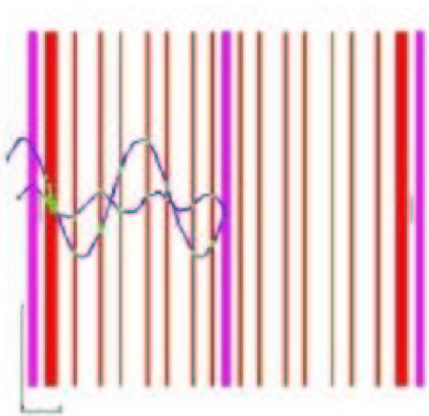
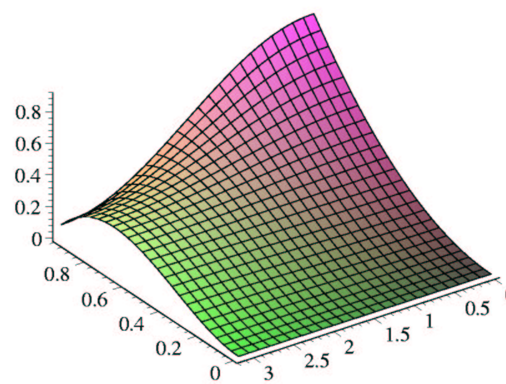
FIRST DATA FROM THE *TWIST* EXPERIMENT

G.M. Marshall, TRIUMF
for the *TWIST* Collaboration

CAP Congress, Charlottetown, 2003





Outline

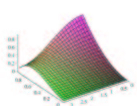
First Data from the *TWIST* Experiment

- Introduction
- Muon decay
  - ▷ Standard model interaction, couplings, parameters, rates and distributions.
  - ▷ Current experimental measurements and predictions for model extensions.
- The *TWIST* spectrometer
  - ▷ The muon beam.
  - ▷ The detector system.
- Status of the experiment
  - ▷ Summary of the first physics run, fall 2002.
  - ▷ Tests of systematic uncertainties
  - ▷ Verification of simulation precision
- Summary

Introduction

TWIST:

- is the *T*RIUMF *W*eak *I*nteraction *S*ymmetry *T*est.
- is a precision measurement of the parameters describing the energy and angular distributions of positrons (e^+) from decay of polarized positive muons (μ^+).
- uses a high luminosity beam of highly polarized muons from pions decaying at rest.
- tracks the μ^+ until they stop in a thin planar target in a high (2 T) uniform solenoidal magnetic field.
- measures points on the tracks of e^+ emitted from the target with a symmetric stack of high precision, low mass, planar drift chambers.
- records this information for several thousand muon decays per second.
- reconstructs the paths of the e^+ to create distributions in momentum ($|\vec{p}|$) and decay direction ($\cos\theta$).
- monitors and controls many other variables which can affect the measurements in different ways.



Muon decay

Assume a completely general, local, derivative-free, lepton-number-conserving, four-fermion point interaction. Written in the charge-changing form, the matrix element is:

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

This includes scalar, vector, and tensor $(\Gamma^S, \Gamma^V, \Gamma^T)$ interactions among charged lepton spinors of definite chirality ($\varepsilon, \mu = R$ or L).

There are 10 complex amplitudes $g^{\gamma}_{\varepsilon\mu}$ (g^T_{LL} and g^T_{RR} are zero), resulting in 19 independent real parameters. In the Standard Model, $g^V_{LL} = 1$ and all others are zero $(V - A)$.

Constraints on the values of the coupling constants are derived from observables.

$\Rightarrow$ *The goal of TWIST is to search for new physics* by improving the measurement of some of those observables (the Michel parameters describing the electron spectrum in muon decay) by up to an order of magnitude.

[See W. Fetscher and H.-J. Gerber, in "Review of Particle Physics", K. Hagiwara *et al.*, Phys. Rev. D 66 (2002) 010001-352–010001-354, and in "Precision Tests of the Standard Electroweak Model", ed. P. Langacker, World Scientific, Singapore (1995) 657–705.]

Differential decay rate and the Michel parameters

Neglecting neutrino masses and (for the moment) radiative corrections, averaging over the polarization of the decay e^+, the differential decay rate is:

$$\frac{d^2\Gamma}{dx\ d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2}\ \{\mathcal{F}_{IS}(x) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x)\}$$

where

$$W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$$

$$x = \frac{E_e}{W_{\mu e}}$$

$$x_0 = \frac{m_e}{W_{\mu e}}$$

$$\mathcal{P}_\mu = |\vec{\mathcal{P}}_\mu|$$

$$\cos\theta = \frac{\vec{\mathcal{P}}_\mu \bullet \vec{p}_e}{|\vec{\mathcal{P}}_\mu|\,|\vec{p}_e|} \sim -\cos\theta_T$$

$$\mathcal{F}_{IS}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

$$\mathcal{F}_{AS}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right]$$

Separate the purely $V-A$ contribution from terms depending explicitly on the Michel parameters ρ, η, δ, and ξ:

$$\mathcal{F}_\nu(x) \quad = \quad \mathcal{F}_\nu^{V-A}(x) + \mathcal{G}_\nu(x), \qquad \nu \in \{IS, AS\}$$

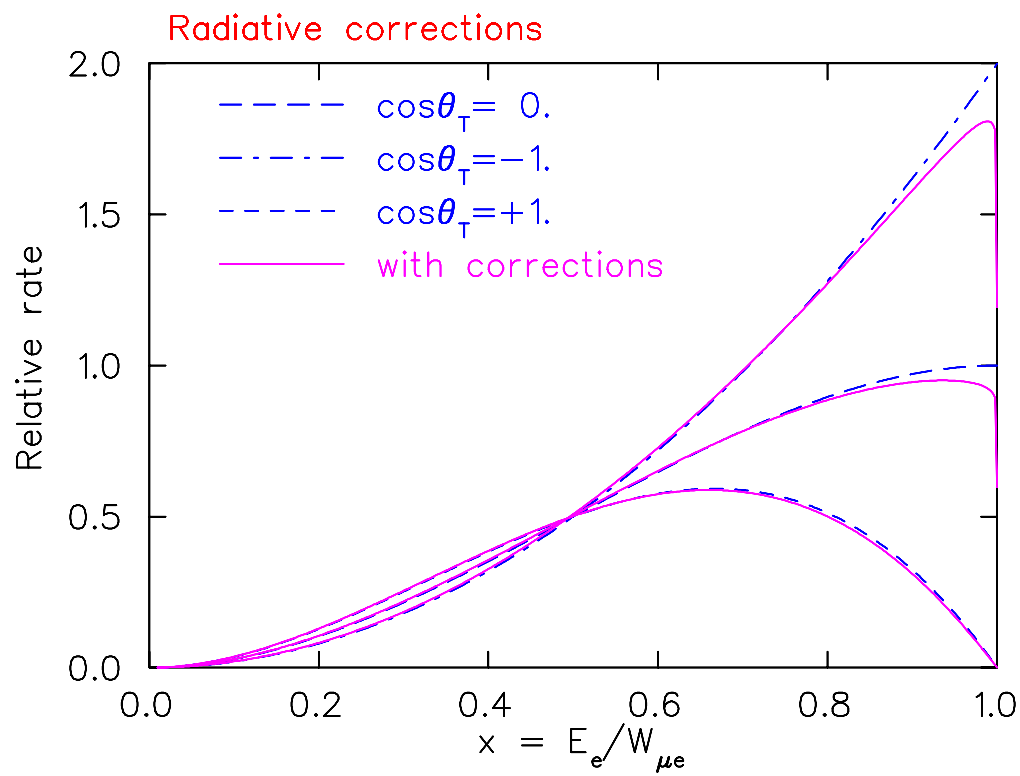
Then:

$$\begin{aligned}
\mathcal{F}_{IS}^{V-A}(x) &= \frac{1}{6}\left\{-2x^2 + 3x - x_0^2\right\} \\
\mathcal{F}_{AS}^{V-A}(x) &= \frac{1}{6}\sqrt{x^2 - x_0^2}\left\{2x - 2 + \sqrt{1 - x_0^2}\right\} \\
\mathcal{G}_{IS}(x) &= \frac{1}{9}\left\{2\left(\rho - \frac{3}{4}\right)\left(4x^2 - 3x - x_0^2\right) + 9\eta\,(1-x)\,x_0\right\} \\
\mathcal{G}_{AS}(x) &= \frac{1}{9}\sqrt{x^2 - x_0^2} \\
&\quad \times \left\{3\,(\xi - 1)\,(1-x) + 2\left(\xi\delta - \frac{3}{4}\right)\left(4x - 4 + \sqrt{1 - x_0^2}\right)\right\}
\end{aligned}$$

For a purely $V-A$ interaction, $\rho = \frac{3}{4}$, $\eta = 0$, $\delta = \frac{3}{4}$, $\xi = 1$, and $\mathcal{G}_\nu(x) = 0$.

Radiative corrections

Lowest order radiative corrections ($\mu \to e\nu\nu\gamma$ and diagrams with one virtual photon loop) have been calculated by many authors ($e.g.$, Kinoshita and Sirlin 1957, 1959, Berman 1959, Källén 1970, Sheck 1982). $\mathcal{TWIST}$ requires higher order estimates which have been undertaken by A. Czarnecki *et al.* in Alberta.



Effect of radiative corrections for different decay angles ($\theta_T \sim \pi - \theta$ is the decay angle in the $\mathcal{TWIST}$ spectrometer).

Current best measurements

From the Review of Particle Physics *(SM values in parentheses)*:

$$\rho = 0.7518 \pm 0.0026 \text{ (Derenzo, 1969)} \quad (0.75)$$

$$\eta = -0.007 \pm 0.013 \text{ (Burkard } et\ al.\text{, 1985)} \quad (0.00)$$

$$\delta = 0.7486 \pm 0.0026 \pm 0.0028 \text{ (Balke } et\ al.\text{, 1988)} \quad (0.75)$$

$$\mathcal{P}_\mu \xi = 1.0027 \pm 0.0079 \pm 0.0030 \text{ (Beltrami } et\ al.\text{, 1987)} \quad (1.00)$$

$$\mathcal{P}_\mu \frac{\xi\delta}{\rho} > 0.99682 \text{ (Jodidio } et\ al.\text{, 1986)} \quad (1.00)$$

The goal of $\mathcal{TWIST}$ is to find any new physics which may become apparent by improving the precision of each of ρ, δ, and $\mathcal{P}_\mu\xi$ by at least one order of magnitude.

Probabilities of left and right in muon decay

Fetscher *et al*. introduced probabilities $Q_{\varepsilon\mu}$ for a μ -handed muon to decay into an ε -handed electron:

$$
\begin{aligned}
Q_{\varepsilon\mu} &= \frac{1}{4}\left|g^S_{\varepsilon\mu}\right|^2 + \left|g^V_{\varepsilon\mu}\right|^2 + 3(1-\delta_{\varepsilon\mu})\left|g^T_{\varepsilon\mu}\right|^2, \\
\delta_{\varepsilon\mu} &= 1(\varepsilon=\mu) \text{ or } 0(\varepsilon\neq\mu) \\
\sum_{\varepsilon,\mu} Q_{\varepsilon\mu} &= 1, \qquad 0 \le Q_{\varepsilon\mu} \le 1
\end{aligned}
$$

In the Standard Model, $Q_{LL} = 1$ and all others are zero $(V-A)$.

The right-handed content of the muon can be expressed as:

$$
\begin{aligned}
Q^\mu_R &= Q_{RR} + Q_{LR} \\
&= \frac{1}{4}\left\{\left|g^S_{RR}\right|^2 + \left|g^S_{LR}\right|^2\right\} + \left|g^V_{RR}\right|^2 + \left|g^V_{LR}\right|^2 + 3\left|g^T_{LR}\right|^2 \\
&= \frac{1}{2}\left\{1 + \frac{1}{9}\left(3\xi - 16\xi\delta\right)\right\}
\end{aligned}
$$

In other words, measurements of ξ and δ measure the muon's *chirality*.

Left-right symmetric models

Without assuming any specific model:

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

In the absence of a tensor interaction, this restricts g^V_{LR} and g^V_{RL}.

A left-right symmetric (LRS) model incorporates a heavier boson W' with mostly right-handed couplings, mixed with W via mixing angle ζ.
For example, with only vector couplings $g^V_{LR} \sim g^V_{RL}$:

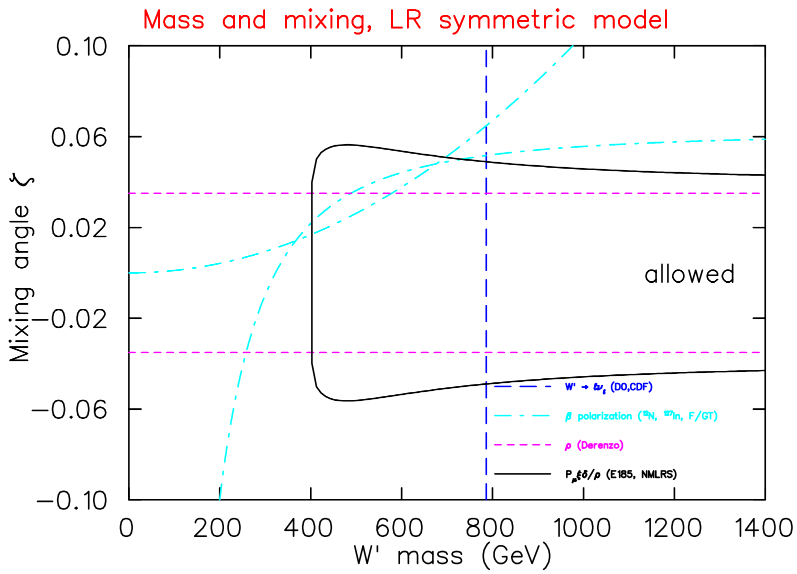
$$\rho = \frac{3}{4}\left(1 - 2\left|g^V_{LR}\right|^2\right) = \frac{3}{4}\left(1 - 2\zeta^2\right) \qquad \eta = 0, \quad \delta = \frac{3}{4}$$

$$\xi = 1 - 2\left|g^V_{RR}\right|^2 - 2\left|g^V_{LR}\right|^2 = 1 - 2(\epsilon^2 + \zeta^2) \qquad \mathcal{P}_\mu = 1 - 2\left(\epsilon\frac{V^{ud}_R}{V^{ud}_L} + \zeta\right)^2$$

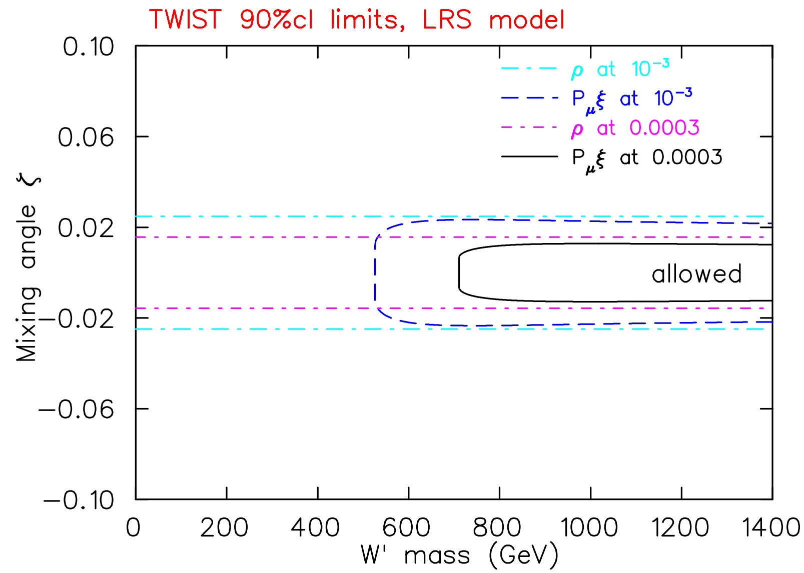
where $\epsilon = (M/M')^2 \sim g^V_{RR}$ and $\zeta \sim g^V_{LR} = g^V_{RL}$ are small parameters, and $V^{ud}_{L,R}$ are left- and right-handed (u,d) CKM matrix elements.

Manifest LR symmetry assumes $V^{ud}_R = V^{ud}_L$, which is assumed in some β polarization and high energy tests.

Left-right symmetric model results and *TWIST*



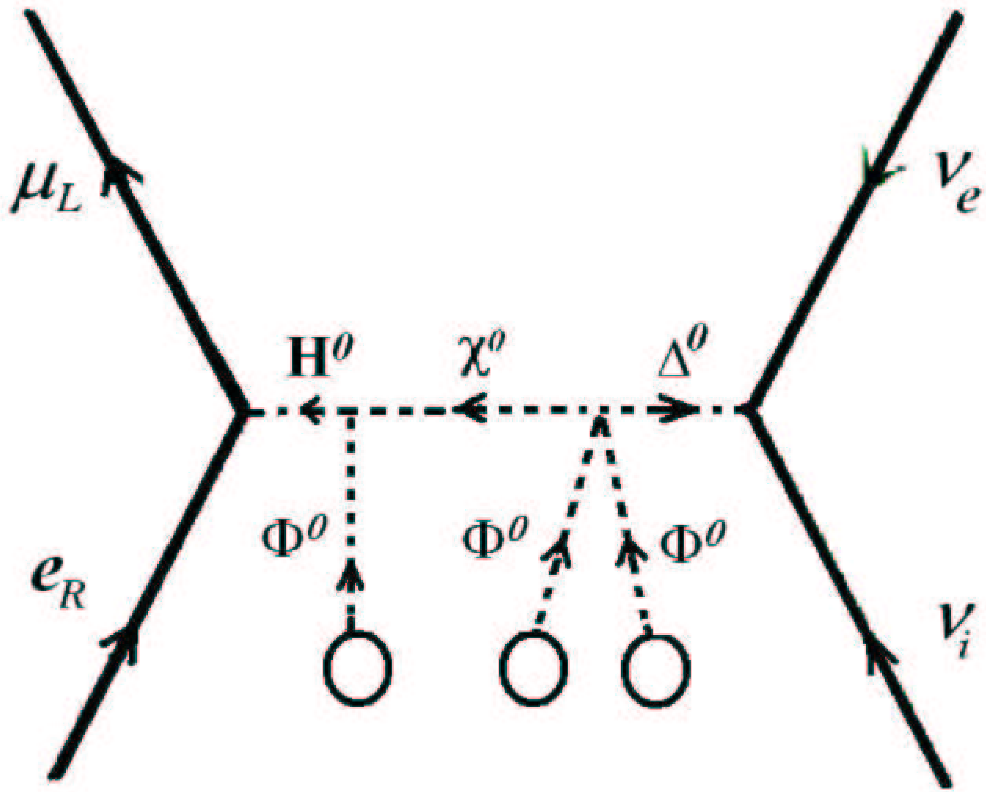
Limits on left-right symmetric model parameters from previous measurements.



Anticipated limits on left-right symmetric model parameters from *TWIST*.

Tests of other Standard Model extensions

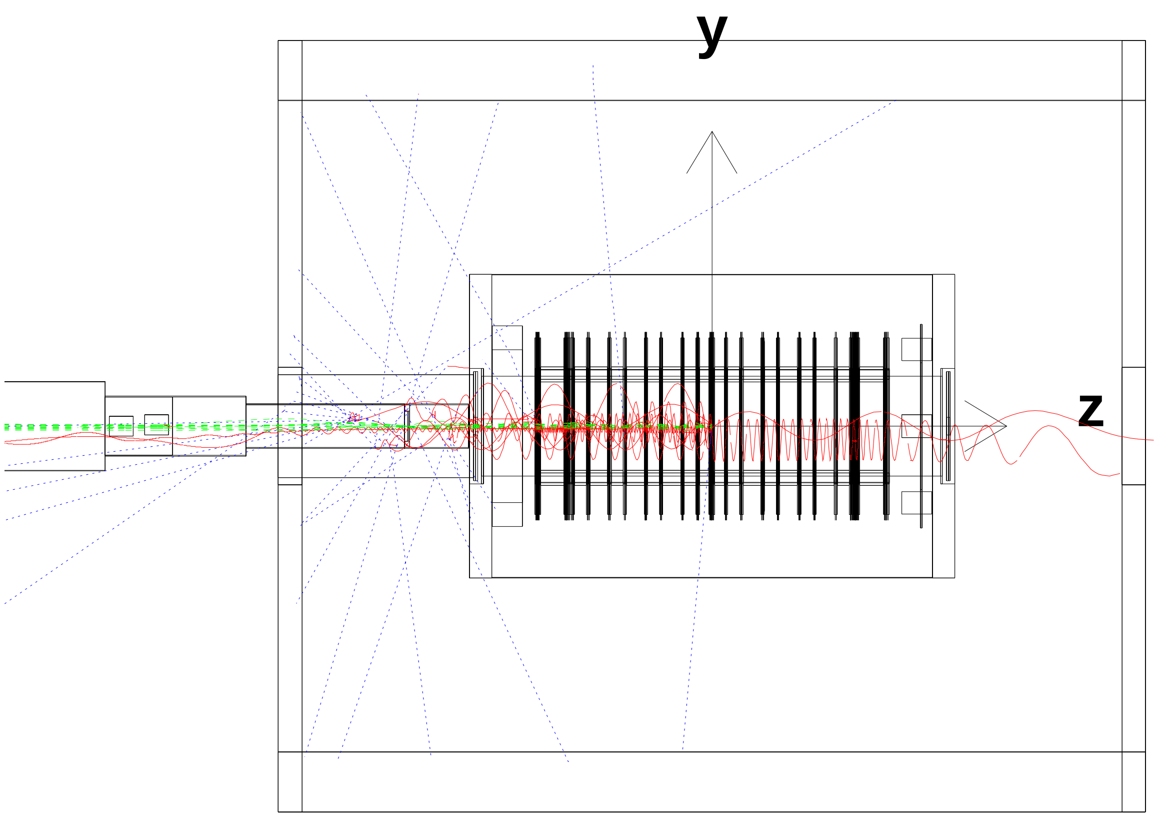
- Babu and Pakvasa (hep-ph/0204236, April 2002) speculate the existence of a mechanism at a mass scale of ~ 500 GeV, which accommodates the LSND result and also predicts $\rho = 0.7485$.



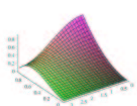
Scalar exchange inducing lepton number violating decay $\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_i$.

The *TWIST* spectrometer

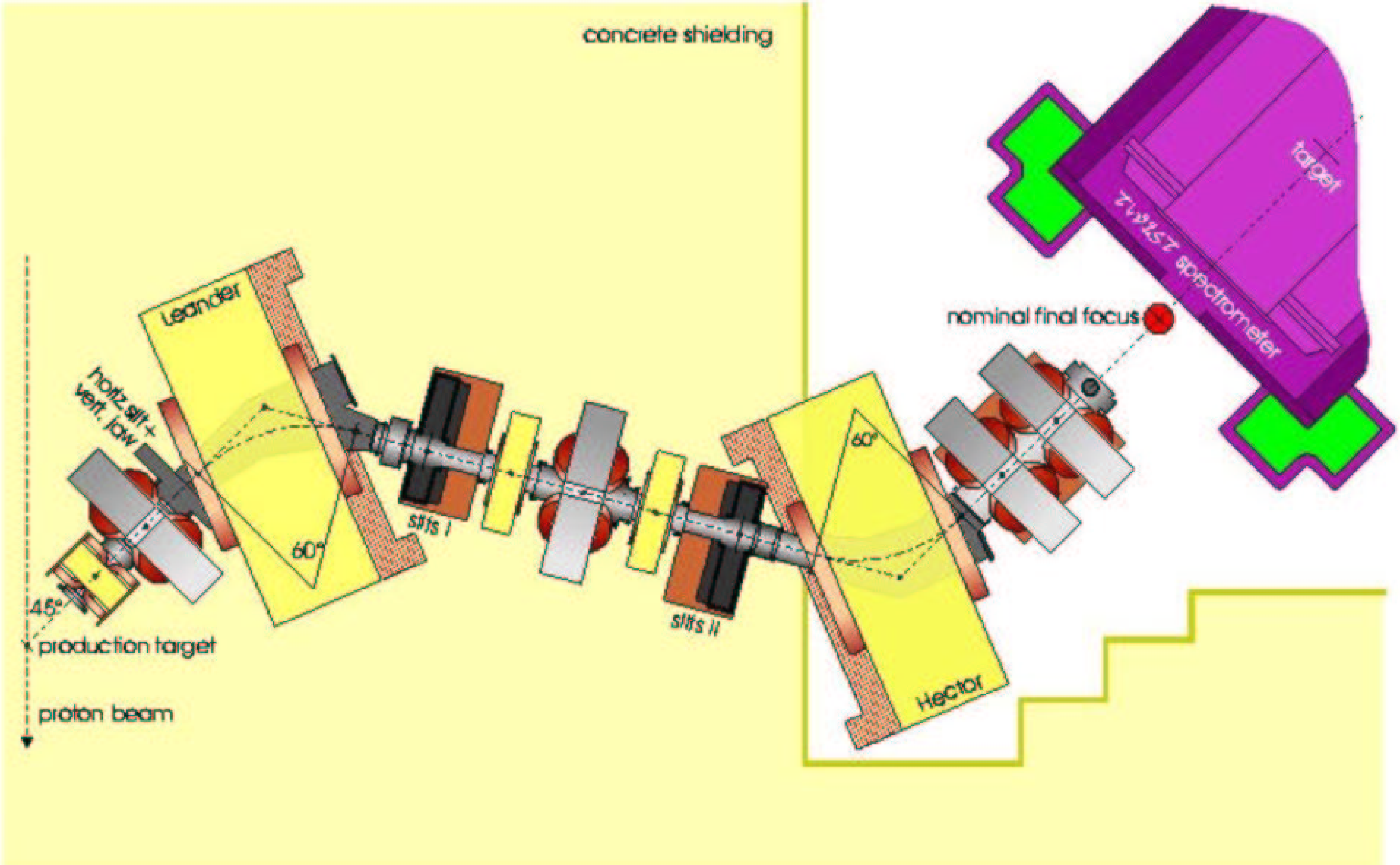
- Highly polarized surface muons (or low polarization cloud muons).
- 2 T longitudinal field for momentum analysis and muon polarization retention.
- Precision planar drift chamber system tracks decay positrons.

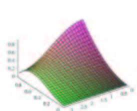


Simulation of 10 events in the *TWIST* spectrometer.

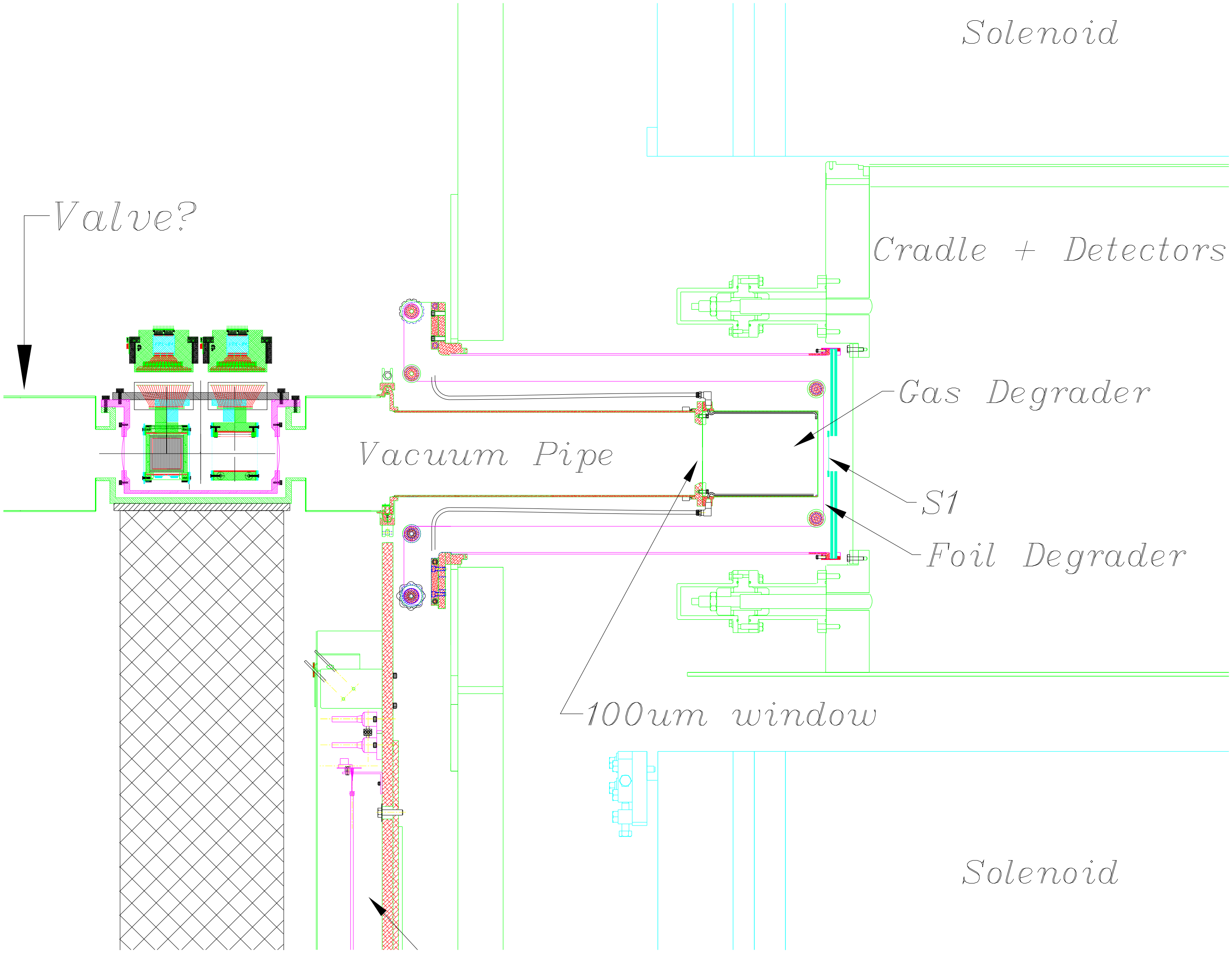


The M13 muon beam

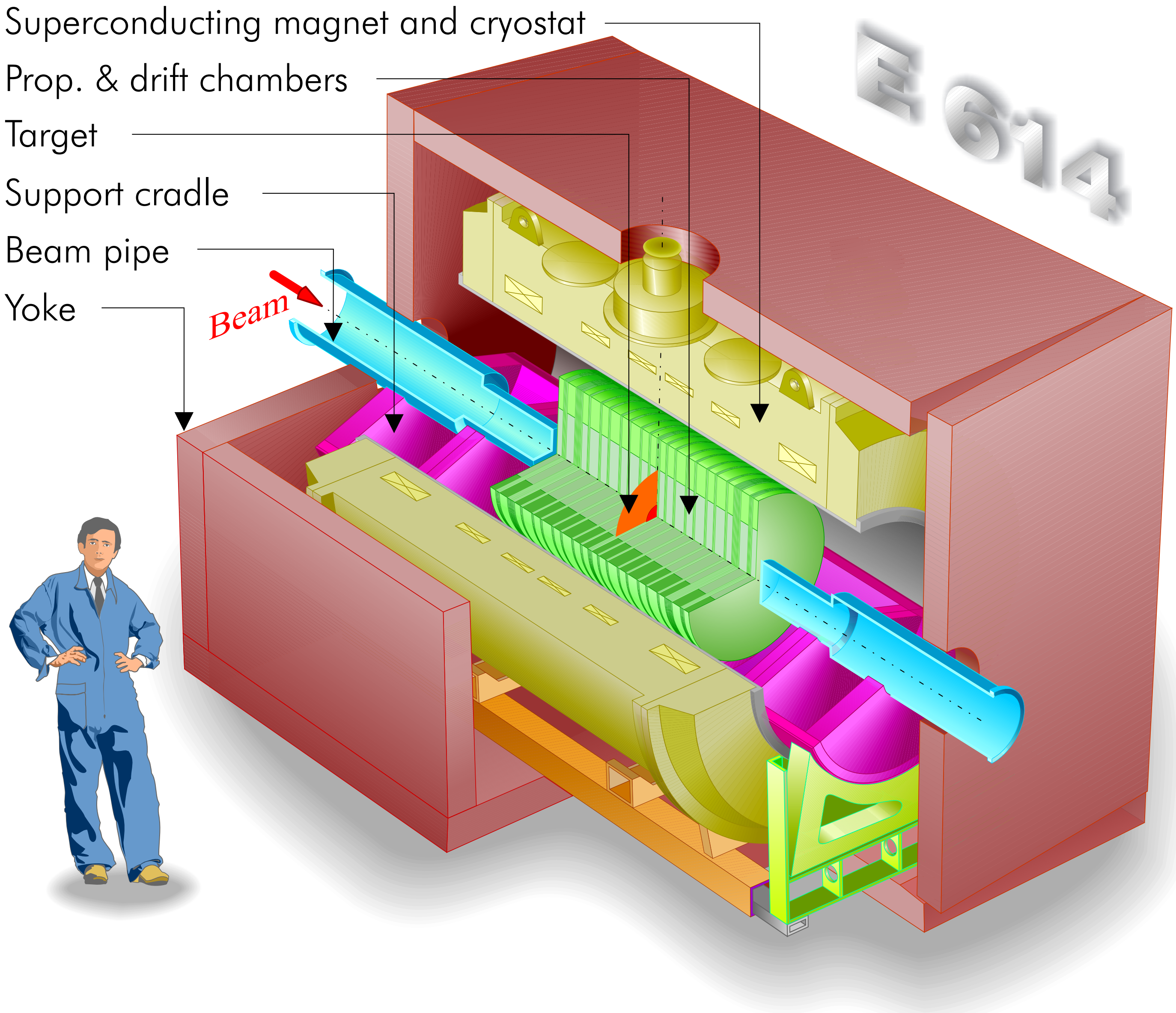




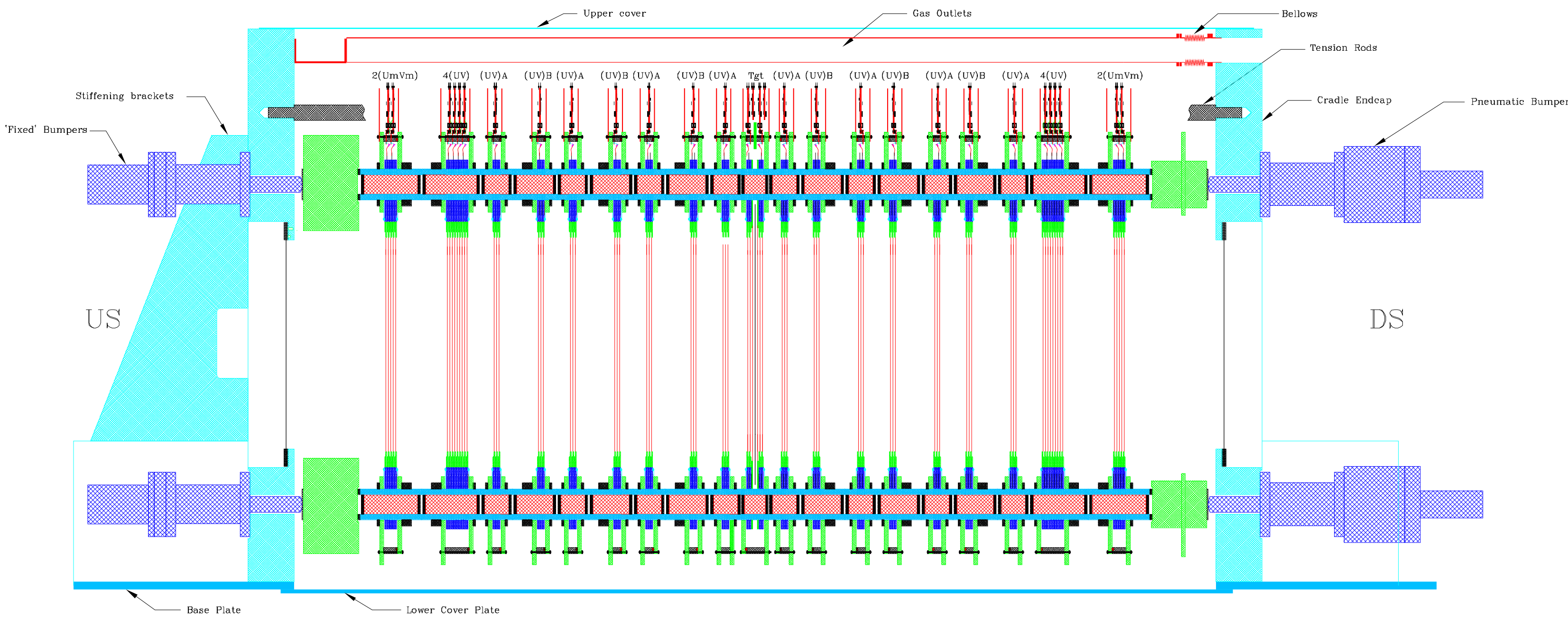
Time Expansion Chamber (TEC) and beam entrance region



The TEC is designed to measure the muon beam properties.


Superconducting magnet and cryostat
Prop. & drift chambers
Target
Support cradle
Beam pipe
Yoke
Beam
E 614

The *TWIST* detector stack



- Muon momentum near 29.97 MeV/c is selected by beam.
- Gas degrader of variable density (He/CO_2) controls stopping position for a given momentum.
- Trigger is a scintillator (250 μm, 6 cm ϕ) in narrow air gap at entrance of detector stack.
- Muons are ranged to stop in target after passing through half of the detector stack.
- Time of decay determined by PCs at each end of stack and surrounding target (12 total).
- DCs measure (u, v) coordinates of decay positron (22 on each side of target).

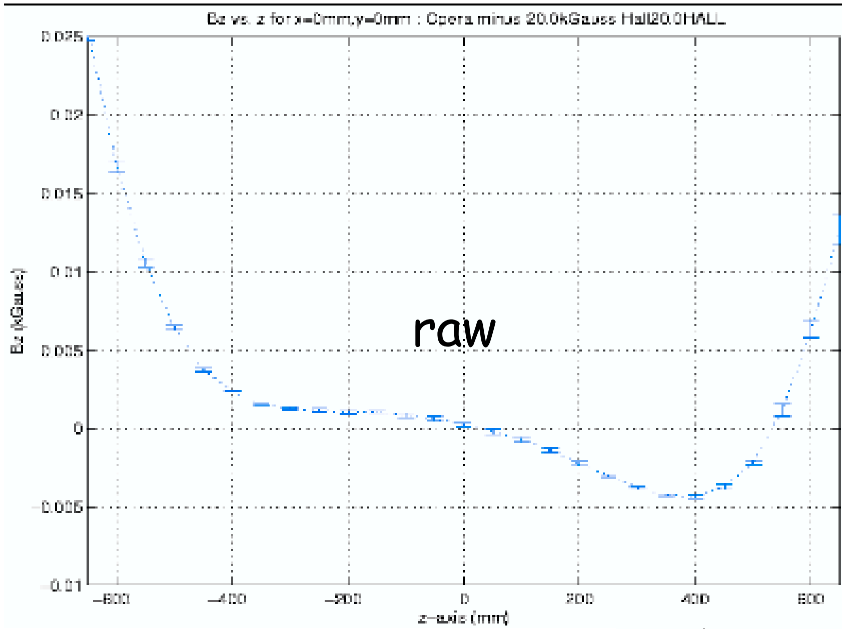
Status of the experiment

We have:

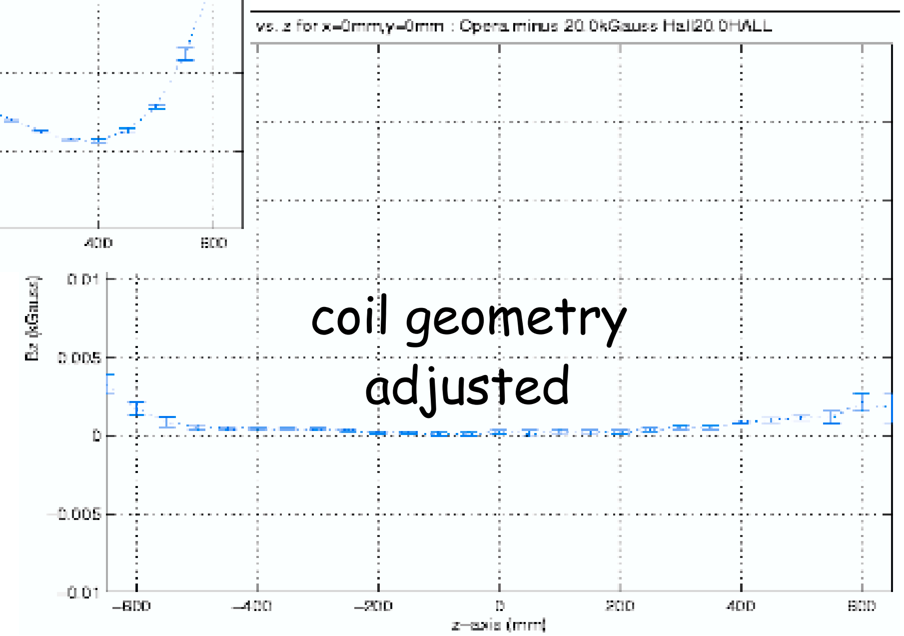
- mapped field of the tracking region, simulated small asymmetries using OPERA, and recovered from a solenoid quench.
- repaired successfully all of the (very few) hardware problems encountered.
- refined, debugged, streamlined, and documented the online data acquisition system, including precise slow monitoring of many variables.
- recorded 6×10^9 events in fall 2002, covering many possible systematic effects aimed at measuring ρ and δ with 10^{-3} precision, *with nearly faultless detector operation.*
- installed and utilized the *TWIST* analysis cluster.
- developed and verified the procedure for alignment of detector planes.
- improved substantially the analysis code, and begun its application to real data.
- extended the GEANT3 simulation, initiated the transition to GEANT4, and developed the strategy for verification.
- invented a method for blind analysis based on fitting experimental distributions to sums of a simulation plus parameter-dependent derivatives.

Magnetic field

Fitting to OPERA



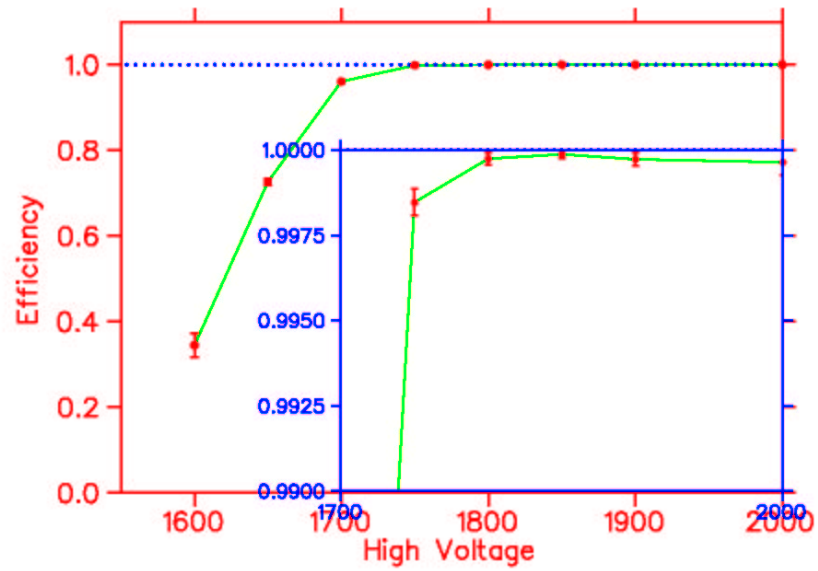
OPERA - map differences



Efficiency

Field On

- Data for decay positrons
  - DC Plane 13 (typical plane)
  - DC plane-to-plane variations < 5×10^{-4}
  - PC plane-to-plane variations < 1×10^{-3}
  - Similar results for field off and on.

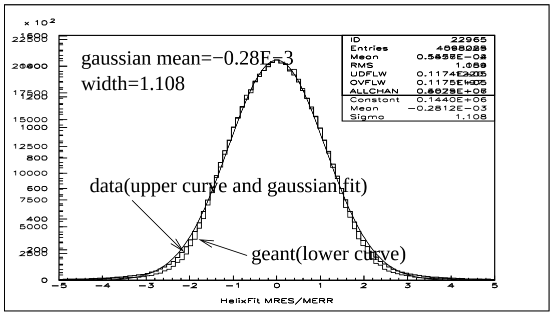


Resolution

Fit residuals and confidence levels

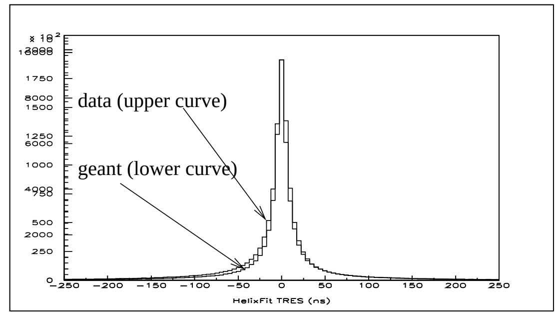
Geant3 simulation: flat momentum and cos(thetaz)
Data: surface muon run 11754
Cuts: decay e+ momentum: 25 to 50 MeV/c, cos(thetaz): 0.5 to 0.9

Wire−center fits

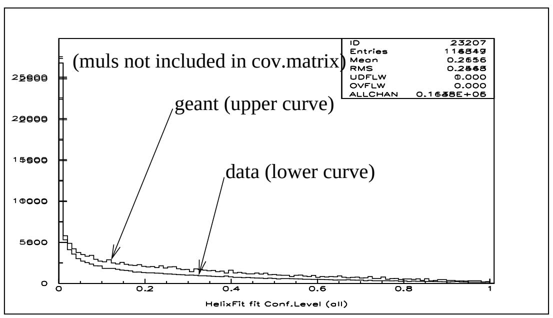


wire−centers fit weighted residuals, cm/cm

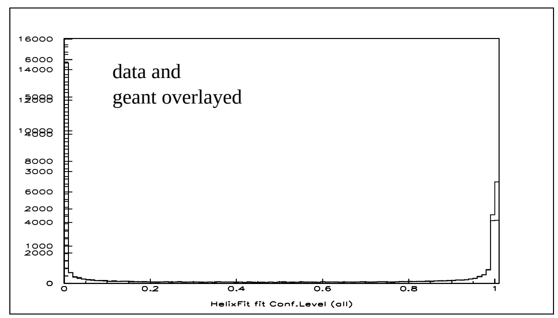
Drift time fits



drift time fit unweighted time residuals, ns



wire−center fit confidence levels



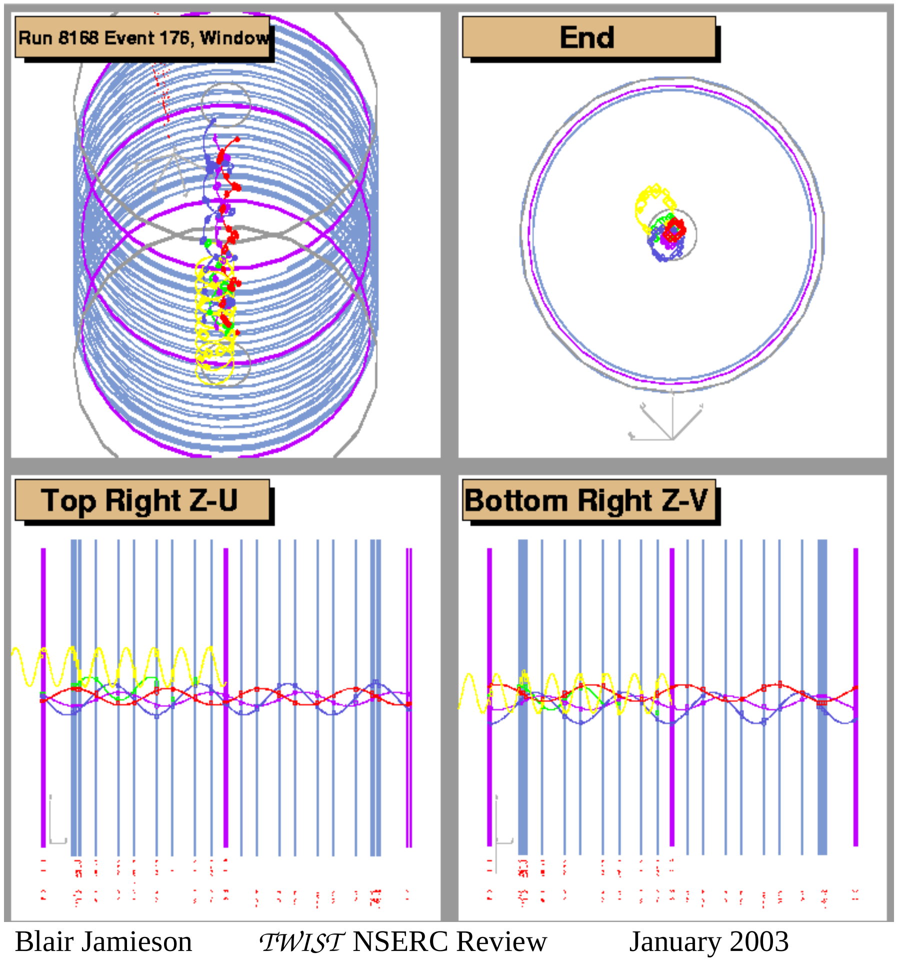
drift time fit confidence levels

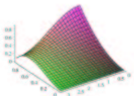
Tests of systematic uncertainties

We obtained many data sets under different conditions, with exaggerated variations, to test systematic effects for ρ and δ at 10^{-3}.
Each set has greater statistical precision.

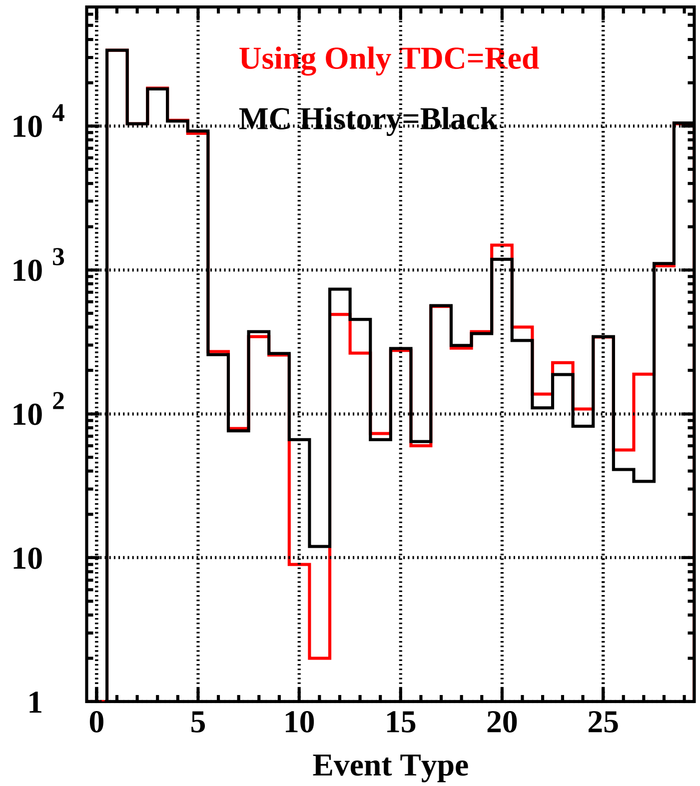
- Physics
  - ▷ Several data sets with standard or nominal conditions (time and environmental stability).
  - ▷ Cloud muons (low and opposite polarization).
- Beam and detector
  - ▷ Muon beam entry position into solenoidal field (beam stability).
  - ▷ DC voltages lowered (tracking efficiency).
  - ▷ PC voltages lowered (pattern recognition efficiency).
- Material asymmetries
  - ▷ Extra material at DS end of detector stack (backscattering tracks).
  - ▷ Muon mean stopping depth in stopping target (energy loss in target).
- Momentum scale
  - ▷ $+2\%$ and -2% from nominal 2 T setting (momentum calibration).
- Analysis
  - ▷ Beam and data rate changed, higher and lower by $\times 2$ (pattern identification).
- GEANT validations
  - ▷ Muon stopping distribution in low density region of detector (muon beam range straggling).
  - ▷ Beam and decay positrons traversing entire detector stack (momentum and angular resolution).

A not-so-typical event

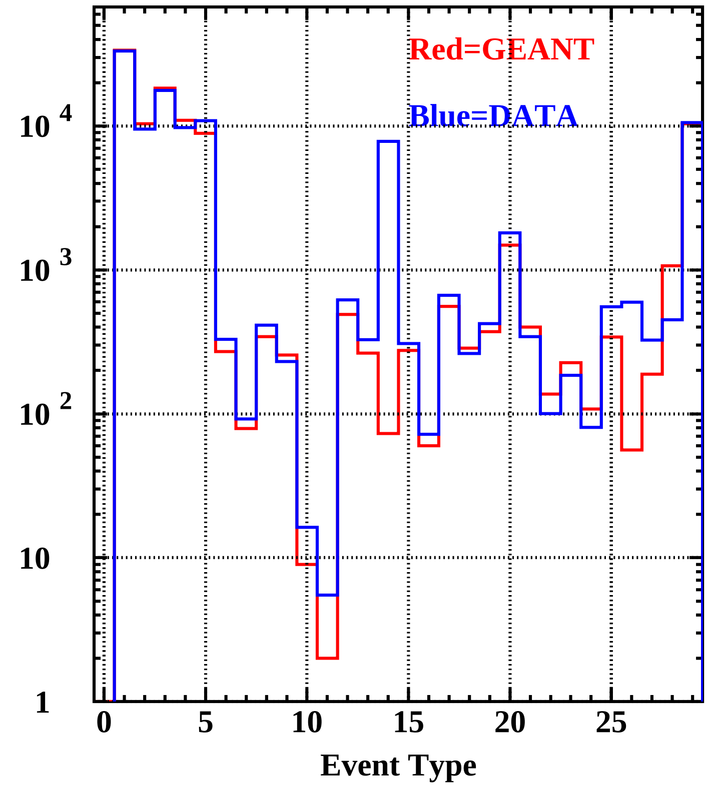




Analysis: tracking and event type recognition



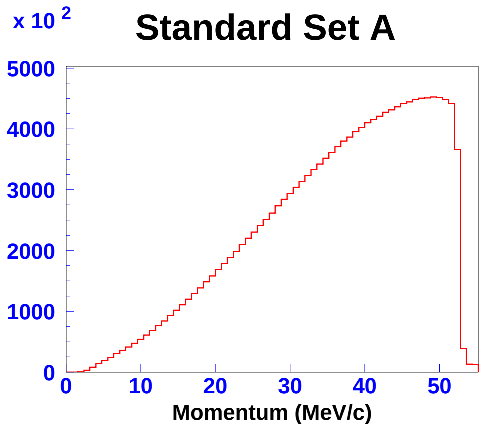
Comparison of event type recognition for simulation, using tracking *vs* using MC history information.



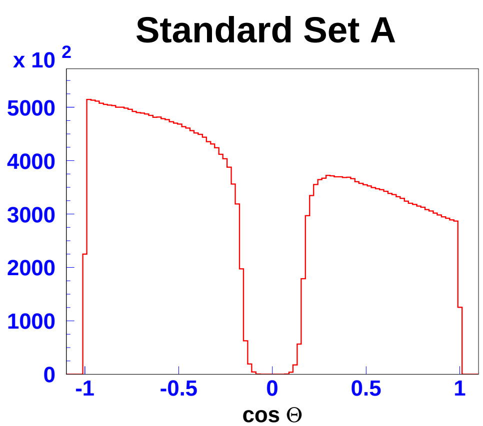
Comparison of event type recognition for simulation, using tracking *vs* tracked experimental data.

We identify 29 different event types according to muon tracks, decay positron tracks, and beam positron tracks. Some are very rare, many can be eliminated without bias.

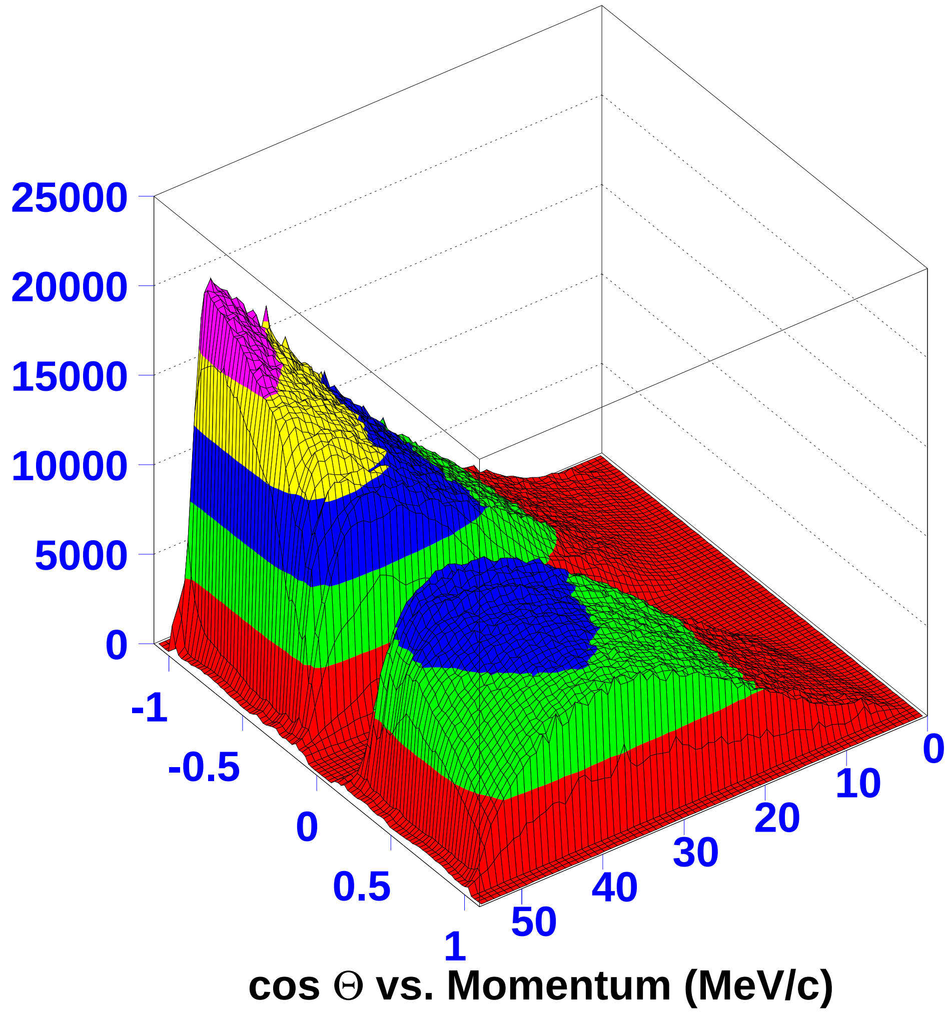
TWIST data distributions



Momentum distribution.

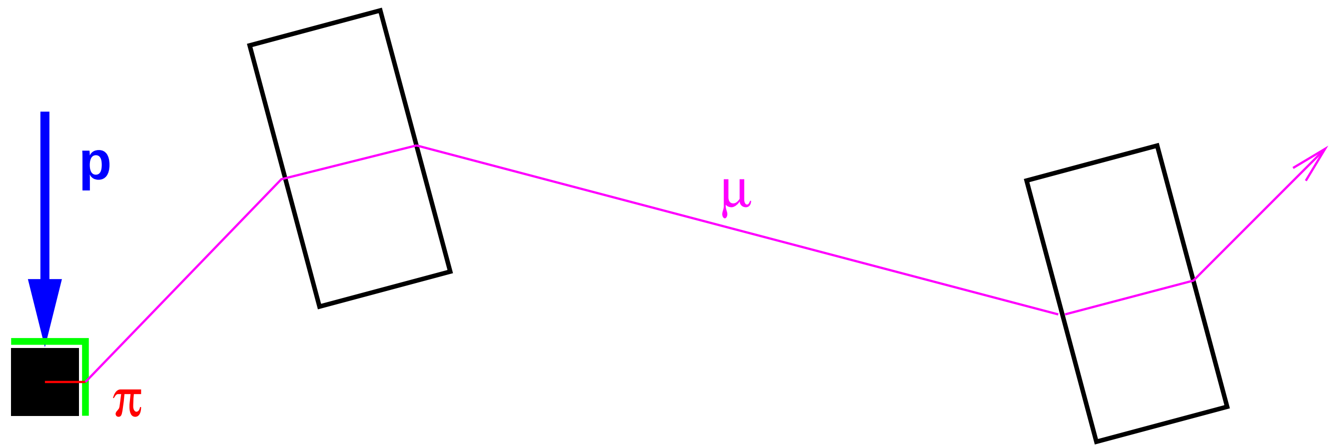


Angular distribution.

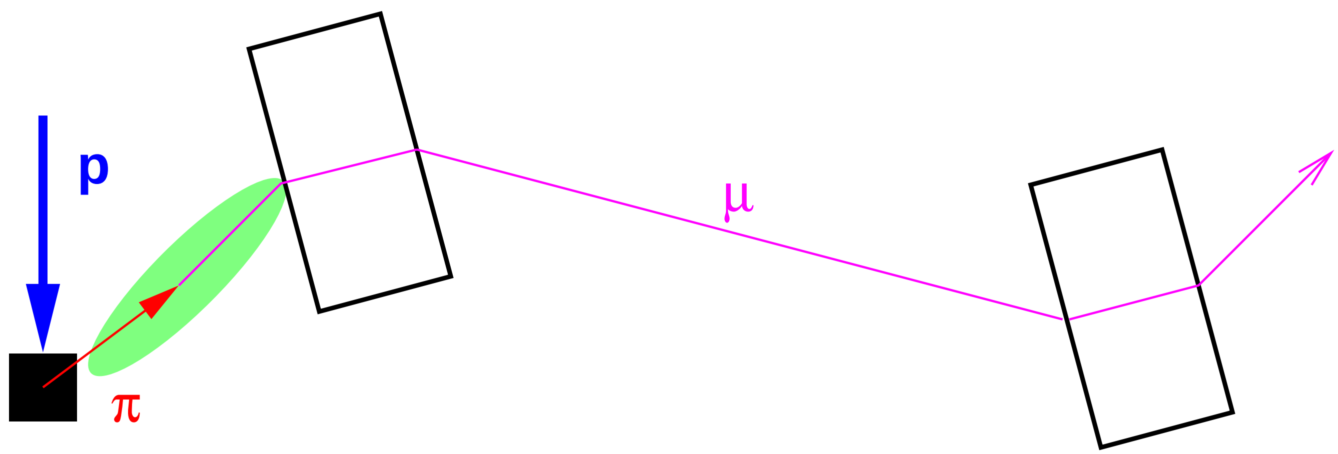


Two dimensional distribution from one data set.

Surface and cloud muons



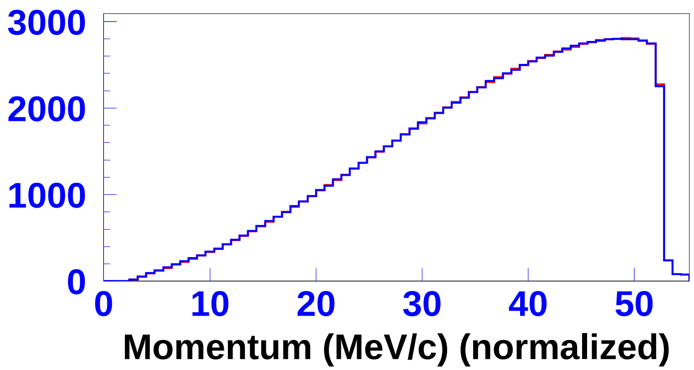
Surface muons from pions at rest in the surface of the primary production target.

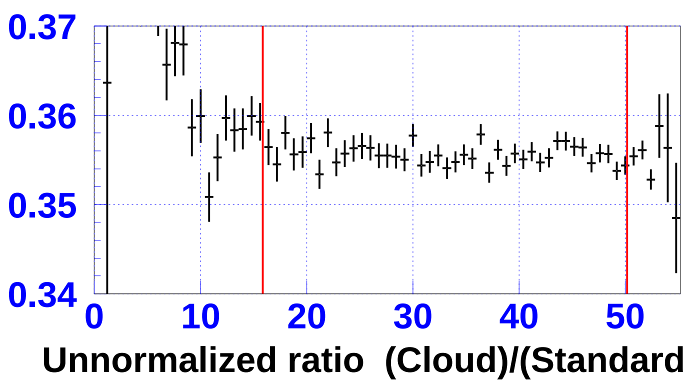


Cloud muons from pions decaying in flight before the first momentum analyzing magnet.

Polarization: surface *vs* cloud muons

Cloud vs. Standard A

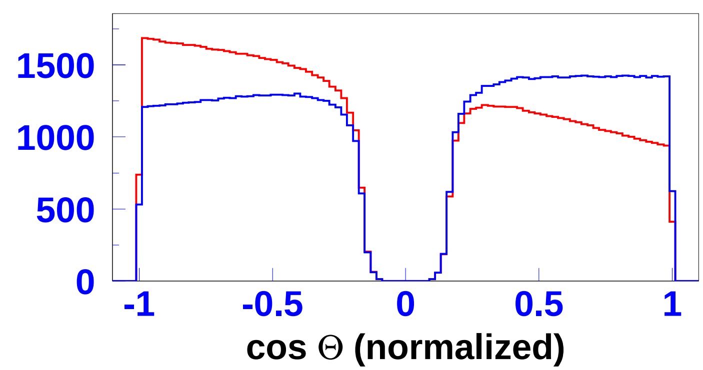


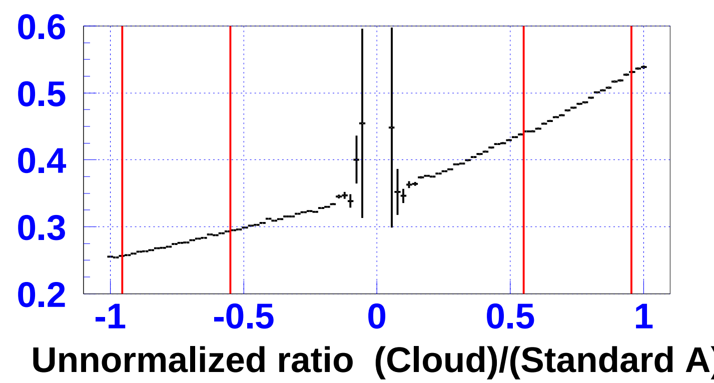


Events in Standard A data set 16112307

Events in Cloud data set 5730232

Cloud vs. Standard A



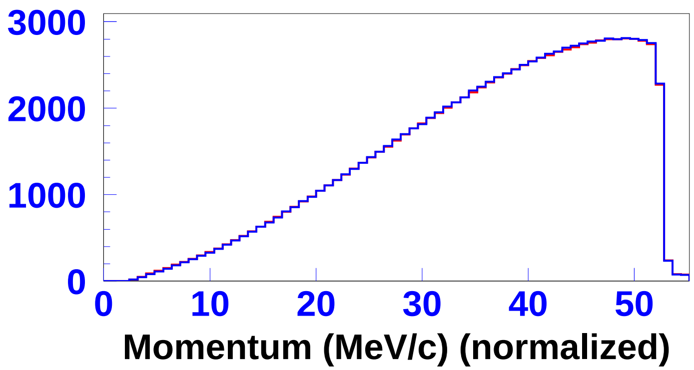


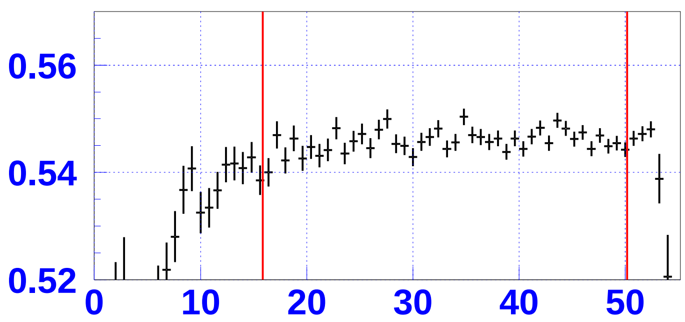
Events in Standard A data set 30534801

Events in Cloud data set 10832352

Detector material asymmetry test

DnStr Al vs. Standard A

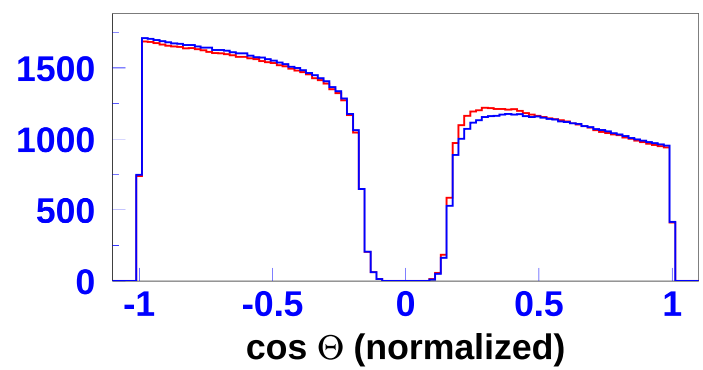


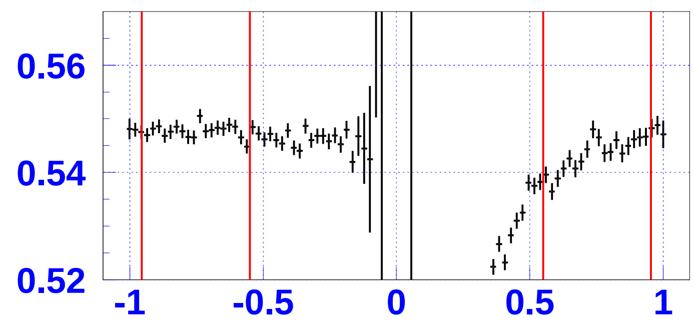


Events in Standard A data set 16112307

Events in DnStr Al data set 8779997

DnStr Al vs. Standard A





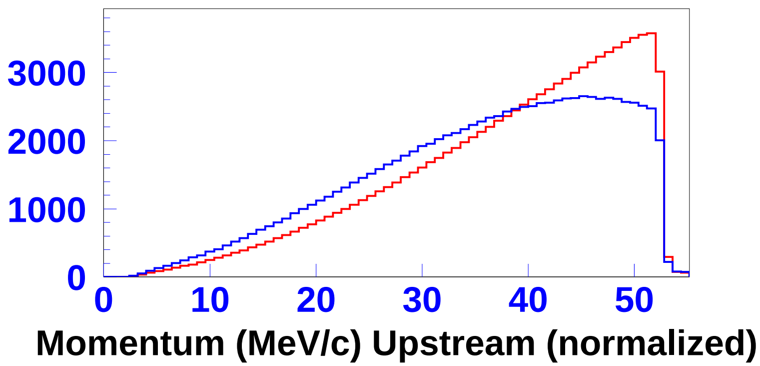
Events in Standard A data set 30534801

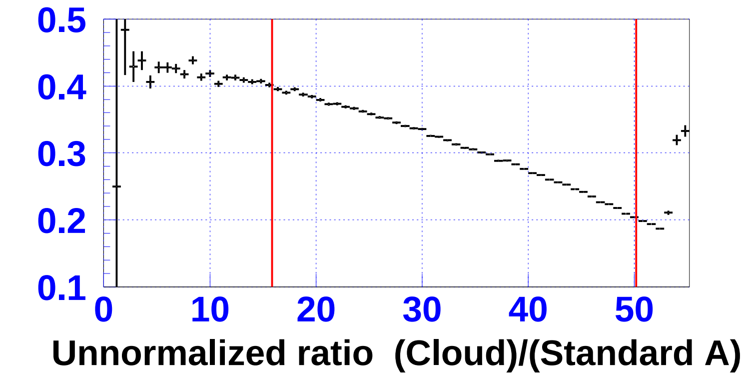
Events in DnStr Al data set 16499435

Additional aluminum plate added to downstream end. Shower increases multiple track events

Polarization: surface *vs* cloud muons

Cloud vs. Standard A

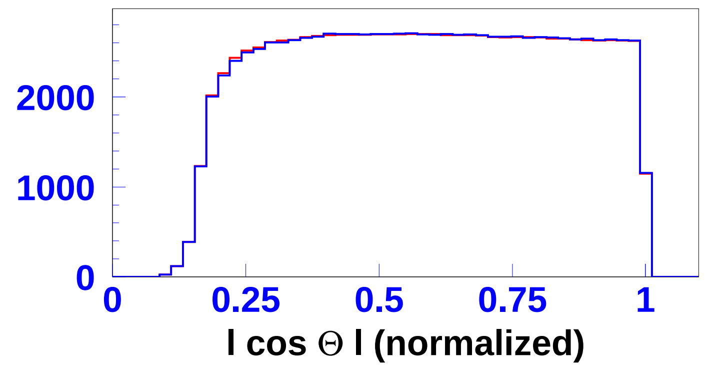


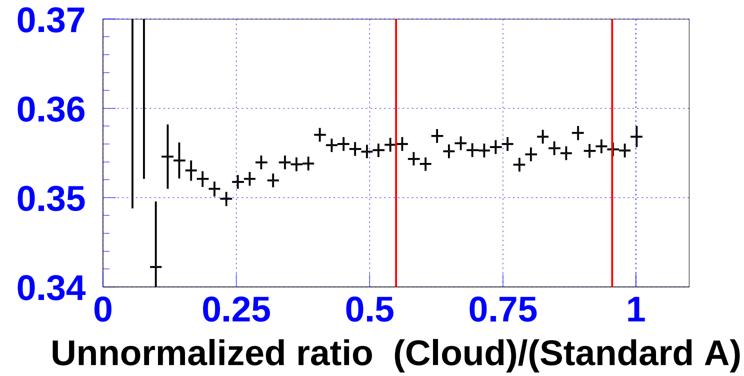


Events in Standard A data set 9579373

Events in Cloud data set 2686038

Cloud vs. Standard A

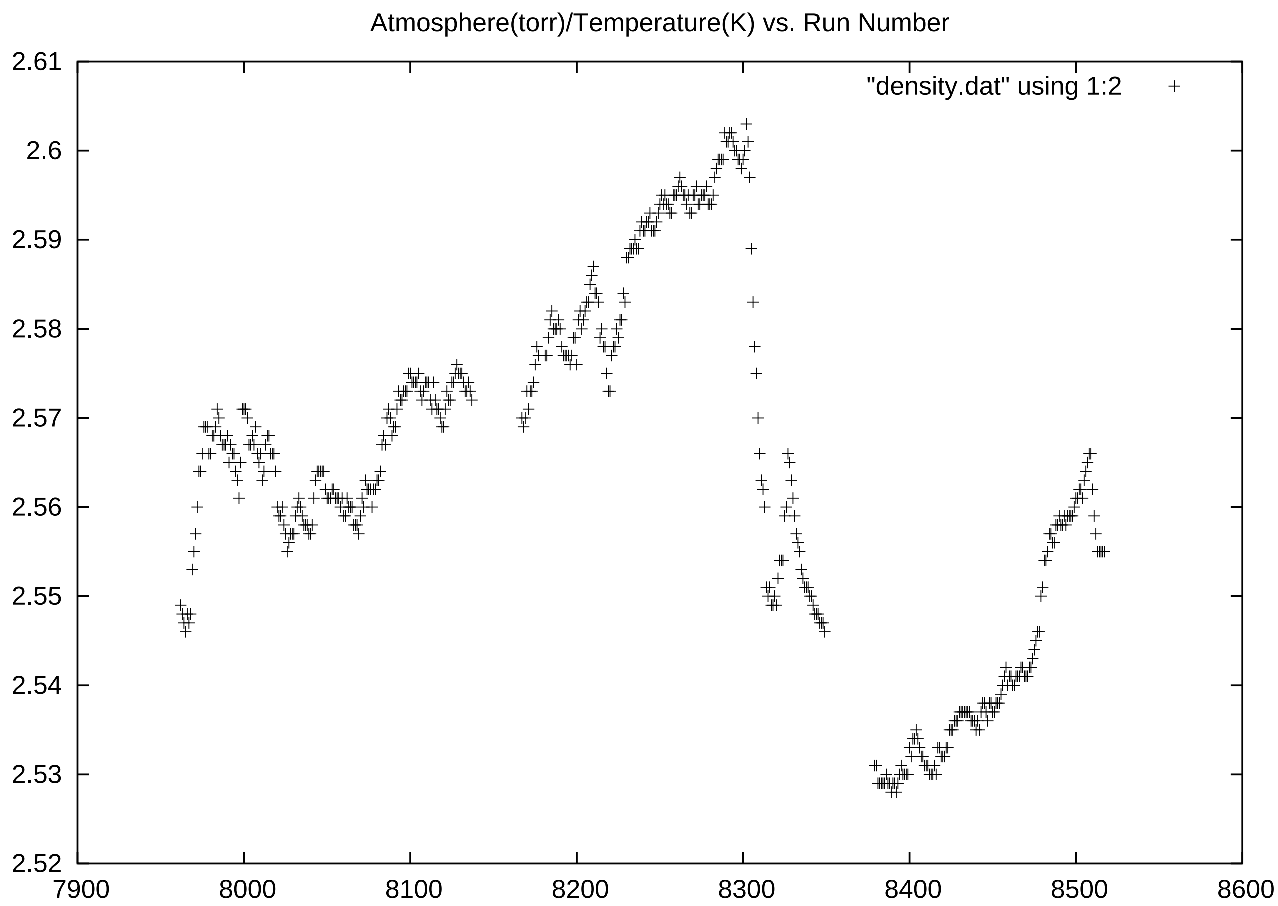




Events in Standard A data set 30534801

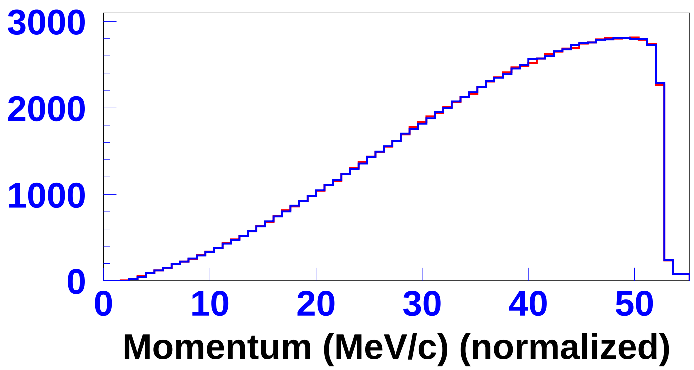
Events in Cloud data set 10832352

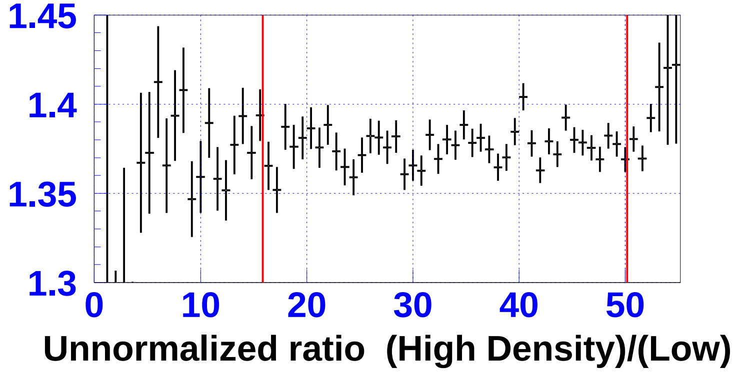
Density variation



Density variation: muon range, chamber characteristics

High Density vs. Low

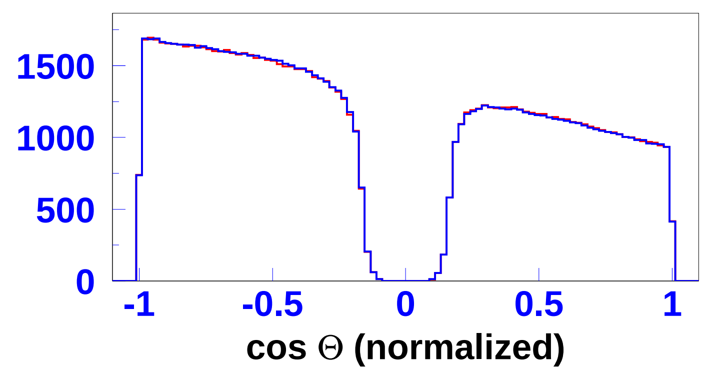


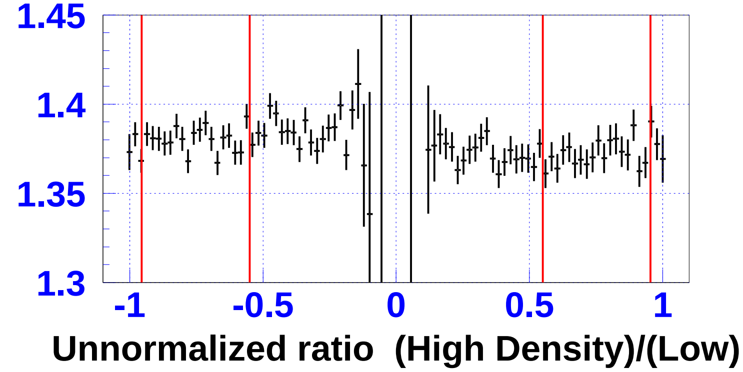


Events in Low data set 2324119

Events in High Density data set 3200343

High Density vs. Low



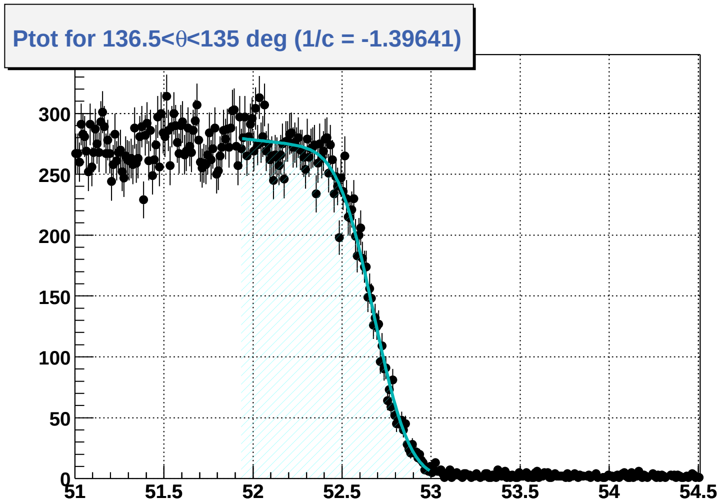


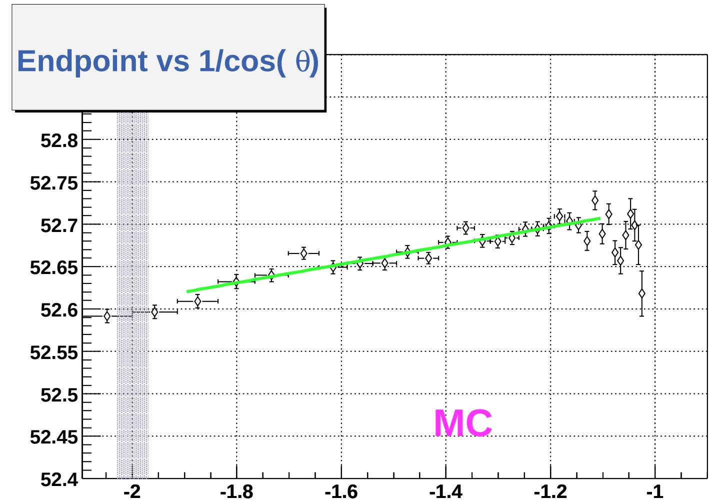
Events in Low data set 4401366

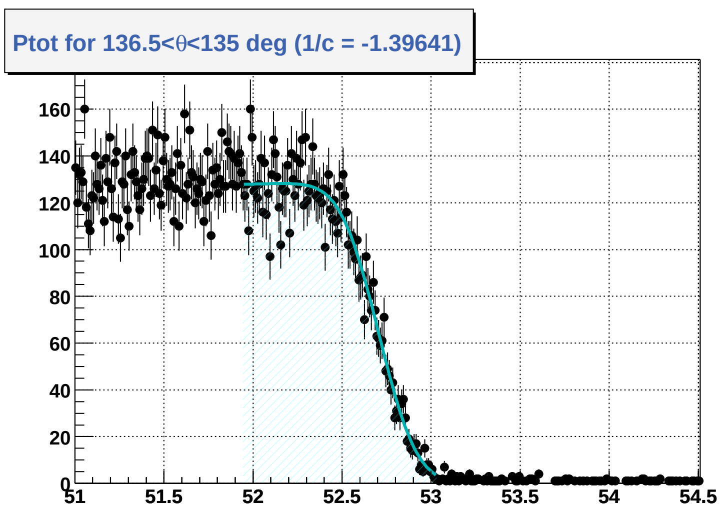
Events in High Density data set 6064934

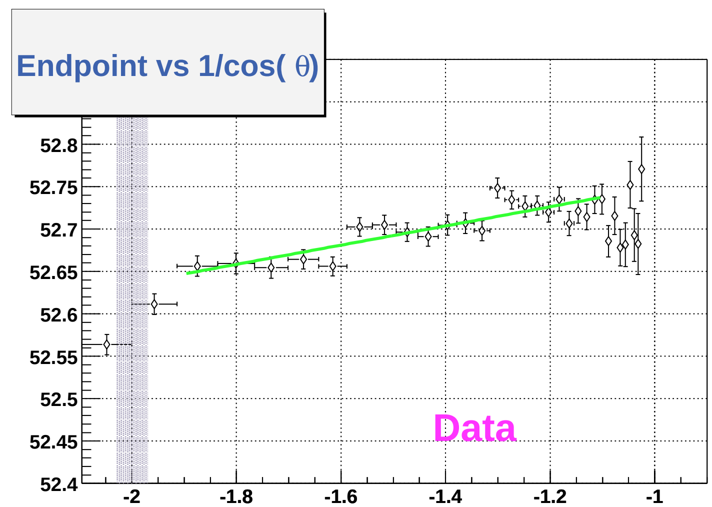
Effect of 2.5% change in density.

Endpoint energy calibration



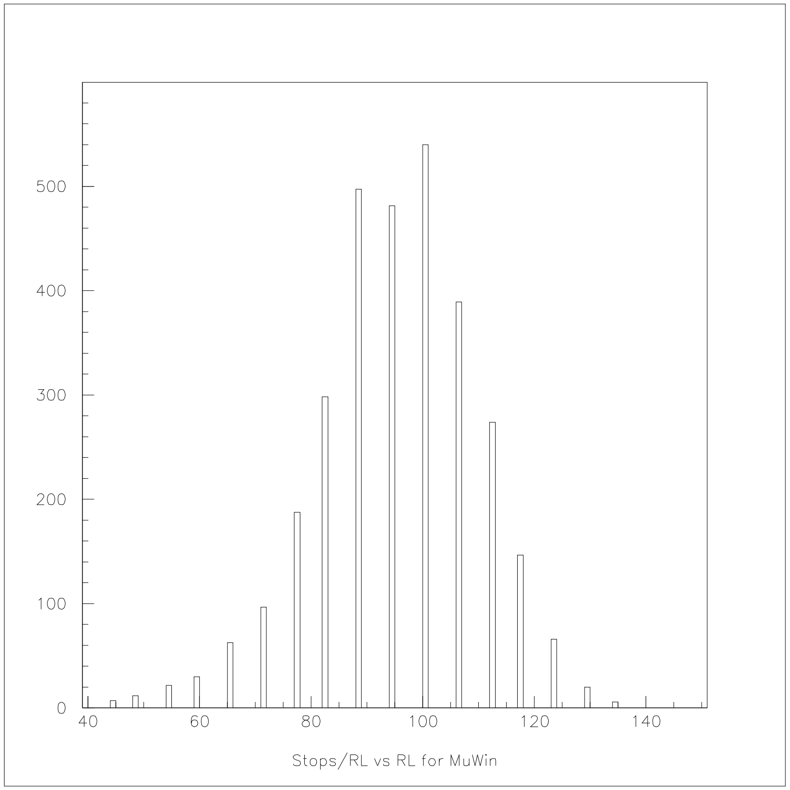




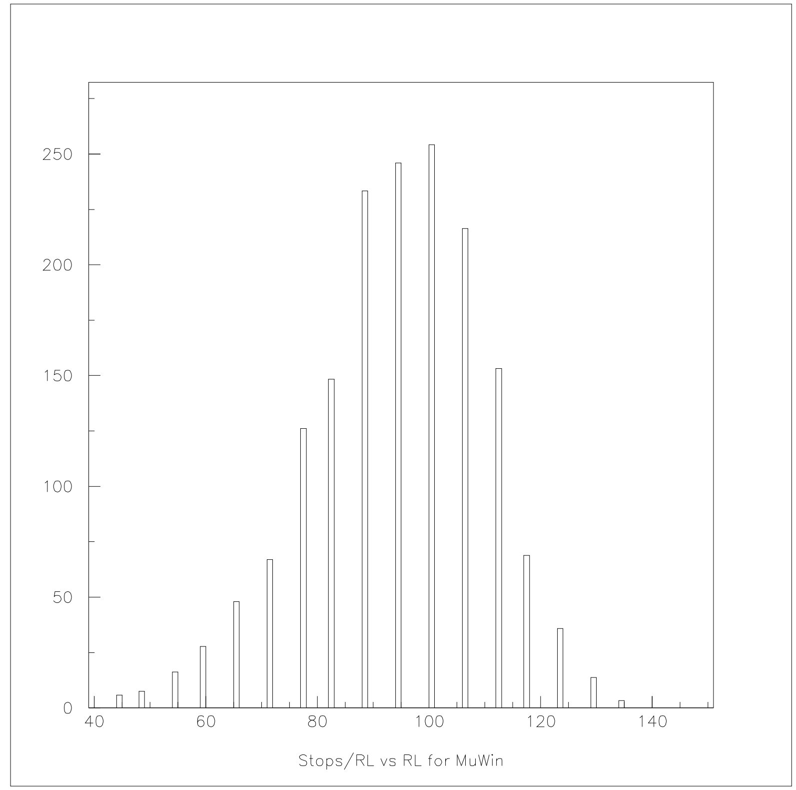


Fit to endpoint energy at 52.8 MeV/c, and dependence on angle.

GEANT3 verification: muon stopping distribution data



Simulation

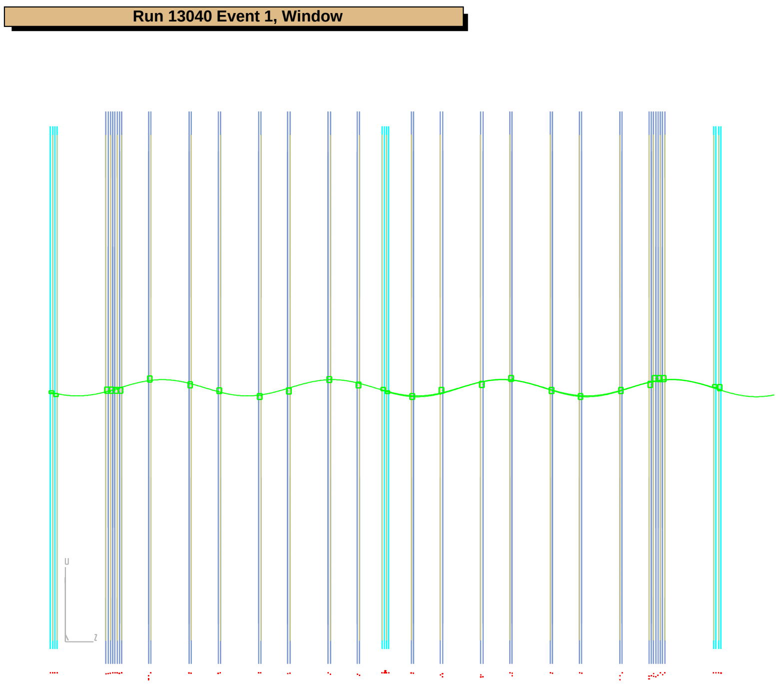


Experimental data

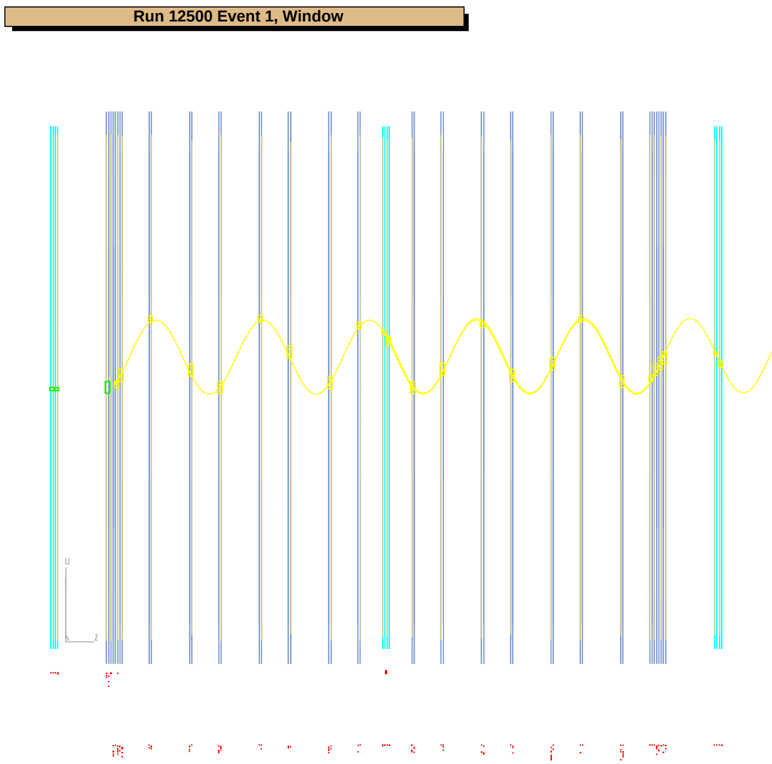
Comparisons of simulation with data for surface muon stops per radiation length *vs* radiation length, for muons ranged to stop in the upstream half of the detector stack.

GEANT3 verification: positron tracking tests

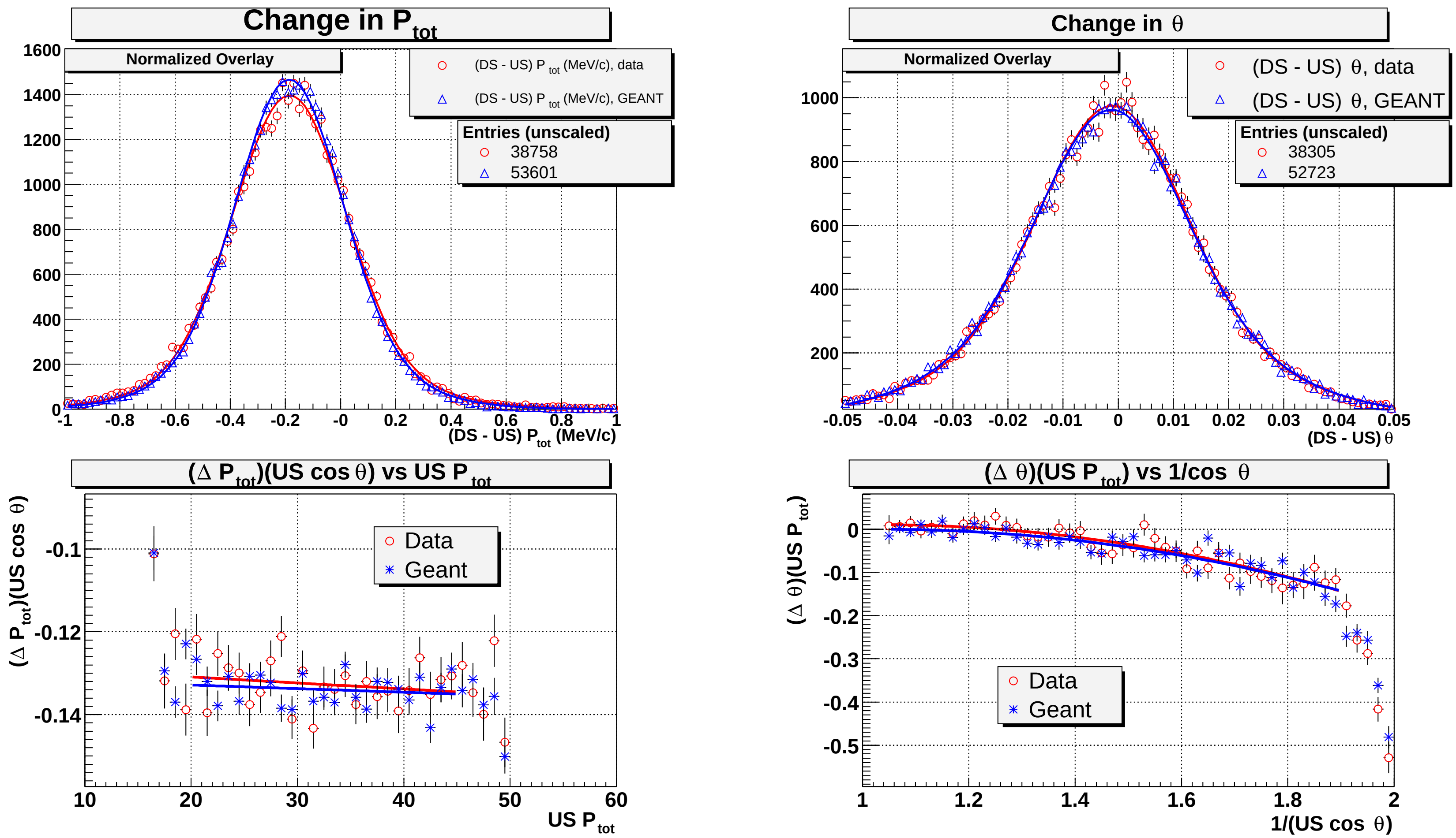
Beam Positrons



Decay Positrons from muons stopping upstream



GEANT3 verification: positron tracking data



Comparisons of simulation with data for decay positrons passing through both halves of detector, fitted separately in each.

Blind analysis strategy

Written in terms of:

$$\rho = \rho_0 + \Delta\rho \qquad \delta = \delta_0 + \Delta\delta$$

$$\eta = \eta_0 + \Delta\eta \qquad \mathcal{P}_\mu\xi = (\mathcal{P}_\mu\xi)_0 + \Delta(\mathcal{P}_\mu\xi)$$

the differential decay rate can be made linear in $\Delta\rho$, $\Delta\eta$, $\Delta\delta$, and $\Delta(\mathcal{P}_\mu\xi)$.

We produce a fit to probability distribution functions generated by the decay rate for hidden ρ_0, η_0, δ_0, and $(\mathcal{P}_\mu\xi)_0$, plus distributions generated by *derivatives* of the decay rate with respect to $\Delta\rho$, $\Delta\eta$, $\Delta\delta$, and $\Delta(\mathcal{P}_\mu\xi)$.

The result of the analysis is revealed when the coefficients of the fit derivative distributions are added to the hidden values.

Summary

- *TWIST* is the first and only experiment designed to measure several Michel parameters simultaneously with high precision.
- *TWIST* is now operational and is taking data very reliably. The detector system operates beyond expectations.
- Data analysis and simulation software are maturing. Problems are being solved as they arise, and we are now learning about physics processes in muon decay.
- Our challenges are understood. We must:
  - ▷ understand quantitatively and correctly the systematic effects.
  - ▷ further test and improve analysis codes to reduce or eliminate biases.
  - ▷ gain better control of depolarization, especially as related to fringe field and muon beam characteristics.
  - ▷ seek additional ways to verify our simulation with comparisons to data.
- Progress on *TWIST* *is not* limited by the amount of data; we expect approximately seven months of beam time per year at our disposal.
- Progress on *TWIST* *is* limited by the human resources that we can apply to improvements in analysis and understanding of potential biases in the physics results.

TWIST participants

TRIUMF
Yuri Davydov†
Jaap Doornbos
Wayne Faszer
David Gill
Rich Helmer
Robert Henderson
John A. Macdonald§
Glen Marshall
Konstantin Olchanski
Art Olin
Robert Openshaw
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer

Alberta
Andrei Gaponenko*†
Peter Kitching
Robert MacDonald*†
Maher Quraan†
Nate Rodning§
John Schaapman
Glen Stinson

British Columbia
Mike Hasinoff
Blair Jamieson*†

Montréal
Pierre Depommier

Northern British Columbia
Tracy Porcelli

Regina
Ted Mathie
Roman Tacik

Saskatchewan
Bill Shin

Russian Research Centre "Kurchatov Institute"
Vladimir Selivanov
Vladimir Torokhov

Los Alamos National Laboratory
Dick Mischke

Texas A&M
Carl Gagliardi
Jim Musser*
Bob Tribble
Maxim Vasiliev

Valparaiso
Don Koetke
Paul Nord
Shirvel Stanislaus

* Graduate PhD thesis students
† NSERC grant supported
§ deceased

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