Final Results for the Muon Decay Parameters from *TWIST*

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

Physics of Fundamental Symmetries and Interactions, PSI, Oct 2010

Decay parameters

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

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

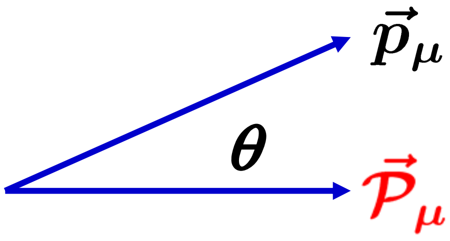
  - where

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

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

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



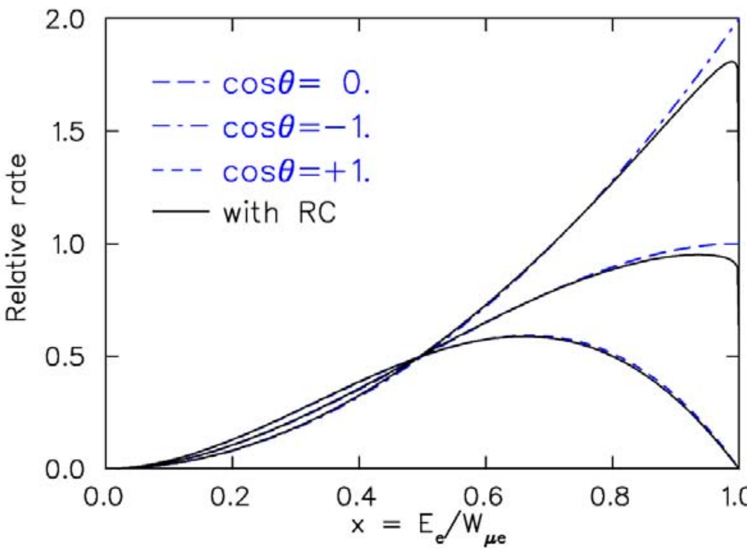
L. Michel, Proc. Phys. Soc. A63 (1950) 514

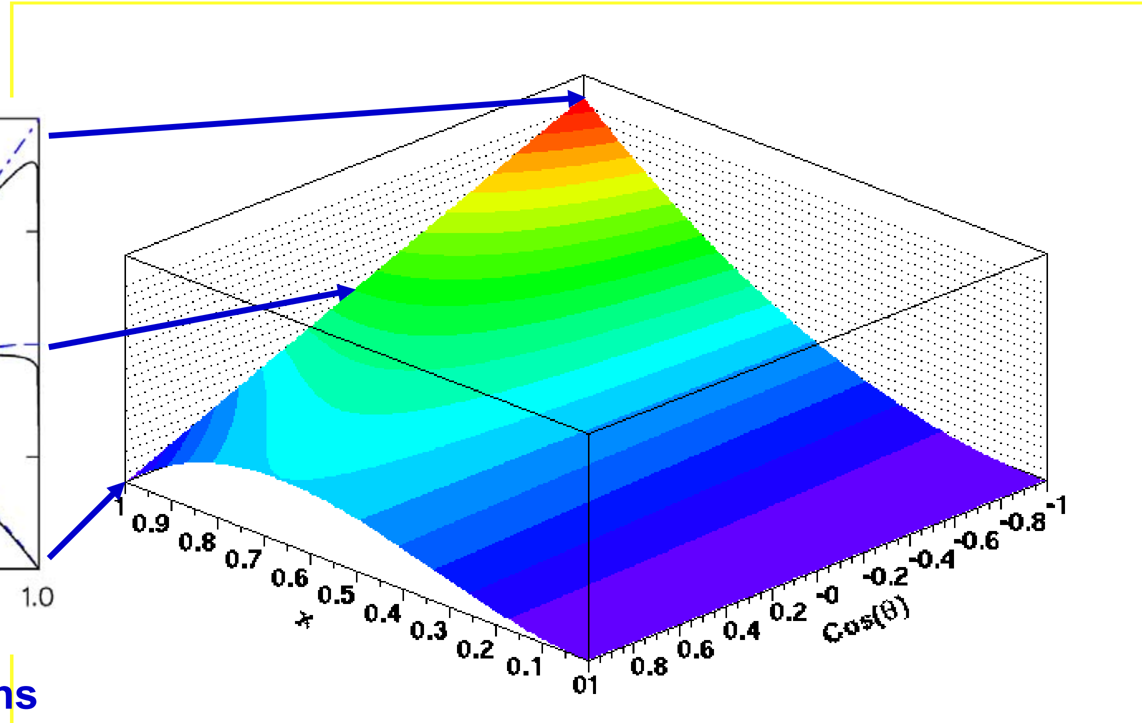
C. Bouchiat and L. Michel, Phys. Rev. 106 (1957) 170.

T. Kinoshita and A. Sirlin, Phys. Rev. 107 (1957) 593.

T. Kinoshita and A. Sirlin, Phys. Rev. 108 (1957) 844.

Spectrum shape and radiative corrections



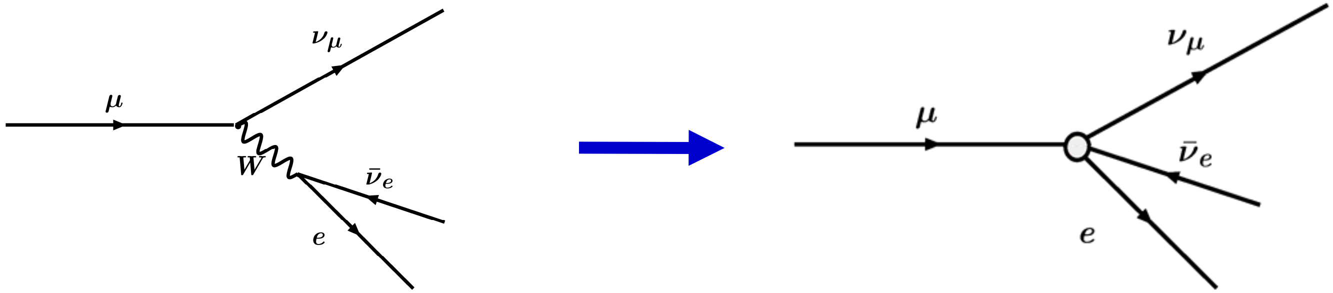


- **Full $\mathcal{O}(\alpha)$ radiative corrections with exact electron mass dependence.**
- **Leading and next-to-leading logarithmic terms of $\mathcal{O}(\alpha^2 L^2)$ and $\mathcal{O}(\alpha^2 L)$, $L = \ln((m_\mu/m_e)^2)$**
- **Leading logarithmic terms of $\mathcal{O}(\alpha^3 L^3)$.**
- **Ignores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

(θ for *TWIST* is (π - θ) in decay parameter definition)

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

Matrix elements



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

- Most general local, Lorentz-invariant, lepton-number conserving interaction determined by 19 real parameters.
- Includes scalar, vector, and tensor (Γ^S,Γ^V,Γ^T) interactions among left- and right-handed μ, e (SM: g^V_{LL} = 1, all others zero).
- Decay parameters are bilinear combinations of $g^{\gamma}_{\varepsilon\mu}$
- Probability for decay of μ–handed muon to ε–handed electron:

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

- For example, 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 (1986) 102-106

Pre-*TWIST* decay parameters

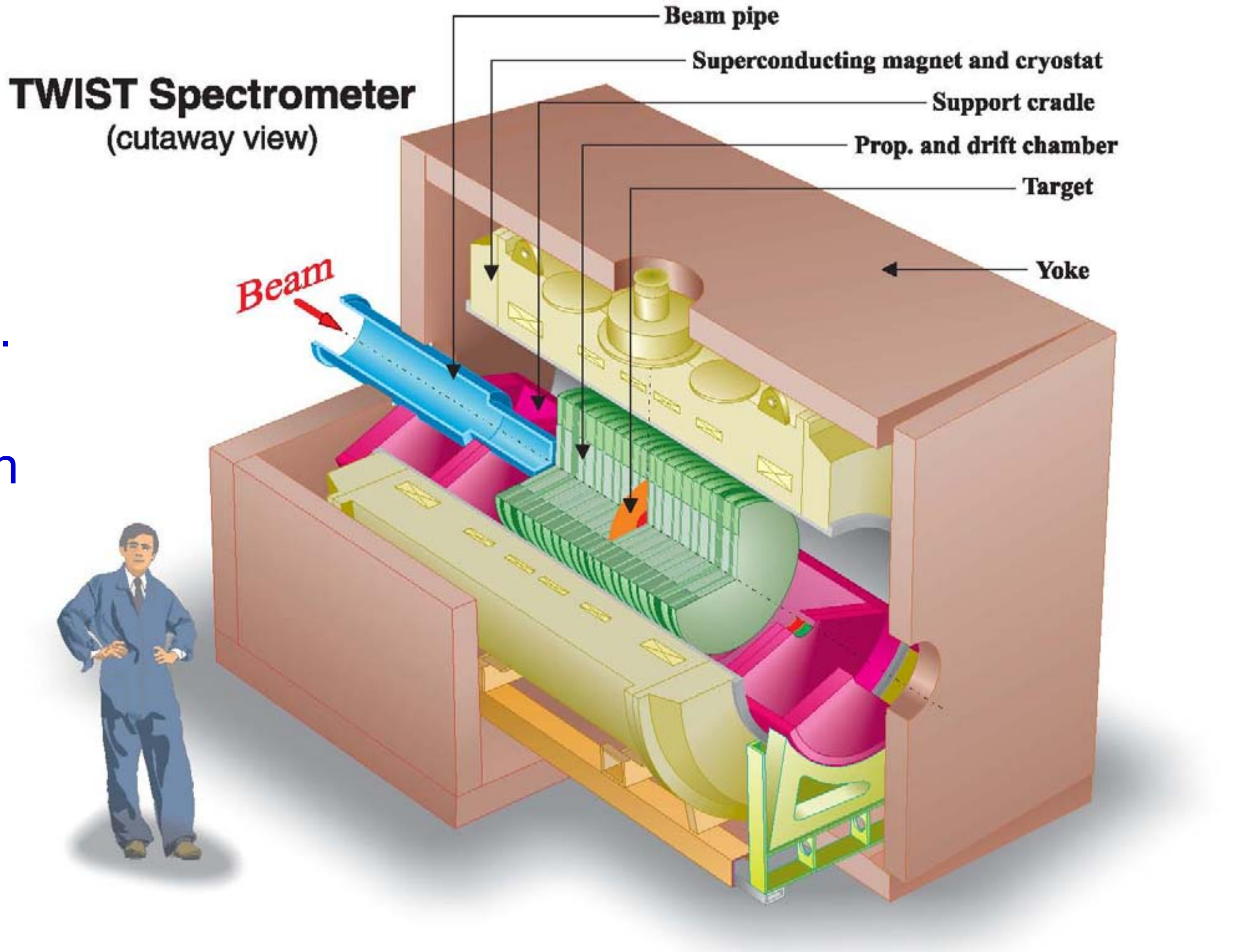
- From the Review of Particle Physics (SM values)
  - ρ = 0.7518 $\pm$ 0.0026 (S.E. Derenzo, Phys. Rev. 184 (1969) 1854) (0.75)
  - δ = 0.7486 $\pm$ 0.0026 $\pm$ 0.0028 (B. Balke *et al.*, Phys. Rev. D37 (1988) 587) (0.75)
  - $\mathcal{P}_\mu \xi$ = 1.0027 $\pm$ 0.0079 $\pm$ 0.0030 (I. Beltrami *et al.*, Phys. Lett. B194 (1987) 326) (1.00)
  - $\mathcal{P}_\mu(\xi\delta/\rho)$ > 0.99682 (90%CL) (A. Jodidio *et al.*, Phys. Rev. D341(1986) 1967, and erratum) (1.00)
  - η = 0.011 $\pm$ 0.085 (H. Burkhardt *et al.*, Phys. Lett. 160B (1985) 343) (now superseded) (0.00)

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.

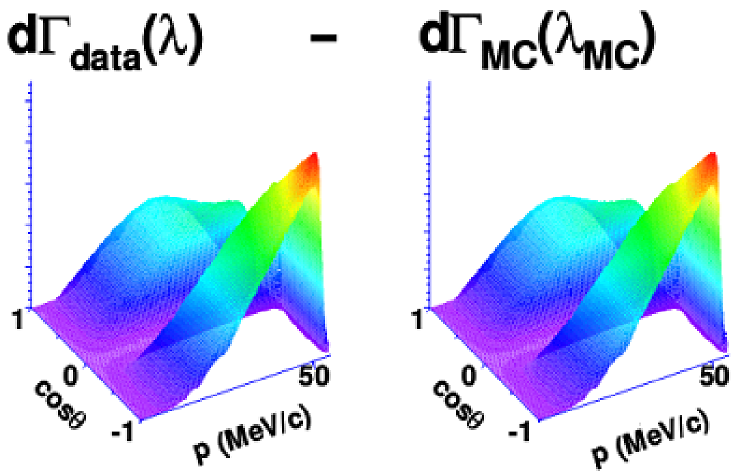
→ measure yield *vs.* energy and angle, and understand depolarization, *to a few parts in 10^4*.

Spectrometer and muon target

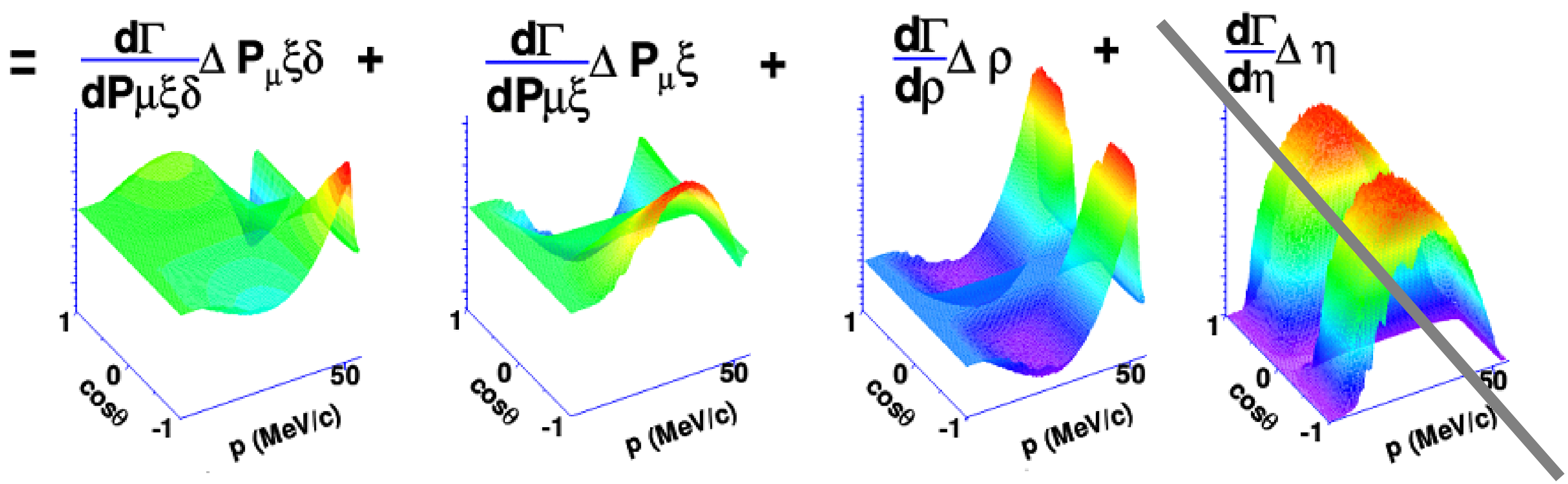
- Uses highly polarized μ^+ beam from M13.
- Stops μ^+ in a symmetric detector.
- Tracks e^+ through uniform, well-known field.
- Completed data taking in 2007.
- Extracts decay parameters by comparison to detailed GEANT3 simulation.



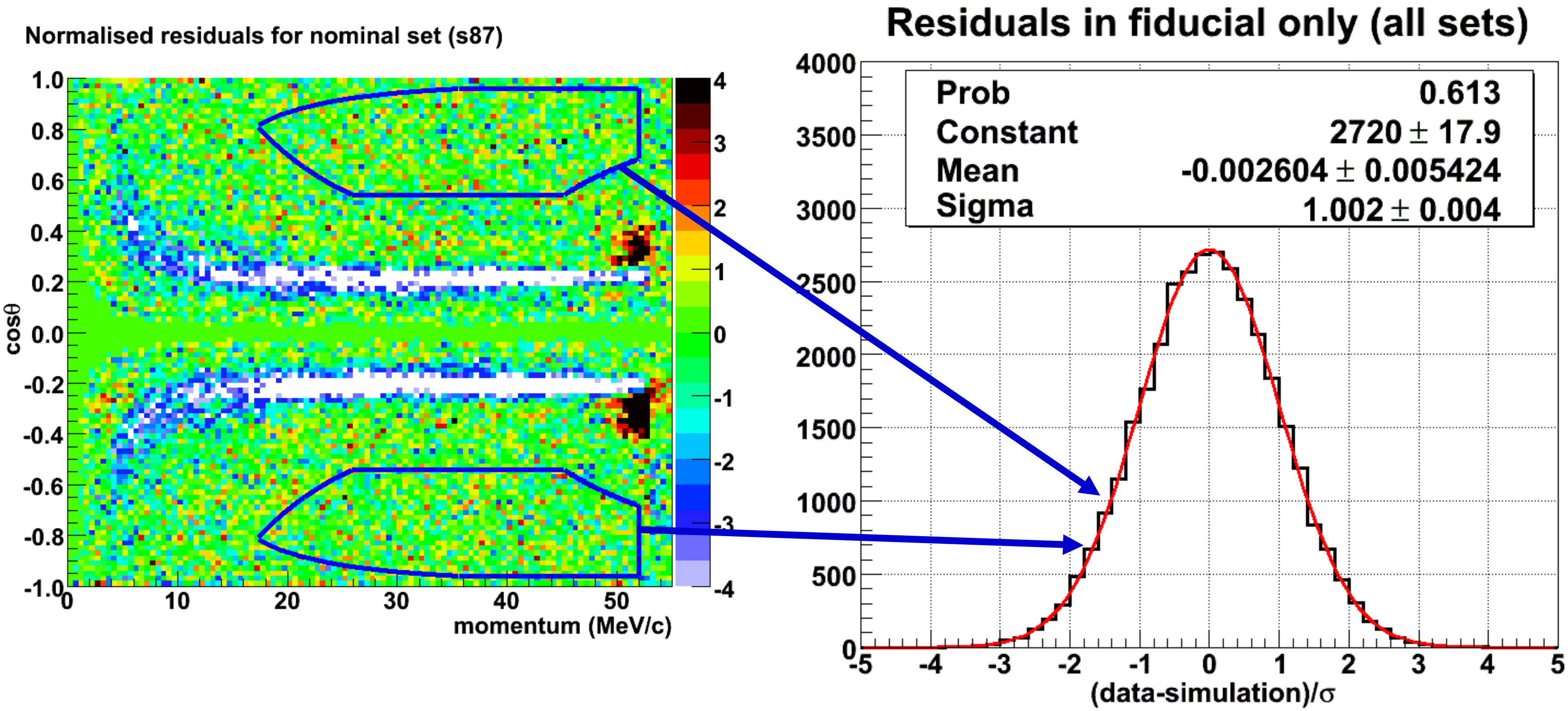
Two-dimensional spectrum fit



- fit data to normalized GEANT3 simulation
- use linearity in $\mathcal{P}_\mu\xi$, $\mathcal{P}_\mu\xi\delta$, ρ, η
- measure ***differences*** from hidden parameters λ_{MC} .

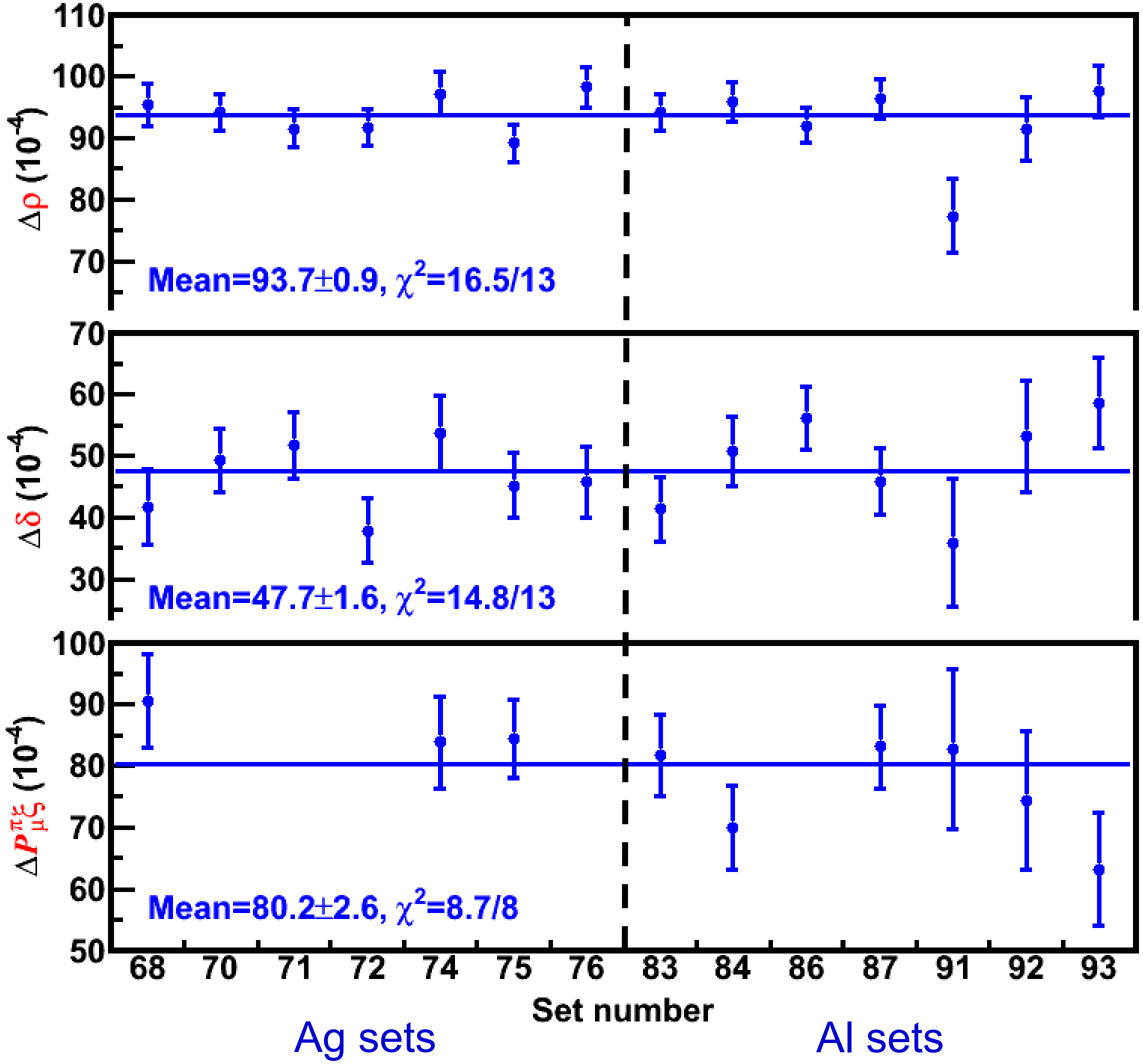


Spectrum fit quality



- 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**×**10**^{9} events, **0.55**×**10**^{9} in (p,cosθ) fiducial
- Simulation sets: 2.7 times data statistics

Set-to-set statistical consistency



Key:

- **Ag target sets**
  - **68- μ stop slightly US**
  - **70- B = 1.96T**
  - **71- B = 2.04T**
  - **72- TECs in**
  - **74- production**
  - **75- production**
  - **76- μ beam mis-steered**
- **Al target sets**
  - **83- DS extra material**
  - **84- production**
  - **86- μ beam mis-steered**
  - **87- production**
  - **91- low beam momentum**
  - **92- low beam momentum**
  - **93- low beam momentum**

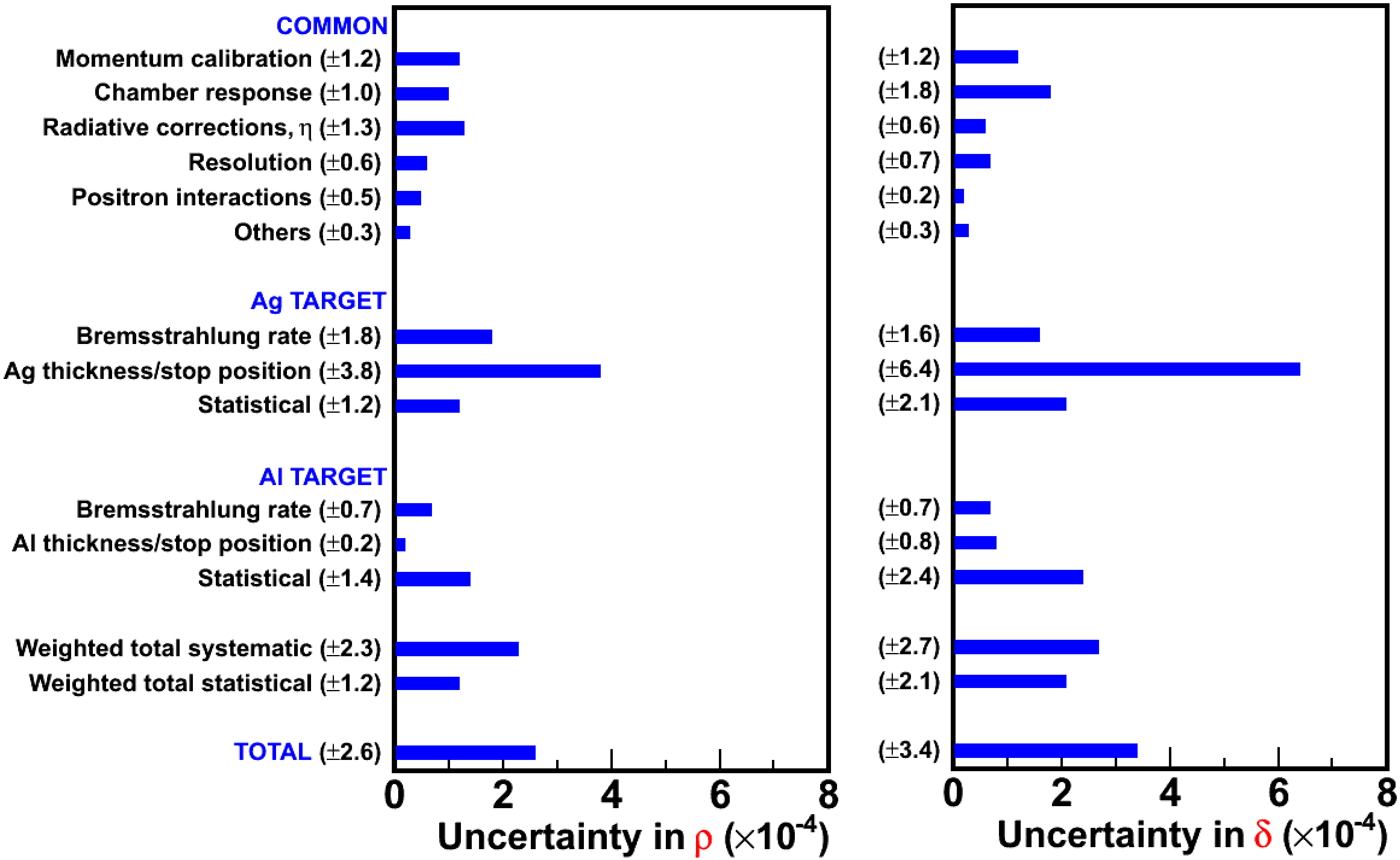
Differences (Δ) are with respect to blind parameters.

Set-dependent corrections are applied; error bars and weights for the means are *statistical only*.

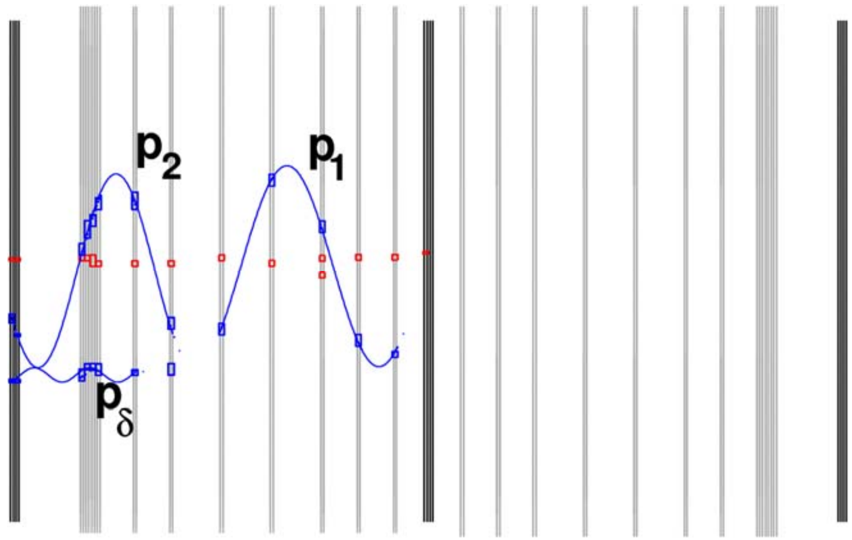
Blind *vs.* revised analysis

- The blind analysis results showed evidence of possible mistakes:
  - set-to-set statistical consistency satisfactory for ρ, δ, and $\mathcal{P}_\mu^\pi\xi$, 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 <1σ.

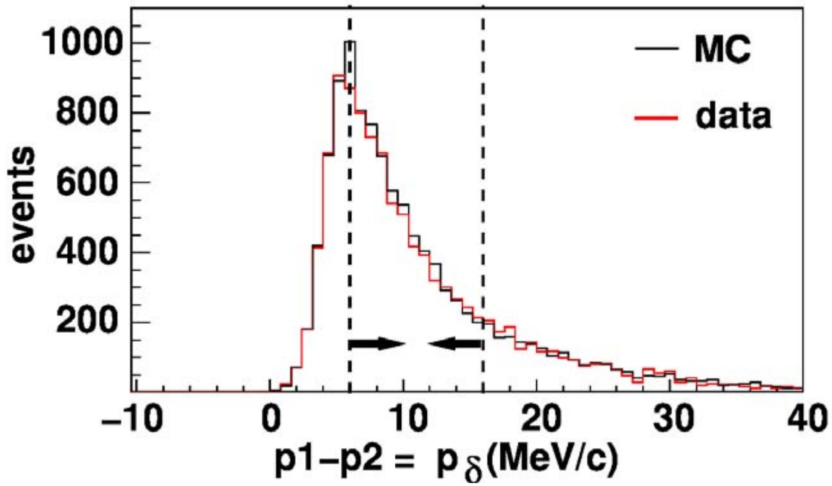
Uncertainties in ρ and δ

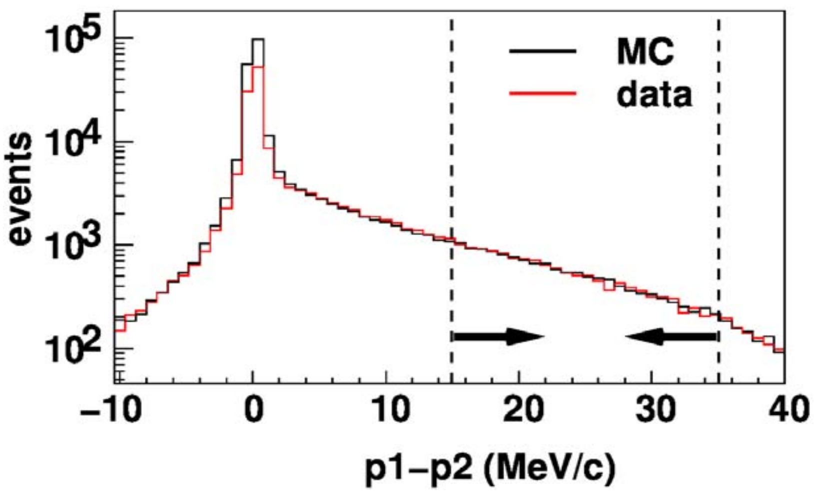


Positron interactions systematic

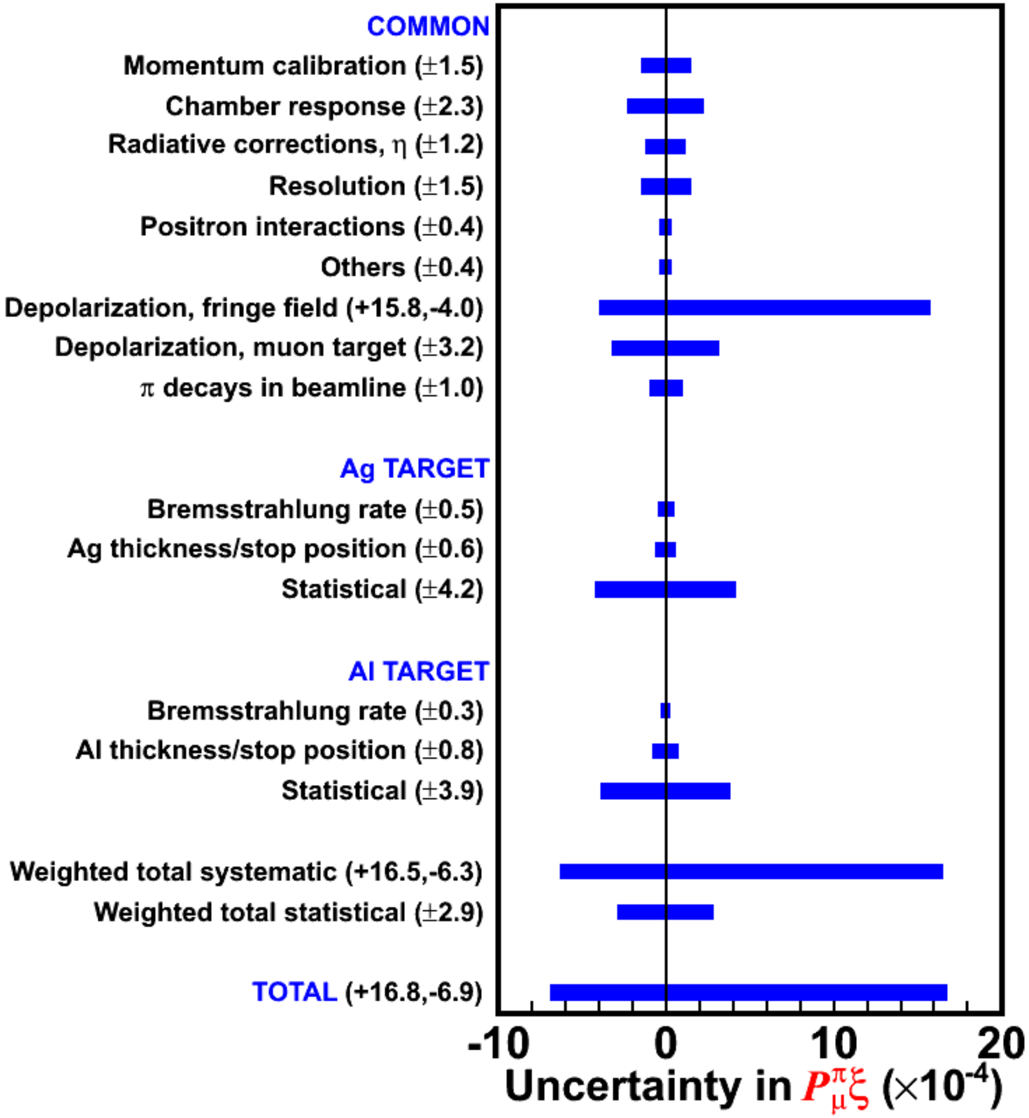


- **"Broken tracks" analysis:**
  - 2 e^- , 1 e^+ ➔ δ -electron
  - 2 e^+ ➔ Bremsstrahlung
- **Agreement of data and sim:**
  - δ -electrons < 1%
  - Bremsstrahlung differs by 2.4%



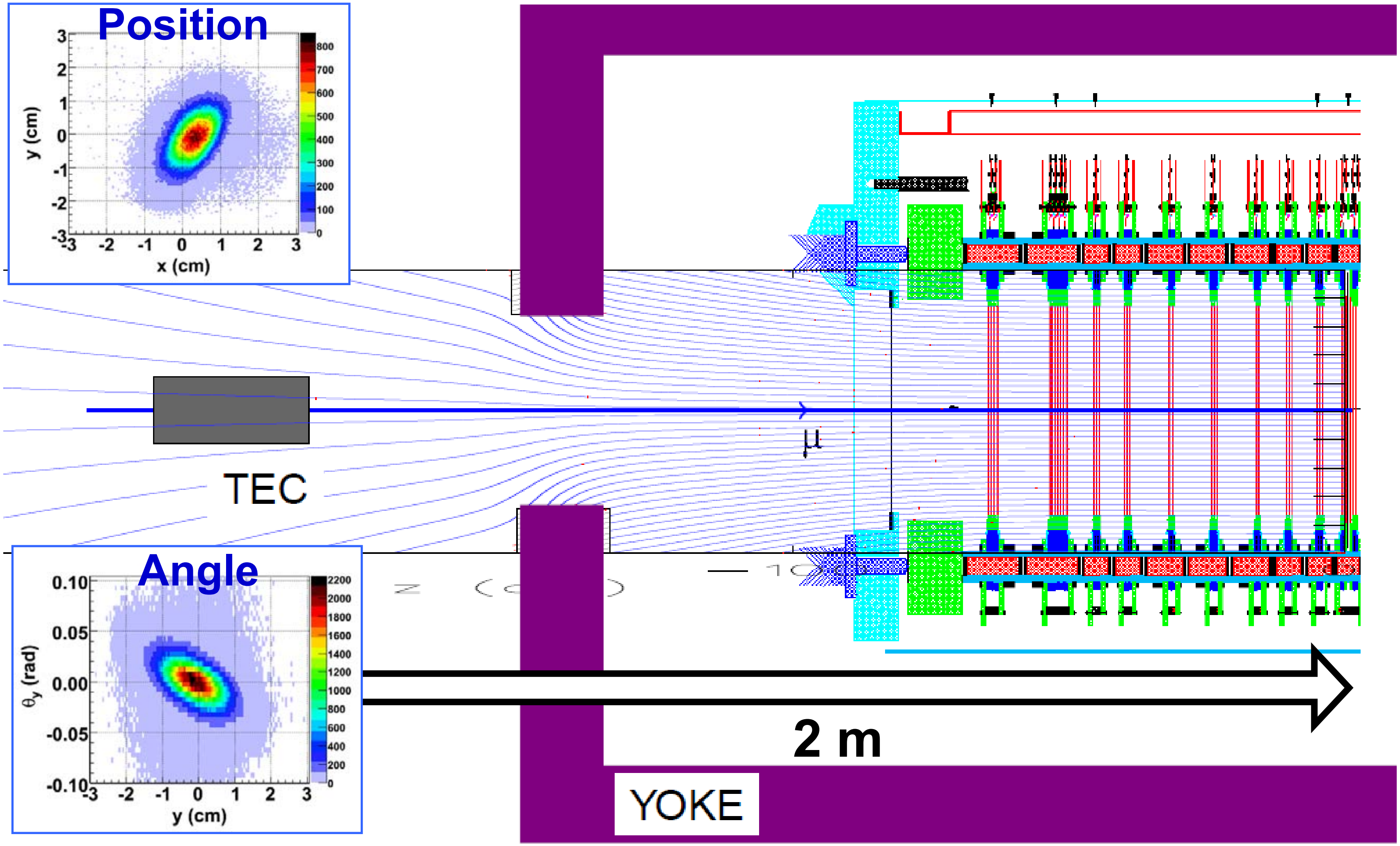


Uncertianties in $\mathcal{P}_\mu^\pi\xi$

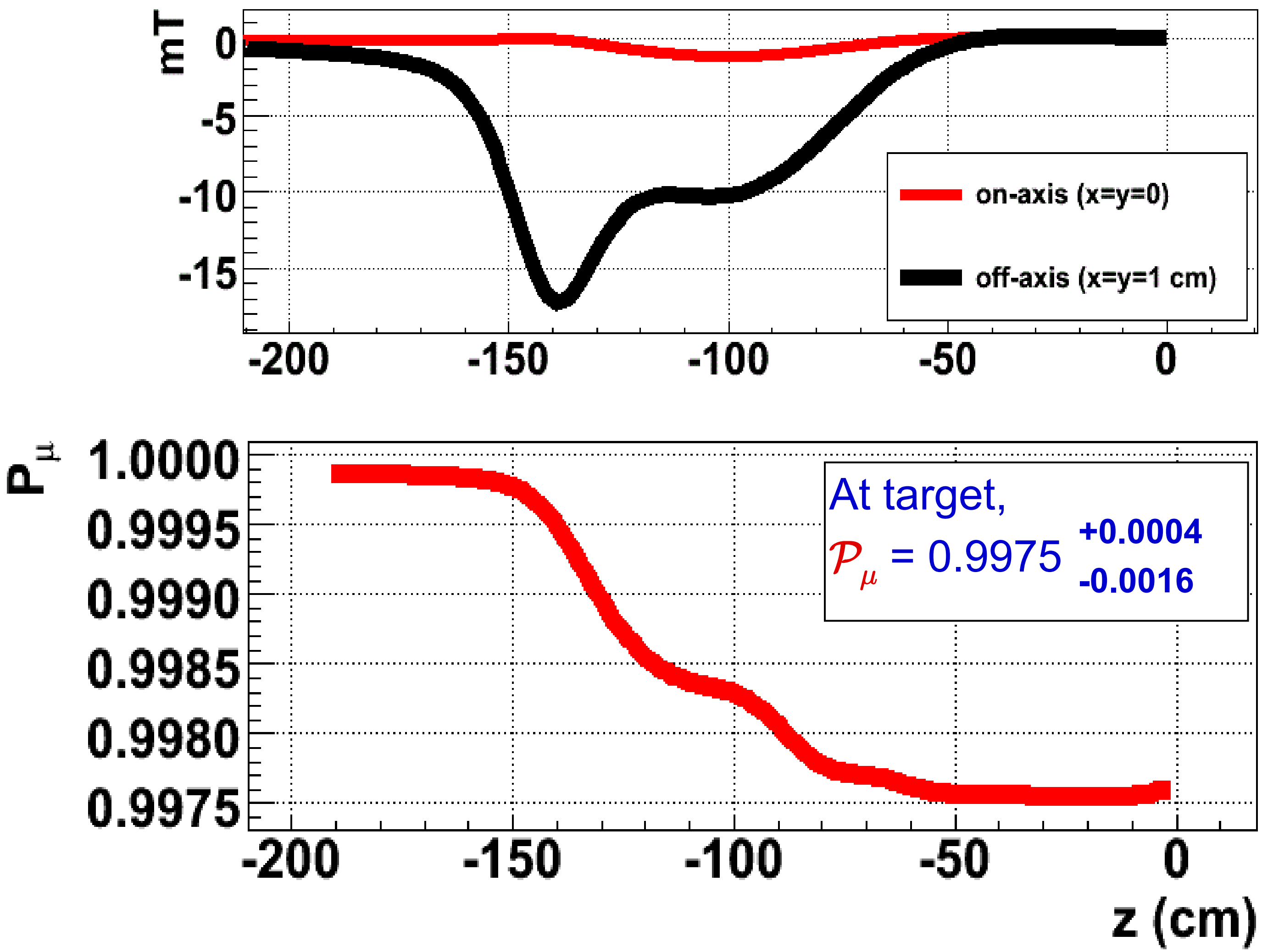


- Uncertainties for all three parameters are from the revised analysis
- Differences to blind results are small:
  - $\sigma(\rho)$ changed by **-0.3×10^{-4}**
  - $\sigma(\delta)$ changed by **$+0.1\times10^{-4}$**
  - $\sigma(\mathcal{P}_\mu^\pi\xi_{avg})$ changed by **-0.2×10^{-4}**
- Difference of $\mathcal{P}_\mu^\pi\xi\delta/\rho$ for Ag and Al is reduced to $<1\sigma$ in the revised analysis.

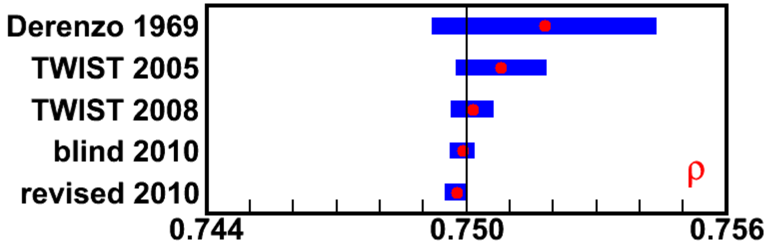
Fringe field depolarization



Asymmetric depolarization systematic

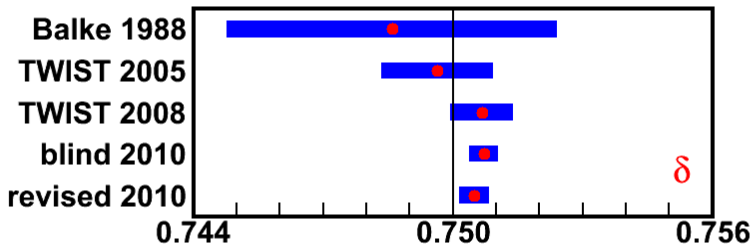


Decay parameter results



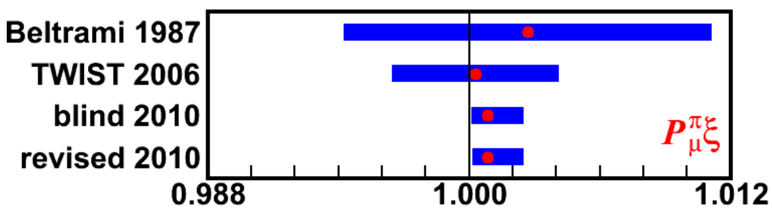
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

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



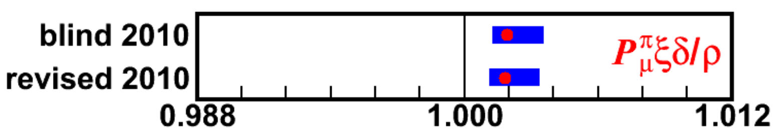
δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

(+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

Left-right symmetric analysis

- Heavy 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 (1986) 3499 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:

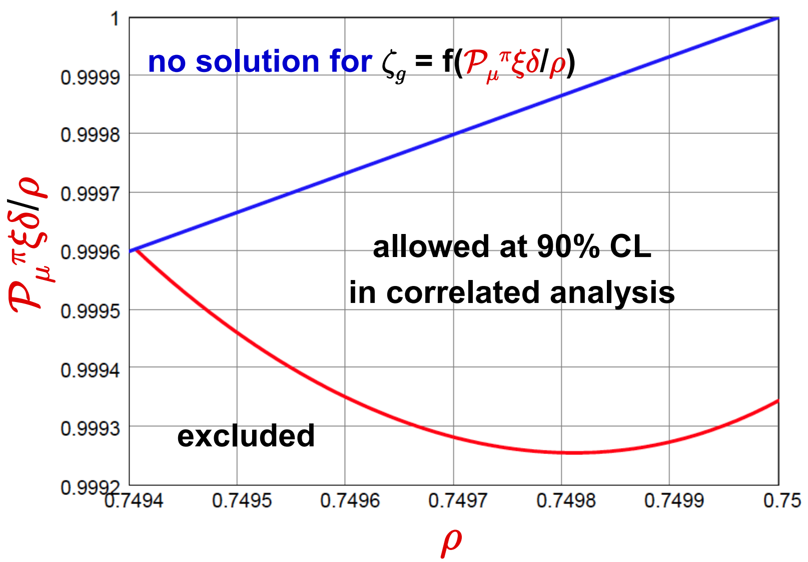
$$\rho \simeq \frac{3}{4}(1 - 2\zeta_g^2), \quad \delta = \frac{3}{4}, \quad \xi \simeq 1 - 2(t^2 + \zeta_g^2),$$

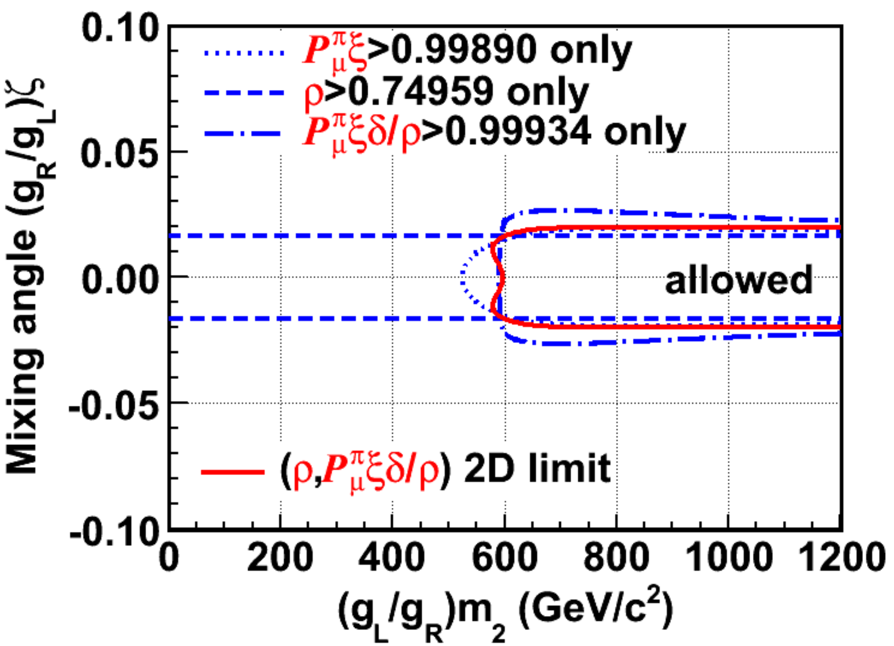
$$\mathcal{P}_\mu^\pi \simeq 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g \cos(\alpha + \omega)$$

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

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

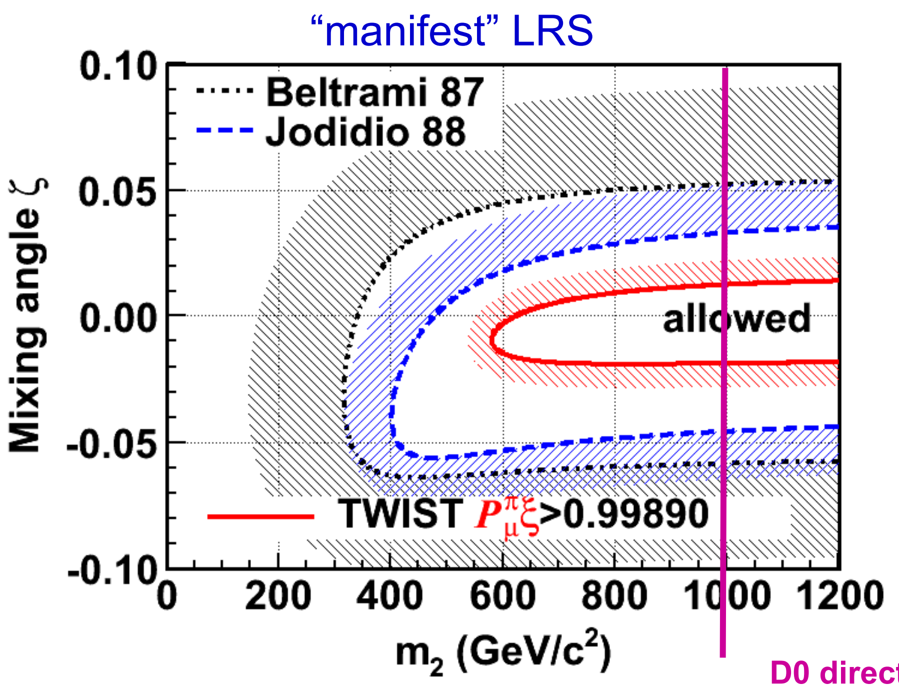
TWIST 2D exclusion plot and LRS limits

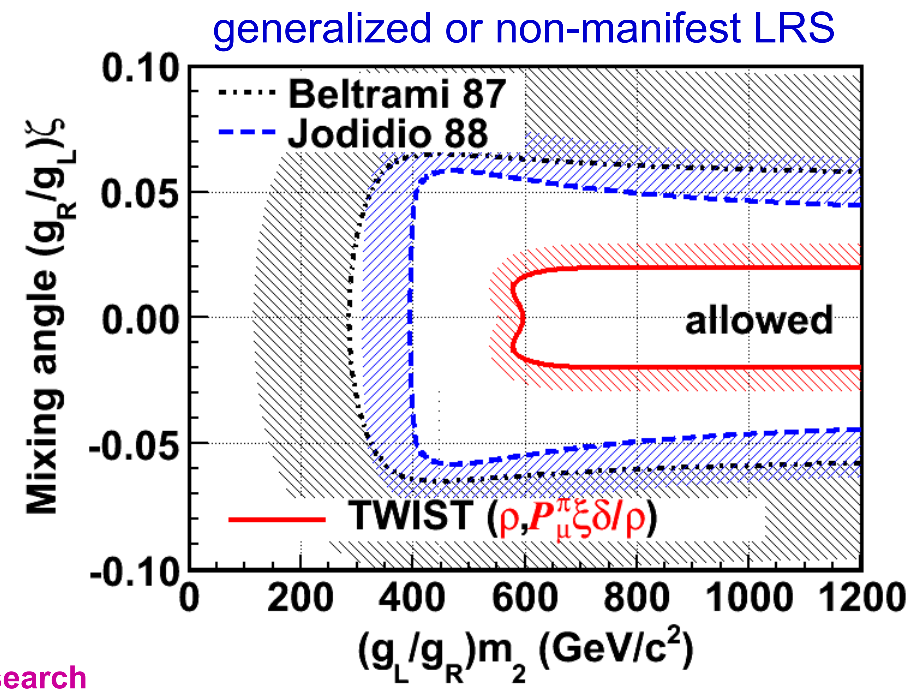




- Previous muon decay LRS parameter limits used individual limits for ρ, $\mathcal{P}_\mu^\pi\xi$, or $\mathcal{P}_\mu^\pi\xi\delta/\rho$.
- *TWIST* has simultaneous measurements of three parameters; correlations contribute to the confidence interval.

LRS limit comparison





D0 direct search lower limit
Abazov et al., Phys. Rev. Lett. 100 (2008) 031804

$m_2 > 582$ GeV/c^2

$-0.019 < \zeta < +0.014$

$(g_L/g_R)m_2 > 578$ GeV/c^2

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

Global analysis result

- Include new results with other muon decay observables to restrict coupling constants
  - influences mostly right-handed muon terms

$$
\begin{aligned}
Q^{\mu}_{R} &= \frac{1}{4}|g^{S}_{LR}|^2 + \frac{1}{4}|g^{S}_{RR}|^2 + |g^{V}_{LR}|^2 + |g^{V}_{RR}|^2 + 3|g^{T}_{LR}|^2 \\
&= \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \\
&< 8.2 \times 10^{-4} \quad (90\%\mathrm{C.L.})
\end{aligned}
$$

  - $\sim 6\times$ reduction

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.

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

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

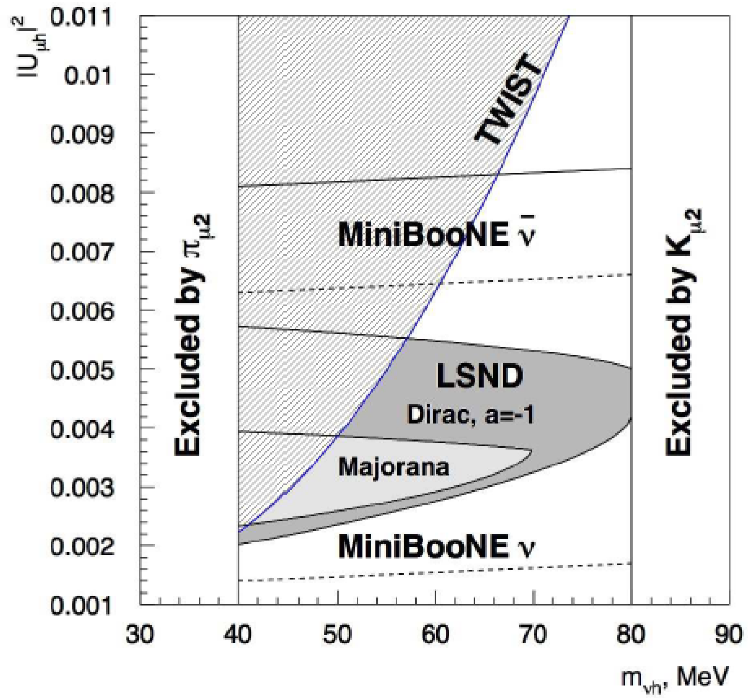


FIG. 24: The 2σ allowed region (dark areas) in the $(m_{\nu_h}; |U_{\mu h}|^2)$ parameter space for Dirac ($a = -1$) and Majorana cases obtained from the combined analysis of LSND and MiniBooNE ν_μ and $\overline{\nu}_\mu$ data. The regions excluded by the $\pi_{\mu 2}$ and $K_{\mu 2}$ decay experiments [36] and allowed bands from MiniBooNe $\overline{\nu}_\mu$ (solid line) and ν_μ (dashed lines) data, are also shown. The hatched region is excluded from the results of precision measurements of the muon decay parameters by the TWIST experiment [37], see Sec. VI.

Heavy sterile neutrino model

S.N. Gninenko, arXiv:1009.5536v2, Sep 2010

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.

TWIST participants, past and present

TRIUMF

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Vladimir Selivanov

Texas A&M

Carl Gagliardi
Jim Musser $**$
Bob Tribble

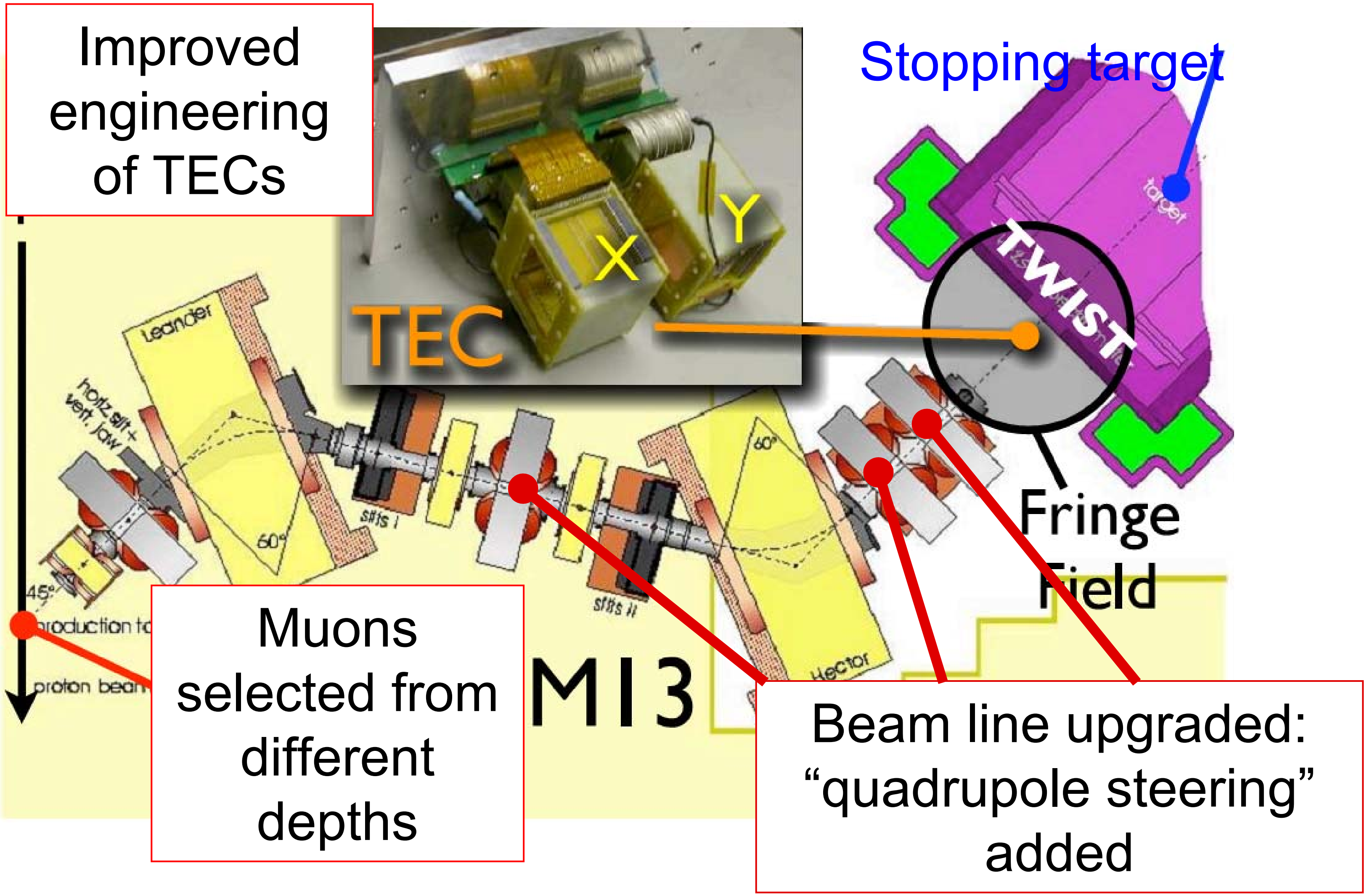
Valparaiso

Don Koetke
Shirvel Stanislaus

$*$ Recently graduated
$**$ Graduated
$\dagger$ also U Vic
$\ddagger\ddagger$ also Saskatchewan
§ deceased

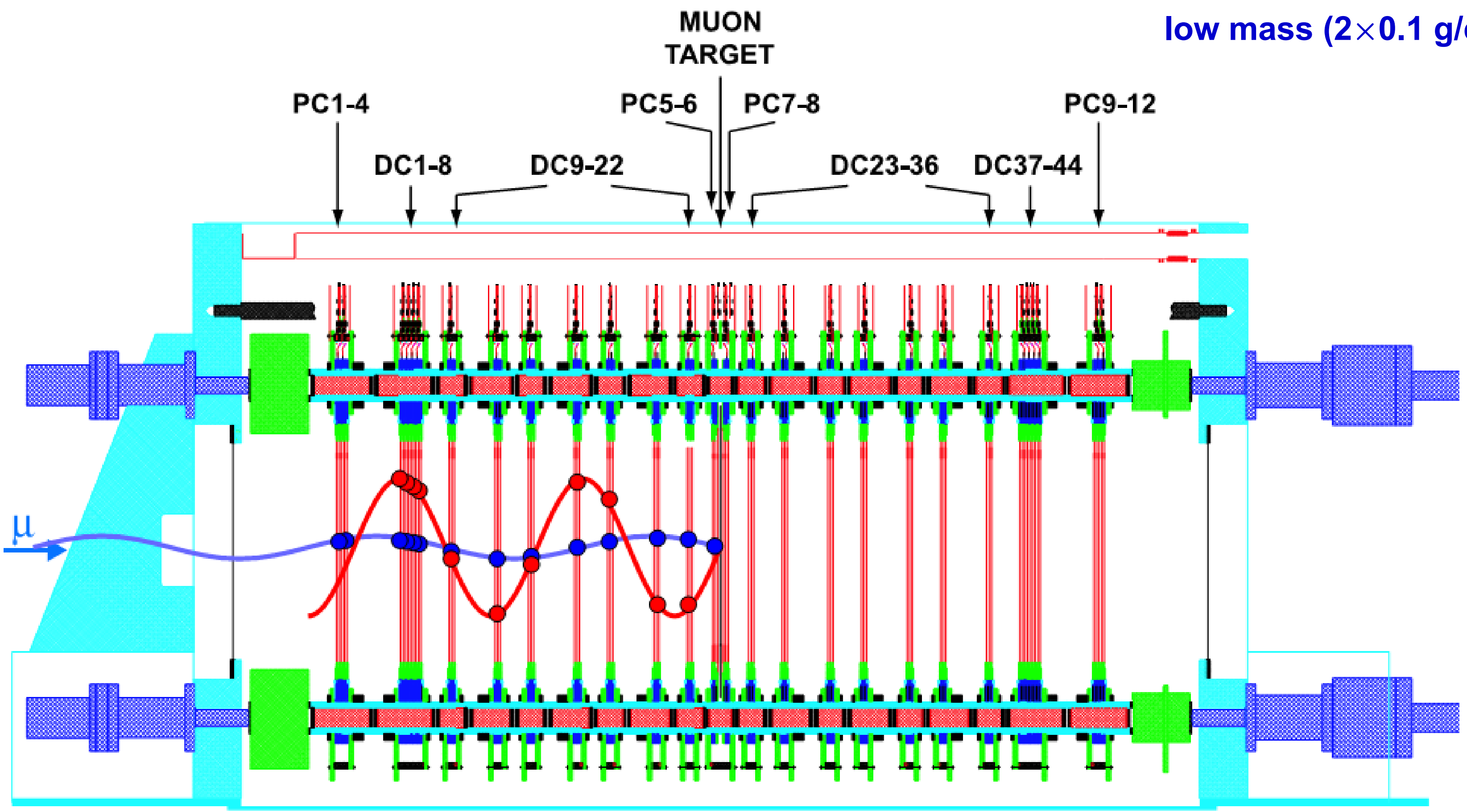
extra slides

Muon production and transport



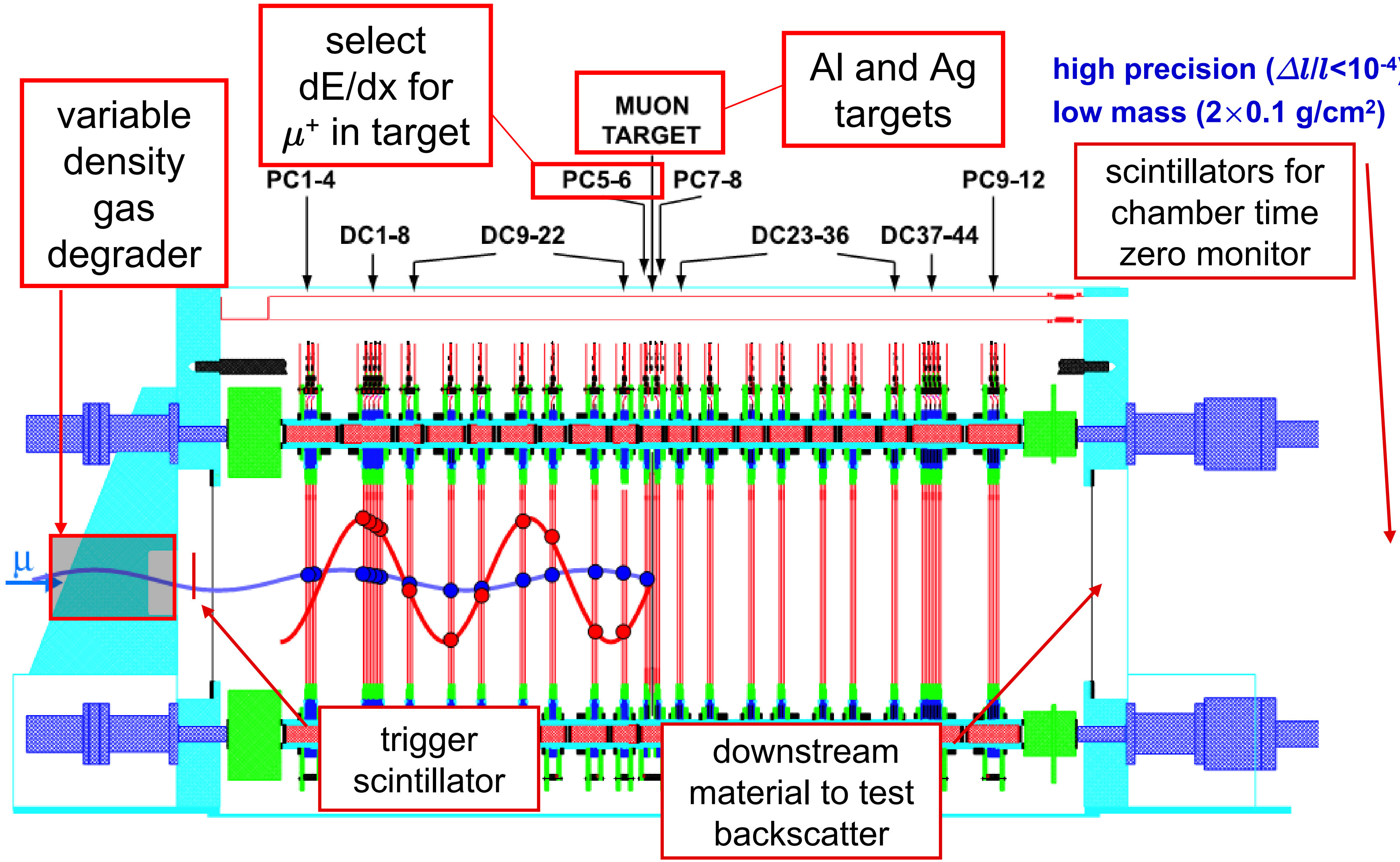
Detector array

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



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

Detector array



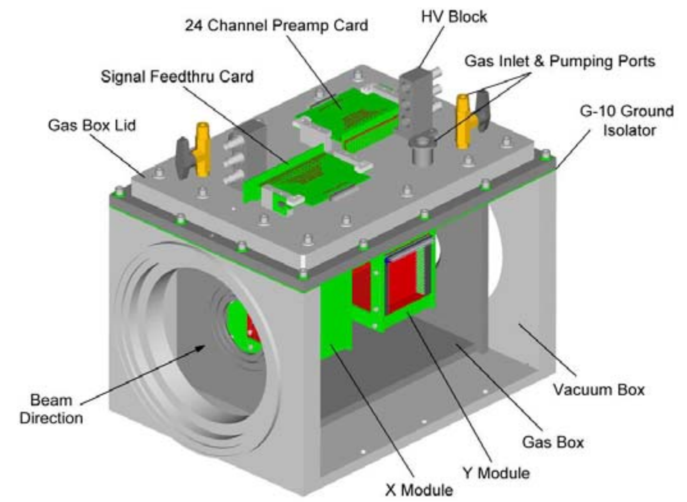
high precision ($\Delta l/l < 10^{-4}$)
low mass (2×0.1 g/cm^2)

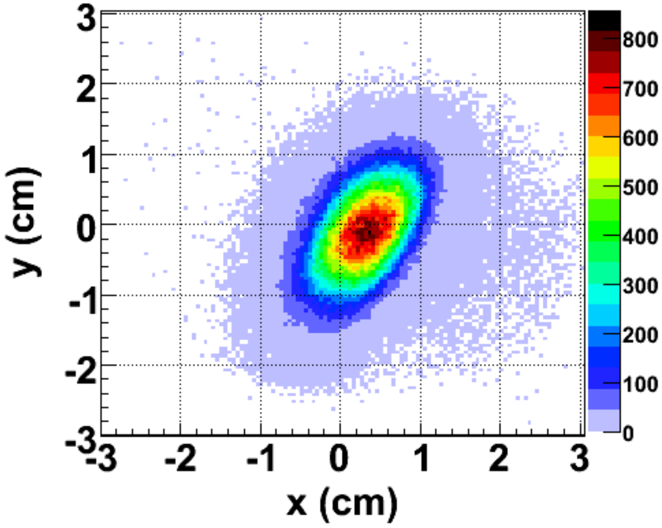
R. Henderson et al., Nucl. Instr. and Meth. A548 (2005) 306-335

TECs for beam characterization

- Need to know x, y, θ_x, θ_y, and correlations, for incident muon beam.
- Measure in two modules of low pressure (80 mbar) time expansion chambers (TEC).
- “Correct” for multiple scattering ($\sim$ 20 mrad rms).
- Simulate by sampling corrected distributions.
- Decay parameters measured with TEC removed; multiple scattering reduces polarization.

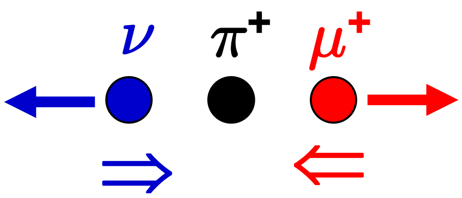
J. Hu et al., NIM A566 (2006) 563-574

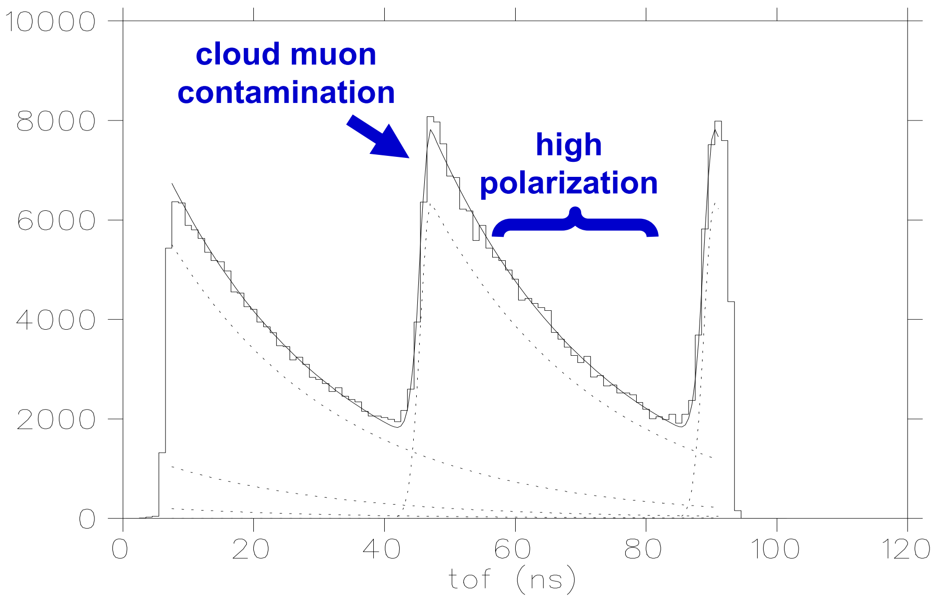




Surface muon polarization

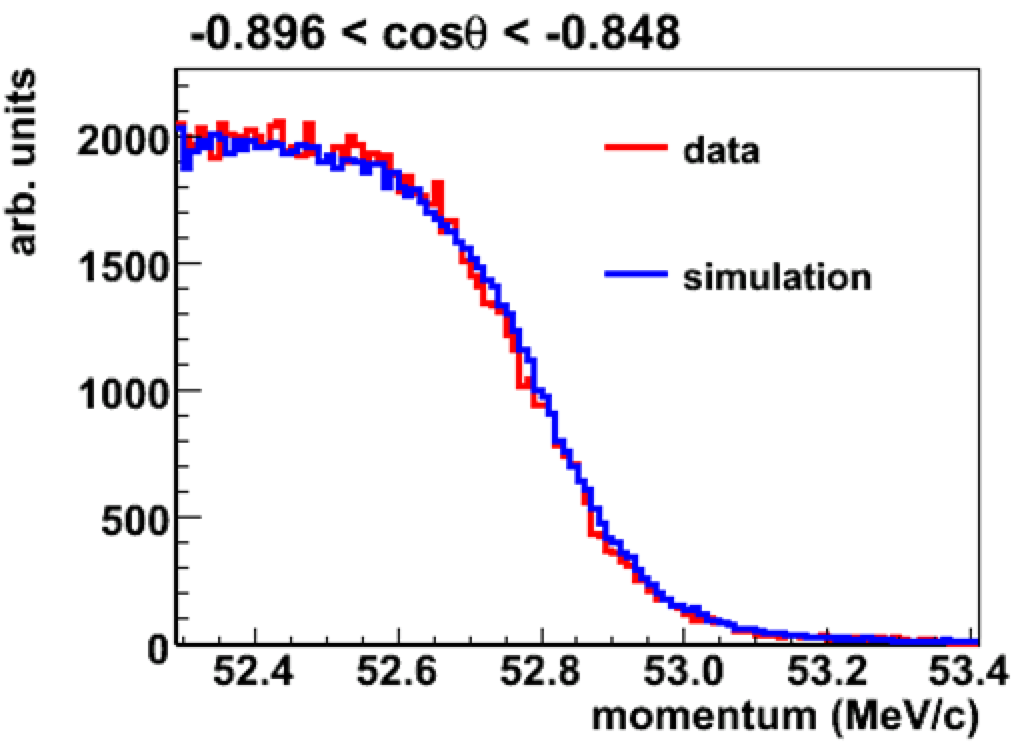
- Pions decaying at rest produce muon beams with $\mathcal{P}_\mu > 99\%$.
- Depolarization must be controlled using small beams near kinematic edge, 29.8 MeV/c.
- Use $\sim 4 \times 10^3\ \mu^+\ s^{-1}$.
- Muon total range at density $\sim$1 only about 1.5 mm!



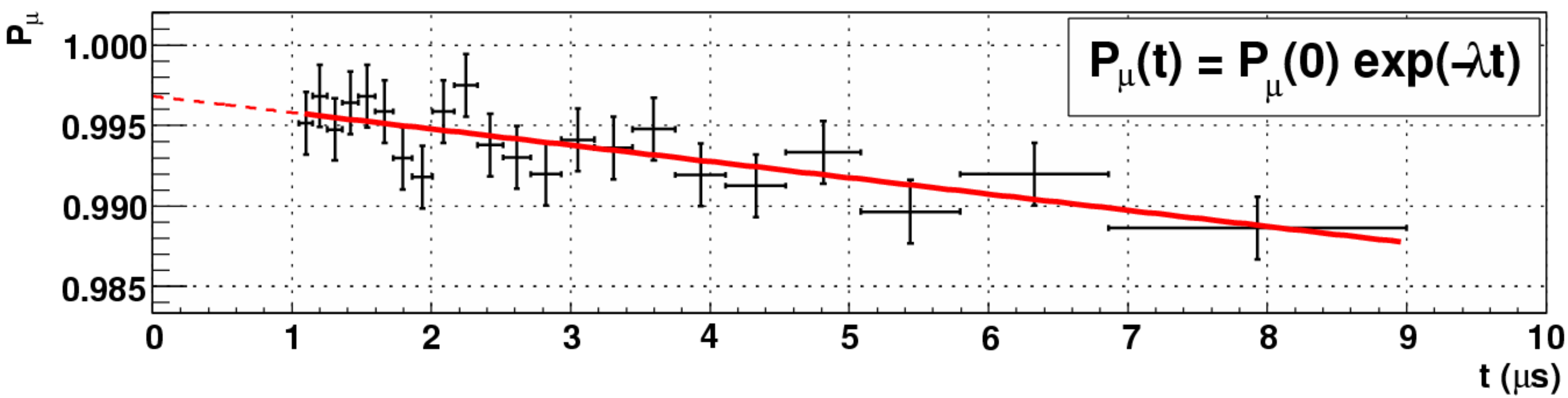


Momentum calibration

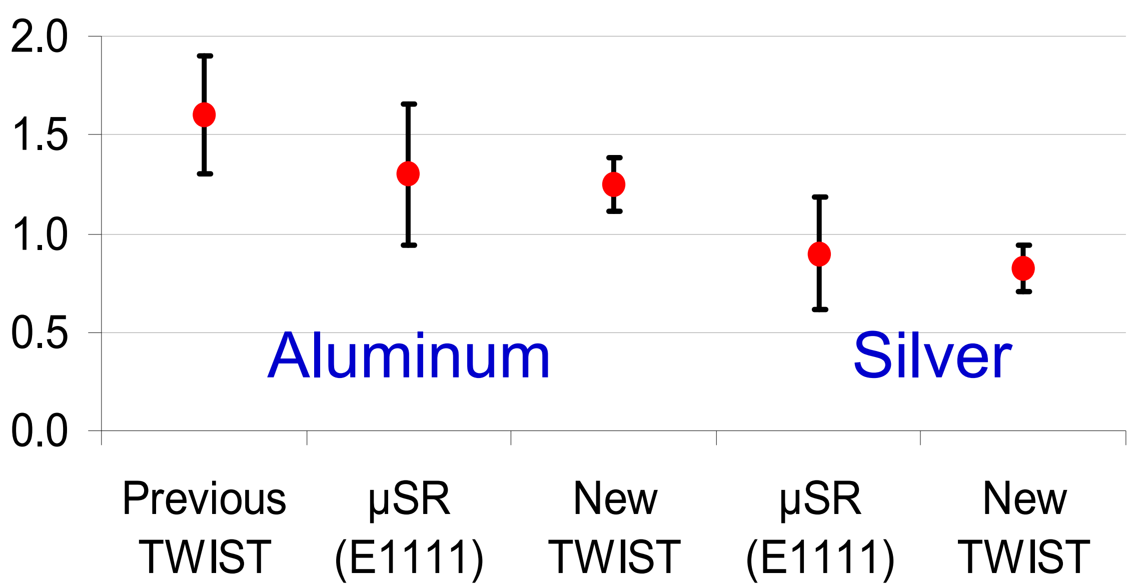
- Use kinematic edge at 52.8 MeV/c: energy loss and planar geometry lead to cosθ dependence.
- Difference of ~10 keV/c prior to calibration.
- Calibration at edge provides no guidance on how to propagate the difference to lower momenta in the spectrum.



Depolarization in muon target material

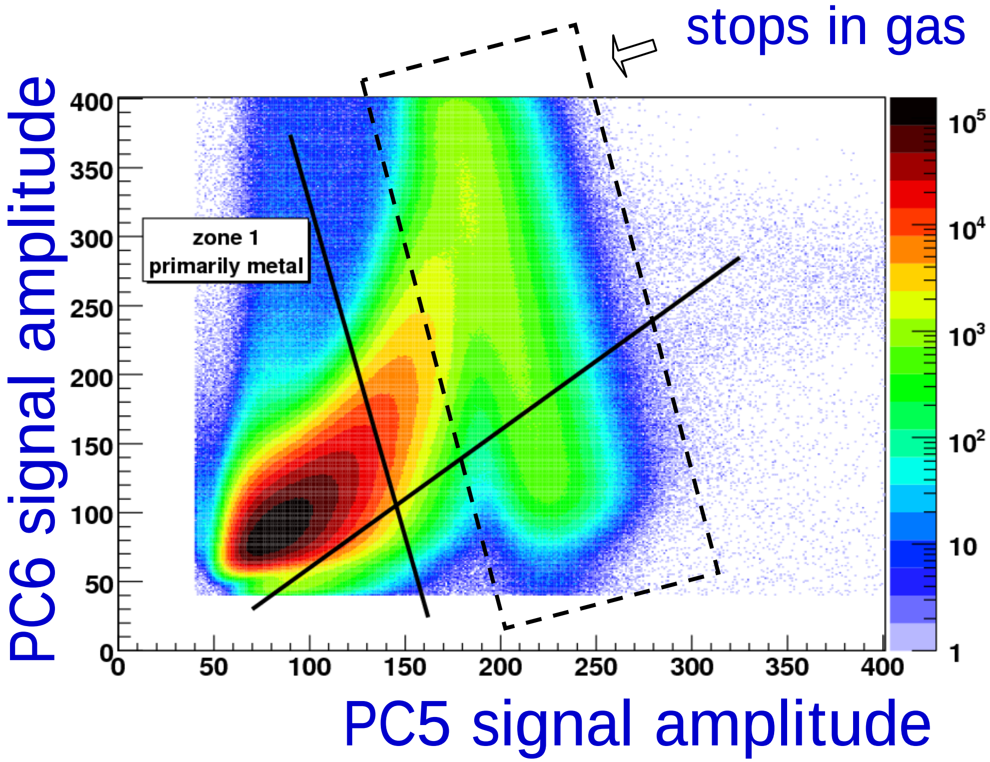


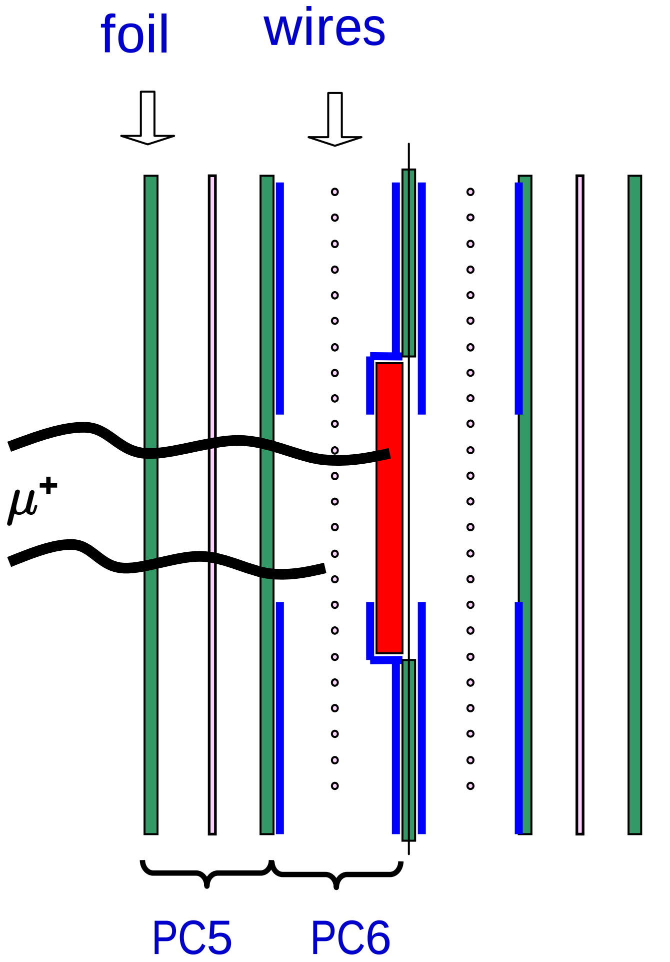
- **Estimate of relaxation is included in simulation; small correction is made to polarization parameter.**
- ***μSR*** **experiment establishes no fast relaxation.**
- **Statistical uncertainty in λ is included in decay parameter statistical uncertainty.**



Selecting muons in metal target

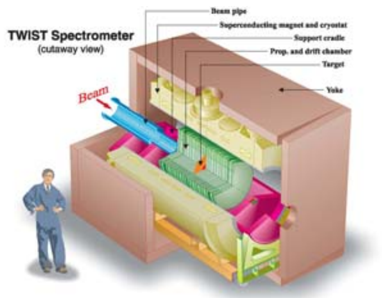
- Place cut on 2-d distribution so that <0.5% of “stops in gas” contaminate “stops in target” region (zone 1).





Blind analysis

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



Data from experiment

Hidden parameter tolerances 0.01

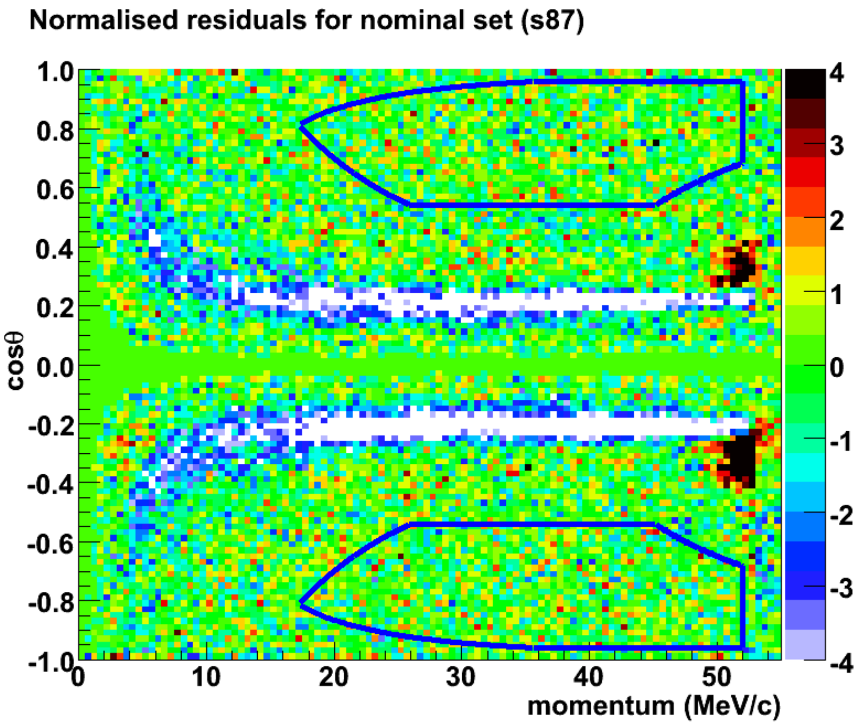
“Data” from simulation

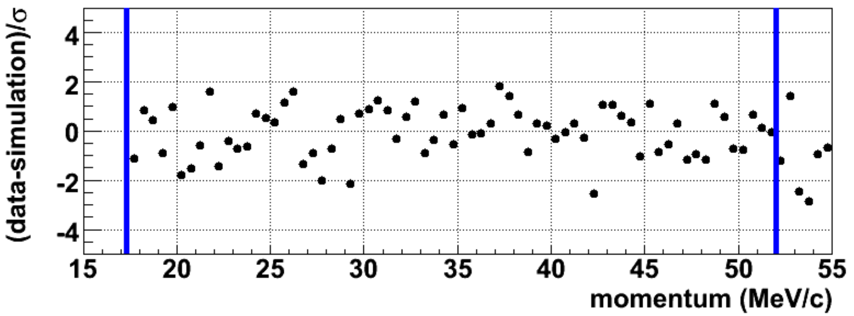
Reconstruction software

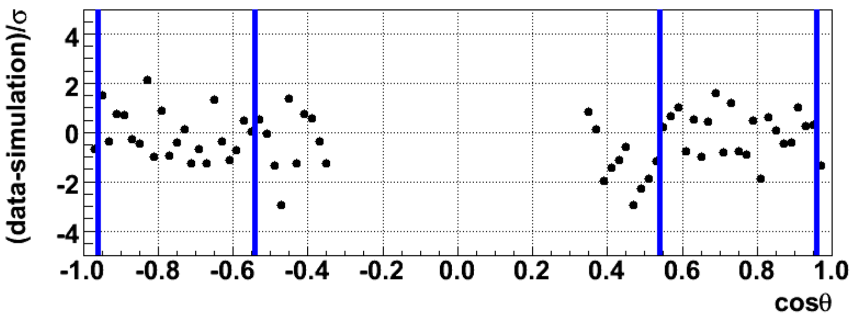
Spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta\mathcal{P}_{\mu}^{\pi}\xi$

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

Spectrum fit quality







Corrections to fit results

- Depolarization from scattering in production target
  - $+0.9\times10^{-4}$ for full momentum sets, $+5.6\times10^{-4}$ for reduced momentum sets, for $\mathcal{P}_\mu\xi$ only.
- Simulations generated with incorrect polarization relaxation rates
  - $+2.9\times10^{-4}$ for Ag sets, $+2.4\times10^{-4}$ for Al sets
- Statistical biases
  - χ^2 fitting of Poisson statistics with 1/N weight is biased
  - in fitting data to simulation, weight includes 1/N from both
    - for unequal statistics, this is biased by $\sim0.5\times10^{-4}$
  - energy calibration fit bias of typically $(-1.1,-0.4,+1.9)\times10^{-4}$ for ρ, δ, $\mathcal{P}_\mu\xi$, applied set-by-set