The TRIUMF Weak Interaction Symmetry Test

Glen Marshall, TRIUMF (for the *TWIST* Collaboration)

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Outline

- Physics of muon decay
- The muon beam and the *TWIST* spectrometer
- Analysis strategies
- Estimation of systematic uncertainties
- Results for decay parameters ρ, δ, and $\mathcal{P}_\mu\xi$

Decay parameters

L. Michel

- Muon decay parameters ρ, η, $\mathcal{P}_\mu\xi$, δ
  - muon differential decay rate *vs.* energy and angle:

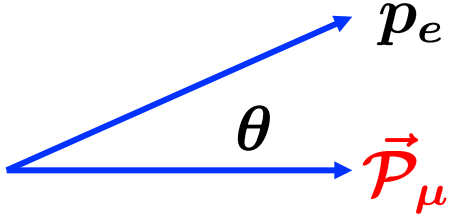
$$\frac{d^2\Gamma}{dx\ d\cos\theta} = \frac{1}{2\pi^3} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2}\cdot \{\mathcal{F}_{IS}(x,\rho,\eta) \pm \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

  - where

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

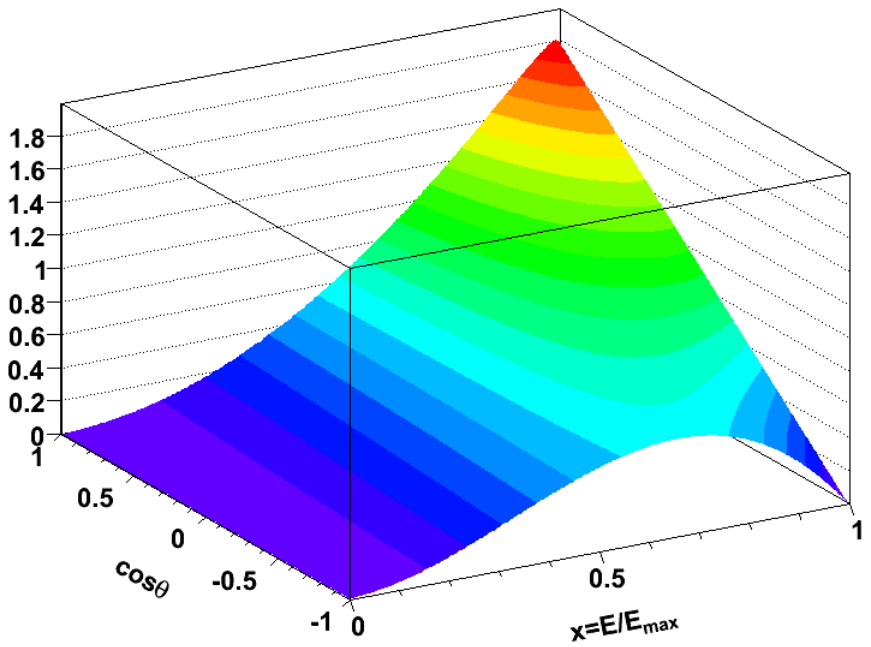
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right]$$

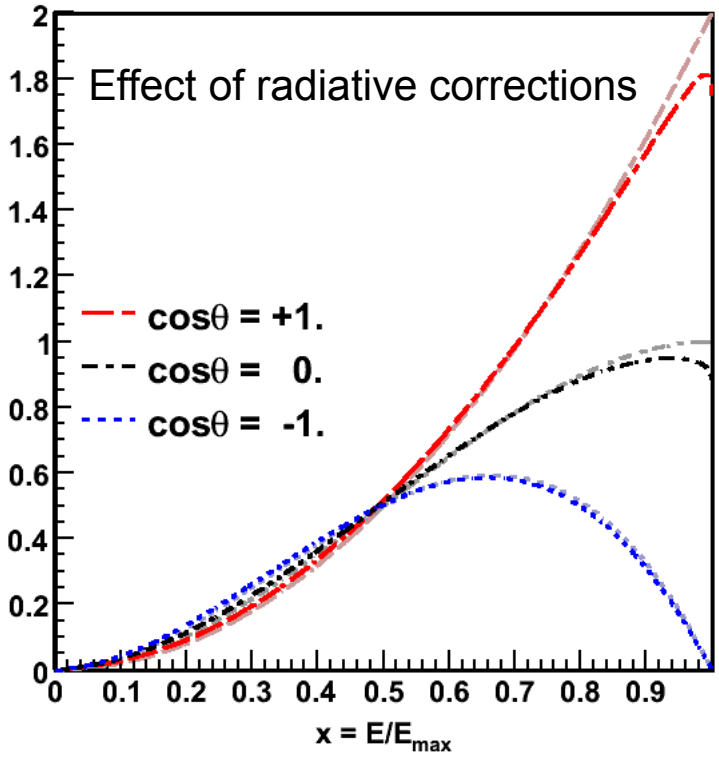
and $W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$, $x = \frac{E_e}{W_{\mu e}}$, $x_0 = \frac{m_e}{W_{\mu e}}$.



L. Michel, Proc. Phys. Soc. A63, 514 (1950).
C. Bouchiat and L. Michel, Phys. Rev. 106, 170 (1957).
T. Kinoshita and A. Sirlin, Phys. Rev. 107, 593 (1957).
T. Kinoshita and A. Sirlin, Phys. Rev. 108, 844 (1957).

Spectrum shape and radiative corrections

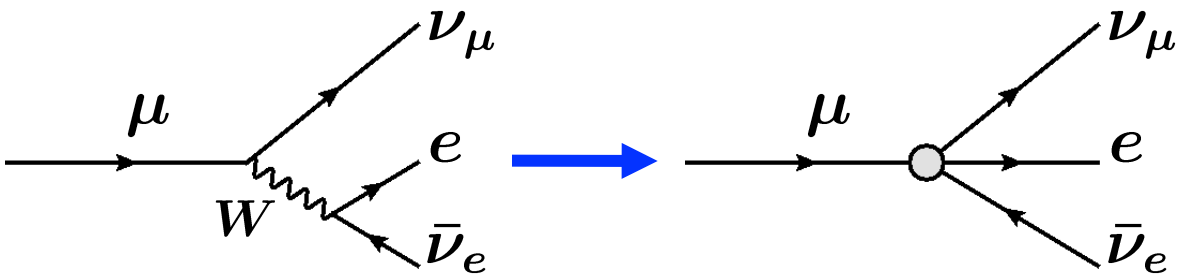




- Full $\mathcal{O}(\alpha)$ radiative corrections with exact electron mass dependence.
- Leading and next-to-leading logarithmic terms of $\mathcal{O}(\alpha^2\mathcal{L}^2)$ and $\mathcal{O}(\alpha^2\mathcal{L})$, $\mathcal{L}=ln((m_\mu/m_e)^2)$
- Leading logarithmic terms of $\mathcal{O}(\alpha^3\mathcal{L}^3)$.
- Ignores $\mathcal{O}(\alpha^2\mathcal{L}^0)$ (2007).

K. Melnikov, J. High Energy Phys. (09):014 (2007)
A. Arbuzov, J. High Energy Phys. (03):063 (2003)
A. Arbuzov et al., Phys. Rev. D66, 93003 (2002)
A. Arbuzov et al., Phys. Rev. D65, 113006 (2002)

Matrix elements



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

- General local, Lorentz-invariant, lepton-number conserving interaction.
- Scalar, vector, tensor (Γ^S,Γ^V,Γ^T) interactions, left and right μ, e
- Decay parameters are bilinear combinations of $g^{\gamma}_{\varepsilon\mu}$.
- Probability for decay of μ–handed muon to ε–handed electron:

$$Q_{\varepsilon\mu} = \frac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1-\delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2$$

- RH coupling in μ decay in terms of decay parameters:

$$Q^\mu_R = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta]$$

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

Pre-*TWIST* decay parameters

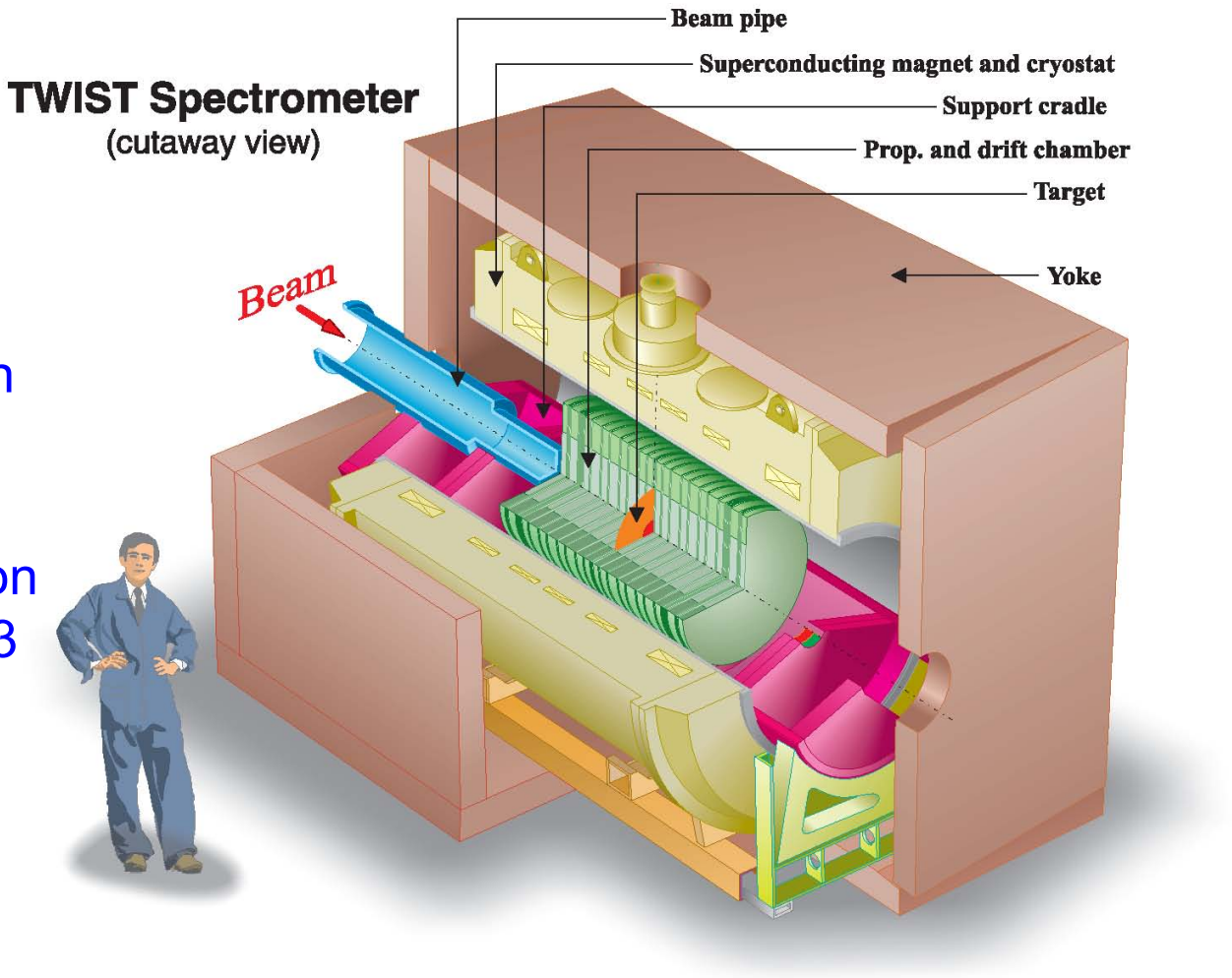
- From the Review of Particle Physics (SM values)
  - ρ = 0.7518 ± 0.0026 (0.75)
    - S.E. Derenzo, Phys. Rev. 184, 1854 (1969) .
  - δ = 0.7486 ± 0.0026 ± 0.0028 (0.75)
    - B. Balke *et al.*, Phys. Rev. D37, 587 (1988) 587.
  - $\mathcal{P}_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (1.00)
    - I. Beltrami *et al.*, Phys. Lett. B194, 326 (1987).
  - $\mathcal{P}_\mu(\xi\delta/\rho)$ > 0.99682 (90%CL) (1.00)
    - A. Jodidio *et al.*, Phys. Rev. D34, 1967 (1986), and erratum.
  - η = 0.011 ± 0.085 (0.00)
    - H. Burkhardt *et al.*, Phys. Lett. 160B, 343 (1985).

The goal of *TWIST* is to find any evidence for new physics that may become apparent by improving the precision of ρ, δ, and $\mathcal{P}_\mu\xi$ by one order of magnitude compared to prior experimental results.

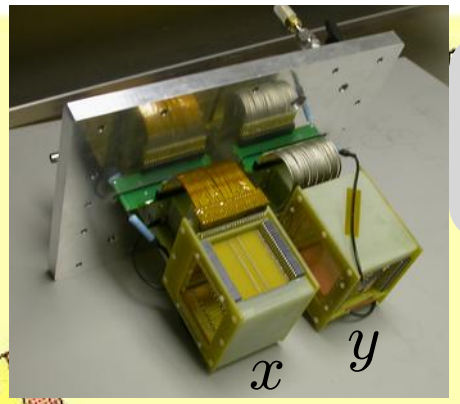
➔ **measure yield *vs.* energy and angle, and understand depolarization, *to a few parts in 10^4*.**

Spectrometer and muon target

- Highly polarized μ^+ beam
- μ^+ stop in a symmetric detector
- e^+ tracked through uniform, well-known field.
- Decay parameters found by comparison to detailed GEANT3 simulation.
- Data taking completed in 2007.



Muon production and transport



500 MeV protons

TECs to characterize muon beam: improve efficiency, reliability

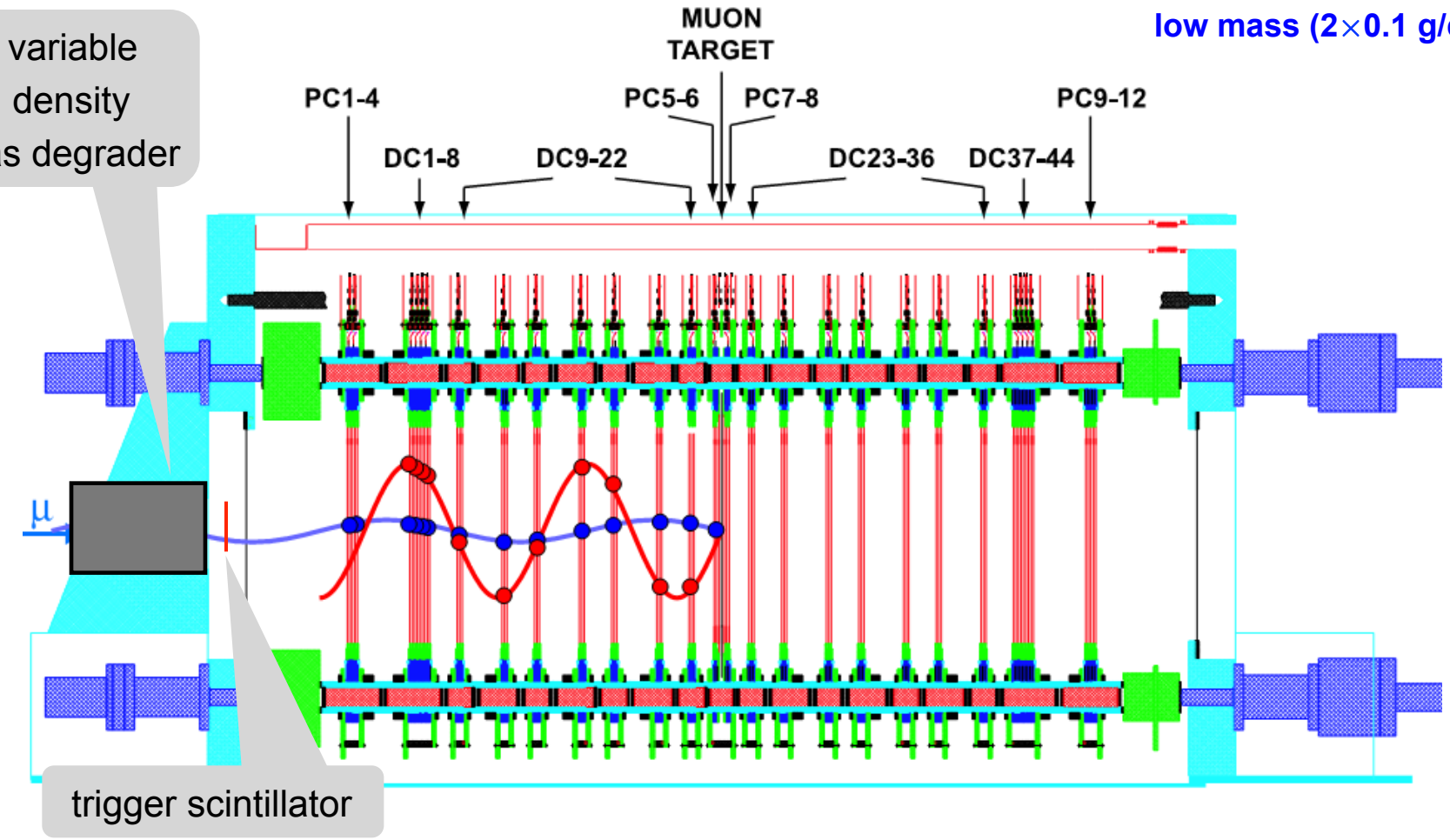
muon targets: HP Al and Ag

polarized muon source: select μ^+ from different depths

beam quadrupoles: add steering to control final beam position/angle

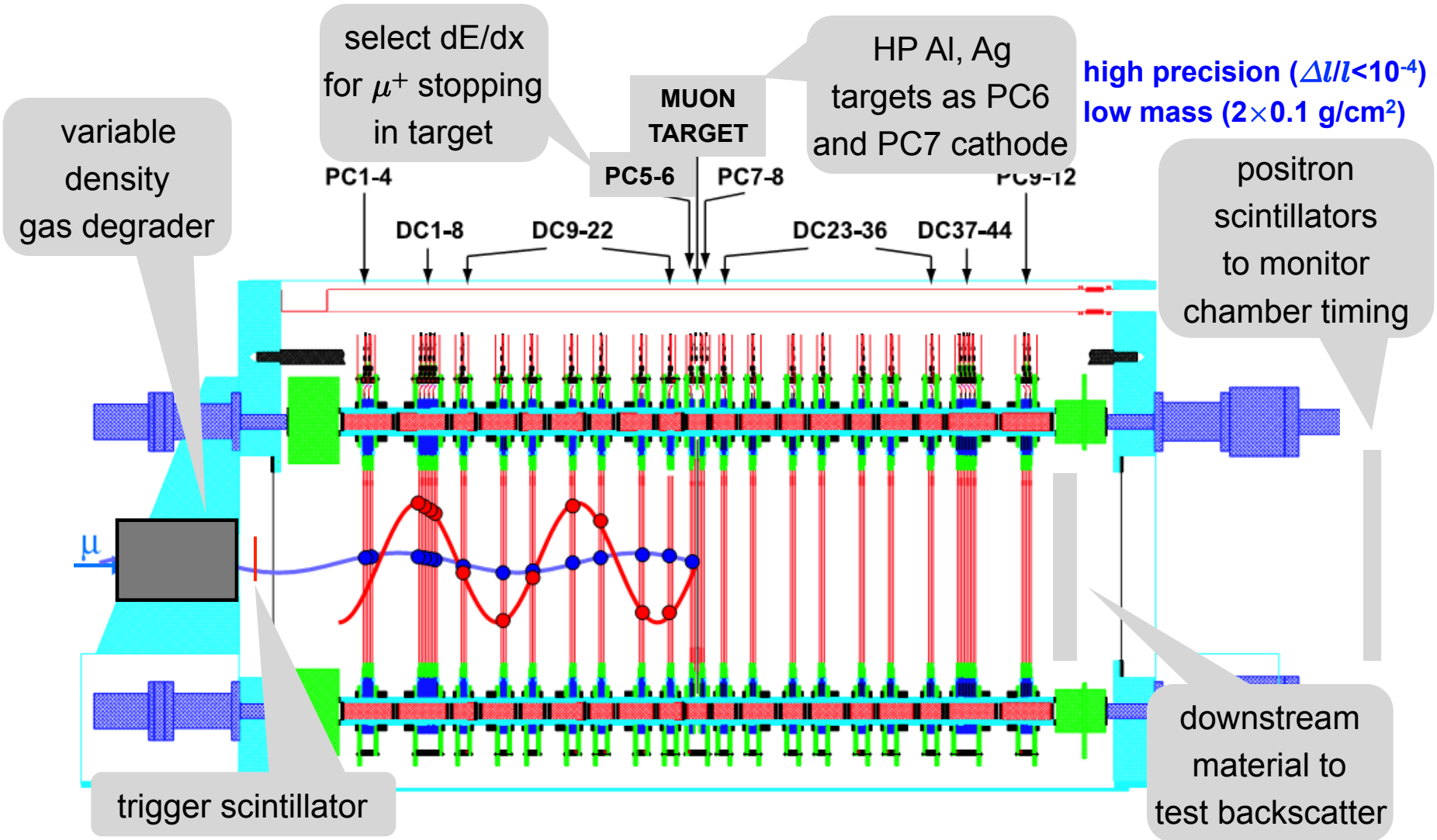
Detector array

high precision ($\Delta l/l < 10^{-4}$)
low mass (2×0.1 g/cm^2)



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

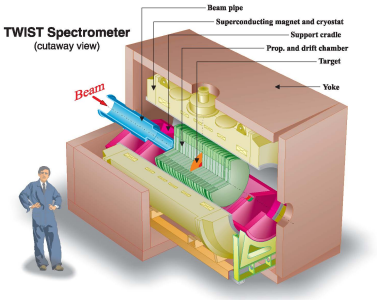
Detector array



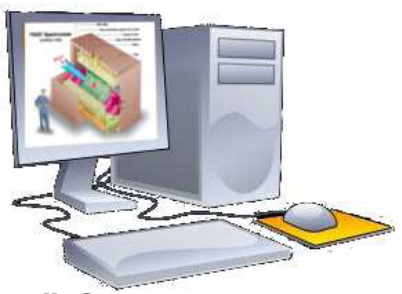
R. Henderson et al., Nucl. Instr. and Meth. A548, 306 (2005).

Analysis

Hidden parameters; ρ_{MC}, δ_{MC}, $\mathcal{P}_\mu{}^\pi\xi_{MC}$



Hidden parameter tolerances 0.01



Data from experiment

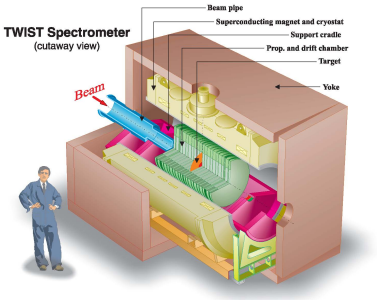
"Data" from simulation

Reconstruction software

Spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta\mathcal{P}_\mu{}^\pi\xi$

Analysis

Hidden parameters; ρ_{MC}, δ_{MC}, $\mathcal{P}_\mu{}^\pi\xi_{MC}$



Data from experiment

Hidden parameter tolerances 0.01

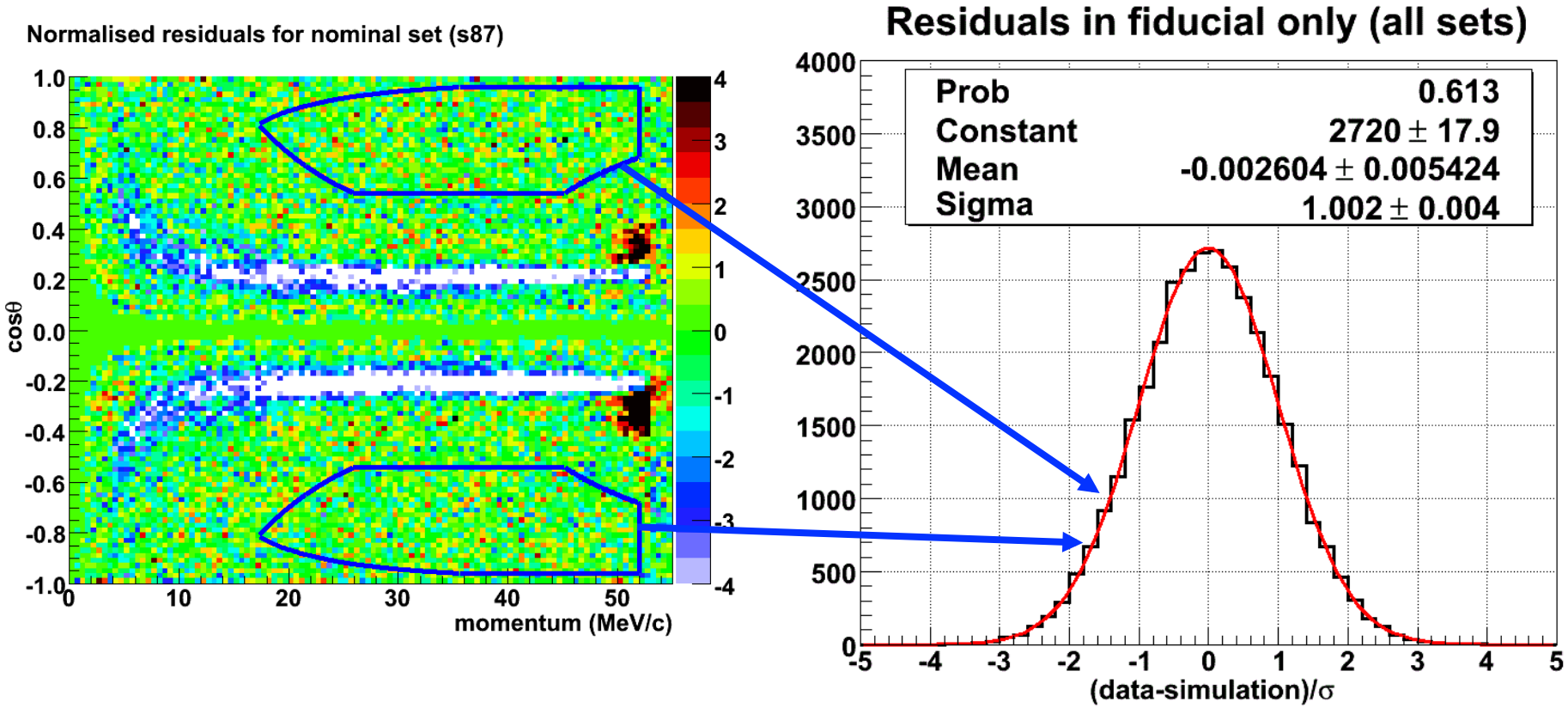
"Data" from simulation

Reconstruction software

Spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta\mathcal{P}_\mu{}^\pi\xi$

Add to hidden parameters; ρ, δ, $\mathcal{P}_\mu{}^\pi\xi$

Spectrum fit quality

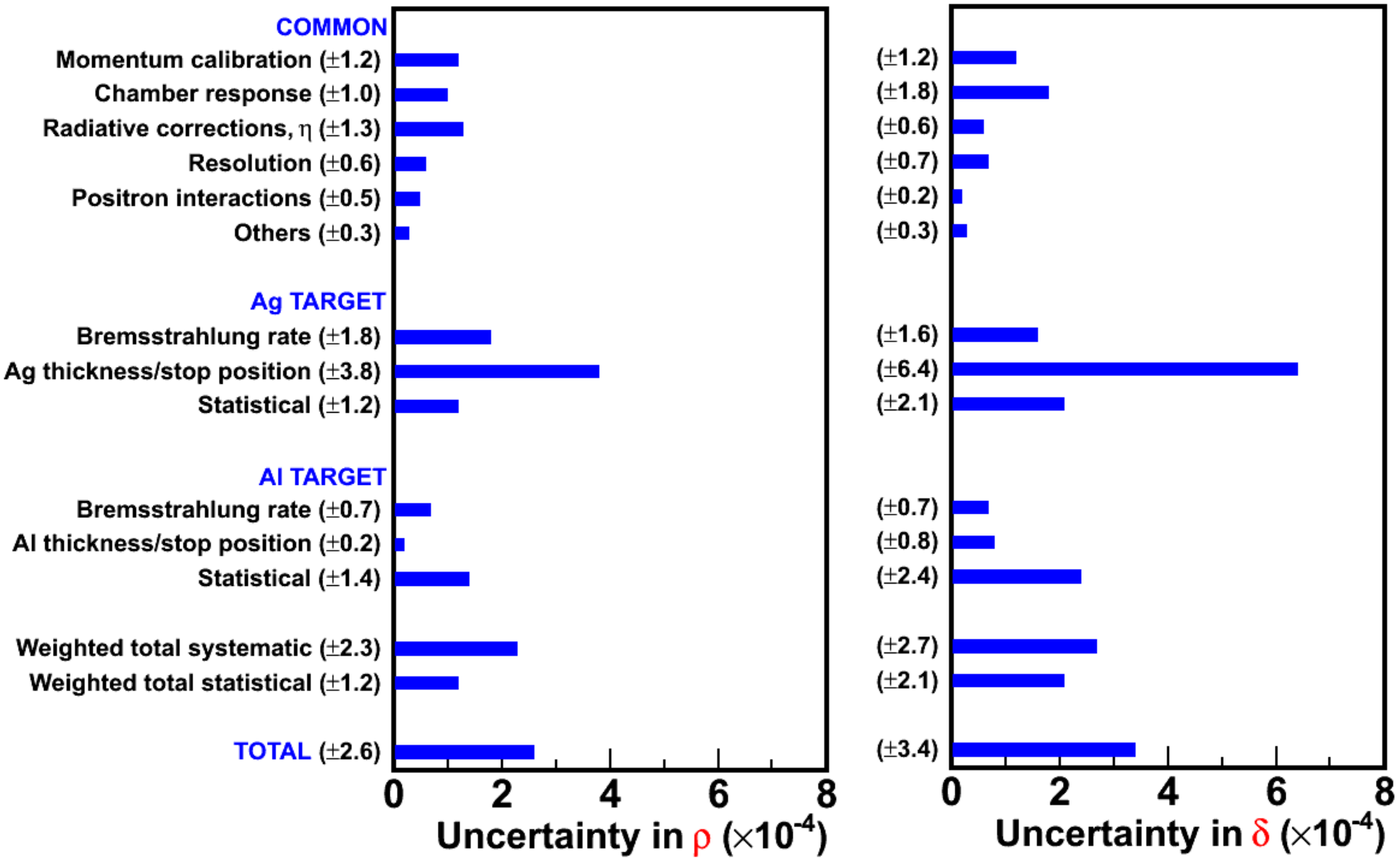


- Fiducial region: p < 52.0 MeV/c, 0.54 < |cosθ| < 0.96,
- 10.0 MeV/c < p_T < 38.0 MeV/c, |p_Z| > 14.0 MeV/c
- All data sets: **11**$\times$**10**^{9} events, **0.55**$\times$**10**^{9} in (p,cosθ) fiducial
- Simulation sets: 2.7 times data statistics

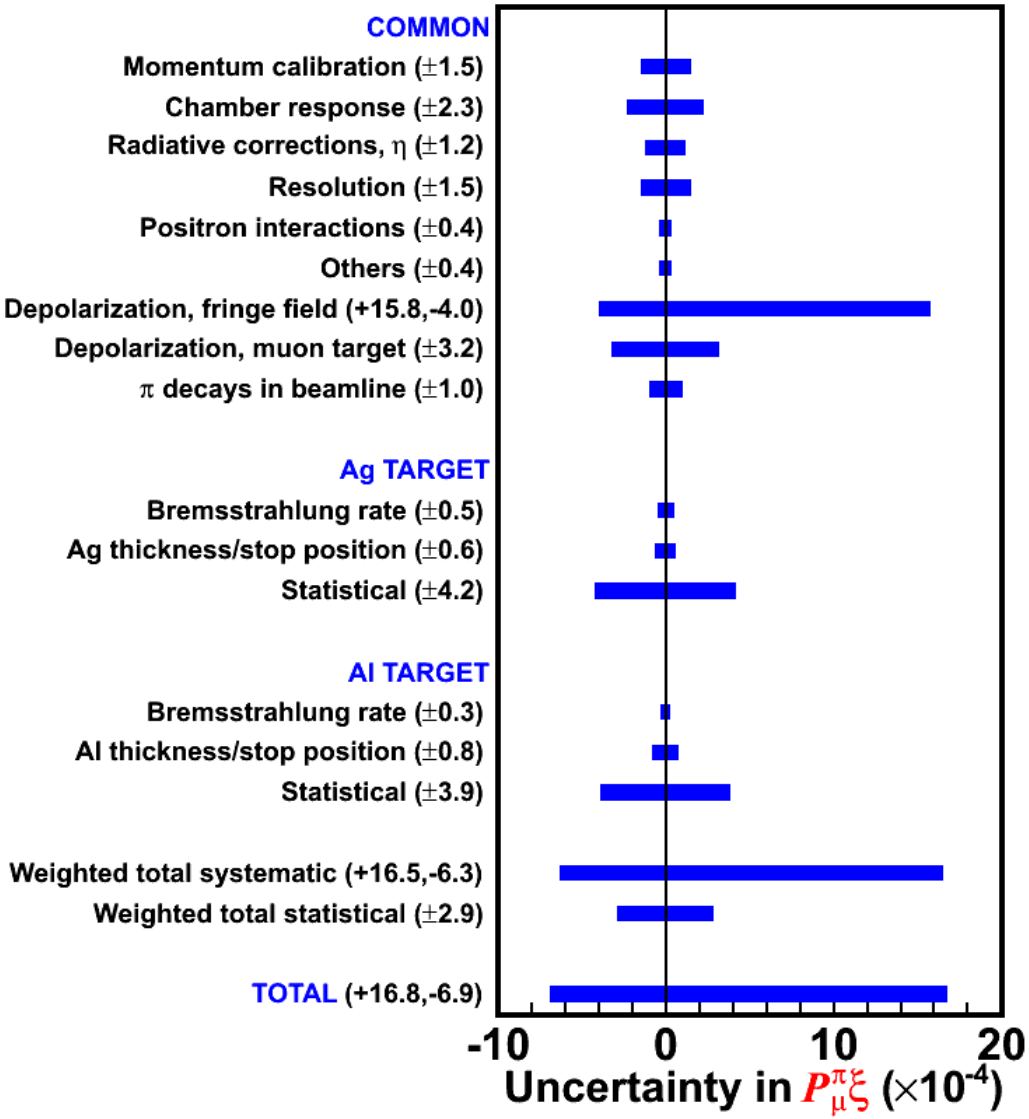
Blind *vs.* revised analysis

- The blind analysis results showed evidence of possible mistakes:
  - set-to-set statistical consistency satisfactory for ρ, δ, $\mathcal{P}_\mu{}^\pi\xi$
    - but $\mathcal{P}_\mu{}^\pi\xi\delta/\rho$ different for Al and Ag targets by 3.9σ.
  - $\mathcal{P}_\mu{}^\pi\xi\delta/\rho$ averaged over all sets was 2.9σ greater than 1.0.
    - unlikely in four-fermion formulation with massless neutrinos.
- Search for mistakes identified two corrections and two procedural changes:
  - radiative decay: small correction for Ag only
  - mean stopping position differences (data *vs.* simulation): corrected set-by-set, based on better analysis of stop position
  - separate systematic uncertainties for Ag and Al targets for bremsstrahlung, target thickness, and mean stopping position
  - ρ and δ correlations from all sets applied to $\mathcal{P}_\mu{}^\pi\xi$
- After the revisions, the Ag-Al $\mathcal{P}_\mu{}^\pi\xi\delta/\rho$ difference becomes $<1\sigma$.

Uncertainties in ρ and δ

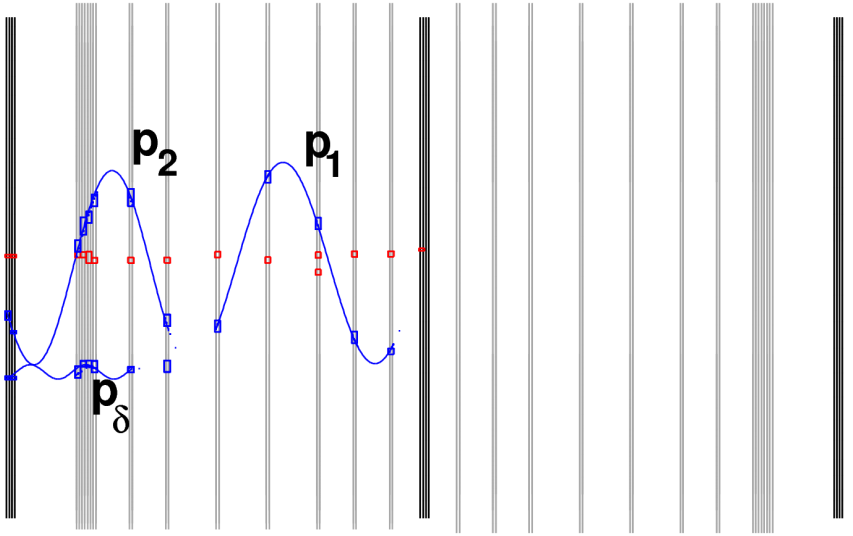


Uncertainties in $\mathcal{P}_\mu{}^\pi\xi$

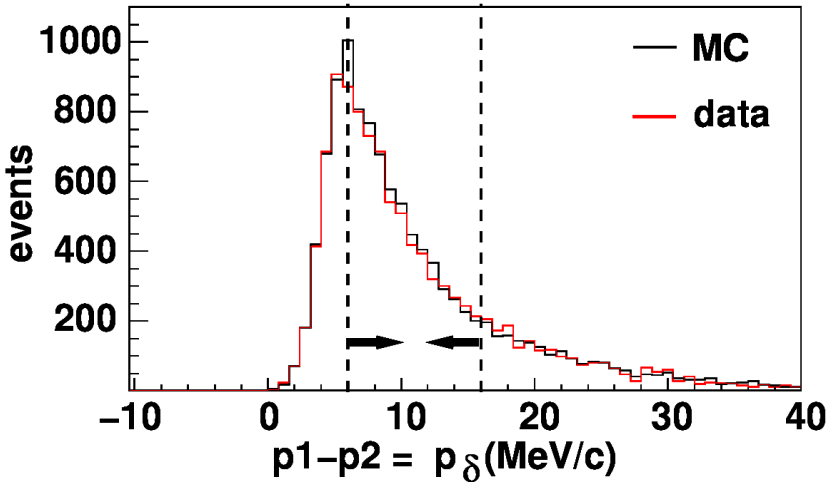


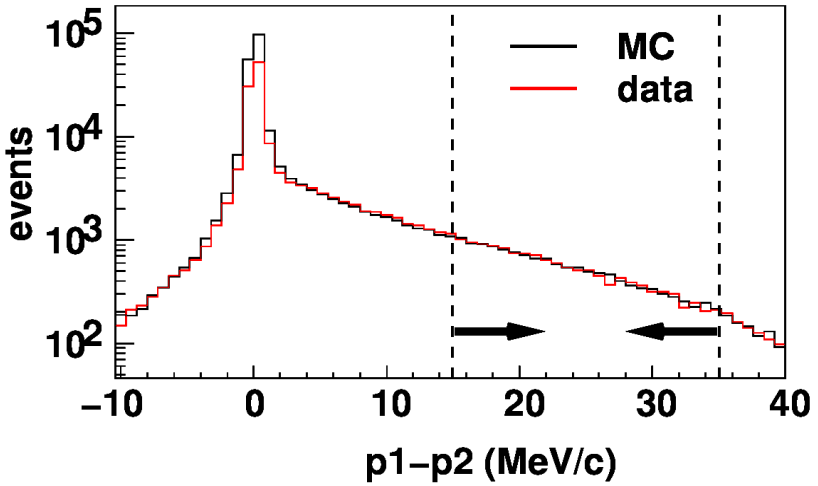
- Uncertainties for all three parameters are from the revised analysis
- Differences to blind results are small:
  - $\sigma(\rho)$ changed by **-0.3×10^{-4}**
  - $\sigma(\delta)$ changed by **$+0.1\times10^{-4}$**
  - $\sigma(\mathcal{P}_\mu{}^\pi\xi_{avg})$ changed by **-0.2×10^{-4}**

Positron interactions systematic

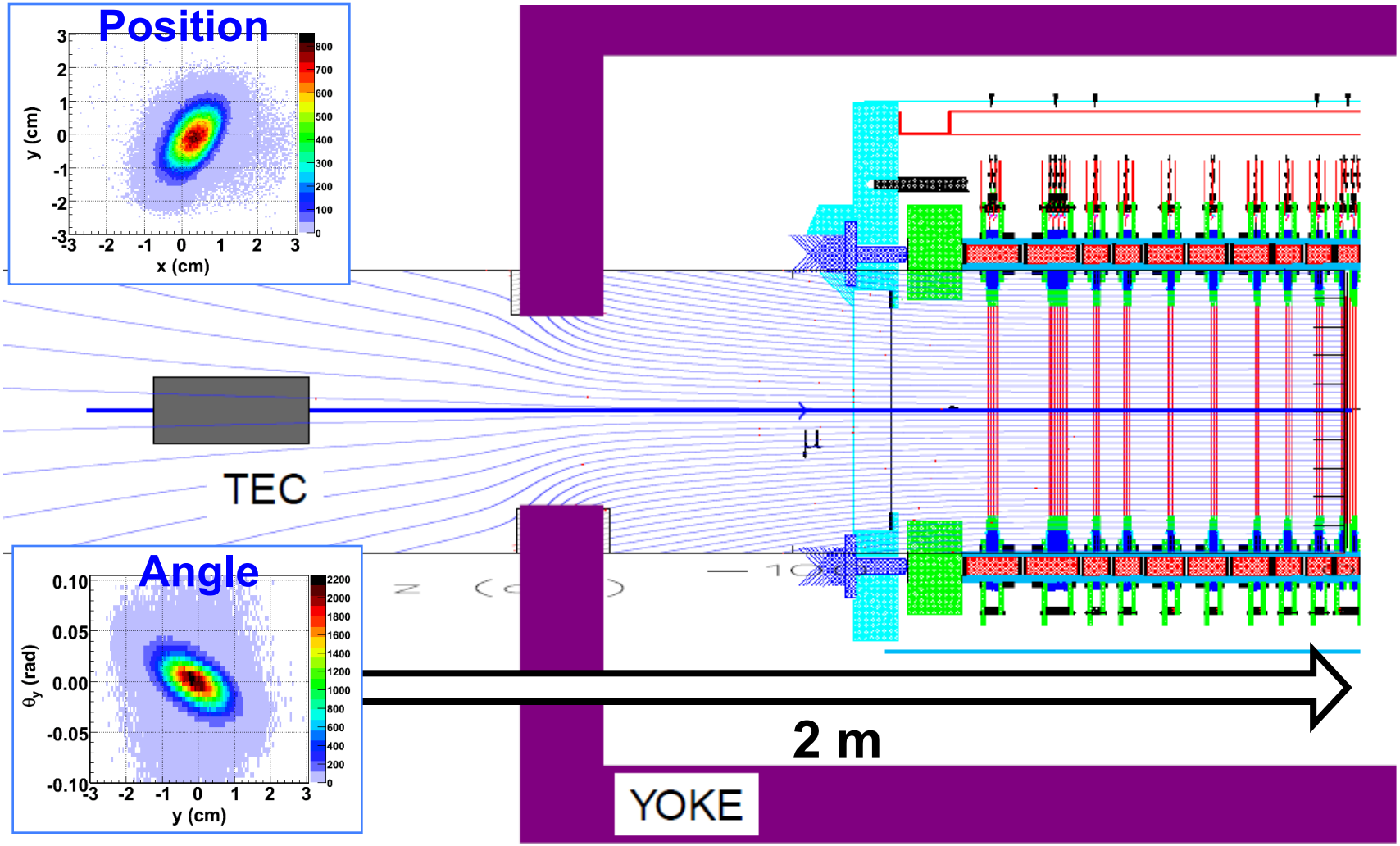


- "Broken tracks" analysis:
  - 2 e^+, 1 e^- ➔ δ -electron
  - 2 e^+ ➔ Bremsstrahlung
- Agreement of data and sim:
  - δ -electrons < 1%
  - Bremsstrahlung differs by 2.4%

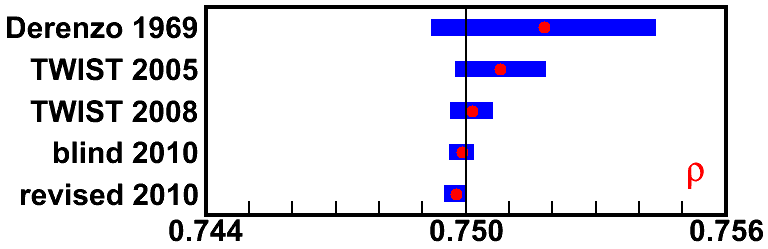




Fringe field depolarization

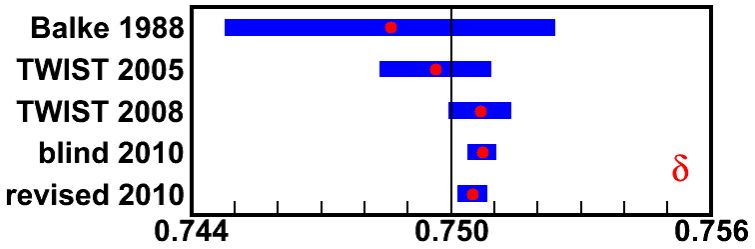


Decay parameter results



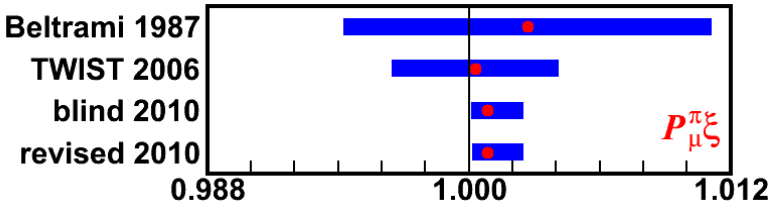
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

(<1σ from SM, -1.4$\times$10^{-4} from blind)



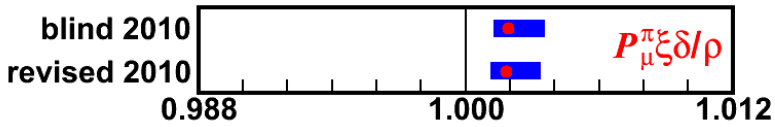
δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

(+1.4σ from SM, -2.3$\times$10^{-4} from blind)



$\mathcal{P}_\mu^{\pi}\xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)

(+1.2σ from SM, same as blind)



$\mathcal{P}_\mu^{\pi}\xi\delta/\rho$ > 0.99909 (90%CL)

from global analysis

TWIST Collaboration, R. Bayes et al., Phys. Rev. Lett. 106, 041804 (2011).

Left-right symmetric analysis

- W_R that mixes with W_L to restore parity at high energy

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

- P. Herczeg, PRD 34, 3499 (1986) uses general parameters:

$$t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \qquad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|} \simeq t\frac{\cos\theta_R}{\cos\theta_{Cab}}, \qquad \zeta_g^2 = \frac{g_R^2}{g_L^2}\zeta^2$$

  - g_L, g_R and $V_{ud}{}^L$, $V_{ud}{}^R$ permit differences in left and right sectors, with possible CP violating phases ω and α, and for muon decay:

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

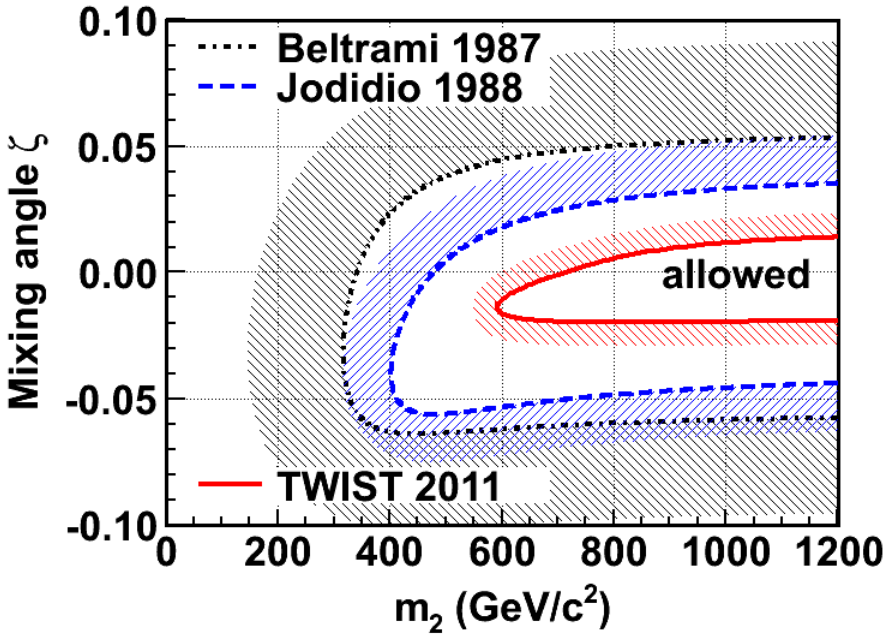
$$\mathcal{P}_\mu^\pi \simeq 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g\cos(\alpha + \omega)$$

  - allowing restrictions to be put on LRS mass m_2 and mixing ζ, e.g.,

$$1 - \frac{\mathcal{P}_\mu^\pi \xi\delta}{\rho} \simeq 2t^2\left(1 + \frac{\cos^2\theta^R}{\cos^2\theta_{Cab}}\right) + 2\zeta_g^2 + 4\zeta_g t\frac{\cos\theta^R}{\cos\theta_{Cab}}\cos(\alpha + \omega)$$

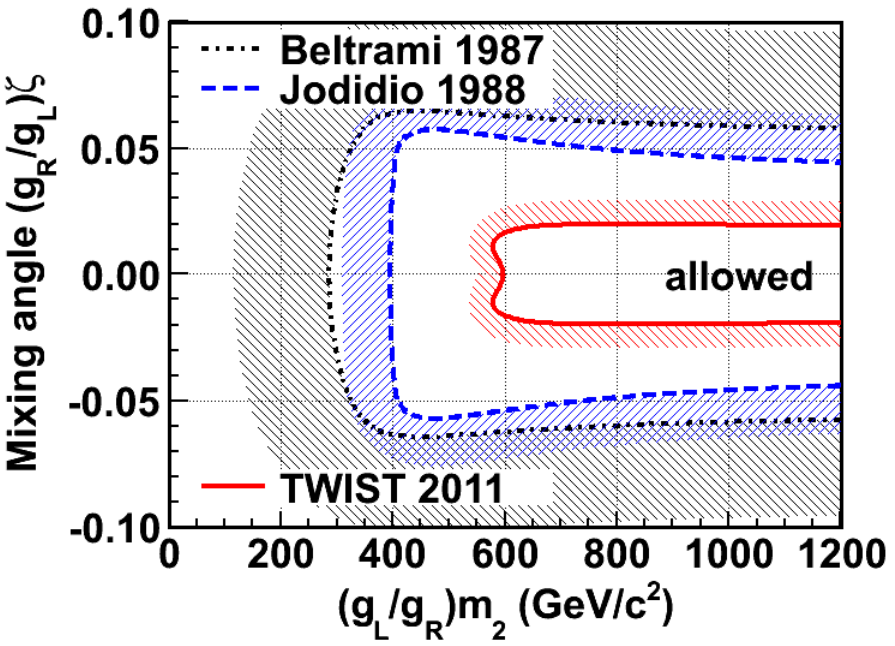
Left-Right Symmetric limit comparison

"manifest" LRS, 90%CL



$m_2 > 592$ GeV/c^2
$-0.020 < \zeta < +0.017$

generalized or non-manifest LRS, 90%CL



$(g_L/g_R)m_2 > 578$ GeV/c^2
$-0.020 < (g_R/g_L)\zeta < +0.020$

- Other W' direct search mass limits
  - ATLAS: >1.49 TeV/c^2, 95%CL (LLWI11)
  - CMS: >1.58 TeV/c^2, 95%CL (LLWI11)
  - CMS: >1.36 TeV/c^2, 95%CL (2011)
  - CDF: >1.12 TeV/c^2, 95%CL (2011)
  - D0: >1.0 TeV/c^2, 95%CL (2008)

- Other limits on mixing angle ζ
  - Hardy and Towner: <0.0005 (MLRS), <0.04 (generalized)
  - K decay: <0.004 (MLRS)

Global analysis result

- Include new results with other muon decay observables to restrict coupling constants
  - summary of all terms (pre-*TWIST* in parentheses)

$$|g^S_{RR}| < 0.035\ (0.066) \qquad |g^V_{RR}| < 0.017\ (0.033) \qquad |g^T_{RR}| \equiv 0$$
$$|g^S_{LR}| < 0.050\ (0.125) \qquad |g^V_{LR}| < 0.023\ (0.060) \qquad |g^T_{LR}| < 0.015\ (0.036)$$
$$|g^S_{RL}| < 0.420\ (0.424) \qquad |g^V_{RL}| < 0.105\ (0.110) \qquad |g^T_{RL}| < 0.105\ (0.122)$$
$$|g^S_{LL}| < 0.550\ (0.550) \qquad |g^V_{LL}| > 0.960\ (0.960) \qquad |g^T_{LL}| \equiv 0$$

  - influences mostly right-handed muon terms

$$\begin{aligned} Q^\mu_R &= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \\ &= \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \\ &< 8.2 \times 10^{-4} \quad (90\%\text{C.L.}) \end{aligned}$$

Limits for heavy sterile neutrinos

- Muon decay spectrum shape places limits on heavy neutrino mass and mixing in a mass region inaccessible with π or K decays.

R.R. Schrock, Phys. Rev. D 24, 1275 (1981).

P. Kalyniak and J.N. Ng,
Phys. Rev. D 25, 1305 (1982).

M.S. Dixit et al., Phys. Rev. D 27, 2216 (1983).

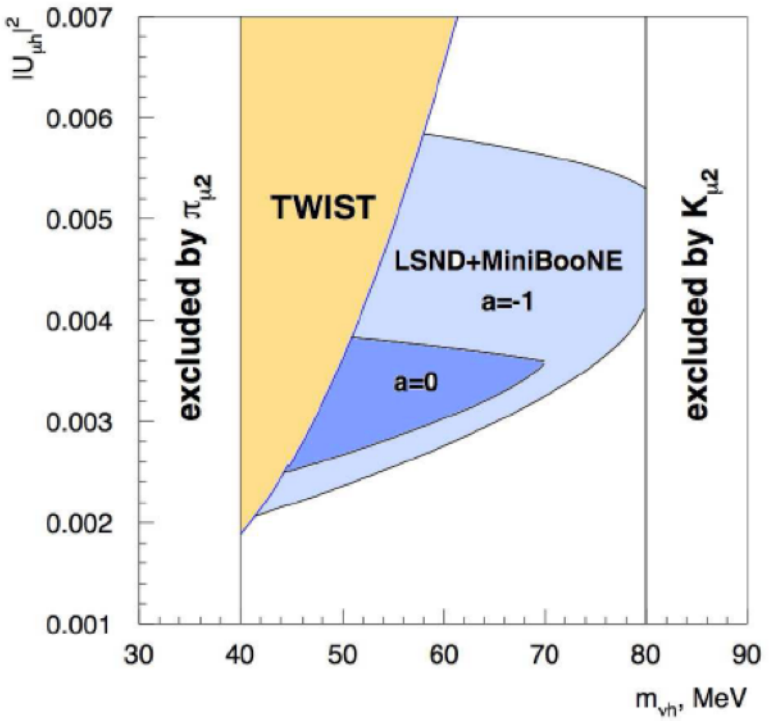


FIG. 24: The 2σ allowed region (dark areas) in the $(m_{\nu_h}; |U_{\mu h}|^2)$ parameter space obtained for different values of the asymmetry parameter a from the combined analysis of LSND and MiniBooNE ν_μ and $\overline{\nu}_\mu$ data. The areas excluded by the $\pi_{\mu 2}$ and $K_{\mu 2}$ decay experiments [45], and the exclusion region obtained in the present work from the results of precision measurements of the muon decay parameters by the TWIST experiment [50] are also shown; see Sec. VI.

Heavy sterile neutrino model

S.N. Gninenko, arXiv:1009.5536v3, Jan 2011

Summary

- Systematic uncertainties in muon decay parameter measurements were substantially reduced in *TWIST*.
- Total uncertainties were reduced by factors of **10**, **11**, and **7** for ρ, δ, and $\mathcal{P}_\mu{}^\pi\xi$ respectively, roughly achieving the goals of the experiment.
- Differences with Standard Model predictions are respectively **-0.9**σ, **+1.4**σ, and **+1.2**σ, after post-blind revisions.
- $\mathcal{P}_\mu{}^\pi\xi\delta/\rho$ deviates by **+2.3**σ from the expected upper limit of 1.0.