Probing The Weak interaction with Muon Decay

Art Olin, for the TWIST Collaboration

TWIST Participants

TRIUMF
Ryan Bayes †
Yuri Davydov
Jaap Doornbos
Wayne Faszer
Makoto Fujiwara
David Gill
Alexander Grossheim
Peter Gumplinger
Anthony Hillairet †
Robert Henderson
Jingliang Hu
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
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

Graduated student
† also U Vic
‡ also Saskatchewan

Supported by NSERC, DOE, RMF, Westgrid

First 2-body μ Decay Searches

The Absorption of Charged Particles fr
2.2-μsec. Meson Decay

E. P. Hincks and B. Pontecorvo
National Research Council of Canada, Chalk River Labor
Chalk River, Ontario, Canada
July 26, 1948

THE energy spectrum of the charged particl monly assumed to be electrons) emittec 2.2-μsec. meson decay is still unknown. Conv Piccioni[1] in 1944 deduced from the relative nu

...

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.

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 1

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.

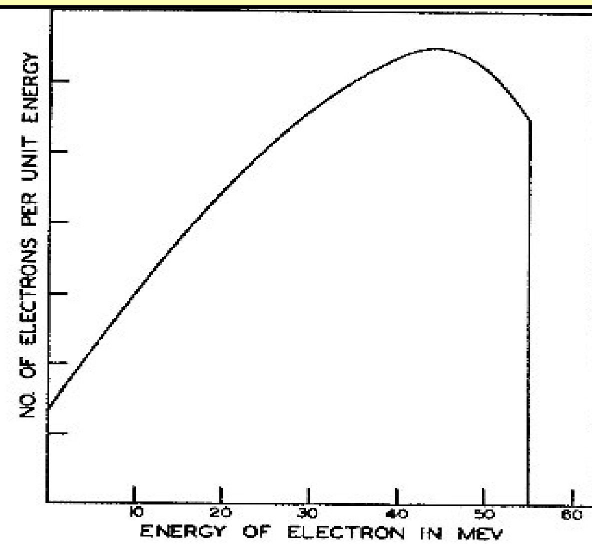
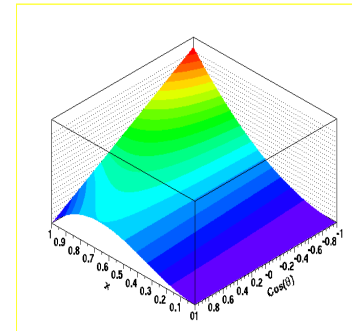


Fig. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.

Muon decay spectrum

The energy and angle distributions of positrons following polarized muon decay obey:



$$\frac{d^2\Gamma}{x^2 dx d(\cos\theta)} \propto (3-3x) + \frac{2}{3}\rho(4x-3) + 3\eta\frac{x_0}{x}(1-x)$$
$$+ P_\mu \xi \cos\theta \left[(1-x) + \frac{2}{3}\delta(4x-3) \right]$$

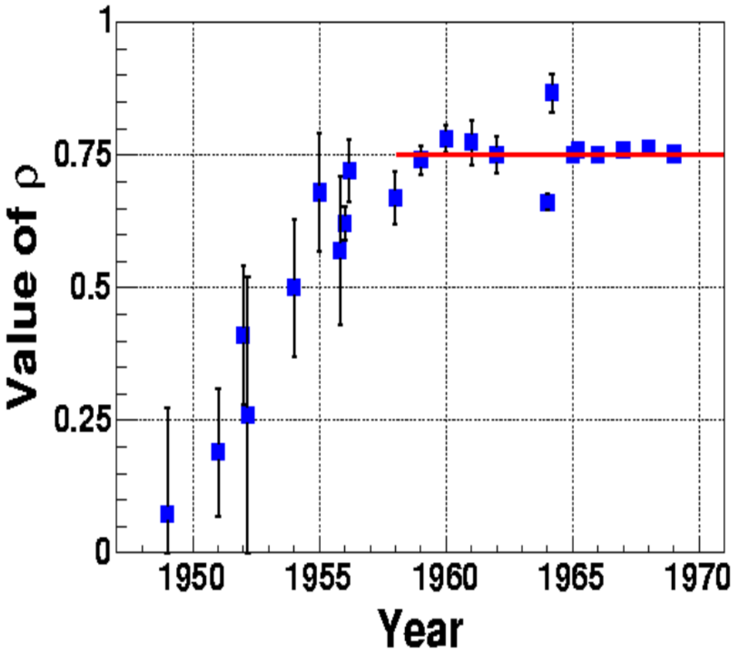
(+ rad. corr.)

where $x = \frac{E_e}{E_{e,\max}}$

- Lorentz invariant, local weak interaction.
- SM postulates maximally parity violating V-A: ρ=δ=3/4; ξ=1;η=0.
- Mediated by W boson.
- Empirically based – tested in present work.

Measurements of ρ

- Initial speculation ρ = 0
- Early test of V-A
- Classic Case for Blind Analysis



Greiner *et al.*, Gauge Theory of Weak Interactions, Springer (1996).

Other μ decay measurements

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

  ρ = 0.7518 ± 0.0026 (Derenzo, 1969, Barton *et al.* 1965) (0.75)

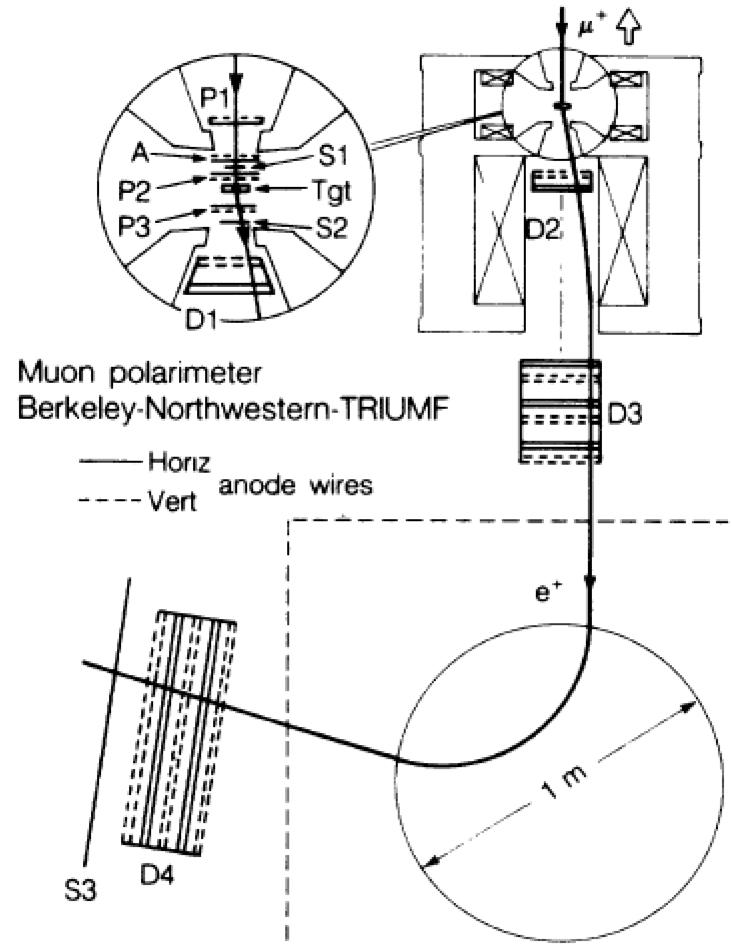
  η = -0.002 ± 0.007 (Dannenberg

  δ = 0.7486 ± 0.0026 ± 0.0028 (Ba

  $P_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (

  $P_\mu(\xi\delta/\rho)$ > 0.99682 (Jodidio *et al.*

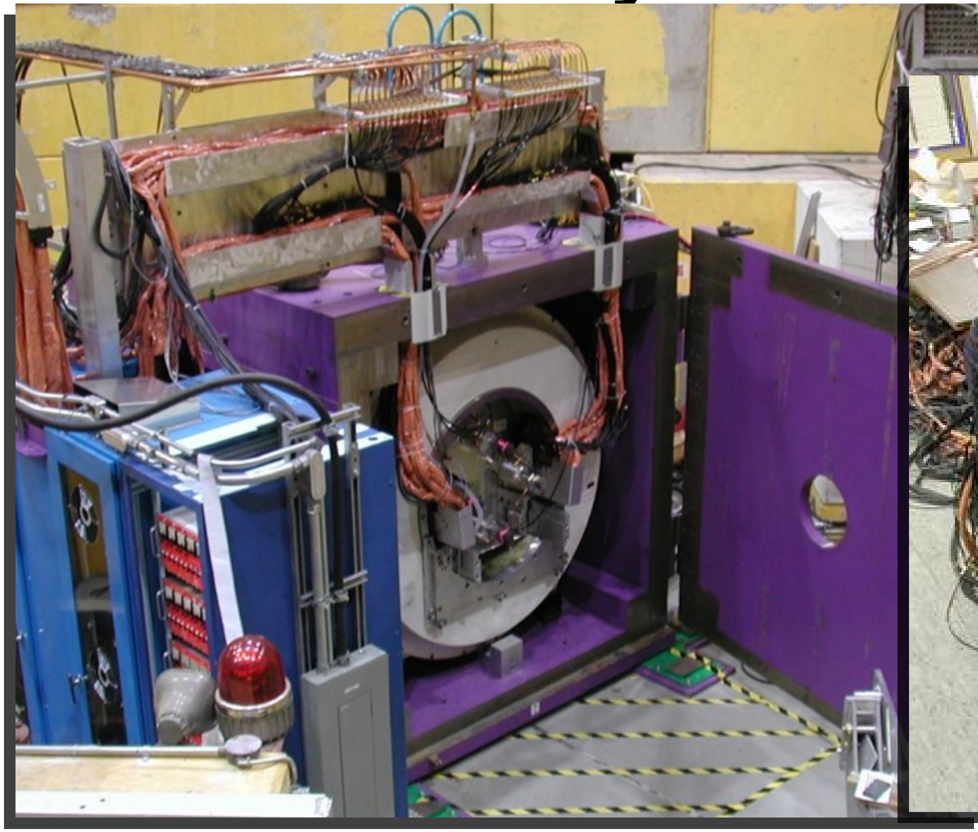
  Additionally, beautiful measuremen



Strovink measurement at TRIUMF used a high resolution forward spectrometer, measuring the phase space not covered in the present measurement.

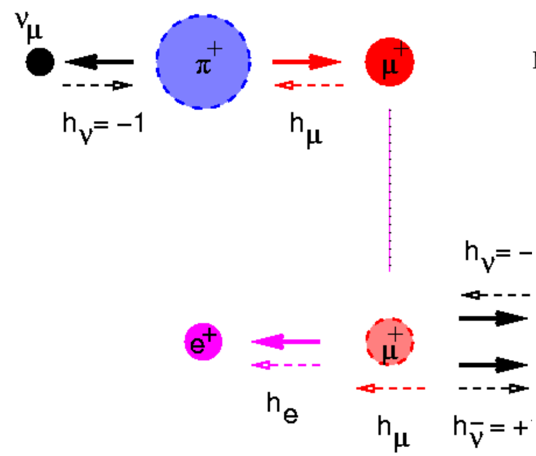
The *TWIST* Experiment

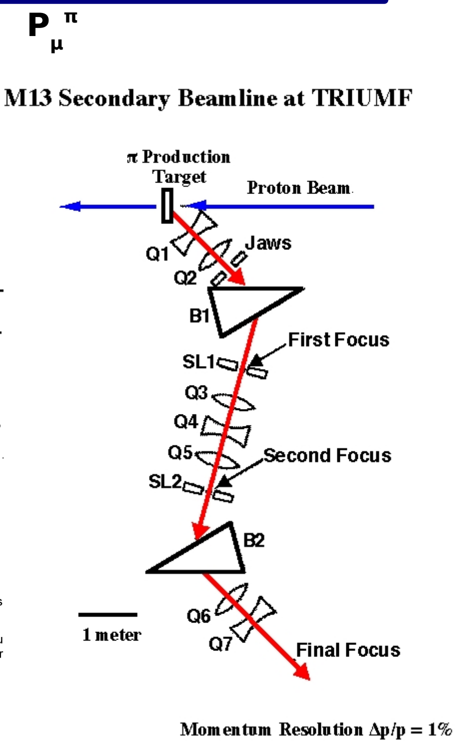
TRIUMF Weak Interaction Symmetry Test

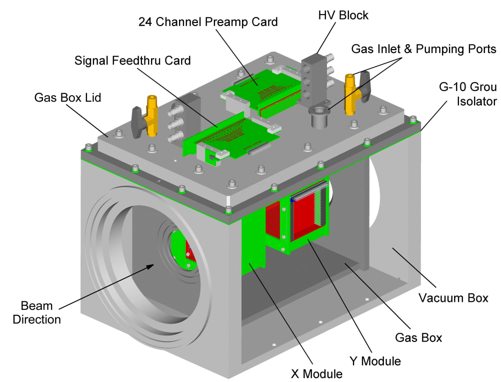


Polarized Muon Production and Transport

- Pions decaying at rest produce muon beams with P_{μ}^{π} =100%. (SM).
- Depolarization must be controlled using small emittance beams near kinematic edge, 29.8 MeV/c.
- Use ≈3 10^3 $\mu^+ s^{-1}$.
- Muon total range at density ≈1 only about 1.5 mm!

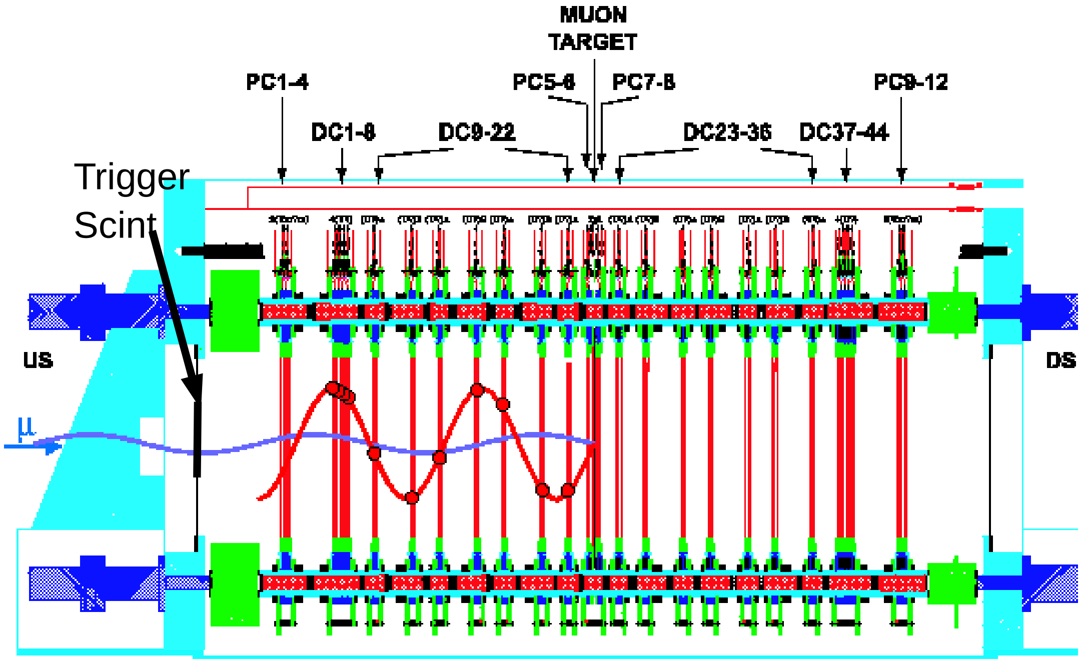






Low Pressure Time Expansion Chamber
NIM A556(2006)563

Typical event



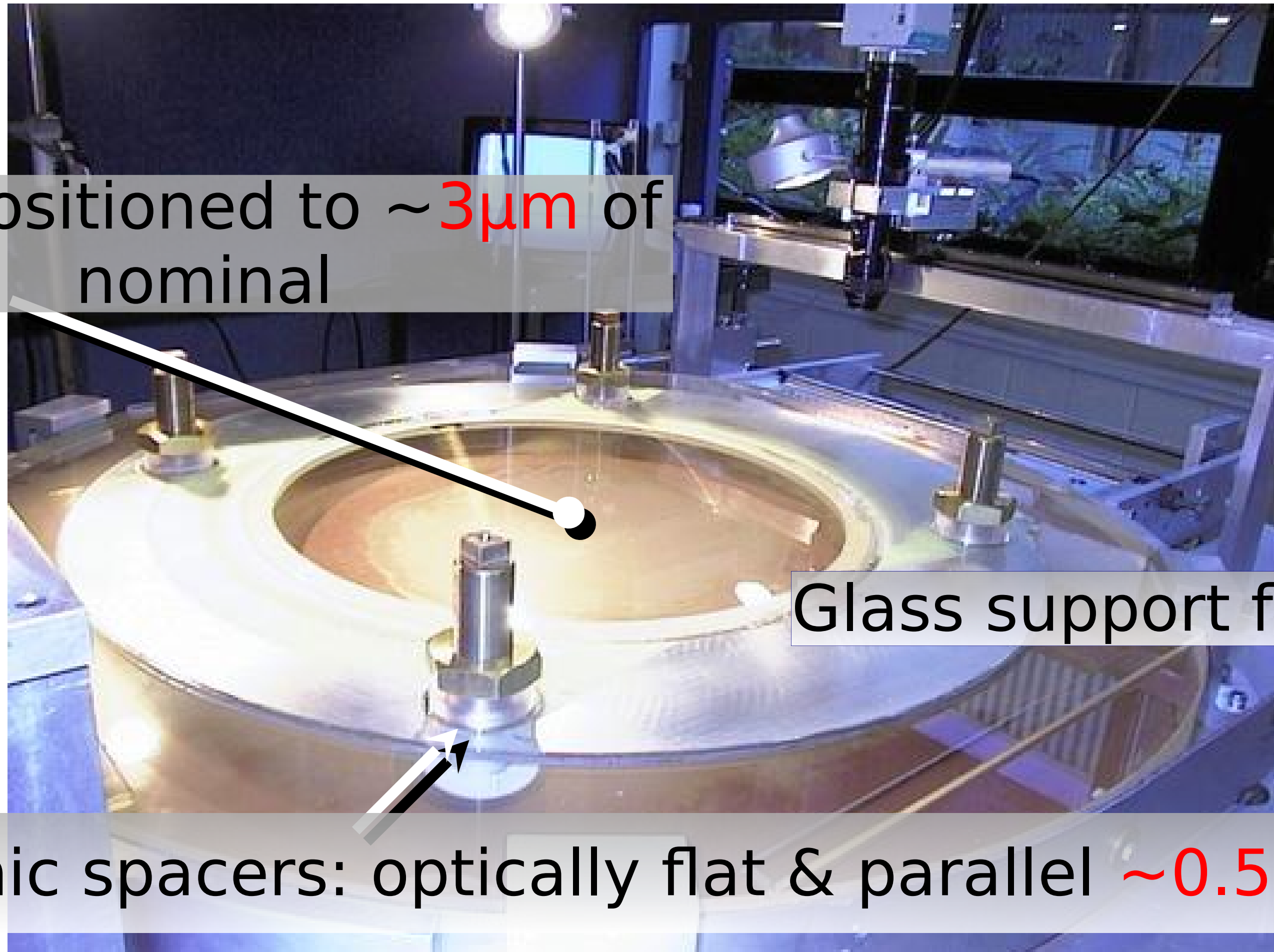
Low-mass high-precision planar chambers symmetrically placed around thin target foil which stops nearly all of surface muon beam. Z precision 5 10^{-5}, wire position 3μ. 44 drift chambers (DME), 12 proportional chambers (CF_4-isobutane), He gaps.

Measurement initiated by single thin scintillation counter at entrance to detector.

Beam stop position controlled by variable He/CO_2 gas degrader.

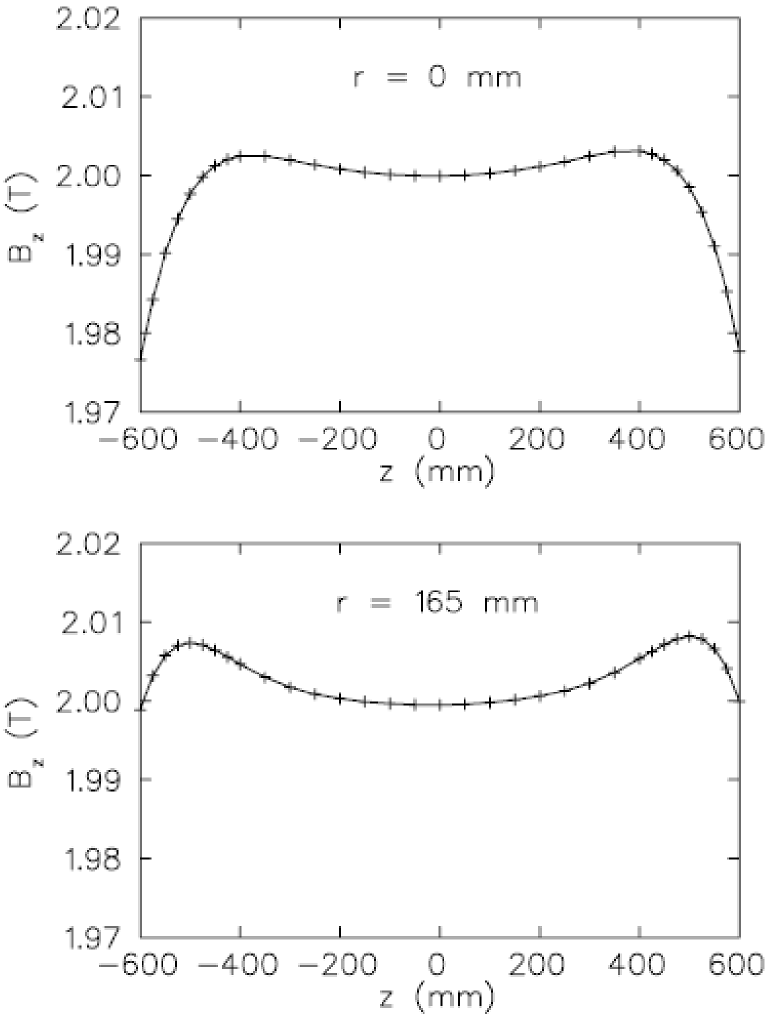
NIM A548(2005)206

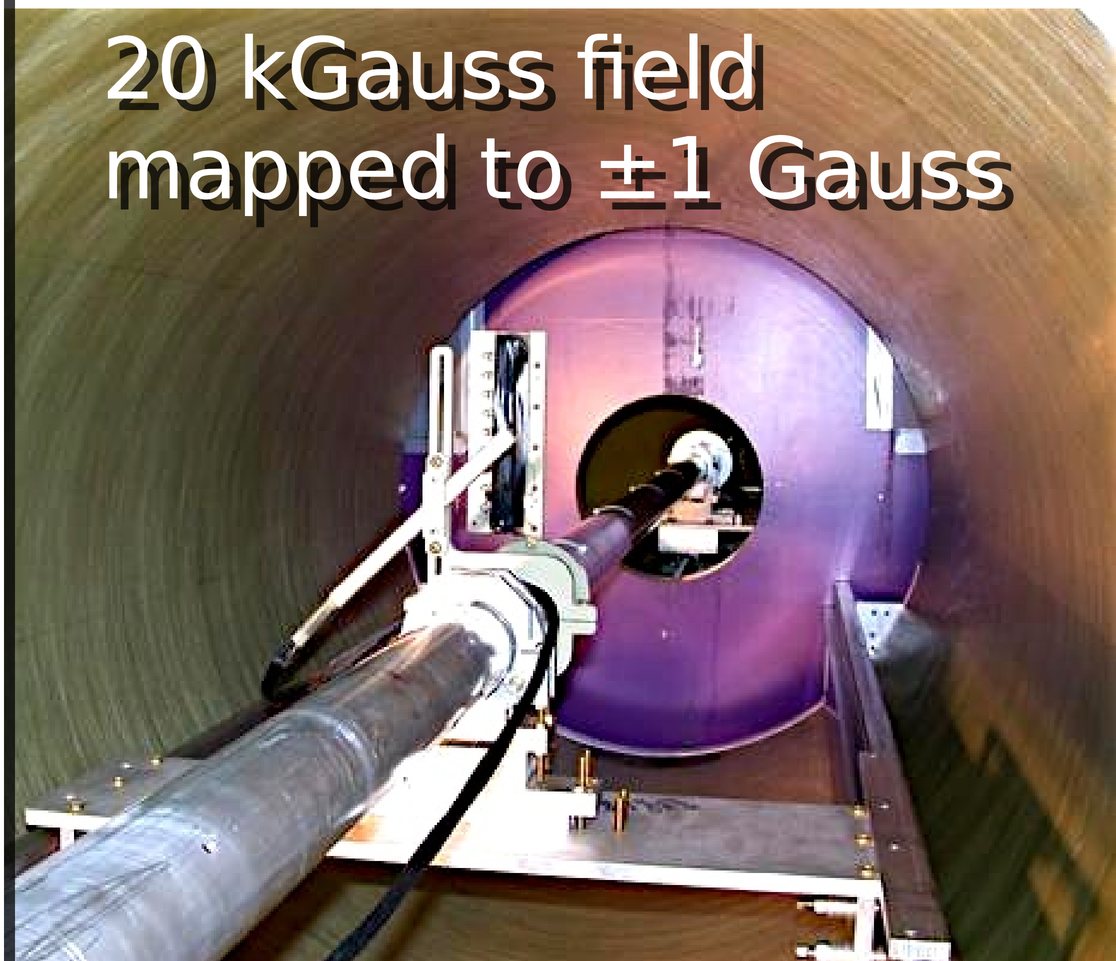
TWIST Drift Chambers



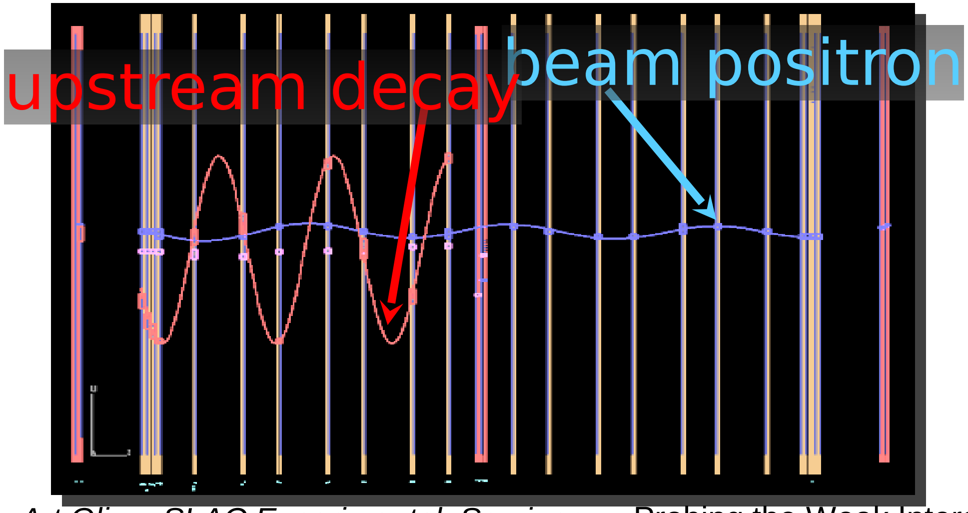
NIM **A548** (2005) 206

The *TWIST* Solenoid

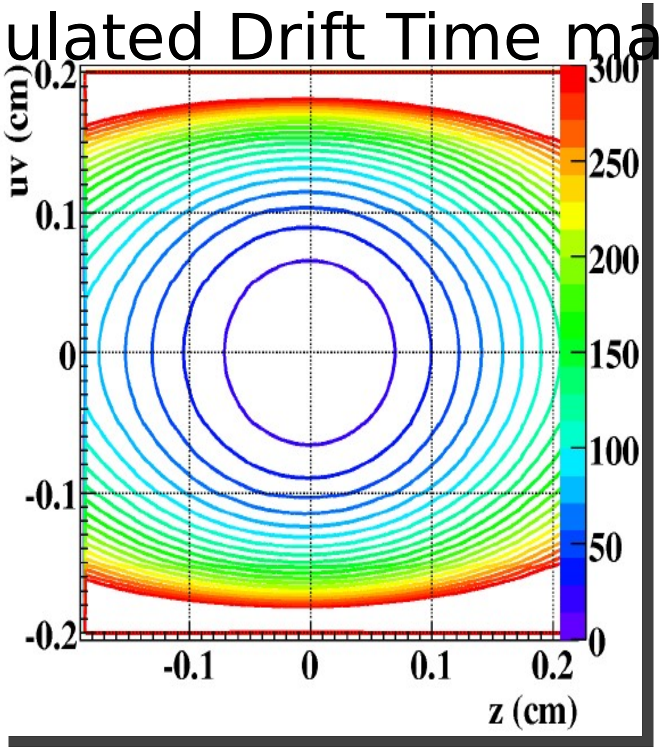




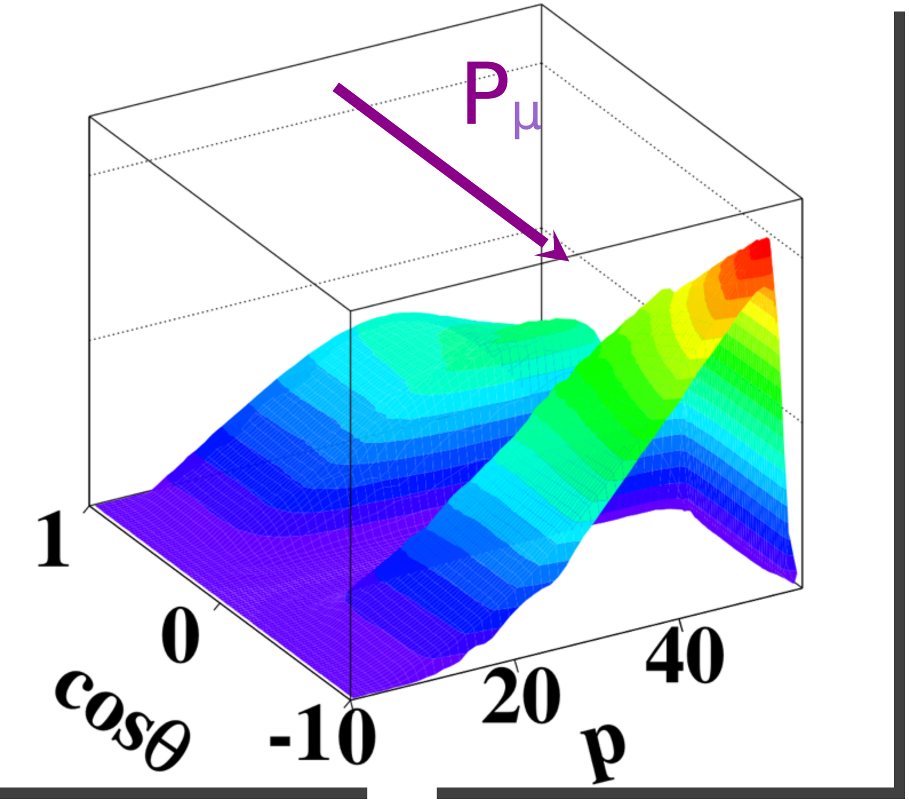
TWIST Analysis

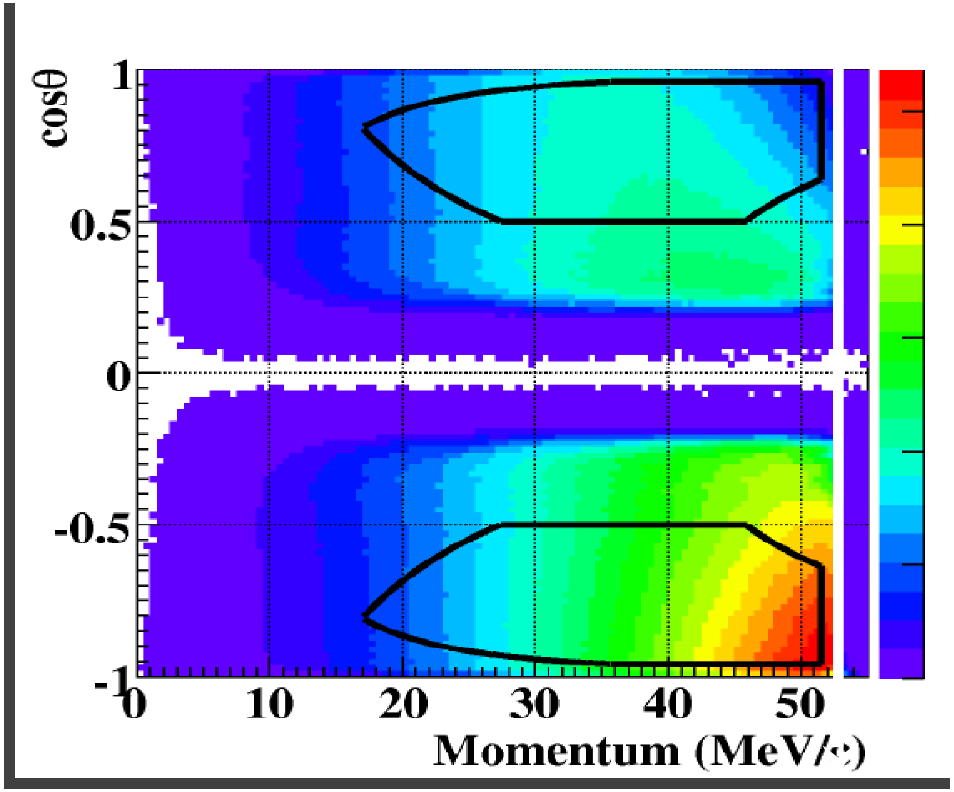


Simulated Drift Time map

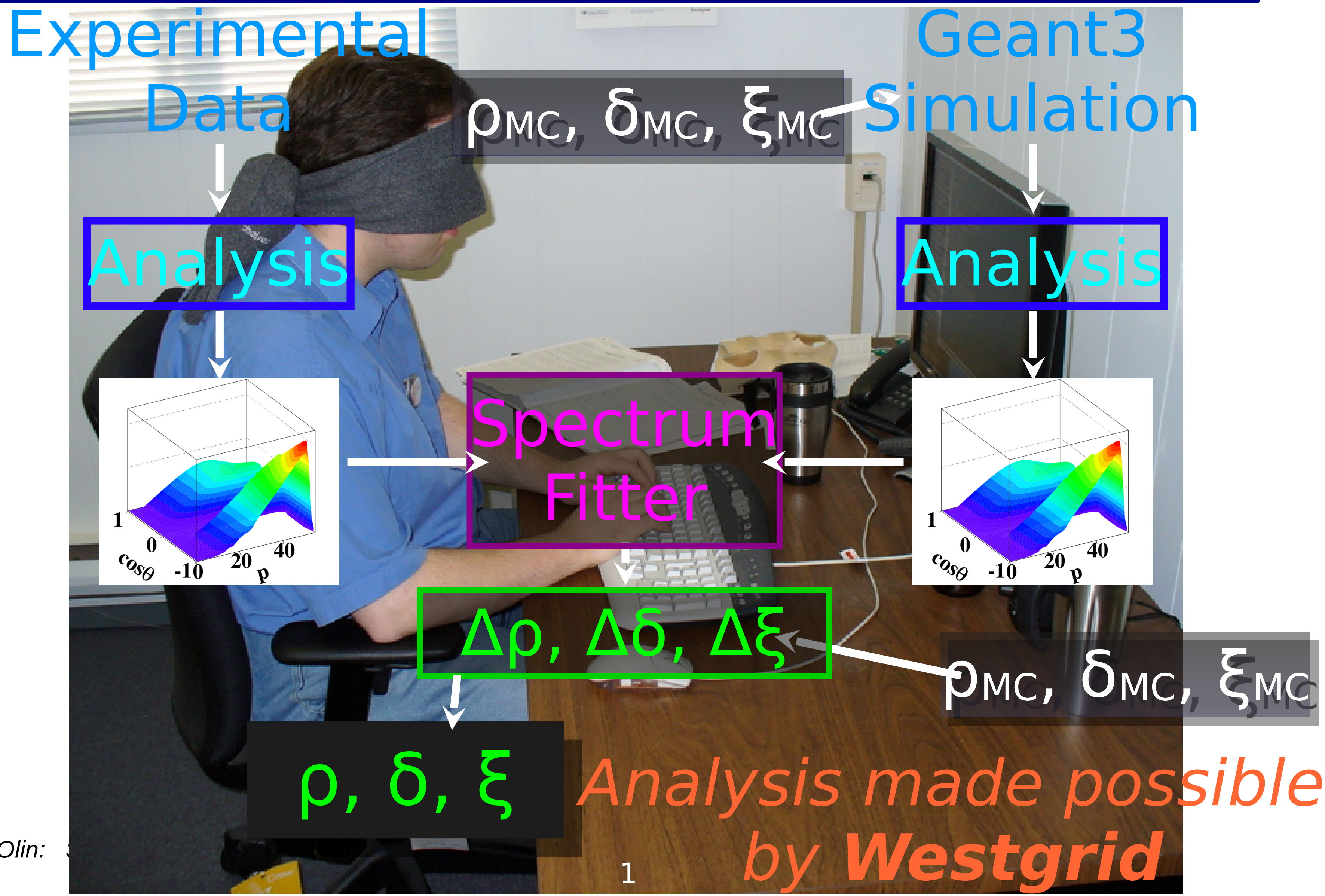


Muon Decay Spectrum and Fiducial



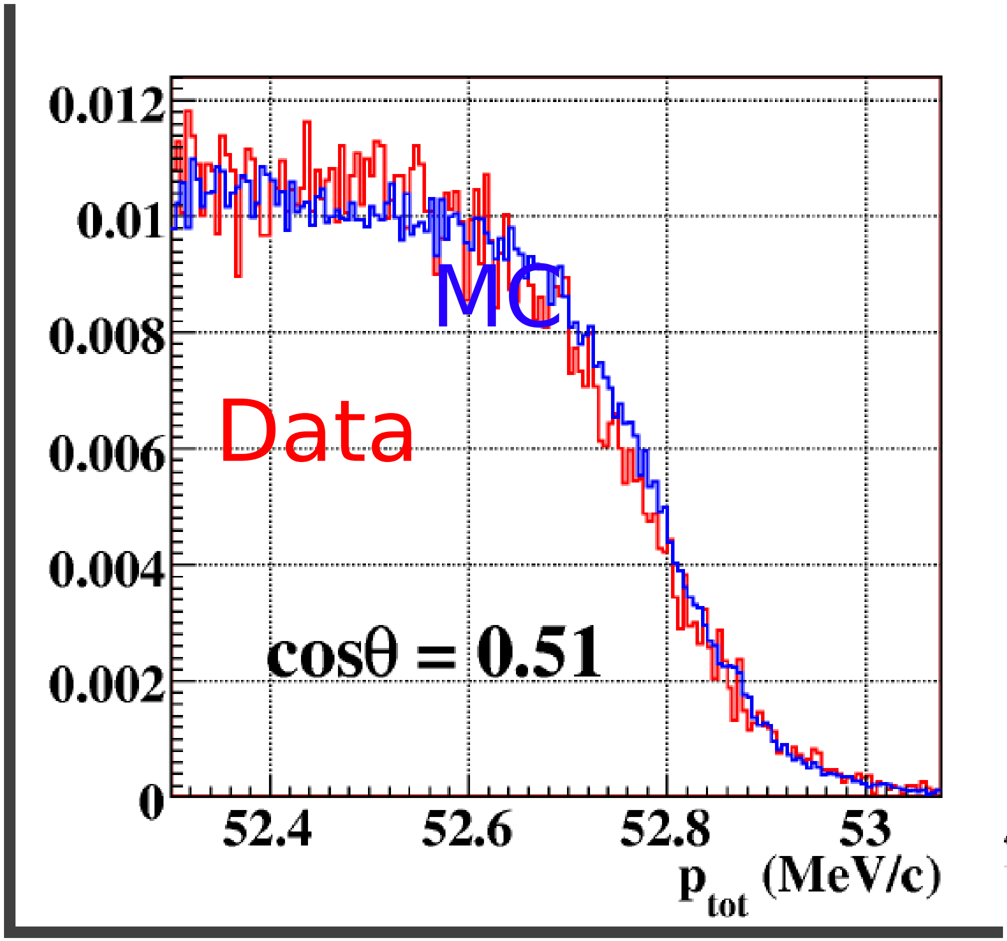


Blind Analysis

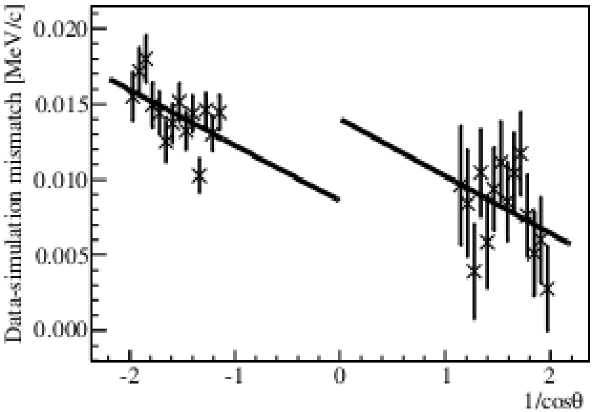


Art Olin:

Momentum Calibration

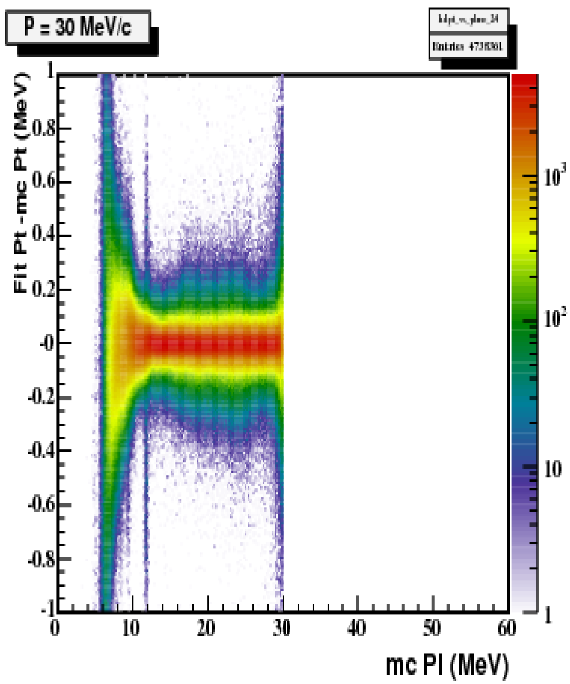


Data Resolution ~70 KeV/c
MC Resolution ~65 KeV/c
Relative Shift ~5 KeV/c
Adjusts for energy loss in target

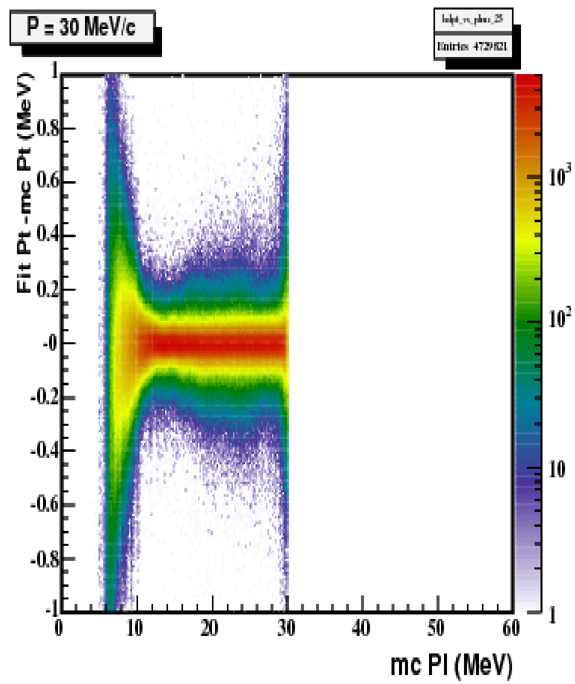


$$E = E^{0} - \Delta E / \cos(\theta)$$

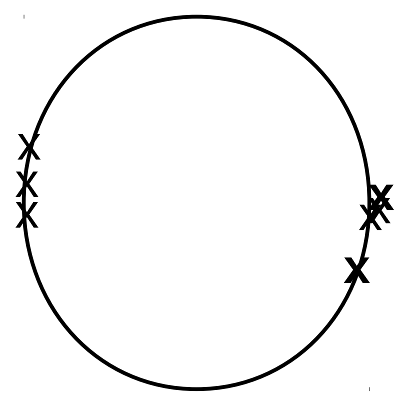
Plane Periodicity Effects



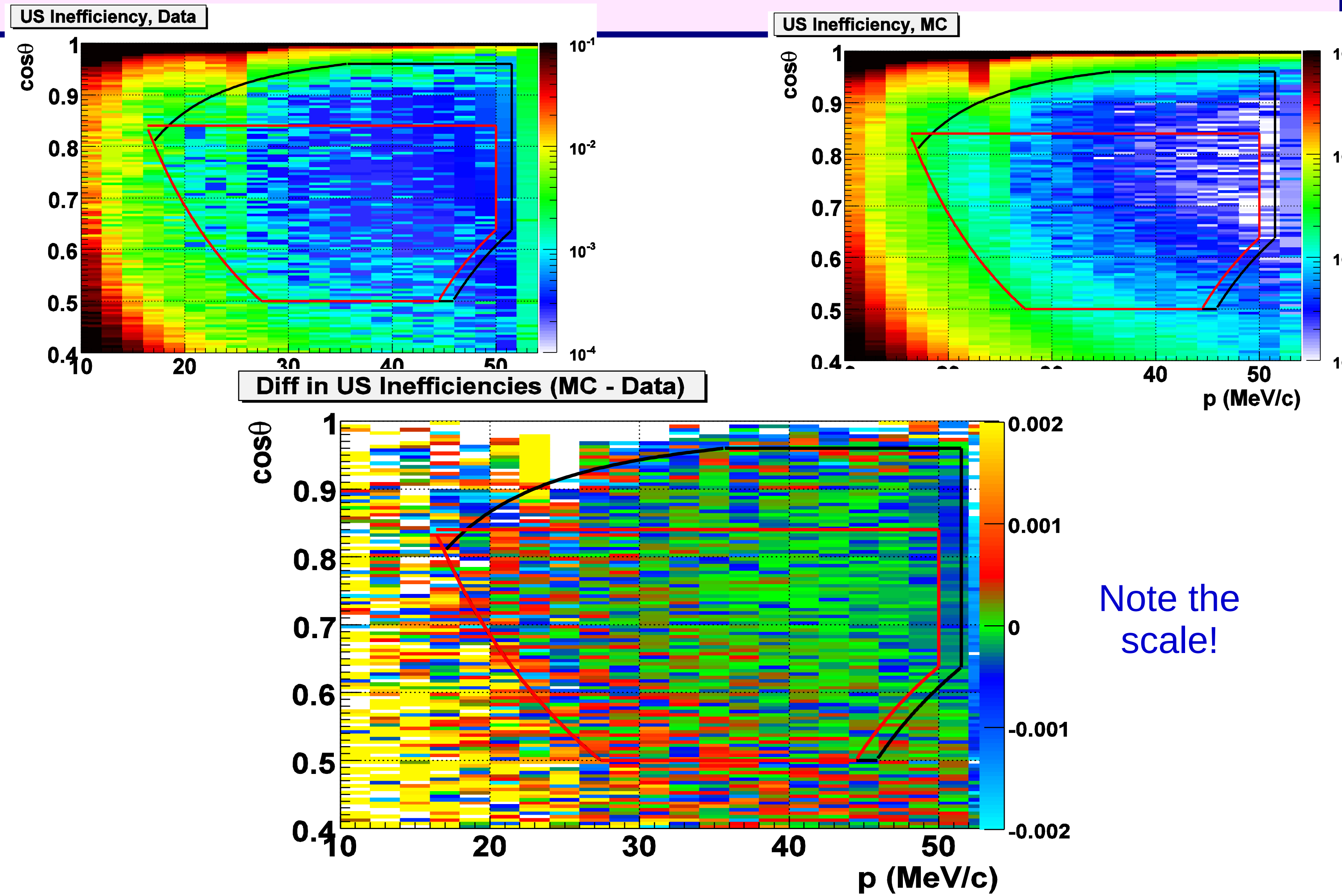
Old geometry



New geometry

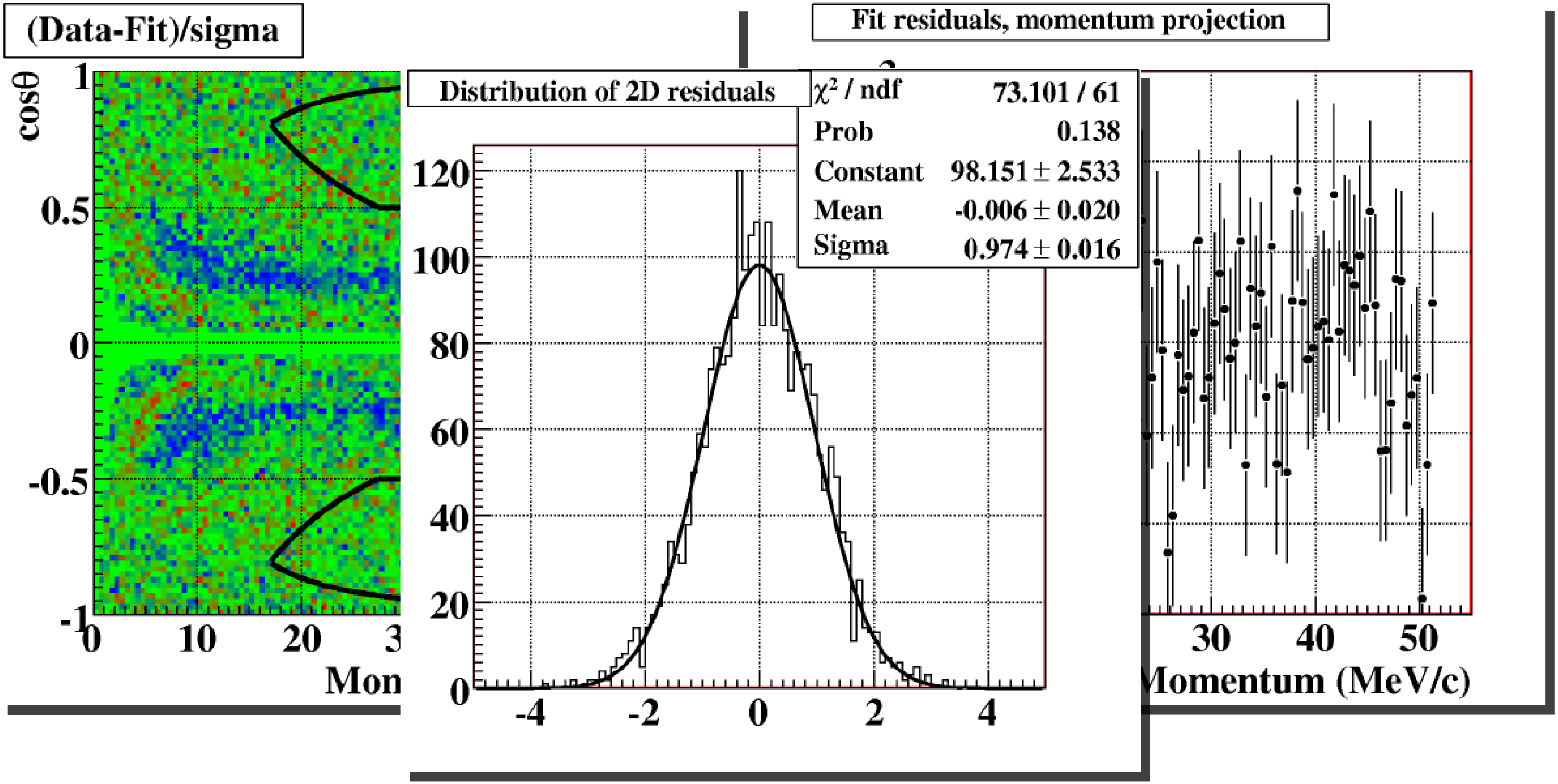


Tracking (in)efficiency

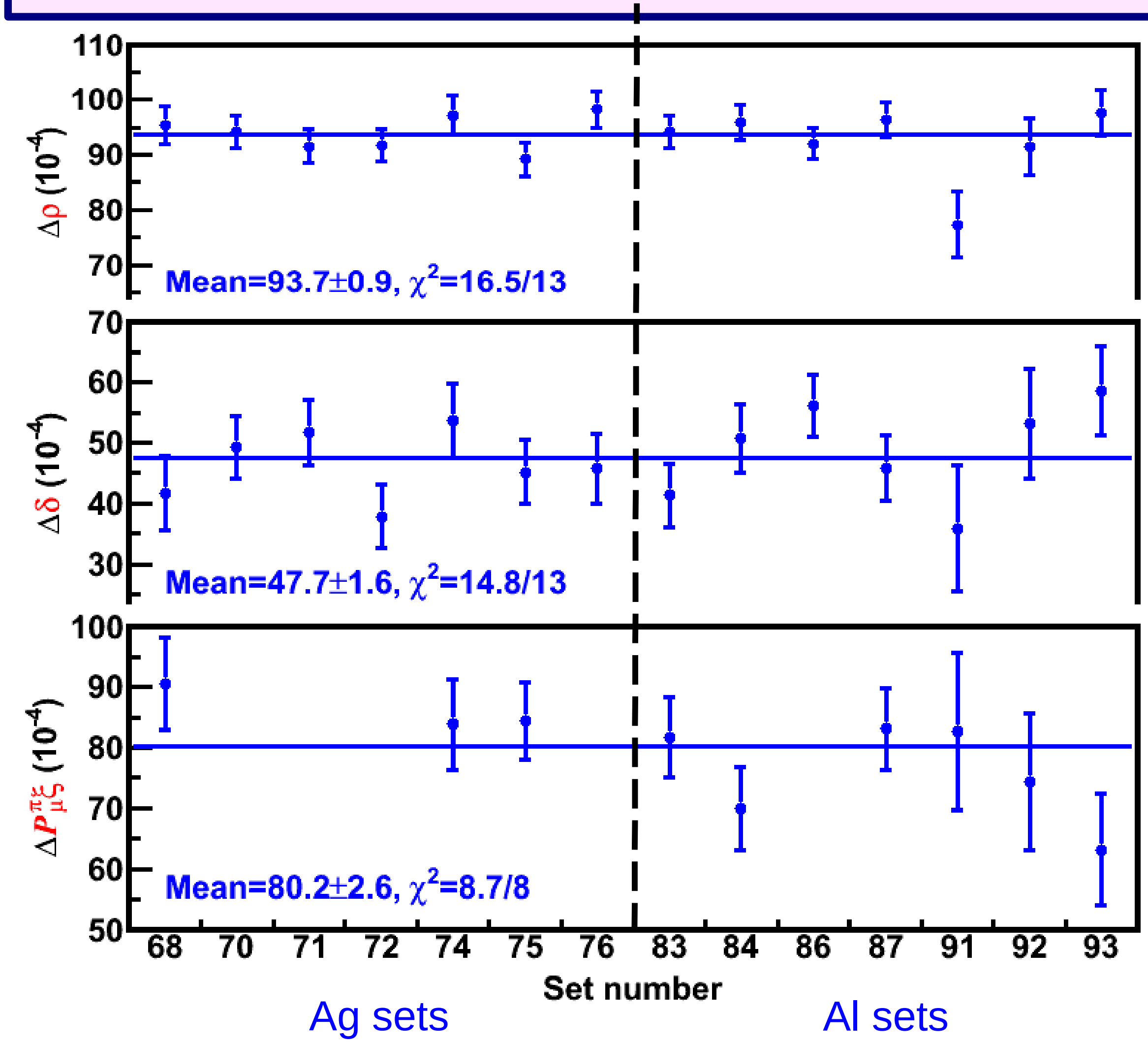


Note the scale!

Spectrum Fit Quality



Set-to-set statistical consistency



Key:

- Ag target sets
  - 68- [1] stop slightly US
  - 70- B = 1.96T
  - 71- B = 2.04T
  - 72- TECs in
  - 74- production
  - 75- production
  - 76- [1] beam mis-steered
- Al target sets
  - 83- DS extra material
  - 84- production
  - 86- [1] beam mis-steered
  - 87- production
  - 91- low beam momentum
  - 92- low beam momentum
  - 93- low beam momentum

Differences (**Δ**) are with respect to blind parameters.

Set-dependent corrections are applied; error bars and weights for the means are *statistical only*.

Opening the Box

When the collaboration is finally satisfied with the consistency of the data sets and the spectrum fit quality

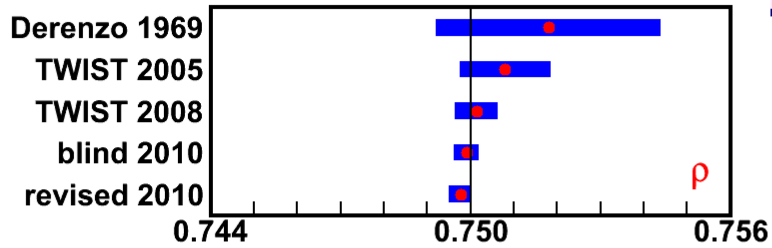
Blind analysis protocol:
- identify data sets to include
- all event selection criteria and cuts ,
- systematic uncertainties and corrections,
- New measurement supersedes previous TWIST measurements
- Publish even if inconsistent with Standard Model

Blind *vs.* revised analysis

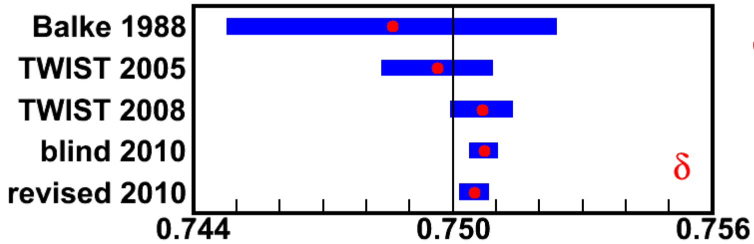
$$\text{At } \mathbf{x} = \mathbf{1}, \cos\theta = -\mathbf{1} : \frac{\partial^2 \Gamma}{\partial \mathbf{x} \partial \cos\theta} \sim \rho - \mathrm{P}^{\mu}\xi\delta >= \mathbf{0}$$

- The blind analysis results showed evidence of possible mistakes:
  - set-to-set statistical consistency satisfactory for ρ, δ, $P^{\mu}\xi$
    - but **$P^{\mu}\xi\delta/\rho$** was different for Al and Ag targets by 3.9σ.
  - **$P^{\mu}\xi\delta/\rho$** averaged over all sets was 2.9σ greater than 1.0.
    - unphysical in four-fermion formulation with massless neutrinos.
- Search for mistakes identified two corrections and two procedural changes:
  - radiative decay: small correction for Ag only
  - mean stopping position differences (data *vs.* simulation): corrected set-by-set, based on better analysis of stop position
  - separate systematic uncertainties for Ag and Al targets for bremsstrahlung, target thickness, and mean stopping position
- After the revisions, the Ag-Al $P^{\mu}\xi\delta/\rho$ difference becomes <1σ.

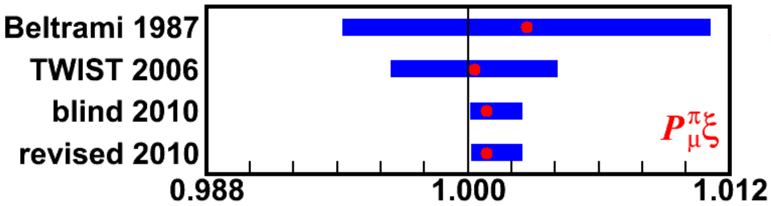
Decay parameter results



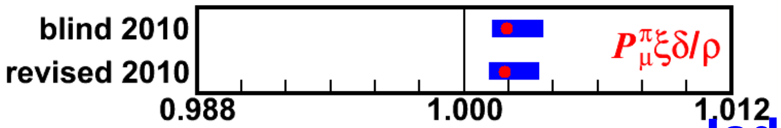
ρ = 0.74977 ± 0.00012(stat) ±0.00023(sys)
<1σ from SM, -1.4 10^{-4} from blind



δ = 0.75049 ± 0.00021(stat) ± 0.00027(sys)
+1.4σ from SM, -2.3 10^{-4} from blind



$P^{\pi}_{\mu}\xi$ = 1.00084 ± 0.00029(stat) $^{+0.00165}_{-0.00063}$ (sys)
+1.2σ from SM, same as blind



$P^{\pi}_{\mu}\xi\delta/\rho$ > 0.99909 (90%CL)
from global analysis
Jodidio et al $P^{\pi}_{\mu}\xi\delta/\rho$ > 0.99682 (90%CL)

TWIST Collaboration, R. Bayes et al., Phys. Rev. Lett. 106, 041804 (2011).

Search for $\mu \to e X^0$ Decays

- Search for two-body decay to unseen neutral particle (WIMP; axion Majoron…)
  - Decays with final state containing charged particles are limited by more sensitive measurements unless the states are very long lived. $\mu \longrightarrow eee$
- Could be asymmetric decay $\frac{\partial \Gamma}{\partial \cos\theta} \propto 1 + A\cos\theta$
  - Eg Hirsch et al Phys.Rev. D 79, 055023 (2009).

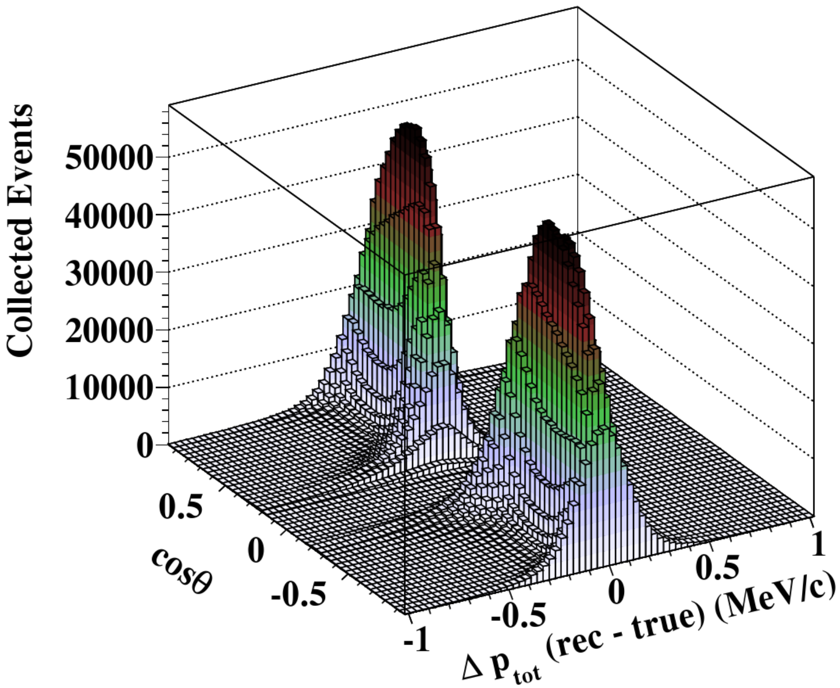
- M(X^O) =0 corresponds to positrons at the endpoint of the three-body spectrum. Kinematic limit is M(X^O)<88 MeV/c^2

Method

- Calculate an X^0 decay distribution $\mathcal{F}_A(M_X)$ using the high-statistics simulation used for the decay parameter analysis. (σ~100keV/c).
- Fit data with $$\frac{\partial^2\Gamma}{\partial x \partial \cos\theta} =$$

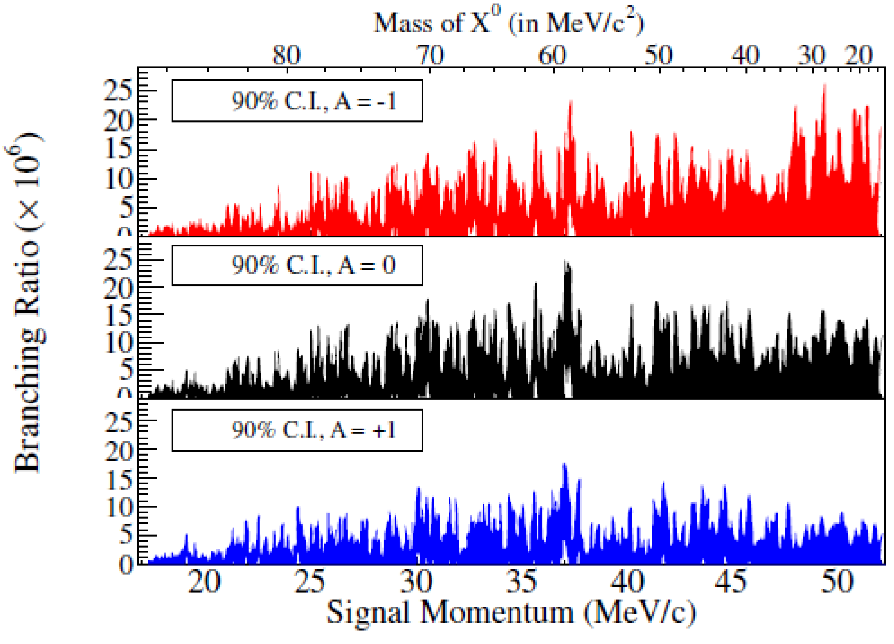
$$\mathcal{F}_0(p_e;\rho,\eta) + P_\mu \mathcal{F}_1(p_e;\xi,\delta)\cos\theta + \mathcal{F}_{\mathcal{A}}(\mathrm{m_X})\mathrm{B}(\mathrm{m_X})$$

- Using simulation for the 2-body and 3-body spectra includes all reconstruction effects.
- Grid is 17.3 MeV/c<p_e <52.8 MeV/c in 50 keV/c steps.
- Muon decay parameters simultaneously fit.
- Fiducial is TWIST standard -high reconstruction efficiency



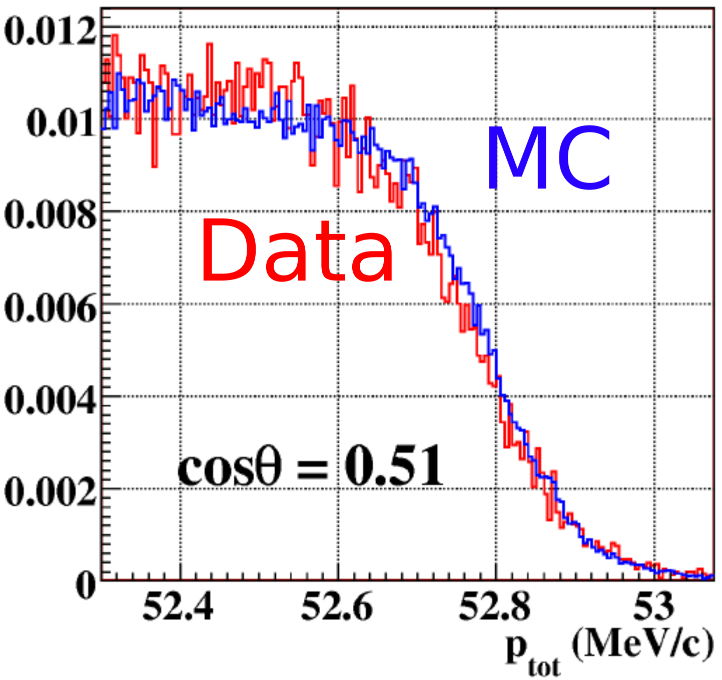
Massive X^0 Decays

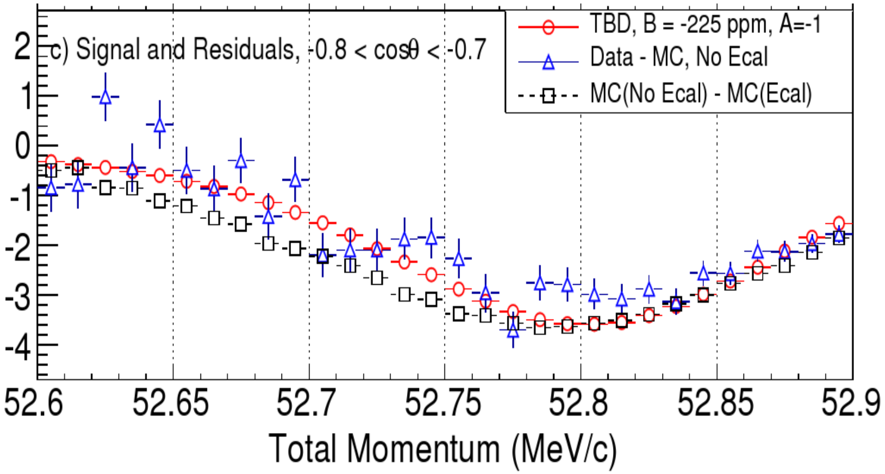
- 90% confidence bands from using Feldman-Cousins.
- Limits are best for A=+1.
- The most significant peaks are consistent with expectations considering the number of trials.
- Balke *et al* branching ratio limits were ~100 ppm.
- $m(X^0)<13$ MeV/c^2 decays are treated as massless.



Momentum Calibration

A momentum calibration offset produces a narrow structure at the endpoint.
Fitting the sim edge to the data could partially mask a peak there.





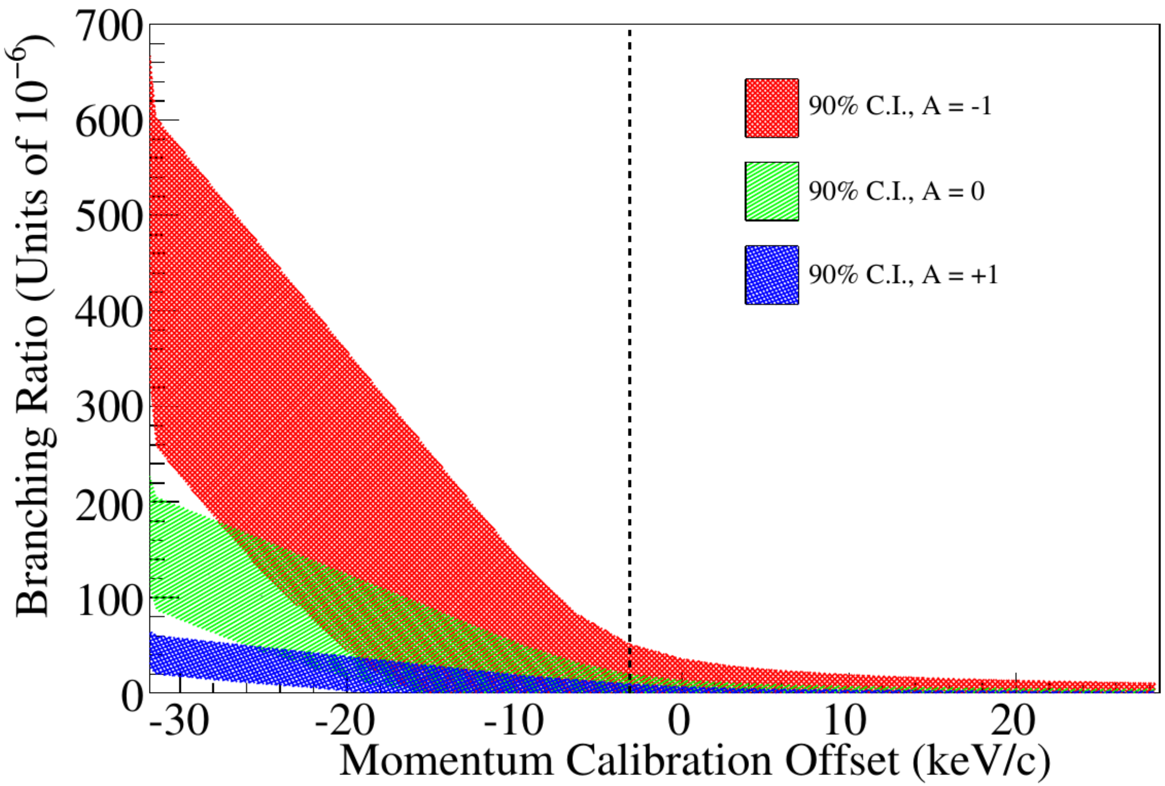
Momentum Calibration Systematic

- Momentum of simulated tracks depends on
  - Magnetic field map
  - Wire and plane spacings
  - Material thicknesses and dE/dx values
- The uncertainties in these values determine the uncertainty in the edge position of 6.1 keV/c, which provides the dominant uncertainty in the branching ratio for a peak at the end point.
- There are additional small corrections to the parameters used in the simulation giving a shift of -4.1 keV/c. They come from post-run destructive measure of the target thicknesses and a better evaluation of the stopping position and magnetic field profile.

Massless X^o BR Limit

Feldman-Cousins 90% CL band calculated.
Limits at the best offset:
A=-1 : 58 ppm
A=0 : 21 ppm
A=+1: 10ppm

Jodidio limit using forward spectrometer
A=0 : 2.6ppm
Their limit would be even stronger for A=+1. However A=-1 decays are suppressed in the forward direction, so there is no sensitivity.



Limits for Heavy Sterile Neutrinos

- Muon decay spectrum shape places limits on heavy neutrino mass and mixing in a mass region inaccessible with π or K decays.

R.R. Schrock, Phys. Rev. D 24, 1275 (1981).

P. Kalyniak and J.N. Ng,
Phys. Rev. D 25, 1305 (1982).

M.S. Dixit et al., Phys. Rev. D 27, 2216 (1983).

Heavy sterile neutrino model
S.N. Gninenko, arXiv:1009.5536v3, Jan 2011

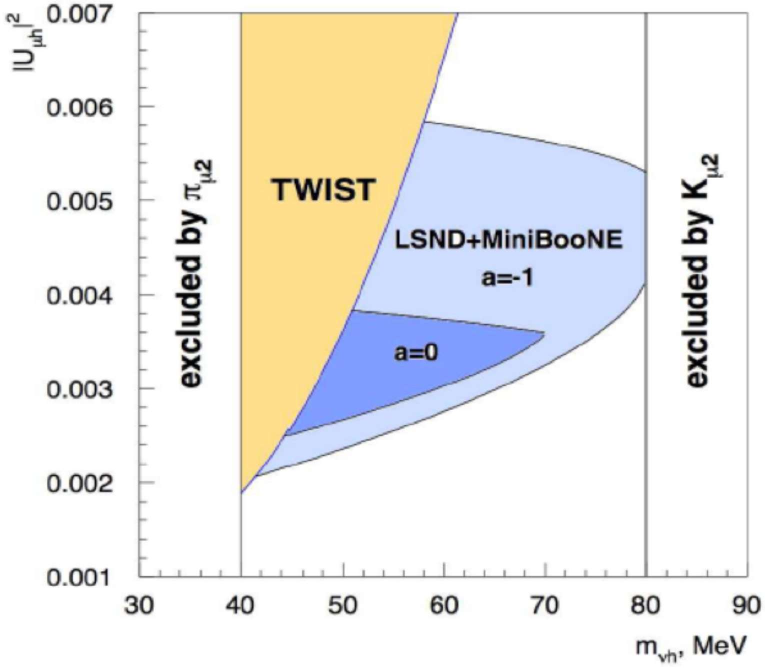


FIG. 24: The 2σ allowed region (dark areas) in the $(m_{\nu_h}; |U_{\mu h}|^2)$ parameter space obtained for different values of the asymmetry parameter a from the combined analysis of LSND and MiniBooNE ν_μ and $\overline{\nu}_\mu$ data. The areas excluded by the $\pi_{\mu 2}$ and $K_{\mu 2}$ decay experiments [45], and the exclusion region obtained in the present work from the results of precision measurements of the muon decay parameters by the TWIST experiment [50] are also shown; see Sec. VI.

Chiral Basis Weak Matrix Elements

- Description of Fetscher and Gerber (see PDG):

$$M = \frac{4G_F}{\sqrt{2}} \sum g^{\gamma}_{\epsilon\mu} \langle \overline{e_\epsilon} \Gamma^{\gamma} \nu_e \rangle \langle \overline{\nu_\mu} \Gamma_{\gamma} \mu_\mu \rangle$$

- Includes scalar, vector, and tensor (Γ^S,Γ^V,Γ^T) interactions among left- and right-handed μ. 19 real parameters.
- SM: $g^V_{LL}=1$, all others 0
- No derivative couplings $\Rightarrow g^T_{LL}, g^T_{RR} = 0$
- Probability for decay of μ–handed muon to ε–handed electron:

$$Q_{\epsilon\mu} = \frac{1}{4}|g^V_{\epsilon\mu}|^2 + |g^S_{\epsilon\mu}|^2 + 3(1-\delta_{\epsilon\mu})|g^T_{\epsilon\mu}|^2$$

Global Analysis of Muon Decay Data

μ decay parameters can be expressed as bilinear combinations of $g^{\gamma}_{\varepsilon\mu}$: $Q_{\varepsilon\mu}$, $B_{\varepsilon\mu}$, I_{α}, I_{β}

$$\rho = \frac{3}{4} + \frac{1}{4}(Q_{\mathrm{LL}} + Q_{RR}) - (B_{LR} + B_{RR})$$

$$\xi = 1 - Q_{RR} - \frac{10}{3} Q_{LR} + \frac{4}{3} Q_{RL} + \frac{16}{3}(B_{LR} - B_{RL})$$

$$\xi\delta = \frac{3}{4} - \frac{3}{2} Q_{RR} - \frac{7}{4} Q_{LR} + \frac{1}{4} Q_{RL} + (B_{LR} - B_{RL})$$

$$\textit{Therefore}\ Q_R^{\mu} = Q_{LR} + Q_{RR} = \frac{1}{2}\left(1 + \frac{\xi}{3} + \frac{16}{9}\xi\delta\right)$$

more positron polarization parameters ...

Allowed ranges of these coupling constants are then obtained by computing the joint probability density function from the experimental measurements.

Gagliardi et al, Phys Rev 72(2005)73002, A. Hillairet et al, Phys. Rev. D85 092013(2012)

Implications for the Weak Couplings

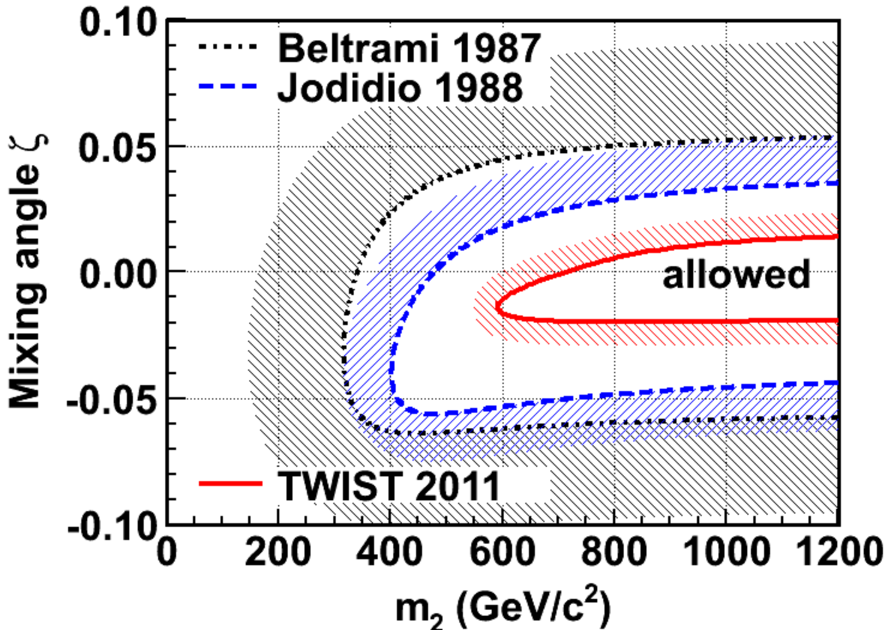
- The final **TWIST** results have been included in a new muon decay global analysis together with all previous muon decay parameter measurements
- Find significantly tighter 90% c.l. upper limits on the coupling of right-handed muons to right- or left-handed electrons:
  - $|g^S_{RR}| < 0.031$
  - $|g^V_{RR}| < 0.015$
  - $|g^S_{LR}| < 0.041$
  - $|g^V_{LR}| < 0.018$
  - $|g^T_{LR}| < 0.012$

  (g^S_{RR}, g^V_{RR}): Factor of ~2 smaller than pre-**TWIST** values

  (g^S_{LR}, g^V_{LR}, g^T_{LR}): Factor of ~3 smaller than pre-**TWIST** values
- New limit on right-handed muon couplings: $Q^{\mu}_{R} < 5.8\times10^{-4}$ **(90% c.l.)**
  - Factor of ~9 smaller than pre-**TWIST** value
- Uncertainty for η reduced by 1/3 compared to 2005 global analysis
  - $\eta = -0.0033 \pm 0.0046$
    - Important for the determination of G_F

Left-Right Symmetric Limit

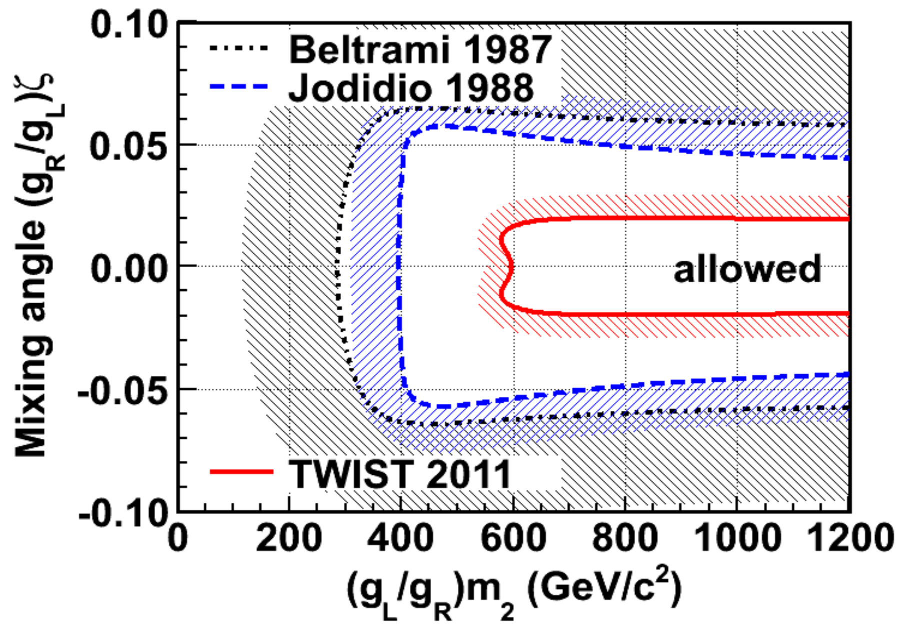
"manifest" LRS, 90%CL



$m_2 > 592$ GeV/c²

$-0.020 < \zeta < +0.017$

generalized or non-manifest LRS, 90%CL



$(g_L/g_R)m_2 > 578$ GeV/c²

$-0.020 < (g_R/g_L)\zeta < +0.020$

- Other **W'** direct search mass limits
  - ATLAS: >1.49 TeV/c², 95%CL (LLWI11)
  - CMS: >1.58 TeV/c², 95%CL (LLWI11)
  - CMS: >1.36 TeV/c², 95%CL (2011)
  - CDF: >1.12 TeV/c², 95%CL (2011)
  - D0: >1.0 TeV/c², 95%CL (2008)

- Other limits on mixing angle **ζ**
  - Hardy and Towner: <0.0005 (MLRS), <0.04 (generalized)
  - K decay: <0.004 (MLRS)

Electron spectrum from μ^-Al

- One week of data with μ^- beam
- Precise measure of muonic aluminum (μ^-Al) decay in orbit (DIO)
  - changes phase space, initial KE
  - competes with nuclear muon capture
- comparison with calculation
  - consistency above 53 MeV, but limited to p<75 MeV(below **μe** conversion signal)
  - mismatch near peak and excess events at lower energies.
- New calculation of DIO radiative corrections by Czarnecki *et al* in excellent agreement with our data. http://arxiv.org/abs/1406.3575

A. Grossheim *et al*. Phys. Rev. D 80, 052012 (2009)

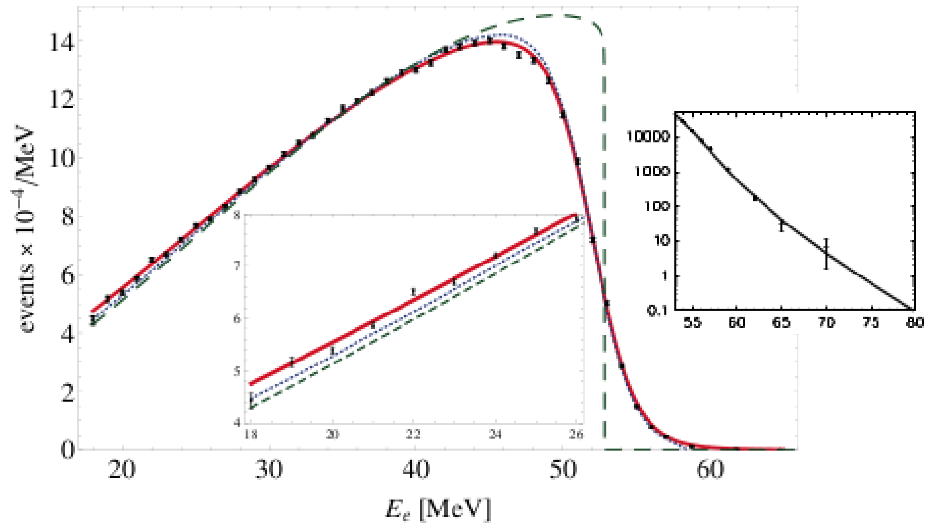
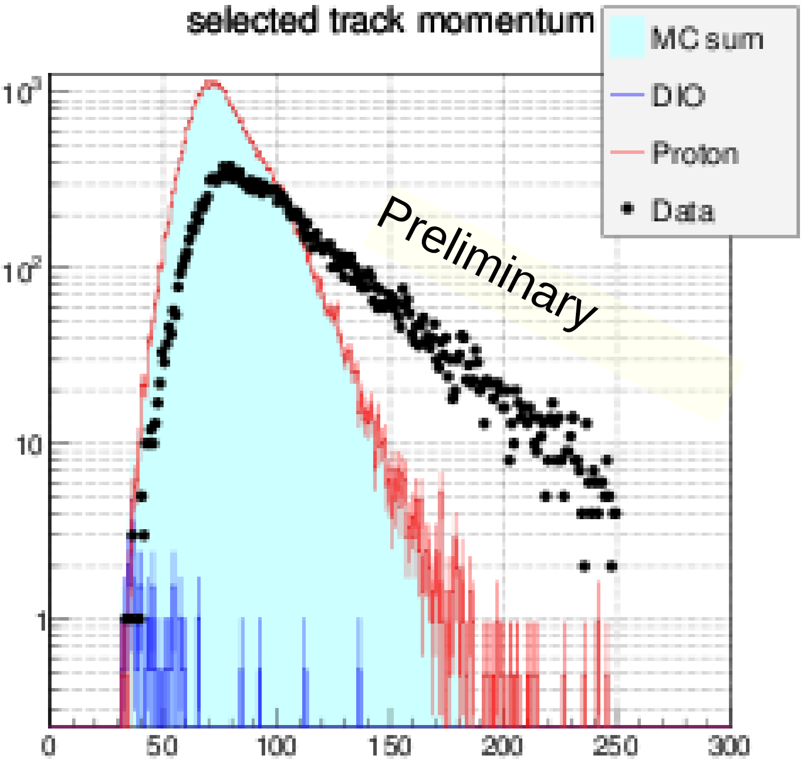


FIG. 2. Theoretical electron-energy spectra for muon DIO compared with TWIST data (black points) [18]. The solid red (dotted blue) line is the spectrum with (without, [17, 20]) $\mathcal{O}(\alpha)$ radiative corrections. The green dashed line represents the spectrum of the free muon decay with radiative corrections [32]. Near the free muon end point, 52.8 MeV, there is a large negative QED correction which pushes the dashed line to zero, and the solid line below the dotted one. In the low-energy region, magnified in the inset, both radiative (dashed) and binding (dotted) corrections are positive, leading to an increase of low-energy electrons. The solid line includes both effects.

Proton Spectrum from μ^-Al Capture

- Needed for mu→e (Fermilab, JPARC)
- Significant energy loss corrections are needed.
- Excess at high momenta from simulation used for background estimates.
- Work in progress incorporating PID for proton/deuteron discrimination.
- Andrei Gaponenko leading this work.



Summary and Outlook

- **TWIST** has significantly improved the measurements of ρ, δ, and $P^{\pi}_{\mu}\xi$. These results are in agreement with the Standard Model, in particular with maximal parity violation.
- Constraints on the weak couplings and LRS models are significantly improved.
- New inclusive bounds on $\mu \rightarrow eX^{o}$ including asymmetry dependence.
- μ^{-}Al decay spectrum tests bound state QED.
- Studies of charged particle emission following μ^{-}Al capture are in progress.
- I hope in the future to look at sidereal variations.