TWIST Muon Decay Asymmetry Measurement

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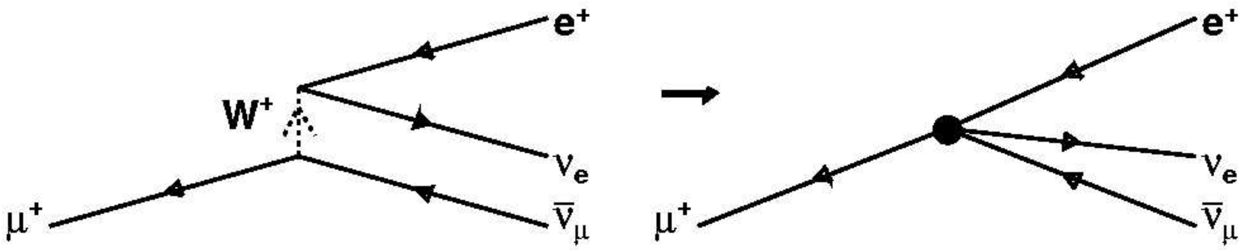
OUTLINE

- Physics of μ decay asymmetry
- Brief review of previous measurements
- Description of detector
- Analysis overview
- Systematic error estimates
- Data Sets, fits, and final results

Muon Decay $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$



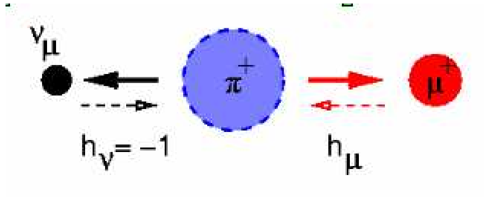
General derivative free interaction matrix element:

$$M = 4\frac{G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \epsilon,\mu=R,L}} g^{\gamma}_{\epsilon\mu} < \bar{e}_\epsilon|\Gamma^\gamma|\nu_e >< \bar{\nu}_\mu|\Gamma_\gamma|\mu_\mu > \qquad (1)$$

- $g^{\gamma}_{\epsilon\mu}$ are the decay coupling constants
- $\gamma = S, V, T$ are the scalar, vector, and tensor interactions
- $\epsilon, \mu = L, R$ are the chirality of the electron or muon
- SM: all zero coupling constants, except $g^V_{LL} = 1$

Physics of μ decay asymmetry

- P_μ is the polarization of the muon, ξ is the asymmetry in angle of the decay positrons from normal μ decay
- Standard Model (V-A) predicts $\xi = 1$ and $P_\mu = -1$

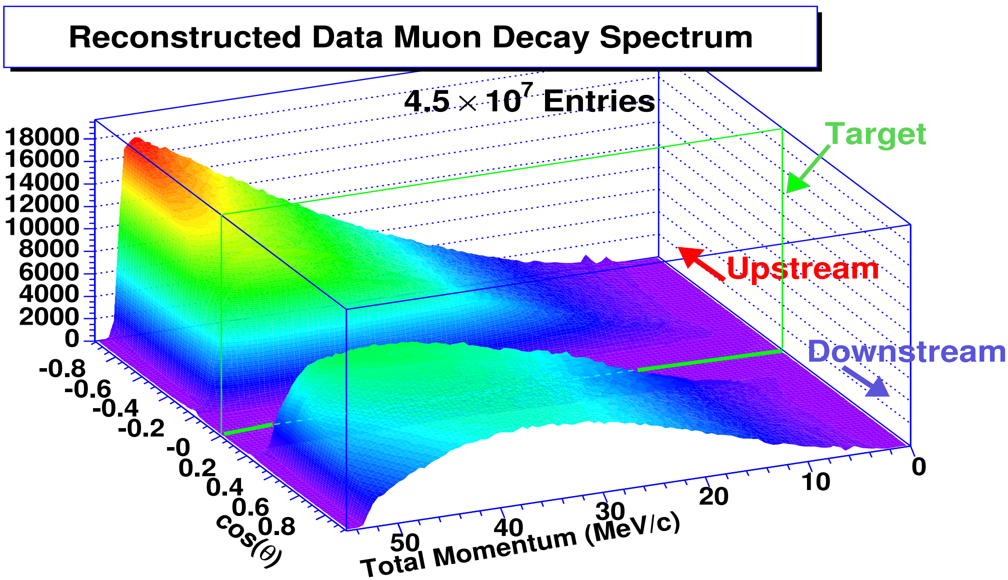


$$\frac{d^2\Gamma}{dx\,d\cos\theta} \propto F_{IS}(x,\rho,\eta) + P_\mu \xi \cos\theta F_{AS}(x,\delta) \qquad (2)$$

$x = E_e/W_{e\mu}$

$W_{e\mu} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$

$x_0 = \frac{m_e}{W_{e\mu}}$



Measurements and Motivation for $P_\mu \xi$

- Direct Measurements:

  - $P_\mu \xi = 1.0027 \pm 0.0079 \pm 0.0030$ (Beltrami et al, PL **B194** 1987)
  - $P_\mu \xi \delta/\rho > 0.99682$, 90% conf. level (Jodidio et al, PR **D34**, PR **D37** 1986)

- Indirect Measurement ($\mathcal{TWIST}$ ρ/δ PRL **94**, 101805 + PRD **71**, 071101(R) (2005)):

$$0.9960 < P_\mu \xi \leq \xi < 1.0040 \text{ at 90\% conf. level}$$

- ξ and δ limit the probability of a right-handed muon decaying into any handed positron:

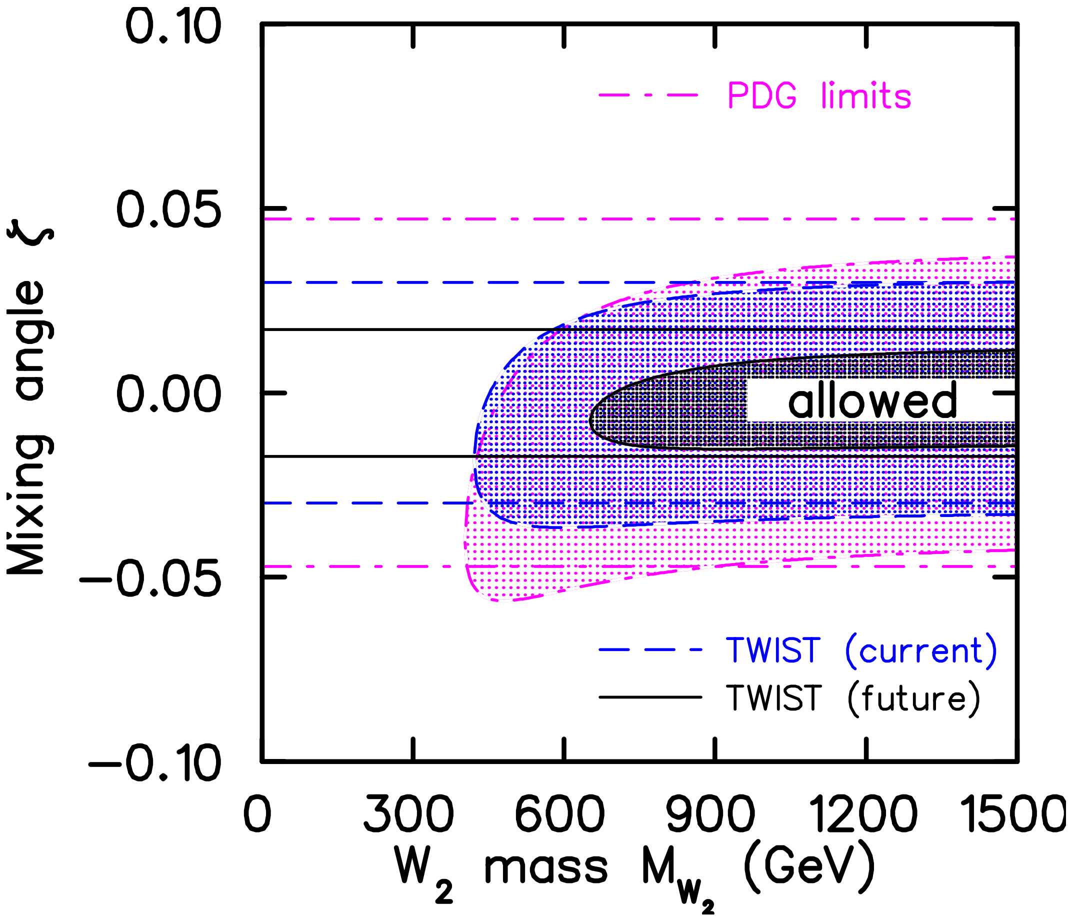
$$Q_R^\mu = \frac{1}{2}\left(1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right) \tag{3}$$

- In Left-Right Symmetric Models, $P_\mu \xi$ sets limit on W_L/W_R mass ($\epsilon = (\frac{g_R M_1}{g_L M_2})^2$) and LR mixing parameter ($\zeta_g = \frac{g_R}{g_L}\zeta$): (Herczeg, PR **D34**)

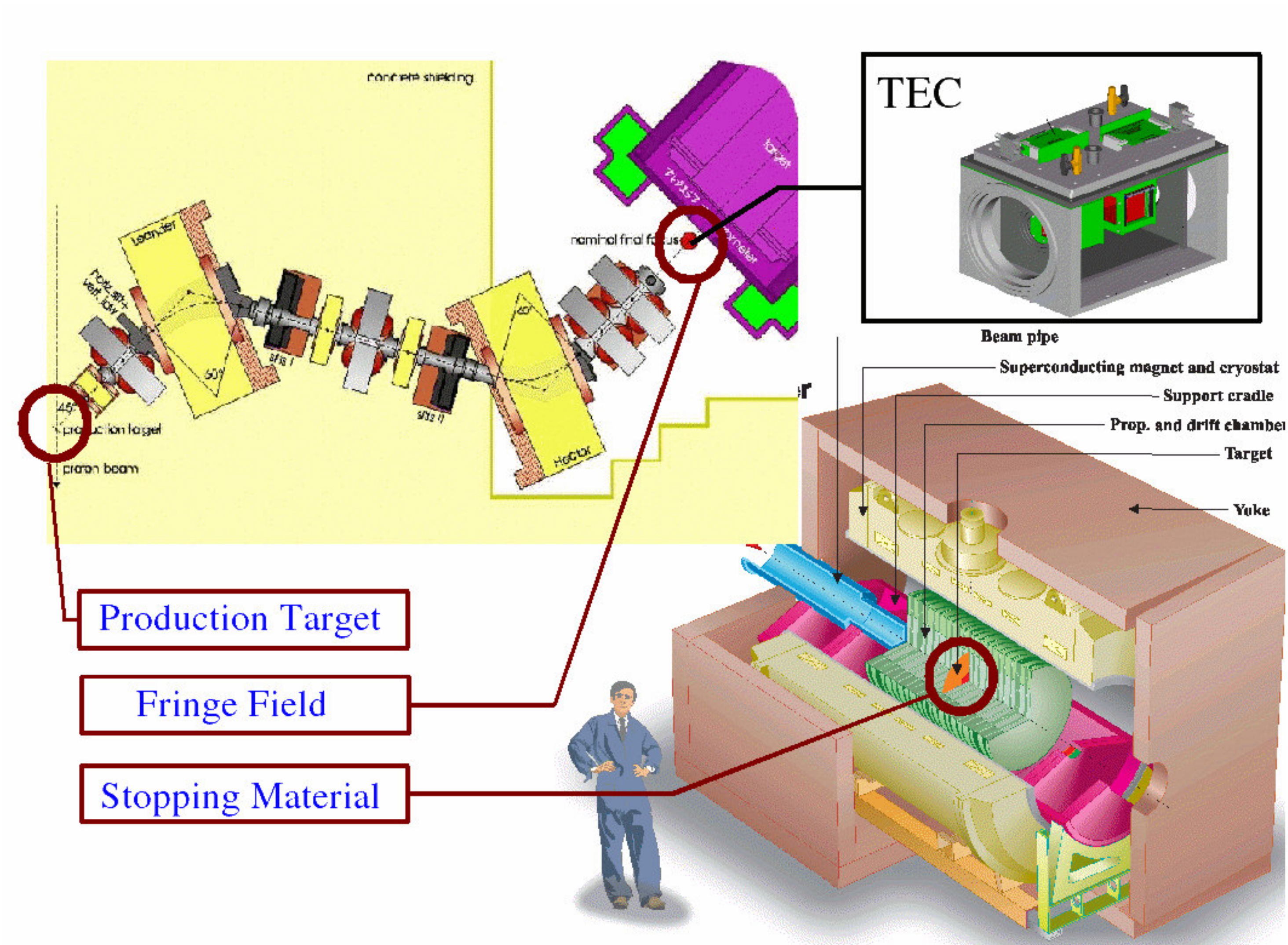
$$P_\mu \xi \approx 1 - 2\epsilon^2 - 4\zeta_g^2 - 2\epsilon^2\left(\frac{cos\theta_1^R}{cos\theta_1^L}\right)^2 - 4\epsilon\zeta_g \frac{cos\theta_1^R}{cos\theta_1^L} cos(\alpha + \omega) \tag{4}$$

Left-Right Symmetric Model Limits

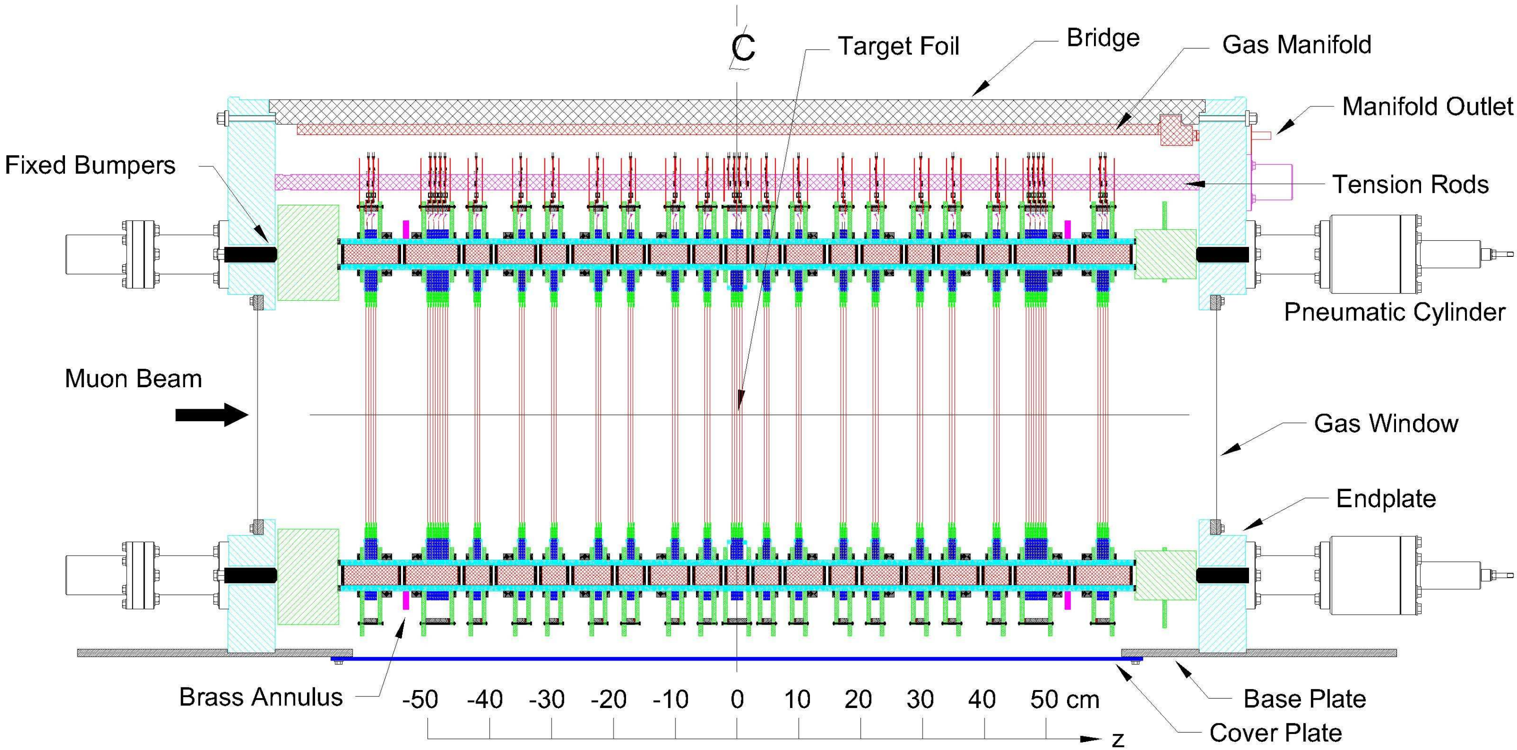
- Pseudomanifest Left-Right Symmetry



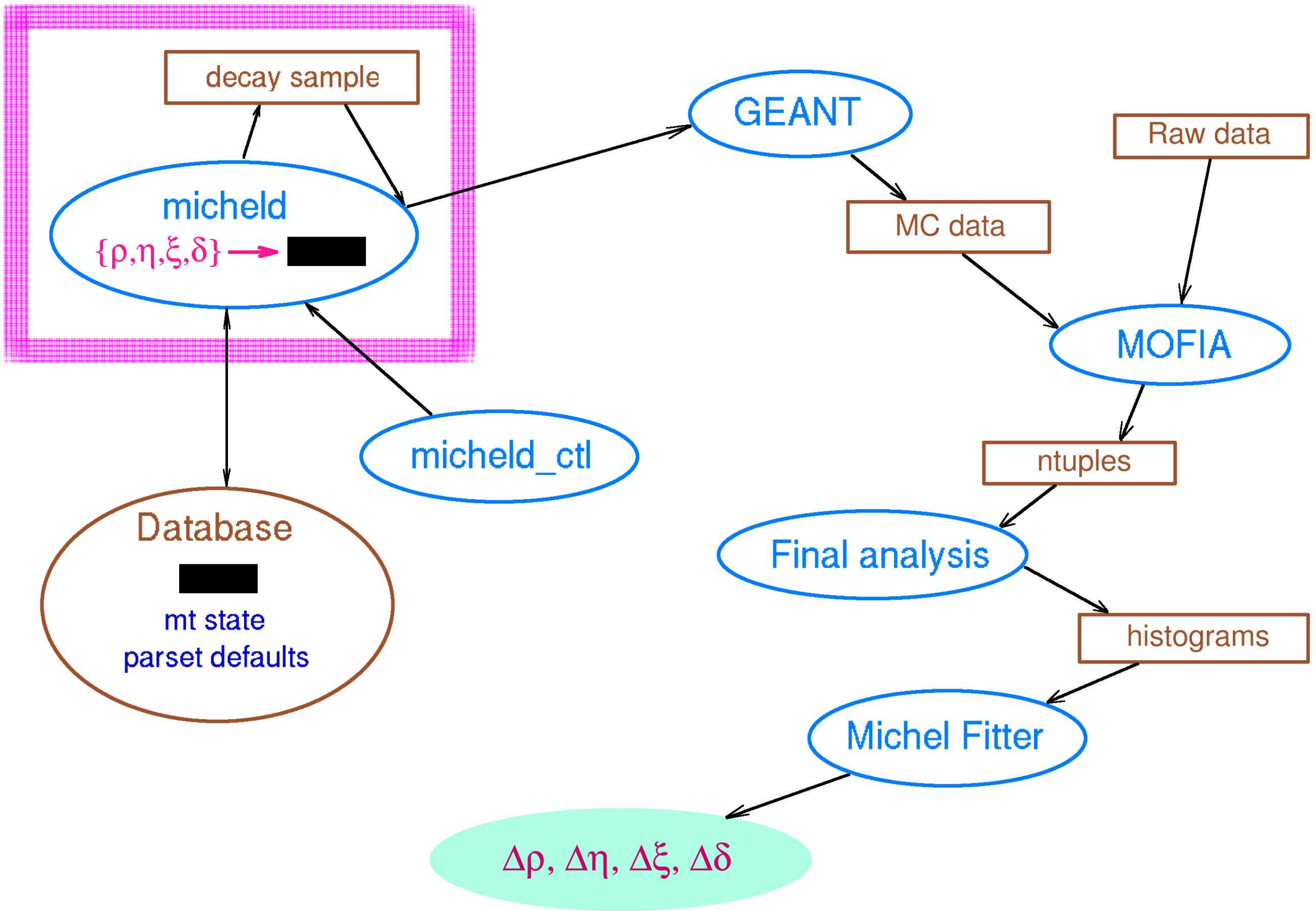
Locations of Muon Depolarization



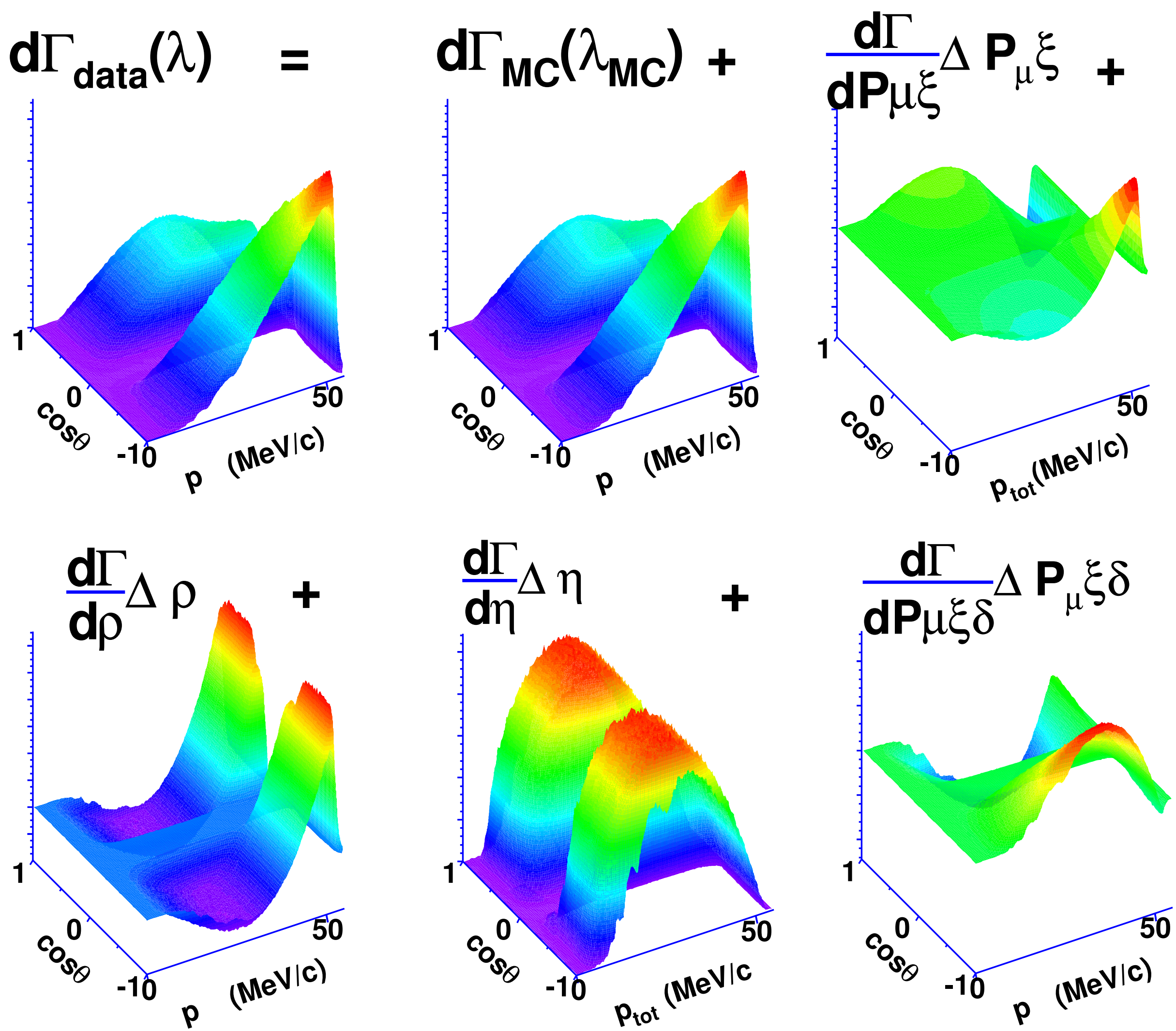
TWIST Detector



Analysis Strategy



Spectrum Fits $\lambda = (\rho, \eta, P_\mu\xi|_{P_\mu\xi\delta}, P_\mu\xi\delta)$



Estimating Systematic Uncertainty

- Total systematic uncertainty is:

$$\epsilon_{sys}^{tot} = \sqrt{\sum_i \frac{\sigma_i^2}{R_i^2} S_i^2} \tag{5}$$

- sensitivity measurement S_i
- scale factor R_i/σ_i
- exaggerated change introduced R_i
- RMS change in data σ_i

Example: t_0 Systematic Uncertainty

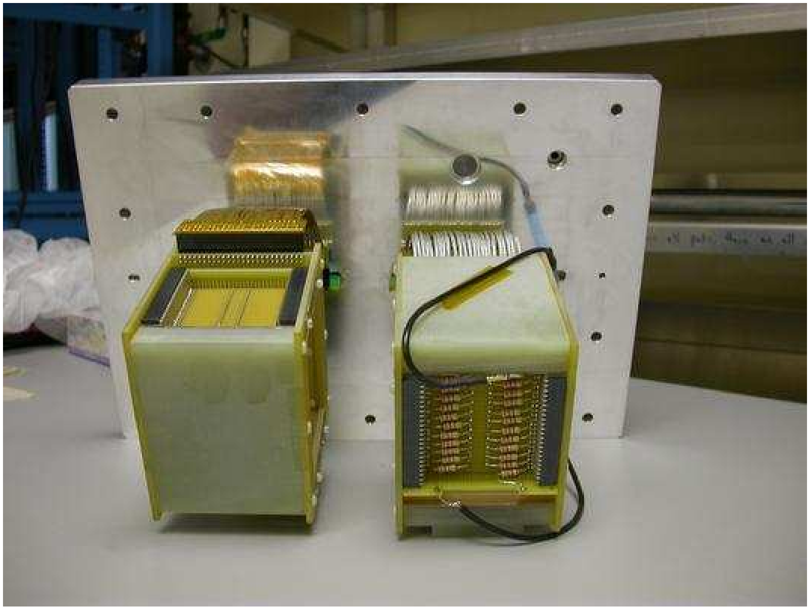
- Sensitivity from fit of spectra from data analyzed with different calibration files:
  - t_0 before data collection
  - t_0 before with offsets of $10 \times (t_0^{begin} - t_0^{end})$
- Find $S_i = (8.9 \pm 2.3) \times 10^{-3}$
- Scale factor R_i/σ_i of 10
- Systematic uncertainty in $P_\mu \xi$: 0.89×10^{-3}
- Also tried with scale factor of 5 to confirm linearity

Systematics for $\mathcal{TWIST}$ $P_\mu\xi$

Systematic Effect	Uncertainty $(\times 10^3)$	Total
Muon Beam and Polarization		3.69
fringe field (ave)	3.40	
stopping target (ave)	1.40	
production target	0.21	
Chamber Response		0.98
t_0 variations (ave)	0.89	
foil bulges (ave)	0.22	
cell asymmetry	0.22	
up-down efficiency	0.19	
density (ave)	0.17	
Spectrometer Alignment		0.31
rotations	0.22	
z position	0.22	
B field to axis	0.03	
Positron Interactions		0.30
hard interactions (ave)	0.29	
multiple scattering	0.08	
outside material	0.02	
Momentum Calibration		0.19
end point fits	0.16	
B field uniformity	0.09	
Radiative Corrections		0.10
Total Systematic Uncertainty		3.8

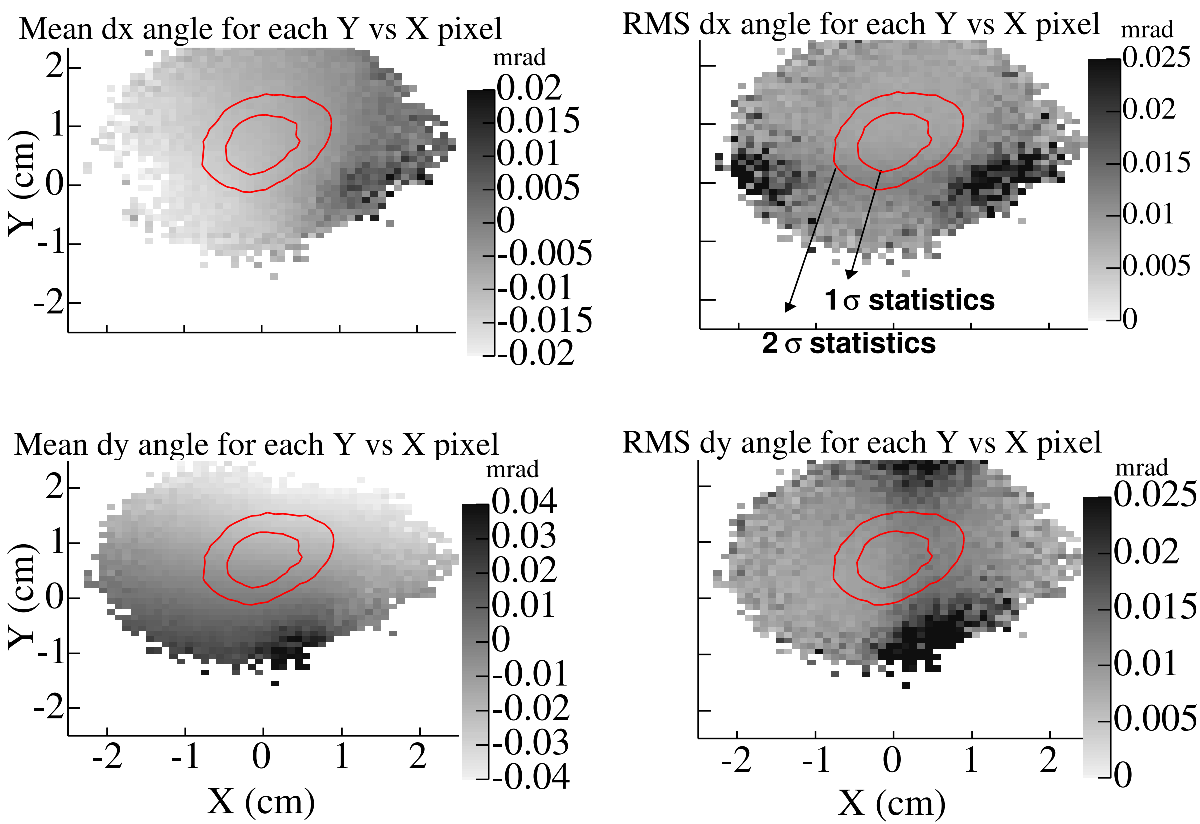
Fringe field depolarization

- Muons depolarized in fringe field of the solenoid
- Estimated three ways:
  - muon beam size + divergence from TEC alignment
  - variation in P_μ from TEC characterizations of "same settings"
  - variation in P_μ from TEC characterizations of nominal runs



Time Expansion Chamber - Muon Beam

- Uncertainty in TEC position of ± 2 mm and ± 5 mrad
- Systematic uncertainty in $P_\mu \xi$ of 1.5 to 3.5×10^{-3}



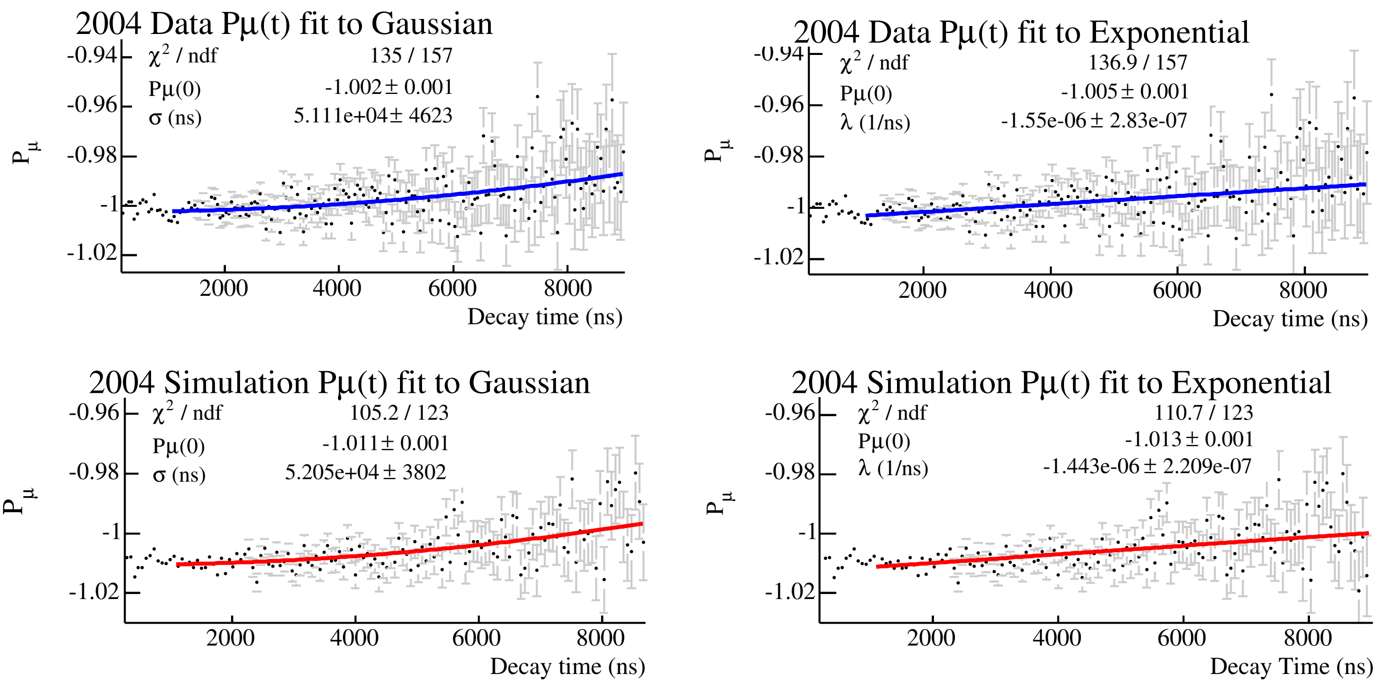
P_μ from TEC runs of "same settings"

- Large difference in $<dy>$
- Systematic uncertainty in $P_\mu\xi$ of 3.3×10^{-3}

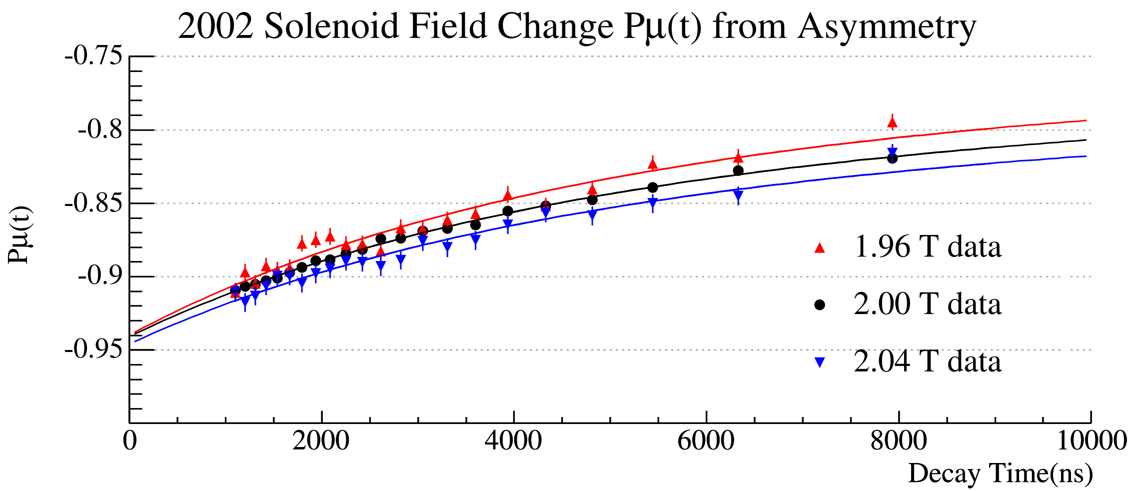
B2 (Gauss)	<x> (cm)	<dx> (mrad)	<y> (cm)	<dy> (mrad)	P_μ^{MC}
949	0.85	-1.1	0.87	-5.0	0.9955
946.5	0.45	-3.4	0.92	1.8	0.9952
944	0.07	-5.9	0.97	7.0	0.9929
941.5	-0.29	-8.3	1.03	10.0	0.9897
949	0.94	-1.5	0.64	-19.2	0.9922
944	0.06	-6.7	0.73	-11.2	0.9941

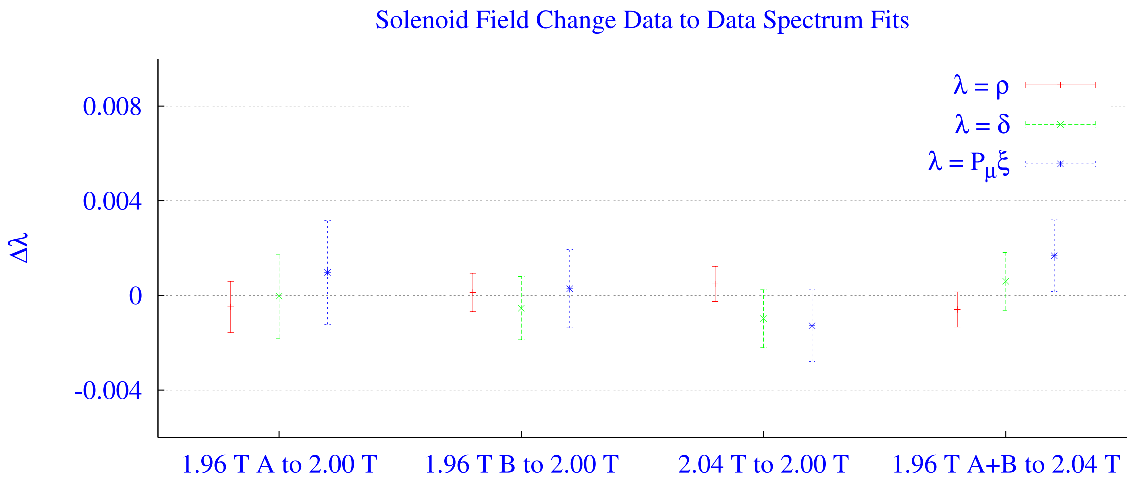
Material Dependent Muon Depolarization

- Partly from 2.5 to 5% gas stops (unkn. form), rest from Al (exponential)
- Gaussian or exponential extrapolation?
- Systematic uncertainty in $P_\mu \xi$ is $\pm\sqrt{2}(0.00099) = \pm 1.4 \times 10^{-3}$



2002 Data: Large Change in P_μ (Top)
2005 Data: No Change in P_μ(Bottom)



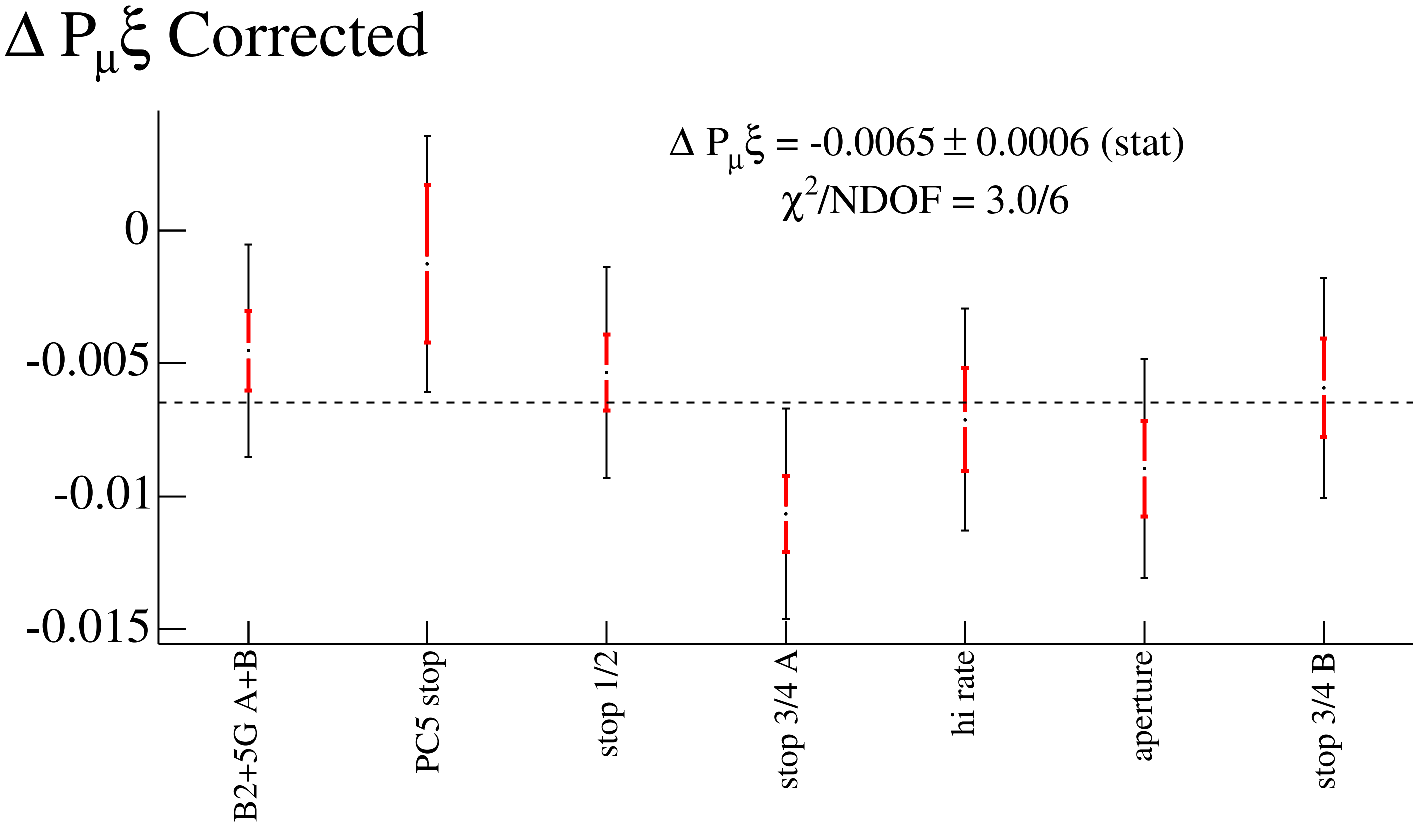


Data Set Summary for $\mathcal{TWIST}$ $P_\mu \xi$

Set #	# Runs (2 GB)	Description
30	60	B2=949G, z cent, M1 Trigger
31	265	B2=949G, z cent, M Trigger
32	120	B2=944G, PC5 Stops
33	91	Far Upstream Stops
34	11	Far Downstream Stops
35	368	2004 Nominal Stops centered
36	390	2004 Stops at 3/4 position
37	281	High Rate
38	303	Aperture In
39	211	2004 Stops at 3/4 position
Total	2100 (4.2 TB)	1998 Nominal Runs

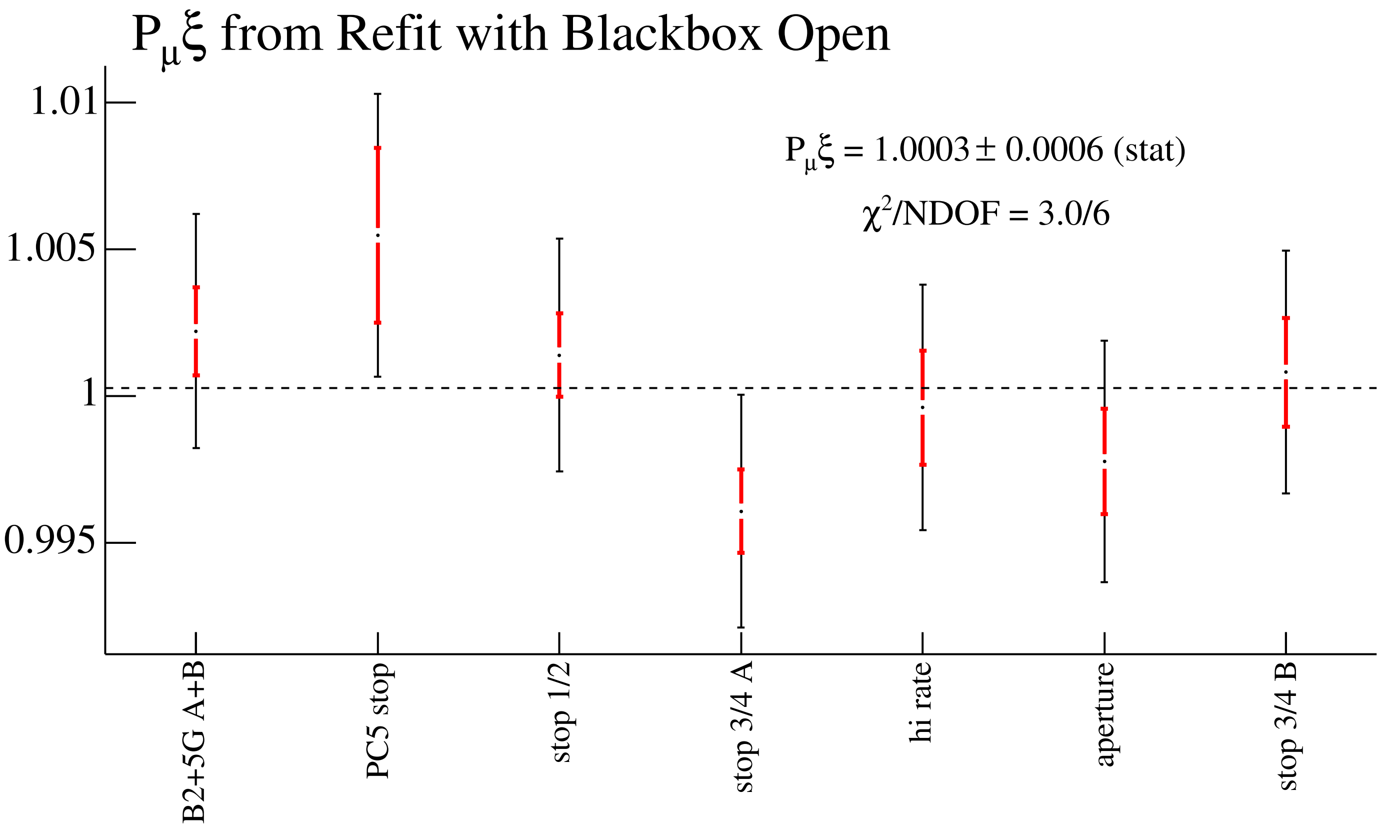
Data Set Consistency

- Consistency check (difference from value hidden in simulation)



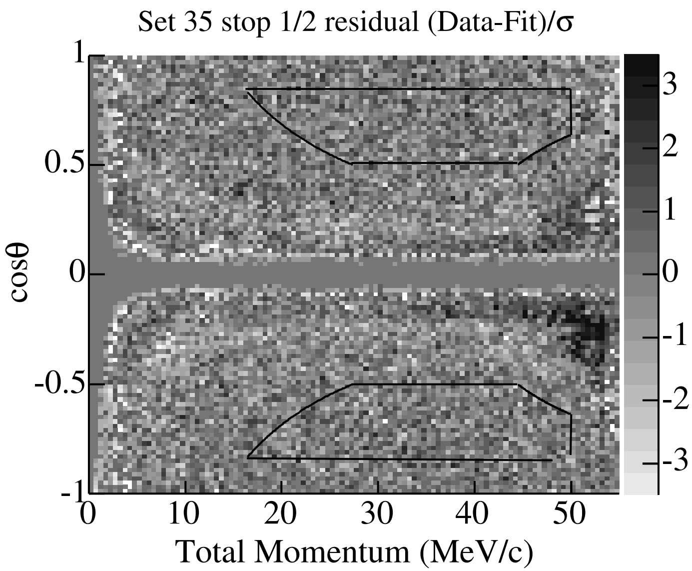
$P_\mu\xi$ Refit with Black Box Open

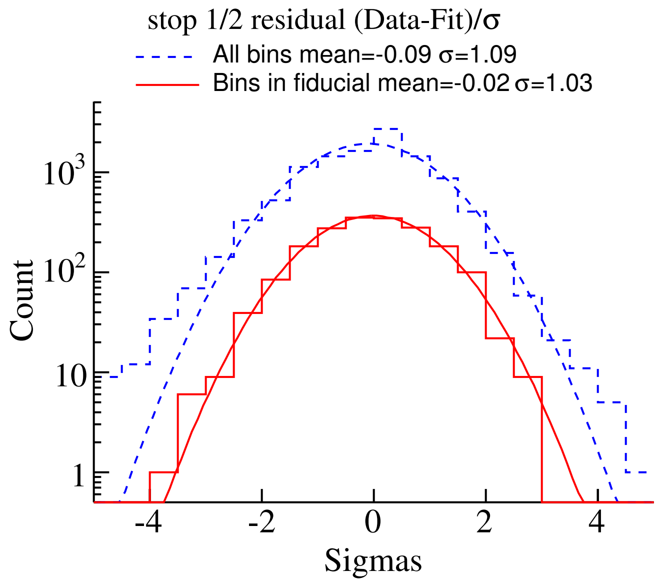
- $P_\mu\xi = 1.0003 \pm 0.0006(\mathrm{stat}) \pm 0.00038(\mathrm{syst})$



Spectrum Fit Residuals

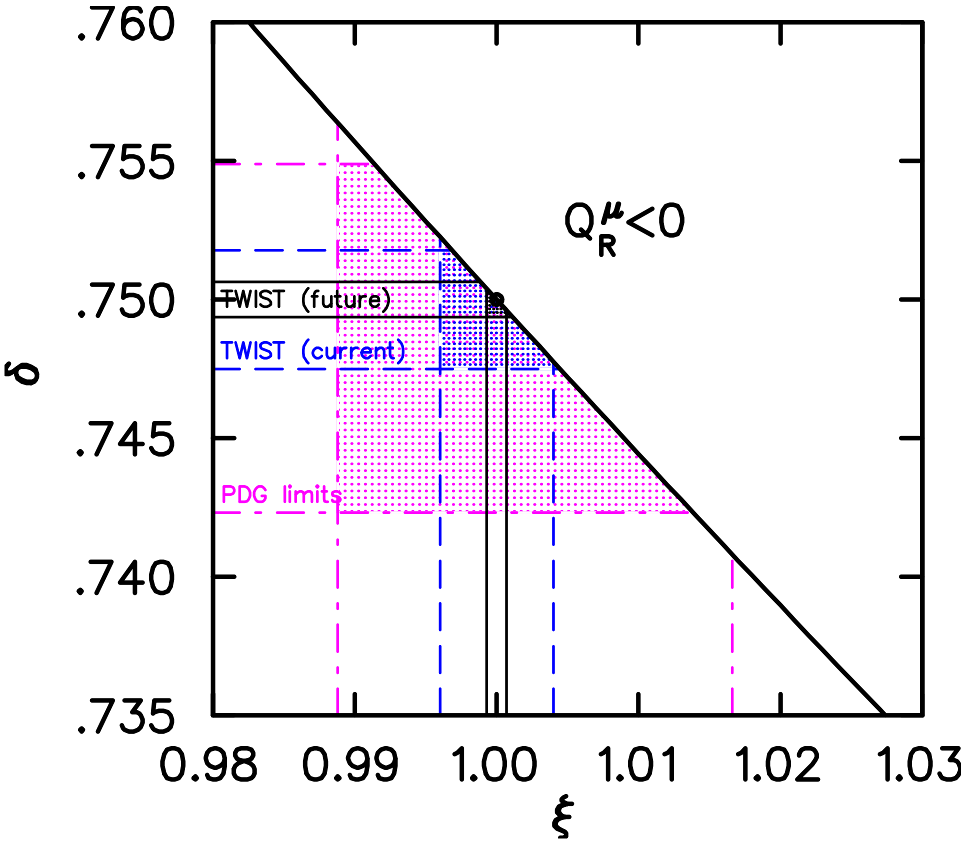
- Data to simulation spectrum fit residals look reasonable
- Residual from all fits look similar





Model Independent Muon Handedness

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



Conclusion

- $\mathcal{TWIST}$ has measured, consistent with standard model:

$$P_\mu \xi \,=\, 1.0003 \pm 0.0006\,(\mathrm{stat}) \pm 0.0038\,(\mathrm{syst})$$

- Result reduces uncertainty in PDG value by a factor of about 2. Current PDG value $= 1.0027 \pm 0.0079 \pm 0.0030$.

- Largest systematic error is due to fringe field depolarization

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TWIST Collaboration

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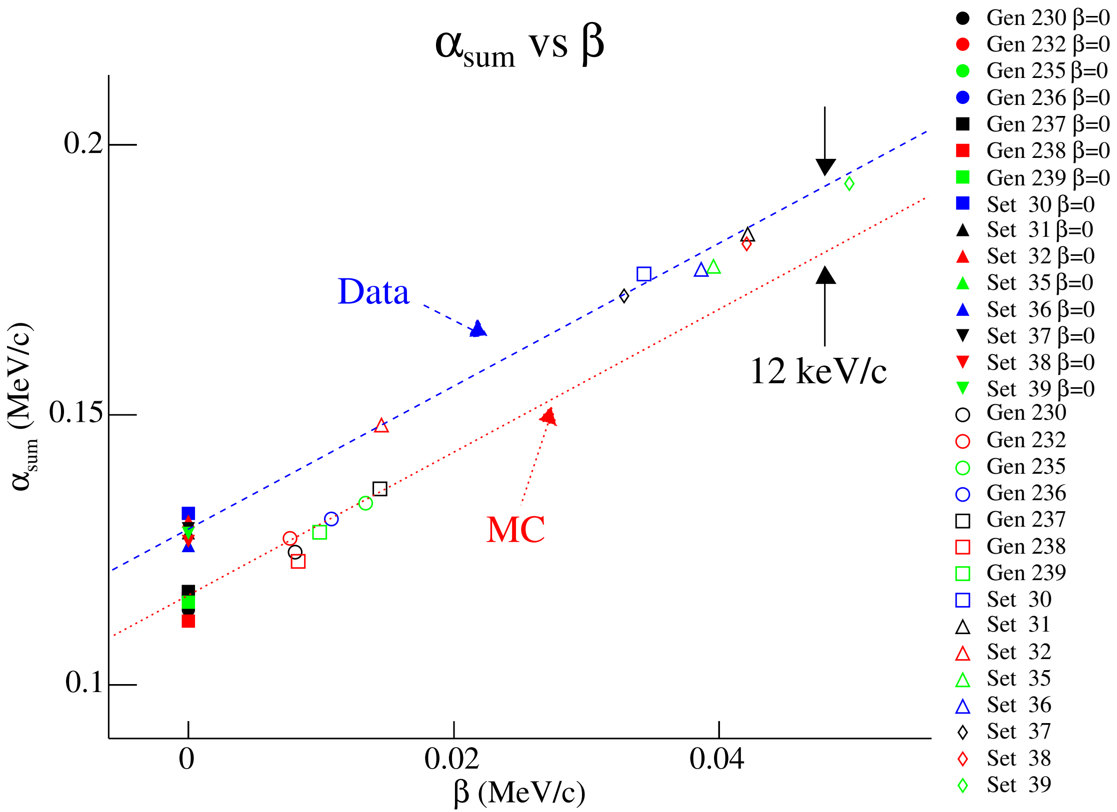
- Previous collaborators:
  Peter Green, Arkadi Khruchinsky, Michael Kroupa, Farhana Sobratee, Sun-Chong Wang, Dennis Wright.

- Professional and technical support:
  Daniel Allen, Pierre Amaudruz, Willy Andersson, Curtis Ballard, Michael Barnes, Brian Evans, Marielle Goyette, Doug Maas, Jan Soukup, Len Wampler, and many undergraduate student research assistants.

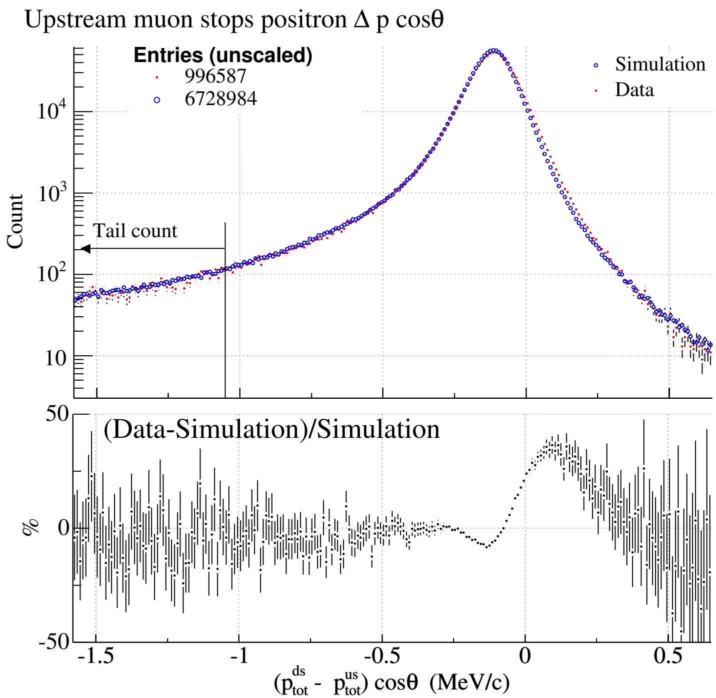
Extra Slides

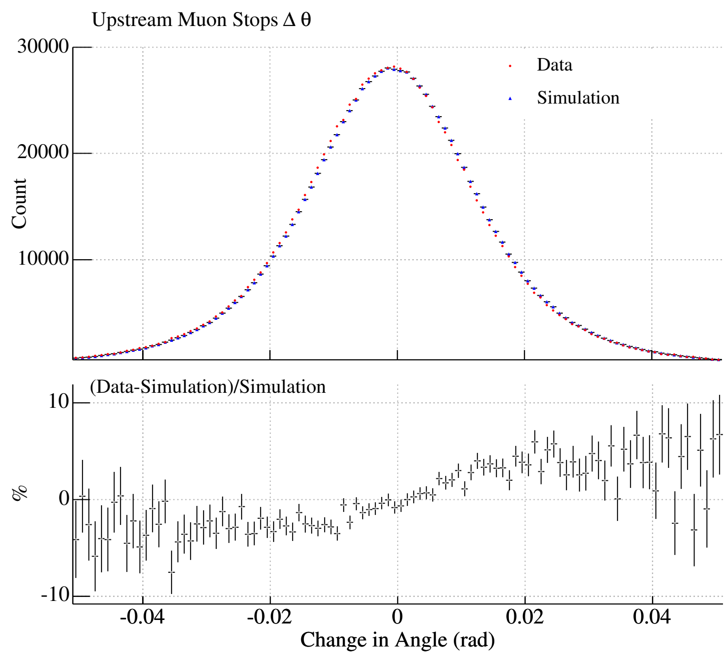
Energy Calibration Correlations



GEANT Validation

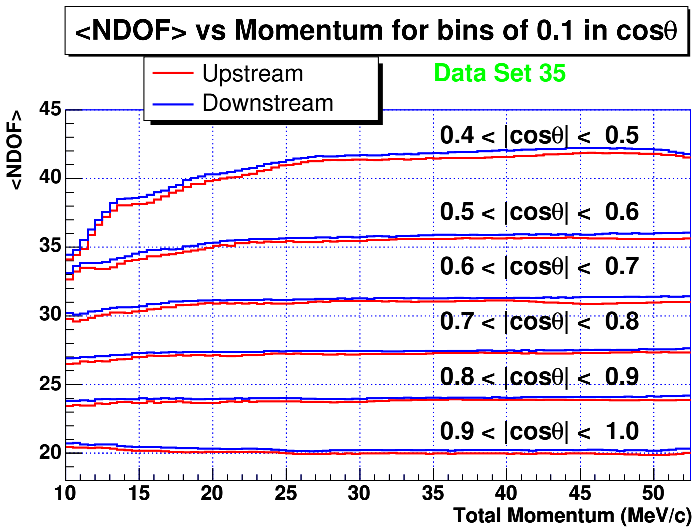
- From fits to two halves of decay positrons from far upstream stops
- Discrepancy in tails in momentum of 4%, and in θ of 8%
- Overall 5% discrepancy in hard interactions

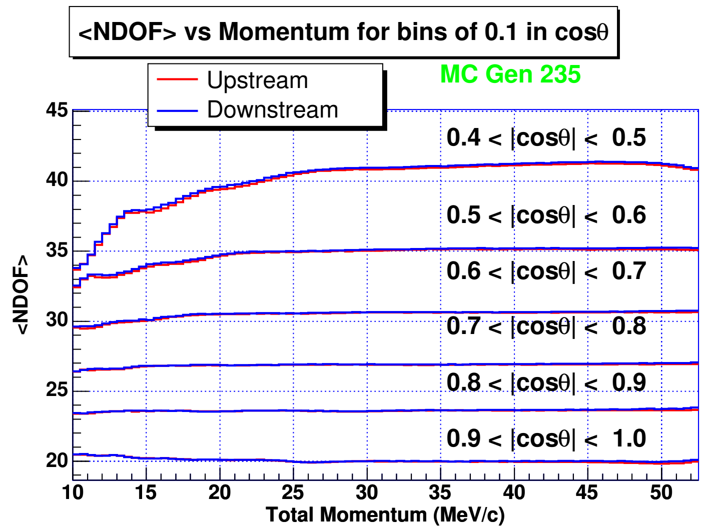




Upstream-Downstream Efficiency

- Difference of 0.18 NDOF between downstream MC and Data
- MC with 5% downstream inefficiency had 1.8 fewer NDOF
- Fit of normal MC to ineffic. MC change in $P_\mu\xi$ of $(1.9 \pm 0.9) \times 10^{-3}$
- Systematic unc. due to US/DS Inefficiency is 0.2×10^{-3}





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