Latest Results on Muon Decay from the TWIST Collaboration

Robert E. Tribble

Texas A&M University

for the **TWIST Collaboration**

Muon decay spectrum

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

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

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

[Radiative corrections not included]

Muon decay matrix element

- Most general local, derivative-free, lepton-number conserving muon decay matrix element:

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

- In the Standard Model, g^{V}_{LL} = 1, all others are zero
- Pre-TWIST global fit results (all 90% c.l.):

$\lvert g^S_{RR} \rvert < 0.066$	$\lvert g^V_{RR} \rvert < 0.033$	$\lvert g^T_{RR} \rvert \equiv 0$
$\lvert g^S_{LR} \rvert < 0.125$	$\lvert g^V_{LR} \rvert < 0.060$	$\lvert g^T_{LR} \rvert < 0.036$
$\lvert g^S_{RL} \rvert < 0.424$	$\lvert g^V_{RL} \rvert < 0.110$	$\lvert g^T_{RL} \rvert < 0.122$
$\lvert g^S_{LL} \rvert < 0.550$	$\lvert g^V_{LL} \rvert > 0.960$	$\lvert g^T_{LL} \rvert \equiv 0$

Muon decay parameters and coupling constants

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

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

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

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

Prior to **TWIST**

	SM
ρ = 0.7518 ± 0.0026	3/4
η = -0.007 ± 0.013	0
$P_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030	1
δ = 0.7486 ± 0.0026 ± 0.0028	3/4
$P_\mu(\xi\delta/\rho)$ > 0.99682 (90% c.l.)	1

Goal of **TWIST**

- Search for new physics that can be revealed by **order-of-magnitude improvements** in our knowledge of **ρ**, **δ**, and $P_\mu\xi$

Two examples

- Model-independent limit on muon handedness

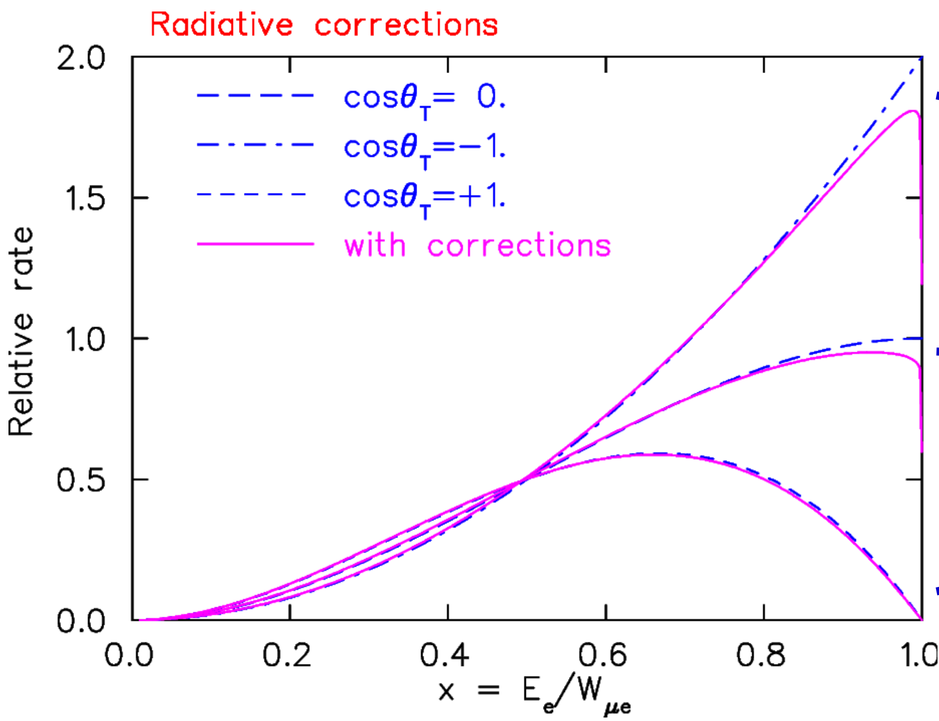
$$Q_R^\mu = \frac{1}{2}\left[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right]$$

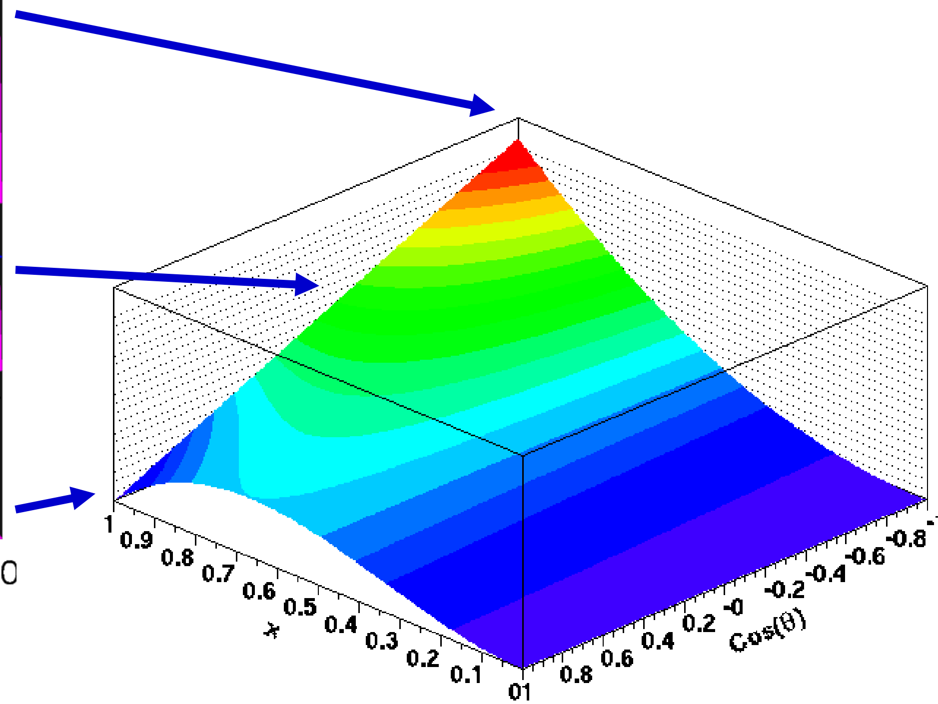
- Left-right symmetric models

$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2 \qquad 1 - P_\mu\xi = 4\left(\zeta^2 + \zeta\left(\frac{M_L}{M_R}\right)^2 + \left(\frac{M_L}{M_R}\right)^4\right)$$

- …..

What is required?



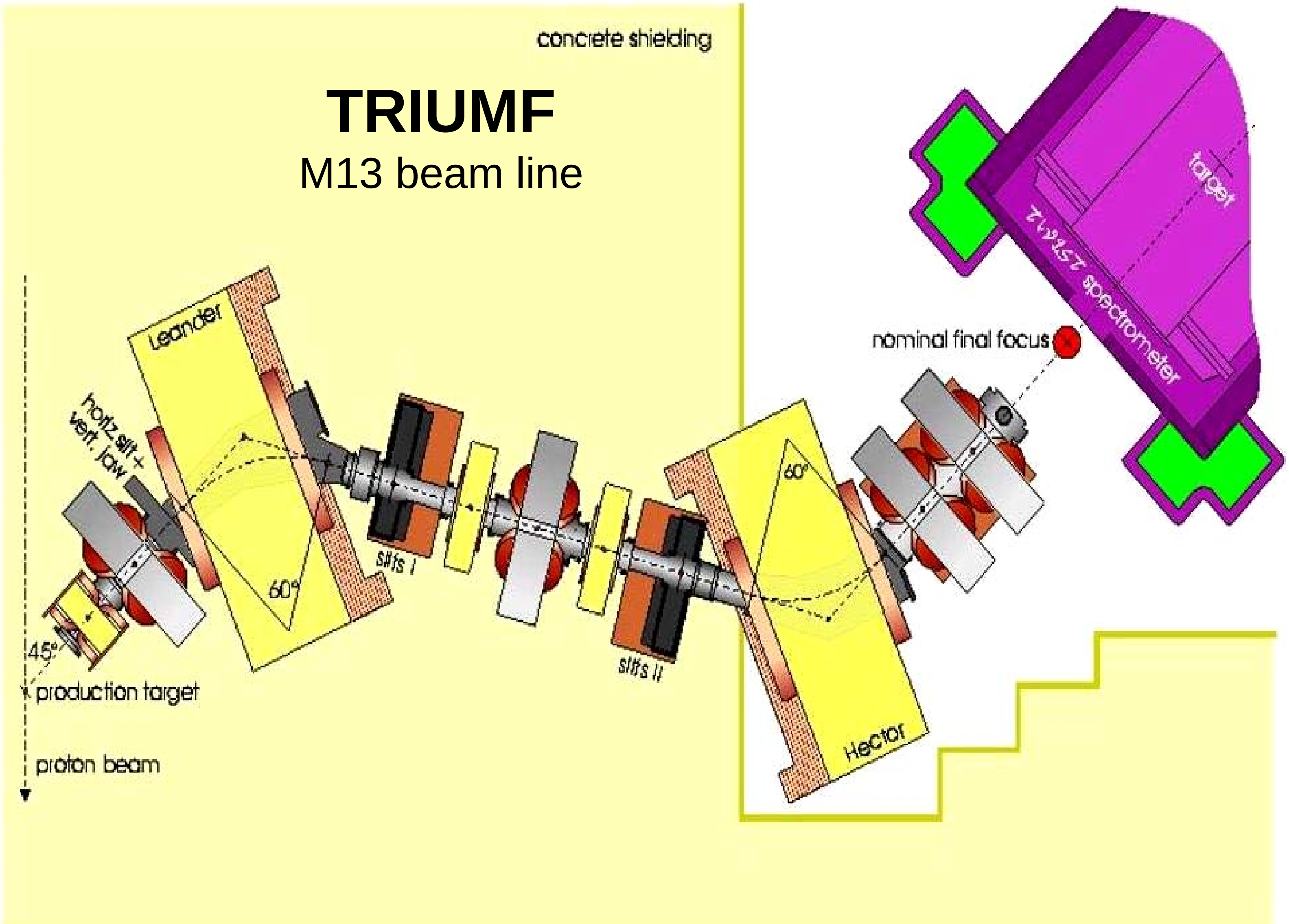


Must:

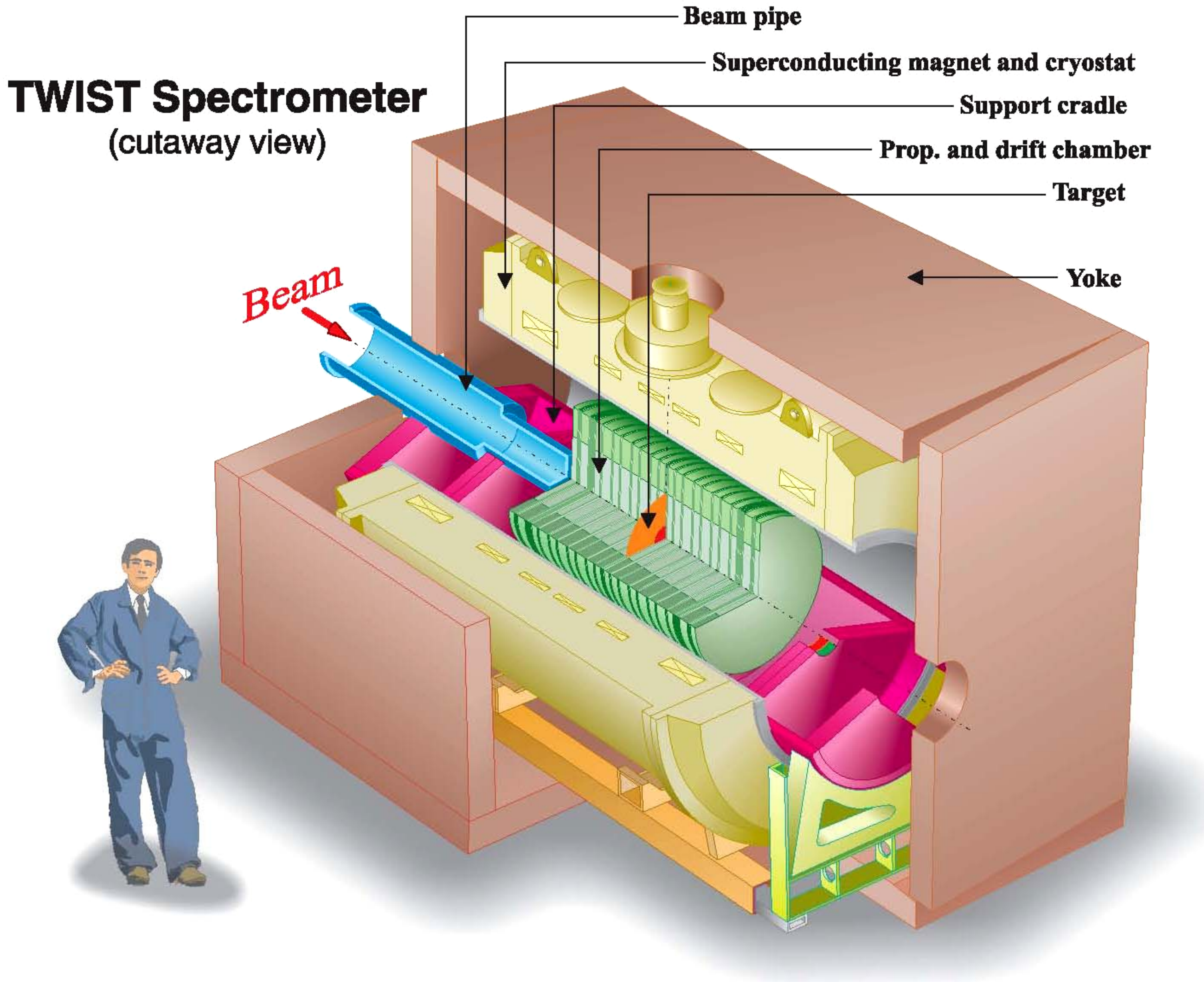
- Understand sources of muon depolarization
  - -- P_μ and ξ come as a product
- Determine spectrum shape
  - -- All three parameters
- Measure forward-backward asymmetry
  - -- For $P_\mu\xi$ and δ

to within a **few parts in 10^4**

Surface muon beam

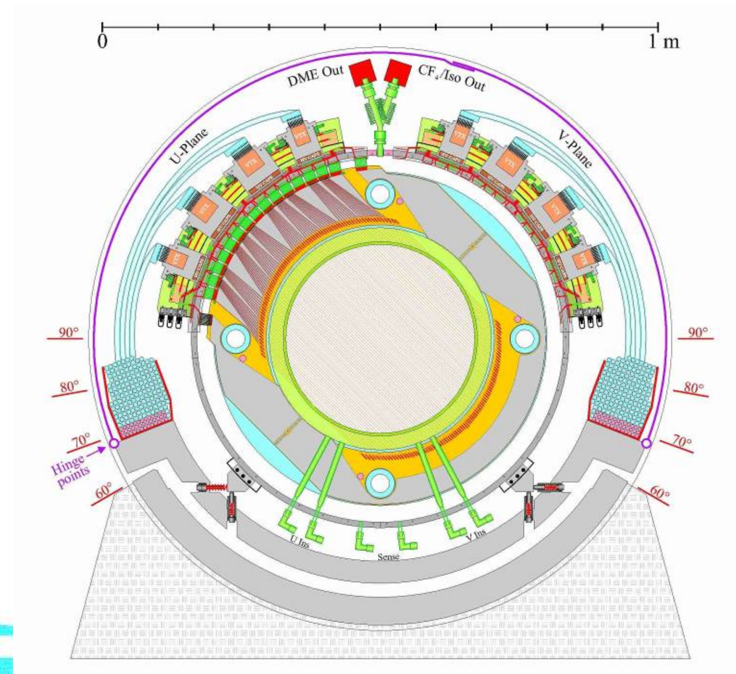


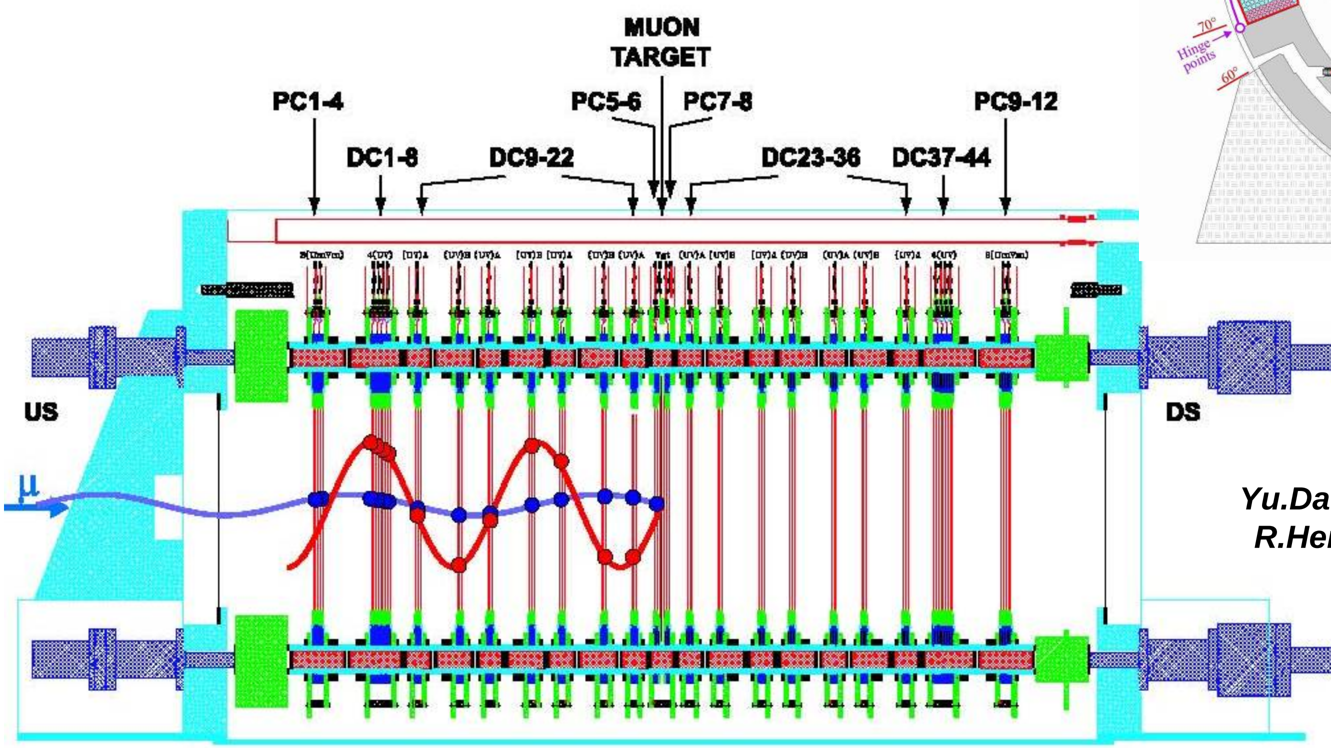
TWIST spectrometer



Detector array

- 56 low-mass high-precision planar chambers symmetrically placed around thin target foil
- Measurement initiated by single thin scintillation counter at entrance to detector
- Beam stop position controlled by variable He/CO2 gas degrader

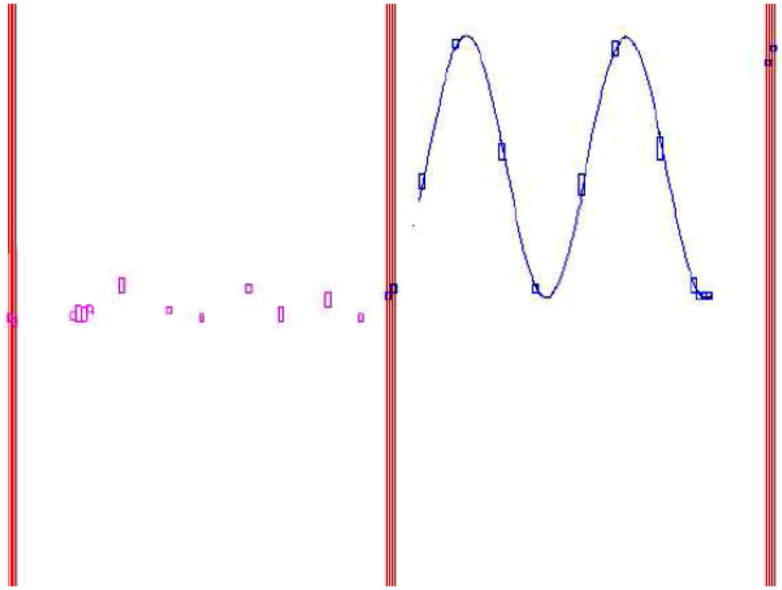




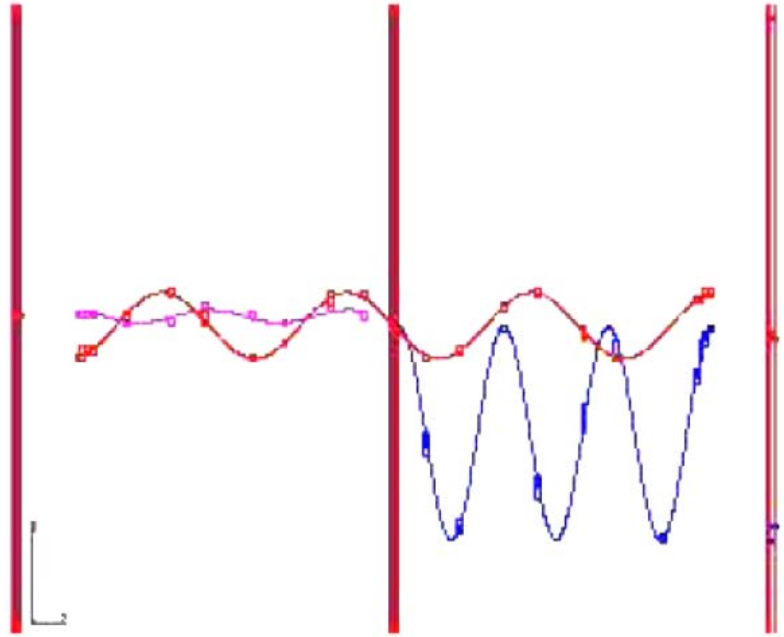
Yu.Davydov et al.   ***NIM A461(2001)68***
R.Henderson et al.   ***NIM A548(2005)306***

Typical events

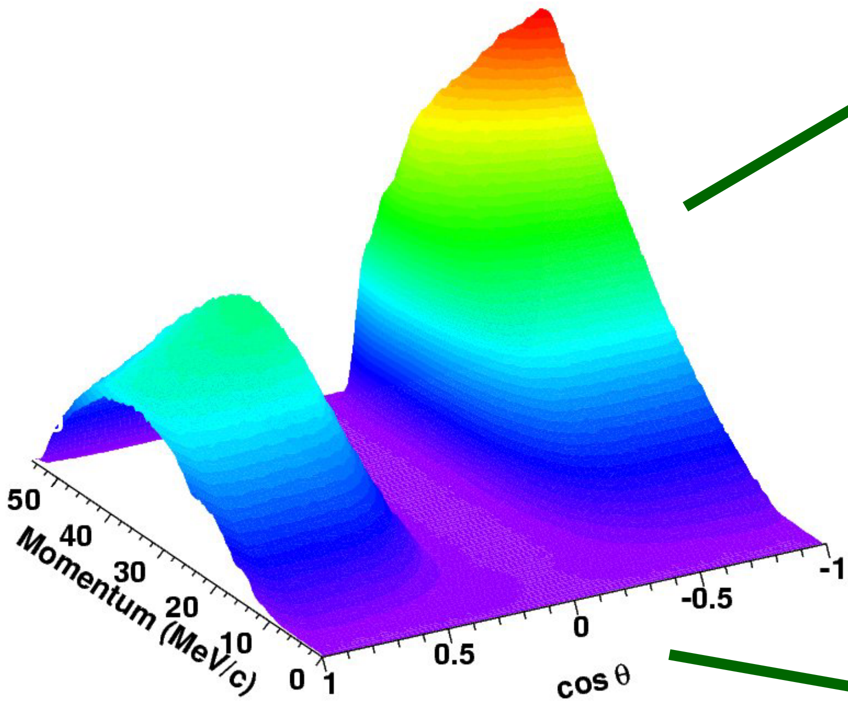
- Use pattern recognition (in position and time) to sort hits into tracks, then fit to helix



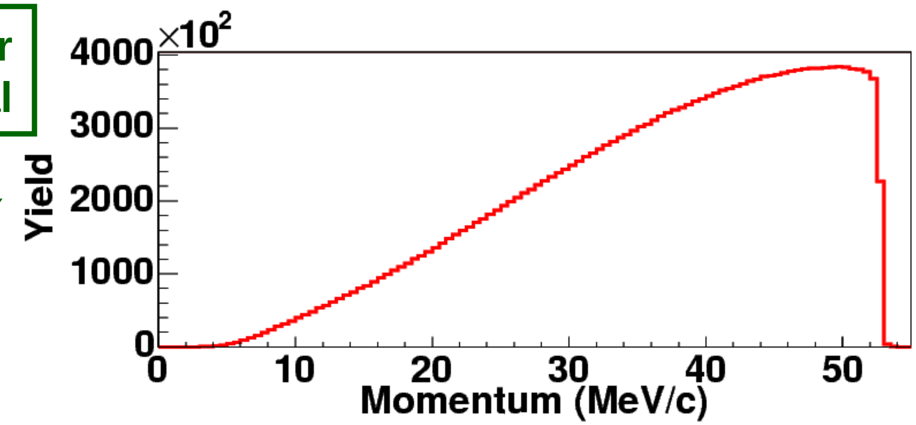
- Must also recognize beam positrons, delta tracks, backscattering tracks



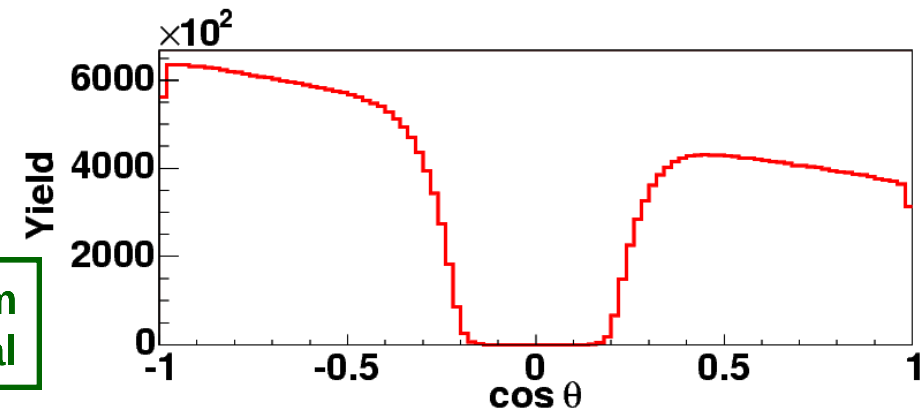
2-d momentum-angle spectrum



In angular fiducial



In momentum fiducial



Acceptance of the **TWIST** spectrometer

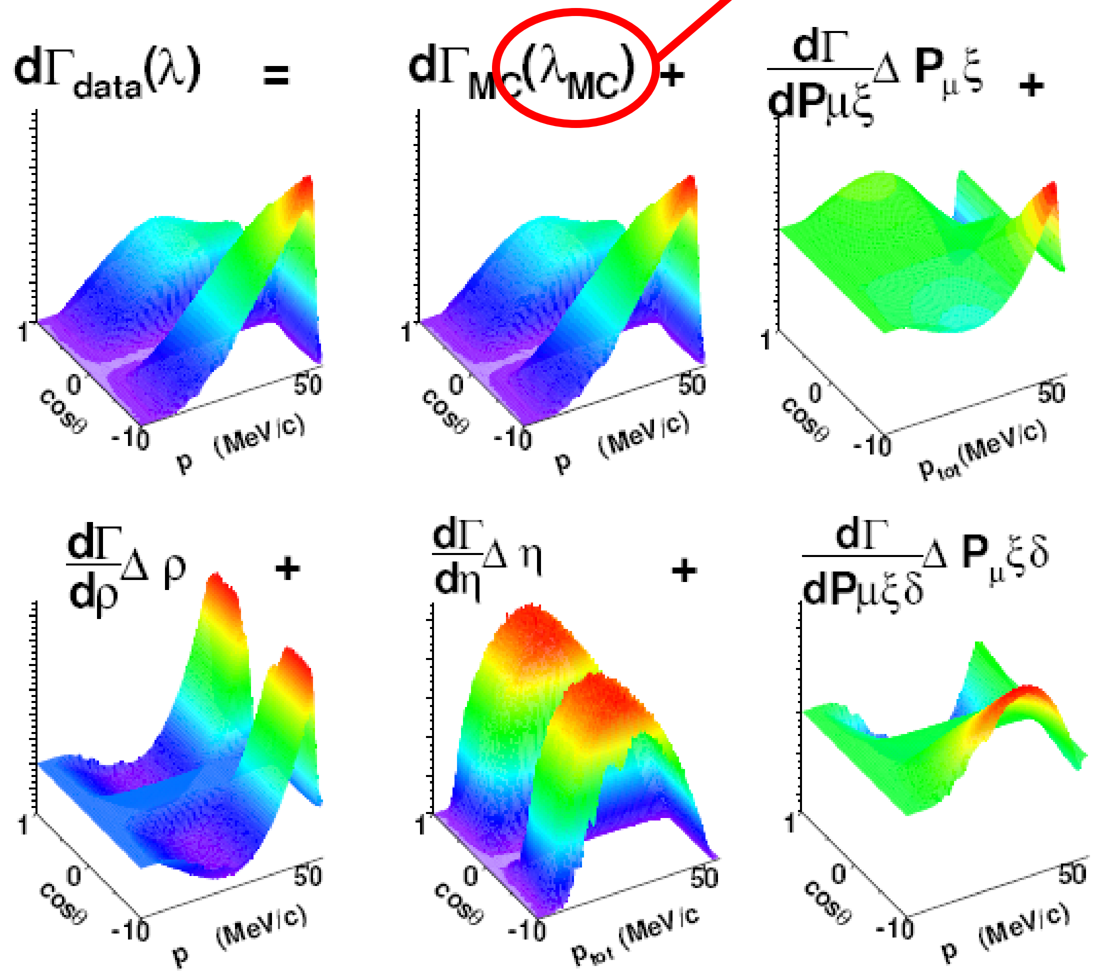
Fitting the data distributions

λ_{MC} **hidden**
➔ blind analysis

- Michel distribution is linear in ρ, η, $P_\mu\xi$, and $P_\mu\xi\delta$, so a fit to first order expansion is exact.

- Fit data to simulated (MC) base distribution with *hidden assumed parameters*,

  $\lambda_{MC} = (\rho, \eta, P_\mu\xi_{|P_\mu\xi\delta}, P_\mu\xi\delta)$ plus MC-generated distributions from analytic derivatives, times fitting parameters ($\Delta\lambda$) representing deviations from base MC.

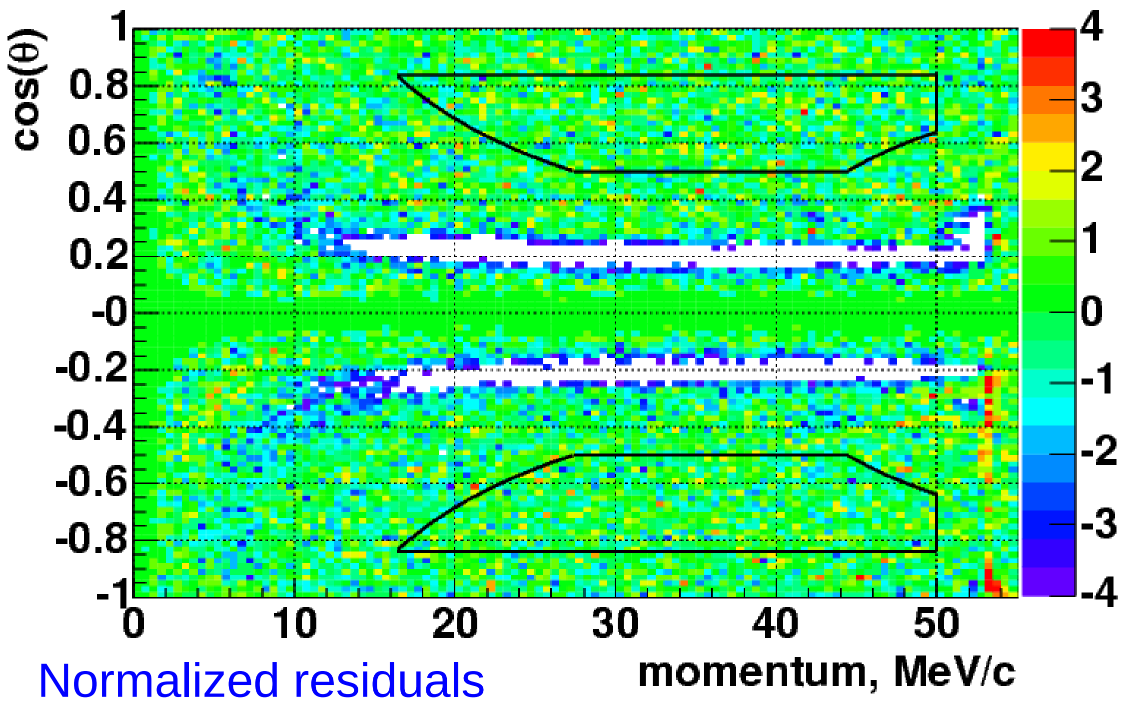


(graphic thanks to Blair Jamieson)

Physics data sets

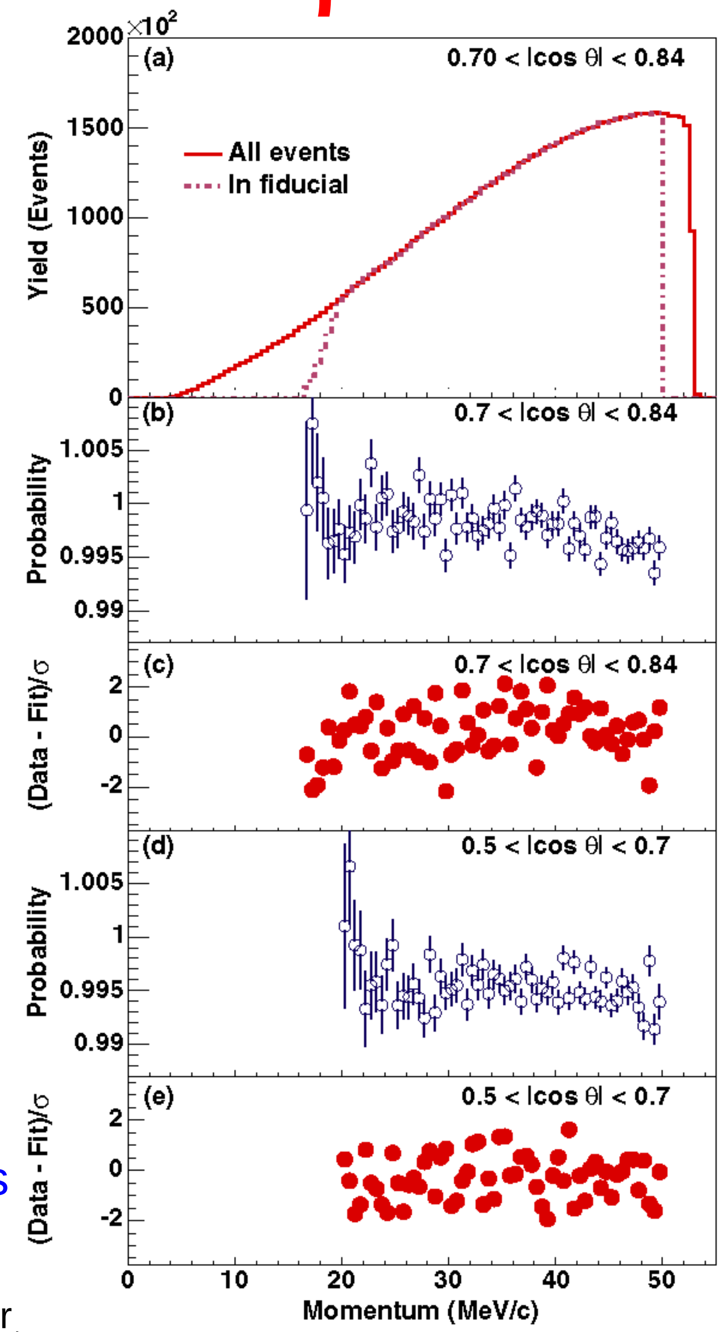
- Fall 2002
  - Test data-taking procedures and develop analysis techniques
  - First physics results – ρ and δ
  - Graphite-coated Mylar target not suitable for $P_\mu\xi$
- Fall 2004
  - Al target and Time Expansion Chamber enabled first $P_\mu\xi$ measurement
  - Improved determinations of ρ and δ are underway
- 2006-07
  - Ag and Al target data
  - Larger data sets and better beam characterization
  - Achieve ultimate **TWIST** precision for ρ, δ, and $P_\mu\xi$

Fitting the 2002 data to determine ρ and δ



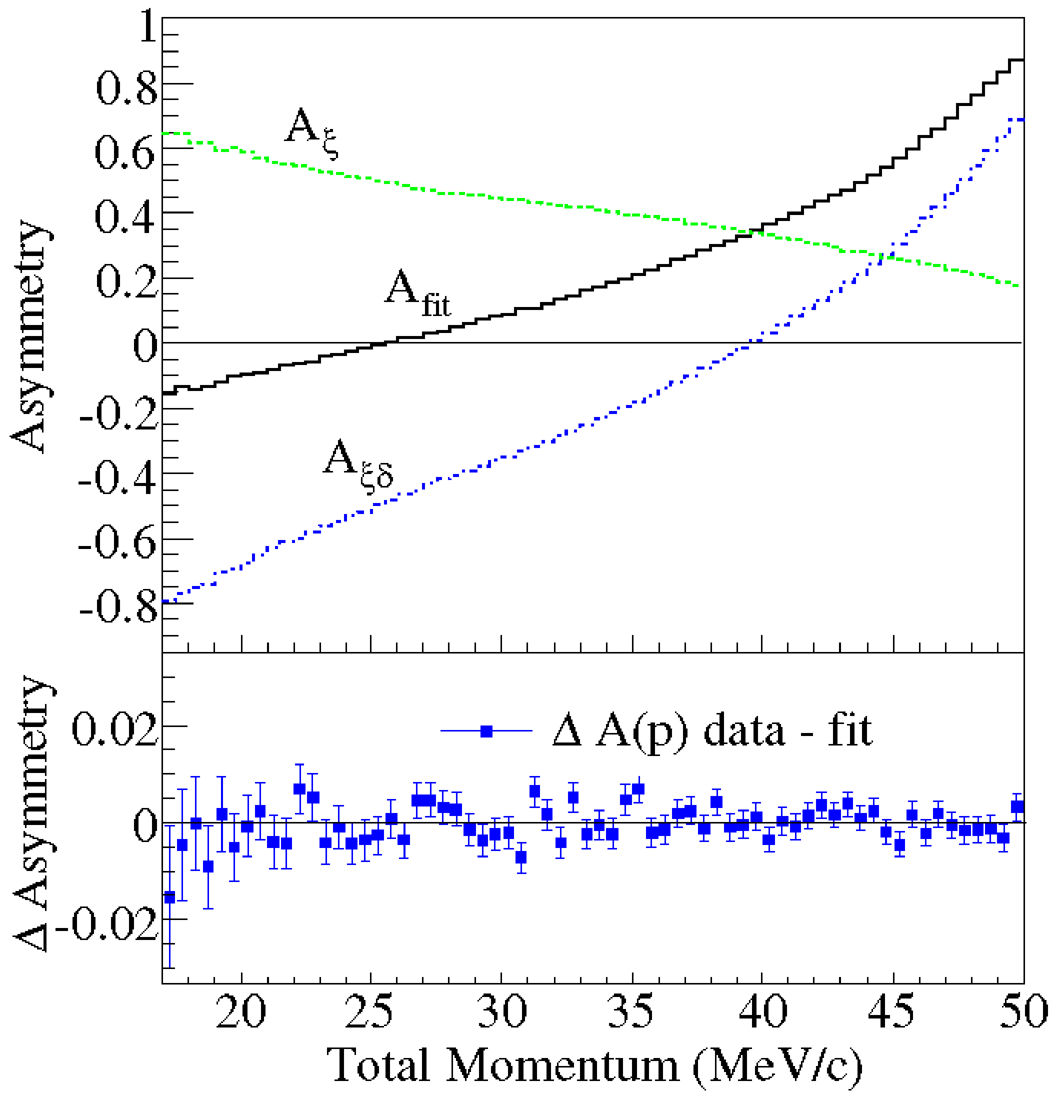
Normalized residuals
[(Data-Fit)/sigma] of the 2-d momentum-angle fit

Fit describes the data well, even when extrapolated far outside the fiducial region



Angle-integrated results

Fitting the 2004 data to determine $P_\mu \xi$



Separating the asymmetry into components

Results to date

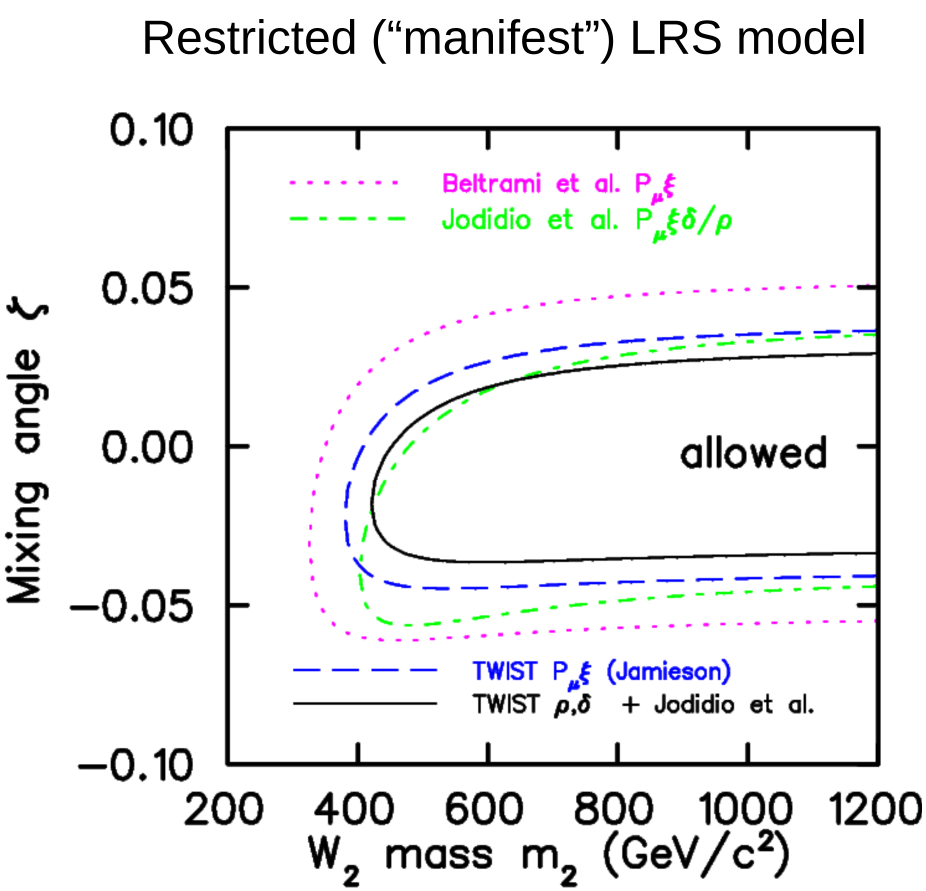
- From Fall, 2002 run:
  - ρ = 0.75080 ± 0.00032 (stat) ± 0.00097 (syst) ± 0.00023 (η)

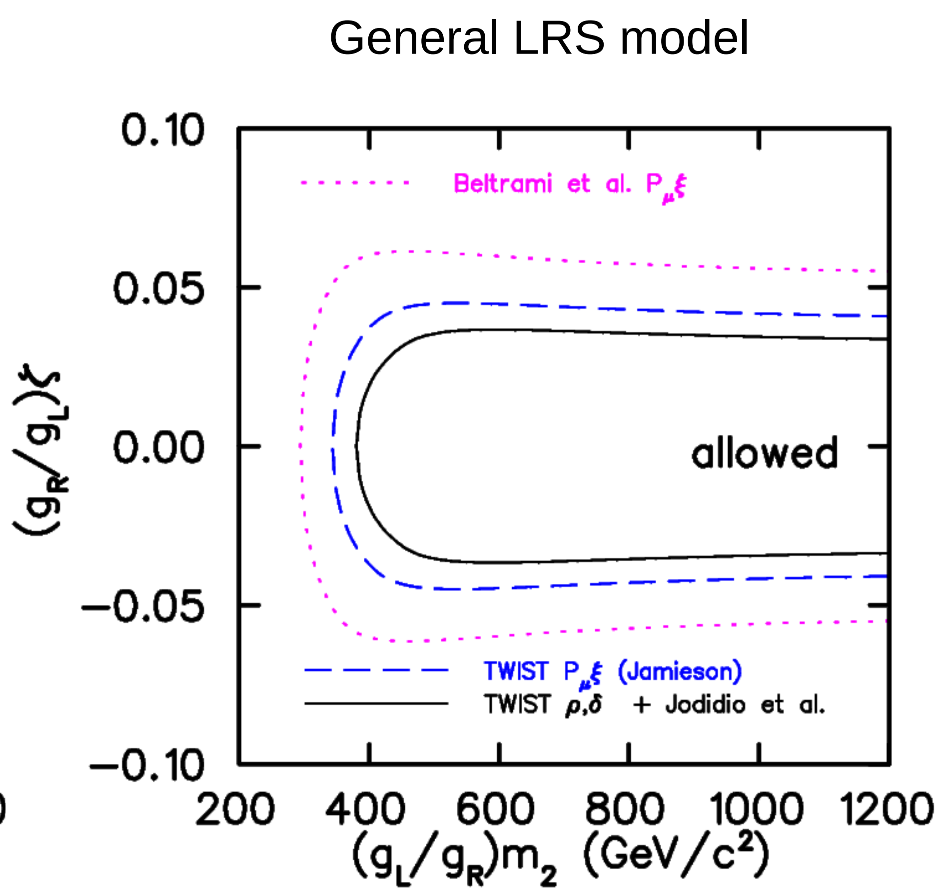
    PRL 94, 101805
  - δ = 0.74964 ± 0.00066 (stat) ± 0.00112 (syst)

    PRD 71, 071101
- New global analysis (PRD 72, 073002) using the ρ and δ results, together with previous measurements and recent e^+ transverse polarization measurements (PRL 94, 021802):
  - Significant improvements in the limits for $g^{S,V,T}{}_{LR}$
  - η = -0.0036 ± 0.0069
- From Fall, 2004 run (so far):
  - $P_\mu\xi$ = 1.0003 ± 0.0006 (stat) ± 0.0038 (syst)

    PRD 74, 072007
- Factors of 2-3 improvements on pre-**TWIST** precisions

New limits in left-right symmetric models





Initial **TWIST** measurements already provide significant new limits

Systematics in the previous measurements

TABLE II. Contributions to the systematic uncertainty in ρ. Average values are given for those denoted (av), which are considered set dependent when performing the weighted average of the data sets.

Effect	Uncertainty
Chamber response (av)	± 0.00051
Stopping target thickness	± 0.00049
Positron interactions	± 0.00046
Spectrometer alignment	± 0.00022
Momentum calibration (av)	± 0.00020
Theoretical radiative corrections [12]	± 0.00020
Track selection algorithm	± 0.00011
Muon beam stability (av)	± 0.00004
Total in quadrature	± 0.00093
Scaled total	± 0.00097

TABLE II. Contributions to the systematic uncertainty for δ. Average values are denoted by (ave), which are considered set-dependent when performing the weighted average of data sets.

Effect	Uncertainty
Spectrometer alignment	± 0.00061
Chamber response(ave)	± 0.00056
Positron interactions	± 0.00055
Stopping target thickness	± 0.00037
Momentum calibration(ave)	± 0.00029
Muon beam stability(ave)	± 0.00010
Theoretical radiative corrections[9]	± 0.00010
Upstream/downstream efficiencies	± 0.00004

TABLE III. Contributions to the systematic uncertainty for $P_\mu^\pi \xi$.

Effect	Uncertainty
Depolarization in fringe field (ave)	0.0034
Depolarization in stopping material (ave)	0.0012
Chamber response (ave)	0.0010
Spectrometer alignment	0.0003
Positron interactions (ave)	0.0003
Depolarization in production target	0.0002
Momentum calibration	0.0002
Upstream-downstream efficiency	0.0002
Background muon contamination (ave)	0.0002
Beam intensity (ave)	0.0002
Michel parameter η	0.0001
Theoretical radiative corrections	0.0001

The same effects tend to dominate the systematic uncertainties for all three parameters.

Reducing the leading systematics

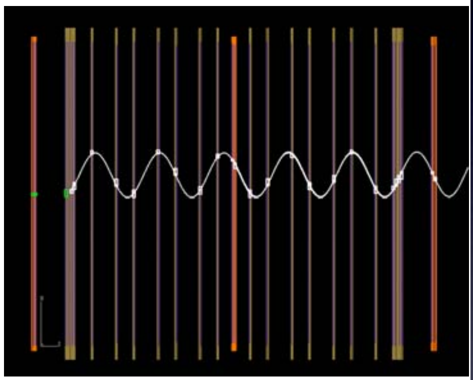
- Issues that were unique to 2002 data
  - Stopping target thickness uncertainty
  - Chamber orientation uncertainty with respect to magnetic field

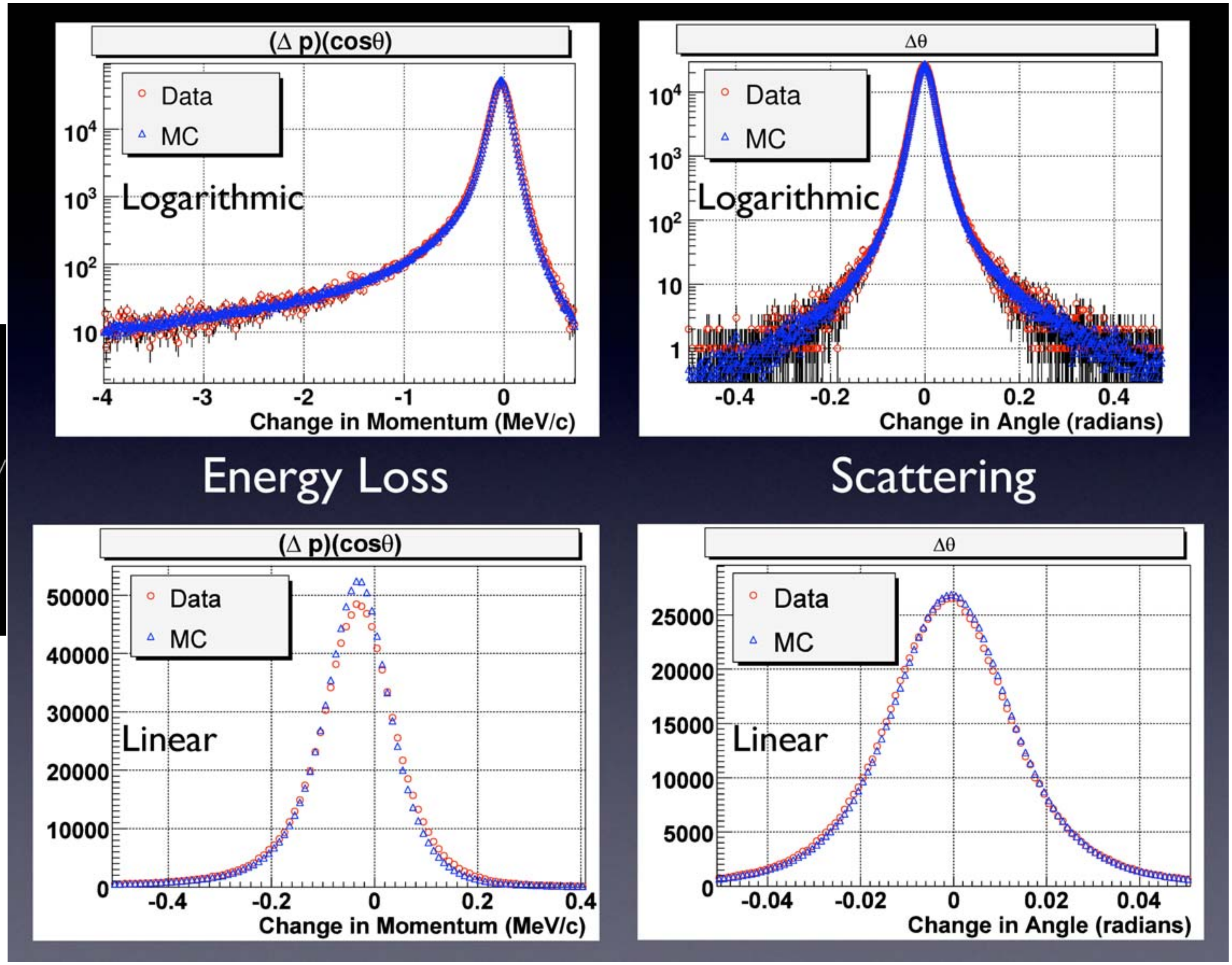
- For all three Michel parameters
  - Chamber response
    - Improved gas system regulation and monitoring
    - Improved determination of foil geometry
    - Improved treatment of drift chamber behavior
  - Positron interactions

- Specific to $P_\mu \xi$
  - Muon depolarization when crossing fringe field
  - Muon depolarization in the stopping target

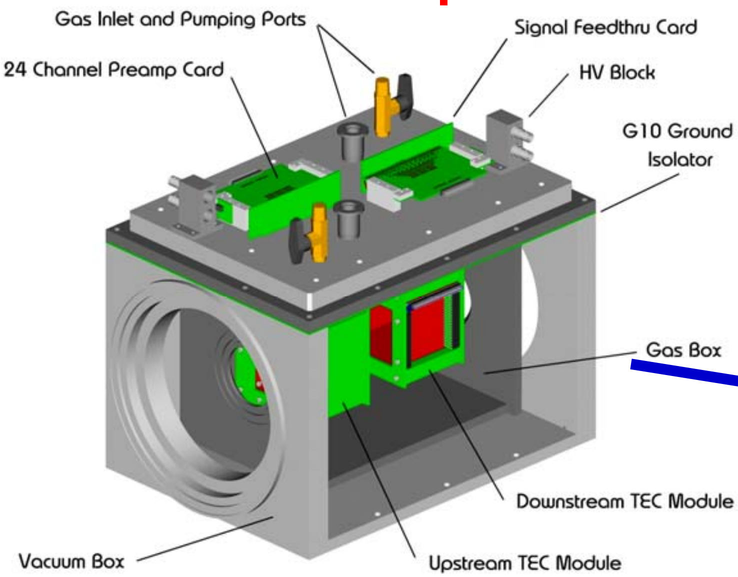
Validating the Monte Carlo with “upstream stops”

(DS-Fit)-(US-Fit)

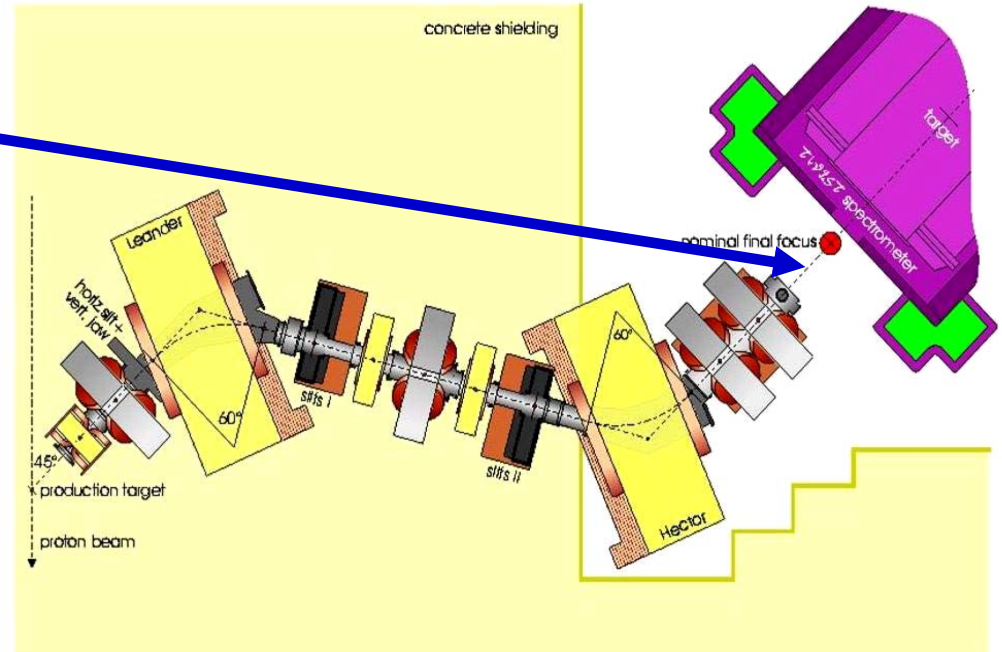


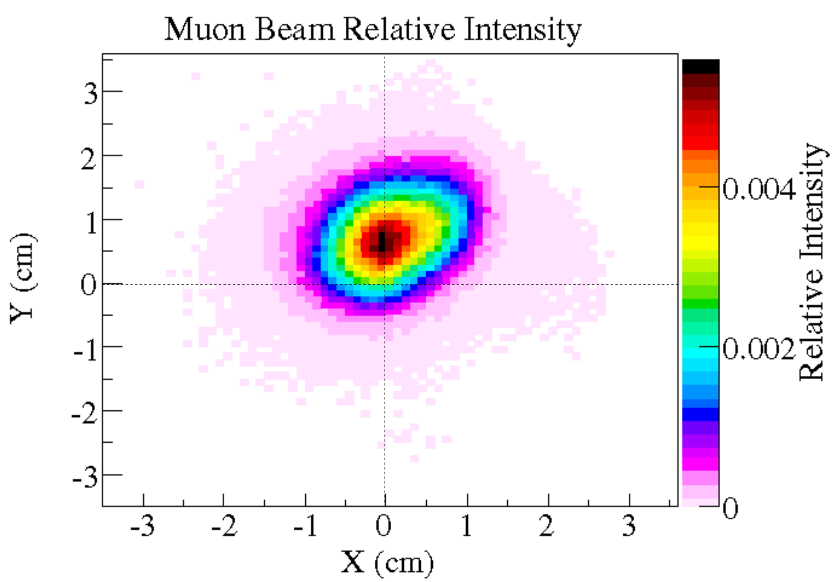


Muon depolarization across the fringe field



Use Time Expansion Chamber (TEC) to measure and **optimize** the muon beam

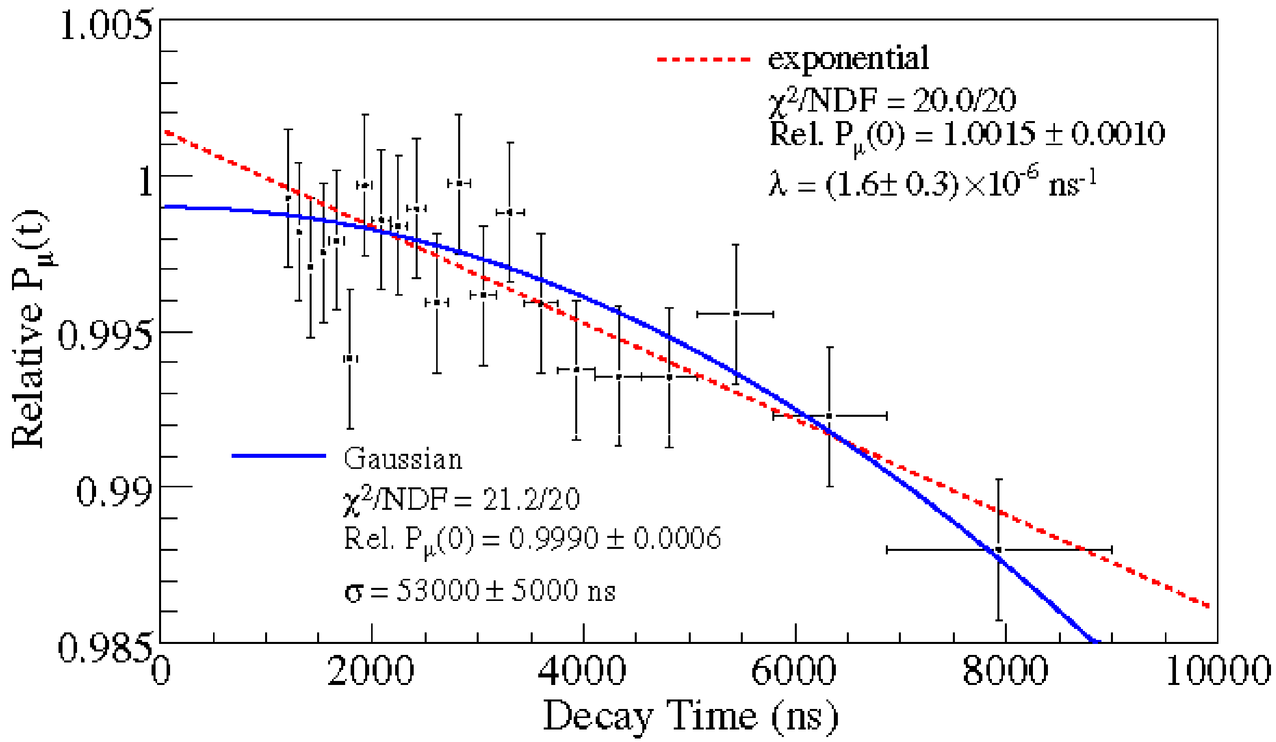




2004 muon beam spot

- First installed for 2004 run
- Found vertical beam offset – now corrected
- Now take frequent beam characterizations
- Have techniques to identify when the beam changes between TEC measurements

Muon depolarization after stopping



- Observed significant depolarization in 2004 data
- New techniques allow us to veto muons that stop outside the metal stopping target
- More sensitive analysis procedures to determine the residual depolarization rate
- Now taking data with a Ag target to explore material dependence

Systematic uncertainties for 2004 data: ρ and δ

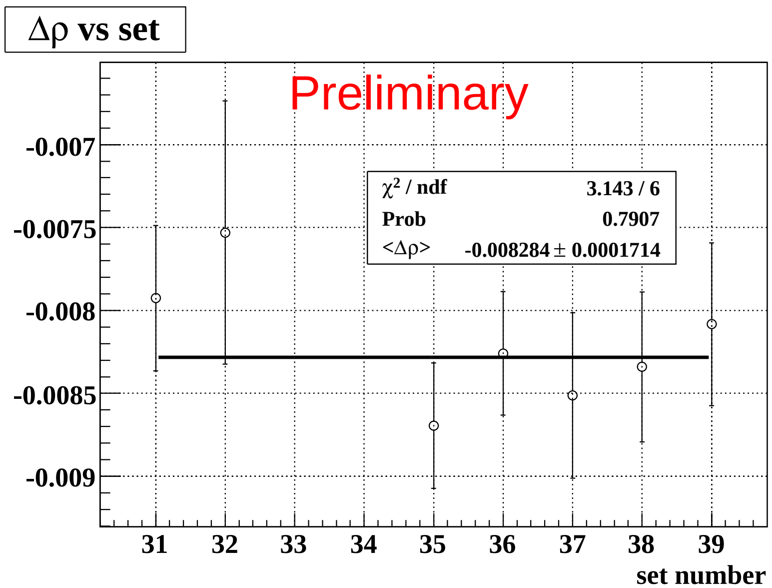
Systematic uncertainties	ρ ($\leq 10^4$)		δ ($\leq 10^4$)	
	published	current	Published	current
Chamber response (ave)	5.1	2.9	5.6	5.2
Stopping target thickness	4.9	-	3.7	-
Positron interactions	4.6	1.6	5.5	1.0
Spectrometer alignment	2.2	0.3	6.1	0.3
Momentum calibration (ave)	2.0	2.8	2.9	4.0
Theoretical radiative correction	2.0	2.0	1.0	1.0
Muon beam stability (ave)	0.4	0.1	1.0	0.2
Track selection algorithm	1.1	-		
Resolution*		1.2		1.4
Asymmetric efficiencies			0.4	0.1
Total in quadrature	**9.3**	**5.1**	**11.2**	**6.9**

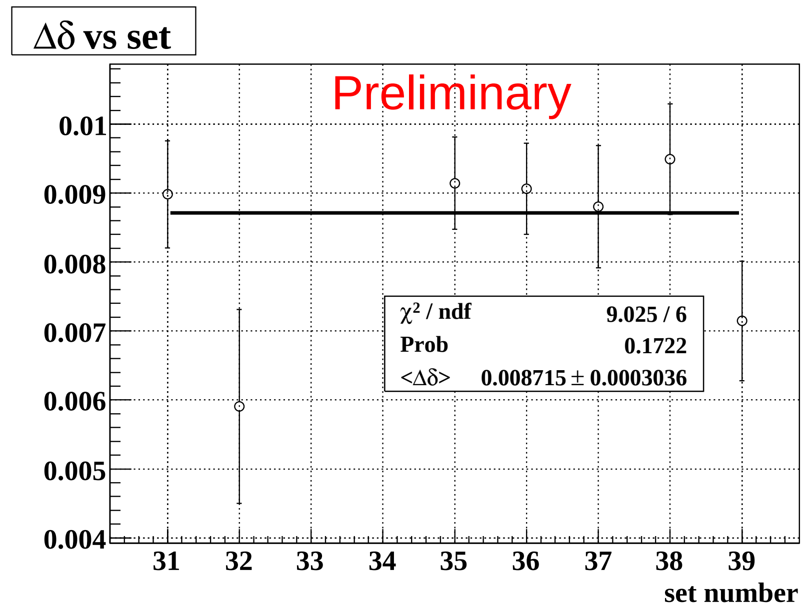
Preliminary

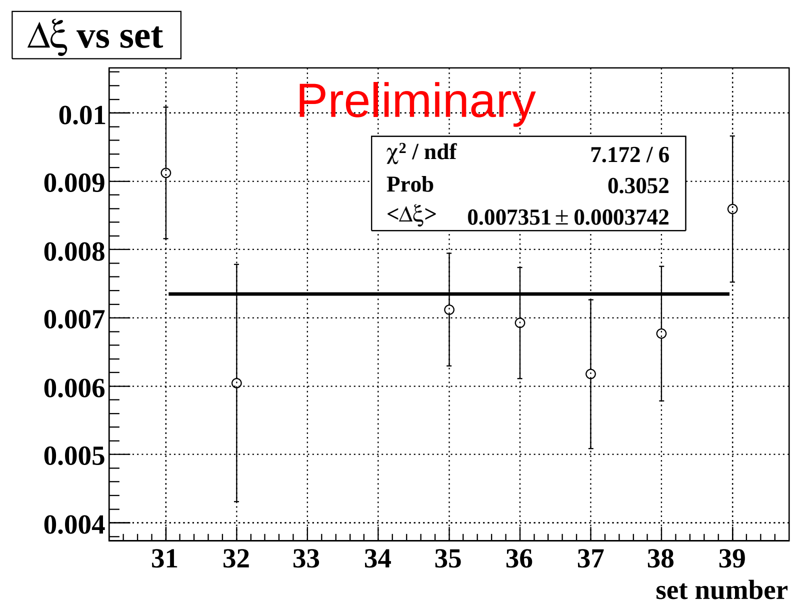
Preliminary

*Included in positron interactions in published results

Consistency Checks: ρ and δ







- Data sets for 2004 analysis
- Δ's from fits to MC
- No corrections applied
- Decay parameters in BB still hidden

Unveiling the Hidden Parameters

Black box opening in about two weeks

Robert Tribble – DNP, October, 2007

Systematics for Final Data

- For all three Michel parameters
  - Chamber response
    - Data driven STR's
    - Temperature and density effects
  - More work on determining effect of endpoint calibration and the momentum scale
- Specific to $P_\mu \xi$
  - More TEC data and better muon beam
  - Better muon beam monitoring and reduced p_T (lower depolarization)
  - Two stopping targets – data on Ag and Au
- Larger data sets to reduce statistical uncertainty

Final Uncertainty Goals

	Published		Final (est.)	
	Statistics	Systematics	Statistics	Systematics
ρ	3.2	9.7	1.3	2.4
δ	6.6	11.2	2.3	2.2
$P_\mu \xi$	6.0	38	2.8	7.5

all values in units of 10^{-4}

Final Publications in 2009

Conclusions

- The initial **TWIST** measurements have improved our knowledge of the Michel parameters ρ, δ, and $P_{\mu}\xi$ by factors of 2-3
- Second round improves ρ and δ by about a factor of 2
- Another factor of 2-3 is anticipated for final data
- Improvements for $P_{\mu}\xi$ by a factor 5 are anticipated

TWIST Participants

TRIUMF

Ryan Bayes ¤y
Yuri Davydov
Jaap Doornbos
Wayne Faszer
Makoto Fujiwara
David Gill
Alex Grossheim
Peter Gumplinger
Anthony Hillairet ¤y
Robert Henderson
Jingliang Hu
John A. Macdonald x
Glen Marshall
Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin y
Robert Openshaw
Tracy Porcelli z
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin zz

Alberta

Andrei Gaponenko ¤¤
Peter Kitching
Robert MacDonald ¤
Maher Quraan
Nate Rodning x
John Schaapman
Glen Stinson

British Columbia

James Bueno ¤
Mike Hasinoff
Blair Jamieson ¤¤

Montréal

Pierre Depommier

Regina

Ted Mathie
Roman Tacik

Kurchatov Institute

Vladimir Selivanov
Vladimir Torokhov

Texas A&M

Carl Gagliardi
Jim Musser ¤¤
Bob Tribble
Maxim Vasiliev

Valparaiso

Don Koetke
Paul Nord
Shirvel Stanislaus

¤ Graduate student
¤¤ Graduated
y also U Vic
z also Manitoba
zz also Saskatchewan
x deceased

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T*WI*ST Collaboration