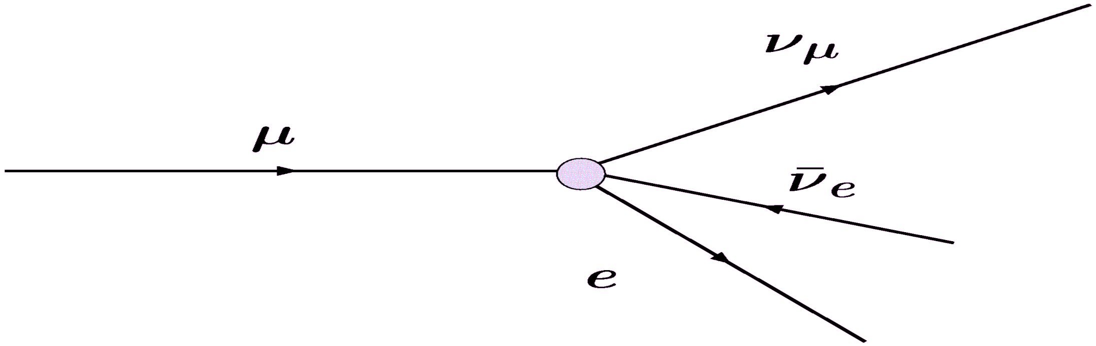
Results of the TRIUMF Weak Interaction Symmetry Test

Art Olin, for the TWIST Collaboration

Muon decay



- Purely leptonic decay at tree level.
- SM: V-A, parity violating, mediated by W boson.
- $M_e/M_W \sim 10^{-5}$ → effectively 4-point interaction.
- V-A empirically based postulate tested in present work.
- Assuming only a spacetime structure that is local, Lorentz-invariant introduces 19 more parameters.

Early μ Decay Measurements

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

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.

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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.

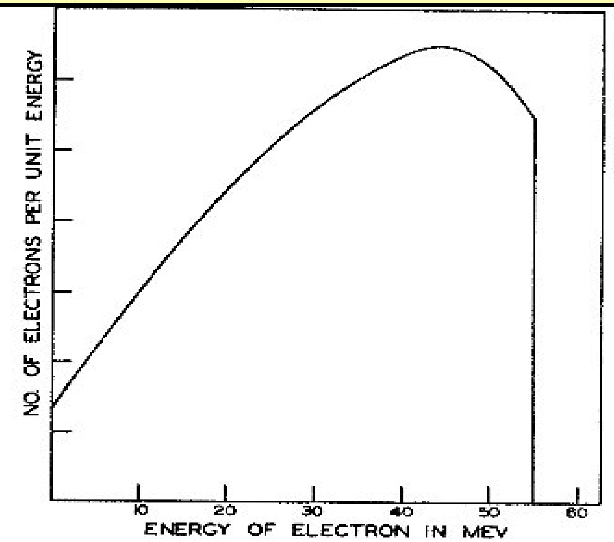
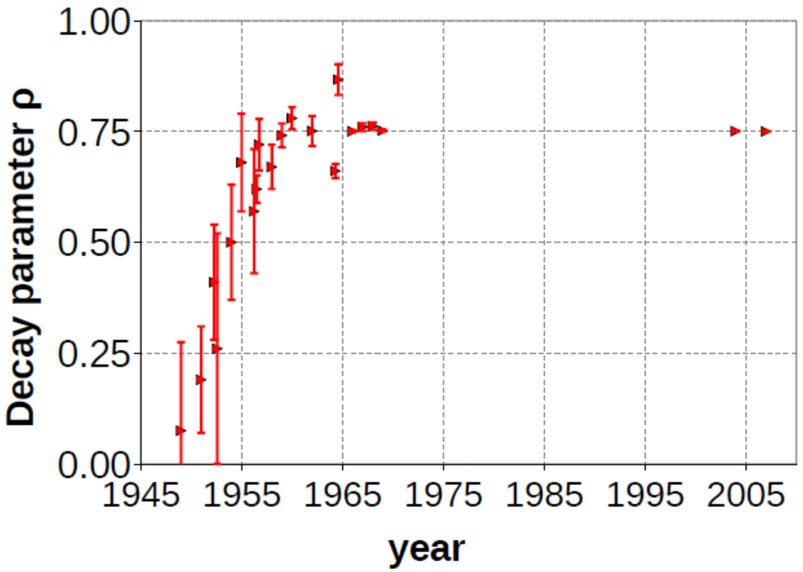


FIG. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.

Measurements of ρ



- Michel ρ parameter describes decay spectrum shape
- Depends on Lorentz structure
- Initial speculation $\rho = 0$
- Early test of V-A
- Textbook case for blind analysis

Greiner *et al.*, Gauge Theory of Weak Interactions, Springer (1996).

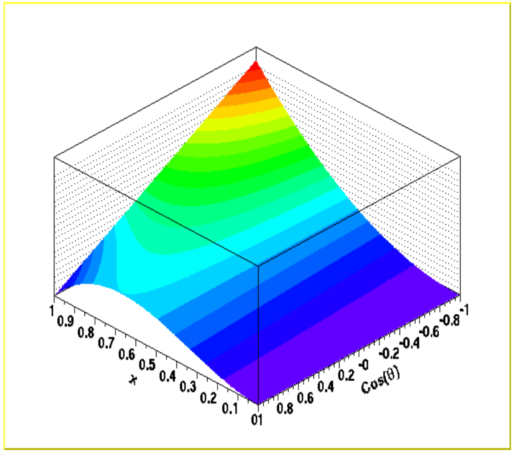
Muon Decay Parameters

Muon decay parameters ρ, η, δ, $P_\mu \xi$: (Michel, Kinoshita and Sirlin)

Polarized muon differential decay rate *vs.* energy and angle:

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

where



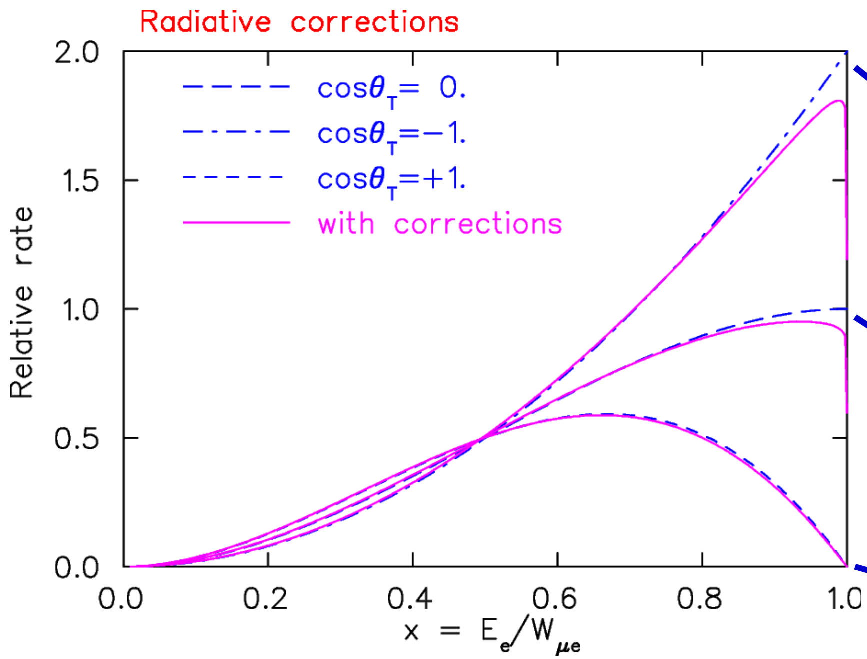
$$\mathcal{F}_{IS}(x,\rho,\eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

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

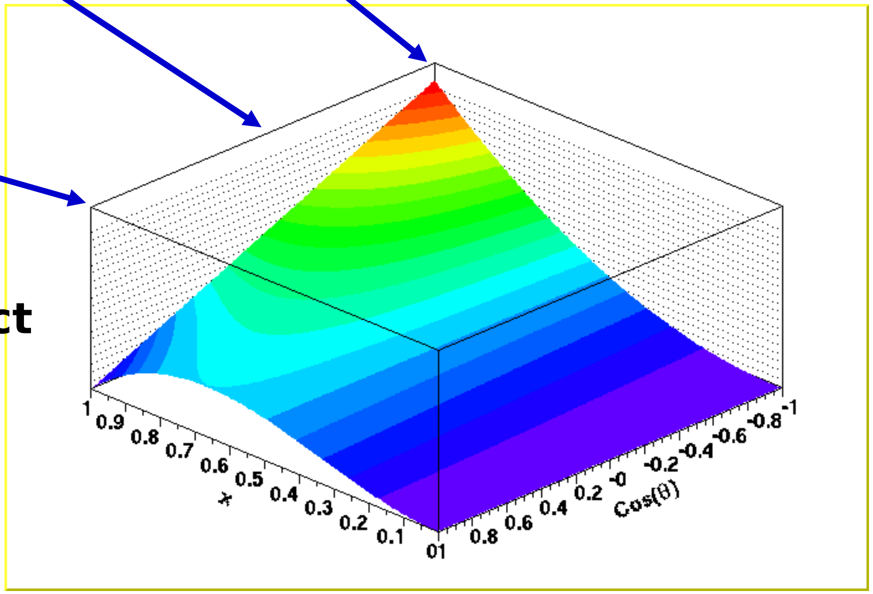
$$W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu},\ x = \frac{E_e}{W_{\mu e}},\ x_0 = \frac{m_e}{W_{\mu e}}.$$

Measurement of positron polarization yields additional important parameters

Radiative corrections



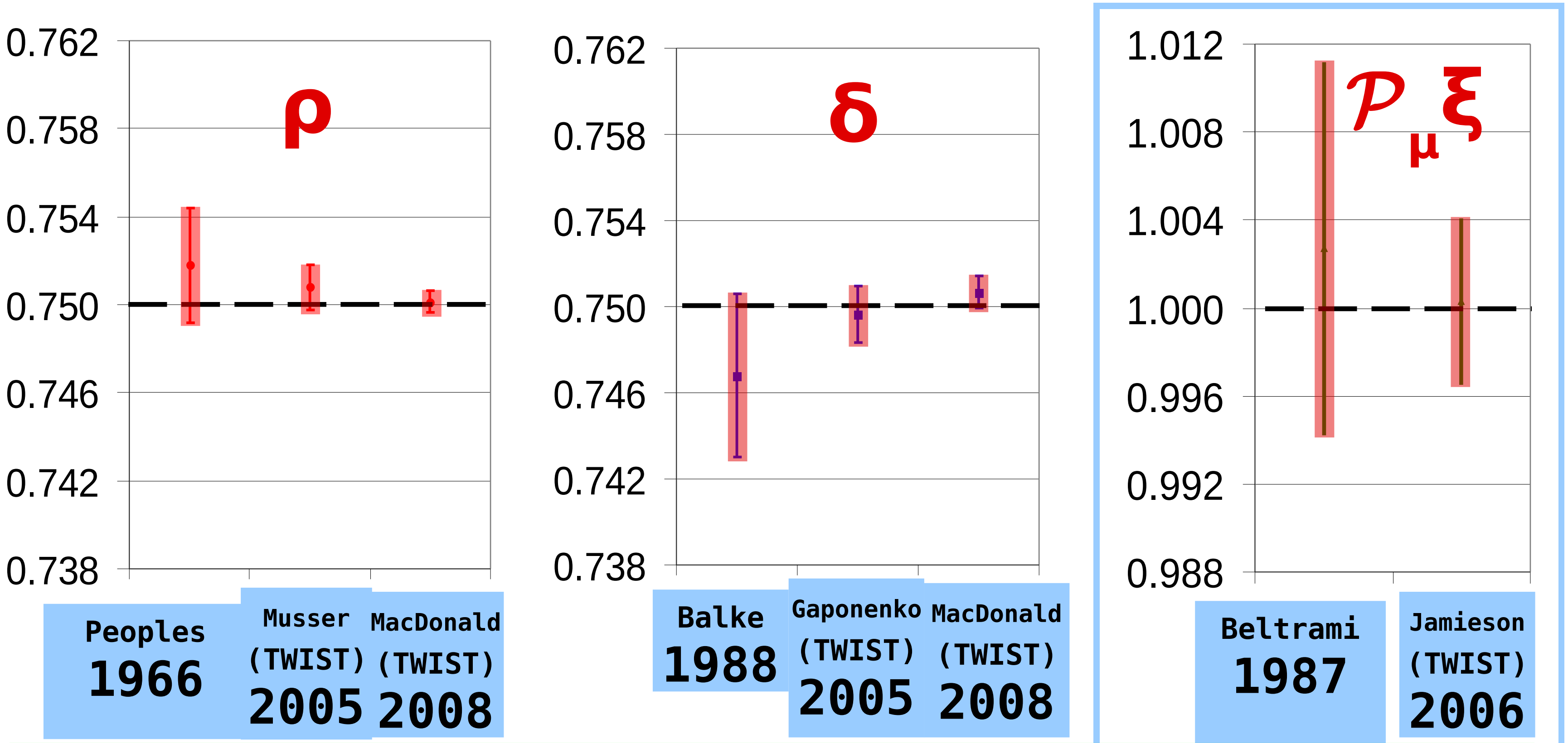
Arbuzov et al., Phys. Rev. D66 (2002) 93003.
Arbuzov et al., Phys. Rev. D65 (2002) 113006.
Arbuzov et al., JHEP03:063(2003).
Anastasiou et al, JHEP0709:014, (2007).



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.

Published results



ρ = 0.75014 ± 0.00017(stat) ± 0.00046(syst) ± 0.00011(η)

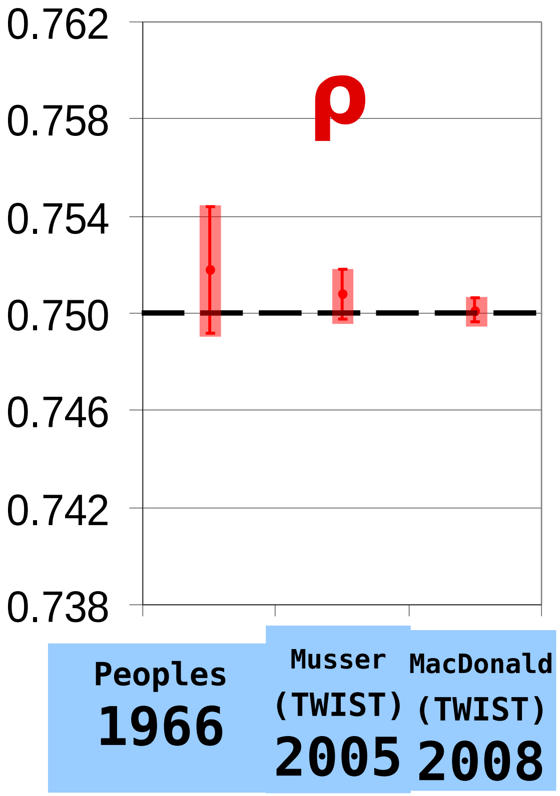
δ = 0.75068 ± 0.00030(stat) ± 0.00067(syst)

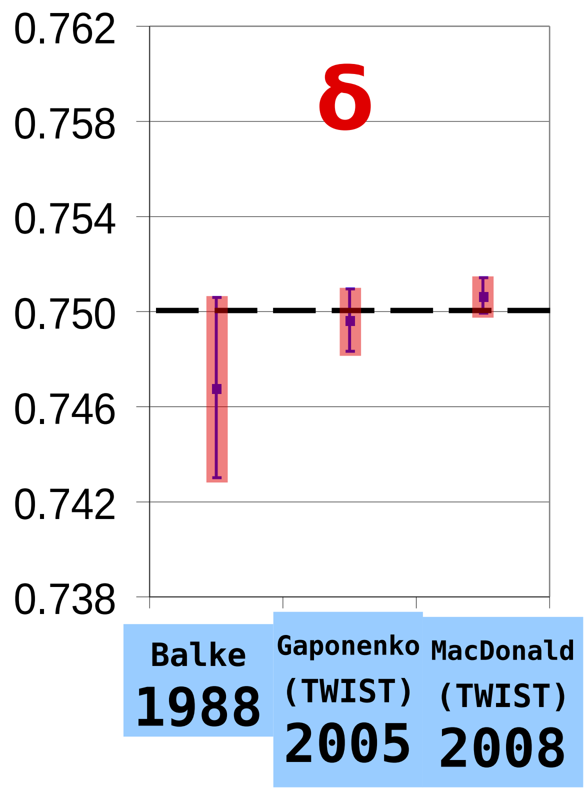
$P_\mu \xi$ = 1.0003 ± 0.0006(stat) ± 0.0038(syst)

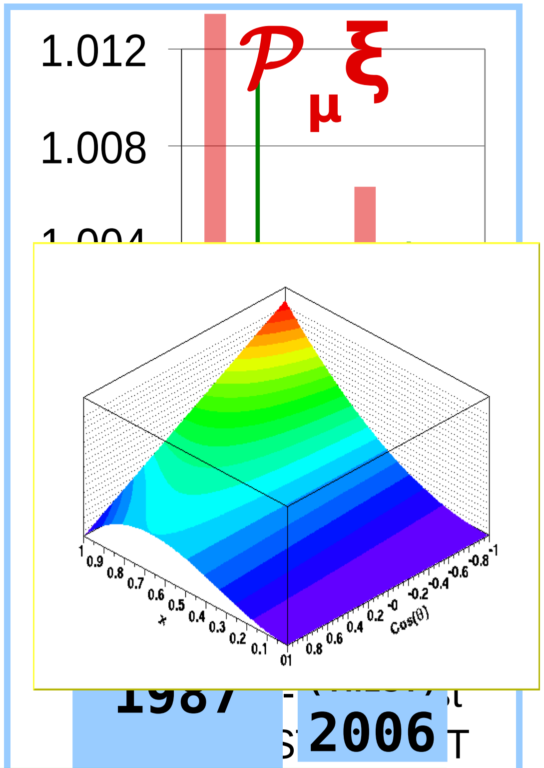
Also $P_\mu \xi\ \delta / \rho$ > 0.99682 (90%CL)from Jodidio *et al*, 1986

η = -0.002 ± 0.007 from PT1(Danneberg *et al.* , 2005)

Published results







ρ = 0.75014 ± 0.00017(stat) ± 0.00046(syst) ± 0.00011(**η**)

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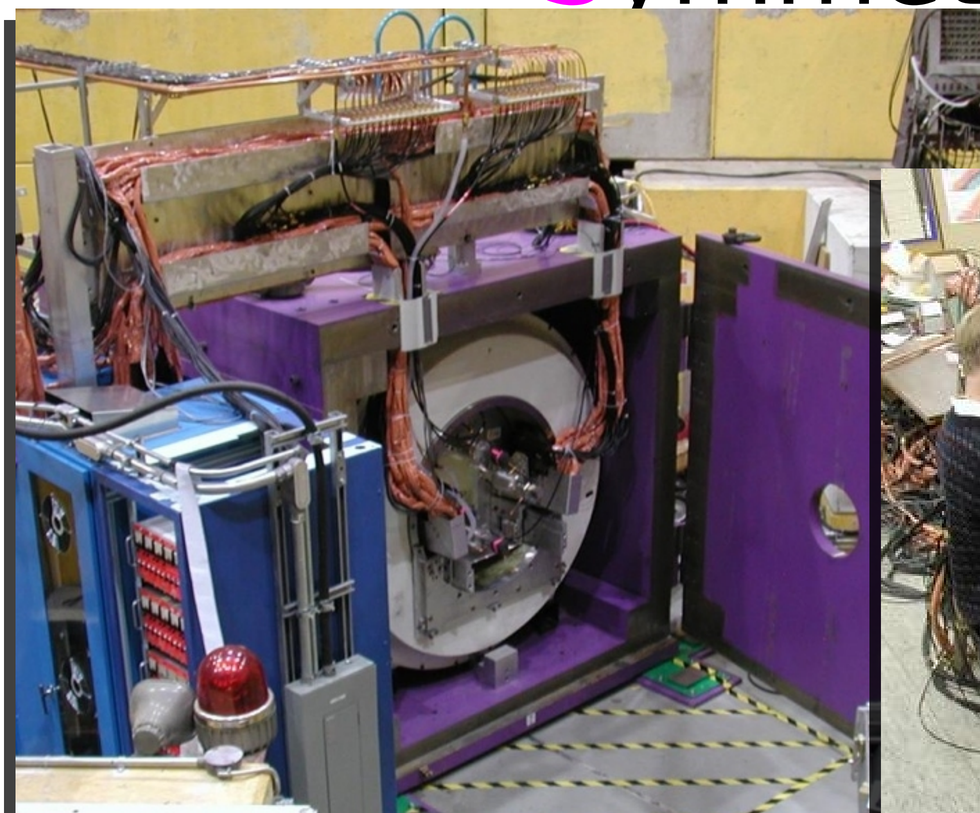
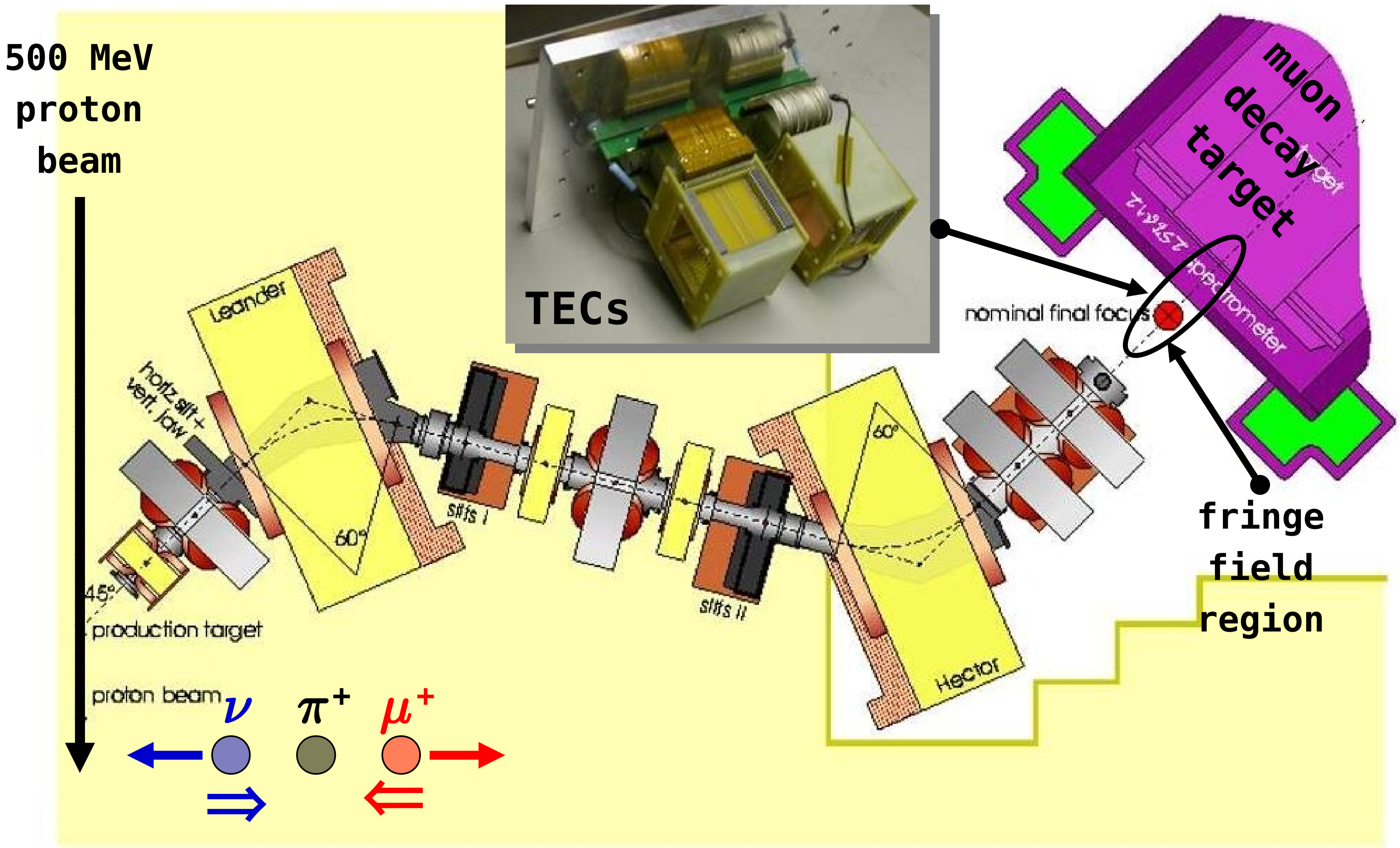
The *TWIST* Experiment

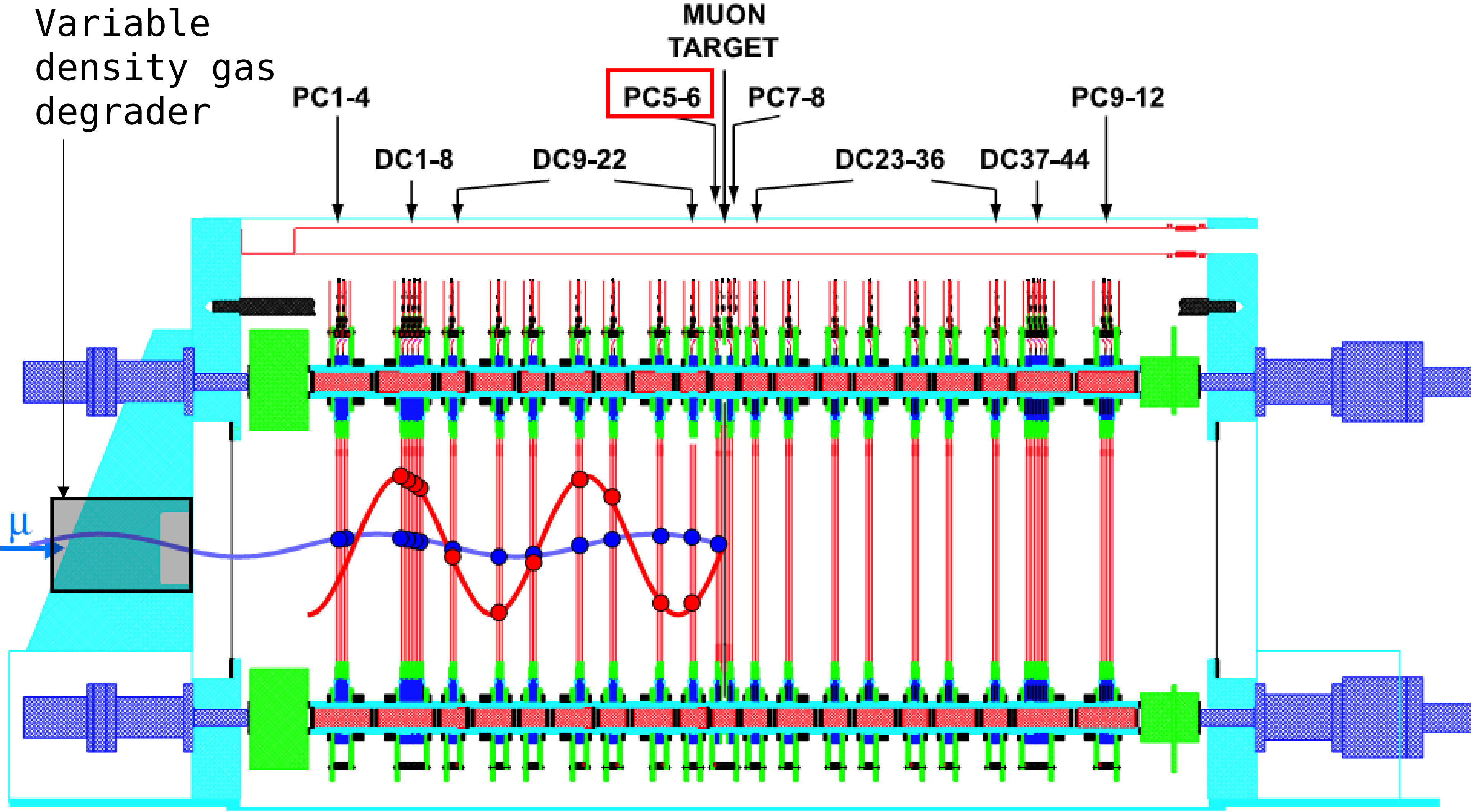
TRIUMF Weak Interaction Symmetry Test



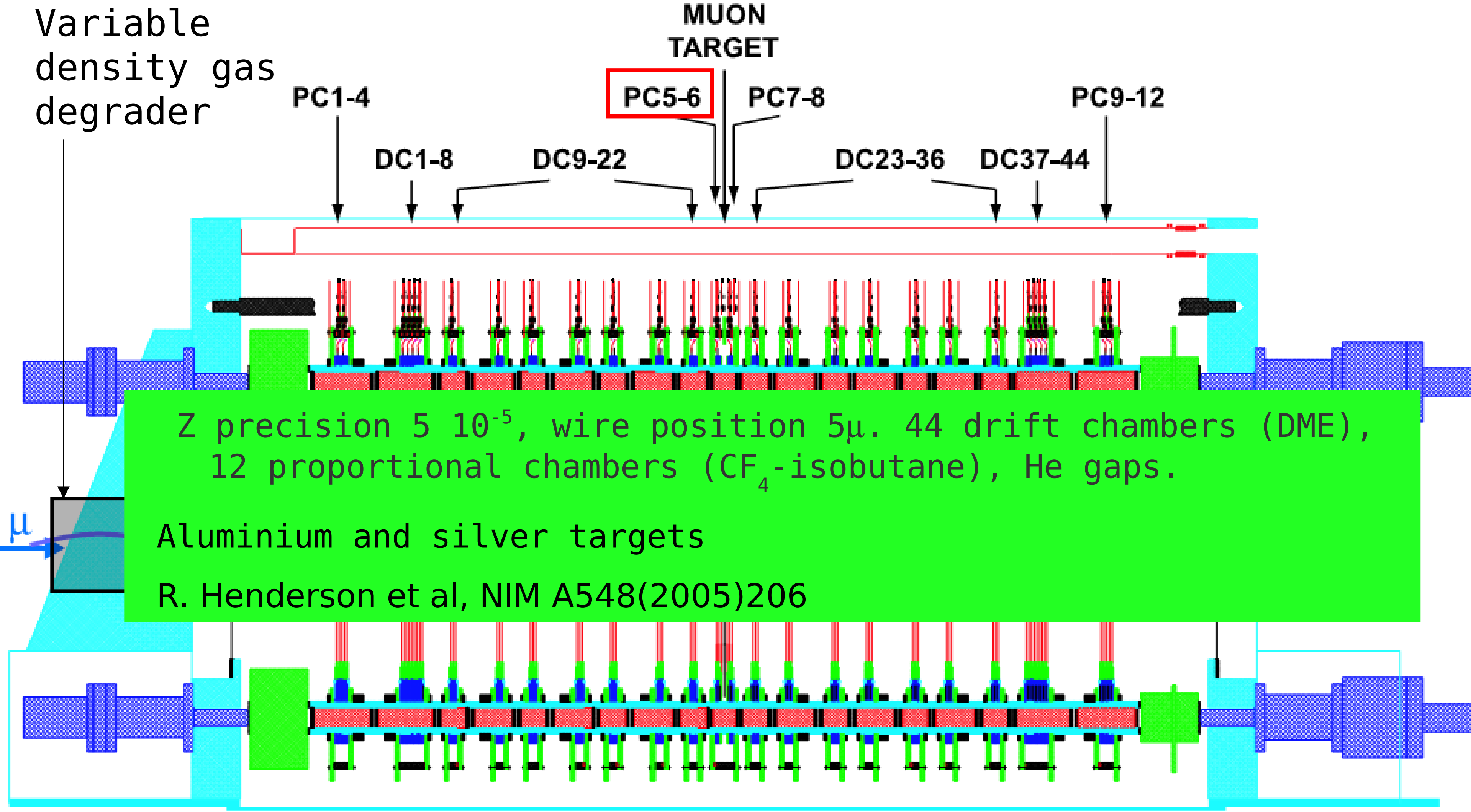
Muon production and transport



Positron tracking



Positron tracking

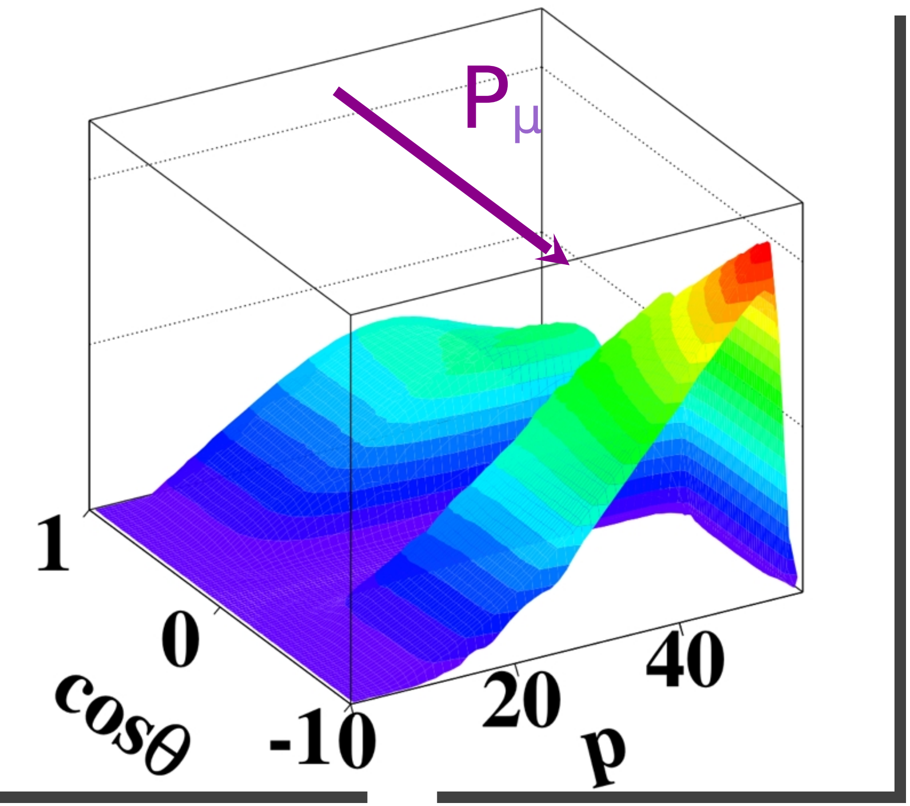


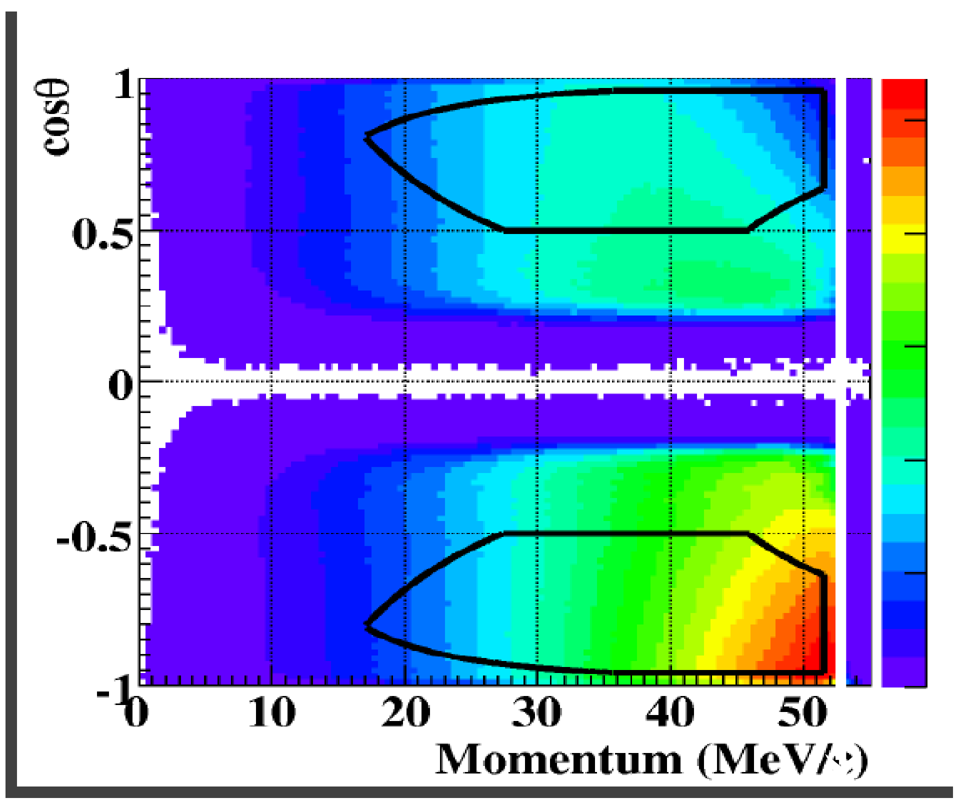
Z precision 5 10^{-5}, wire position 5μ. 44 drift chambers (DME), 12 proportional chambers (CF_4-isobutane), He gaps.

Aluminium and silver targets

R. Henderson et al, NIM A548(2005)206

Muon Decay Spectrum

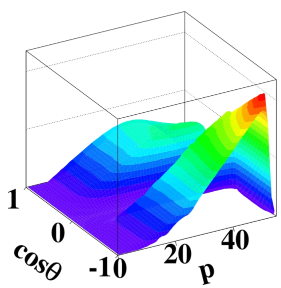


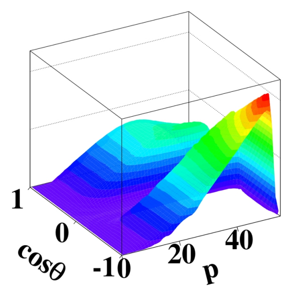


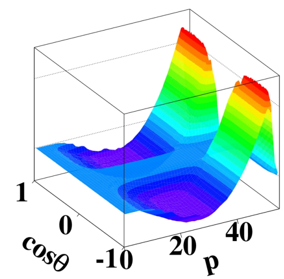
Spectrum Fitter

Decay spectrum linear in ρ, $P_\mu\xi$, $P_\mu\xi\delta$.

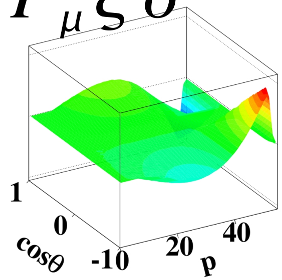
$$N(Data) = N(MC) + \frac{\partial N}{\partial \rho}\Delta\rho$$

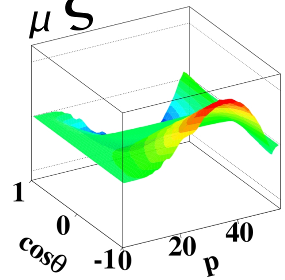






$$+ \frac{\partial N}{\partial P_\mu \xi \delta}\Delta P_\mu \xi \delta + \frac{\partial N}{\partial P_\mu \xi}\Delta P_\mu \xi$$





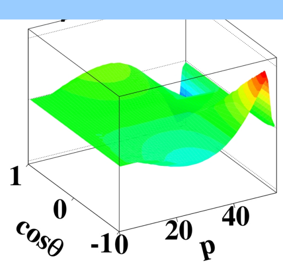
Spectrum Fitter

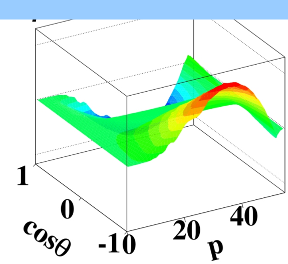
Decay spectrum linear in ρ, $P_\mu\xi$, $P_\mu\xi\delta$.

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

Simulation is blinded by introducing random offsets to ρ, δ, and ξ.

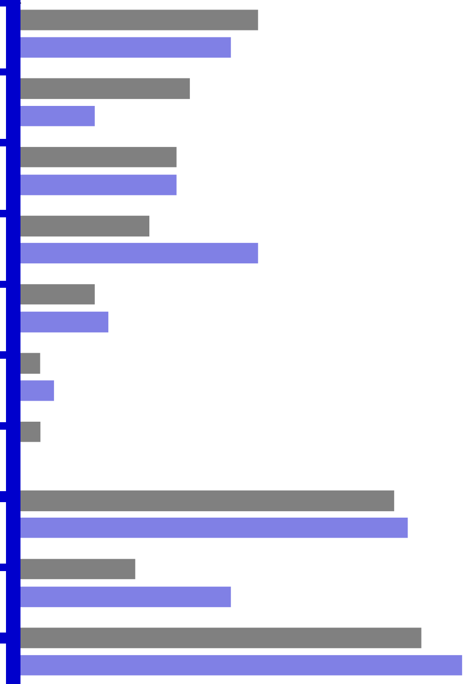
Spectrum edge is fit in angle slices to the simulation and the Michel parameter fit is iterated.



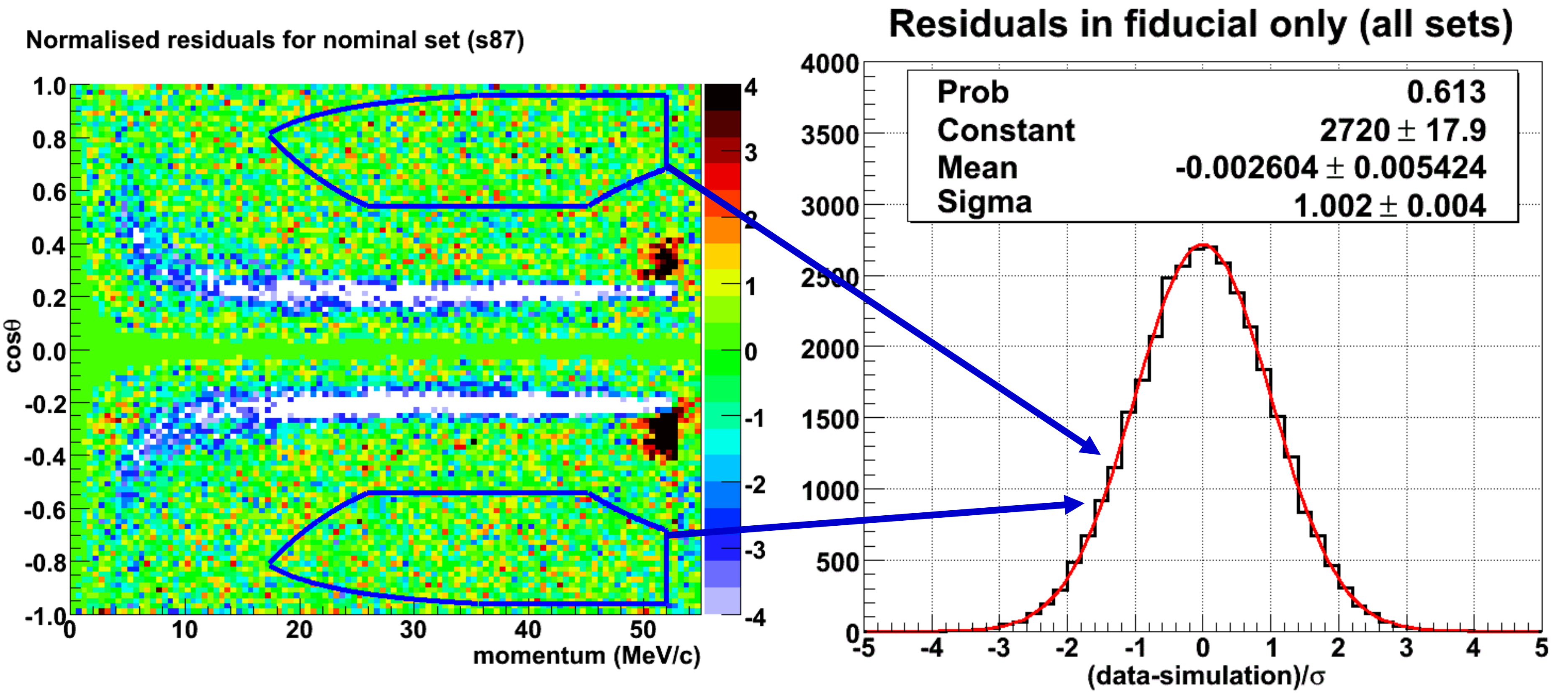


ρ and δ uncertainties

Uncertainties	ρ (x10^{-4})	δ (x10^{-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*

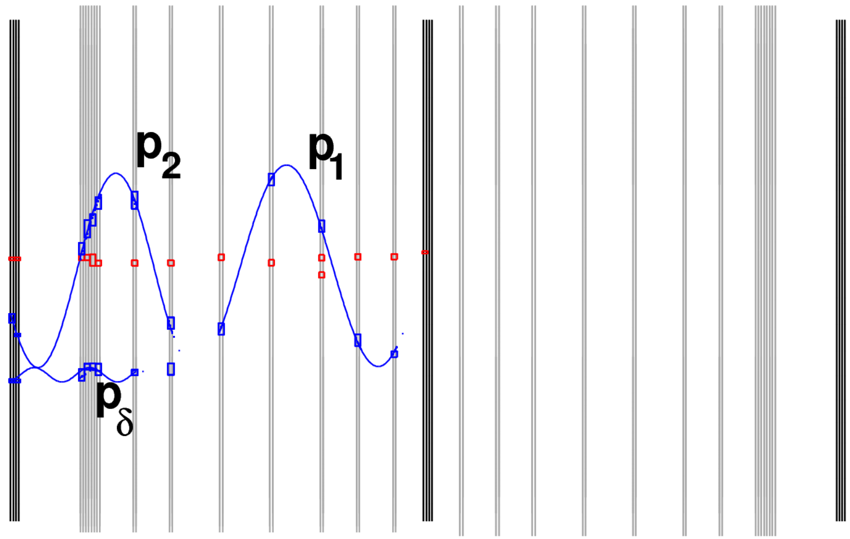


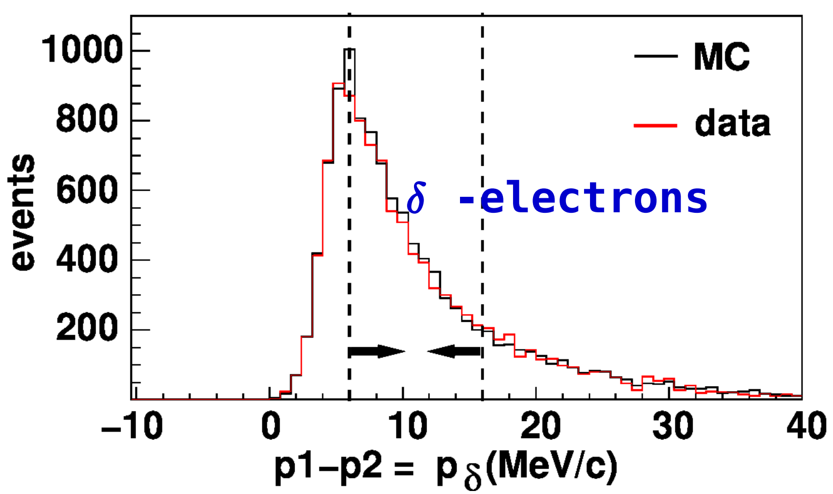
Spectrum fit quality

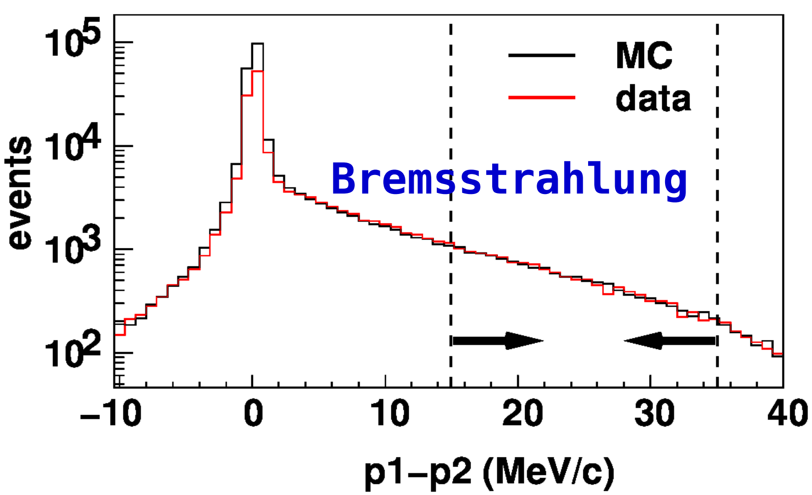


- All data sets: **11×10^9** events, **0.55×10^9** in $(p, \cos\theta)$ fiducial
- Simulation sets: **2.7** times data statistics

Positron interactions

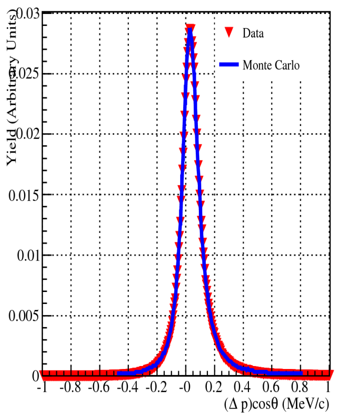


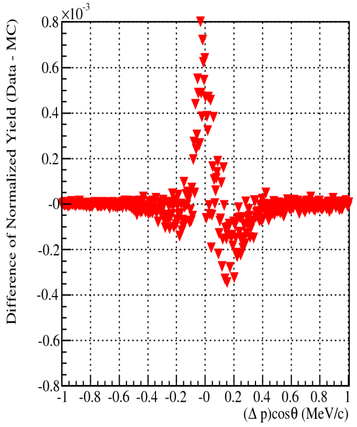


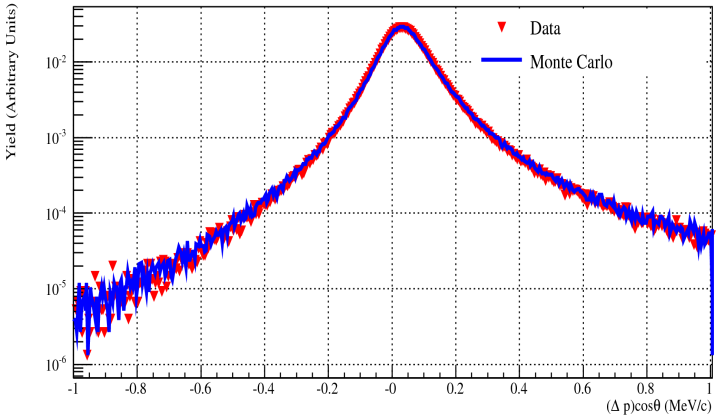


Positron interactions

- GEANT simulation must be validated for e⁺ energy loss and multiple scattering.
- Stop muons at one end of detector
- Measure e⁺ track on each side of target, before and after passage through it.
- Compare differences between data and simulation.
- Simulations with this difference exaggerated determine associated change in muon decay parameters







Positron interactions

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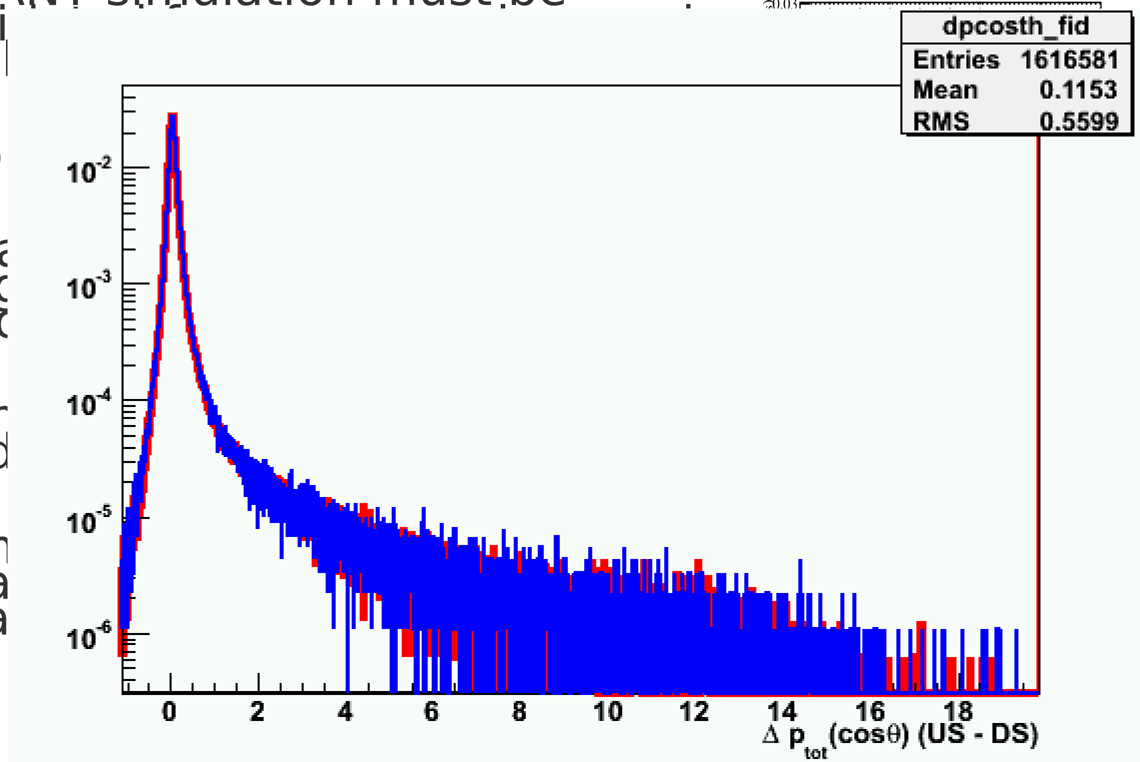
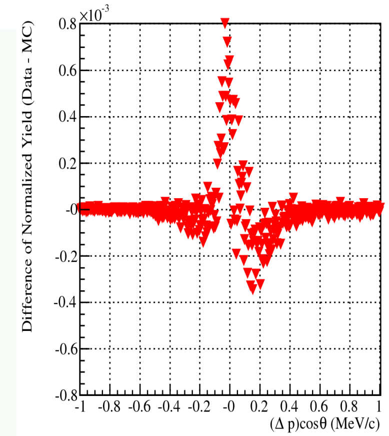
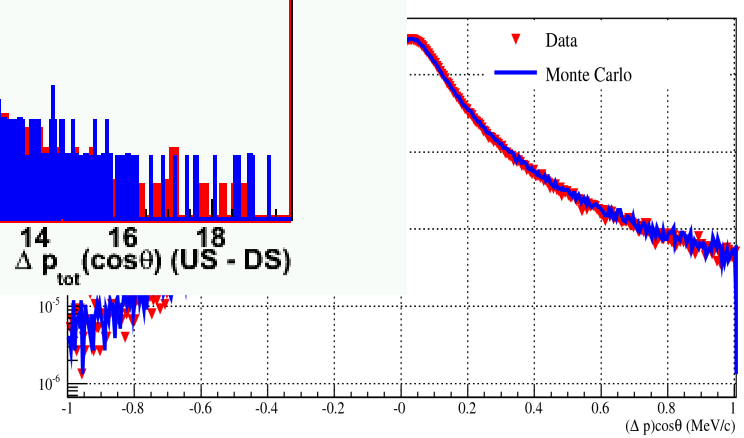
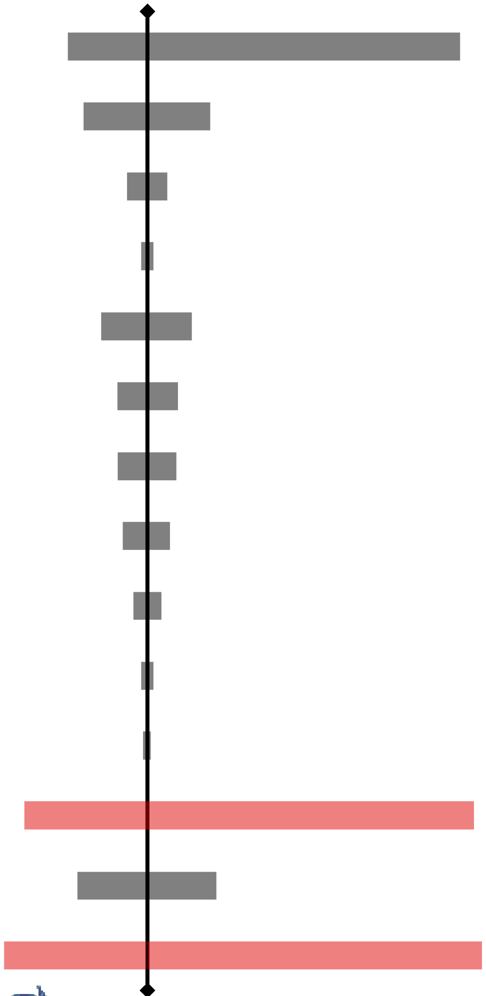




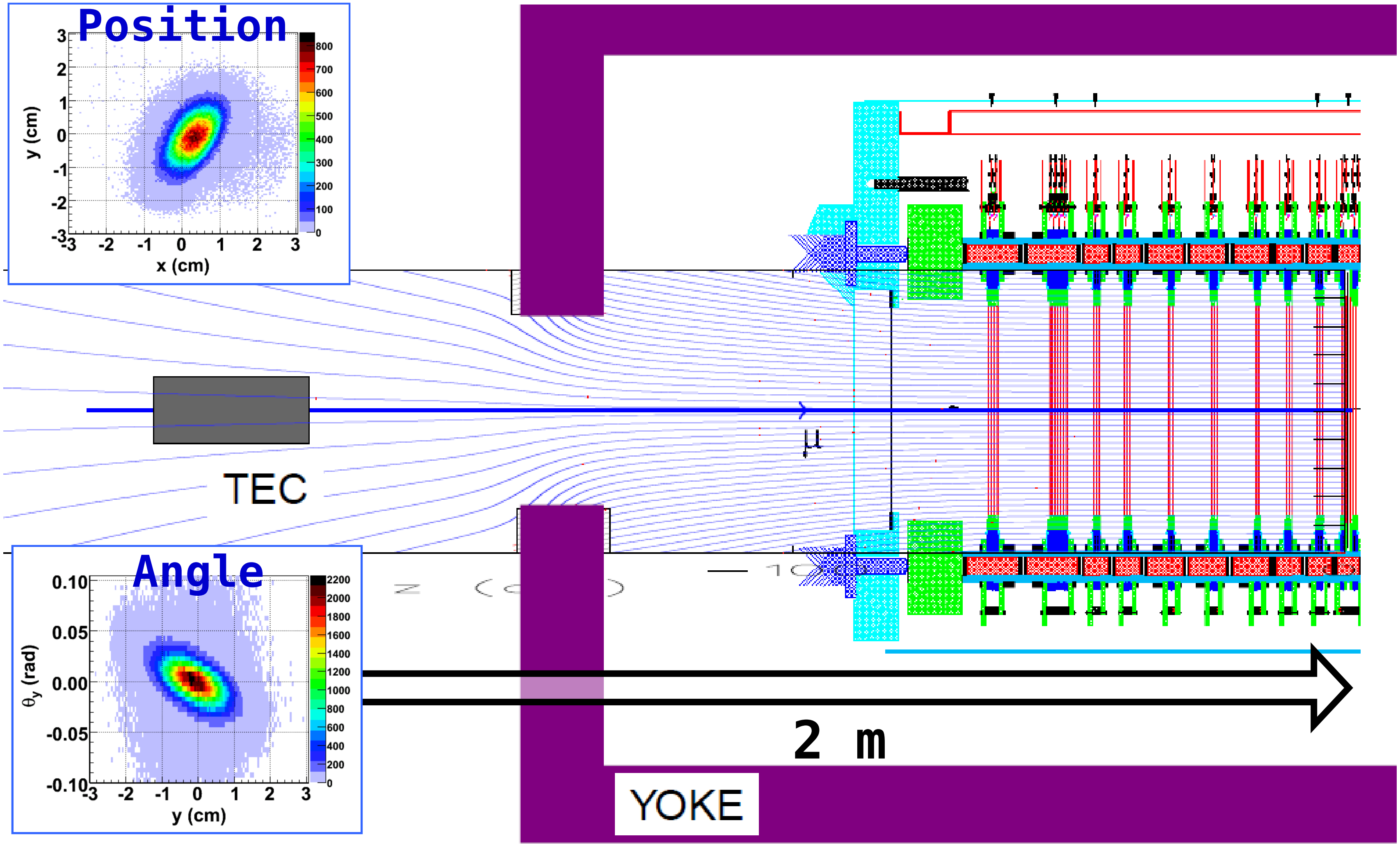


$\mathcal{P}_\mu \xi$ uncertainties

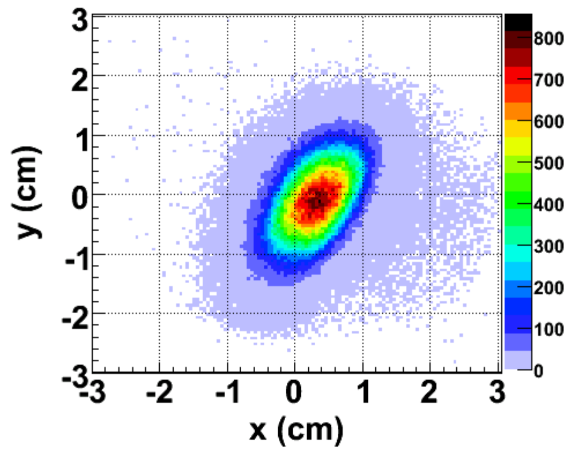
Uncertainties	$\mathcal{P}_\mu \xi$ ($\times 10^{-4}$)
Depolarization in fringe field	+15.8, -4.0
Depolarization in stopping material	3.2
Background muons	1.0
Depolarization in production target	0.3
Chamber response	2.3
Resolution	1.5
Momentum calibration	1.5
External uncertainties	1.2
Positron interactions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

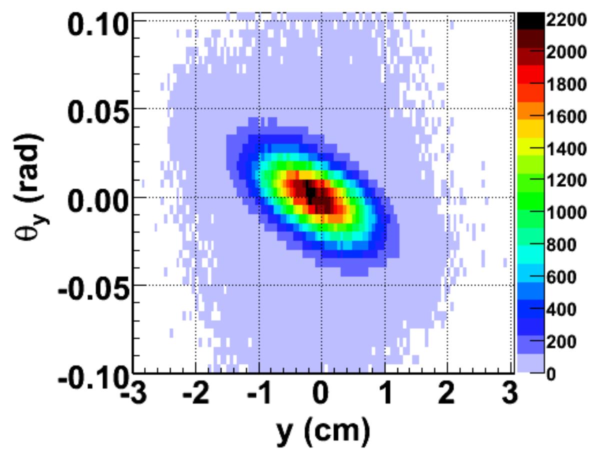


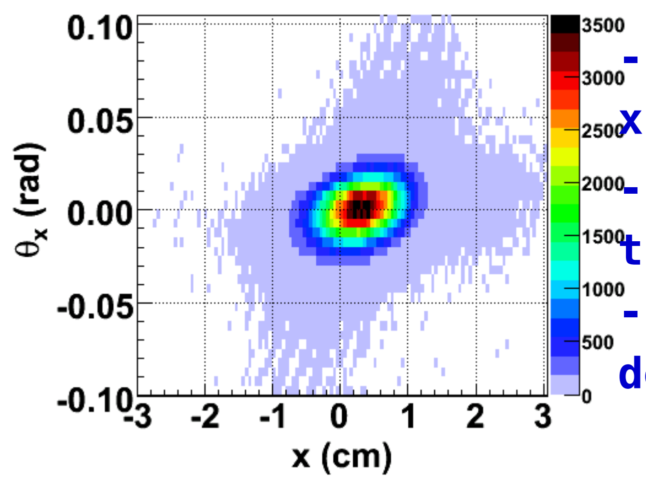
Fringe field, solenoid entrance



Fringe field depolarization





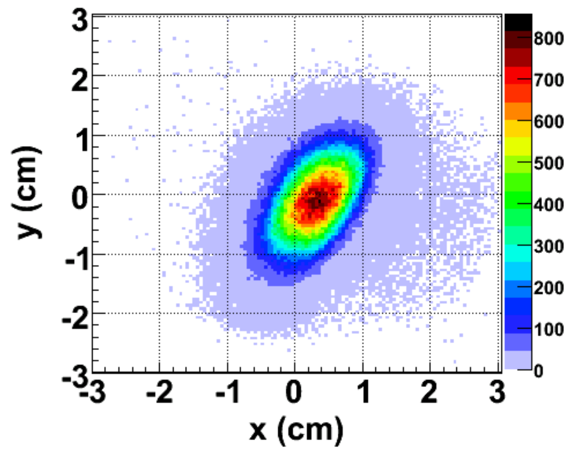


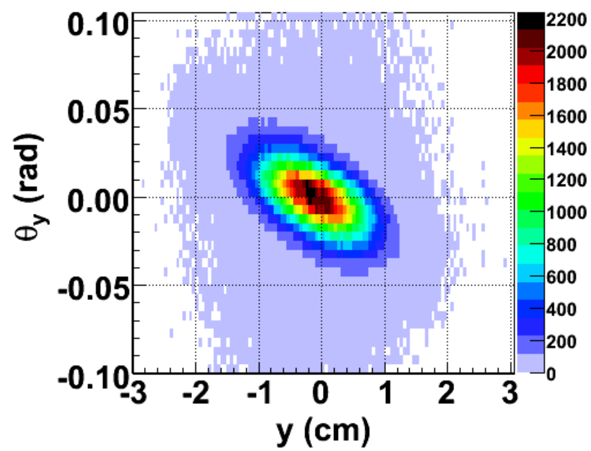
- TEC modules measure distributions in x, y, θ_x, θ_y, and correlations.

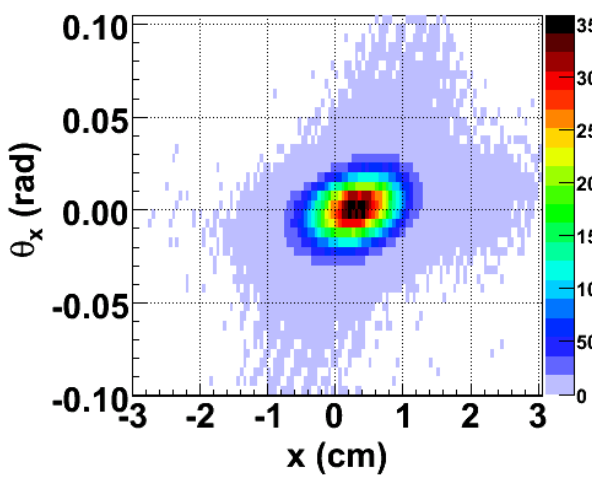
- After correction for TEC scattering, they are used to generate beam in simulation.

- Comparisons are used to test fringe field depolarization systematics.

Fringe field depolarization







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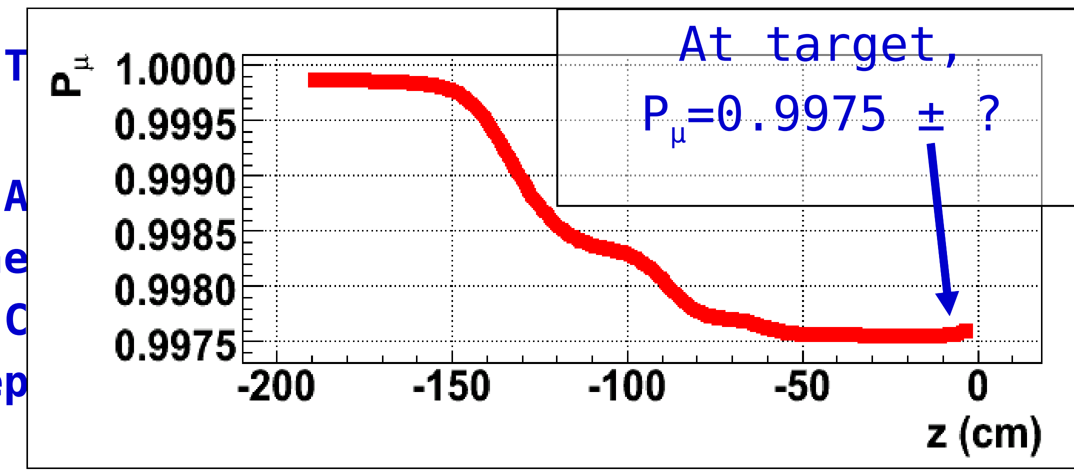
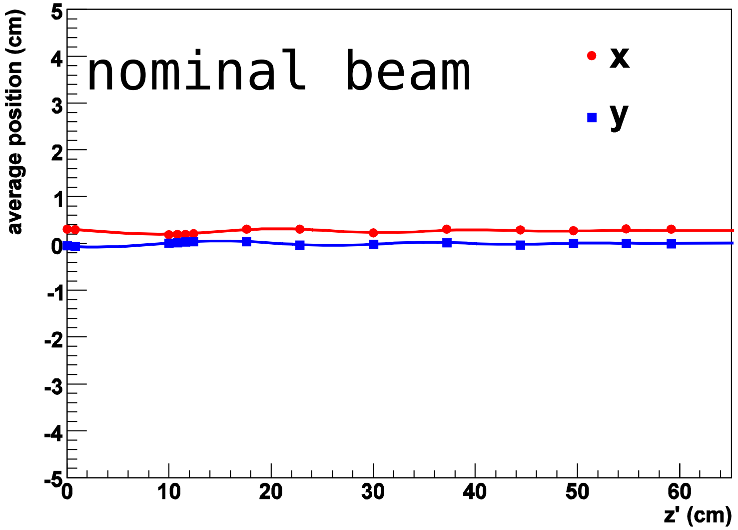
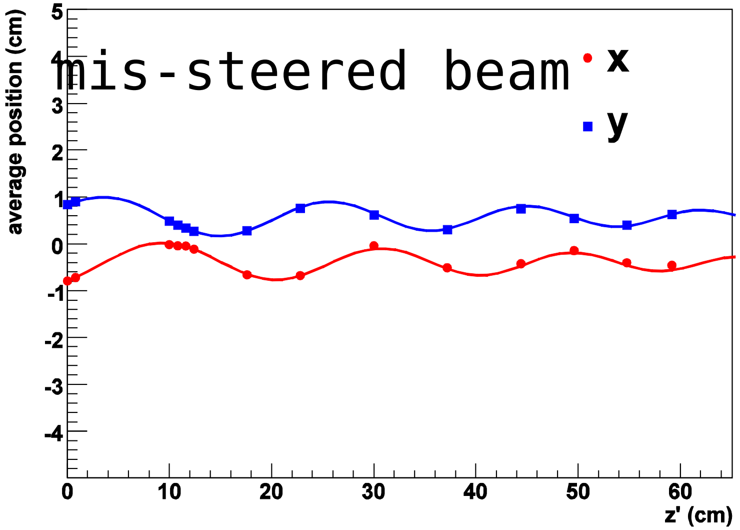


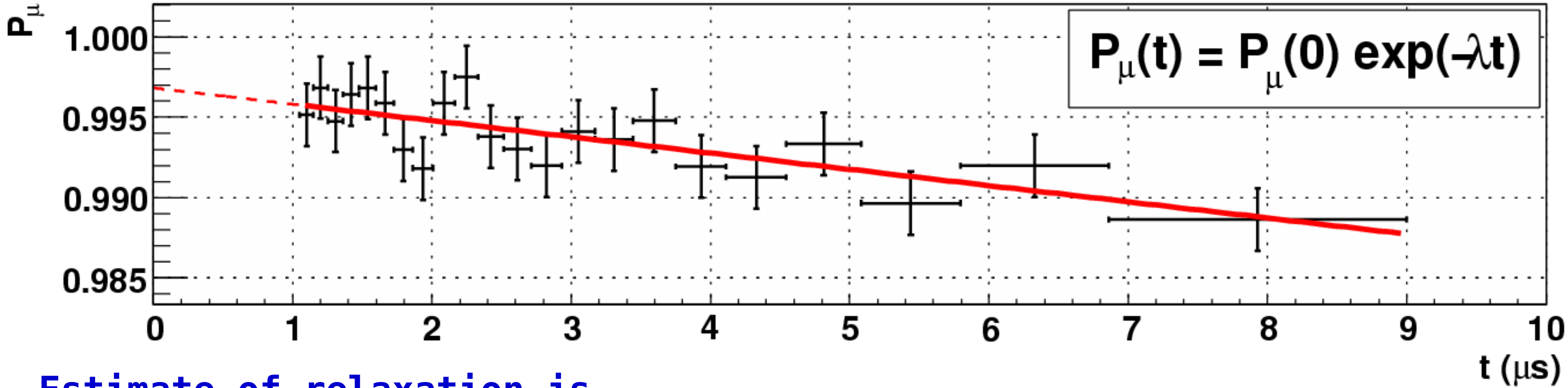
Measured average muon positions



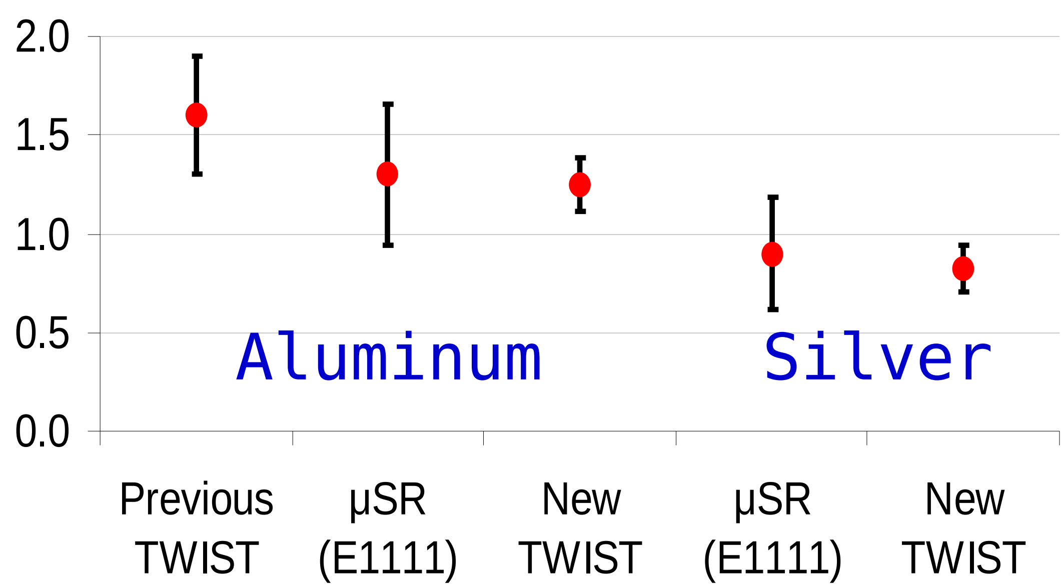


- Each point represents the average muon beam position at a detector plane.
- Simulated data can be analyzed in the same way.
- Fit both to “shrinking helix”.
- Comparison of fits of data and simulation is a powerful way to verify the simulation, *e.g.* , influence of fringe field on muon beam, detector-field alignment.
- Use “internal beam” to test fringe field depolarization limitations.

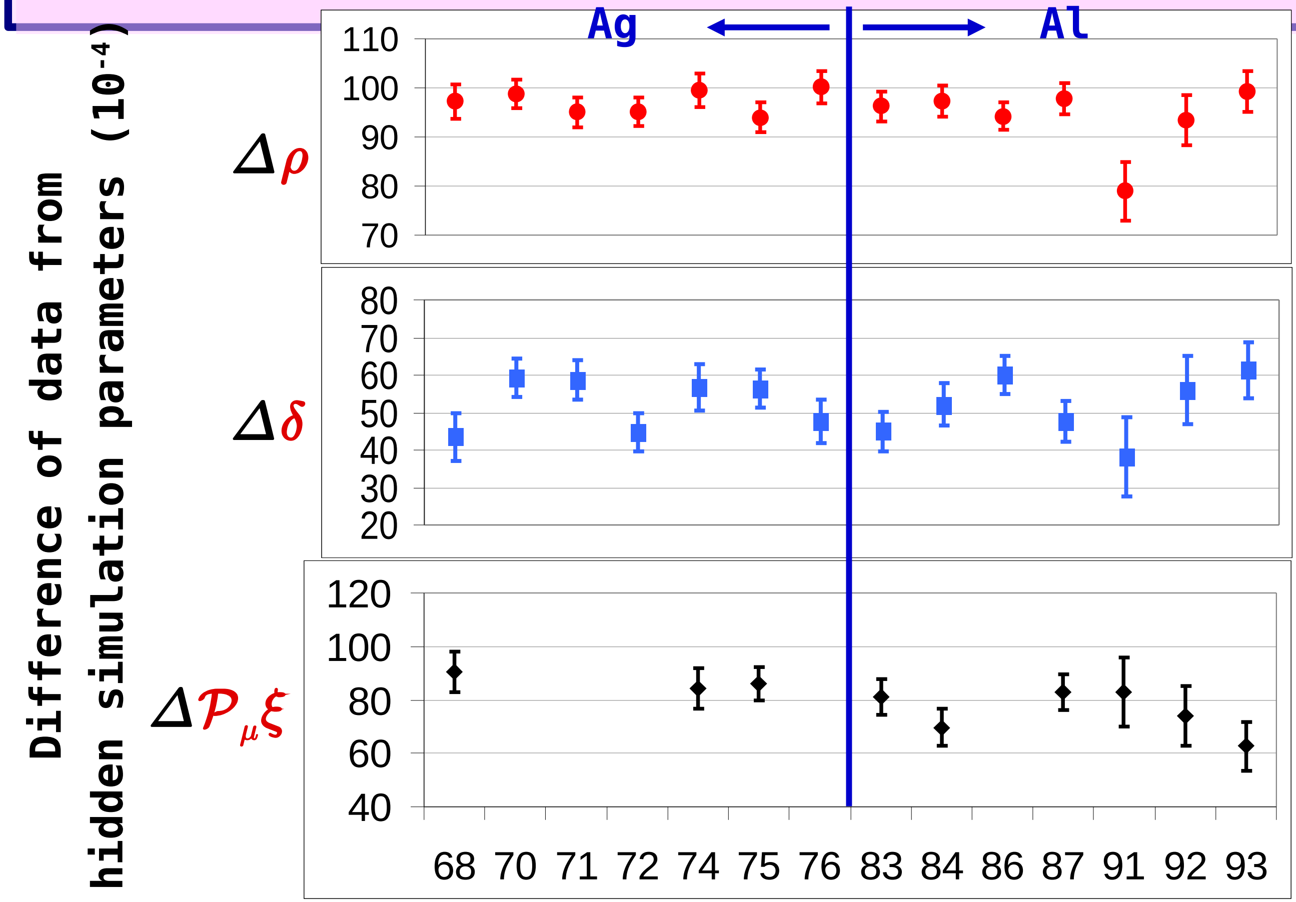
Depolarization in target material



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



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

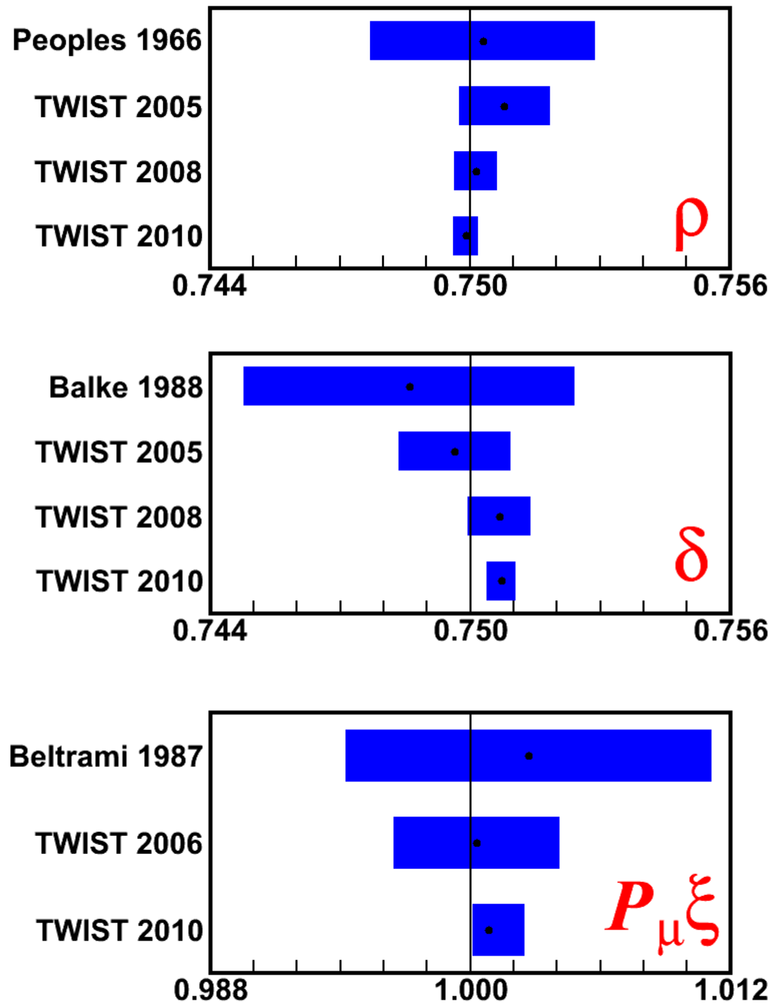
- **14 data sets for ρ and δ, χ^2 of 14.0 and 17.7 respectively**
- **9 data sets used for $P_\mu\xi$, $\chi^2 = 9.7$**
- **statistical uncertainties only, after corrections**

Blind Analysis Results

(*vs.* SM)

- ρ **= 0.74991 ± 0.00009 (stat) ± 0.00028 (syst) (-0.3σ)**
- δ **= 0.75072 ± 0.00016 (stat) ± 0.00029 (syst) (+2.2σ)**
- $\mathcal{P}_\mu\xi$ **= 1.00084 ± 0.00035 (stat)** $^{+0.00165}_{-0.00063}$ **(syst) (+1.2σ)**
- **correlations:**
  corr(ρ,δ)=+0.69, corr(ρ,$\mathcal{P}_\mu\xi$)=-0.06/-0.14, corr(δ,$\mathcal{P}_\mu\xi$)=-0.18/-0.43
- **Combine:** $\mathcal{P}_\mu\xi\delta/\rho$ **= 1.00192** $^{+0.00167}_{-0.00066}$ **(+2.9σ)**
  - investigating possible instrumental sources of error
  - Positive decay rate at downstream endpoint →$\mathcal{P}_\mu\xi\delta/\rho > 1.0$
  - Significant statistical difference in $\mathcal{P}_\mu\xi\delta/\rho$ between Al and Ag
  - Candidate effect identified – to early to confirm.

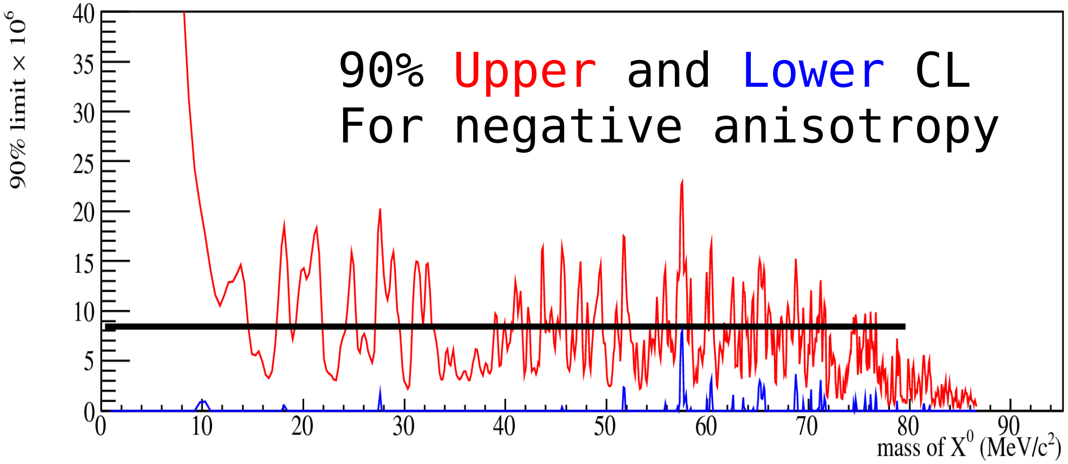
Comparisons with previous results



- **New results are consistent with previous results.**
- **δ is consistent with SM within 2.2σ.**
- **$P_\mu\xi$ is consistent with SM values at the level of 1.2σ.**

Limits on μ→e X^0

- Include a peak with the shape of the response function in the fit.
- Isotropic, positive and negative anisotropic angular distributions
- Sensitivity to massless X^0 limited by ability to match data and sim edge.



Decay signal	Region	90% Upper CL
Isotropic	Fiducial Average	8.1×10^{-6}
	Edge	3.3×10^{-5}
Negative	Fiducial Average	8.4×10^{-6}
Anisotropy	Edge	6.7×10^{-5}
Positive	Fiducial Average	5.7×10^{-6}
Anisotropy	Edge	8.5×10^{-6}
Bryman 86	Fiducial Average	3×10^{-4}
Jodidio 86	Edge	2.5×10^{-6}

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:

$$t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \quad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}, \quad \zeta_g^2 = \frac{g_R^2}{g_L^2}\zeta^2$$

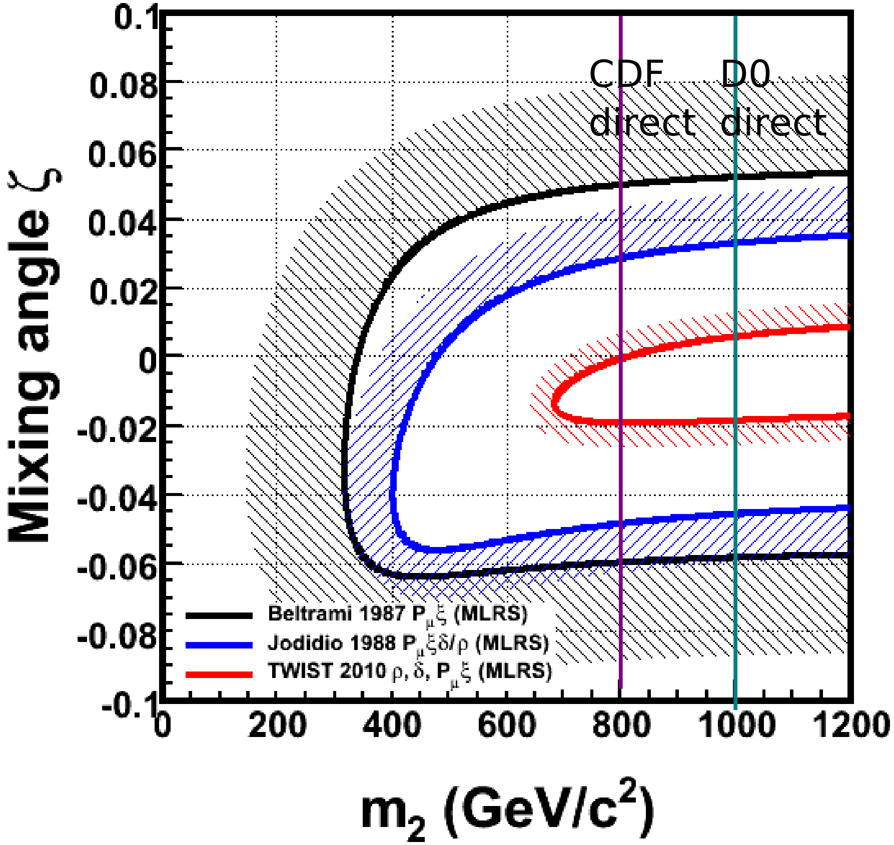
- Then, for muon decay, the Michel parameters are modified:

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

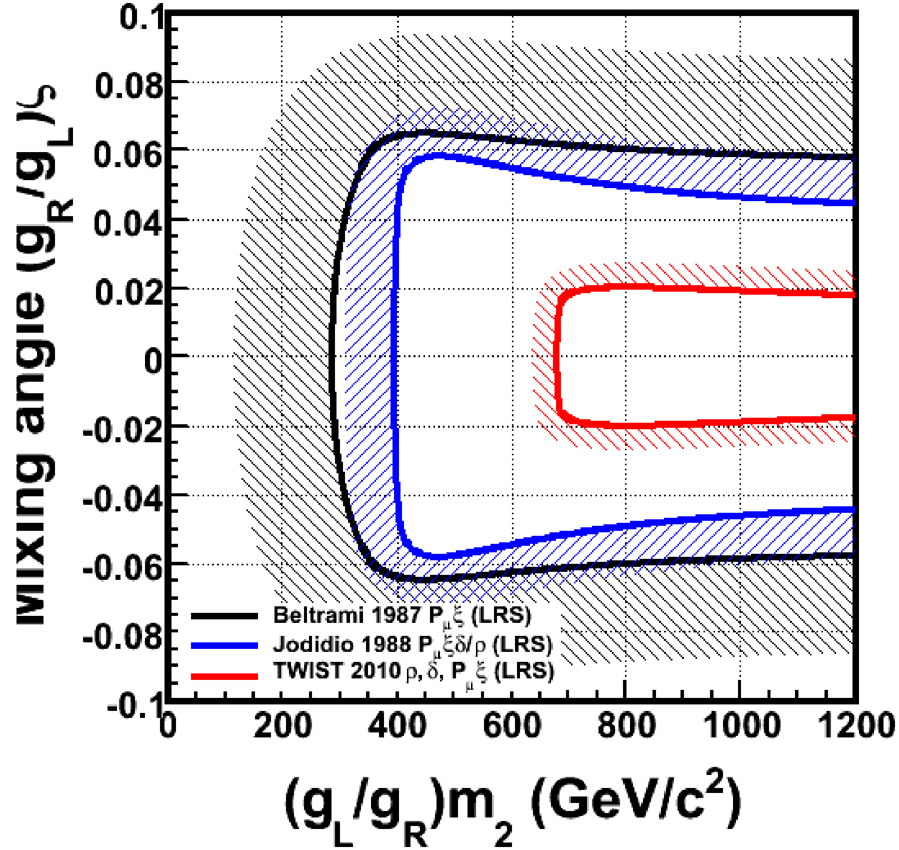
  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\omega = 0$ (no CP violation).
  - "pseudo-manifest" LRS allows CP violation, but $V^R = (V^L)^*$ and $g_R = g_L$.
  - LRS "non-manifest" or generalized LRS makes no such assumptions.

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

LRS parameters from muon decay



General LRS



$m_2 > 684\ \mathrm{GeV}/c^2$

$-0.019 < \zeta < +0.010$

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 are reexamining our data for a possible explanation.

TWIST Collaboration

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Supported by NSERC, DOE, RMF, Westgrid

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Graduated student
y also U Vic
zz also Saskatchewan

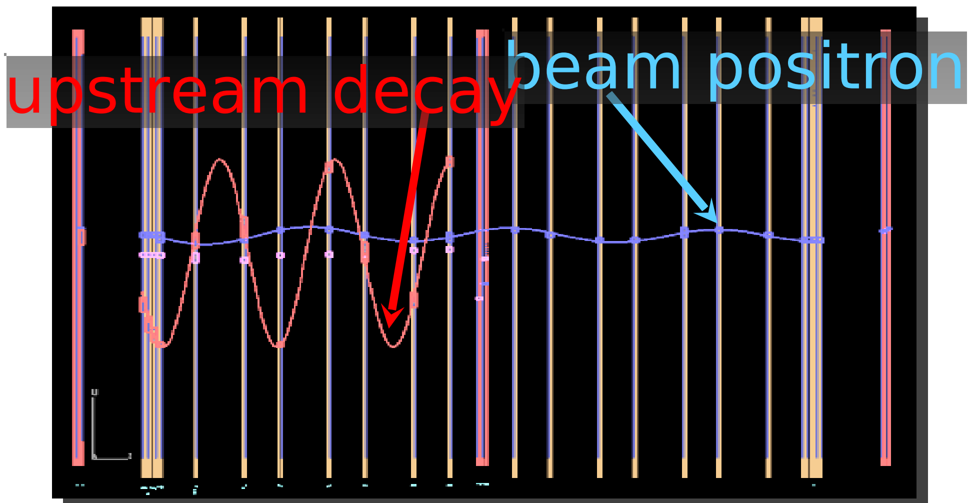
Extras

Outline

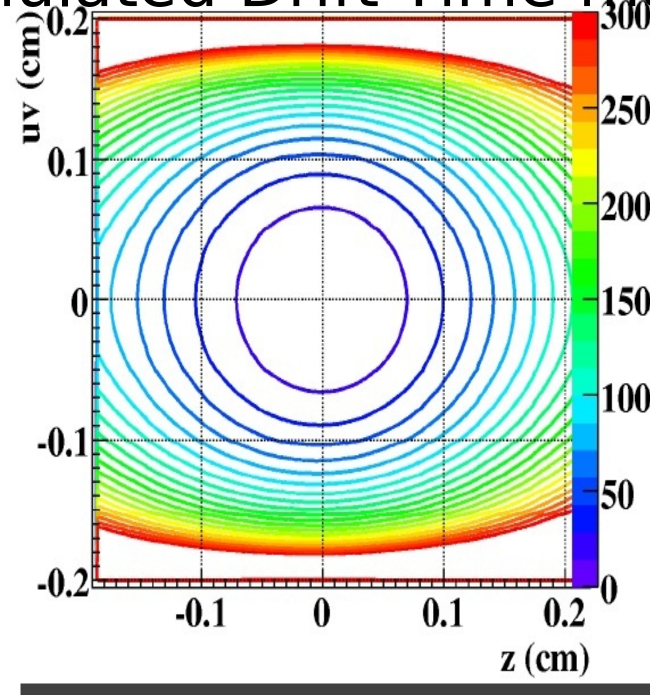
- A little historical background
- Muon decay description
- Summary of measurements
- Standard Model tests
- **TWIST** experiment overview
  - Detectors
  - Beams
  - Analysis methods
- Systematic uncertainties
  - for **ρ** and **δ**
  - for **$P_\mu \xi$** - depolarization
- Results of the Blind Analysis

- Outlook

TWIST Analysis

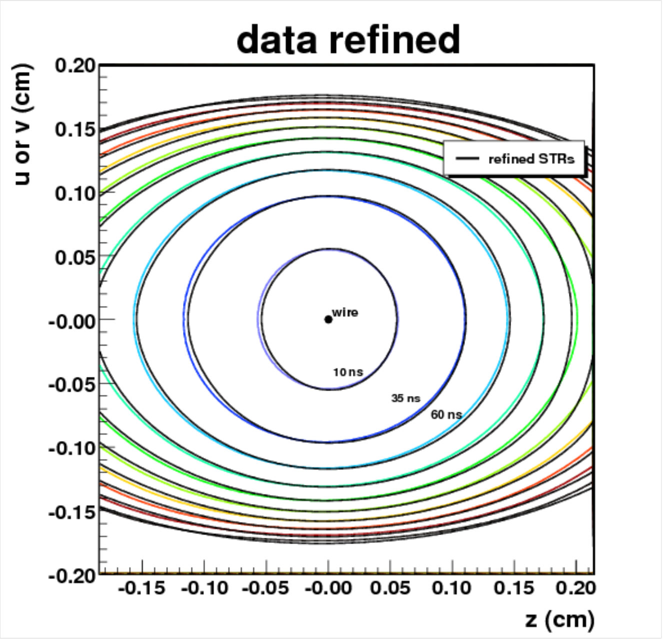


Simulated Drift Time map



Chamber response

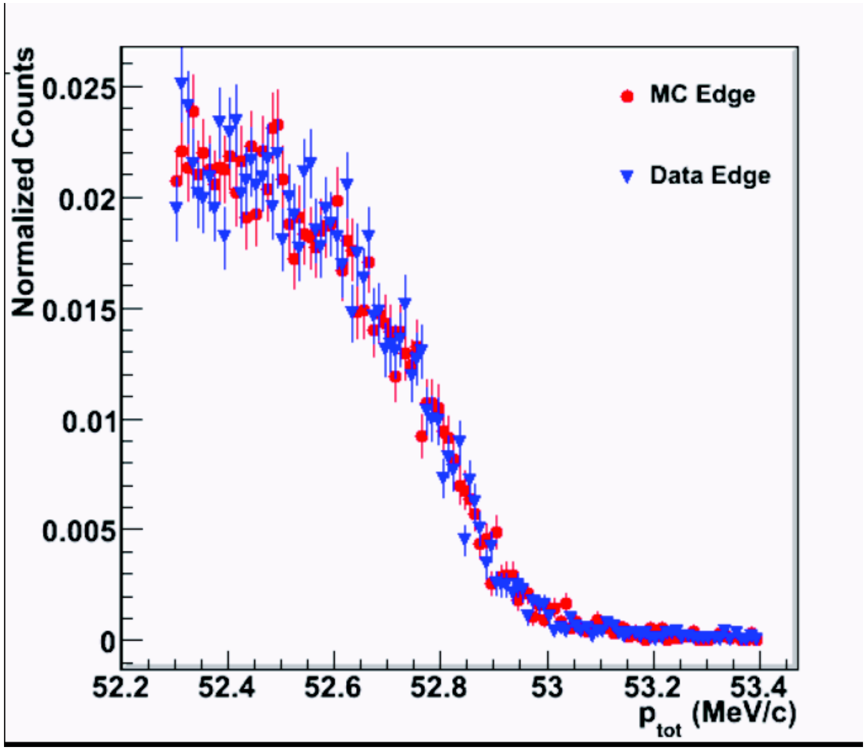
- Improvements benefit all three parameters, ρ,δ, and $P_\mu\xi$.
- Detector position response:
- Use drift chamber Space Time Relationships as determined from data tracks for data analysis, as well as from simulated tracks for simulation analysis (common biases).
- accounts for geometry variations, drift model dependence, tracking biases



Drift time isochrones for data, GARFIELD, before and after correction from track residual analysis.

A Grossheim et al, submitted to NIM

Energy Resolution



Energy calibration procedure matches the position of data and simulation edges

Ag

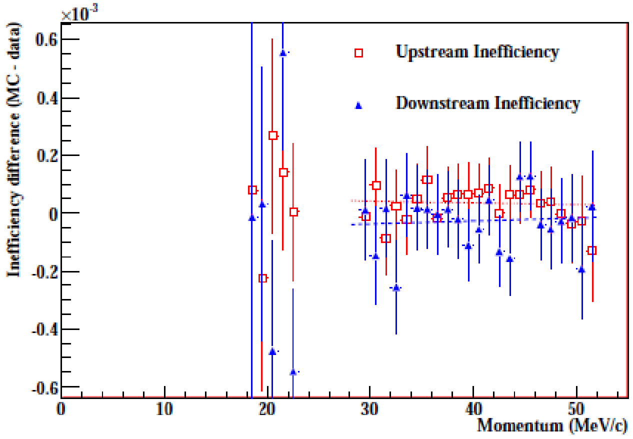
Data Resolution 59.5±0.2 keV/c
MC Resolution 59.5±0.2 keV/c
Response func diff 1.2 keV/c

Al

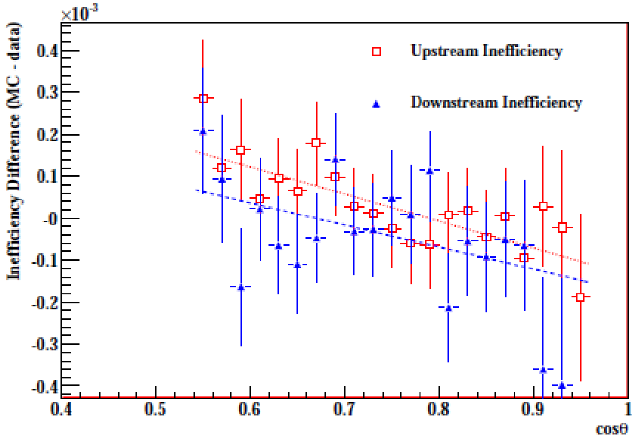
Data Resolution 58.5±0.2 keV/c
MC Resolution 58.4±0.2 keV/c
Response func diff 2.0 keV/c

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

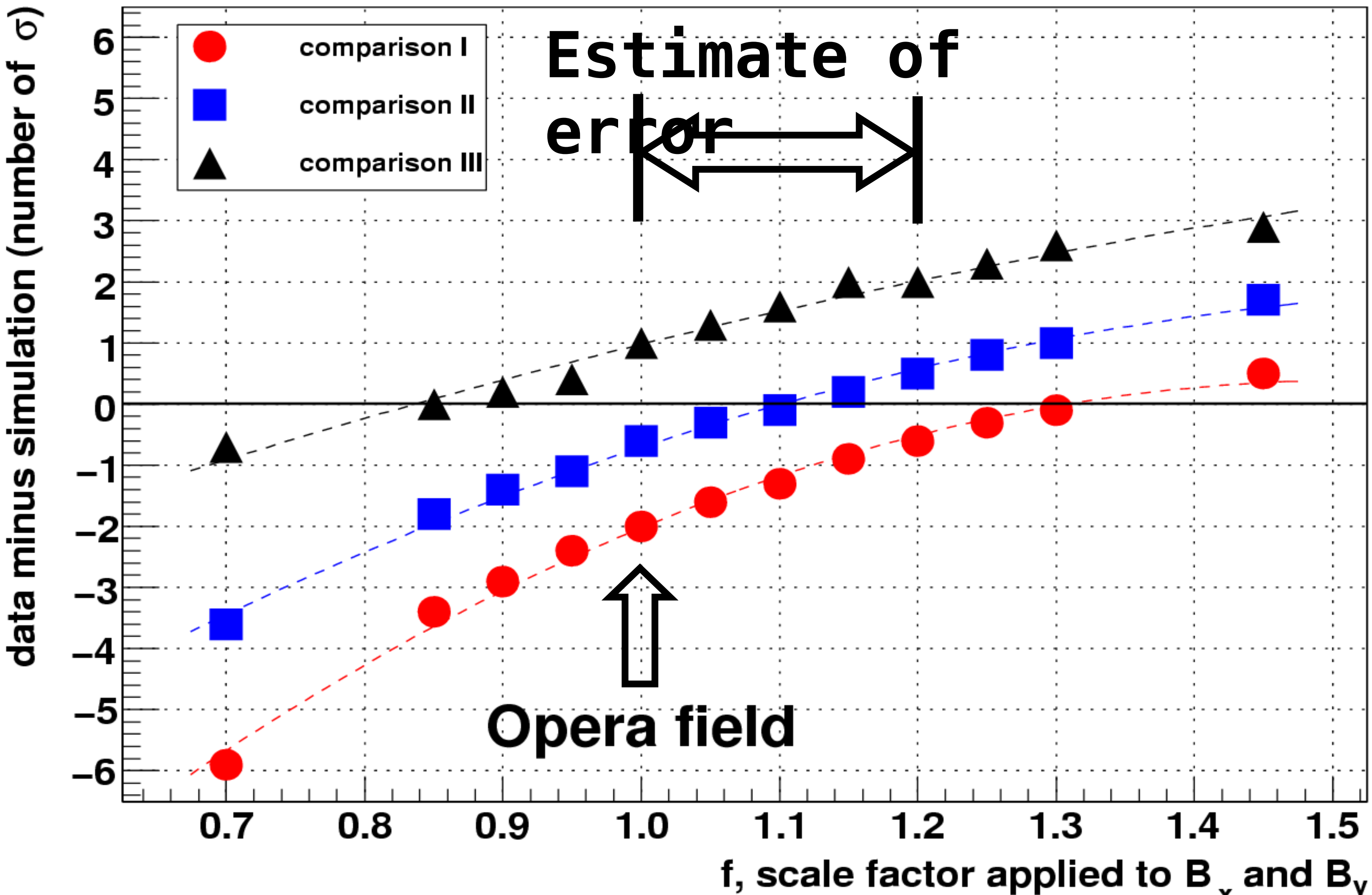


(b) Difference between inefficiencies from data and Monte Carlo averaged with respect to momenta over the fiducial region

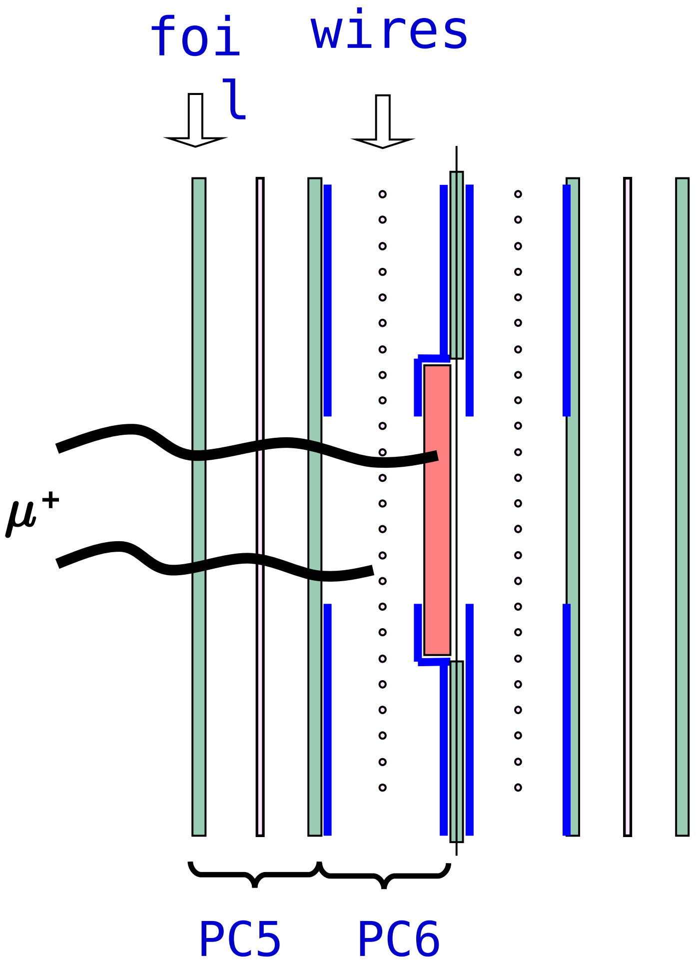
BSM Physics

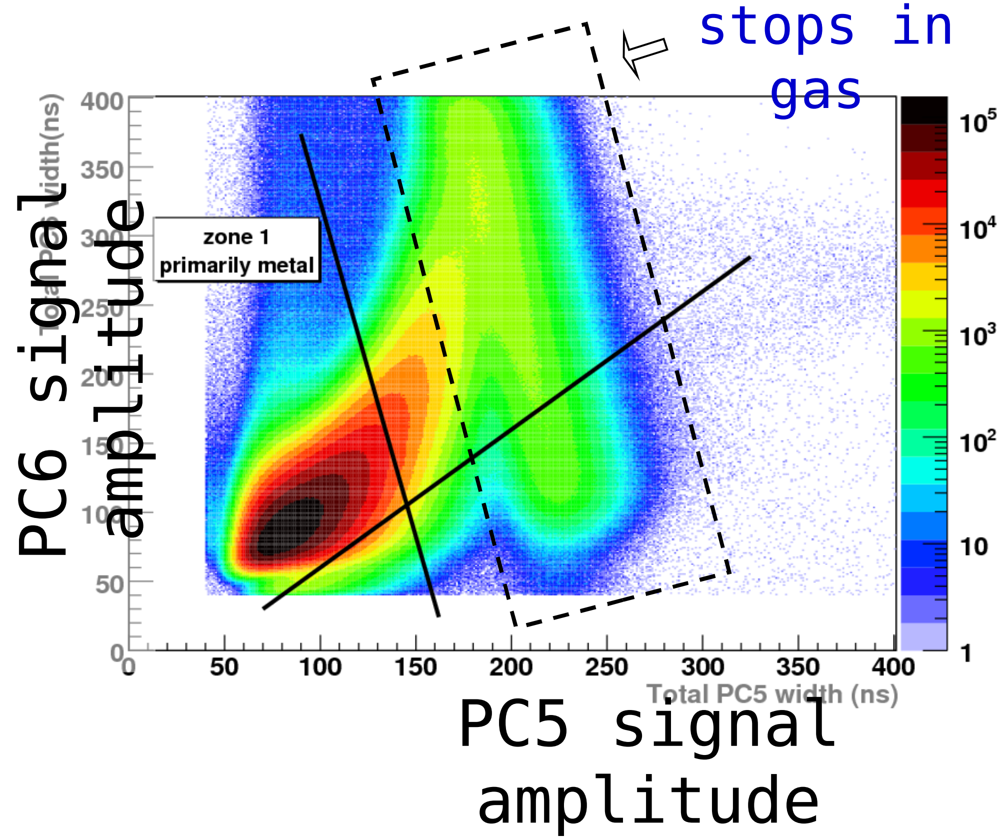
- Right-Left Symmetric Models
  - Spontaneous breaking of parity
  - Herczeg, Phys Rev. D34,3449 (1986).
- R-Parity Violating Supersymmetric Models
  - Profumo et al, Phys. Rev. D75, 075017 (2007).
- Lepton Flavour Violating 2-body decays $\mu \Rightarrow e X^0$
  - Strong limits exist when X^0 or it's 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



Selecting muons in metal target



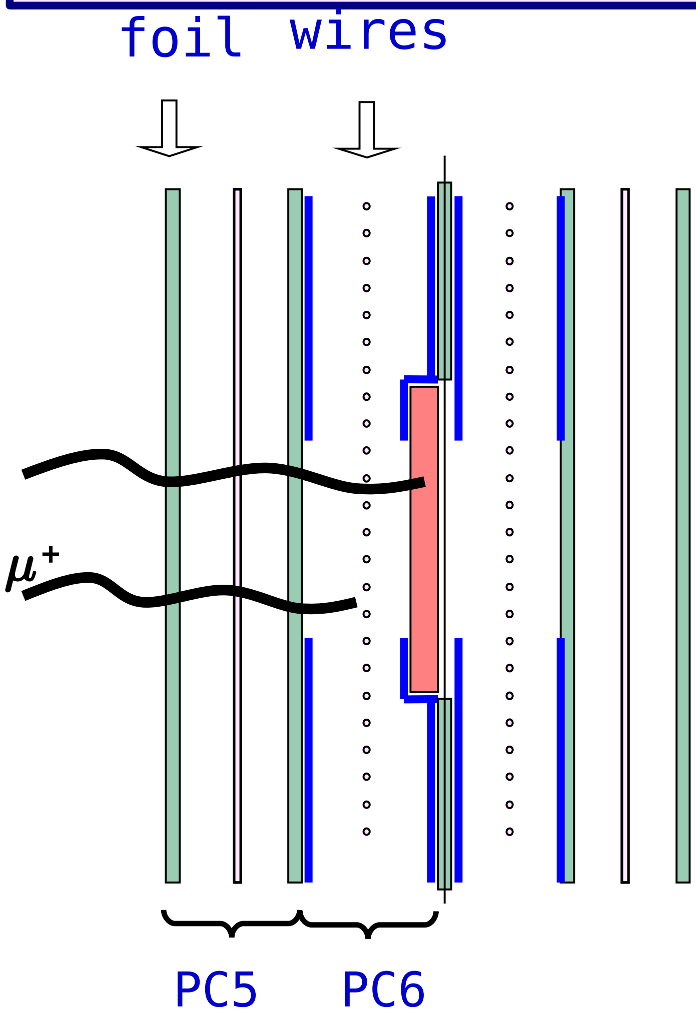


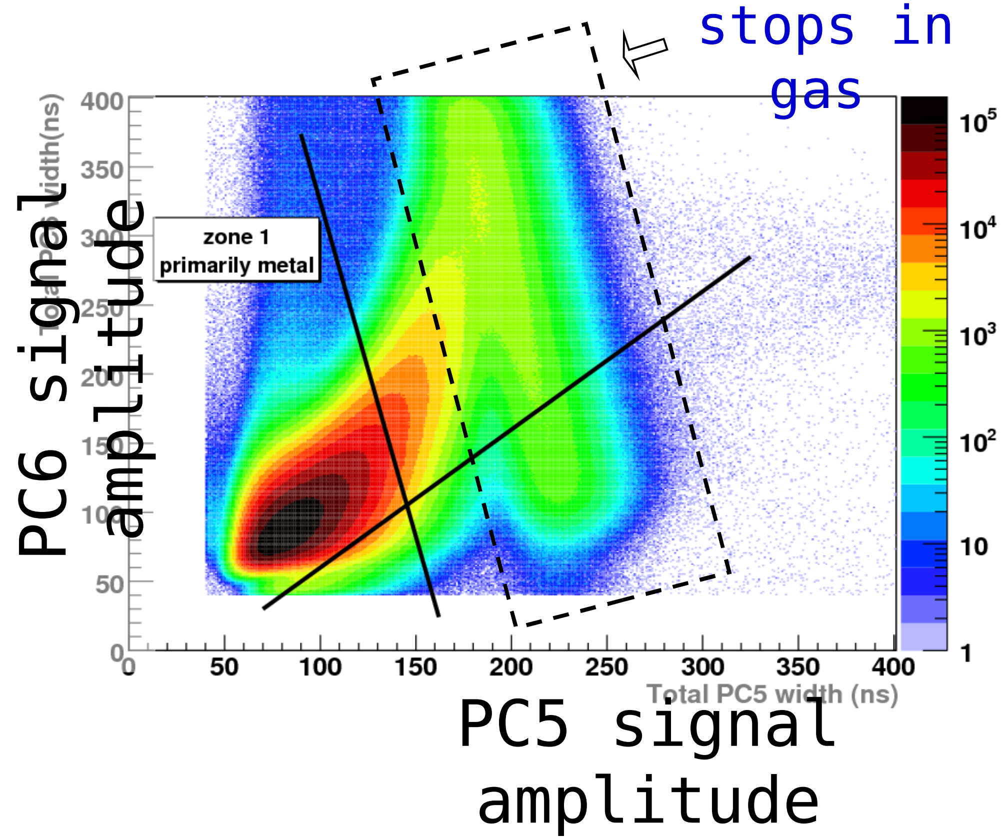
Place cut on 2-d distribution so that <0.5% of "stops in gas" contaminate "stops in target" region (zone 1).

Limits on LRS parameters

Observable	m_2 (GeV/c_2)	$\vert\zeta\vert$	+	-
$m(K_L - K_S)$	>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

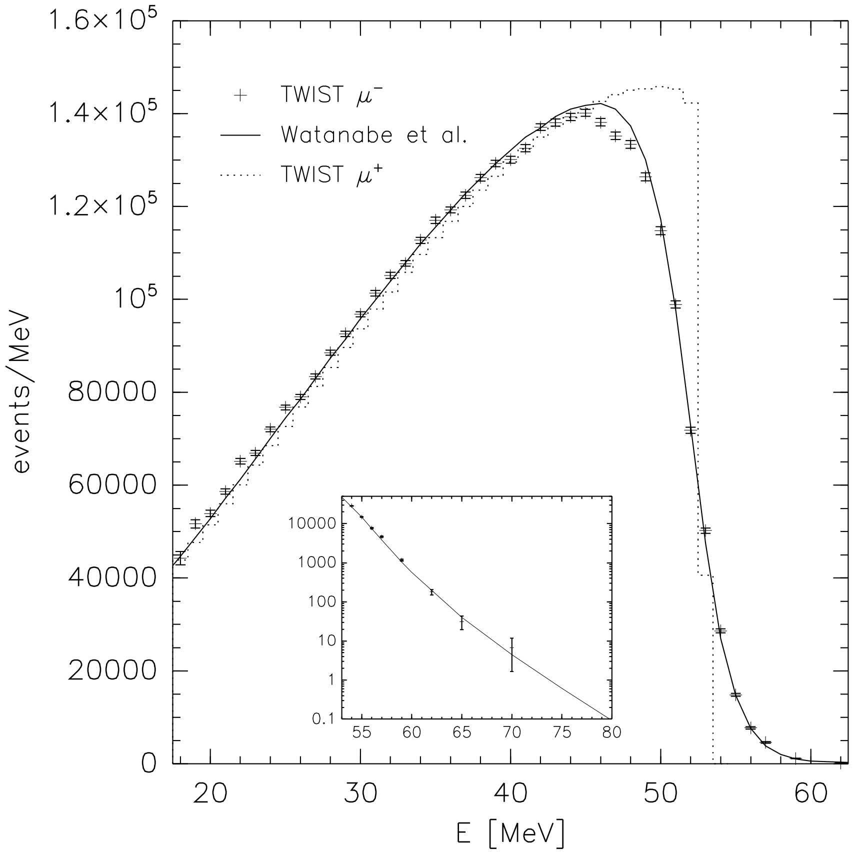




Place cut on 2-d distribution so that <0.5% of "stops in gas" contaminate "stops in target" region (zone 1).

Electron spectrum from μ^-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)