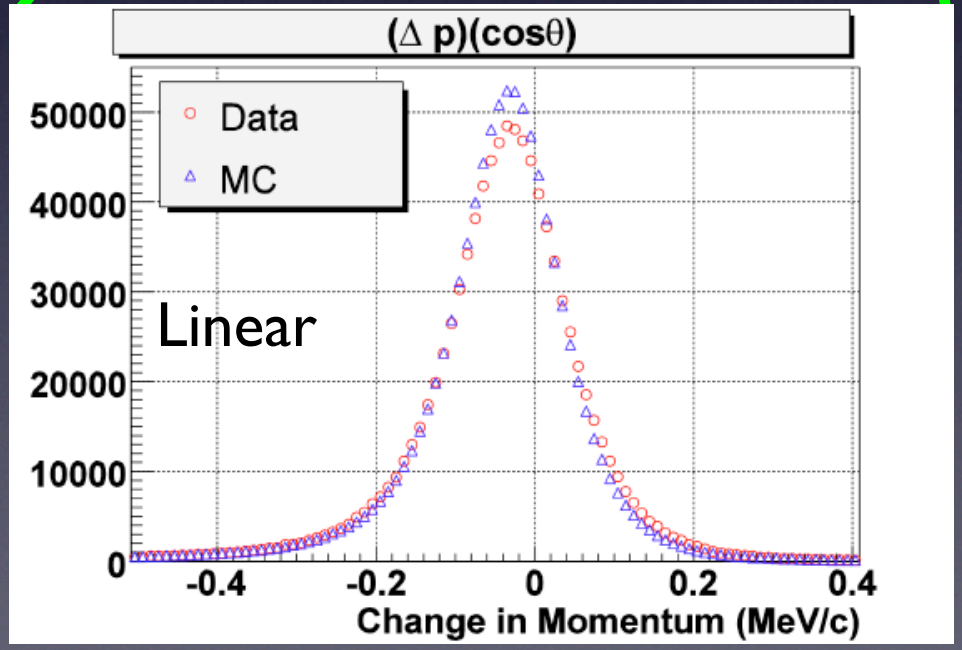
Scattering

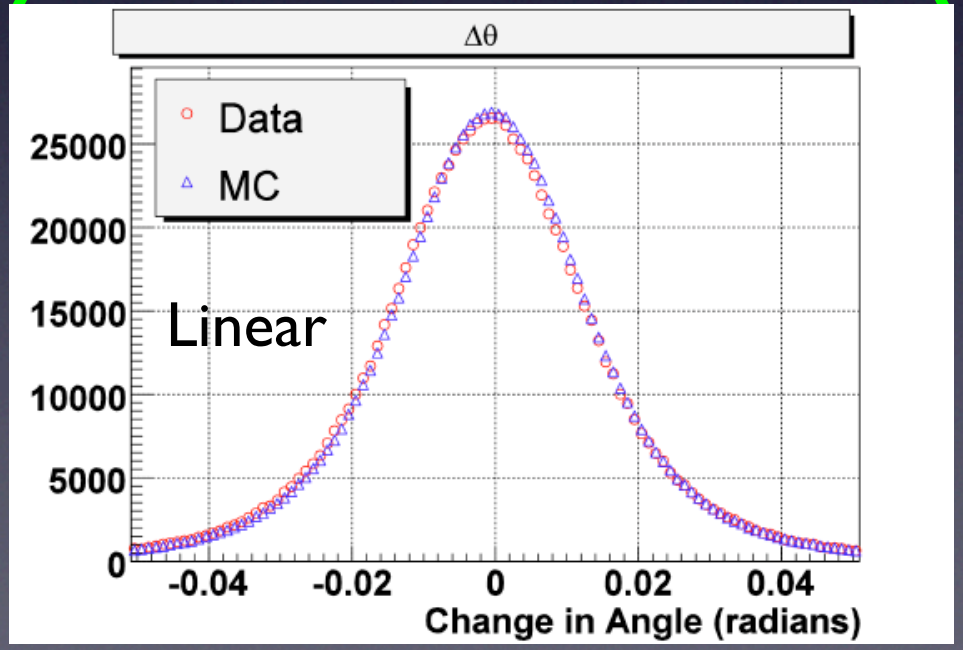




Energy Loss

Scattering





Improvements to Systematics

Chamber response	online monitoring, increased instrumentation
Target thickness	precision target geometry
Positron interactions	improved upstream stops data
Alignment	improved techniques, better understanding of uncertainties
Momentum calibration	new calibration techniques, uncertainty is statistical
Radiative corrections	higher-order corrections, uncertainty tested directly

Limits on Right-Handed Muon Decay

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

Pre-*TWIST*: $Q_R^\mu < 0.014$

Gagliardi: $Q_R^\mu < 0.007$

Current: $Q_R^\mu < 0.006$

*Gagliardi et al., PRD **72** 073002 (2005)*

Left-Right Symmetry

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

$$\zeta_g = \left|\frac{g_R}{g_L}\zeta\right| = \sqrt{\frac{1}{2}\left(1 - \frac{4}{3}\rho\right)}$$

Pre-*TWIST*: $|\zeta_g| < 0.066$

TWIST Published: $|\zeta_g| < 0.028$

Current: $|\zeta_g| < 0.022$