Measurement of $P_{\mu\xi}$ in Polarized Muon Decay

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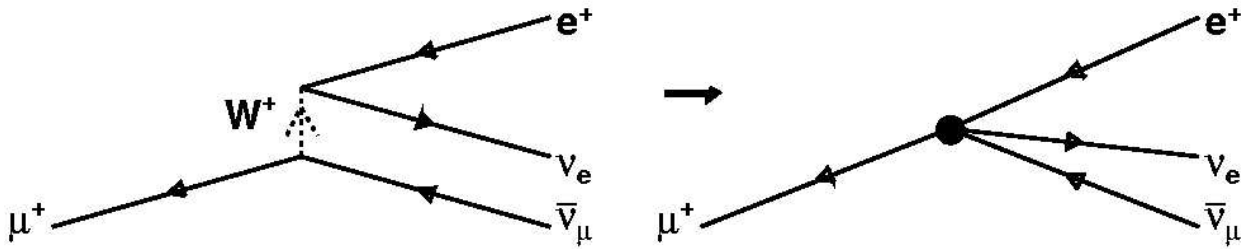
OUTLINE

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

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



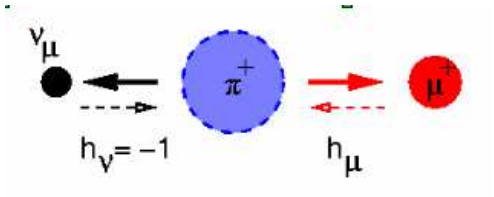
General derivative free interaction matrix element:

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

- $g^{\gamma}_{\epsilon\mu}$ 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 $P_\mu = 1$

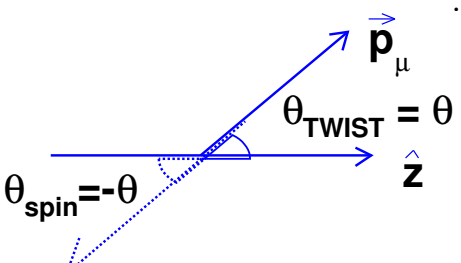


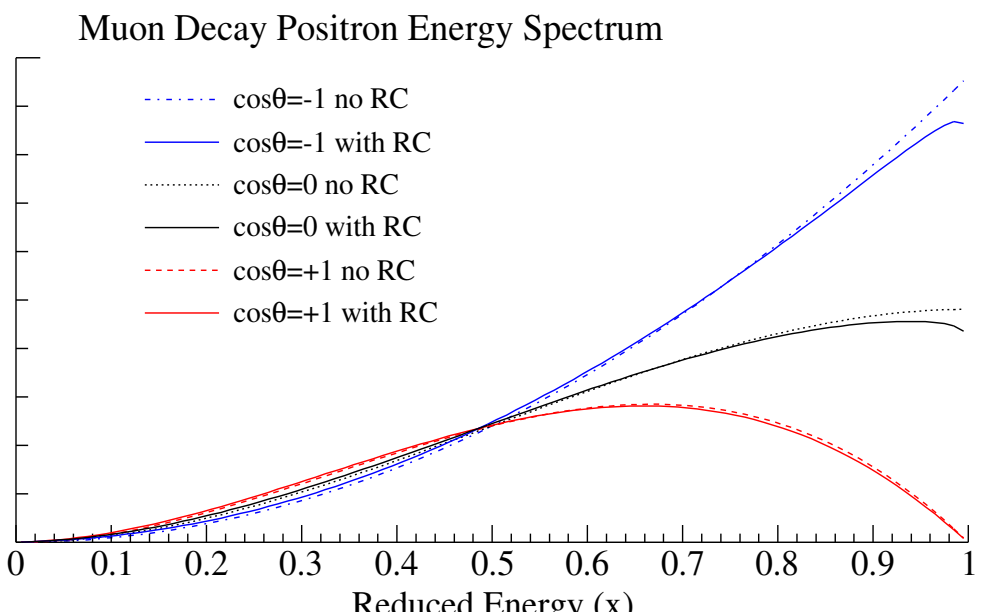
$$\frac{d^2\Gamma}{dx\,d\cos\theta} \propto F_{IS}(x,\rho,\eta) + P_\mu \xi \cos\theta_{\text{spin}} F_{AS}(x,\delta) \qquad (2)$$

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

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

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





Measurements and Motivation for $P_\mu\xi$

- Direct Measurements at PSI and TRIUMF:
  - $P_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$ (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:

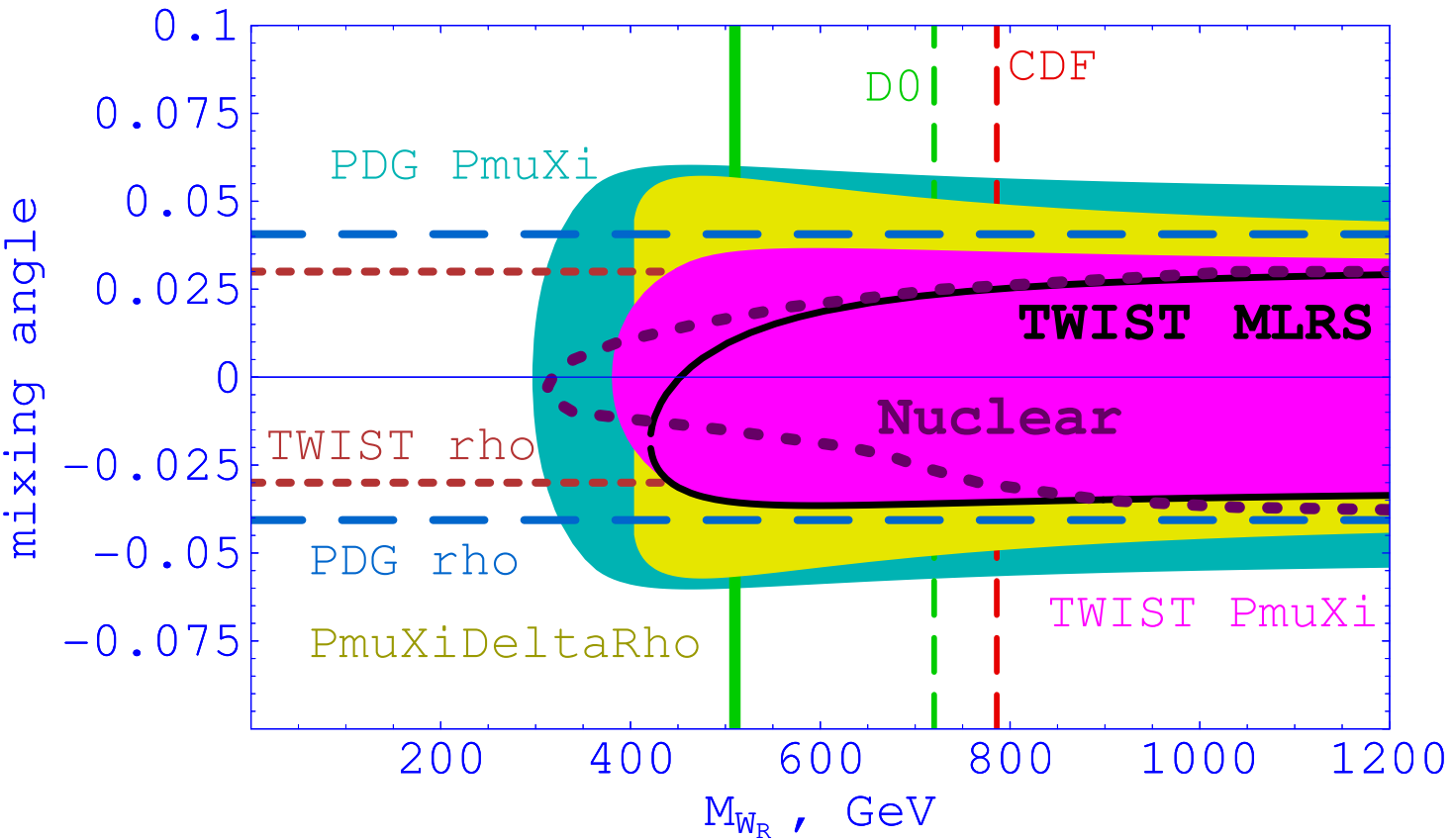
$$Q_R^\mu = \frac{1}{2}(1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta) \tag{3}$$

- 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**)

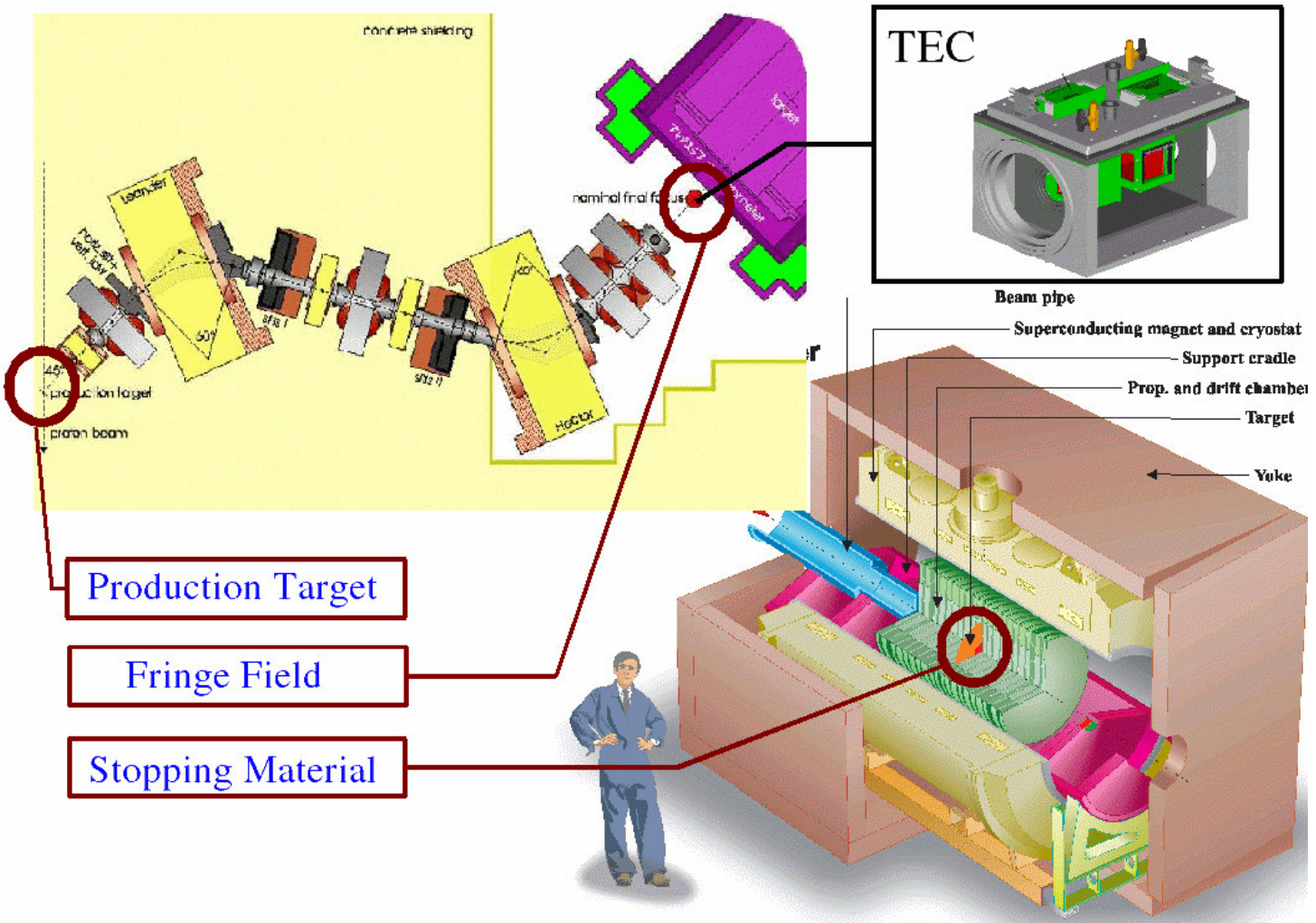
$$P_\mu\xi \approx 1 - 2\epsilon^2 - 4\zeta_g^2 - 2\epsilon^2(\frac{cos\theta_1^R}{cos\theta_1^L})^2 - 4\epsilon\zeta_g\frac{cos\theta_1^R}{cos\theta_1^L}cos(\alpha+\omega) \tag{4}$$

Left-Right Symmetric Model Limits

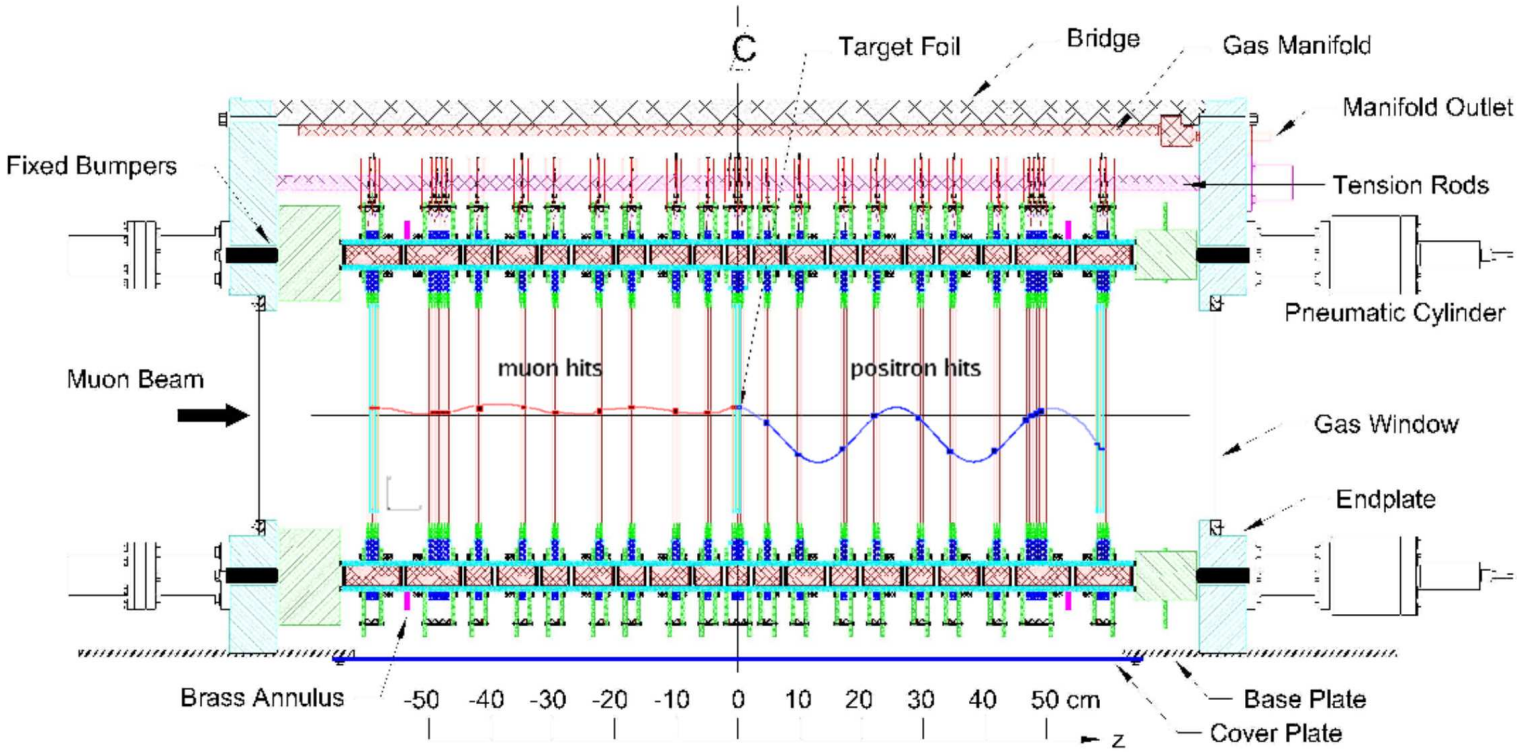
- Various LRS model constraints (and assumptions)



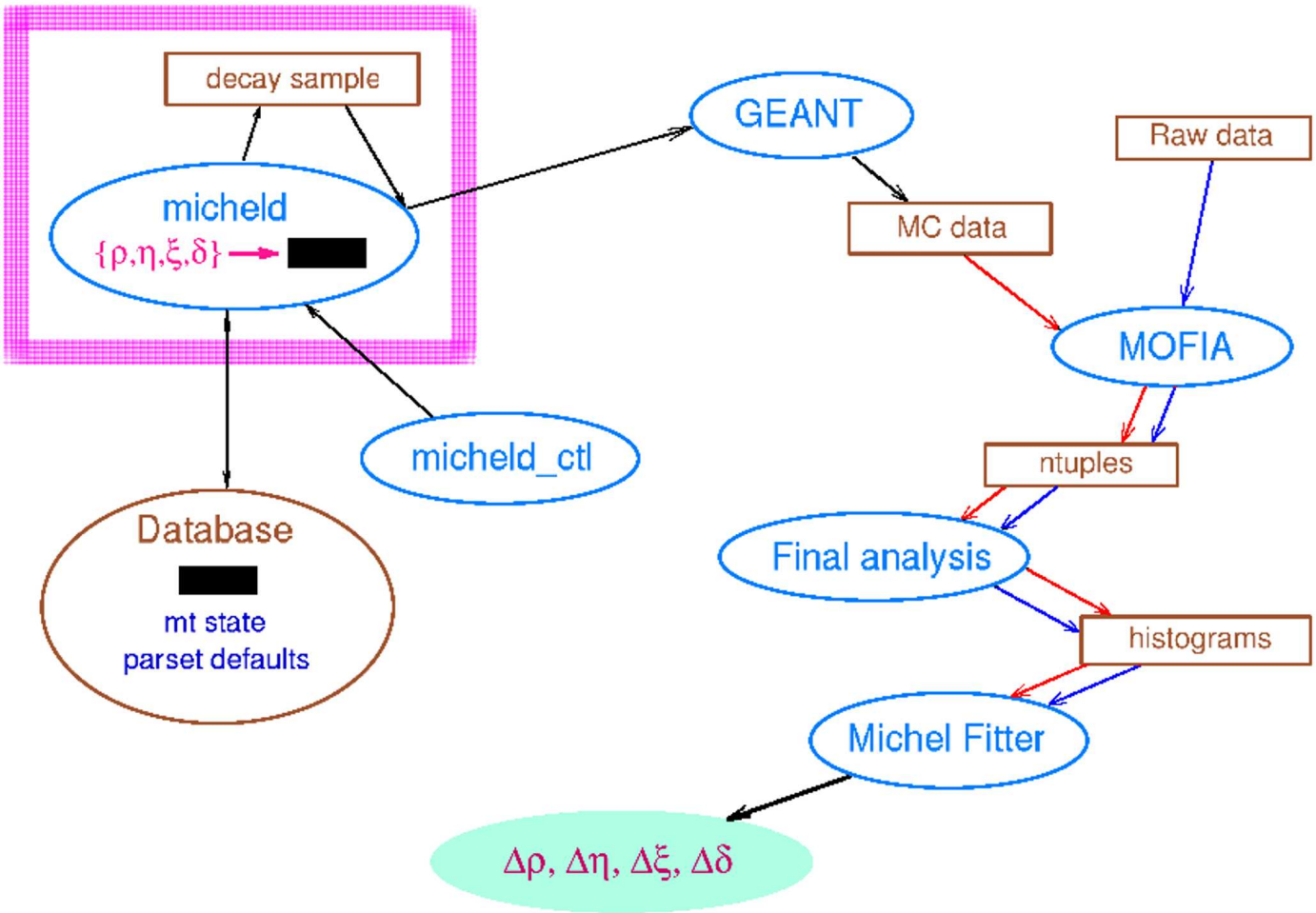
Locations of Muon Depolarization



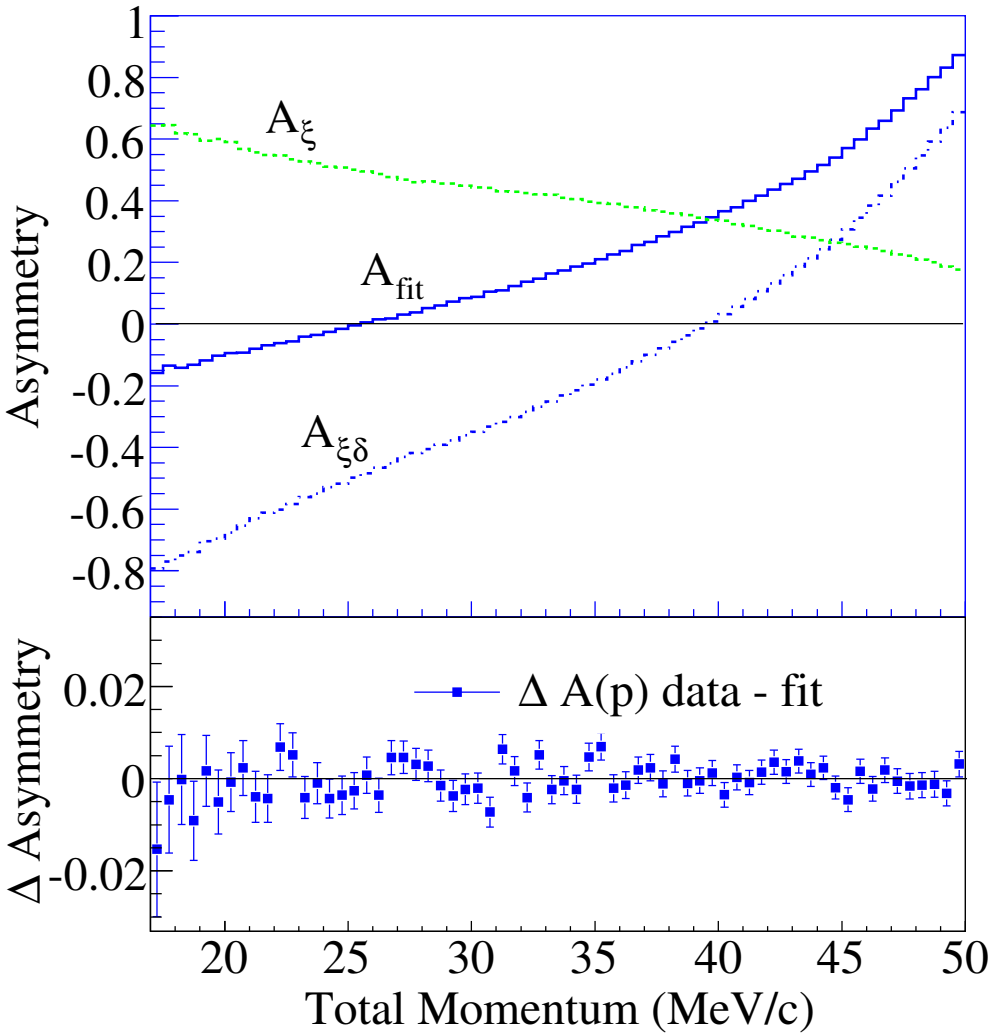
TWIST Detector



Blind Analysis Strategy



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

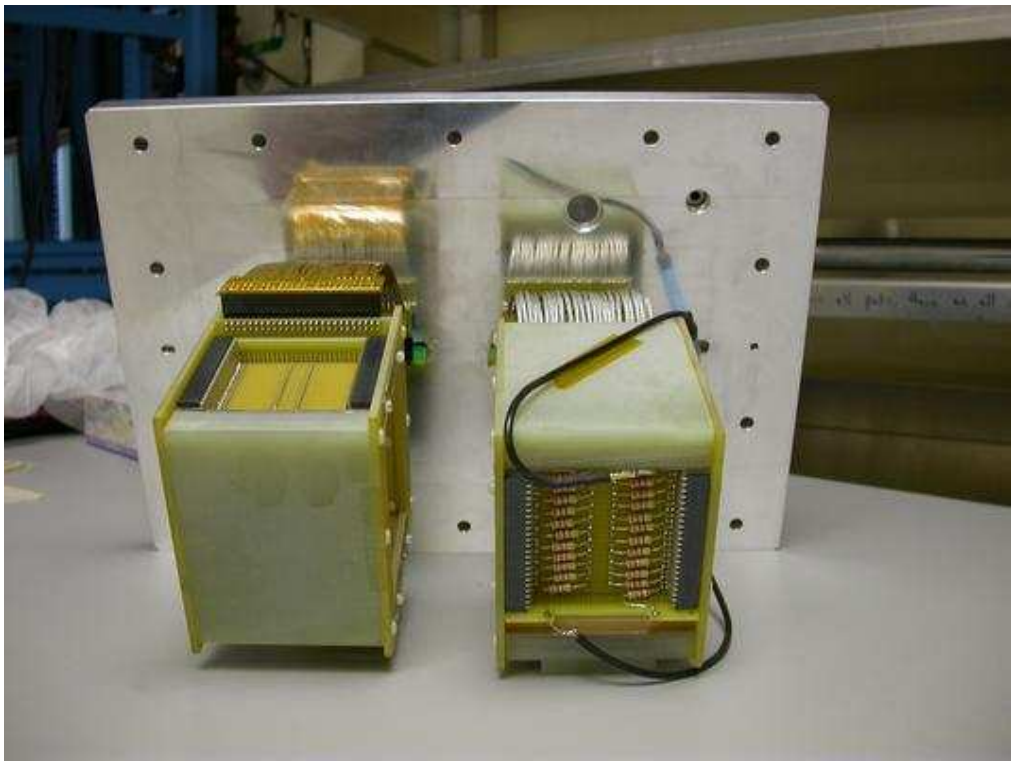


Systematics for $TWIST$ $P_\mu\xi$

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

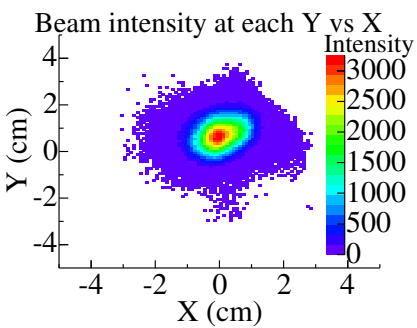
Fringe field depolarization

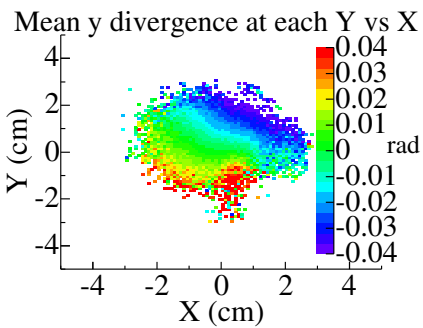
- Muons depolarized in fringe field of the solenoid: $P_\mu \propto \theta_\mu^2/2$
- Estimated from difference in begin and end run beam characterization

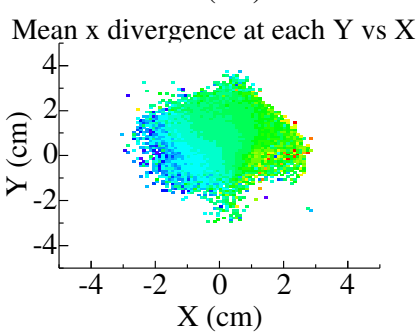


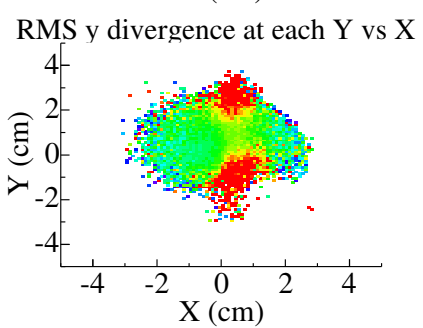
P_μ from TEC beam reproducibility

B2 (mT)	$\bar{x}$ (cm)	$\bar{\theta}_x$ (mrad)	$\bar{y}$ (cm)	$\bar{\theta}_y$ (mrad)	$P_\mu^{\rm sim}$
94.4	0.07	-5.9	0.97	7.0	0.9929
94.9	0.85	-1.1	0.87	-5.0	0.9955
94.4	0.06	-6.7	0.73	-11.2	0.9941
94.9	0.94	-1.5	0.64	-19.2	0.9922



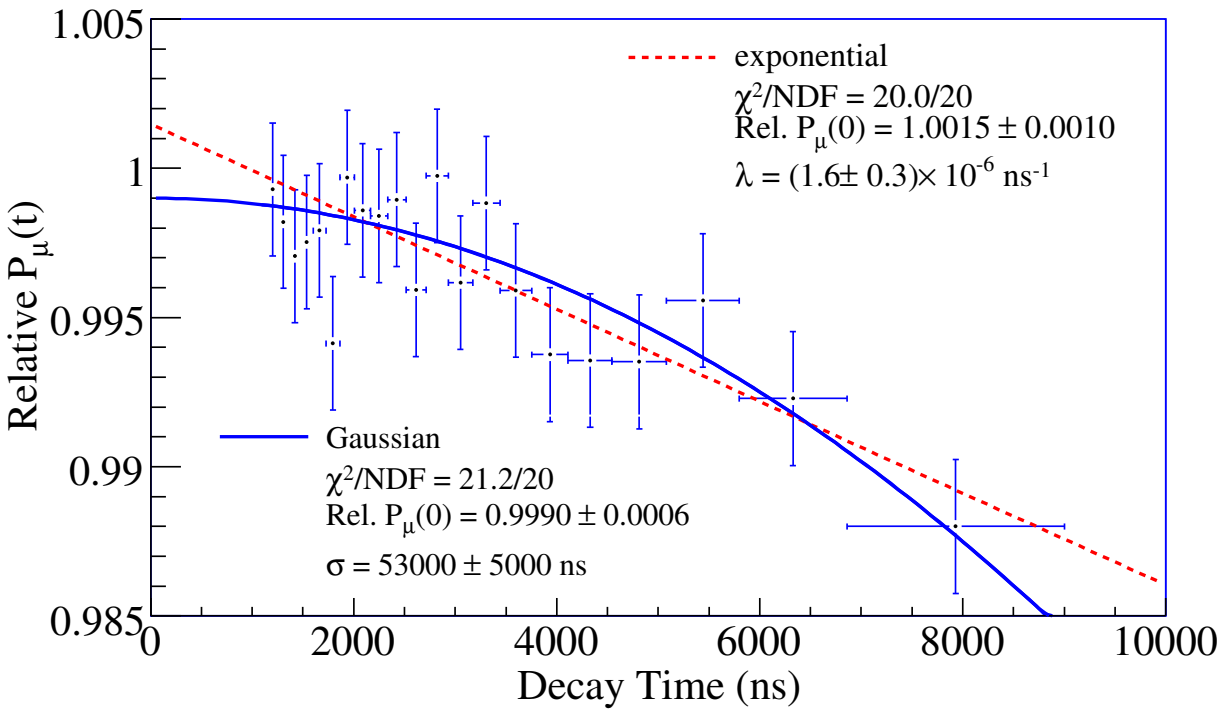






Material Dependent Muon Depolarization

- Gaussian or exponential extrapolation?
- Systematic uncertainty in $P_\mu \xi$ is 0.0012

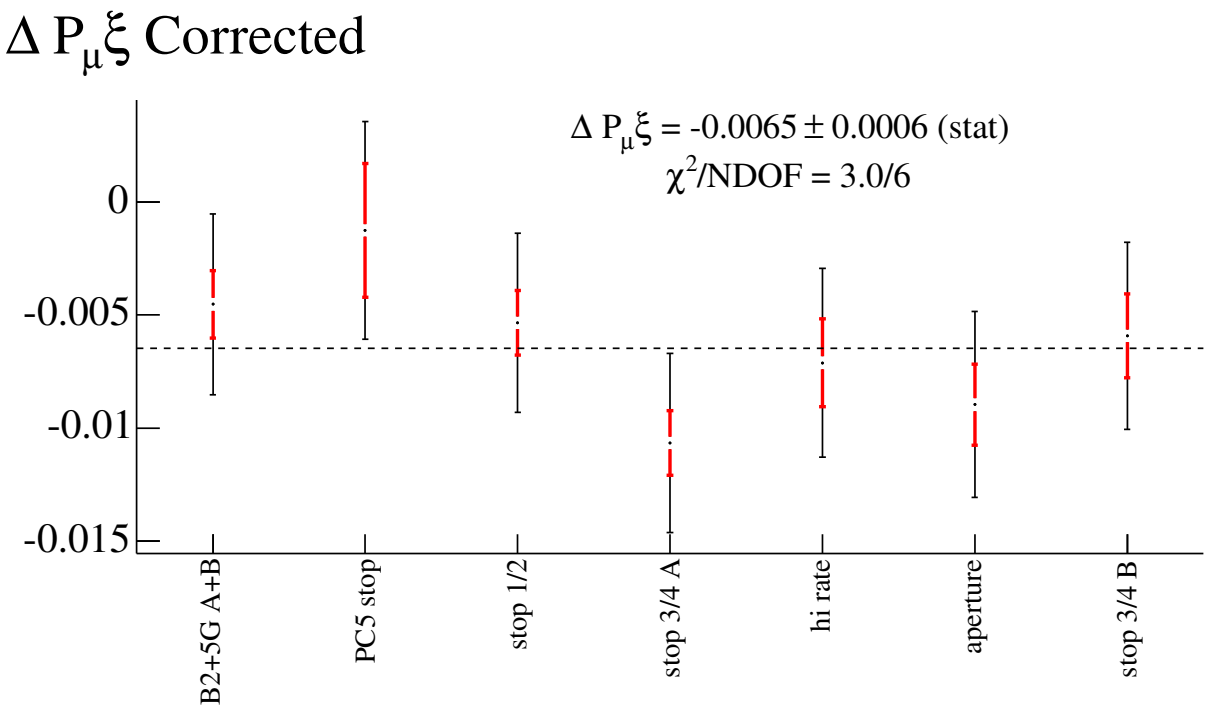


Data Set Summary for $TWIST$ $P_\mu\xi$

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

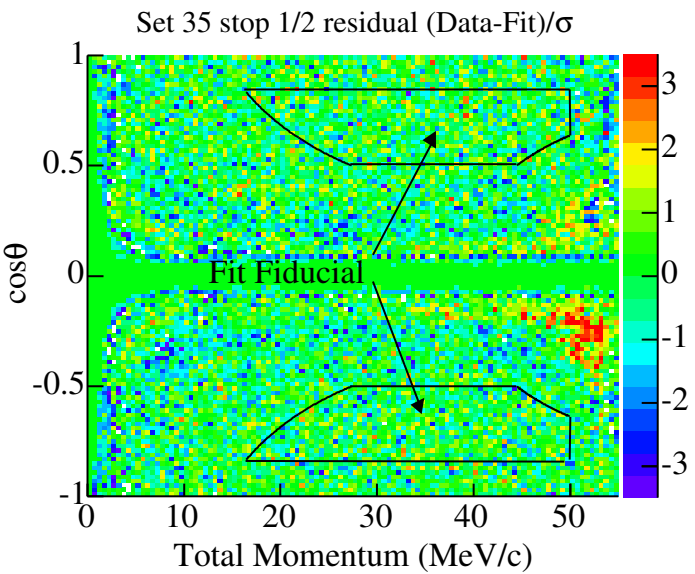
Data Set Consistency

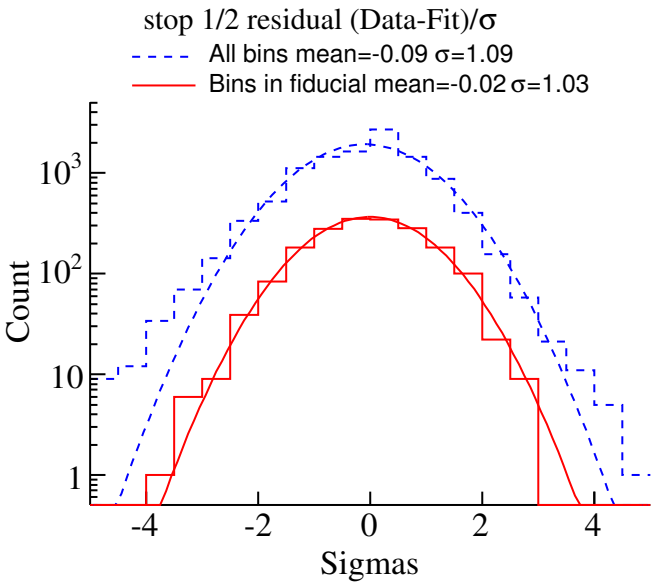
- Consistency check (difference from value hidden in simulation)
- Red=statistical uncertainty, Black=stat+set-to-set systematic unc.



Spectrum Fit Result

- Data to simulation spectrum fit residals look reasonable
- Residual from all fits look similar
- $P_\mu \xi = 1.0003 \pm 0.0006\,(\text{stat}) \pm 0.0038\,(\text{syst})$
  (hep-ex/0605100)





Conclusion

- Preliminary $\mathcal{TWIST}$ measurement, consistent with standard model (hep-ex/0605100):

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

- 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 uncertainty is due to fringe field depolarization

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TWIST Collaboration

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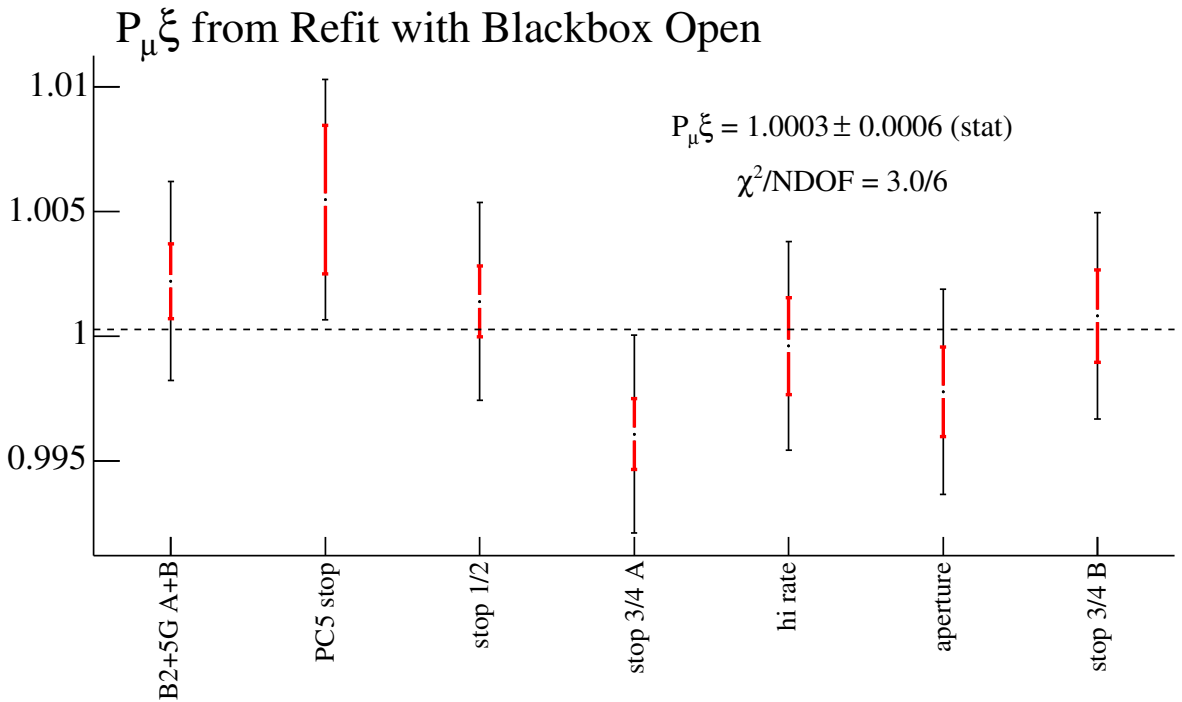
- Previous collaborators:
  Peter Green, Arkadi Khruchinsky, Michael Kroupa, Farhana Sobratee, Sun-Chong Wang, Dennis Wright.

- 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

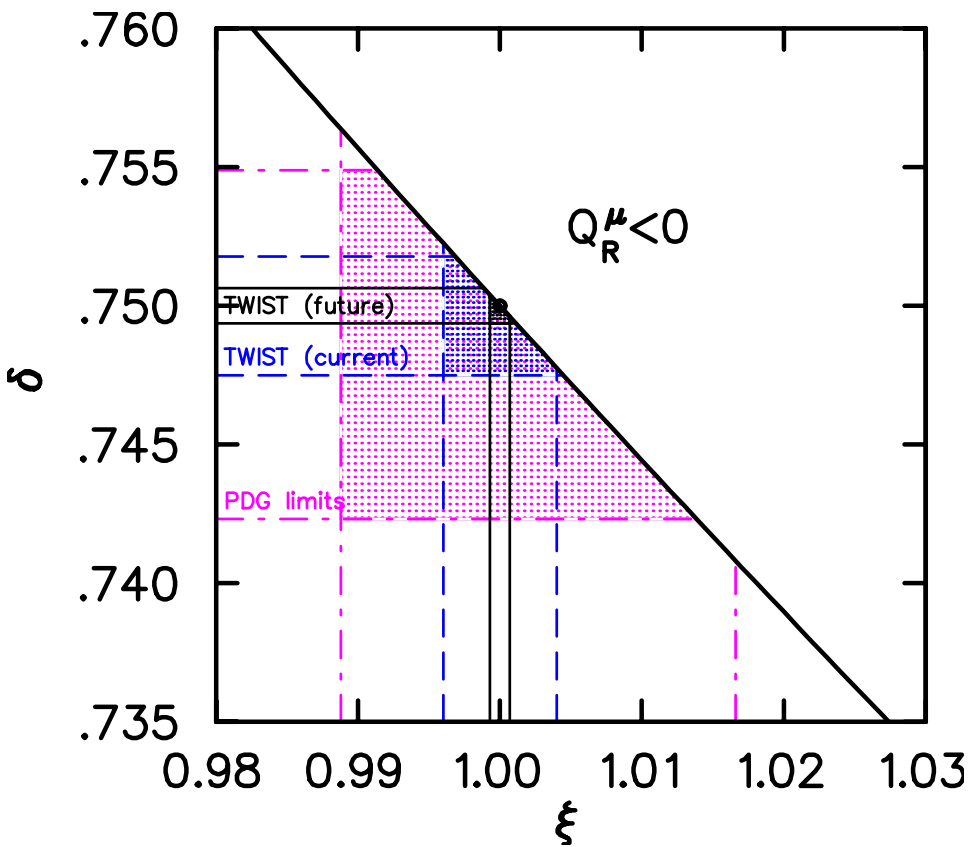
Preliminary Unblinded $P_\mu \xi$

- $P_\mu \xi = 1.0003 \pm 0.0006(\text{stat}) \pm 0.0038(\text{syst})$
- Red=statistical uncertainty, Black=stat+set-to-set systematic unc.



Model Independent Muon Handedness

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

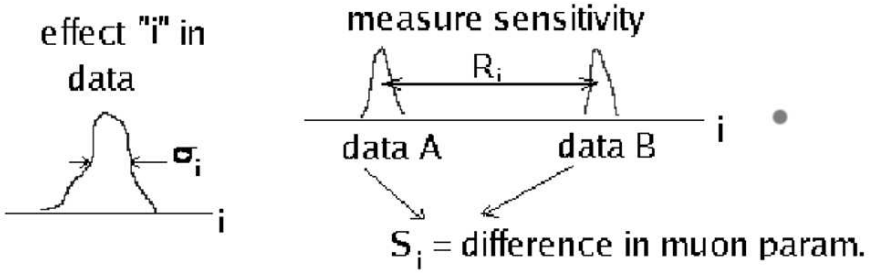


Estimating Systematic Uncertainty

- Total systematic uncertainty is:

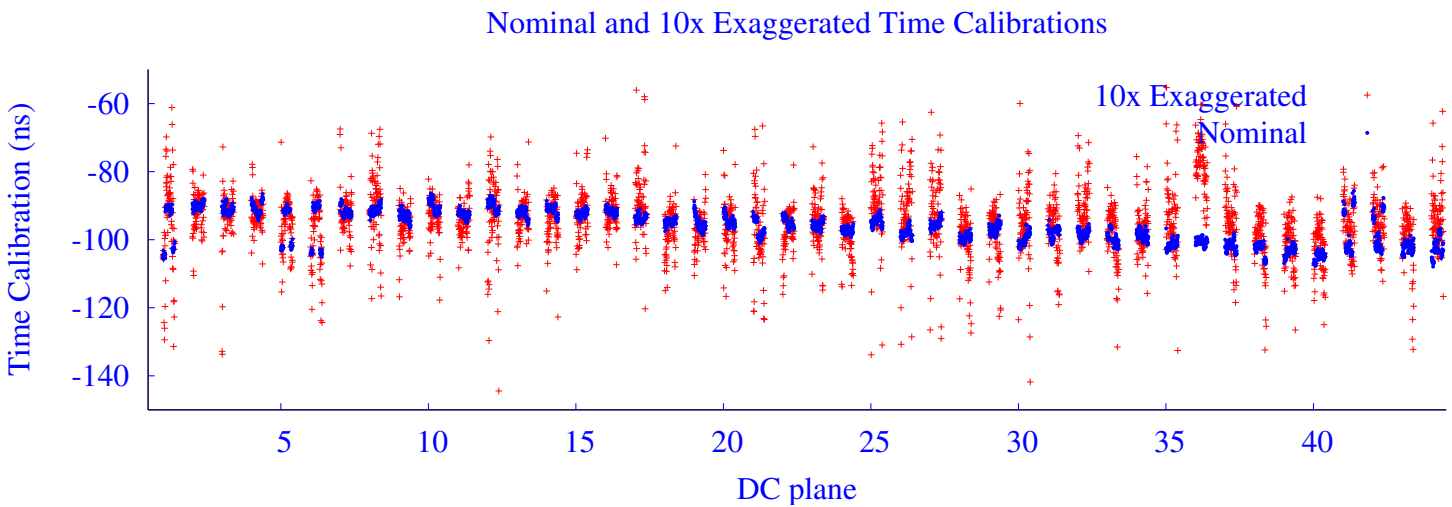
$$\epsilon_{sys}^{tot} = \sqrt{\sum_i (\epsilon_{sys}^i)^2} = \sqrt{\sum_i \frac{\sigma_i^2}{R_i^2} S_i^2} \tag{5}$$

- sensitivity measurement S_i, is difference in muon decay parameter for an ...
- ... exaggerated change R_i in an effect
- RMS change in an effect in data σ_i
- scale factor R_i/σ_i

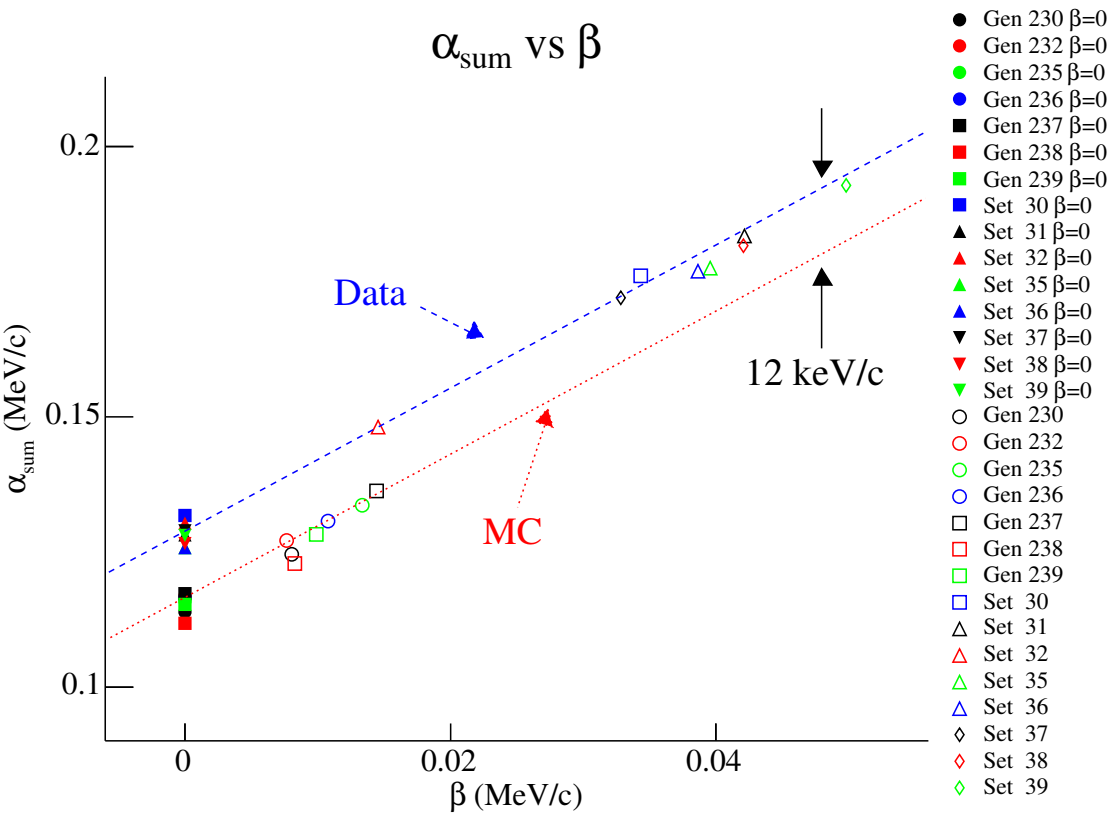


Time Calibration Systematic Uncertainty

- Sensitivity from fit of spectra from data analyzed with different calibration files:
  - nominal
  - offset by $10 \times \sigma_i$
- measure $S_i = (8.9 \pm 2.3) \times 10^{-3}$, 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

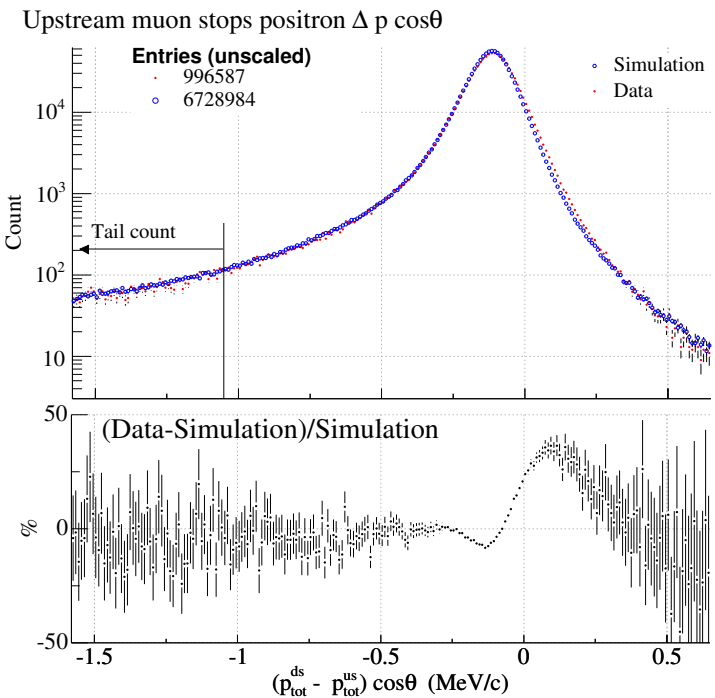


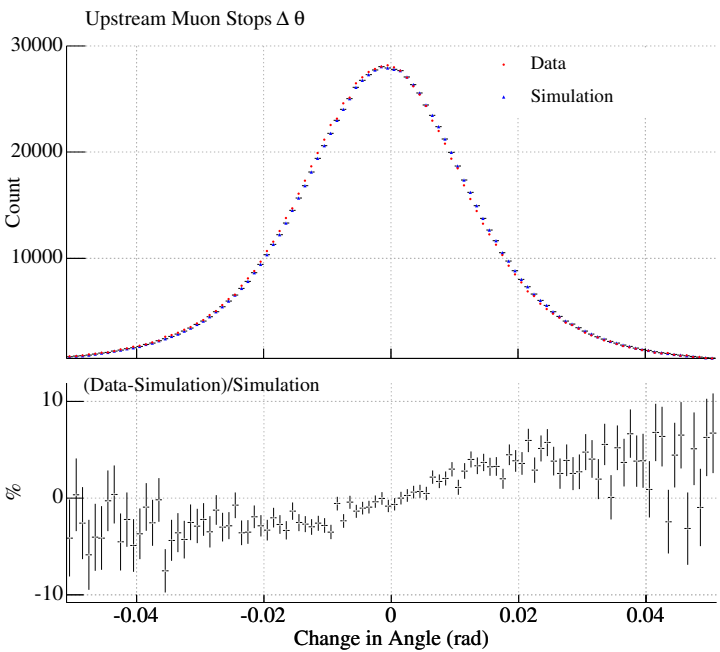
Energy Calibration Correlations



GEANT Validation

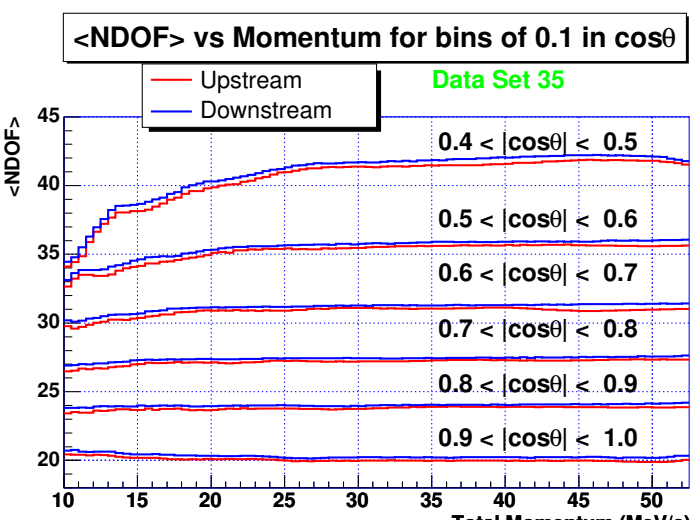
- From fits to two halves of decay positrons from far upstream stops
- Discrepancy in tails in momentum of 4%, and in θ of 8%
- Overall 5% discrepancy in hard interactions

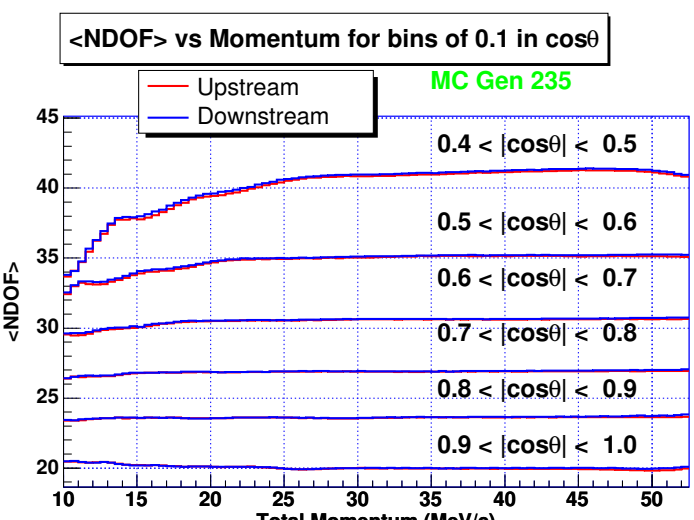




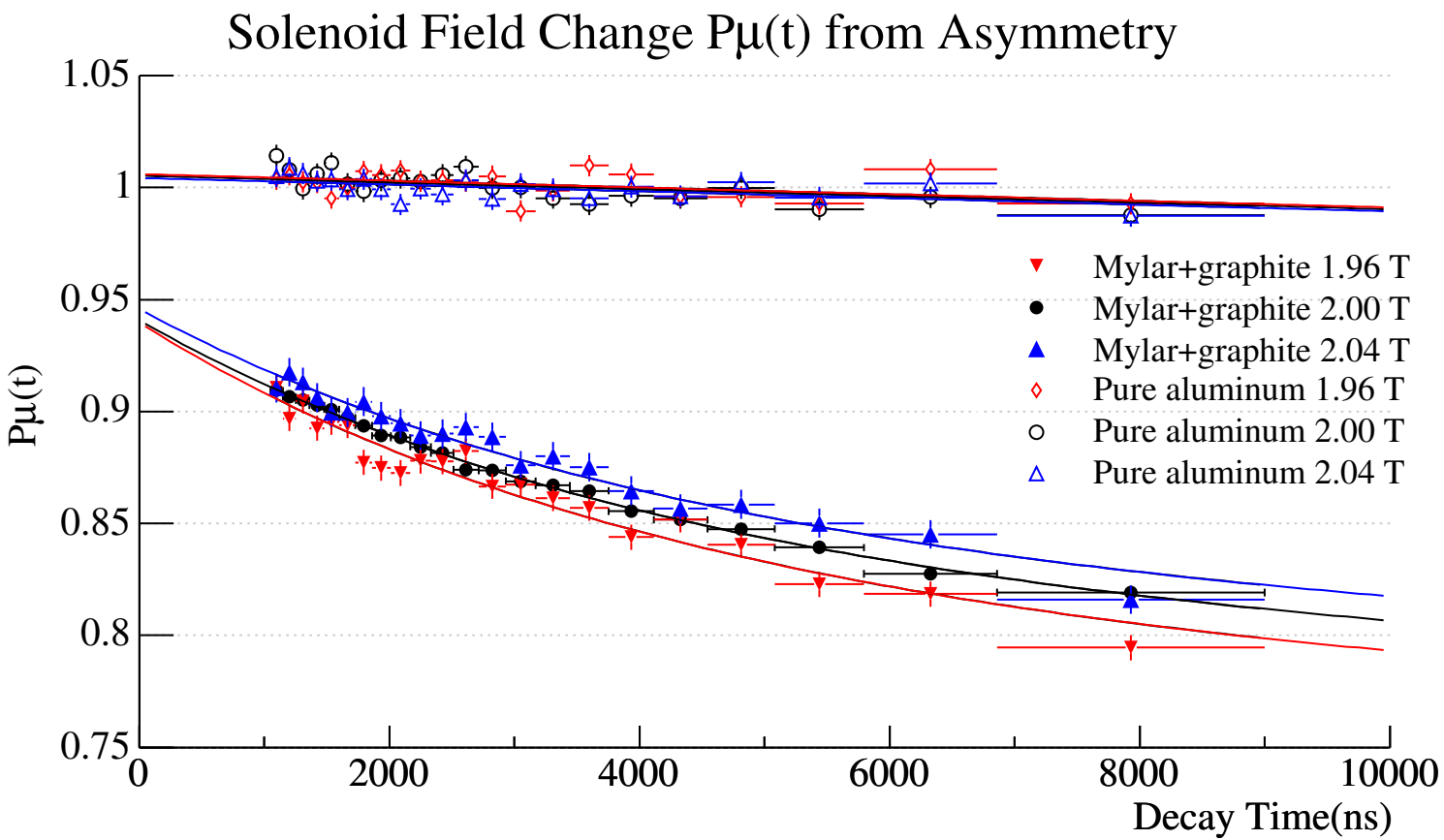
Upstream-Downstream Efficiency

- 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}





Material Depolarization, Solenoid Field Change



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