Results for muon decay parameters from *TWIST*

Glen Marshall, for the *TWIST* Collaboration
Université de Montréal, April 12, 2010

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TRIUMF

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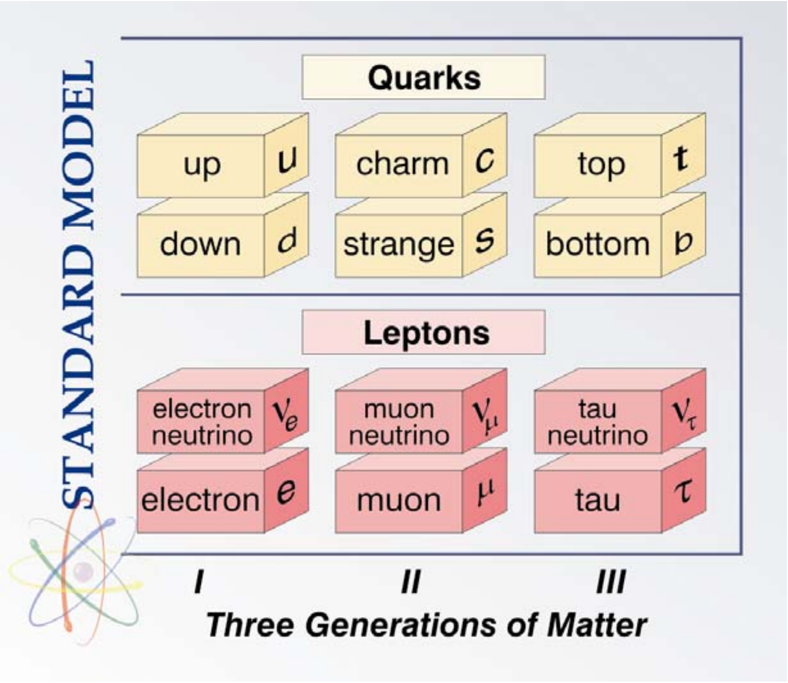
Outline

- Description of muon decay
  - coupling constants, decay parameters
- The experiment: how muon decay is measured
  - beam and detectors
- Data and analysis techniques
  - simulation and blind analysis
- Evaluation of systematic uncertainties
  - general approach and specific examples
- Presentation and interpretation of results
  - new results, comparisons with previous results, validity check, and consequences

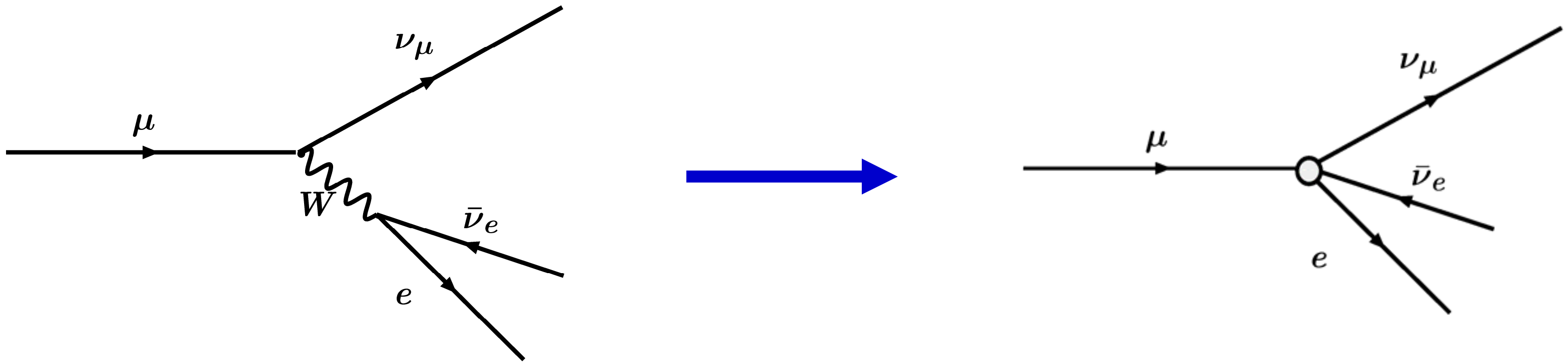
Description of Muon Decay

- Muons (μ^-, μ^+):
  - are **leptons**.
  - are not affected by strong interactions (***great*** for weak interaction tests!)



- Mass:
  - 105.658369(9) MeV/c^2
  - $200 \times m_e$, $1/9 \times m_p$
- Lifetime:
  - 2.197019(21) μs
- Decay:
  - E_e^{max} = 52.8 MeV
  - 99% $\mu \to e\bar{\nu}_e\nu_\mu$
  - $(1.4\pm0.4)\%$ $\mu \to e\bar{\nu}_e\nu_\mu\gamma$
  - $(3.4\pm0.4)\times 10^{-5}$ $\mu \to eee\bar{\nu}_e\nu_\mu$
- Spin:
  - ½
  - easily produced with high polarization.
  - $a_\mu \equiv (g_\mu - 2)/2 = 116592089(63) \times 10^{-10}$ (0.54 ppm)

Muon decay made simple



- Assume a four-fermion interaction that is:
  - Lorentz invariant
  - local
  - lepton-number-conserving
- Allows scalar, vector, or tensor;
  left or right; or combinations.

Matrix elements

- Description of Fetscher and Gerber (see PDG Review):

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

- Includes includes scalar, vector, and tensor (Γ^S,Γ^V,Γ^T) interactions among left- and right-handed μ, e.
- Probability for decay of μ–handed muon to ε–handed electron is easily expressed:

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

Coupling constants

- Coupling constants $g^\gamma_{\varepsilon\mu}$ can be related to handedness, *e.g.*, total muon right-handed coupling:

$$
\begin{aligned}
Q_R^\mu &\equiv Q_{RR} + Q_{LR} \\
&= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2
\end{aligned}
$$

- Global analysis from PDG2004 for pre-*TWIST* results
  - in parentheses, Gagliardi *et al.*, PRD **72**, 073002 (2005)

$\lvert g^S_{RR}\rvert < 0.066(0.067)$	$\lvert g^V_{RR}\rvert < 0.033(0.034)$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125(0.088)$	$\lvert g^V_{LR}\rvert < 0.060(0.036)$	$\lvert g^T_{LR}\rvert < 0.036(0.025)$
$\lvert g^S_{RL}\rvert < 0.424(0.417)$	$\lvert g^V_{RL}\rvert < 0.110(0.104)$	$\lvert g^T_{RL}\rvert < 0.122(0.104)$
$\lvert g^S_{LL}\rvert < 0.550(0.550)$	$\lvert g^V_{LL}\rvert > 0.960(0.960)$	$\lvert g^T_{LL}\rvert \equiv 0$

Muon decay parameters and coupling constants

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

$$\eta = \frac{1}{2}\mathbb{R}e[g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})]$$

$$\xi = 1 - \frac{1}{2}\left|g^S_{LR}\right|^2 - \frac{1}{2}\left|g^S_{RR}\right|^2 - 4\left|g^V_{RL}\right|^2 + 2\left|g^V_{LR}\right|^2 - 2\left|g^V_{RR}\right|^2$$
$$+2\left|g^T_{LR}\right|^2 - 8\left|g^T_{RL}\right|^2 + 4\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

$$\xi\delta = \frac{3}{4} - \frac{3}{8}\left|g^S_{RR}\right|^2 - \frac{3}{8}\left|g^S_{LR}\right|^2 - \frac{3}{2}\left|g^V_{RR}\right|^2 - \frac{3}{4}\left|g^V_{RL}\right|^2 - \frac{3}{4}\left|g^V_{LR}\right|^2$$
$$-\frac{3}{2}\left|g^T_{RL}\right|^2 - 3\left|g^T_{LR}\right|^2 + \frac{3}{4}\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

Decay parameter description

◎ Muon decay ("Michel") parameters ρ, η, $\mathcal{P}_\mu\xi$, δ

Louis Michel

⊙ muon differential decay rate *vs.* energy and angle:

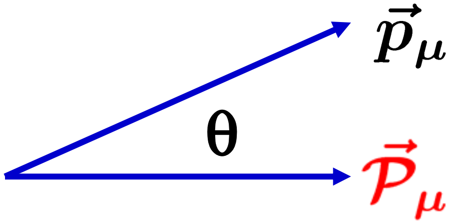
$$\frac{d^2\Gamma}{dx\; d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot \{\mathcal{F}_{IS}(x, \rho, \eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x, \xi, \delta)\} + R.C.$$

⊙ where

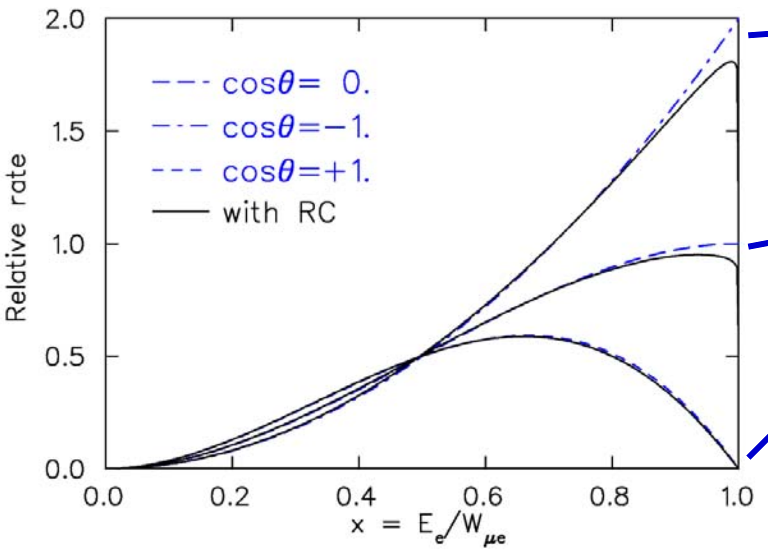
$$\mathcal{F}_{IS}(x, \rho, \eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

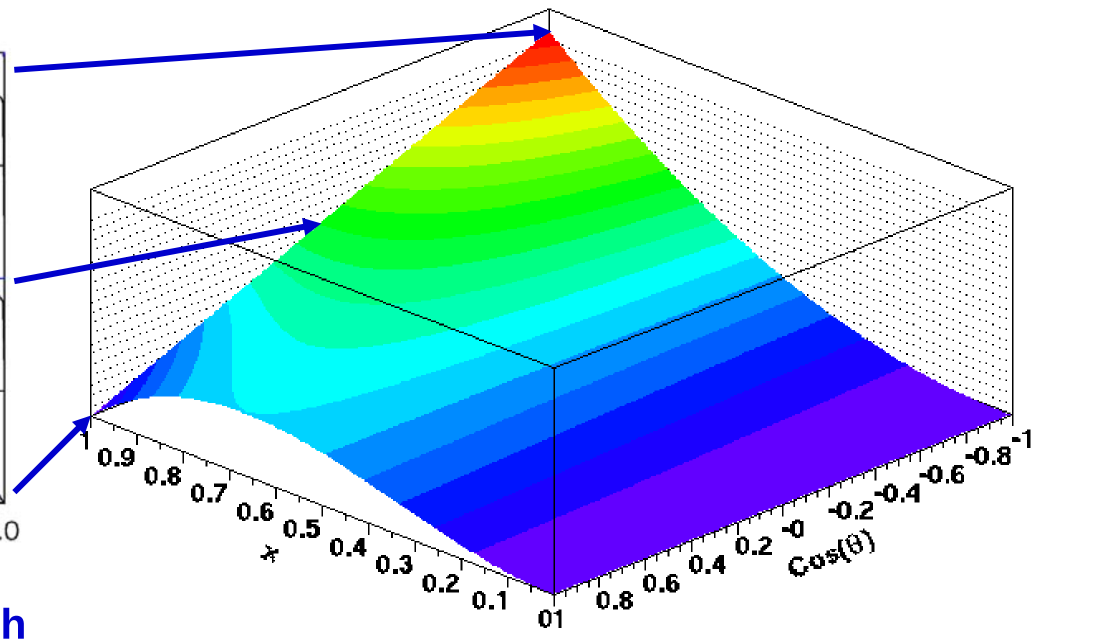
$$\mathcal{F}_{AS}(x, \xi, \delta) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right]$$

and $W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$, $x = \frac{E_e}{W_{\mu e}}$, $x_0 = \frac{m_e}{W_{\mu e}}$.



Decay spectrum shape, graphically





- Full $\mathcal{O}(\alpha)$ radiative corrections with exact electron mass dependence.
- Leading and next-to-leading logarithmic terms of $\mathcal{O}(\alpha^2 L^2)$ and $\mathcal{O}(\alpha^2 L)$, $L=\ln((m_\mu/m_e)^2)$
- Leading logarithmic terms of $\mathcal{O}(\alpha^3 L^3)$.
- Ignores $\mathcal{O}(\alpha^2 L^0)$ (2007).

K. Melnikov, J. High Energy Phys. (09):014 (2007)
A. Arbuzov, J. High Energy Phys. 2003(03):063 (2003)
A. Arbuzov et al., Phys. Rev. D66, 93003 (2002)
A. Arbuzov et al., Phys. Rev. D65, 113006 (2002)

Pre-*TWIST* decay parameters

- From the Review of Particle Physics (SM values)
  - ρ = 0.7518 ± 0.0026 (Derenzo, 1969) (0.75)
  - δ = 0.7486 ± 0.0026 ± 0.0028 (Balke *et al.*, 1988) (0.75)
  - $\mathcal{P}_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (Beltrami *et al.*, 1987) (1.00)
  - $\mathcal{P}_\mu(\xi\delta/\rho)$ > 0.99682 (90%CL) (Jodidio *et al.*, 1986) (1.00)
  - η = -0.007 ± 0.013 (Burkard *et al.*, 1985) (0.00)

The goal of *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 one order of magnitude compared to prior experimental results.

Early history of μ decay

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

E. P. Hincks and B. Pontecorvo
National Research Council of Canada, Chalk River Laboratory, Chalk River, Ontario, Canada

July 26, 1948

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

'SICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

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.

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.

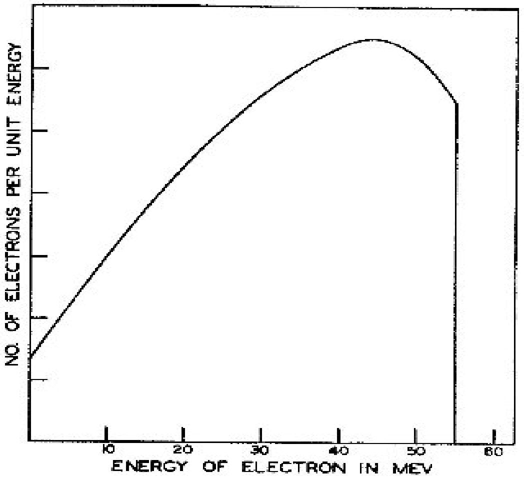
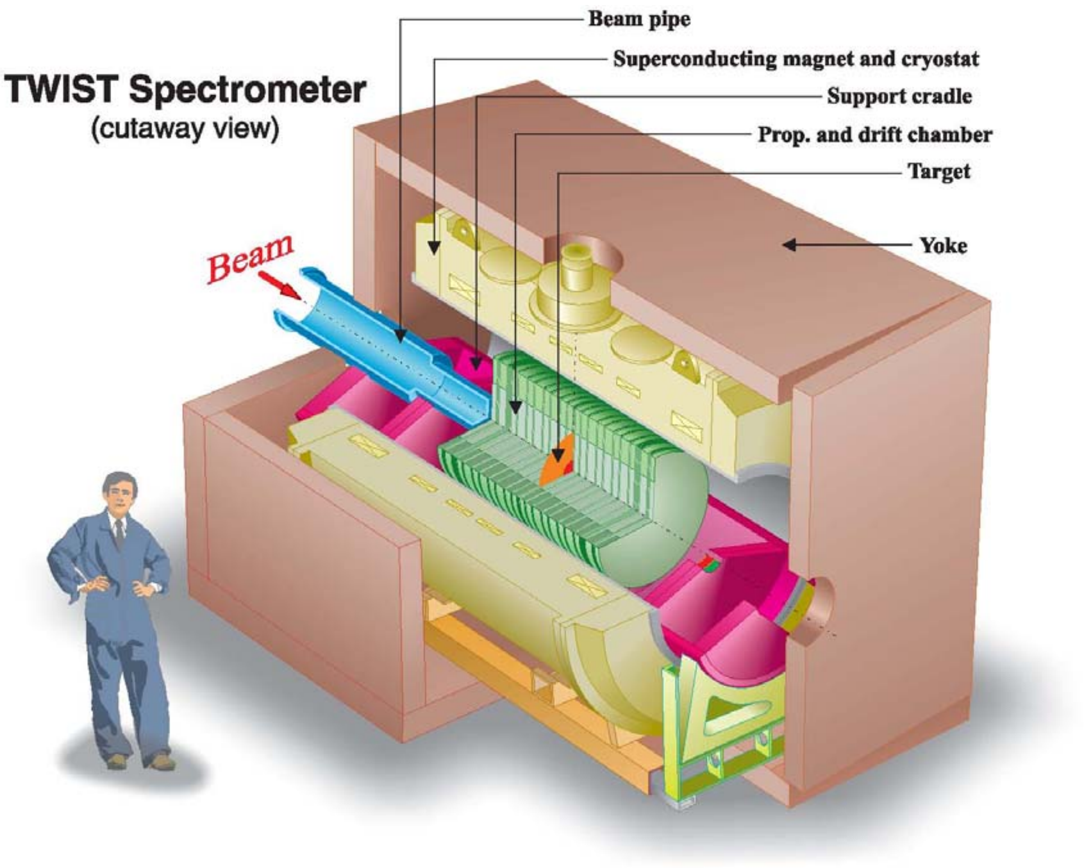


Fig. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.

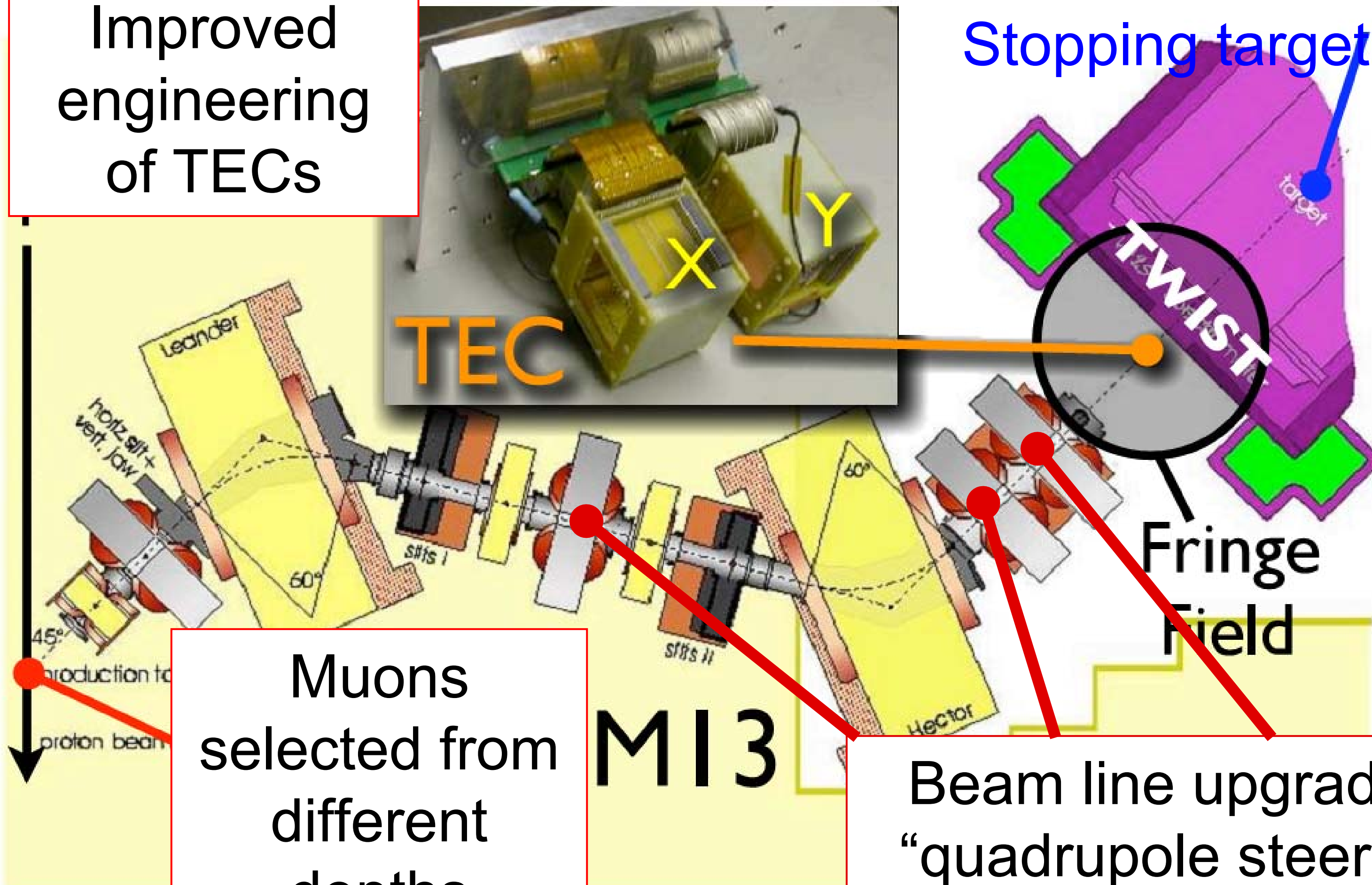
The TRIUMF Weak Interaction Symmetry Test

- Uses highly polarized μ^+ beam from M13.
- Stops μ^+ in a very symmetric detector.
- Tracks e^+ through uniform, well-known field.
- Completed data taking in 2007.
- Extracts decay parameters by comparison to detailed GEANT3 simulation.



Muon production and transport

Improved engineering of TECs

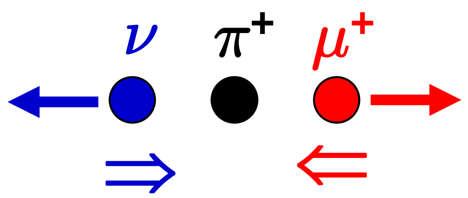


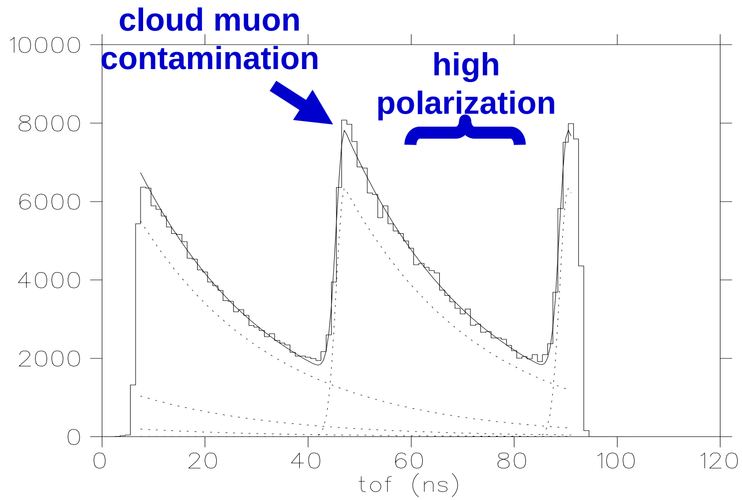
Muons selected from different depths

Beam line upgraded: “quadrupole steering” added

Surface muon beam

- Pions decaying at rest produce muon beams with $\mathcal{P}_\mu > 99\%$.
- Depolarization must be controlled using small beams near kinematic edge, 29.8 MeV/c.
- Use $\sim 4 \times 10^3\ \mu^+\ s^{-1}$.
- Muon total range at density $\sim$1 only about 1.5 mm!

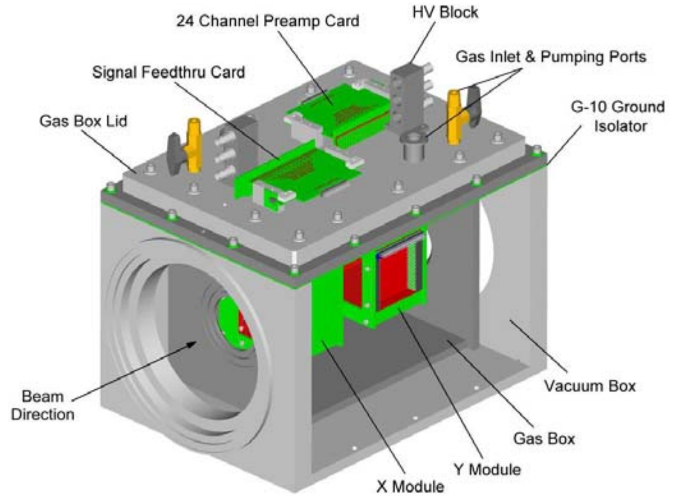


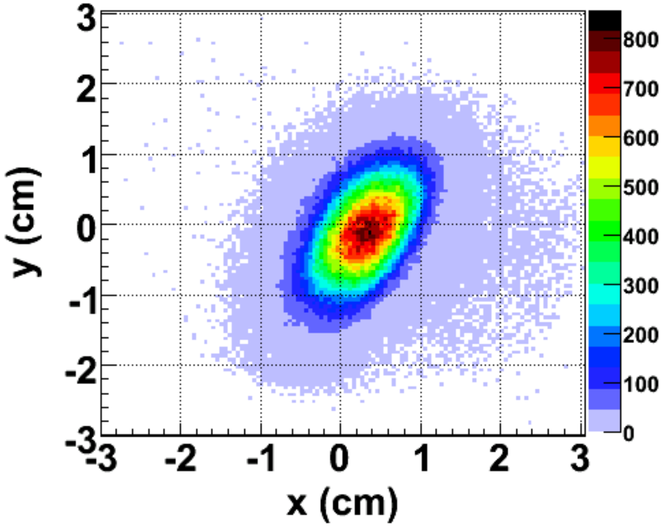


TEC beam characterization

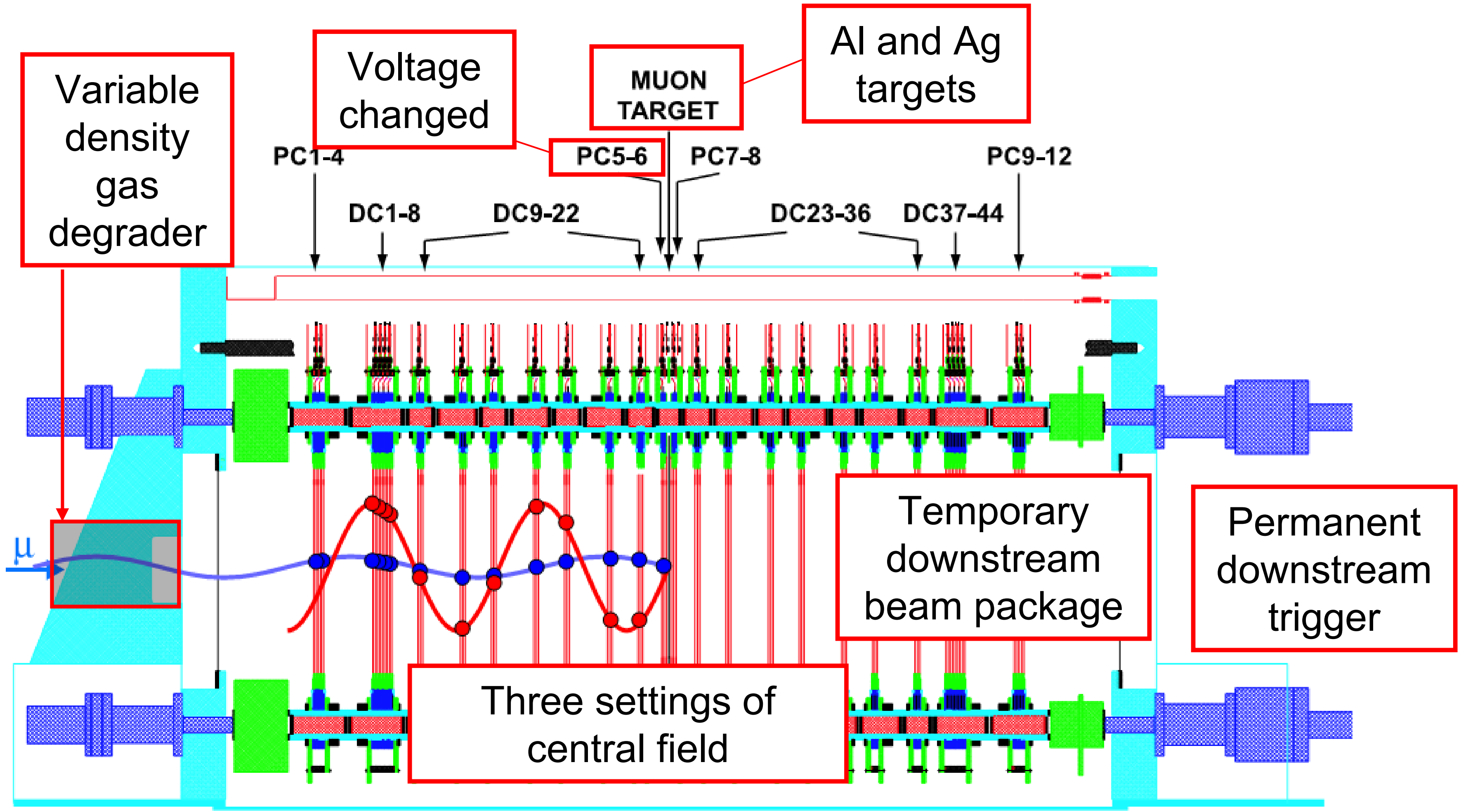
- Need to know x, y, θ_x, θ_y, and correlations, for incident muon beam.
- Measure in two modules of low pressure (80 mbar) time expansion chambers (TEC).
- "Correct" for multiple scattering ($\sim$ 20 mrad rms).
- Simulate by sampling corrected distributions.
- Decay parameters measured with TEC removed; multiple scattering reduces polarization.

J. Hu et al., NIM A566 (2006) 563-574





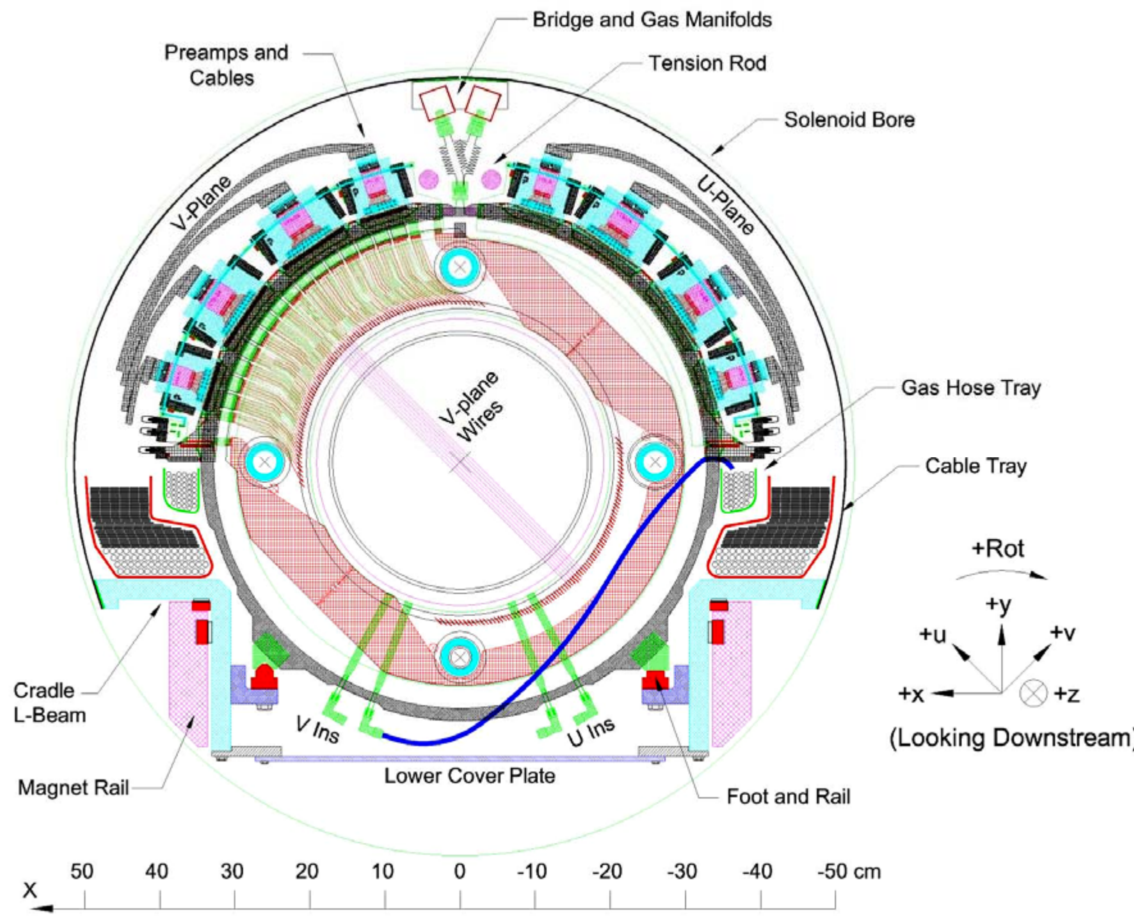
Detector array



R. Henderson et al., Nucl. Instr. and Meth. A548 (2005) 306-335

Detector precision

- Longitudinal precision of wire planes: 30 μm over 1 m detector length
  ➔ 3 × 10^{-5}
- Transverse precision of wire spacing: 3.3 μm rms for 4 mm cell size
  ➔ 8 × 10^{-4}
- Low mass
- Field uniformity:
  ➔ 4 × 10^{-3}
- Field map precision:
  ➔ 5 × 10^{-5}
- Slow control monitor/control (e.g., dipole fields, temperature, atmospheric pressure)



Cradle with detector array

Data and Analysis

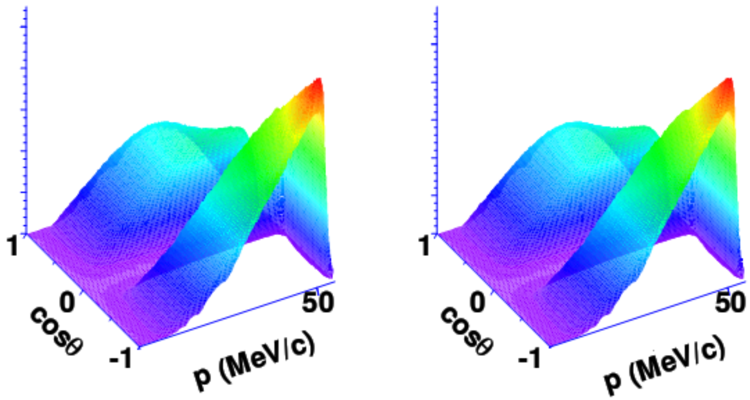
- Data obtained in 2006 (Ag target) and 2007 (Al target)
  - total events: $\mathbf{11\times10^9}$
  - after quality checks, cuts, and selections: $\mathbf{0.55\times10^9}$
  - roughly divided between Ag and Al
- Simulation: $\sim \times\mathbf{2.7}$ compared to data statistics
  - custom GEANT3 contains detailed physical processes
  - produces "data" exactly as experiment does, plus MC "truth"
- Other systematic test data and many simulation systematics tests
  - different beam situations, stopping distributions, physics processes in simulation

Treatment of data

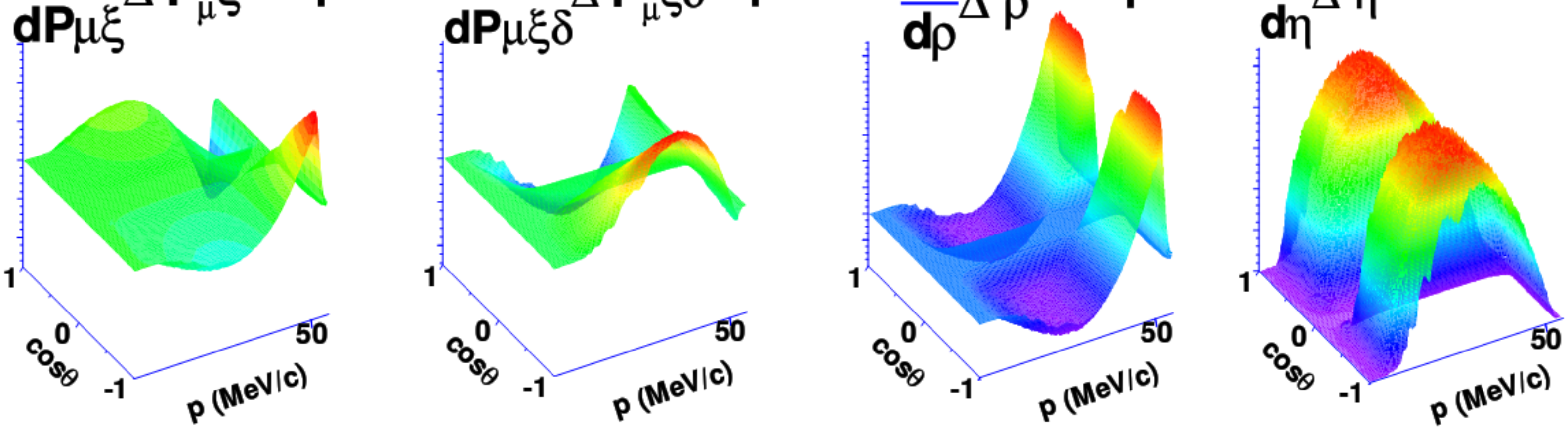
- Event reconstruction
  - event identification by event topology
    - primarily using PC information (time resolution)
  - two-stage track reconstruction
    - pattern recognition; hits approximate a helix
    - high-precision helix fit using drift times
- Event selection
  - trigger information (muon TOF)
  - event topology selection (event type cut)
  - muon stop selection (last plane hit, radius, PC5/6 energy)
  - track selection: charge, direction, vertex at target, decay time

Analysis: fit to simulation (MCfit)

$$d\Gamma_{data}(\lambda) \quad - \quad d\Gamma_{MC}(\lambda_{MC})$$



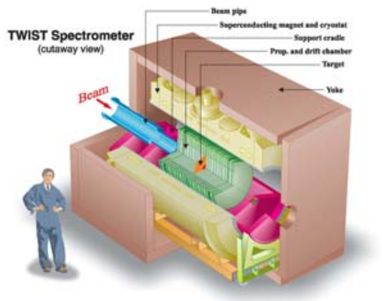
$$= \frac{d\Gamma}{dP_\mu\xi}\Delta P_\mu\xi \quad + \quad \frac{d\Gamma}{dP_\mu\xi\delta}\Delta P_\mu\xi\delta \quad + \quad \frac{d\Gamma}{d\rho}\Delta\rho \quad + \quad \frac{d\Gamma}{d\eta}\Delta\eta$$



- fit data to normalized GEANT3 simulation distribution is linear in $\mathcal{P}_\mu\xi$, $\mathcal{P}_\mu\xi\delta$, ρ, η
- Use η measured by other means, rather than fit it (3 parameters in fit)

Blind analysis

Hidden parameters; ρ_{MC}, δ_{MC}, $\mathcal{P}_{\mu}\xi_{MC}$



Data from experiment

Hidden parameter tolerances 0.01

"Data" from simulation

Reconstruction software

MCfit spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta\mathcal{P}_{\mu}\xi$

Add to hidden parameters; ρ, δ, $\mathcal{P}_{\mu}\xi$

Systematic estimation

Simulation

Modified simulation

Reconstruction software

MCfit spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta\mathcal{P}_\mu\xi$

Scale; **d(ρ, δ, $\mathcal{P}_\mu\xi$)/d(modification)**

Systematic uncertainties

Where we were before this analysis

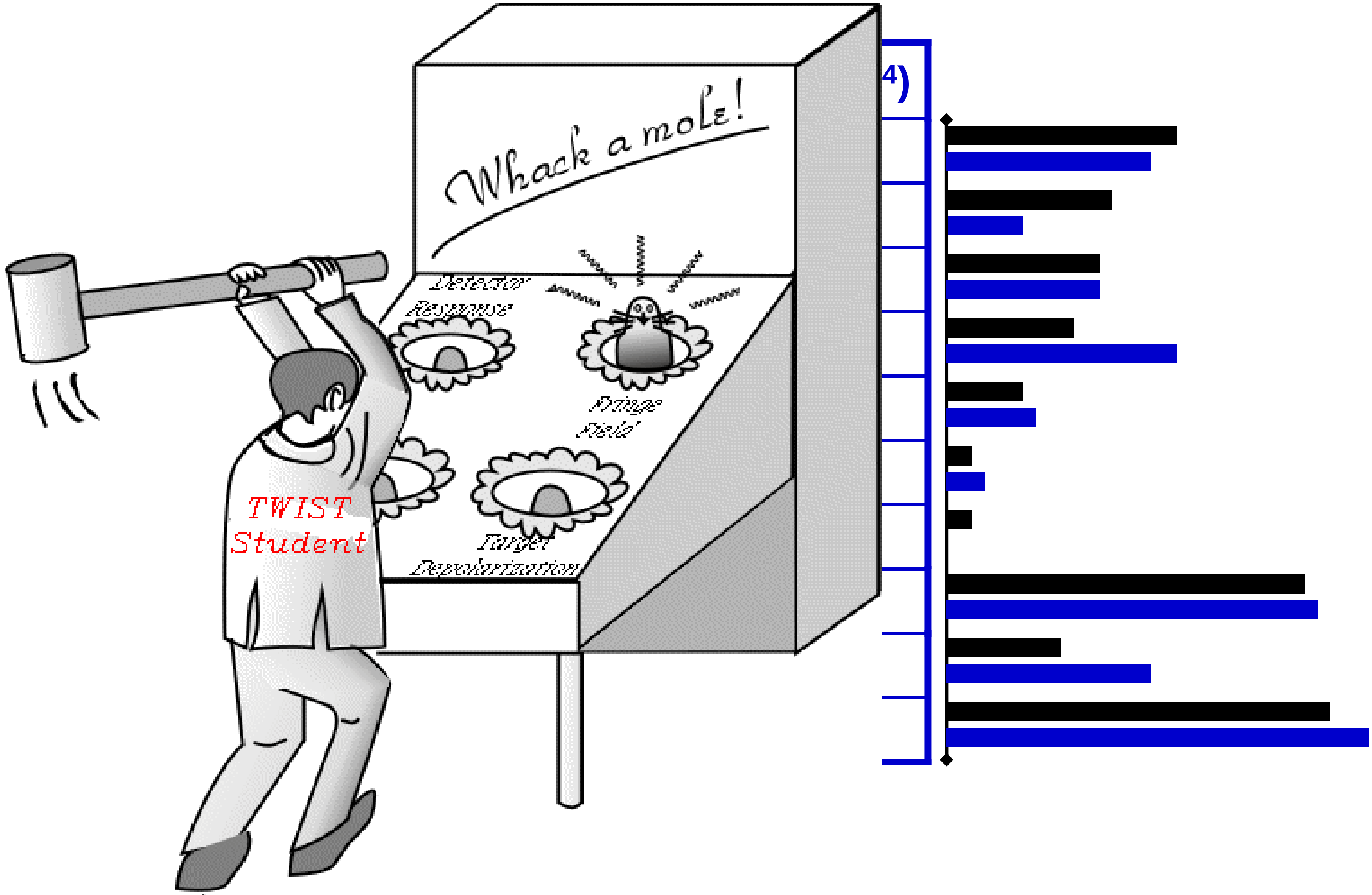
	Published ($\times 10^{-4}$) Statistical	Published ($\times 10^{-4}$) Systematic	Improvement factor vs pre-*TWIST*
ρ	1.7	4.4	$\times 5$
δ	3.0	6.7	$\times 5$
$\mathcal{P}_\mu \xi$	6.0	38	$\times 2$

Intermediate *TWIST* results have been published based on 2004 data:

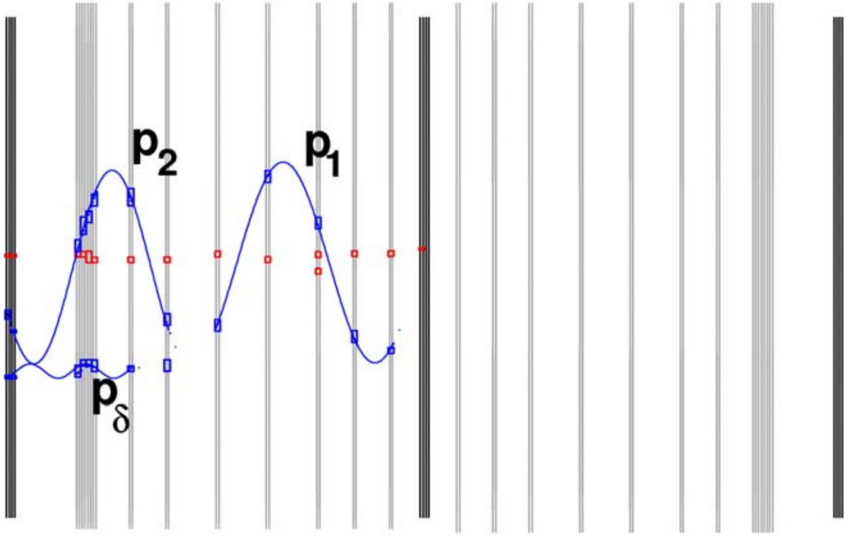
B. Jamieson et al., Phys. Rev. D 74 (2006) 072007

R.P. MacDonald et al., Phys. Rev. D 78 (2008) 032010

Improved ρ and δ uncertainties



Positron interactions



“Broken tracks” analysis:

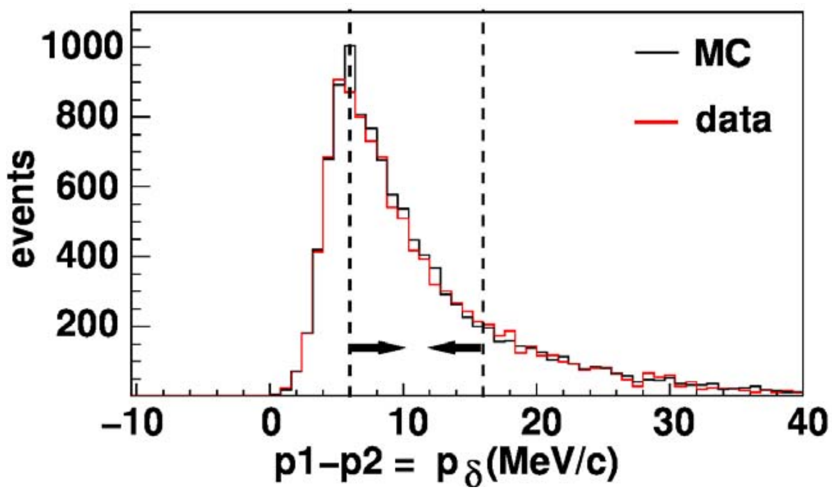
$2e^+$, 1 e^- $\equiv$ δ-electron

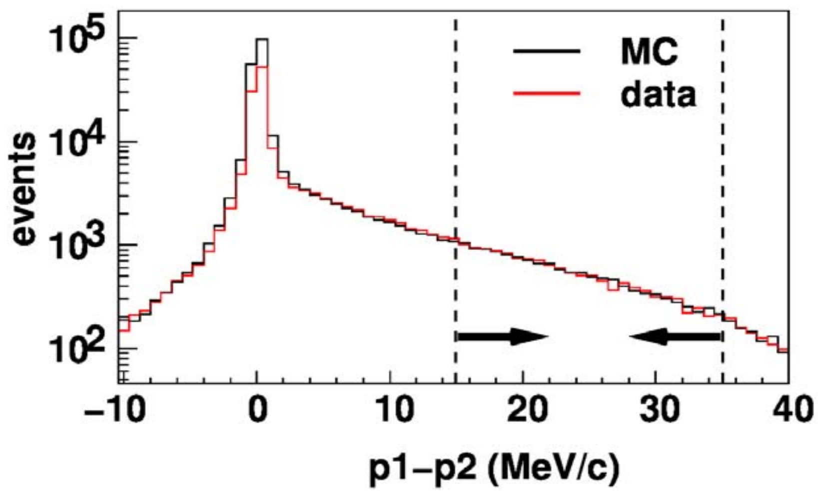
2 e^+ $\equiv$ Bremsstrahlung

Agreement of data and sim:

δ-electrons < 1%

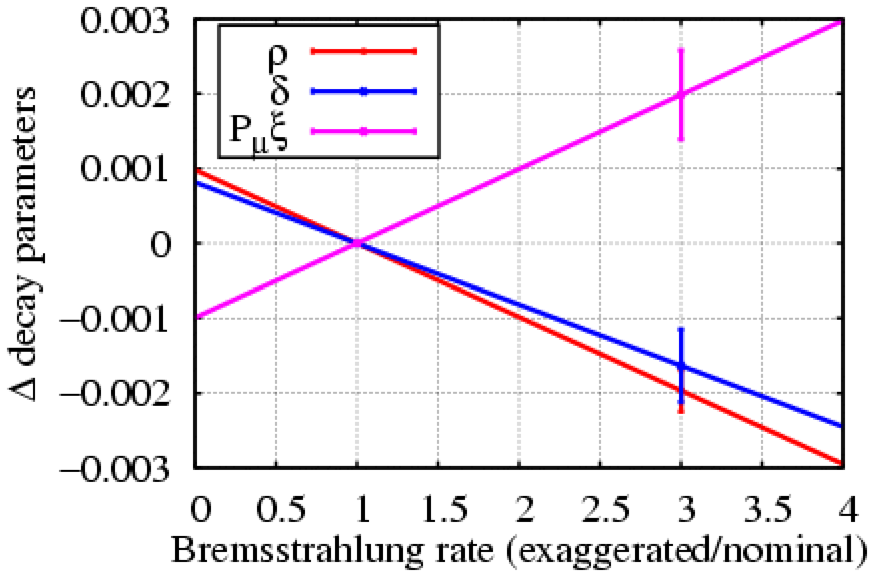
Bremsstrahlung differs by 2.4%



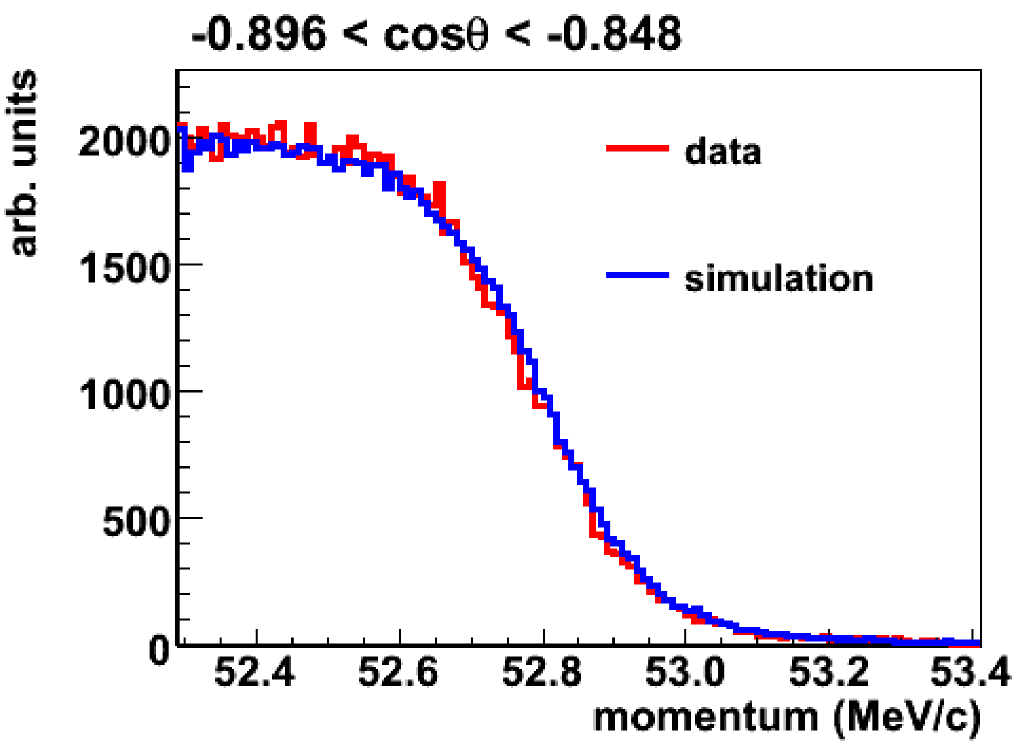


Systematics via exaggeration

- Bremsstrahlung example
  - exaggerate: adjust (with care!) the rate in the simulation
  - compare simulated runs, exaggerated vs. normal, to assess effects of increase on decay parameters
  - compare normal simulation with data to assess difference in brem
  - evaluate difference in terms of decay parameter uncertainties



Momentum calibration



- Use kinematic edge at 52.8 MeV/c: energy loss and planar geometry lead to cosθ dependence.

- Difference of $\sim$10 keV/c prior to calibration.

- Calibration at edge provides no guidance on how to propagate the difference to lower momenta in the spectrum.

Momentum calibration

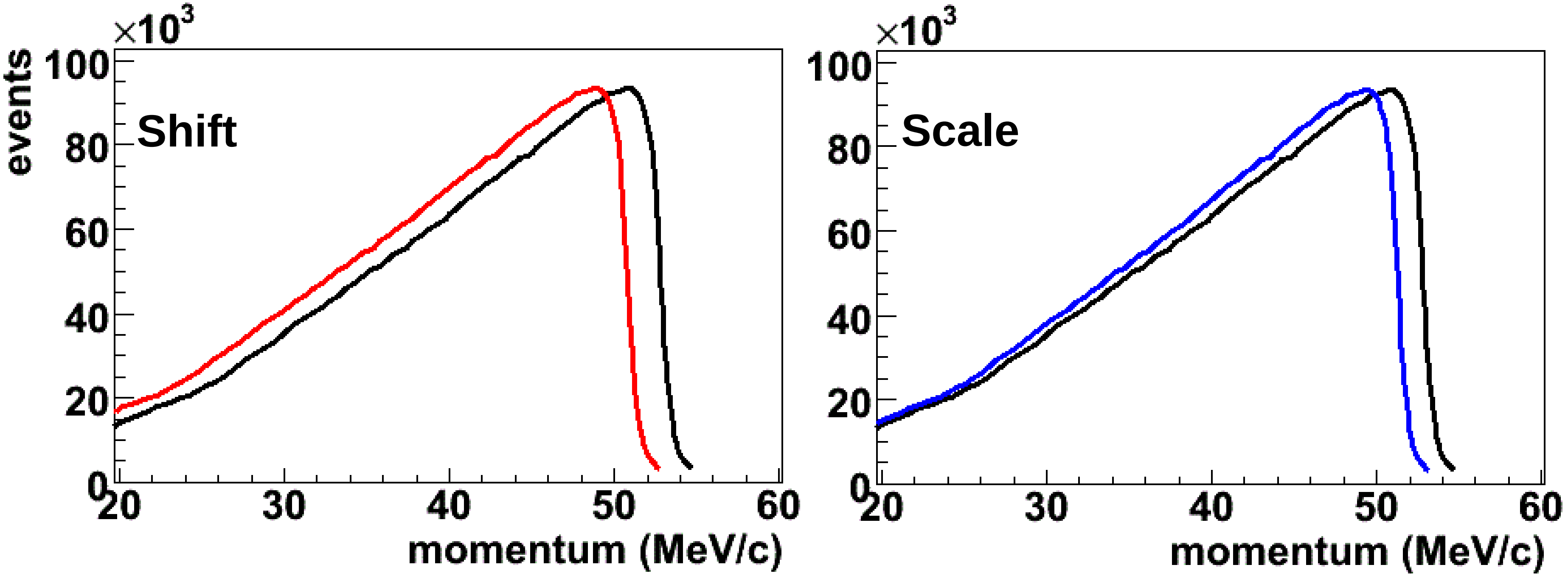
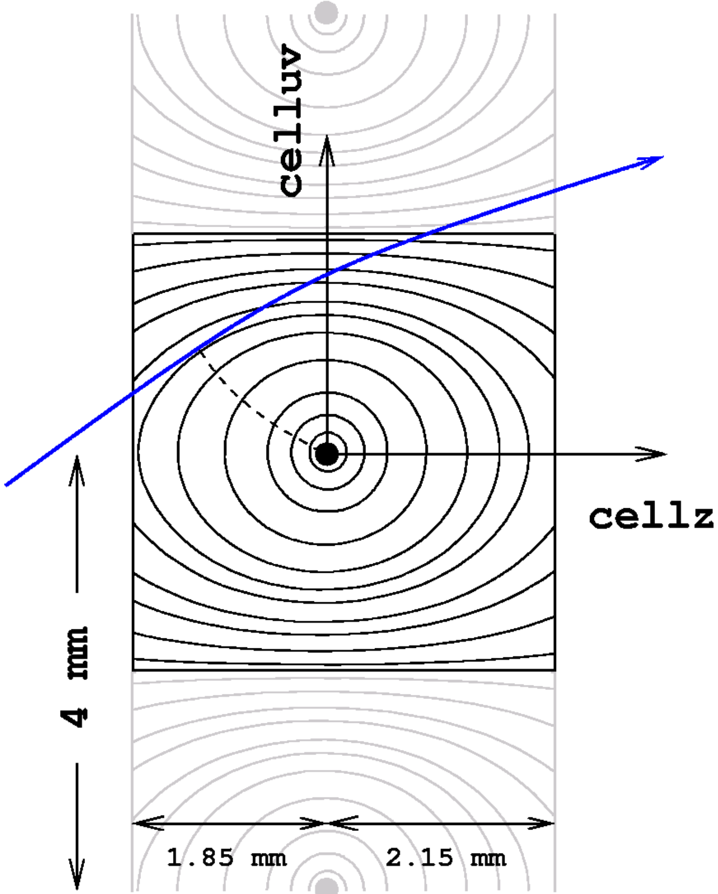


Illustration of shift vs. scale:

Difference leads to uncertainties of

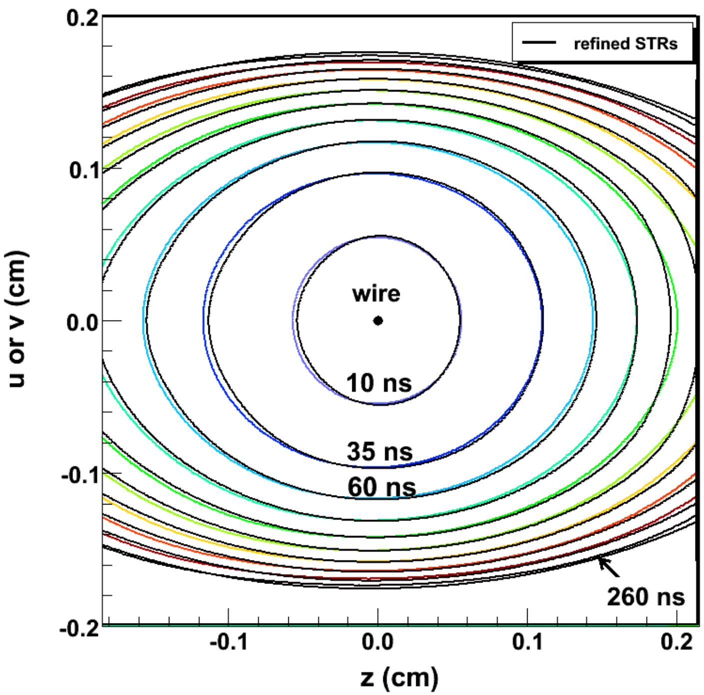
$\delta(\rho) = 1.0\times10^{-4}$ and $\delta(\delta) = 1.1\times10^{-4}$.

Chamber response



Space-time relations (STRs) are calibrated with data for data analysis, or simulation for MC analysis, to include common biases.

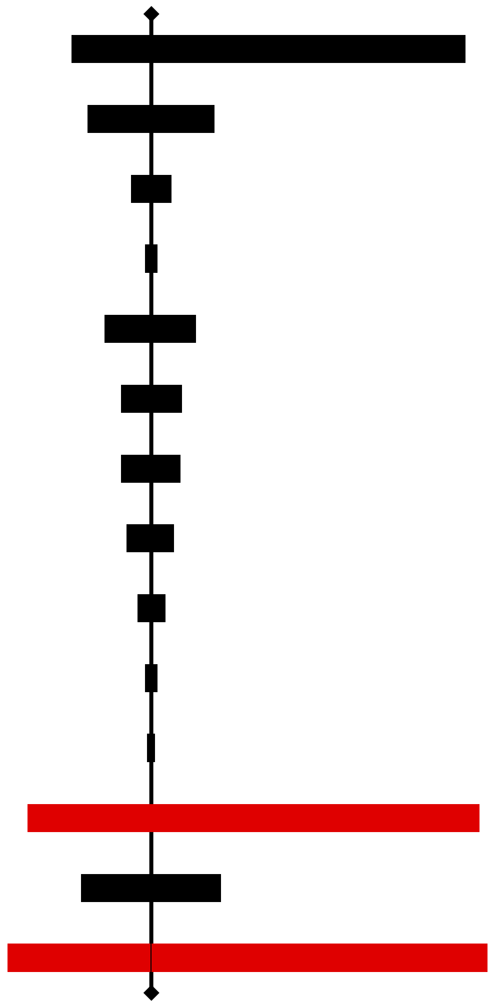
Isochrones from calibrated STRs can account for detector plane geometry differences in data and biases in helix fitting.



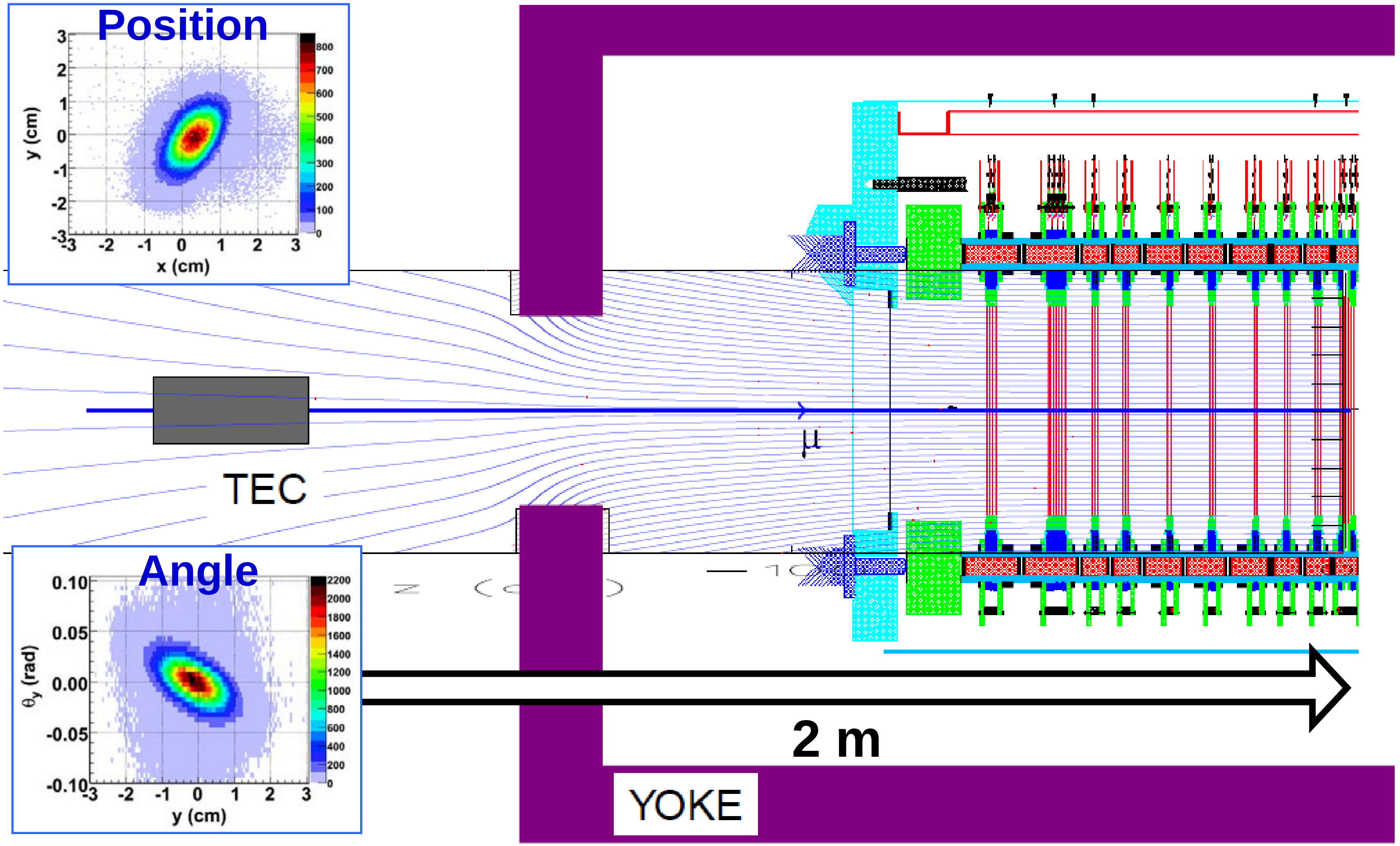
A. Grossheim et al., submitted to NIM

Improved $\mathcal{P}_{\mu}\xi$ uncertainties

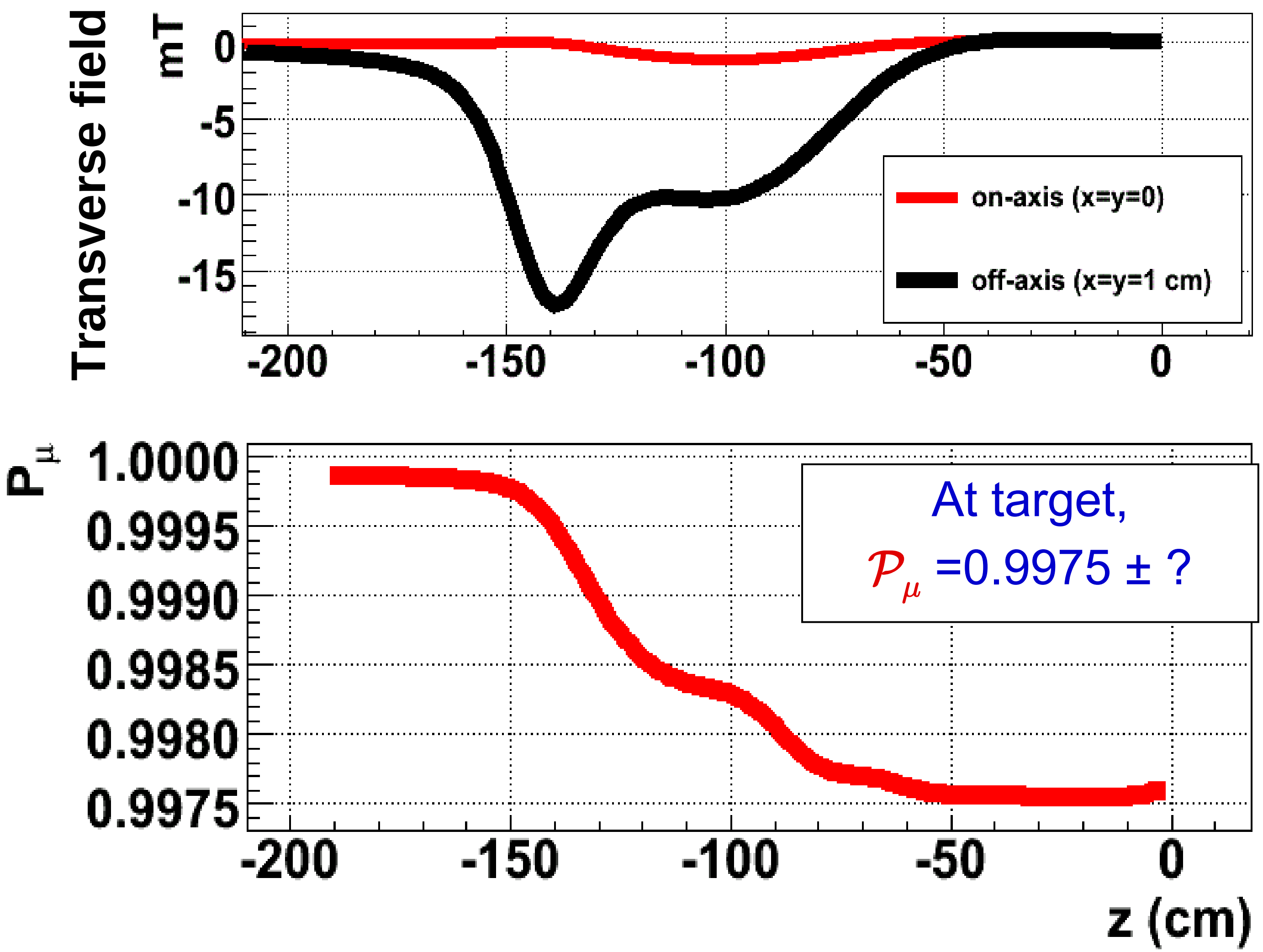
Uncertainties	$\mathcal{P}_{\mu}\xi$ ($\times 10^{-4}$)
Depolarization in fringe field	+15.8, -4.0
Depolarization in stopping material	3.2
Background muons	1.0
Depolarization in production target	0.3
Chamber response	2.3
Resolution	1.5
Momentum calibration	1.5
External uncertainties	1.2
Positron interactions	0.7
Beam stability	0.3
Spectrometer alignment	0.2
Systematics in quadrature	*+16.5, -6.2*
Statistical uncertainty	3.5
Total uncertainty	*+16.9, -7.2*



Fringe field, solenoid entrance



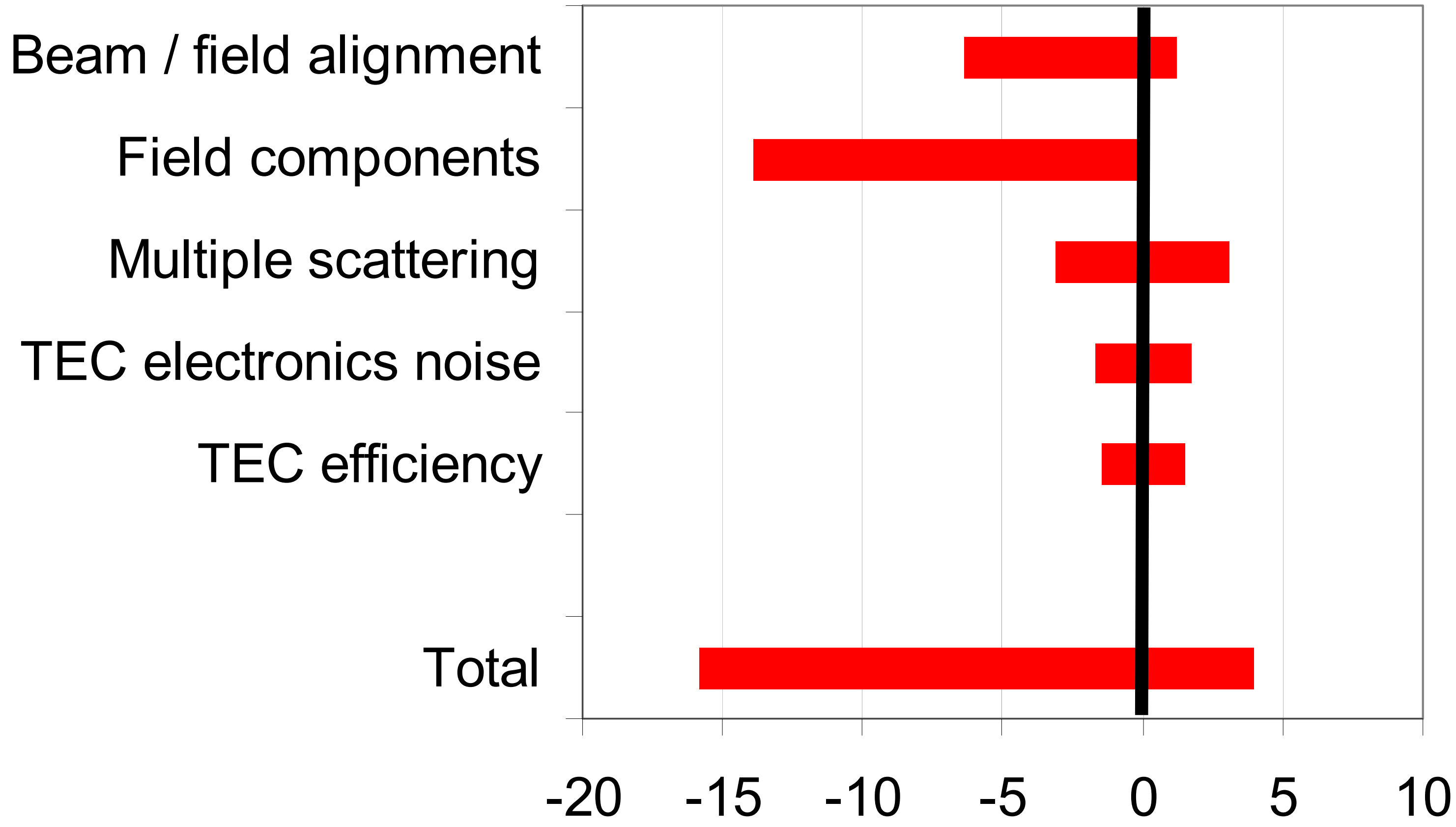
Transverse field and depolarization



At target,

$\mathcal{P}_\mu$ =0.9975 ± ?

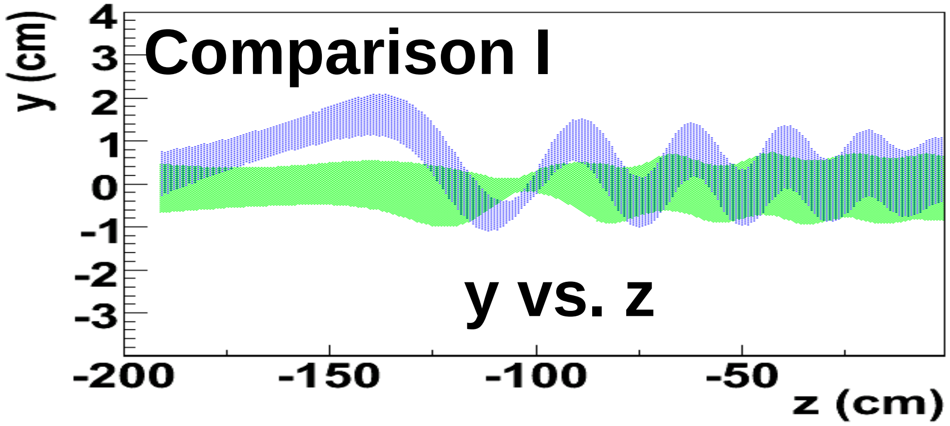
Fringe field systematics summary

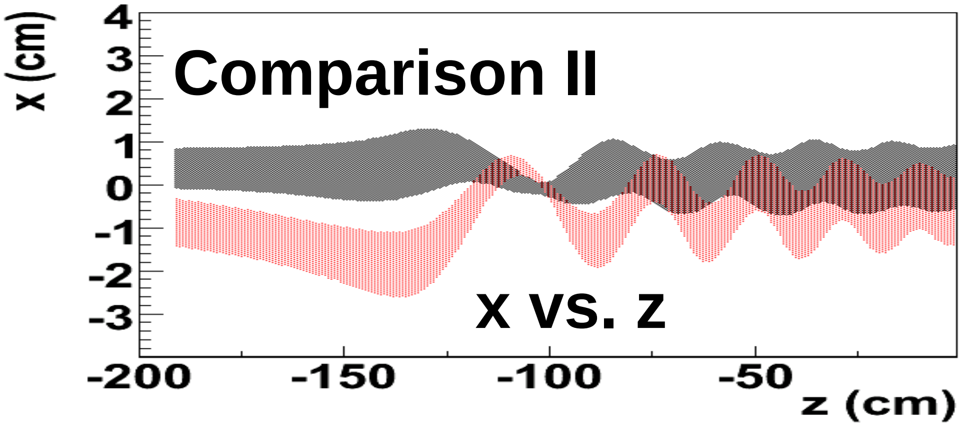


Polarization uncertainty in simulation (units 10^{-4})

(note sign is opposite to uncertainty in result)

Fringe field and mis-steered beam





Move beam away from optimum position and/or angle to observe change in polarization:

- Comparison I: steer in θ_y by 28 mrad.

➔ $\Delta\mathcal{P}_\mu = -105 \pm 9 \times 10^{-4}$

- Comparison II: steer in x by 10 mm and in θ_x by 10 mrad.

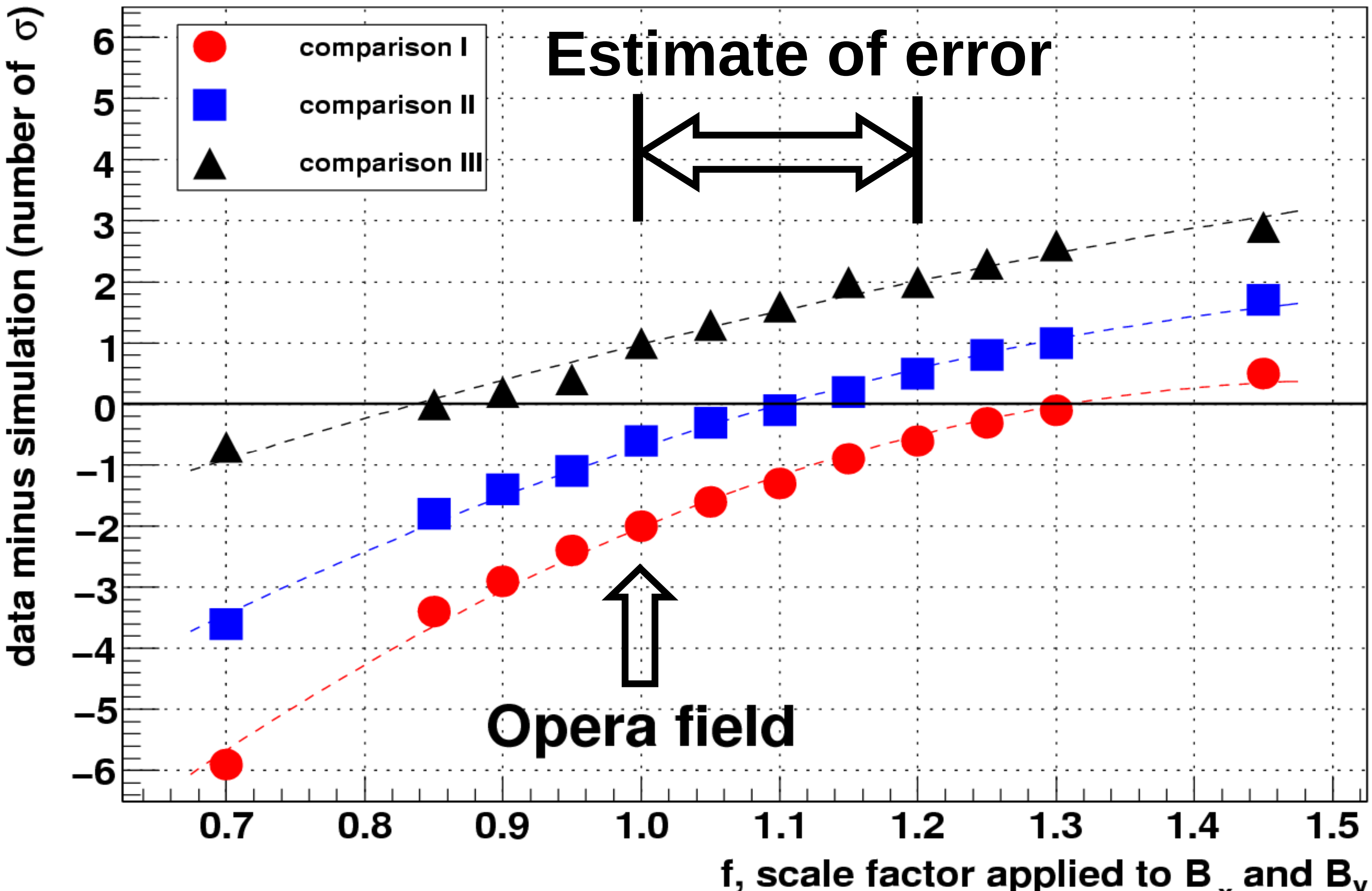
➔ $\Delta\mathcal{P}_\mu = -62 \pm 8 \times 10^{-4}$

- Comparison III: leave TEC in to introduce scattering.

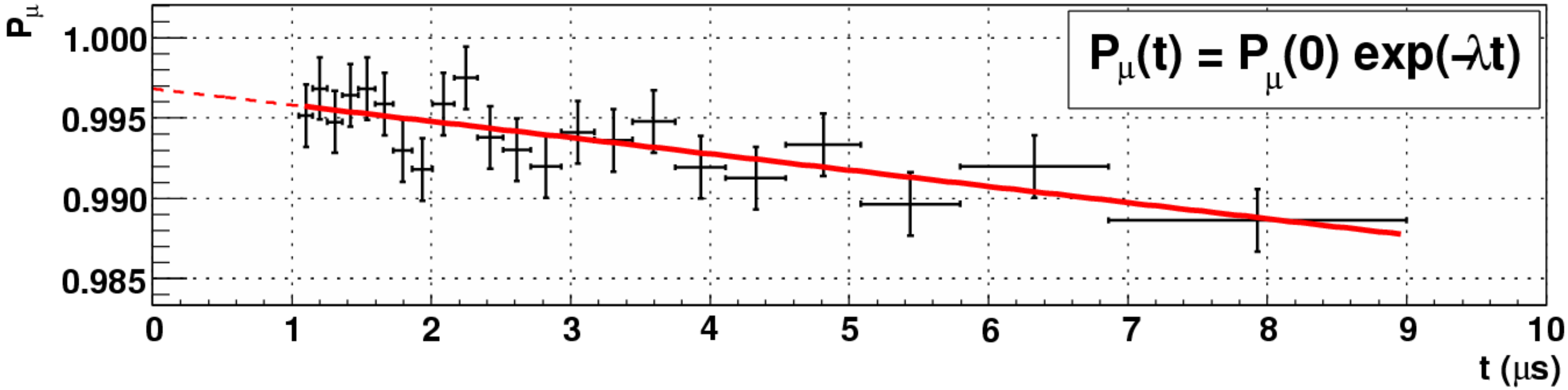
➔ $\Delta\mathcal{P}_\mu = -18 \pm 9 \times 10^{-4}$

Compare these differences with simulation to check fringe field systematic.

Estimating field component effects

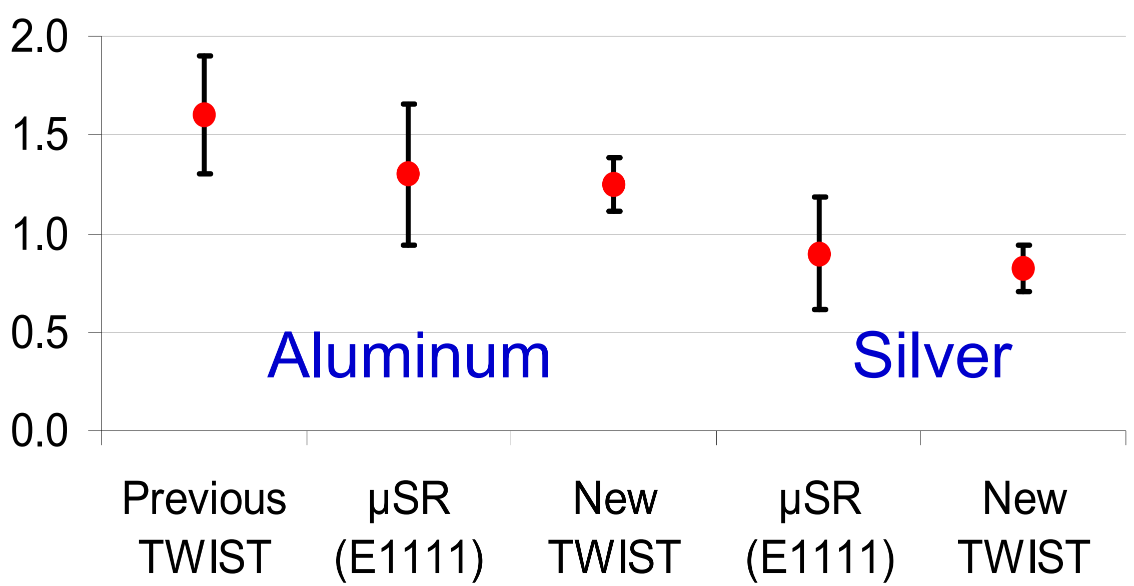


Depolarization in target material

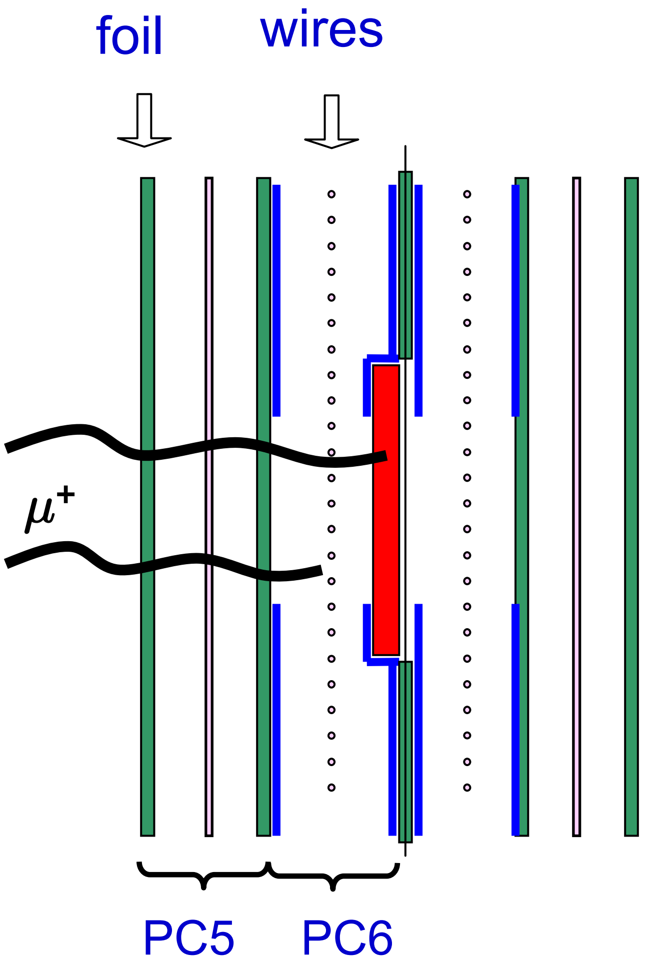


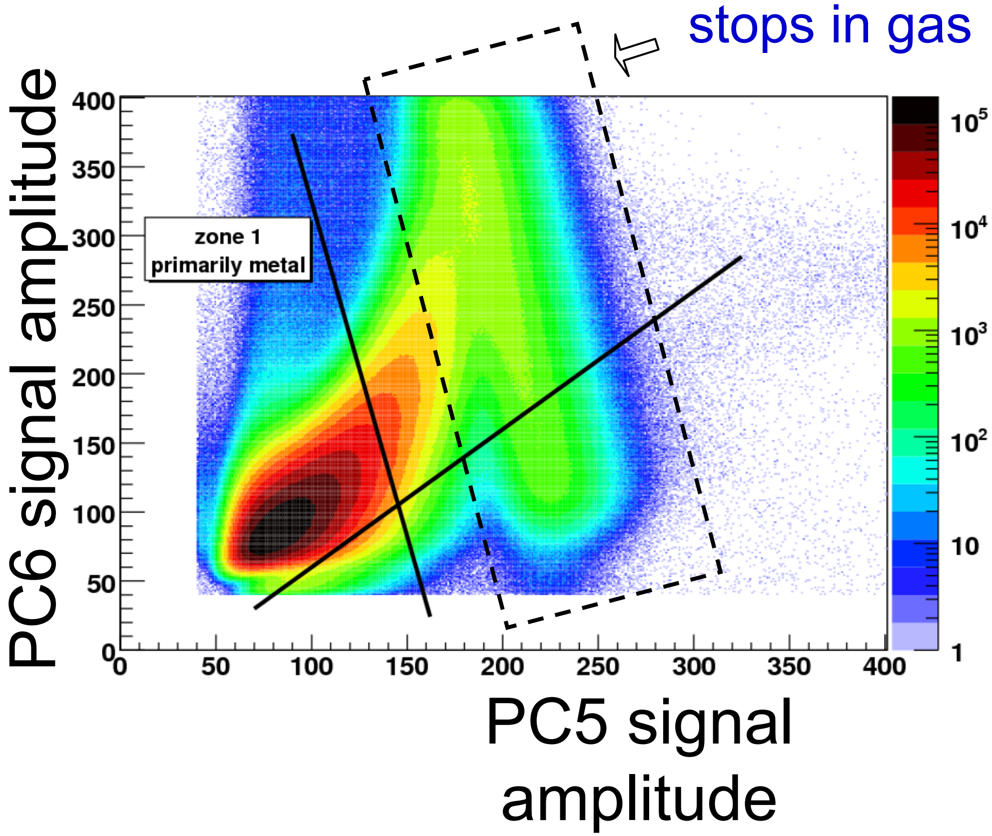
- Estimate of relaxation is included in simulation; small correction is made to polarization parameter.
- μSR experiment establishes no fast relaxation.
- Statistical uncertainty in λ is included in decay parameter statistical uncertainty.

U. de Montréal, April 12, 2010



Selecting muons in metal target



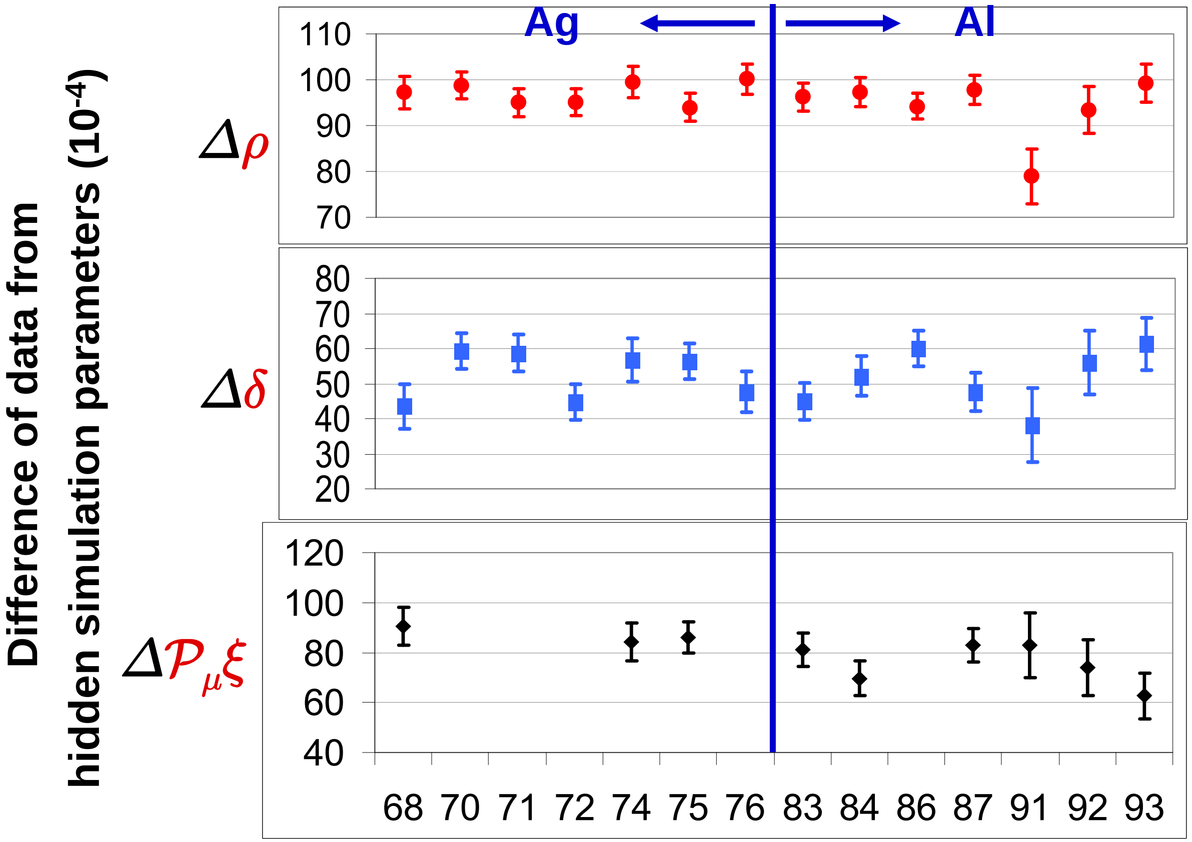


Place cut on 2-d distribution so that <0.5% of "stops in gas" contaminate "stops in target" region (zone 1).

Corrections to fitted data

- Depolarization from scattering in production target
  - $+0.9\times10^{-4}$ for full momentum sets, $+5.6\times10^{-4}$ for reduced momentum sets, for $\mathcal{P}_\mu\xi$ only.
- Simulations generated with incorrect polarization relaxation rates
  - $+2.9\times10^{-4}$ for Ag sets, $+2.4\times10^{-4}$ for Al sets
- Statistical biases
  - χ^2 fitting of Poisson statistics with 1/N weight is biased
  - in fitting data to simulation, weight includes 1/N from both
    - for unequal statistics, this is biased
  - MCfit biases of order 0.5×10^{-4}
  - Energy calibration fit bias of typically $(-1.1,-0.4,+1.9)\times10^{-4}$ for ρ, δ, $\mathcal{P}_\mu\xi$, applied set-by-set

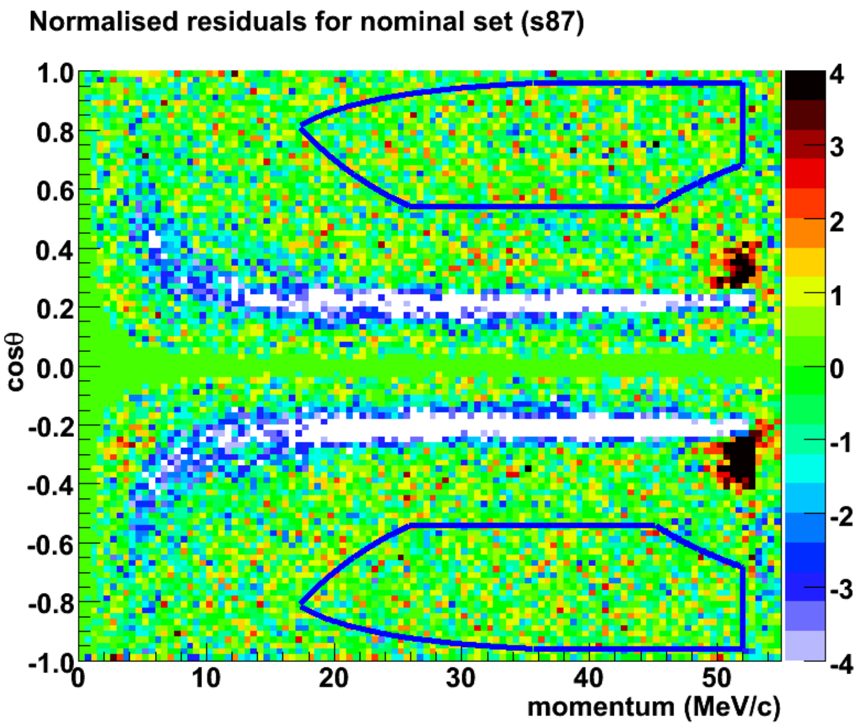
Consistency of data sets

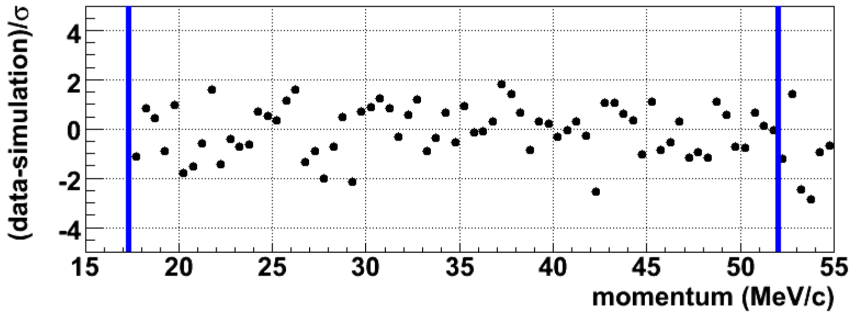


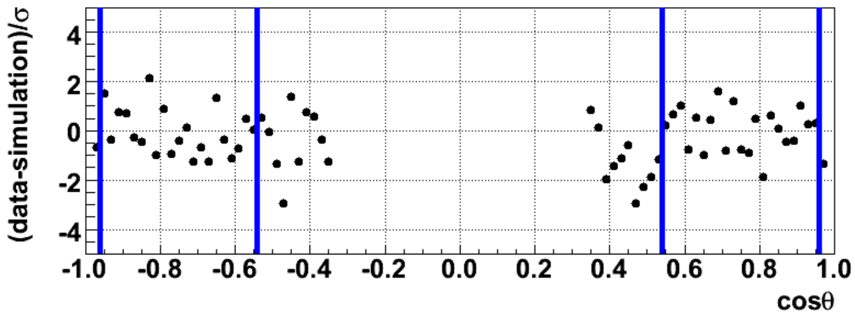
Key:
68 – z_{stop} shifted
70 – B = 1.96 T
71 – B = 2.04 T
72 – TEC in
74 – Nominal
75 – Nominal
76 – Mis-steered
83 – External material
84 – Nominal
86 – Mis-steered
87 – Nominal
91 – Low momentum
92 – Low momentum
93 – Low momentum

- **14 data sets for ρ and δ, χ^2 of 14.0 and 17.7 respectively**
- **9 data sets used for $\mathcal{P}_\mu\xi$, χ^2 = 9.7**
- **statistical uncertainties only, after corrections**

Spectrum fit quality

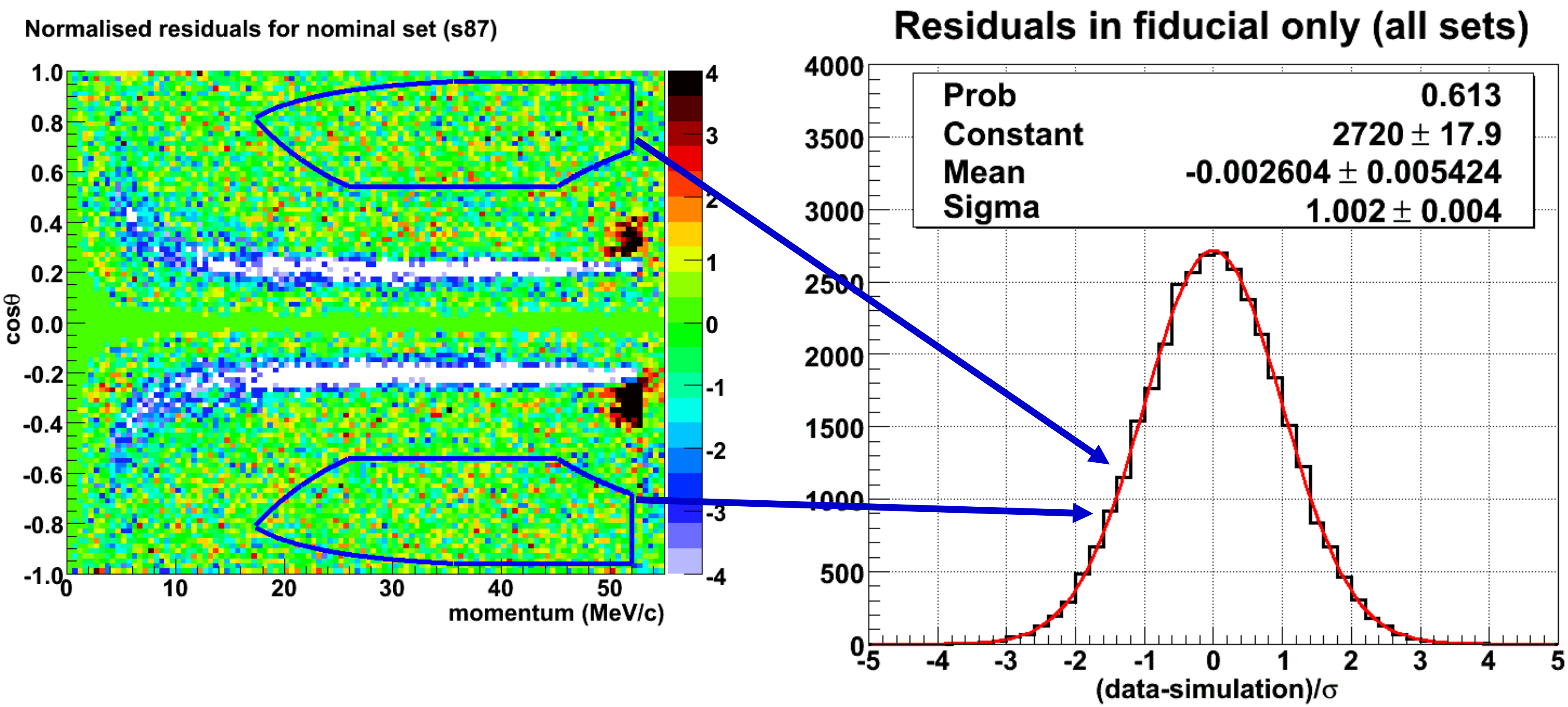






- Fiducial region: p < 52.0 MeV/c, 0.54 < $cos\theta$ < 0.96,
  10.0 MeV/c < p_T < 38.0 MeV/c, $|p_z|$ > 14.0 MeV/c
- All data sets: **11**×**10⁹** events, **0.55**×**10⁹** in (p,$cos\theta$) fiducial
- Simulation sets: **2.7** times data statistics

Spectrum fit quality



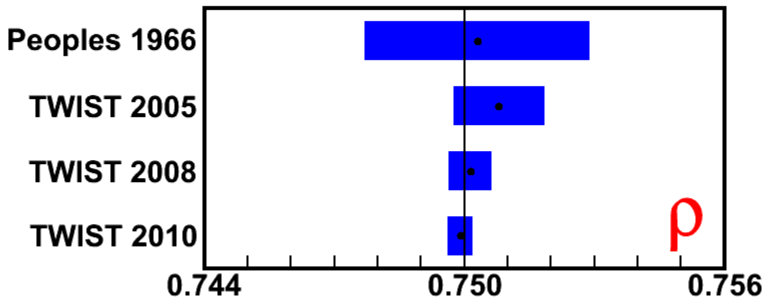
◎ Excellent fit quality over $(p, cos\theta)$ fiducial

Results and interpretations

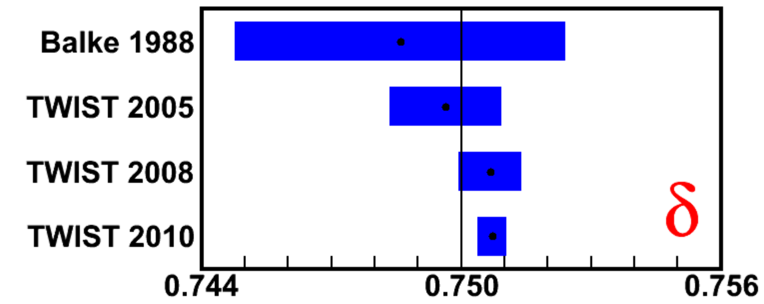
- Before revealing hidden parameters, check
  - consistency of data sets
  - spectrum fit quality
- Blind analysis protocol:
  - identify data sets to include
  - all event selection criteria and cuts , e.g., $(p, cos\theta)$ fiducial
  - systematic uncertainties and corrections
  - level of required consistency with previous results
  - new measurement supersedes previous *TWIST* measurements
  - publish even if inconsistent with Standard Model
- Including hidden parameters, we get
  - results
  - comparisons with previous results
  - consequences for fundamental interactions

“The box”

Comparisons with previous results

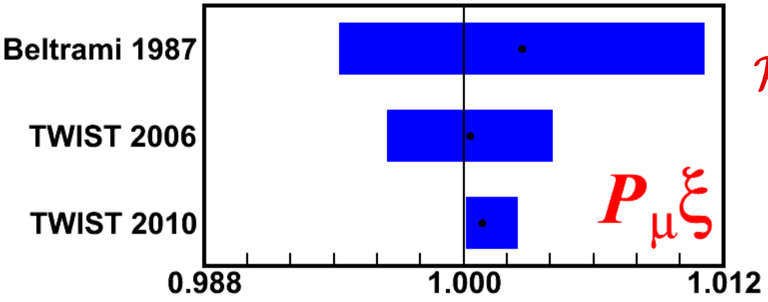


ρ = 0.74991 ± 0.00009 (stat) ± 0.00028 (syst)



δ = 0.75072 ± 0.00016 (stat) ± 0.00029 (syst)

(+2.2σ)

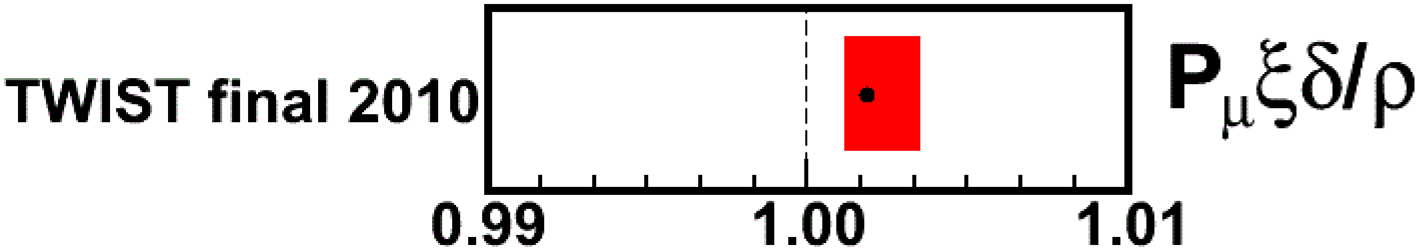


$\mathcal{P}_\mu\xi$ = 1.00084 ± 0.00035 (stat) $^{+\,0.00165}_{-\,0.00063}$ (syst)

(+1.2σ)

Are these results final?

- **Combine:** $\mathcal{P}_{\mu}\xi\delta/\rho = 1.00192 \; ^{+0.00167}_{-0.00066}$



- **result is 2.9 σ above "physical" limit of 1.0 from matrix element constraints, using correlations for three parameters**
- $\mathcal{P}_{\mu}\xi\delta/\rho$ **greater for Ag target than Al target**
- **many possible sources of error were checked and rejected**
- **precision of muon stopping location in data *vs.* simulation appears to be leading candidate; affects mostly ρ and δ**
- **physics interpretations should be considered *preliminary***

SM extension: Left-Right Symmetric

- Weak eigenstates in terms of mass eigenstates and mixing angle:

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

- Assume possible differences in left and right couplings and CKM character (P. Herczeg, 1986)
  Use notation: $t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \qquad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}, \qquad \zeta_g^2 = \frac{g_R^2}{g_L^2}\zeta^2$

- Then, for muon decay, the muon decay parameters are modified:

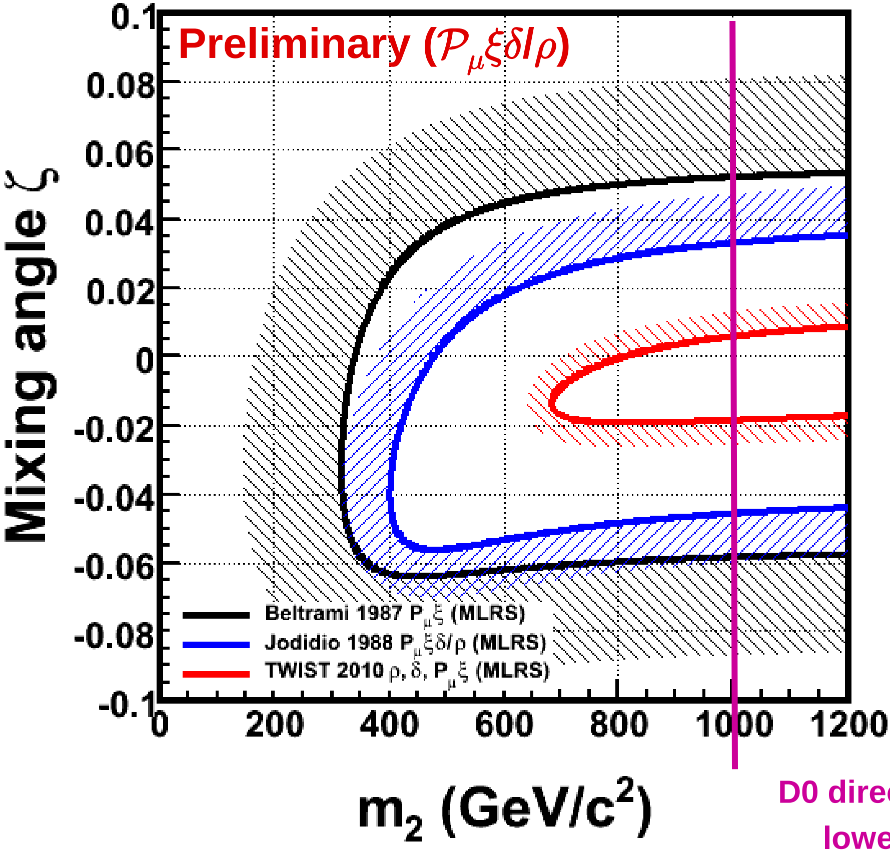
$$\rho = \frac{3}{4}(1 - 2\zeta_g^2), \quad \delta = \frac{3}{4}, \quad \xi = 1 - 2(t^2 + \zeta_g^2),$$

$$\mathcal{P}_\mu = 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g \cos(\alpha + \omega)$$

  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\alpha,\omega = 0$ (no CP violation).
  - "pseudo-manifest" LRS allows CP violation, but $V^R = (V^L)^*$ and $g_R = g_L$.
  - LRS "non-manifest" or generalized LRS makes no such assumptions.

LRS parameters from muon decay

Restricted ("manifest") LRS



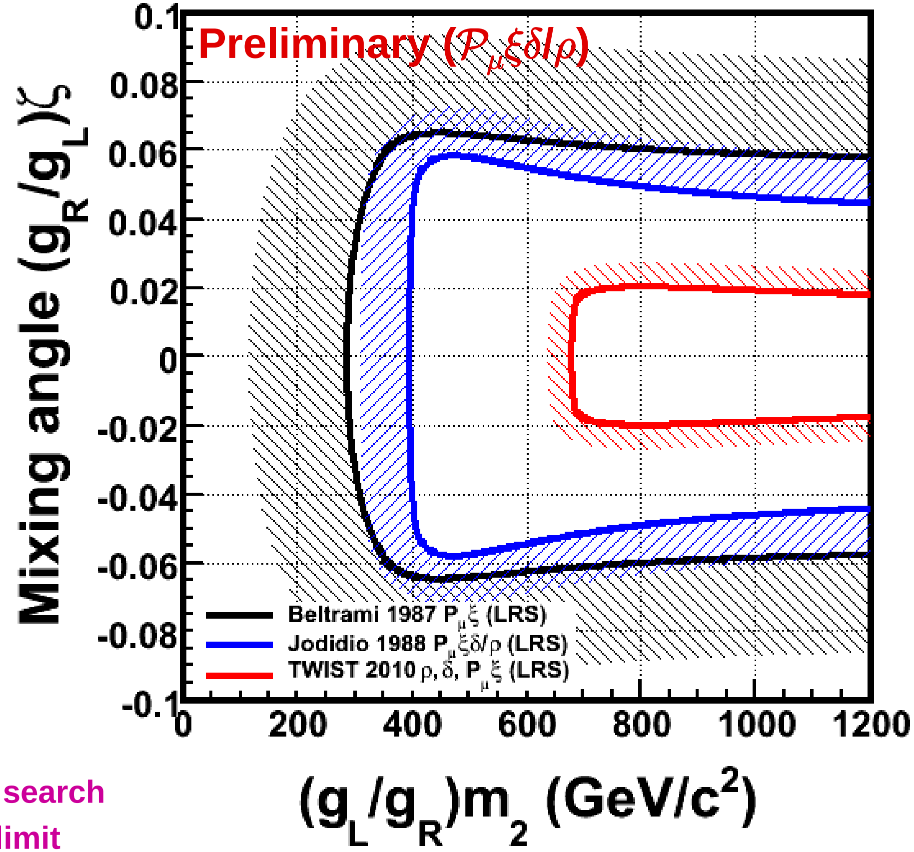
$m_2 > 684$ GeV/c^2

$-0.019 < \zeta < +0.010$

D0 direct search lower limit

Phys. Rev. Lett. 100, 031804 (2008)

General LRS



$(g_L/g_R)m_2 > 684$ GeV/c^2

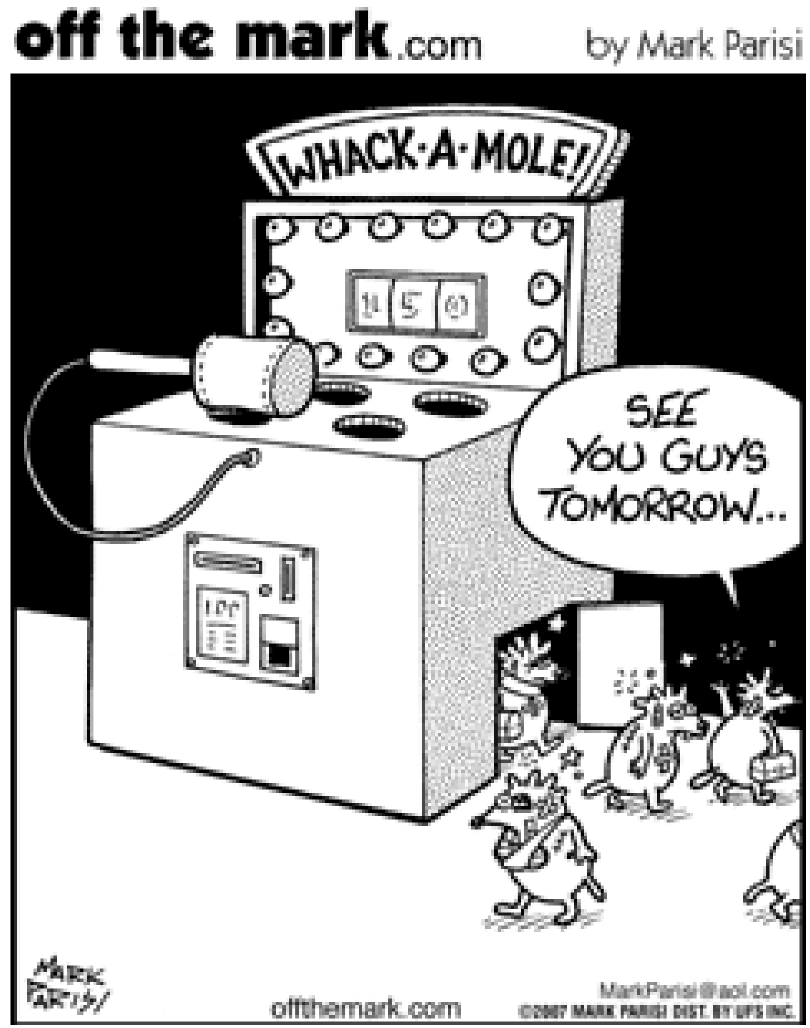
$-0.020 < (g_R/g_L)\zeta < +0.020$

Summary

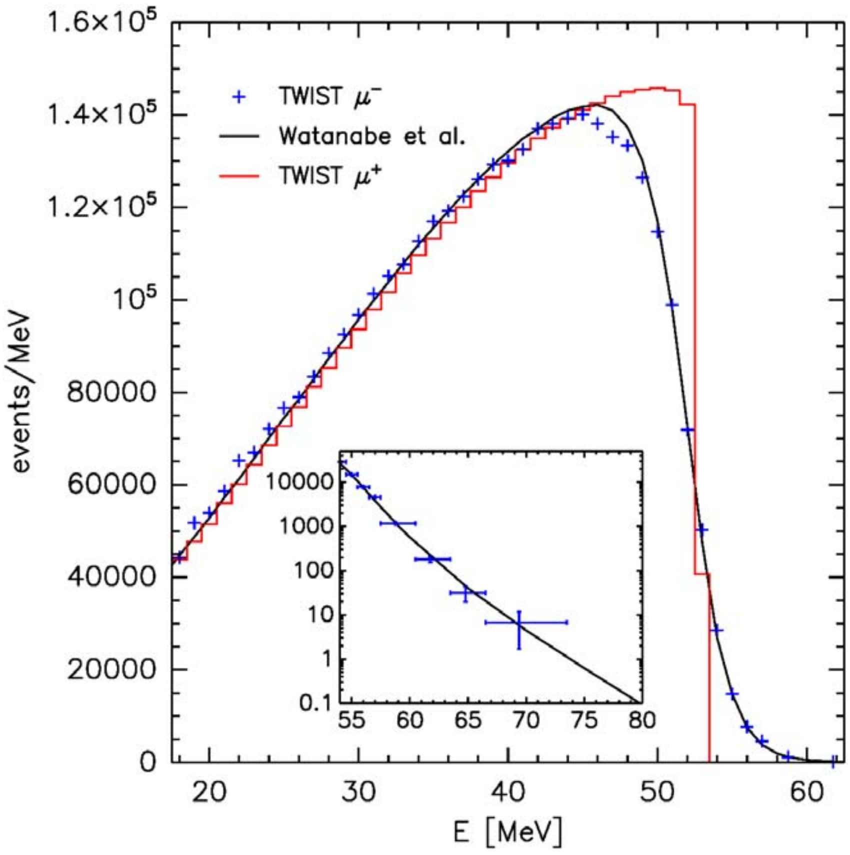
- Systematic uncertainties in muon decay parameter measurements were substantially reduced in *TWIST*.
- Total uncertainties were reduced by factors of **8.7**, **11.6**, and **7.0** for ρ, δ, and $\mathcal{P}_\mu\xi$ respectively, roughly achieving the goals of the experiment.
- Differences with Standard Model predictions are respectively **-0.3**σ, **+2.2**σ, and **+1.2**σ.
- The significant deviation of $\mathcal{P}_\mu\xi\delta/\rho$ above the limit of 1.0 is assumed to be due to an additional systematic uncertainty, to be resolve prior to publication.

Many Thanks!

Supported by TRIUMF and NRC, and through grants from NSERC (Canada) and DOE (USA).
Computing facilities of WestGrid are gratefully acknowledged.

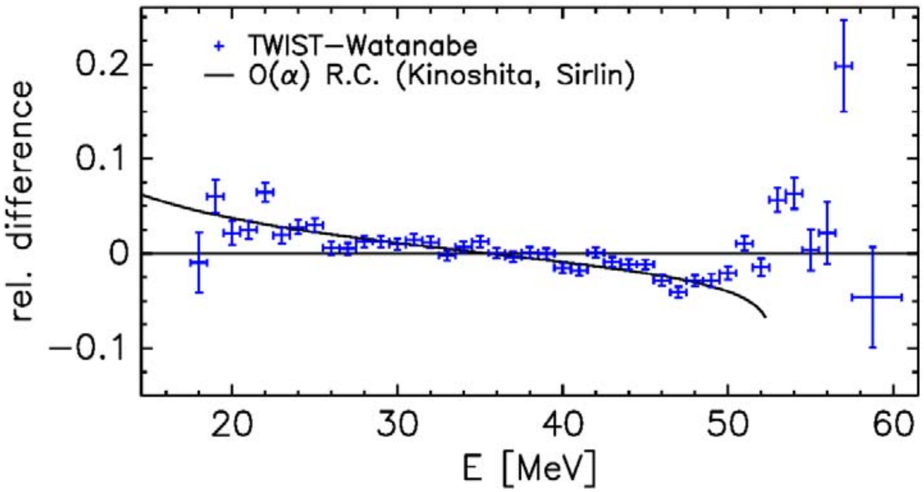


Aside: electron spectrum from μ^-Al



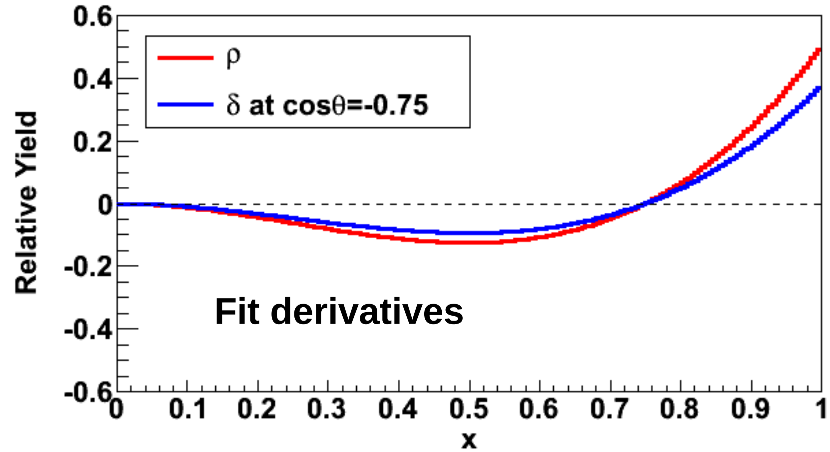
A. Grossheim et al., Phys. Rev. D 80, 052012 (2009)

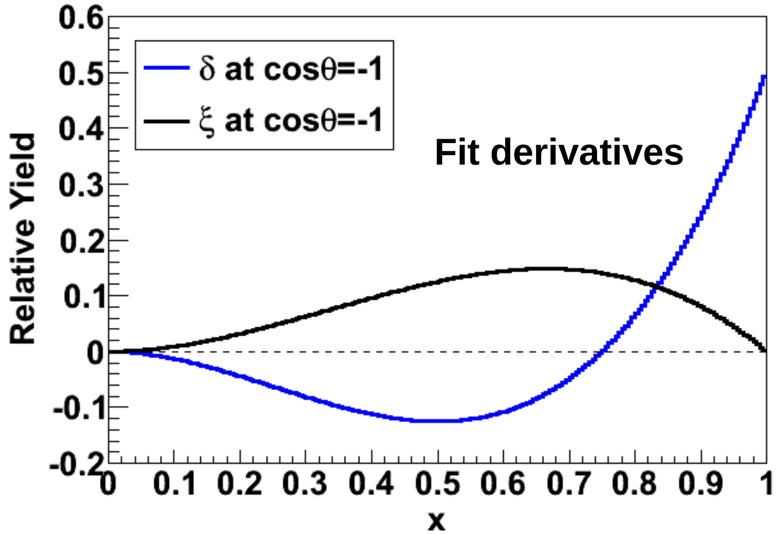
- One week of data with μ^- beam
- Precise measure of muonic aluminum (μ^-Al) decay in orbit (DIO)
  - changes phase space, initial KE
  - competes with nuclear muon capture
- comparison with calculation
  - consistency above 53 MeV, but limited to p<75 MeV (below μe conversion signal)
  - mismatch near peak and excess events at lower energies
  - $\mathcal{O}(\alpha)$ corrections explain shape

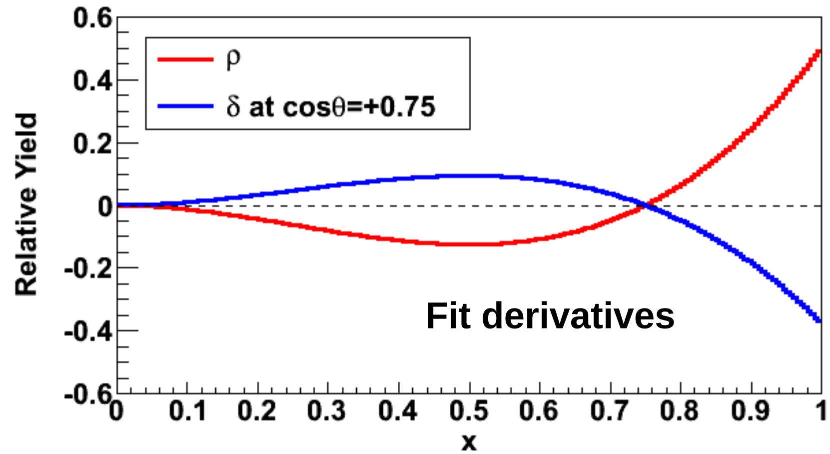


Parameter correlations

- corr(ρ,δ) = +0.69
- corr(ρ,$\mathcal{P}_\mu\xi$) = -0.06 (+), -0.14(-)
- corr(δ,$\mathcal{P}_\mu\xi$) = -0.18 (+), -0.43(-)

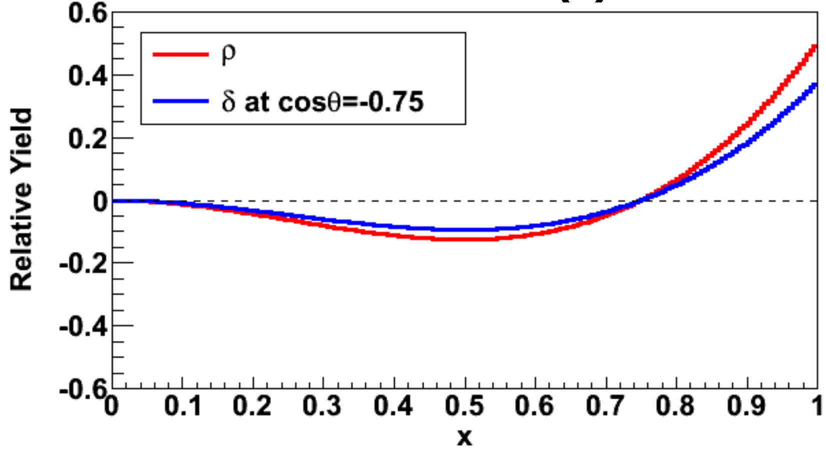


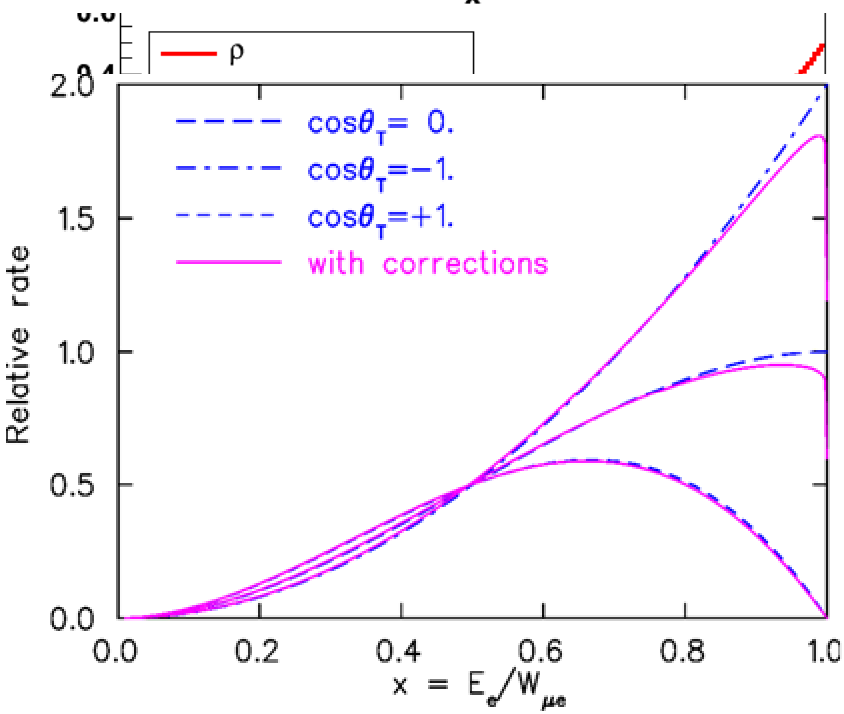




ρ and δ systematic correlations

Derivatives at cos(θ) = ±0.75





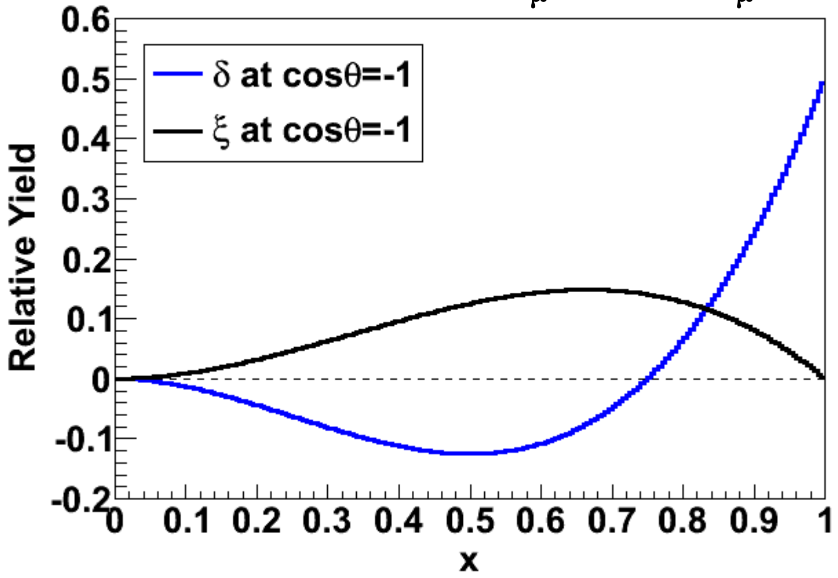
- The **ρ** and **δ** involve the momentum-dependence of the yield and asymmetry
- They have:
  - same upstream shapes
  - opposite downstream shapes
- Effects that
  - distort the momentum, and
  - couple to the yield

  distort **ρ** and **δ** similarly

- Example: **bremsstrahlung**

Why are δ and $P_\mu\xi$ anti-correlated?

Fit derivatives for $P_\mu\xi\delta$ and $P_\mu\xi$



In **TWIST**, the fit parameters are $P_\mu\xi$ and $P_\mu\xi\delta$

$$\delta = \frac{P_\mu\xi\delta}{P_\mu\xi}$$

- Anti-correlation between statistical uncertainties for δ and $P_\mu\xi$
- Three types of systematics influence the asymmetry measurements
  - Distort P_μ; only impact $P_\mu\xi$
  - Distort contribution of $P_\mu\xi\delta$ derivative; only impact δ
  - Distort contribution of $P_\mu\xi$ derivative; impact **BOTH** $P_\mu\xi$ and δ

Testing the Standard Model

- Model independent muon handedness:

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

(SM value is 0)

- Left-right symmetric models (simplified!):

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta, \qquad W_R = -W_1 \sin\zeta + W_2 \cos\zeta$$

$$\tfrac{3}{4} - \rho = \tfrac{3}{2}\zeta^2, \qquad 1 - \mathcal{P}_\mu \xi = 4\{\zeta^2 + \tfrac{m_1^4}{m_2^4} + \zeta \tfrac{m_1^2}{m_2^2}\}$$

  - more on this later…

Limits on LRS parameters: PDG08

Observable	m_2 (GeV/c_2)	$\|\zeta\|$		
$m(K_L{}^0)$-$m(K_S{}^0)$	>700		reach	(P)MLRS
Direct W_R searches	>1000 (D0) >788 (CDF)		clear signal	(P)MLRS decay model
Electro-weak fit		<0.013	fit	(P)MLRS
β decay	>310	<0.040	both parameters	(P)MLRS light ν_R
μ decay*, *TWIST*	>475 (>530)	<0.021 (<0.016)	model independence	light ν_R

*** in generalized LRS model; to be interpreted as $m_2(g_L/g_R)$, $\zeta(g_R/g_L)$.**