Final Results on Muon Decay from TWIST

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for the **TWIST Collaboration**

Outline

- Introduction to muon decay
- **TWIST** experiment
- Previous **TWIST** results
- Final **TWIST** results

Muon decay spectrum

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

$$\frac{d^2\Gamma}{x^2 dx d(\cos\theta)} \propto (3-3x) + \frac{2}{3}\rho(4x-3) + 3\eta\frac{x_0}{x}(1-x)$$

$$+ P_\mu \xi \cos\theta\left[(1-x) + \frac{2}{3}\delta(4x-3)\right] \quad \text{(+ rad. corr.)}$$

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

- Pre-**TWIST** accepted values for the muon decay (Michel) parameters:

	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

Muon decay matrix element

- Most general Lorentz-invariant, local, lepton-number conserving muon decay matrix element:

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

- The muon decay parameters are bi-linear combinations of the $g^{\gamma}_{\varepsilon\mu}$
- In the Standard Model, $g^{V}_{LL} = 1$, all others are zero
- Pre-**TWIST** global fit results (all 90% c.l.):

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

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 model: $SU(2)_L$ x $SU(2)_R$ x $U(1)$

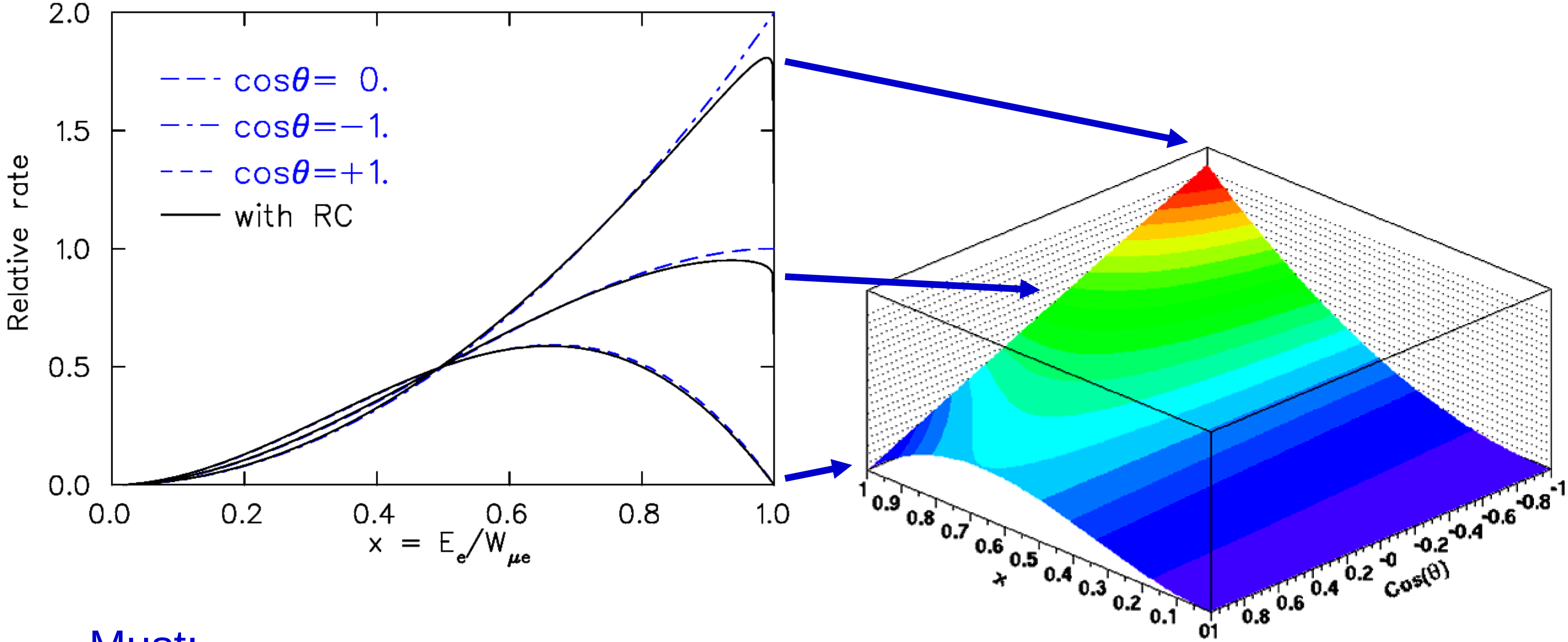
$$W_L = W_1 \cos\zeta + W_2 \sin\zeta$$
$$W_R = e^{i\omega}\left(-W_1 \sin\zeta + W_2 \cos\zeta\right)$$

$$\Rightarrow$$

$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2$$
$$1 - P_\mu \xi = 4\left(\zeta^2 + \zeta\left(\frac{M_1}{M_2}\right)^2 + \left(\frac{M_1}{M_2}\right)^4\right)$$

- …..

What is required?

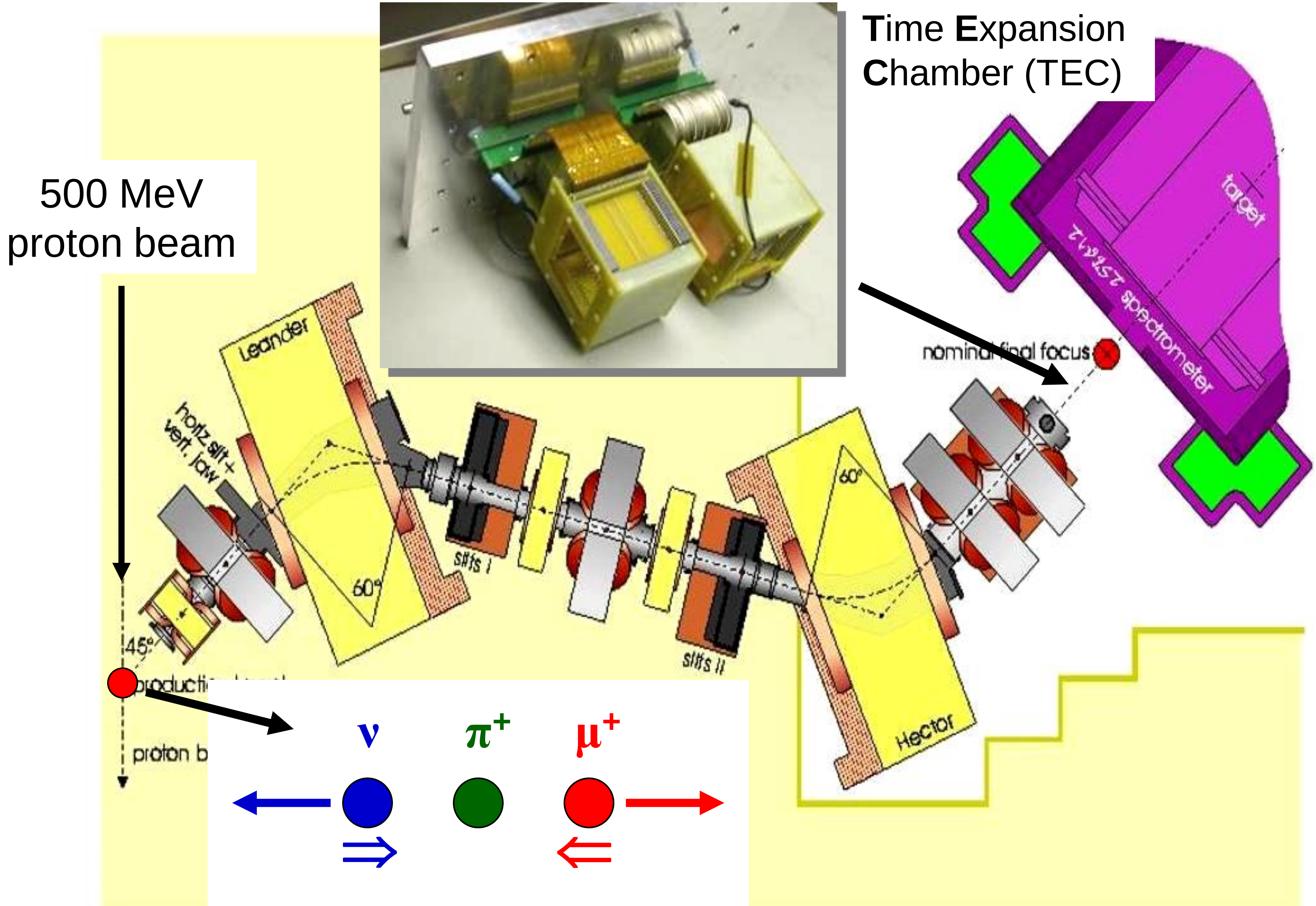


Must:

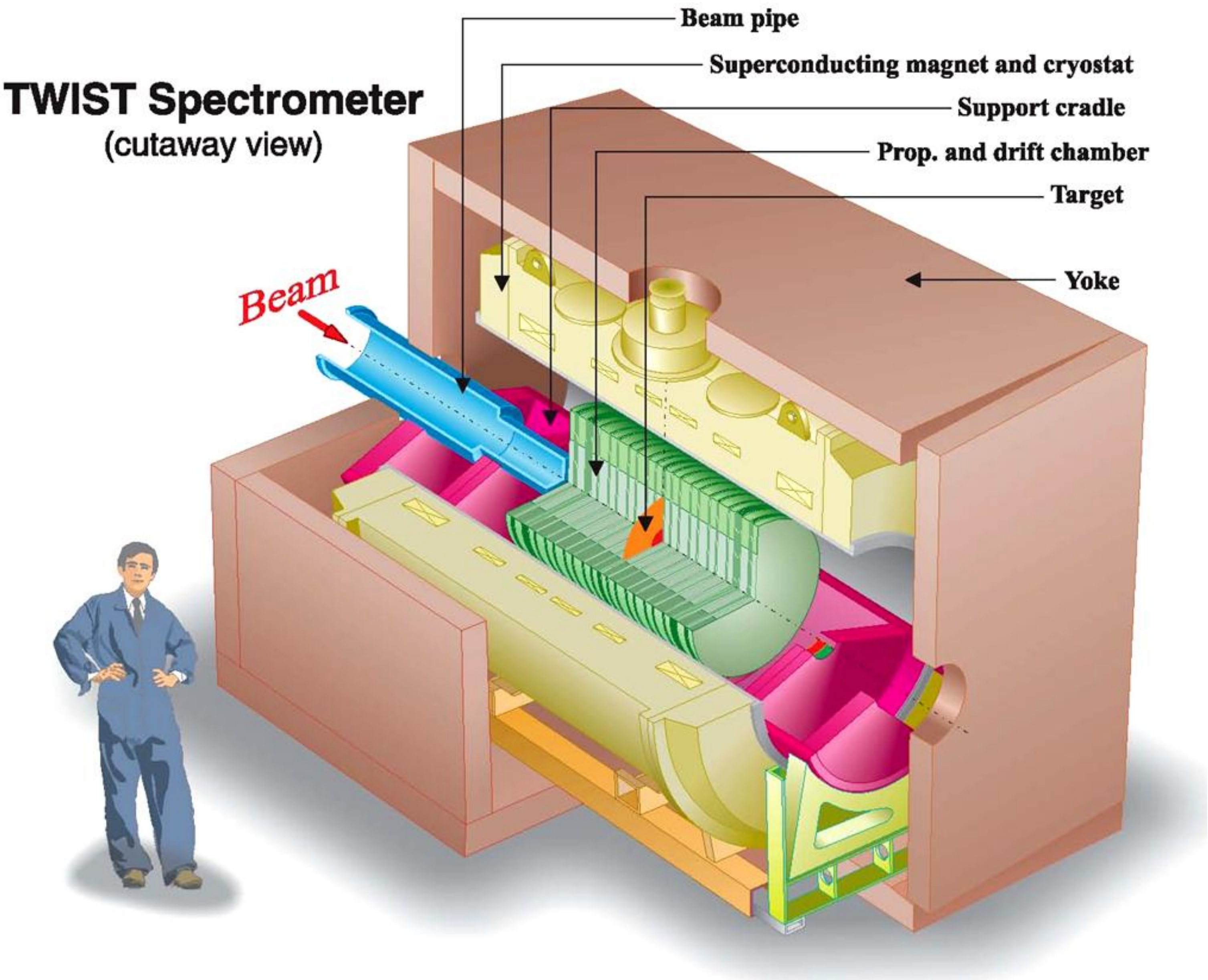
- Understand sources of **muon depolarization**
  - -- P_μ and ξ come as a product
- Determine positron **yield vs. momentum and angle**
  - -- All three parameters

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

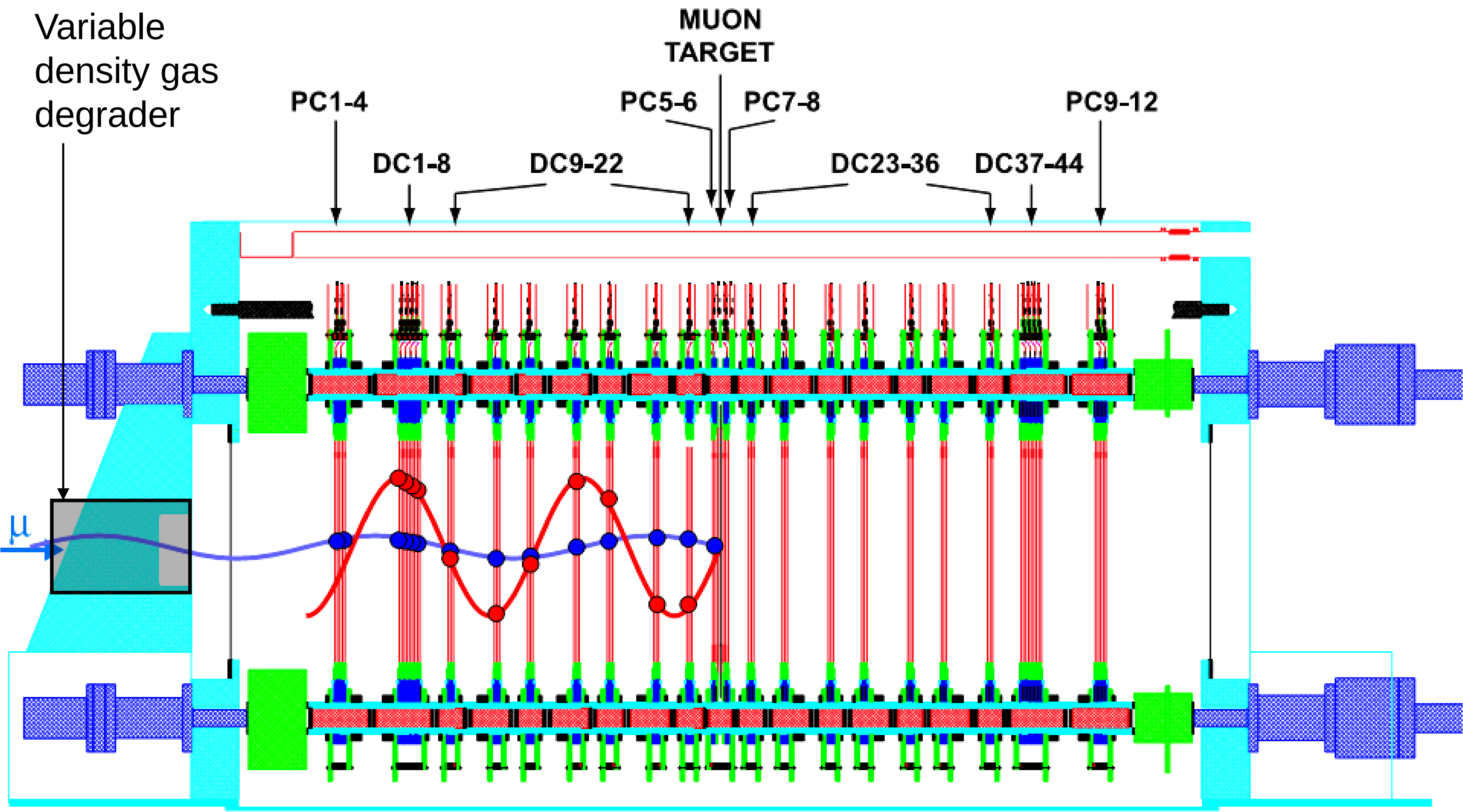
Surface muon beam



TWIST spectrometer

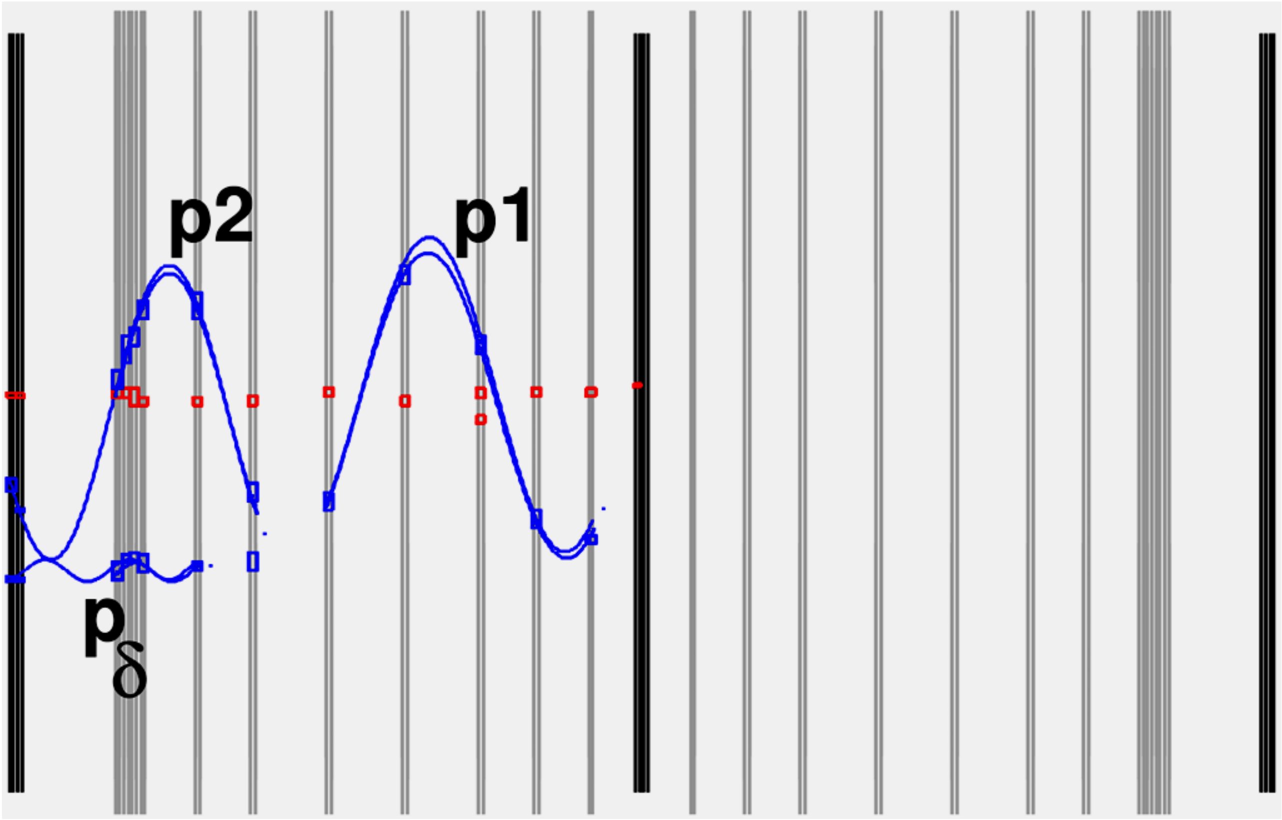


Detector array



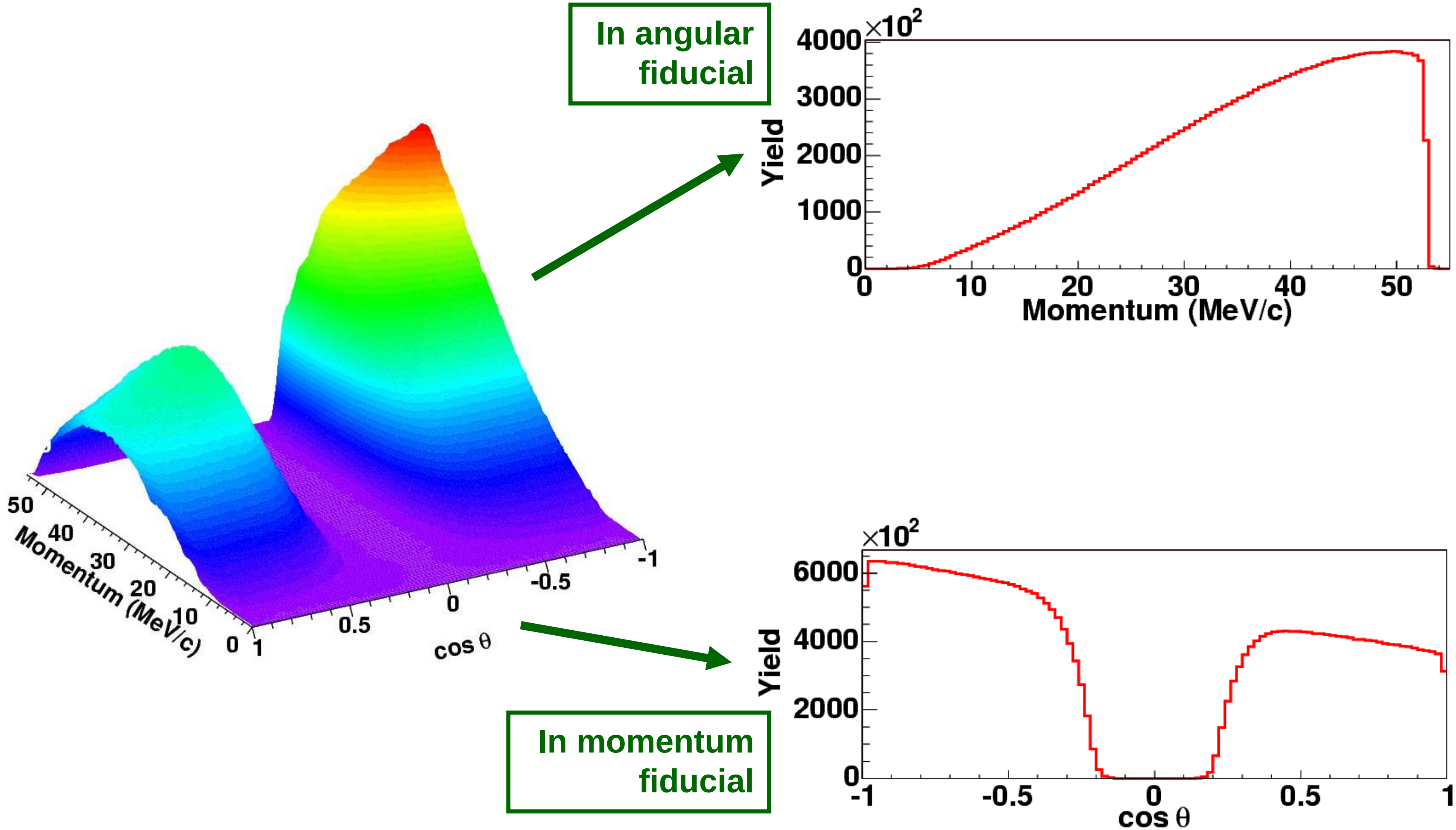
Event topologies

- Many events are simple
  - A muon enters and stops
  - The decay positron leaves
- Other events **aren't simple**



- We must be able to handle all kinds

2-d momentum-angle spectrum



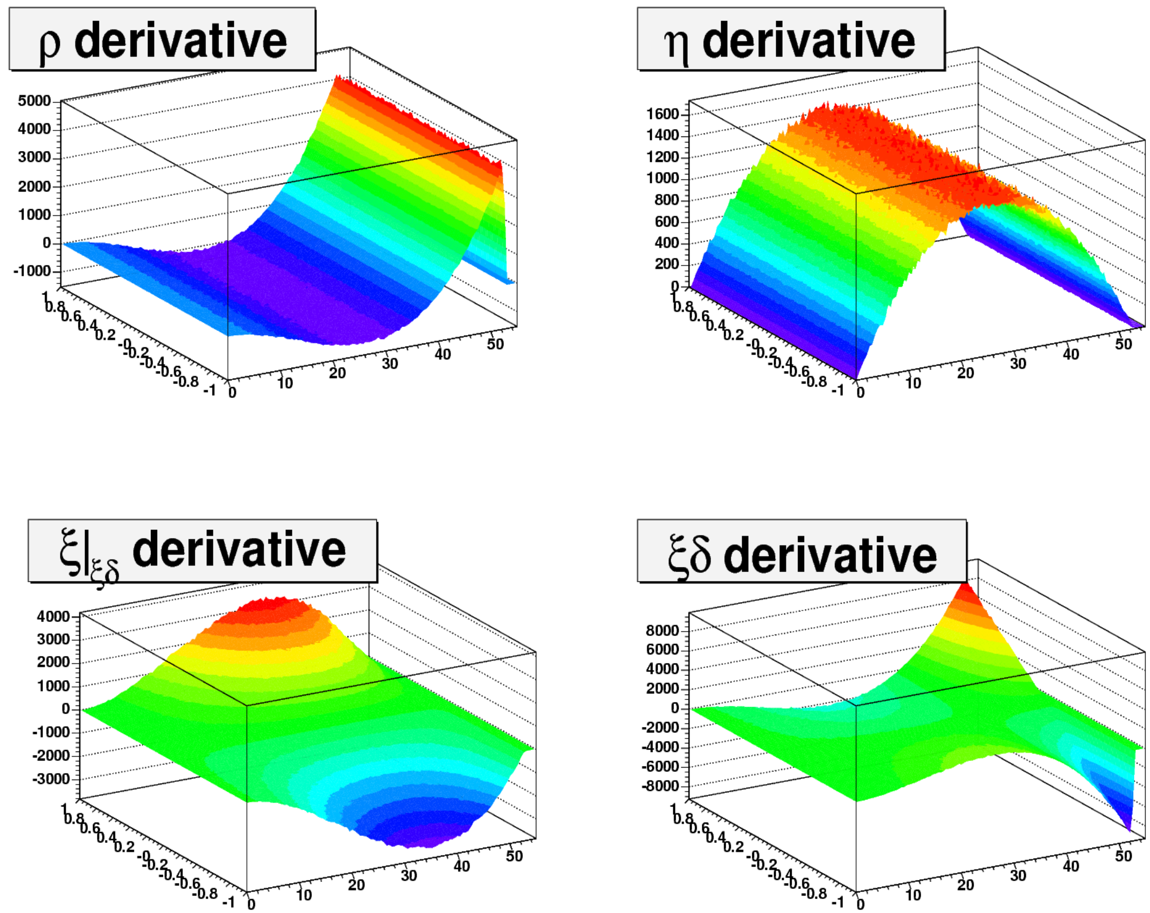
Acceptance of the **TWIST** spectrometer

Fitting the data distributions

α_{MC} **hidden**
→ blind analysis

$$n_i(\alpha_{\mathrm{data}}) = n_i(\alpha_{\mathrm{MC}}) + \frac{\partial n_i}{\partial \alpha}\Delta\alpha,$$
$$\alpha = [\rho, \eta, \xi, \xi\delta]$$

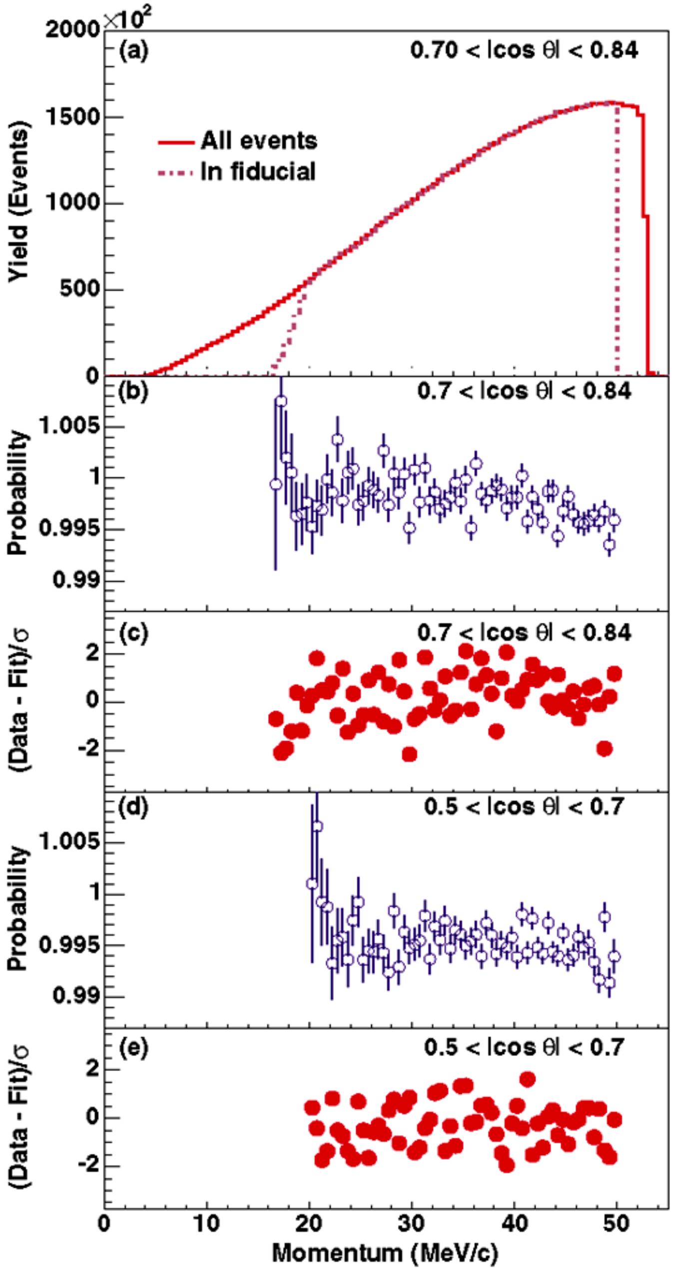
- Fit data to sum of a MC base spectrum plus MC-generated derivative distributions.
- Decay distribution is linear in the muon decay parameters, so this is exact, no matter what values (α_{MC}) are used in the MC base spectrum.



Physics data sets

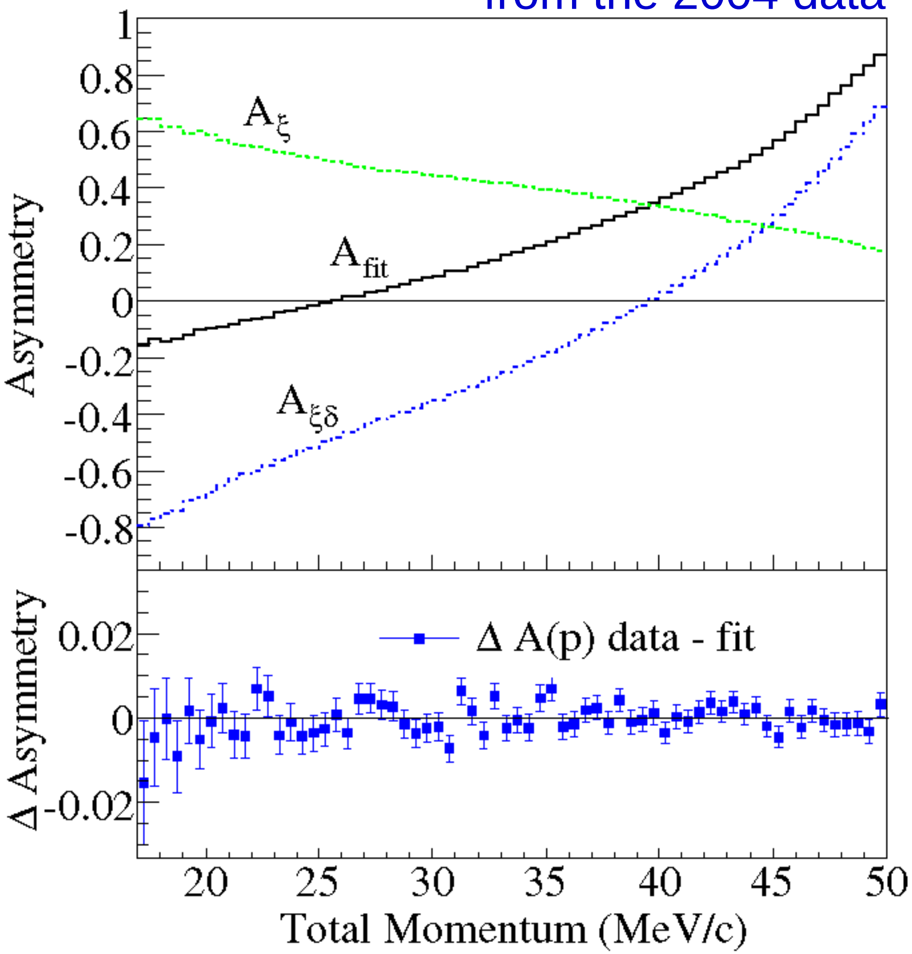
- Fall 2002
  - Test data-taking procedures and develop analysis techniques
  - First physics results – **ρ** and **δ**
  - Graphite-coated Mylar target not suitable for $P_\mu\xi$
- Fall 2004
  - Aluminum target and Time Expansion Chamber enabled first $P_\mu\xi$ measurement
  - Improved determinations of **ρ** and **δ**
- 2006-07
  - Both silver (2006) and aluminum (2007) targets
  - Ultimate **TWIST** precision for **ρ**, **δ**, and $P_\mu\xi$
  - Also measured negative muon decay-in-orbit when bound to Al

Data distributions from 2002 and 2004

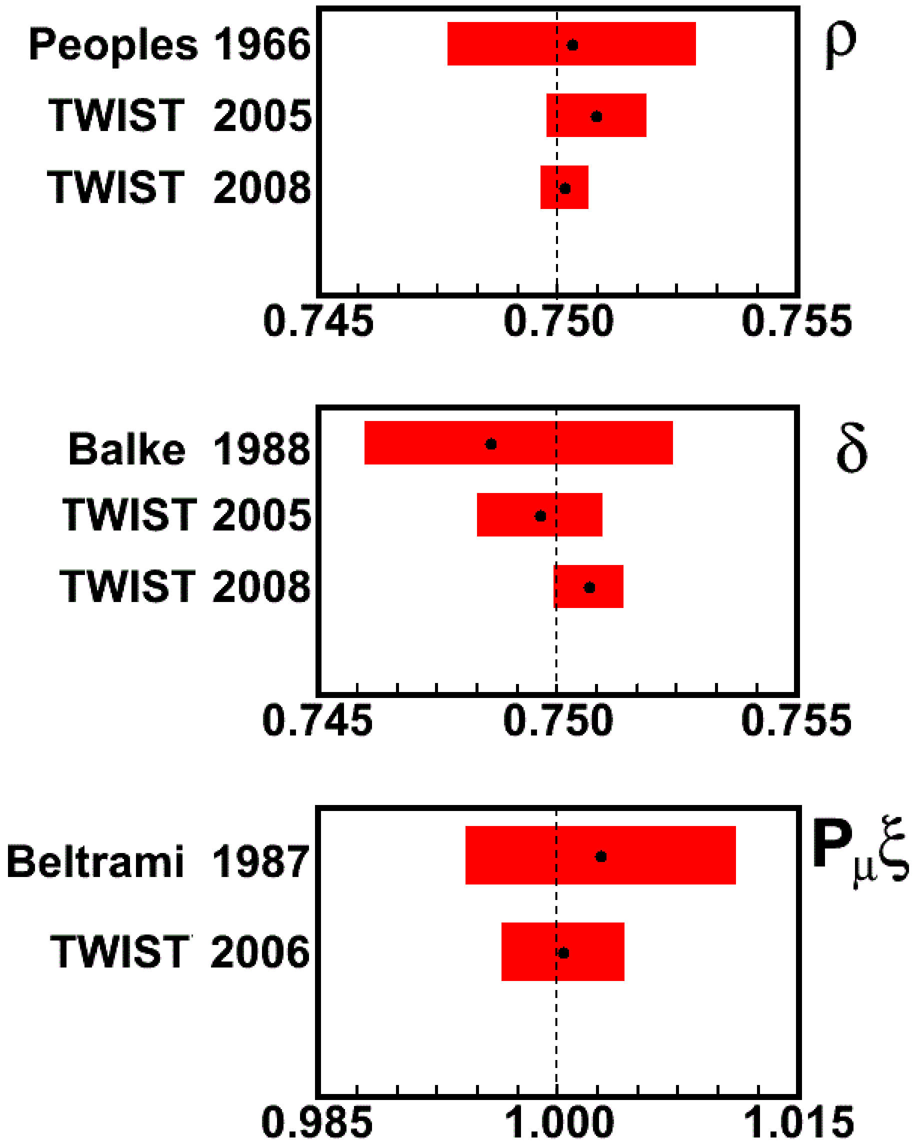


Angle-integrated spectrum from the 2002 data

Asymmetry vs momentum from the 2004 data



TWIST results before now



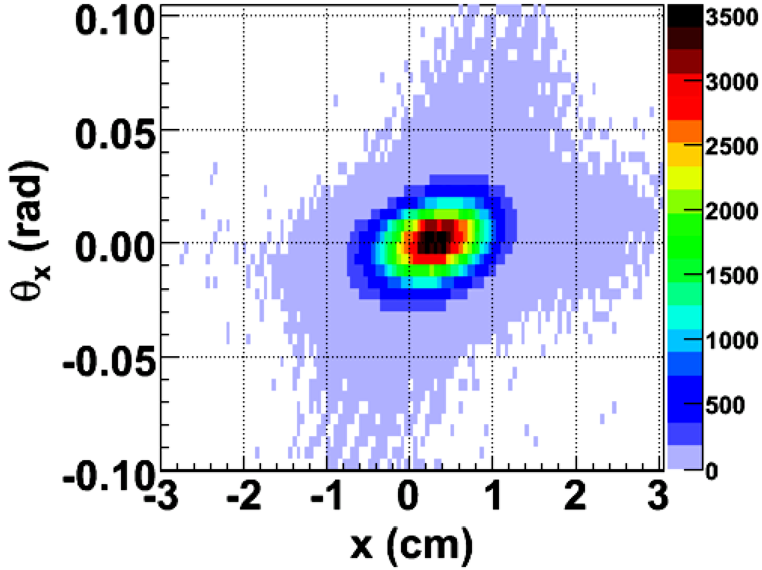
A global analysis that combined the first TWIST ρ and δ results and a concurrent measurement from PSI of the e+ transverse polarization (PRL 94, 021802) together with all pre-TWIST muon decay parameter measurements found:

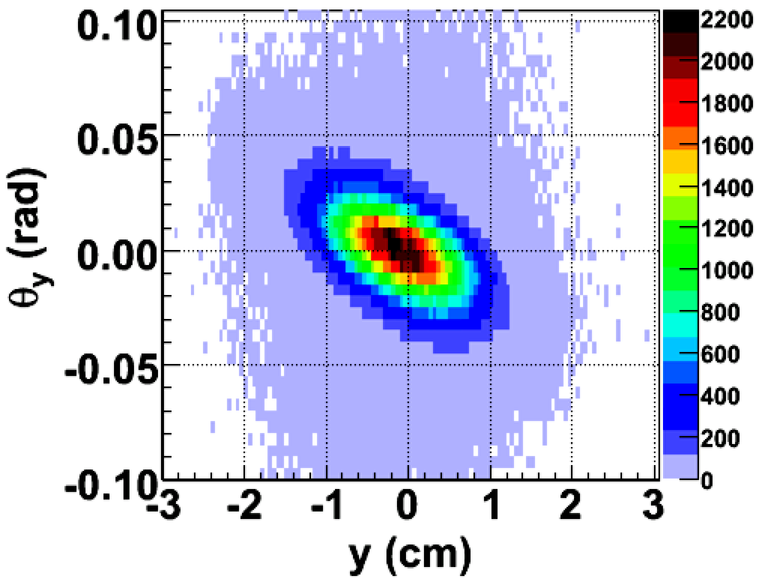
$$\eta = -0.0036 \pm 0.0069$$

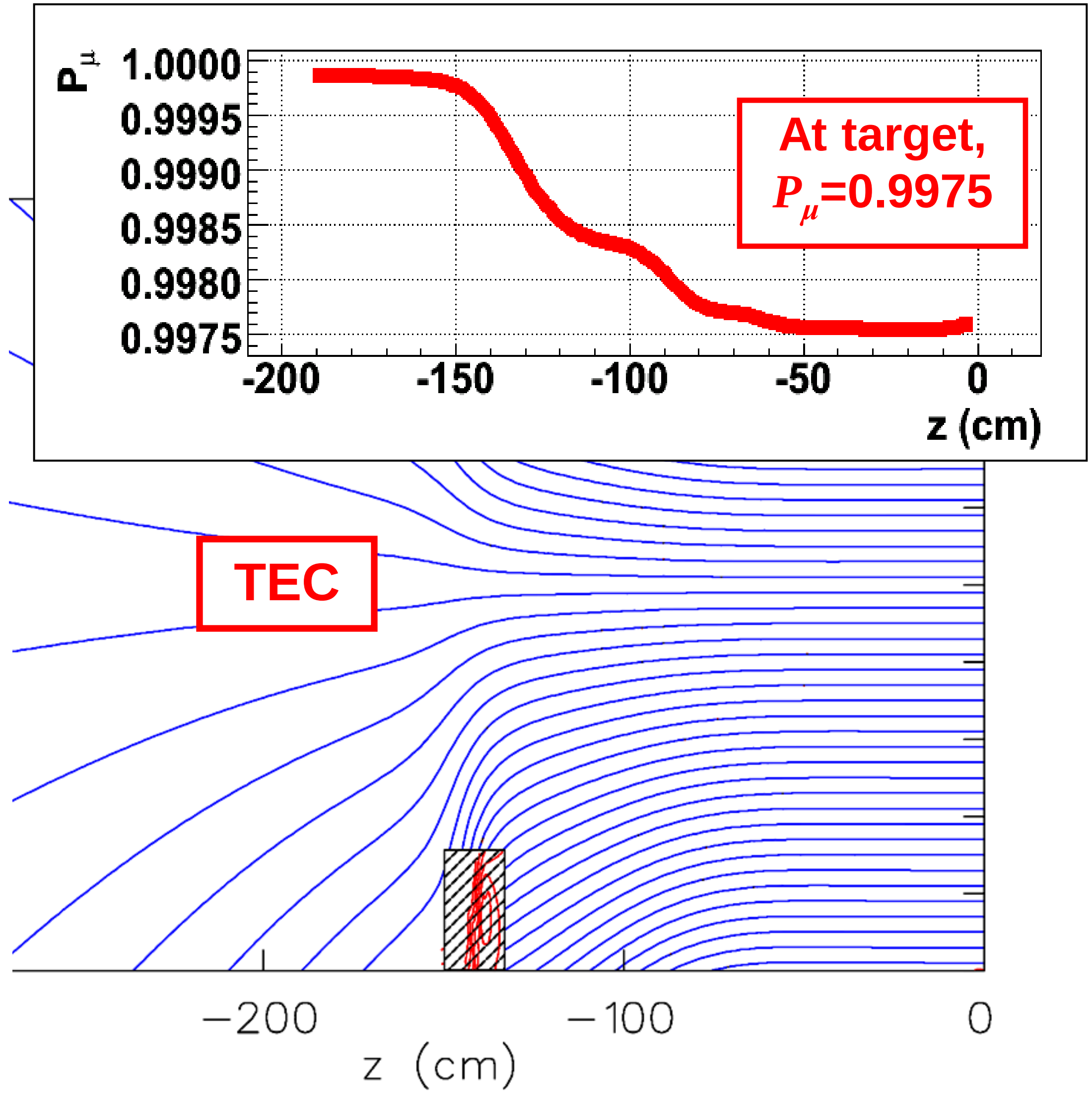
How to do better?

- **TWIST** is a **systematics-dominated experiment**
- Must have:
  - Improved data-taking procedures
  - Better understanding of the detector
  - Improved analysis techniques
- Leading systematics in our previous $P_\mu\xi$ measurement
  - Muon depolarization while entering the solenoid
  - Time-dependent muon depolarization in the stopping target
- Leading systematics in our previous ρ and δ measurements
  - Chamber response
  - Momentum calibration
  - Positron interactions

Entering the solenoid

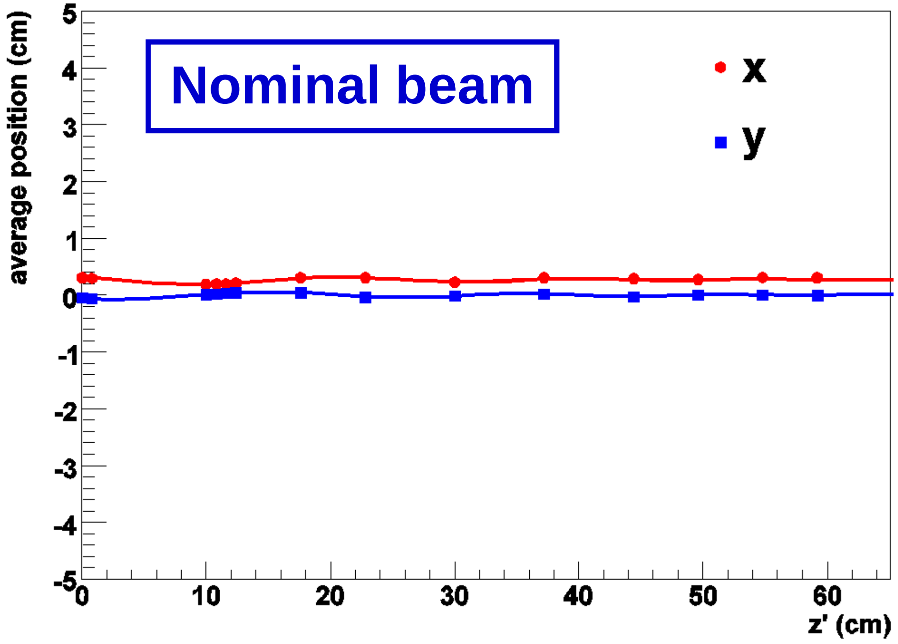


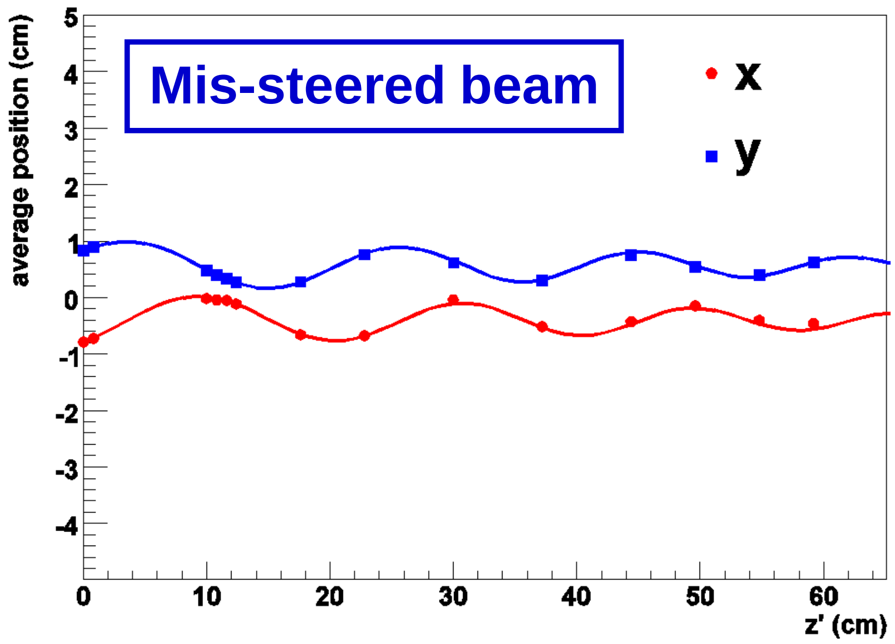




Muons can be depolarized as they cross flux lines when entering the solenoid

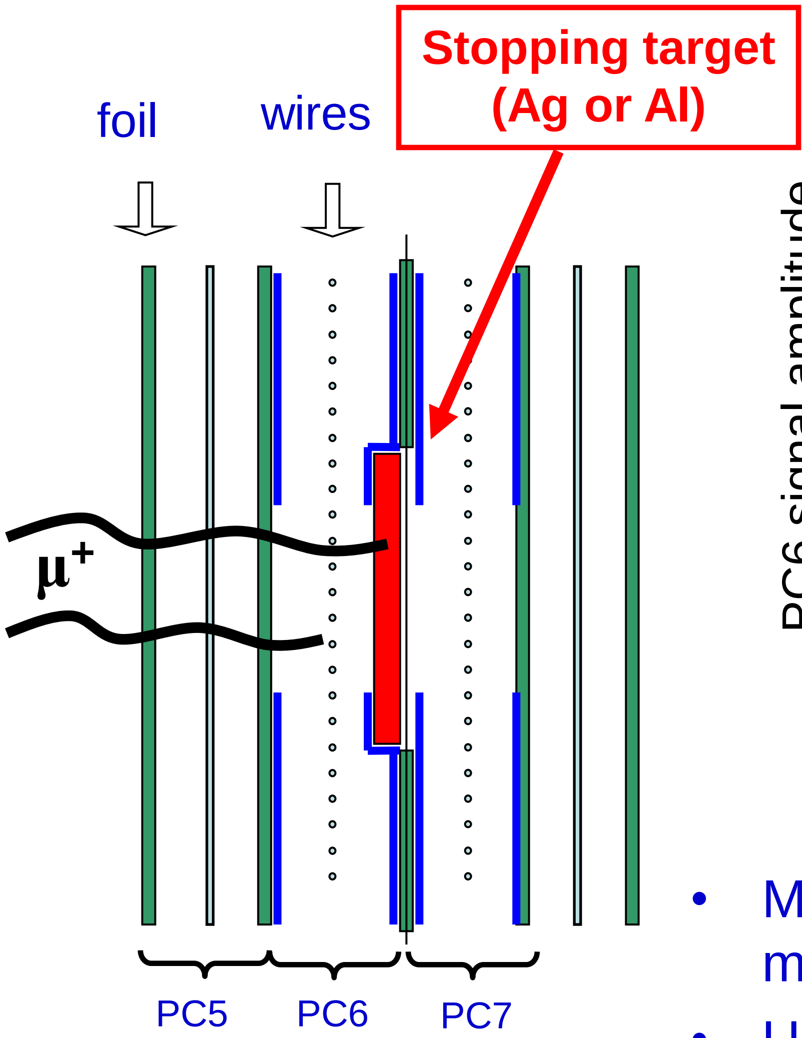
Validating the fringe field effects

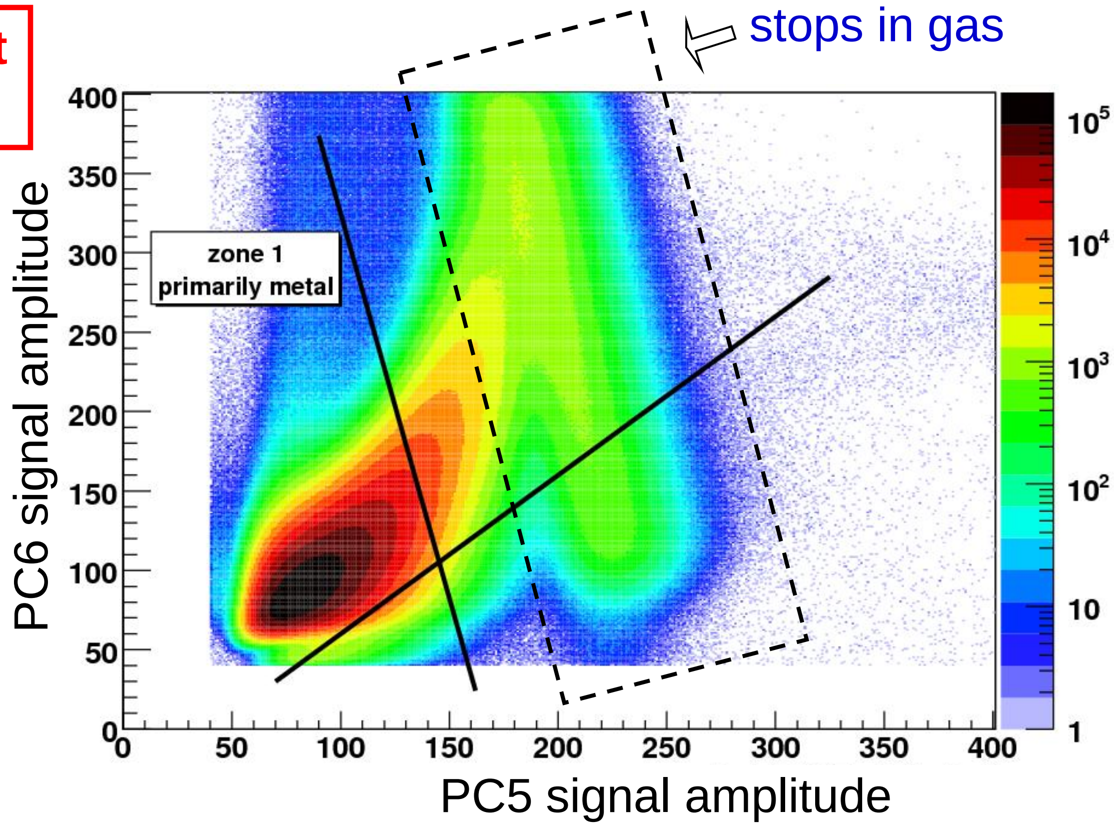




- The average muon beam trajectory inside the detector is sensitive to the **muon transverse momentum**
- Identify changes in muon beam properties between TEC measurements
- Comparisons between nominal and mis-steered beams
  - Observed muon beam trajectories within the detector
  - Difference in the decay asymmetry in data vs that predicted by the Monte Carlo

Ensuring muons stop in the metal target

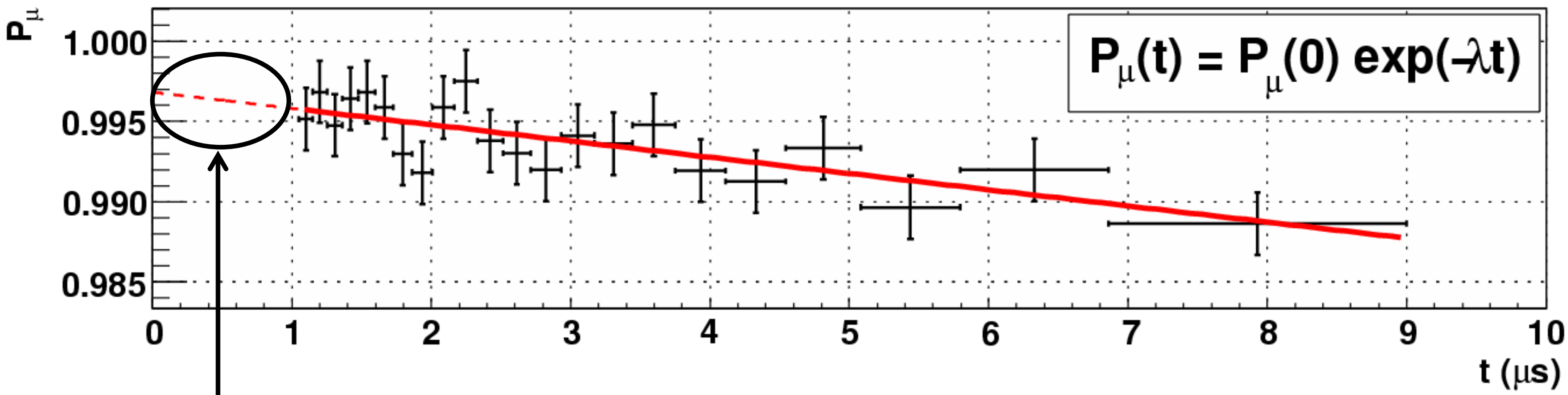




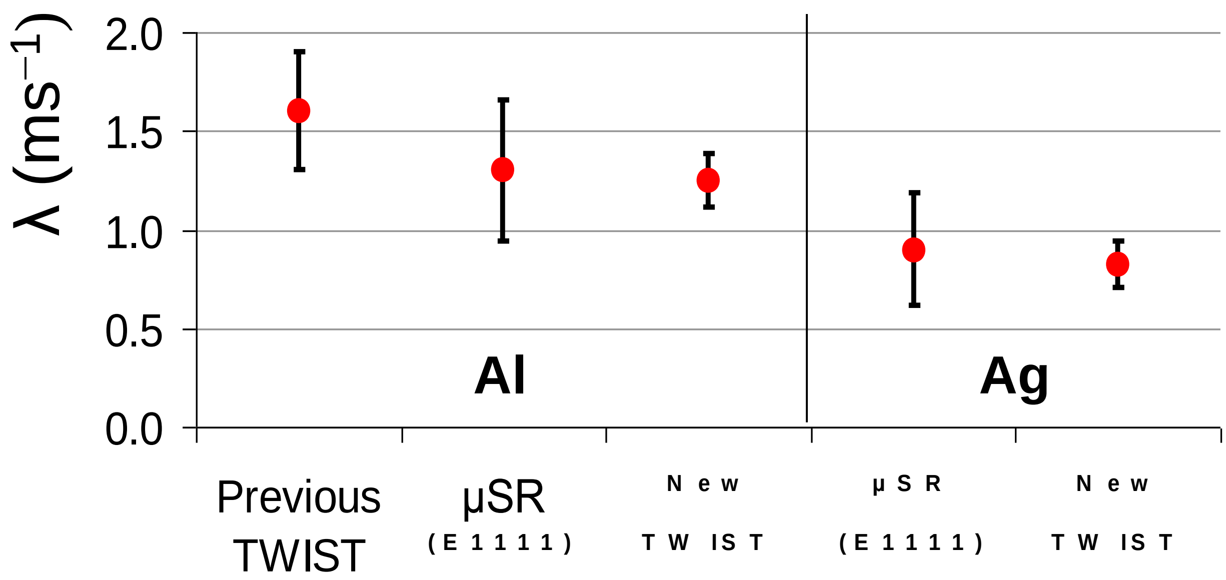
- Muons that stop in gas can depolarize through muonium formation
- Use muon energy depositions near the stopping target to reject those that stop in gas

Measuring depolarization after stopping

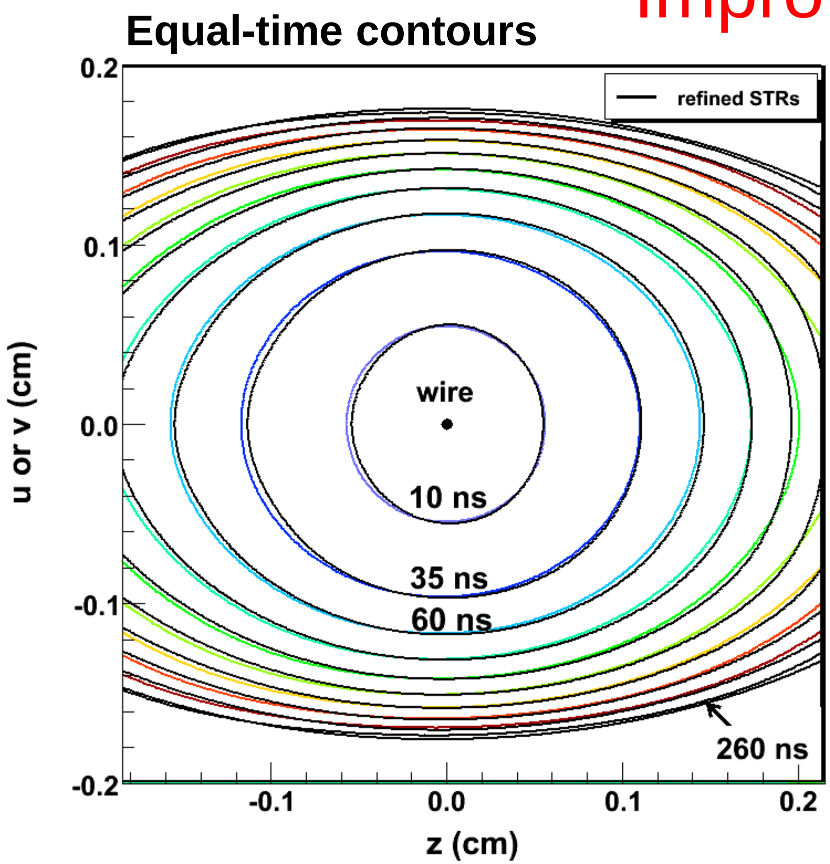
High purity (>99.999% purity) Al and Ag targets

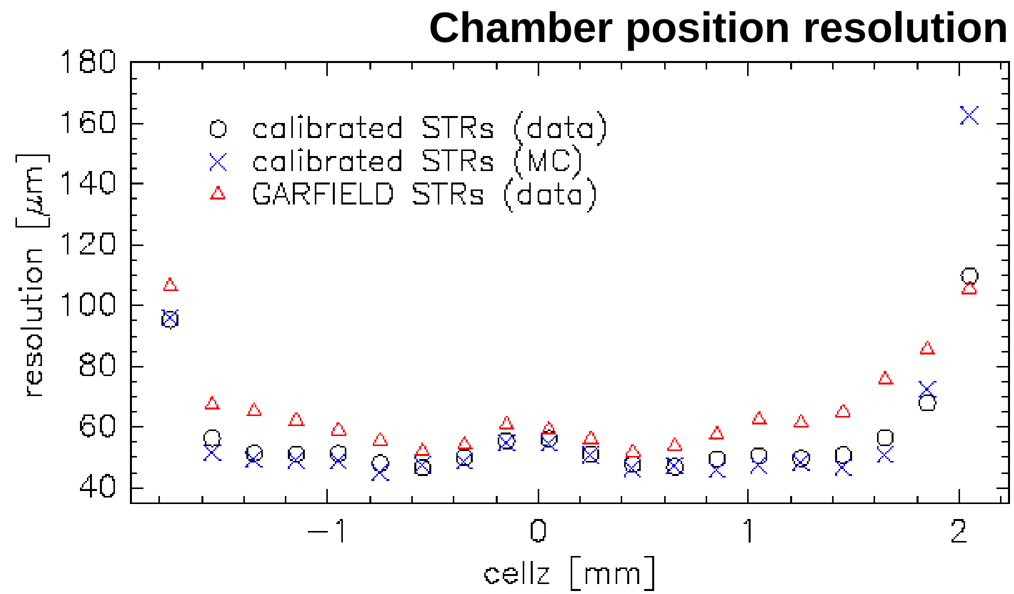


Subsidiary μ^+SR study:
no “fast depolarisation”
down to 5 ns



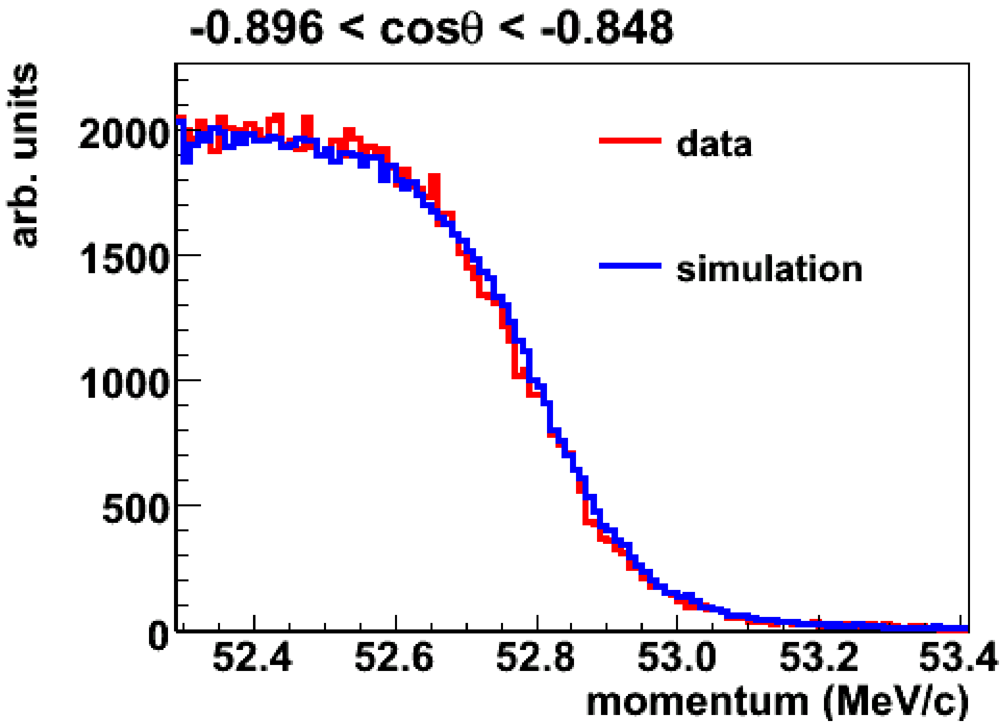
Improved drift chamber calibration





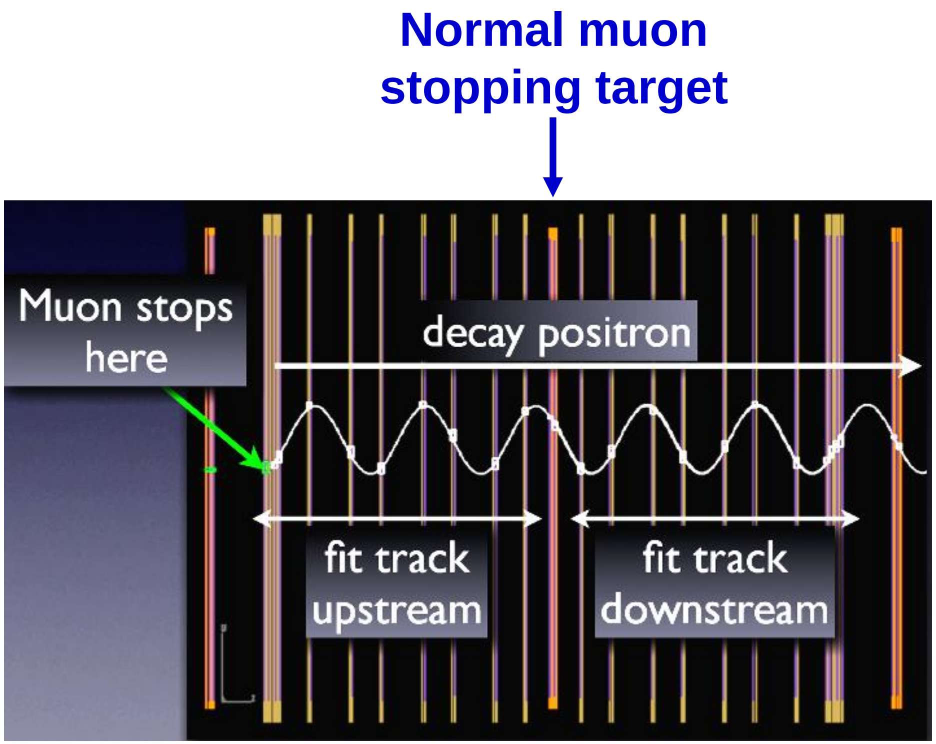
- Direct determination of the effective distance vs time relation
- Accounts for small plane-to-plane fabrication differences
- Compensates for small (few keV) biases in the helix fitter
- Improved momentum resolution (near the endpoint)
  - Was ~ 69 keV/sin(θ) in Monte Carlo and ~ 74 keV/sin(θ) in data
  - Now ~ 58 keV/sin(θ) **in both**

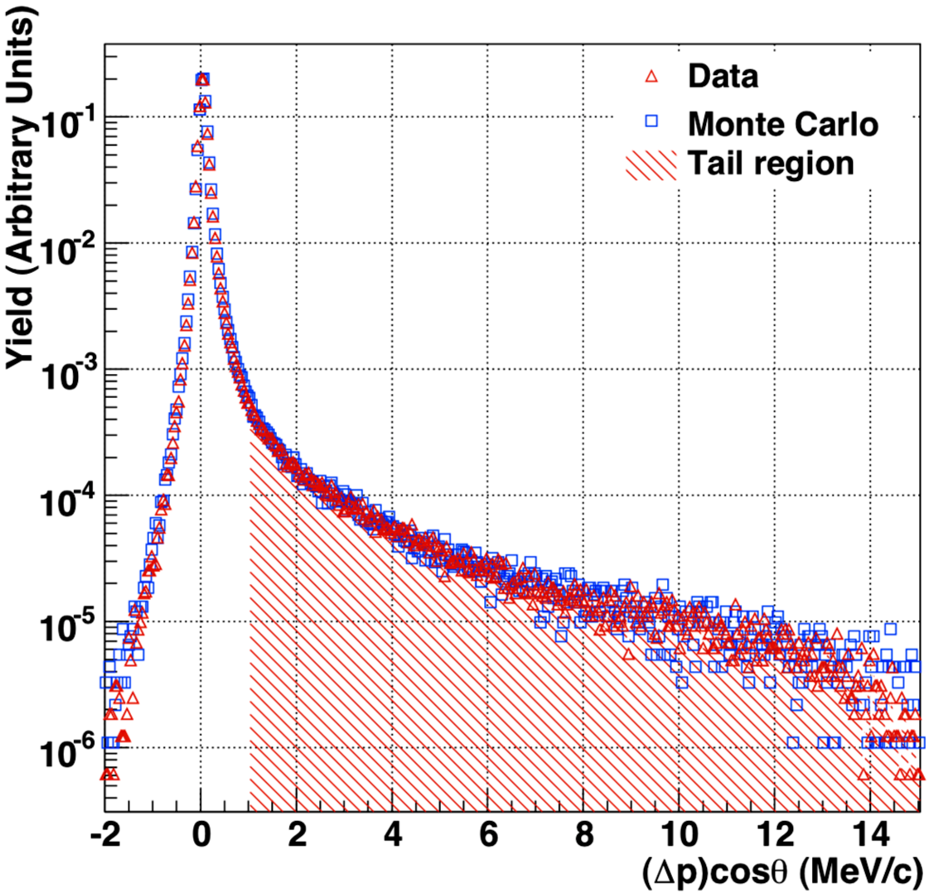
Momentum calibration



- The endpoint at 52.83 MeV/c provides a calibration point
- Improvements in the endpoint fitter reduced previous small biases
- Find a ~10 keV/c difference in the **absolute calibration** of the data vs Monte Carlo
- Propagate this through the entire spectrum twice
  - Shift by a constant
  - Rescale the momentum axis

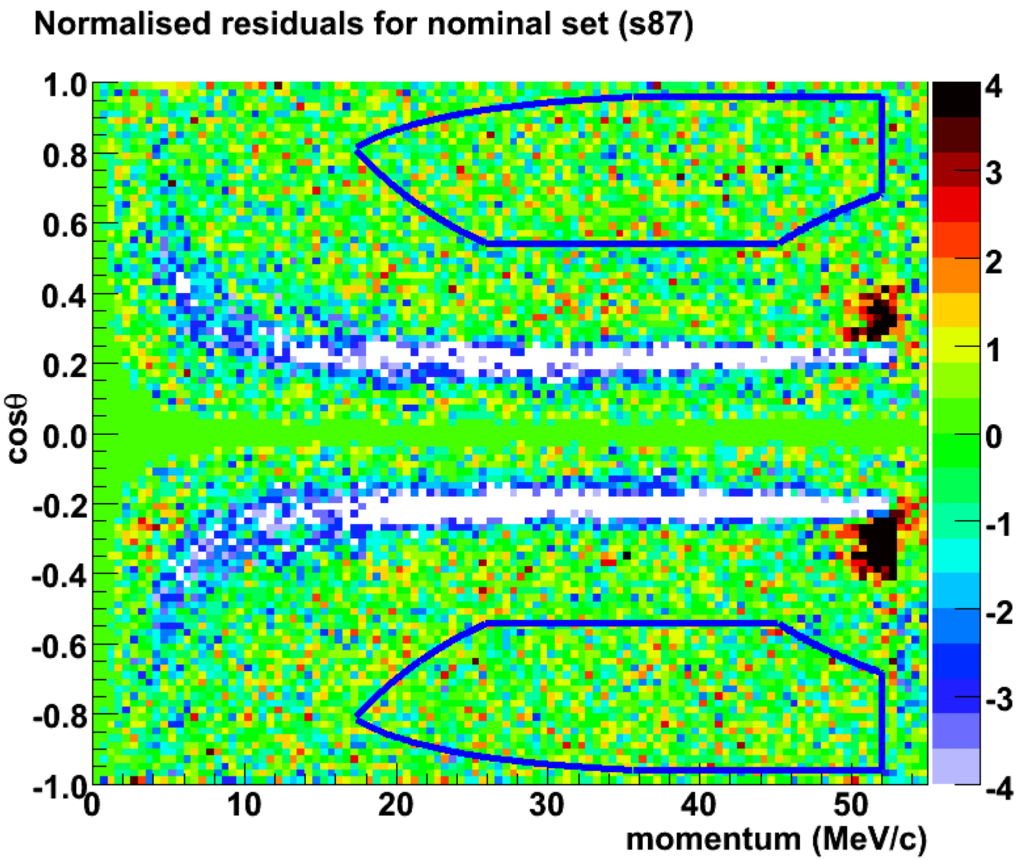
Bremsstrahlung

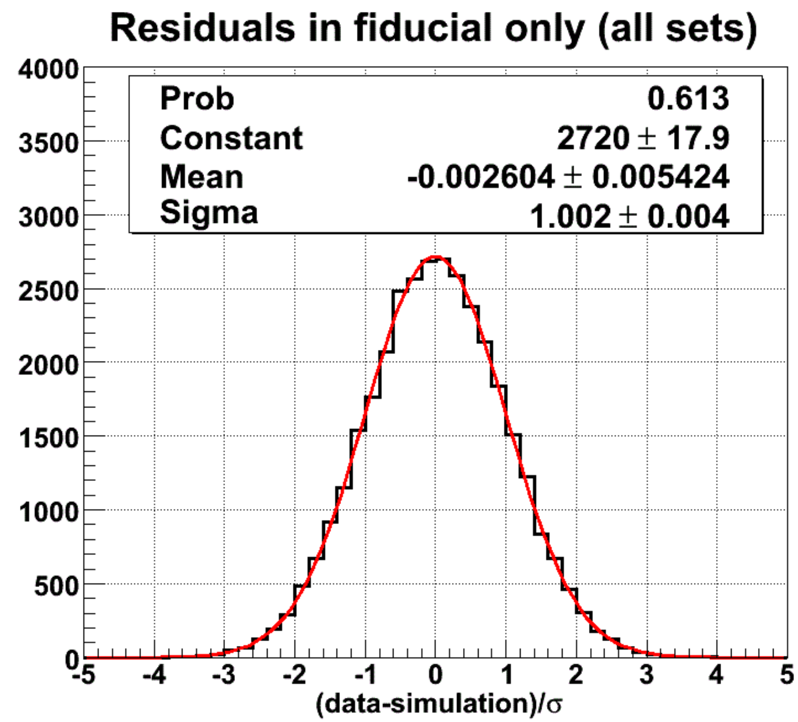




- Leading systematic for ρ and δ
- Two separate measurements
  - "Upstream stops"
  - "Broken" decay tracks
- Consistent results validate bremsstrahlung simulation in our GEANT3 Monte Carlo at the 2.5% level

Overall quality of data vs Monte Carlo match

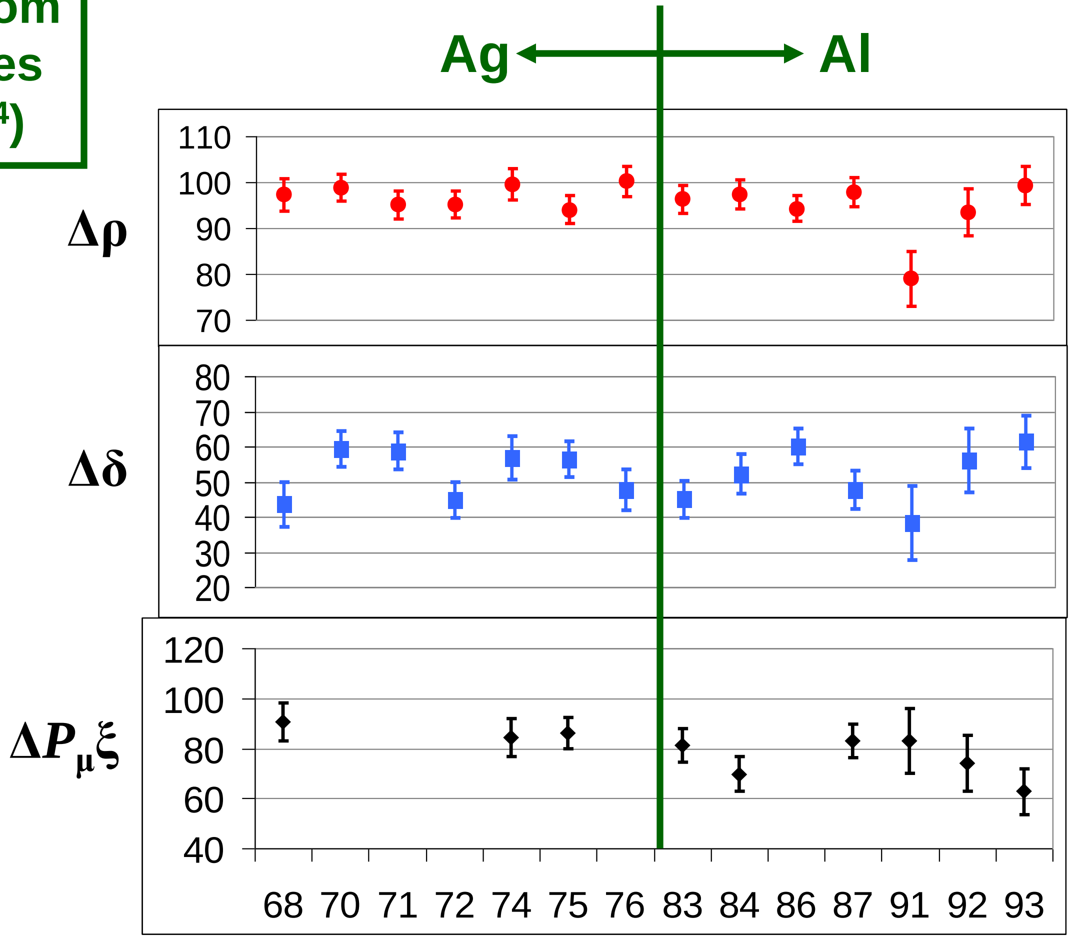




- Monte Carlo reproduces the data very well, even very far outside the fiducial region

Reproducibility of the results

Difference from hidden values (units = 10^{-4})



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 separate measurements under various experimental conditions
- All 14 data sets are used for **ρ** and **δ**, χ^2 = 14.0 and 17.7
- 9 of the data sets are used for $P_\mu\xi$, χ^2 = 9.6

Total uncertainty budget – ρ and δ

Uncertainties	ρ (x 10^{-4})	δ (x 10^{-4})	Comparison to 2004 leading systematics
Positron interactions	1.8	1.6	Similar magnitude
External uncertainties	1.3	0.6	
Momentum calibration	1.2	1.2	Down factor of ~3
Chamber response	1.0	1.8	Down factor of ~3
Resolution	0.6	0.7	
Spectrometer alignment	0.2	0.3	
Beam stability	0.2	0.0	
Systematics added in quadrature	*2.8*	*2.9*	
Statistical uncertainty	0.9	1.6	
Total uncertainty	*3.0*	*3.3*	Down factor of ~2

Total uncertainty budget – $P_\mu \xi$

Comparison to 2004 leading systematics

Uncertainties	$P_\mu \xi$ (x 10^{-4})	
Depolarization in fringe field	+15.8, -4.0	Down factor of ~3
Depolarization in stopping material	3.2	Down factor of ~4
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 added in quadrature	*+16.5, -6.2*	
Statistical uncertainty	3.5	
Total uncertainty	*+16.9, -7.2*	Down factor of ~3

Final **TWIST** results

- ρ = 0.74991 ± 0.00009 (stat) ± 0.00028 (syst)
- δ = 0.75072 ± 0.00016 (stat) ± 0.00029 (syst)
- $P_\mu\xi = 1.00084 \pm 0.00035\ (\text{stat})\ ^{+0.00165}_{-0.00063}\ (\text{syst})$
- Correlations:
  - Corr(ρ,δ) = +0.69
  - Corr(ρ,$P_\mu\xi$) = -0.06 (for $P_\mu\xi$ high) and -0.14 (for $P_\mu\xi$ low)
  - Corr(δ,$P_\mu\xi$) = -0.18 (for $P_\mu\xi$ high) and -0.43 (for $P_\mu\xi$ low)
- Can combine the above to find $P_\mu\xi\delta/\rho = 1.00192^{+0.00167}_{-0.00066}$
  - This is asymmetry at endpoint → must be ≤1
  - This 2.9σ surprise is currently under investigation

Implications for the muon decay matrix element

- 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:
  - $|g^S_{RR}| < 0.031$
  - $|g^V_{RR}| < 0.015$

  } Factor of ~2 smaller than pre-**TWIST** values

  - $|g^S_{LR}| < 0.041$
  - $|g^V_{LR}| < 0.018$
  - $|g^T_{LR}| < 0.012$

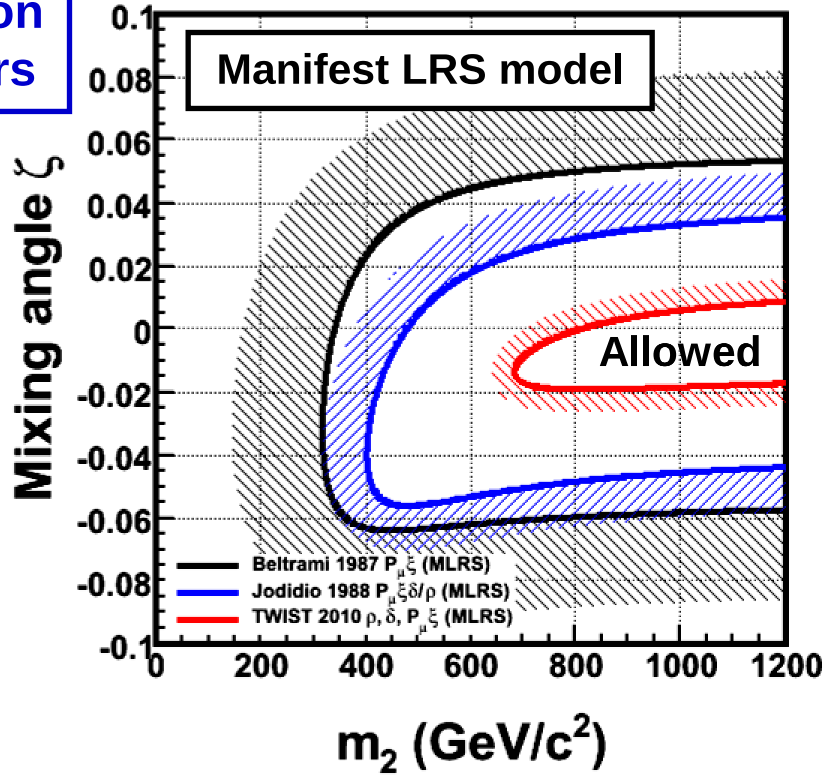
  } Factor of ~3 smaller than pre-**TWIST** values

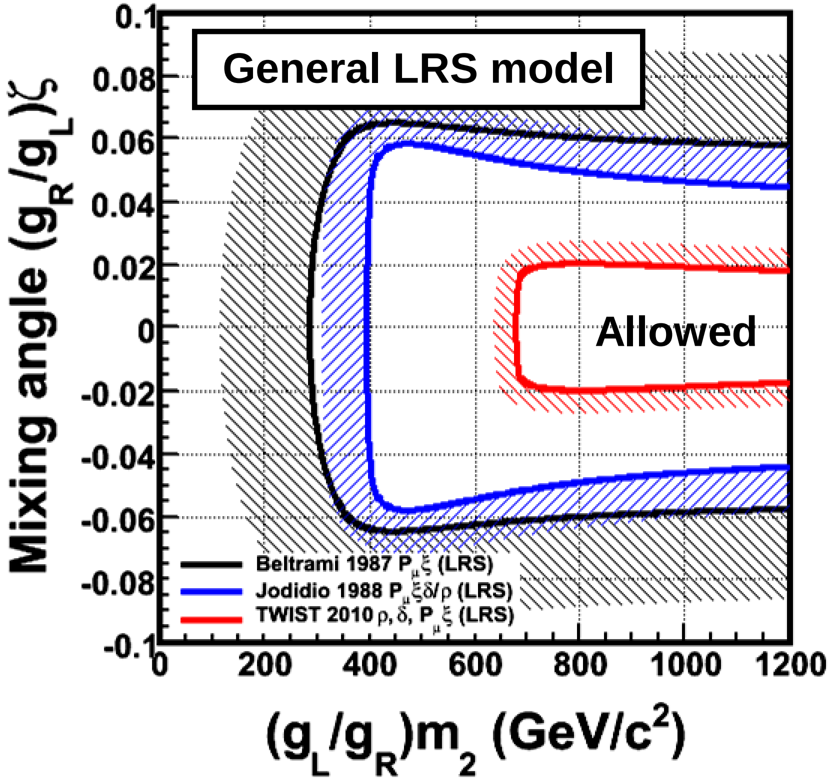
- New limit on right-handed muon couplings: Q^μ_R **< 5.8 x 10^{-4} (90% c.l.)**
  - Factor of ~9 smaller than pre-**TWIST** value
- Uncertainty for η reduced by 1/3 compared to 2005 global analysis
  - $\boldsymbol{\eta = -0.0033 \pm 0.0046}$
  - Important for the determination of G_F

Implications for left-right symmetric models

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

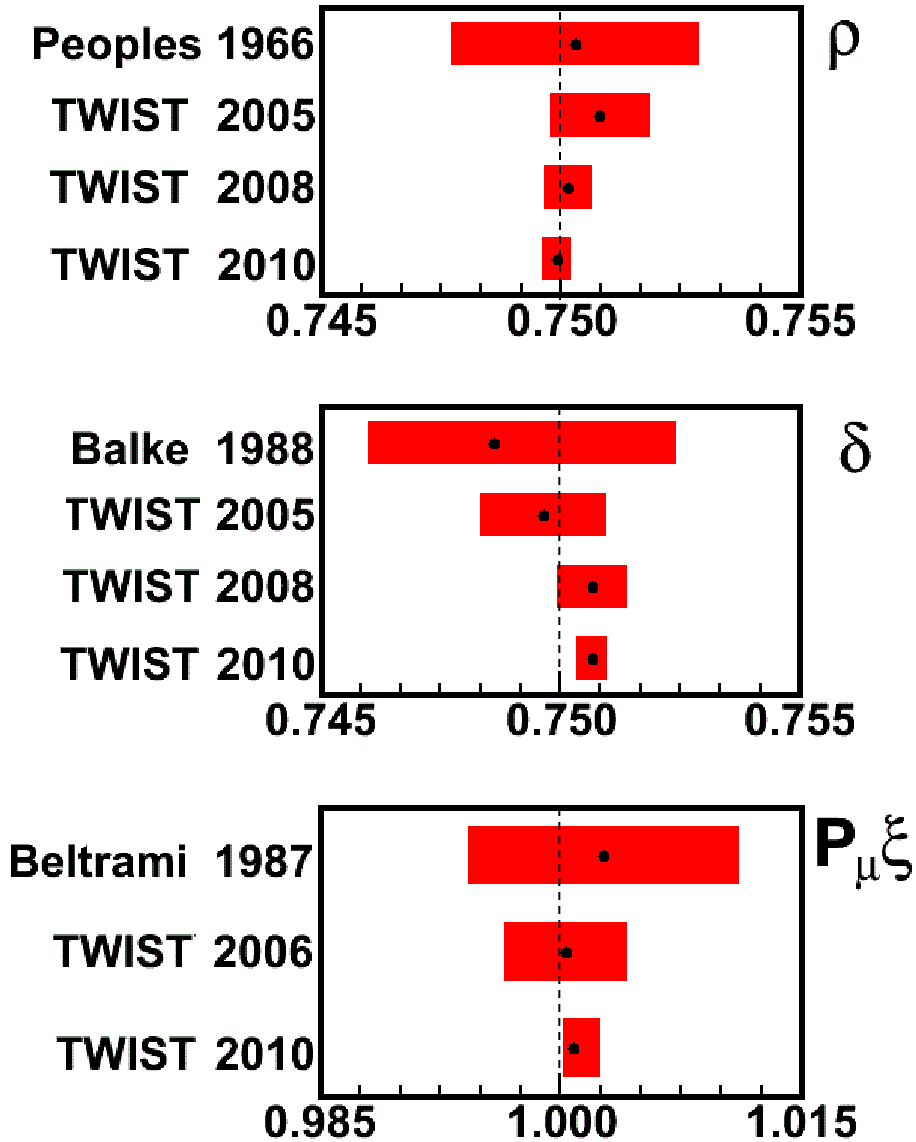
90% c.l. exclusion contours





- Significantly improved limits on both W_R mass and L-R mixing angle ζ
- Many **other limits** also apply **if V_{ud}^R is near 1**; for example:
  - Direct production at the Tevatron finds $M(W_R) > 1$ TeV
  - $0^+ \rightarrow 0^+$ nuclear beta decay finds $|\zeta| < 0.0005$
- **TWIST** limits in the general case make **no assumption about V_{ud}^R**

Conclusions



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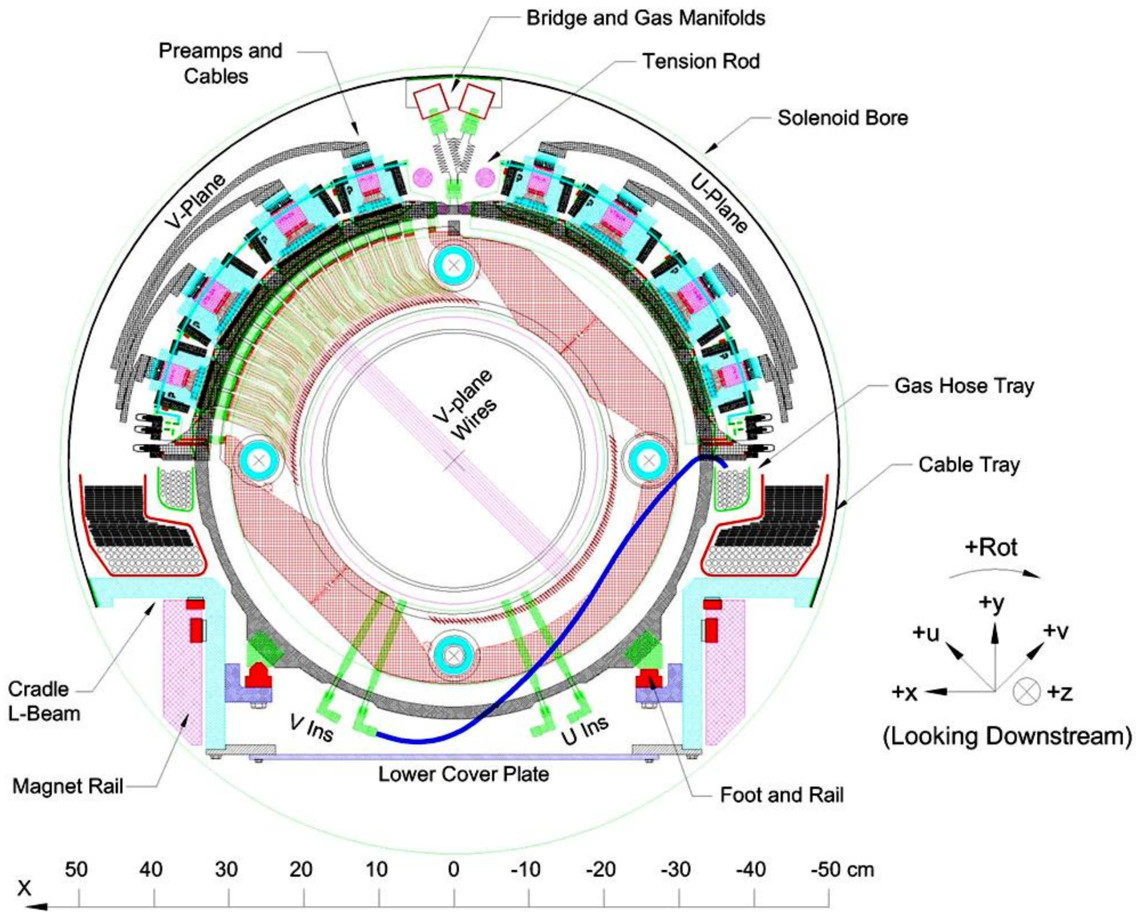
Coupling constants and Michel parameters

- The Michel parameters are bilinear combinations of the coupling constants:

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

Precision detector construction

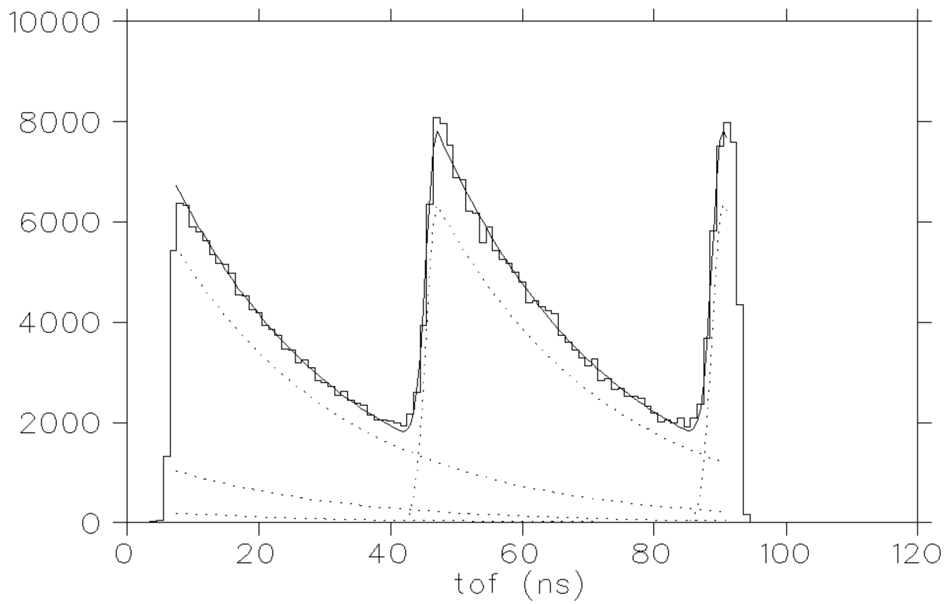


- Very low mass (~10^{-4} X_0 per U-V pair), high precision chambers
- Longitudinal alignment by engineering
- Transverse alignment using particle tracks

} To a few parts in 10^5

- >5000 wires, efficiency >99.8%

"Good muons" vs "bad muons"



- Positive muons can arise from pion decay at rest or in flight
  - At rest ("surface") muons have large (~1) negative polarization
  - In flight ("cloud") muons have small (~20%) positive polarization
- In TWIST, we (usually) want the former and not the latter
- Achieved by cutting on the muon arrival time at the spectrometer

Previous muon decay parameter results

- 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, plus recent e^+ transverse polarization measurements from PSI (PRL 94, 021802):
  - Significant improvements in the limits for $g^{S,V,T}_{LR}$
  - η = -0.0036 ± 0.0069
- From Fall, 2004 run:
  - $P_\mu\xi$ = 1.0003 ± 0.0006 (stat) ± 0.0038 (syst)

    PRD 74, 072007
  - ρ = 0.75014 ± 0.00017 (stat) ± 0.00044 (syst) ± 0.00011 (η)
  - δ = 0.75067 ± 0.00030 (stat) ± 0.00067 (syst)

    PRD 78, 032010
- Factors of 2 ($P_\mu\xi$) to 5 (ρ,δ) increased precision vs. pre-**TWIST**

Systematic uncertainties for 2004 data

TABLE II. Summary of systematic uncertainties by category.

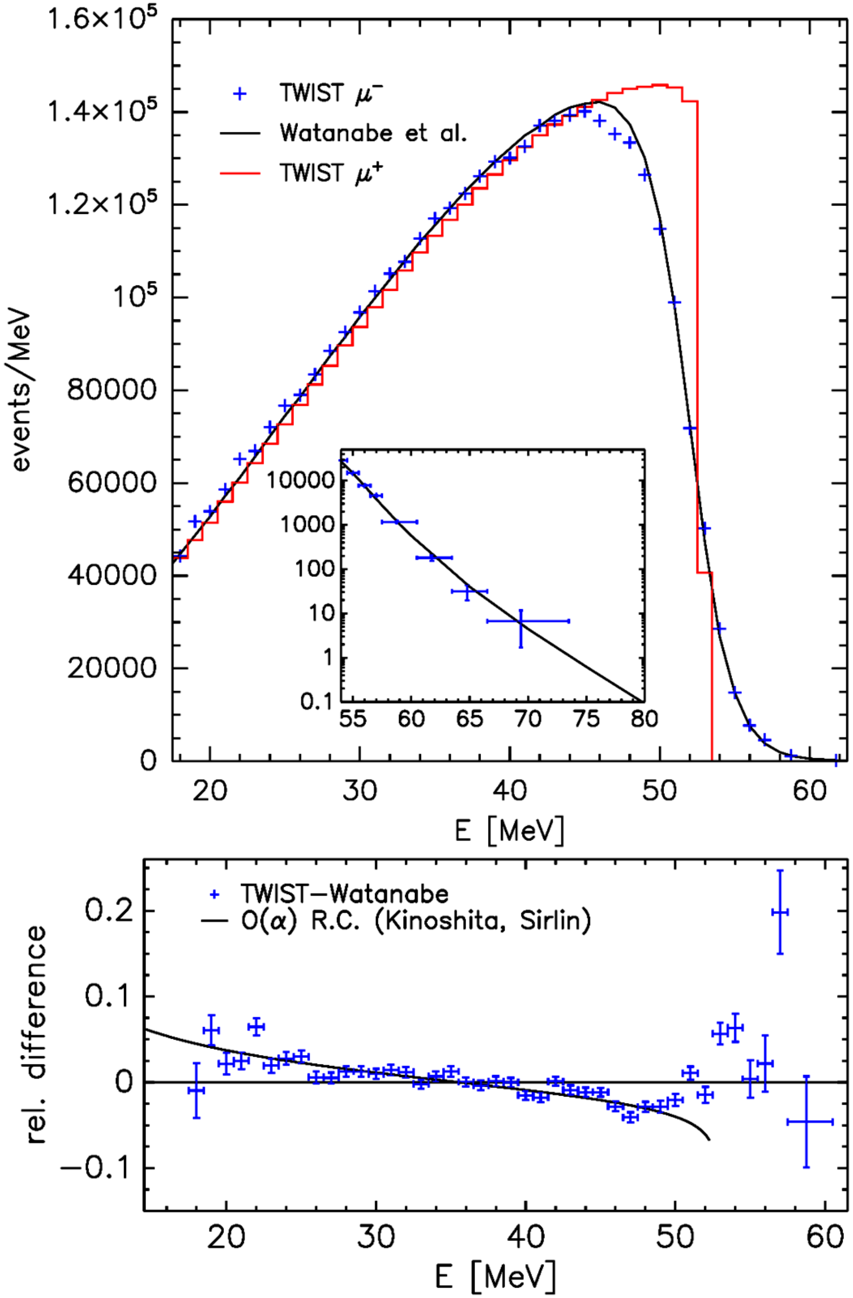
Category	$\Delta\rho$	$\Delta\delta$
Chamber response	0.000 29	0.000 52
Energy scale	0.000 29	0.000 41
Positron interactions	0.000 16	0.000 09
Resolution	0.000 02	0.000 03
Alignment and lengths	0.000 03	0.000 03
Beam intensity	0.000 01	0.000 02
Correlations with η	0.000 11	0.000 01
Theory	0.000 03	0.000 01
Total	0.000 46	0.000 67

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

Negative muon decay-in-orbit

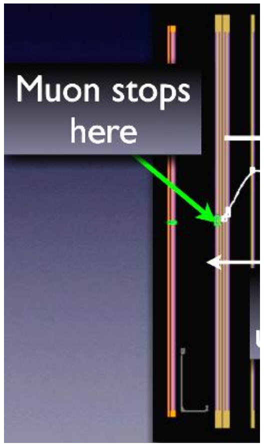
PRD 80, 052012

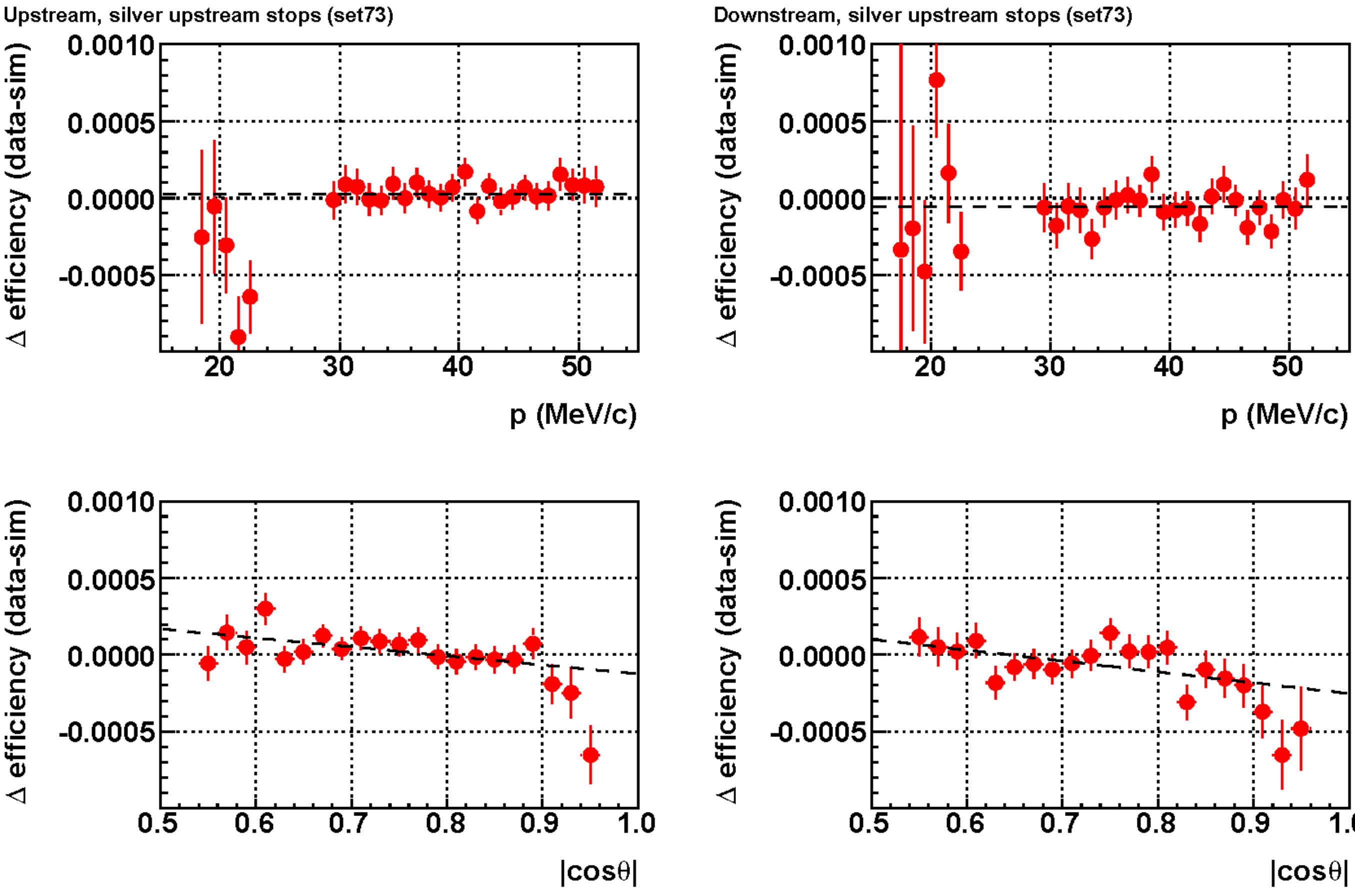


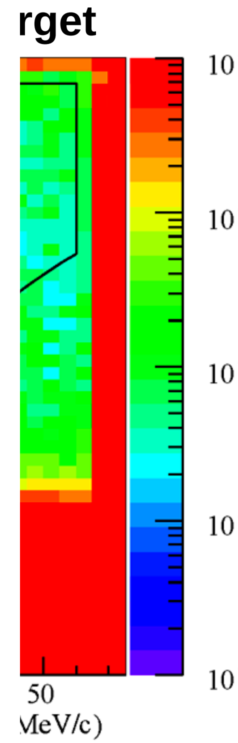
- Future $\mu \to e$ conversion experiments plan to study negative muons bound to Al
- Most precise measurement ever of the muon decay-in-orbit spectrum
- Theoretical predictions include higher-order contributions from the muon+nucleus potential

- Need to include the $O(\alpha)$ radiative corrections that arise from the interaction between the muon and the outgoing electron

Tracking (in)efficiency

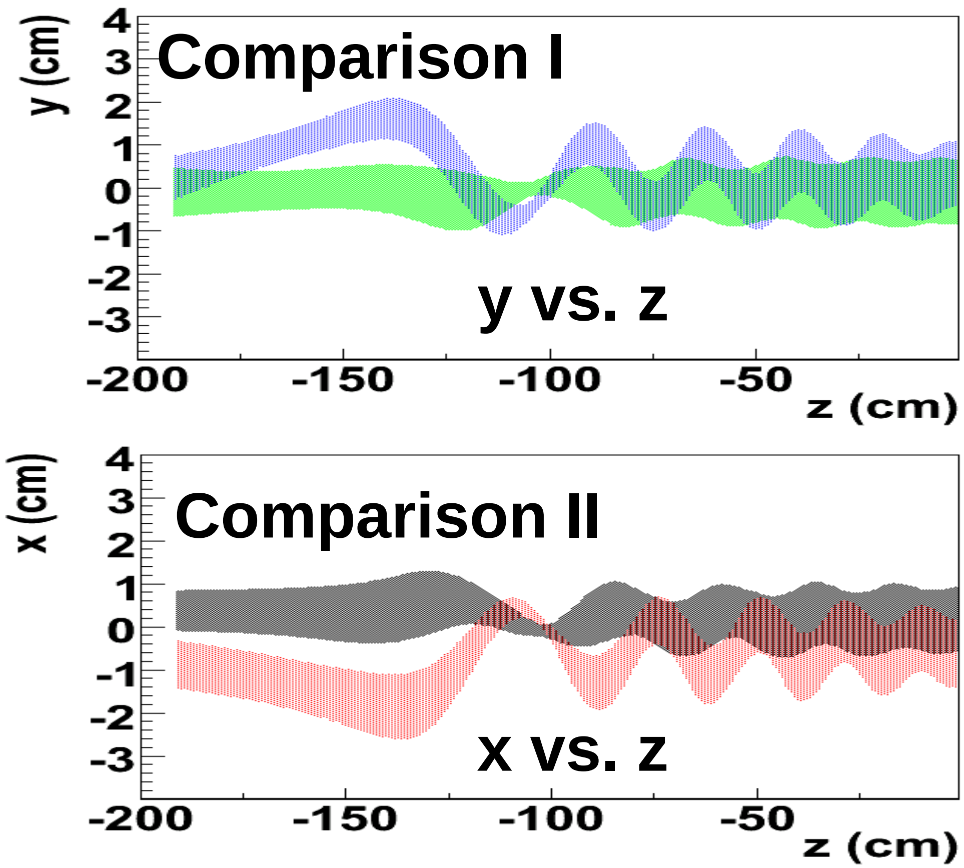






- Measure the tracking efficiency with "upstream stops" data
  - Reconstruct a track with a particular (p,cos(θ)) in one half
  - Do we reconstruct a track in the other half?
- Inefficiency in data is <0.5% throughout the fiducial region
- Inefficiency in data and Monte Carlo match to <0.05%

Fringe field and mis-steered beam

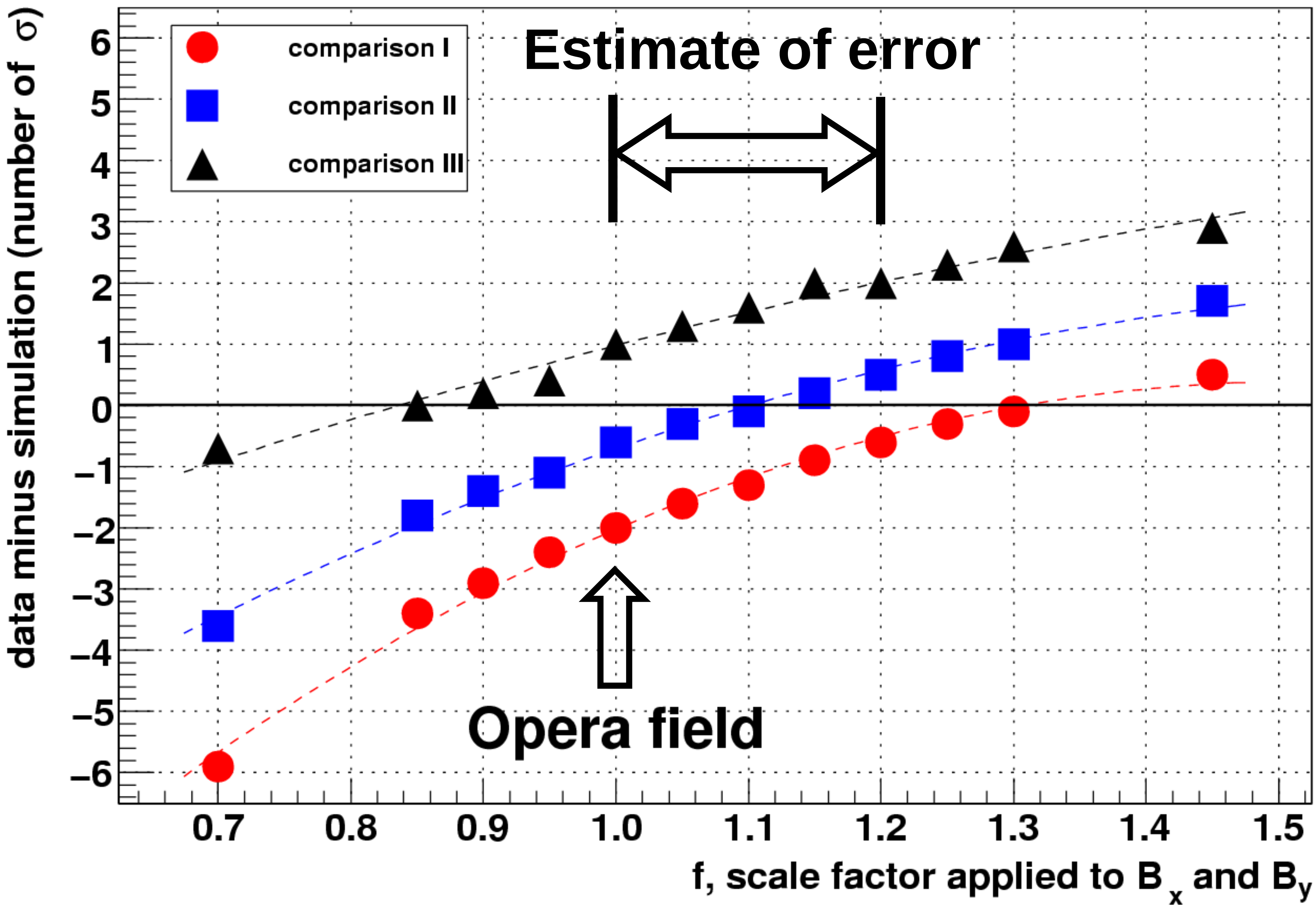


Move beam away from optimum position and/or angle to observe change in polarization:

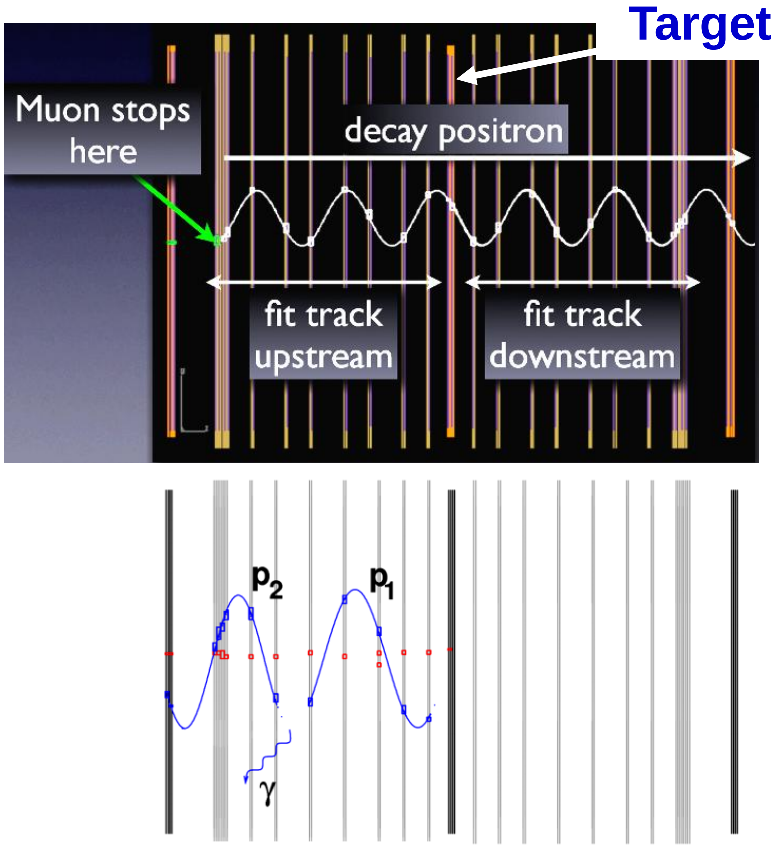
- Comparison I: mis-steer y direction by 28 mrad
  Find: ΔP_μ **= -105 ± 9 x 10^{-4}**
- Comparison II: mis-steer x position by 10 mm and direction by 10 mrad
  Find: ΔP_μ **= -62 ± 8 x 10^{-4}**
- Comparison III: leave TEC in to introduce scattering
  Find: ΔP_μ **= -18 ± 9 x 10^{-4}**

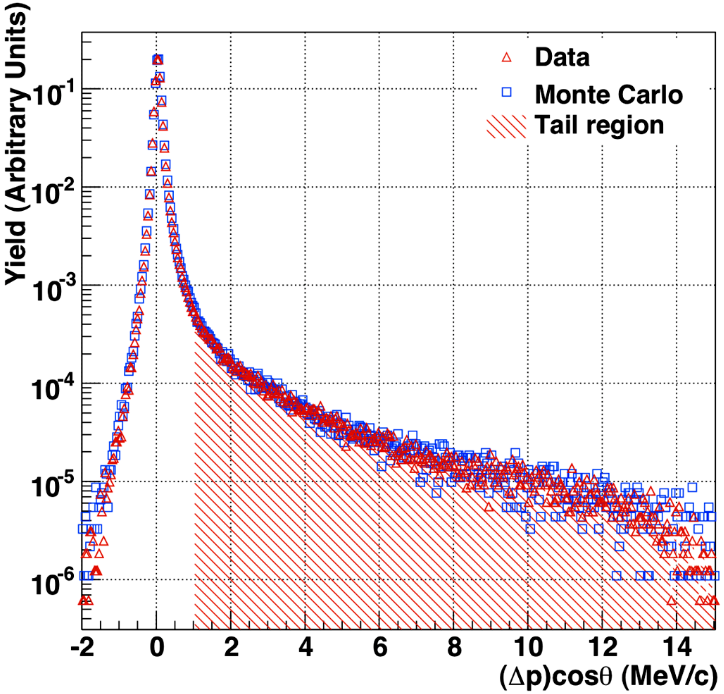
Compare differences with simulation to check fringe field systematic

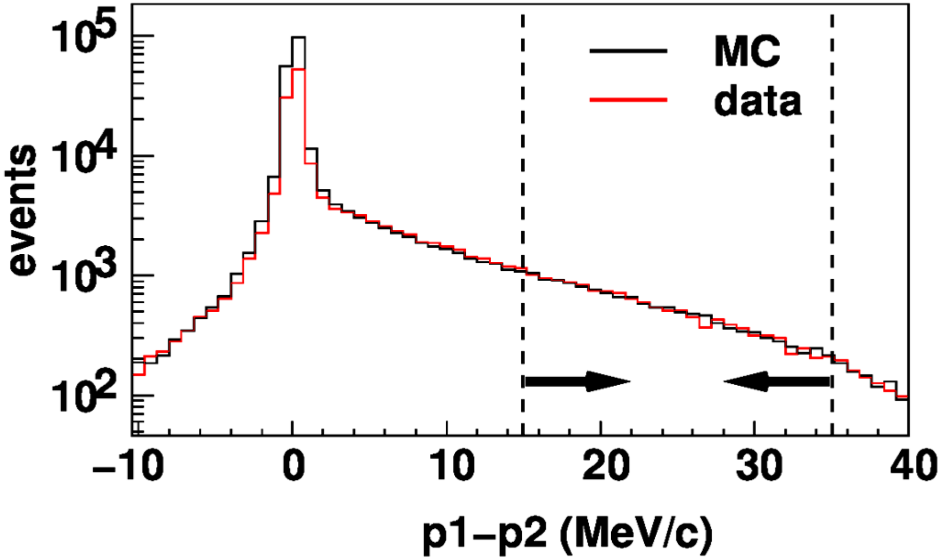
Sensitivity to fringe field transverse components



Bremsstrahlung



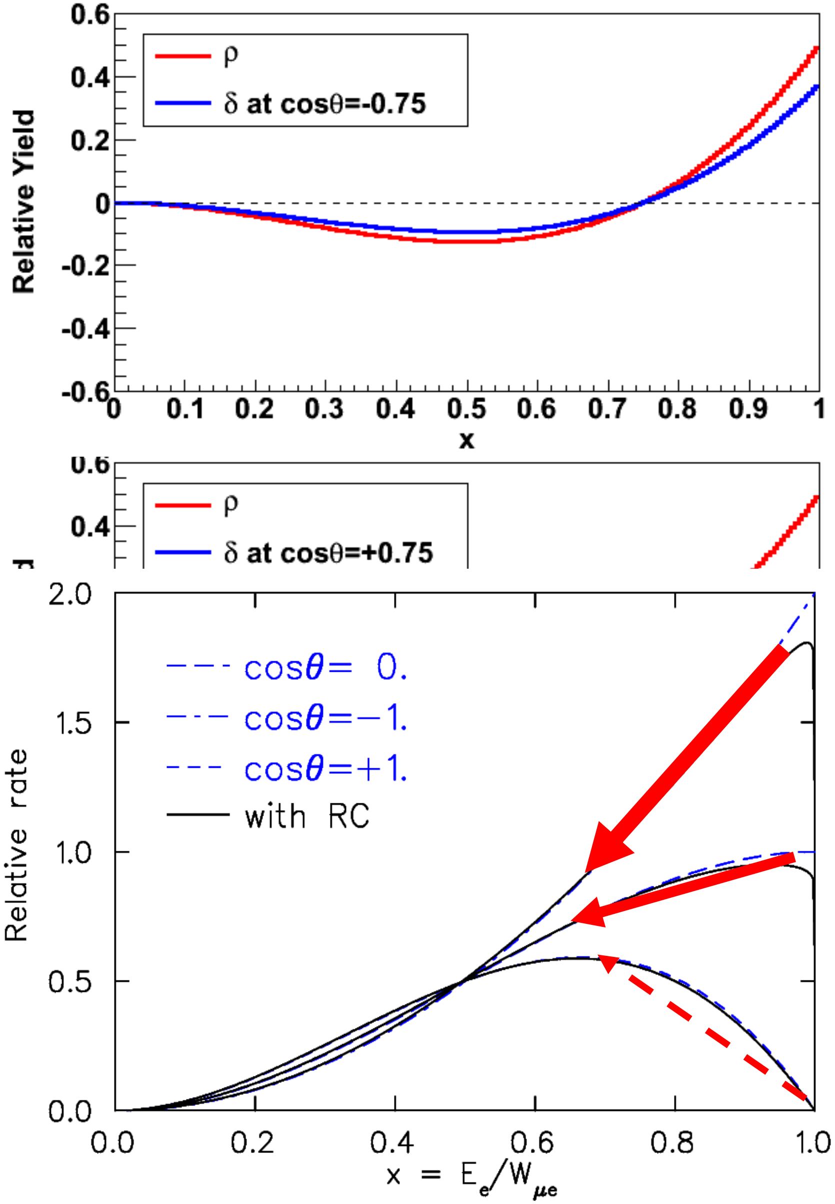




- Leading systematic for ρ and δ
- Two separate measurements
  - "Upstream stops"
  - "Broken tracks"
- Consistent results validate bremsstrahlung simulation in our GEANT3 Monte Carlo at the 2.5% level

Why are ρ and δ systematics correlated?

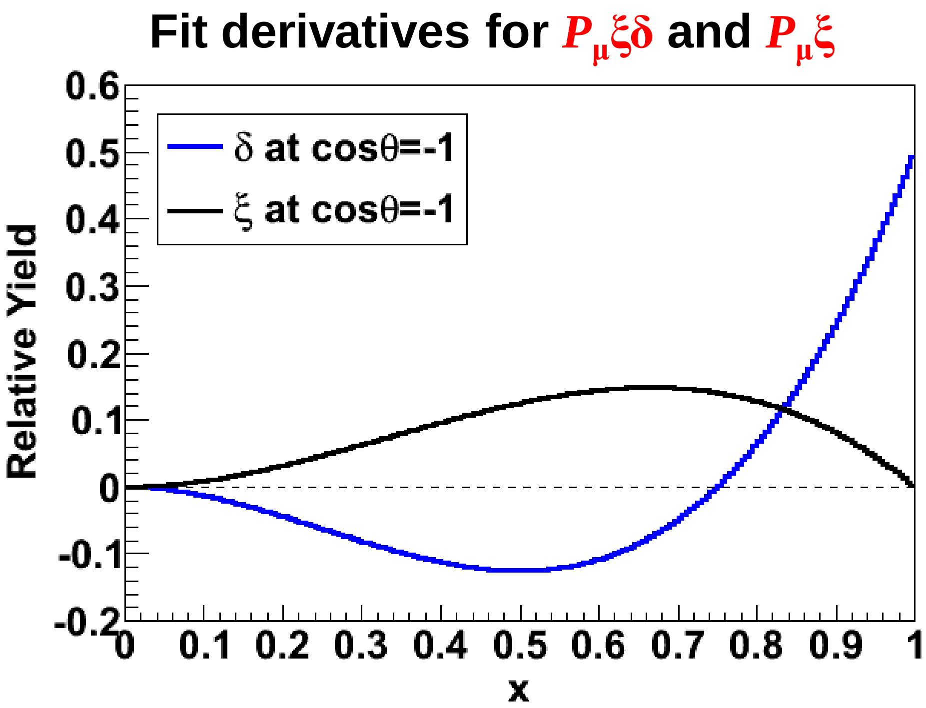
Derivatives at cos(θ) = ±0.75



- 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?



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

Muon decay parameters in the global analysis

(Phys Rev D 72, 073002)

$$Q_{RR} = \frac{1}{4}|g^S_{RR}|^2 + |g^V_{RR}|^2,$$
$$Q_{LR} = \frac{1}{4}|g^S_{LR}|^2 + |g^V_{LR}|^2 + 3|g^T_{LR}|^2,$$
$$Q_{RL} = \frac{1}{4}|g^S_{RL}|^2 + |g^V_{RL}|^2 + 3|g^T_{RL}|^2,$$
$$Q_{LL} = \frac{1}{4}|g^S_{LL}|^2 + |g^V_{LL}|^2,$$
$$B_{LR} = \frac{1}{16}|g^S_{LR} + 6g^T_{LR}|^2 + |g^V_{LR}|^2,$$
$$B_{RL} = \frac{1}{16}|g^S_{RL} + 6g^T_{RL}|^2 + |g^V_{RL}|^2,$$
$$I_\alpha = \frac{1}{4}[g^V_{LR}(g^S_{RL} + 6g^T_{RL})^* + (g^V_{RL})^*(g^S_{LR} + 6g^T_{LR})]$$
$$= (\alpha + i\alpha')/2A,$$
$$I_\beta = \frac{1}{2}[g^V_{LL}(g^S_{RR})^* + (g^V_{RR})^* g^S_{LL}] = -2(\beta + i\beta')/A.$$

$$0 \le Q_{\epsilon\mu} \le 1, \quad \text{where } \epsilon, \mu = R, L,$$
$$0 \le B_{\epsilon\mu} \le Q_{\epsilon\mu}, \quad \text{where } \epsilon\mu = RL, LR,$$
$$|I_\alpha|^2 \le B_{LR}B_{RL}, \qquad |I_\beta|^2 \le Q_{LL}Q_{RR},$$
$$Q_{RR} + Q_{LR} + Q_{RL} + Q_{LL} = 1.$$

$$\rho = \frac{3}{4} + \frac{1}{4}(Q_{LR} + Q_{RL}) - (B_{LR} + B_{RL}),$$
$$\xi = 1 - 2Q_{RR} - \frac{10}{3}Q_{LR} + \frac{4}{3}Q_{RL} + \frac{16}{3}(B_{LR} - B_{RL}),$$
$$\xi\delta = \frac{3}{4} - \frac{3}{2}Q_{RR} - \frac{7}{4}Q_{LR} + \frac{1}{4}Q_{RL} + (B_{LR} - B_{RL}),$$
$$\xi' = 1 - 2Q_{RR} - 2Q_{RL},$$
$$\xi'' = 1 - \frac{10}{3}(Q_{LR} + Q_{RL}) + \frac{16}{3}(B_{LR} + B_{RL}),$$
$$\bar{\eta} = \frac{1}{3}(Q_{LR} + Q_{RL}) + \frac{2}{3}(B_{LR} + B_{RL}),$$
$$\eta = (\alpha - 2\beta)/A, \qquad \eta'' = (3\alpha + 2\beta)/A.$$

- The global analysis combines the final **TWIST** results with all non-**TWIST** muon decay parameter measurements
- The fit parameters are ***Q_{RR}, Q_{LR}, Q_{RL}, B_{LR}, B_{RL}, α/A, β/A, α'/A, β'/A***