*TWIST**: Precision Measurement of the Muon Decay Parameters

***TRIUMF Weak Interaction Symmetry Test**

Standard Model Tests and Fundamental Symmetries Session

International Nuclear Physics Conference

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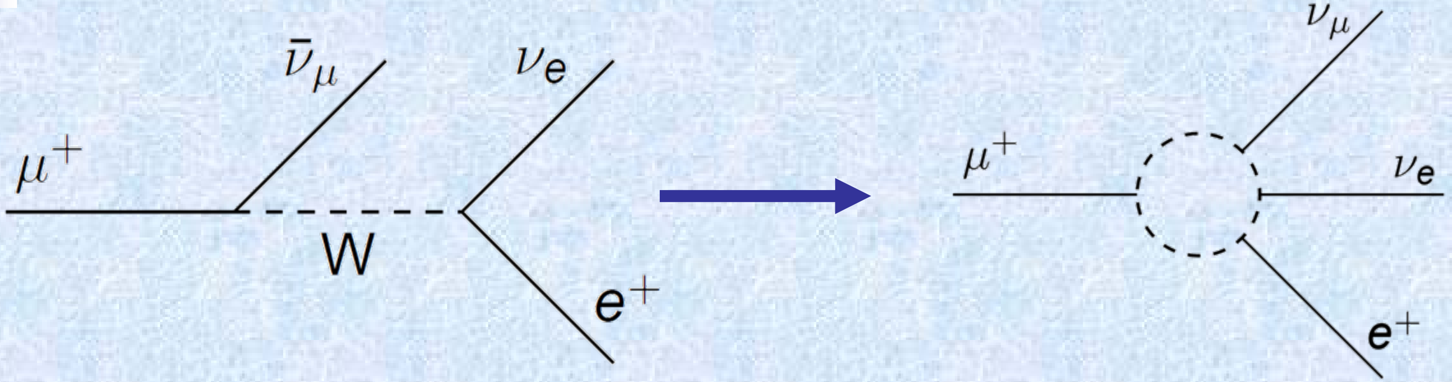
on behalf of the *TWIST* collaboration

Muon decay formalism



- Assume a four-fermion interaction that is:
  - local, derivative-free, lepton-number-conserving
  - Allows scalar, vector, or tensor; left or right
- Description of Fetscher and Gerber (see PDG):

Fetscher, Gerber and Johnson, Phys. Lett. B173 (1986) 102-106

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

Coupling constants

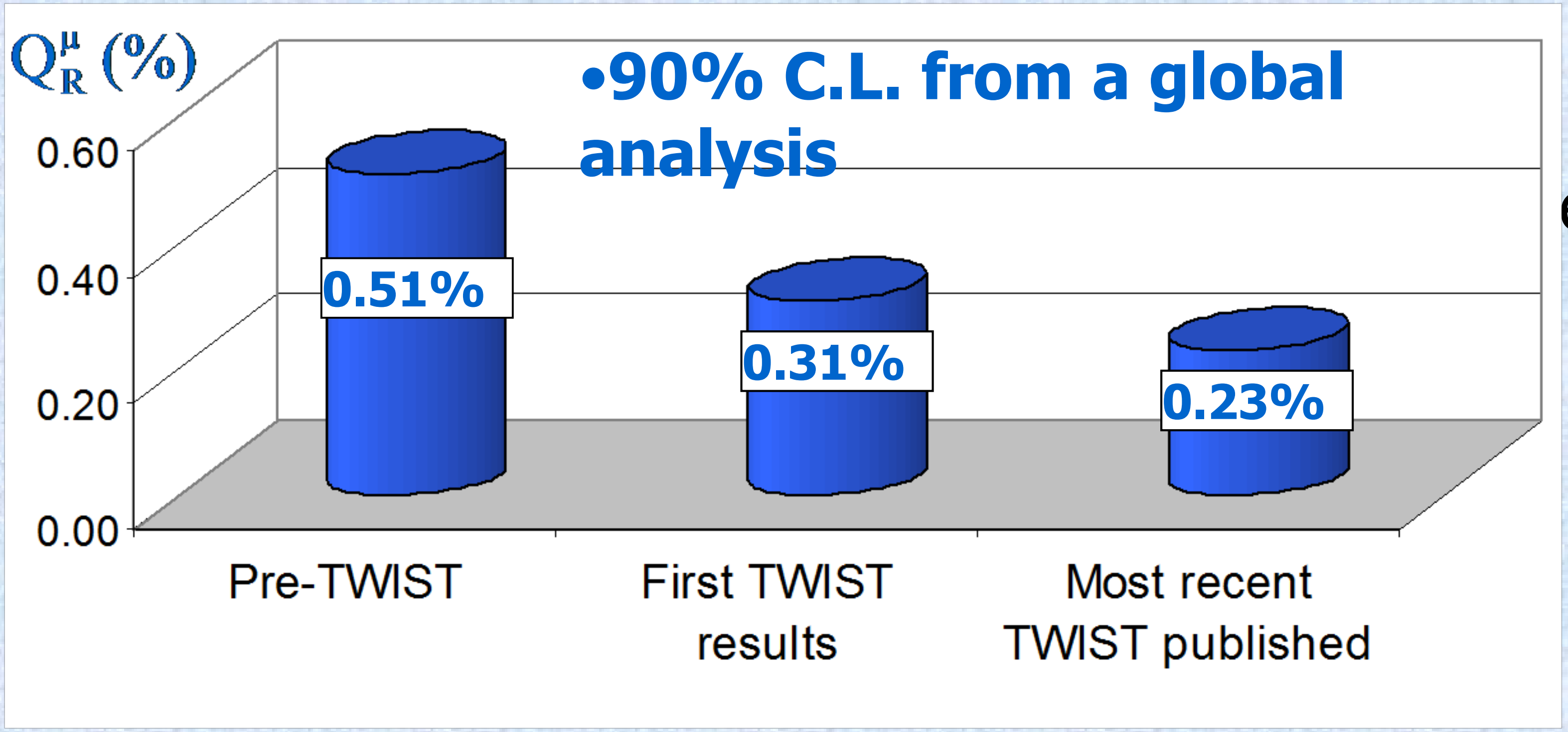
- PDG limits on all couplings (pre *TWIST*):

  (in parentheses, Gagliardi *et al.*, PRD **72**, 073002 (2005))

$$|g^S_{RR}| < 0.066(0.067) \qquad |g^V_{RR}| < 0.033(0.034) \qquad |g^T_{RR}| \equiv 0$$

$$|g^S_{LR}| < 0.125(0.088) \qquad |g^V_{LR}| < 0.060(0.036) \qquad |g^T_{LR}| < 0.036(0.025)$$

- ess



Muon parameter description

- Muon decay (Michel) parameters **ρ, η, $P_\mu\xi$, δ**:
  muon differential decay rate *vs.* energy and angle:

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

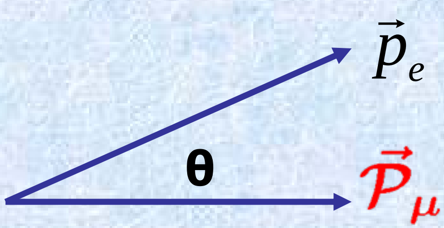
Very important ↗

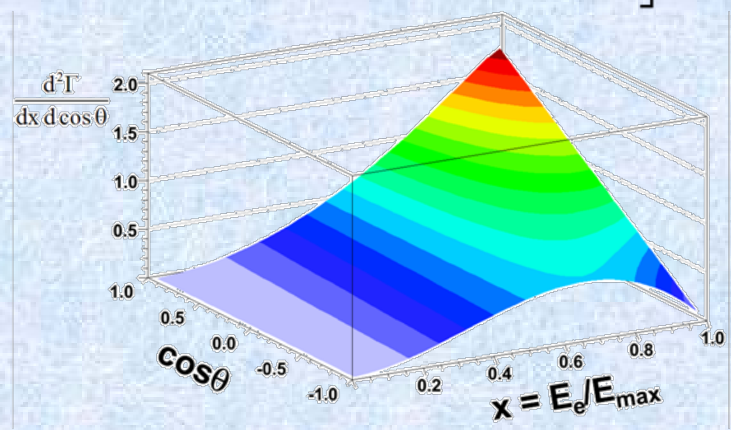
where

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

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

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





Pre- *TWIST* decay parameters

- From the Review of Particle Physics

		Year	SM
η	= -0.007 ± 0.013	1985	0.00
ρ	= 0.7518 ± 0.0026	1969	0.75
δ	= 0.7486 ± 0.0026 ± 0.0028	1988	0.75
$\mathbf{P}_\mu\xi$	= 1.0027 ± 0.0079 ± 0.0030	1987	1.00
$\mathbf{P}_\mu(\xi\delta/\rho)$	> 0.99682 (90% CL)	1986	1.00

The goal of *TWIST* is to find any
new physics that may be revealed
by improving the precision of each of the
muon decay parameters ρ, δ, and $\mathbf{P}_\mu\xi$
by at least one order of magnitude.

Physics data sets

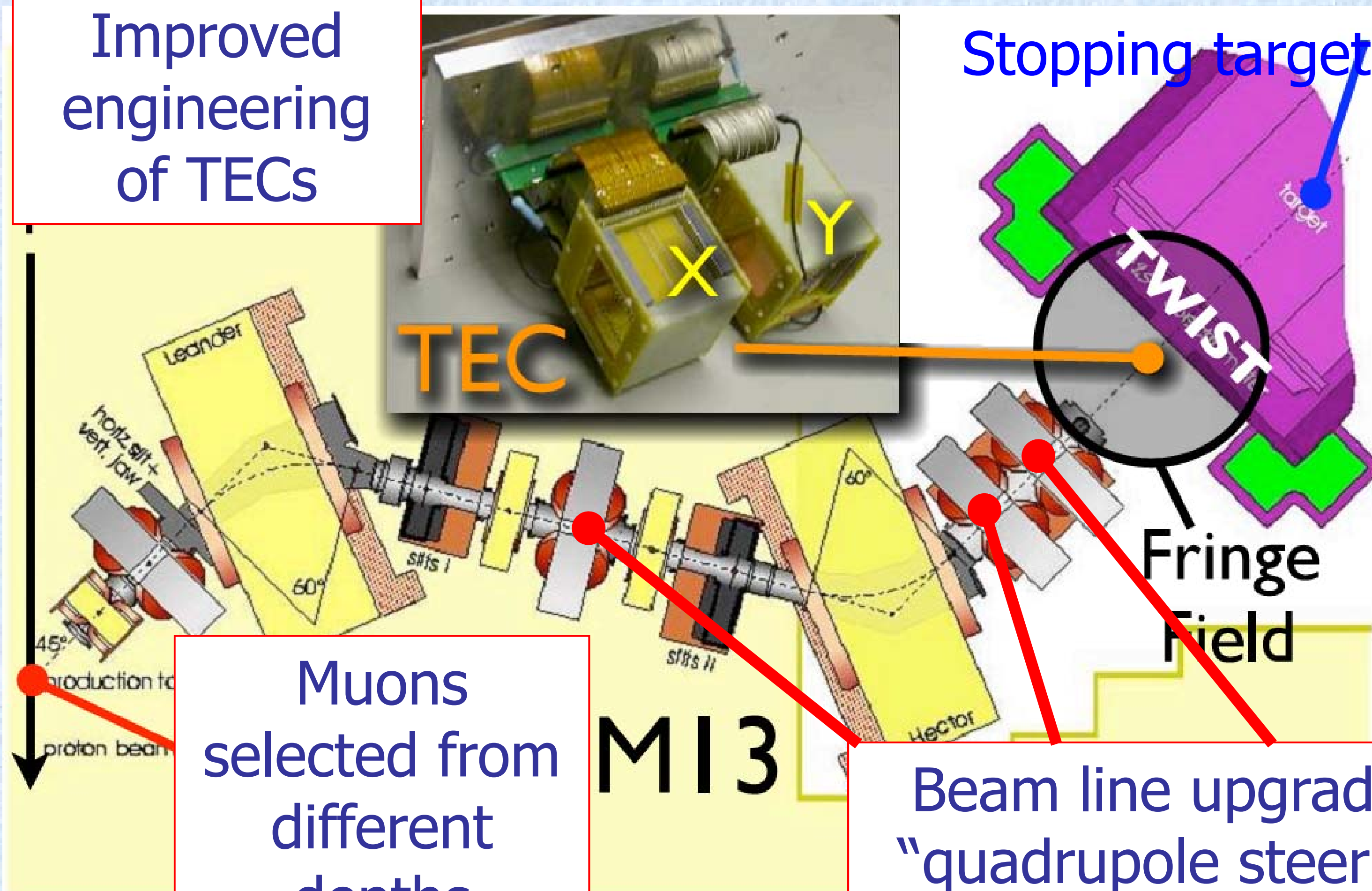
- Fall 2002
  - Test data-taking procedures and develop analysis techniques
  - First physics results – **ρ** and **δ**
  - Graphite-coated Mylar target not suitable for $P_\mu\xi$

- Fall 2004
  - Aluminum target and Time Expansion Chamber enabled first $P_\mu\xi$ measurement
  - Improved determinations of **ρ** and **δ**

- 2006-07
  - Both Ag (2006) and Al (2007) targets (1.1×10^{10} events)
  - Ultimate *TWIST* precision for **ρ**, **δ**, and $P_\mu\xi$
  - Also measured negative muon decay-in-orbit when bound to Al

Muon production and transport

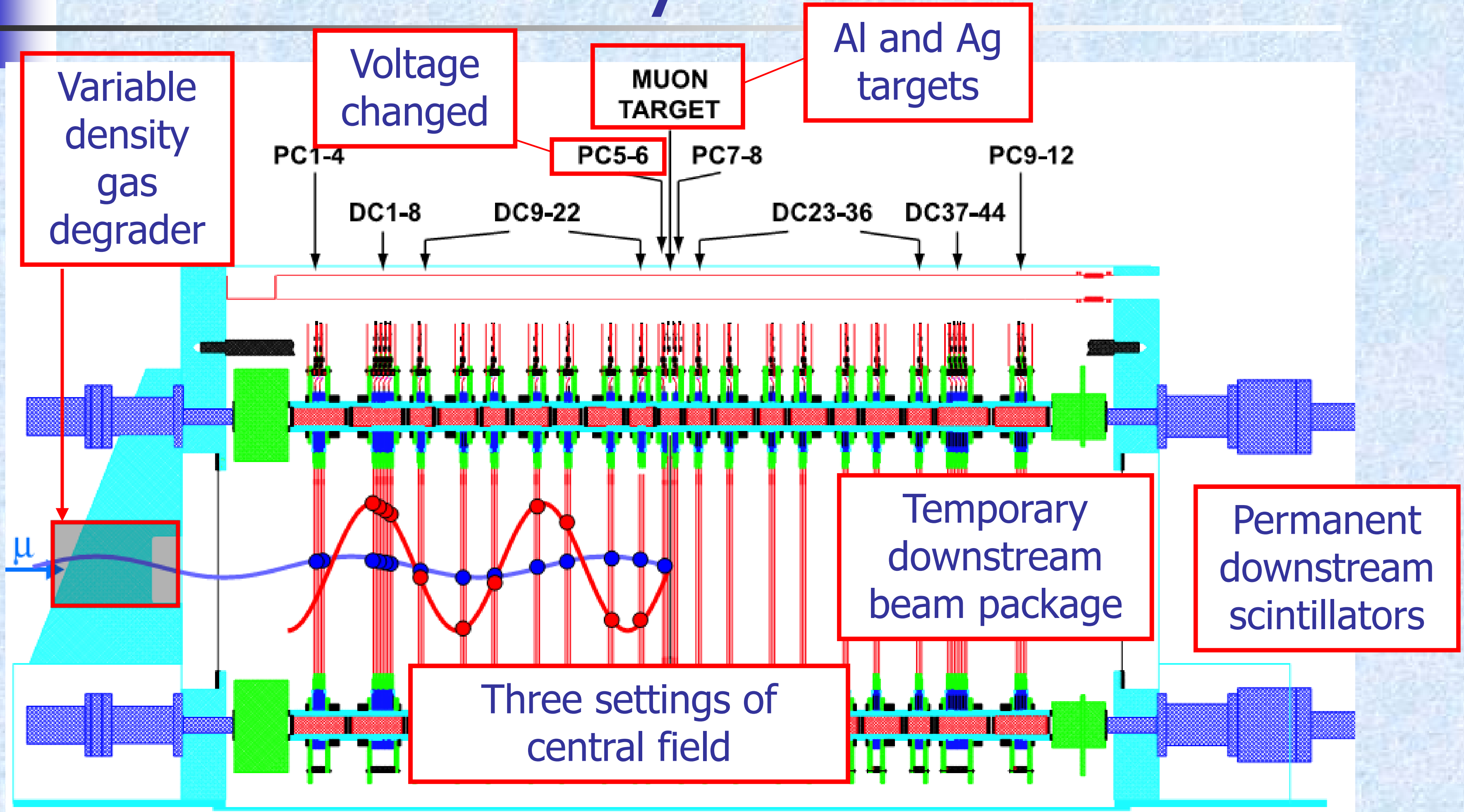
Improved engineering of TECs



Muons selected from different depths

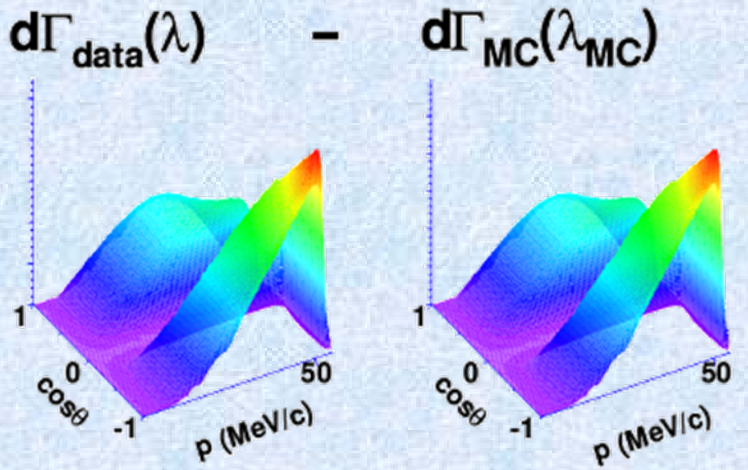
Beam line upgraded: "quadrupole steering" added

Detector array



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

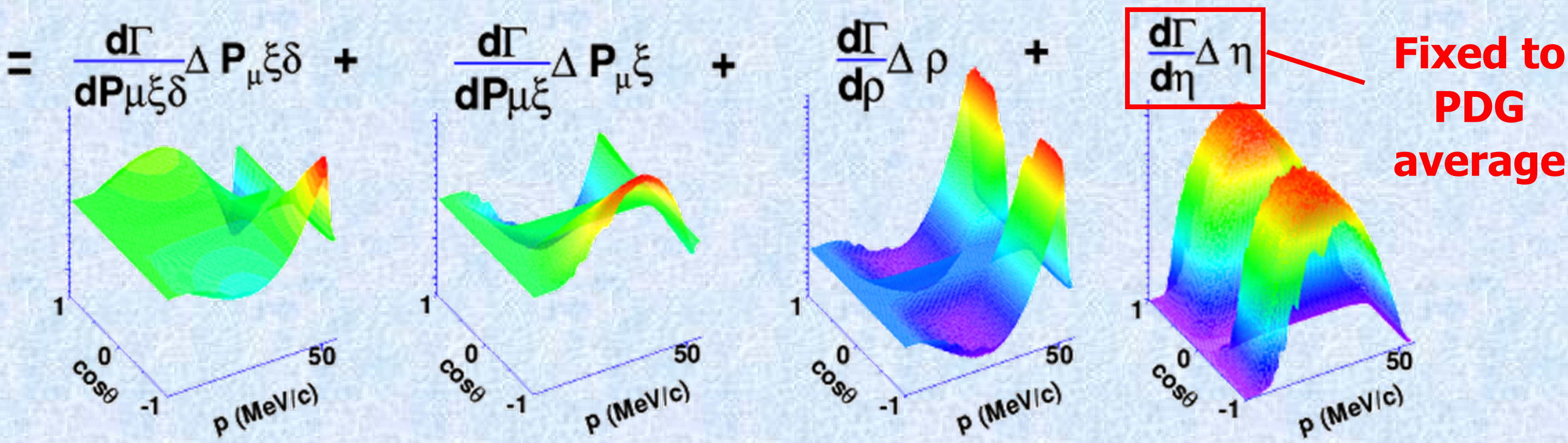
Analysis: fit to simulation (MCfit)



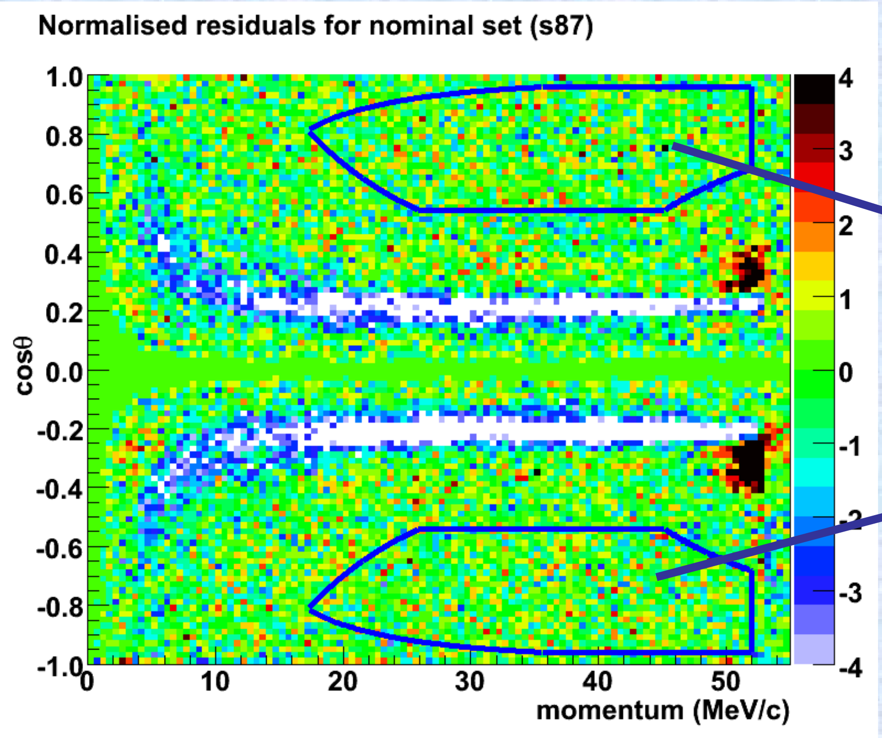
- We fit data minus simulation
- Spectrum is linear in

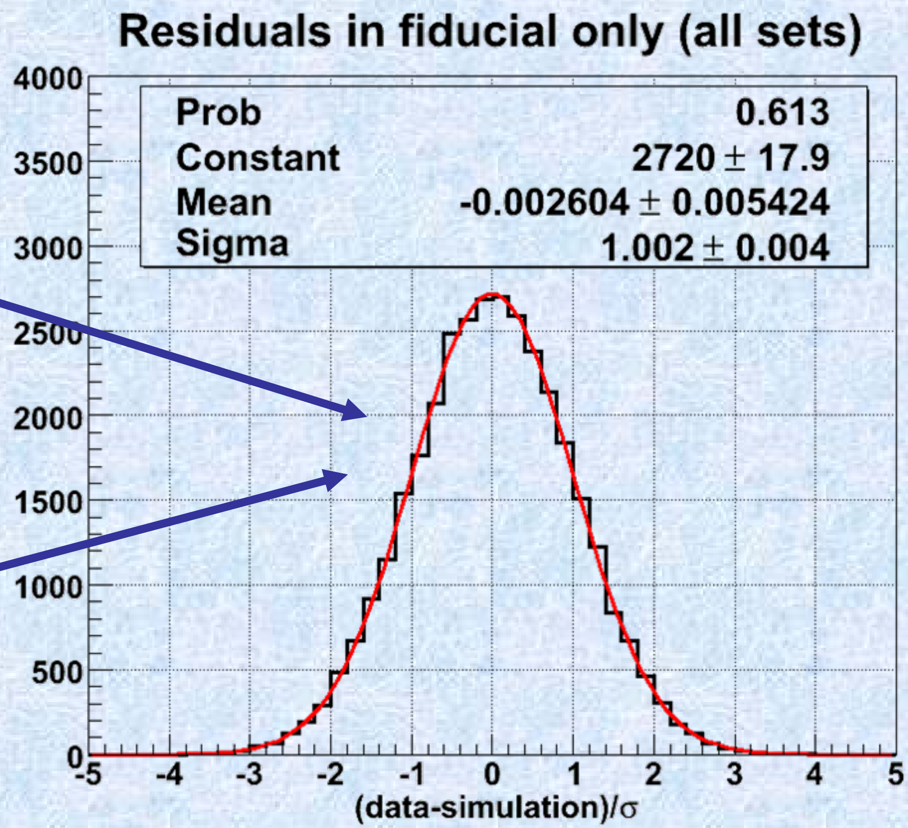
  $P_\mu \xi$, $P_\mu \xi\delta$, ρ, η

- Differences from hidden parameters are measured.



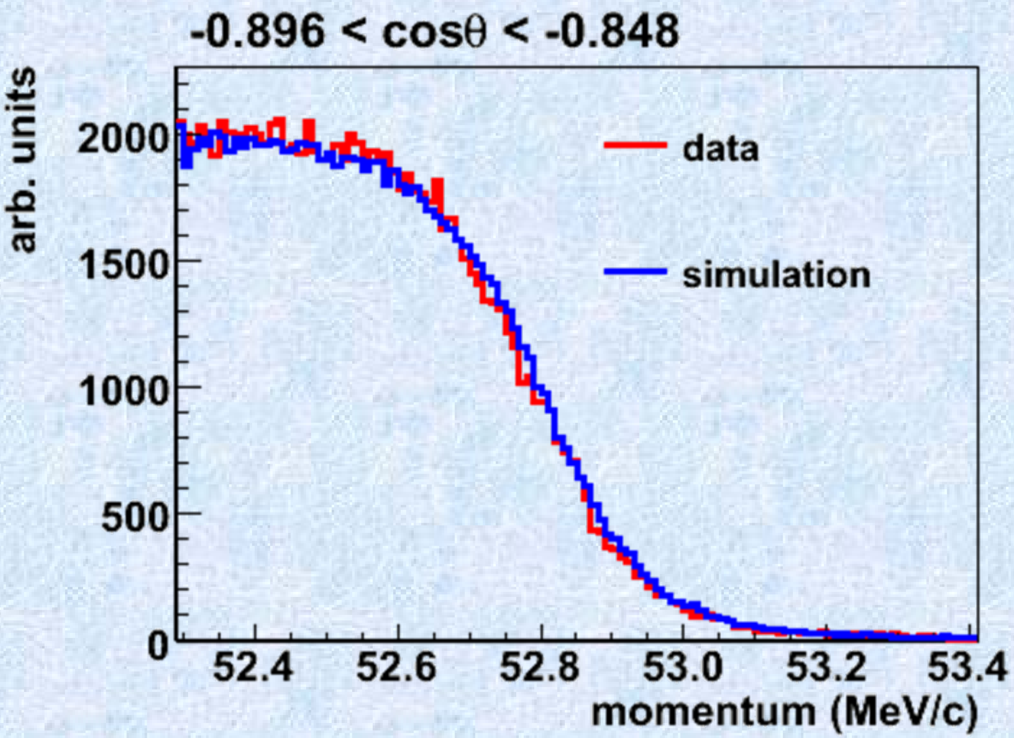
Spectrum fit quality





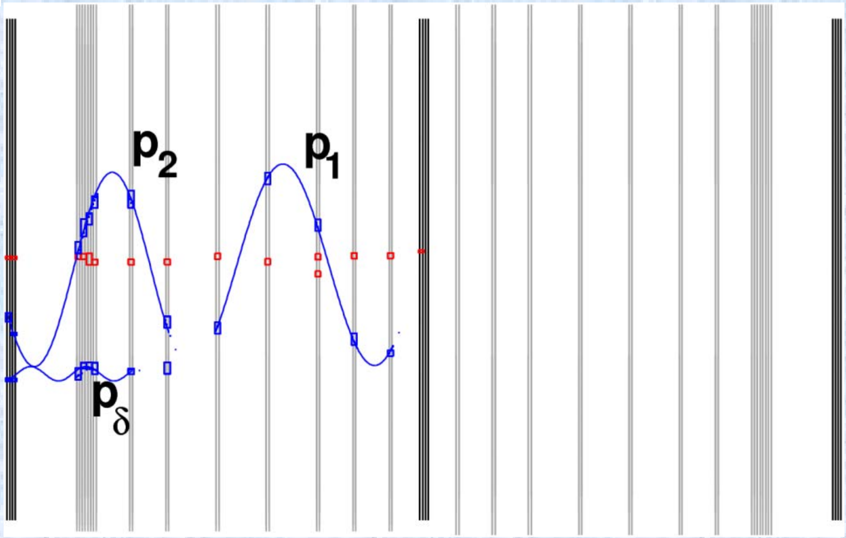
- Excellent fit quality over (p,cos**θ**) fiducial region: p < 52.0 MeV/c, 0.54 < cos**θ** < 0.96, 10.0 MeV/c < p_T < 38.0 MeV/c, $|p_z|$ > 14.0 MeV/c

Momentum calibration



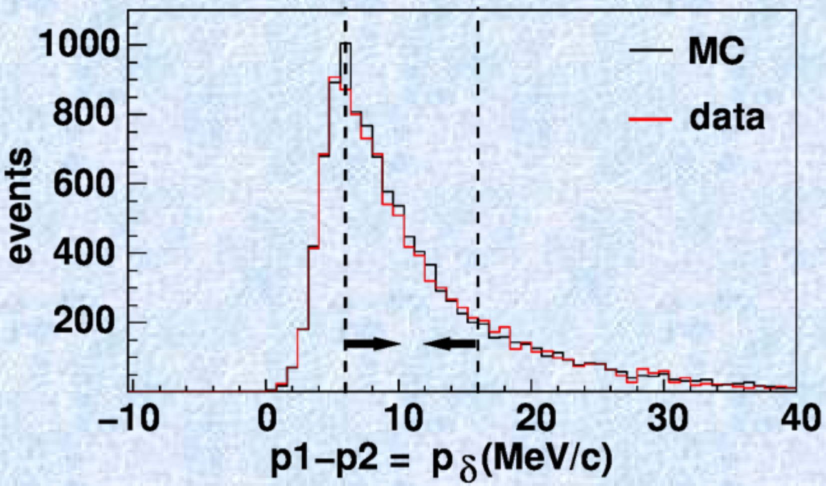
- Use kinematic edge at 52.8 MeV/c: energy loss and planar geometry lead to cosθ dependence.
- Difference of ~10 keV/c prior to calibration.
- Calibration at edge provides no guidance on how to propagate the difference to lower momenta in the spectrum.

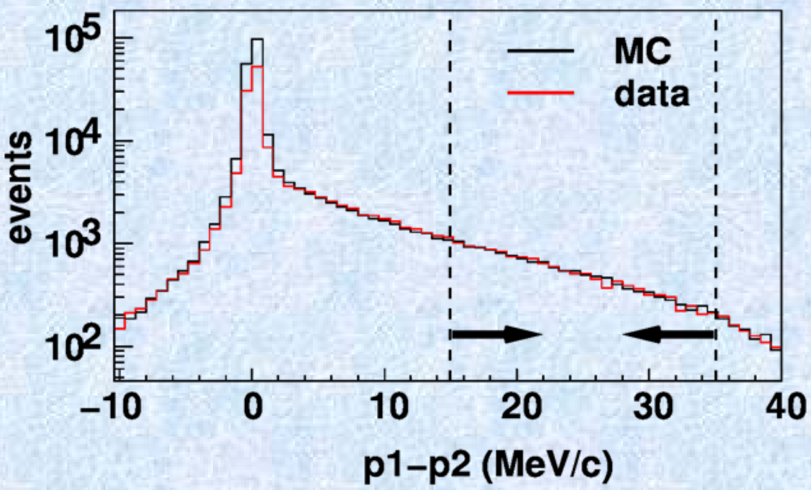
Positron interactions



"Broken tracks" analysis:
$2e^+$, 1 e^- ≡ δ-electron
2 e^+ ≡ Bremsstrahlung

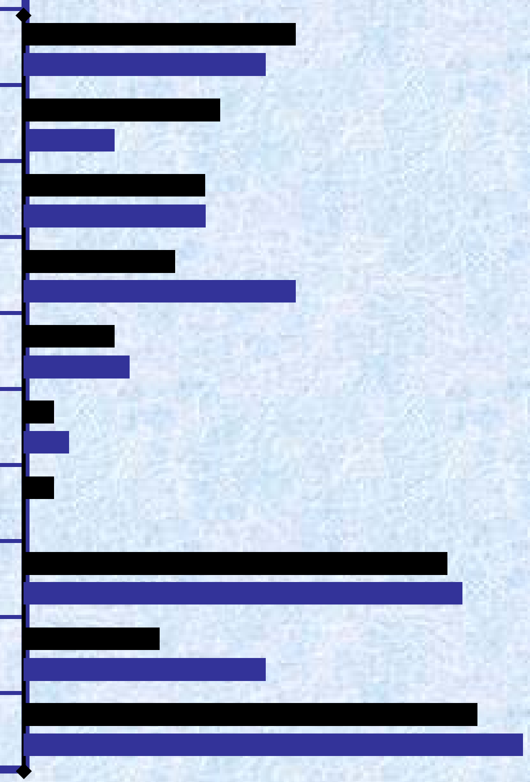
Agreement of data and sim:
δ -electrons < 1%
Bremsstrahlung differs by 2.4%





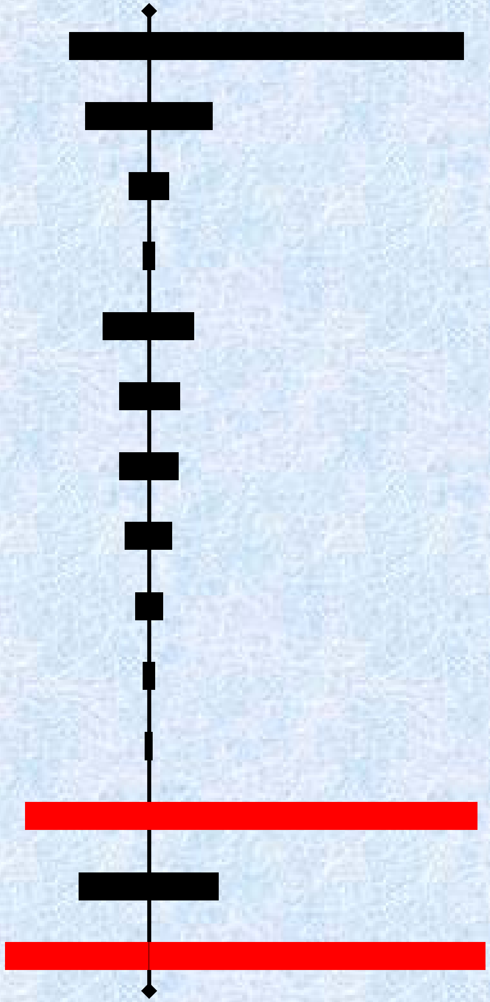
Improved ρ and δ uncertainties

Uncertainties	ρ (×10^{-4})	δ (×10^{-4})
Positron interactions	**1.8**	**1.6**
External uncertainties	**1.3**	**0.6**
Momentum calibration	**1.2**	**1.2**
Chamber response	**1.0**	**1.8**
Resolution	**0.6**	**0.7**
Spectrometer alignment	**0.2**	**0.3**
Beam stability	**0.2**	**0.0**
Systematics in quadrature	***2.8***	***2.9***
Statistical uncertainty	**0.9**	**1.6**
Total uncertainty	***3.0***	***3.3***



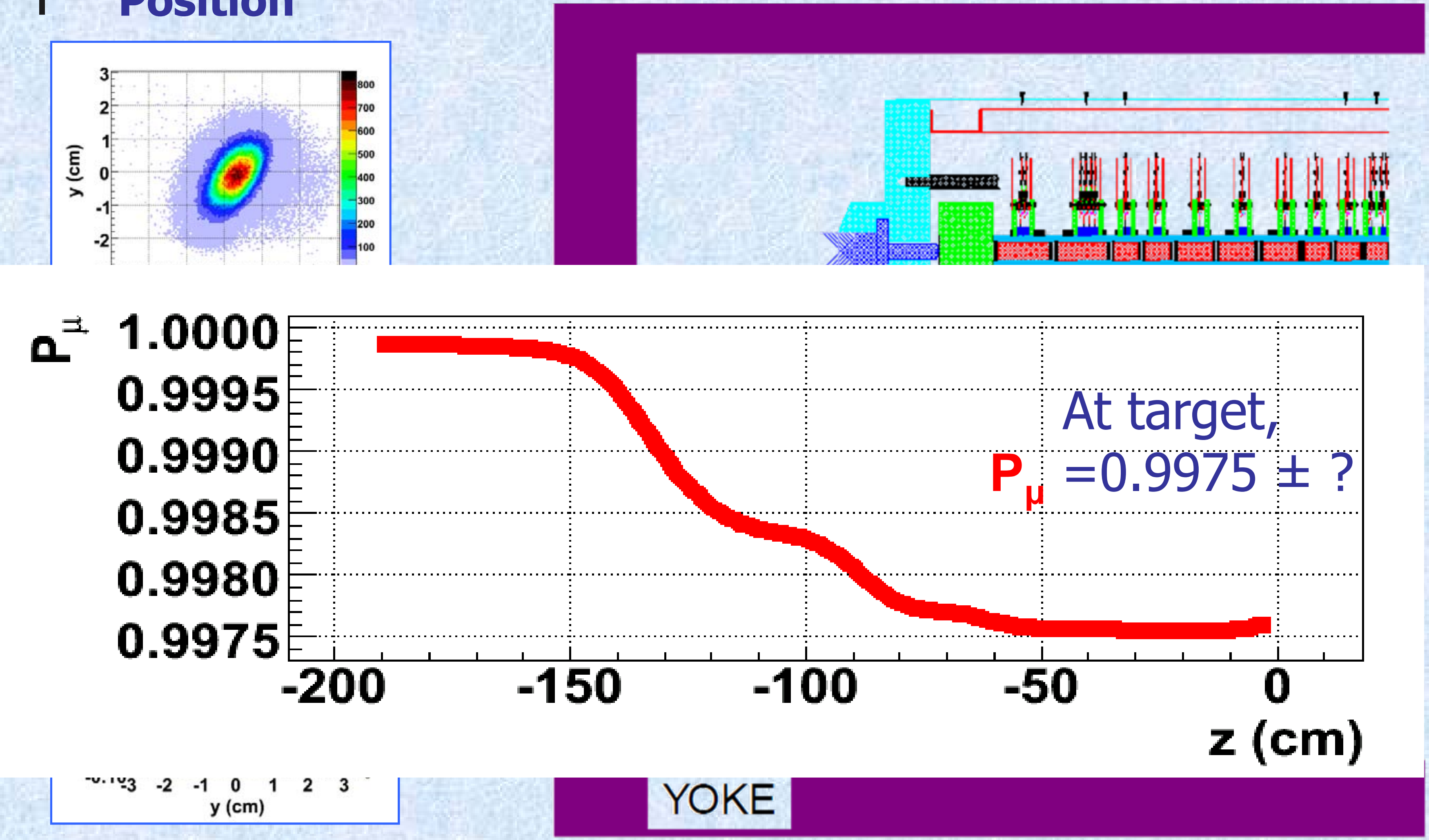
Improved $P_\mu\xi$ uncertainties

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

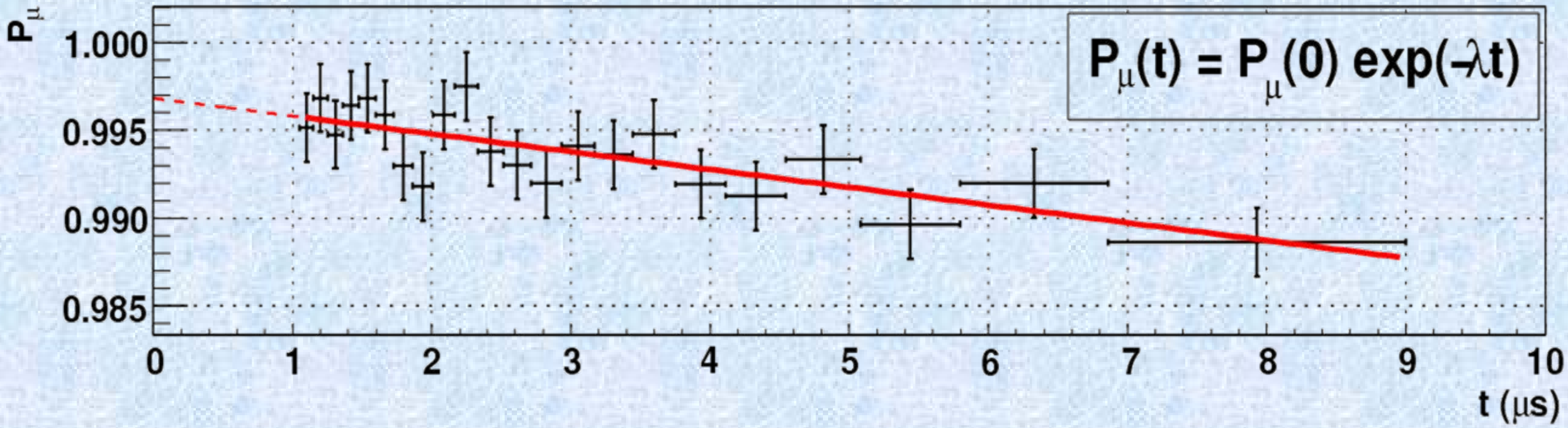


Fringe field, solenoid entrance

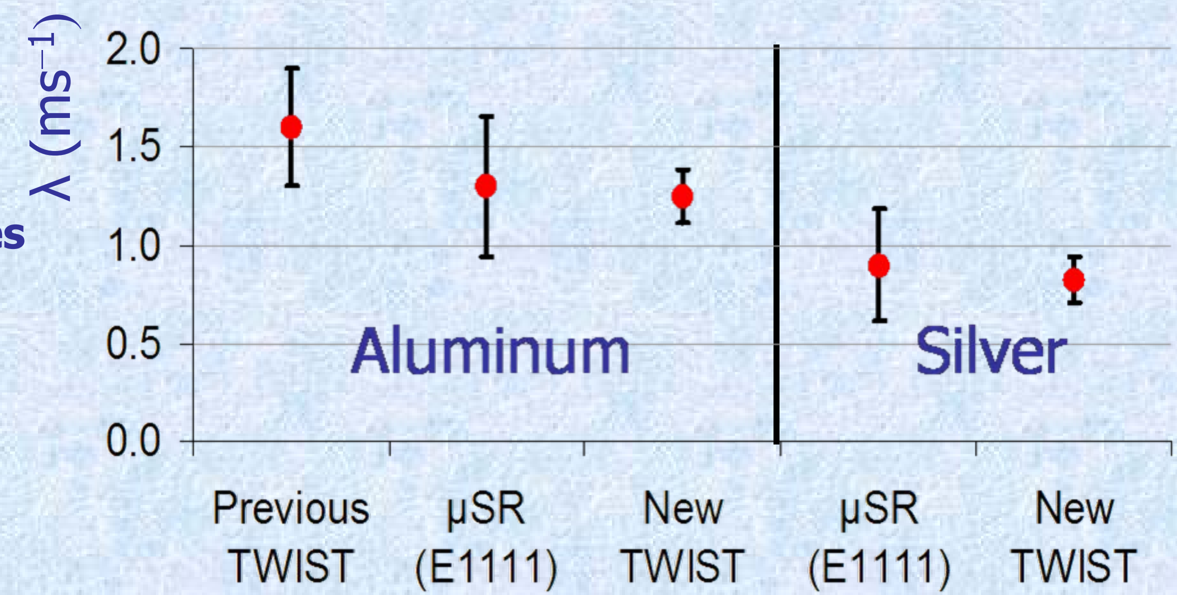
Position



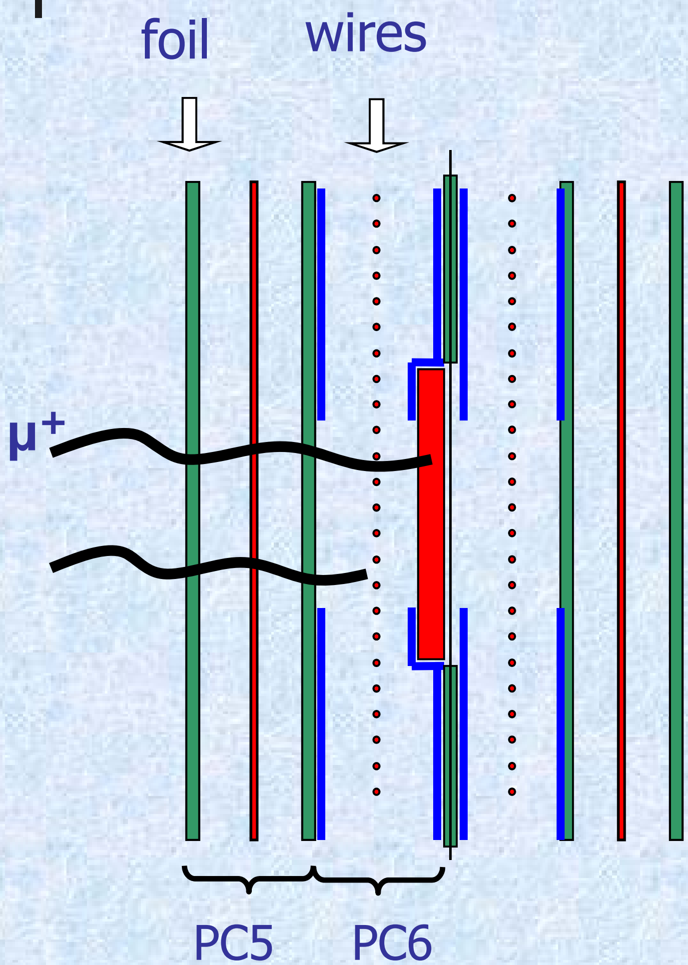
Depolarization in target material

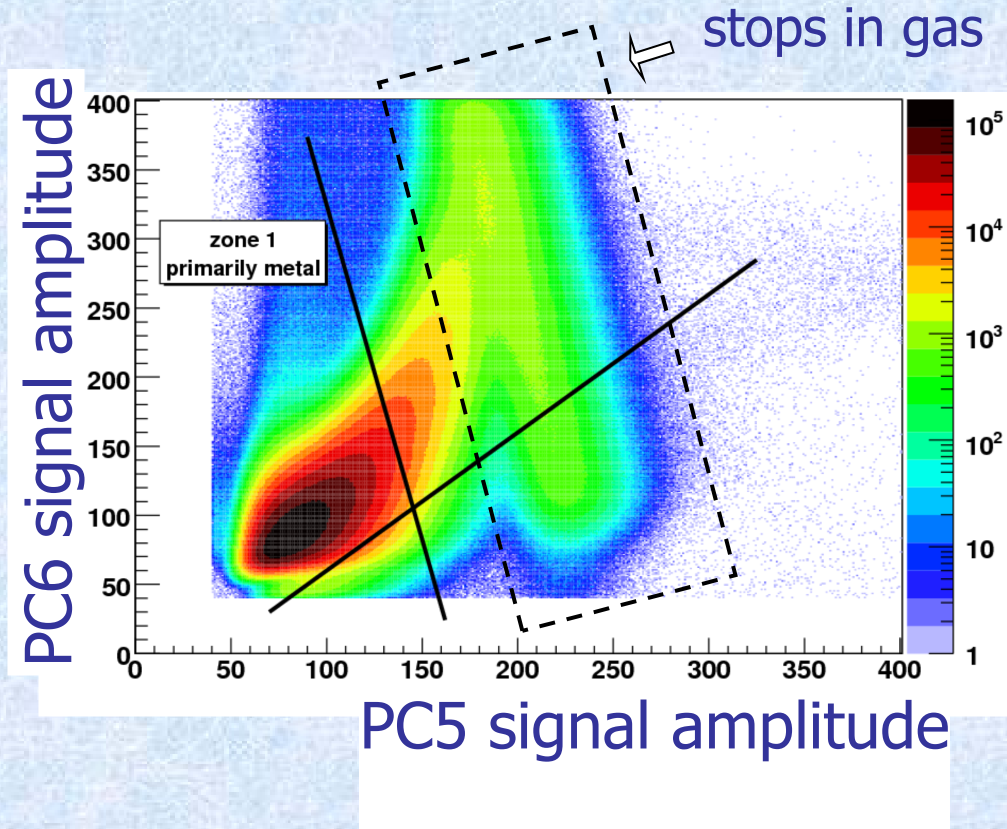


- Estimate of relaxation is included in simulation; correction is made to polarization parameter.
- μSR experiment establishes no fast relaxation.
- Statistical uncertainty in λ is included in decay parameter statistical uncertainty.



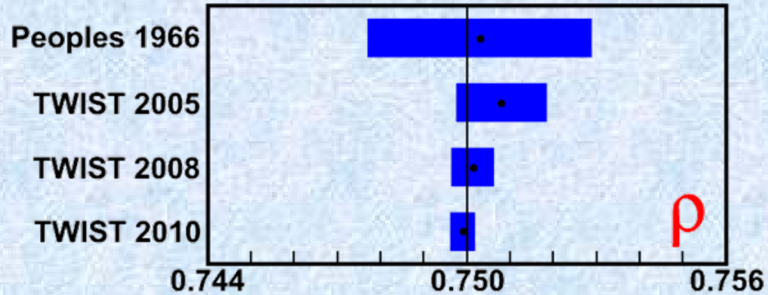
Selecting muons in metal target



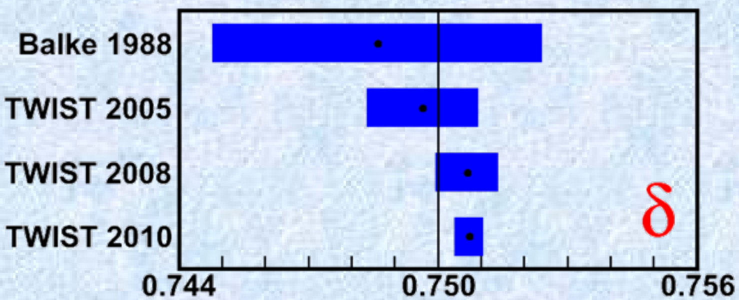


Place cut on 2-d distribution so that <0.5% of "stops in gas" contaminate "stops in target" region (zone 1).

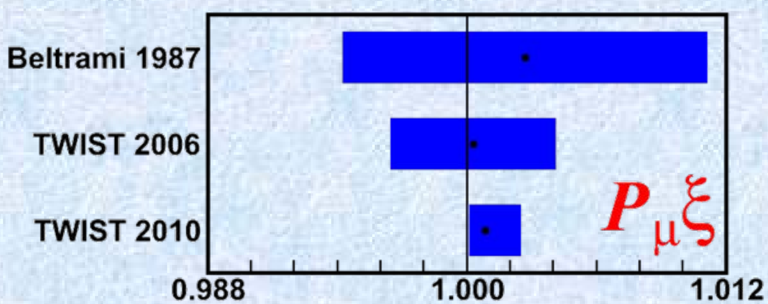
Comparisons with previous results



ρ = 0.74991 ± 0.00009 (stat) ± 0.00028 (syst)



δ = 0.75072 ± 0.00016 (stat) ± 0.00029 (syst)



$P_\mu \xi$ = 1.00084 ± 0.00035 (stat) $^{+0.00165}_{-0.00063}$ (syst)

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 (P. Herczeg, Phys. Rev. D 34, 3449 - 3456 (1986))
  Use notation: $t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \quad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}, \quad \zeta_g^2 = \frac{g_R^2}{g_L^2}\zeta^2$
- Then, for muon decay, the muon decay parameters are modified:

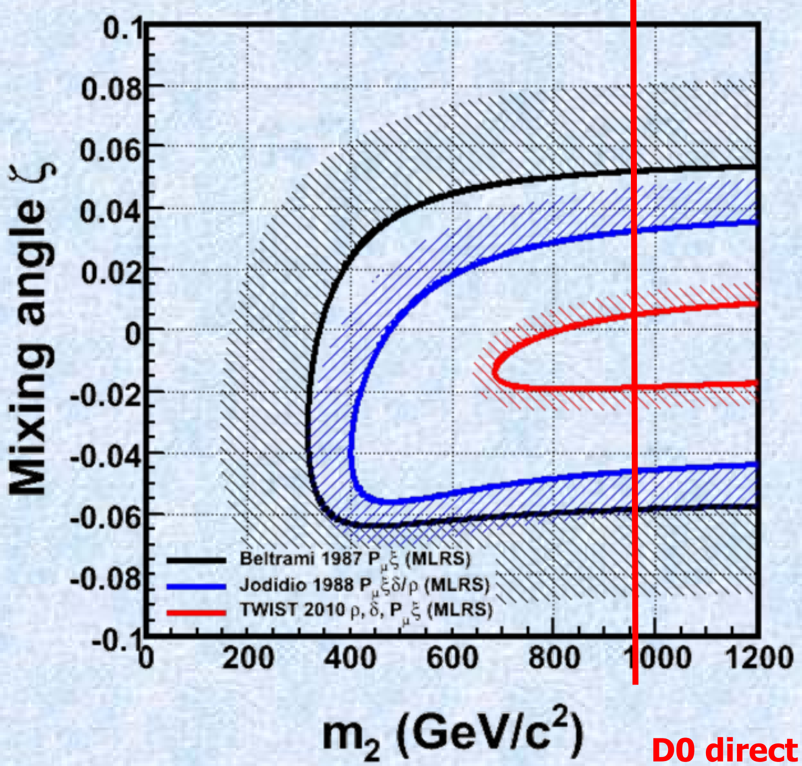
$$\rho = \frac{3}{4}(1 - 2\zeta_g^2), \quad \delta = \frac{3}{4}, \quad \xi = 1 - 2(t^2 + \zeta_g^2),$$

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

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

LRS parameters from muon decay

Restricted ("manifest") LRS
Preliminary ($P_\mu \xi \delta / \rho$)

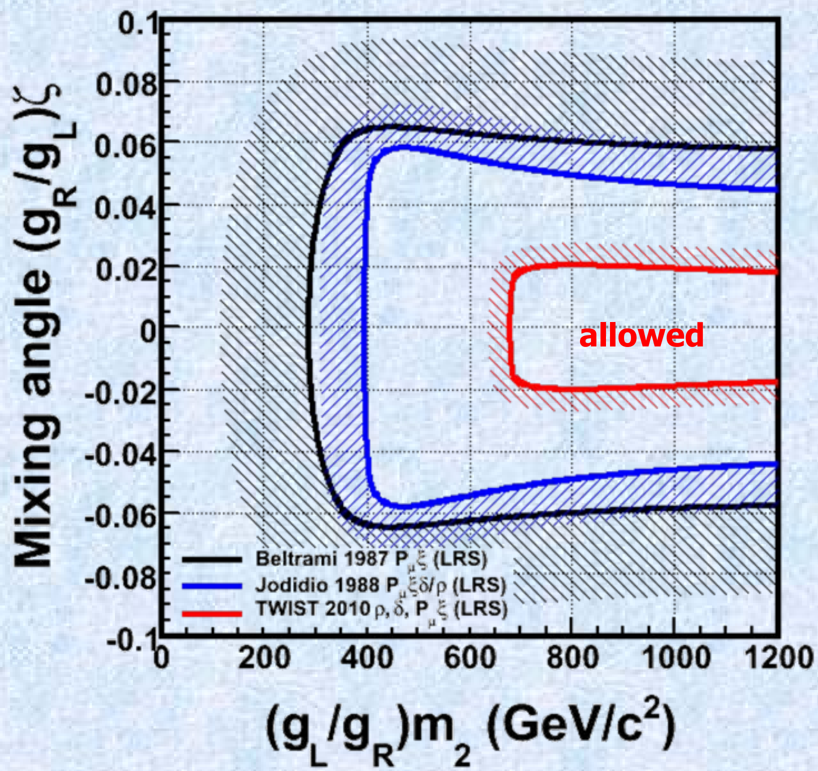


D0 direct search lower limit (95% CL)
Phys. Rev. Lett. 100, 031804 (2008)

$m_2 > 684$ GeV/c^2

$-0.019 < \zeta < +0.010$

General LRS
Preliminary ($P_\mu \xi \delta / \rho$)



$(g_L/g_R)m_2 > 684$ GeV/c^2

$-0.020 < (g_R/g_L)\zeta < +0.020$

Are these results final?

- **Combine: $P_\mu \xi \delta / \rho$ = 1.00192 $^{+0.00167}_{-0.00066}$**

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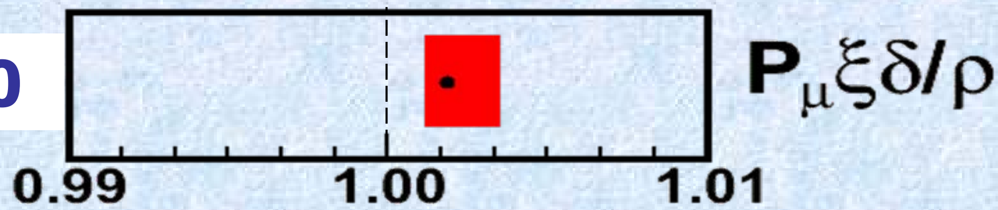

  - **result is 2.9 σ above "physical" limit of 1.0 from matrix element constraints, using correlations for three parameters**
  - **$P_\mu \xi \delta / \rho$ greater for Ag target than Al target**
  - **many possible sources of error were checked and rejected**
  - **muon stopping location in data *vs.* simulation appears to be leading candidate; affects mostly ρ and δ**
  - **physics interpretations must be considered *preliminary***
    - **LRS result will change slightly, Q^μ_R will be sensitive**

TWIST Participants

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