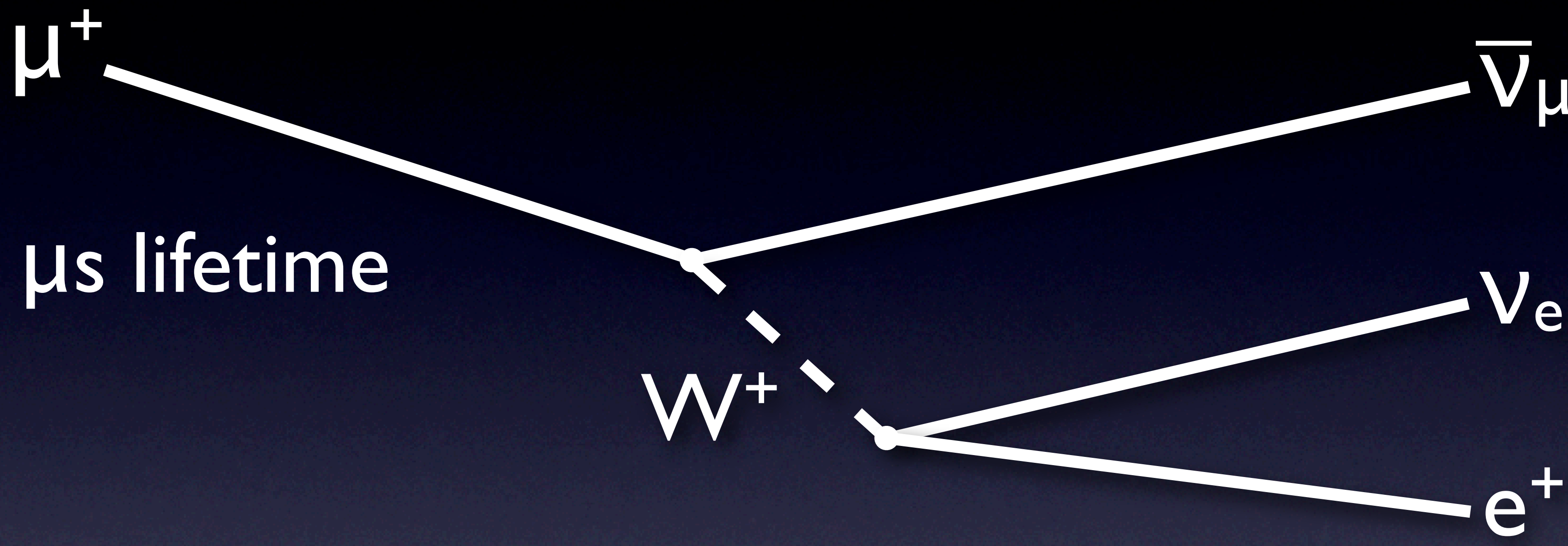
Results of a new muon decay measurement by *TWIST*

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

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

TRIUMF Seminar, 15 November 2007

Muon Decay

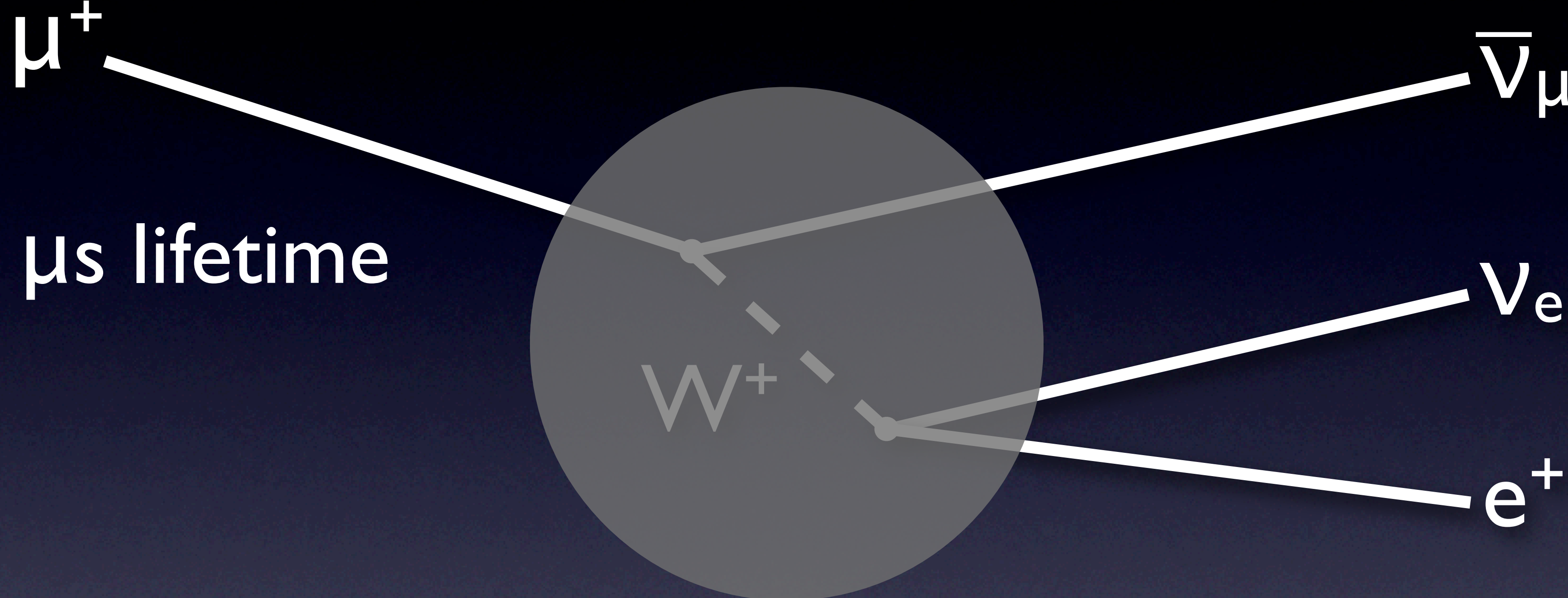


2 μs lifetime

EM radiative corrections calculable

Strong interactions are at < 1e-6 level

Muon Decay



2 μs lifetime

EM radiative corrections calculable

Strong interactions are at < 1e-6 level

Weak Matrix Element

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

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Weak Matrix Element

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In Standard Model ("V-A"):

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

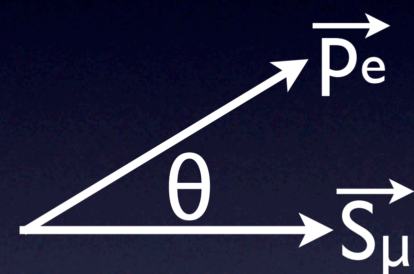
$g^{\kappa}_{\epsilon m} = 0$ otherwise

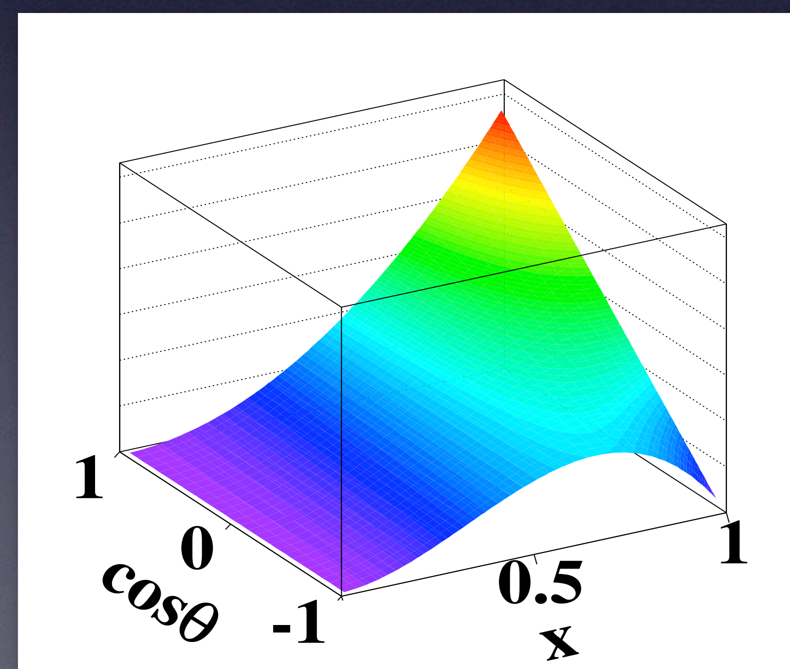
$g^{\kappa}_{\epsilon m}$ constrained by muon decay, inverse decay, etc.

Decay ("Michel") Spectrum

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

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





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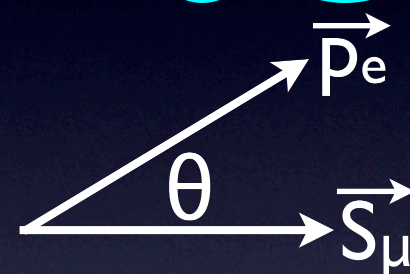
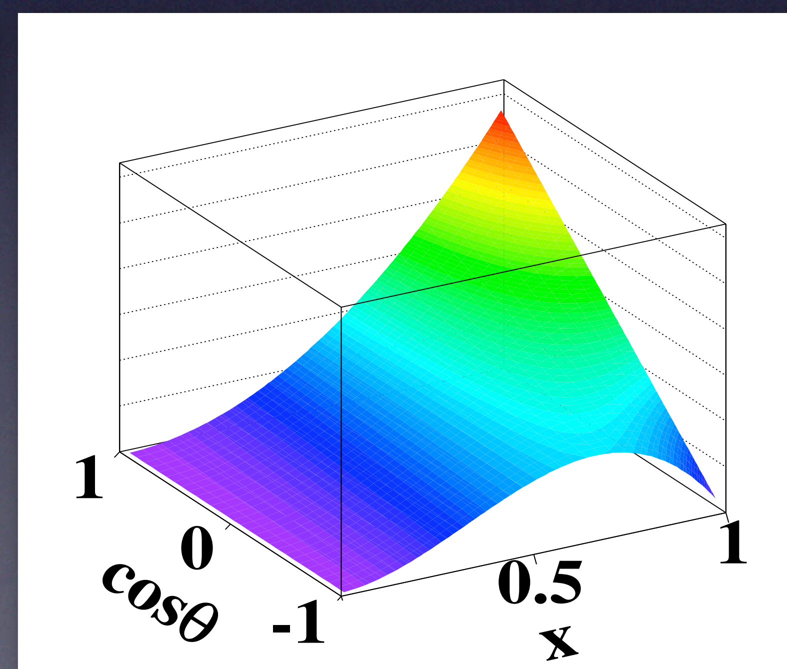
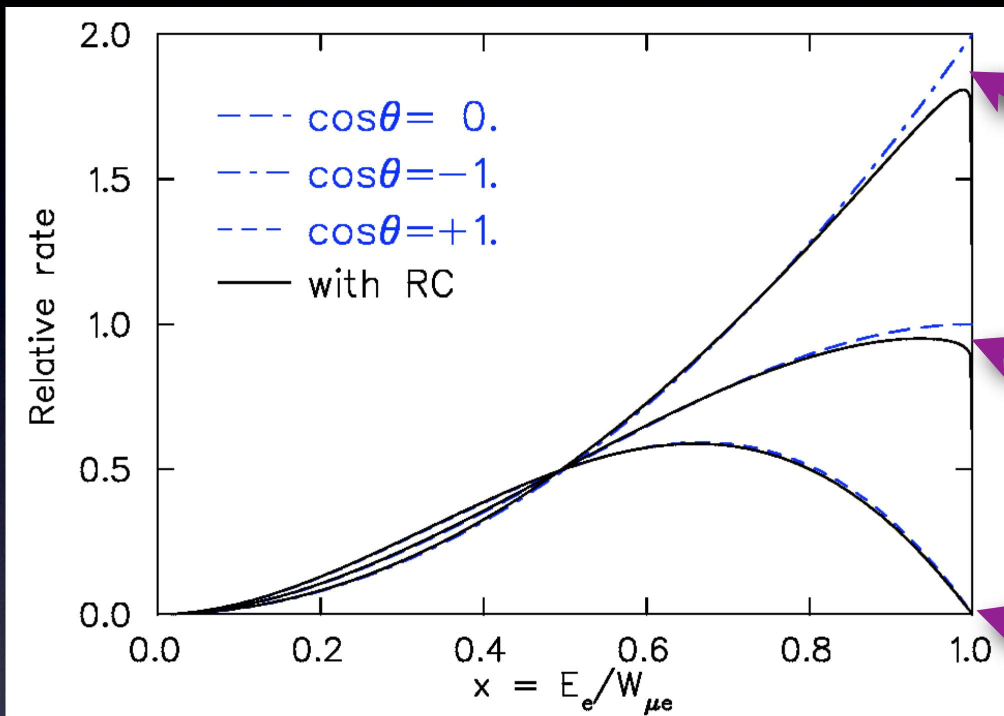


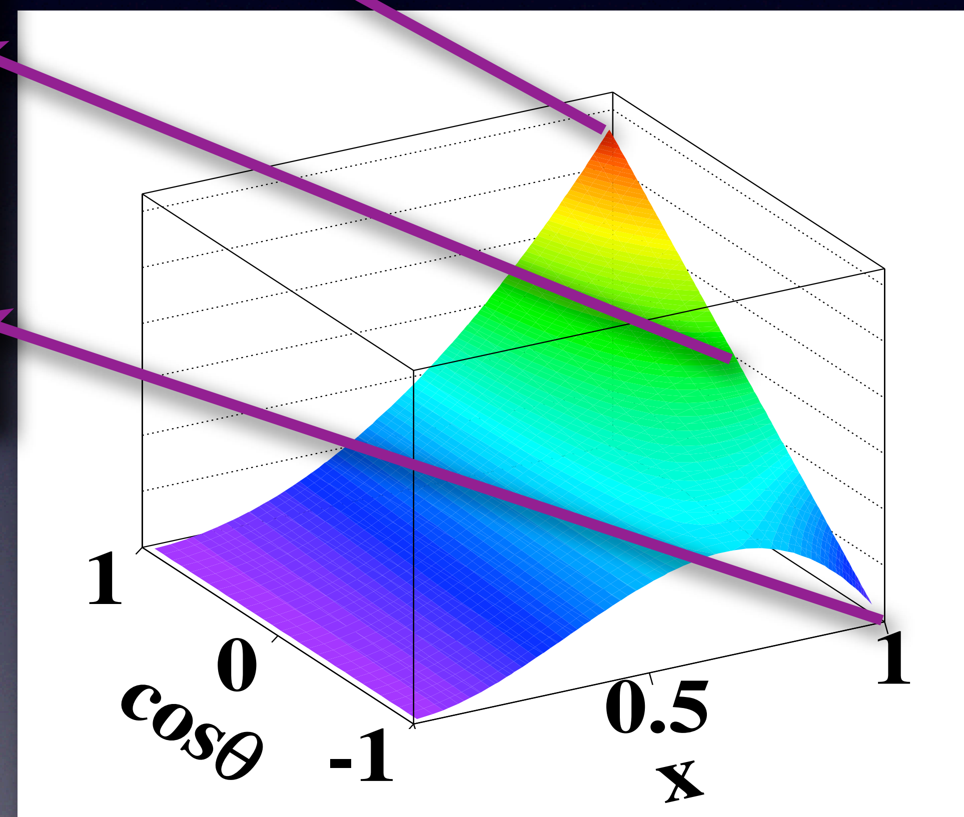
	Pre-TWIST	SM
ρ	0.7518 ± 0.0026	0.75
η	-0.007 ± 0.013	0
$P_\mu\xi$	1.0027 ± 0.0085	1
δ	0.7486 ± 0.0038	0.75



Today's results: new ρ and δ

Radiative Corrections





$O(\alpha)$: Full tree-level RCs, exact electron mass

$O(\alpha^2)$: Leading-Order (LO) and NLO in $L=\ln(m_\mu/m_e)$

Early Measurements

26 July, 1948 -- Chalk River

The Absorption of Charged Particles from the 2.2-μsec. Meson Decay

E. P. HINCKS AND B. PONTECORVO
National Research Council of Canada, Chalk River Laboratory, Chalk River, Ontario, Canada
July 26, 1948

THE energy spectrum of the charged particles (commonly assumed to be electrons) emitted in the 2.2-μsec. meson decay is still unknown. Conversi and Piccioni[1] in 1944 deduced from the relative numbers of decay electrons emerging from iron plates 0.6 cm and 5 cm

Early Measurements

26 July, 1948 -- Chalk River

The Absorption of Charged Particles from the 2.2-μsec. Meson Decay

2) that less than 0.03 count per hour can be due to radiation from 25-Mev electrons in our arrangement. Consequently, it may be seen from Table I that at least a substantial fraction of the electrons must have a range greater than 15 g/cm² of carbon. Therefore, we conclude that there are decay electrons having energies greater than 25 Mev and therefore that the 2-particle decay process (Eq. (1)), with a *unique* energy of about 25 Mev for the decay electron, is incompatible with our results.

We observe, however, that a *maximum* energy of about 50 Mev for the decay electrons would be consistent with the data of Table I.

Early Measurements

26 July, 1948 -- Chalk River

April 15, 1949 -- Chicago/Colorado

On the Range of the Electrons in Meson Decay

J. STEINBERGER*
The Institute for Nuclear Study, University of Chicago, Chicago, Illinois

(Received January 10, 1949)

An experiment has been carried out both at Chicago and on Mt. Evans, Colorado, to determine the absorption of the electrons emitted in the decay of cosmic-ray mesons. Approximately 8000 counts have been obtained, using a hydrocarbon as the absorbing material. These data are used to deduce some features of the energy spectrum of the decay electrons. The resolution of the apparatus is calculated, taking the geometry, scattering, and radiation into account. The results indicate that the spectrum is either continuous, from 0 to about 55 Mev with an average energy ~32 Mev or consists of three or more discrete energies. No variation of the lifetime with the thickness of the absorber is observed. The experiment, therefore, offers some evidence in favor of the hypothesis that the μ-meson disintegrates into 3 light particles.

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Early Measurements

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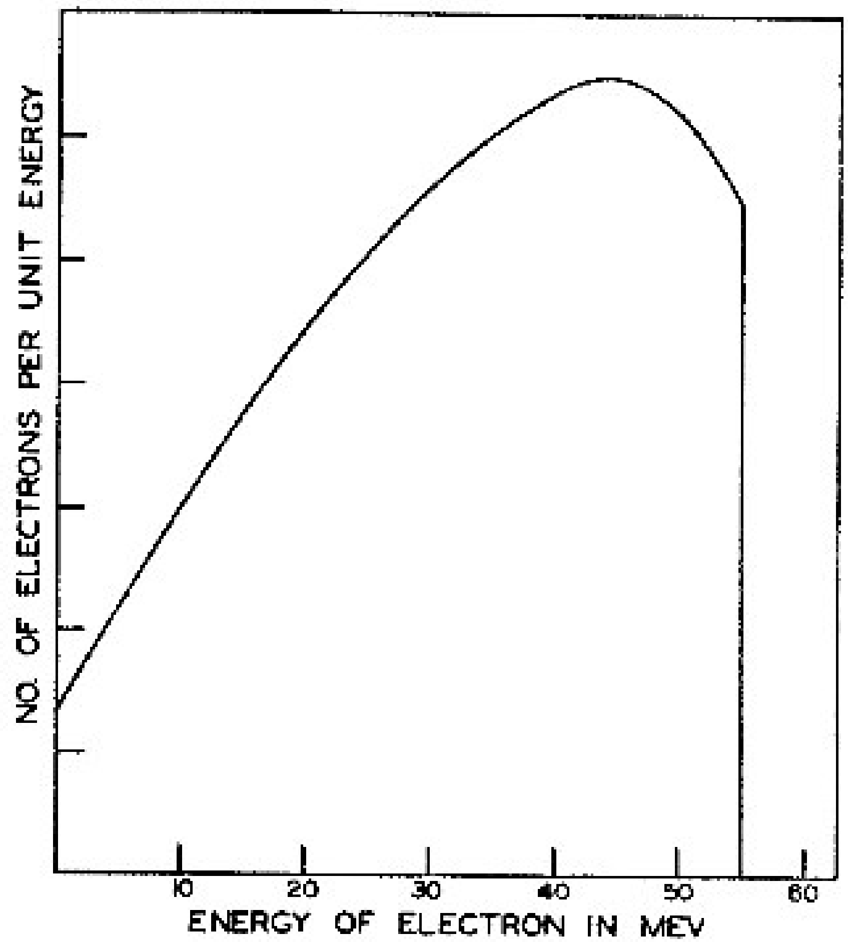
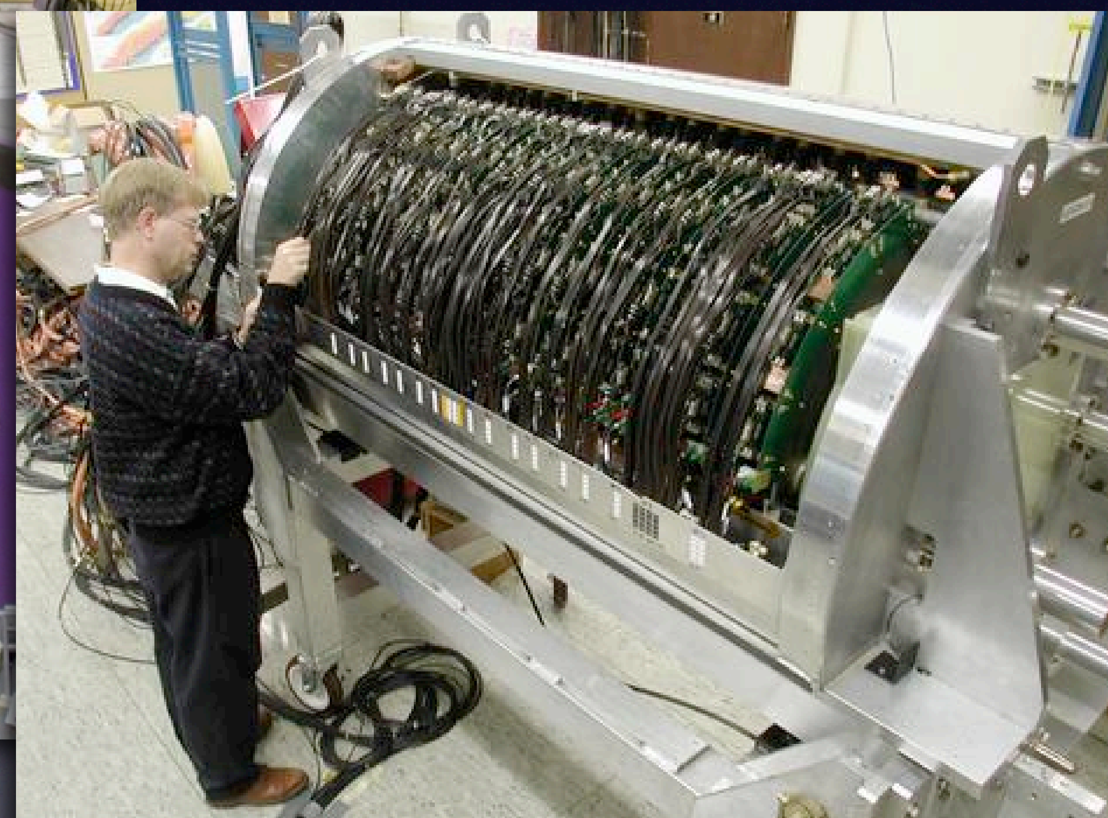


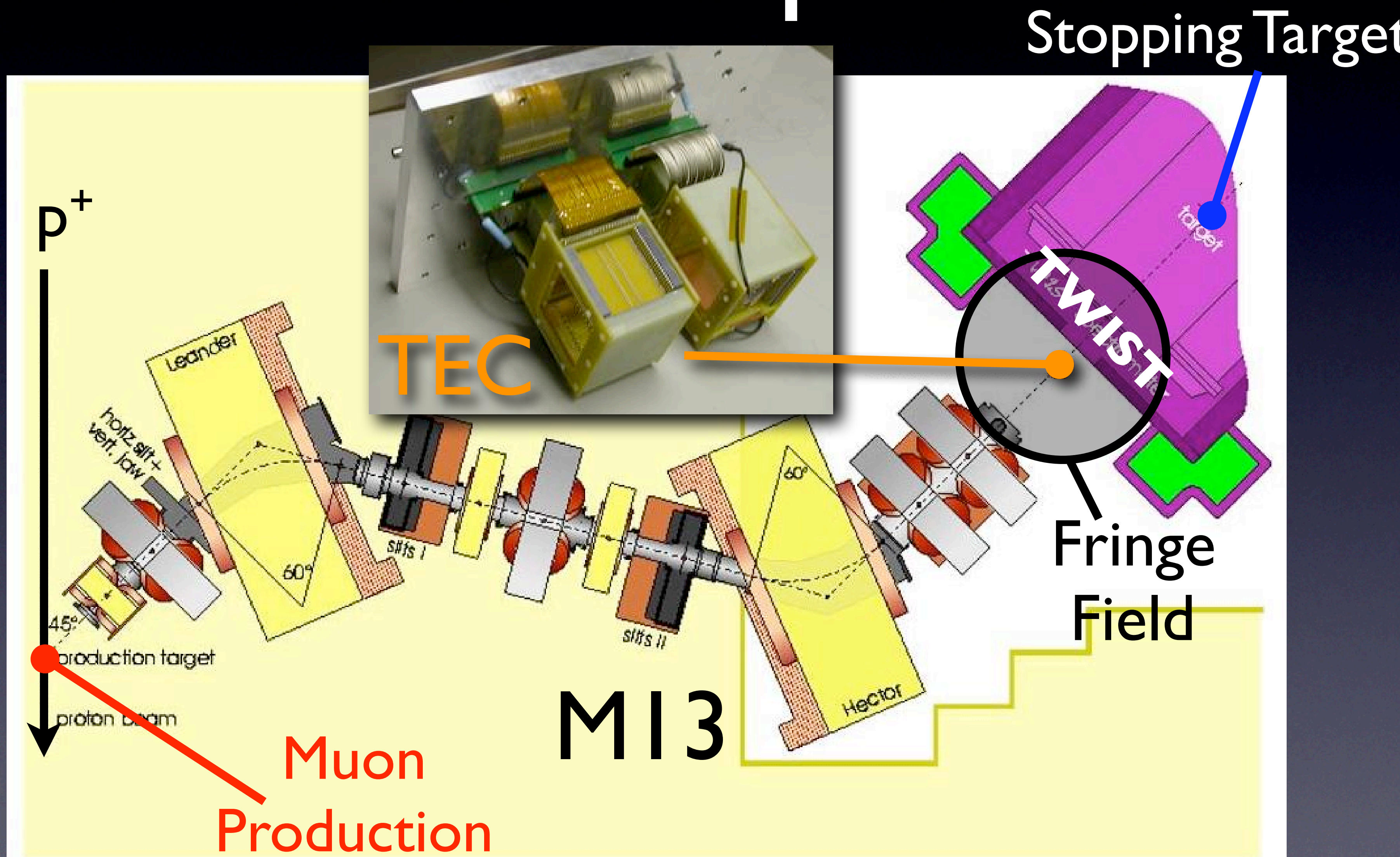
FIG. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.

The *TWIST* Experiment

TRIUMF Weak Interaction Symmetry Test

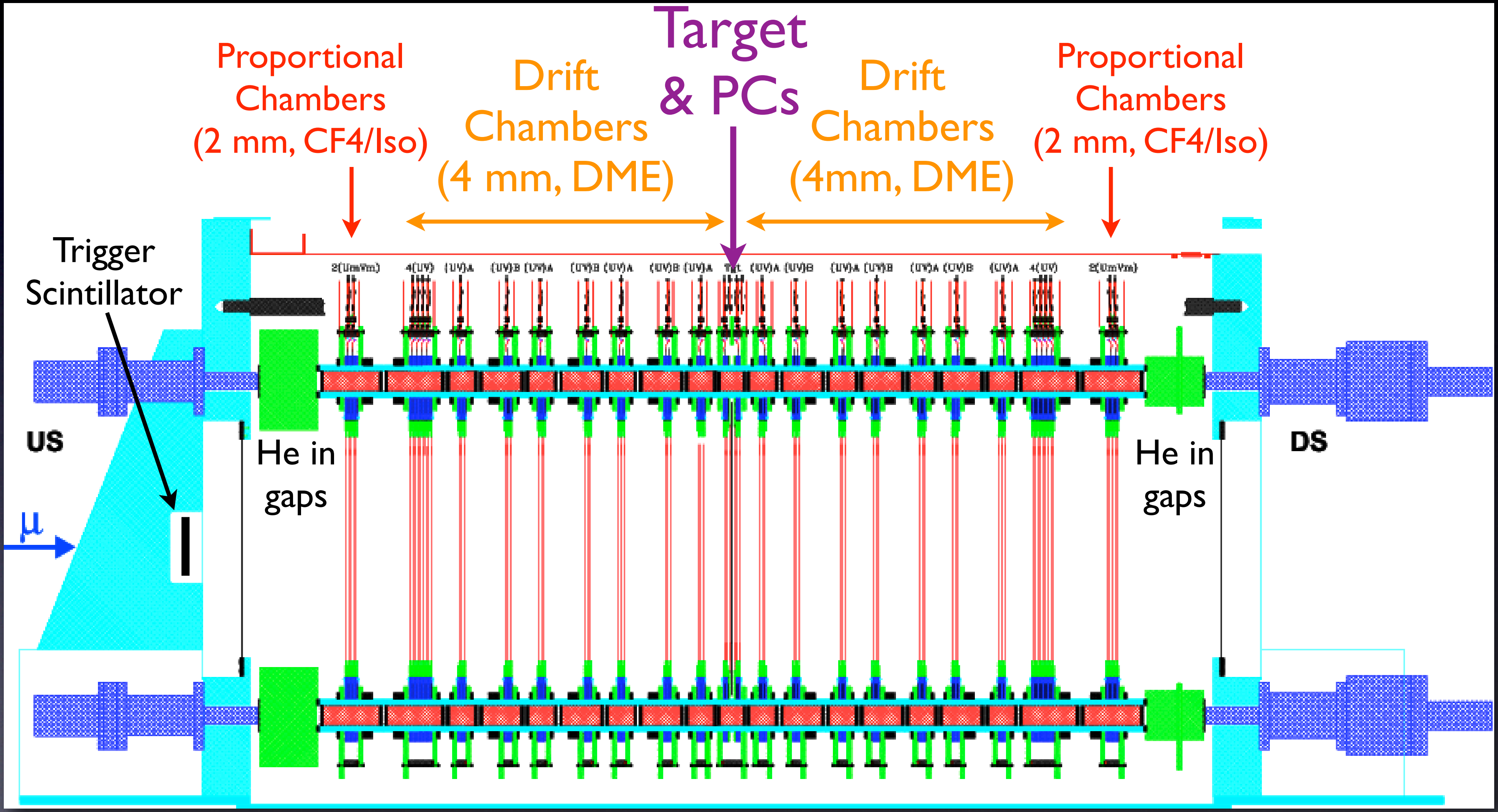


Muon Production and Transport



TEC: NIM A566 (2006), 563

The *TWIST* Detector

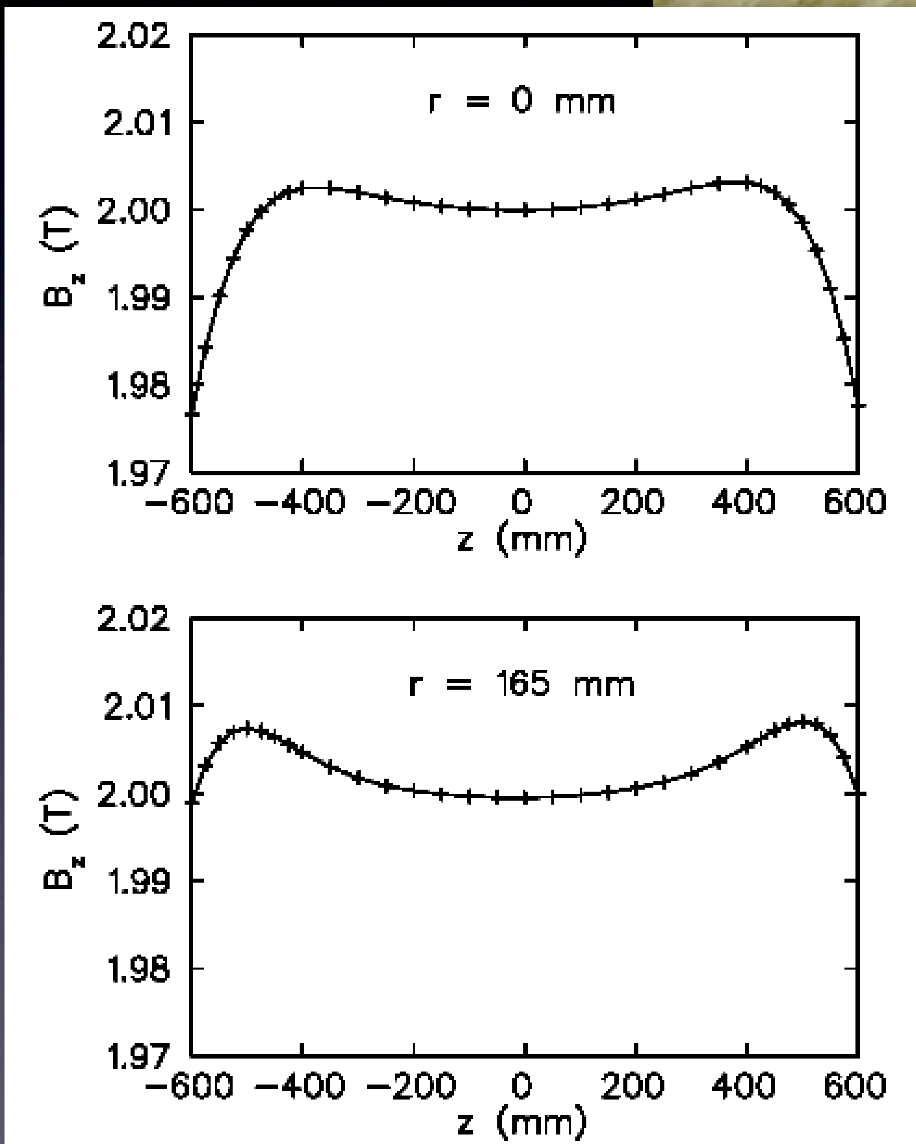


NIM **A548** (2005) 206

TWIST Drift Chambers

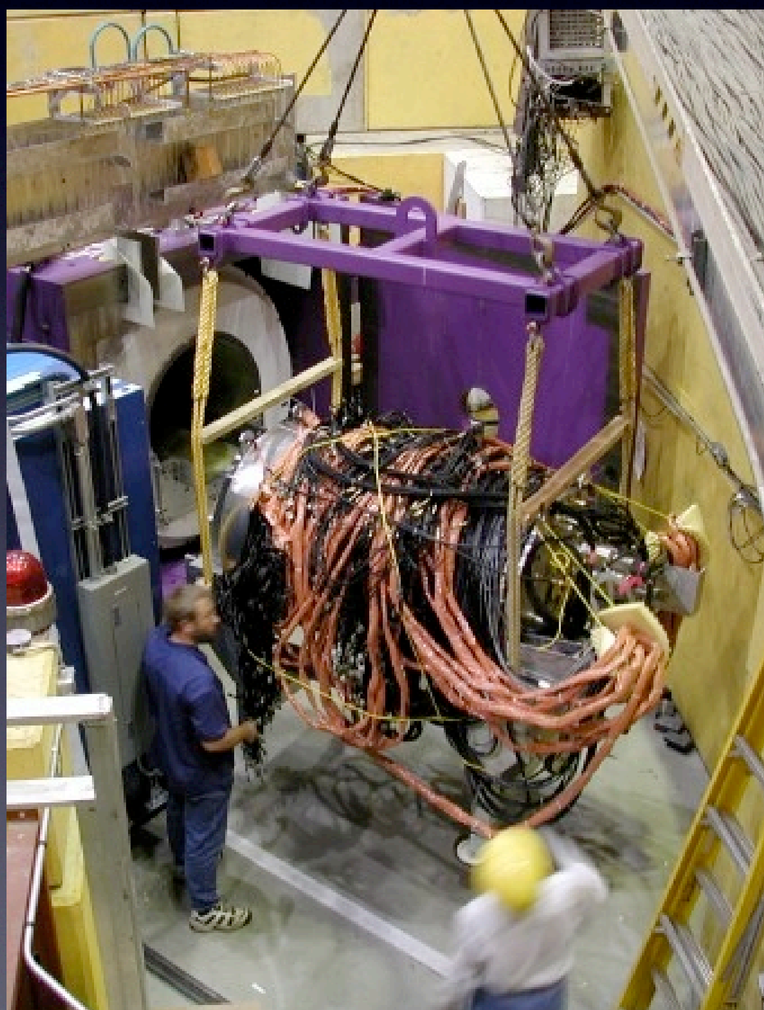
NIM **A548** (2005) 206

The *TWIST* Solenoid



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!

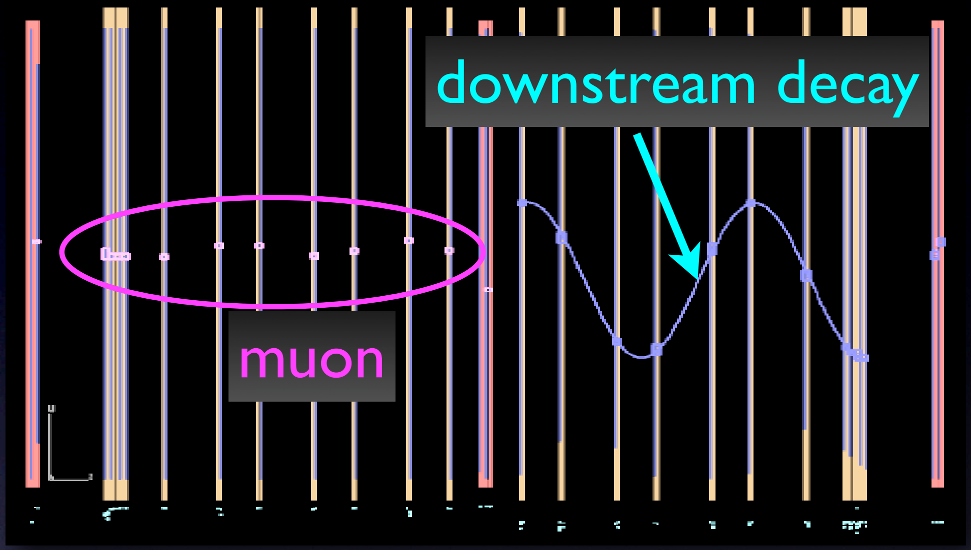
TWIST ρ and δ publications (2005) used 2002 data.

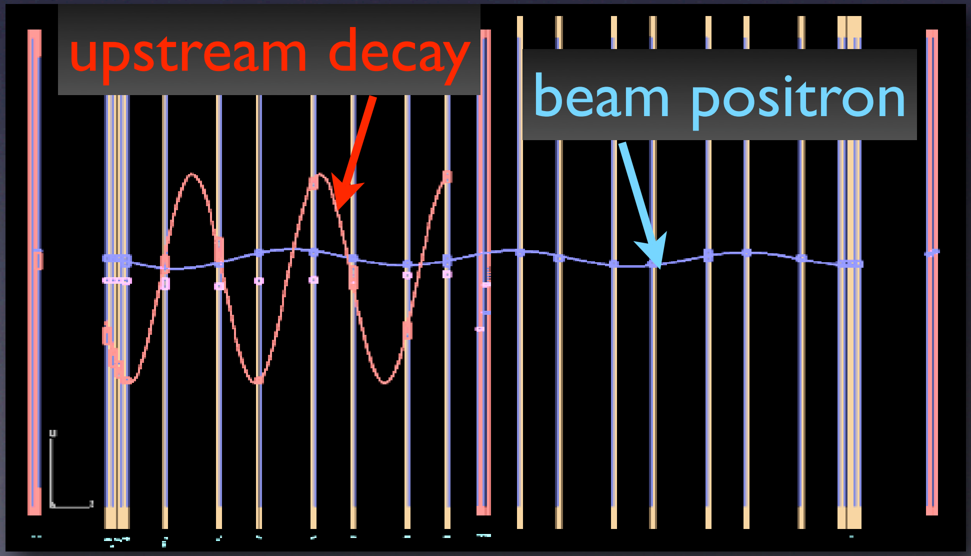
TWIST $P_\mu\xi$ publication (2006) used 2004 data.

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

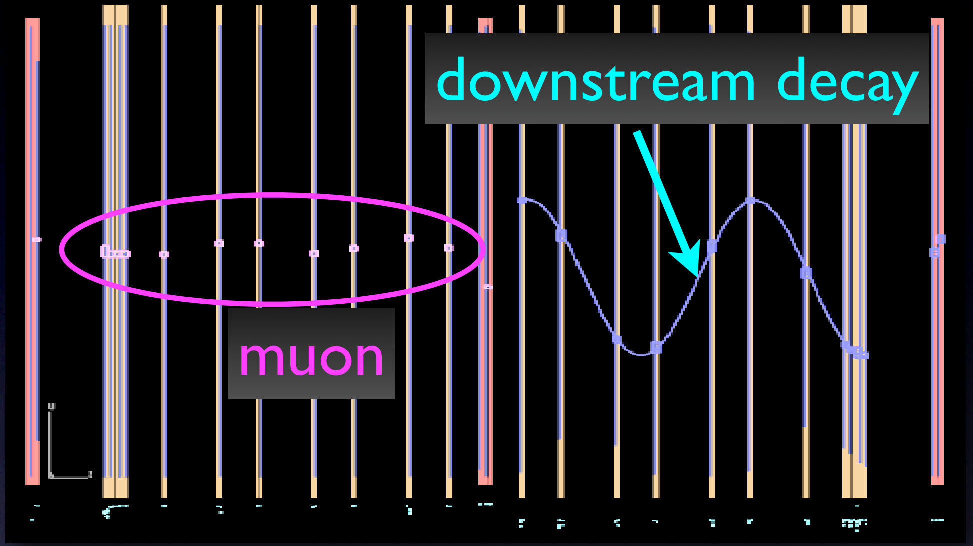
Measurements from 2006/2007 data still to come!

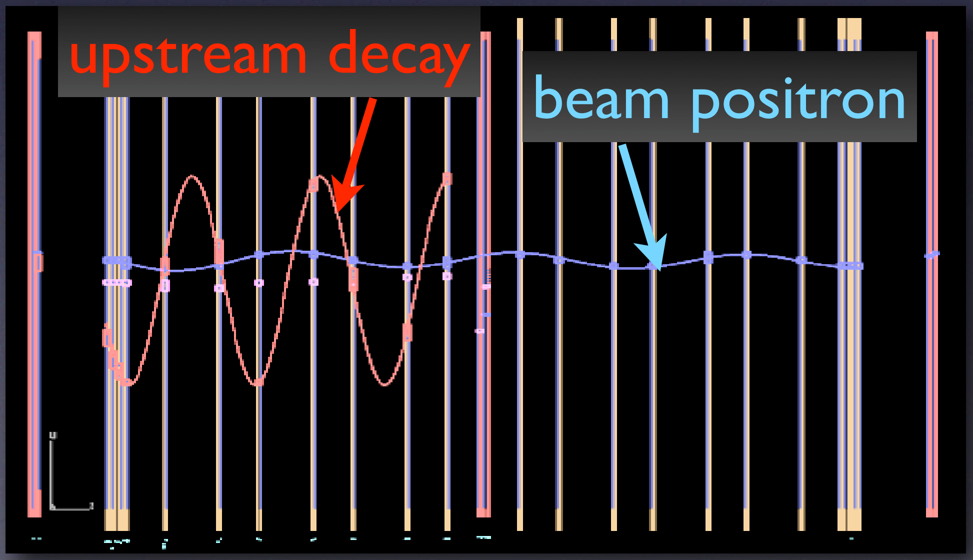
TWIST Analysis

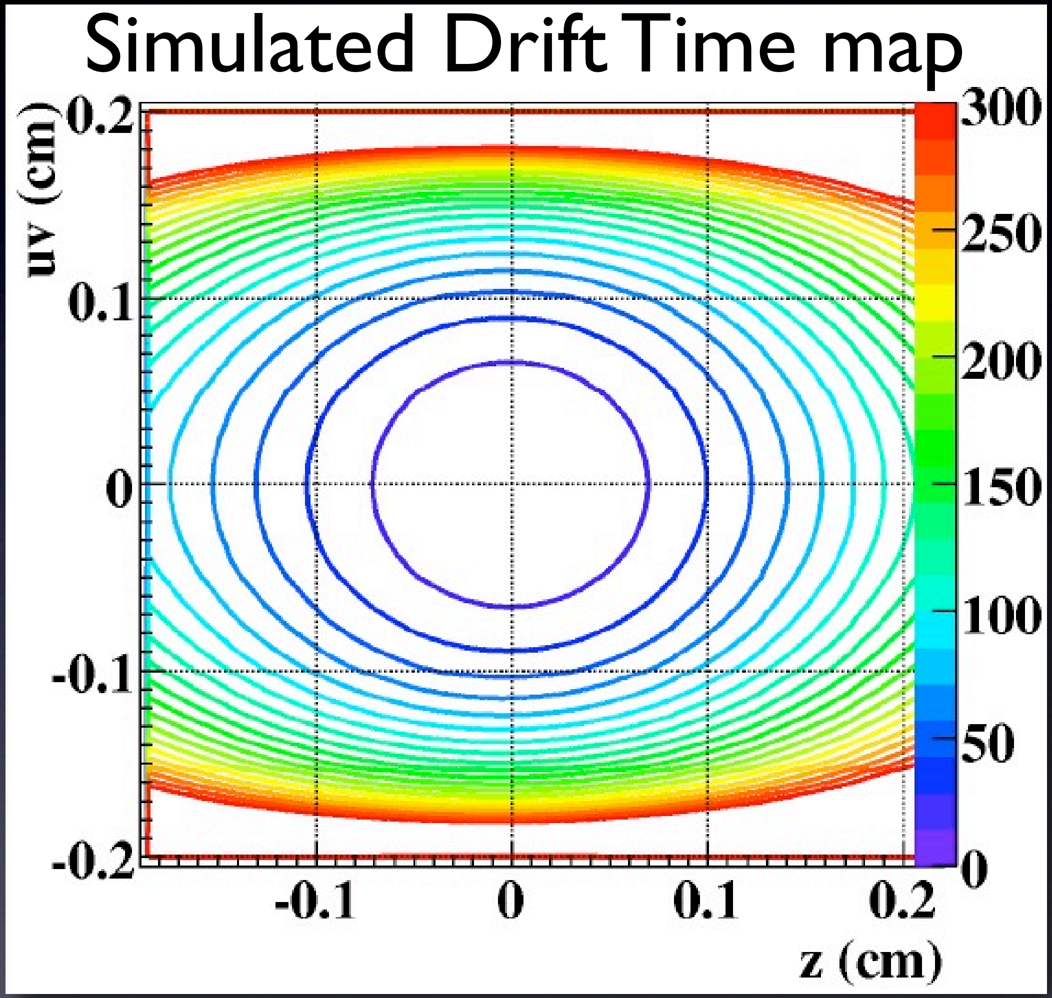




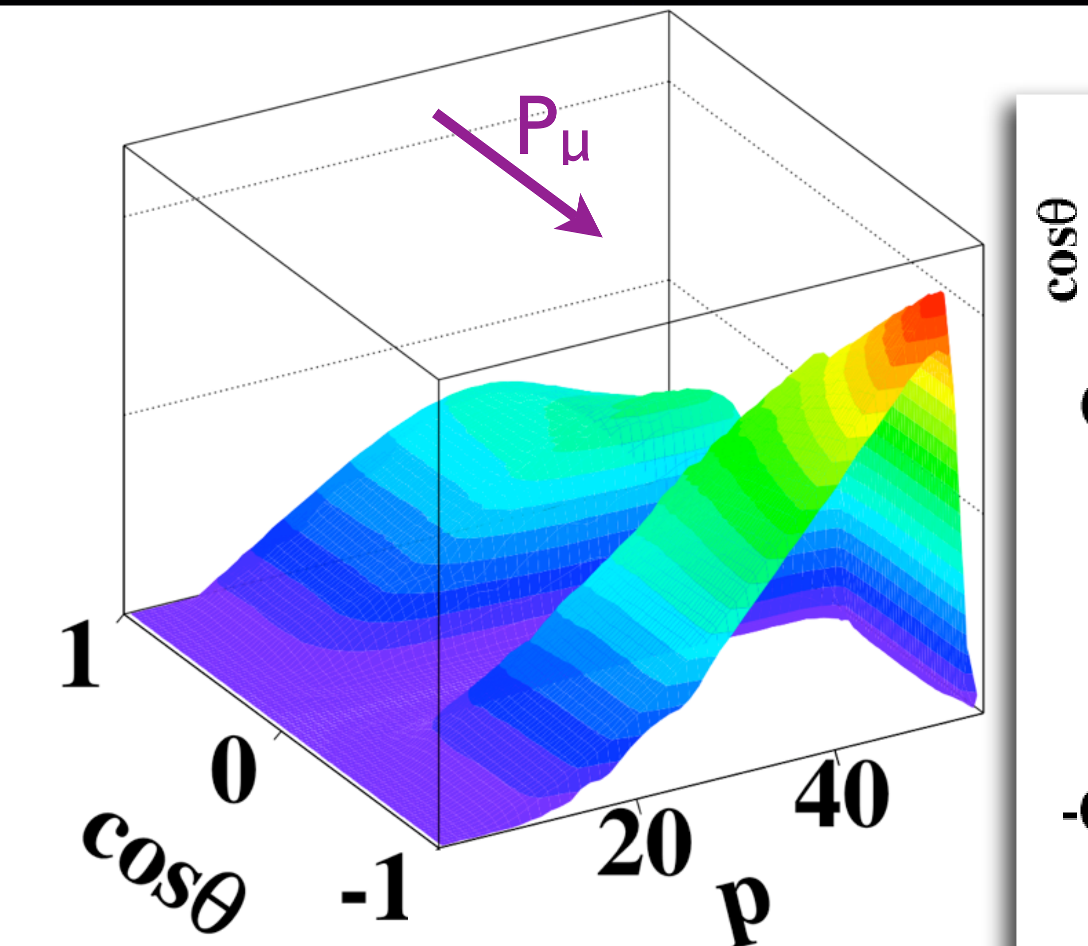
TWIST Analysis

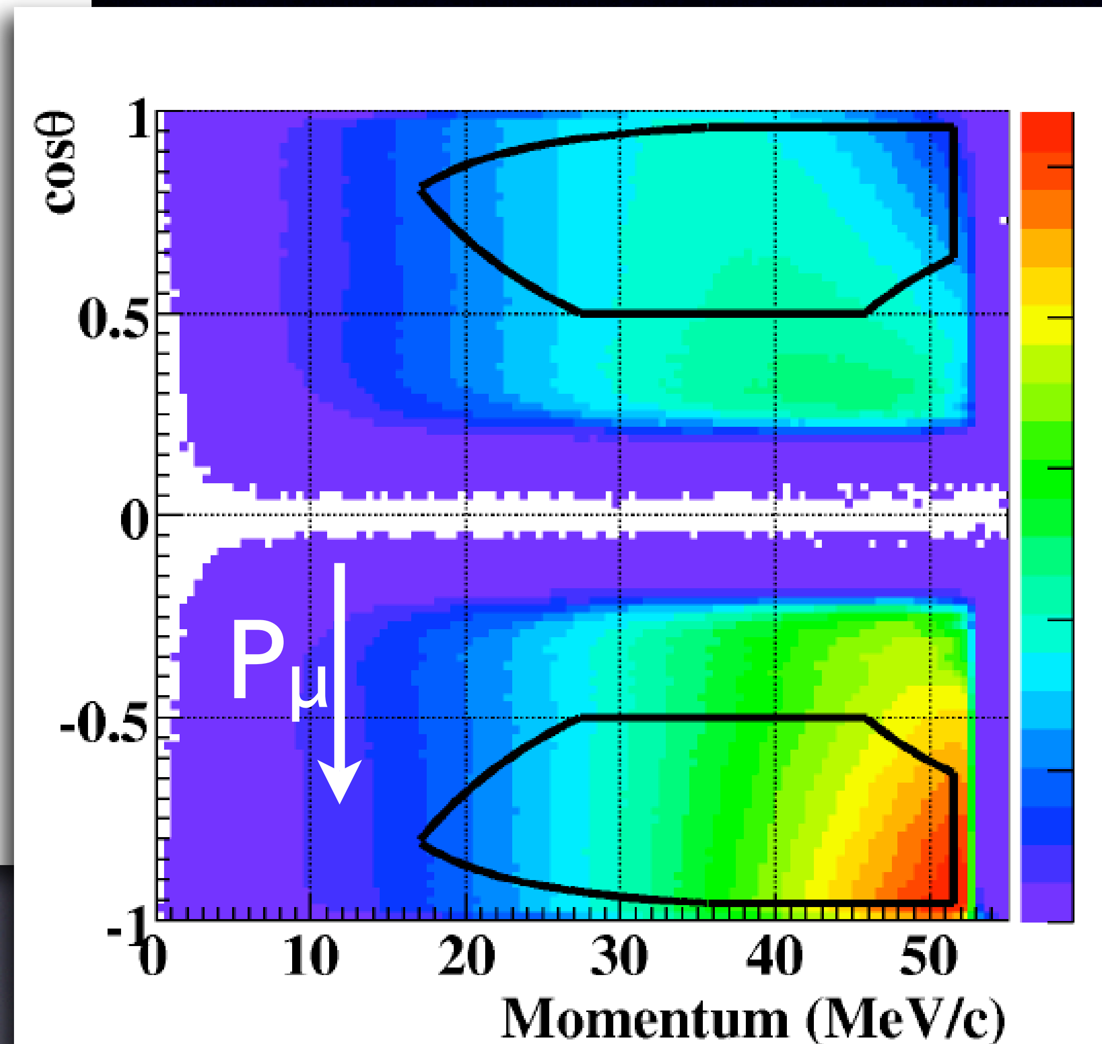




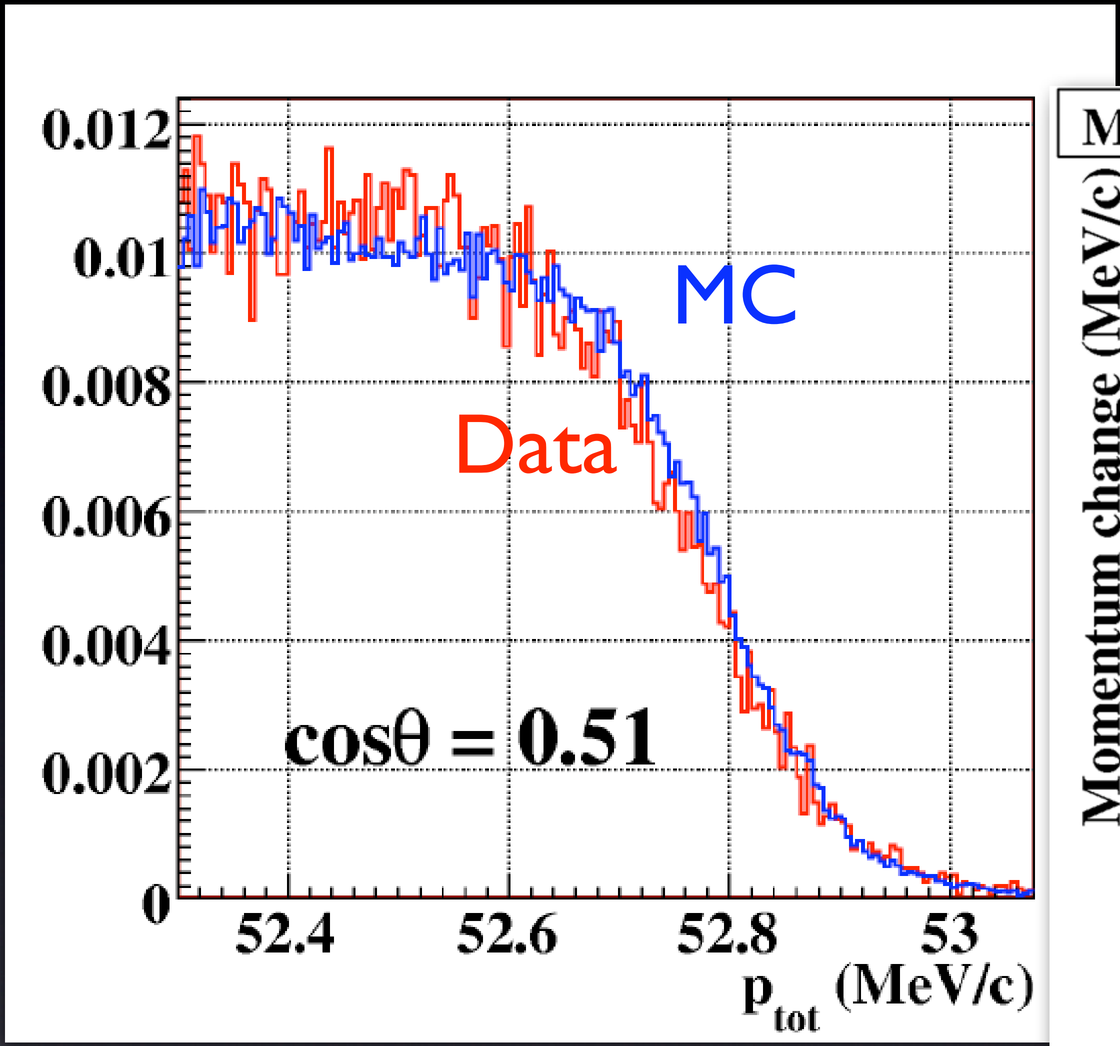


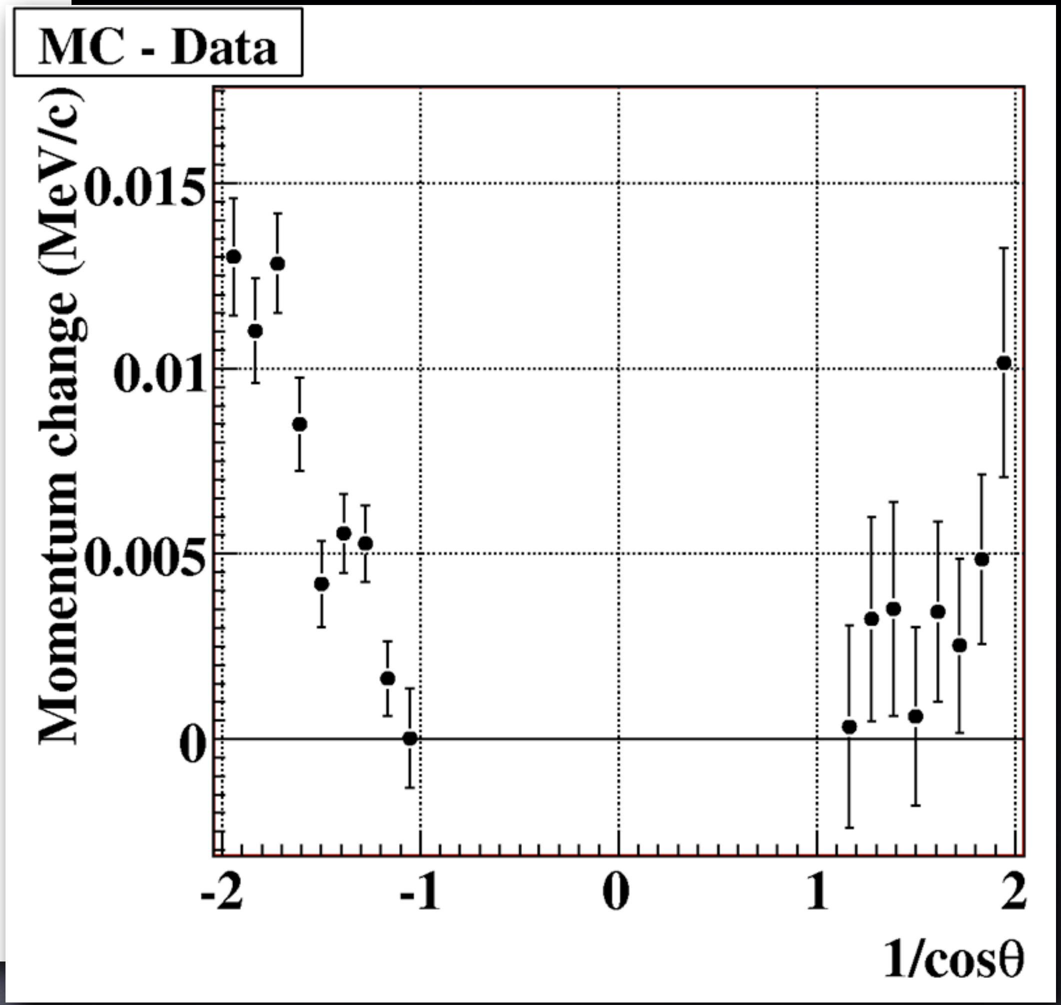
Muon Decay Spectrum





Energy Calibration

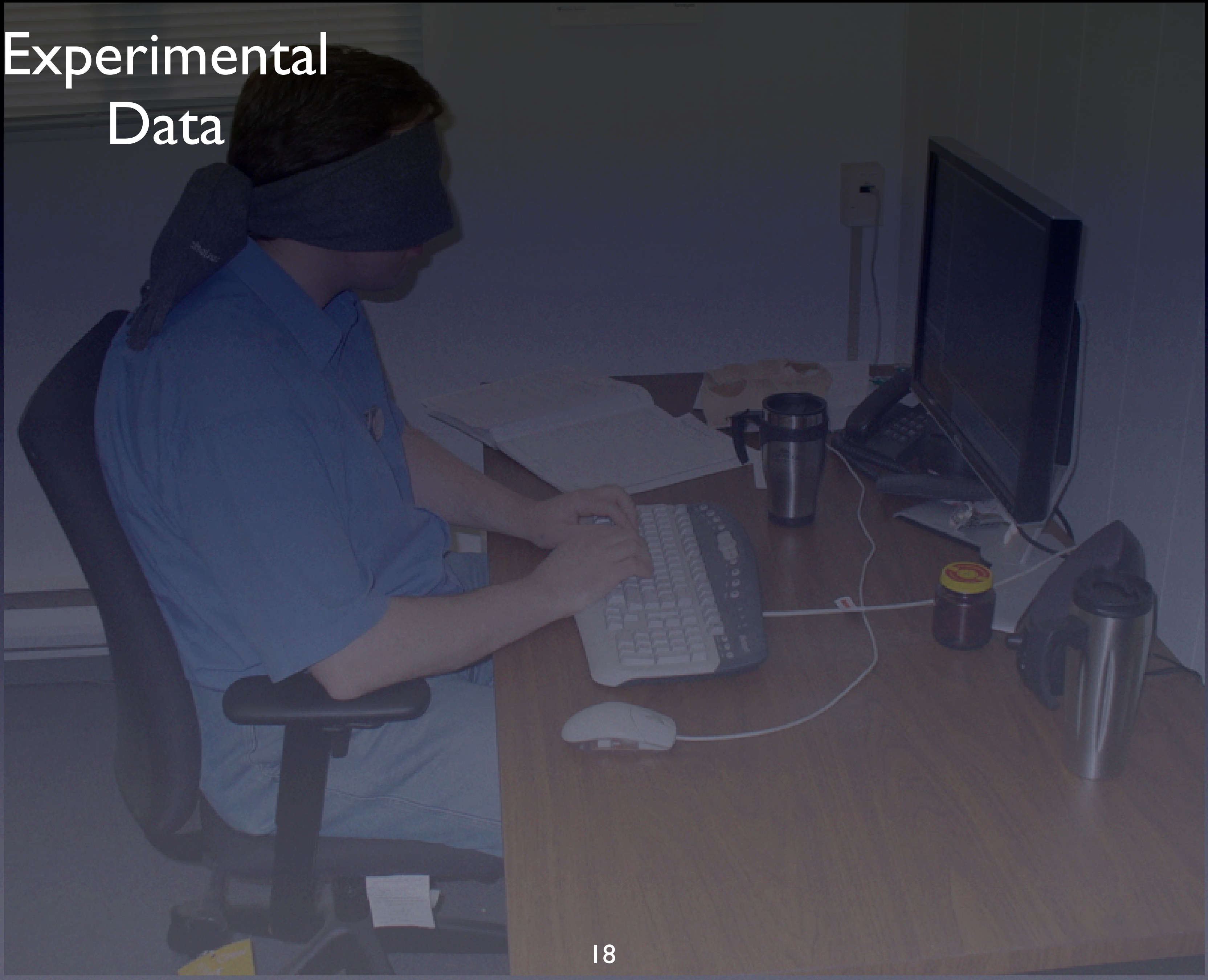




Resolution from edge shape: Data - MC = 5 keV

Blind Analysis

Blind Analysis



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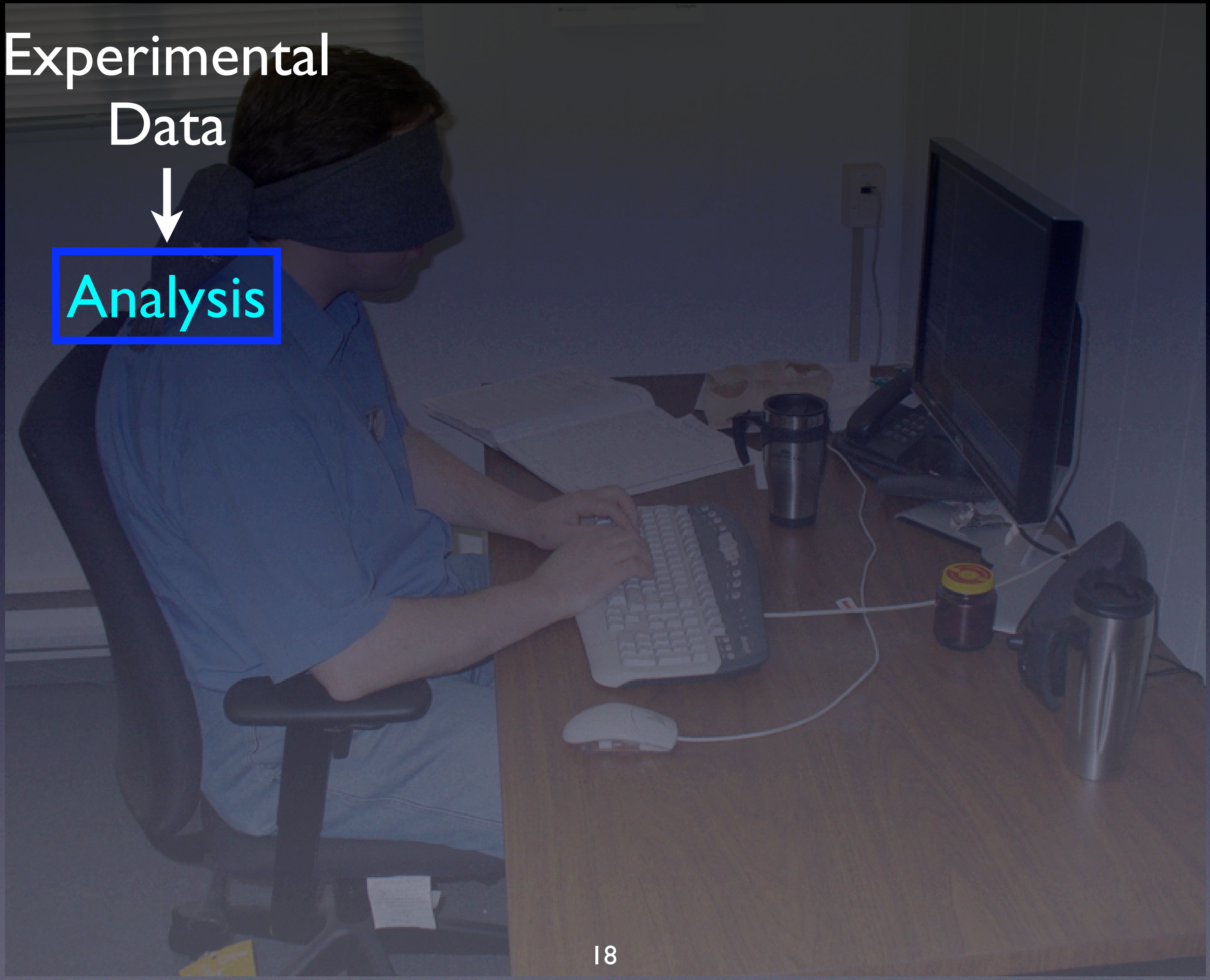

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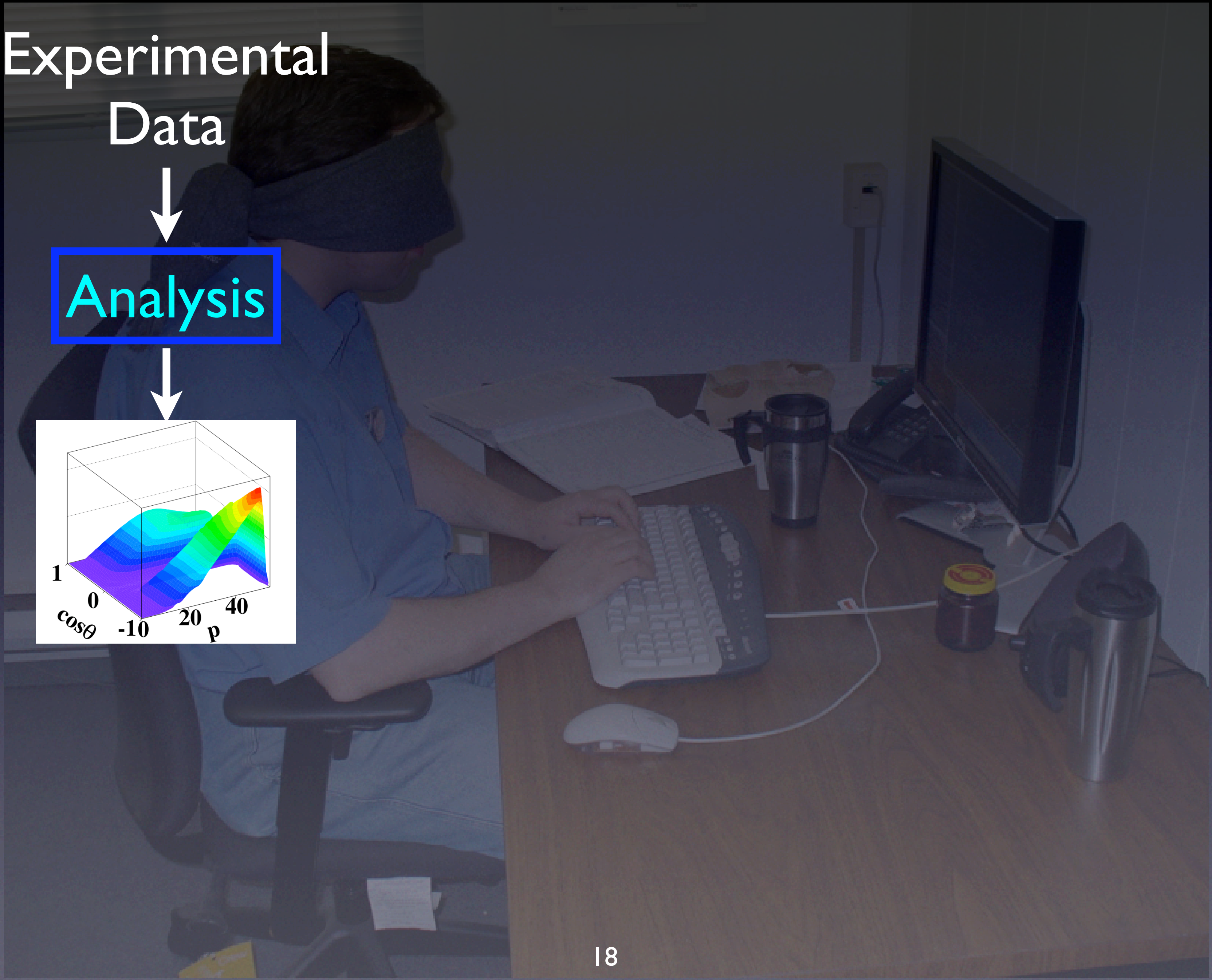

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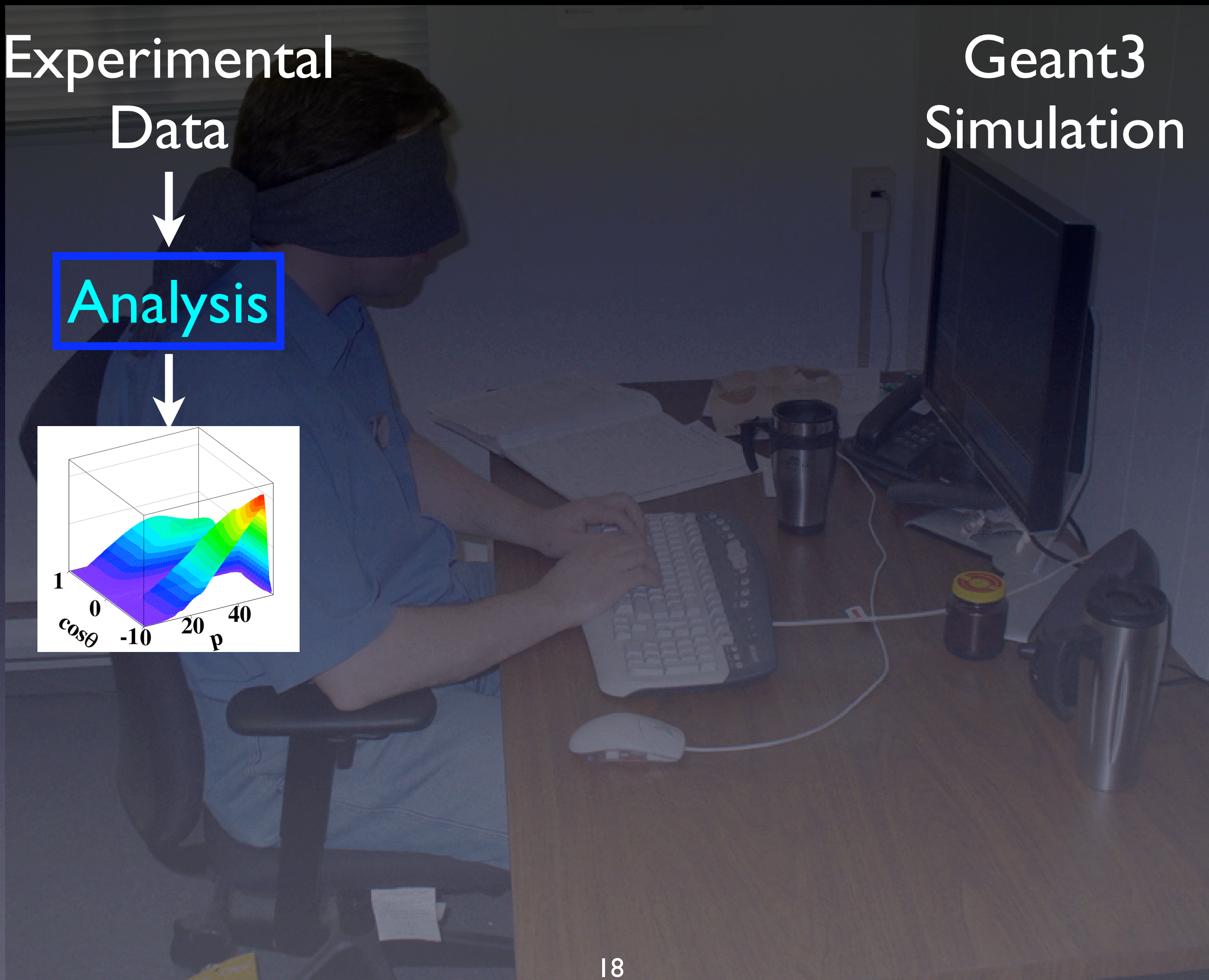

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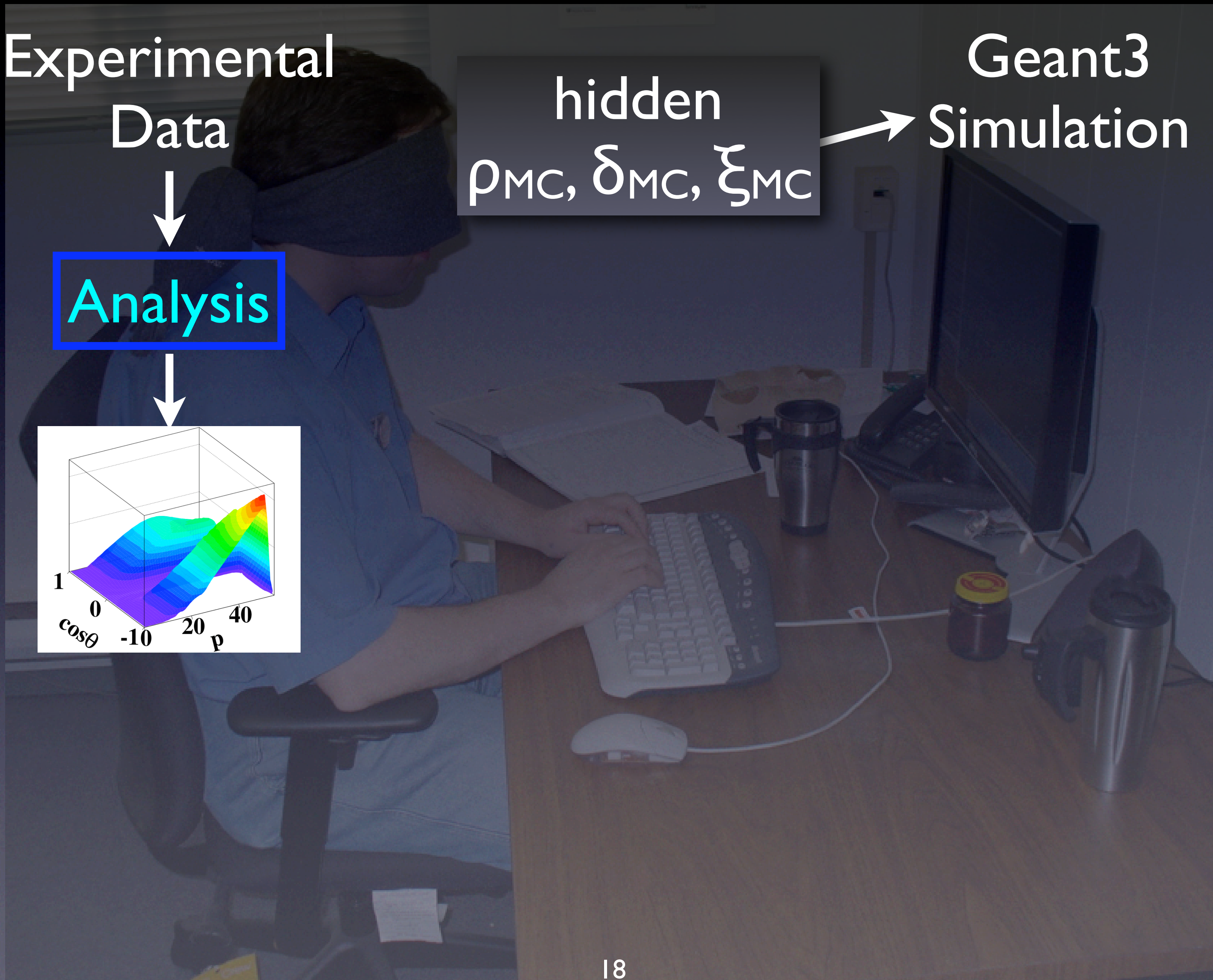

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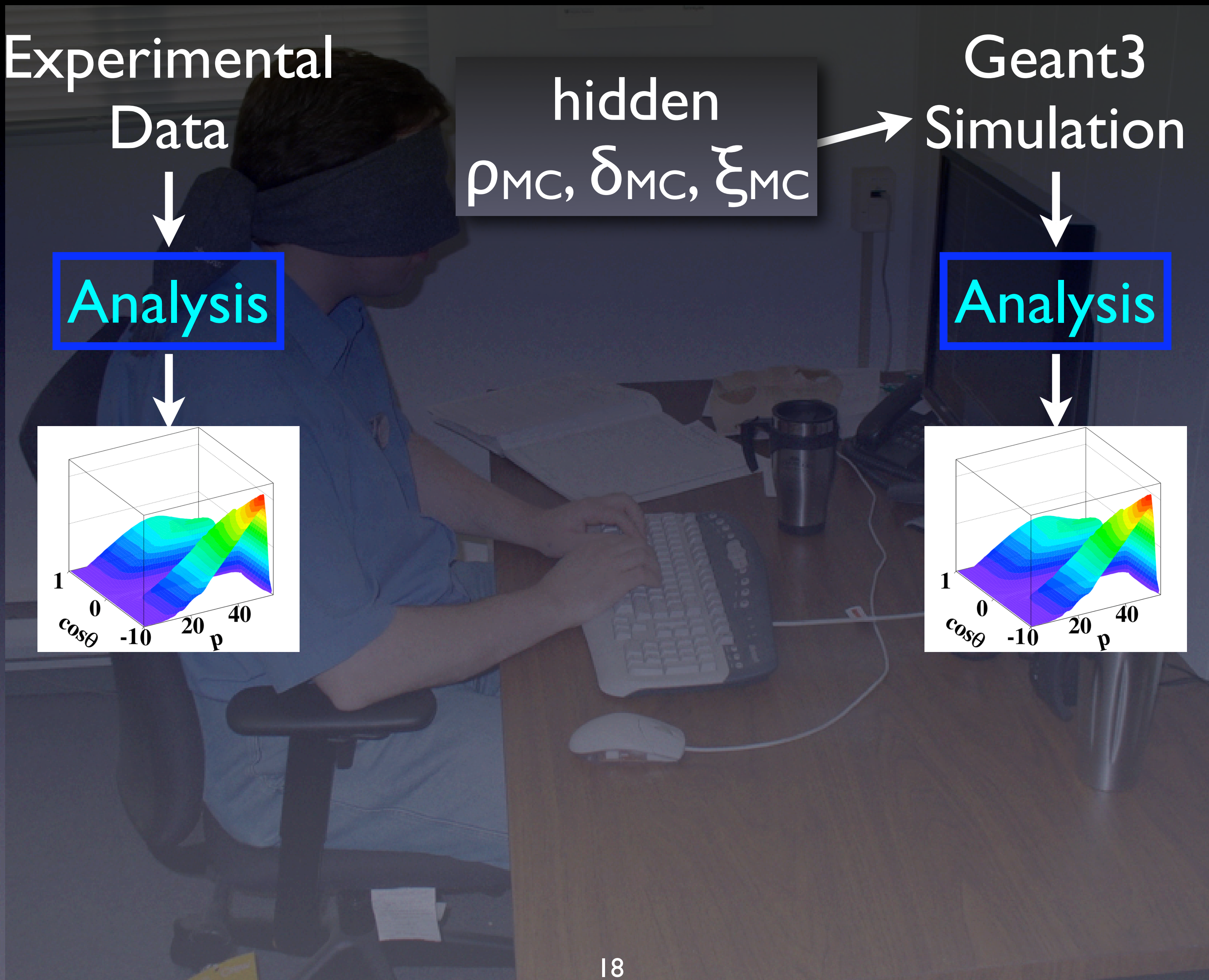

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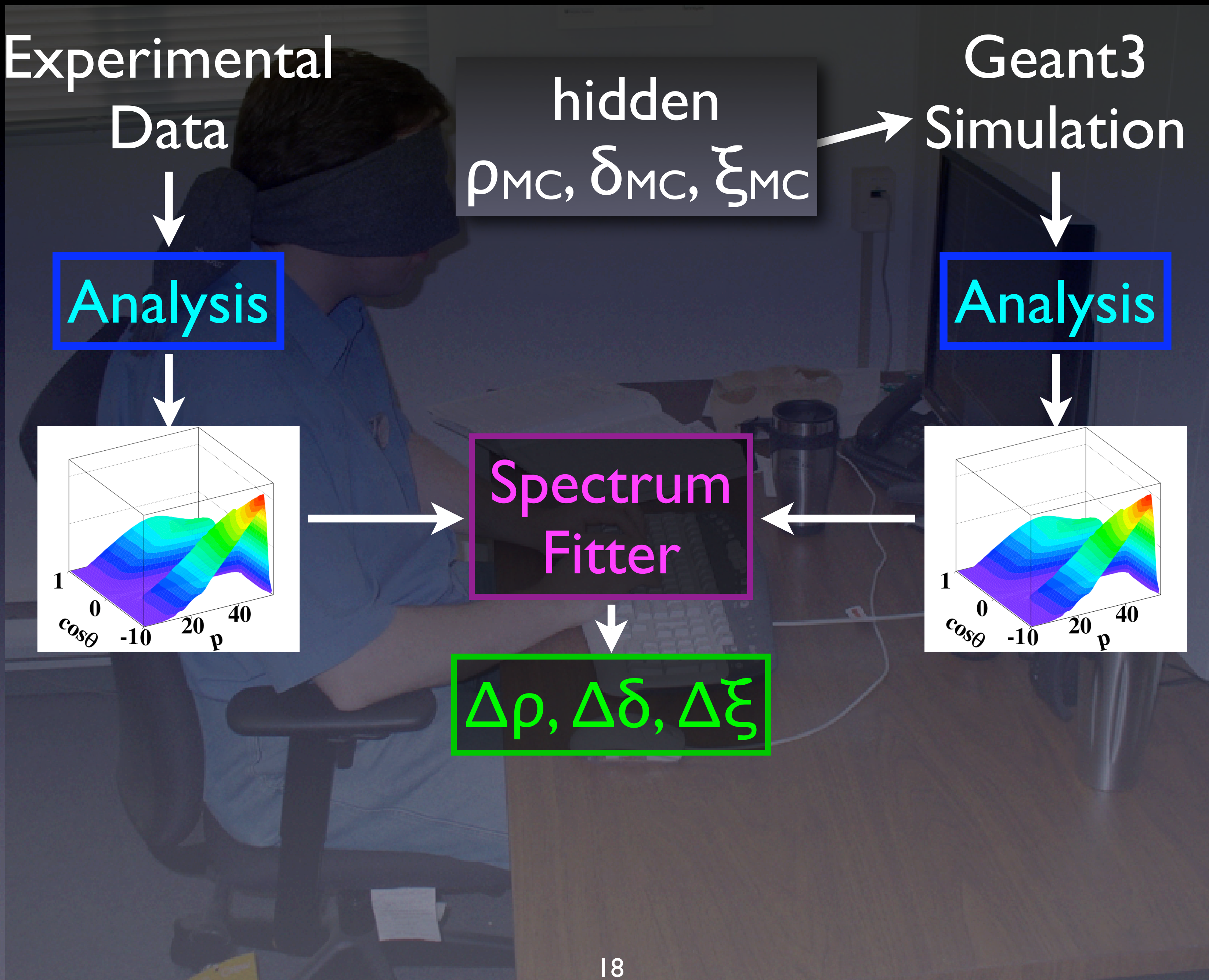

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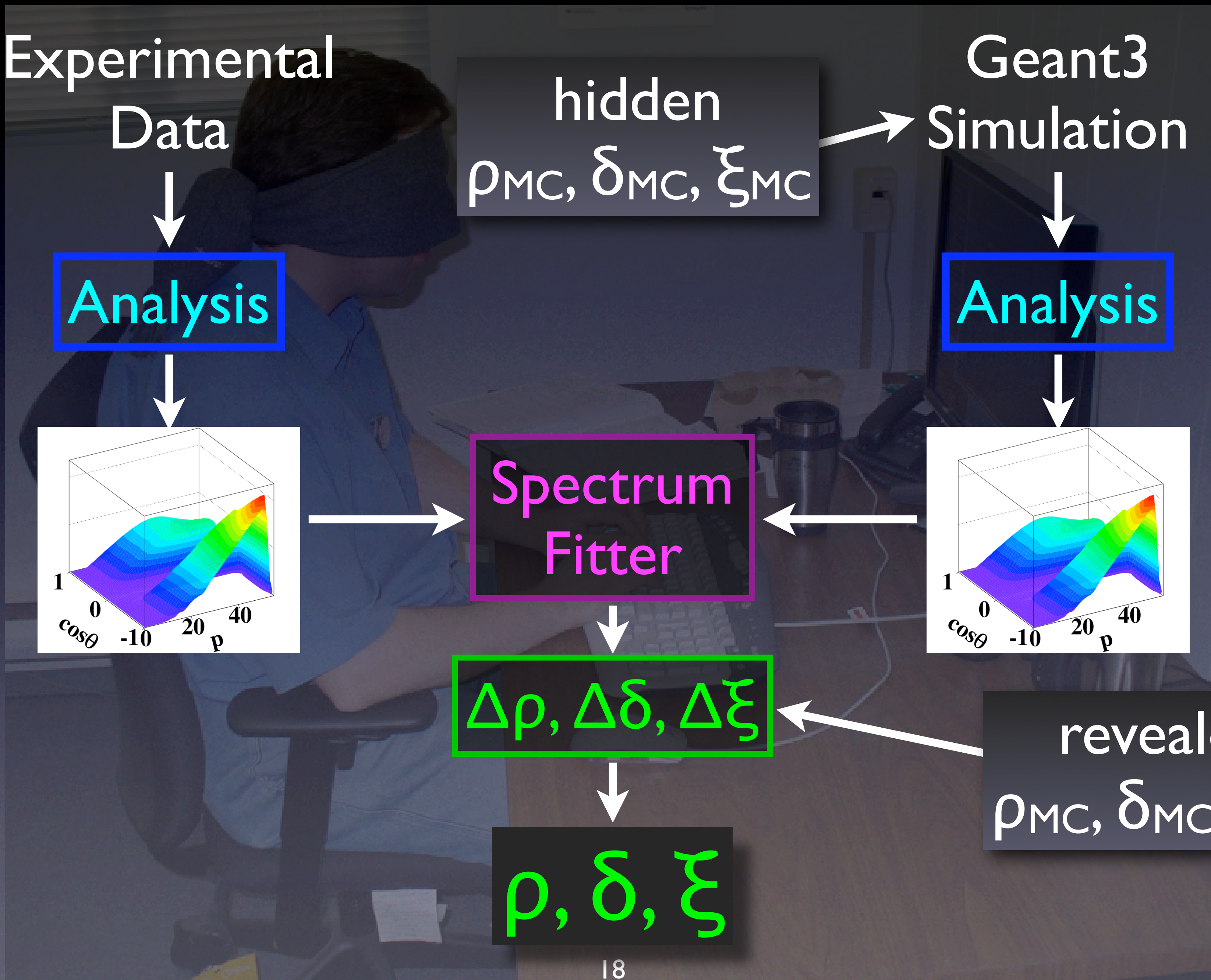

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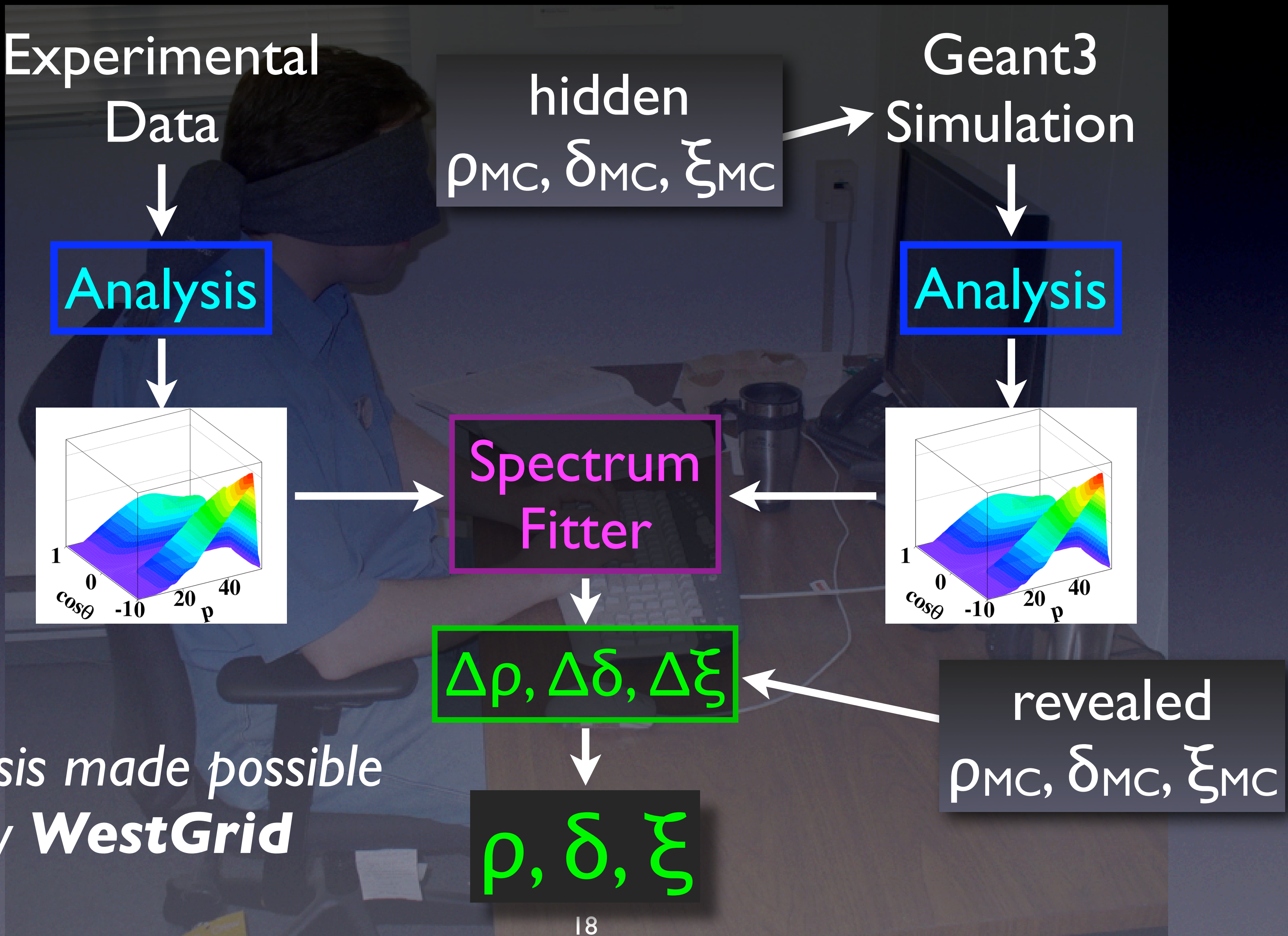


*Analysis made possible by **WestGrid***

Spectrum Fitter

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

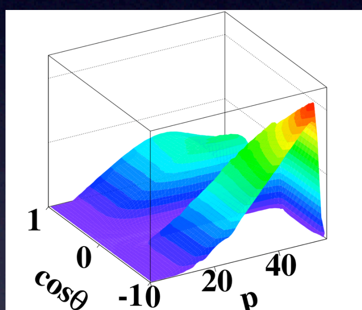
Spectrum Fitter

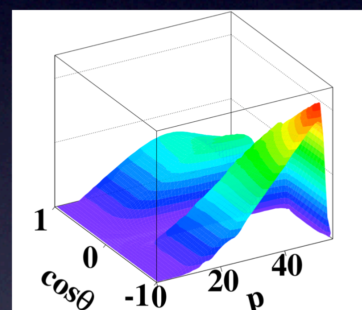
$$\frac{d^2\Gamma}{dx\,d(\cos\theta_s)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\xi,\xi\delta)P_\mu\cos\theta$$

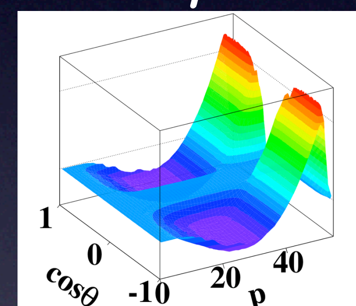
Spectrum Fitter

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

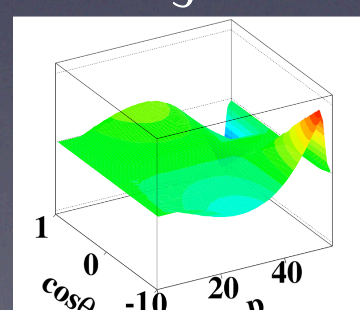
$$N(\alpha_{\mathrm{Data}}) = N(\alpha_{\mathrm{MC}}) + \frac{\partial N}{\partial \rho}\Delta\rho$$

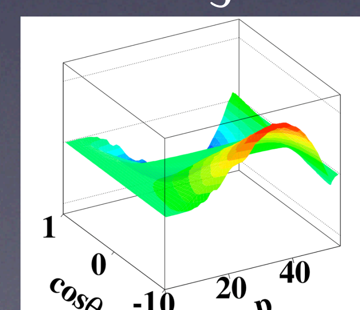






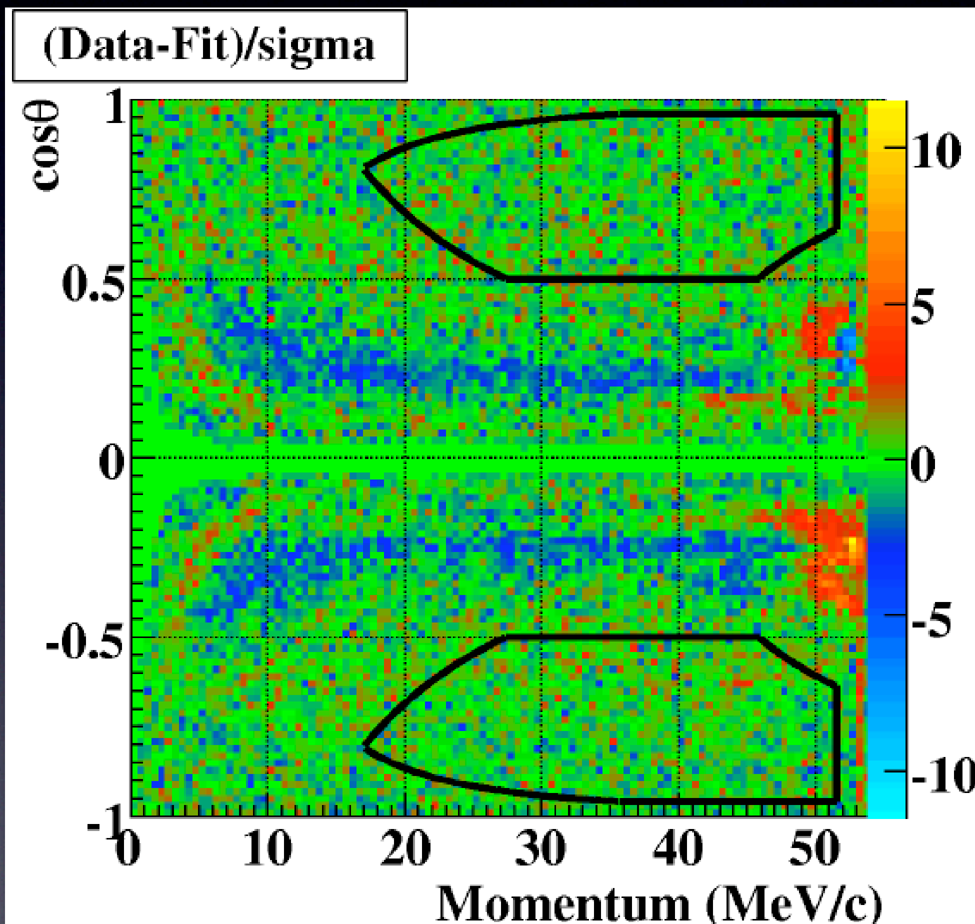
$$+ \frac{\partial N}{\partial \xi\delta}\Delta P_\mu \xi\delta + \frac{\partial N}{\partial \xi}\Delta P_\mu \xi$$

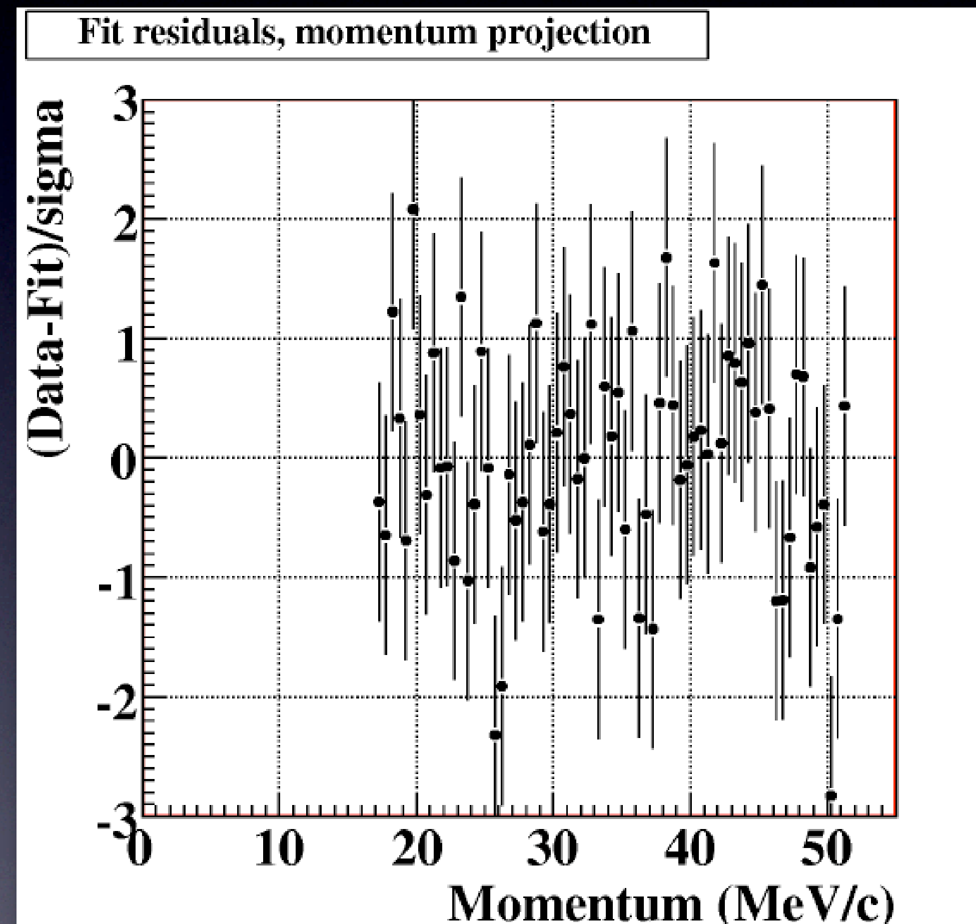




$\alpha = \{\rho, \delta, \xi\}$

Spectrum Fit Quality





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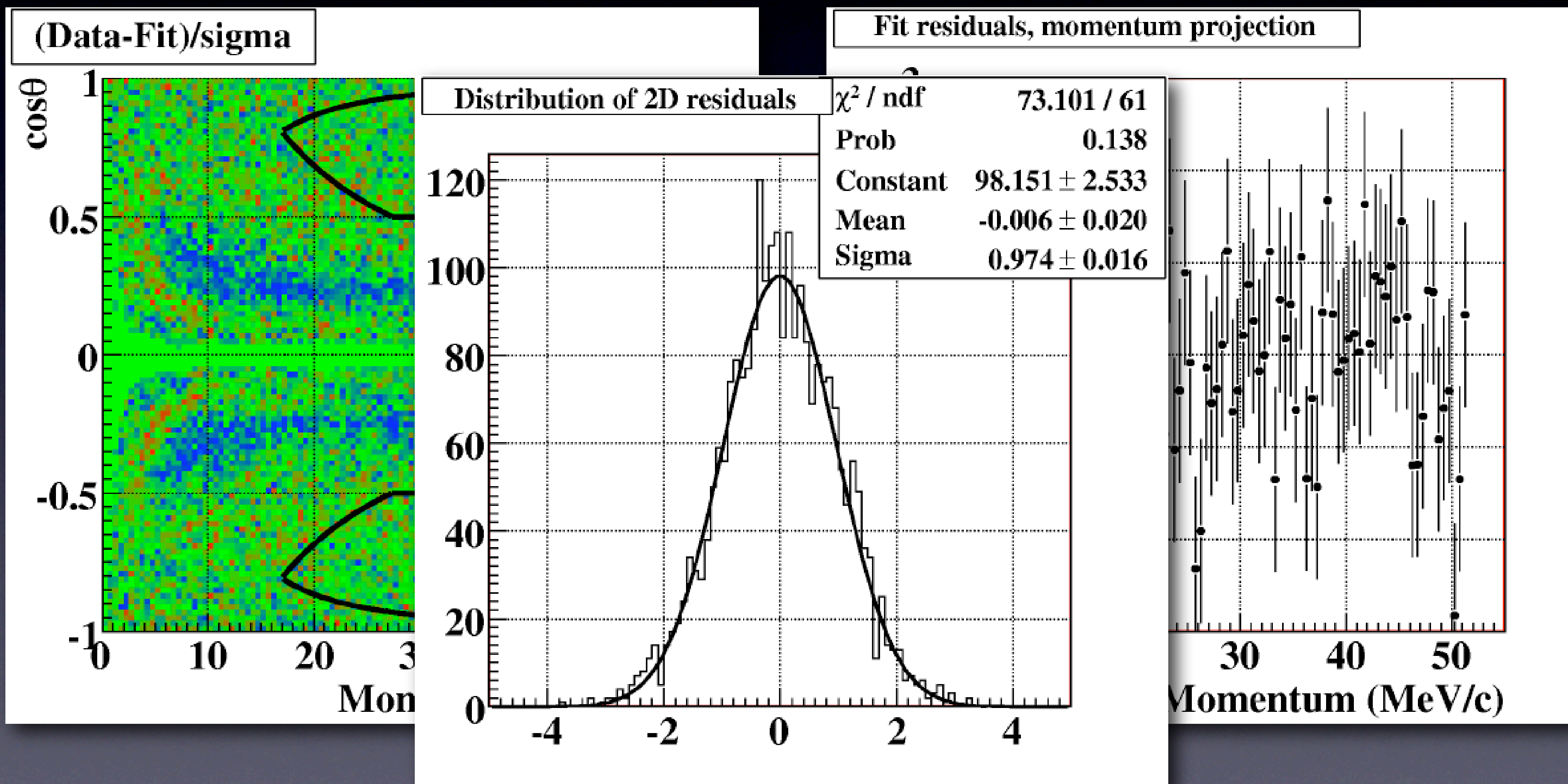
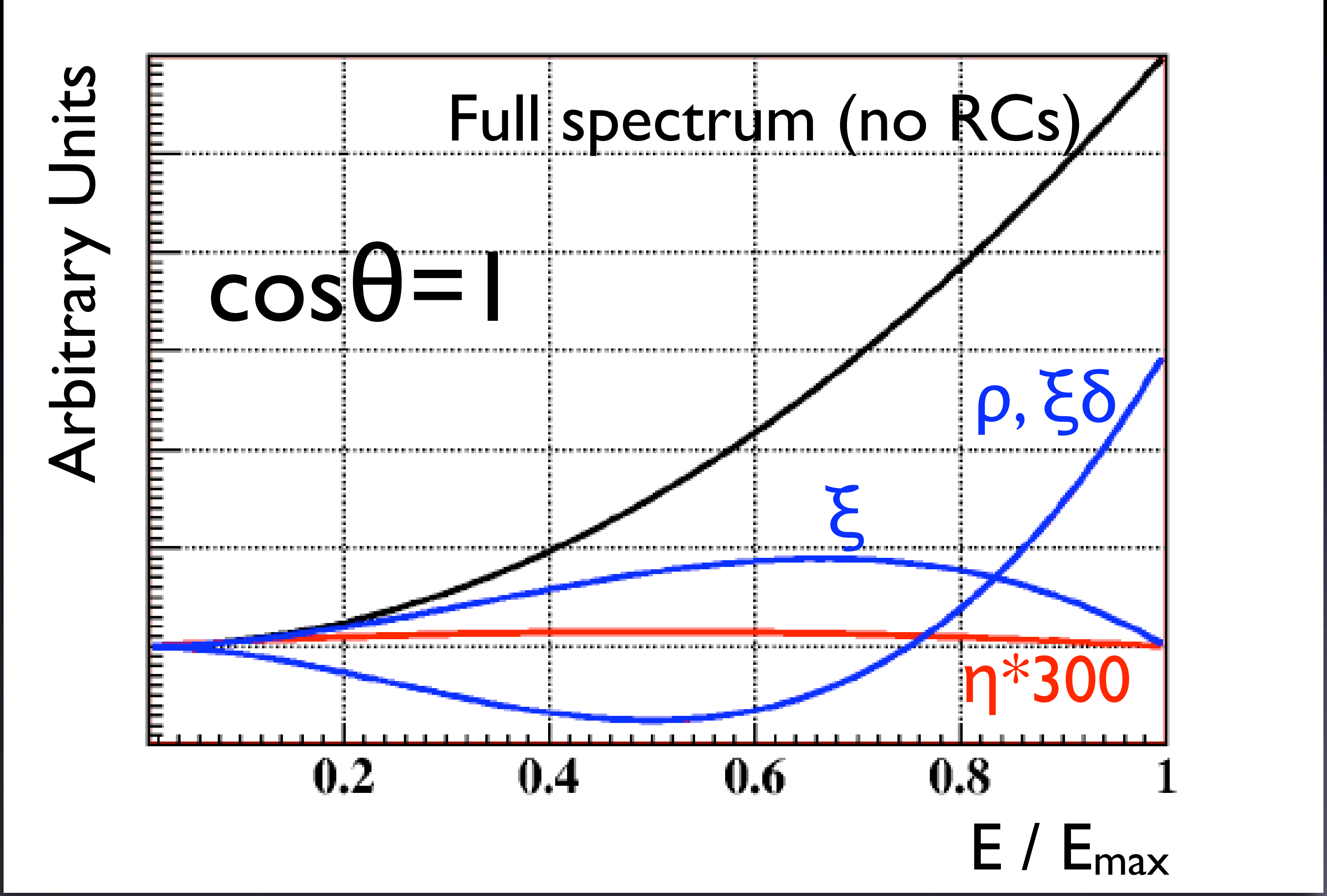
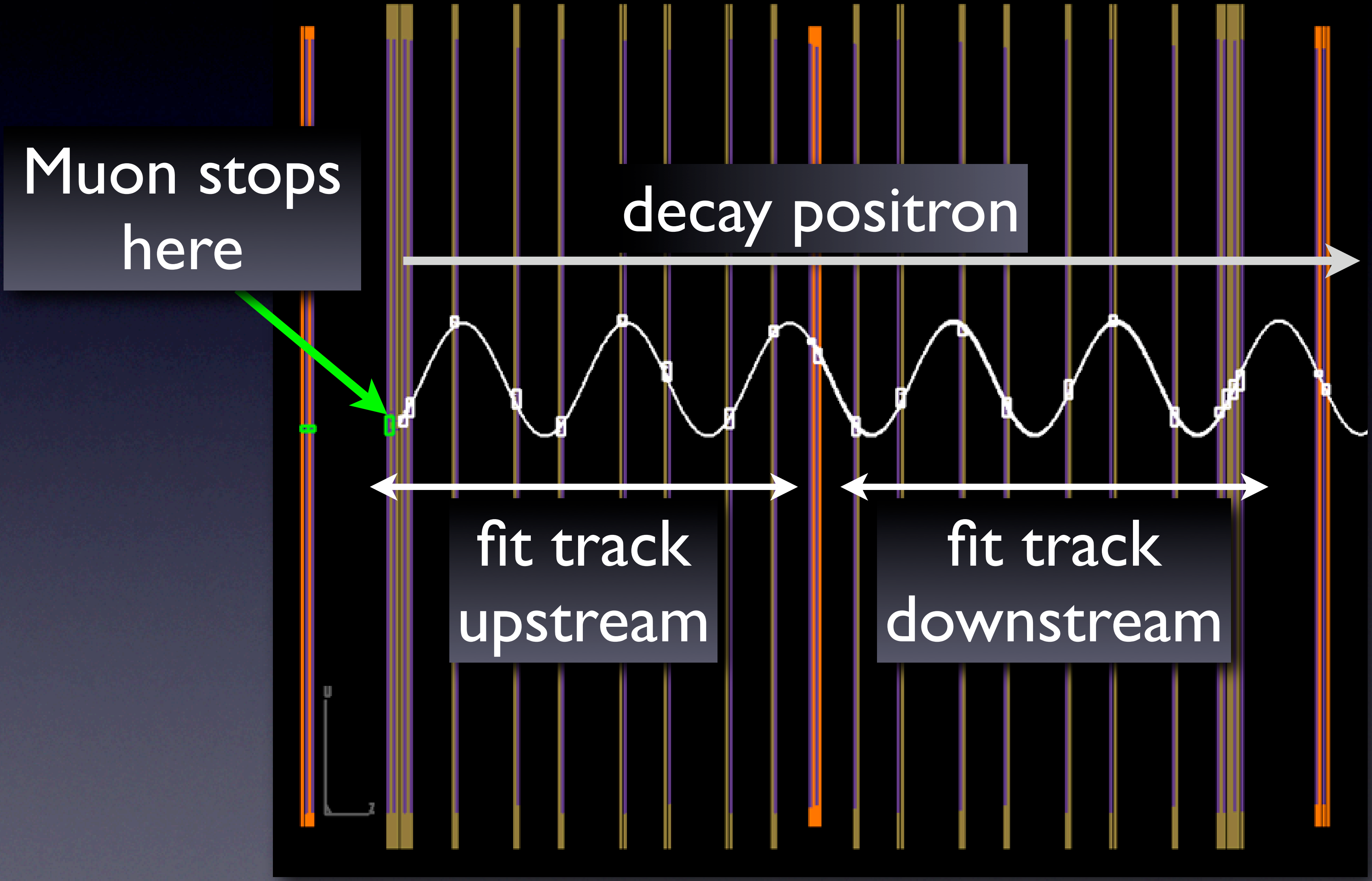
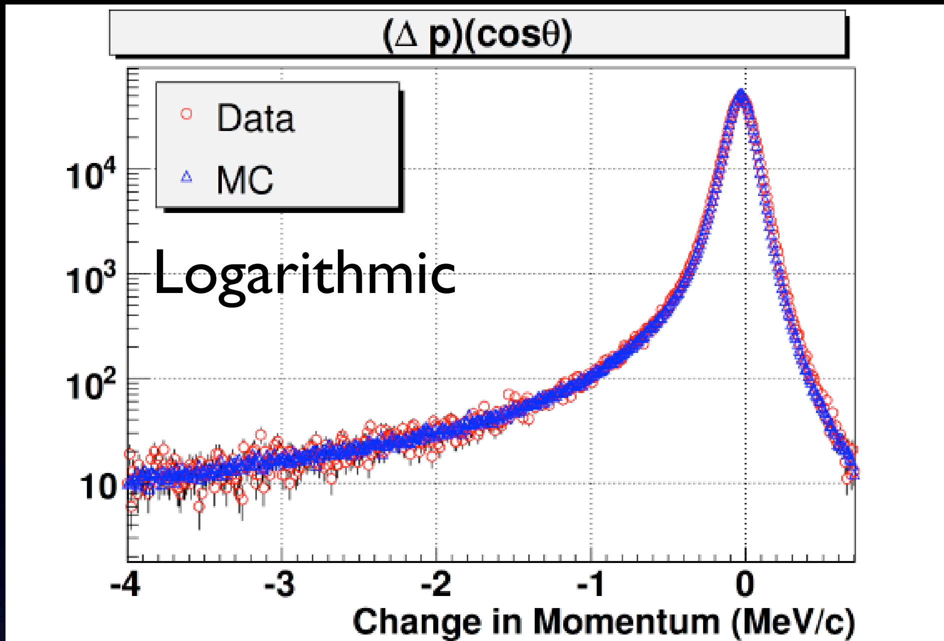


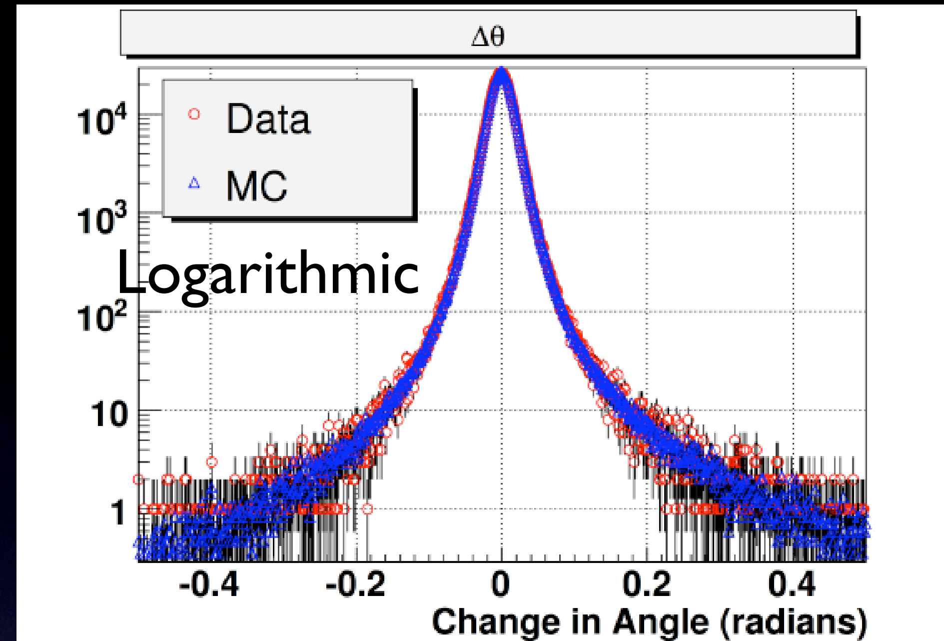
Parameter Sensitivity



Verifying our Simulation

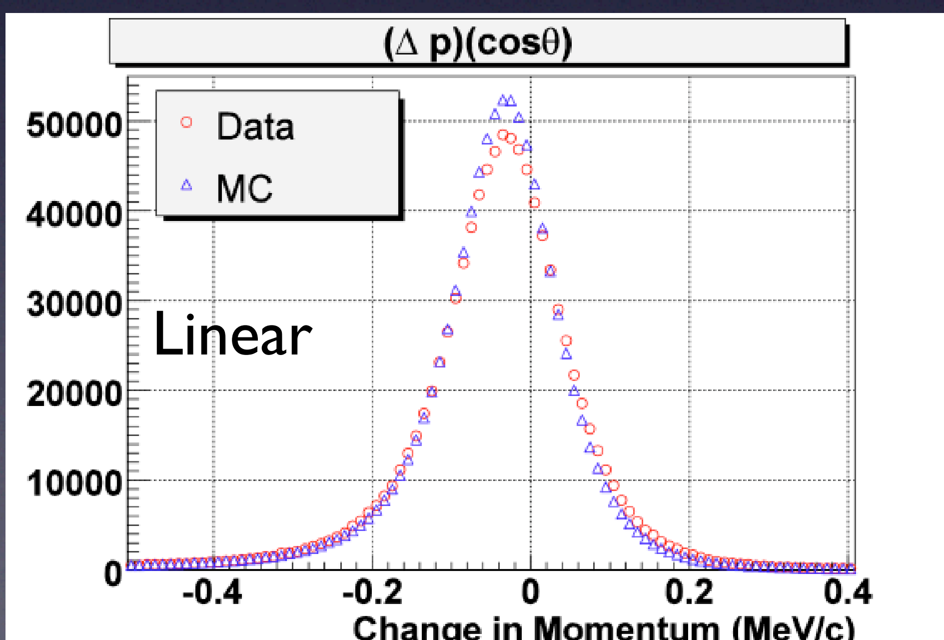


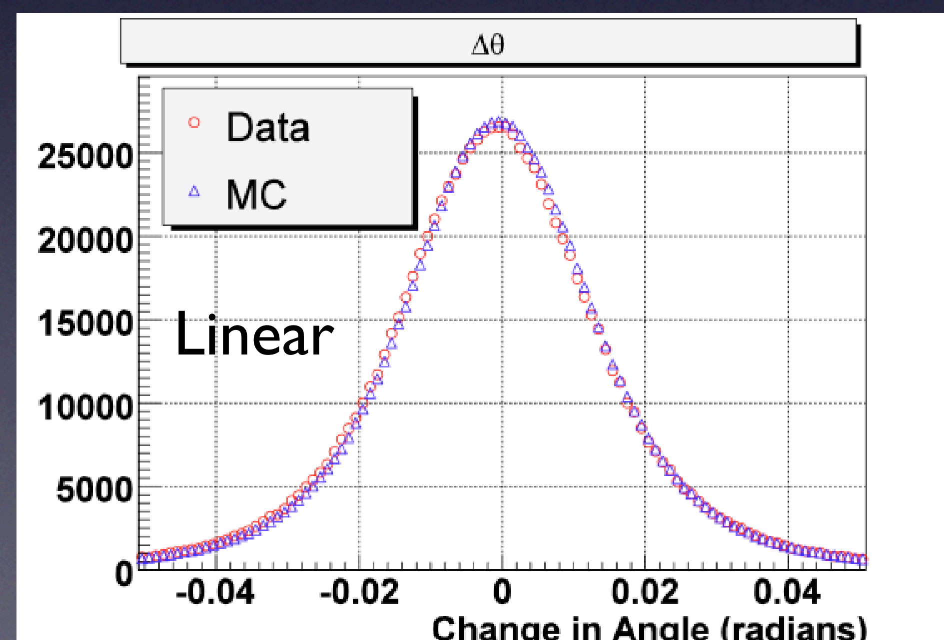




Energy Loss

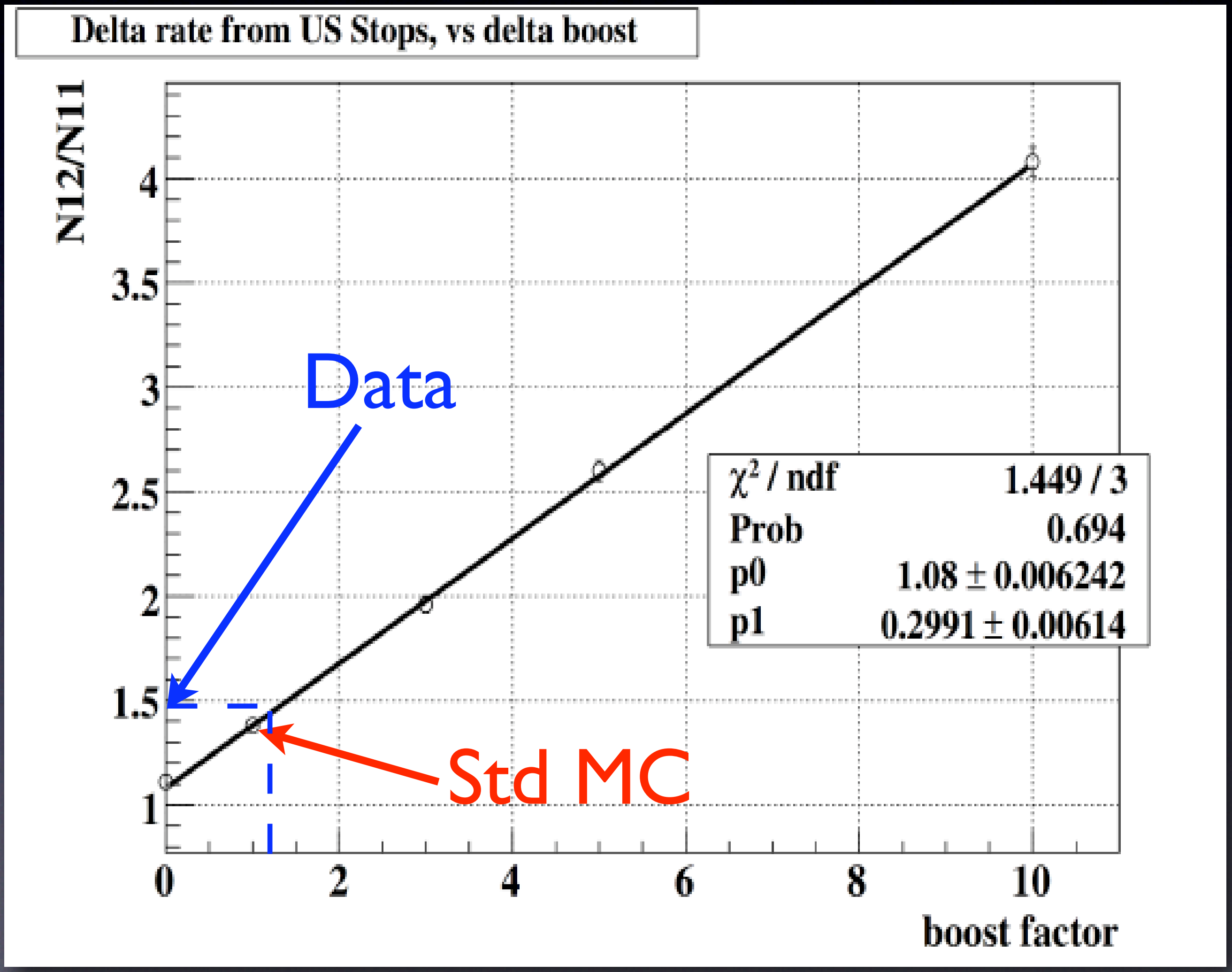
Scattering



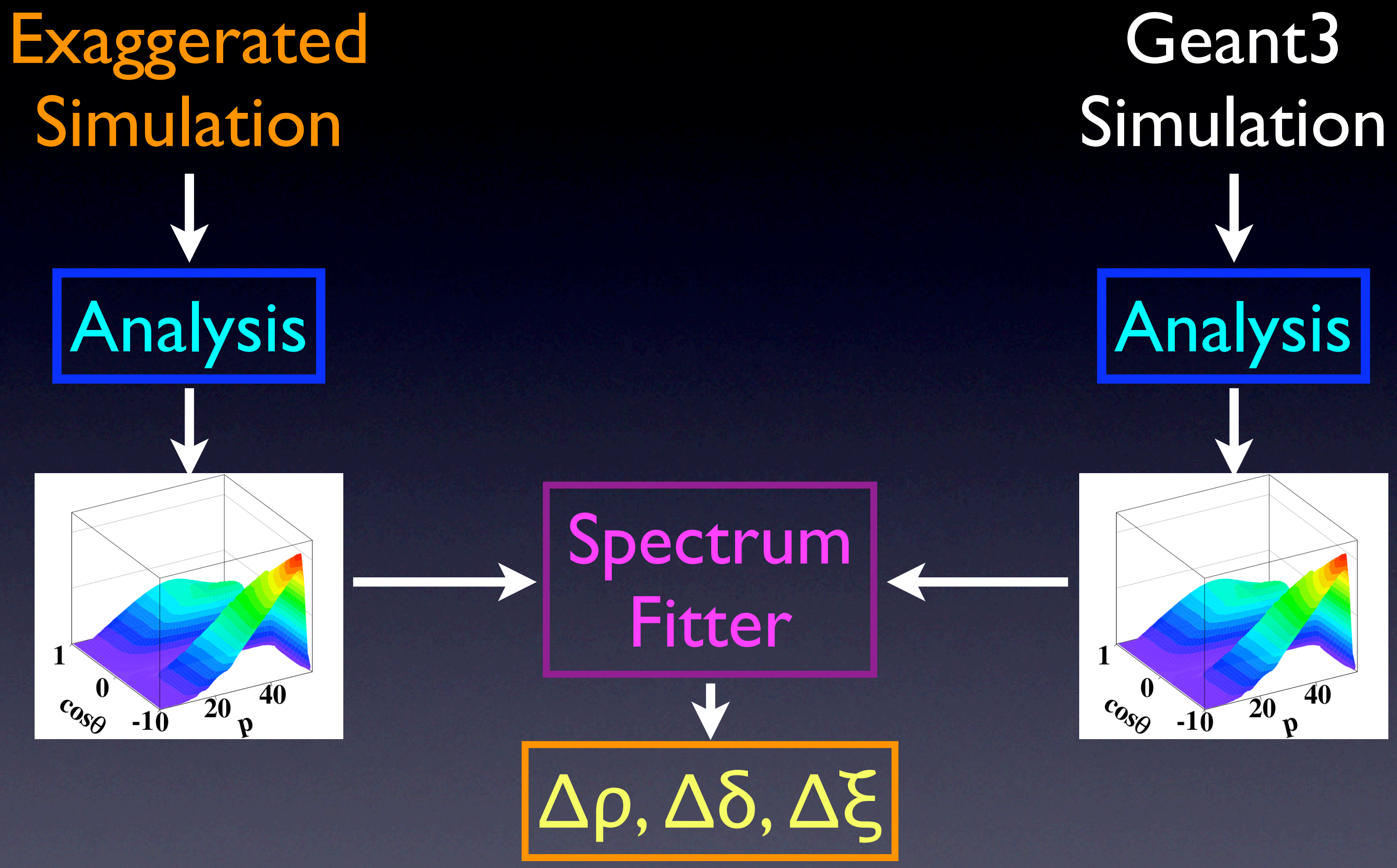


Delta-Ray Production Rate

- Using Upstream Stops, count events with one track upstream and two tracks downstream.
  - Not all of these are deltas!
- Plot MC count rate vs retuned delta rate.
- Compare data count rate to plot: apparent data rate is 18% high.



Determining Systematics



Determining Systematics

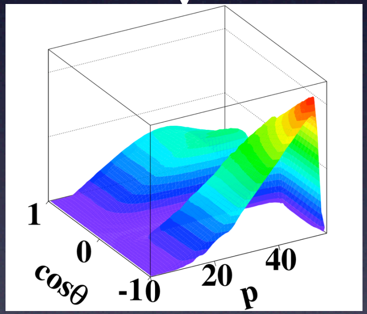
Exaggerated Simulation

- Bremsstrahlung
- Chamber geometry
- …

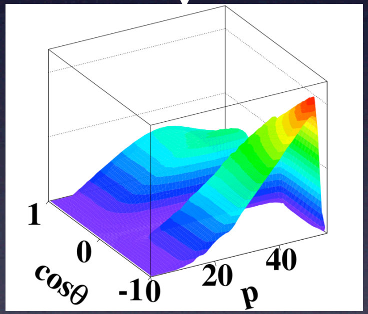
Geant3 Simulation

Analysis

Analysis



Spectrum Fitter



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

Determining Systematics

Exaggerated Simulation

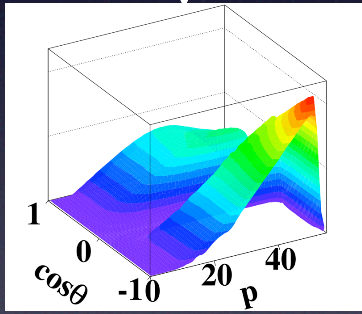
- Bremsstrahlung
- Chamber geometry
- …

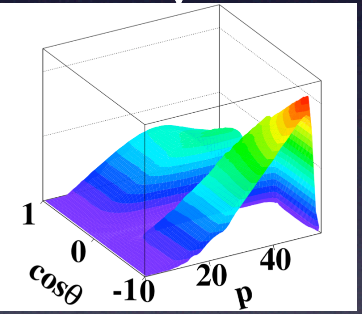
Geant3 Simulation

↓

Analysis

↓





→ Spectrum Fitter ←

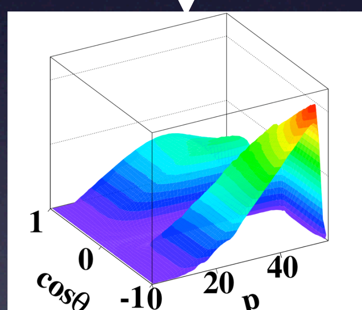
↓

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

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

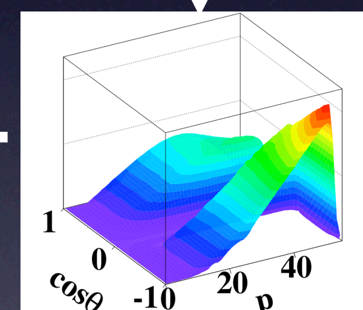
Determining Systematics

Geant3 Simulation → **Exaggerated Analysis** →



→ **Spectrum Fitter** ←

Geant3 Simulation → **Analysis** →



Spectrum Fitter → $\Delta\rho, \Delta\delta, \Delta\xi$

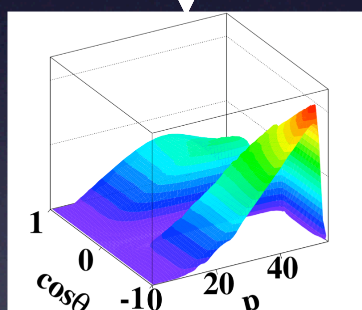
$$\text{Systematic Uncertainty} = \frac{(\Delta\rho, \Delta\delta, \Delta\xi)}{\text{Exaggeration}}$$

Determining Systematics

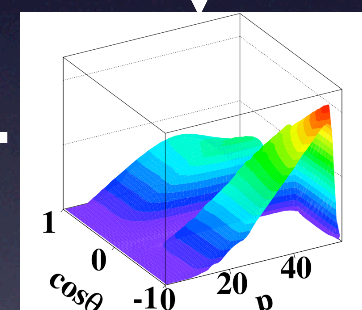
Geant3 Simulation → Exaggerated Analysis

- Magnetic field
- Chamber alignment
- …

Geant3 Simulation → Analysis



→ Spectrum Fitter ←



Spectrum Fitter → $\Delta\rho, \Delta\delta, \Delta\xi$

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

Example Systematic: Delta Rays

- MC delta ray production is (conservatively) 18% too low
- Run simulation with x3 delta rays:
  Scale factor is (3-1)/0.18 = 11
- Compare exaggerated vs standard:
  $\Delta\rho = -0.00171, \quad \Delta\delta = -0.00098$
- Apply scale factor for final systematic uncertainty:
  $\Delta\rho = -0.00015, \quad \Delta\delta = -0.00009$

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**

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ρ: *Phys. Rev. Lett.* ***94****, 101805 (2005)*

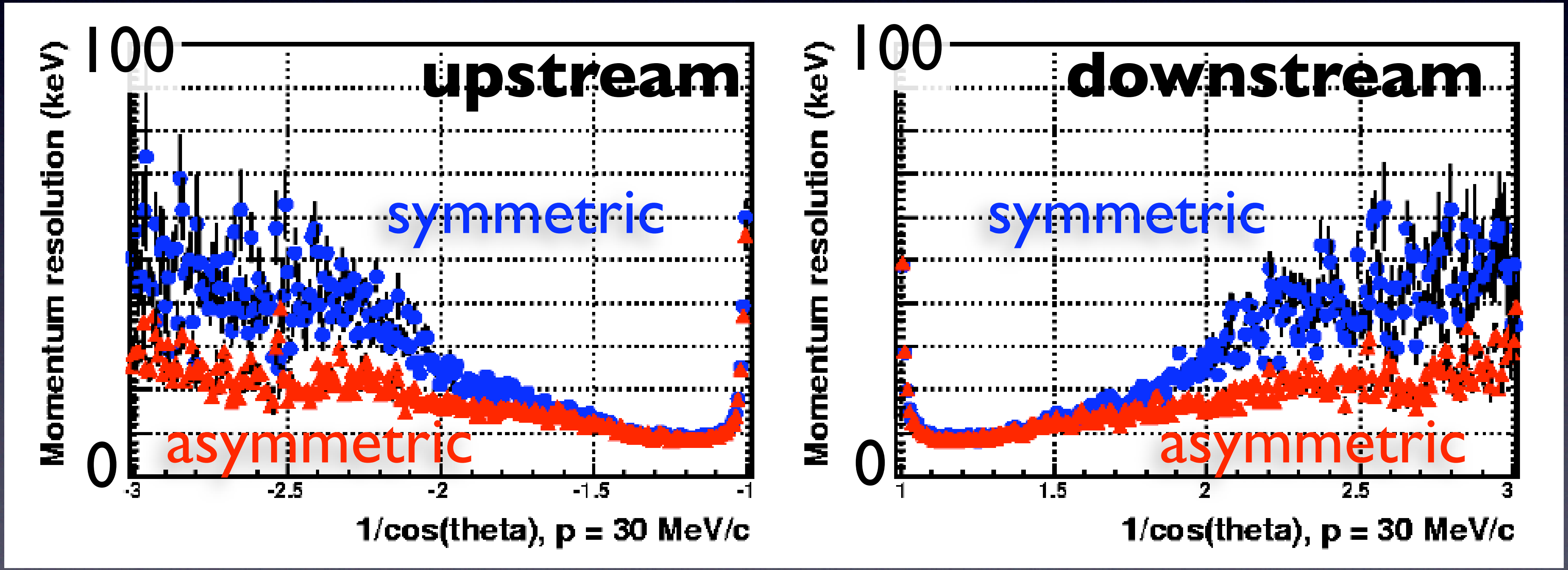
δ: *Phys. Rev. D* ***71****, 071101(R) (2005)*

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

Assumed Drift Cell Geometry in Analysis

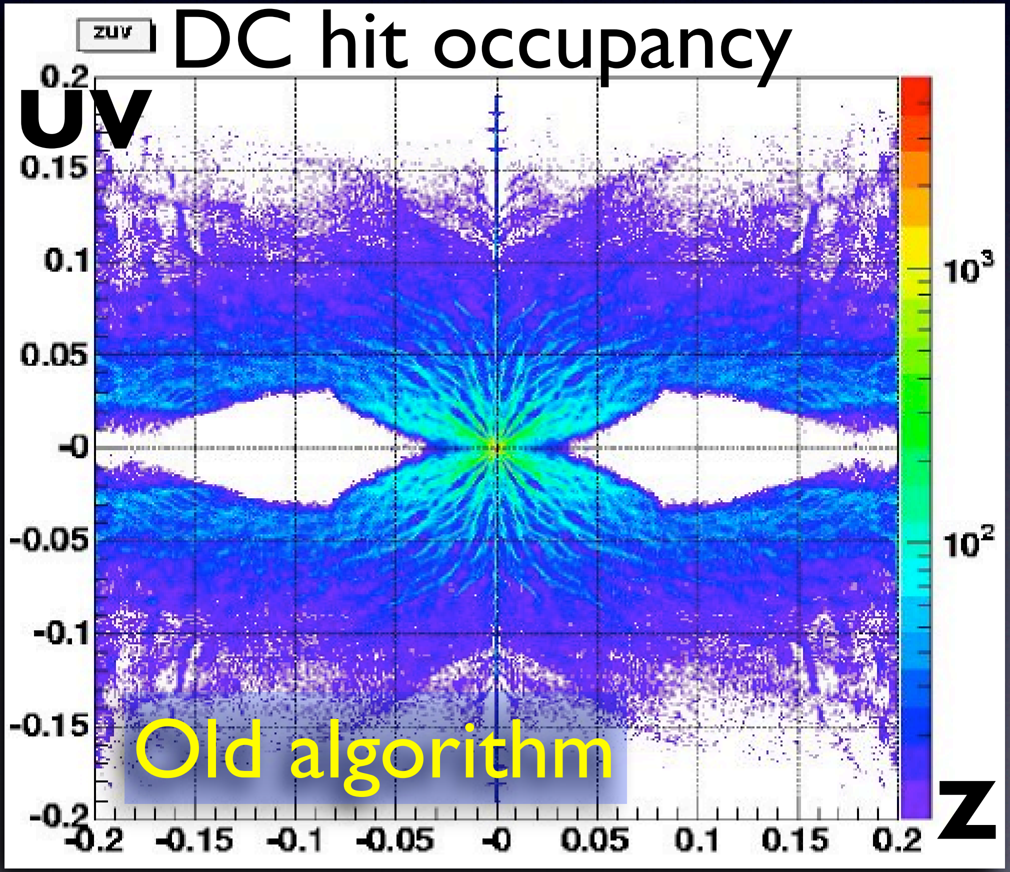
STRs now with asymmetric drift cells

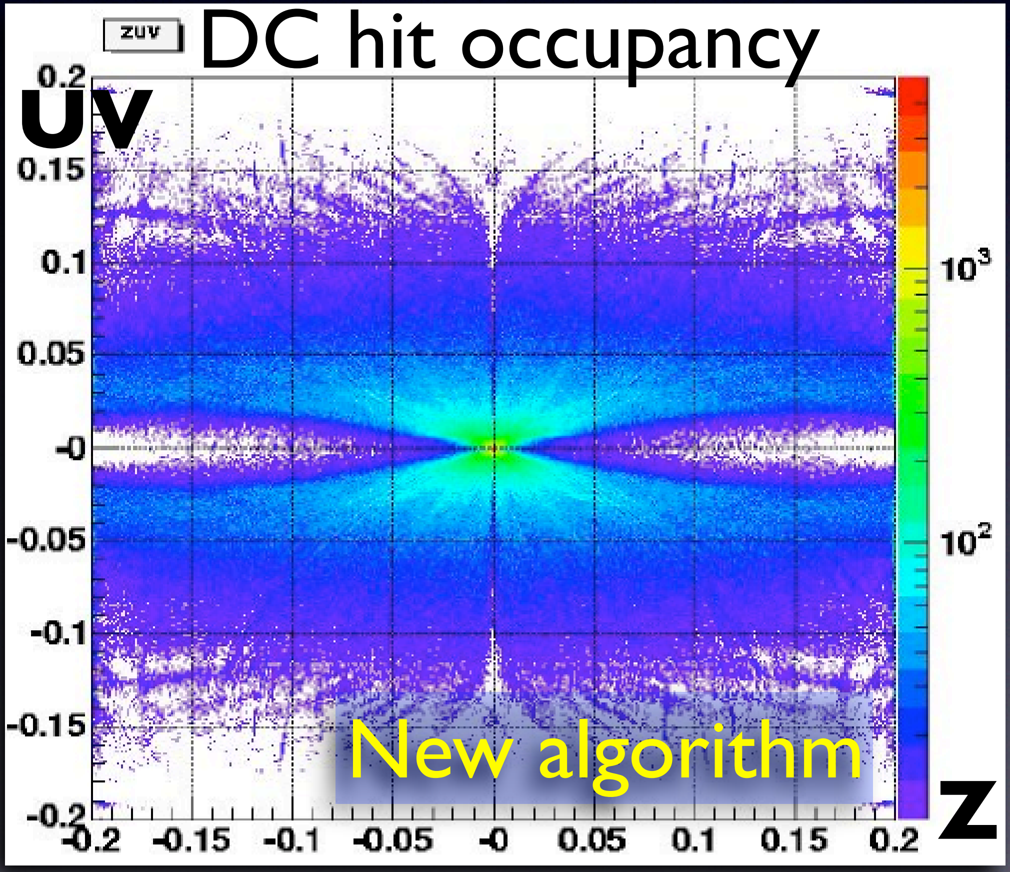


Much better momentum resolution

Tracking Improvements

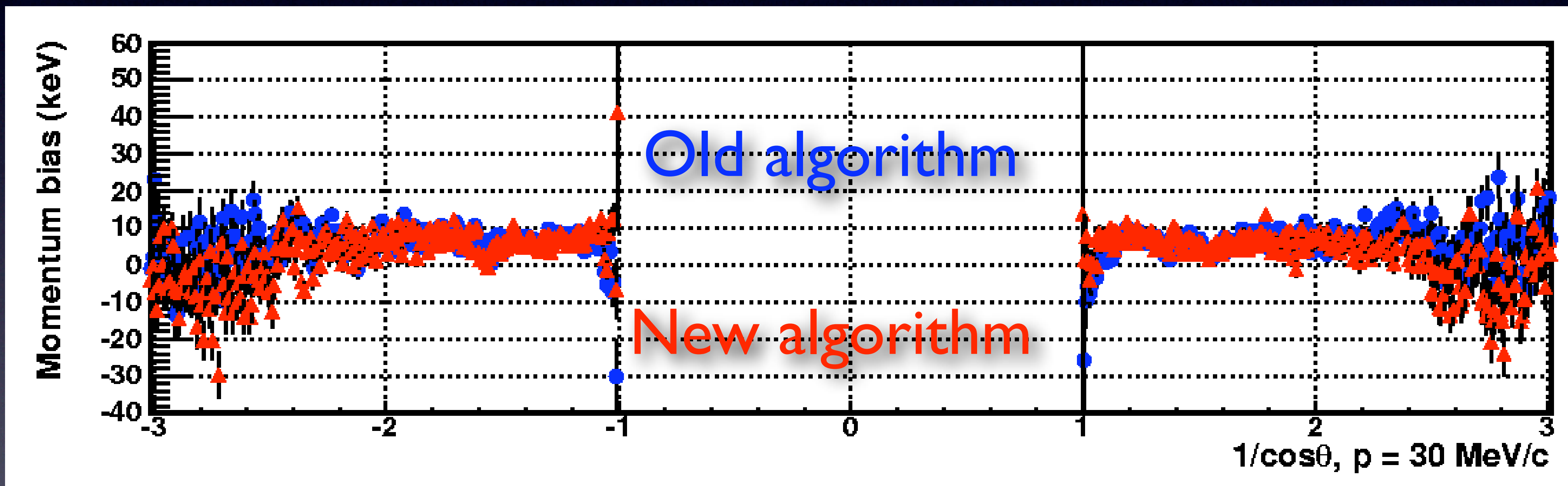
Increased drift time map precision and new hit position algorithm in tracker...





Tracking Improvements

...reduces momentum bias,
especially for small angles



Tracking Improvements

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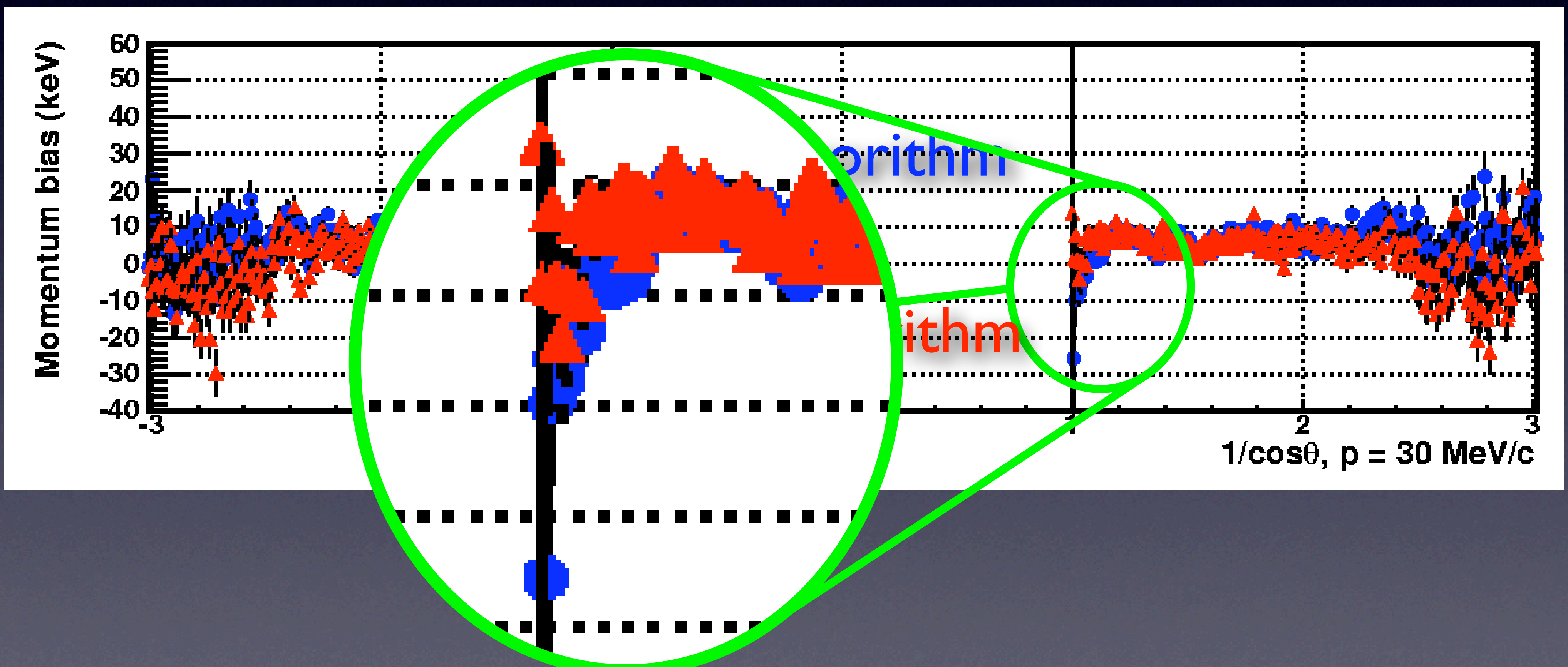
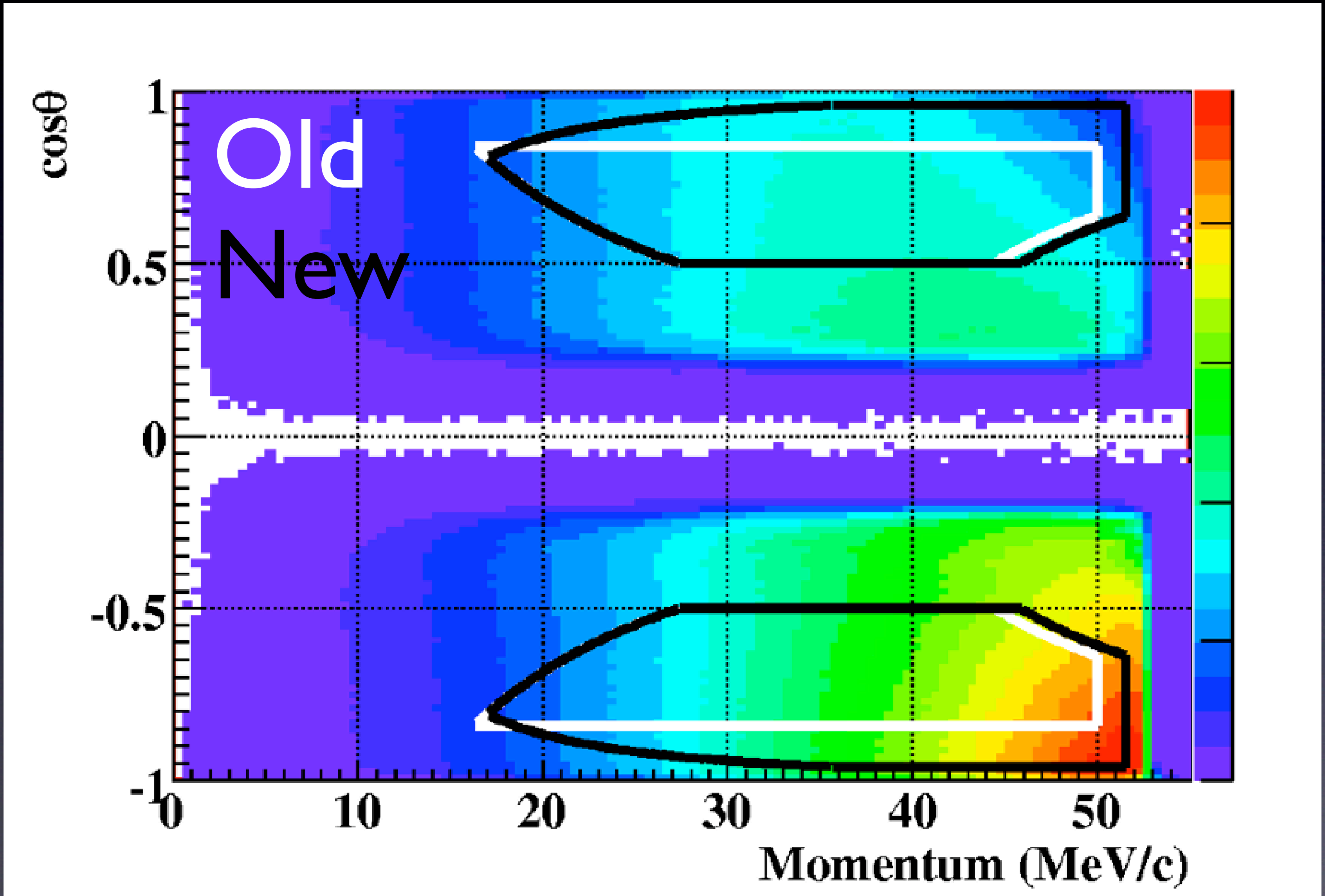
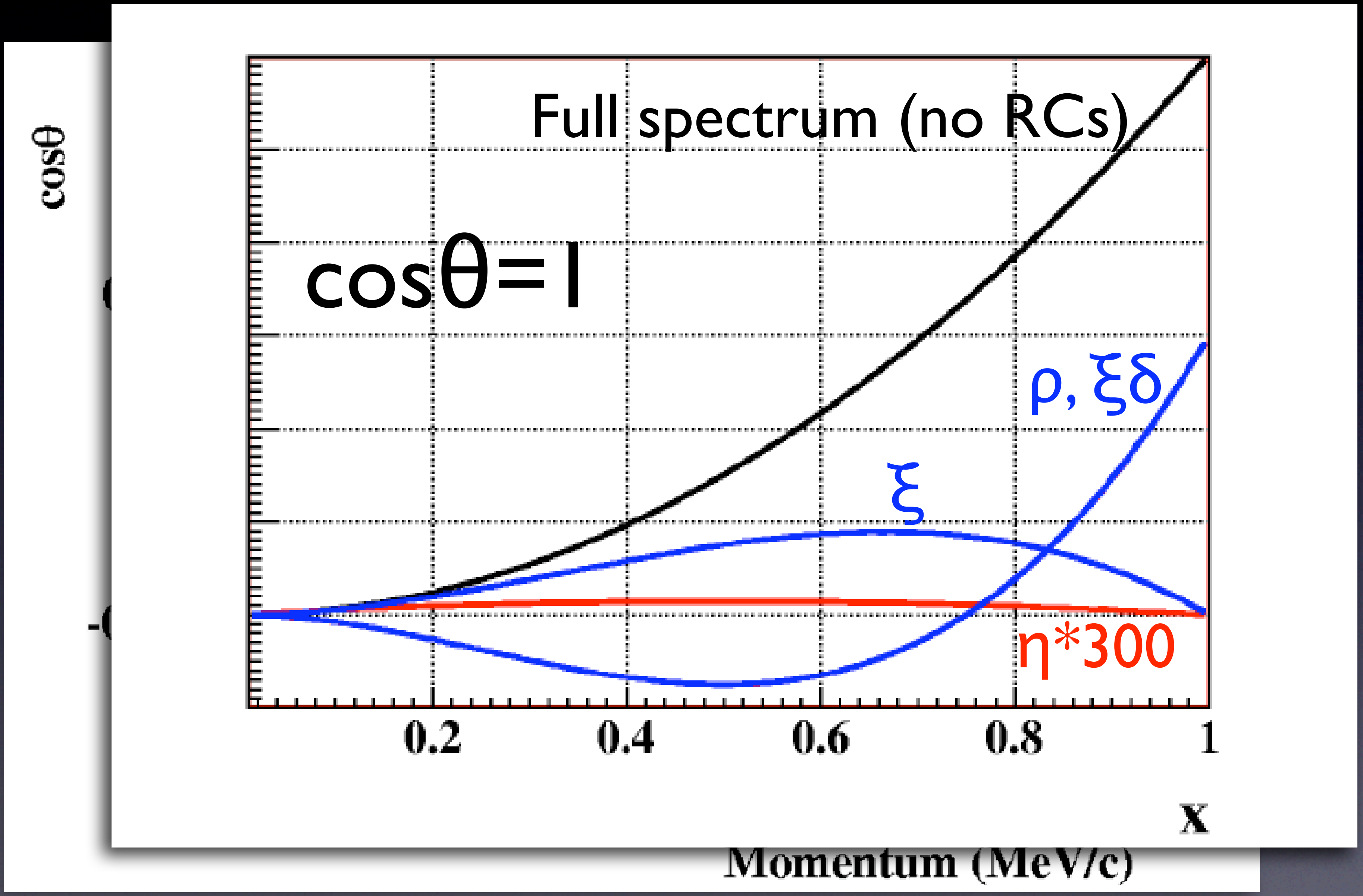


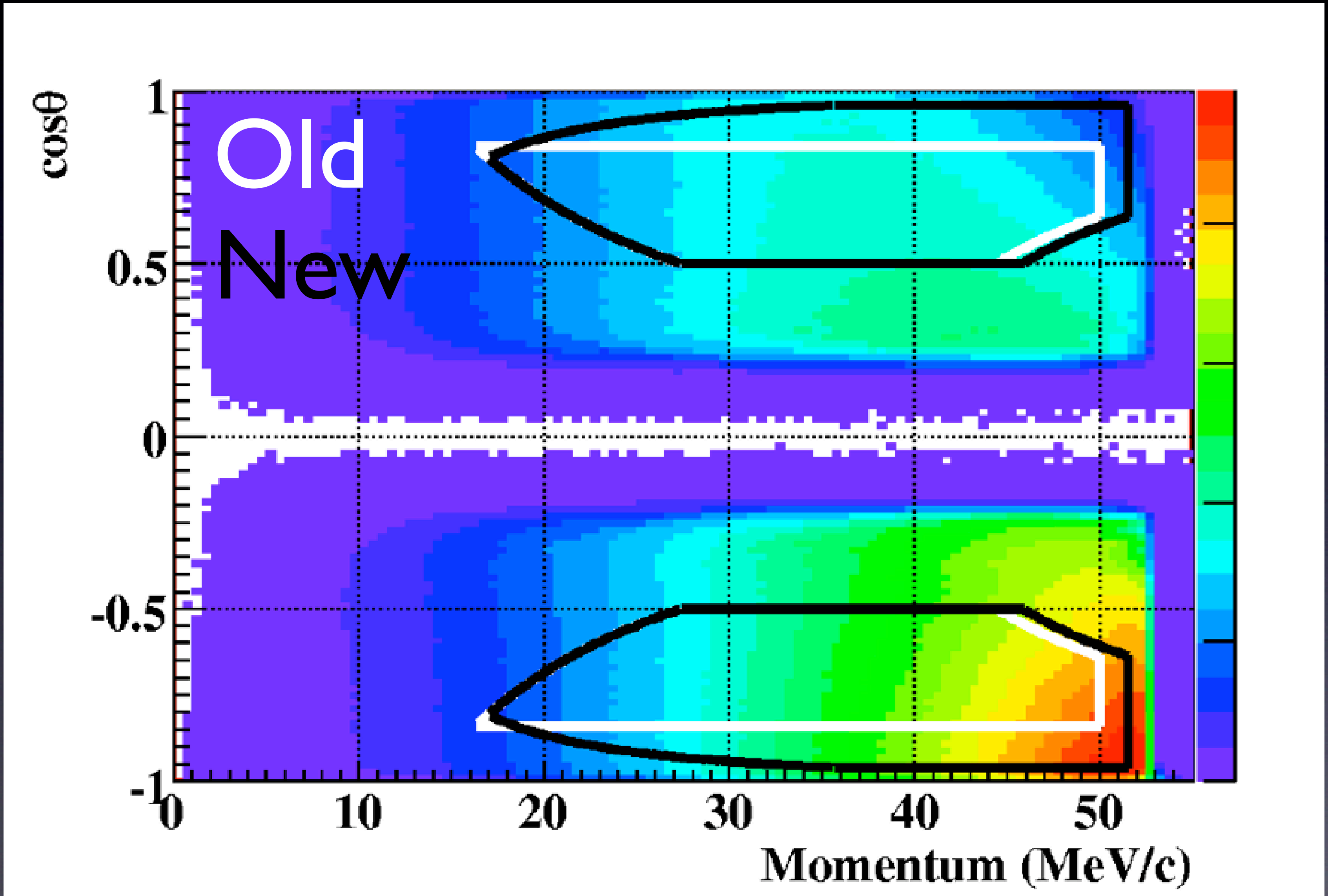
Increased Fiducial Volume



Increased Fiducial Volume

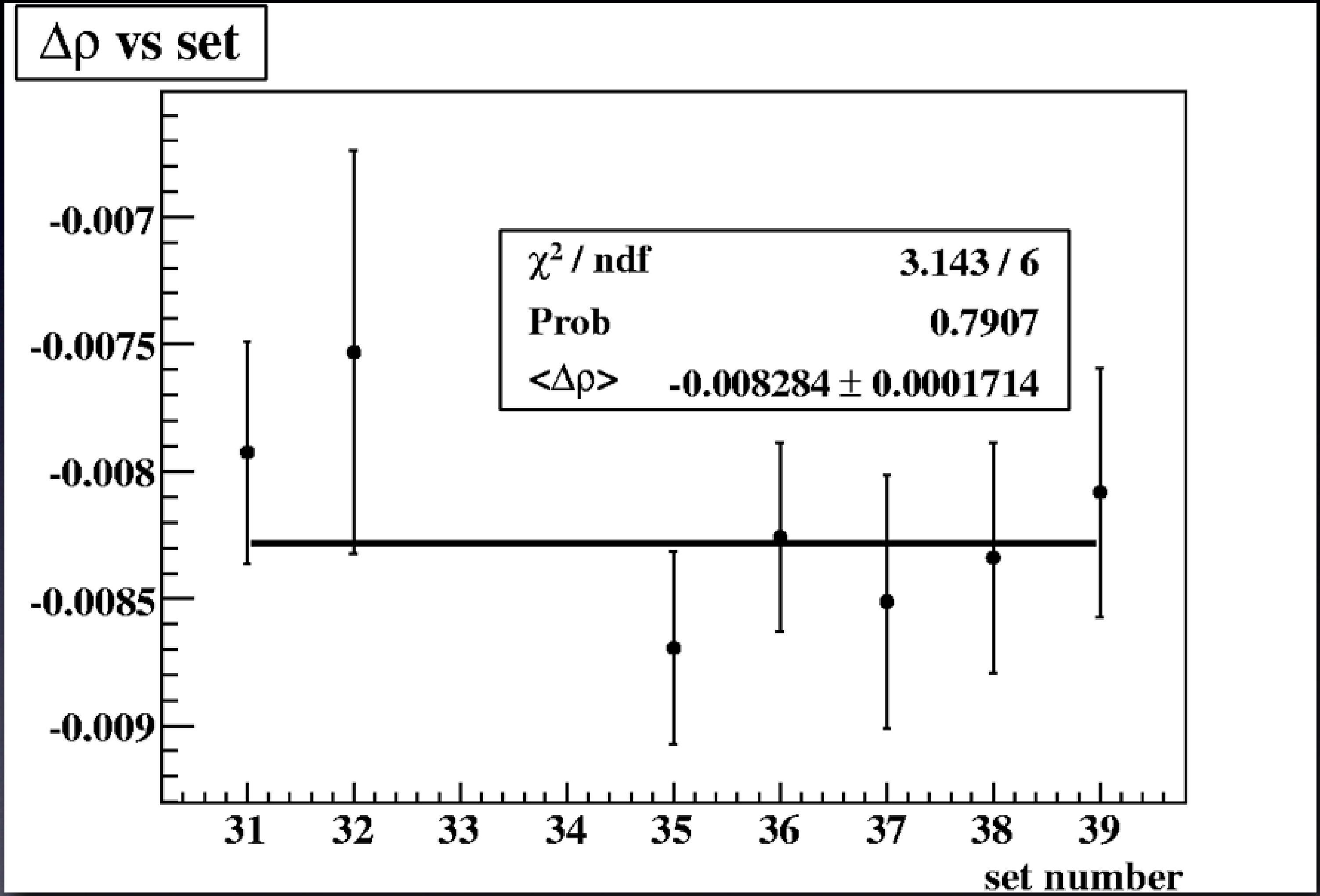


Increased Fiducial Volume



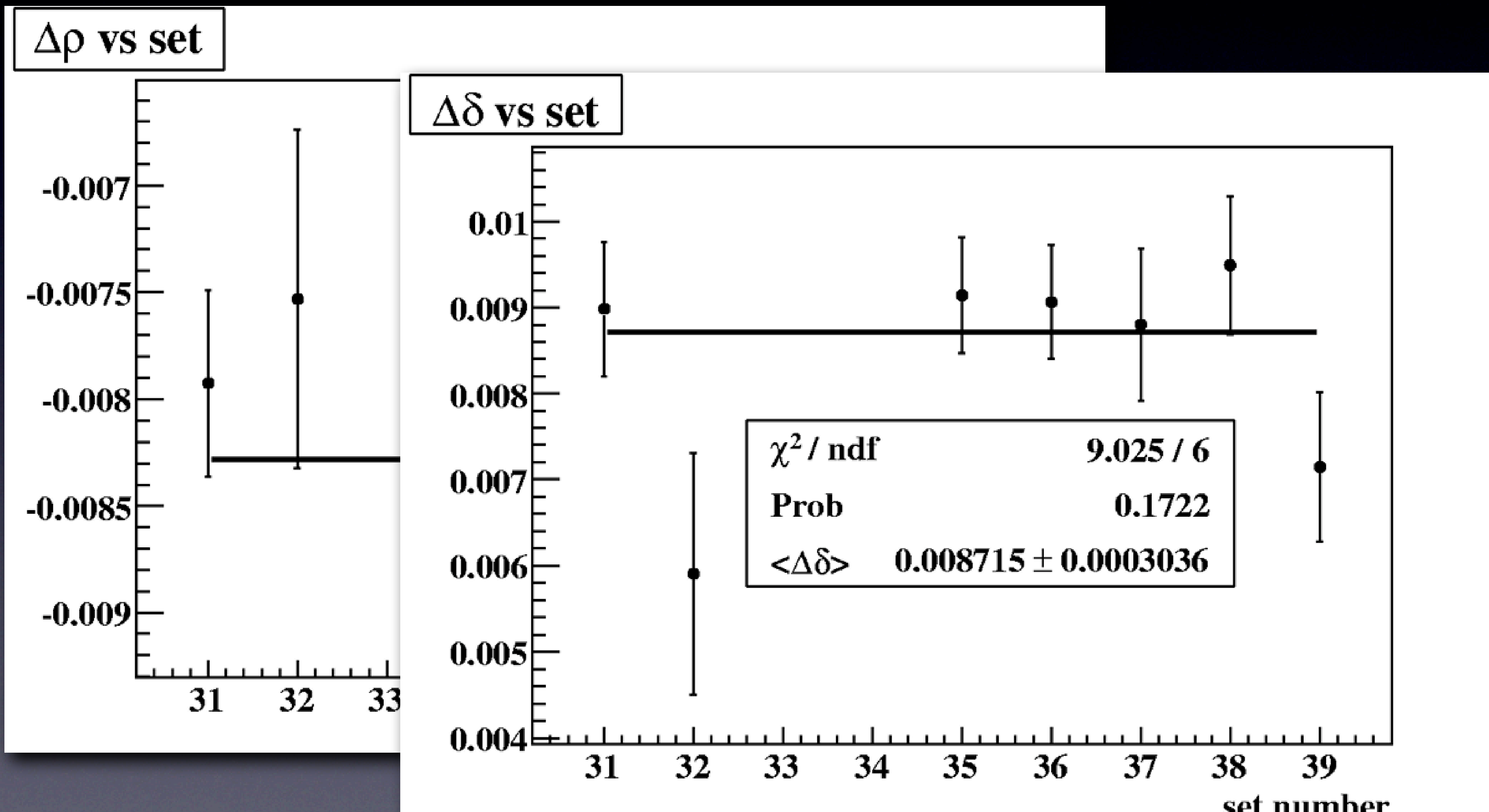
Consistency of Fits

Multiple data sets taken under different conditions



Consistency of Fits

Multiple data sets taken under different conditions



Corrections

	$\Delta\rho$	$\Delta\delta$
STR simulation	-1.99 ± 2.92	+1.61 ± 5.17
Momentum resolution	+1.22 ± 0.24	+1.31 ± 0.26
Total:	**-0.77**	**+2.92**

Units of 0.0001

New Measurements

ρ

δ

New Measurements

ρ

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)

δ

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
$\lvert g^T_{LL}\rvert$	≡ 0	≡ 0	≡ 0
$\lvert g^T_{LR}\rvert$	**< 0.036**	**< 0.025**	**< 0.022**
$\lvert g^T_{RL}\rvert$	< 0.112	< 0.104	< 0.104
$\lvert g^T_{RR}\rvert$	≡ 0	≡ 0	≡ 0

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90% Confidence Limits

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

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: $Q_R^\mu < 0.006$

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*: $|\zeta_g| < 0.066$

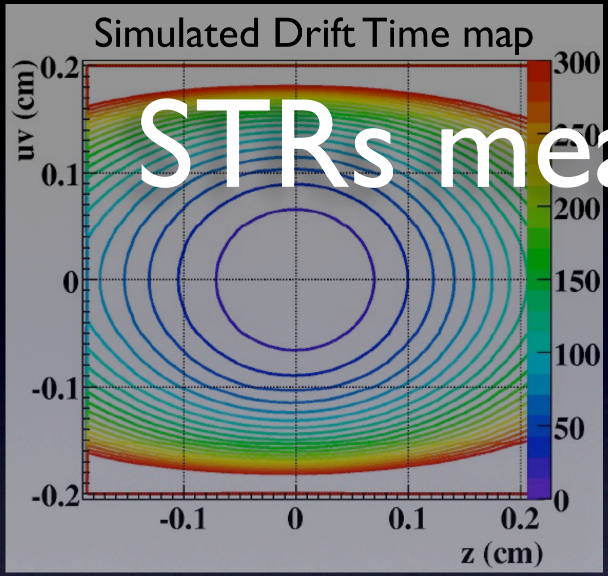
TWIST Published: $|\zeta_g| < 0.028$

Current: $|\zeta_g| < 0.022$

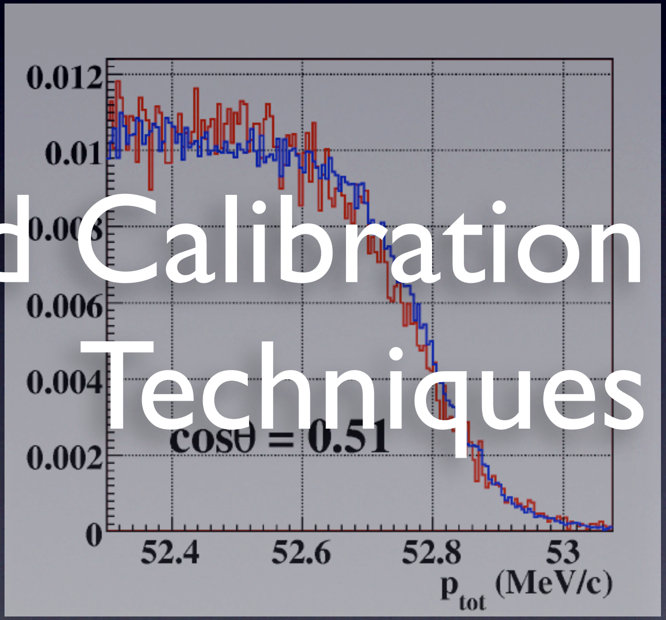
Tests of LRS

Observable	m_2 (GeV/c^2)	$\|\zeta\|$	+	-
$m(K_L - K_S)$	>1600		reach	(P)MLRS
Direct W_R searches	>1000 (D0) >786 (CDF)		clear signal	(P)MLRS 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 (<0.022)	**model independence**	light ν_R

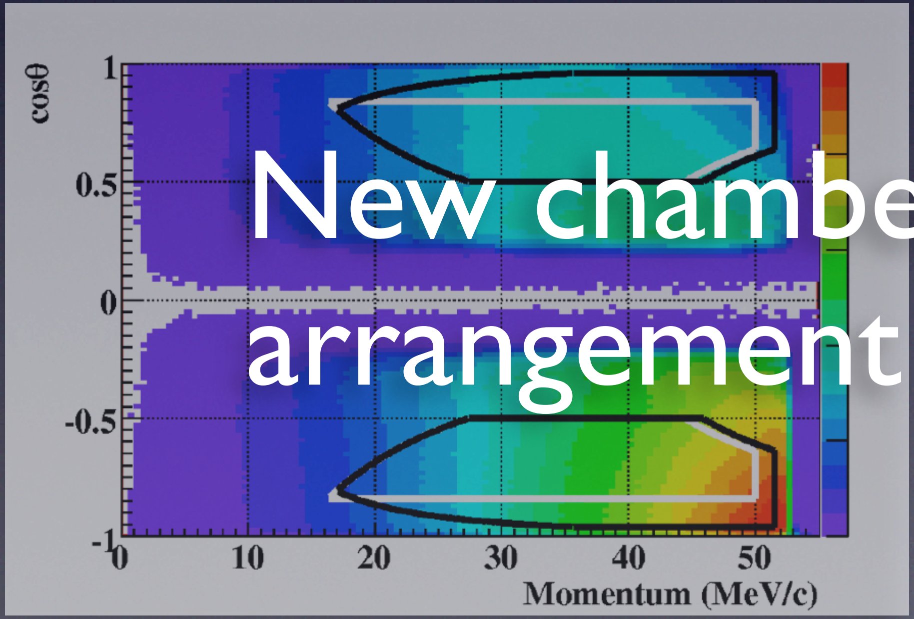
Ongoing Improvements



STRs measured directly



Improved Calibration Techniques



New chamber arrangement

...and more!

The *TWIST* Experiment

New high-precision measurement!

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

PRELIMINARY

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

Systematics well understood

Significant (x2!) 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 ✪ ✻
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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

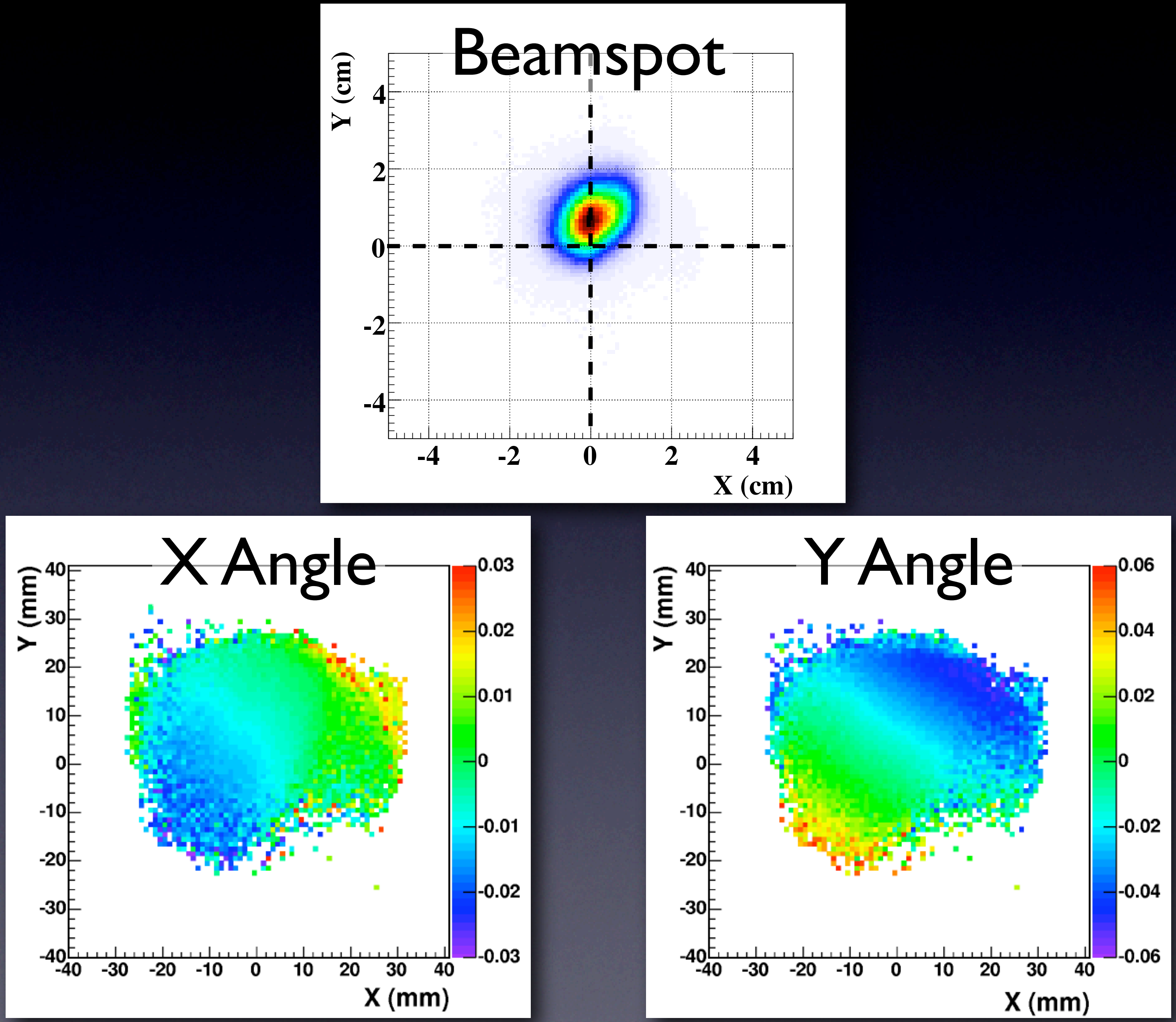
Valparaiso
Don Koetke
Shirvel Stanislaus

✪ 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.

2004 Muon Beam Profile



Decay Parameters and Coupling Constants

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

LRS Model Limits