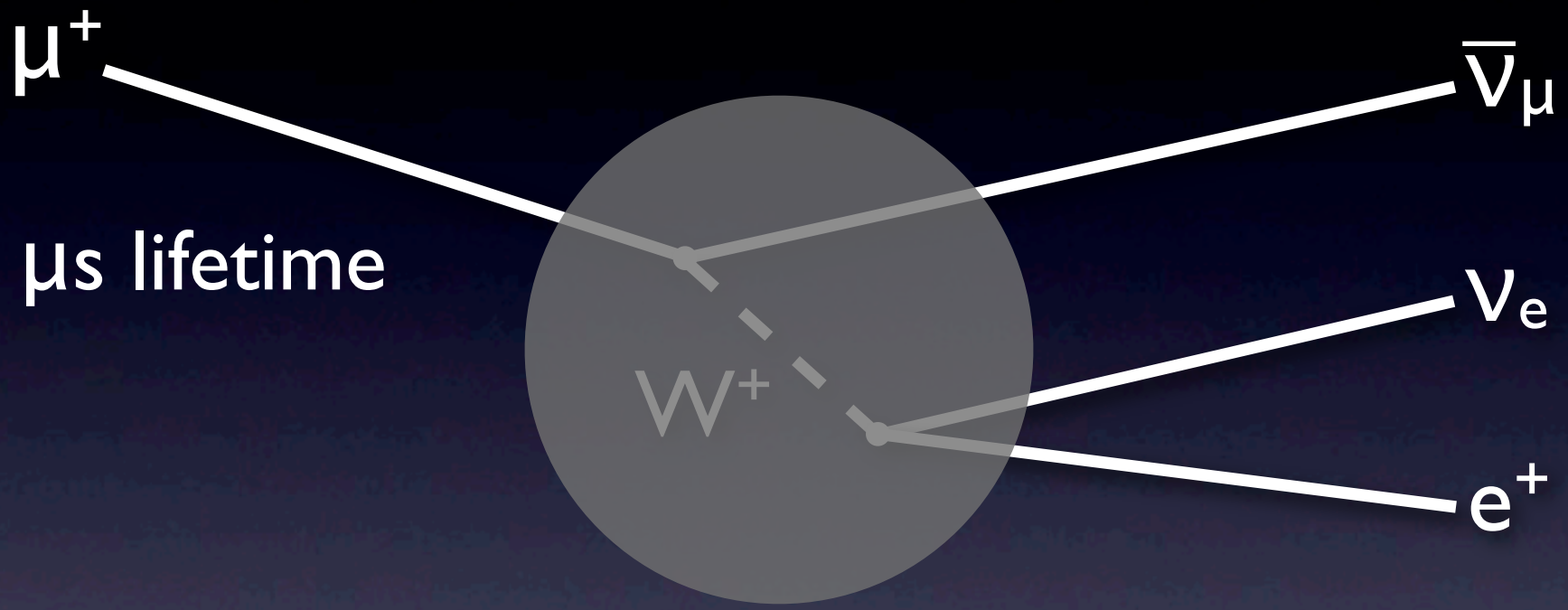
A Precision Muon Decay Measurement by *TWIST*

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

- Muon Decay and the Weak Interaction
- *TWIST* apparatus and analysis
- Intermediate results

WNPPC, Banff, AB, 12–14 February, 2010

Muon Decay



2 μs lifetime

EM radiative corrections calculable

Strong interactions are at < 1e-6 level

Weak Matrix Element

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

In Standard Model ("V-A"):

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

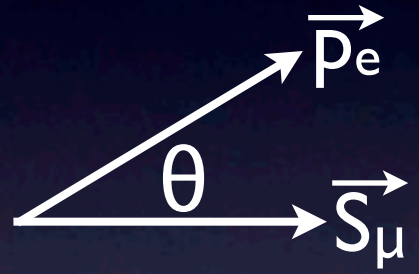
$$g^{\kappa}_{\epsilon m} = 0 \quad \text{otherwise}$$

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

Decay ("Michel") Spectrum

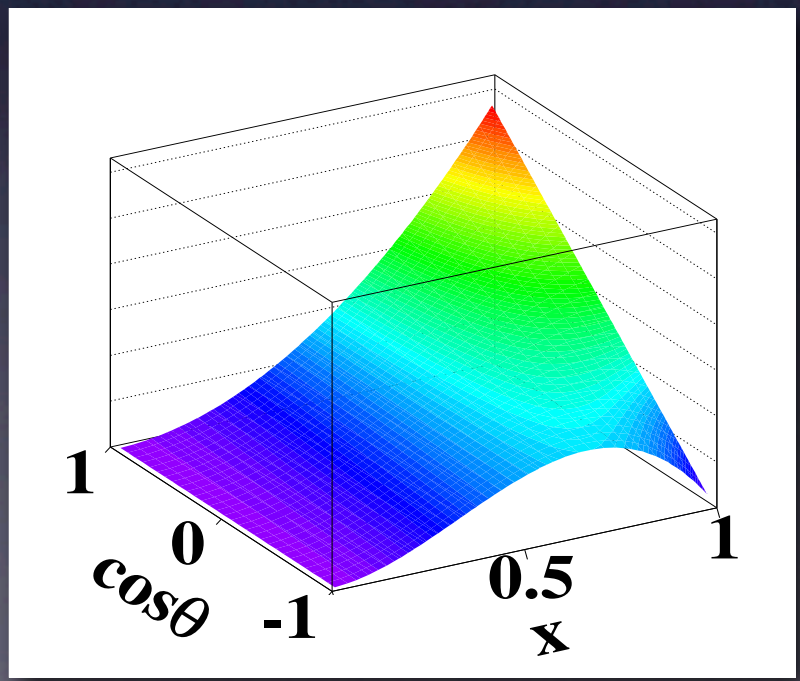
$$\frac{d^2\Gamma}{dx\, d(\cos\theta)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\delta) P_\mu \xi \cos\theta$$

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

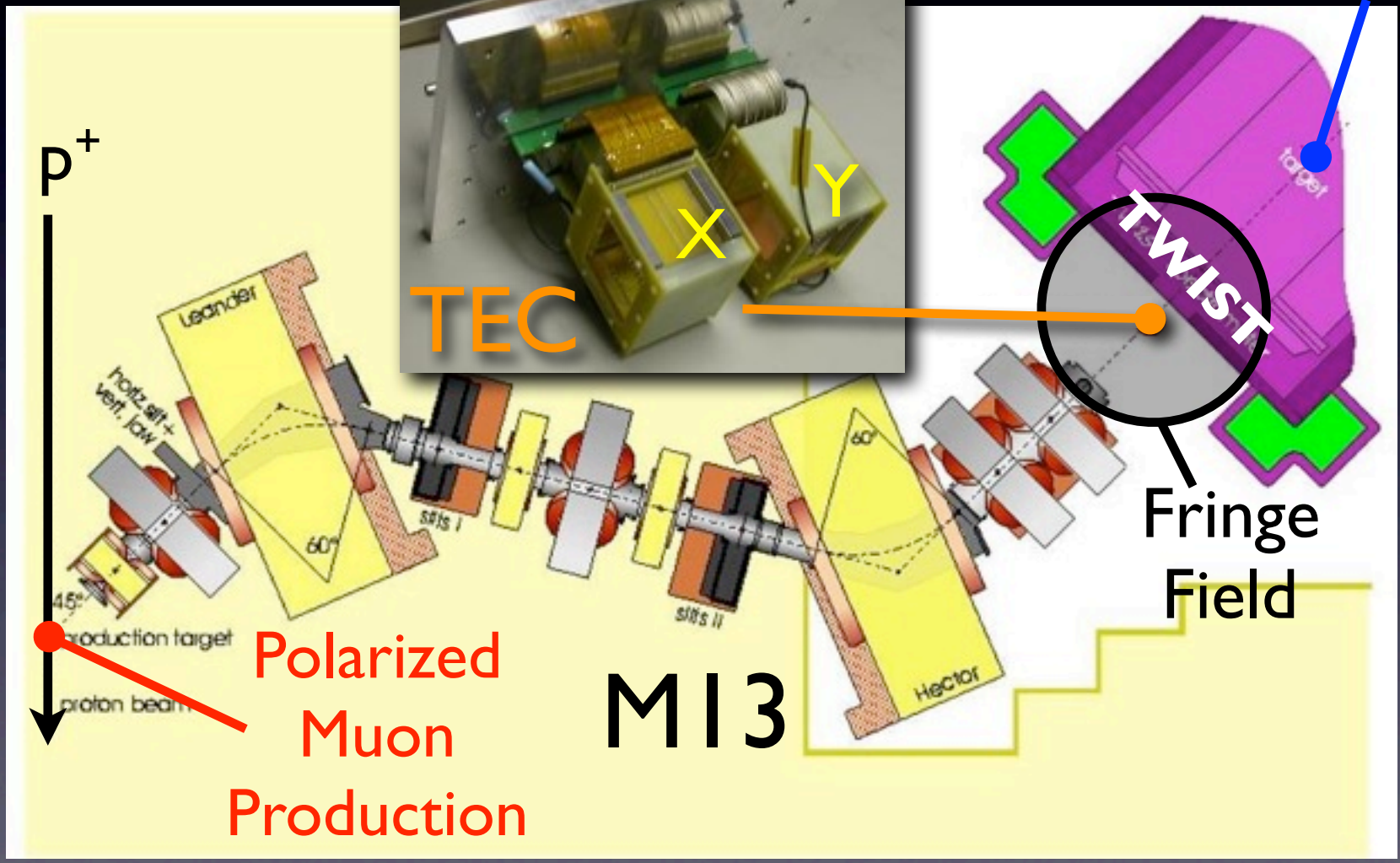


	Pre-TWIST	SM
ρ	0.7518 ± 0.0026	0.75
η	-0.007 ± 0.013	0
$P_\mu\xi$	1.0027 ± 0.0085	1
δ	0.7486 ± 0.0038	0.75

Focus of this talk: ρ and δ



Muon Production and Transport



More by James Bueno, next talk.

TEC: NIM A566 (2006), 563

The *TWIST* Experiment

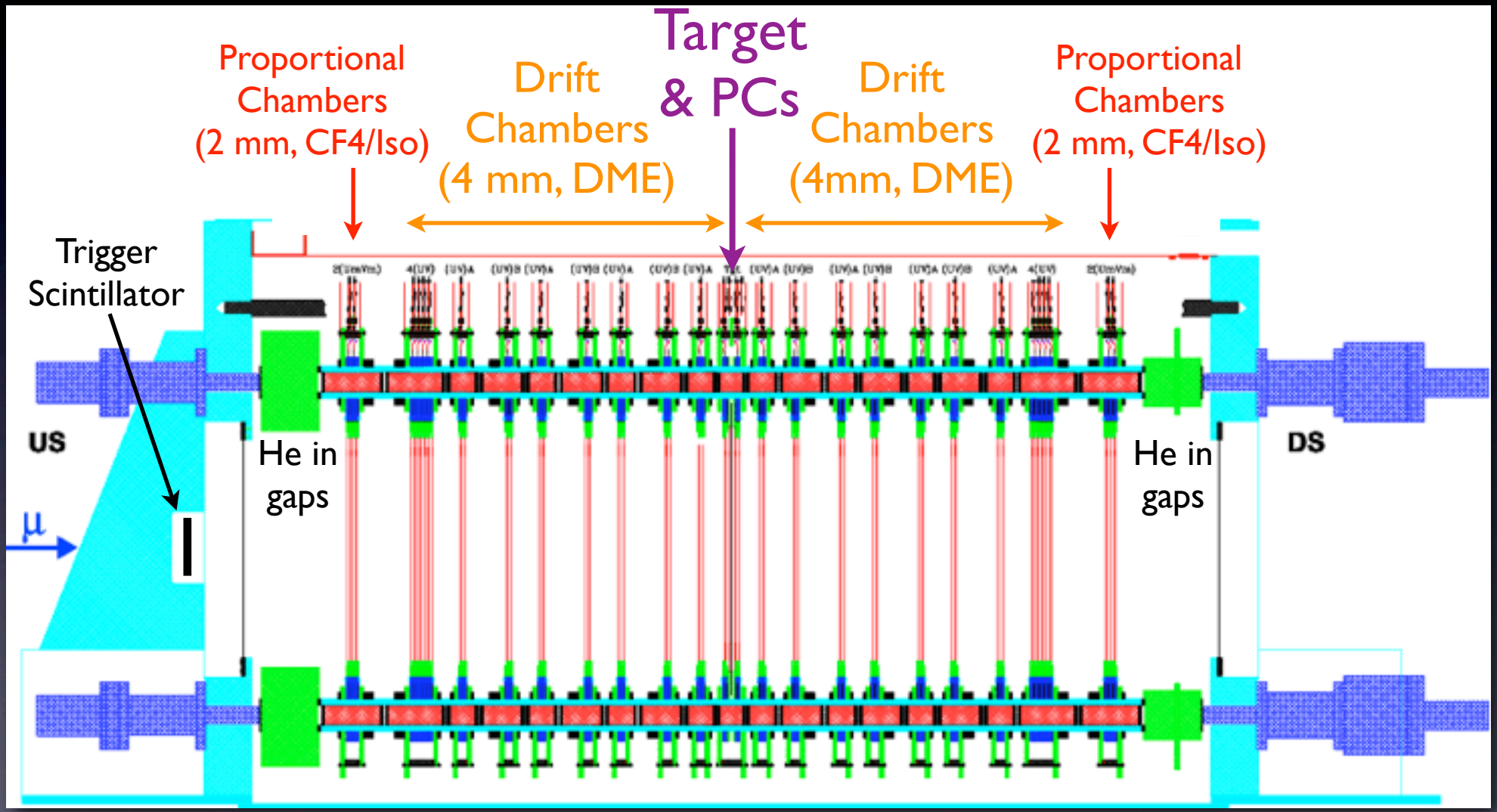
TRIUMF Weak Interaction Symmetry Test

2 Tesla Magnetic Field

Planar Drift Chambers

The *TWIST* Detector

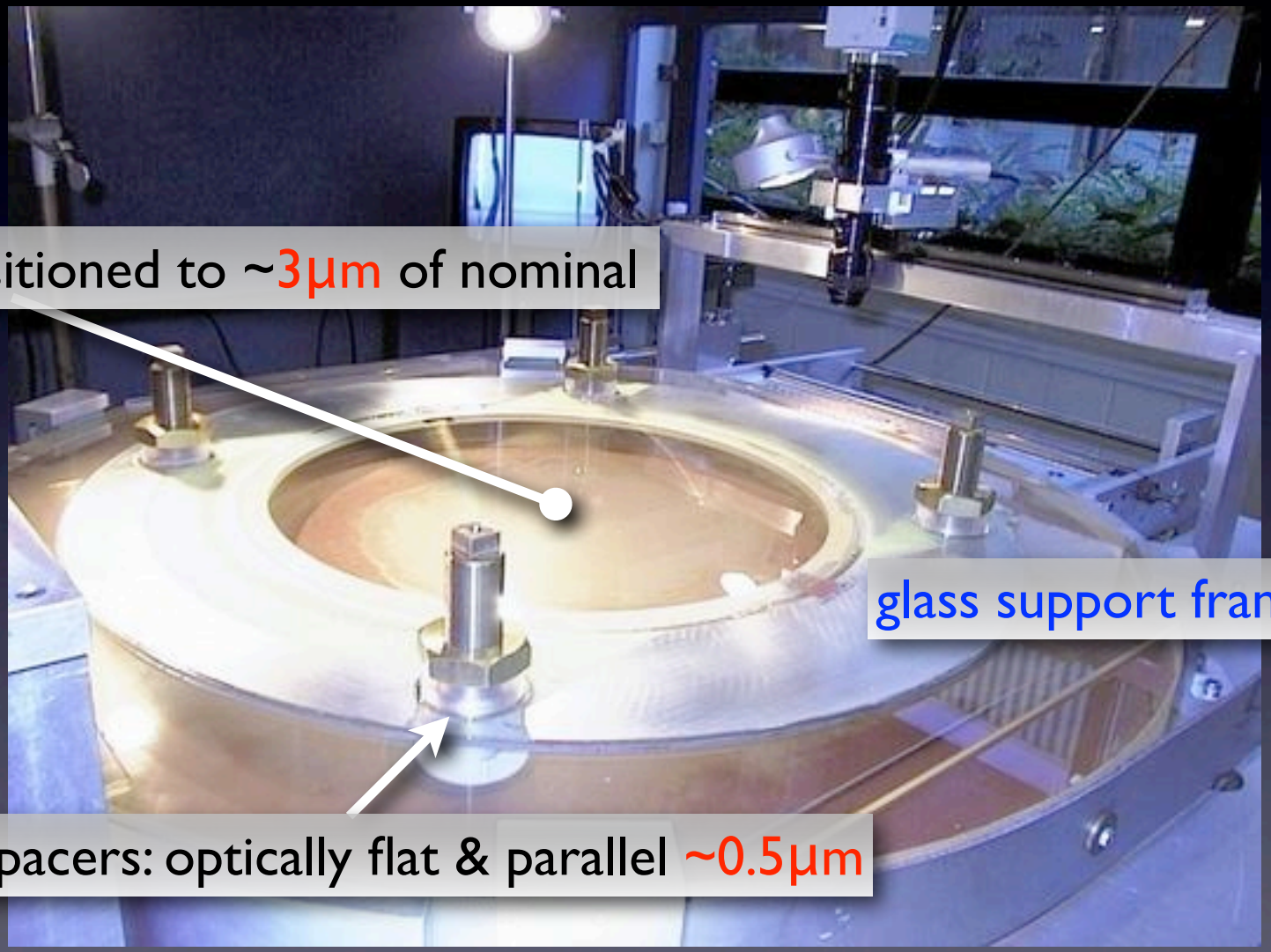
Low mass, symmetric, high-precision construction



Assembled by hand at TRIUMF

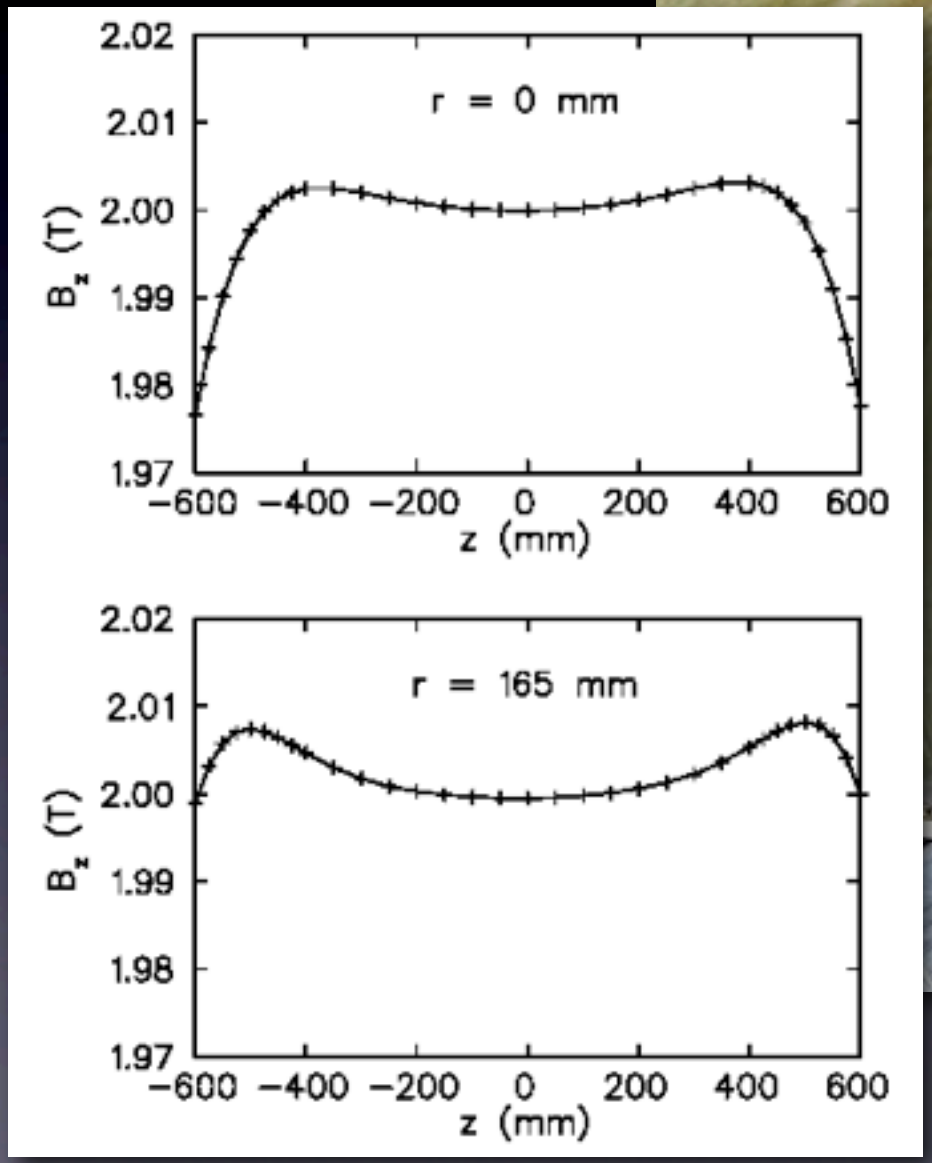
NIM **A548** (2005) 206

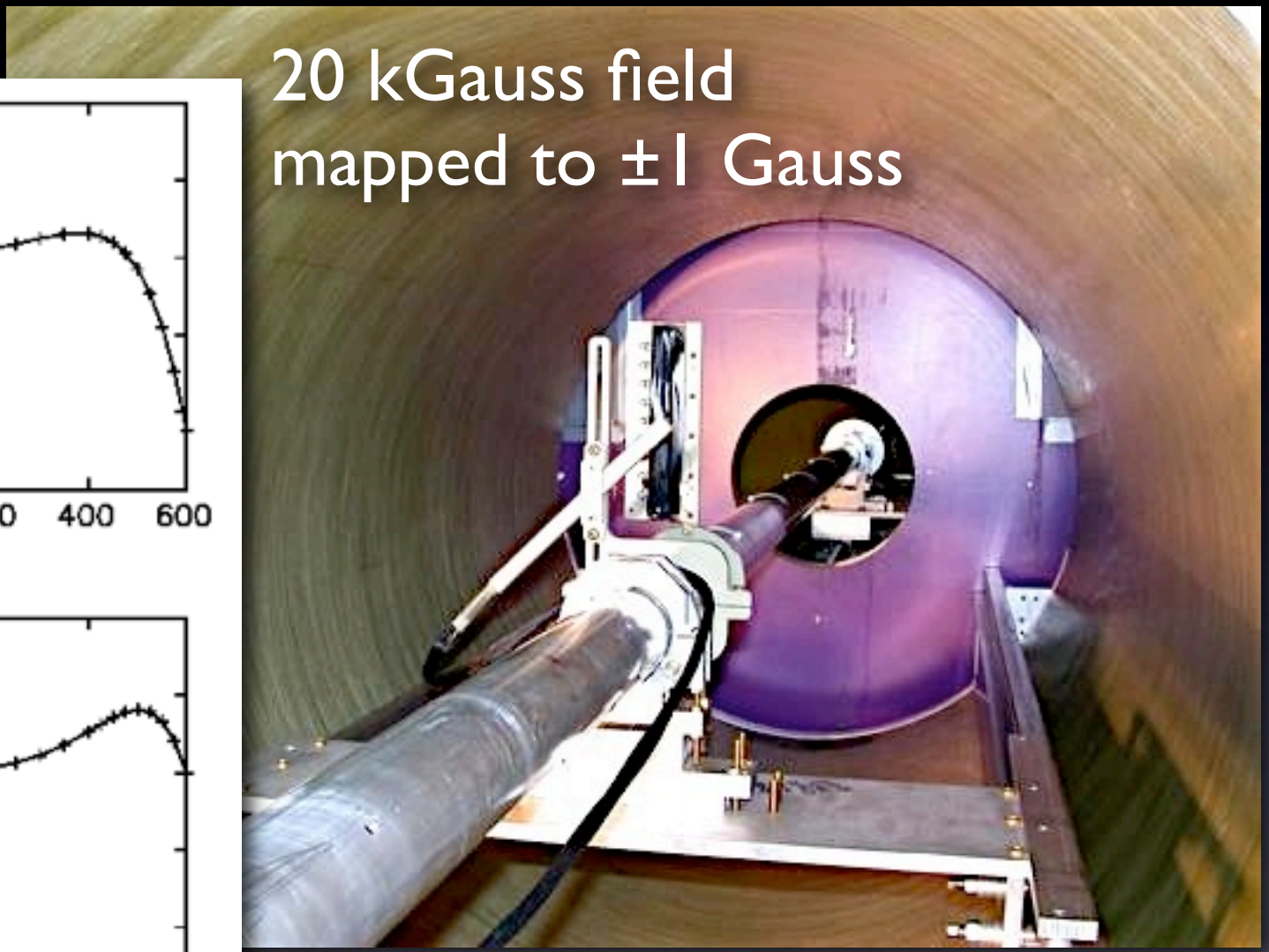
TWIST Drift Chambers



NIM **A548** (2005) 206

The *TWIST* Solenoid

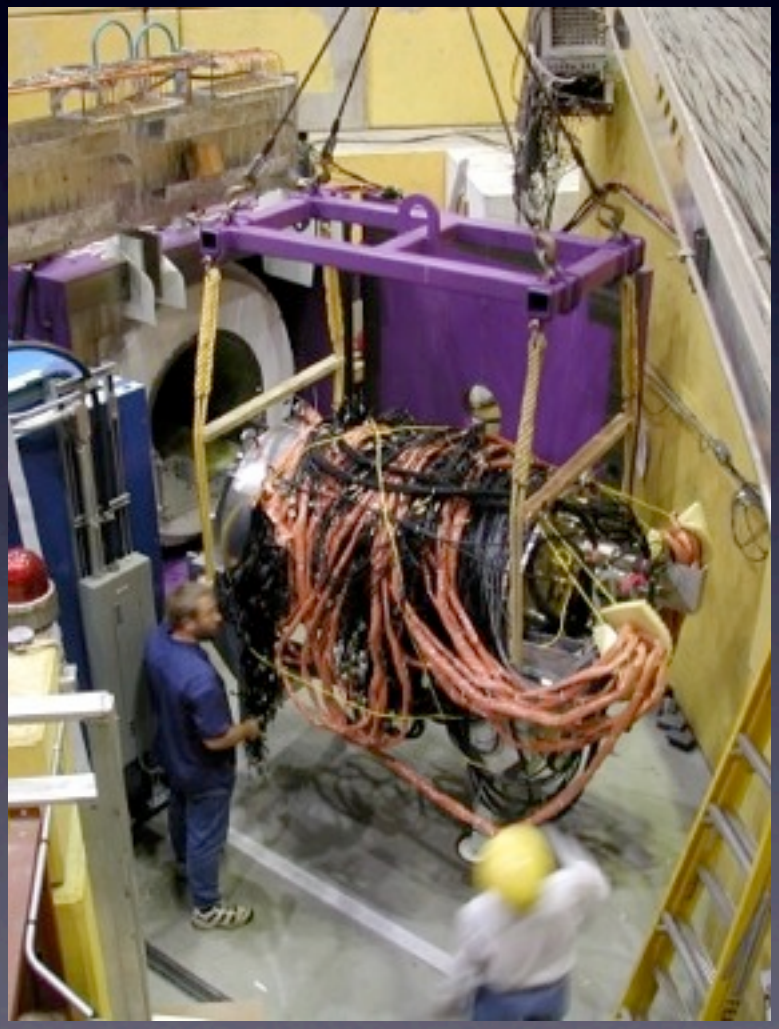




Field is uniform to 80 Gauss in tracking region (± 50 cm)

Data taking: start to finish

15 November, 2001



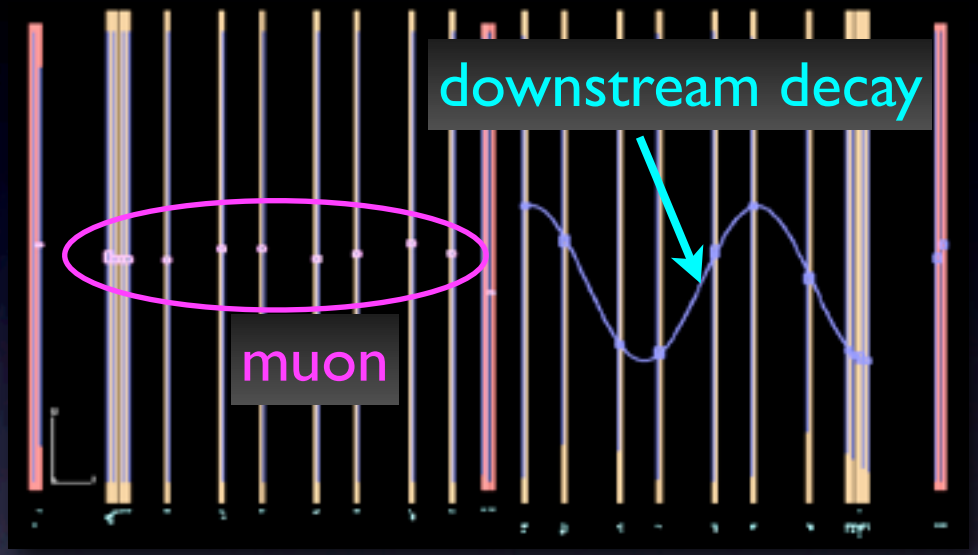
2 November, 2007

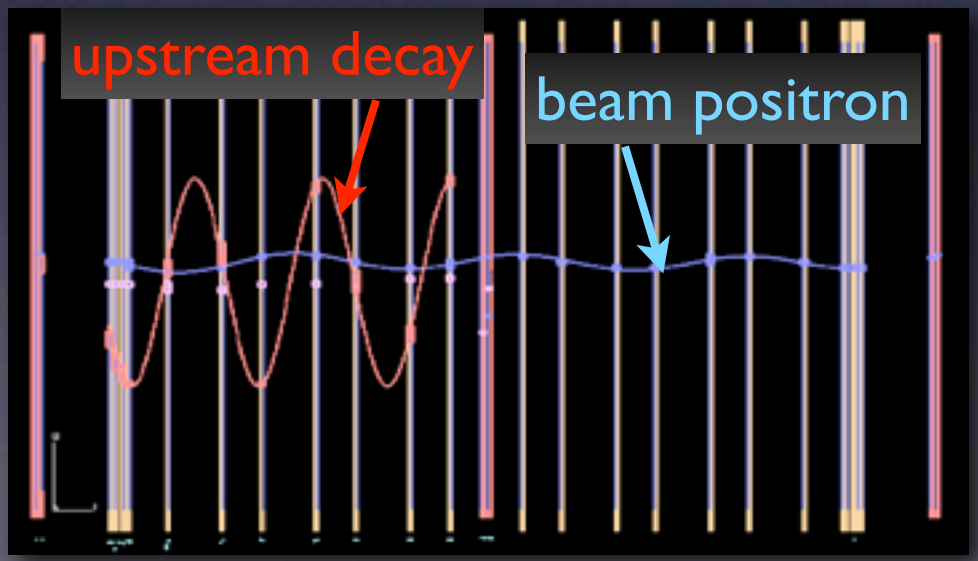
Phases of *TWIST*

- First physics results
  - ρ and δ from 2002 data,
    $P_\mu\xi$ from 2004 data
- Intermediate physics results (this work)
  - ρ and δ from 2004 data
- Final physics results
  - ρ, δ, $P_\mu\xi$ from 2006/2007 data:
    See talk by James Bueno, next!

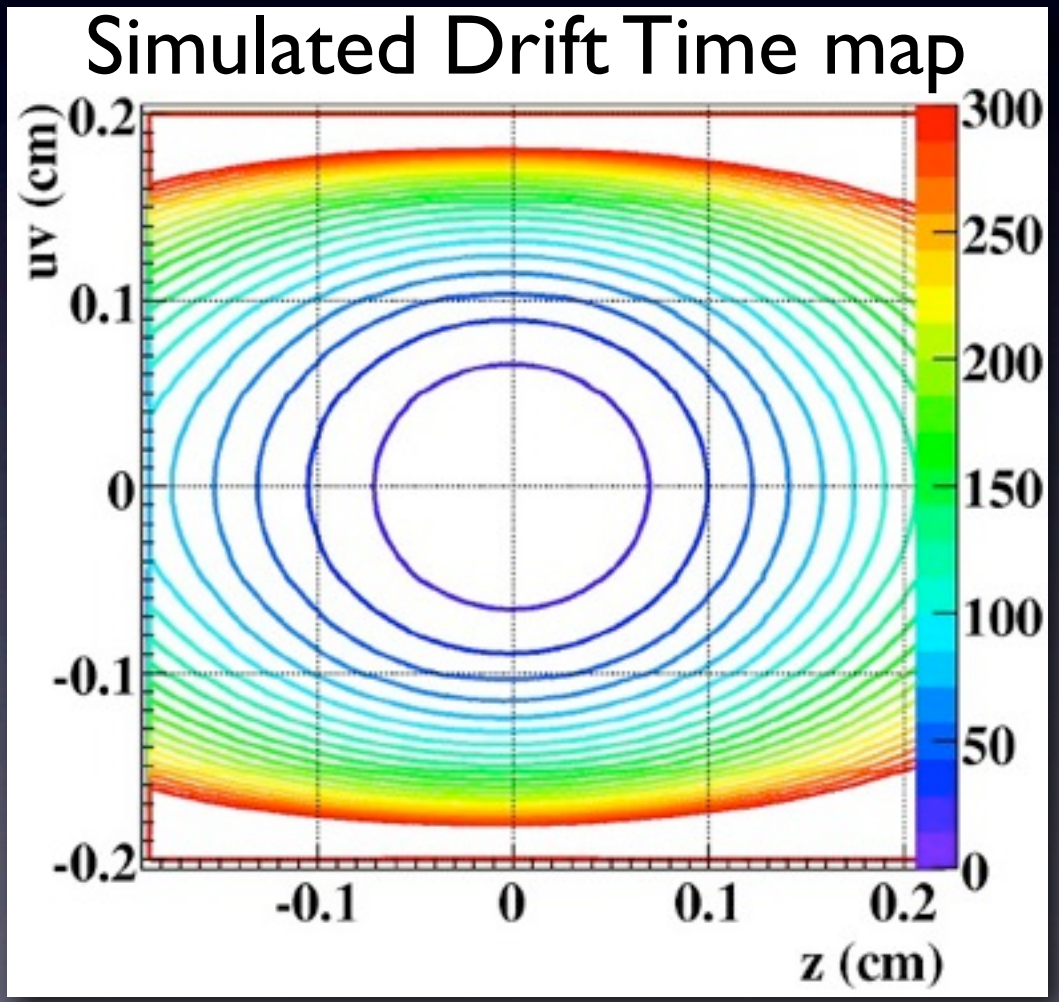
TWIST Analysis

Particle ID using space & time distributions of hits.



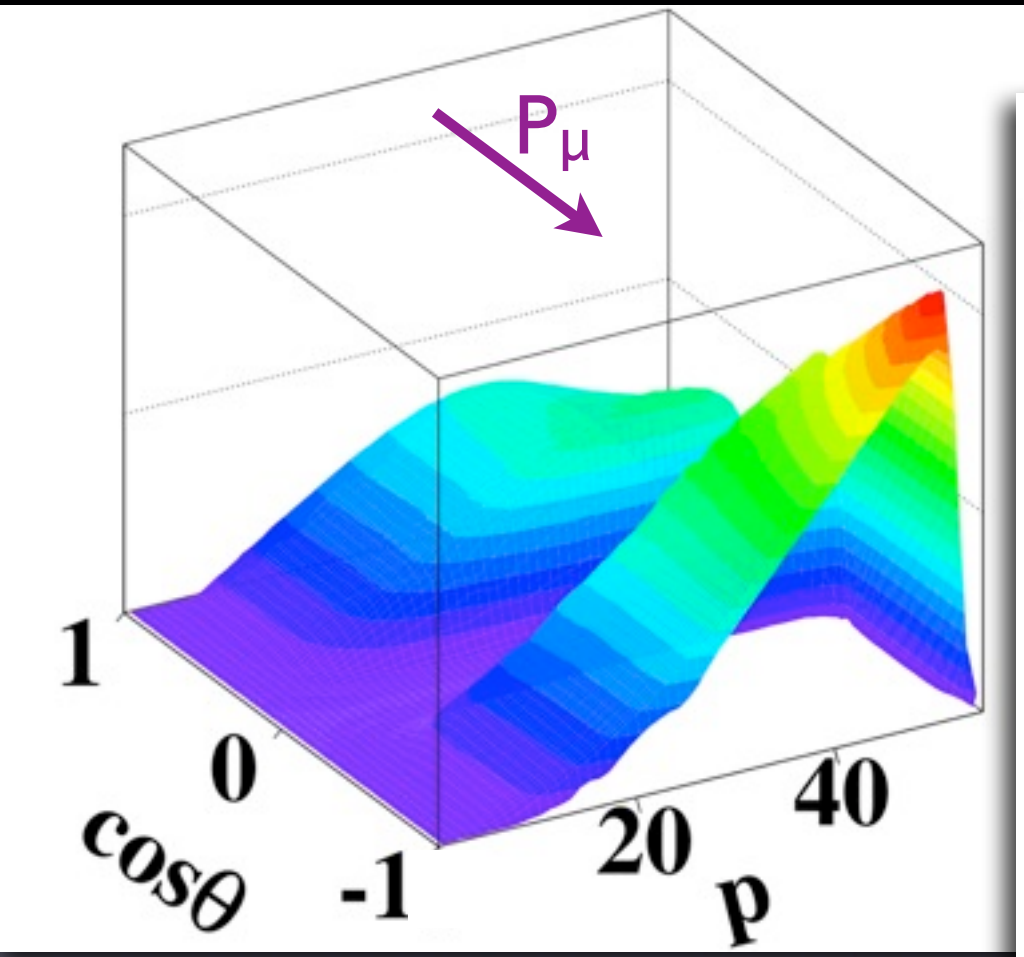


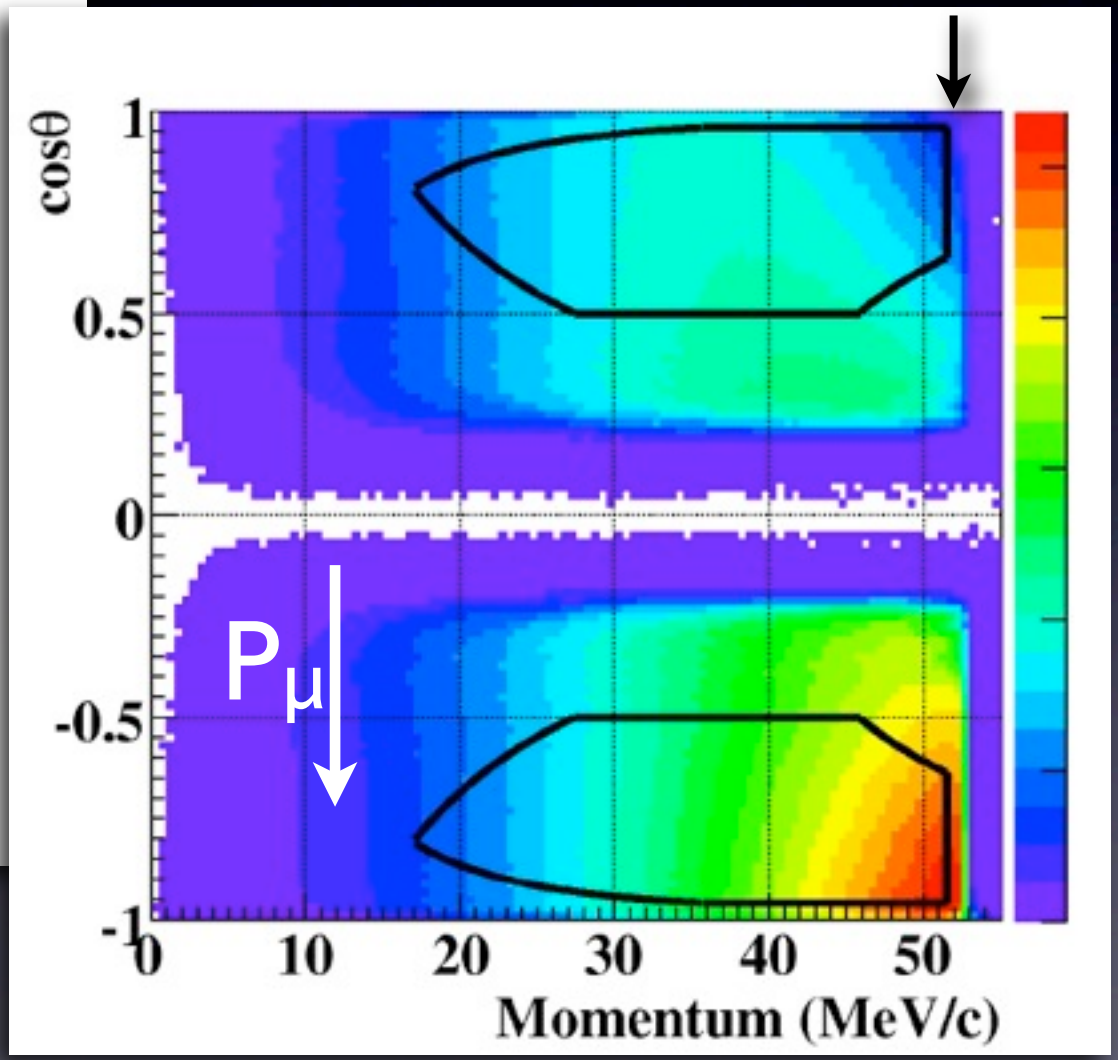
Track reconstruction: first using wire centres, then using DC drift times.



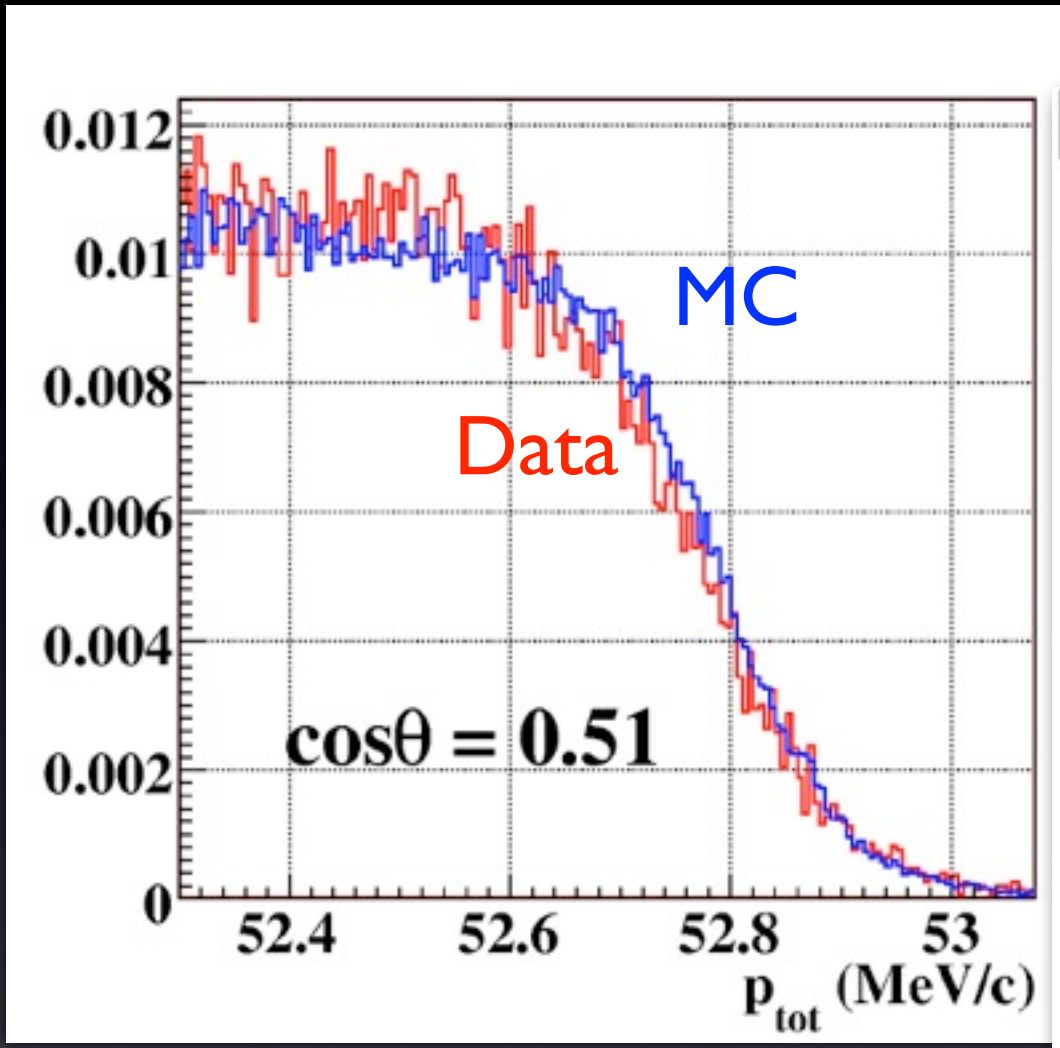
Muon Decay Spectrum

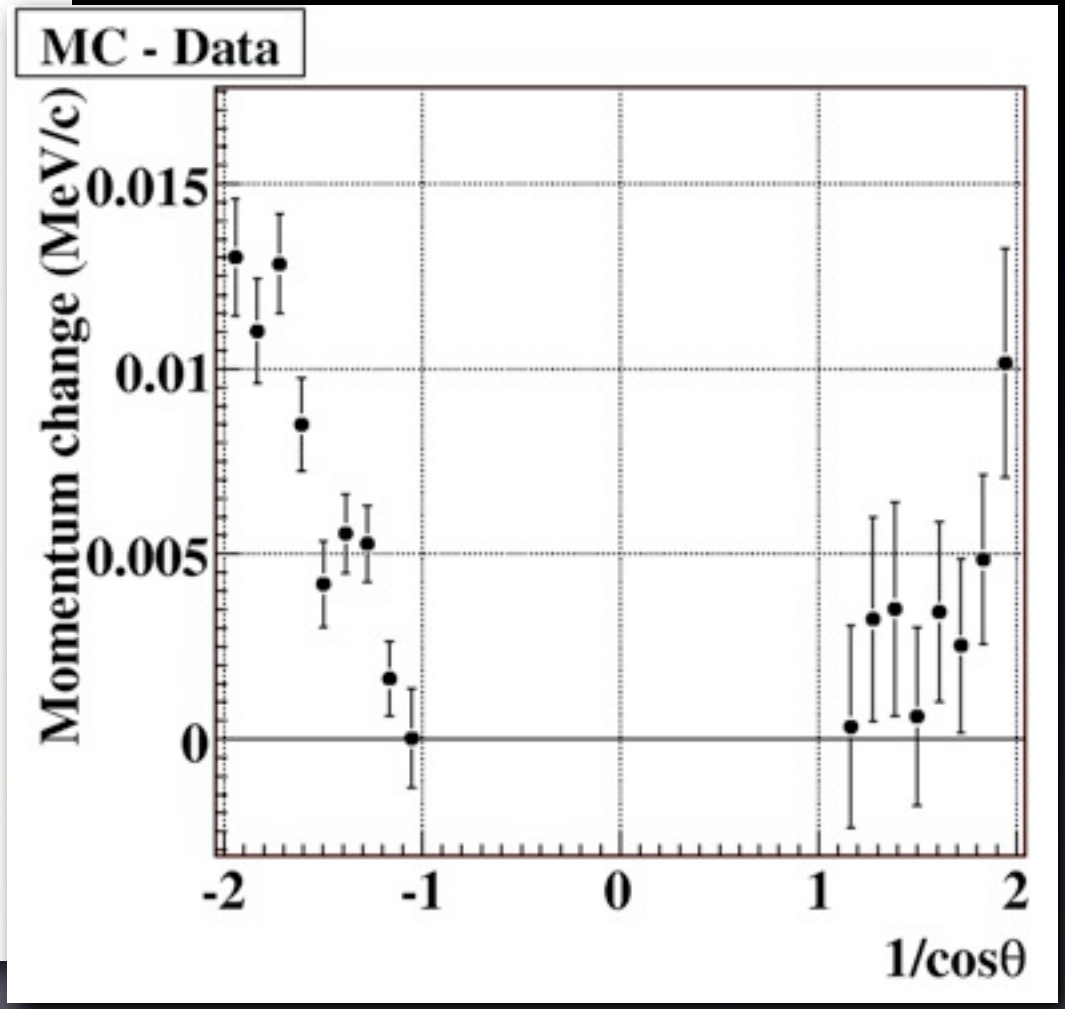
Endpoint excluded





Energy Calibration





Resolution from edge shape: Data – MC = 5 keV

Blind Analysis

Blind Analysis

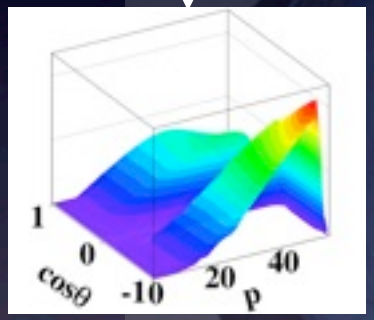
Experimental Data

Geant3 Simulation

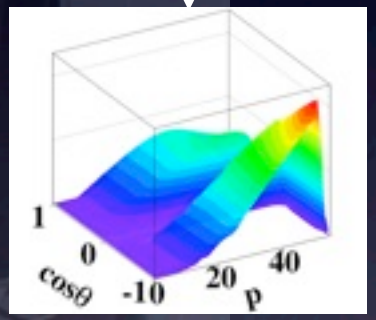
hidden
ρ_{MC}, δ_{MC}, ξ_{MC}

Analysis

Analysis



Energy Calibration



Spectrum Fitter

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

revealed
ρ_{MC}, δ_{MC}, ξ_{MC}

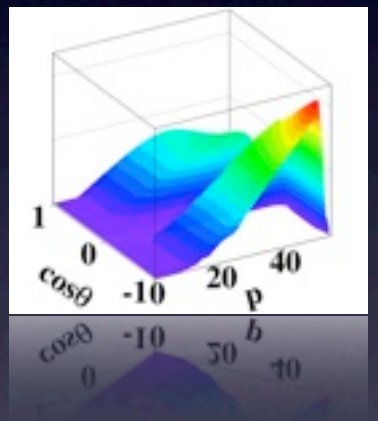
ρ, δ, ξ

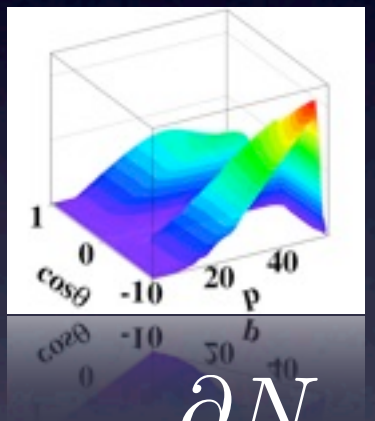
Analysis made possible by ***WestGrid***

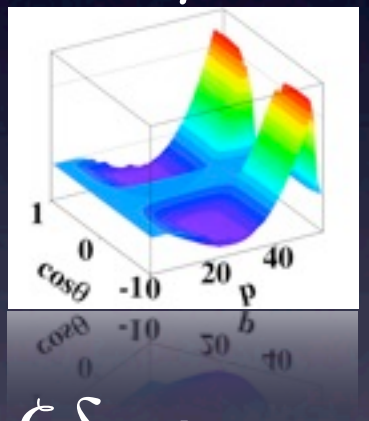
Spectrum Fitter

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

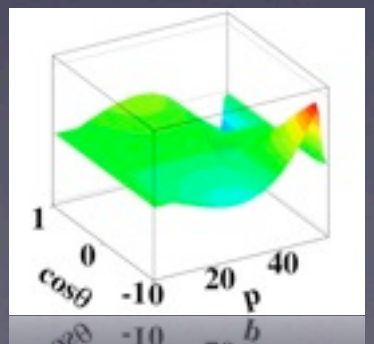
$$N(\alpha_{\mathrm{Data}}) = N(\alpha_{\mathrm{MC}}) + \frac{\partial N}{\partial \rho}\Delta\rho$$

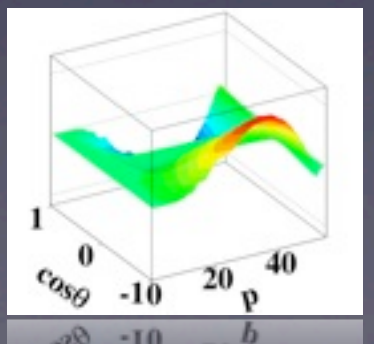






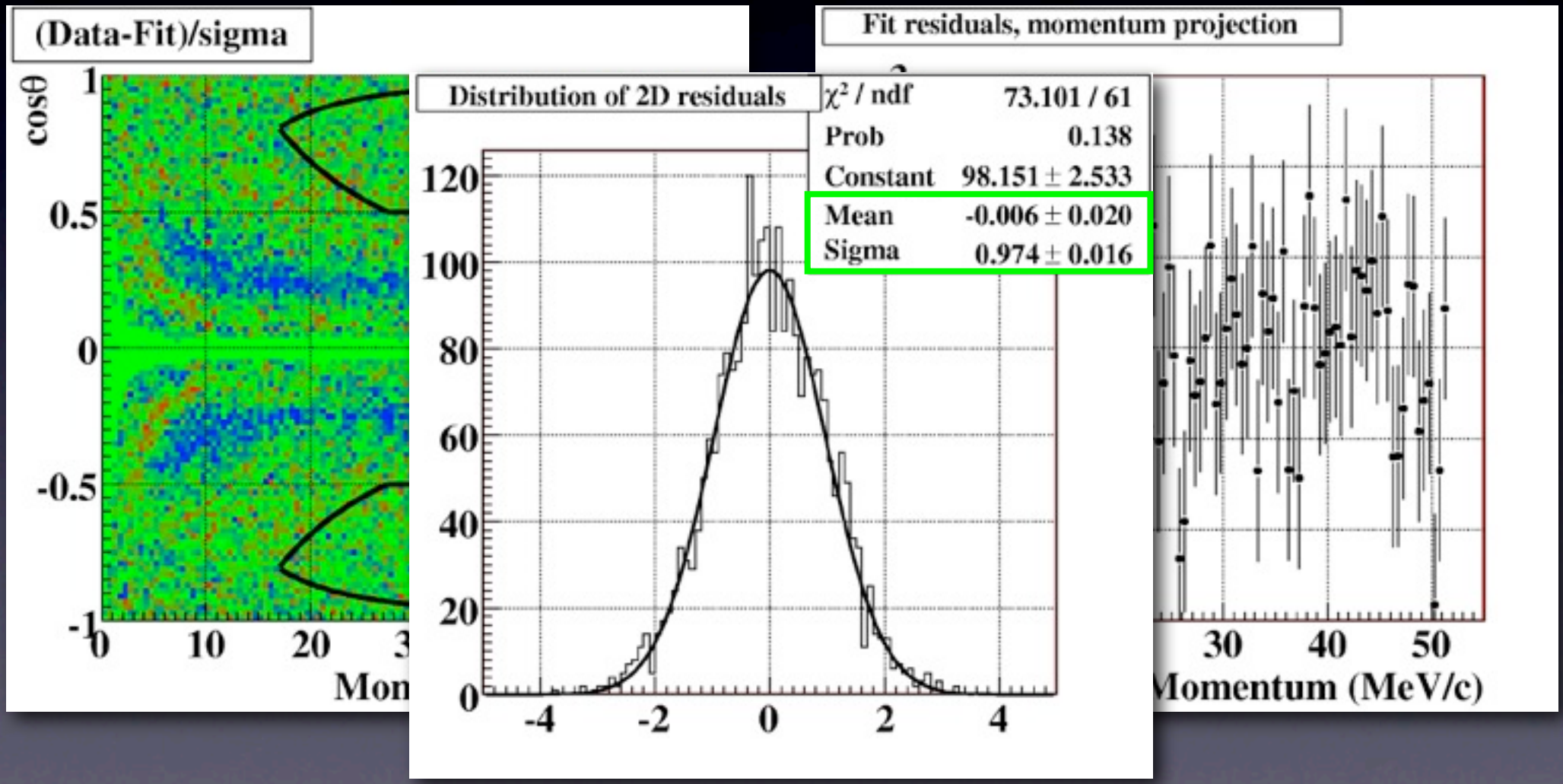
$$+ \frac{\partial N}{\partial \xi\delta}\Delta P_\mu\xi\delta + \frac{\partial N}{\partial \xi}\Delta P_\mu\xi$$





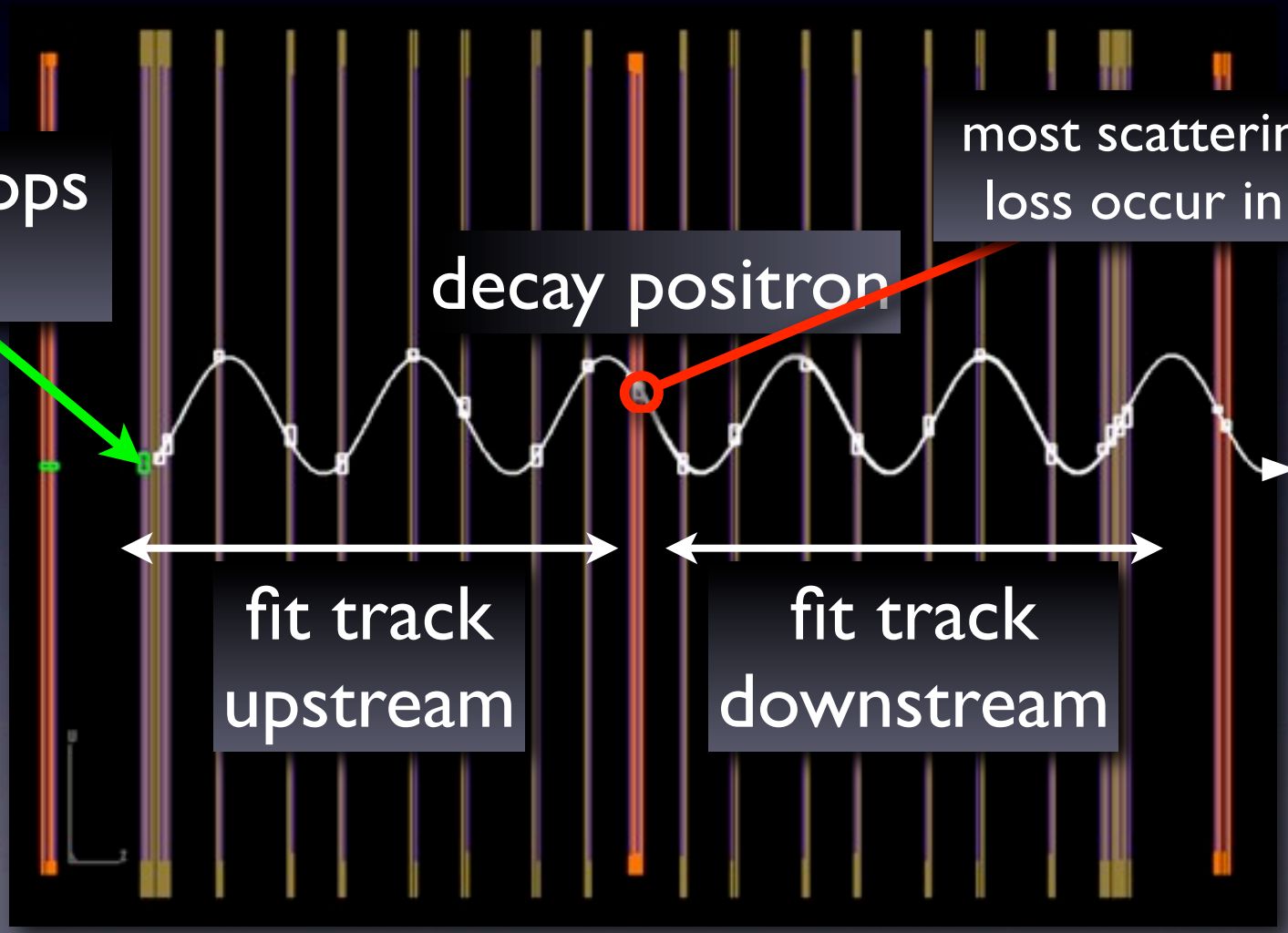
$\alpha = \{\rho, \delta, \xi\}$

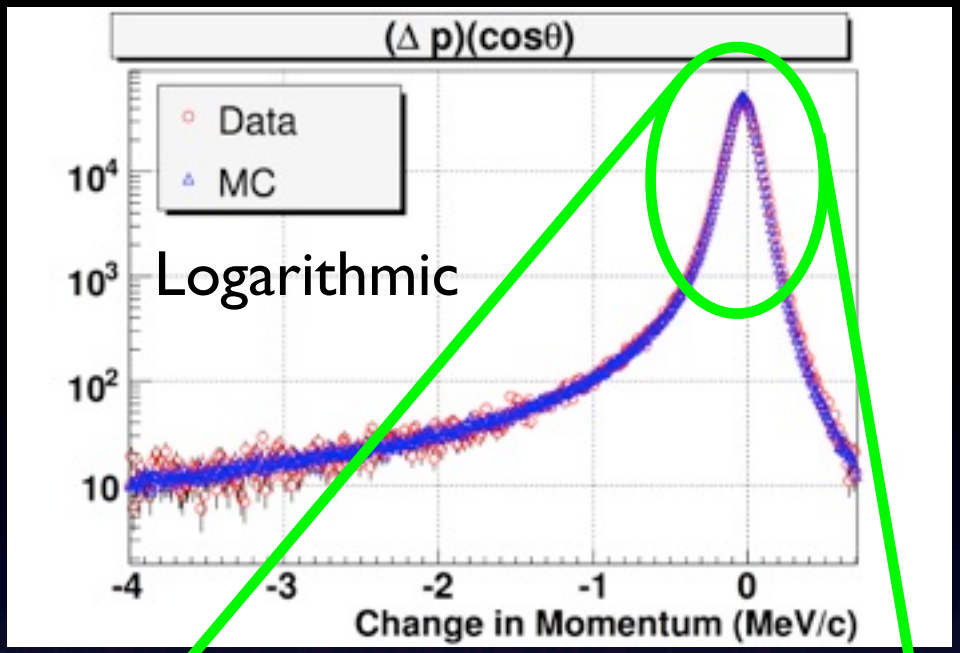
Spectrum Fit Quality

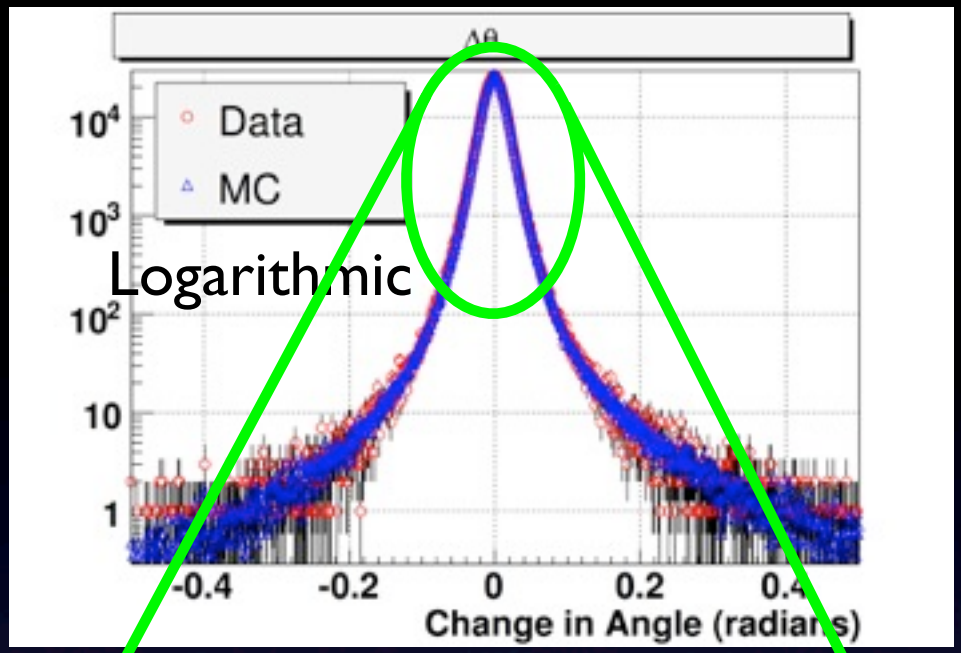


Verifying our Simulation

Specialized data, reproduced in simulation
→ independent of Michel parameters

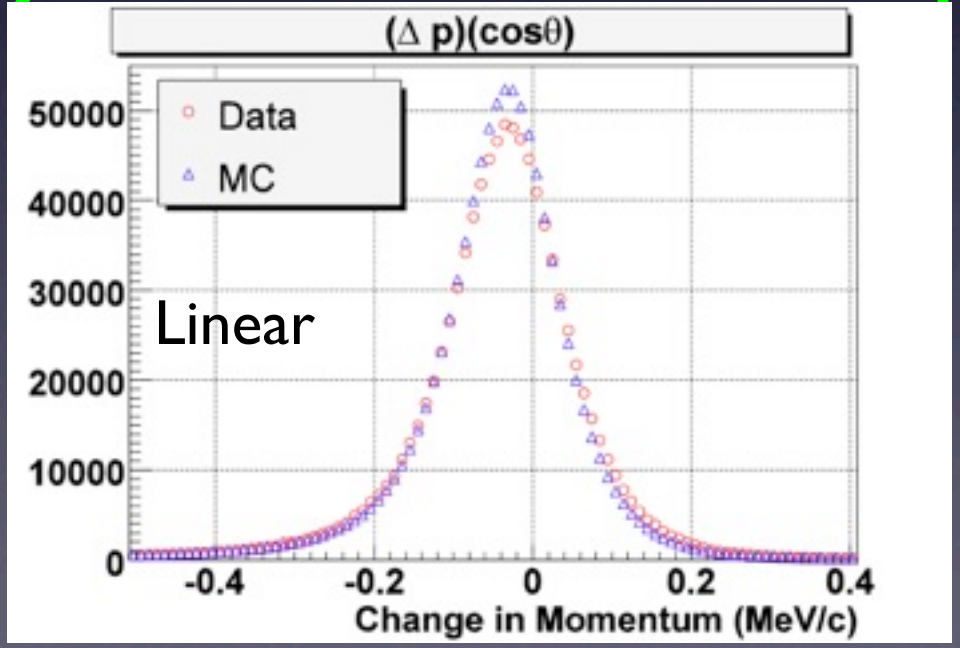


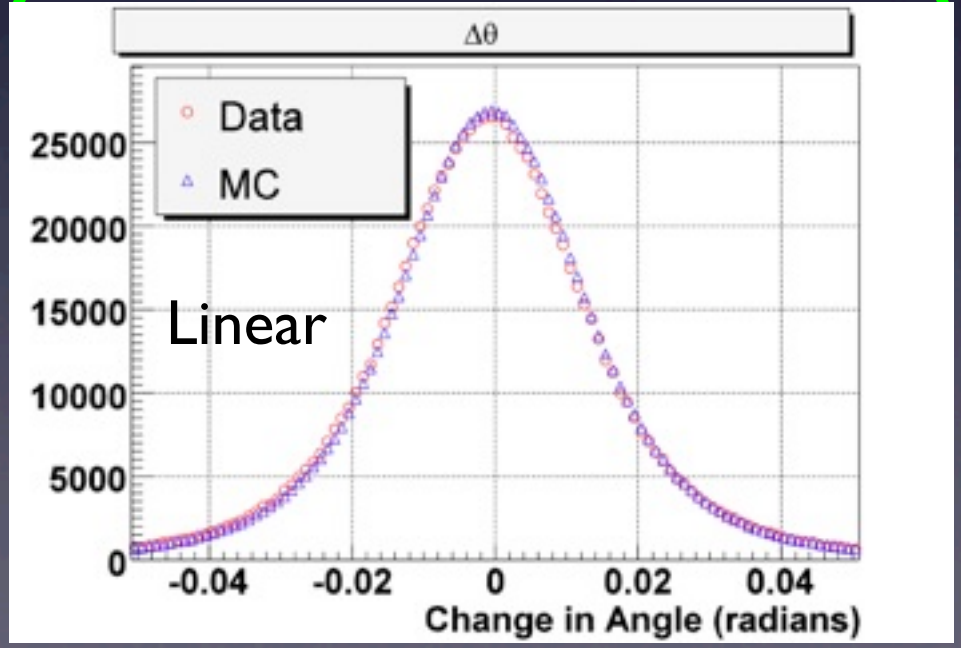




Energy Loss

Scattering





Determining Systematics

Exaggerated Geant3 Simulation

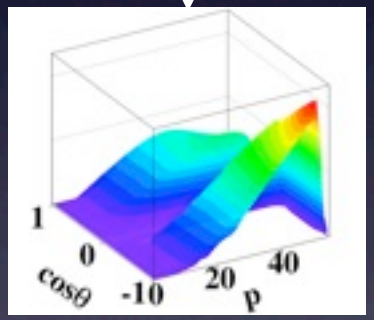
- Bremsstrahlung
- Chamber geometry
- …

Geant3 Simulation

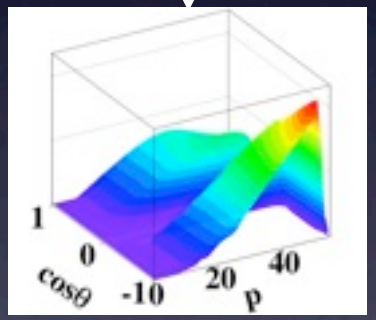
Exaggerated Analysis

- Magnetic field
- Chamber alignment
- …

Analysis



Spectrum Fitter



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

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

Units of 0.0001	First TWIST ρ	This ρ	First TWIST δ	This 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**

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

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

Highlights of Improvements

Target thickness	precision target geometry
Positron interactions	improved upstream stops data
Momentum calibration	New calibration technique; uncertainty is statistical

The Intermediate *TWIST* Results

Pre-*TWIST*: 0.7518 ± 0.0026
First *TWIST* result: 0.75080 ± 0.00032(stat) ± 0.00097(sys)
This work: 0.75014 ± 0.00017(stat) ± 0.00046(sys) ± 0.00011(η)

Pre-*TWIST*: 0.7468 ± 0.0026(stat) ± 0.0028(sys)
First *TWIST* result: 0.74964 ± 0.00066(stat) ± 0.00112(sys)
This work: 0.75068 ± 0.00030(stat) ± 0.00067(sys)

Phys. Rev. D 78, 032010 (2008)

The *TWIST* Experiment

Strong limit on weak physics!

Systematics well understood.

Sometimes, if you pay real close attention to the pebbles you find out about the ocean.
-Terry Pratchett

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 ✾
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Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin ⁂
Robert Openshaw
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin ✧

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Andrei Gaponenko ★
Peter Kitching
Robert MacDonald ★
Nate Rodning ✾
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Kurchatov Institute
Vladimir Selivanov

Texas A&M
Carl Gagliardi
Jim Musser ★
Bob Tribble

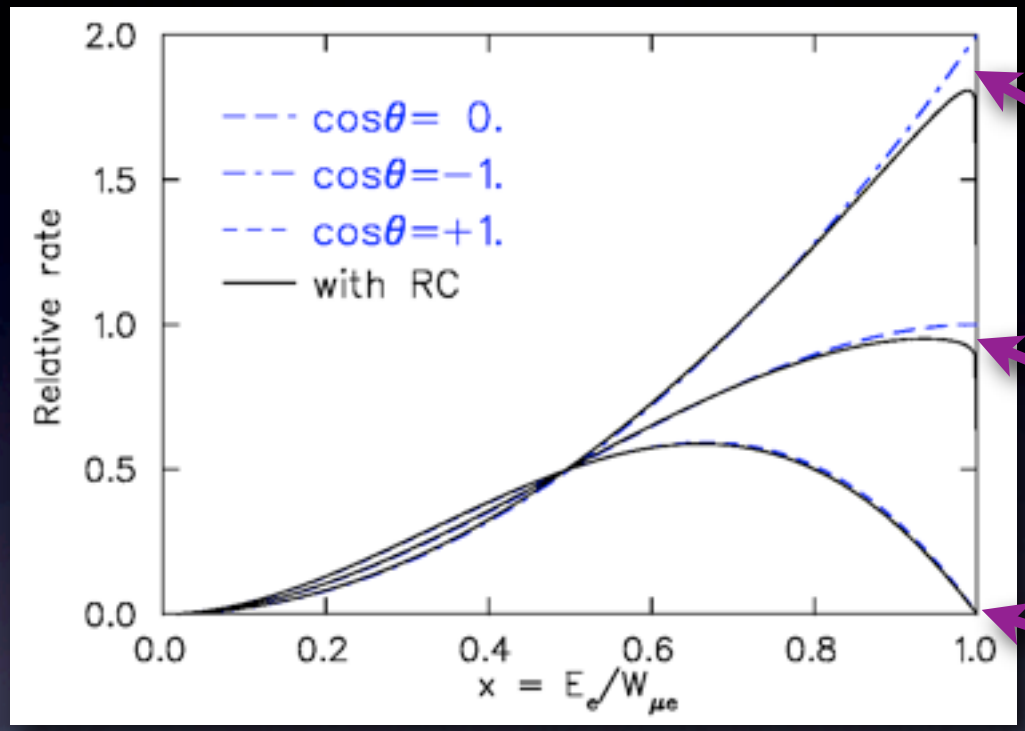
Valparaiso
Don Koetke
Shirvel Stanislaus

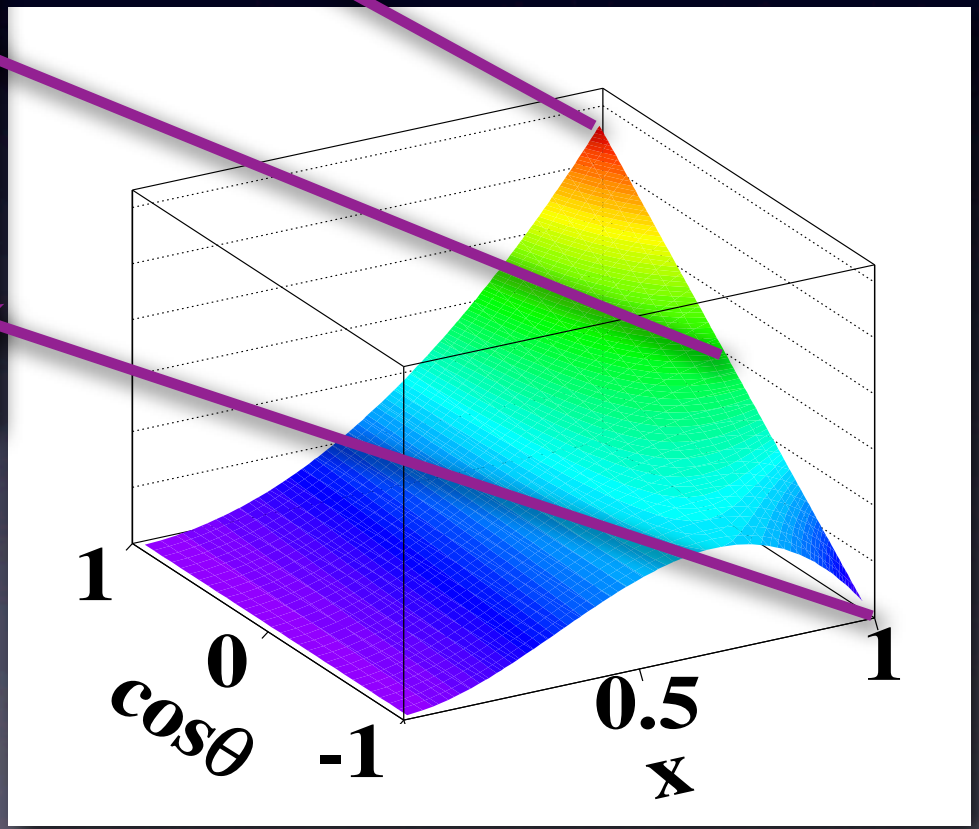
✪ graduate student
★ graduated
⁂ also U Vic
✧ also Saskatchewan
✾ deceased

http://twist.triumf.ca

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

Radiative Corrections





O(α): Full tree-level RCs, exact electron mass

O(α^2): Leading-Order (LO) and NLO in L=ln(m_μ/m_e)

Early Measurements

April 15, 1949

On the

The Instit

An experiment has bee
absorption of the electro
have been obtained, usin
some features of the ener
culated, taking the geom
spectrum is either contin
of three or more discrete
observed. The experimen
disintegrates into 3 light

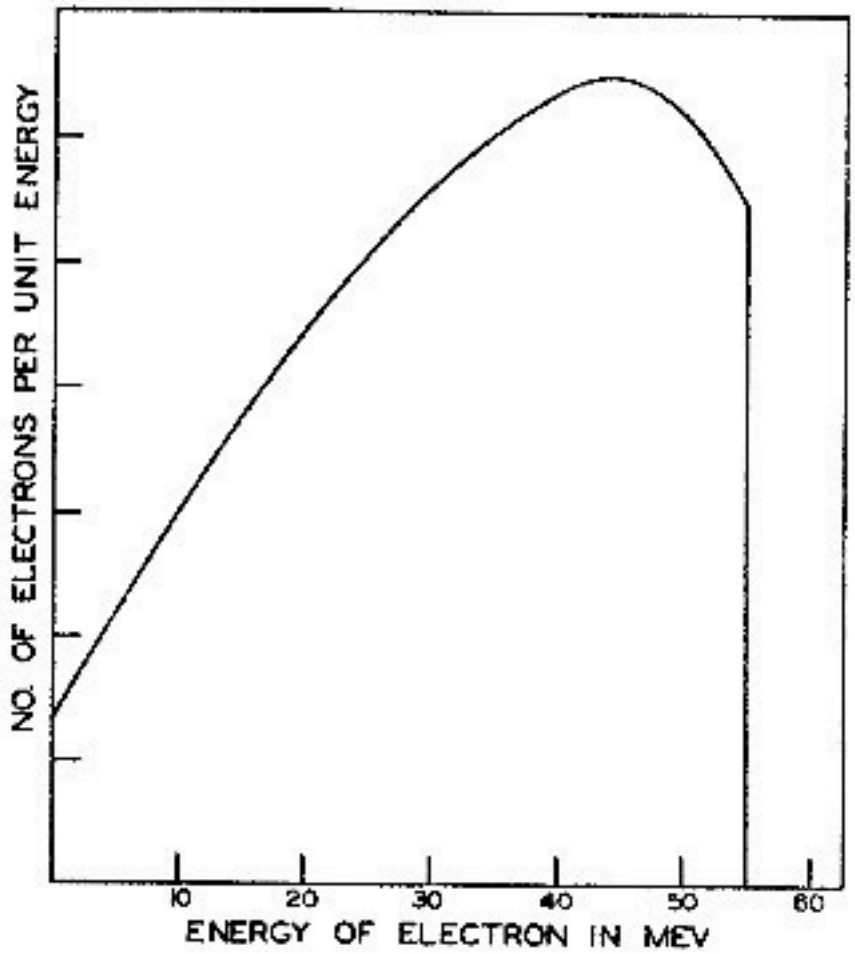
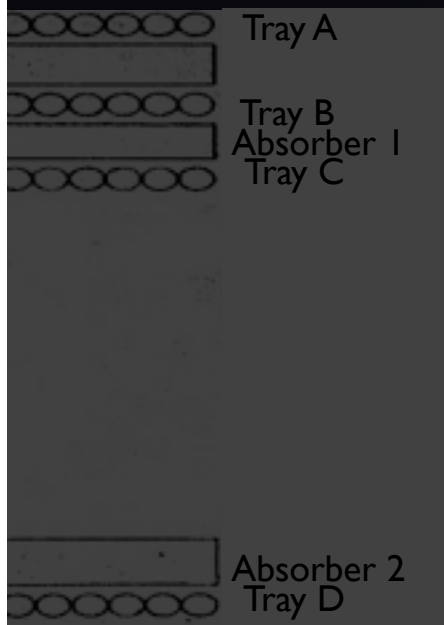
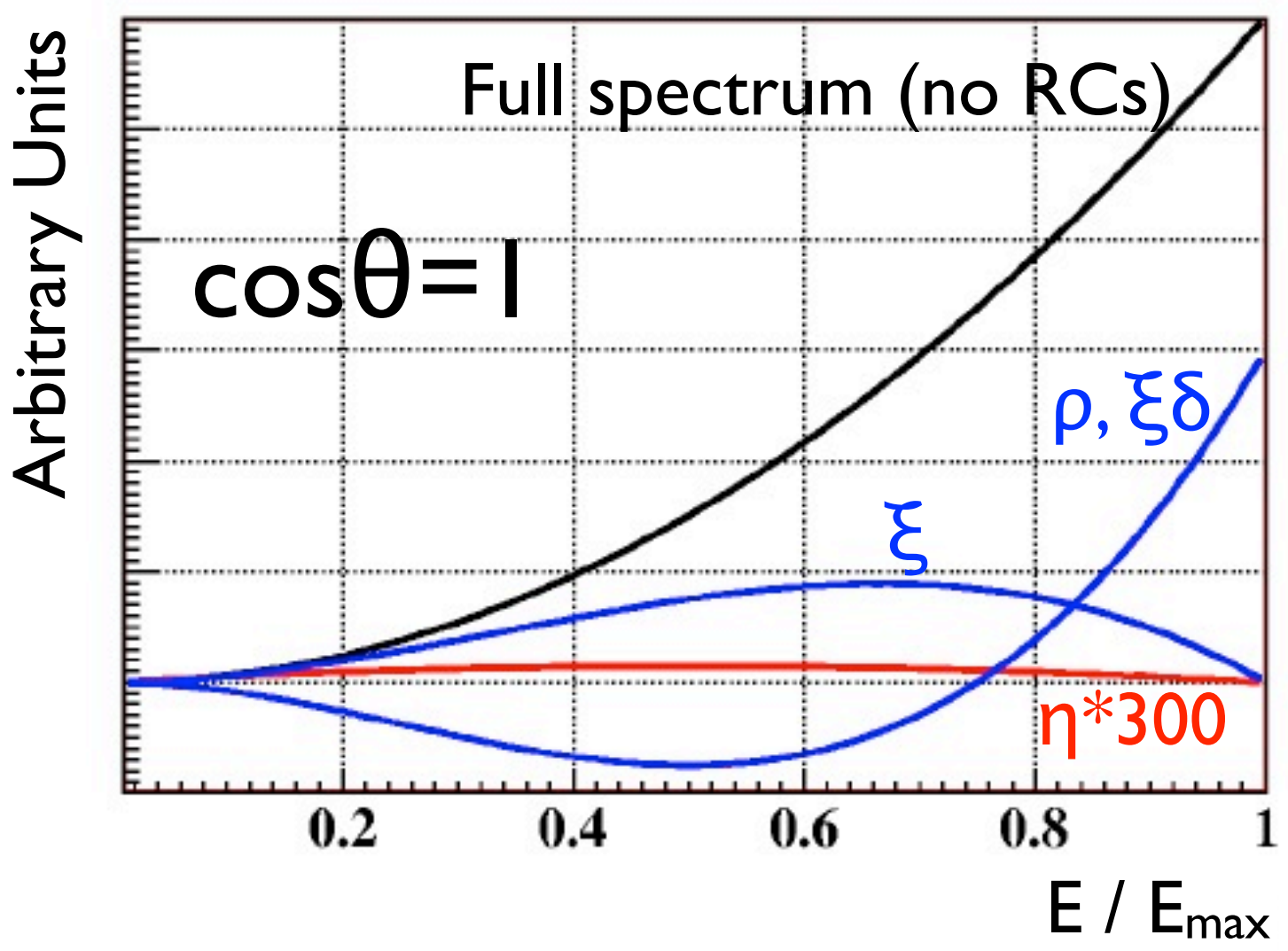


FIG. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.



Parameter Sensitivity



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

Weak Coupling	pre-*TWIST*	Gagliardi*	This Work
$\|g^S_{RR}\|$	< 0.066	< 0.067	< 0.063
$\|g^S_{LR}\|$	**< 0.125**	**< 0.088**	**< 0.076**
$\|g^S_{RL}\|$	< 0.424	< 0.417	< 0.415
$\|g^S_{LL}\|$	< 0.550	< 0.550	< 0.550
$\|g^V_{RR}\|$	< 0.033	< 0.034	< 0.032
$\|g^V_{LR}\|$	**< 0.066**	**< 0.036**	**< 0.027**
$\|g^V_{RL}\|$	< 0.110	< 0.104	< 0.104
$\|g^V_{LL}\|$	> 0.960	> 0.960	> 0.960
$\|g^T_{LL}\|$	≡ 0	≡ 0	≡ 0
$\|g^T_{LR}\|$	**< 0.036**	**< 0.025**	**< 0.022**
$\|g^T_{RL}\|$	< 0.112	< 0.104	< 0.104
$\|g^T_{RR}\|$	≡ 0	≡ 0	≡ 0

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)	$\lvert\zeta\rvert$	+	-
$m(K_L - K_S)$	>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