Language: 英語/English

KEK 物理セミナー Physics Seminar

12月02日 (火) December 02 (Tue)
16:00 ~ 17:00

4号館 345号室 Room 345 in the 4th Building

TWIST, A PRECISION MEASUREMENT of MUON DECAY PARAMETERS

Peter Kitching
(TRIUMF)

- Abstract:
The TRIUMF Weak Interaction Symmetry Test (TWIST) is a measurement of the Michel Parameters describing normal muon decay. The experiment has been designed to measure rho, delta and PmuXi with a precision of parts in 10^4, an order of magnitude better than previous experiments, which are consistent with Standard Model values. TWIST has a model independent sensitivity to deviations indicative of physics beyond the Standard Model, such as left/right symmetric models.

Past presentations are archived at our home page, http://seminar.kek.jp/physics/ .

Organizers: T. Komatsubara and I. Adachi

2003.11.06

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TWIST

Measuring the Space-Time Structure of Muon Decay

Peter Kitching
TRIUMF

TWIST Collaboration

- Physics of TWIST
- Introduction to the Experiment
- Current Status

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Past collaborators: Peter Green, Arkadi Khruchinsky, Michael Kroupa, Sun-Chong Wang, and Dennis Wright.

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TRIUMF WEAK INTERACTION SYMMETRY TEST

- Uses intense "Surface Muon" beam of polarised muons from pions decaying at rest on surface of production target
- Incoming muon is tracked and stopped in thin,planar target
- Decay positron is tracked through 2T uniform field with a symmetric stack of high precision, low mass, planar drift chambers

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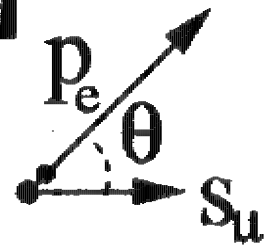
What *TWIST* measures

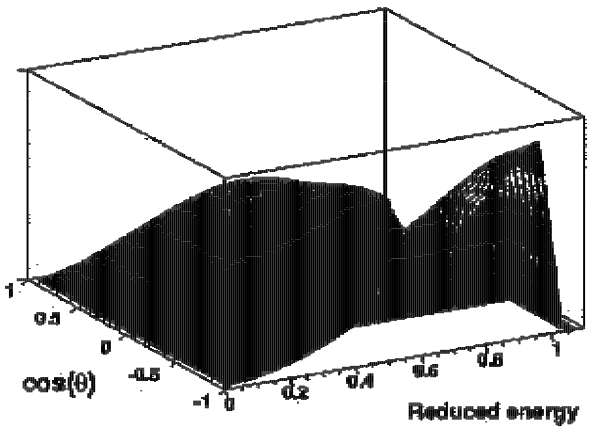


Muon decay parameters define the shape of the spectrum

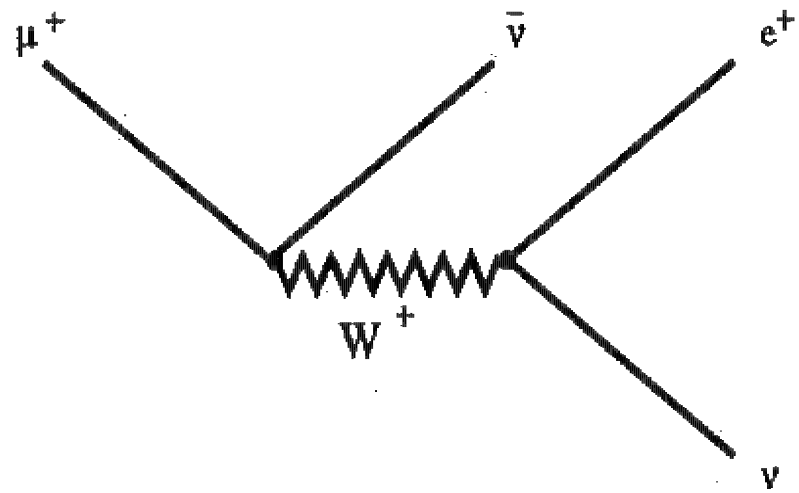
$$\frac{d^2\Gamma}{x^2\,dx\,d\cos(\theta)} \propto 1-x+\frac{2}{9}\rho\,(4x-3)$$

$$+\frac{1}{3}P_\mu\cos(\theta)\,\xi\,(1-x)$$

$$+\frac{2}{9}P_\mu\cos(\theta)\,\xi\delta\,(4x-3)$$



Normal μ^+ decay



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

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Muon Decay in a Model-Independent Form

The muon decay matrix element can be written as:

$$\frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,,T \\ \epsilon,\mu=,L}} g^{\gamma} \ \langle \bar{e}_{\epsilon} | \Gamma^{\gamma} | \nu_e \rangle \langle \bar{\nu}_{\mu} | \Gamma_{\gamma} | \mu_{\mu} \rangle$$

with 19 real-valued parameters and one overall phase. In the Standard Model, $g^{V}_{LL} = 1$ and all others are zero.

The right-handed coupling of the muon can be written in terms of these parameters as:

$$Q^{\mu}_{R} = \frac{1}{4}|g^{S}_{LR}|^2 + \frac{1}{4}|g^{S}_{RR}|^2 + |g^{V}_{LR}|^2 + |g^{V}_{RR}|^2 + 3|g^{T}_{LR}|^2$$

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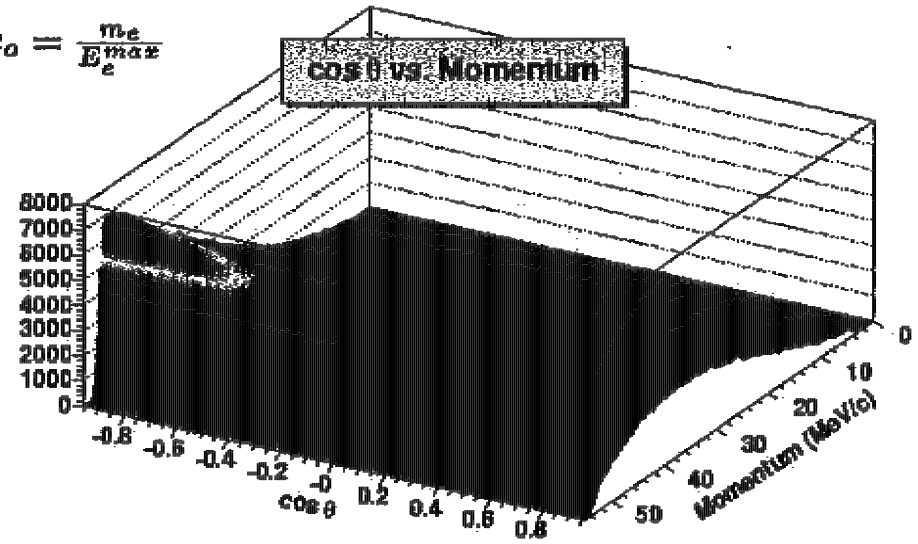
Muon Decay Distribution

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

$$F_{IS}(x,\rho,\eta) = (x - x^2) + \tfrac{2}{9}\rho(4x^2 - 3x) + \eta x_o(1-x)$$

$$F_{AS}(x,\xi,\delta) = \tfrac{1}{3}\xi(x - x^2) + \tfrac{2}{9}\xi\delta(4x^2 - 3x)$$

$$x = \frac{E_e}{E_e^{max}} \qquad x_o = \frac{m_e}{E_e^{max}}$$



BOTH WAYS ARE EQUIVALENT

IN STANDARD MODEL, ONLY FIRST TERM

IN $\rho, \xi\delta, \delta$ SURVIVES AND $\eta = 0$

$$\rho = \frac{3}{4} - \frac{3}{4}\left[|g_{LR}^{V}|^2 + |g_{RL}^{V}|^2 + 2|g_{LR}^{T}|^2 + 2|g_{RL}^{T}|^2 + Re(g_R^S \right.$$

$$\xi\delta = \frac{3}{4} - \frac{3}{4}\left[|g_{LR}^{V}|^2 + |g_{RL}^{V}|^2 + 4|g_{LR}^{T}|^2 + 2|g_{RL}^{T}|^2 + 2|g_{RR}^{V}|^2 \right.$$
$$\left. + Re(g_{RL}^{S} g_{RL}^{T*} - g_{LR}^{S} g_{LR}^{T*}) \right]$$

$$\xi = 1 - \left[\tfrac{1}{2}|g_{RR}^{S}|^2 + \tfrac{1}{2}|g_{LR}^{S}|^2 + 2|g_{RR}^{V}|^2 + 4|g_{RL}^{V}|^2 - 2|g_{LR}^{V}|^2 \right.$$
$$\left. + 4Re(g_{RL}^{S} g_{RL}^{T*} - g_{LR}^{S} g_{LR}^{T*}) \right]$$

$$\eta = \frac{1}{2} Re\left[g_{LL}^{V} g_{RR}^{S*} + g_{RL}^{V}(g_{LR}^{S*} + 6 g_{LR}^{T*}) + g_{LR}^{V}(g_{RL}^{S*} + 6 g^{\cdot} \right.$$

	ρ	δ	η	ξ
ρ	1	0.22	0.97	0.83
δ		1	0.15	-0.29
η			1	0.53
ξ				1

Table 3: Correlations between the Michel parameters in the raw μ decay spectrometer allows for the production of data samples with differing co

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Muon Decay Parameter Values

$$\rho = \frac{3}{4} - \frac{3}{4}|g^V_{LR}|^2 - \frac{3}{4}|g^V_{RL}|^2 - \frac{3}{2}|g^T_{LR}|^2 - \frac{3}{2}|g^T_{RL}|^2 - \frac{3}{4}Re\left[g^S_{LR}g^{T*}_{LR} + g^S_{RL}g^{T*}_{RL}\right]$$

Standard Model: $g^V_{LL} = 1$, all others are zero

Parameter	Standard Model	World Average	(Year)
ρ	$\frac{3}{4}$	0.7518 ± 0.0026	**(1969)**
η	0	-0.007 ± 0.013	(1985)
ξ	1	$(P_\mu\xi)\ 1.0027 \pm 0.0079 \pm 0.0030$	(1987)
δ	$\frac{3}{4}$	$0.7486 \pm 0.0026 \pm 0.0028$	(1988)
$\frac{P_\mu\xi\delta}{\rho}$	1	> 0.99682 90% CL	(1986)

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Right-handed Content of the Muon

The probability that the muon is right-handed, Q_R^μ, can be expressed as

$$Q_R^\mu = \tfrac{1}{4}|g_{RR}^S|^2 + \tfrac{1}{4}|g_{LR}^S|^2 + |g_{RR}^V|^2 + |g_{LR}^V|^2 + 3|g_{LR}^T|^2$$
$$= \tfrac{1}{2}\left[1 + \tfrac{1}{9}(3\xi - 16\xi\delta)\right]$$

(W. Fetscher and H.-J. Gerber)

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Standard Model Extensions

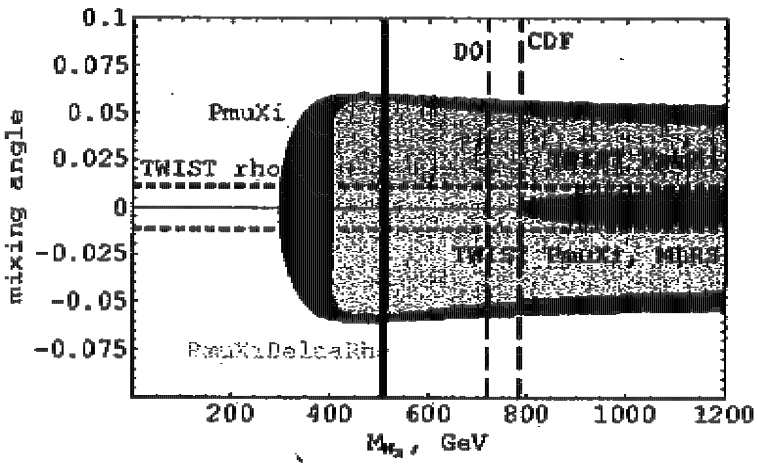
Example: Left-Right Symmetric Models

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

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

$$\zeta = \sqrt{\frac{1}{2} - \frac{2}{3}\rho}$$

$$\epsilon = \sqrt{\frac{2}{3}\rho - \frac{1}{2}\xi}$$



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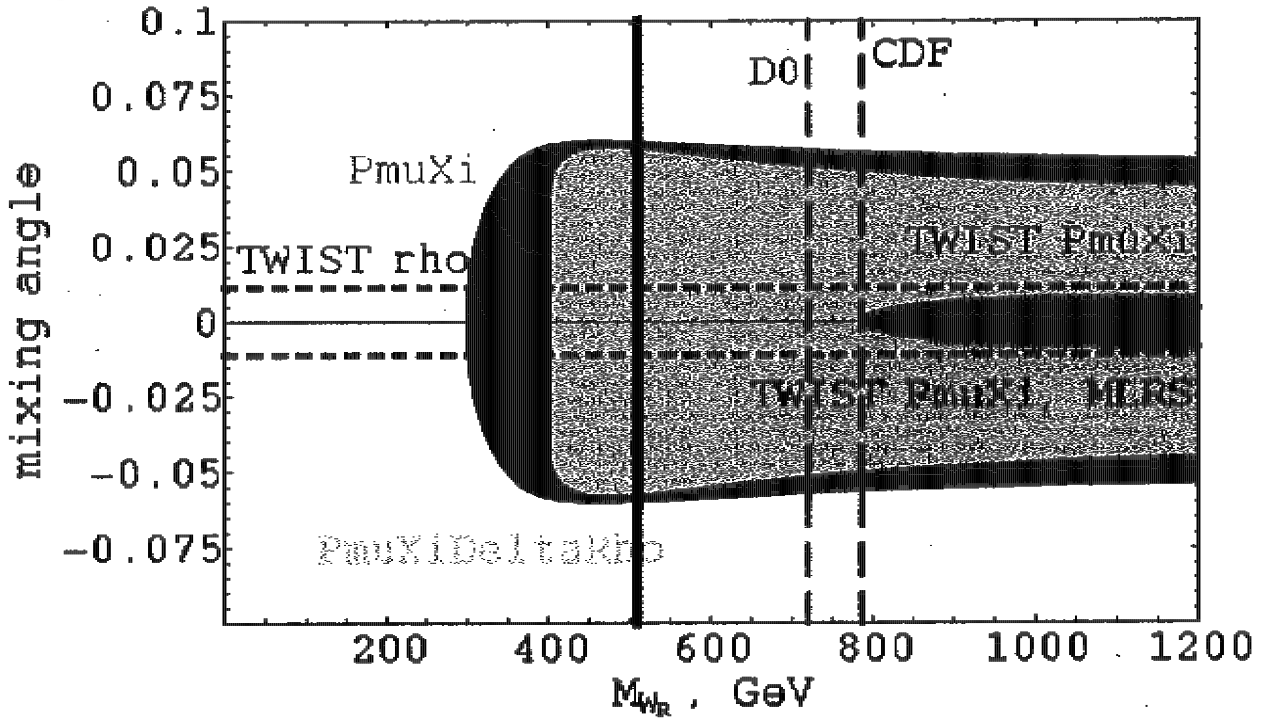
Goals of TWIST

- Search for new physics through **measurements of** ρ, δ, **and** $P_\mu\xi$ **to a few parts in** 10^4.
- Model-independent limit on right-handed muon coupling:

$$Q_R^\mu = \frac{1}{2}\left[1 + \frac{1}{3}\xi - \frac{16}{9}\delta\right]$$

- In left-right symmetric models:



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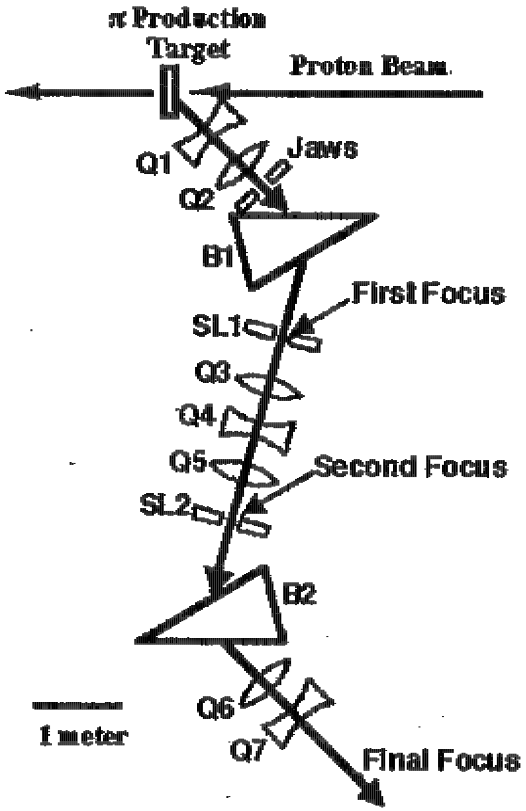
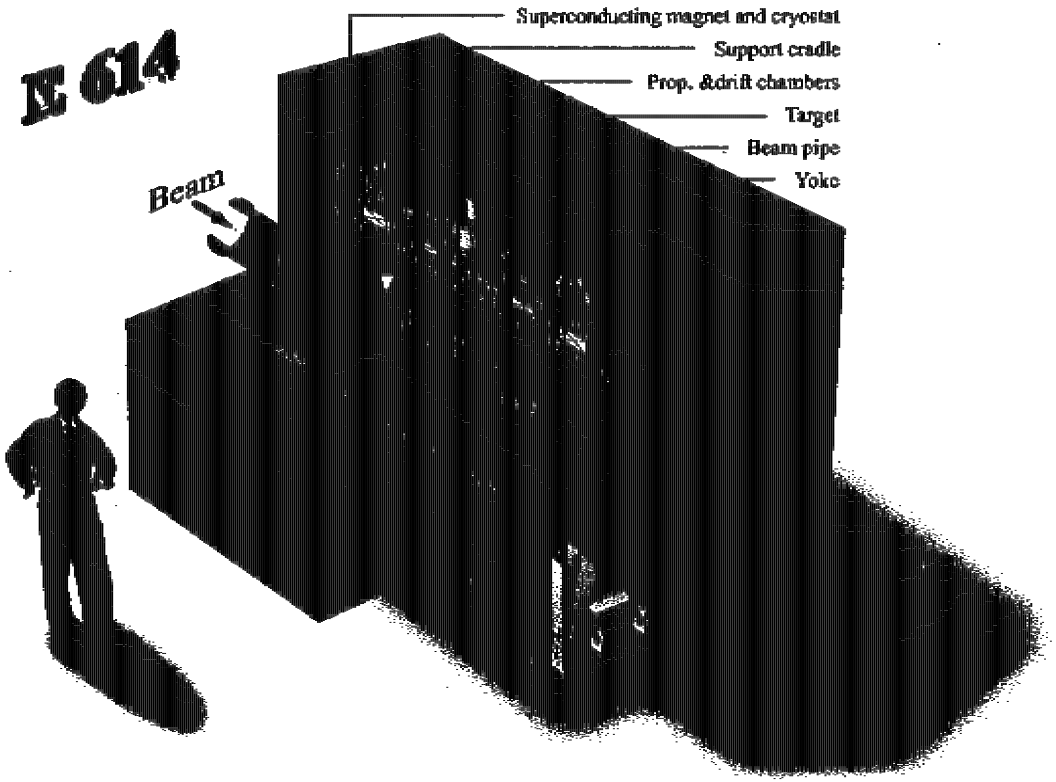
M13 Secondary Beamline at TRIUMF



Momentum Resolution $\Delta p/p = 1\%$



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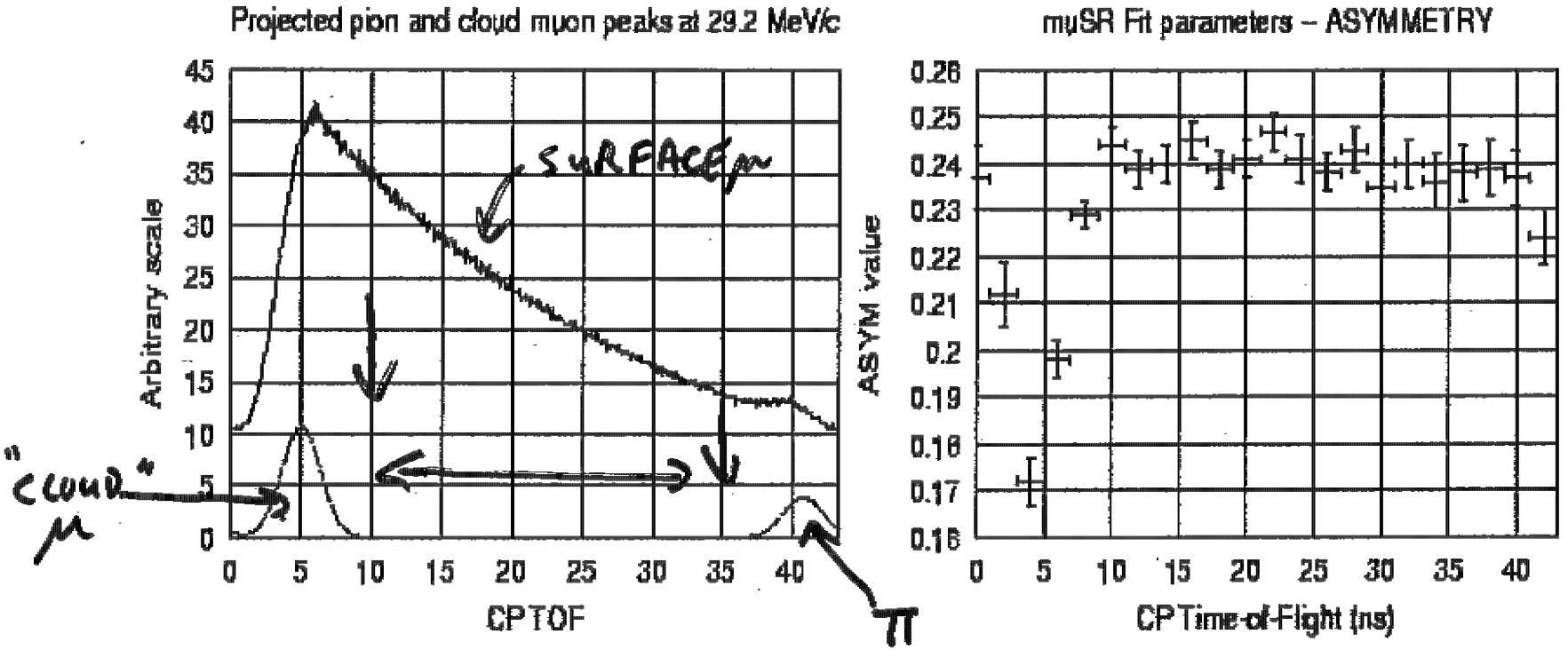

Figure 7: The upper curve in the figure at the left is the Time-of-flight of the surface muons. The distribution is characteristic of the $\pi+$ half life, since the pions are at rest on the surface of the production target when they decay. The lower curve at the left is the distribution of background particles, measured at slightly higher momentum and extrapolated to the momentum of the surface muons. Muons are visible near 5 ns in the figure, and pions near 42 ns. Both of these contaminants can be removed by the use of a timing cut. The figure at the right shows the polarization asymmetry measured across the the same cyclotron timing window.

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STATISTICAL ERROR

Can easily be made negligible;
at max counting rate (5kHz) we can get 10^9 events in 4 days

SYSTEMATIC ERROR – MAJOR SOURCES

Anything which distorts the 2-D spectrum shape will change our result.

1) Mechanical precision in wire plane construction and location – few microns
2) Efficiency of wire planes for detecting positrons - >99.9 %
3) Magnetic field map – measure to 0.2 mT (10^{-4})
4) Energy Calibration – use spectrum endpoint, change solenoid field
5) Muon beam properties – vary beamline elements
6) Muon polarisation – change muon polarisation and stopping target
7) Accuracy of Monte Carlo simulation - test with data
8) Software reconstruction efficiency – take data at 1.25, 2.5, 5 kHz

Because of high data rate we can take many complete data sets under different conditions. By a complete data set we mean one with enough events to evaluate the Michel parameters to the desired precision

9) HUMAN BIAS – BLIND ANALYSIS

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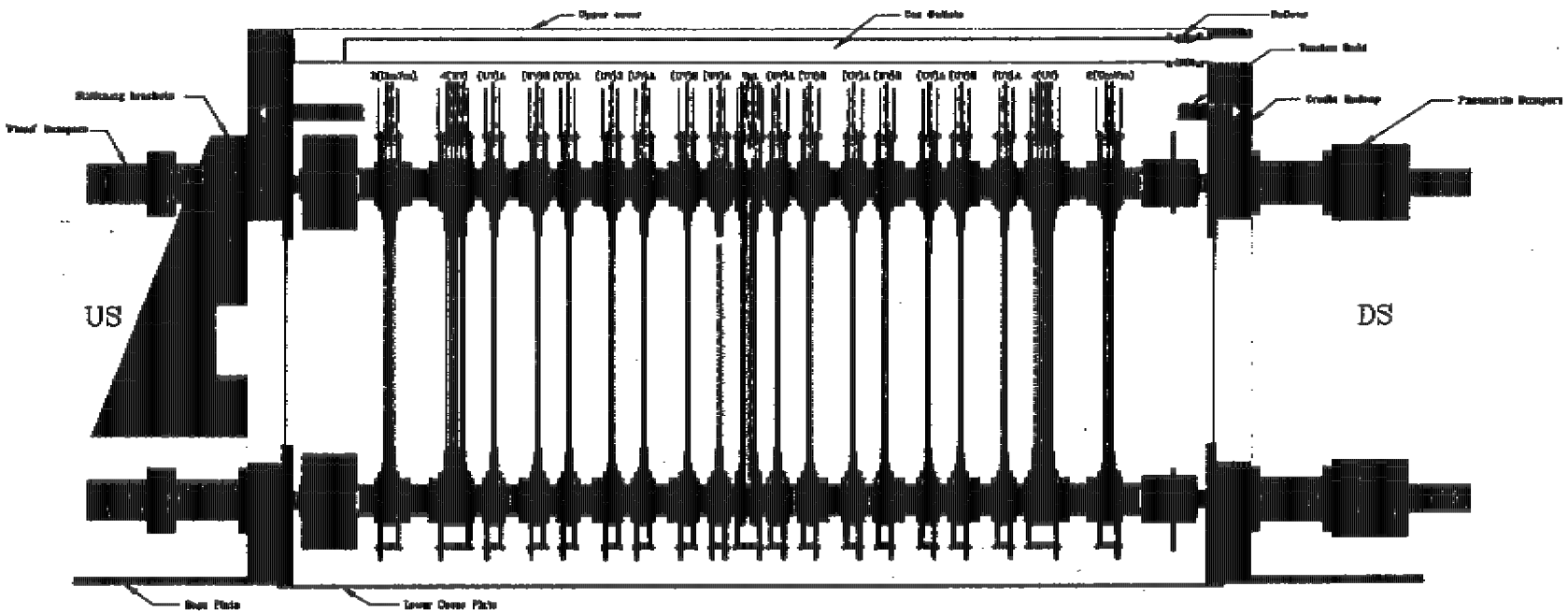
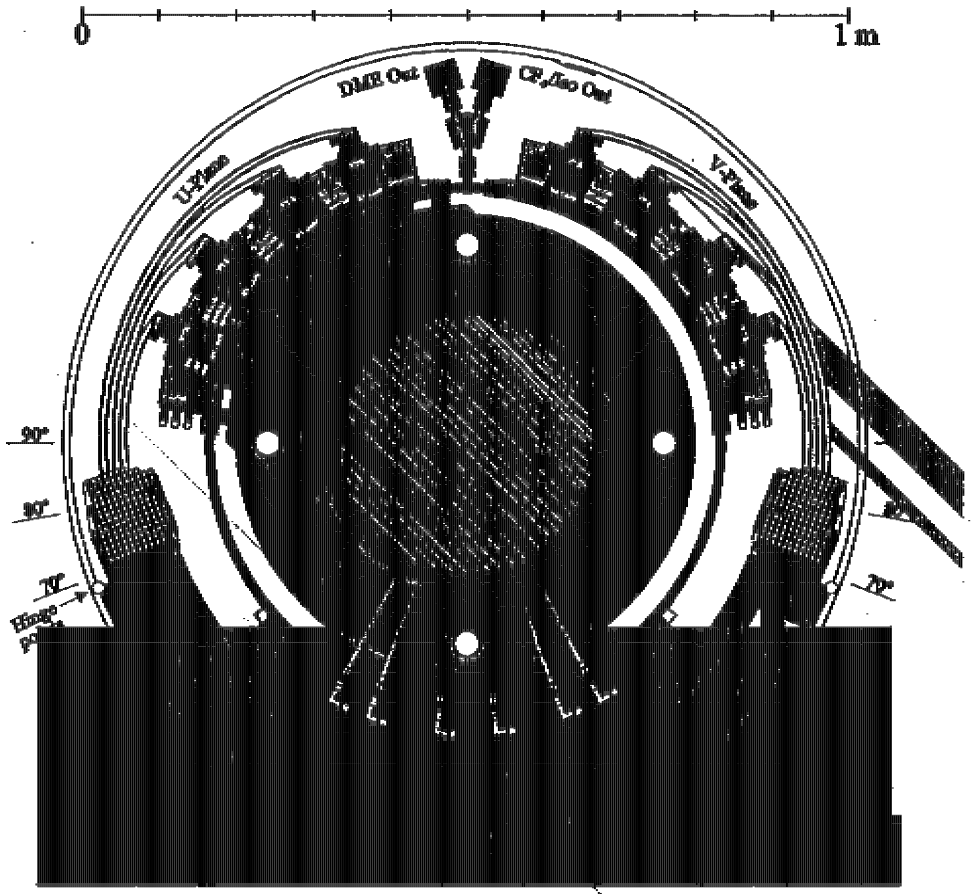
TWIST Wire Chambers



- 44 drift chambers and 12 MWPCs
- Very thin -- only ~5 x 10^{-5} X_0 per chamber
- ~ 5000 wires positioned with ~ 3 μm accuracy
- Longitudinal and transverse distances known to < 5 parts in 10^5

TWIST Wire Chamber Modules



- DCs:
  80 wires/plane
  DME
- MWPCs:
  160 wires/plane
  CF_4 iso-C_4H_{10}

- All wires 15 μm W(Au)
- 2, 4 or 8 planes per module

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Wire chamber precision

	Required tolerances:	Actual:
• Random errors in sense wire positions	< 20 μm	< 5 μm
• Deviation of wire pitch in planes	< 2 μm	< 0.1 μm
• Deviation of average distances between planes in assembly	< 2 μm/4mm	<0.19μm/4mm
• Wire tension limits	4g < T < 43g	30.80±1.25g

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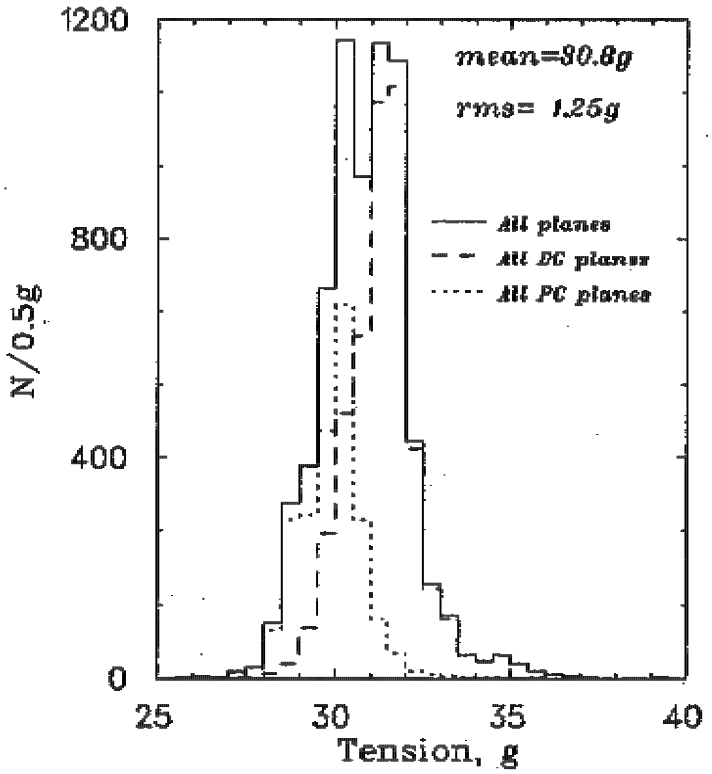
Tension of all DC and PC sense wires
(6784 wires total)



Requirement

$4\,g < T < 43\,g$

Electrostatic Stability

Elastic limit

Gravitational sag

(L=40 cm, T=30 g, ø15μm, 90°):

$S = 1.8\ \mu m$

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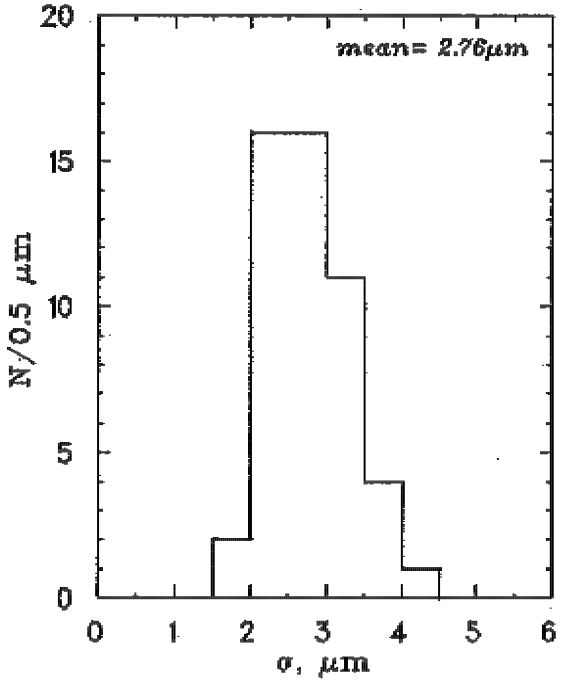
Precision of wire X/Y positioning

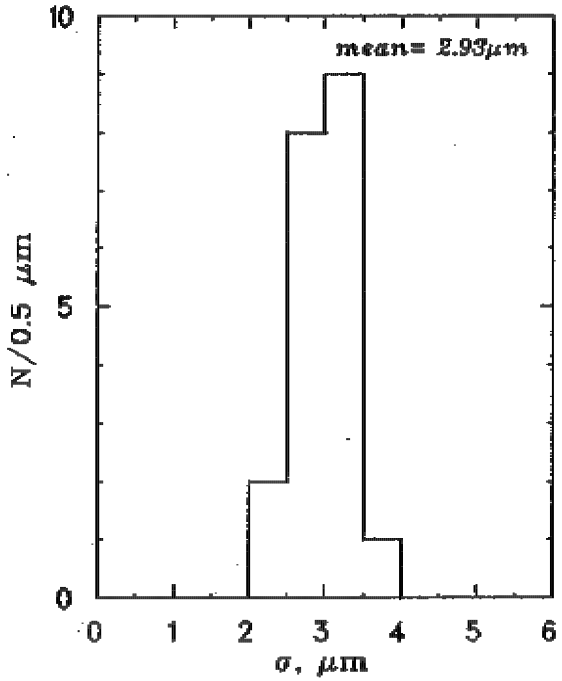
50 DC planes



x=(3.99995±0.00004)n±(0.00276±0.00050) mm

Requirement: x=(4.000±0.002)n±0.020 mm

12 PC and 8 PCT planes



x=(2.00003±0.00005)n±(0.00293±0.00035) mm

Requirement: x=(2.000±0.002)n±0.020 mm

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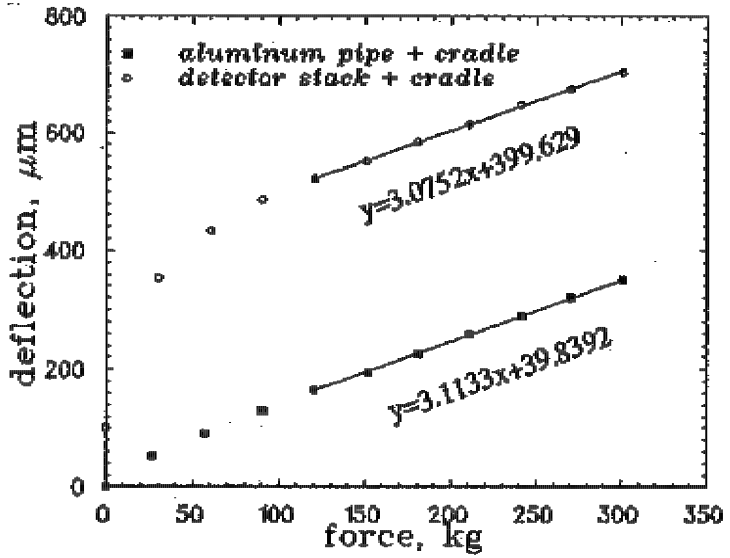
Z-positioning: compression tests

Measurement of deflection:



Direct measurement of length of detector between two dense stacks:

- Gage block: L=1080.030±0.005mm
- Dial gage

At 150 kg: L=1083.751±0.015 mm
Data base: L=1083.787±0.005 mm
At 300 kg: ΔL(300-150)=-27±5 μm
Calculation: ΔL(300-150)=-24 μm

Error in knowing of detector length:
<50 μm/108cm or 0.19μm/4mm
Requirement: <2 μm/4mm

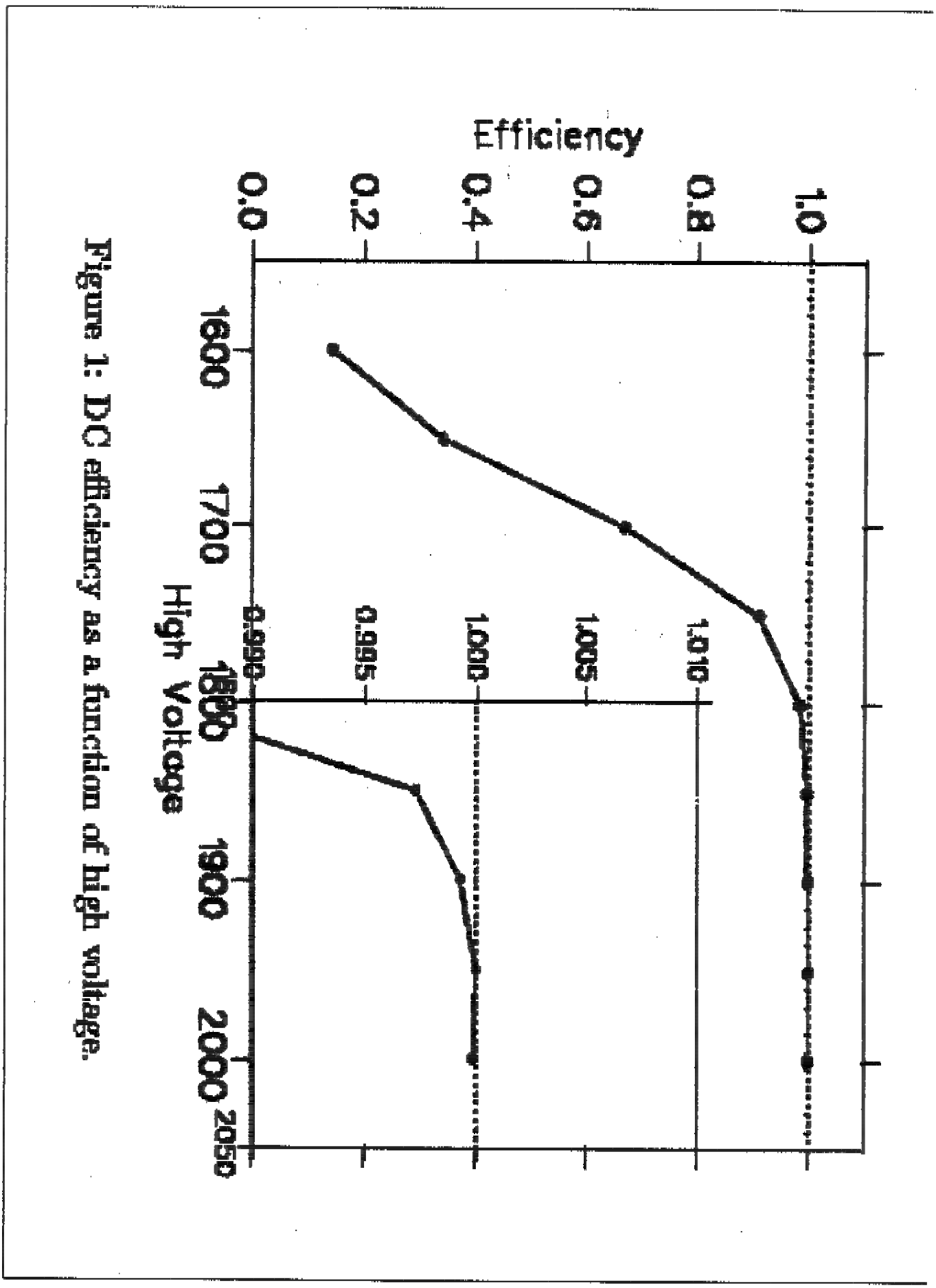


Figure 1: DC efficiency as a function of high voltage.

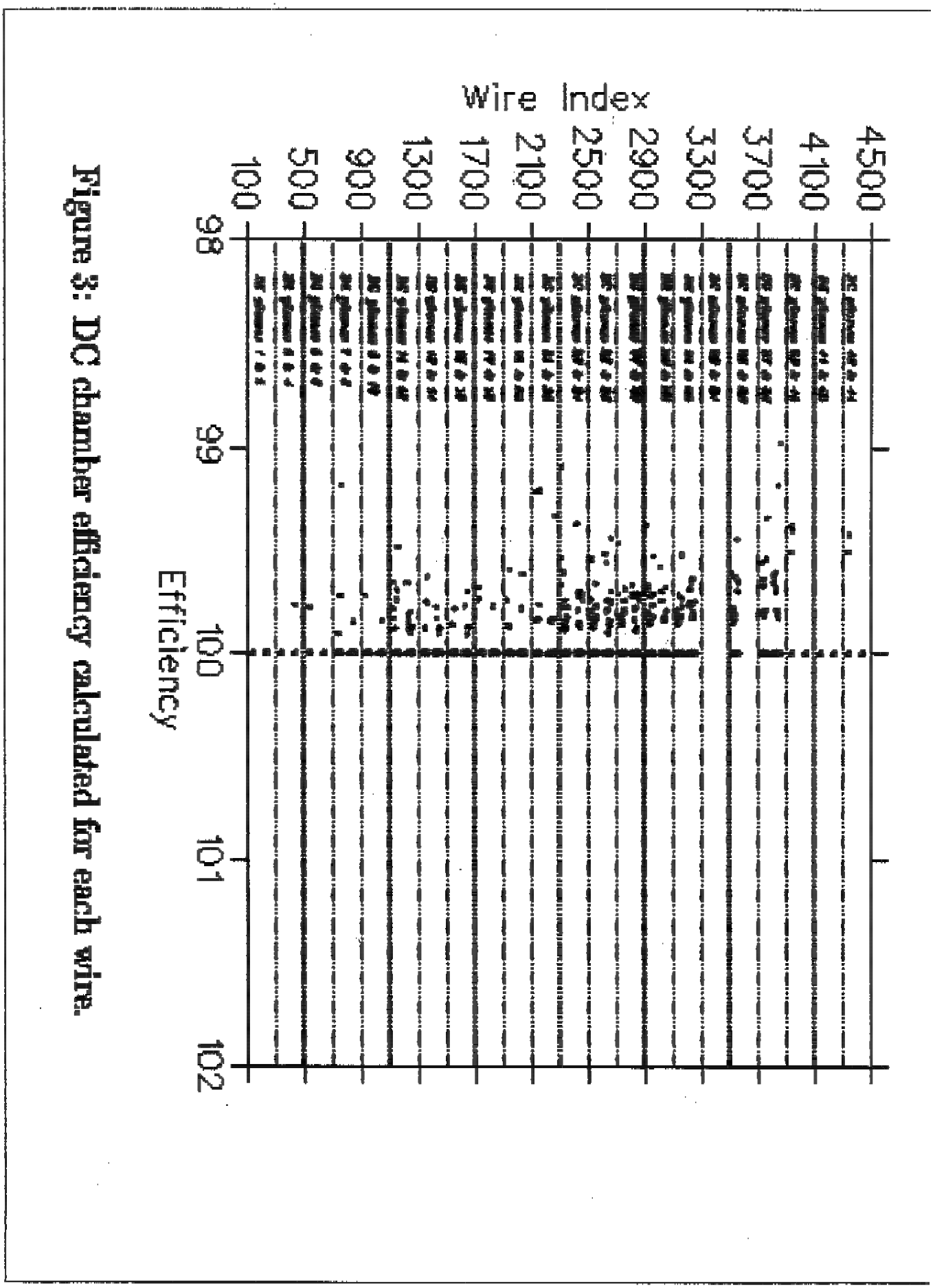


Figure 3: DC chamber efficiency calculated for each wire.

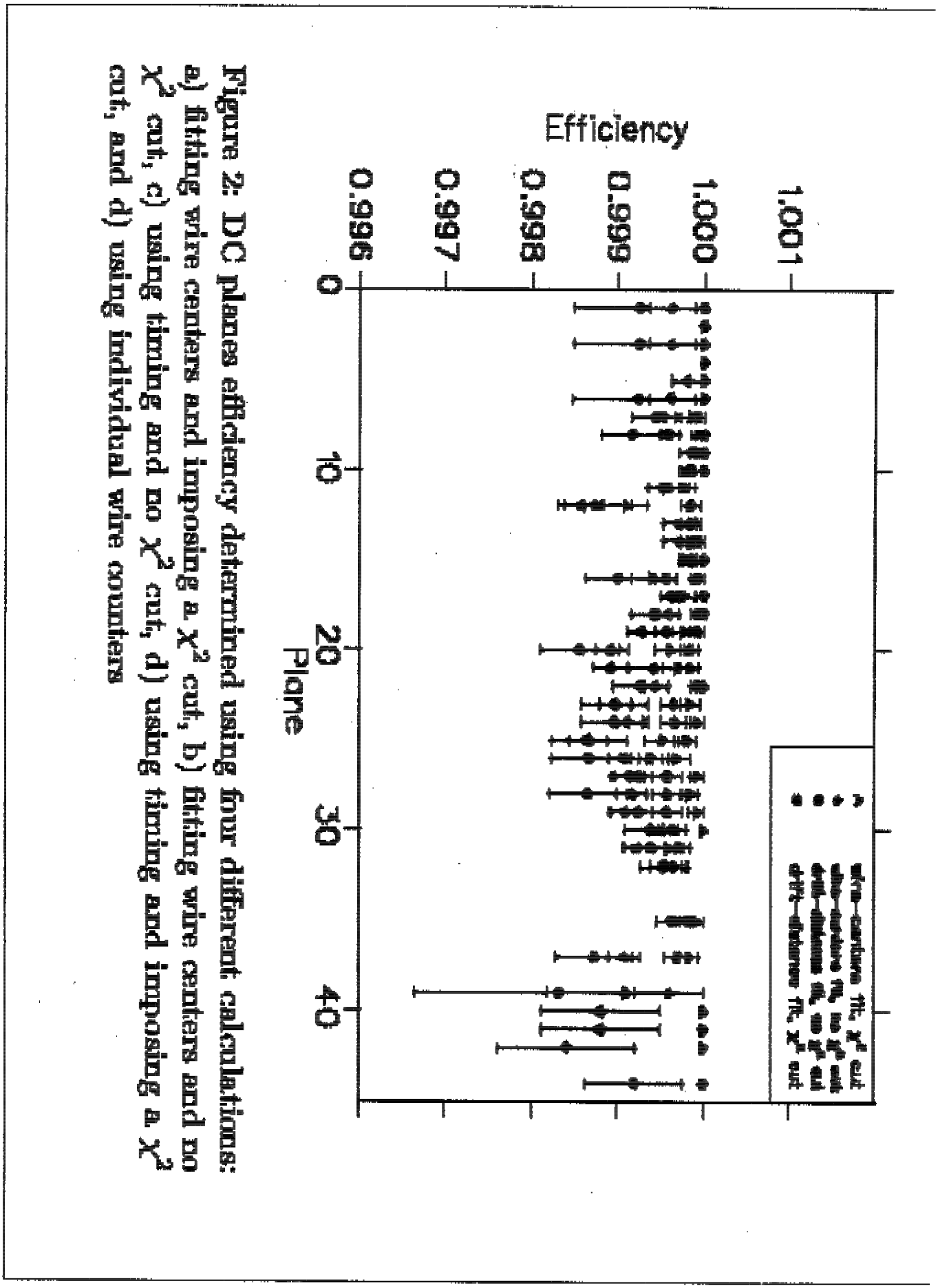
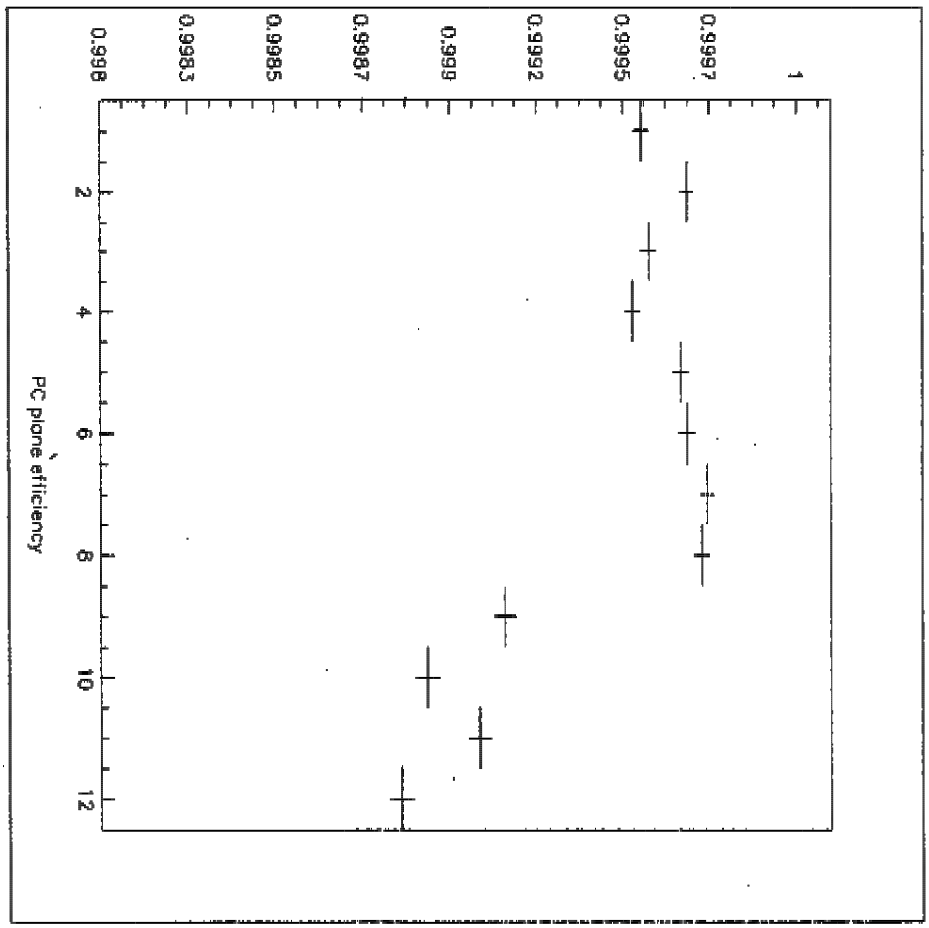


Figure 2: DC planes efficiency determined using four different calculations: a) fitting wire centers and imposing a χ^2 cut, b) fitting wire centers and no χ^2 cut, c) using timing and no χ^2 cut, d) using timing and imposing a χ^2 cut, and d) using individual wire counters


PC plane efficiency
0.998
0.9983
0.9986
0.9987
0.999
0.9992
0.9995
0.9997
1
2
4
6
8
10
12

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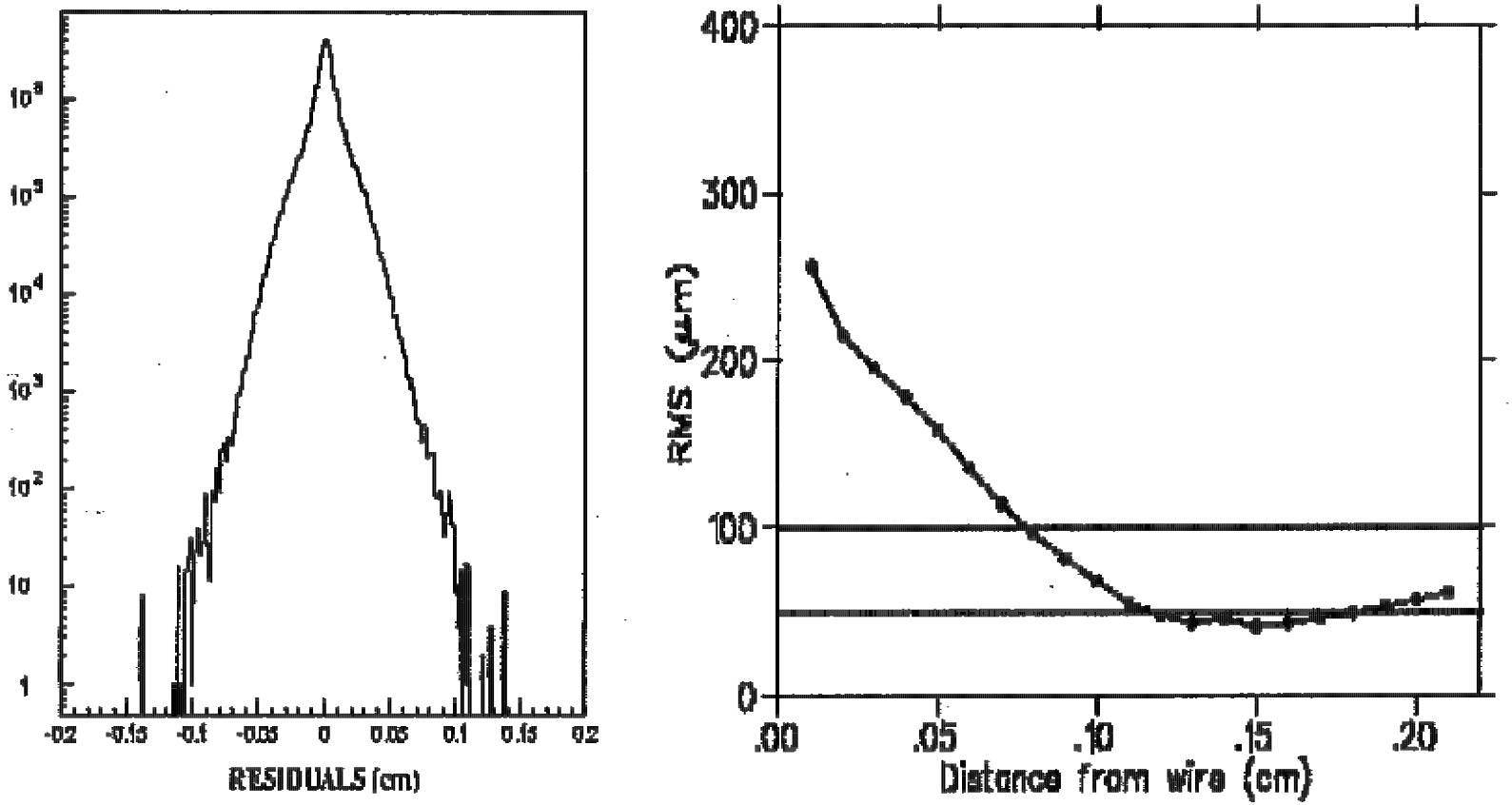

Figure 4: Tracking residuals averaged over planes and over drift distances (left), and RMS trackit error as a function of drift distance across a cell. (Preliminary result, August 2001 data.)

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Chamber performance

- Gas system keeps chambers at stable operational conditions
- Slow control and online analysis monitor all aspects of chamber performance during the run
- Chambers have demonstrated full efficiency and high stability during an engineering run (2001). Problems from the engineering run - 1 broken wire; 3 oscillating planes (bad grounding) - Fixed before 2002 runs
- No serious hardware and high voltage related problems during 2002 runs (~6 months beam time)

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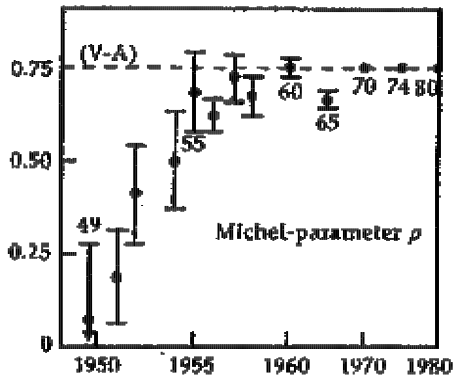
Motivation for blind analysis

- Tool to eliminate **human systematics:** avoid (even subconscious) biases.
- The method: Keep the final result hidden till the measurement is done.
- The value of a measurement does not contain any information about its correctness!



W. Greiner, B. Müller,
Gauge theory of weak interactions,
Springer (1996)

For examples see: P.F. Harrison, Advanced Statistical Techniques in Particle Physics, Durham, 18 - 22 March 2002. http://www.ippp.dur.ac.uk/Workshops/02/statistics/proceedings.shtml

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Analysis Strategy

If the **decay rate** is written as a function of:

$$\rho = \rho_0 + \Delta\rho$$
$$\eta = \eta_0 + \Delta\eta$$
$$P_\mu\xi = P_\mu\xi_0 + \Delta P_\mu\xi$$
$$\delta = \delta_0 + \Delta\delta$$

It can be made **linear in** $\Delta\rho$, $\Delta\eta$, $\Delta P_\mu\xi$, **and** $\Delta\delta$.

This provides the basis for our **blind analysis scheme**. We will fit our measured spectrum to a sum of a **GEANT "standard" spectrum**, produced with **unknown** ρ_0, η_0, $P_\mu\xi_0$, **and** δ_0, together with GEANT distributions thrown according to:

$$d\Gamma/d(\Delta\rho),\ d\Gamma/d(\Delta\eta),\ d\Gamma/d(\Delta P_\mu\xi),\ \text{and}\ d\Gamma/d(\Delta\delta).$$

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Fitting the shape

Need to take into account detector response. The technique:

$$\underbrace{n_i(\rho_{\mathrm{Data}})}_{\text{Data}} = \underbrace{n_i(\rho_{\mathrm{MC}}) + \frac{\partial n_i}{\partial \rho}}_{\text{MC}} \underbrace{(\rho_{\mathrm{Data}} - \rho_{\mathrm{MC}})}_{\text{Fit parameter}}$$

- Many effects of reconstruction cancel.
- Monte-Carlo must reproduce effects of the detector.
  - ▷ But spectrum distortions by the thin detector are small.

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TWIST implementation

The idea:

$$n_i(\rho_{\mathrm{Data}}) = n_i(\rho_{\mathrm{MC}}) + \frac{\partial n_i}{\partial \rho}\Delta\rho$$

- **Blind MC samples**, not the fitter.
- Use public key cryptography to encrypt the "secret" values.
- Clear text values are known only to a process running on a server which is not accessible by *TWIST* people.
- Keep and re-use generated decay samples. We do not know the secret parameters, but know that they do not change between MC productions.

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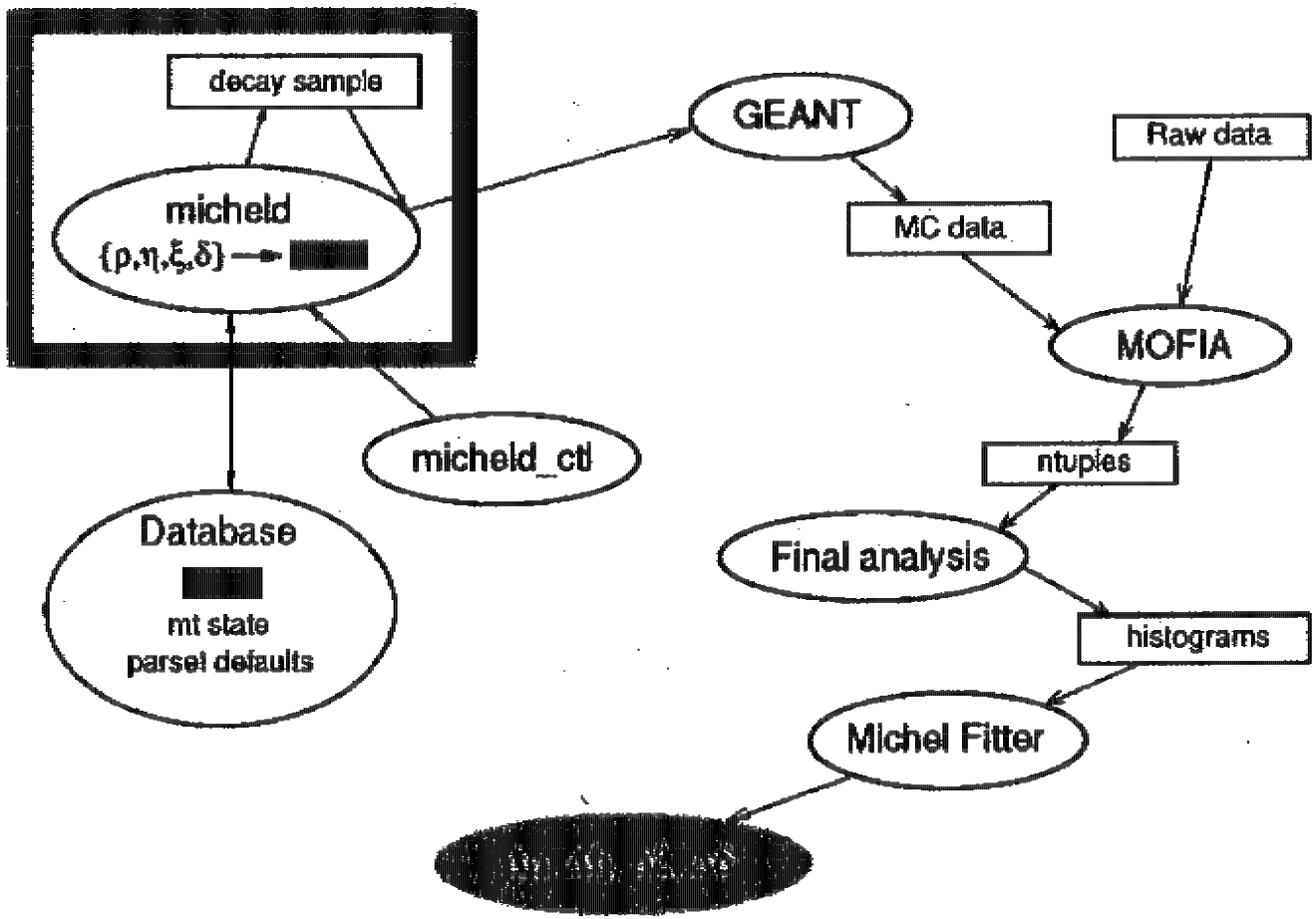
scan for file

Implementation-3



03-12- 3:12:45 ;BELLE GROUP scan for file ;+81-298-64-5340 # 35/ 52

First Physics Run: Sept-Dec, '02

- **Goal: Determine ρ and δ to 10^{-3}.**
- **Recorded ~6 x 10^9 events to tape. Note that 3 x 10^8 events suffice to measure ρ and δ with a statistical precision of ~6 x 10^{-4}.**
- **Basic philosophy: If we might be sensitive to a particular systematic effect, can we take data in a configuration that will make it "really big"?**
- Recorded many separate 3 x 10^8 event data sets under various experimental conditions to investigate:
  - GEANT simulation quality
  - Varying beam polarization
  - Beam line and detector performance
  - Upstream-downstream symmetry
  - Momentum scale
  - Analysis codes

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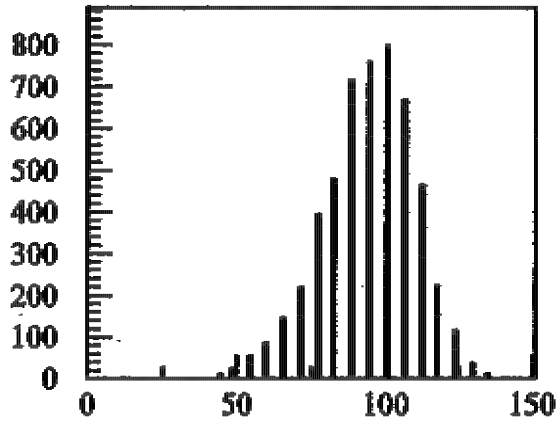
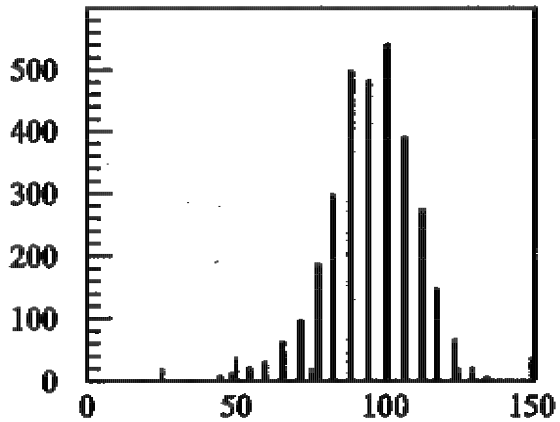
Validating the Muon Stopping Distribution in GEANT

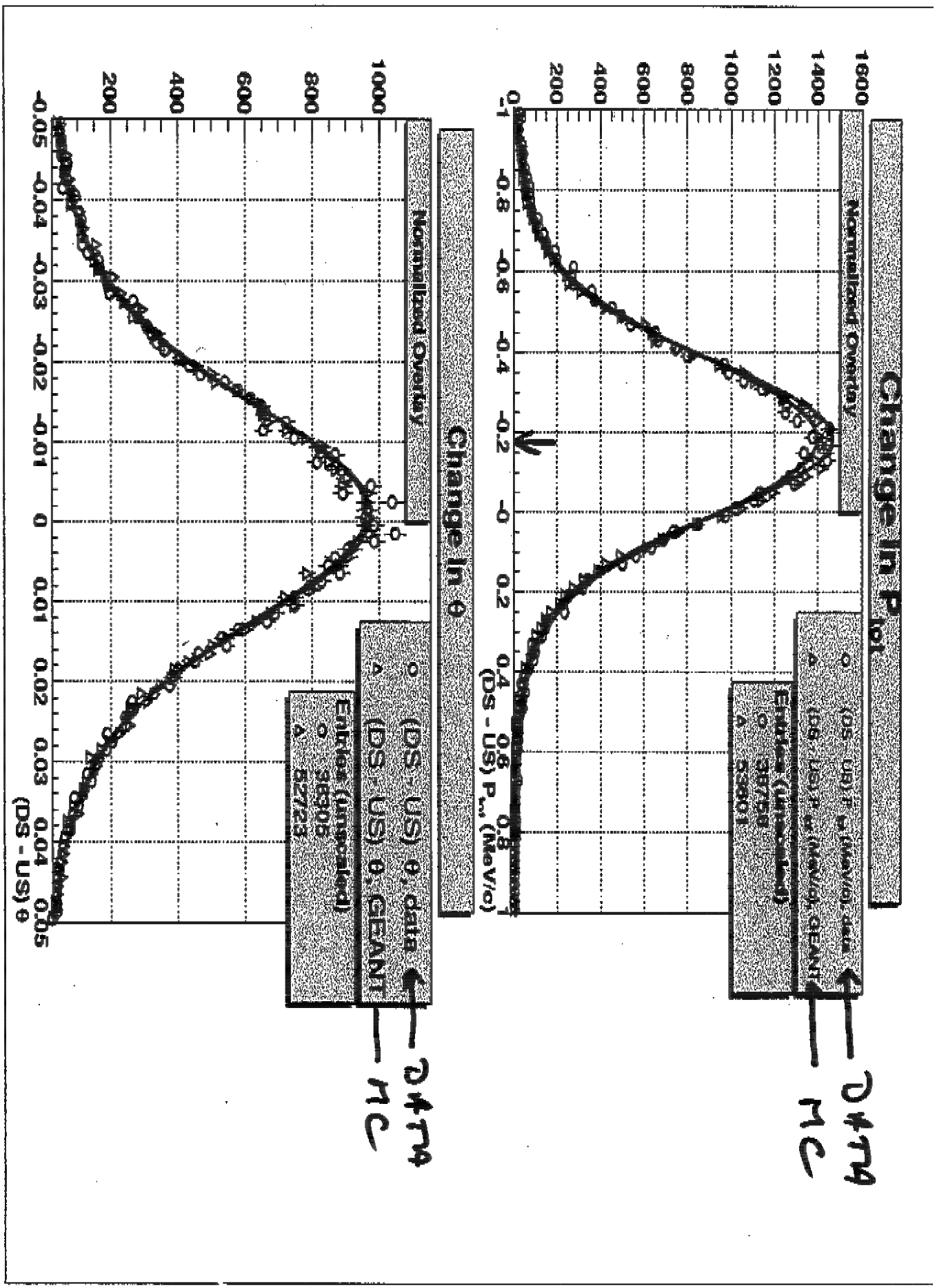


Muon Stops/RL vs RL (units of 10^{-5})



Muon Stops/RL vs RL (units of 10^{-5})

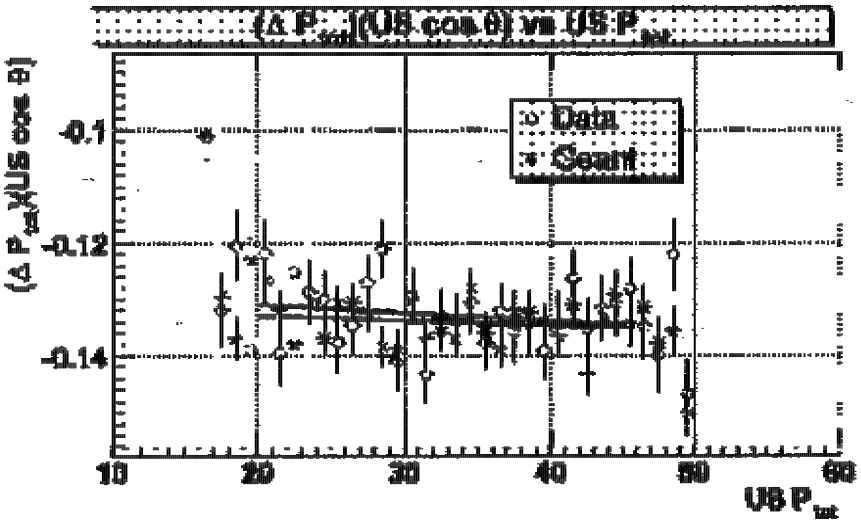
- Began with muons stopping in the center of the target in both **experiment** and **Monte Carlo**
- Inserted an upstream mylar degrader with the same known thickness in both
- Measured the new stopping distribution in the upstream half of the detector stack


Change in p
Normalized Overlay
Change in θ
Normalized Overlay
データ
MC
データ
MC

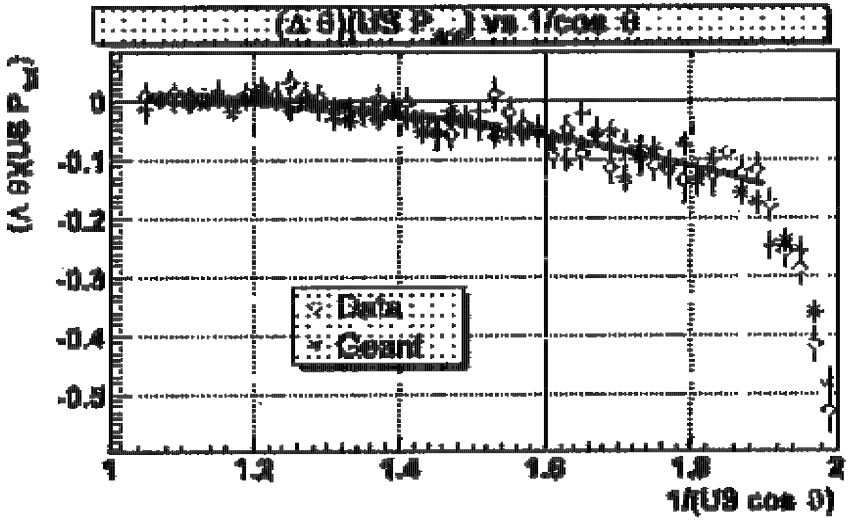
03-12- 3:12:45 :BELLE GROUP scan for file :+81-298-64-5340 # 38/ 52

Validating the Positron Interactions in GEANT

Energy loss



Multiple scattering



- Stop muons near the upstream end of the system
- Track decay positrons **independently** before and after the target
- Compare the two reconstructions
- Measures energy loss and multiple scattering in data and GEANT

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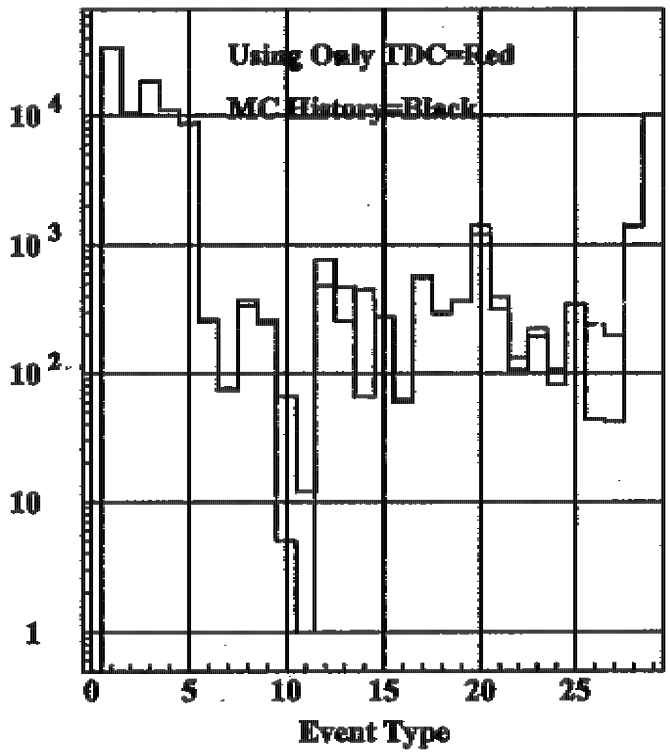
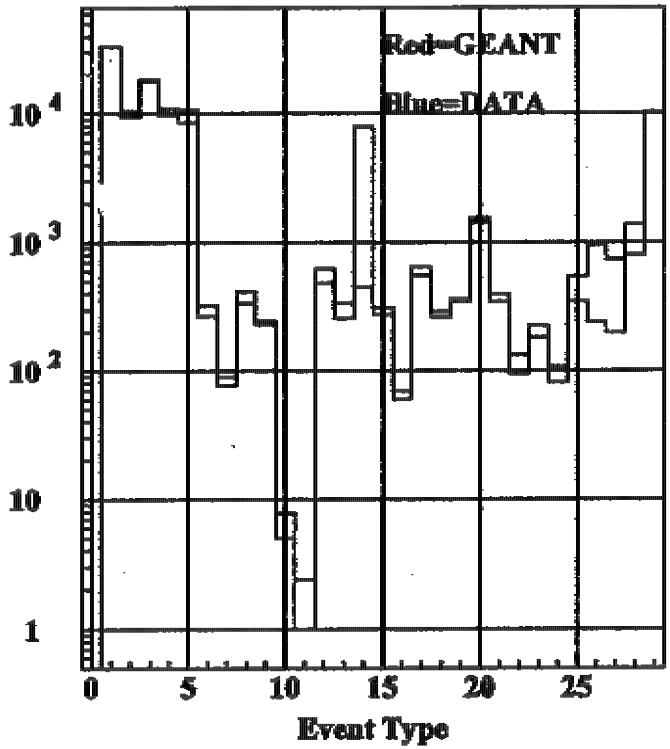
Classifying Events: What Really Happened?

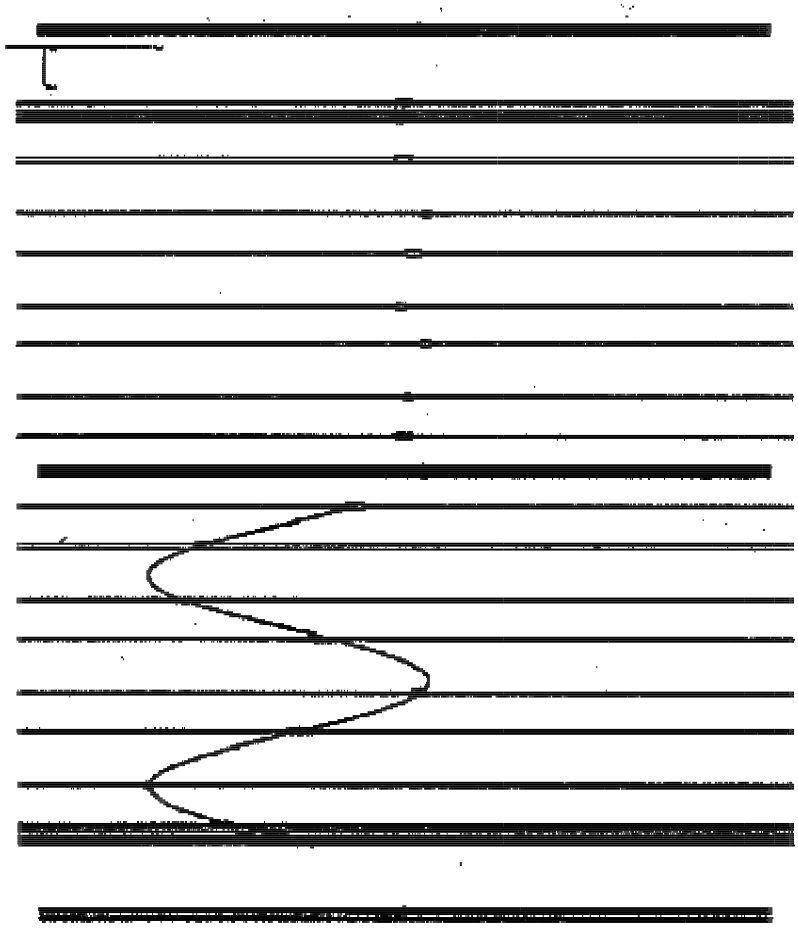




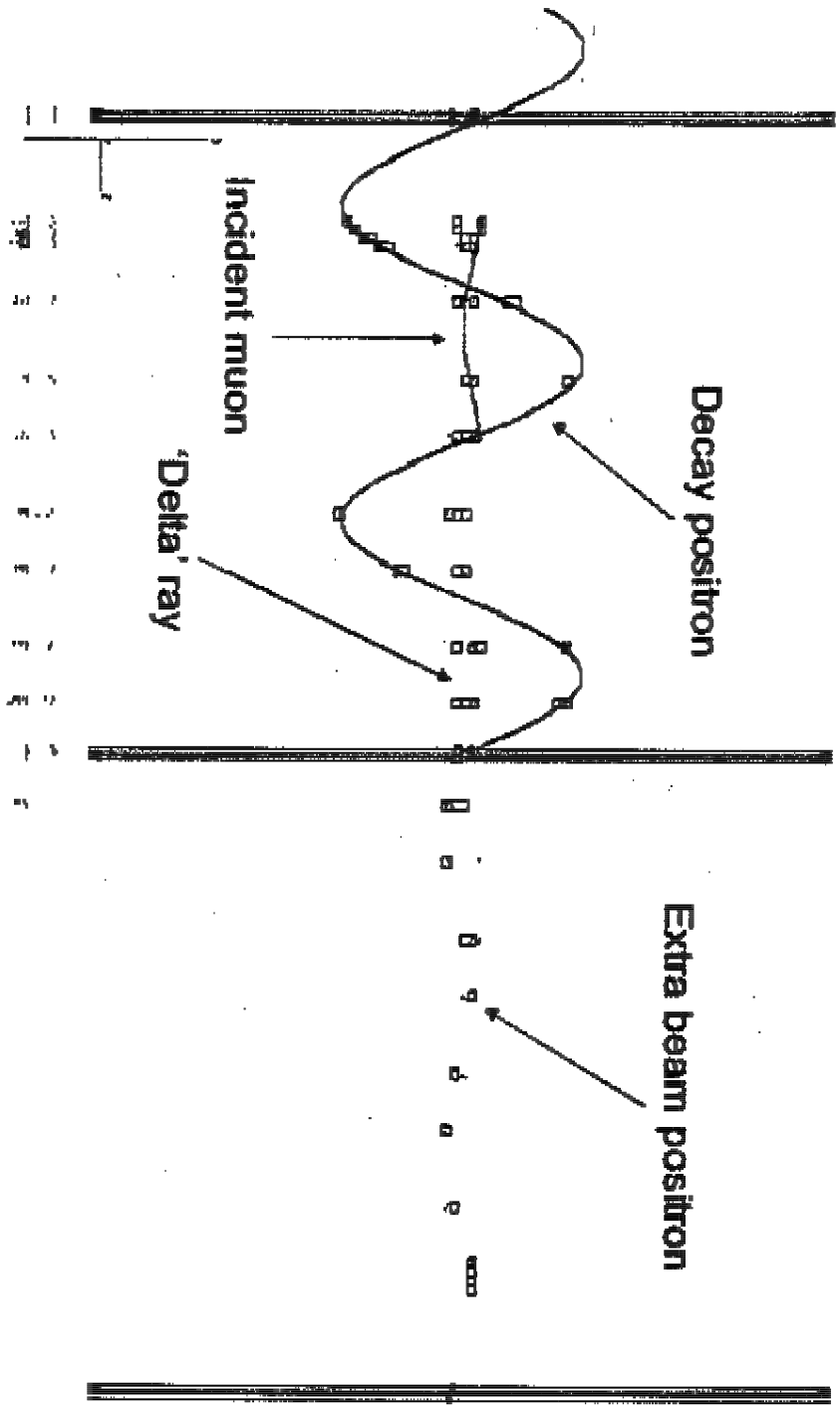
Do MC analysis and history match?

Do MC and data match?

Same Monte Carlo analysis



Muon Decay Event


Incident muon
'Delta' ray
Decay positron
Extra beam positron

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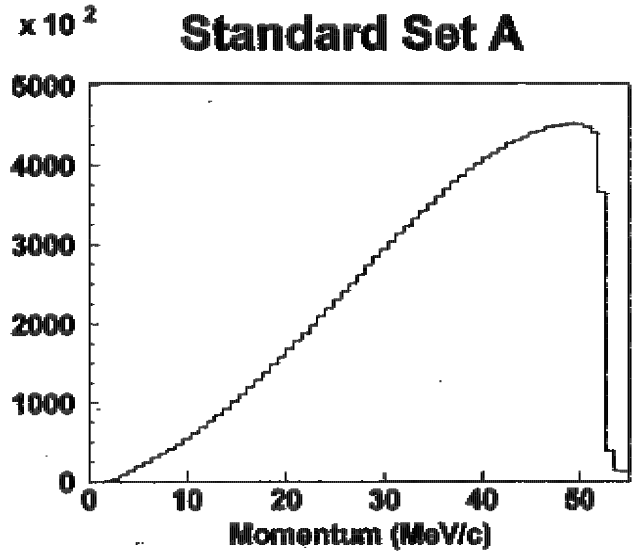

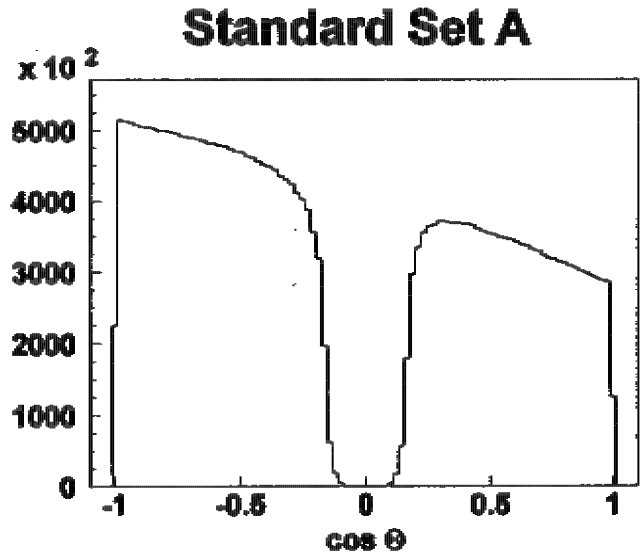

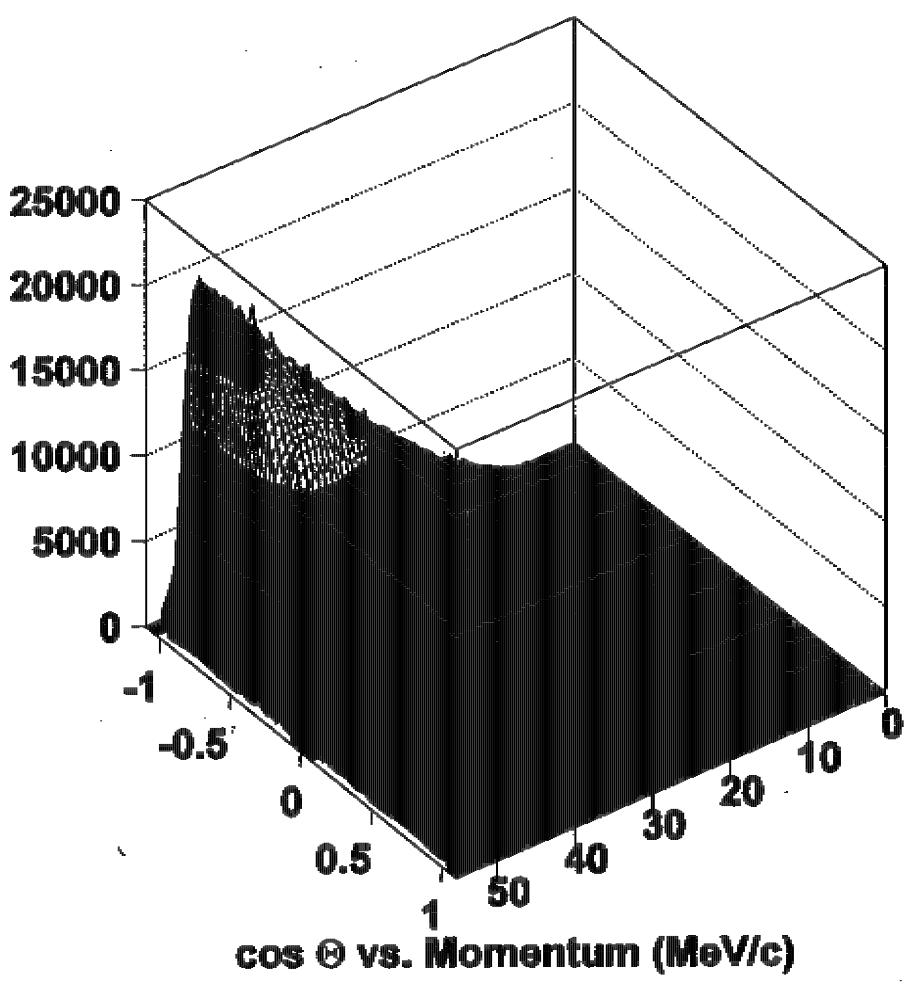

Evaluating Systematic Errors

Methodology: Exaggerate possible sources of error and measure the effect on the fit of the decay parameters.

Systematic Data Sets (Each a full data set)

- **Drift chamber high voltage reduced by 50V and 100V**–drift chamber efficiencies
- **Proportional chamber high voltage reduced by 50V and 100V**–proportional chamber efficiencies
- **Different chamber gas density**–μ^+ stopping position
- **Various μ^+ trigger rates**–separation of time overlapped events
- **Different μ^+ polarization**–upstream/downstream asymmetries
- **Different beam e^+ rate**–separation of extra particles
- **Modified M13 beamline steering**–transport of polarization and stopping position
- **Aluminum and lucite installed downstream**–effect of scintillator package
- **Slightly upstream and downstream μ^+ stops**–e^+ interactions in target
- **Field varied by ±2%**–energy calibration

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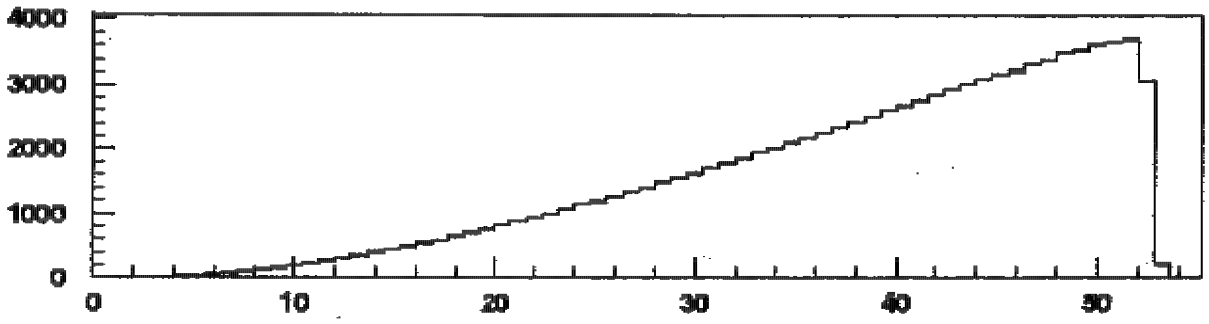
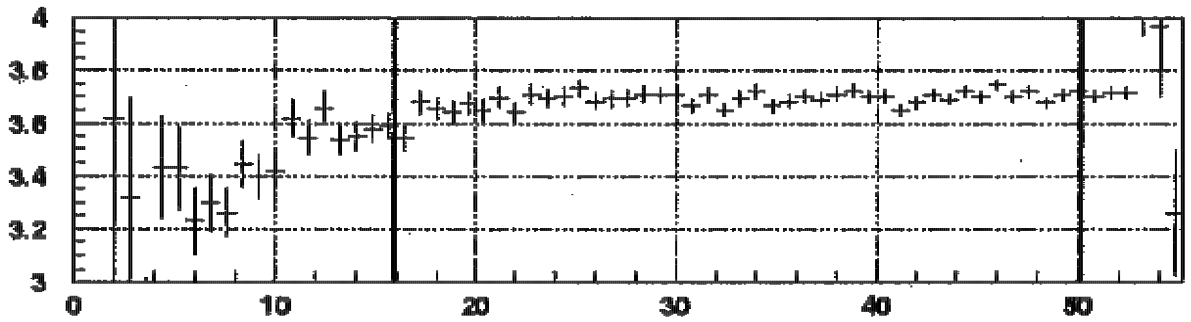
2003/05/12 19.12

DCHV 1850V vs. Standard A



Normalized overlay of Momentum (MeV/c), Upstream



Unnormalized ratio of histograms, (DCHV 1850V)/(Standard A)

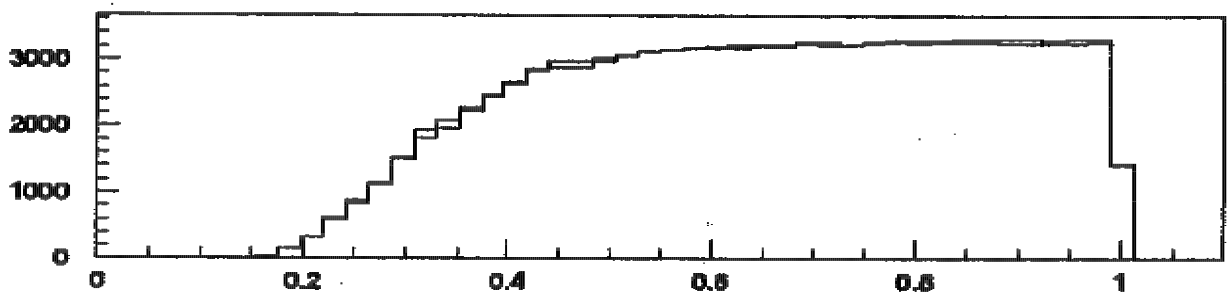
Events in Standard A data set 1481827

Events in DCHV 1850V data set 5472748

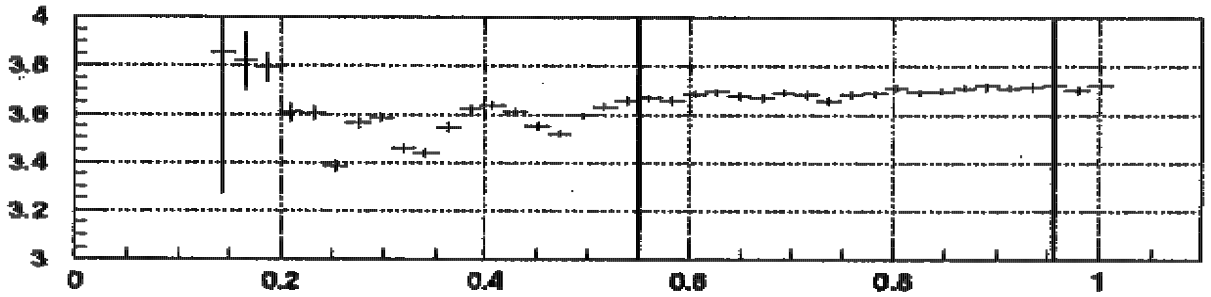
03-12- 3:12:45 ;BELLE GROUP ;+81-298-64-5340 scan for file # 45/ 52

2003/05/12 19.12

DCHV 1850V vs. Standard A



Normalized overlay of ABS(cos(theta))



Unnormalized ratio of histograms, (DCHV 1850V)/(Standard A)

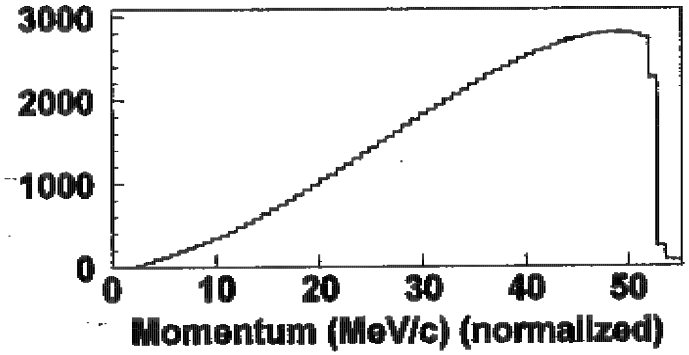
Events in Standard A data set 3957969

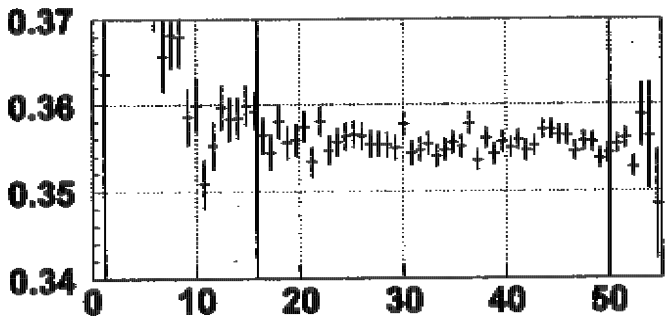
Events in DCHV 1850V data set 14454754

03-12- 3:12:45 ;BELLE GROUP scan for file ;+81-298-64-5340 # 46/ 52

Comparing Cloud Muons to Surface Muons

Cloud vs. Standard A

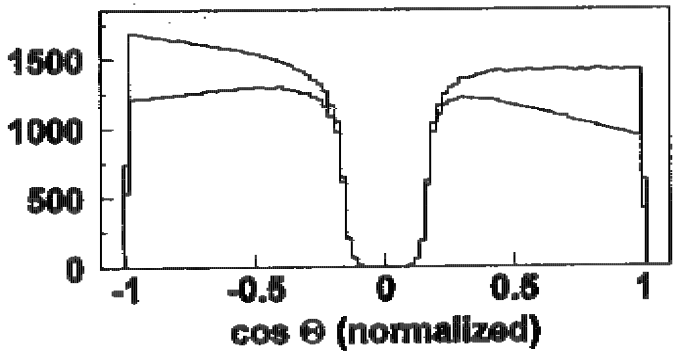


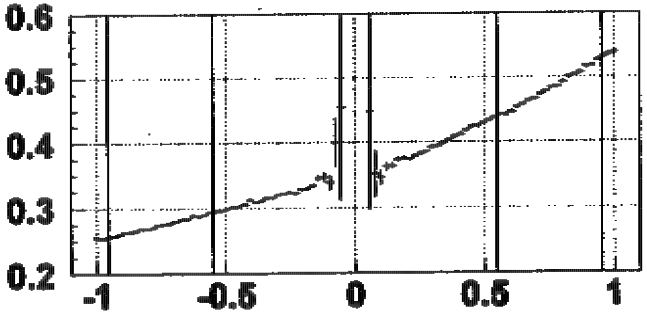


Events in Standard A data set 16112307

Events in Cloud data set 5730232

Cloud vs. Standard A





Events in Standard A data set 30534801

Events in Cloud data set 10832352

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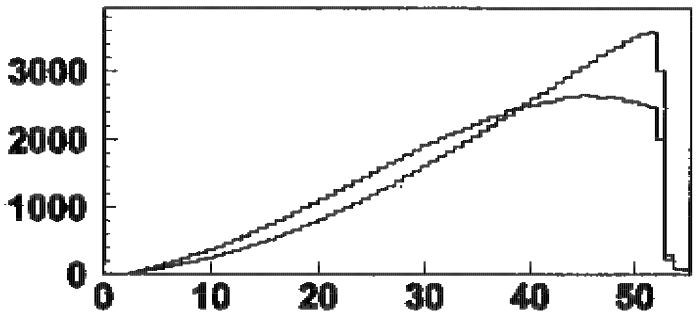
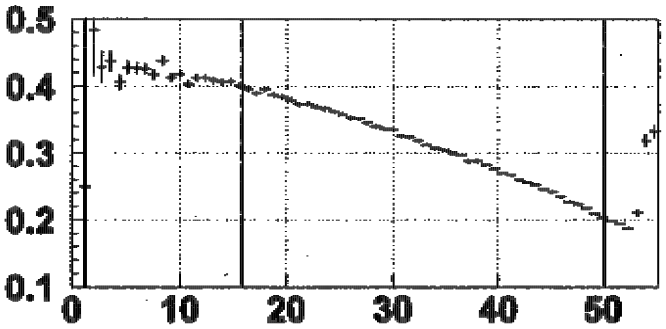
More Cloud Muons vs. Surface Muons

Cloud vs. Standard A





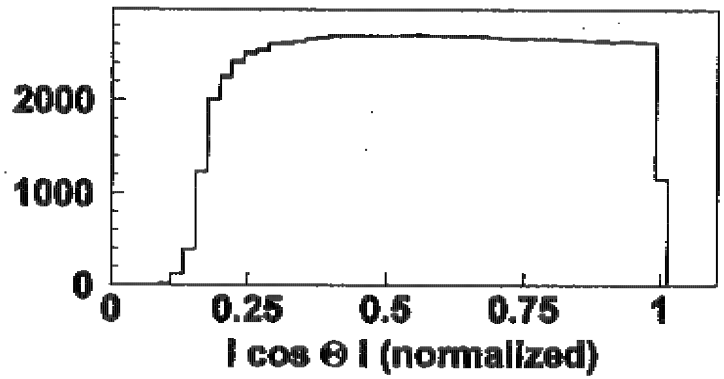
Events in Standard A data set 9579373

Events in Cloud data set 2686038

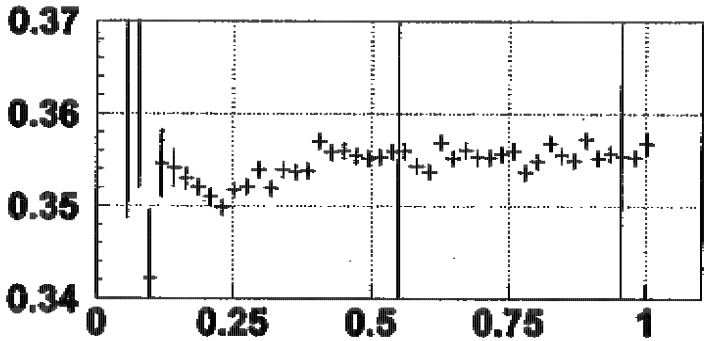
03-12- 3:12:45 ;BELLE GROUP ;+81-298-64-5340 # 48/ 52
scan for file

More Cloud Muons vs. Surface Muons

Cloud vs. Standard A



— SURFACE
— CLOUD



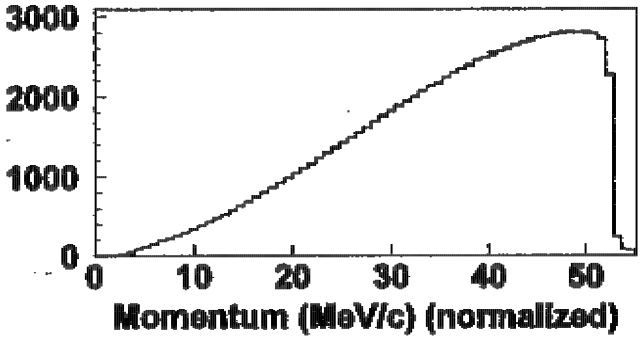
Events in Standard A data set 30534801

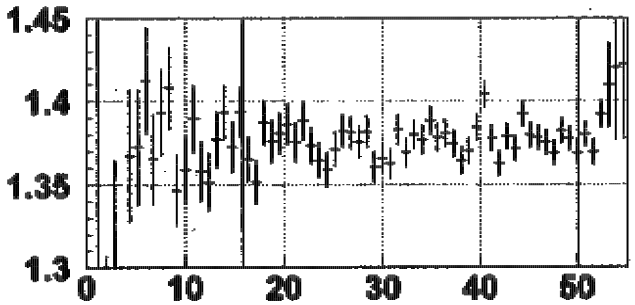
Events in Cloud data set 10832352

03-12- 3:12:45 ;BELLE GROUP scan for file ;+81-298-64-5340 # 49/ 52

Atmospheric Pressure and Muon Stopping Location

High Density vs. Low

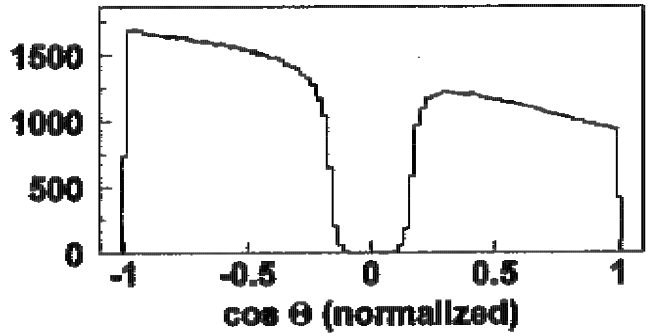


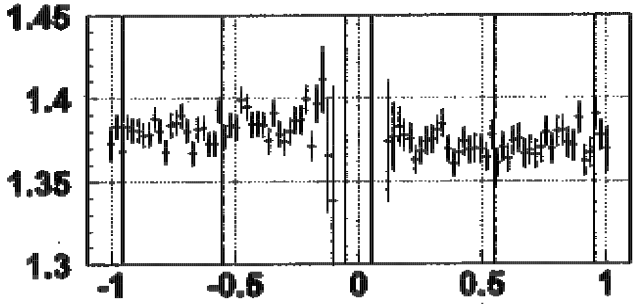


Events in Low data set 2324119

Events in High Density data set 3200343

High Density vs. Low





Events in Low data set 4401366

Events in High Density data set 6064934

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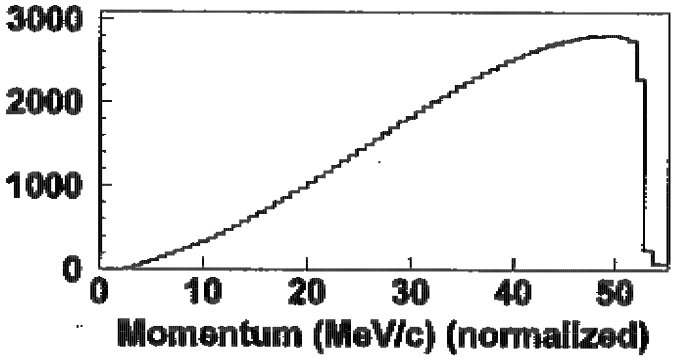
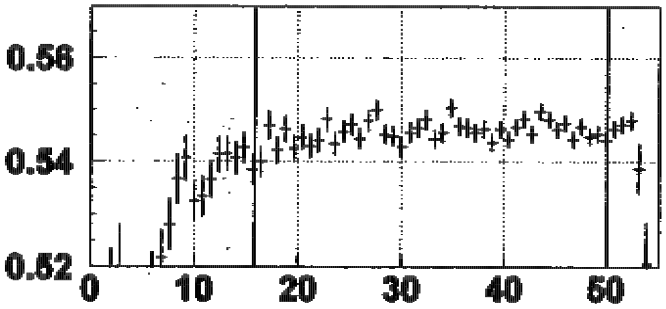
Additional Material Downstream of the Detector

DnStr Al vs. Standard A

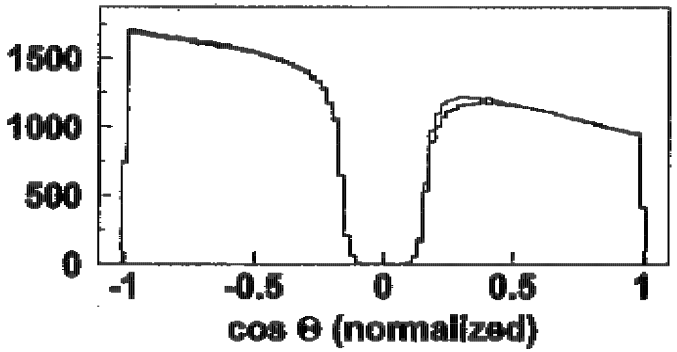


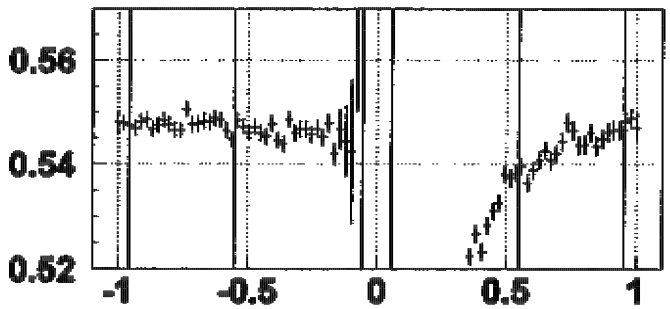


Events in Standard A data set 16112307

Events in DnStr Al data set 8779997

DnStr Al vs. Standard A

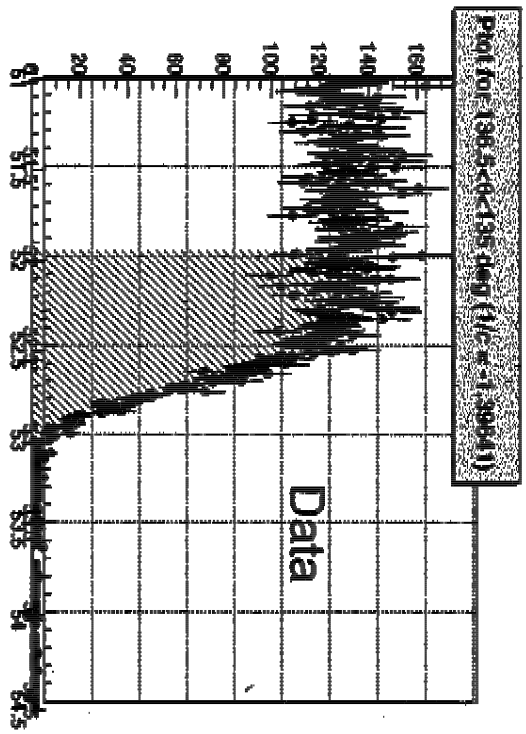


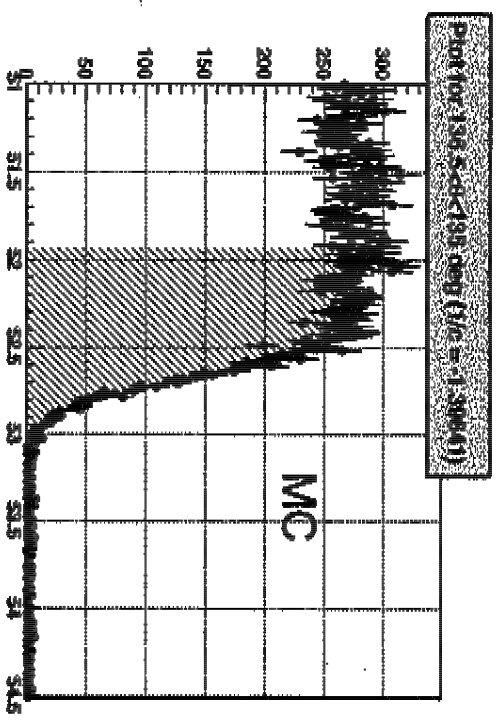


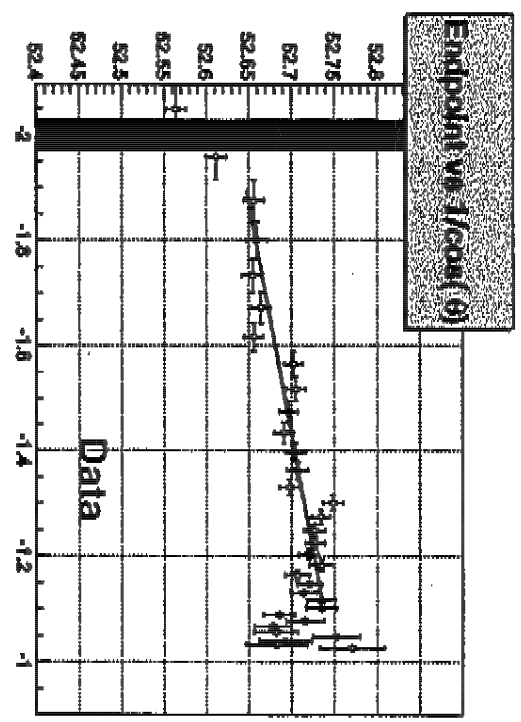
Events in Standard A data set 30534801

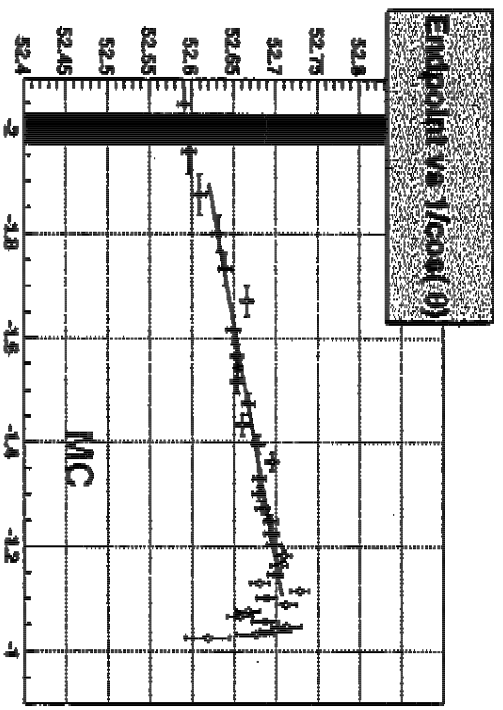
Events in DnStr Al data set 16499435

Endpoint Fits for Momentum Calibration Check









03-12- 3:12:45 ;BELLE GROUP scan for file ;+81-298-64-5340 # 52/ 52

Conclusions

- TWIST is the first experiment ever to measure the full muon decay energy-angle spectrum simultaneously.

- The ultimate goal of TWIST is to improve our knowledge of ρ, δ, and $P_\mu \xi$ by over an order of magnitude in each case. We may also improve our knowledge of η. This will give us model-independent sensitivity to right-handed vector bosons with masses up to 800 GeV in left-right symmetric theories, plus sensitivity to right-handed muon coupling through scalar or tensor interactions.

- The data in hand should provide measurements of ρ and δ to ~10^{-3}.

- We hope to have the existing data analyzed by the end of this year.