TWIST muon decay analysis: recent progress

Glen Marshall, for the *TWIST* Collaboration

NuFact09
11th International Workshop on
Neutrino Factories, Superbeams and Beta Beams

Illinois Institute of Technology
Chicago, July 2009

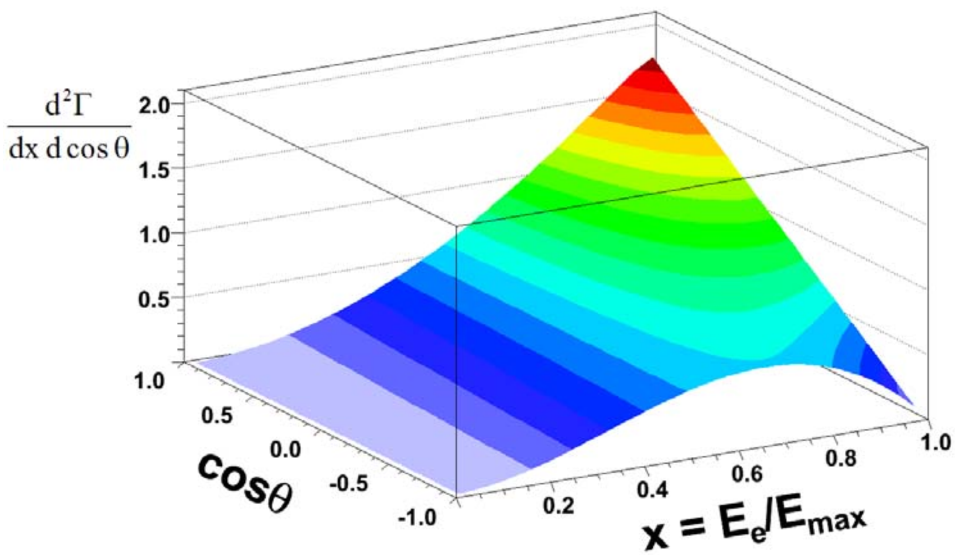
Outline

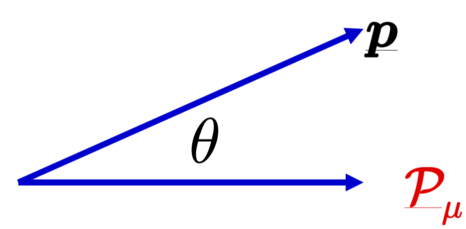
- Muon decay description
  - parametrizations and summary of measurements
  - Standard Model tests
- *TWIST* experiment – detectors, beam, and analysis
- Reduction of systematic uncertainties
  - for ρ and δ
  - for $\mathcal{P}_\mu \xi$ - depolarization
  - expectations for final analysis
- Electron energy spectrum from μ^-Al
- Summary

Muon decay parameters

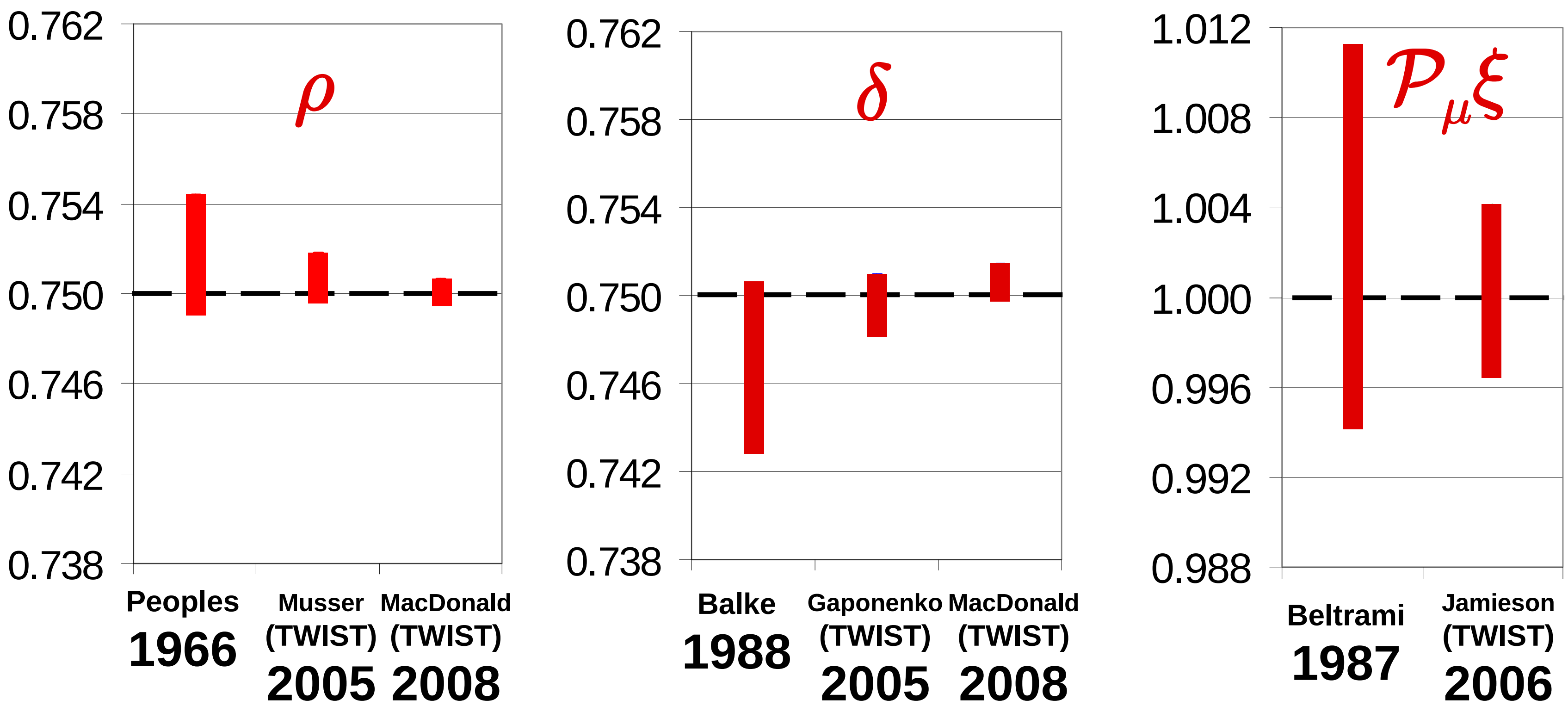
- Muon decay parameters ρ, η, $\mathcal{P}_\mu\xi$, δ
  - muon differential decay rate *vs.* energy and angle:

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





Published results



$\rho = 0.75014 \pm 0.00017(\text{stat}) \pm 0.00046(\text{syst}) \pm 0.00011(\eta)$

$\delta = 0.75068 \pm 0.00030(\text{stat}) \pm 0.00067(\text{syst})$

$\mathcal{P}_\mu\xi = 1.0003 \pm 0.0006(\text{stat}) \pm 0.0038(\text{syst})$

Also $\mathcal{P}_\mu\xi\delta/\rho > 0.99682$ from Jodidio et al, 1986

Decay parameters and coupling constants

- Fetscher and Gerber coupling constants (see PDG):

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

$$\begin{aligned}
\rho &= \frac{3}{4} - \frac{3}{4}[|g^V_{RL}|^2 + |g^V_{LR}|^2 + 2|g^T_{RL}|^2 + 2|g^T_{LR}|^2 \\
&\quad + \mathbb{R}e\,(g^S_{RL} g^{T*}_{RL} + g^S_{LR} g^{T*}_{LR})] \\
\eta &= \frac{1}{2}\mathbb{R}e[g^V_{RR} g^{S*}_{LL} + g^V_{LL} g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})] \\
\xi &= 1 - \frac{1}{2}|g^S_{LR}|^2 - \frac{1}{2}|g^S_{RR}|^2 - 4|g^V_{RL}|^2 + 2|g^V_{LR}|^2 - 2|g^V_{RR}|^2 \\
&\quad + 2|g^T_{LR}|^2 - 8|g^T_{RL}|^2 + 4\mathbb{R}e(g^S_{LR} g^{T*}_{LR} - g^S_{RL} g^{T*}_{RL}) \\
\xi\delta &= \frac{3}{4} - \frac{3}{8}|g^S_{RR}|^2 - \frac{3}{8}|g^S_{LR}|^2 - \frac{3}{2}|g^V_{RR}|^2 - \frac{3}{4}|g^V_{RL}|^2 - \frac{3}{4}|g^V_{LR}|^2 \\
&\quad - \frac{3}{2}|g^T_{RL}|^2 - 3|g^T_{LR}|^2 + \frac{3}{4}\mathbb{R}e(g^S_{LR} g^{T*}_{LR} - g^S_{RL} g^{T*}_{RL})
\end{aligned}$$

Global analysis results

Standard model:

g^V_{LL} = 1, all others zero

Global analysis:

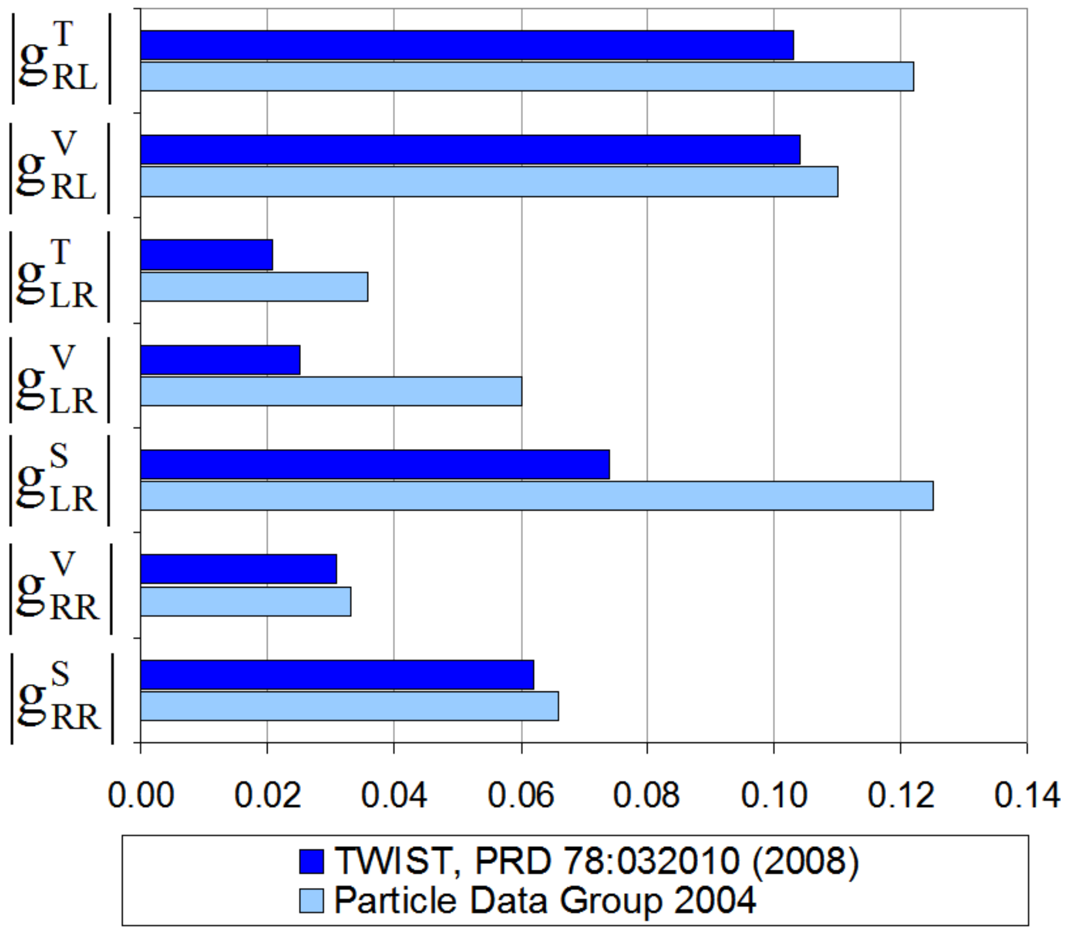
$|g^V_{LL}|$ > 0.96 (90%CL)

Muon RH coupling:

$$
\begin{aligned}
Q^\mu_R &= \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \\
&\geq 0 \\
&< 0.0024(90\%CL)
\end{aligned}
$$

(previously 0.014)

Upper limits on non-SM couplings



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.
  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 Michel parameters are modified:

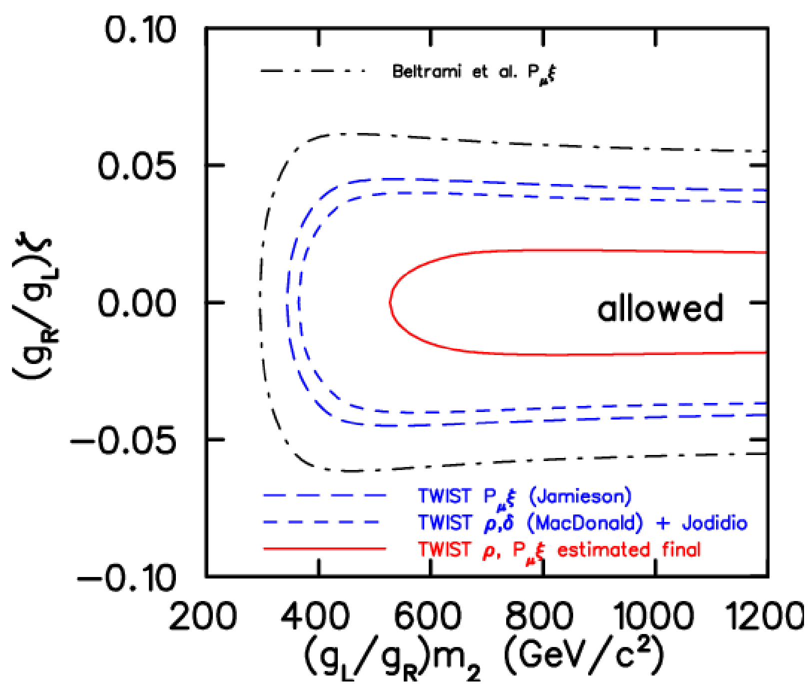
$$\rho = \frac{3}{4}(1 - 2\zeta_g^2), \qquad \xi = 1 - 2(t^2 + \zeta_g^2),$$

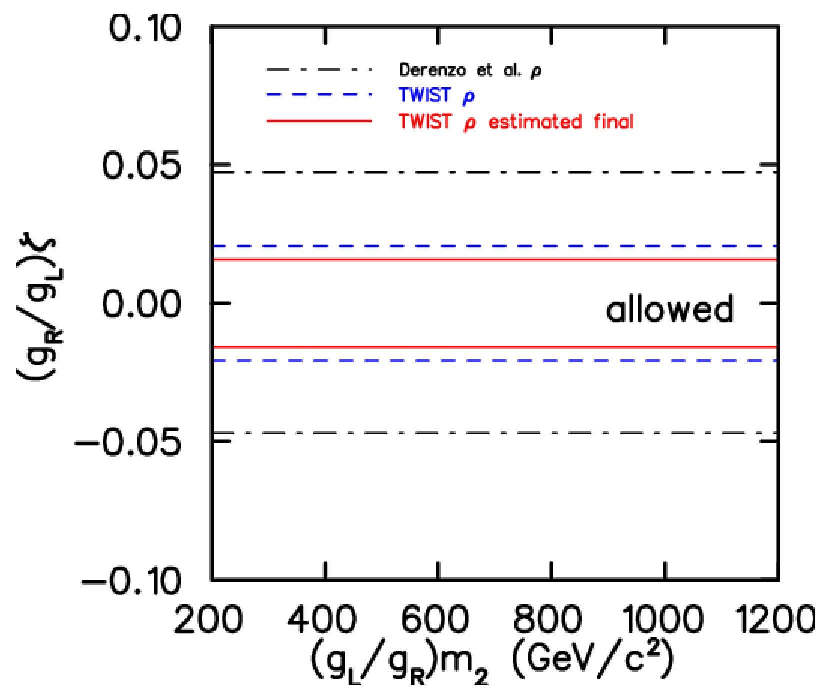
$$\mathcal{P}_\mu = 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g^2 \cos(\alpha + \omega)$$

  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\omega = 0$ (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.

- ***Many experiments must make assumptions about LRS models!***

Muon decay LRS limits

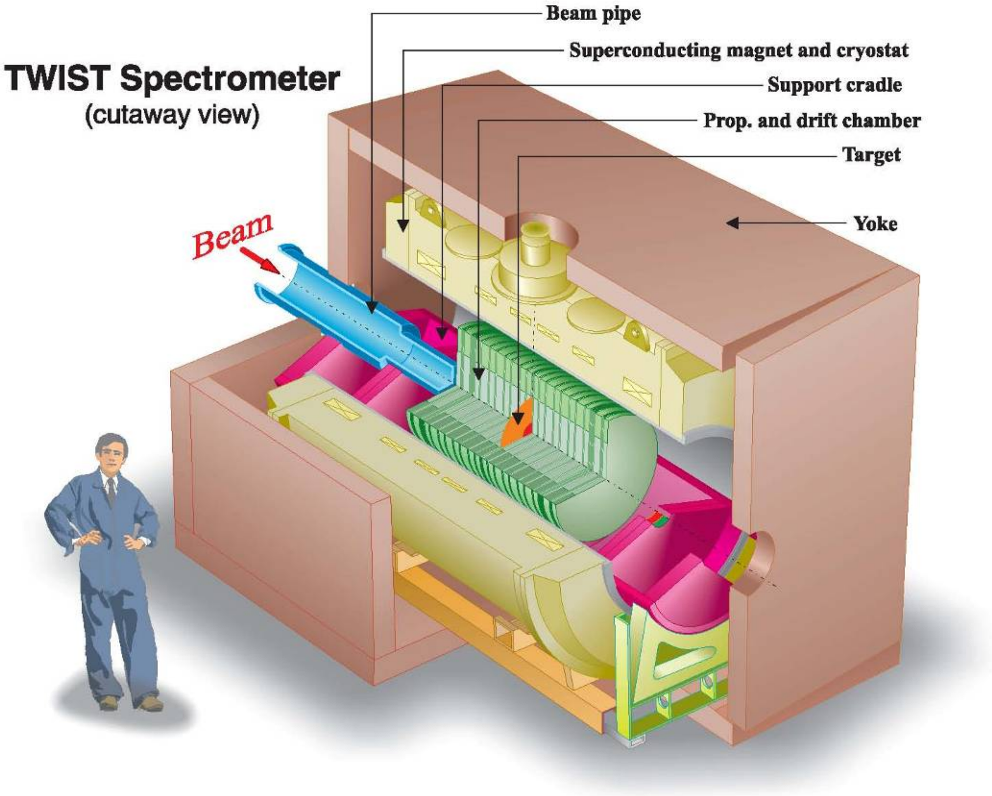




- Exclusion (90% cl) plots for left-right symmetric model mixing angle ζ and W_2 mass $\mathbf{m_2}$.
- "Generalized LRS" model; no assumptions on RH CKM matrix elements.
- Complementary to other experiments: e.g., D∅ and CDF for $\mathbf{m}_2$, $K^0_L - K^0_S$ mass difference for ζ

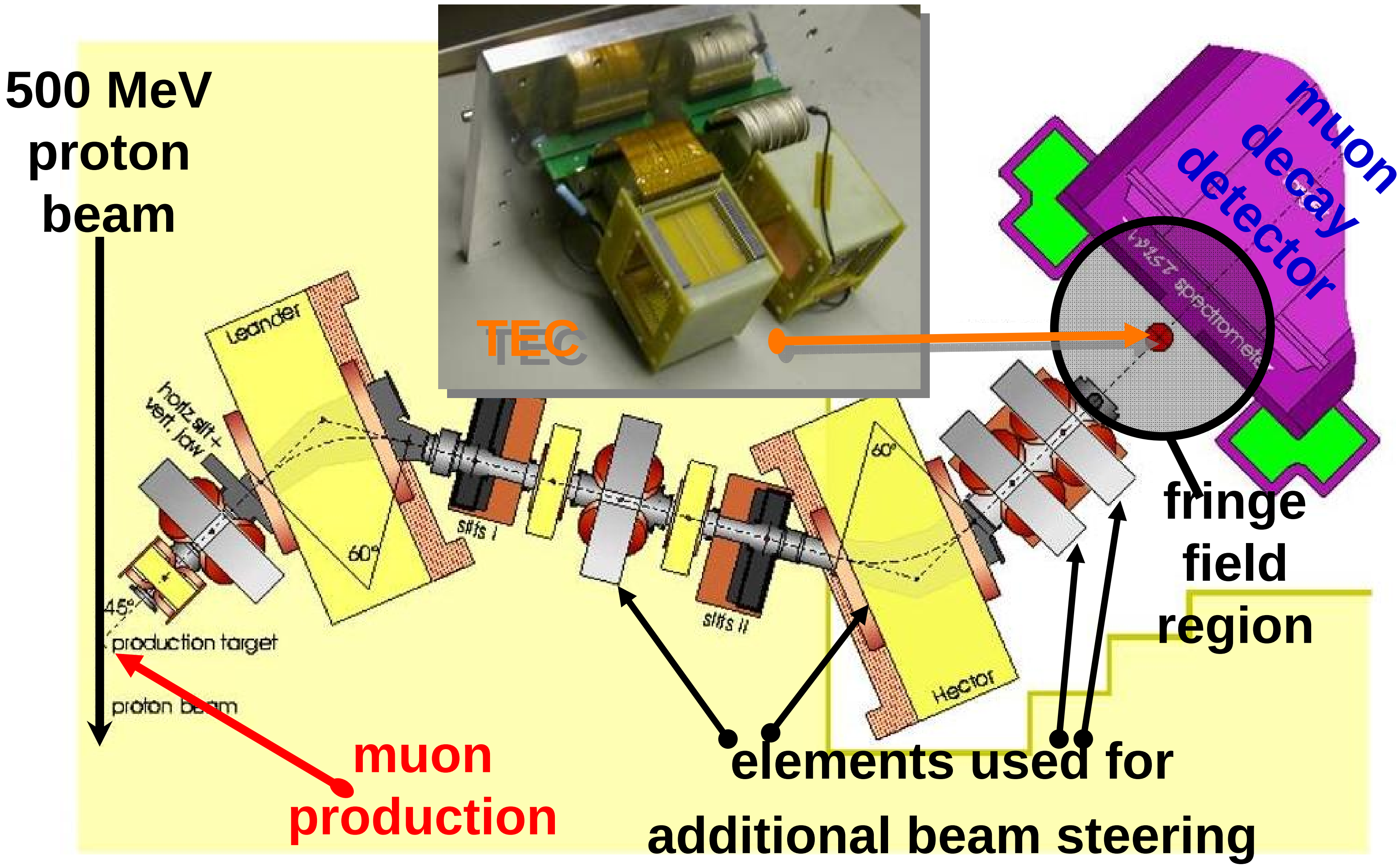
TWIST spectrometer

- Uses highly polarized μ^+ beam ($\mathcal{P}_\mu \sim$ -1 w.r.t beam)
- Stops μ^+ in a very symmetric detector.
- Tracks e^+ through uniform, well-known field.
- Extracts decay parameters by comparison to detailed and verified simulation.



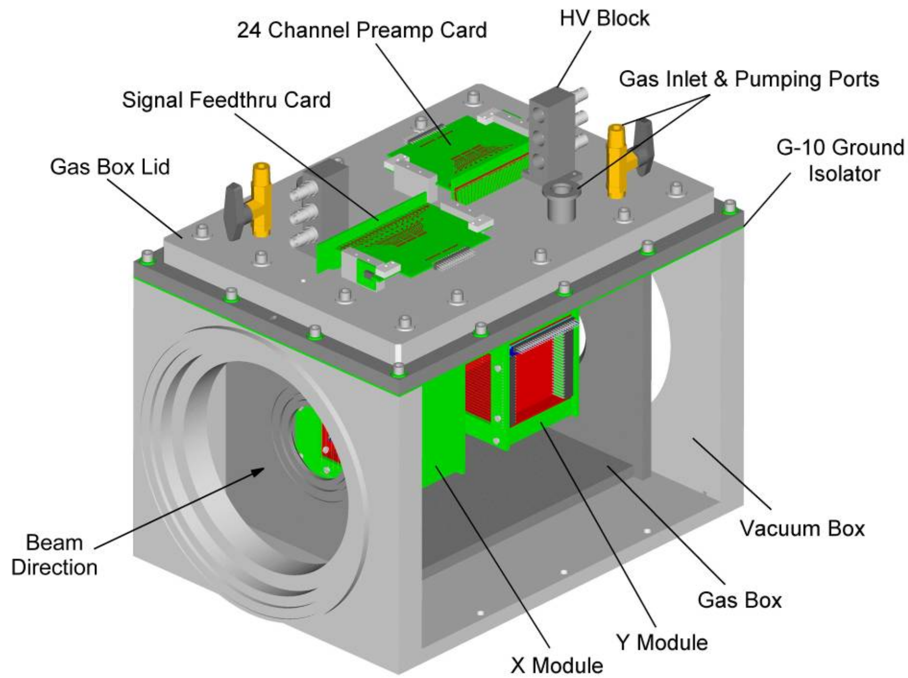
R. Henderson et al., Nucl. Instr. and Meth. A548 (2005) 306-335

Muon production and transport



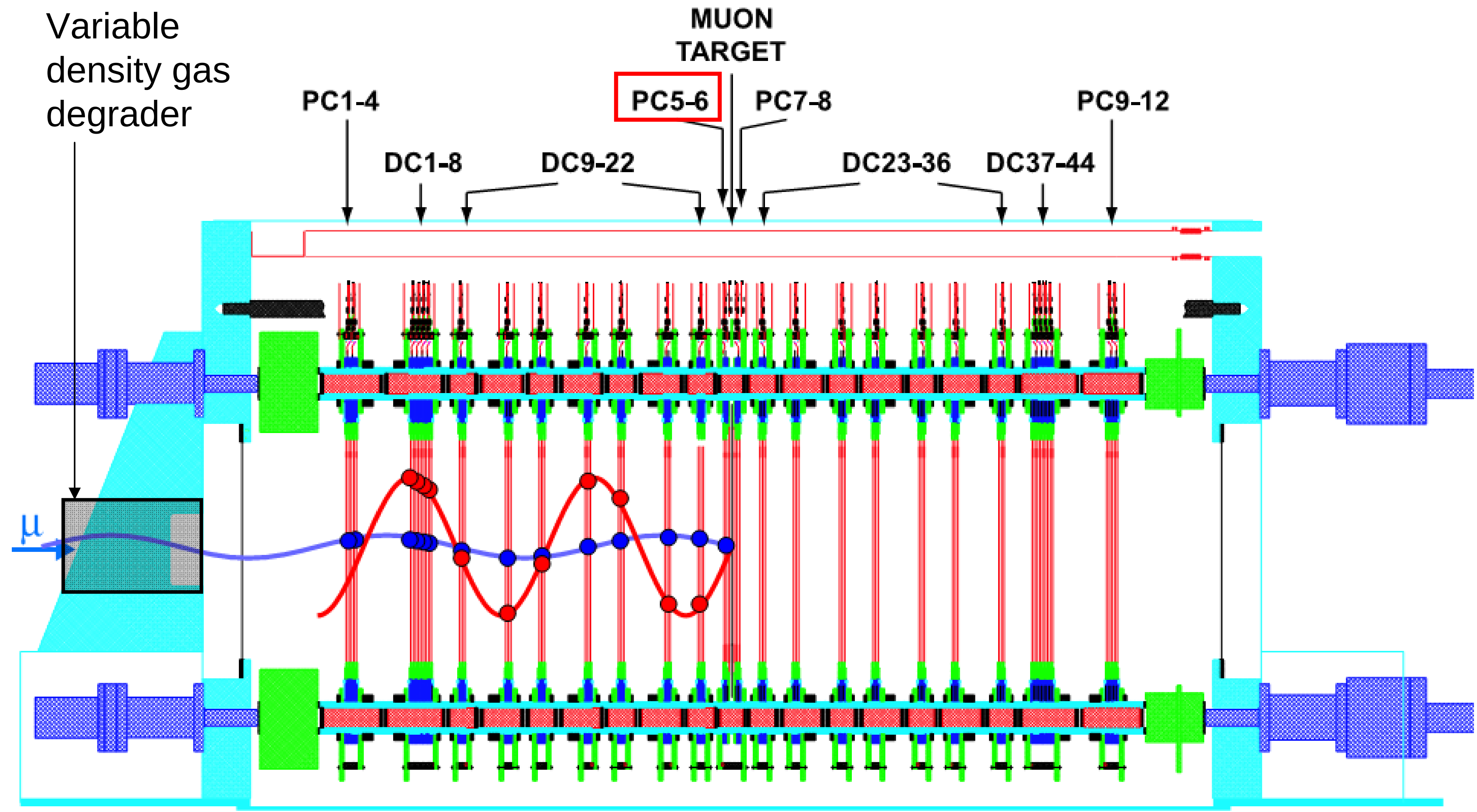
TEC beam characterization

- 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.

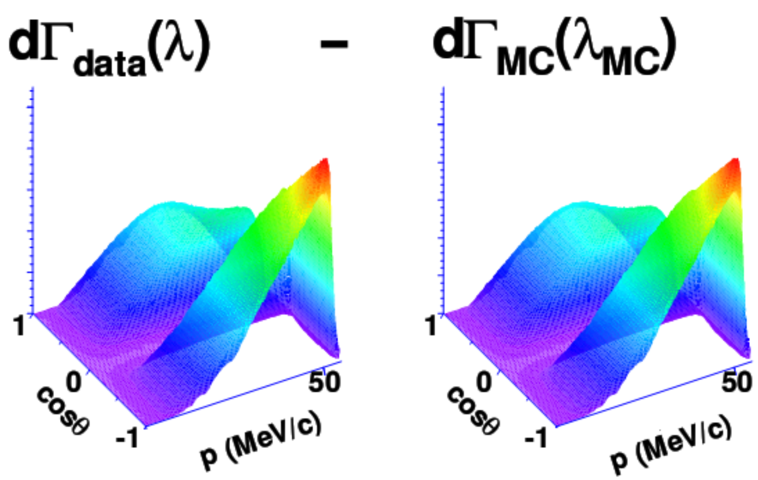


J. Hu et al., NIM A566 (2006) 563-574

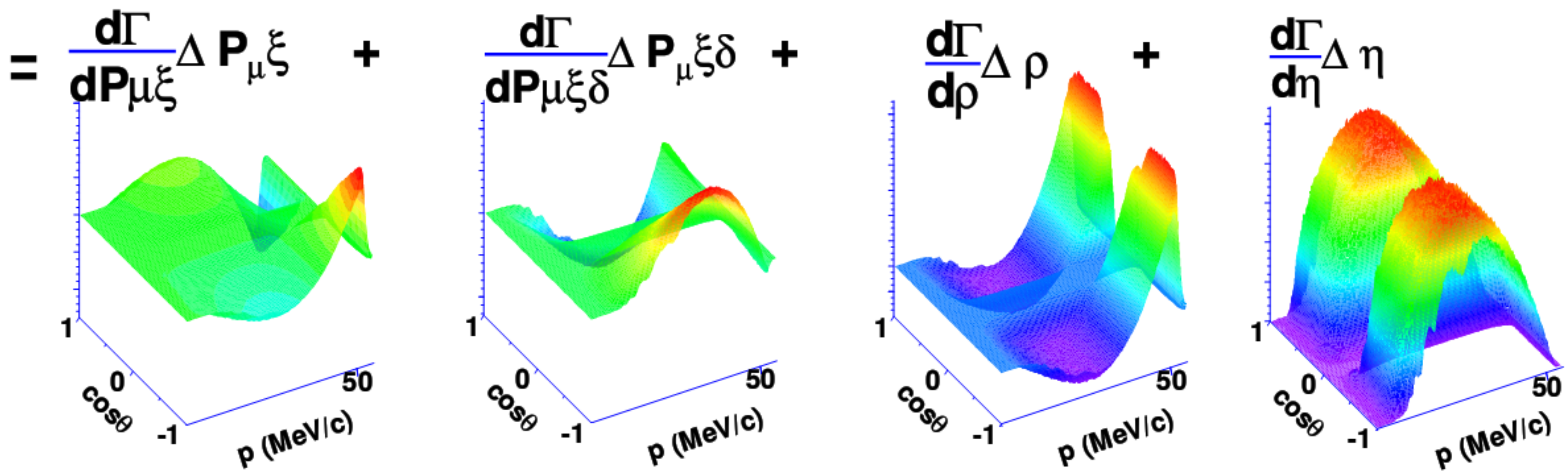
Positron tracking



Analysis: fit to simulation

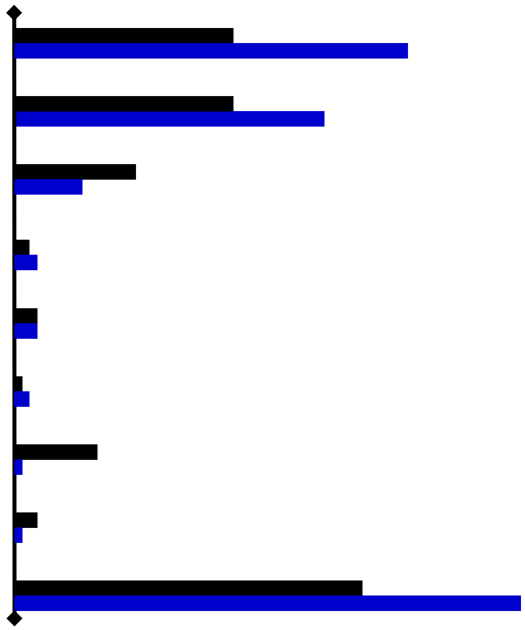


- fit data to GEANT3 simulation with hidden parameters
- distribution is linear in $\mathcal{P}_\mu\xi$, $\mathcal{P}_\mu\xi\delta$, ρ, η
- fits to data or MC with systematically changed conditions show decay parameter dependence on systematics
- Use *measured* η, rather than fit it



Systematics for ρ and δ

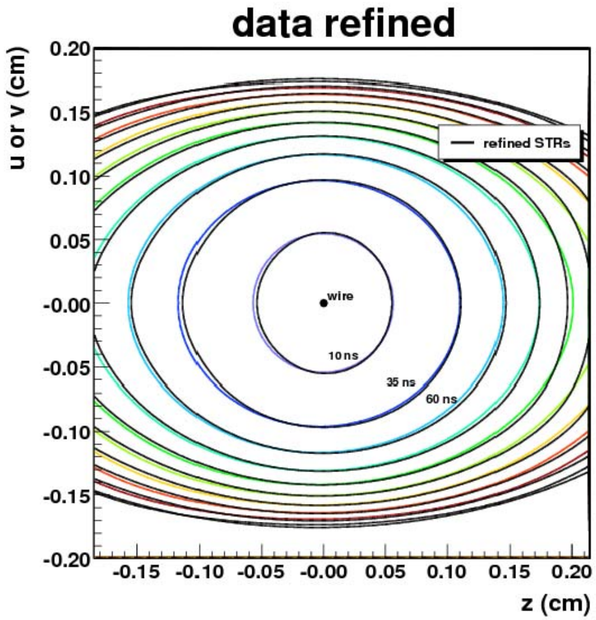
Systematic uncertainties	ρ ($\times 10^{-4}$)	δ ($\times 10^{-4}$)
Chamber response	2.9	5.2
Energy scale	2.9	4.1
Positron interactions	1.6	0.9
Resolution	0.2	0.3
Alignment and lengths	0.3	0.3
Beam intensity (ave)	0.1	0.2
Correlations with η	1.1	0.1
Theoretical radiative correction	0.3	0.1
Total in quadrature	***4.6***	***6.7***



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

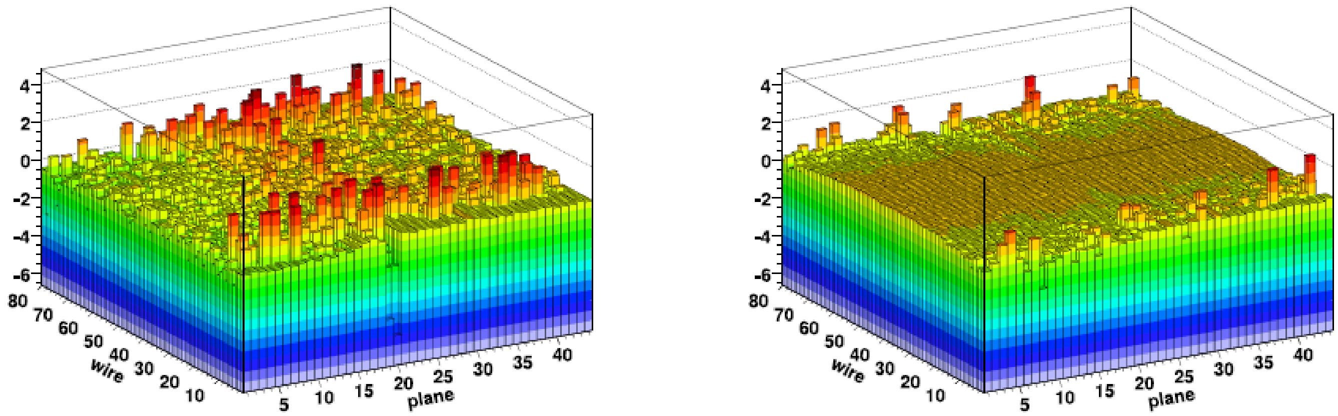
Chamber response

- Improvements benefit all three parameters, ρ, δ, and $\mathcal{P}_\mu\xi$.
- Detector position response:
  - use drift chamber Space Time Relationships as determined from data tracks for data analysis, as well as from simulated tracks for simulation analysis (common biases).
  - accounts for geometry variations, drift model dependence, tracking biases



Drift time isochrones for data, before (GARFIELD) and after correction from track residual analysis (developed by A. Grossheim)

DC wire time offset calibration

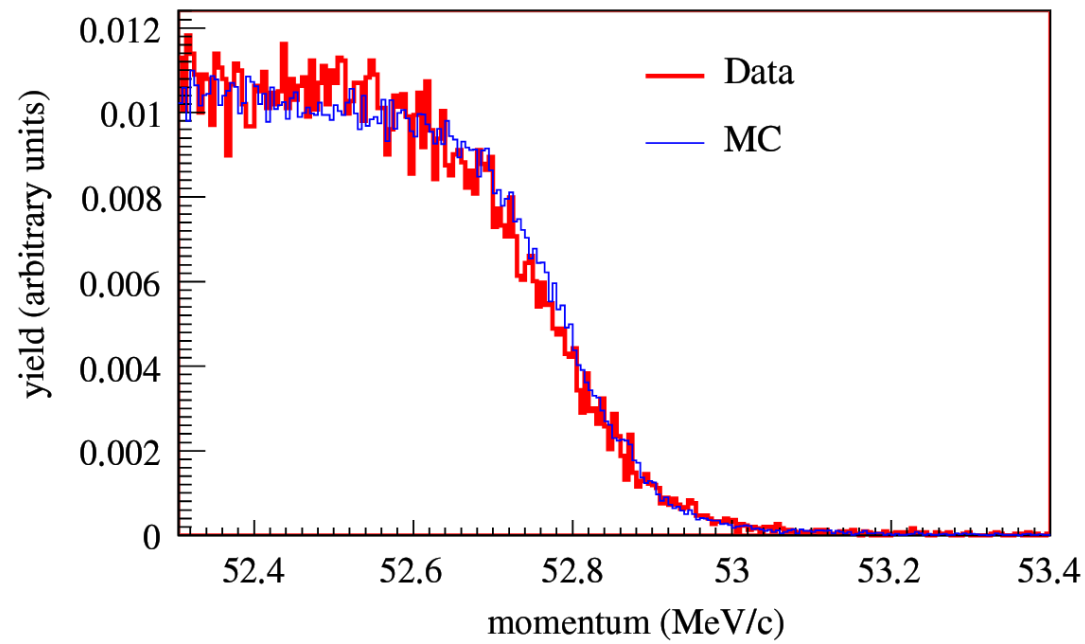


Wire time offsets extracted from simulation (initial values all zero) before (left) and after (right) improvements in the procedure (developed by A. Olin)

- time offsets (t0's) of >3000 wires required
- fit decay e^+ time distributions vs. scintillator signals
  - careful event selection, careful time-of-flight corrections
  - realistic function (Gaussian-exponential convolution)
- tested for simulation and also for data with beam e^+

Energy calibration

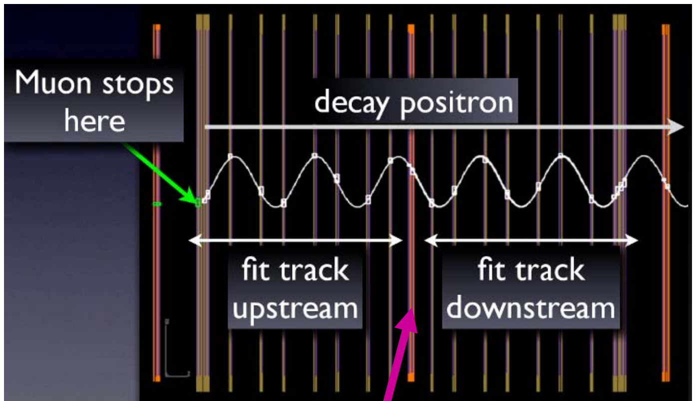
- Correct for small differences between data and simulation
  - magnetic field shape and magnitude
  - muon stopping position in foil target
  - target thickness
  - dE/dx differences

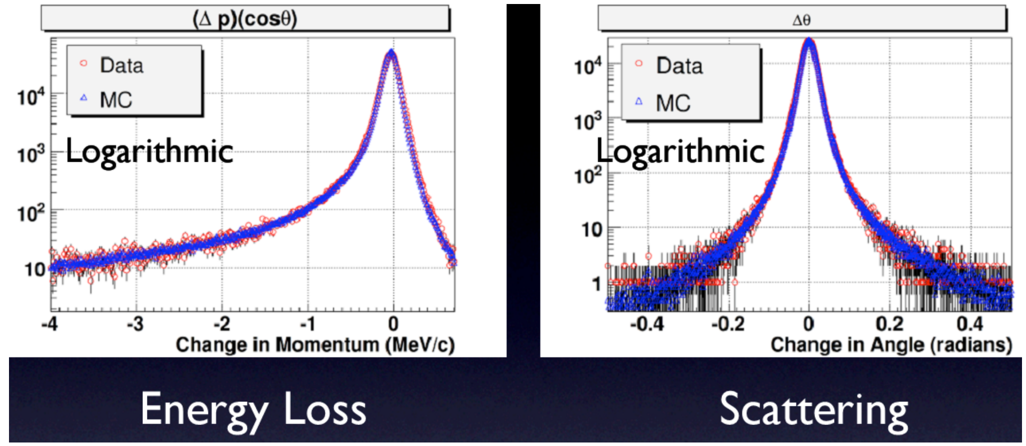


- Compare kinematic edge at 52.8 MeV for small angular range
  - $p_i = B_i + A_i/\cos\theta$, for $i \in$[US,DS], from planar geometry
  - fit data and simulation to find relative difference, then correct
  - 1-point calibration: propagation of correction to lower energy must be otherwise determined

Positron interactions

- Test GEANT3 energy loss and scattering – “upstream stops”



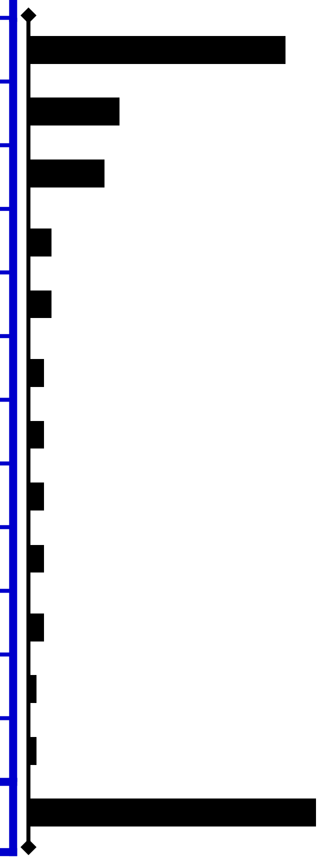


Stopping target for decay data

- Test GEANT3 δ-ray and bremsstrahlung – broken tracks
- Check agreement of data and simulation
  - δ ’s: 3 tracks (2+, 1-, e^- from 6 to 16 MeV/c) from primary positron
  - brem: 2 tracks (2+, Δp from 15 to 35 MeV/c)
  - compare with simulation with δ, brem increase (x3).

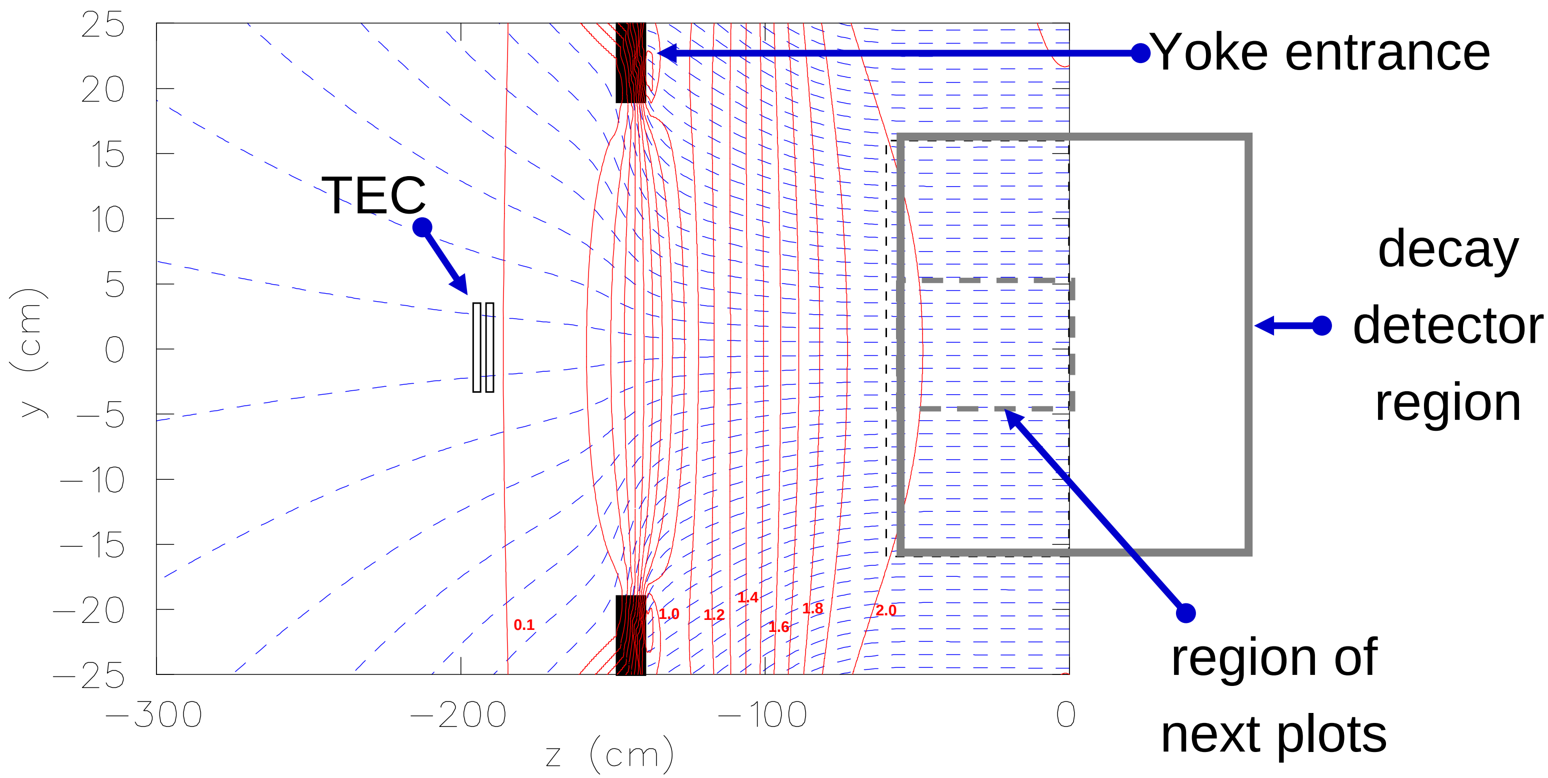
Systematics for $\mathcal{P}_\mu \xi$

Systematic uncertainties	$\mathcal{P}_\mu \xi$ ($\times 10^{-4}$)
Depolarization in fringe field (ave)	34
Depolarization in muon stopping material (ave)	12
Chamber response (ave)	10
Spectrometer alignment	3
Positron interactions (ave)	3
Depolarization in muon production target	2
Momentum calibration	2
Upstream-downstream efficiency	2
Background muon contamination (ave)	2
Beam intensity (ave)	2
Decay η parameter	1
Theoretical radiative correction	1
Total in quadrature	**38**



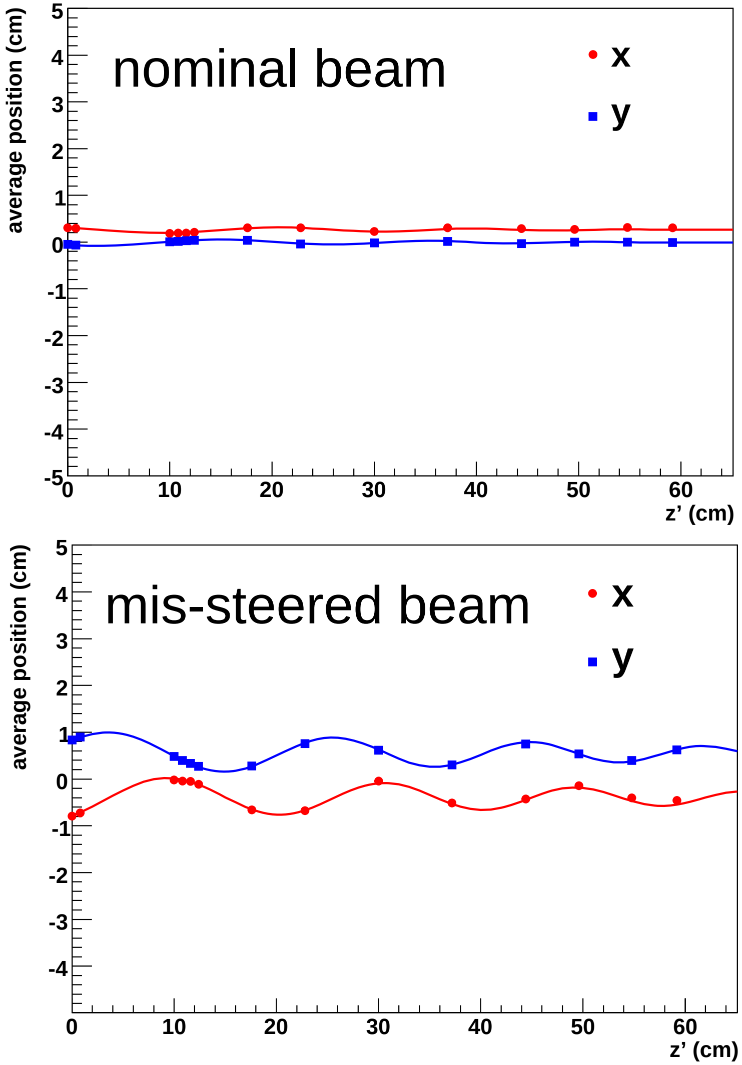
B. Jamieson et al., Phys. Rev. D 74 (2006) 072007

Fringe field, solenoid entrance



The central field is 2 T, with a strong gradient near the solenoid yoke entrance.
Muon tracks are measured by the TEC, to establish incident beam parameters.
Muons are also tracked in the upstream part of the decay detector

Measured average muon positions



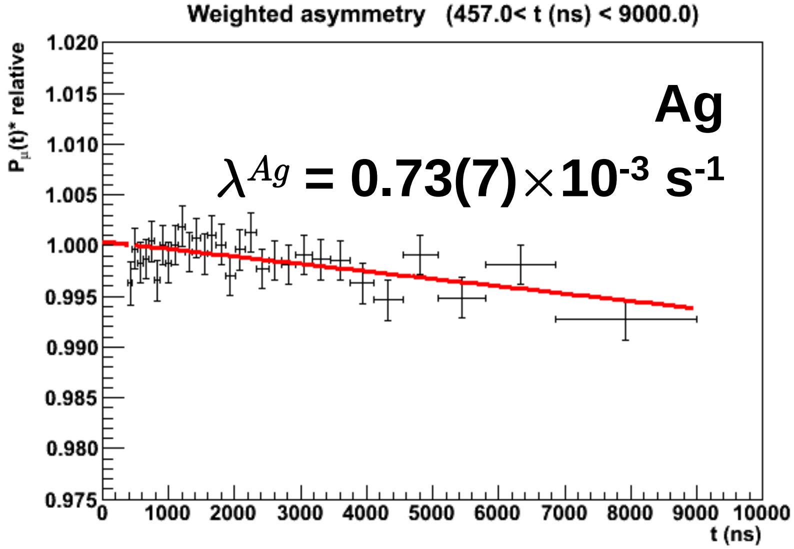
- Each point represents the average muon beam position at a detector plane.
- Simulated data can be analyzed in the same way.
- Fit both to "shrinking helix".
- Comparison of fits of data and simulation is a powerful way to verify the simulation, *e.g.* , influence of fringe field on muon beam, detector-field alignment.

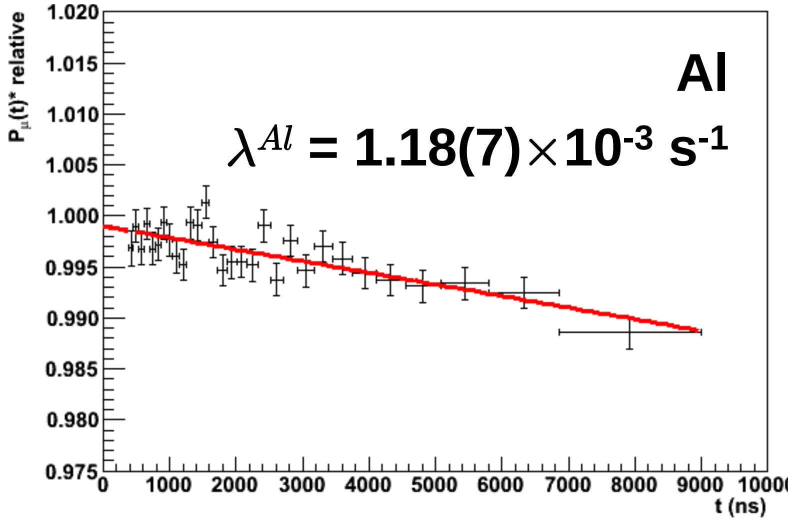
- ➔ Use "internal beam" to test fringe field depolarization limitations.

  (developed by J. Bueno)

Systematic correction for relaxation

- *TWIST* detector is a very powerful μSR device:
  - uniform field, excellent background rejection.
  - e^+ momentum available for weighting the asymmetry.
  - ... but not very versatile...
- Observed relaxation rate is included in the simulation:
  - accounts realistically for relaxation.
  - statistical uncertainty in λ is a source of target depolarization systematic uncertainty in $\mathcal{P}_\mu^\pi \xi$.





Preliminary estimated total uncertainties

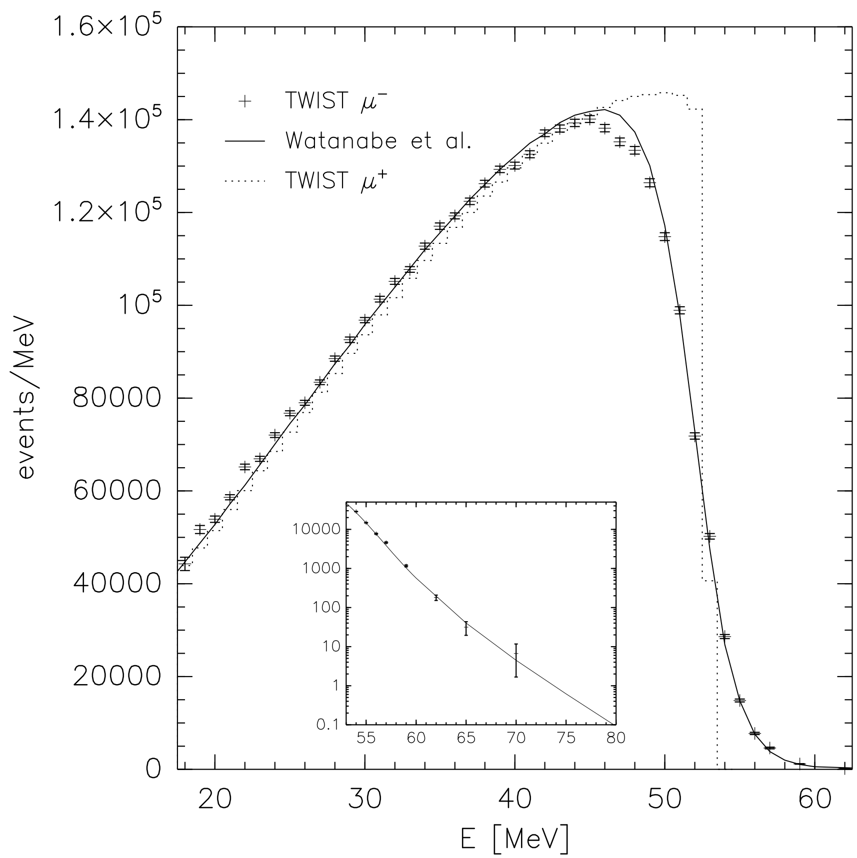
	Published ($\times 10^4$)		Improvement factor	Final, estimated ($\times 10^4$)		Improvement factor
	Statistical	Systematic	vs pre-*TWIST*	Statistical	Systematic	vs pre-*TWIST*
ρ	1.7	4.4	$\times 5$	1.0	2.4	$\times 11$
δ	3.0	6.7	$\times 5$	1.9	2.4	$\times 12$
$\mathcal{P}_\mu \xi$	6.0	38	$\times 2$	2.4	10*	$\times 8$*

* Some challenges remain for final systematic uncertainty for $\mathcal{P}_\mu \xi$.

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
  - higher order corrections required?

Preliminary only!



A. Grossheim et al., in preparation

Summary

- *TWIST* has completed data taking; analysis well underway.
  - Systematic and statistical precision roughly as expected
  - The polarization measurement has unique challenges
    - depolarization systematics especially

- Final results expected by NuFact10

Thank you to:

- NuFact organizers and conveners
- our support agencies: NSERC, DOE, TRIUMF
- WestGrid, for lots of CPU power
- the audience, for your attention
- the *TWIST* collaboration

TWIST Participants

TRIUMF

Ryan Bayes $*\dagger$
Yuri Davydov
Wayne Faszer
Makoto Fujiwara
David Gill
Alex Grossheim
Peter Gumplinger
Anthony Hillairet $*\dagger$
Robert Henderson
Jingliang Hu
Glen Marshall
Dick Mischke
Konstantin Olchanski
Art Olin $\dagger$
Robert Openshaw
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin $\ddagger\ddagger$

Alberta

Andrei Gaponenko $**$
Robert MacDonald $**$

British Columbia

James Bueno $*$
Mike Hasinoff

Montréal

Pierre Depommier

Regina

Ted Mathie
Roman Tacik

Kurchatov Institute

Vladimir Selivanov

Texas A&M

Carl Gagliardi
Bob Tribble

Valparaiso

Don Koetke
Shirvel Stanislaus

$*$ Graduate student
$**$ Graduated
$\dagger$ also U Vic
$\ddagger\ddagger$ also Saskatchewan
§ deceased

Supported under grants from NSERC (Canada) and DOE (USA),
by TRIUMF and NRC Canada, and the Russian Ministry of Science.
Computing facilities of WestGrid are gratefully acknowledged.

Muon decay parameters

- Muon decay parameters ρ, η, $\mathcal{P}_\mu\xi$, δ
  - muon differential decay rate *vs.* energy and angle:

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

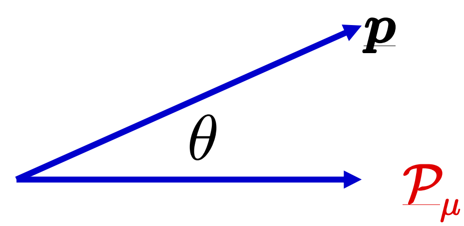
  - where

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

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

  - and

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

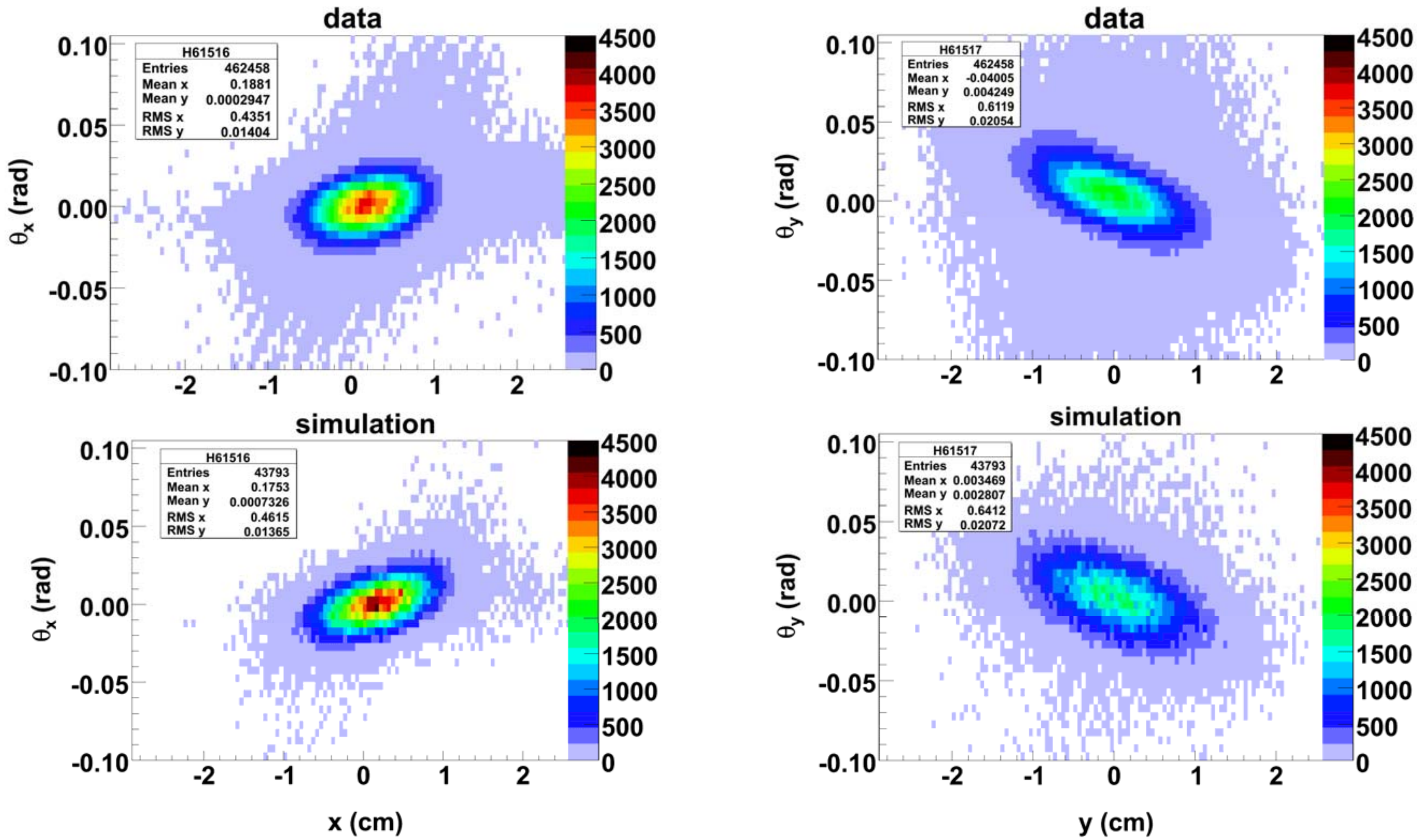


Limits on LRS parameters: PDG08

Observable	$\mathbf{m_2}$ (GeV/c_2)	$\lvert\zeta\rvert$		
$m(K_L^0)$-$m(K_S^0)$	>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

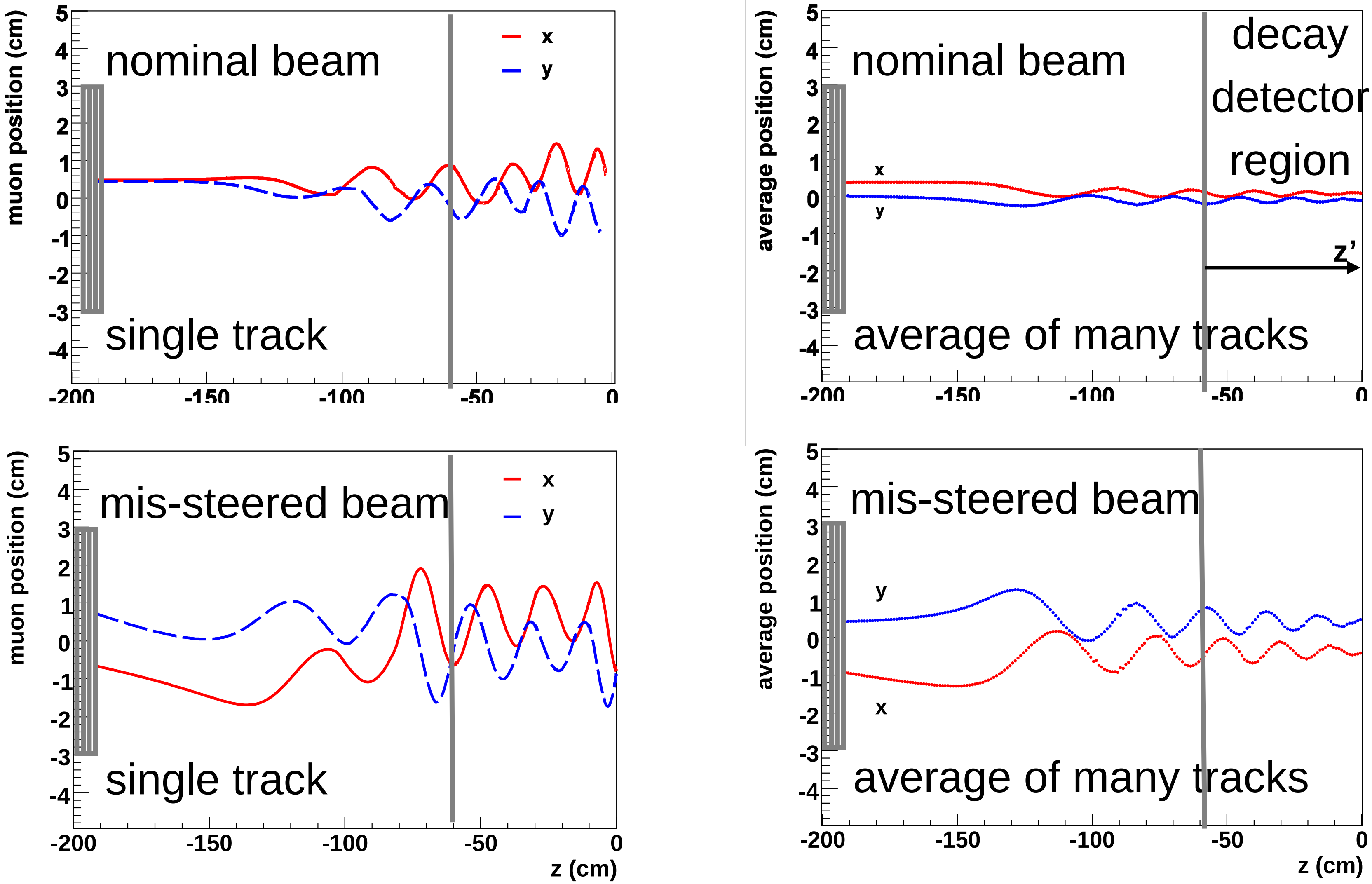
*** in generalized LRS model; to be interpreted as $m_2(g_L/g_R)$, $\geq(g_R/g_L)$.**

Simulating the muon beam



Comparison of TEC data and corresponding simulation of beam profiles

Muon paths in fringe field



Depolarization in stopping target

- " $\mu\mathcal{SR}$ " effect -- minimize by use of high-purity metal targets:
  - main mechanism at room temperature is via interaction with conduction electrons (Korringa relaxation), studied in $\mu\mathcal{SR}$ experiments.
  - asymmetry is a function of time: $\mathcal{P}_\mu(t) = \mathcal{P}_\mu^\circ\, exp(-\lambda t)$.
  - different targets, Al (76 μm) and Ag (28 μm) provide test of possible systematic bias.

- Stopping target forms anode of adjacent MWPC detectors:
  - energy loss (ionization charge) information discriminates against muons stopping in other detector materials, to reduce depolarization from
    - ($\mu^+ e^-$) formation (*e.g.* in MWPC gas, He), which depolarizes muons (depolarization also reduced by high longitudinal field).
    - chemical reactions (analogous to hydrogen atom).