Muon Decay Parameters from *TWIST*

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

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TWIST participants, past and present

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∗ Recently graduated
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Outline

- Muon decay parameters
- The *TWIST* spectrometer
- Analysis strategies
- Systematic uncertainties
- Results and for decay parameters ρ, δ, and $\mathcal{P}_\mu\xi$
- Consequences for physics beyond the SM

Decay parameters

L. Michel

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

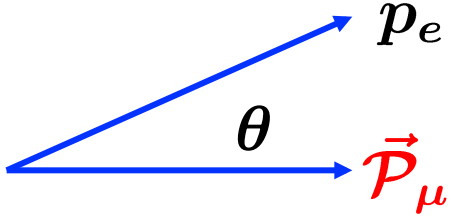
$$\frac{d^2\Gamma}{dx\ d\cos\theta} = \frac{1}{2\pi^3} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2}\cdot$$
$$\{\mathcal{F}_{IS}(x,\rho,\eta) \pm \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

  - where

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

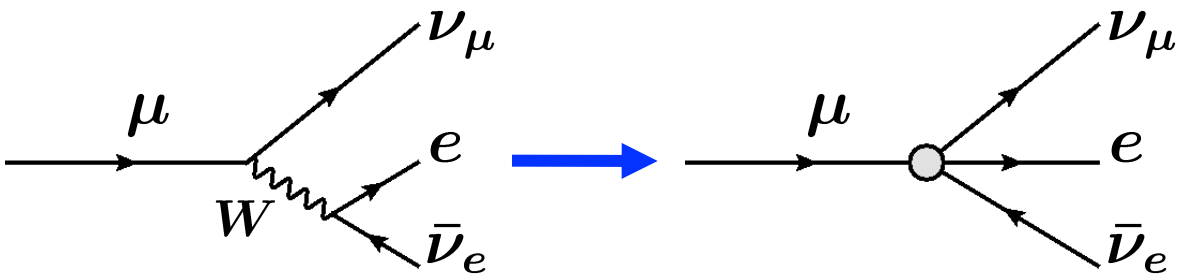
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right]$$

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).

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) .

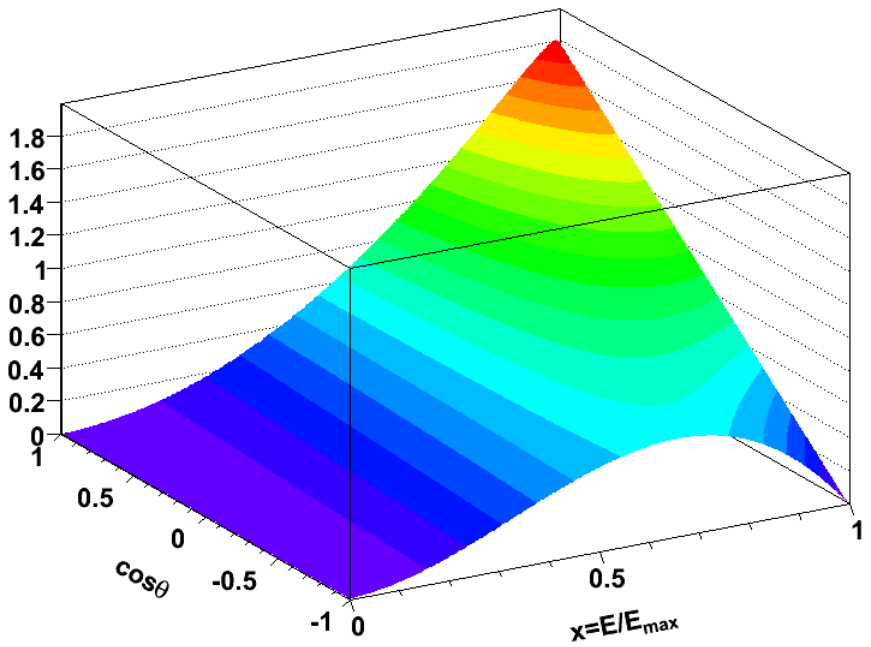
Pre-*TWIST* decay parameters

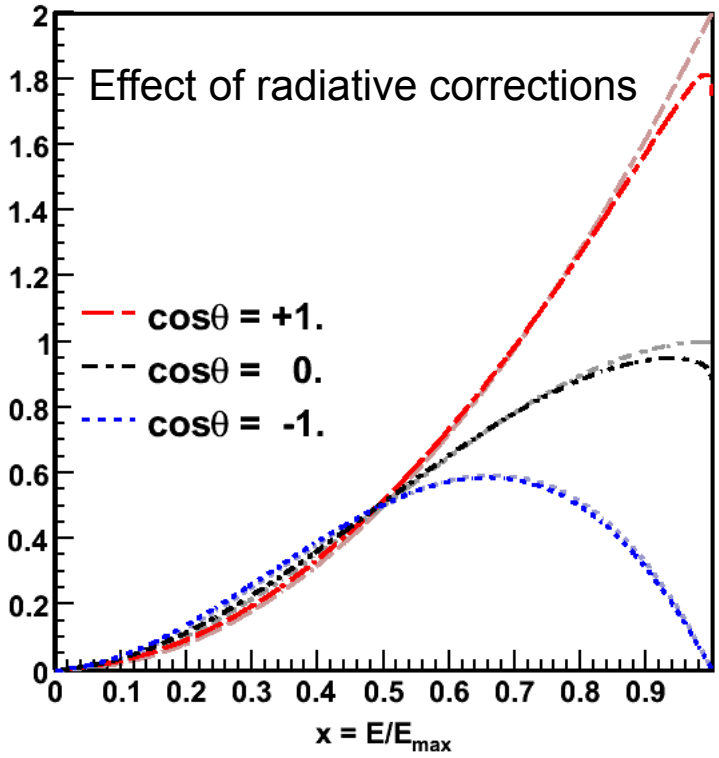
- From the Review of Particle Physics (SM values)
  - ρ = 0.7518 ± 0.0026 (0.75)
    - S.E. Derenzo, Phys. Rev. 184, 1854 (1969) .
  - δ = 0.7486 ± 0.0026 ± 0.0028 (0.75)
    - B. Balke *et al.*, Phys. Rev. D37, 587 (1988) 587.
  - $\mathcal{P}_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (1.00)
    - I. Beltrami *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*.**

Spectrum shape and radiative corrections



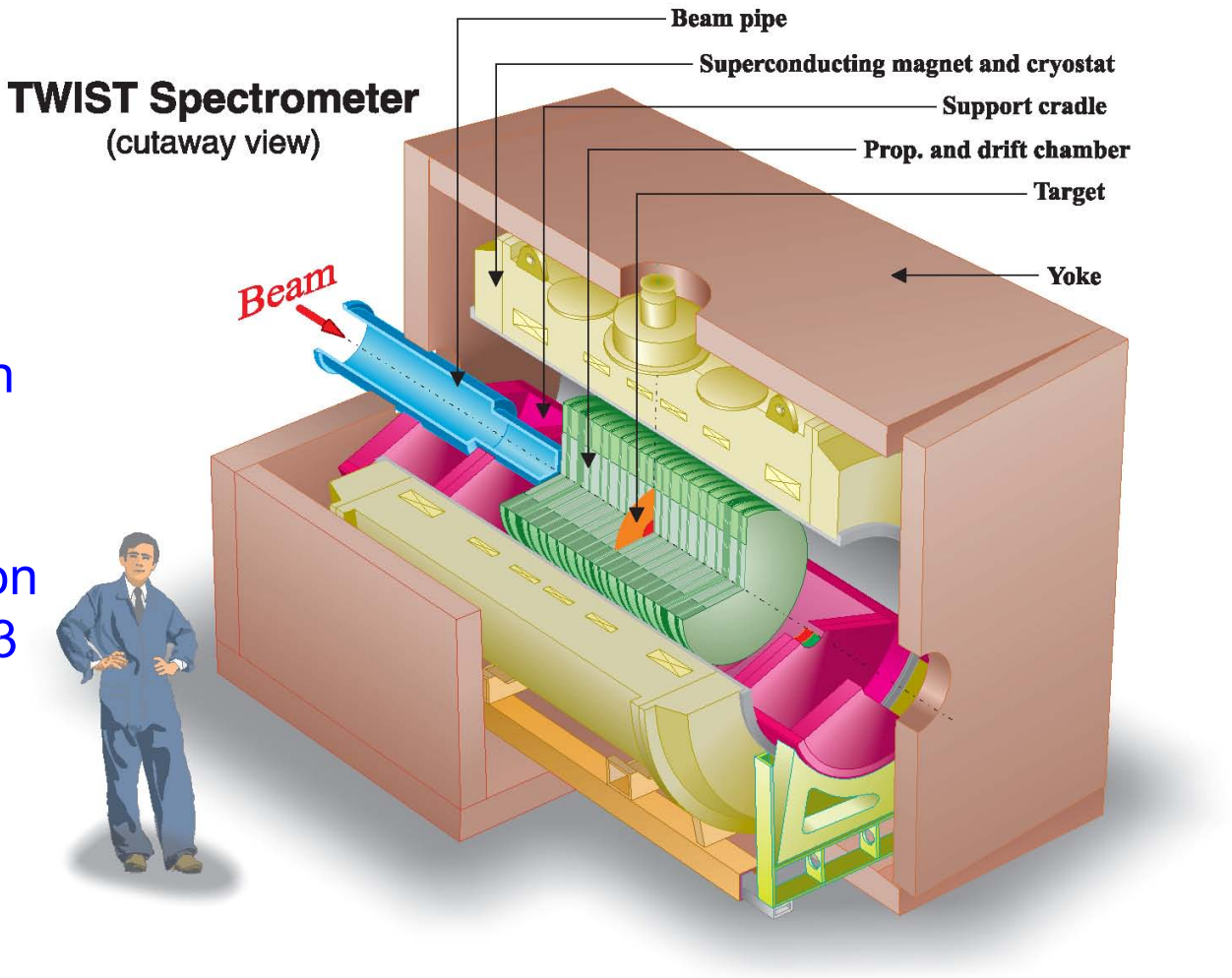


- Full $\mathcal{O}(\alpha)$ radiative corrections with exact electron mass dependence.
- Leading and next-to-leading logarithmic terms of $\mathcal{O}(\alpha^2\mathcal{L}^2)$ and $\mathcal{O}(\alpha^2\mathcal{L})$, $\mathcal{L}=ln((m_\mu/m_e)^2)$
- Leading logarithmic terms of $\mathcal{O}(\alpha^3\mathcal{L}^3)$.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

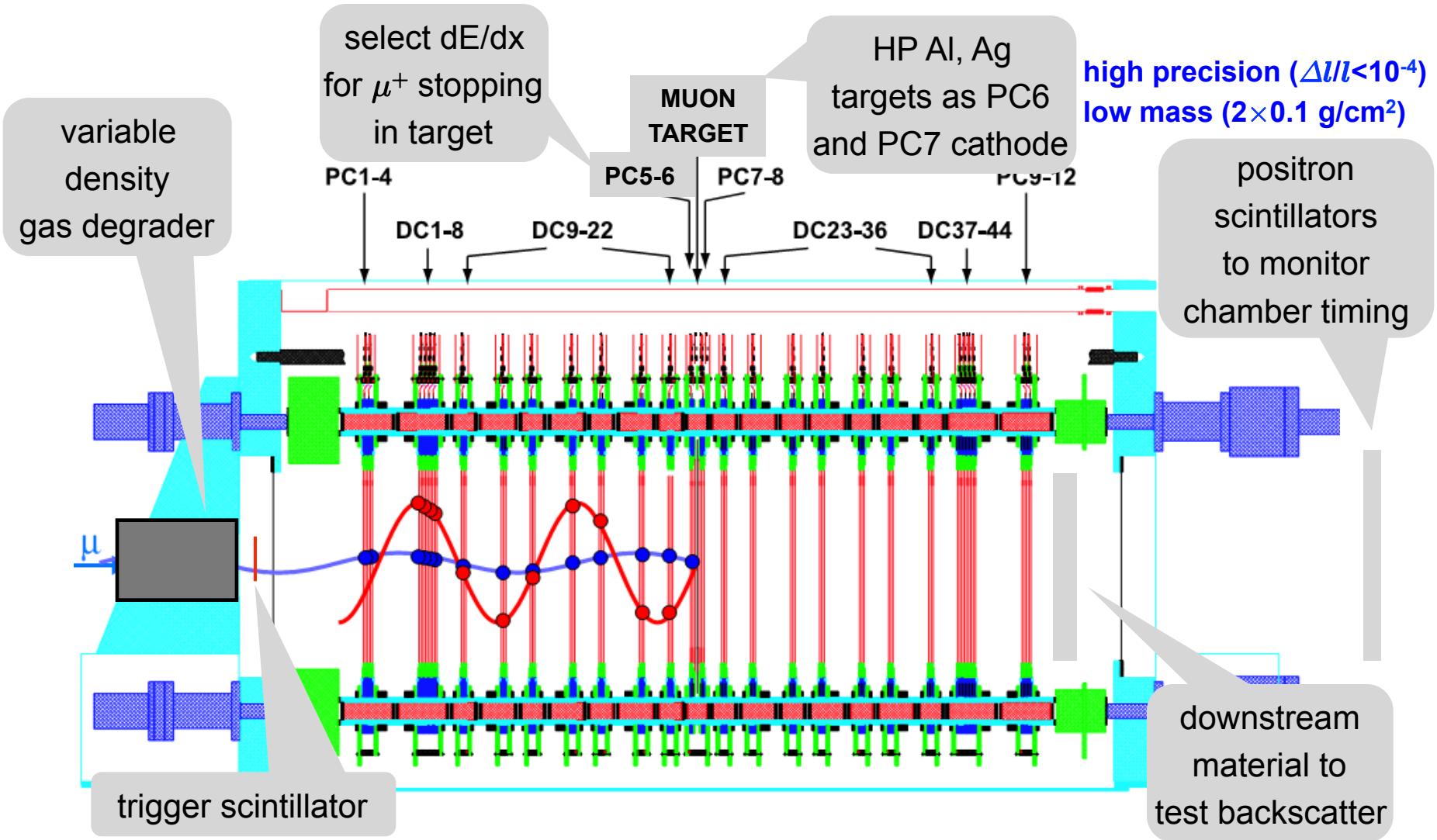
K. Melnikov, J. High Energy Phys. (09):014 (2007)
A. Arbuzov, J. High Energy Phys. (03):063 (2003)
A. Arbuzov et al., Phys. Rev. D66, 93003 (2002)
A. Arbuzov et al., Phys. Rev. D65, 113006 (2002)

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.



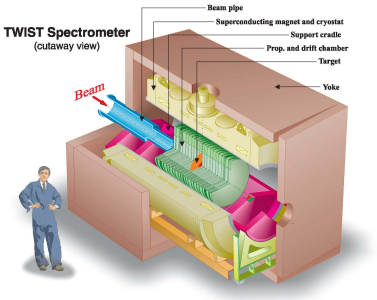
Detector array



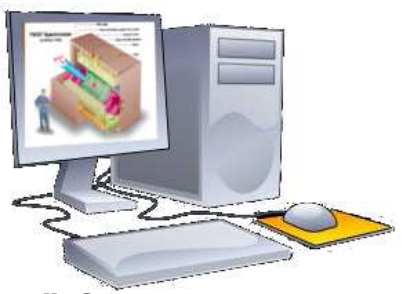
R. Henderson et al., Nucl. Instr. and Meth. A548, 306 (2005).

Analysis

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



Hidden parameter tolerances 0.01



Data from experiment

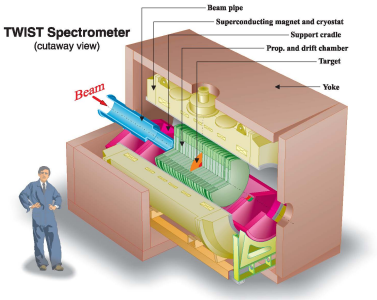
"Data" from simulation

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

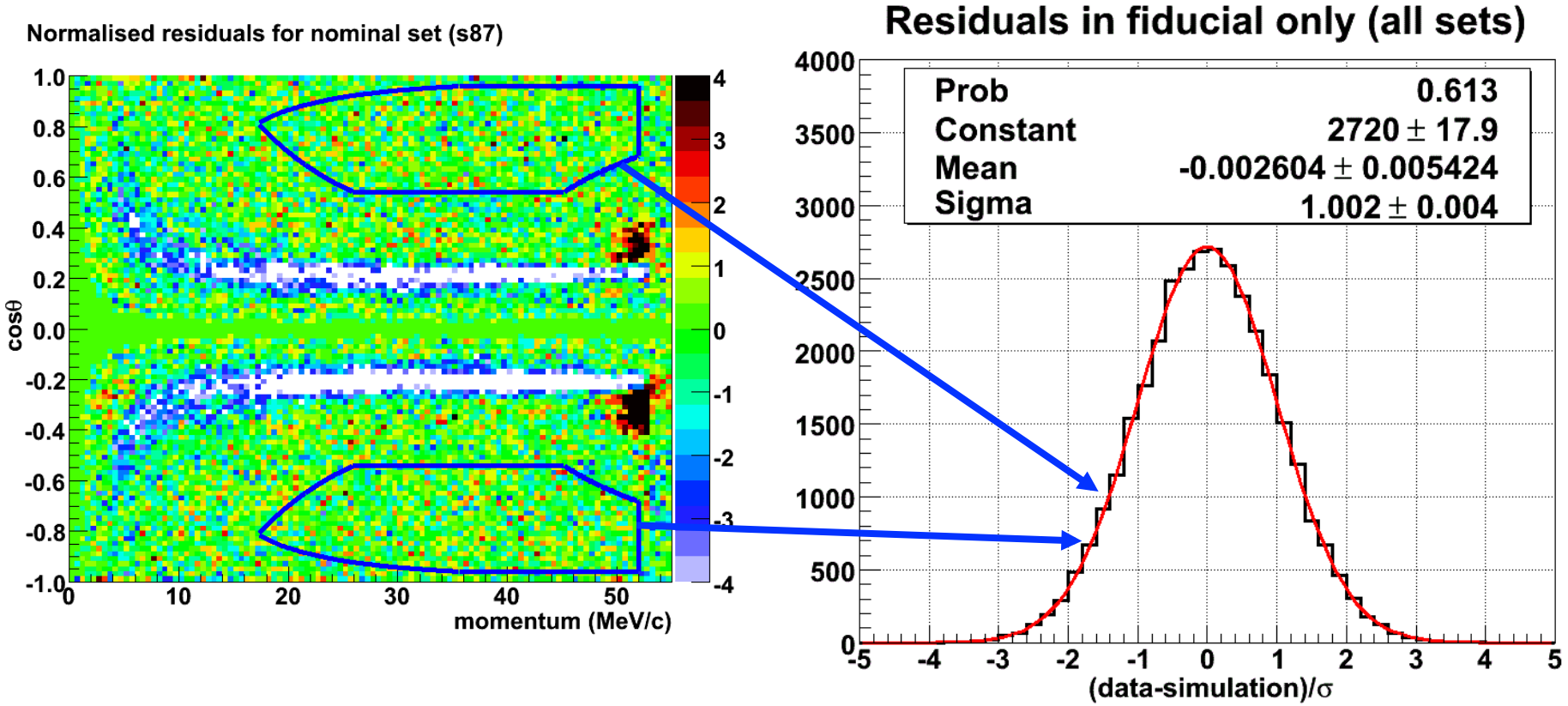
"Data" from simulation

Reconstruction software

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

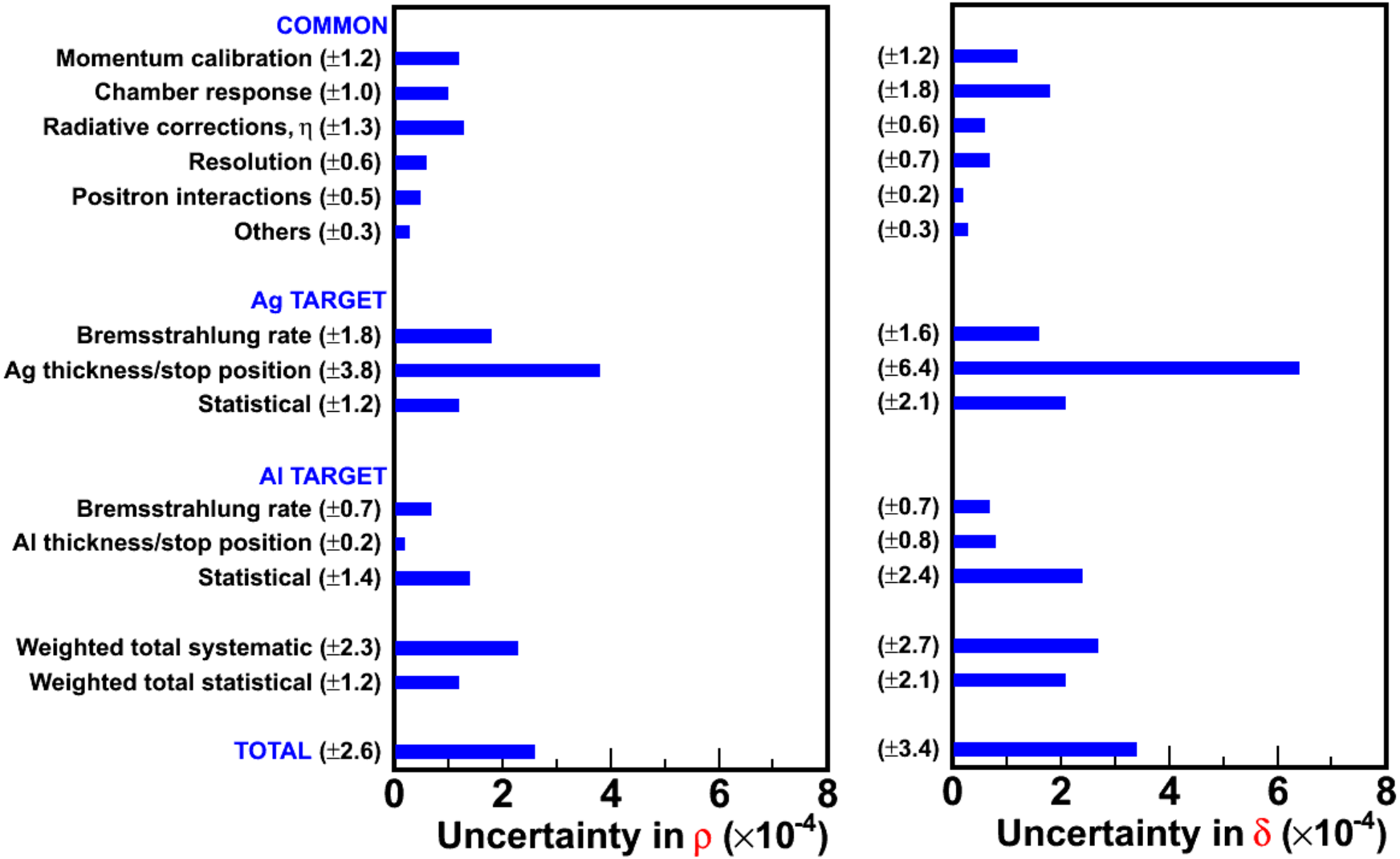
Add to hidden parameters; ρ, δ, $\mathcal{P}_\mu{}^\pi\xi$

Spectrum fit quality

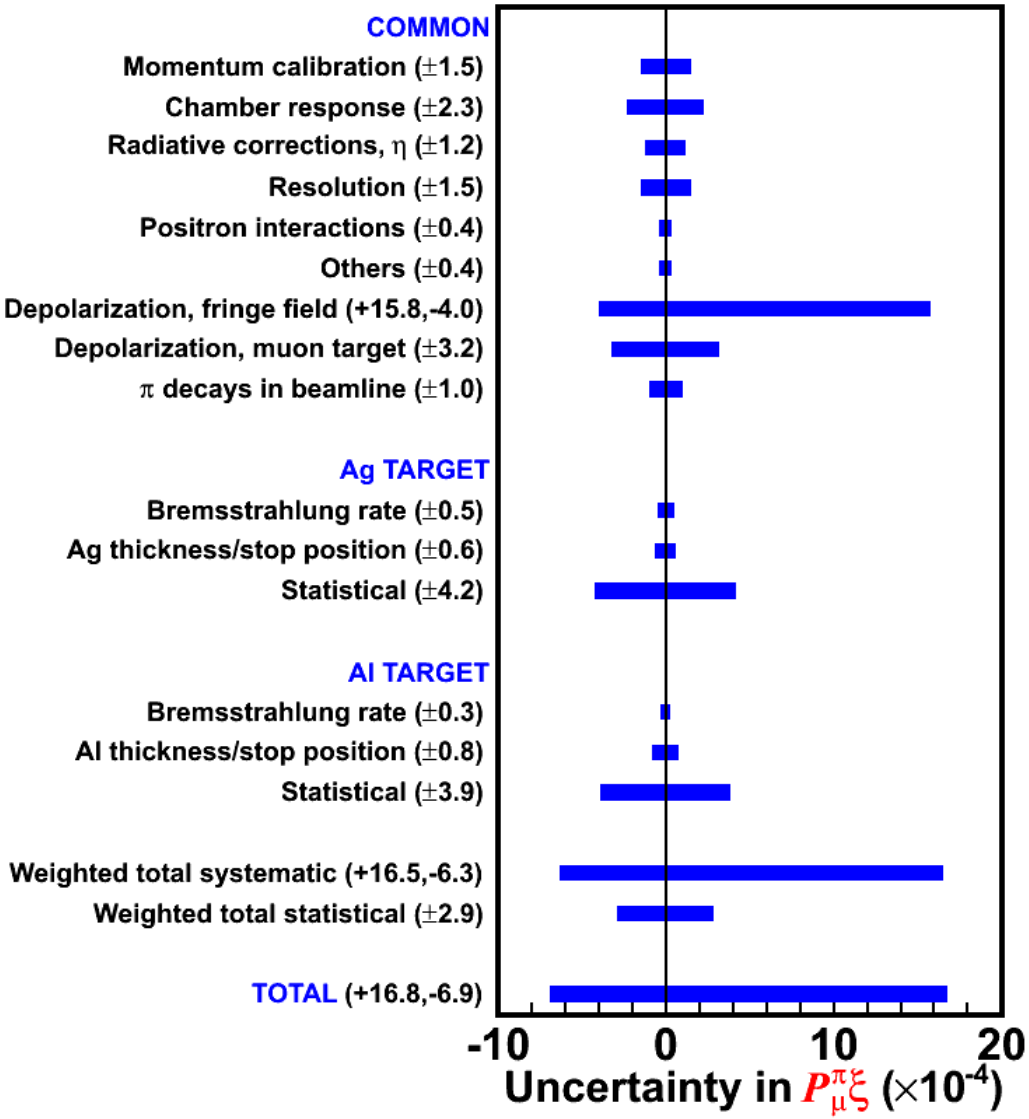


- Fiducial region: p < 52.0 MeV/c, 0.54 < |cosθ| < 0.96,
- 10.0 MeV/c < p_T < 38.0 MeV/c, |p_Z| > 14.0 MeV/c
- All data sets: **11**$\times$**10**^{9} events, **0.55**$\times$**10**^{9} in (p,cosθ) fiducial
- Simulation sets: 2.7 times data statistics

Uncertainties in ρ and δ

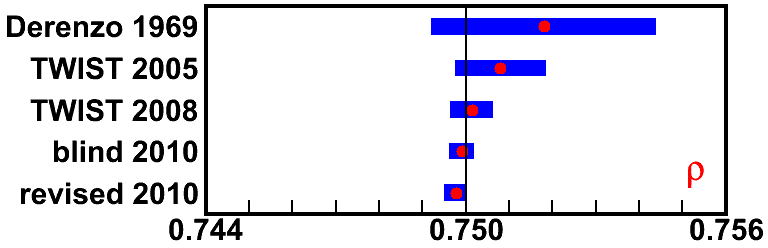


Uncertainties in $\mathcal{P}_\mu{}^\pi\xi$

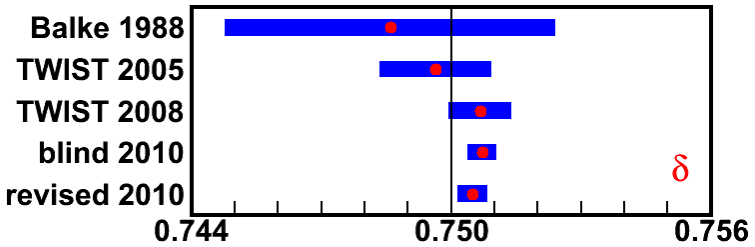


- Uncertainties for all three parameters are from the revised analysis
- Differences to blind results are small:
  - $\sigma(\rho)$ changed by **-0.3×10^{-4}**
  - $\sigma(\delta)$ changed by **$+0.1\times10^{-4}$**
  - $\sigma(\mathcal{P}_\mu{}^\pi\xi_{avg})$ changed by **-0.2×10^{-4}**

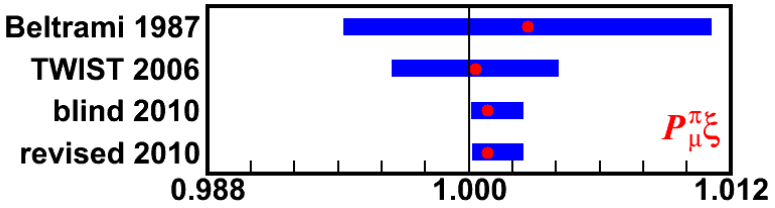
Decay parameter results



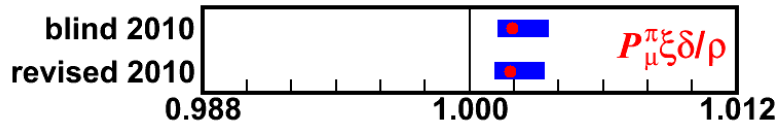
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)
(<1σ from SM)



δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)
(+1.4σ from SM)



$\mathcal{P}_\mu^{\pi}\xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)
(+1.2σ from SM)

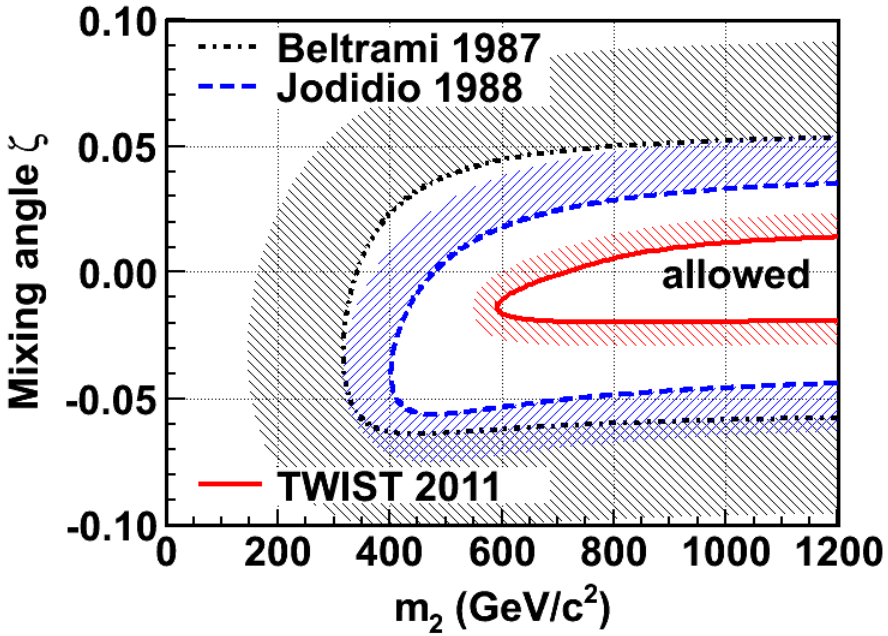


$\mathcal{P}_\mu^{\pi}\xi\delta/\rho$ > 0.99909 (90%CL)
from global analysis

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

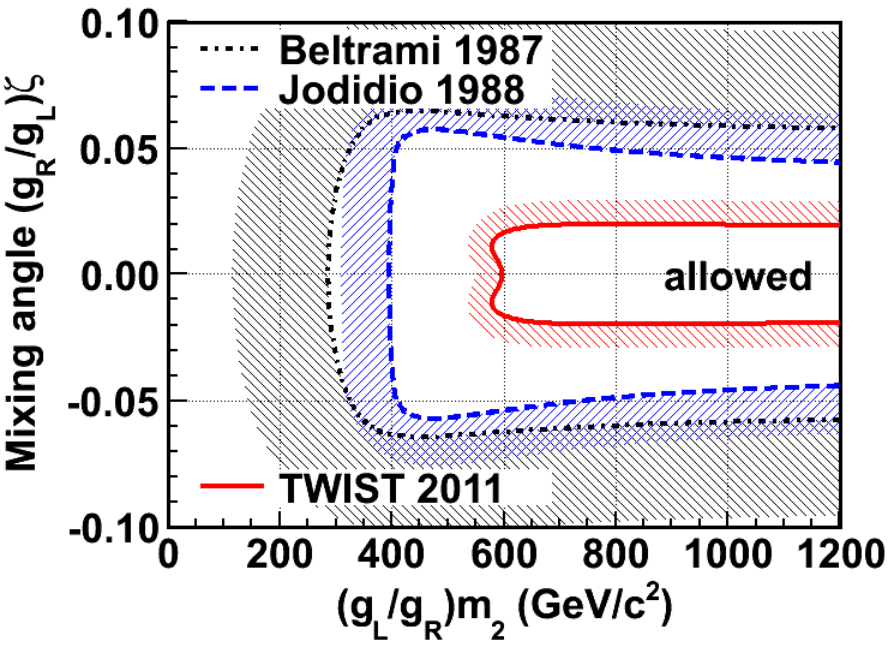
Left-Right Symmetric limit comparison

"manifest" LRS, 90%CL



$m_2 > 592$ GeV/c²
$-0.020 < \zeta < +0.017$

generalized or non-manifest LRS, 90%CL



$(g_L/g_R)m_2 > 578$ GeV/c²
$-0.020 < (g_R/g_L)\zeta < +0.020$

- W' direct search mass limits
  - ATLAS: >1.49 TeV/c², 95%CL (LLWI11)
  - CMS: >1.58 TeV/c², 95%CL (LLWI11)
  - CMS: >1.36 TeV/c², 95%CL (2011)
  - CDF: >1.12 TeV/c², 95%CL (2011)
  - D0: >1.0 TeV/c², 95%CL (2008)

- Some limits on mixing angle ζ (MLRS only)
  - 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).

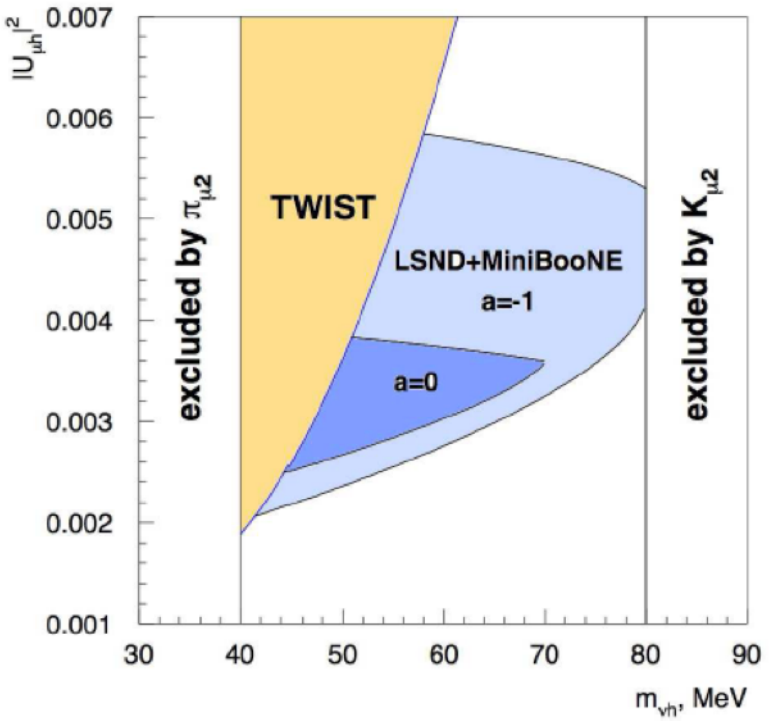


FIG. 24: The 2σ allowed region (dark areas) in the $(m_{\nu_h}; |U_{\mu h}|^2)$ parameter space obtained for different values of the asymmetry parameter a from the combined analysis of LSND and MiniBooNE ν_μ and $\overline{\nu}_\mu$ data. The areas excluded by the $\pi_{\mu 2}$ and $K_{\mu 2}$ decay 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

TWIST recent graduates

James Bueno, Ryan Bayes, and Anthony Hillairet

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.
- $\mathcal{P}_\mu{}^\pi\xi\delta/\rho$ deviates by **+2.3**σ from the expected upper limit of 1.0.
- Substantial improvements in generalized LRS limits and muon coupling strengths were obtained.