Muon Decay Parameters From TWIST

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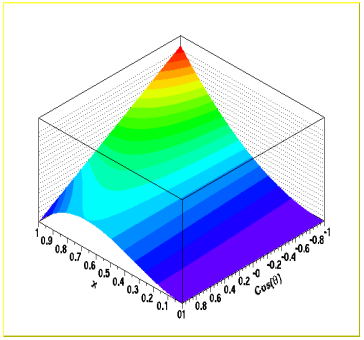
for the TWIST Collaboration

Outline

- Muon decay physics
- TWIST Experiment
- Systematics
- Results

Muon decay spectrum

The energy and angle distributions of positrons following polarized muon decay obey:



$$\frac{d^2\Gamma}{x^2\,dx\,d(\cos\theta)} \propto (3-3x)+\frac{2}{3}\rho(4x-3)+3\eta\frac{x_0}{x}(1-x)$$
$$+P_\mu\xi\cos\theta\left[(1-x)+\frac{2}{3}\delta(4x-3)\right]$$

(+ rad. corr.)

where $x=\frac{E_e}{E_{e,\max}}$

- Lorentz invariant, local weak interaction.
- SM postulates maximally parity violating V-A: ρ=δ=3/4; ξ=1;η=0.
- Mediated by W boson.
- Empirically based – tested in present work.

Muon decay matrix element

- Most general Lorentz-invariant, local, lepton-number conserving muon decay matrix element:

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

- The muon decay parameters are bi-linear combinations of the $g^{\gamma}_{\varepsilon\mu}$
- In the Standard Model, g^{V}_{LL} = 1, all others are zero
- Pre-**TWIST** global fit results (all 90% c.l.):

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.550$	$\lvert g^V_{LL}\rvert > 0.960$	$\lvert g^T_{LL}\rvert \equiv 0$

Goal of TWIST

- Search for new physics that can be revealed by **order-of-magnitude improvements** in our knowledge of **ρ**, **δ**, and $P_\mu\xi$

Two examples

- Model-independent limit on muon handedness

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

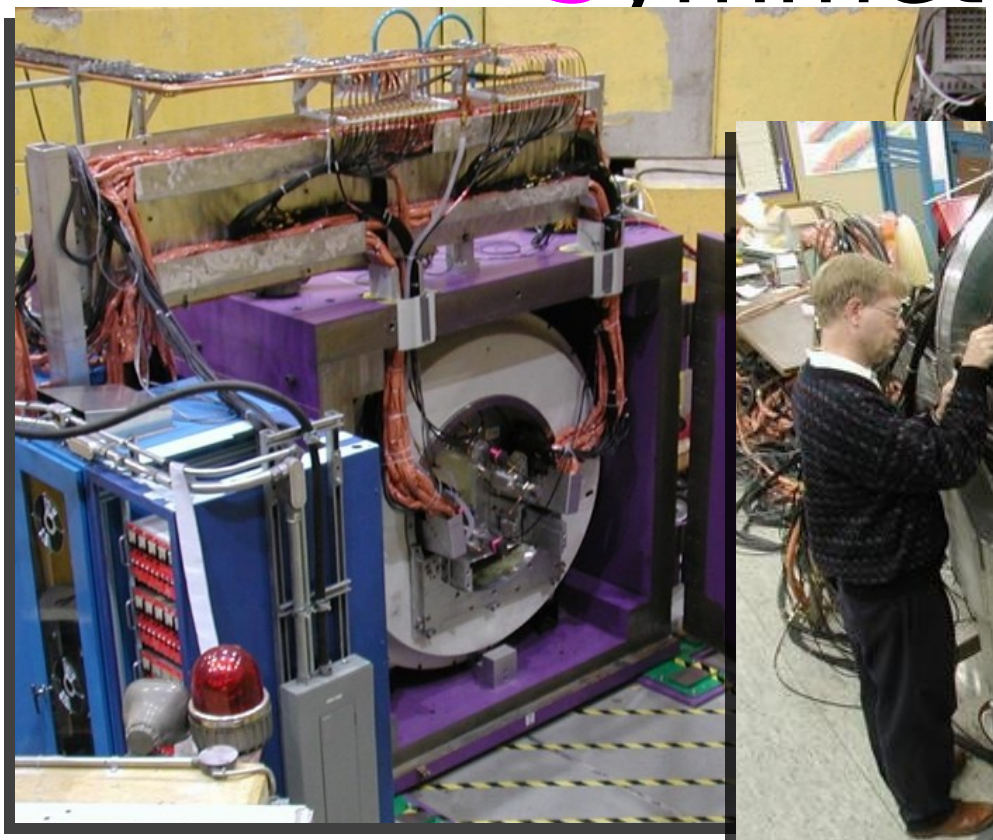
- Left-right symmetric model: $SU(2)_L \times SU(2)_R \times U(1)$

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

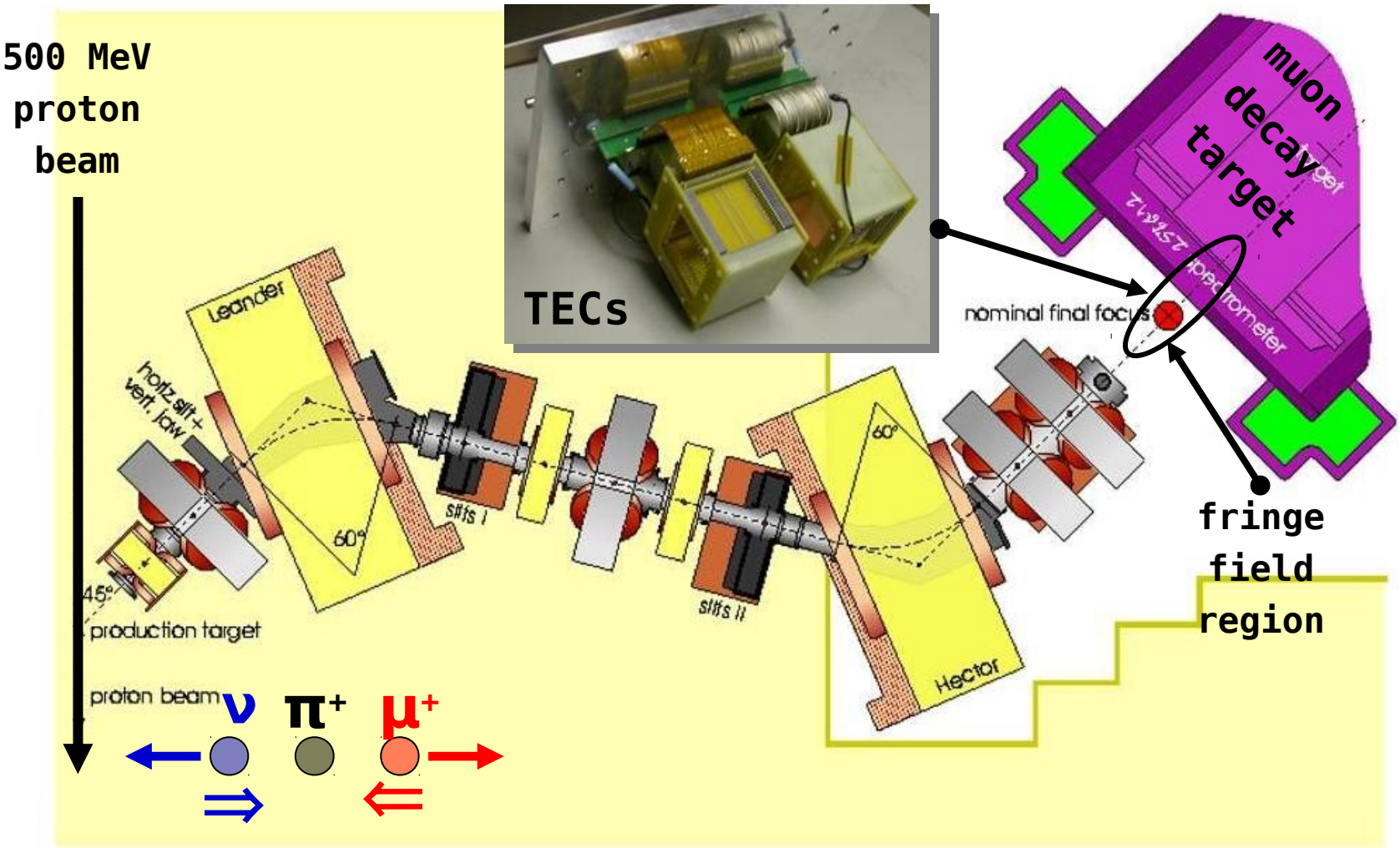
$$\Rightarrow \quad \frac{3}{4} - \rho = \frac{3}{2}\zeta^2$$
$$1 - P_\mu\xi = 4\left(\zeta^2 + \zeta\left(\frac{M_1}{M_2}\right)^2 + \left(\frac{M_1}{M_2}\right)^4\right)$$

The *TWIST* Experiment

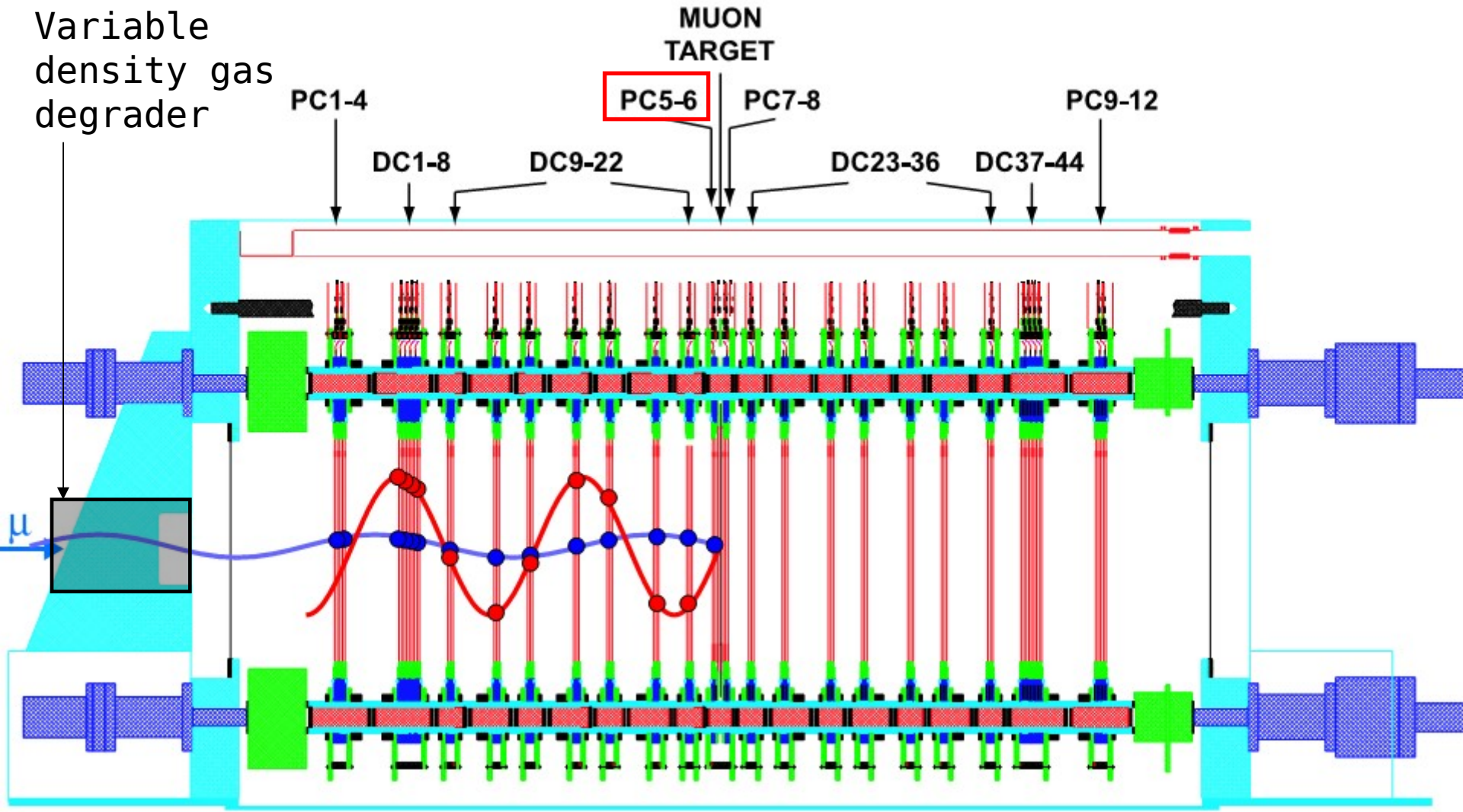
TRIUMF Weak Interaction Symmetry Test



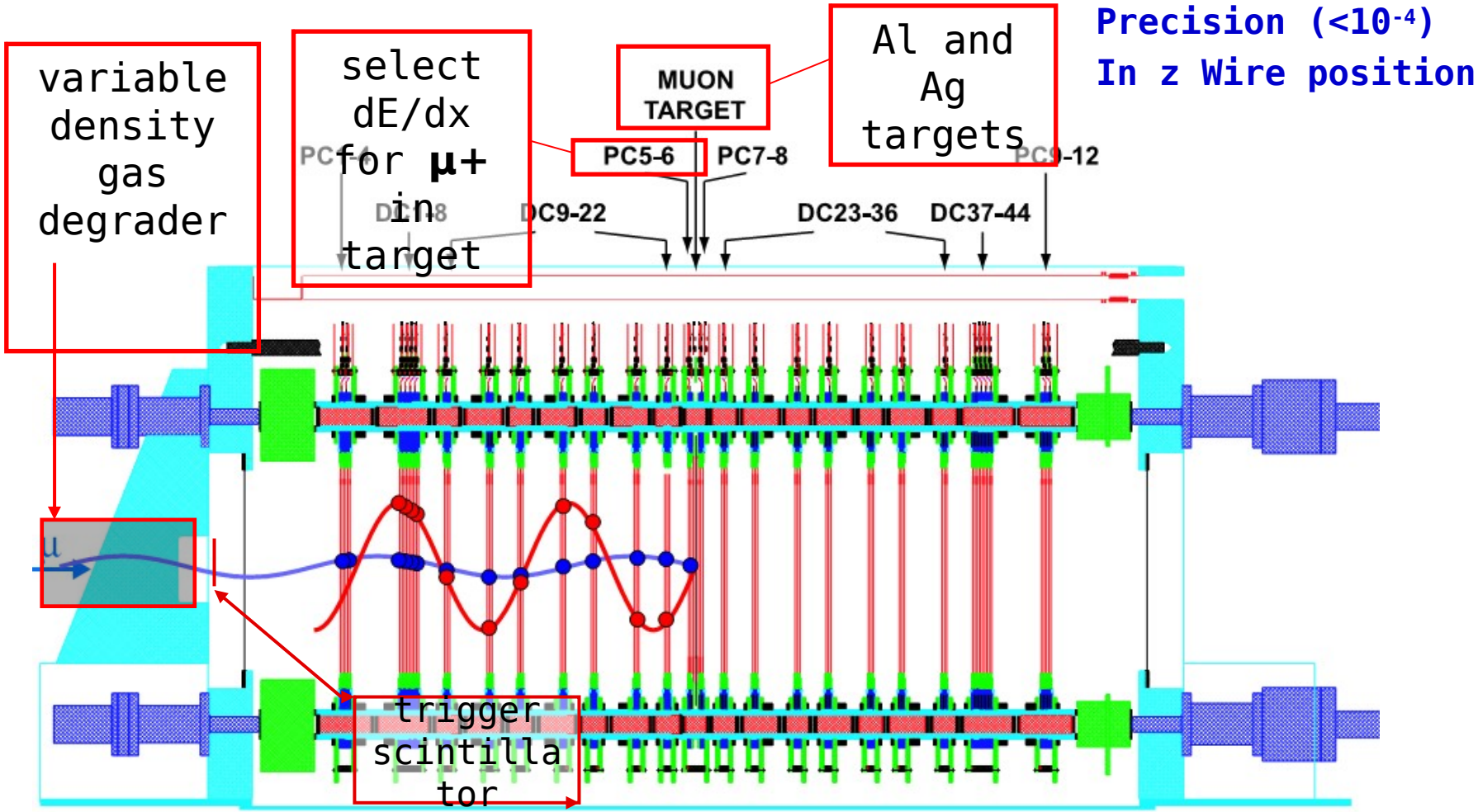
Muon production and transport



Positron tracking

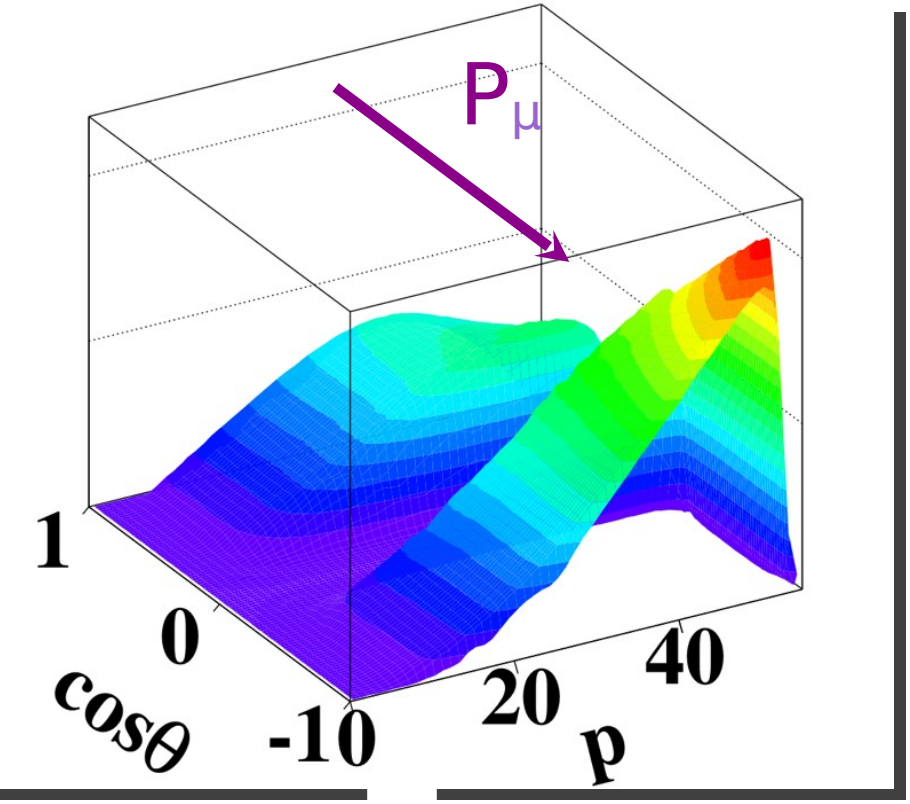


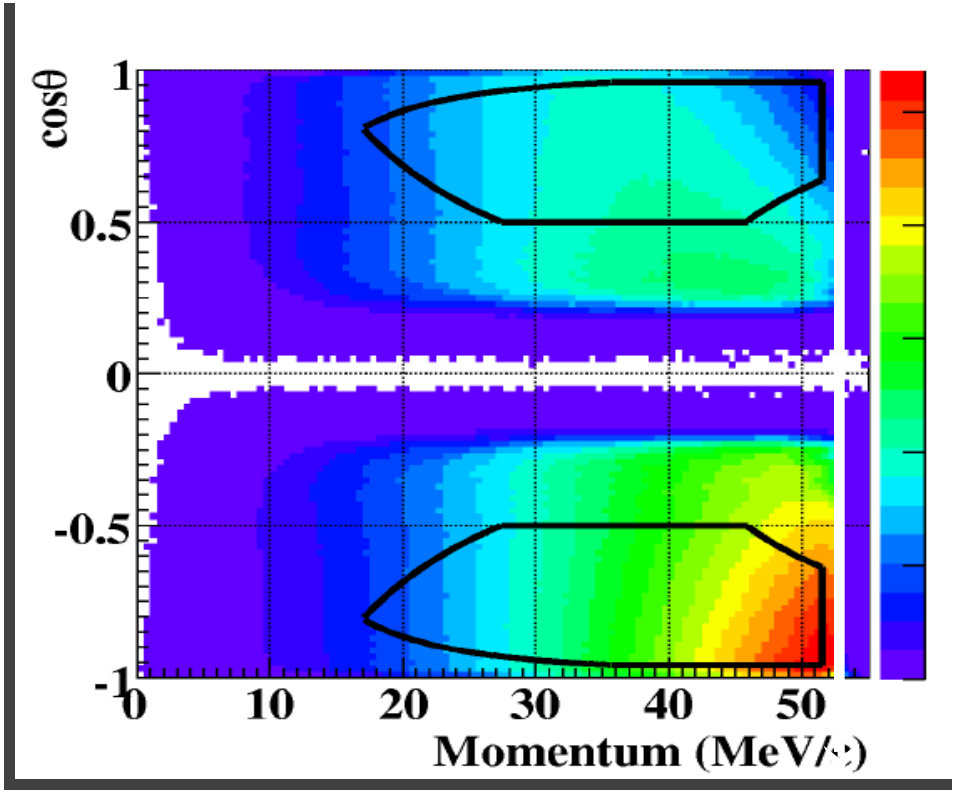
Detector Array



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

Muon Decay Spectrum Acceptance

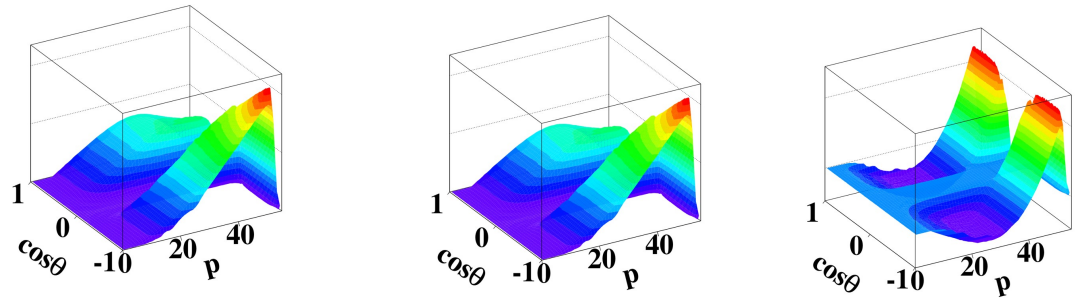




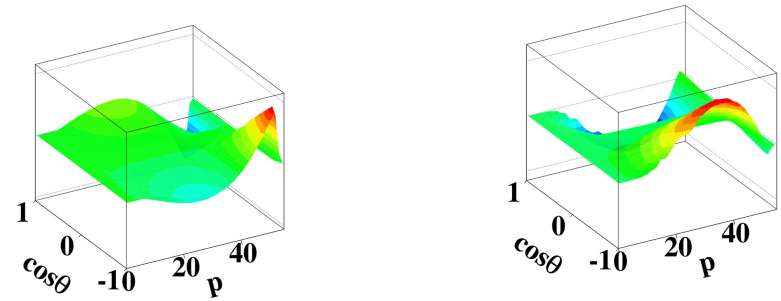
Spectrum Fit Procedure

- Decay spectrum linear in ρ, $P_\mu\xi$, $P_\mu\xi\delta$.
- Derivative spectra are simulated.
- Offset added to parameters to blind them.
- Consistency is tested and systematics determined before unblinding.
- Spectrum edge is fit in angle slices to the simulation. A momentum – calibrated spectrum is regenerated and fit.

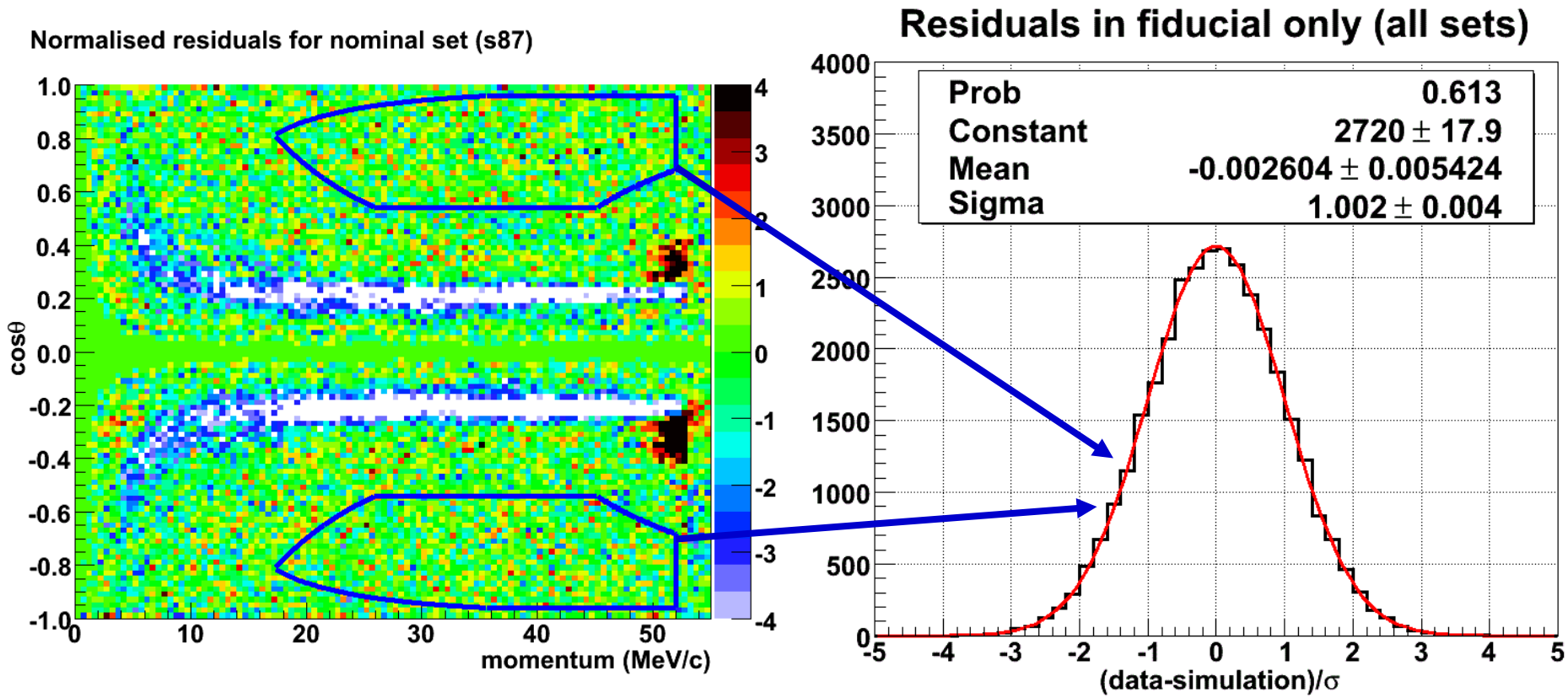
$$N(Data) = N(MC) + \frac{\partial N}{\partial \rho}\Delta\rho$$



$$+ \frac{\partial N}{\partial P_\mu \xi \delta}\Delta P_\mu \xi \delta + \frac{\partial N}{\partial P_\mu \xi}\Delta P_\mu \xi$$

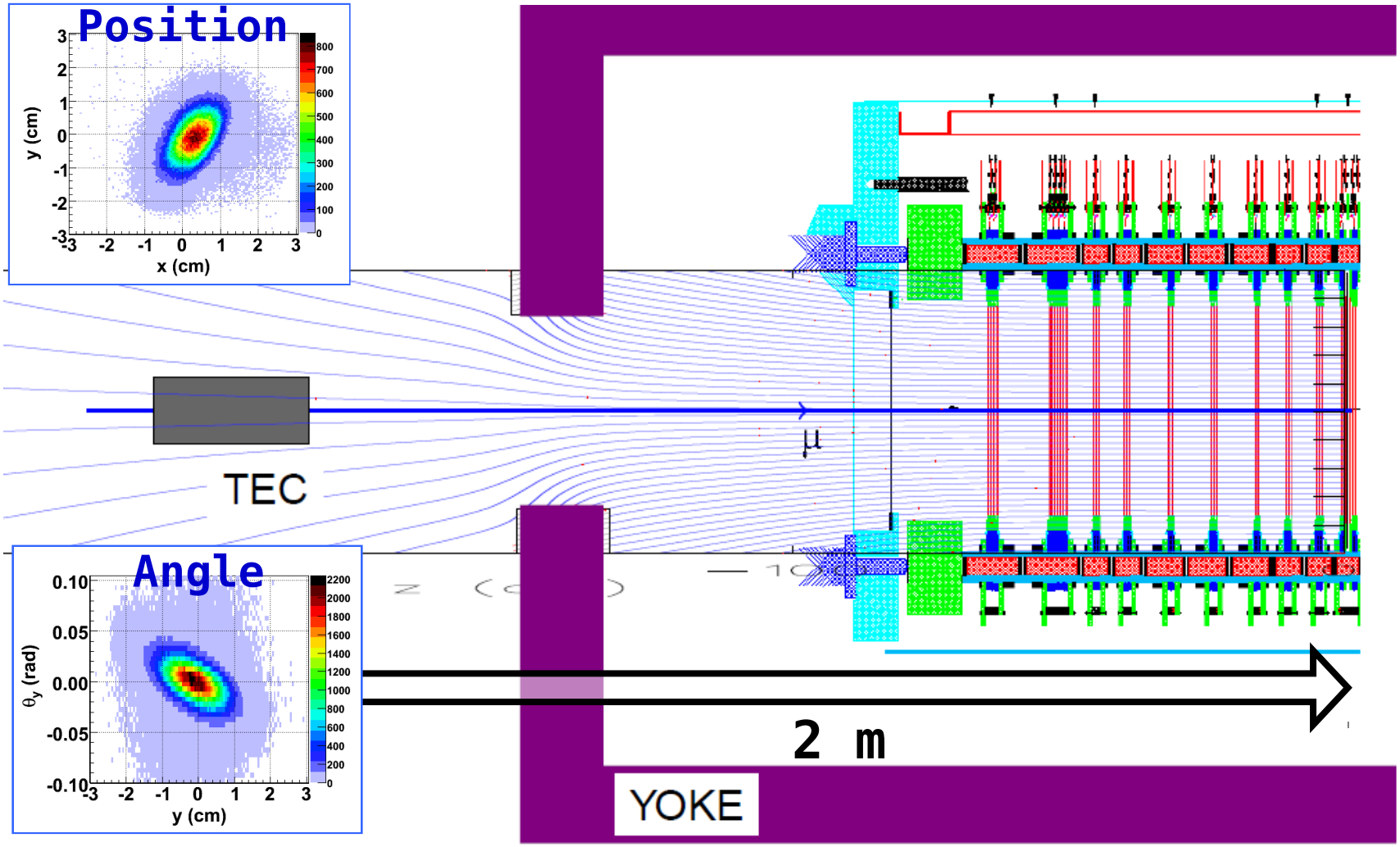


Spectrum fit quality

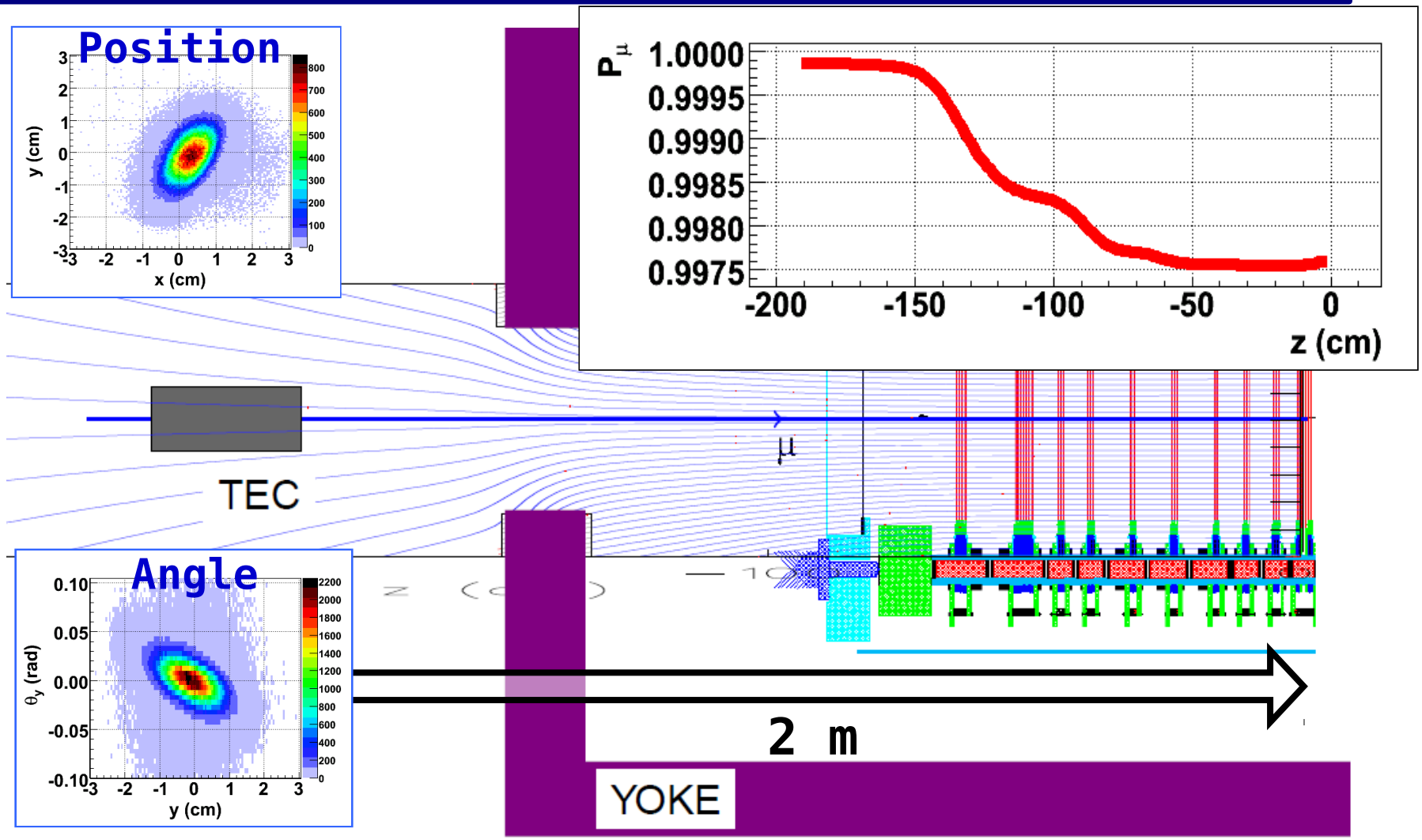


- All data sets: **11x10⁹** events, **0.55x10⁹** in (**p,cosμ**) fiducial
- Simulation sets: **2.7** times data statistics

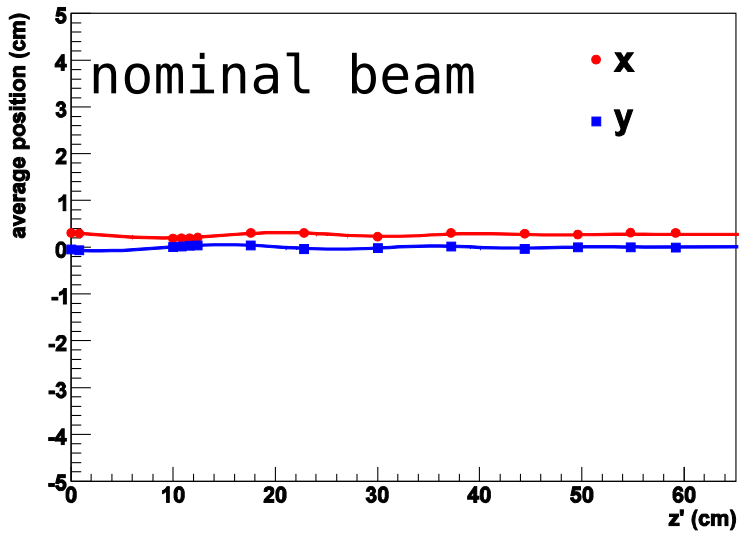
Fringe field, solenoid entrance

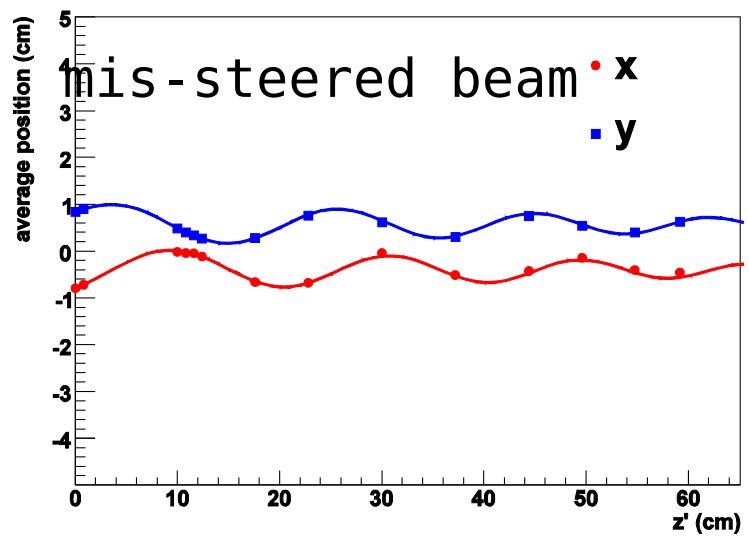


Fringe field, solenoid entrance



Measured average muon positions

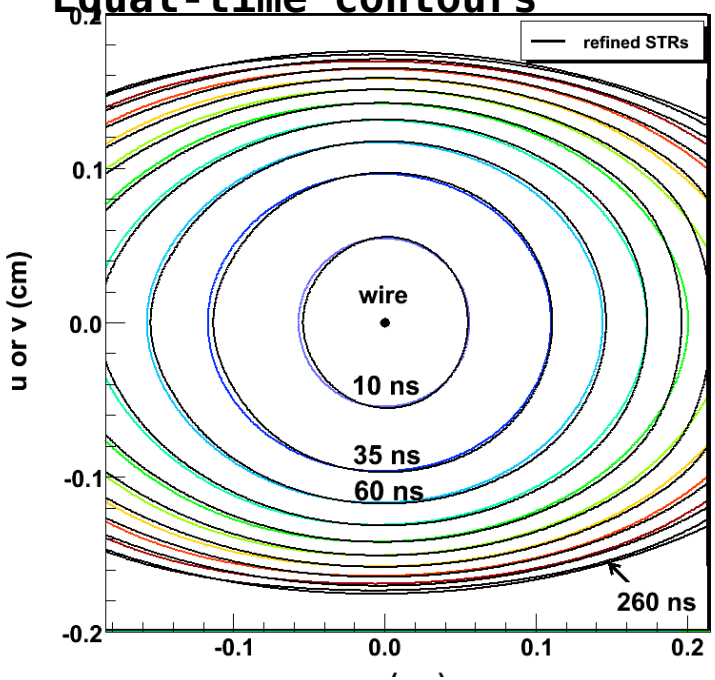




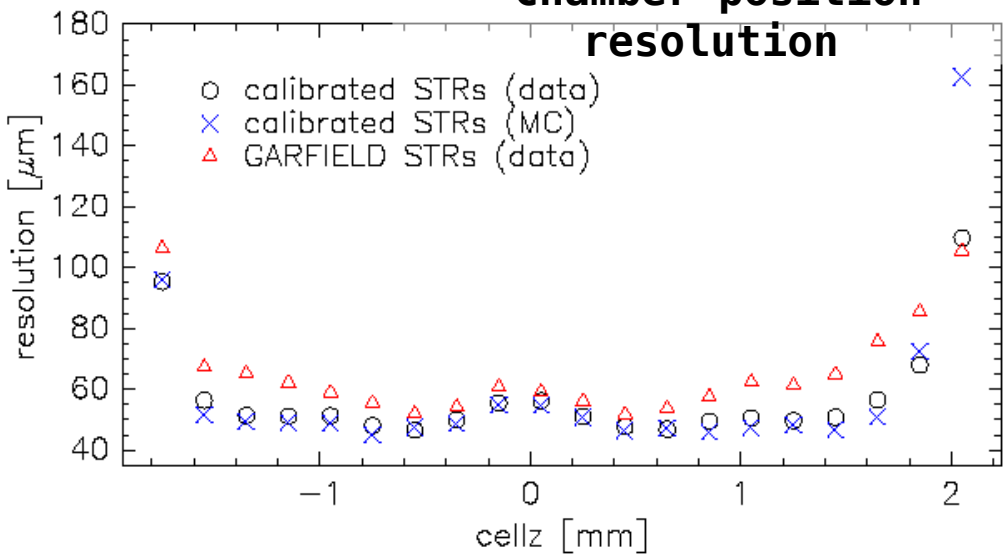
- The average muon beam trajectory inside the detector is sensitive to the **muon transverse momentum**
  - Identify changes in muon beam properties between TEC measurements
- Comparisons between nominal and mis-steered beams
  - Observed muon beam trajectories within the detector
  - Difference in the decay asymmetry in data vs that predicted by the simulation.
- Resulting uncertainties are **asymmetric.**

Improved drift chamber calibration

Equal-time contours



Chamber position resolution

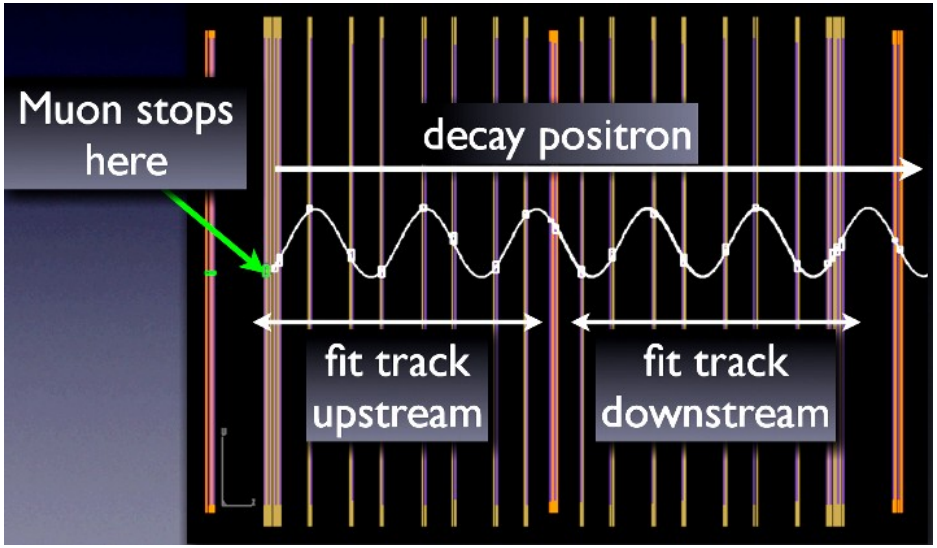


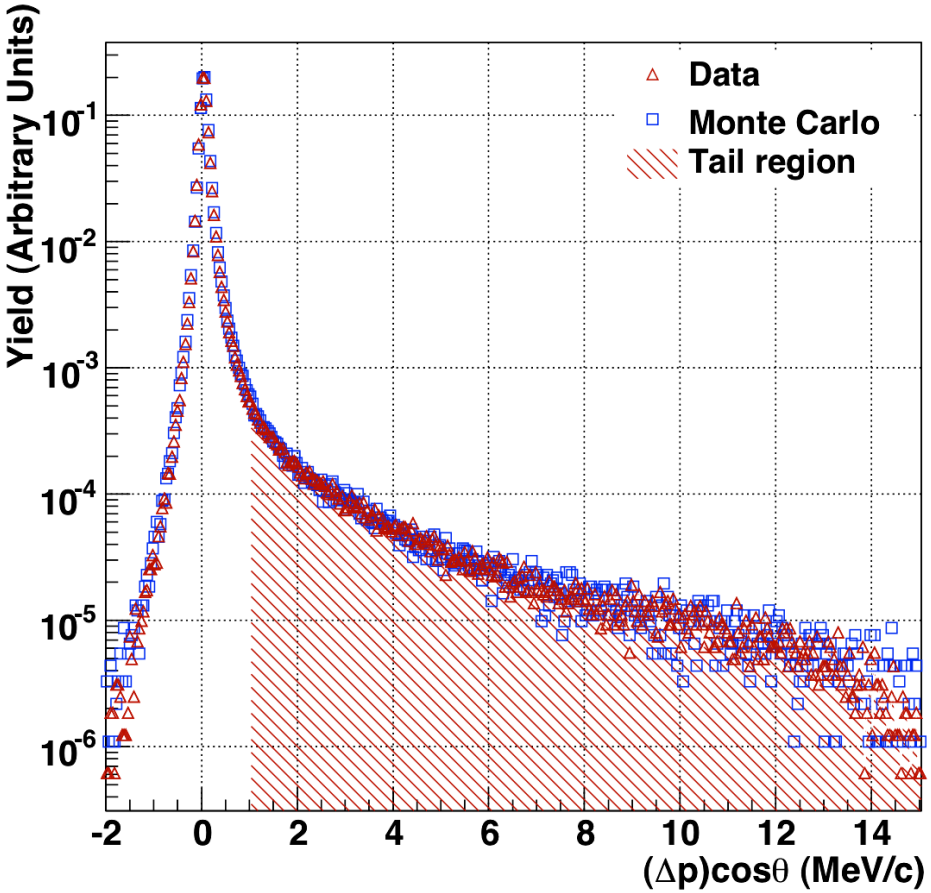
- Direct determination of the effective distance vs time relation.
- Accounts for small plane-to-plane fabrication differences.
- Improved momentum resolution (near the endpoint)
  - Was ~ 69 keV/sin(θ) in simulation and ~ 74 keV/sin(θ) in data.
  - Now ~ 58 keV/sin(θ) **in both.**

A. Grossheim et al., Nucl. Instrum. Methods A 623, 954 (2010).

Bremsstrahlung

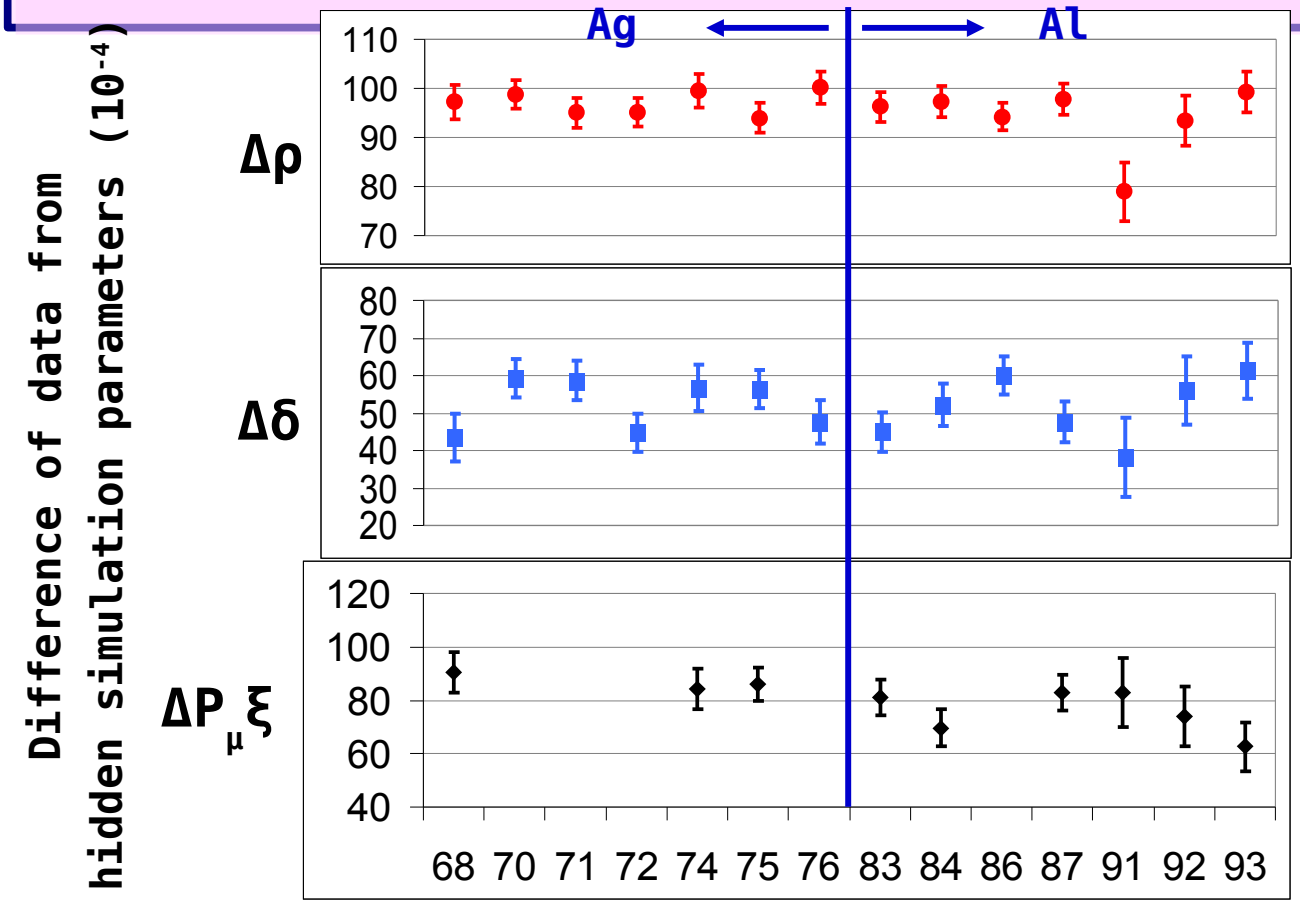
Normal muon stopping target





- Leading systematic for **ρ** and **δ**.
- Separately determined from *upstream stops* and *broken decay tracks*.
- Larger in Ag target.
- Both consistent with GEANT3 simulation at 2.5% level.

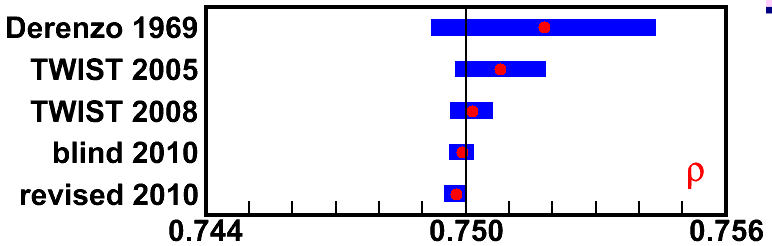
Consistency of data sets



Key:
68 – z_{stop} shifted
70 – B = 1.96 T
71 – B = 2.04 T
72 – TEC in
74 – Nominal
75 – Nominal
76 – Mis-steered
83 – External material
84 – Nominal
86 – Mis-steered
87 – Nominal
91 – Low momentum
92 – Low momentum
93 – Low momentum

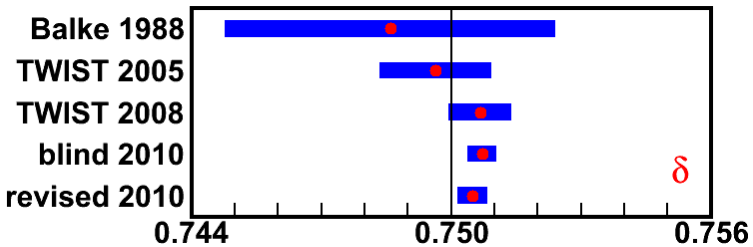
- **14 data sets for ρ and δ, χ^2 of 14.0 and 17.7 respectively**
- **9 data sets used for $P_\mu \xi$, $\chi^2 = 9.7$**
- **statistical uncertainties only, after corrections**

Decay parameter results



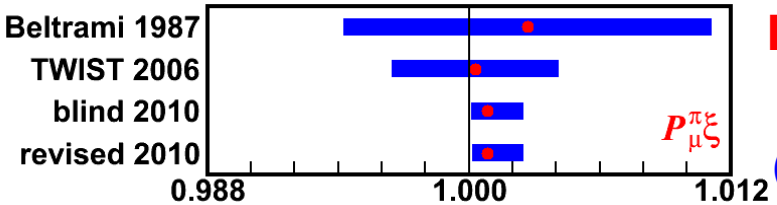
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

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



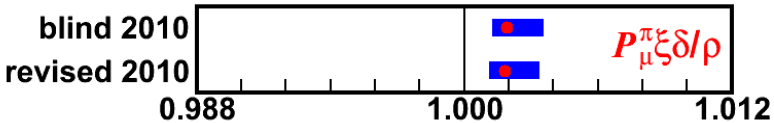
δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

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



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

(+1.2σ from SM, same as blind)



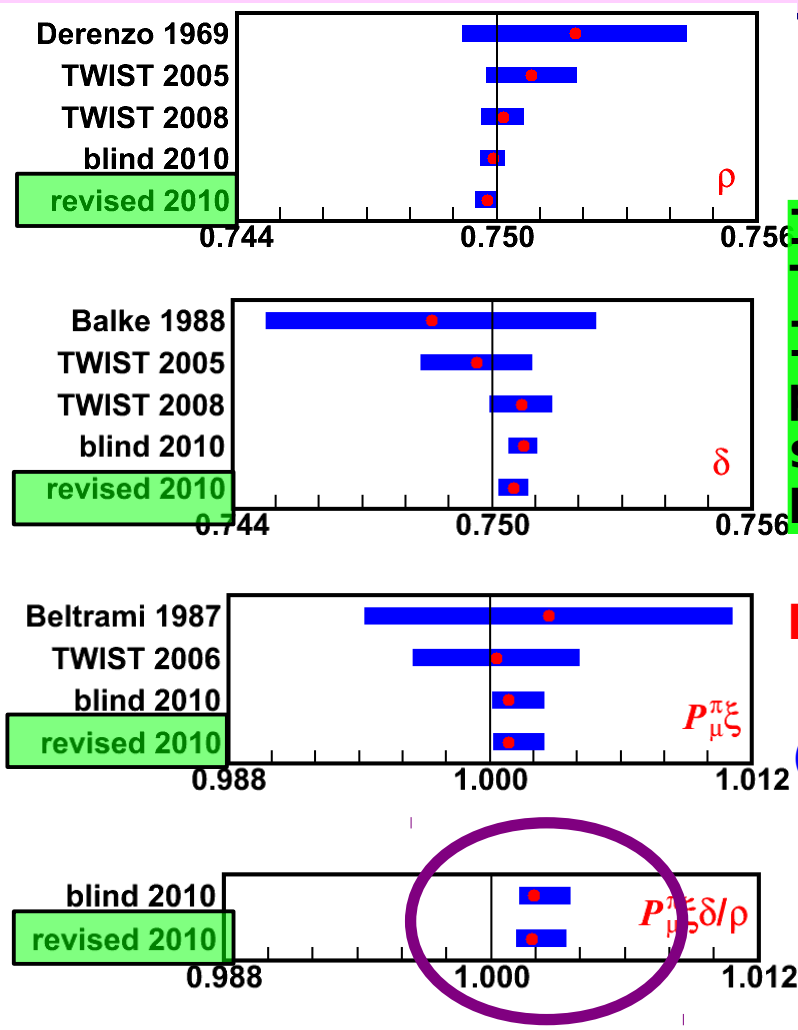
$P^\pi_\mu\xi\delta/\rho$ > 0.99909 (90%CL)

from global analysis

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

J. Bueno et al., Phys. Rev.D (August).

Decay parameter results



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

(+1.3σ from SM, -1.4x10^{-4} from blind)

δ = 0.75049 ± 0.00021 (stat) ± 0.00037 (syst)

(+2.4σ from SM, -2.3x10^{-4} from blind)

Implies a negative decay rate!
Triggered a full analysis review.
Identified sensitivity to stop position, target-dependent systematics.
Final results are slightly modified.

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

(+1.2σ from SM, same as blind)

$P^\pi_\mu\xi\delta/\rho$ > 0.99909 (90%CL)

from global analysis

Implications for the Weak Couplings

- The final **TWIST** results have been included in a new muon decay global analysis together with all previous muon decay parameter measurements
- Find significantly tighter 90% c.l. upper limits on the coupling of right-handed muons to right- or left-handed electrons:
  - $|g^S_{RR}| < 0.031$
  - $|g^V_{RR}| < 0.015$
  - $|g^S_{LR}| < 0.041$
  - $|g^V_{LR}| < 0.018$
  - $|g^T_{LR}| < 0.012$

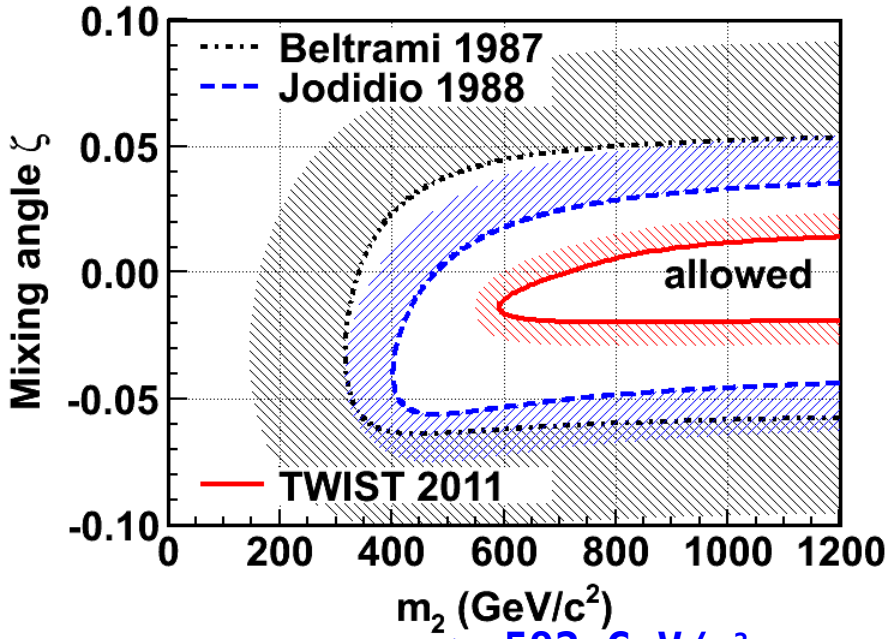
  Factor of ~2 smaller than pre-**TWIST** values

  Factor of ~3 smaller than pre-**TWIST** values

- New limit on right-handed muon couplings: $Q^{\mu}_{R} < 5.8\times10^{-4}$ (90% c.l.)
  - Factor of ~9 smaller than pre-**TWIST** value
- Uncertainty for η reduced by 1/3 compared to 2005 global analysis
  - η = **-0.0033 ± 0.0046**
  - Important for the determination of G_F

Left-Right Symmetric limit comparison

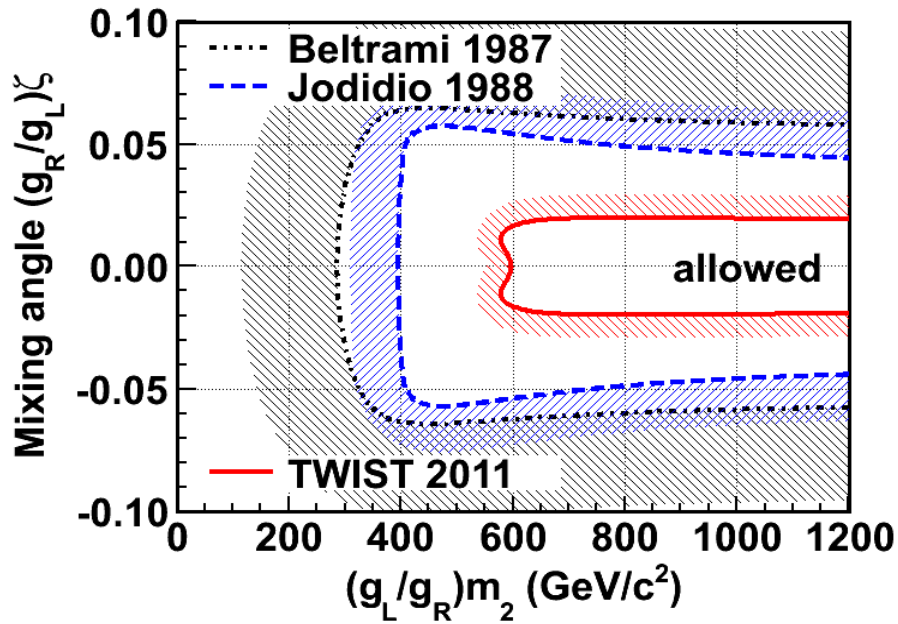
"manifest" LRS, 90%CL



$m_2 > 592$ GeV/c²

$-0.020 < \zeta < +0.017$

generalized or non-manifest LRS, 90%CL



$(g_L/g_R)m_2 > 578$ GeV/c²

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

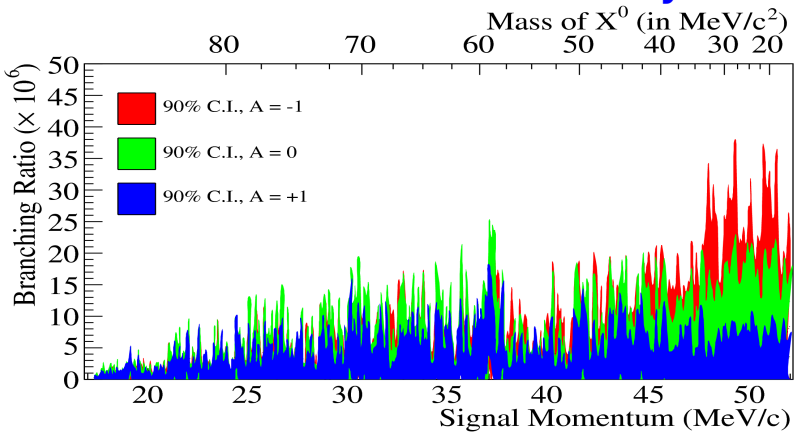
- Other **W'** direct search mass limits
  - ATLAS: >1.49 TeV/c², 95%CL (LLWI11)
  - CMS: >1.58 TeV/c², 95%CL (LLWI11)
  - CMS: >1.36 TeV/c², 95%CL (2011)
  - CDF: >1.12 TeV/c², 95%CL (2011)
  - D0: >1.0 TeV/c², 95%CL (2008)

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

Inclusive Limits on $\mu \rightarrow e\, X^0$

- Limits when X^0 is undetectable.
- First search for two-body decays with possible asymmetries.
- Order of magnitude improvement for massive isotropic decays.
- Peak structures at the endpoint are produced by small momentum scale mismatches, so this sets the systematic limit.
- Jodidio more sensitive to isotropic signal but completely insensitive to asymmetric decay.
- Limits on 3-body X0 decays are obtained from decay parameter values.

Massive X0 Decays



Decay Anisotropy	Massless $\mathcal{B}$ 90% CL
A= -1	52×10^{-6}
A=0	20×10^{-6}
A=+1	10×10^{-6}
Jodidio A=0 PRD34,1967(1986)	2.6×10^{-6}

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).

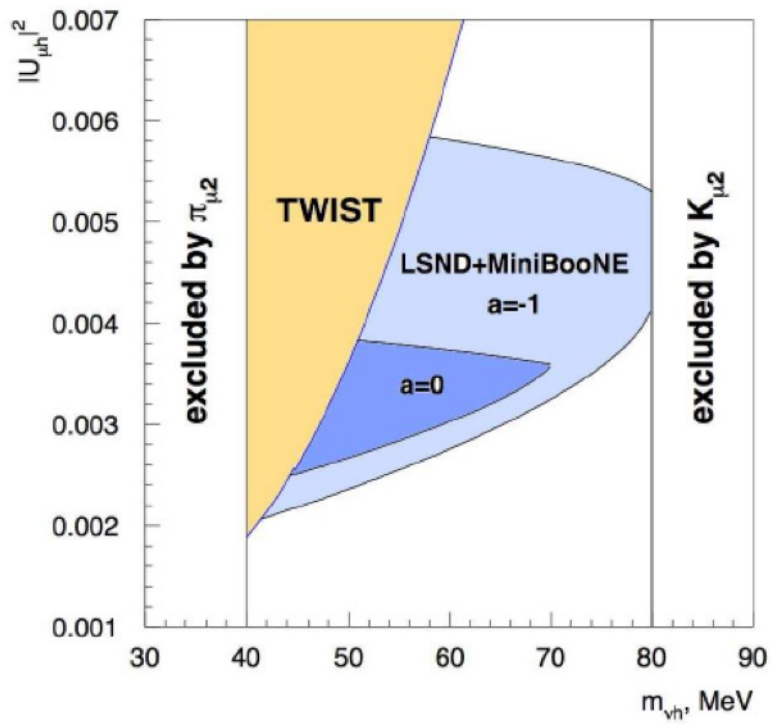


FIG. 24: The 2σ allowed region (dark areas) in the $(m_{\nu_h}; |U_{\mu h}|^2)$ parameter space obtained for different values of the asymmetry parameter a from the combined analysis of LSND and MiniBooNE ν_μ and $\overline{\nu}_\mu$ data. The areas excluded by the $\pi_{\mu 2}$ and $K_{\mu 2}$ decay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

- **TWIST** has significantly improved the measurements of ρ, δ, and $P^{\pi}_{\mu}\xi$. These results are in agreement with the Standard Model.
- The value of $P^{\pi}_{\mu}\xi\delta/\rho > 1$ disagrees even with the general weak interaction. We have reexamined all of our key assumptions and repeated the analysis, leading only to small changes.
- Constraints on the weak couplings and LRS models are significantly improved.
- New inclusive bounds on $\mu \rightarrow e\, X^0$
- μ^-Al decay spectrum – not presented.

TWIST Collaboration

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Supported by NSERC, DOE, RMF, Westgrid

Extras

Early μ Decay Measurements

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 1

The Absorption of Charged Particles from the 2.2-μsec. Meson Decay

E. P. HINCKS AND B. PONTECORVO
National Research Council of Canada, Chalk River Laboratory, Chalk River, Ontario, Canada
July 26, 1948

THE energy spectrum of the charged particles (commonly assumed to be electrons) emitted in the 2.2-μsec. meson decay is still unknown. Conversi and Piccioni[1] in 1944 deduced from the relative numbers of decay electrons escaping from iron plates 0.6 cm and 5 cm

2) that less than 0.03 count per hour can be due to radiation from 25-Mev electrons in our arrangement. Consequently, it may be seen from Table I that at least a substantial fraction of the electrons must have a range greater than 15 g/cm² of carbon. Therefore, we conclude that there are decay electrons having energies greater than 25 Mev and therefore that the 2-particle decay process (Eq. (1)), with a *unique* energy of about 25 Mev for the decay electron, is incompatible with our results.

We observe, however, that a *maximum* energy of about 50 Mev for the decay electrons would be consistent with the data of Table I.

On the Range of the Electrons in Meson Decay

J. STEINBERGER*
The Institute for Nuclear Study, University of Chicago, Chicago, Illinois
(Received January 10, 1949)

An experiment has been carried out both at Chicago and on Mt. Evans, Colorado, to determine the absorption of the electrons emitted in the decay of cosmic-ray mesons. Approximately 8000 counts have been obtained, using a hydrocarbon as the absorbing material. These data are used to deduce some features of the energy spectrum of the decay electrons. The resolution of the apparatus is calculated, taking the geometry, scattering, and radiation into account. The results indicate that the spectrum is either continuous, from 0 to about 55 Mev with an average energy ~32 Mev or consists of three or more discrete energies. No variation of the lifetime with the thickness of the absorber is observed. The experiment, therefore, offers some evidence in favor of the hypothesis that the μ-meson disintegrates into 3 light particles.

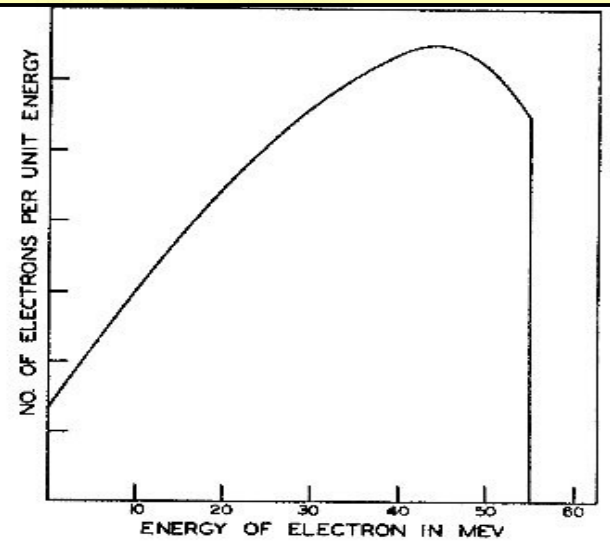
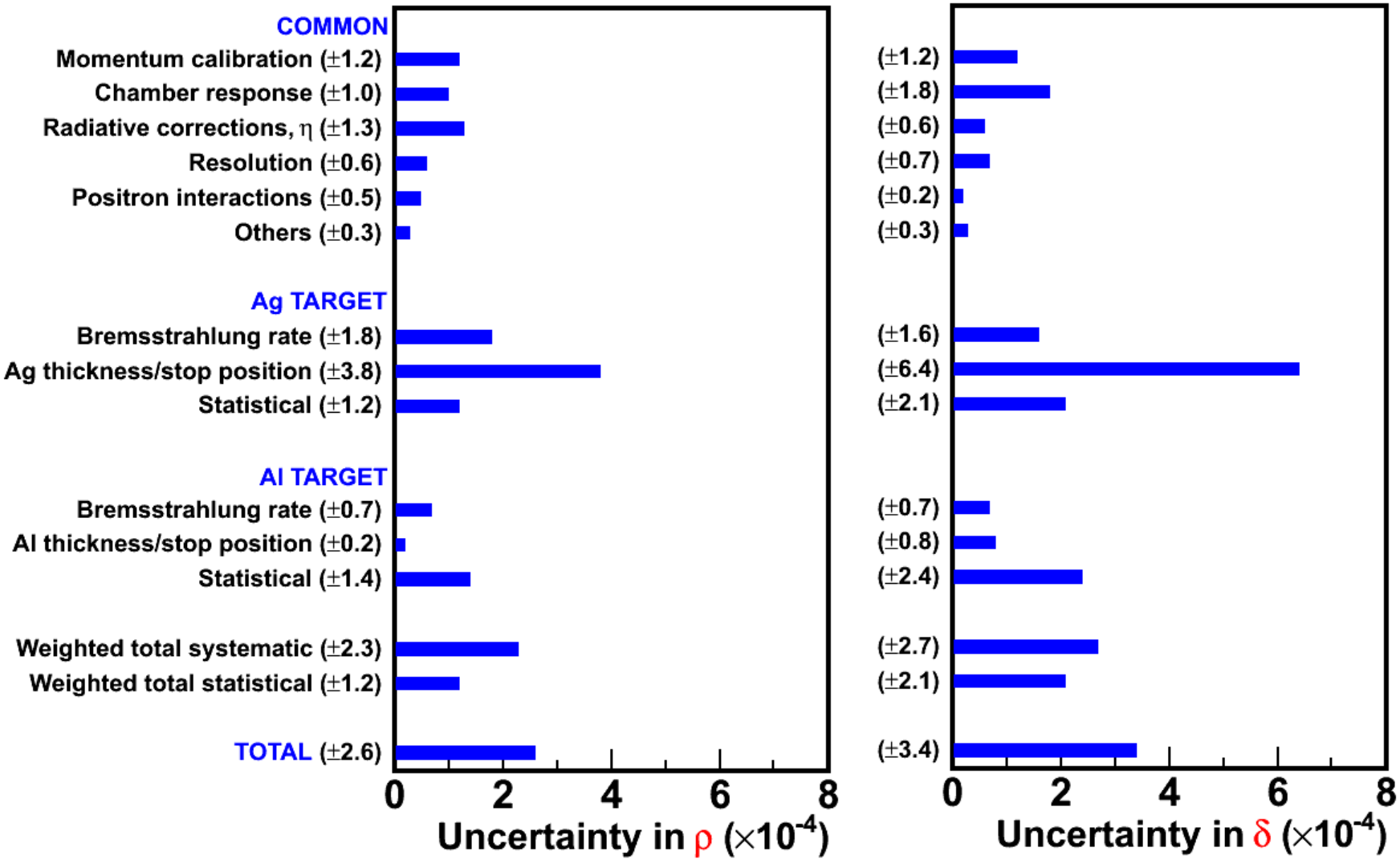


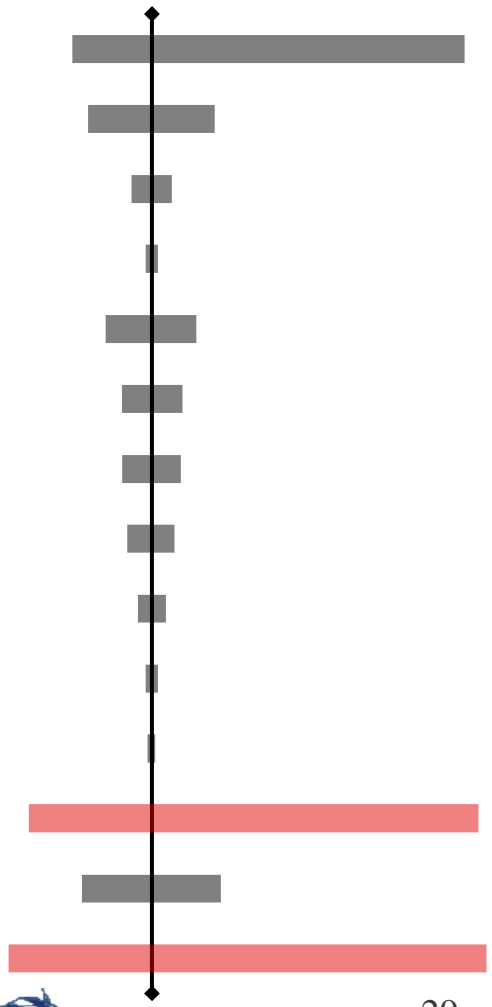
FIG. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.

Uncertainties in ρ and δ

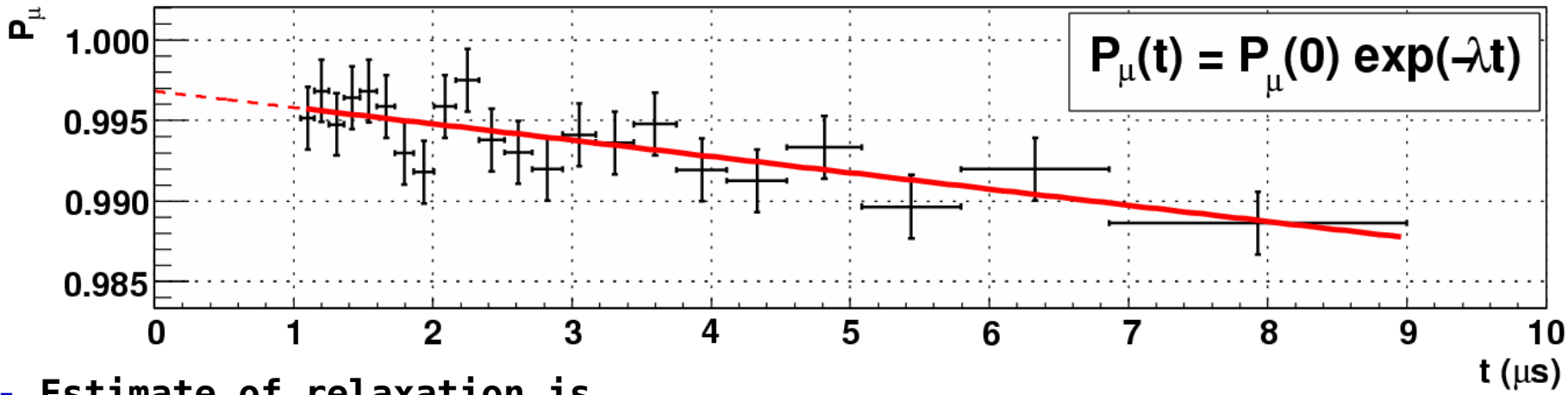


$P_\mu\xi$ uncertainties

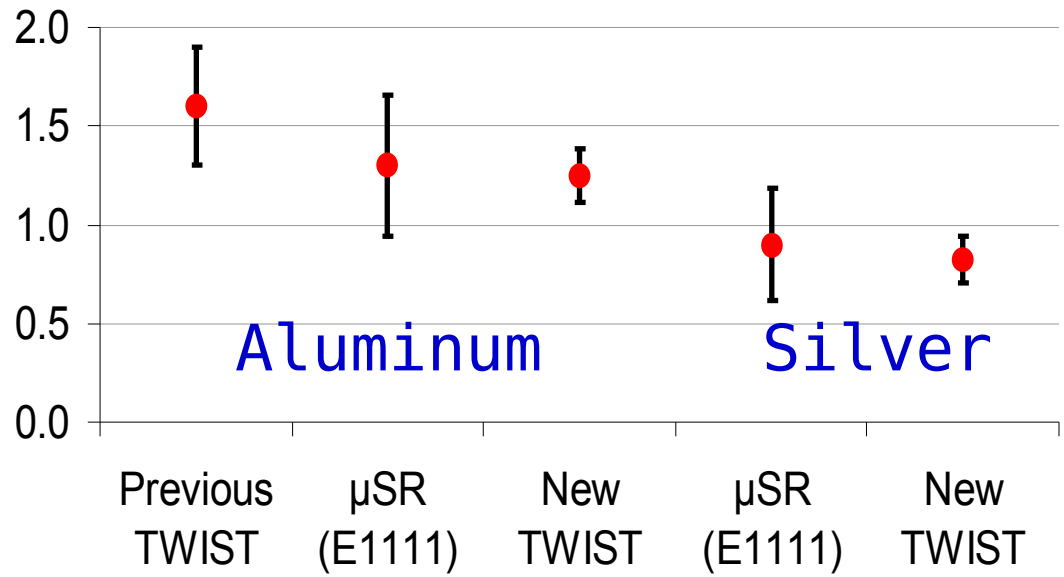
Uncertainties	$P_\mu\xi$ ($\times 10^{-4}$)
Depolarization in fringe field	+15.8, -4.0
Depolarization in stopping material	3.2
Background muons	1.0
Depolarization in production target	0.3
Chamber response	2.3
Resolution	1.5
Momentum calibration	1.5
External uncertainties	1.2
Positron interactions	0.7
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*



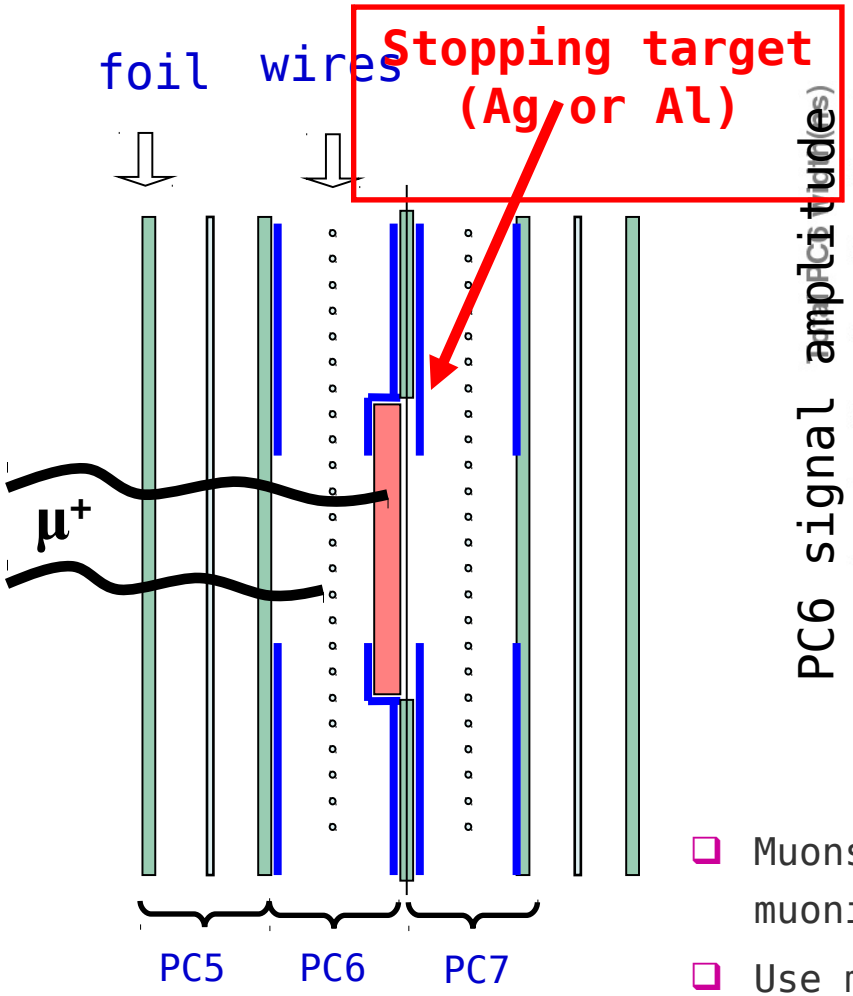
Depolarization in target material

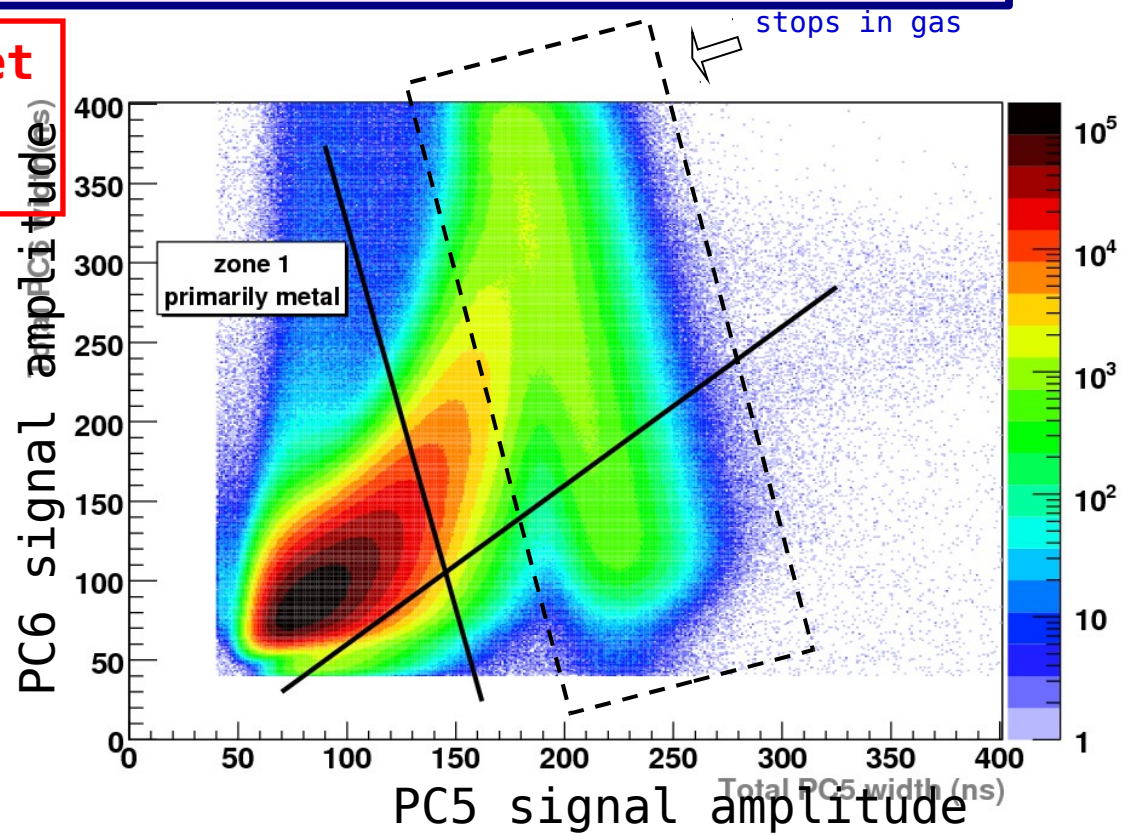


- Estimate of relaxation is included in simulation;small correction is made to polarization parameter.
- μSR experiment establishes no fast relaxation.
- Statistical uncertainty in , is included in decay parameter systematic uncertainty.



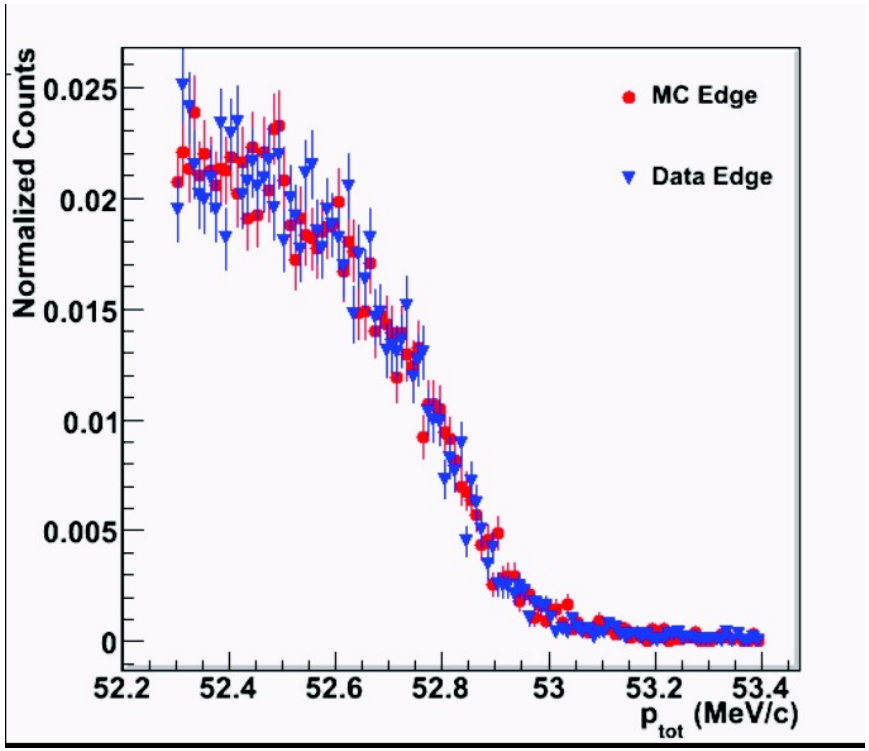
Ensuring muons stop in the metal target





- Muons that stop in gas can depolarize through muonium formation
- Use muon energy depositions near the stopping target to reject those that stop in gas

Energy Resolution



Energy calibration procedure matches the position of data and simulation edges

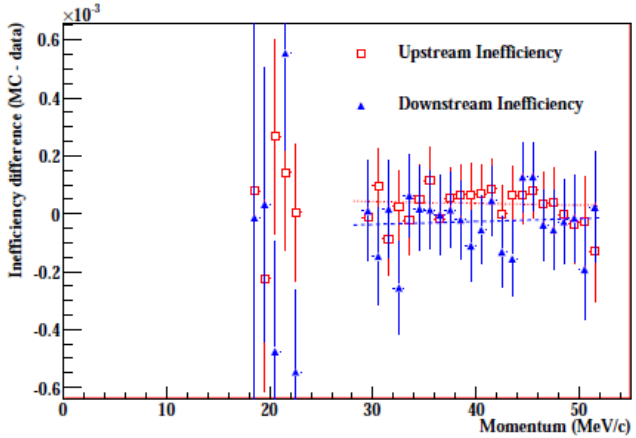
Ag

Data Resolution 59.5±0.2 keV/c
MC Resolution 59.5±0.2 keV/c
Response func diff 1.2 keV/c

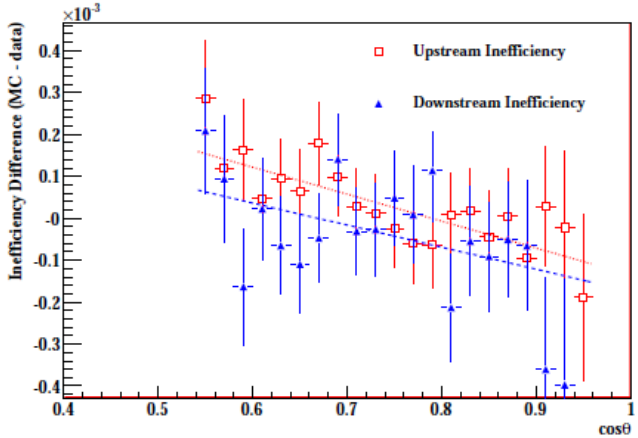
Al

Data Resolution 58.5±0.2 keV/c
MC Resolution 58.4±0.2 keV/c
Response func diff 2.0 keV/c
2004 analysis
Data Resolution 65 keV/c
MC resolution 60 keV/c

Reconstruction Inefficiency



(a) Difference between inefficiencies from data and Monte Carlo averaged with respect to angles over the fiducial region



(b) Difference between inefficiencies from data and Monte Carlo averaged with respect to momenta over the fiducial region

Left-Right Symmetric Models

- Weak eigenstates in terms of mass eigenstates and mixing angle:

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

- Assume possible differences in left and right couplings and CKM character.

  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 Michel parameters are modified:

$$\rho = \frac{3}{4}(1 - 2\zeta_g^2), \quad \xi = 1 - 2(t^2\zeta_g^2)$$
$$P_\mu \xi = 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g^2 \cos(\alpha + \omega)$$

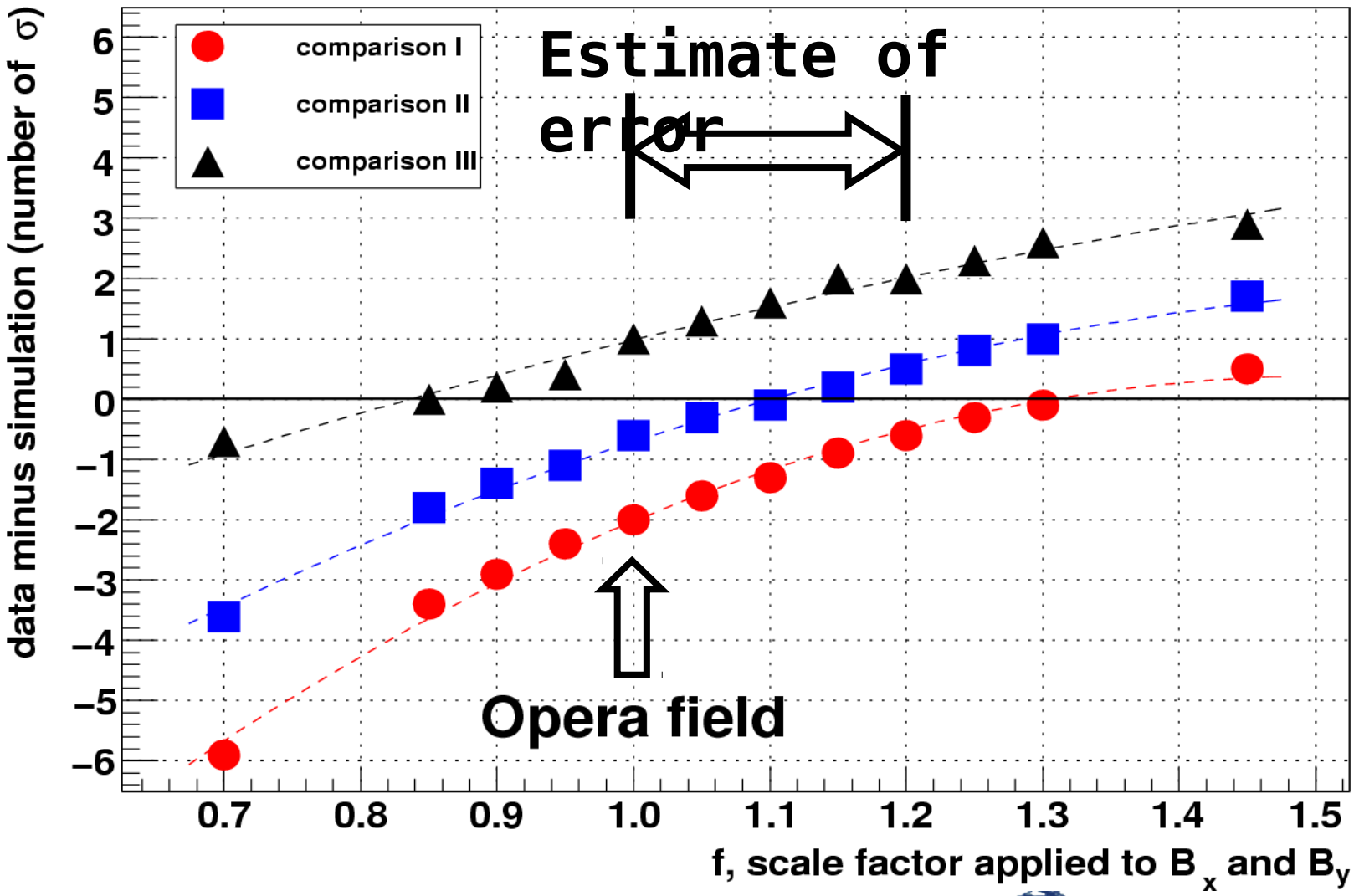
  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\omega = 0$ (no CP violation).
  - "pseudo-manifest" LRS allows CP violation, but $V^R = (V^L)^*$ and $g_R = g_L$.
  - LRS "non-manifest" or generalized LRS makes no such assumptions.

- ***Many experiments must make assumptions about LRS models!***

BSM Physics

- Right-Left Symmetric Models
  - Spontaneous breaking of parity
  - Herczeg, Phys Rev. D34,3449 (1986).
- R-Parity Violating Supersymmetric Models
  - Profumo et al, Phys. Rev. D75, 075017 (2007).
- Lepton Flavour Violating 2-body decays $\mu \Rightarrow e X^0$
  - Strong limits exist when X^0 or it's products are detectable
  - μ decay limits interesting when X^0 is not detectable.
  - Hirsch et al, Phys Rev D 79,055023 (2009)

Estimating field component effects



Coupling constants and Michel parameters

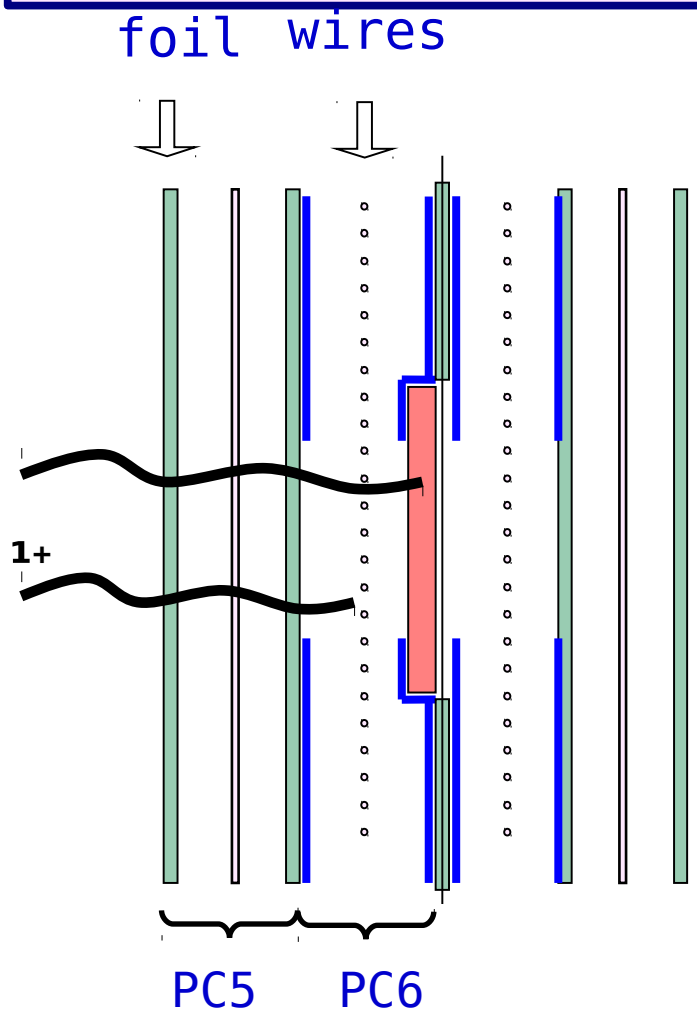
- The Michel parameters are bilinear combinations of the coupling constants:

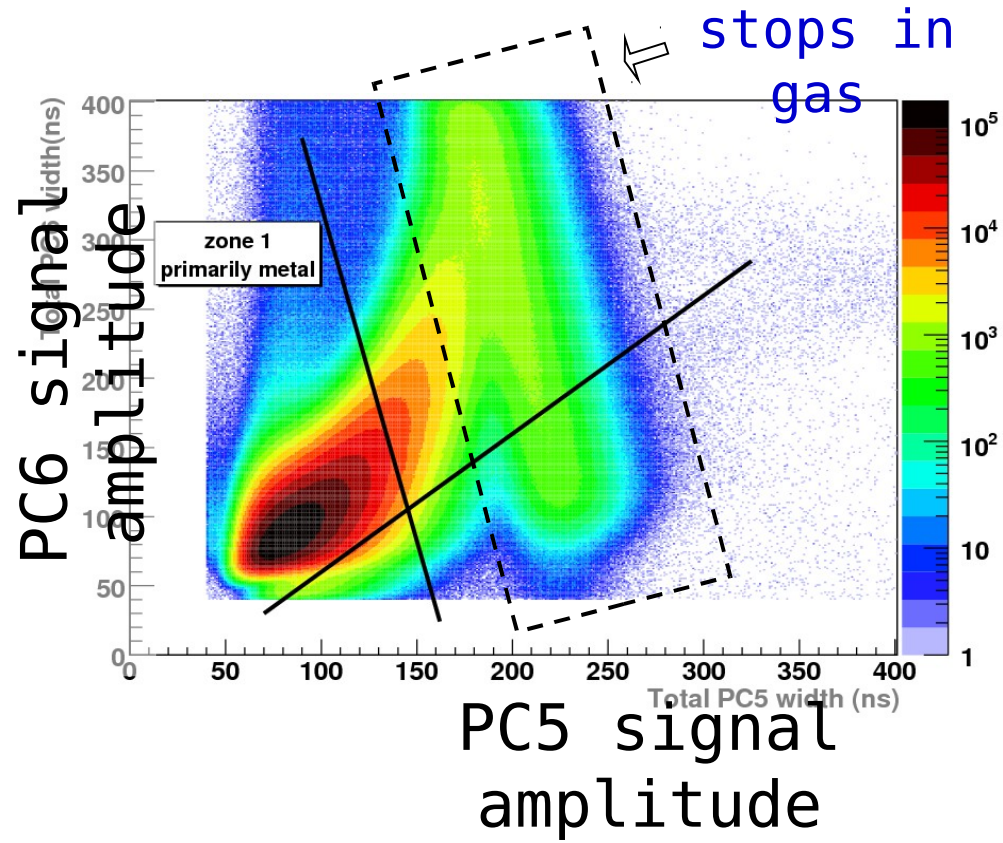
$$
\begin{aligned}
\rho &= \frac{3}{4} - \frac{3}{4}[\left|g_{RL}^{V}\right|^2 + \left|g_{LR}^{V}\right|^2 + 2\left|g_{RL}^{T}\right|^2 + 2\left|g_{LR}^{T}\right|^2 \\
&\quad + \mathbb{R}e\left(g_{RL}^{S} g_{RL}^{T*} + g_{LR}^{S} g_{LR}^{T*}\right)] \\
\eta &= \frac{1}{2}\mathbb{R}e[g_{RR}^{V} g_{LL}^{S*} + g_{LL}^{V} g_{RR}^{S*} + g_{RL}^{V}(g_{LR}^{S*} + 6g_{LR}^{T*}) + g_{LR}^{V}(g_{RL}^{S*} + 6g_{RL}^{T*})] \\
\xi &= 1 - \frac{1}{2}\left|g_{LR}^{S}\right|^2 - \frac{1}{2}\left|g_{RR}^{S}\right|^2 - 4\left|g_{RL}^{V}\right|^2 + 2\left|g_{LR}^{V}\right|^2 - 2\left|g_{RR}^{V}\right|^2 \\
&\quad + 2\left|g_{LR}^{T}\right|^2 - 8\left|g_{RL}^{T}\right|^2 + 4\mathbb{R}e(g_{LR}^{S} g_{LR}^{T*} - g_{RL}^{S} g_{RL}^{T*}) \\
\xi\delta &= \frac{3}{4} - \frac{3}{8}\left|g_{RR}^{S}\right|^2 - \frac{3}{8}\left|g_{LR}^{S}\right|^2 - \frac{3}{2}\left|g_{RR}^{V}\right|^2 - \frac{3}{4}\left|g_{RL}^{V}\right|^2 - \frac{3}{4}\left|g_{LR}^{V}\right|^2 \\
&\quad - \frac{3}{2}\left|g_{RL}^{T}\right|^2 - 3\left|g_{LR}^{T}\right|^2 + \frac{3}{4}\mathbb{R}e(g_{LR}^{S} g_{LR}^{T*} - g_{RL}^{S} g_{RL}^{T*})
\end{aligned}
$$

Limits on LRS parameters

Observable	m_2 (GeV/c_2)	$\lvert\zeta\rvert$	+	-
$m(K_L - K_S)$	>1600		reach	(P)MLRS
Direct W_R searches	>1000 (D0) >652 (CDF)		clear signal	(P)MLRS decay model
CKM unitarity		$<10^{-3}$	sensitivity	(P)MLRS heavy ν_R
β decay	>310	<0.040	both parameters	(P)MLRS light ν_R
μ decay (**TWIST**)	>420	<0.022	model independence	light ν_R

Selecting muons in metal target

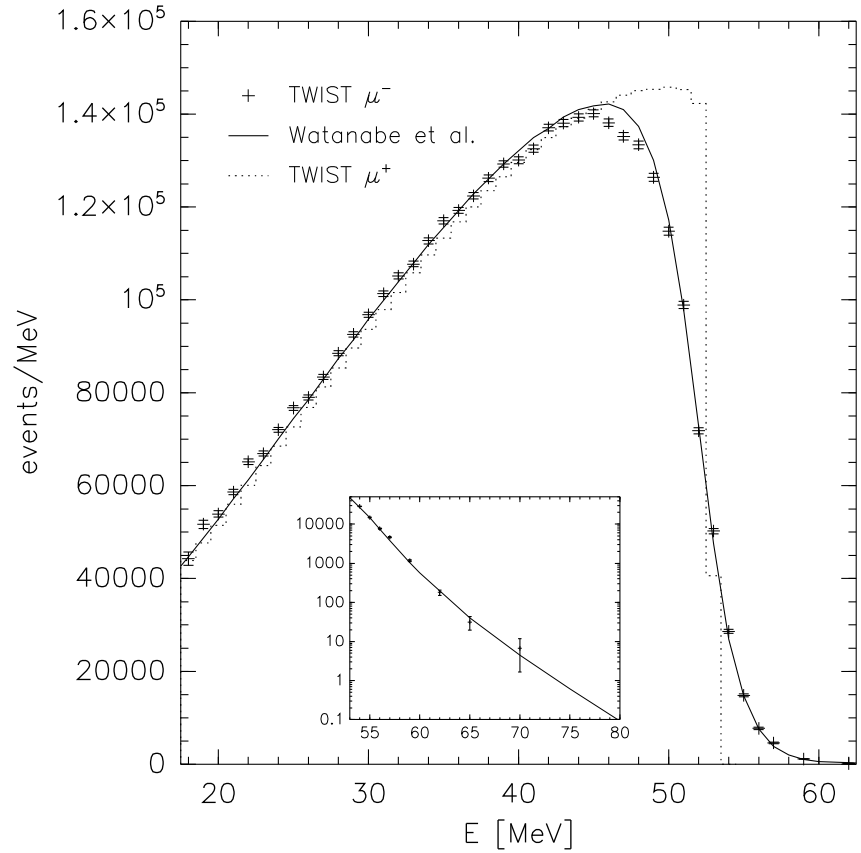




Place cut on 2-d distribution so that <0.5% of "stops in gas" contaminate "stops in target" region (zone 1).

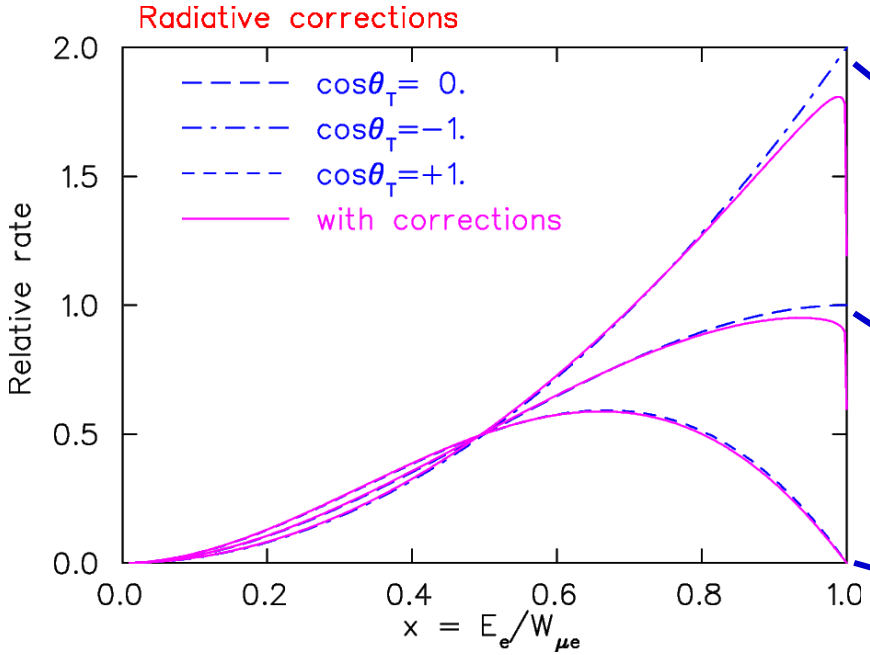
Electron spectrum from $^{1-}$Al

- One week of data with μ^- beam
- Precise measure of muonic aluminum (μ^-Al) decay in orbit (DIO)
  - changes phase space, initial KE
  - competes with nuclear muon capture
- comparison with calculation
  - consistency above 53 MeV, but limited to p<75 MeV
    - (below μ**e** conversion signal)
  - mismatch near peak and excess events at lower energies
  - higher order corrections required?

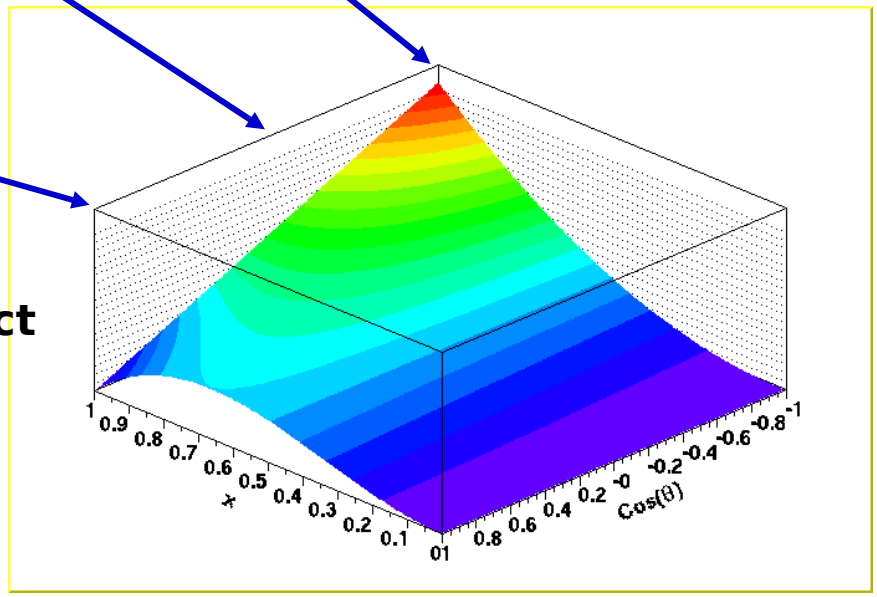


A. Grossheim et al.,
Phys. Rev. D 80, 052012 (2009)

Radiative corrections



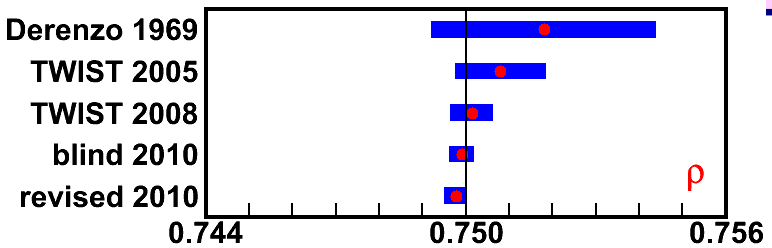
Arbuzov et al., Phys. Rev. D66 (2002) 93003.
Arbuzov et al., Phys. Rev. D65 (2002) 113006.
Arbuzov et al., JHEP03:063(2003).
Anastasiou et al, JHEP0709:014, (2007).



Included in TWIST simulation

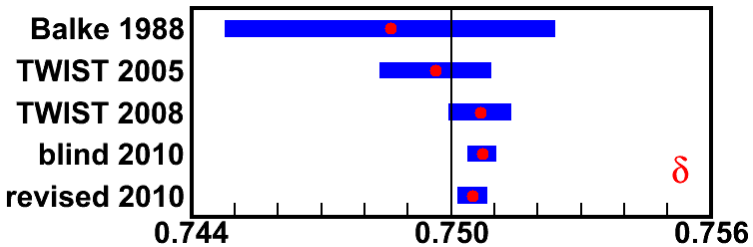
Full O(α) radiative corrections with exact electron mass dependence.
Leading and next-to-leading large log terms of O(α²).
Corrections for soft pairs, virtual pairs, and an ad-hoc exponentiation.
Uncertainty is non-log O(α²) term recently calculated.

Decay parameter results



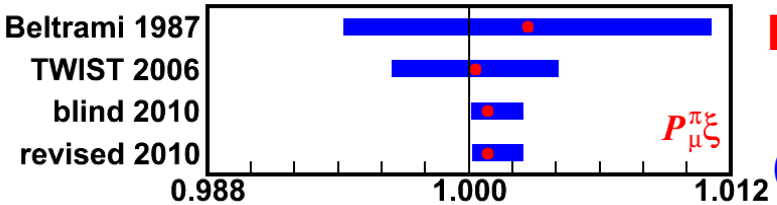
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

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



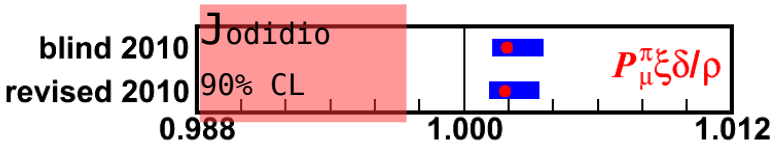
δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

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



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

(+1.2σ from SM, same as blind)



$P^\pi_\mu\xi\delta/\rho$ > 0.99909 (90%CL)

from global analysis

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

J. Bueno et al., Phys. Rev.D (August).