New Experimental Constraints for the Standard Model from Muon Decay

HE Seminar

Dept. of Physics, UC Davis

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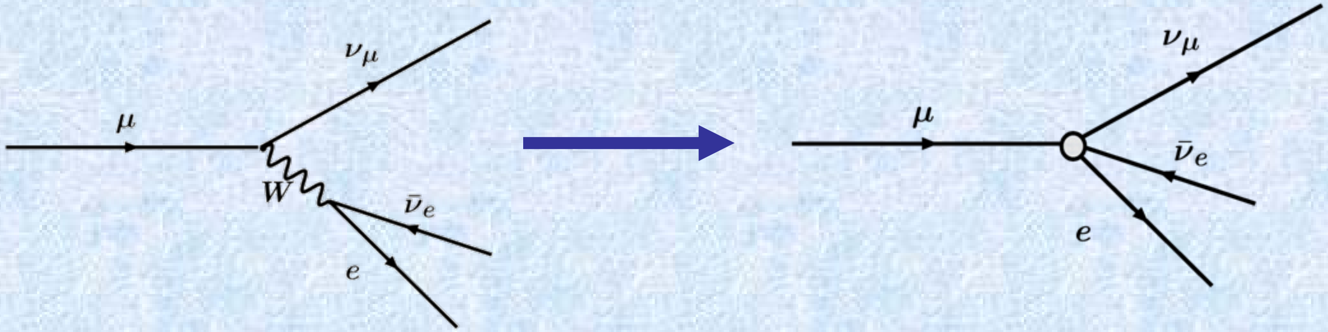
on behalf of the *TWIST* collaboration

Outline

- Physics of Muon Decay
- The *TWIST* Spectrometer
- Analysis Method
- Evaluation of Systematic Uncertainties
- New Results for ρ, δ, and $P_\mu\xi$
- Physics Implications

Muon decay formalism



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

- 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).

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

Coupling constants

- PDG limits on all couplings (pre *TWIST*):

  (in parentheses, R.P. MacDonald *et al.*, PRD **78**, 032010 (2008))

$|g^S_{RR}| < 0.066\ (0.062)$	$|g^V_{RR}| < 0.033\ (0.031)$	$|g^T_{RR}| \equiv 0.0$
$|g^S_{LR}| < 0.125\ (0.074)$	$|g^V_{LR}| < 0.060\ (0.025)$	$|g^T_{LR}| < 0.036\ (0.021)$
$|g^S_{RL}| < 0.424\ (0.412)$	$|g^V_{RL}| < 0.110\ (0.104)$	$|g^T_{RL}| < 0.122\ (0.103)$
$|g^S_{LL}| < 0.550\ (0.550)$	$|g^V_{LL}| > 0.960\ (0.960)$	$|g^T_{LL}| \equiv 0.0$

- Coupling constants $\mathbf{g}^{\gamma}_{\varepsilon\mu}$ can be related to handedness

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

e.g., total muon right-handed coupling:

$$\begin{aligned} Q^\mu_R &\equiv Q_{RR} + Q_{LR} \\ &= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \end{aligned}$$

Michel parameter description

- Muon decay (Michel) parameters ρ, η, $P_\mu\xi$, δ:
  muon differential decay rate *vs.* energy and angle:

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

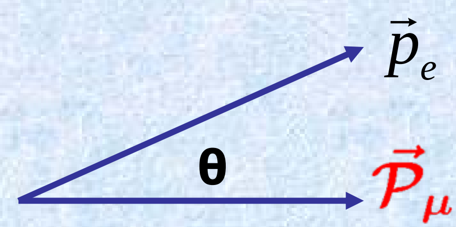
where

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

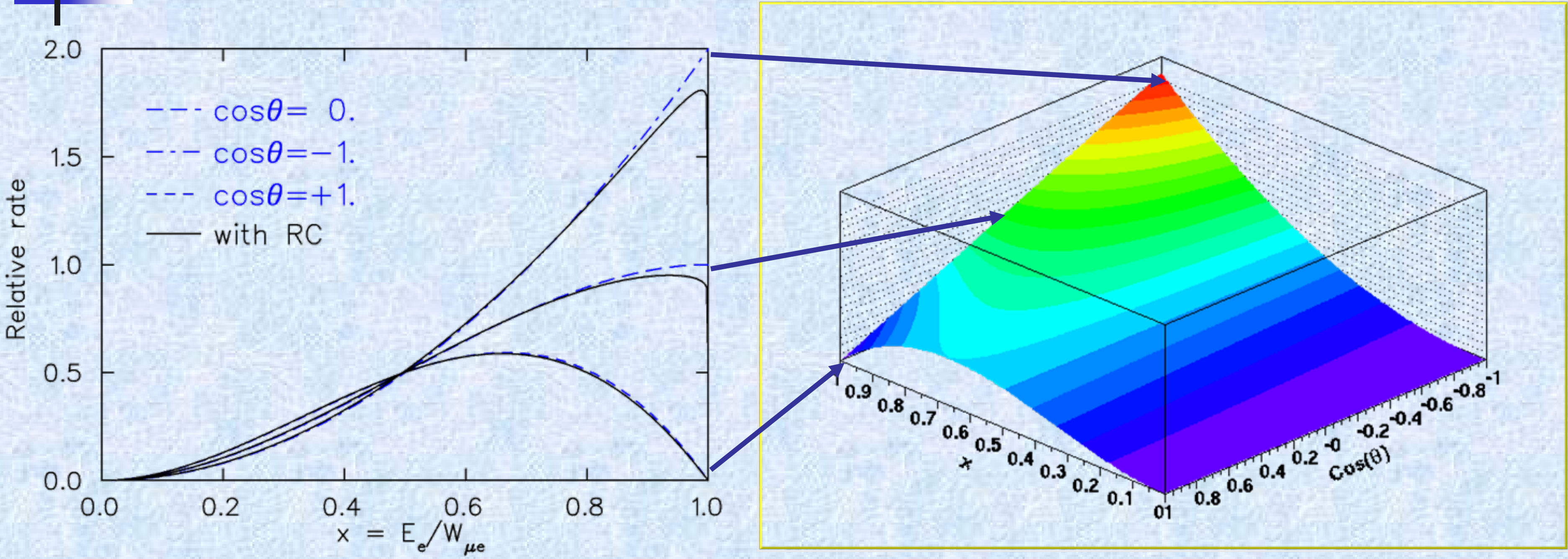
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right]$$

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, 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).



Radiative corrections



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

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

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

Pre- *TWIST* decay parameters

- From the Review of Particle Physics

		Year	SM
η	$= -0.007 \pm 0.013$	1985	0.00
ρ	$= 0.7518 \pm 0.0026$	1969	0.75
δ	$= 0.7486 \pm 0.0026 \pm 0.0028$	1988	0.75
$\mathbf{P}_\mu\xi$	$= 1.0027 \pm 0.0079 \pm 0.0030$	1987	1.00
$\mathbf{P}_\mu(\xi\delta/\rho)$	> 0.99682 (90% CL)	1986	1.00

The goal of *TWIST* is to find any new physics that may be revealed by improving the precision of each of the muon decay parameters ρ, δ, and $\mathbf{P}_\mu\xi$ by at least one order of magnitude.

TWIST Participants

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Peter Gumplinger
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Valparaiso
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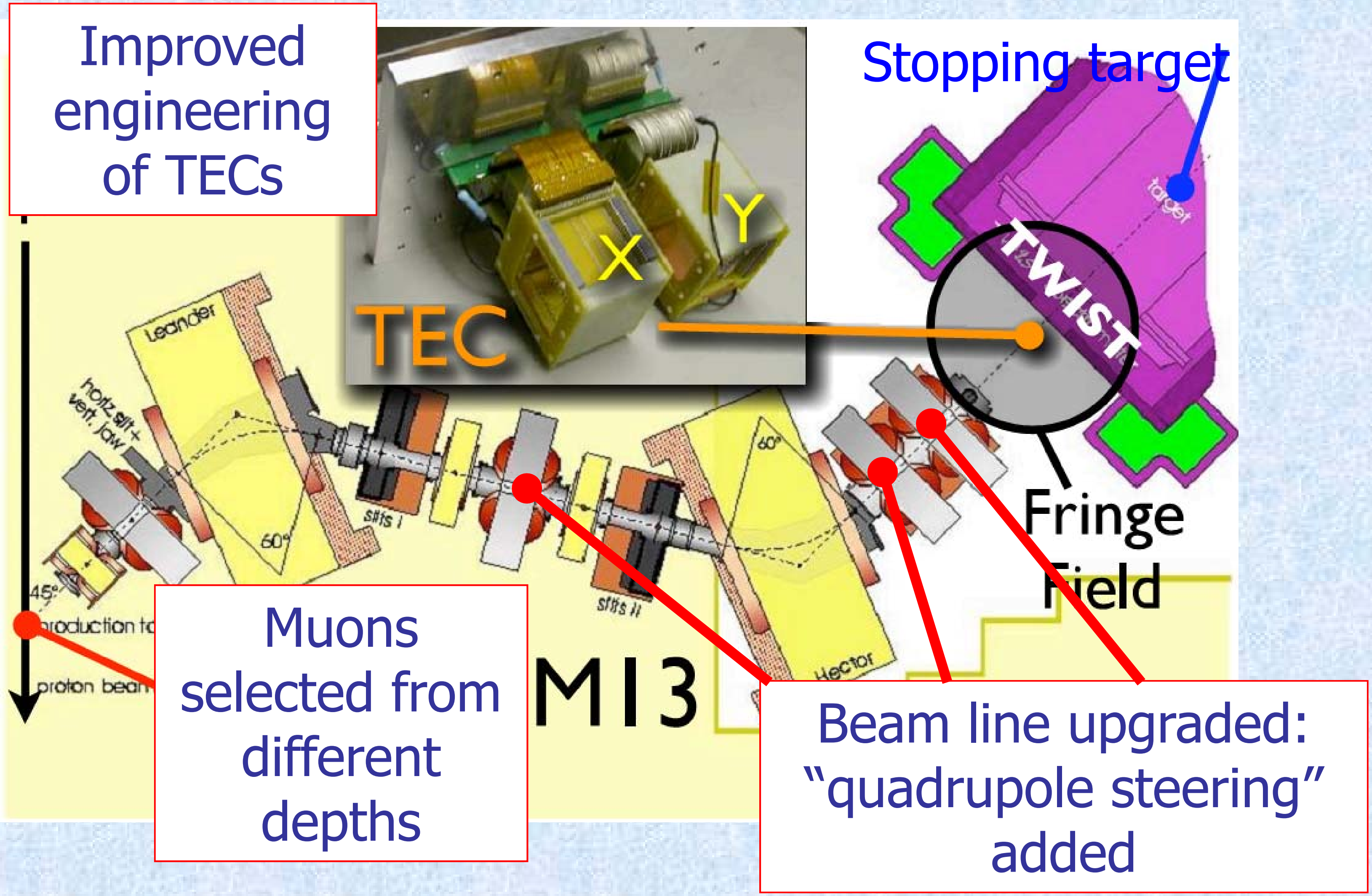
Graduate student

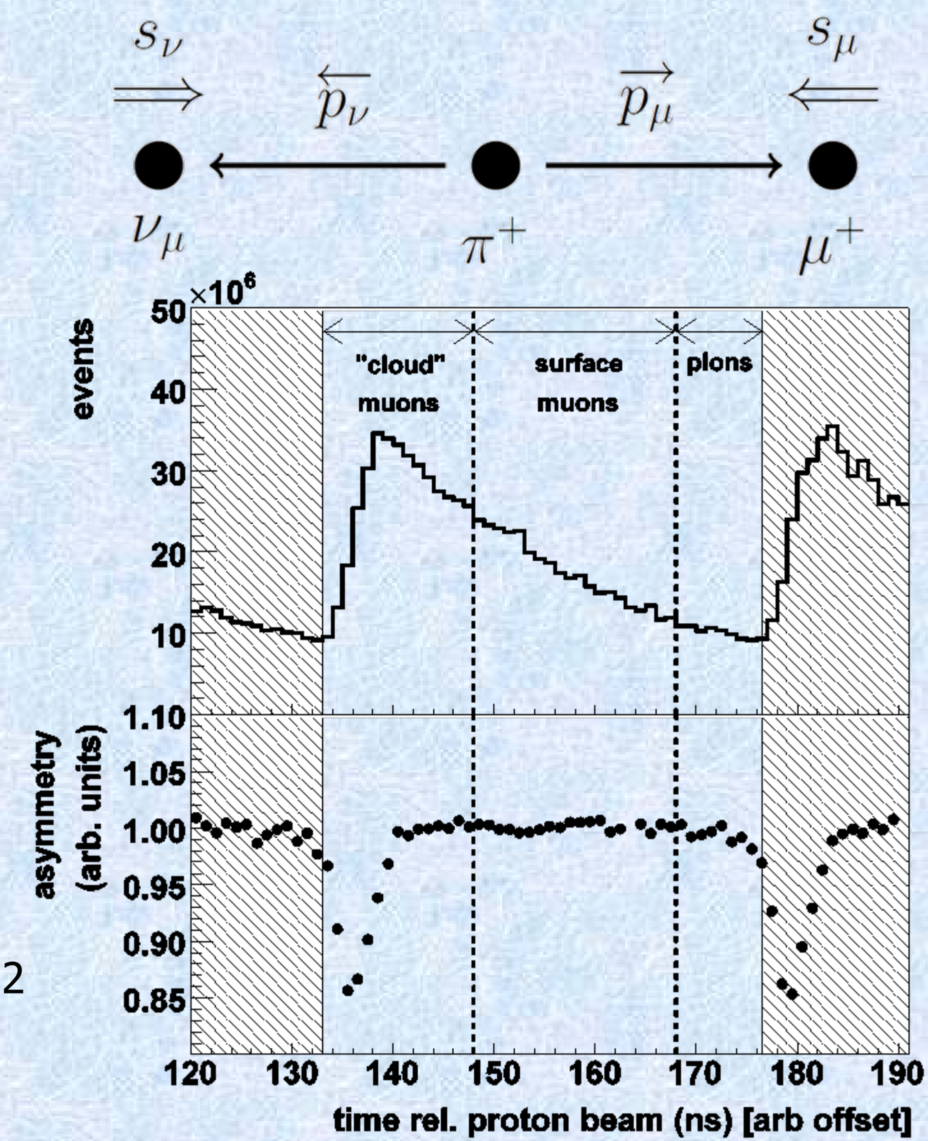
y also U Vic
z also Manitoba
zz also Saskatchewan
x deceased

Muon production and transport



Surface muon beam

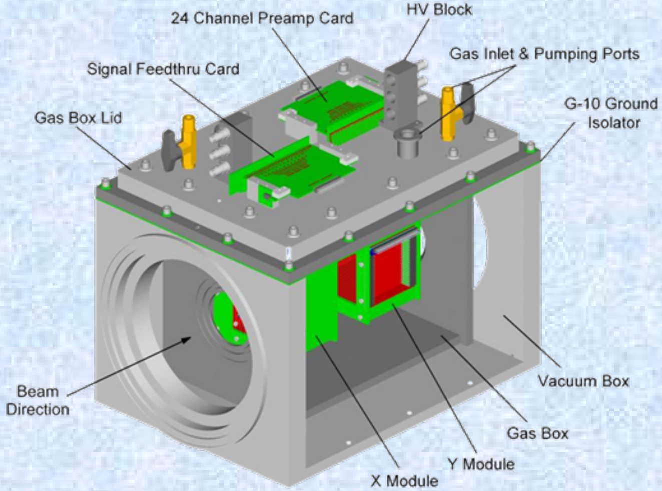
- Pions decaying at rest produce muon beams with P_μ > 99%.
- Control depolarization:
  - small solid angle
  - narrow momentum bite near 29.8 MeV/c
  - TOF cut
- Use 2 to 5×10^3 μ^+ s^{-1} (unseparated: e^+/μ^+ ~10)
- Muon total range is only about 140 mg/cm^2

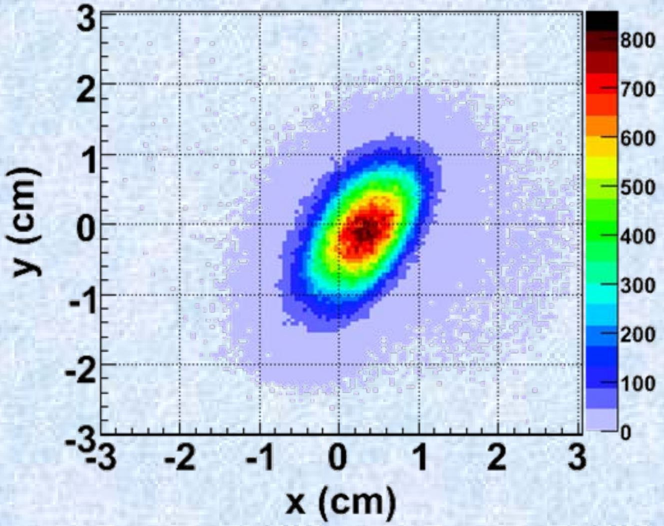


TEC beam characterization

- 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).
- Decay parameters measured with TEC removed; multiple scattering reduces polarization.
- Simulate by sampling distributions corrected for multiple scattering (~ 20 mrad rms).

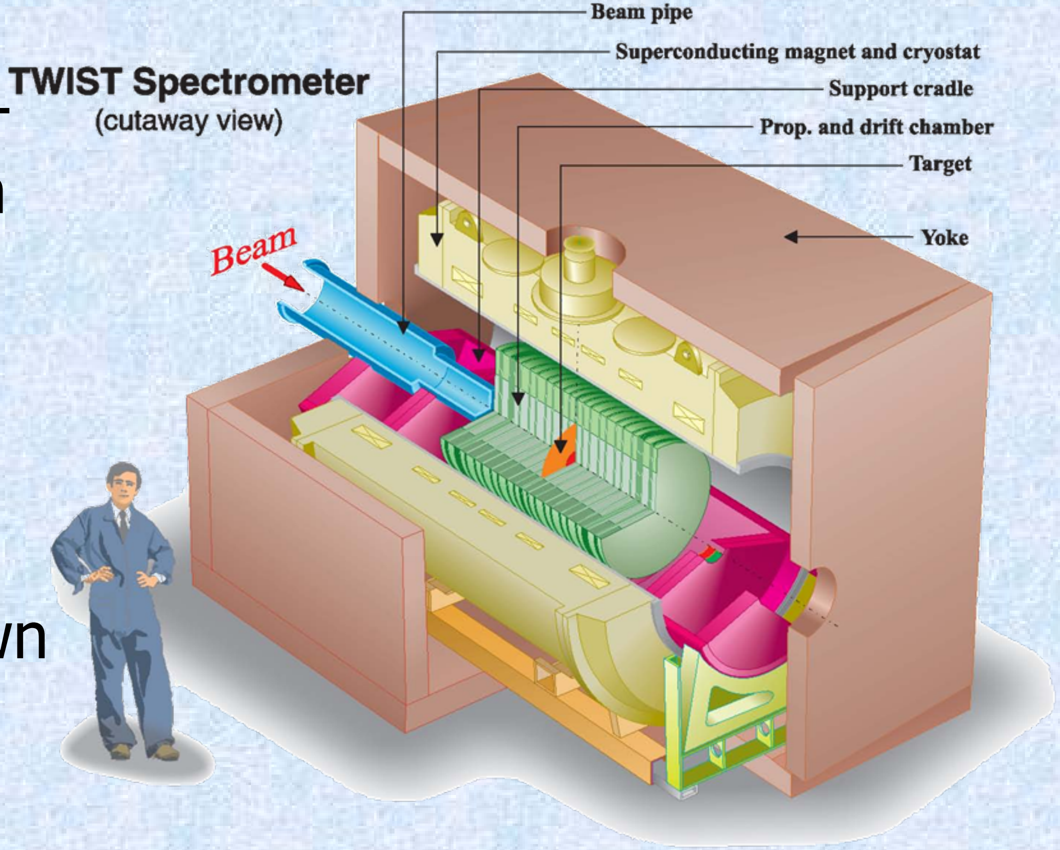
J. Hu et al., NIM A566, 563 (2006).





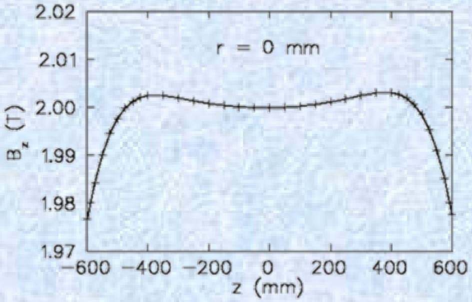
The *TWIST* Spectrometer

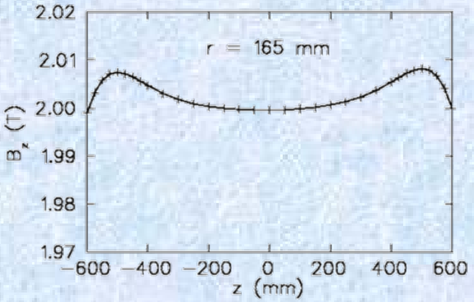
- Highly polarized μ^+ beam is stopped in a very symmetric detector.
- Decay e^+ are tracked through uniform, well-known solenoidal field.



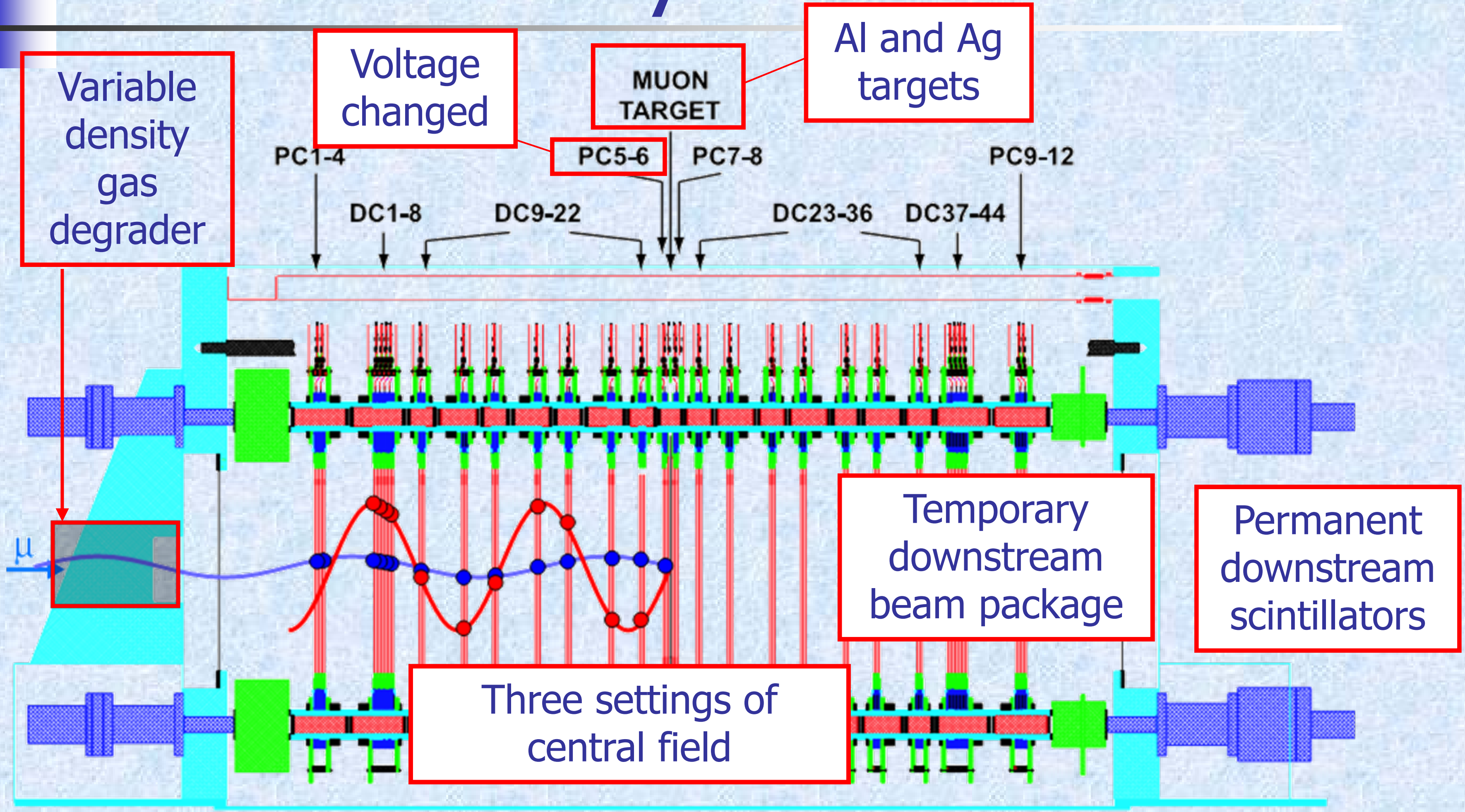
Solenoid field

- 20 year old ex-MRI superconducting solenoid provides 2 T field.
- Steel yoke improves uniformity, reduces stray fields.
- Uniform to 4×10^{-3}, mapped to precision of 5×10^{-5}.





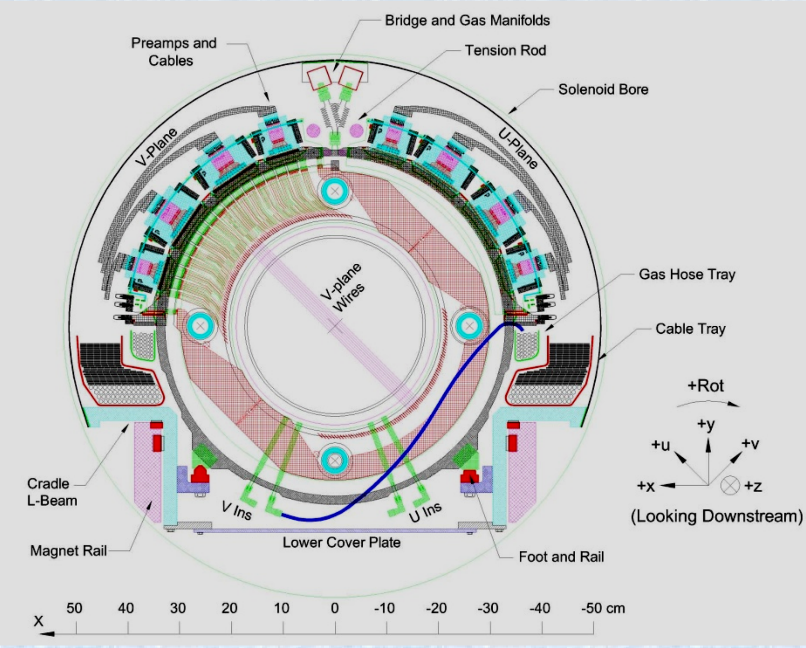
Detector array

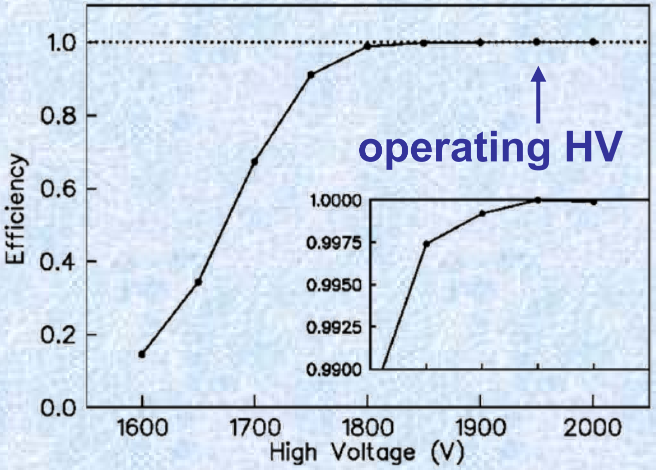


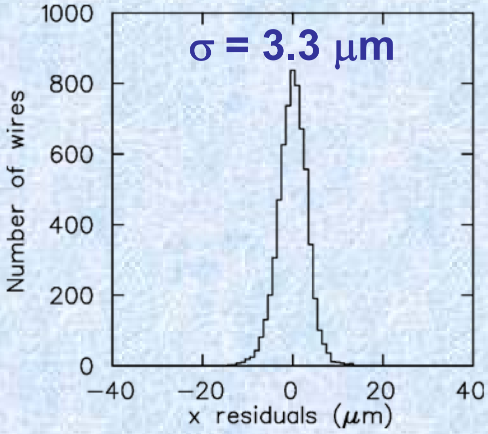
R.S. Henderson et al., Nucl. Instr. and Meth. A548, 306 (2005).

Precision of detector construction

- longitudinal alignment by engineering (3×10^{-5}).
- transverse (10 μm) using particle tracks.
- ~5000 wires, efficiency >99.8% at 1900V, no dead or hot wires at installation.







Detector planes assembled

- 15 Nov 2001

- 2 Nov 2007

Physics data sets

- Fall 2002
  - Test data-taking procedures and develop analysis techniques
  - First physics results – **ρ** and **δ**
  - Graphite-coated Mylar target not suitable for $P_\mu\xi$

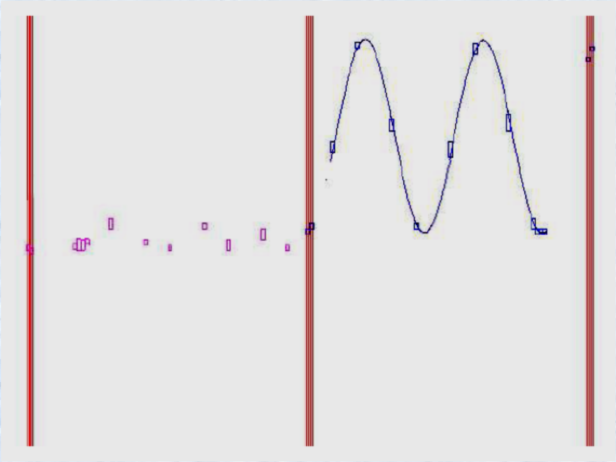
- Fall 2004
  - Aluminum target and Time Expansion Chamber enabled first $P_\mu\xi$ measurement
  - Improved determinations of **ρ** and **δ**

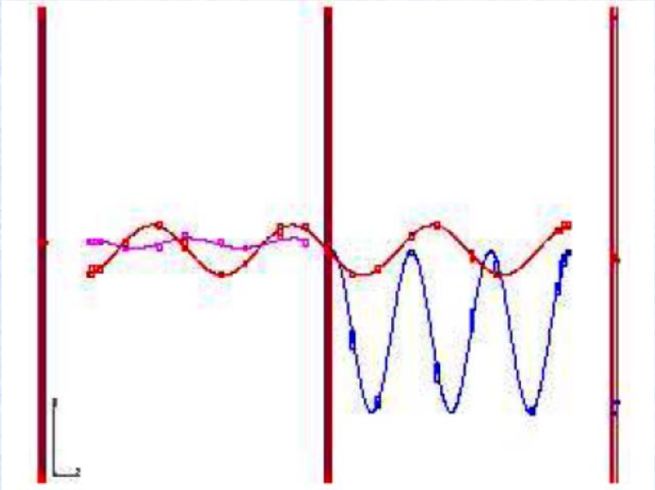
- 2006-07
  - Both Ag (2006) and Al (2007) targets (1.1×10^{10} events)
  - Ultimate *TWIST* precision for **ρ**, **δ**, and $P_\mu\xi$
  - Also measured negative muon decay-in-orbit when bound to Al

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

Typical events

- Read out chamber hits in time interval [-6,+10] μs.
- Use pattern recognition (in position and time) to sort hits into tracks, then fit to helix.
- Write track parameters and other variables.
- Must recognize beam positrons, delta tracks, backscattering tracks.



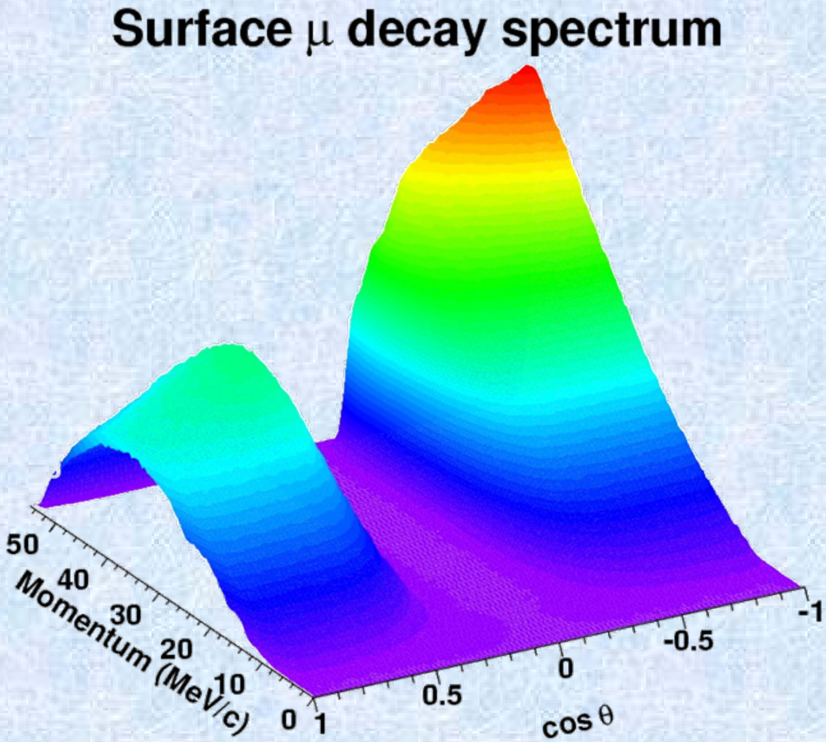


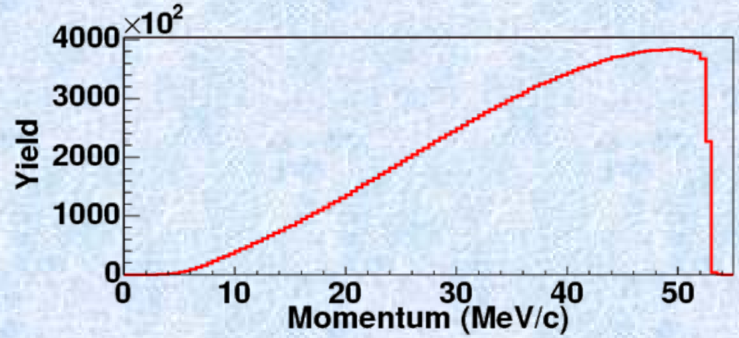
Analysis Method

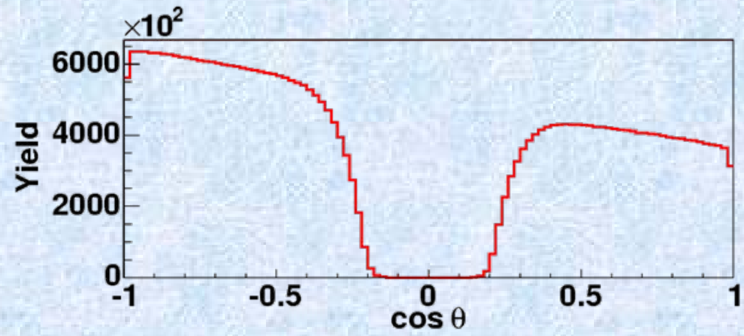
- Extract energy and angle distributions for data:
  - apply (unbiased) cuts on muon variables.
  - reject fast decays and backgrounds.
  - calibrate e^+ energy to match the simulation at the kinematic end point of ~52.8 MeV.

- Fit to identically derived distributions from simulation:
  - GEANT3 geometry contains virtually all detector components.
  - simulate detector response in detail (clusters of ionization).
  - realistic, measured beam profile and divergence.
  - extra muon and beam positron contamination included.
  - output into digitized format, identical to real data.
  - fit to hidden variables with blind analysis method.

Data distributions

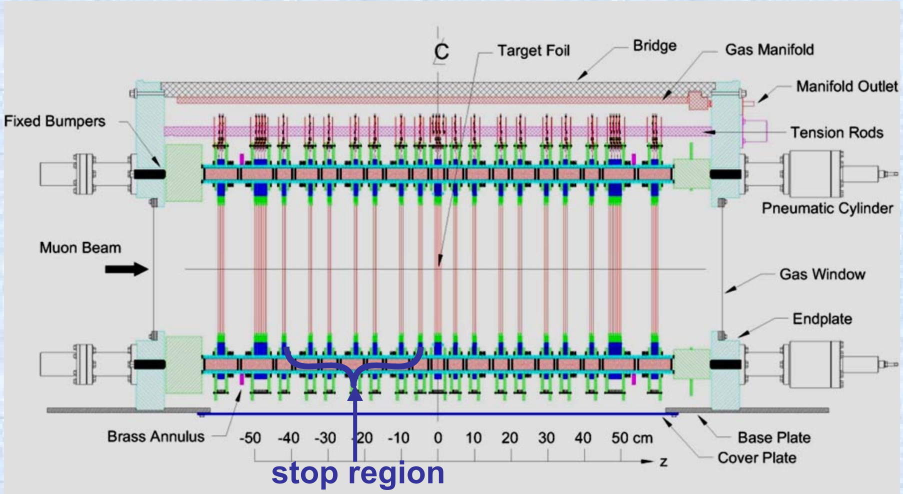


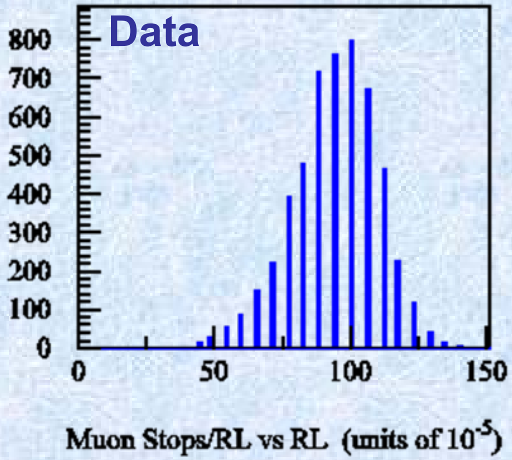


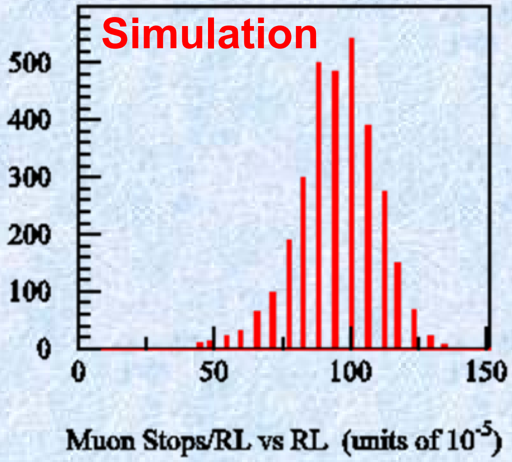


Acceptance of *TWIST* spectrometer

Simulation: muon interactions

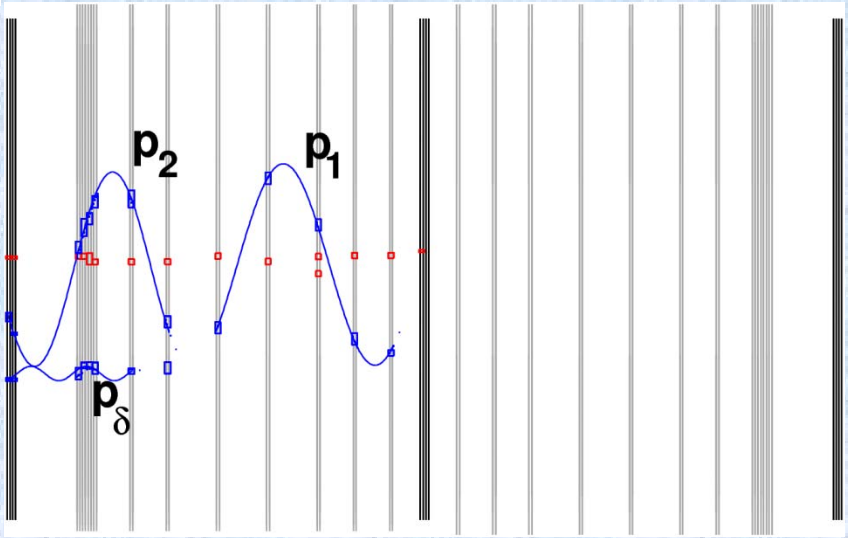






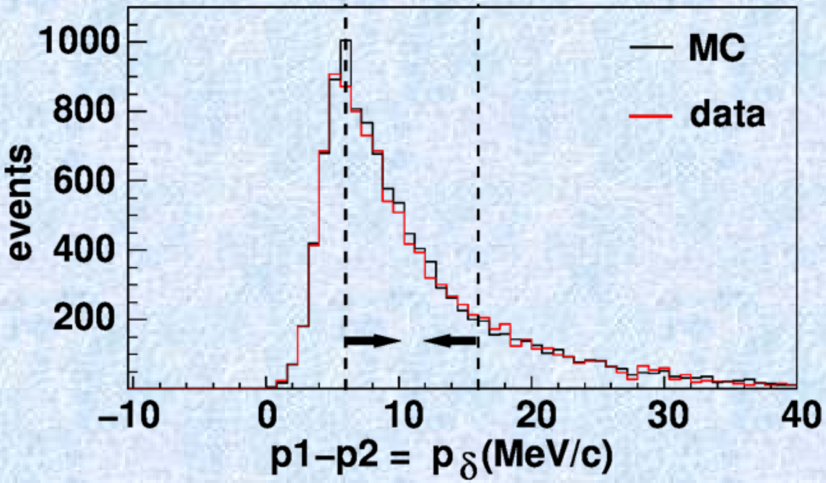
- Simulation must reliably predict muon stopping distributions.
- Verify by comparison in low-mass detector region.

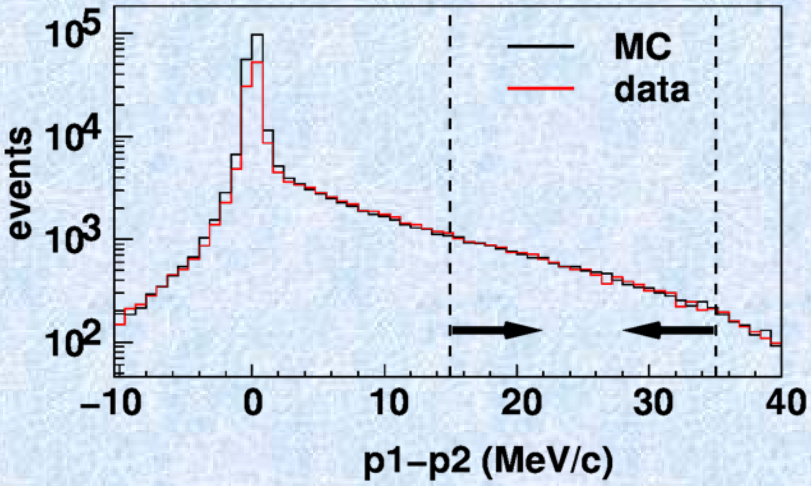
Positron interactions



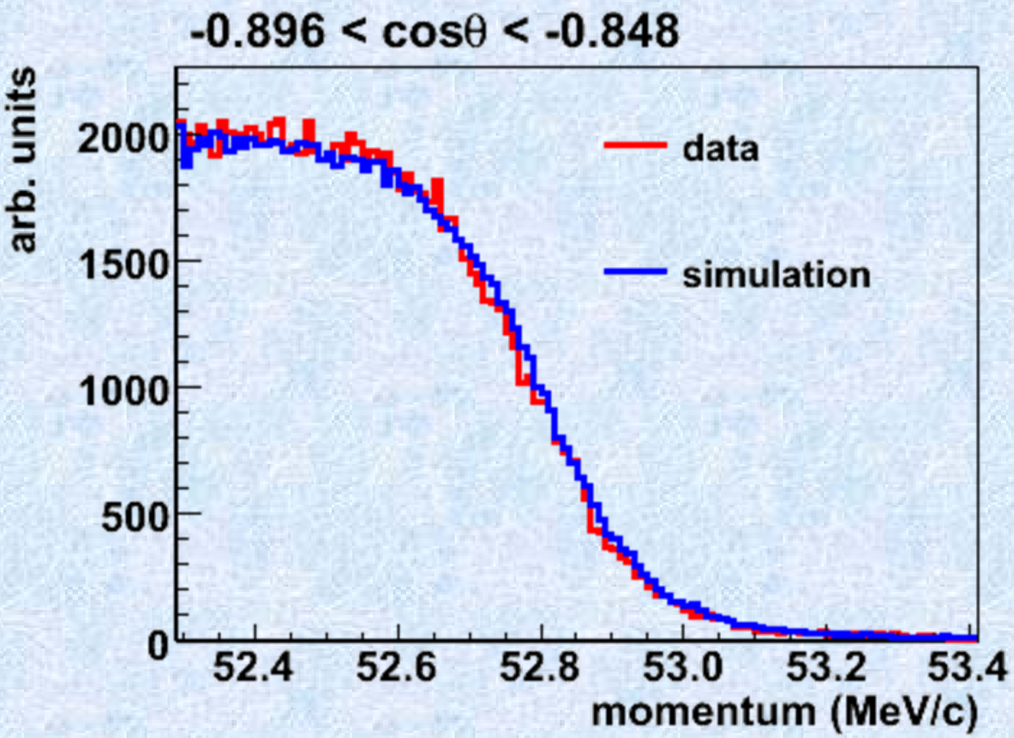
"Broken tracks" analysis:
$2e^+$, 1 e^- ≡ δ-electron
2 e^+ ≡ Bremsstrahlung

Agreement of data and sim:
δ -electrons < 1%
Bremsstrahlung differs by 2.4%





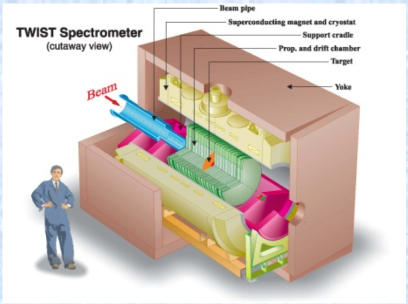
Momentum calibration



- 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.

Blind analysis

Hidden parameters; ρ_{MC}, δ_{MC}, $\mathbf{P_\mu \xi_{MC}}$



Data from experiment

Hidden parameter tolerances 0.01

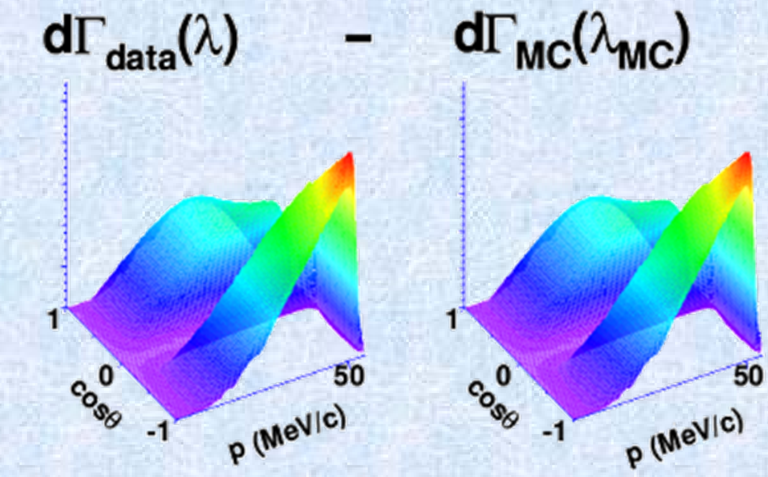
"Data" from simulation

Reconstruction software

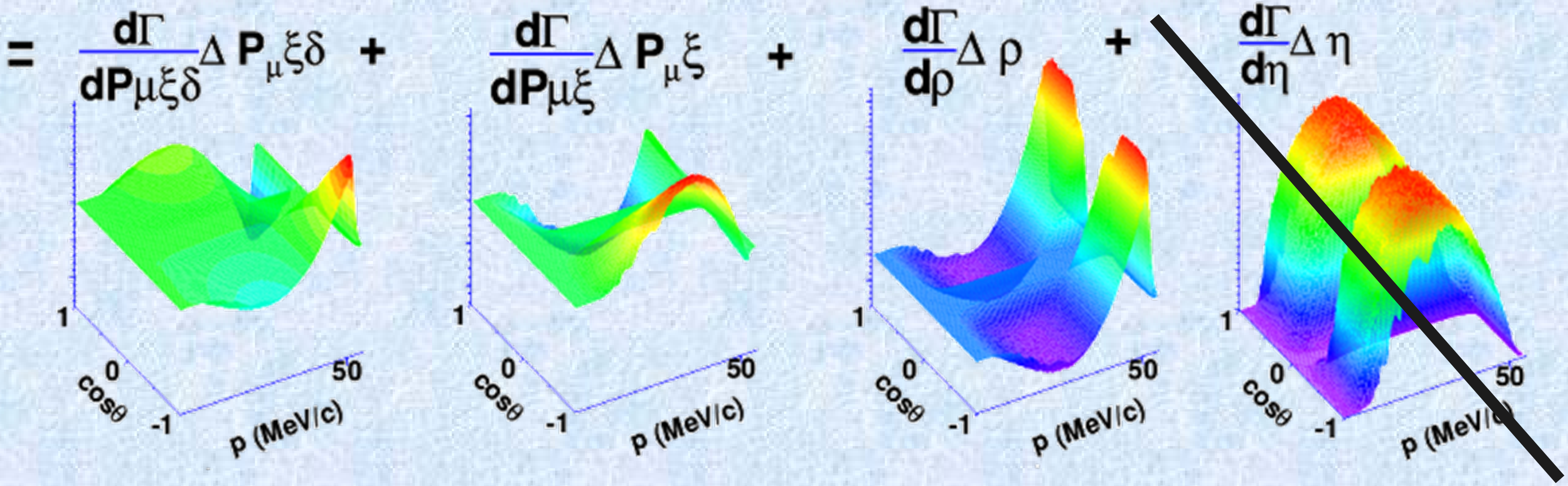
MCfit spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta \mathbf{P_\mu \xi}$

Add to hidden parameters; ρ, δ, $\mathbf{P_\mu \xi}$

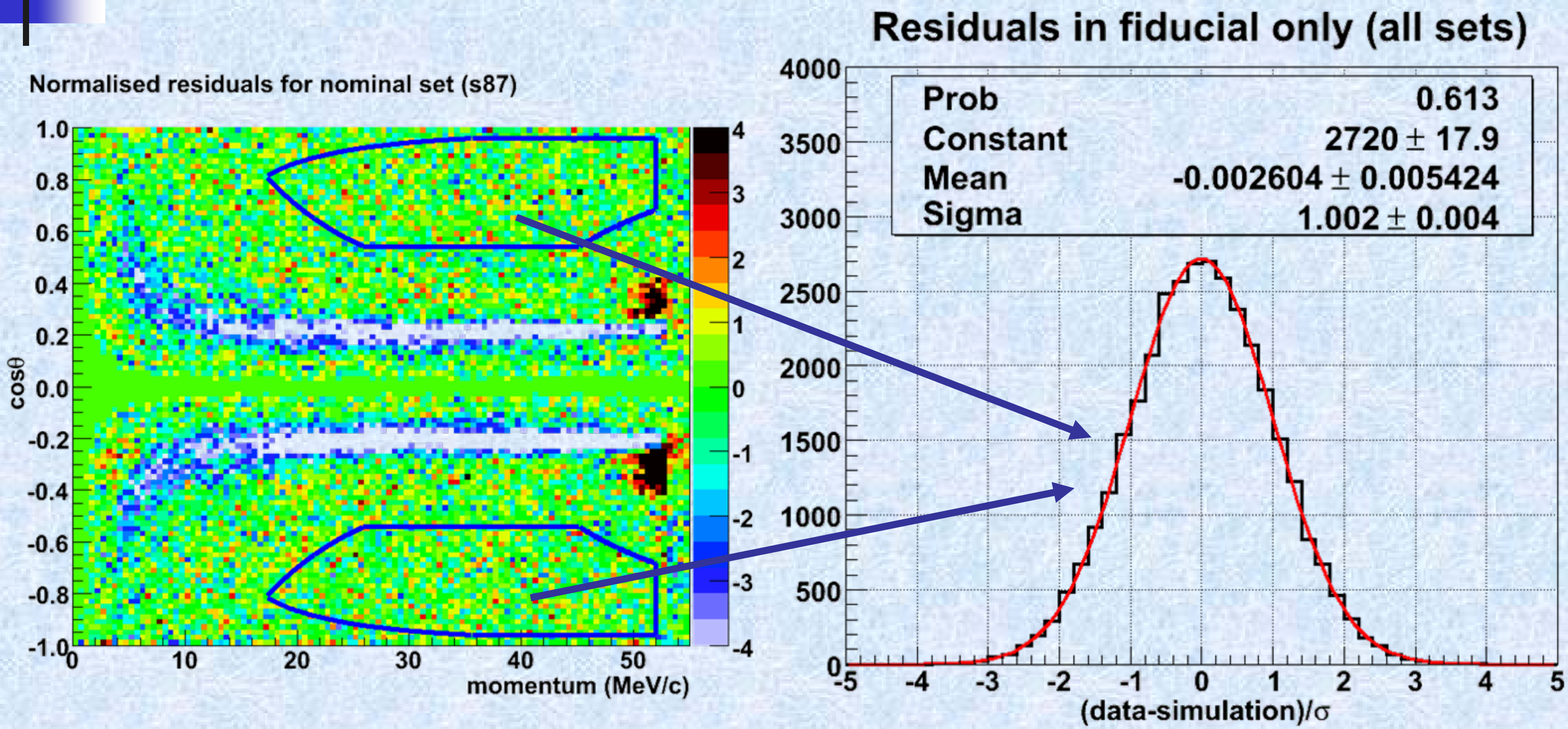
Analysis: fit to simulation (MCfit)



- fit data to normalized GEANT3 simulation
- use linearity in $P_\mu\xi$, $P_\mu\xi\delta$, ρ, η
- η not fit; use best measured value with uncertainty



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,cos θ) fiducial**
- **Simulation sets: 2.7 times data statistics**

List of systematics

- Positro … calibration:
  - Ene … t fits
  - Mul … ropagation)
  - Har … roduction
  (Brer … ut
  - Mat …
  - Mat … ngle
- Chamb … stability:
  - DC a … location
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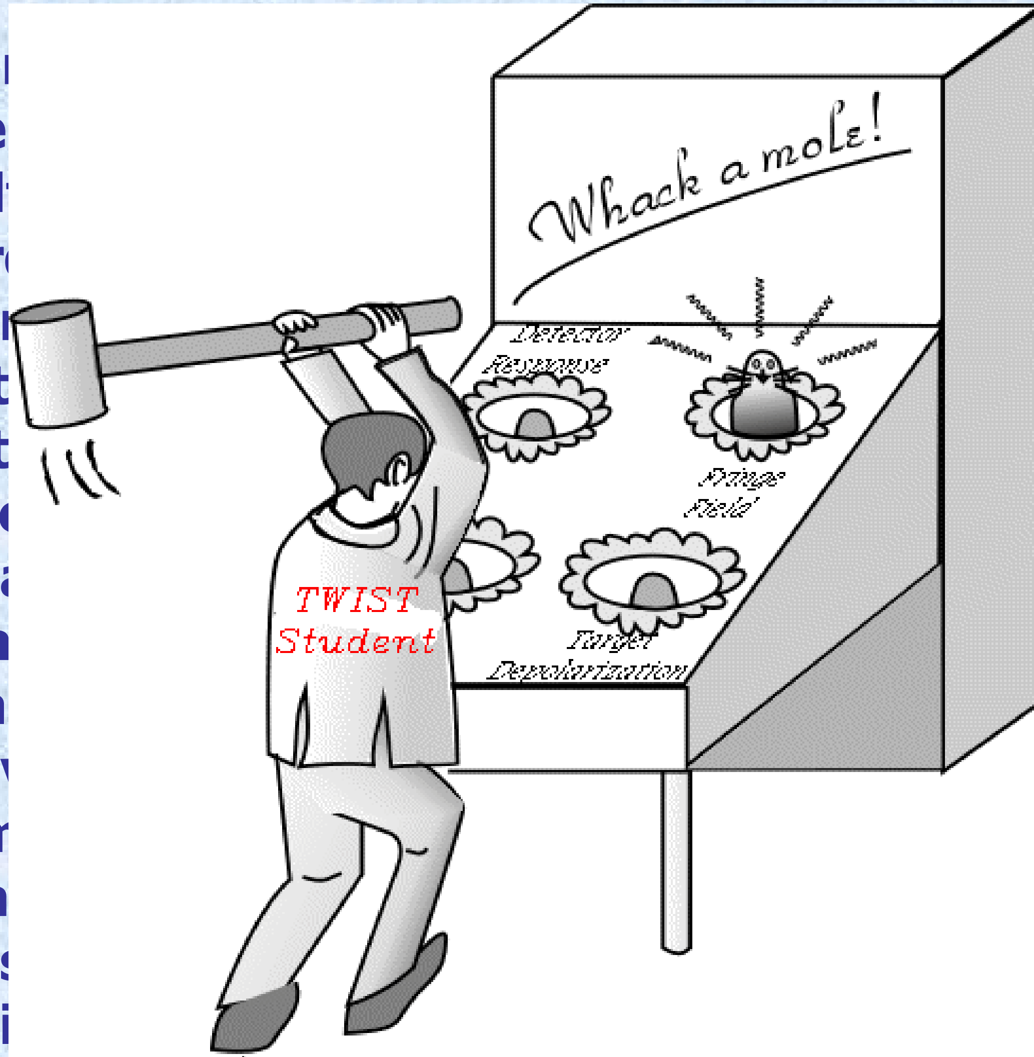
  - Tem … ons
  - Cha … s
  - Cros … inal
  - Vari … letector axis



Systematic estimation

Simulation

Modified simulation

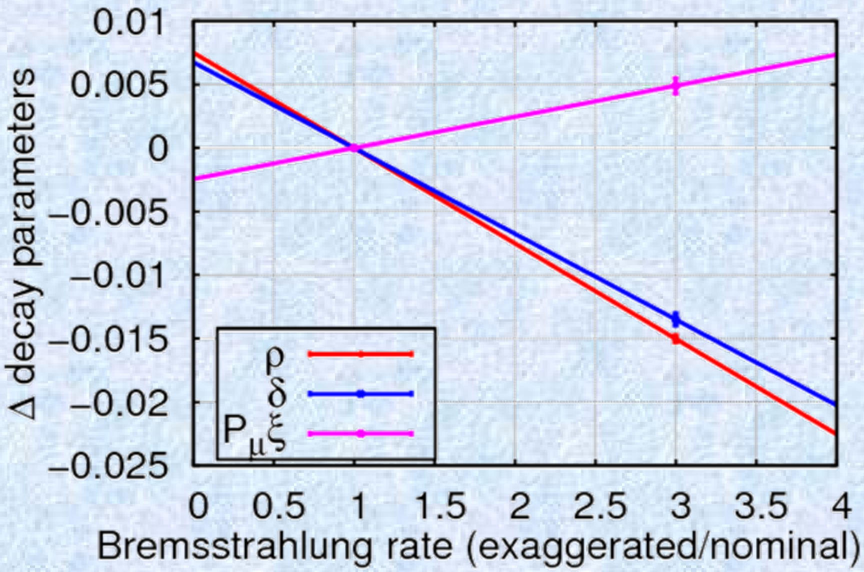
Reconstruction software

MCfit spectrum fit; $\Delta\,\rho$, $\Delta\,\delta$, $\Delta\,P_\mu\xi$

Scale; **d(ρ, δ, $P_\mu\xi$)/d(modification)**

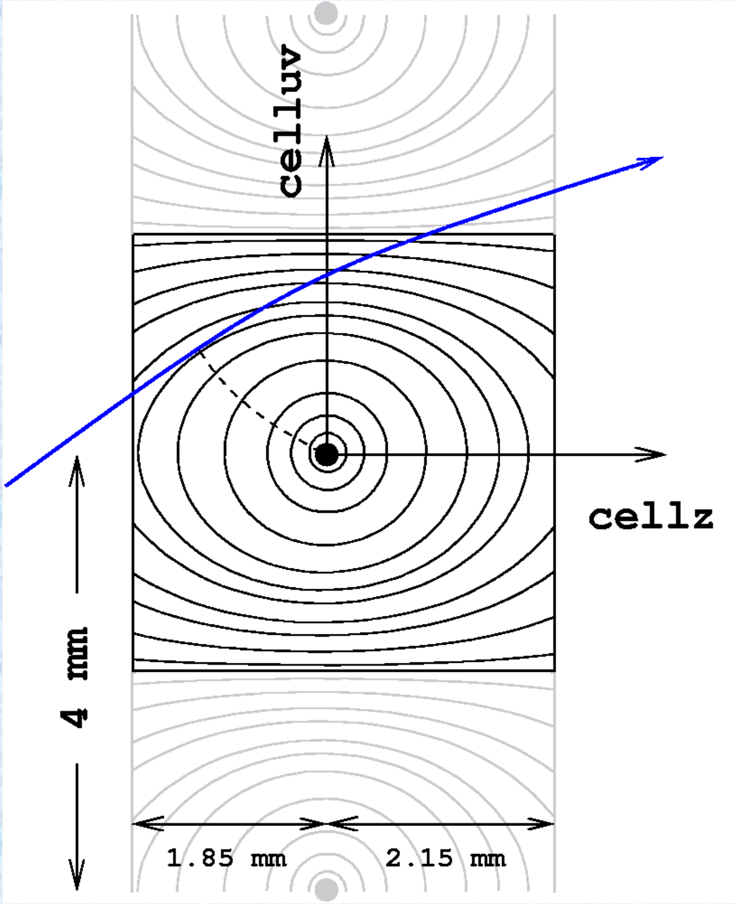
Bremsstrahlung example

- adjust (with care!) the rate in the simulation
- fit simulations: exaggerated vs. normal to obtain changes in decay parameters (sensitivity)
- compare normal simulation with data to assess difference in Bremsstrahlung
- scale factor = exaggeration/(data-MC match)
- systematic uncertainty = sensitivity/scale factor



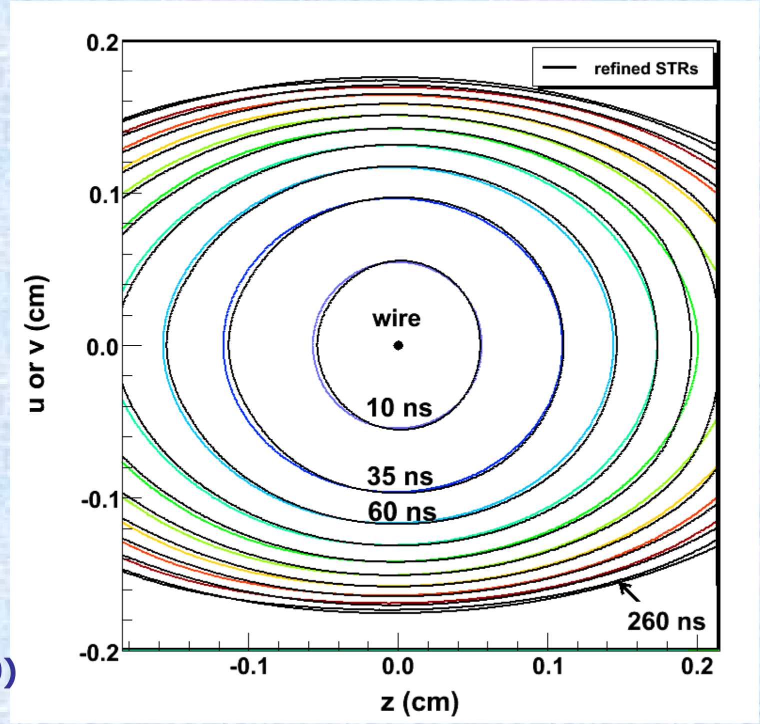
$\Delta\rho$ = -0.0015/83 ~ 2×10^{-4}

Chamber response



Space-time relations (STRs) are calibrated with data for data analysis, or simulation for MC analysis, to include common biases.

Isochrones from calibrated STRs can account for detector plane geometry differences in data and biases in helix fitting.



A. Grossheim, J. Hu and A. Olin, NIM A 623, 954 (2010)

Momentum calibration

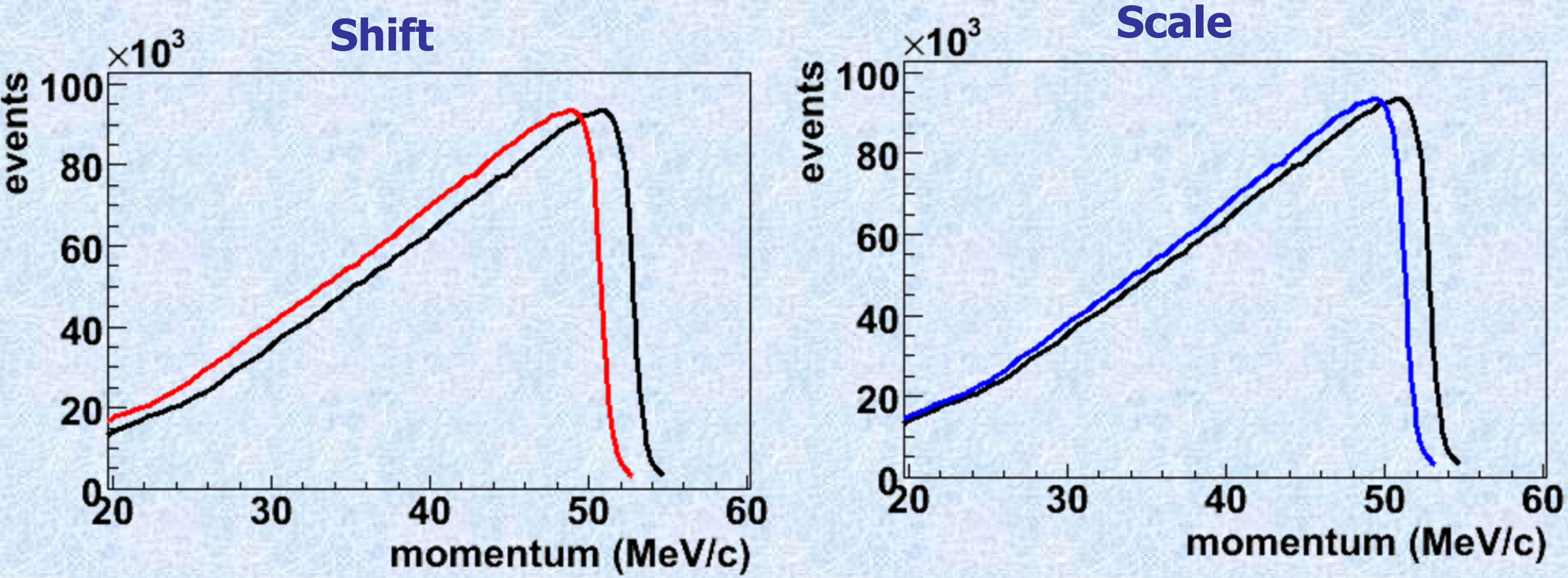
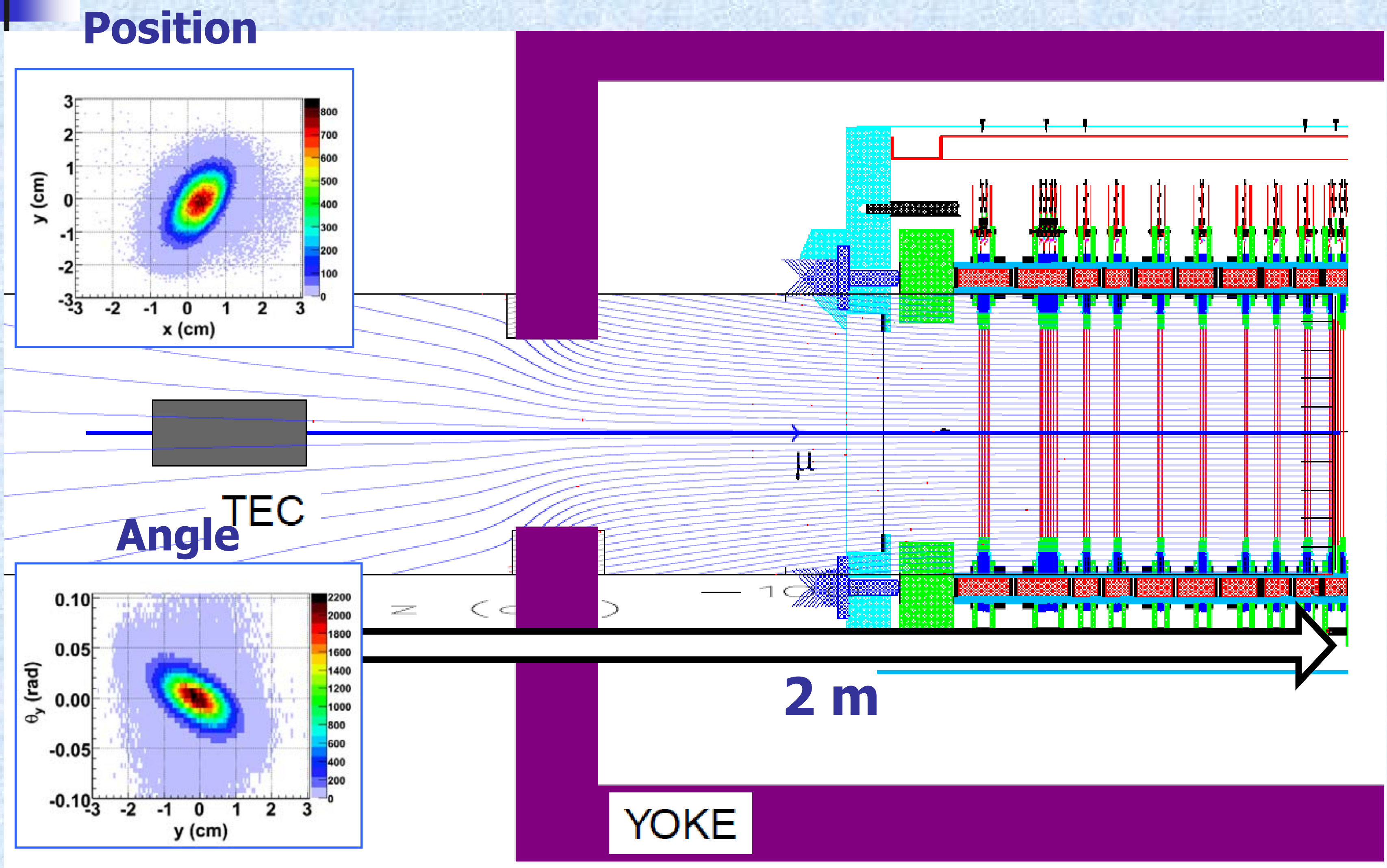
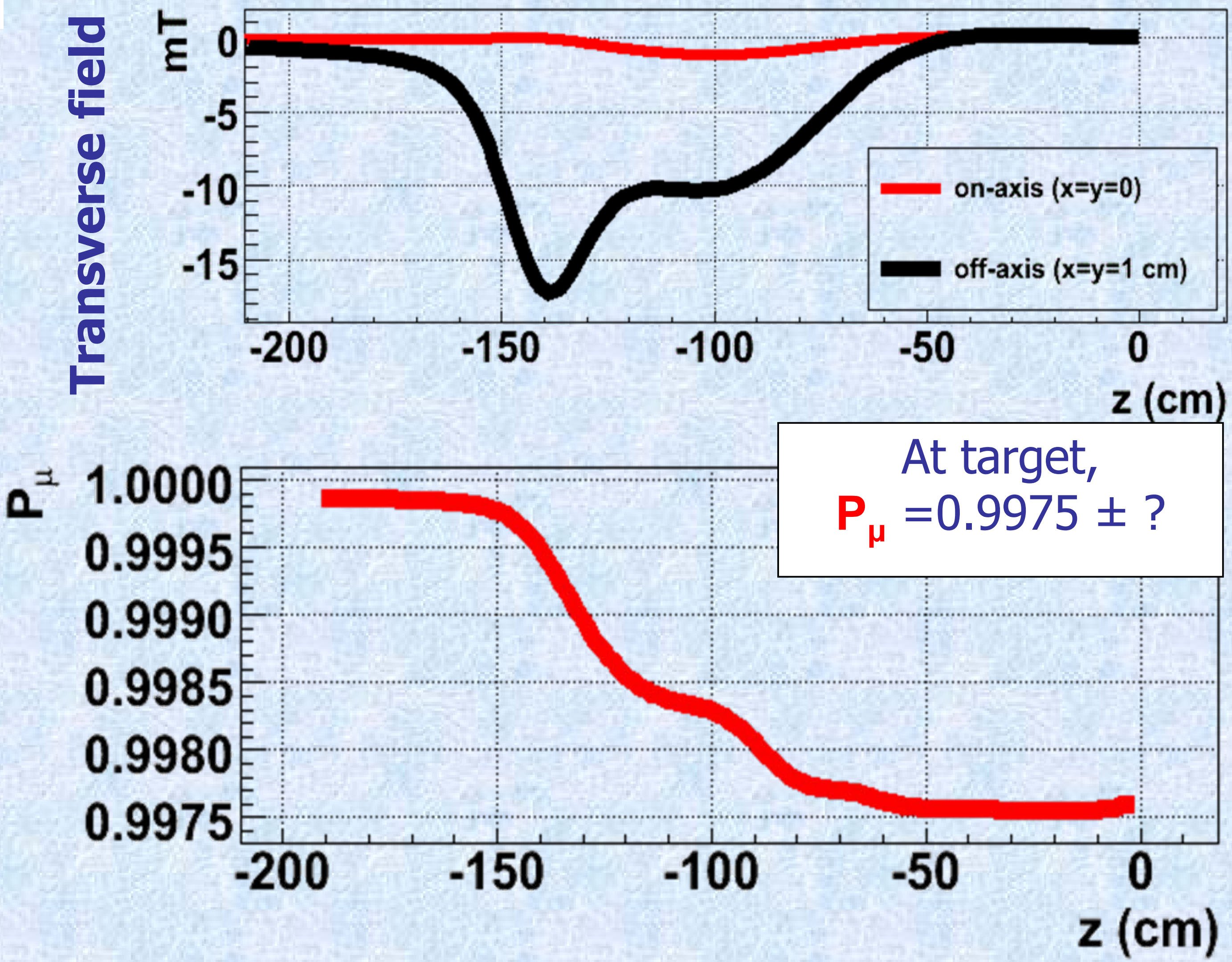


Illustration of shift vs. scale:
Difference leads to uncertainties of
$\delta(\rho) = 1.0\times10^{-4}$ and $\delta(\delta) = 1.1\times10^{-4}$.

Fringe field, solenoid entrance



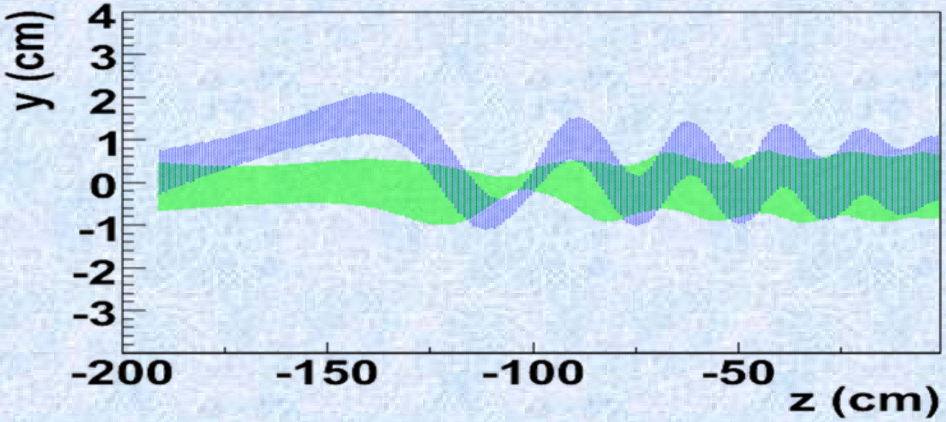
Transverse field and depolarization



At target,
P_μ =0.9975 ± ?

Magnetic field components

Indirect validation: polarization of real beam lowered. How well does the simulation reproduce the changes?



Example: angle θ_y ~28 mrad introduced

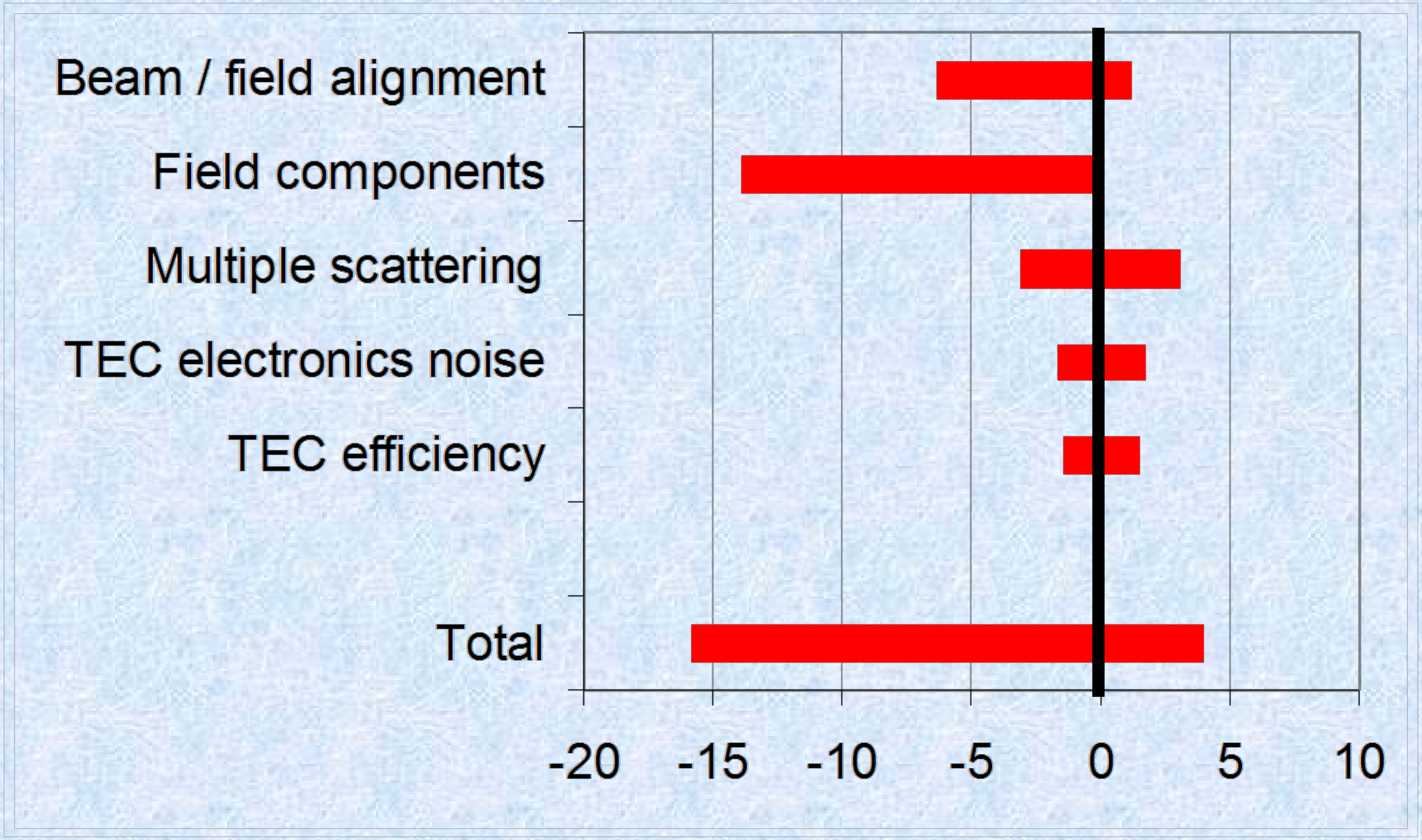
Polarization decrease of **(105 ± 9) x 10^{-4}**

Comparison II: position off axis by ~1 cm, angle θ_x ~10 mrad introduced.

Comparison III: TECs-in through entire set, increasing multiple scattering upstream of fringe field.

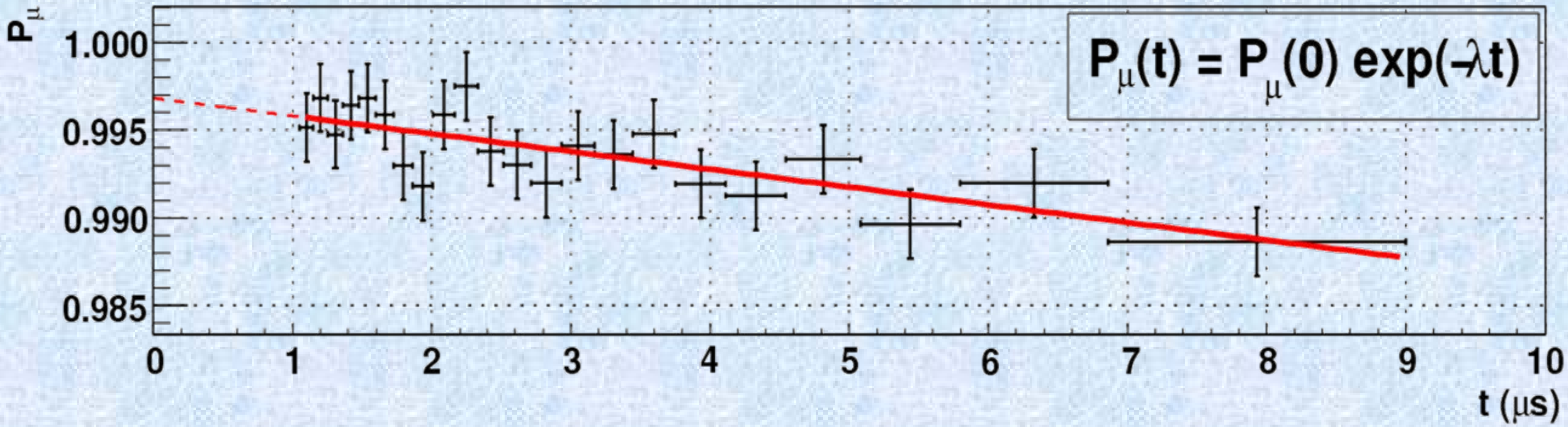
Small transverse field components need increasing by 10% to improve data and simulation agreement.

Fringe field systematics summary

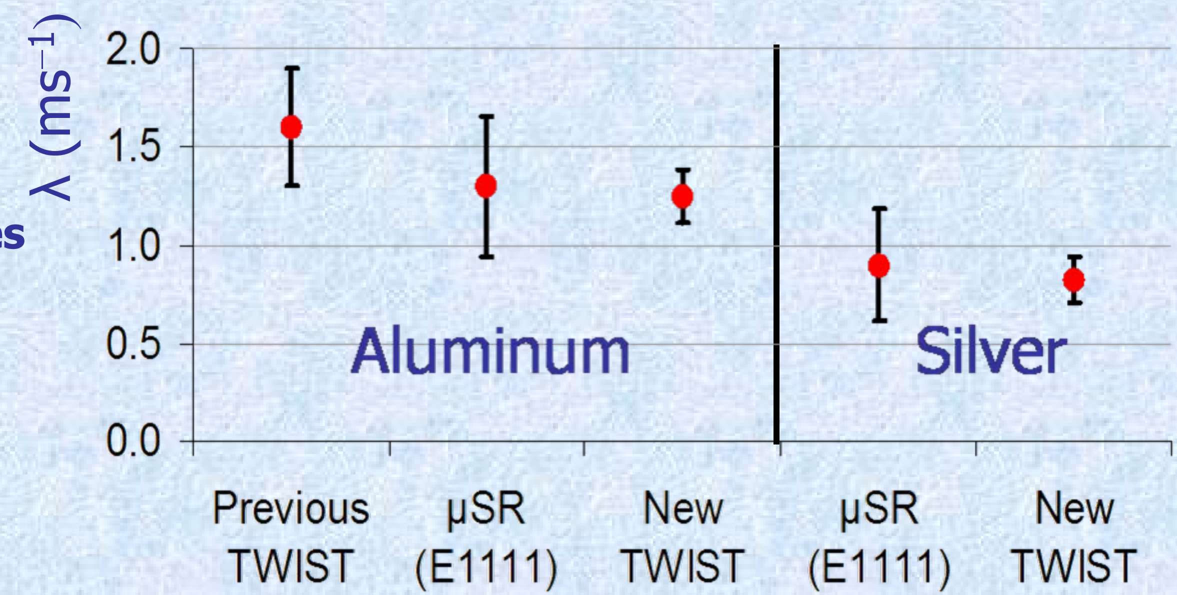


Polarization uncertainty in simulation (units 10^{-4})
(note sign is opposite to uncertainty in result)

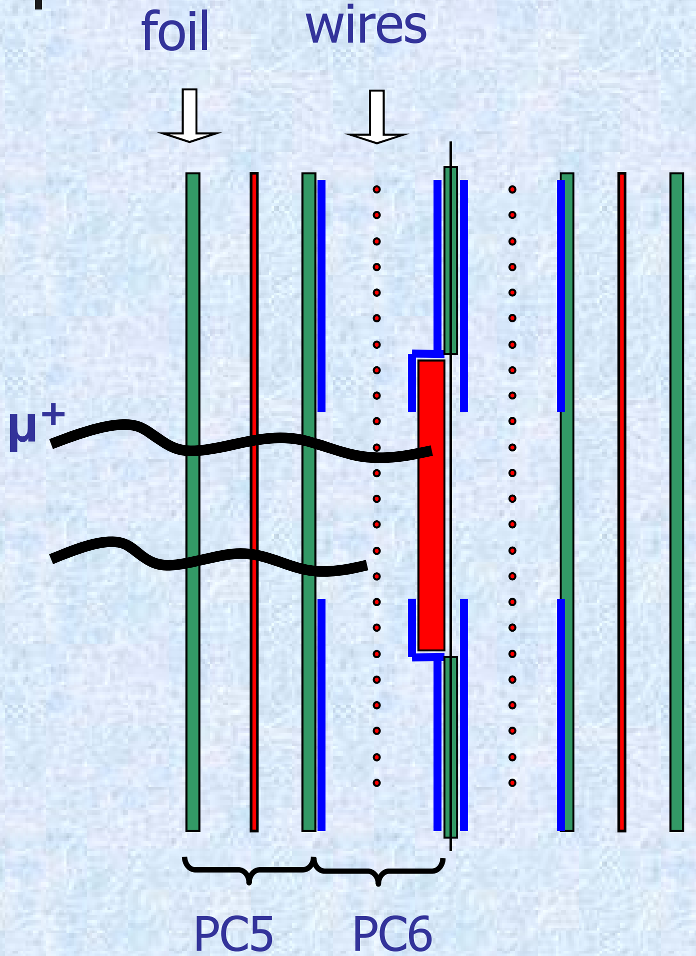
Depolarization in target material

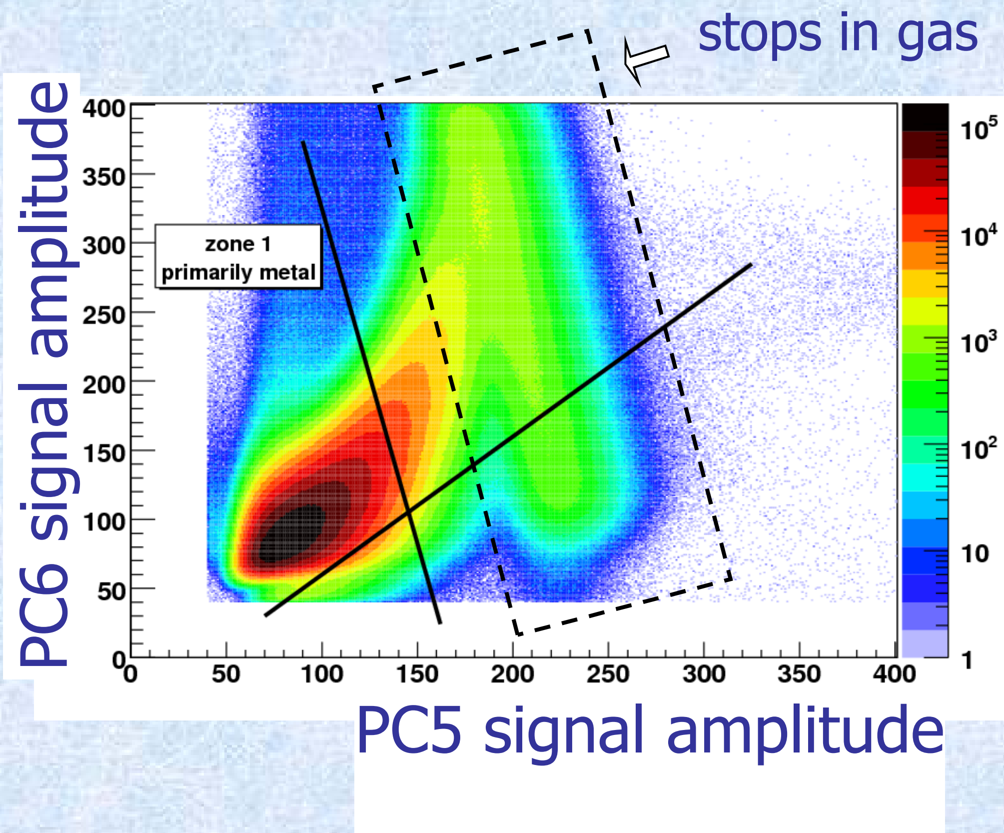


- Estimate of relaxation is included in simulation; correction is made to polarization parameter.
- μSR experiment establishes no fast relaxation.
- Statistical uncertainty in λ is included in decay parameter statistical uncertainty.



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).

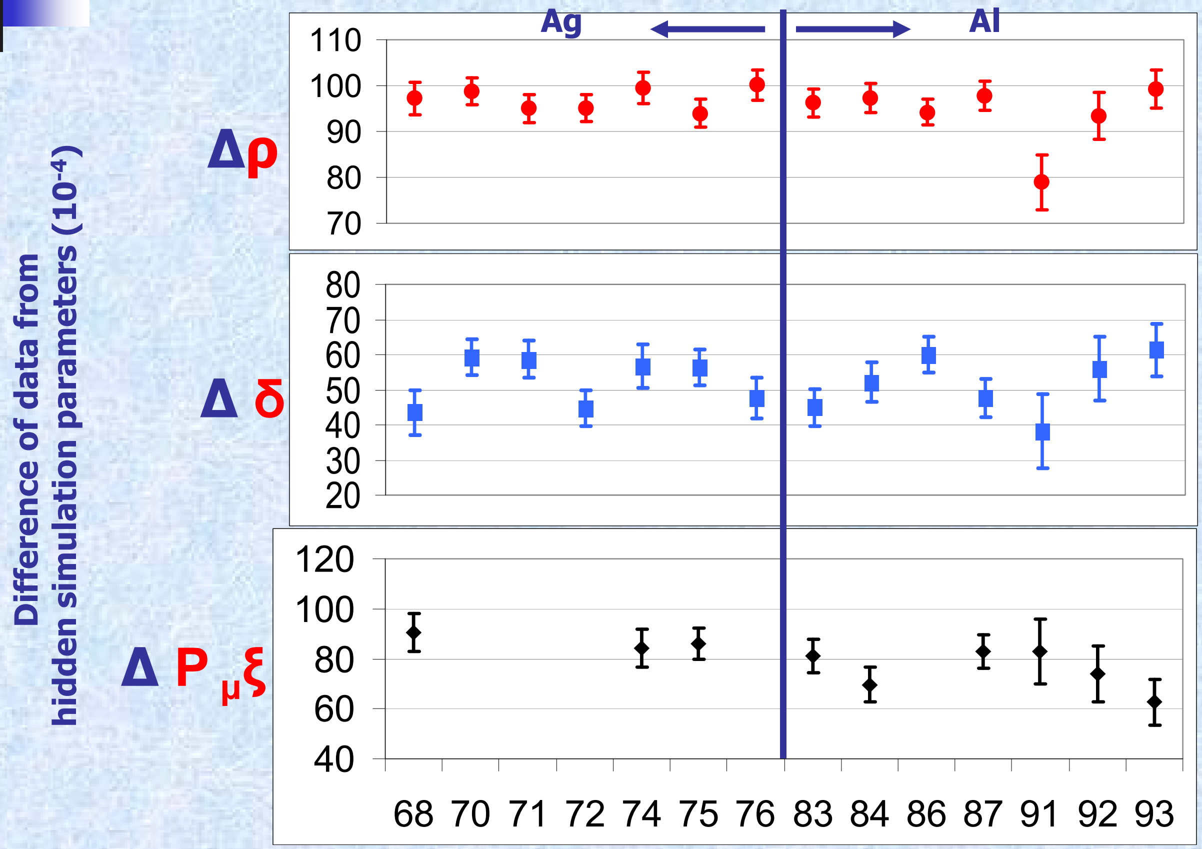
Corrections

(applied to data minus simulation, units 10^{-4})

Polarization	Production target multiple scattering	+ 0.3 at 29.60 MeV/c + 1.6 at 28.85 MeV/c + 1.9 at 28.75 MeV/c
	Final relaxation rate	+ 2.7 for silver + 3.3 for aluminium

		ρ	δ	$P_\mu \xi$
Unmatched statistics	Spectrum fitter	−0.2	−0.1	−0.5
	Energy calibration (set dependent)	−1.3 to −1.7	−0.3 to −0.5	+1.3 to +2.4

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 $P_\mu\xi$, χ^2 = 9.7**
- **statistical uncertainties only, after corrections**

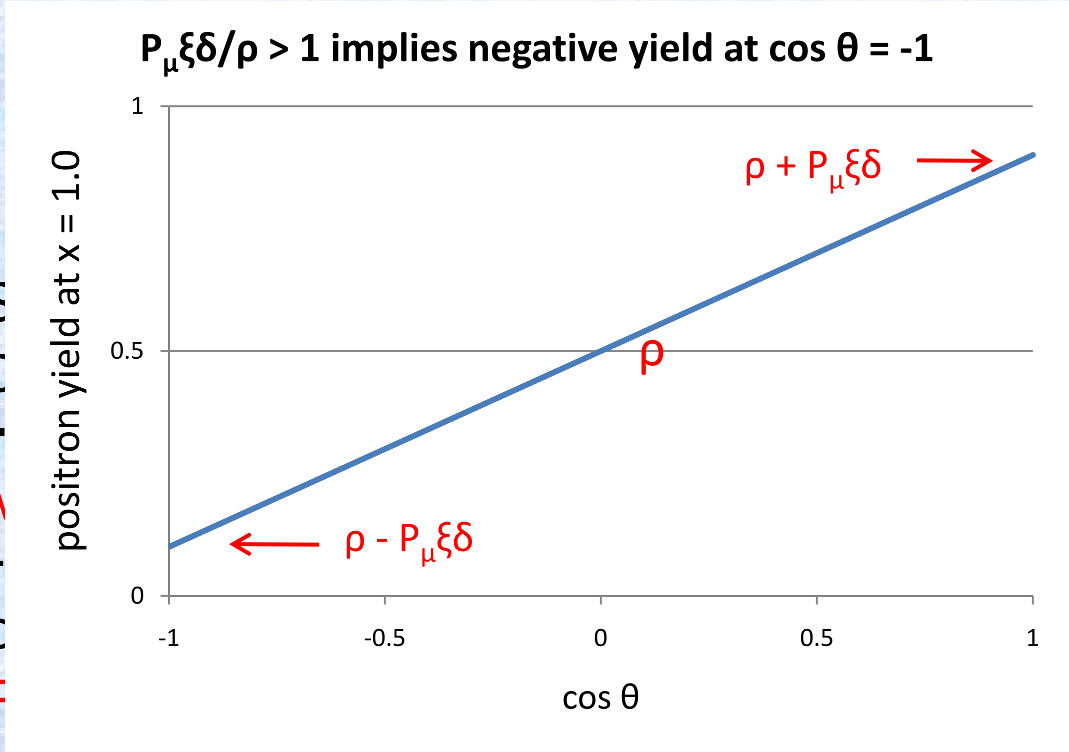
Results and interpretations

- Before revealing hidden parameters, check
  - consistency of data sets
  - spectrum fit quality
- Blind analysis protocol:
  - identify data sets to include
  - all event selection criteria and cuts , e.g., (p,cosθ) fiducial
  - systematic uncertainties and corrections
  - level of required consistency with previous results
  - new measurement supersedes previous *TWIST* measurements
  - publish even if inconsistent with Standard Model
- Including hidden parameters, we get
  - results
  - comparisons with previous results
  - consequences for fundamental interactions

"The box"

Why the blind results were not final

Results (blind analysis)



yst)

syst)

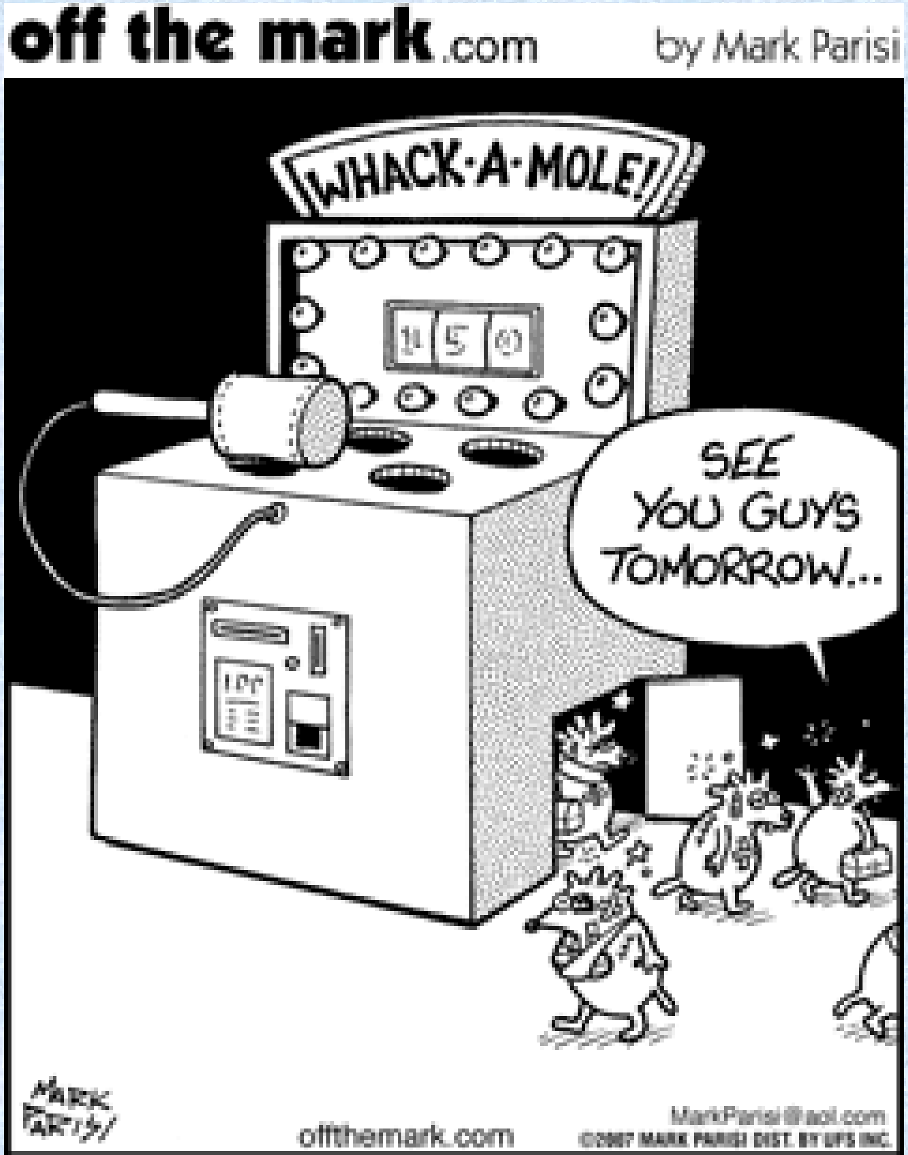
syst)

- S … or **ρ**, **δ**, and $P_\mu\xi$
- D … re respectively
  -

How

- r … m matrix element
  c … neters
- F … **3.9 σ**.

The battle continues …

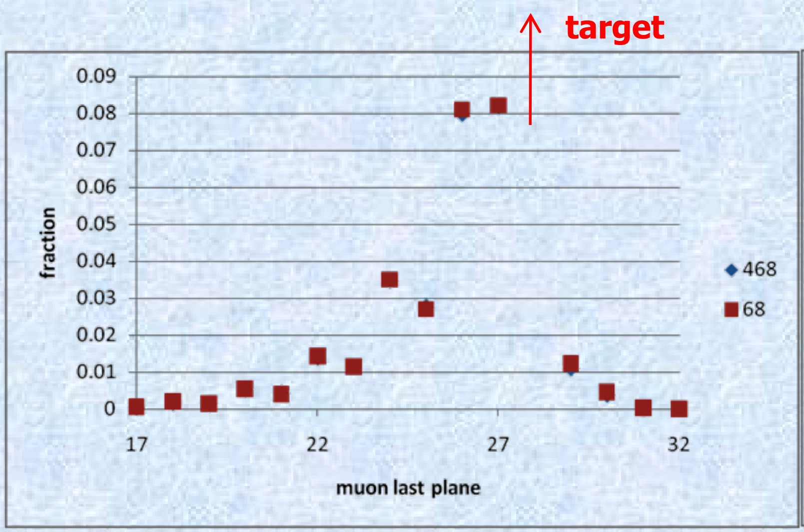


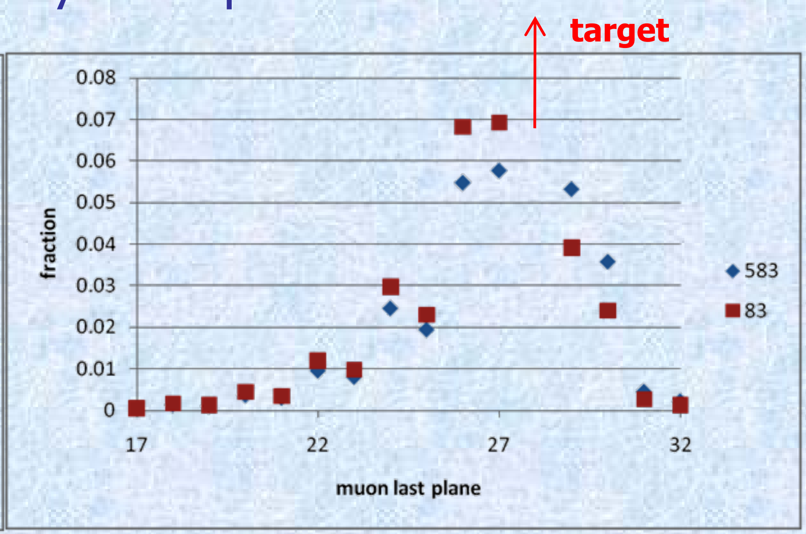
Revised results

- Many possible sources of error were checked and rejected
- Muon stopping location in data *vs.* simulation identified as a problem; affects mostly ρ and δ
- Search for mistakes identified two corrections and two procedural changes:
  - radiative decay: small correction of 0.3×10^{-4} 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
  - $\boldsymbol{\delta}$ correlations from all sets applied to $P_\mu\xi$
- After the revisions, the Ag-Al $\boldsymbol{P_\mu\xi\delta/\rho}$ difference becomes $<1\boldsymbol{\sigma}$.

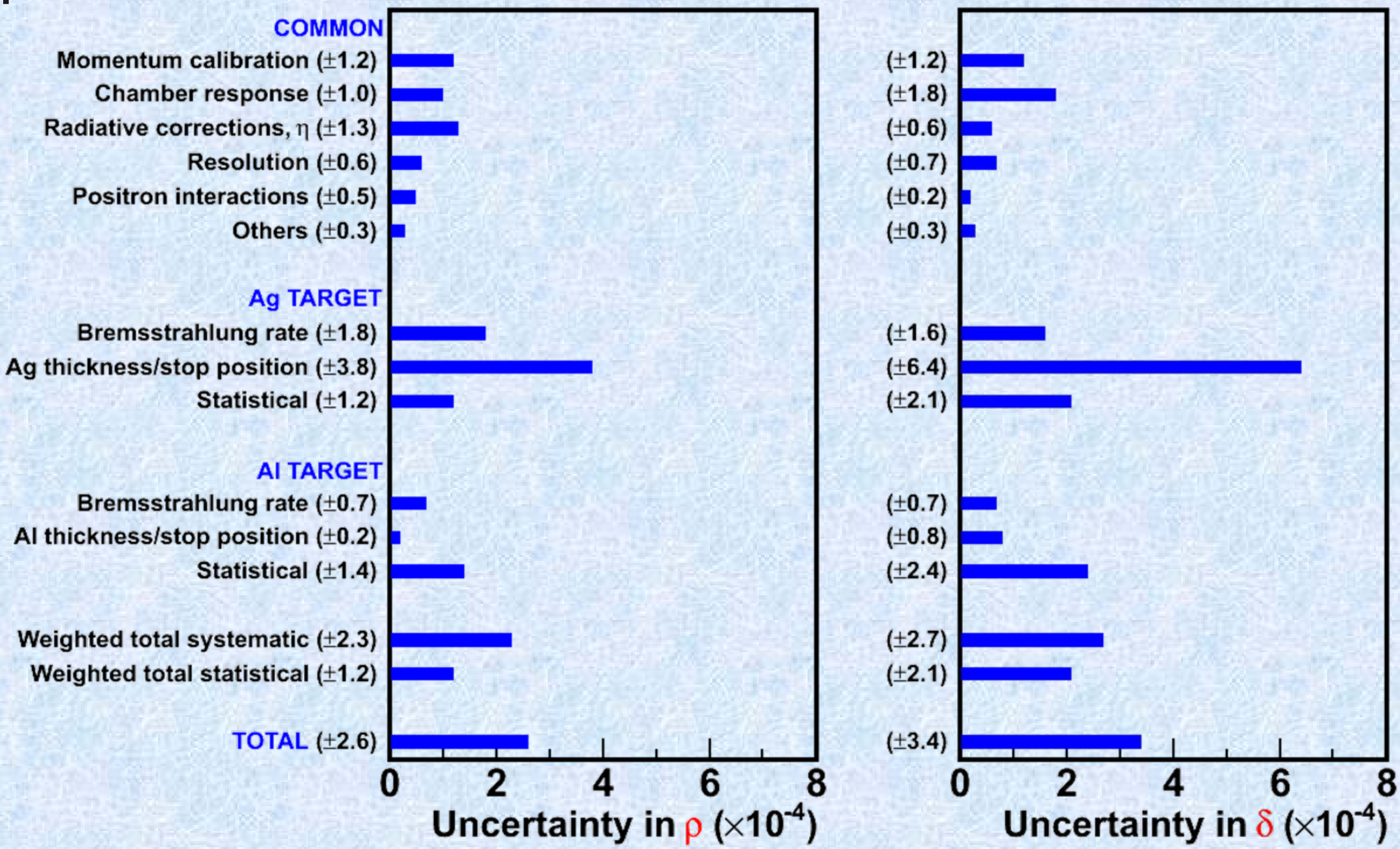
Muon Stopping Distribution

- Energy calibration should remove the effect of any mismatch
  - adequate sensitivity: 1 keV out of 52.8 MeV
  - unknown "zero"
- Very thin stopping targets: 30 μm for Ag and 70 μm for Al
  - 80% of muons stop in target
  - mismatch between data and simulation of up to 2 μm
- Use tails of stopping distribution outside of target
  - match of data and simulation for all planes defines zero
- Calibrate and determine sensitivity to fit parameters with sim.

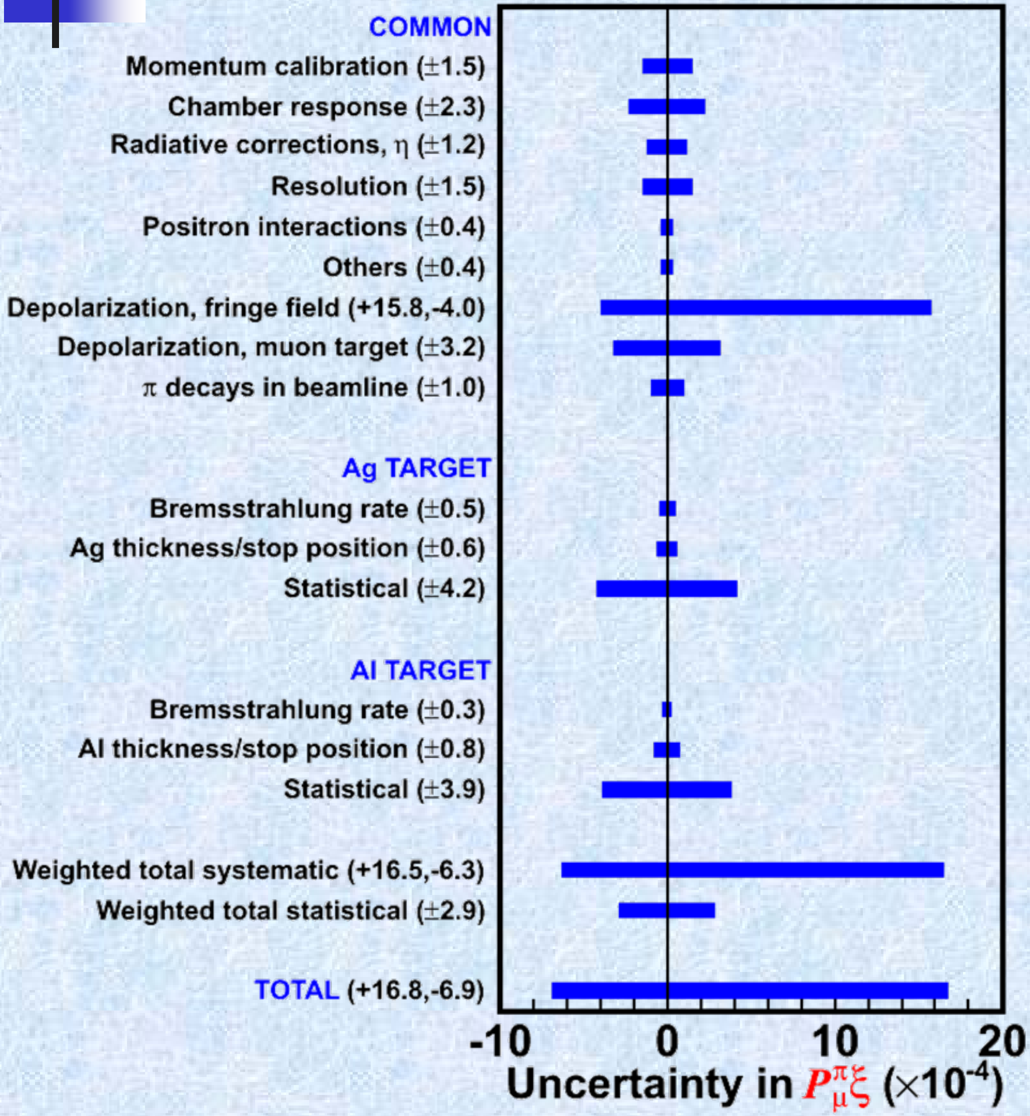




Uncertainties in ρ and δ

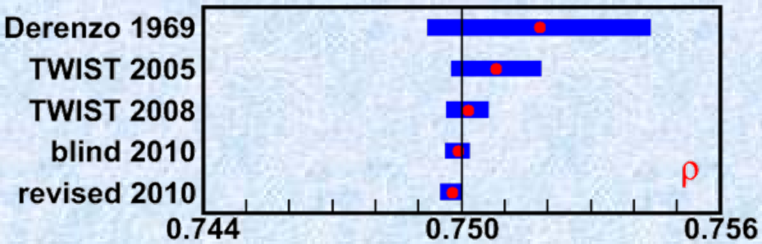


Uncertianties in $P_\mu \xi$

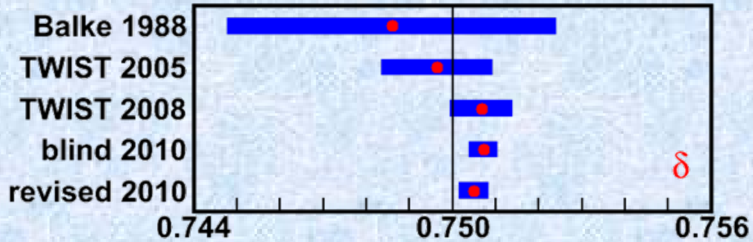


- Uncertainties for all three parameters are from the revised analysis
- Differences to blind results are small:
  - **σ**(**ρ**) changed by **-0.3×10^{-4}**
  - **σ**(**δ**) changed by **$+0.1\times10^{-4}$**
  - **σ**($P_\mu\xi_{avg}$) changed by **-0.2×10^{-4}**

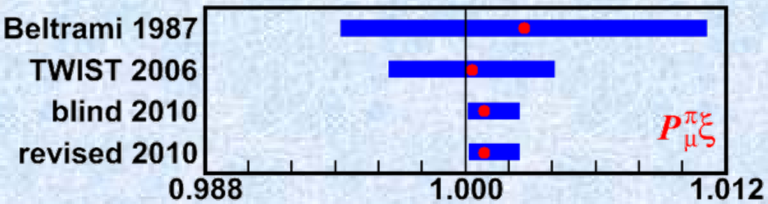
Decay parameter results



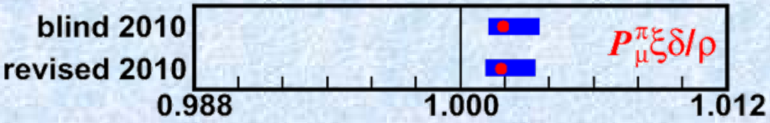
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)
(<1 σ from SM, -1.4×10^{-4} from blind)



δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)
(+1.4 σ from SM, -2.3×10^{-4} from blind)



$P_\mu\xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)
(+1.2 σ from SM, same as blind)



$P_\mu\xi\delta/\rho$ > 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, 3499 (1986) uses general parameters:

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

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

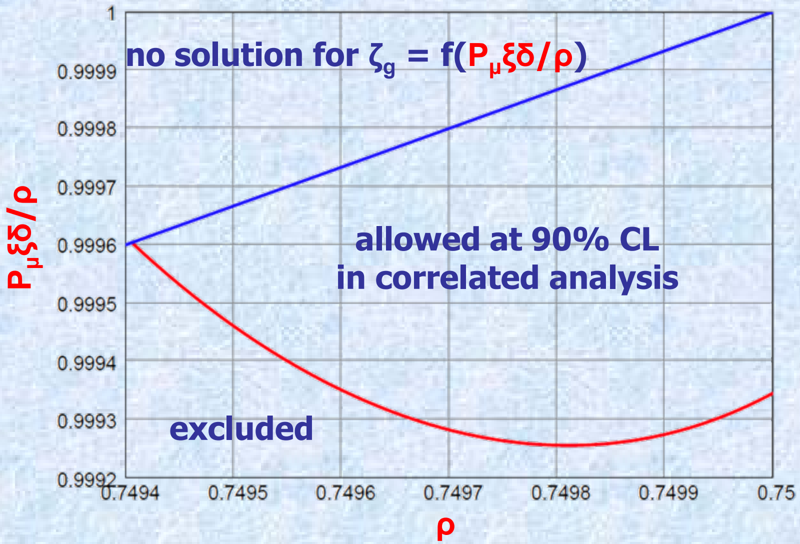
$$\rho \simeq \frac{3}{4}(1 - 2\zeta_g^2), \quad \delta = \frac{3}{4}, \quad \xi \simeq 1 - 2(t^2 + \zeta_g^2),$$

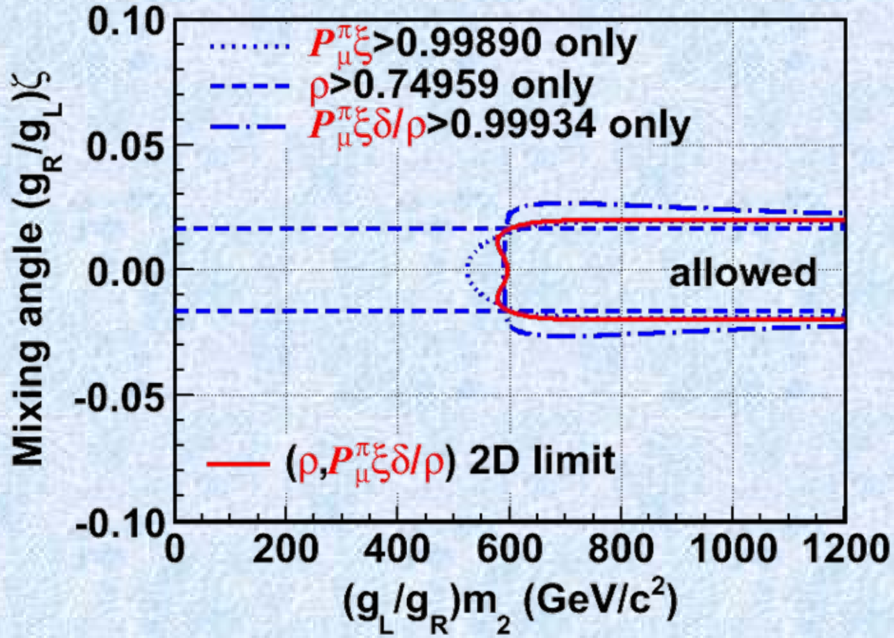
$$\mathcal{P}_\mu^\pi \simeq 1 - 2t_\theta^2 - 2\zeta_g^2 - 4t_\theta\zeta_g \cos(\alpha + \omega)$$

  - 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

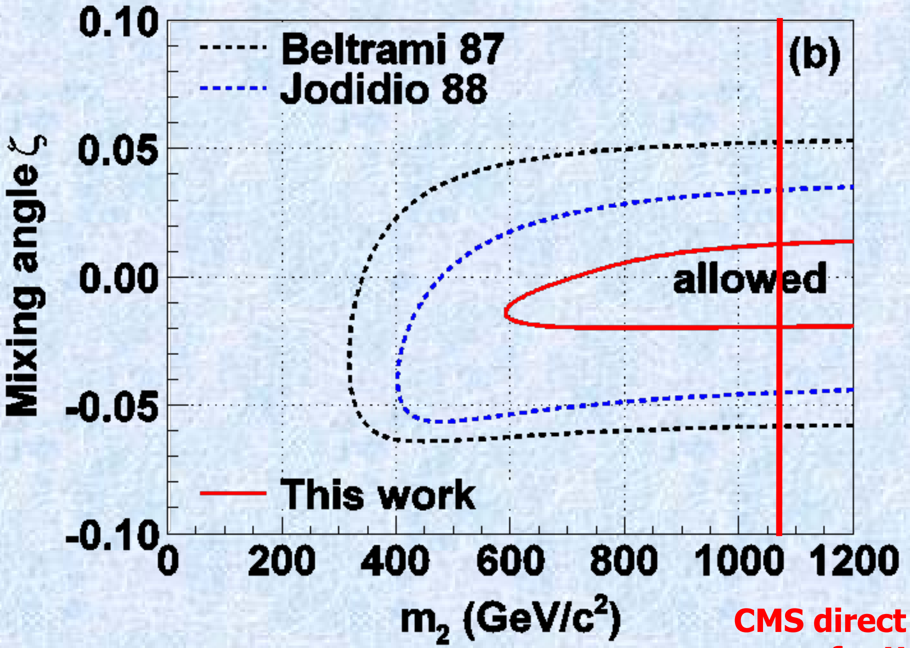




- Previous muon decay LRS parameter limits used individual limits for **ρ**, $P_\mu\xi$, or **$P_\mu\xi\delta/\rho$**
- *TWIST* has simultaneous measurements of three parameters; correlations contribute to the confidence interval.

LRS limit comparison

“manifest” LRS

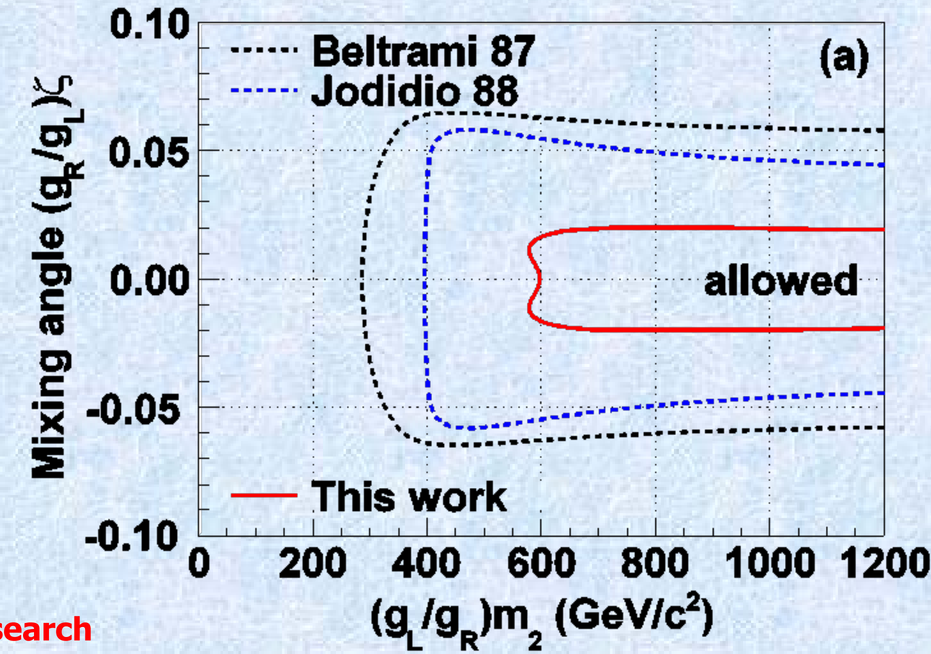


CMS direct search for W’ >1.36 TeV/c^2
D0 > 1.0 TeV/c^2
CDF > 1.12 TeV/c^2

m_2 > 592 GeV/c^2

-0.020 < ζ < +0.017

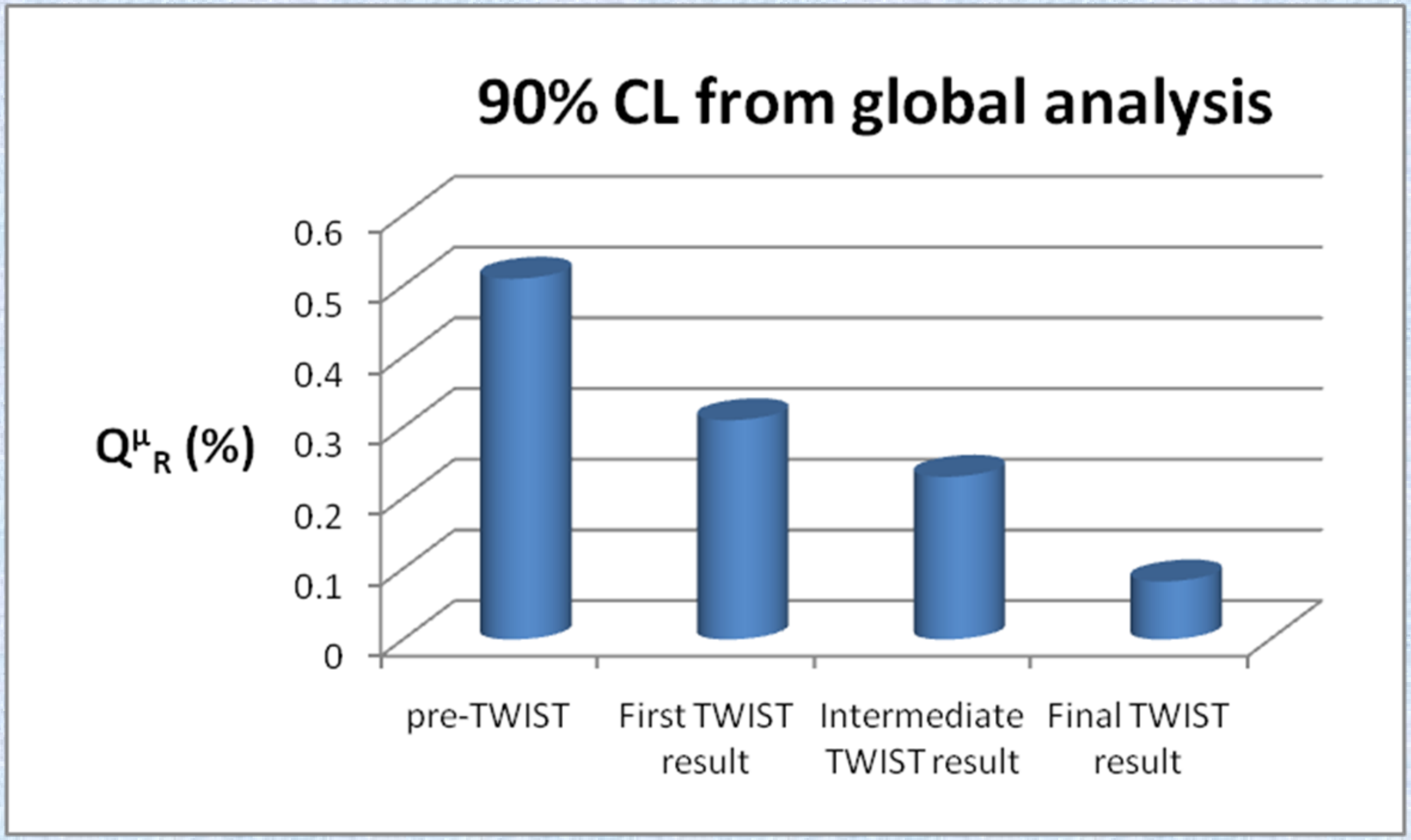
generalized or non-manifest LRS



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

-0.020 < (g_R/g_L) ζ < +0.020

Global analysis result



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.

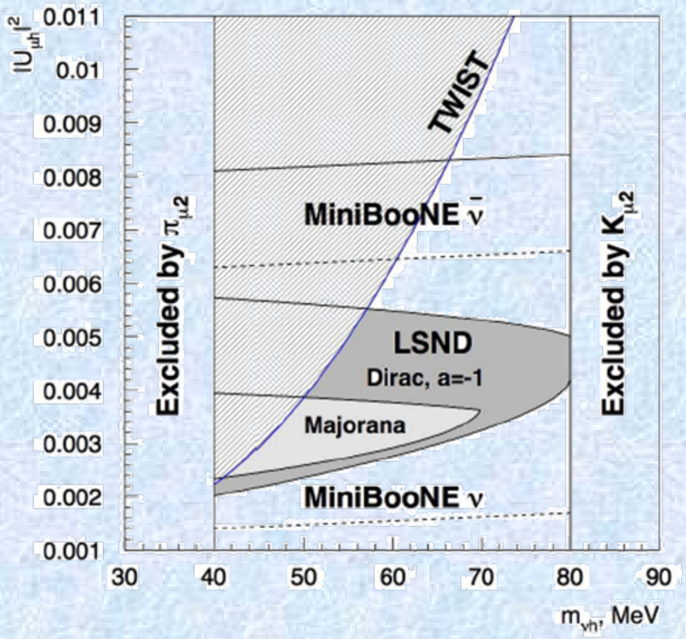


FIG. 24: The 2σ allowed region (dark areas) in the $(m_{\nu_h}; |U_{\mu h}|^2)$ parameter space for Dirac ($a = -1$) and Majorana cases obtained from the combined analysis of LSND and MiniBooNE ν_μ and $\overline{\nu}_\mu$ data. The regions excluded by the $\pi_{\mu 2}$ and $K_{\mu 2}$ decay experiments [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

R.E. Shrock,
Phys. Re. 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).

Summary

- *TWIST* substantially reduced both statistical and systematic uncertainties in muon decay parameter measurements.
- Total uncertainties were reduced by factors of **10**, **11**, and **7** for **ρ**, **δ**, and **$P_\mu\xi$** respectively, roughly achieving the goals of the experiment.
- Differences with standard model predictions are respectively **-0.9σ**, **+1.4 σ**, and **+1.2 σ**, after the post-blind revisions.
- **$P_\mu\xi\delta/\rho$** deviates by **+2.3 σ** from the expected upper limit of 1.0.
- Significant improvements to limits on extensions to the standard model have been obtained.