Final results for muon decay parameters from *TWIST*

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Rencontres de Moriond, 6-13 March 2010

Outline

- Description of muon decay
  - decay parameters and coupling constants
- The experiment
  - beam and detectors, briefly
- The data
  - blind analysis and summary of uncertainties
  - consistency of data
- Presentation and interpretation of results
  - new results, comparisons with previous results, implications

Decay parameter description

◎ Muon decay parameters ρ, η, $\mathcal{P}_\mu\xi$, δ

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

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

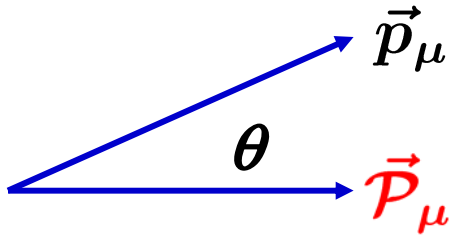
Louis Michel

⊙ where

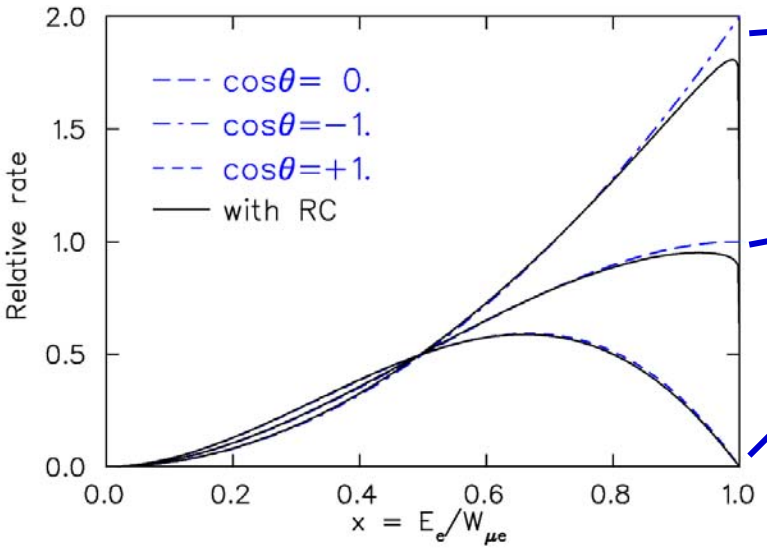
$$\mathcal{F}_{IS}(x,\rho,\eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

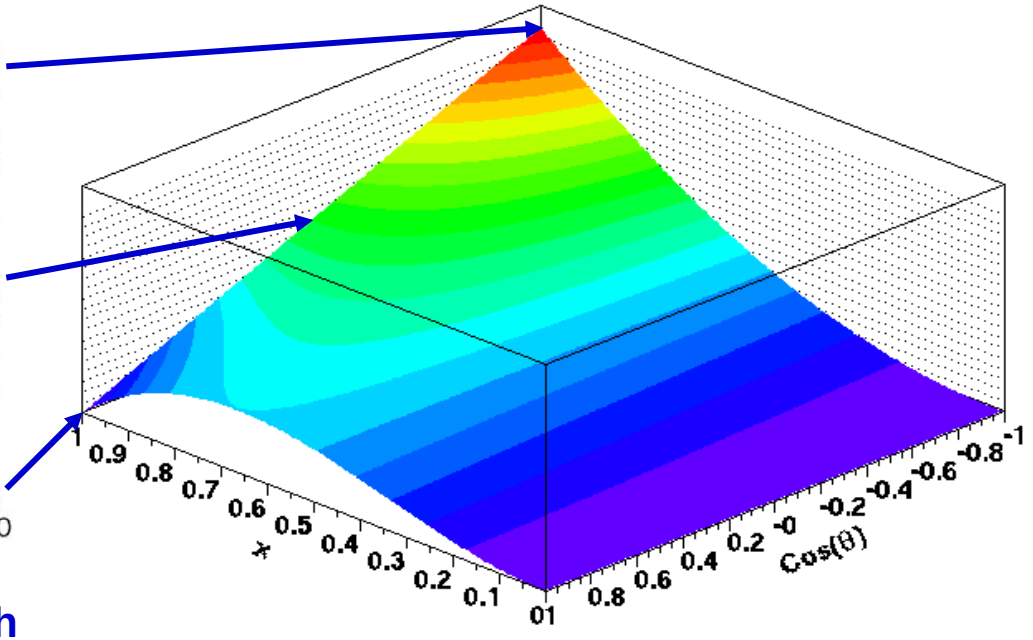
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right]$$

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



Decay spectrum shape and RC





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

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

- Description of Fetscher and Gerber (see PDG Review):

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

- Most general local, Lorentz-invariant, lepton-number conserving interaction.
- Includes 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 μ decay in terms of decay parameters:

$$Q^{\mu}_{R} = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta]$$

Pre-*TWIST* decay parameters

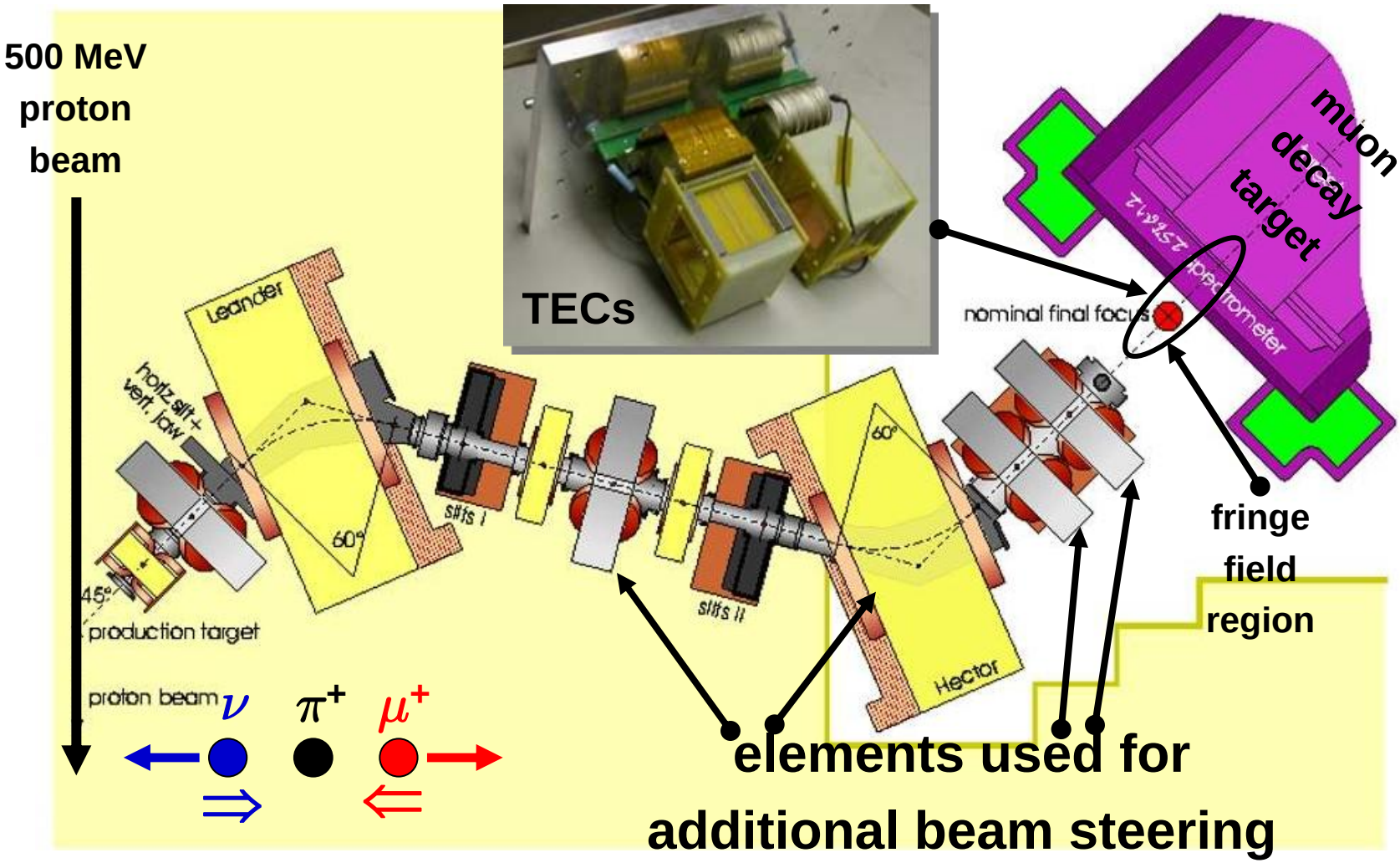
◎ From the Review of Particle Physics (SM values)

- ⊙ ρ = 0.7518 ± 0.0026 (Derenzo 1969, Peoples) (0.75)
- ⊙ δ = 0.7486 ± 0.0026 ± 0.0028 (Balke *et al.*, 1988) (0.75)
- ⊙ $\mathcal{P}_\mu\xi$ = 1.0027 ± 0.0079 ± 0.0030 (Beltrami *et al.*, 1987) (1.00)
- ⊙ $\mathcal{P}_\mu(\xi\delta/\rho)$ > 0.99682 (90%CL) (Jodidio *et al.*, 1986) (1.00)
- ⊙ η = -0.007 ± 0.013 (Burkard *et al.*, 1985) (0.00)

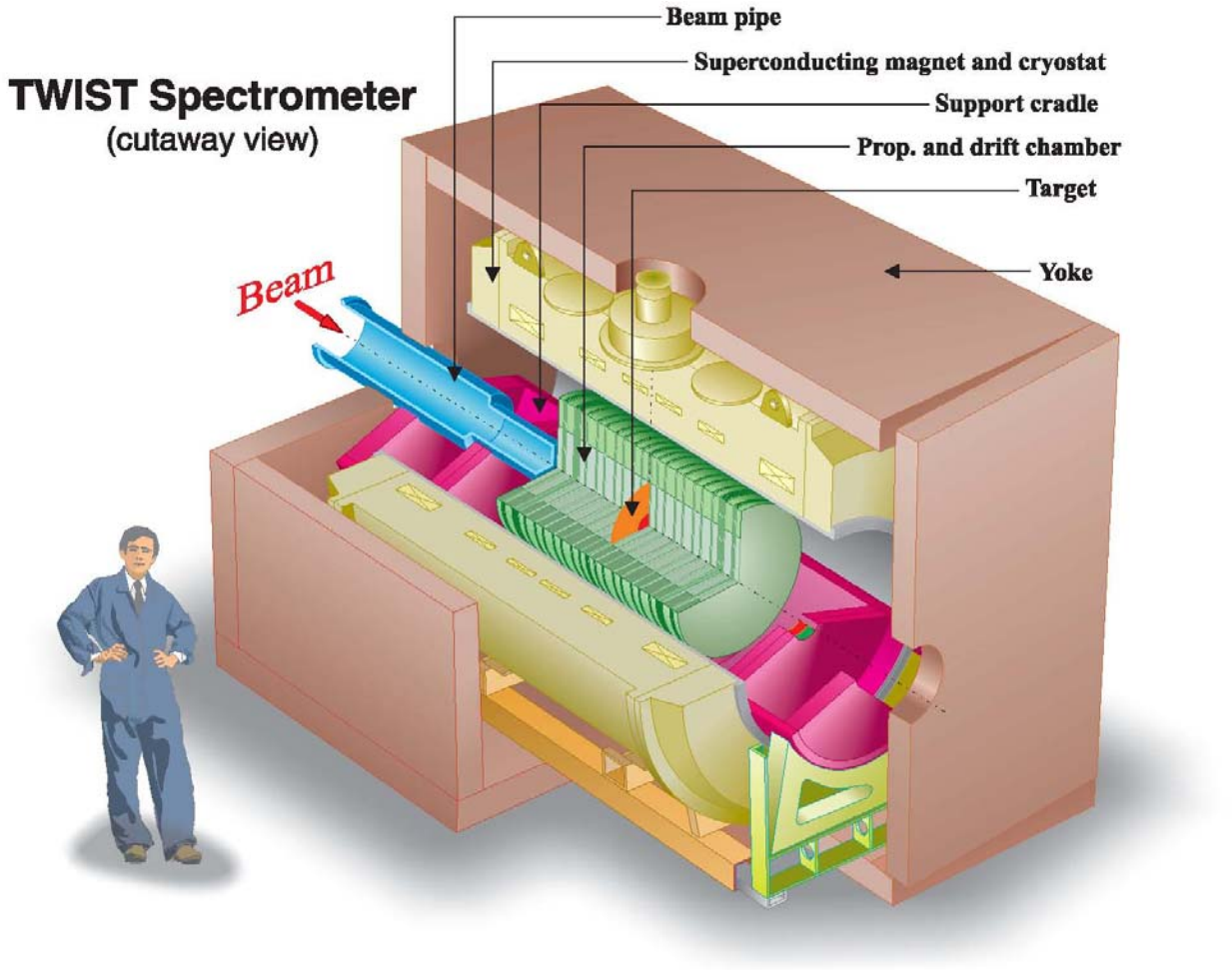
The goal of *TWIST* is to find any new physics which may become apparent by improving the precision of each of
ρ, δ, and $\mathcal{P}_\mu\xi$
by one order of magnitude compared to prior experimental results.

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

Muon production and transport



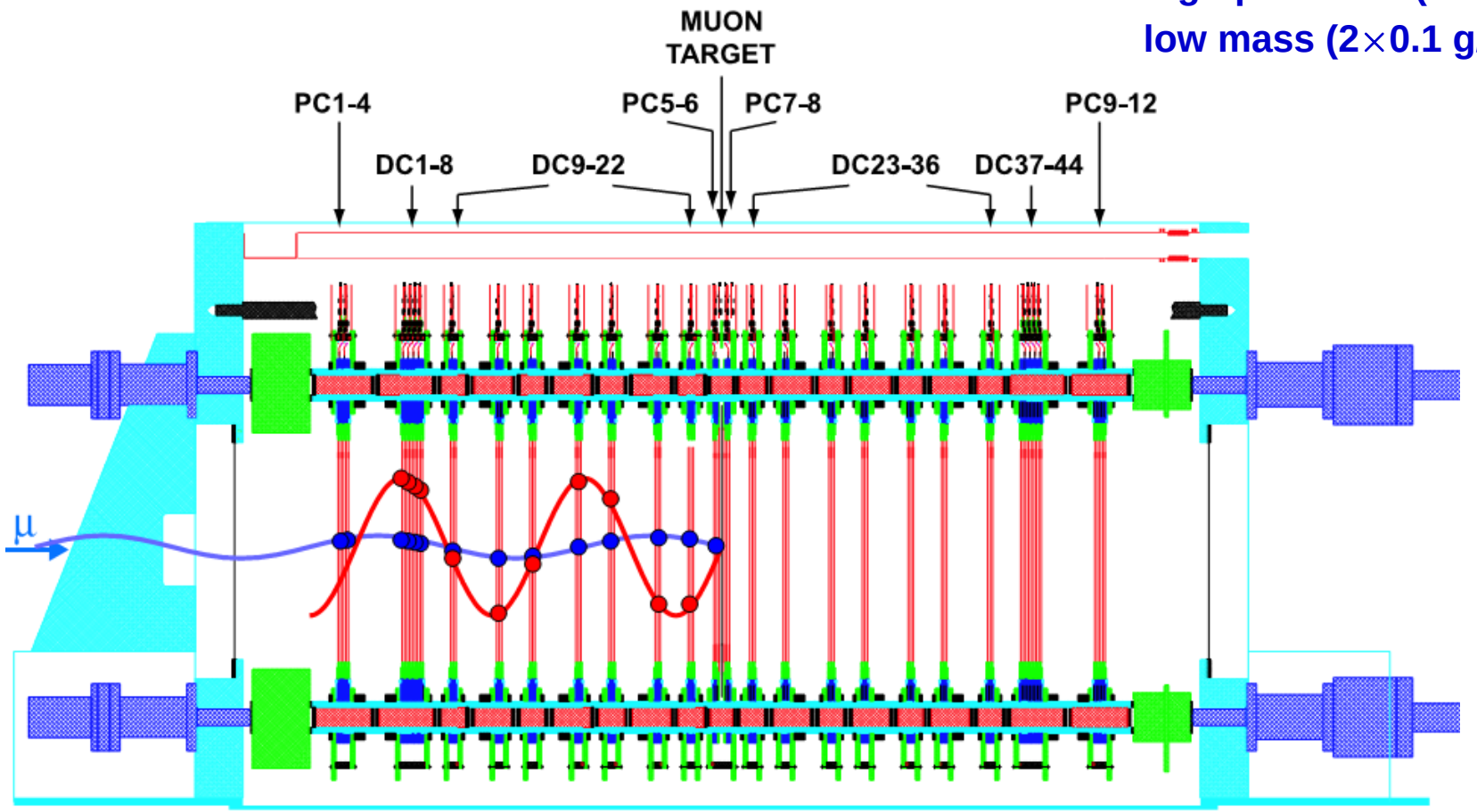
The TRIUMF Weak Interaction Symmetry Test



Detector array

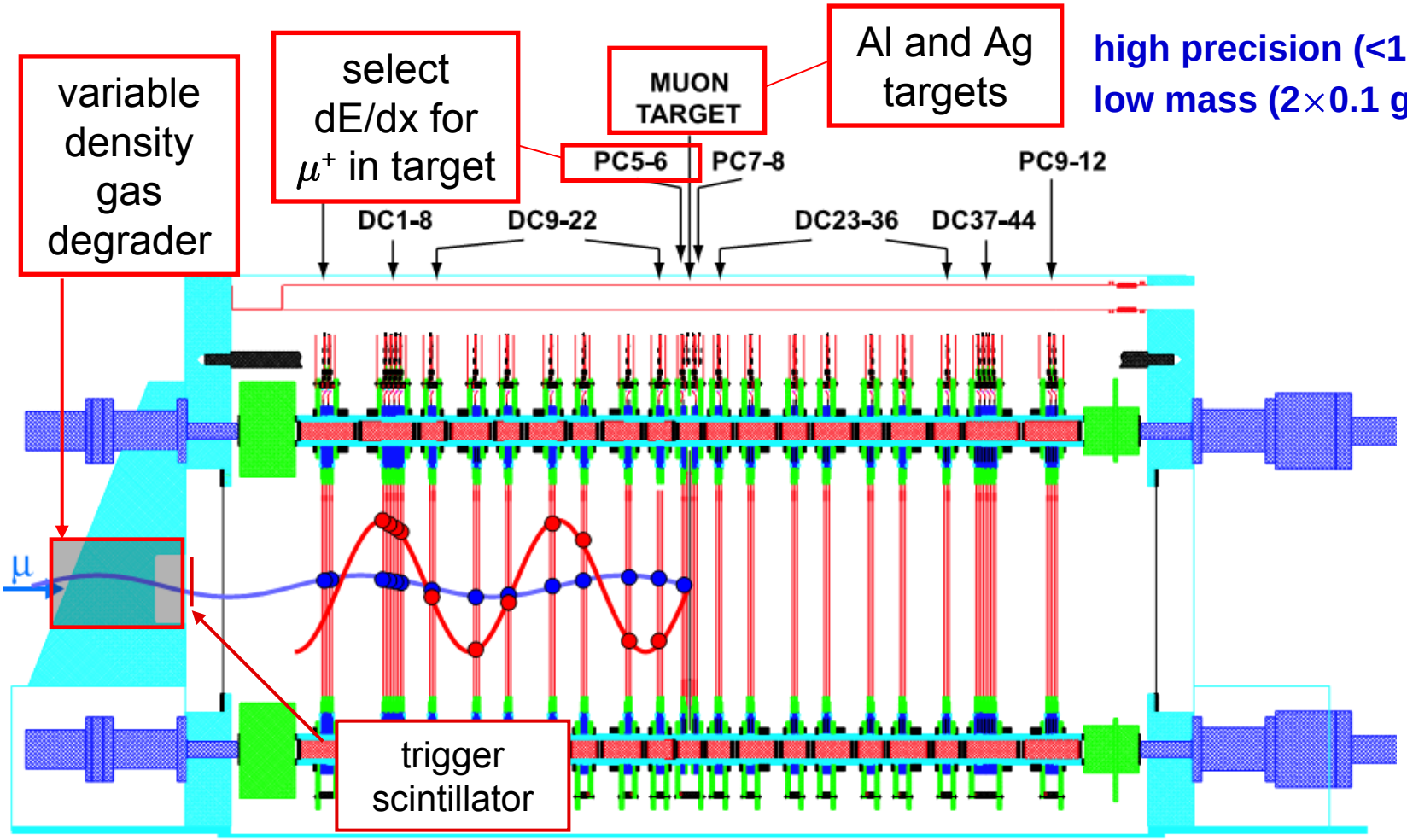
high precision ($<10^{-4}$)

low mass (2×0.1 g/cm^2)



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

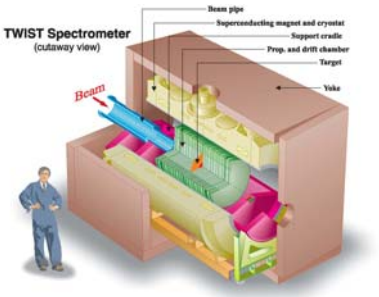
Detector array



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

Blind analysis

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



Hidden parameter tolerances 0.01

Data from experiment

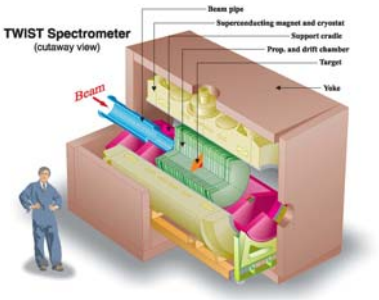
"Data" from simulation

Reconstruction software

MCfit spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta\mathcal{P}_\mu\xi$

Blind analysis

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



Data from experiment

Hidden parameter tolerances 0.01

"Data" from simulation

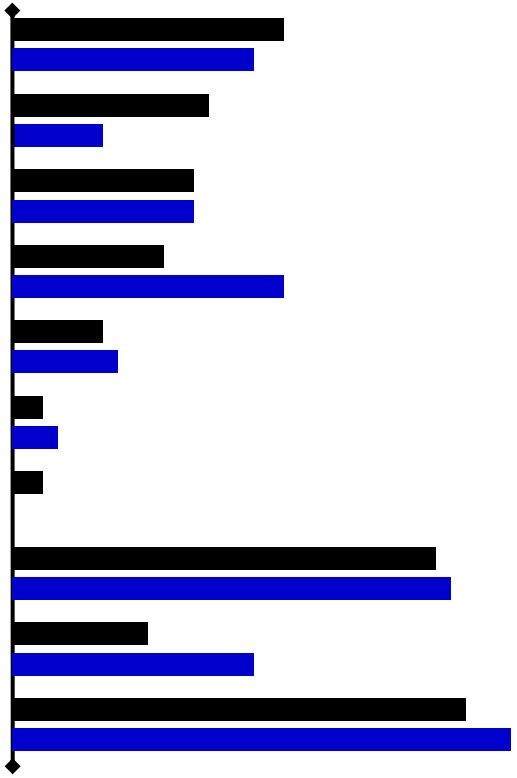
Reconstruction software

MCfit spectrum fit; $\Delta\rho$, $\Delta\delta$, $\Delta\mathcal{P}_\mu\xi$

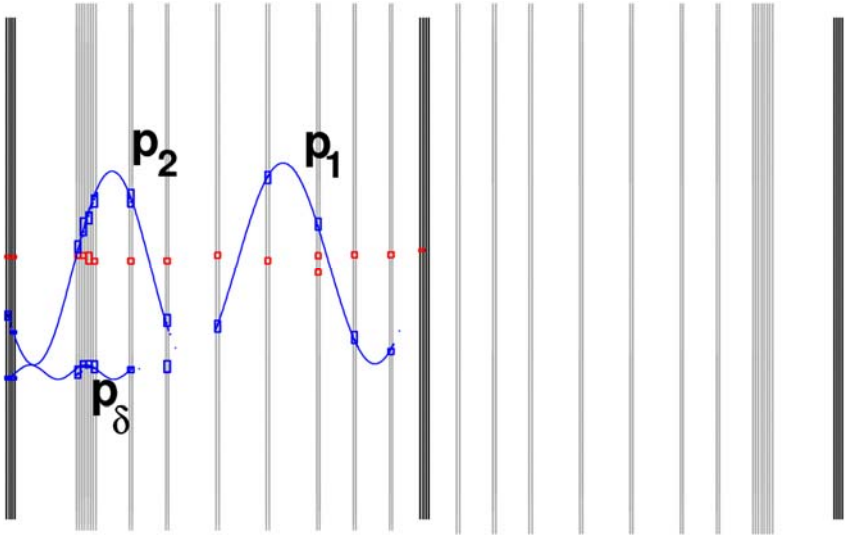
Add to hidden parameters; ρ, δ, $\mathcal{P}_\mu\xi$

ρ and δ uncertainties

Uncertainties	ρ ($\times 10^{-4}$)	δ ($\times 10^{-4}$)
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*



Positron interactions



"Broken tracks" analysis:

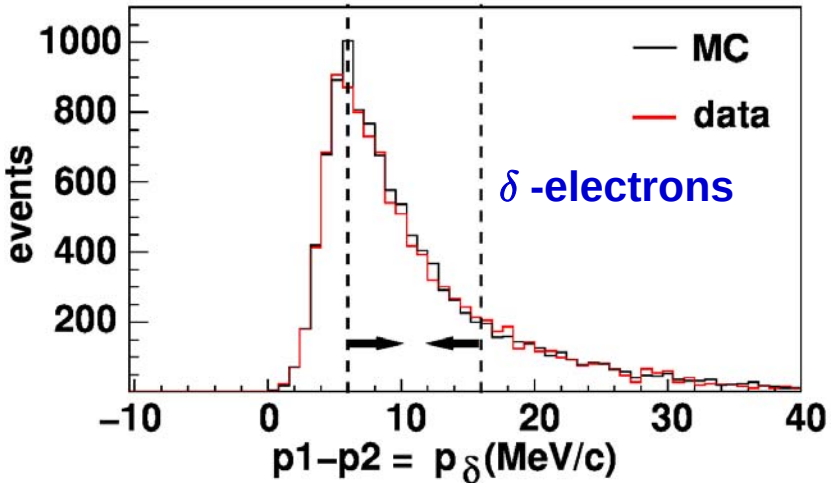
$2e^+$, 1 e^- $\equiv$ δ-electron

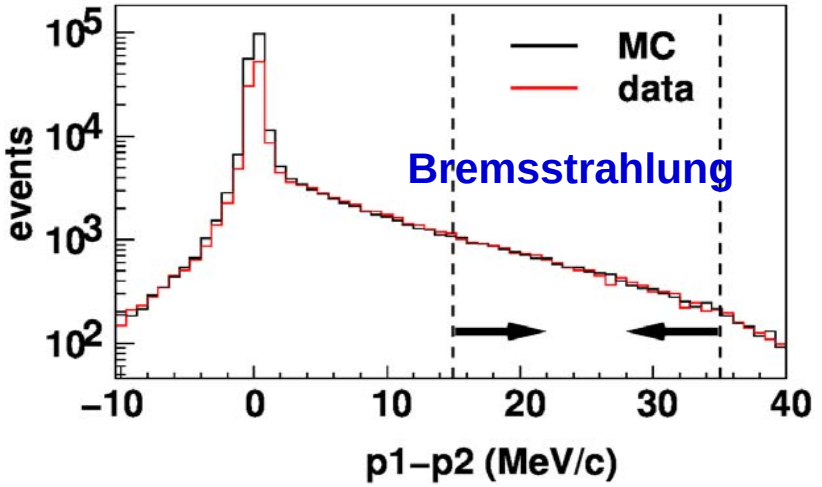
2 e^+ $\equiv$ Bremsstrahlung

Agreement of data and sim:

δ-electrons < 1%

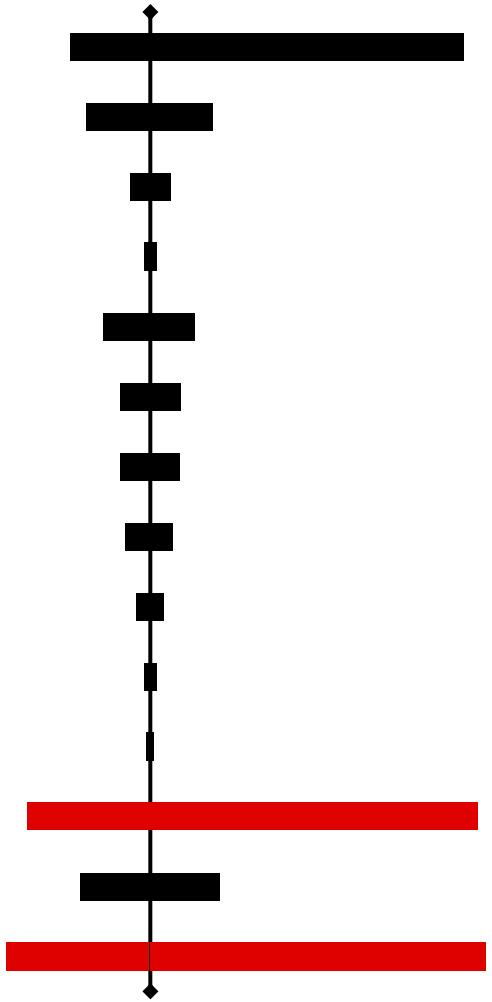
Bremsstrahlung differs by 2.4%



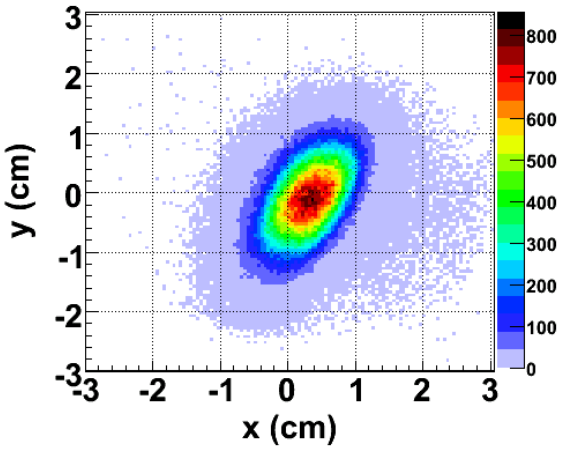


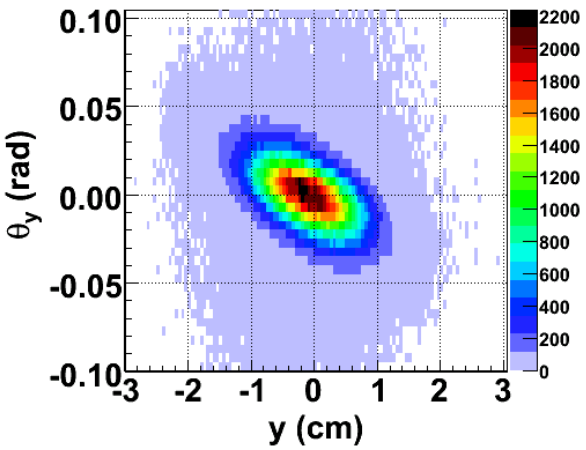
$\mathcal{P}_\mu\xi$ uncertainties

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*



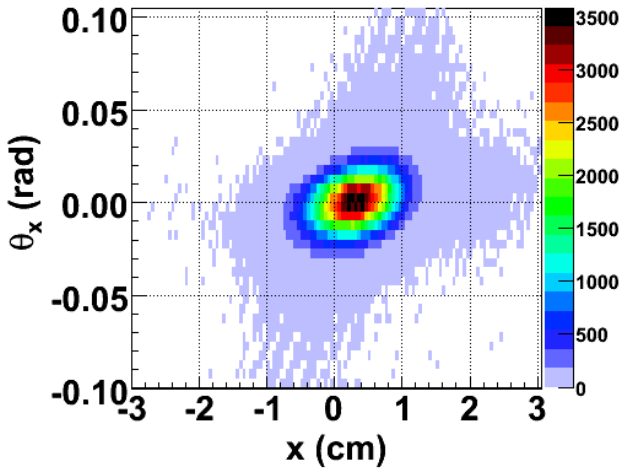
Fringe field depolarization

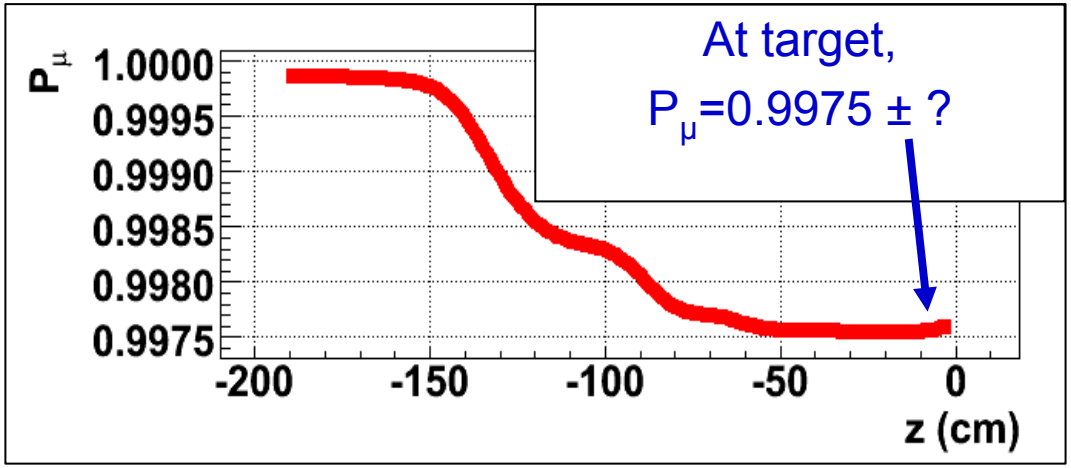




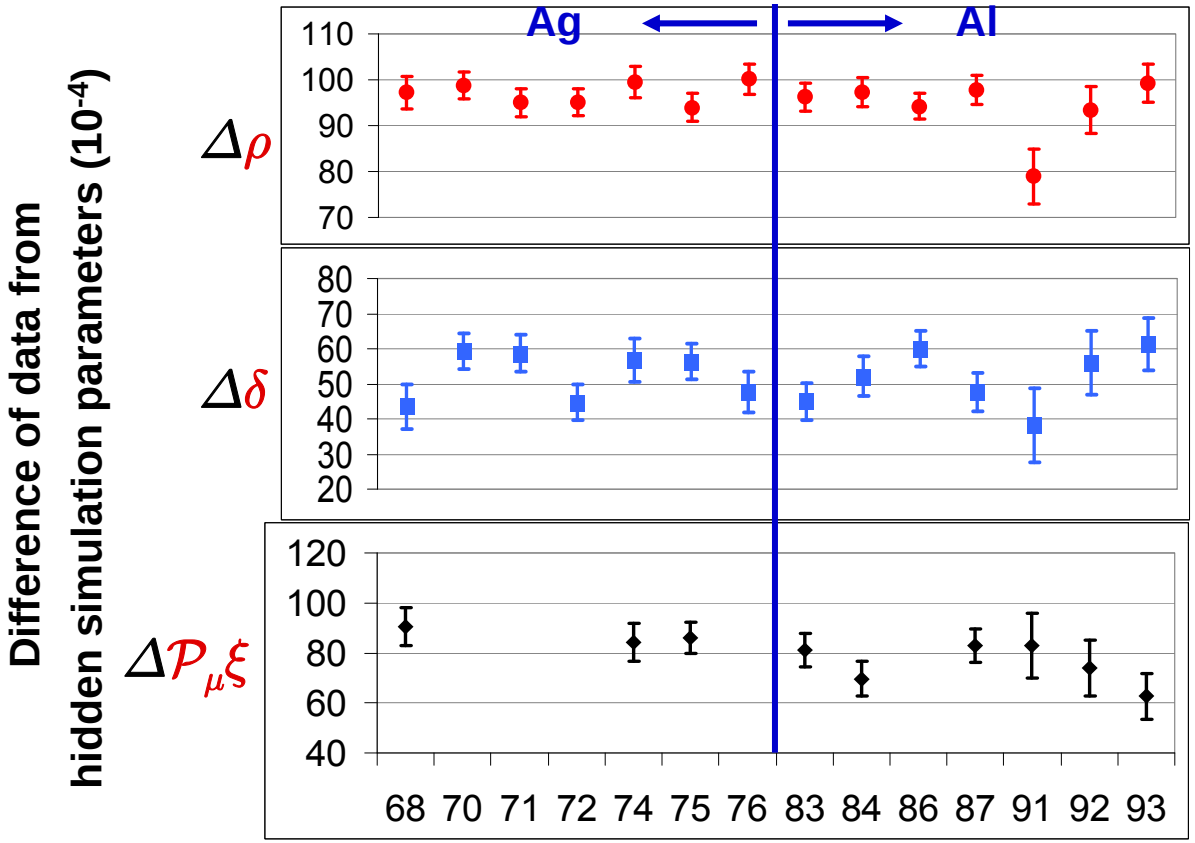
The TECs measure beam x, y, θ_x, and θ_y, and thus $\mathcal{P}_\mu$ prior to the fringe field.

The simulation describes its evolution to the decay target.





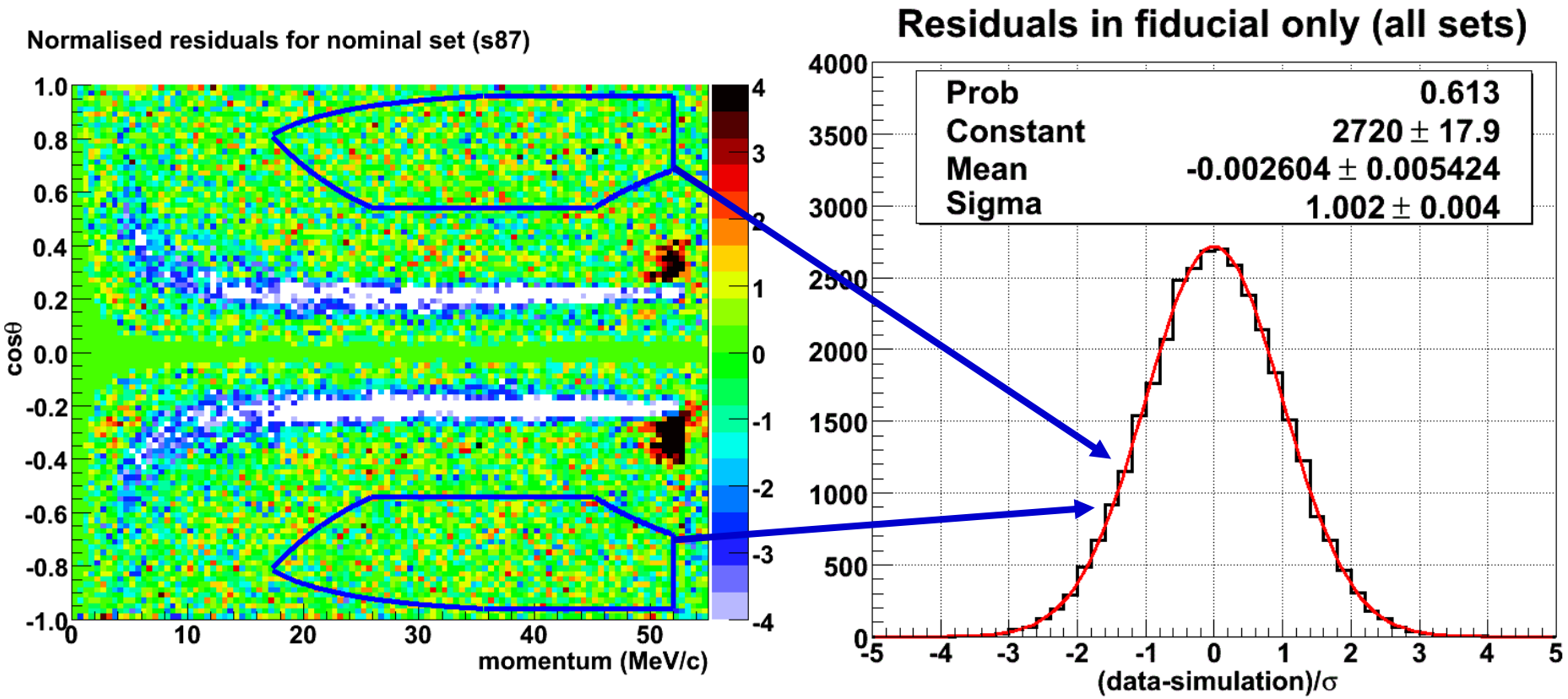
Consistency of data sets



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 $\mathcal{P}_\mu\xi$, $\chi^2 = 9.7$**
- **statistical uncertainties only, after corrections**

Spectrum fit quality



- All data sets: **11**×**10⁹** events, **0.55**×**10⁹** in (p,$cos\theta$) fiducial
- Simulation sets: **2.7** times data statistics

Results

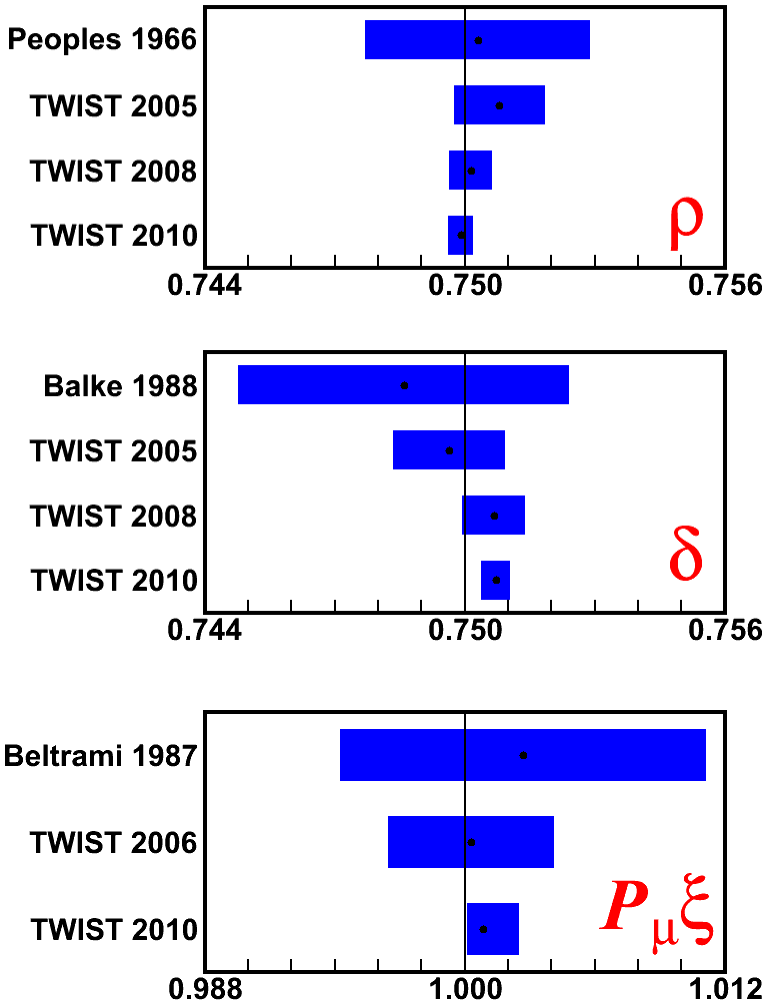
(*vs.* SM)

- 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)
  - defines asymmetry at endpoint: must be $\leq$ 1.0
  - investigating possible instrumental sources of error; none yet found

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.

Implications for global analysis

- A new global analysis provides tighter restrictions on some coupling constants (pre-*TWIST* in parentheses):

$$|g^S_{RR}| < 0.031 (0.066) \qquad |g^V_{RR}| < 0.015 (0.033)$$
$$|g^S_{LR}| < 0.041 (0.125) \qquad |g^V_{LR}| < 0.018 (0.060) \qquad |g^T_{LR}| < 0.012 (0.036)$$

- New limit on $Q^{\mu}{}_{R}$ **< 5.8×10^{-4}** (×**9** lower than pre-*TWIST*)

- Uncertainty on η reduced by 1/3 compared to 2005 global analysis: we find η = -0.0033 ± 0.0046
  - uncertainty for G_F from muon lifetime depends on η uncertainty

SM extension: Left-Right Symmetric

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

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

- Assume possible differences in left and right couplings and CKM character (P. Herczeg, 1986)
  Use notation: $t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}, \qquad t_\theta = t\frac{|V_{ud}^R|}{|V_{ud}^L|}, \qquad \zeta_g^2 = \frac{g_R^2}{g_L^2}\zeta^2$

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

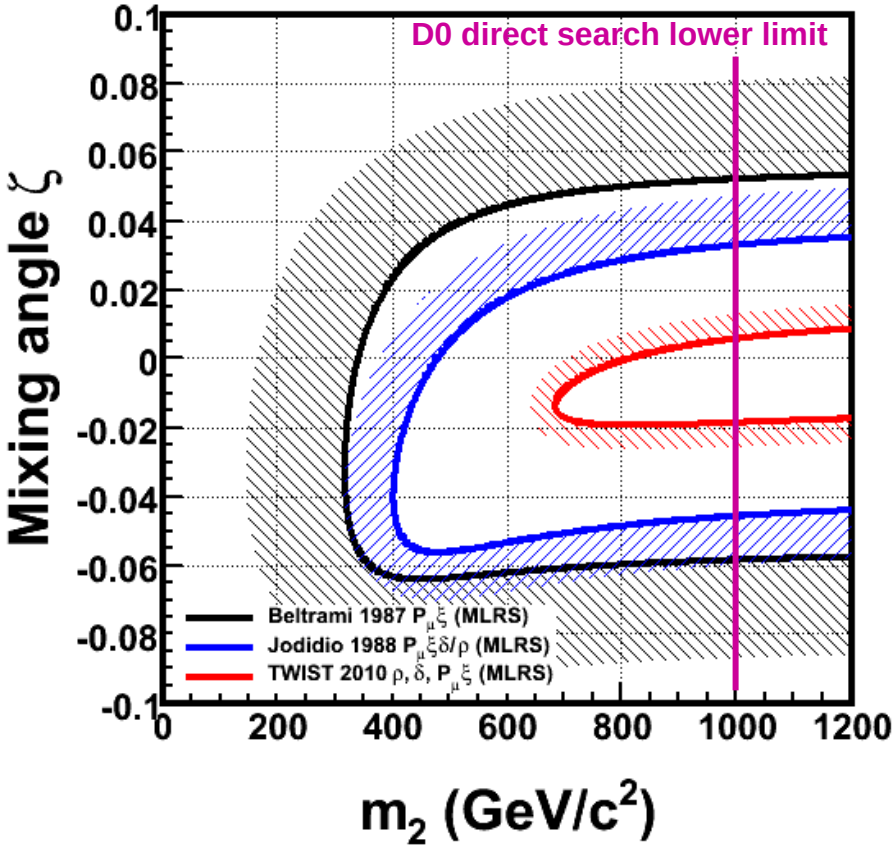
$$\rho = \tfrac{3}{4}(1 - 2\zeta_g^2), \quad \delta = \tfrac{3}{4}, \quad \xi = 1 - 2(t^2 + \zeta_g^2),$$

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

  - "manifest" LRS assumes $g_R = g_L$, $V^R = V^L$, $\alpha,\omega = 0$ (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.

LRS parameters from muon decay

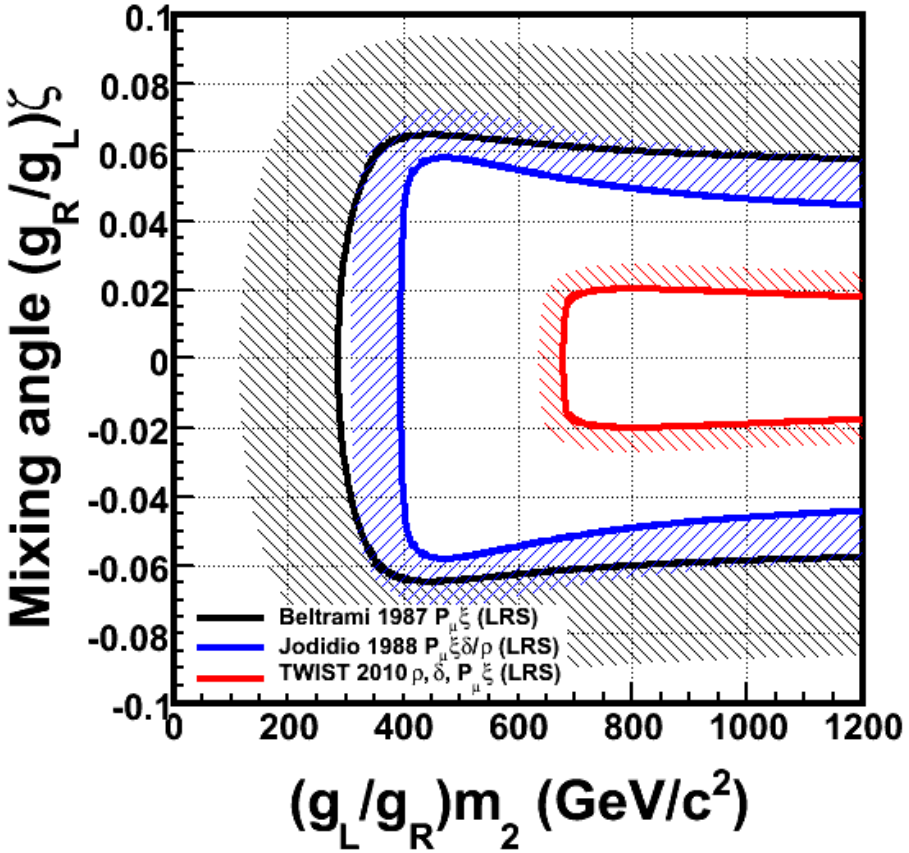
Restricted ("manifest") LRS



$m_2 > 684$ GeV/c^2

$-0.019 < \zeta < +0.010$

General LRS



$(g_L/g_R)m_2 > 684$ GeV/c^2

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

Summary

- Total uncertainties were reduced by factors of **8.7**, **11.6**, and **7.0** for ρ, δ, and $\mathcal{P}_\mu\xi$ respectively, roughly achieving the goals of the experiment.
- Differences with Standard Model predictions are respectively **-0.3**σ, **+2.2**σ, and **+1.2**σ.
- We cannot yet explain the more significant deviation of $\mathcal{P}_\mu\xi\delta/\rho$ above the limit of 1.0.

TWIST Participants

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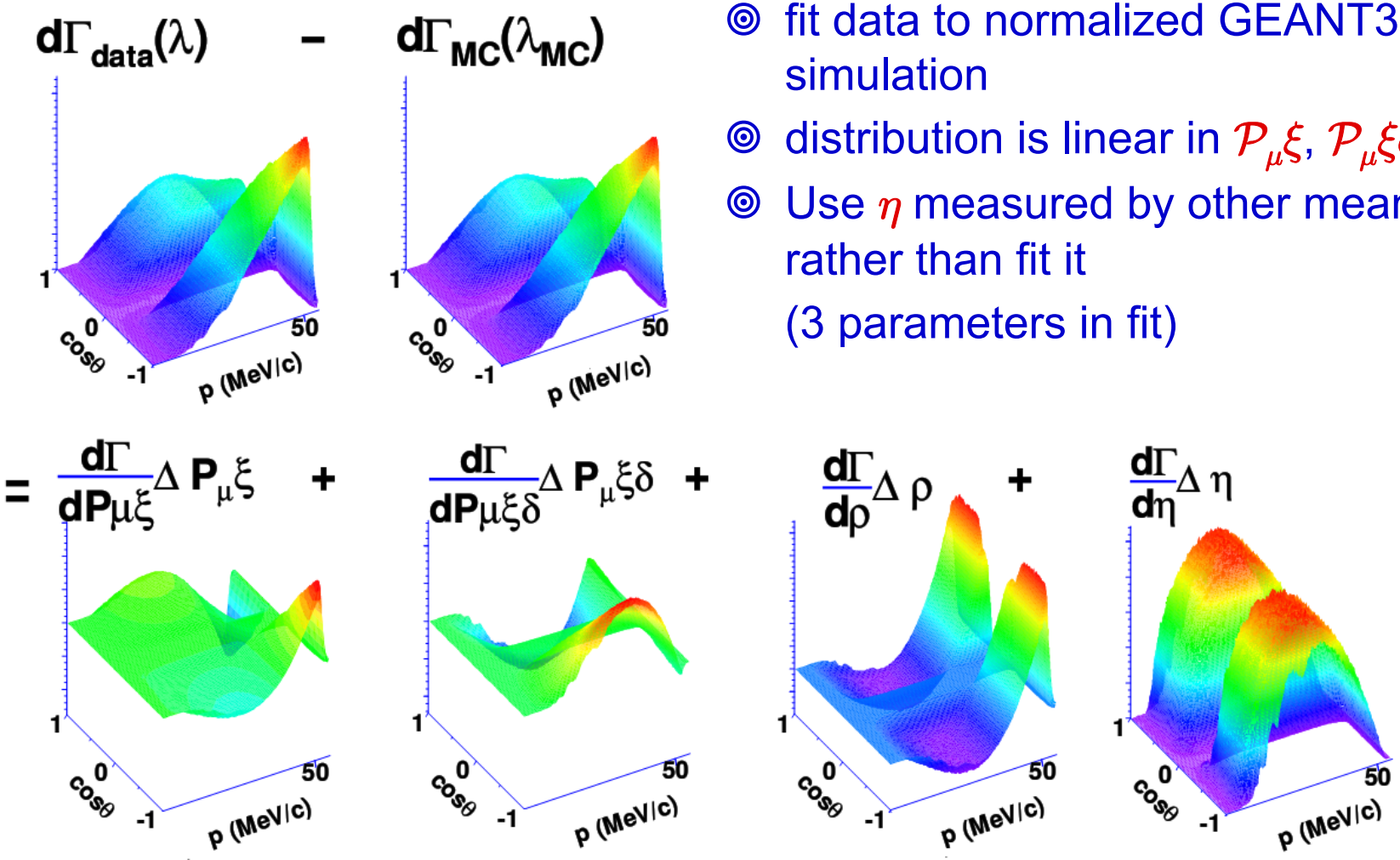
Valparaiso
Don Koetke
Shirvel Stanislaus

∗ Graduate student
∗∗ Graduated
† also U Vic
‡‡ also Saskatchewan
§ deceased

Extras

Analysis: fit to simulation



- fit data to normalized GEANT3 simulation
- distribution is linear in $\mathcal{P}_\mu\xi$, $\mathcal{P}_\mu\xi\delta$, ρ, η
- Use η measured by other means, rather than fit it

  (3 parameters in fit)

Corrections to fitted data

- For $\mathcal{P}_\mu \xi$ only:
  - Depolarization from scattering in production target
    - $+0.9 \times 10^{-4}$ for full momentum sets, $+5.6 \times 10^{-4}$ for reduced momentum sets.
  - Simulations generated with incorrect polarization relaxation rate
    - $+2.9 \times 10^{-4}$ for Ag sets, $+2.4 \times 10^{-4}$ for Al sets
- Statistical biases, all parameters:
  - 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
    - MCfit biases of order 0.5×10^{-4}
    - Energy calibration fit bias of $\sim (-1.1, -0.4, +1.9) \times 10^{-4}$, set-by-set

Muon decay parameters and coupling constants

$$\rho = \frac{3}{4} - \frac{3}{4}[\left|g_{RL}^{V}\right|^2 + \left|g_{LR}^{V}\right|^2 + 2\left|g_{RL}^{T}\right|^2 + 2\left|g_{LR}^{T}\right|^2 + \mathbb{R}e\left(g_{RL}^{S}g_{RL}^{T*} + g_{LR}^{S}g_{LR}^{T*}\right)]$$

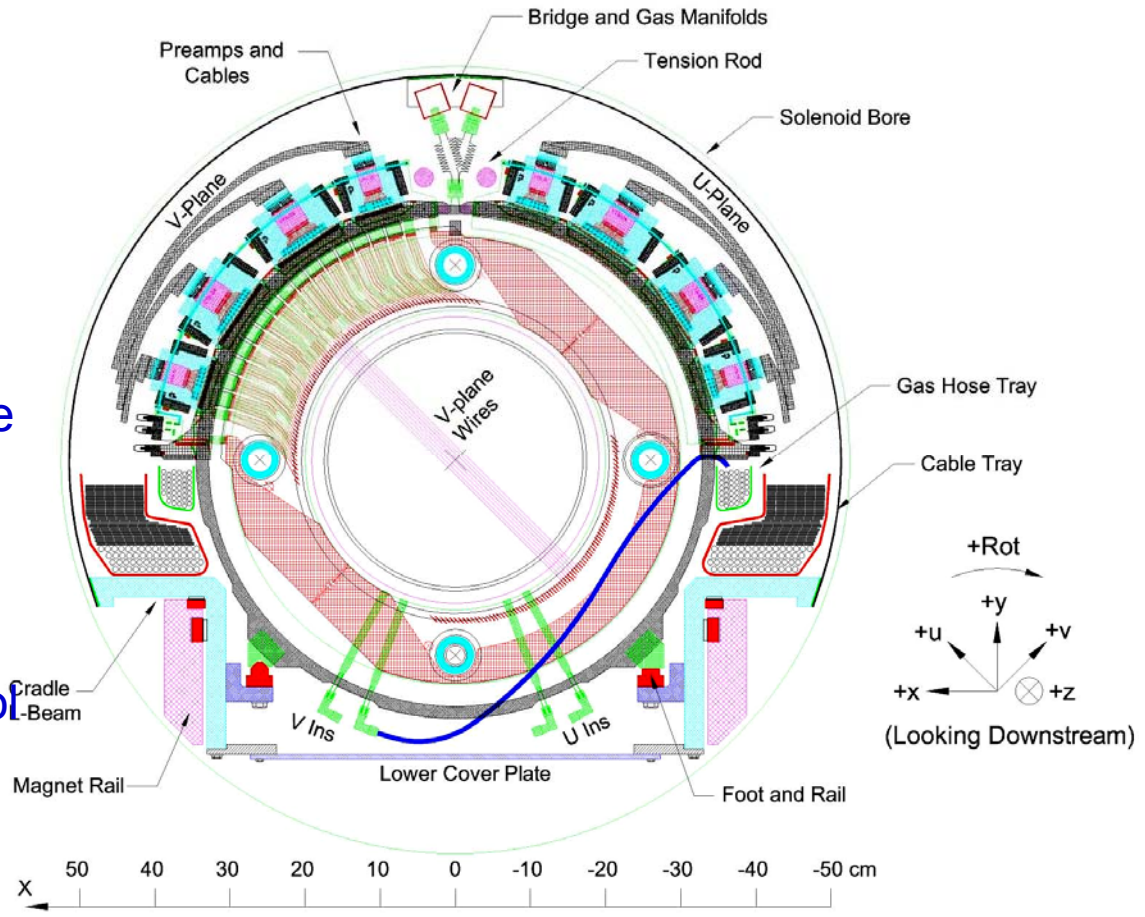
$$\eta = \frac{1}{2}\mathbb{R}e[g_{RR}^{V}g_{LL}^{S*} + g_{LL}^{V}g_{RR}^{S*} + g_{RL}^{V}(g_{LR}^{S*} + 6g_{LR}^{T*}) + g_{LR}^{V}(g_{RL}^{S*} + 6g_{RL}^{T*})]$$

$$\xi = 1 - \frac{1}{2}\left|g_{LR}^{S}\right|^2 - \frac{1}{2}\left|g_{RR}^{S}\right|^2 - 4\left|g_{RL}^{V}\right|^2 + 2\left|g_{LR}^{V}\right|^2 - 2\left|g_{RR}^{V}\right|^2 + 2\left|g_{LR}^{T}\right|^2 - 8\left|g_{RL}^{T}\right|^2 + 4\mathbb{R}e(g_{LR}^{S}g_{LR}^{T*} - g_{RL}^{S}g_{RL}^{T*})$$

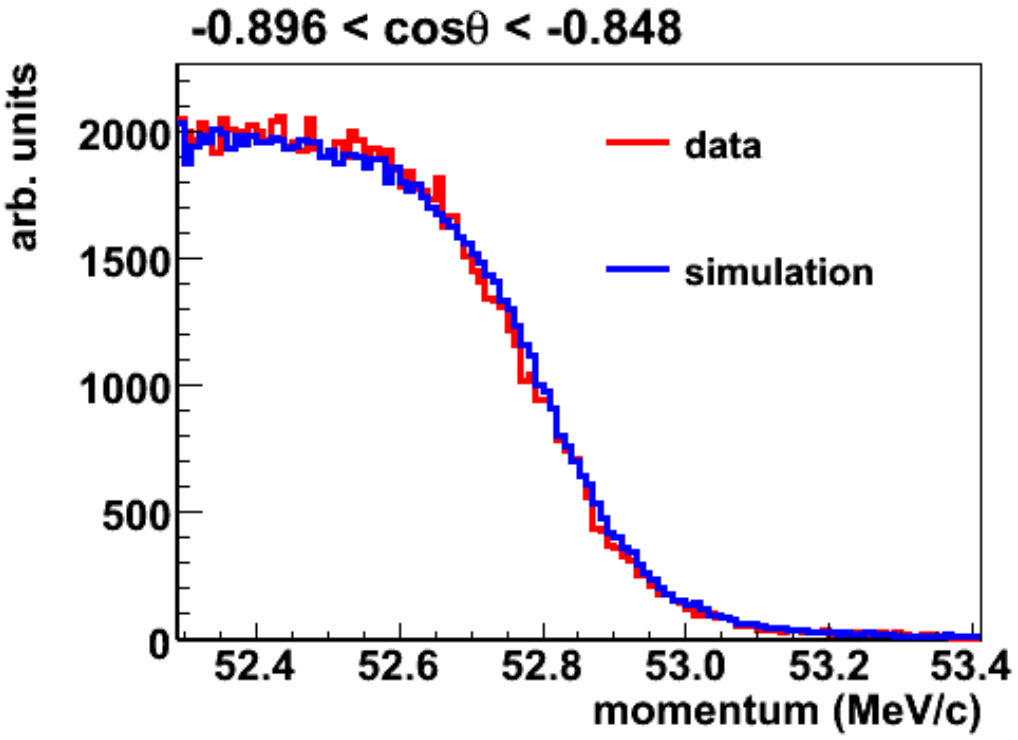
$$\xi\delta = \frac{3}{4} - \frac{3}{8}\left|g_{RR}^{S}\right|^2 - \frac{3}{8}\left|g_{LR}^{S}\right|^2 - \frac{3}{2}\left|g_{RR}^{V}\right|^2 - \frac{3}{4}\left|g_{RL}^{V}\right|^2 - \frac{3}{4}\left|g_{LR}^{V}\right|^2 - \frac{3}{2}\left|g_{RL}^{T}\right|^2 - 3\left|g_{LR}^{T}\right|^2 + \frac{3}{4}\mathbb{R}e(g_{LR}^{S}g_{LR}^{T*} - g_{RL}^{S}g_{RL}^{T*})$$

Detector precision

- Longitudinal precision of wire planes: 30 μm over 1 m detector length
  ➔ **3×10^{-5}**
- Transverse precision of wire spacing: 3.3 μm rms for 4 mm cell size
  ➔ **8×10^{-4}**
- Low mass < 0.1 g/cm^2 /side
- Field uniformity:
  ➔ **4×10^{-3}**
- Field map precision:
  ➔ **5×10^{-5}**
- Slow control monitor/control (e.g., dipole fields, temperature, atmospheric pressure)



Momentum calibration

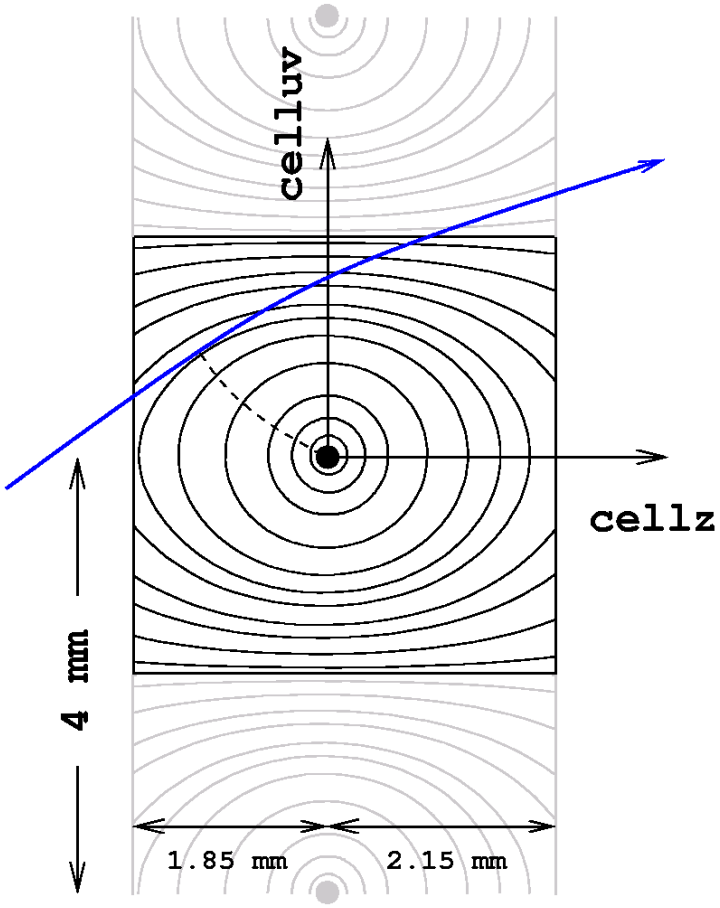


- Use kinematic edge at 52.8 MeV/c: energy loss and planar geometry lead to cosθ dependence.

- Difference of $\sim$10 keV/c prior to calibration.

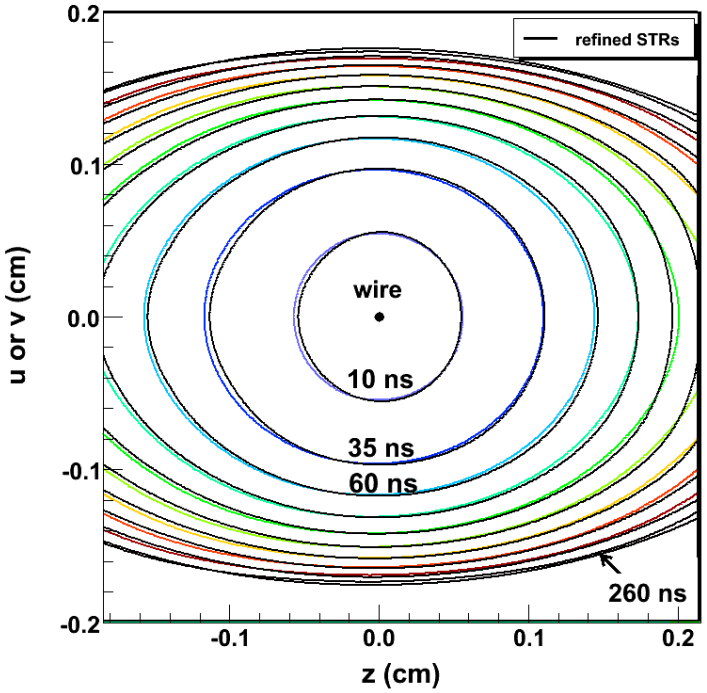
- Calibration at edge provides no guidance on how to propagate the difference to lower momenta in the spectrum.

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.



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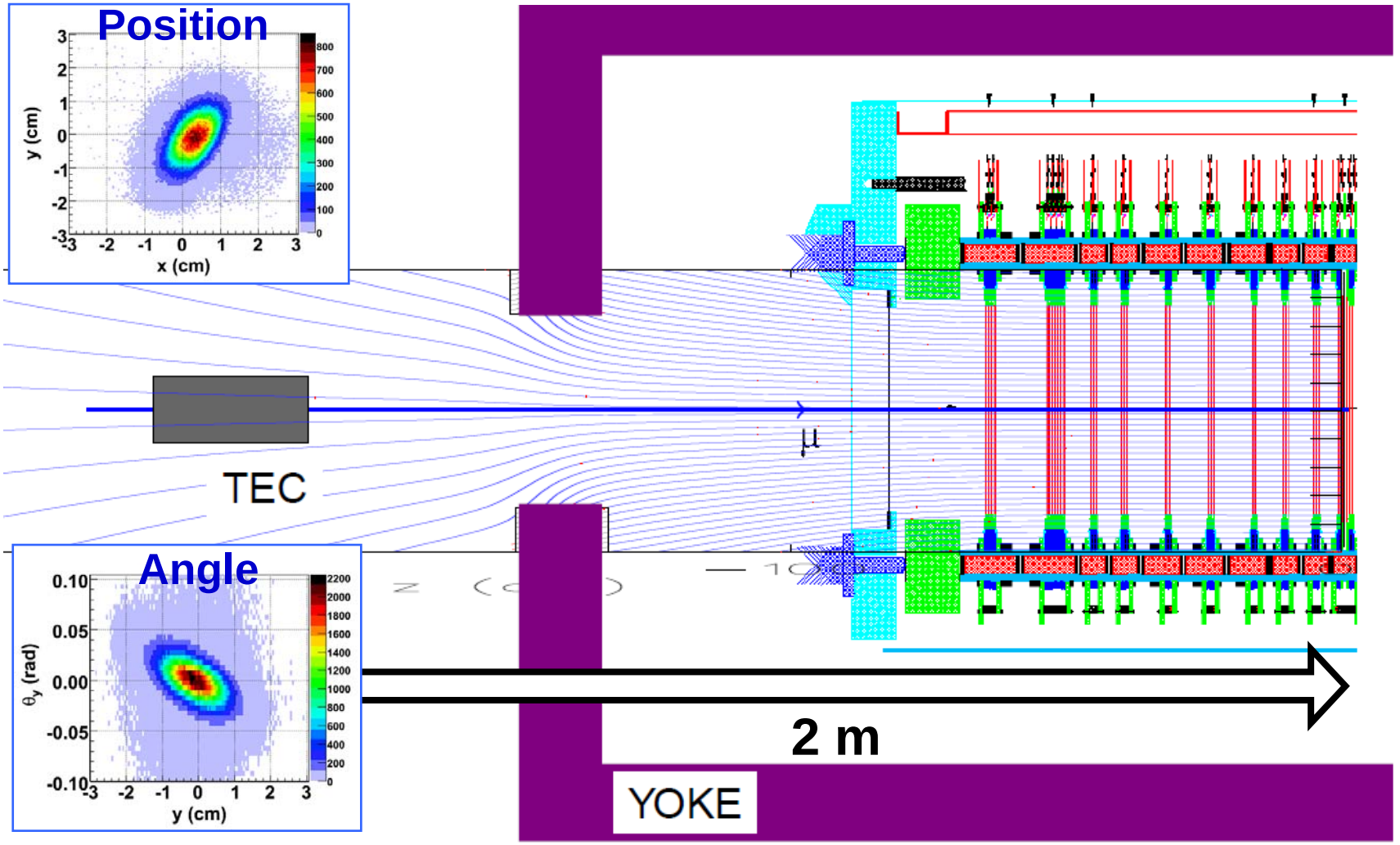
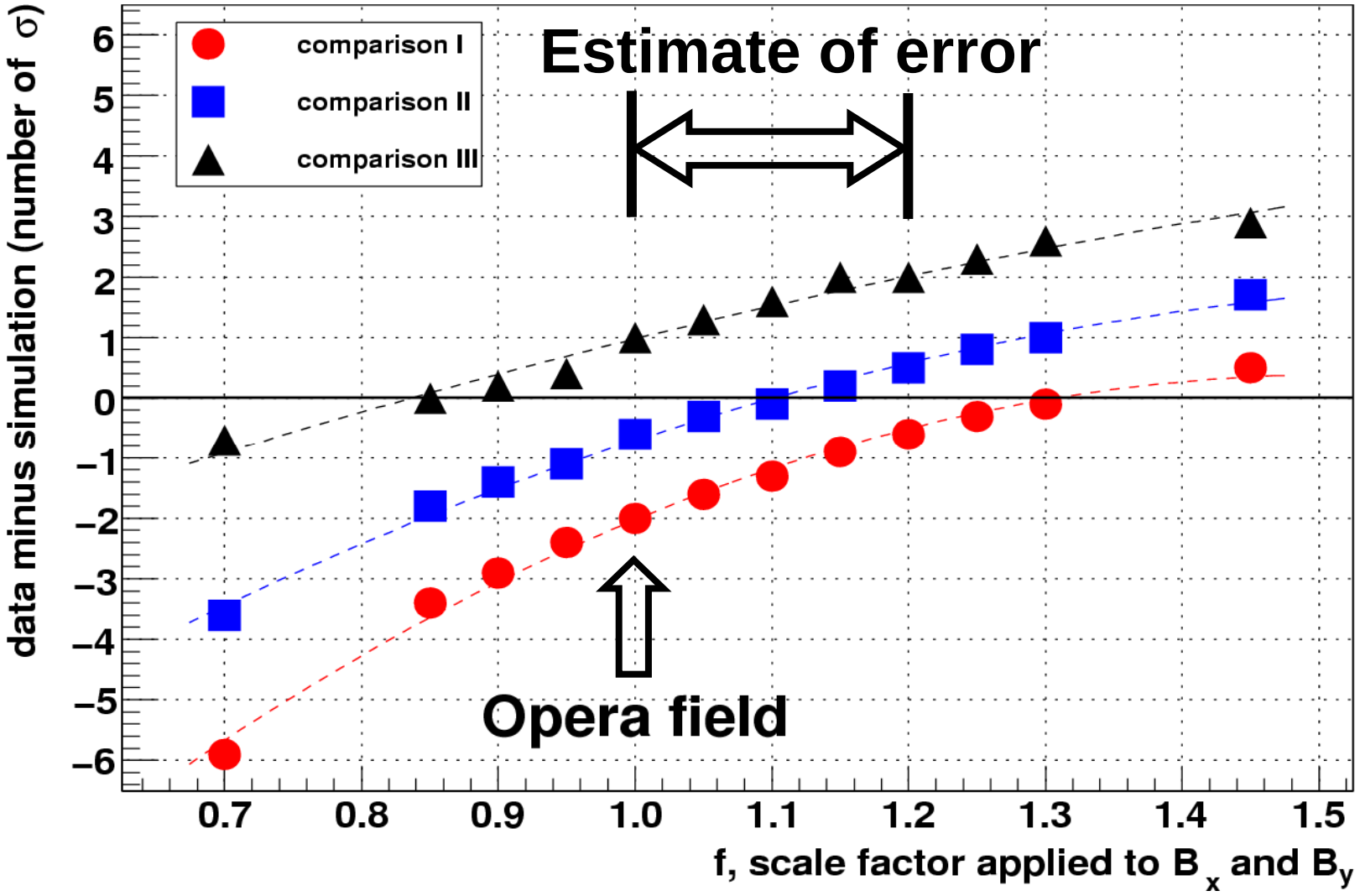
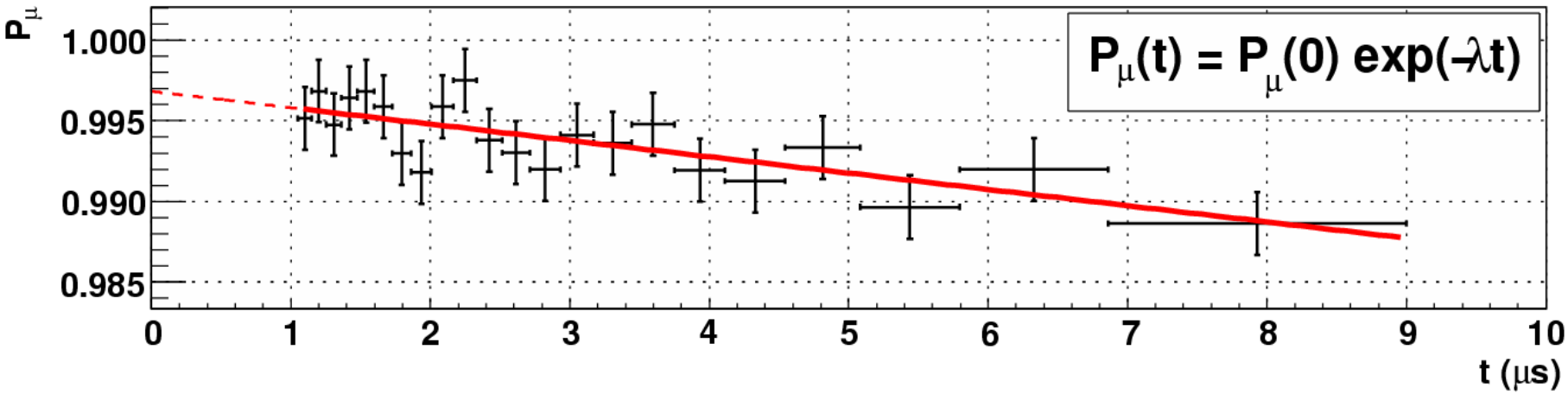
Fringe field, solenoid entrance



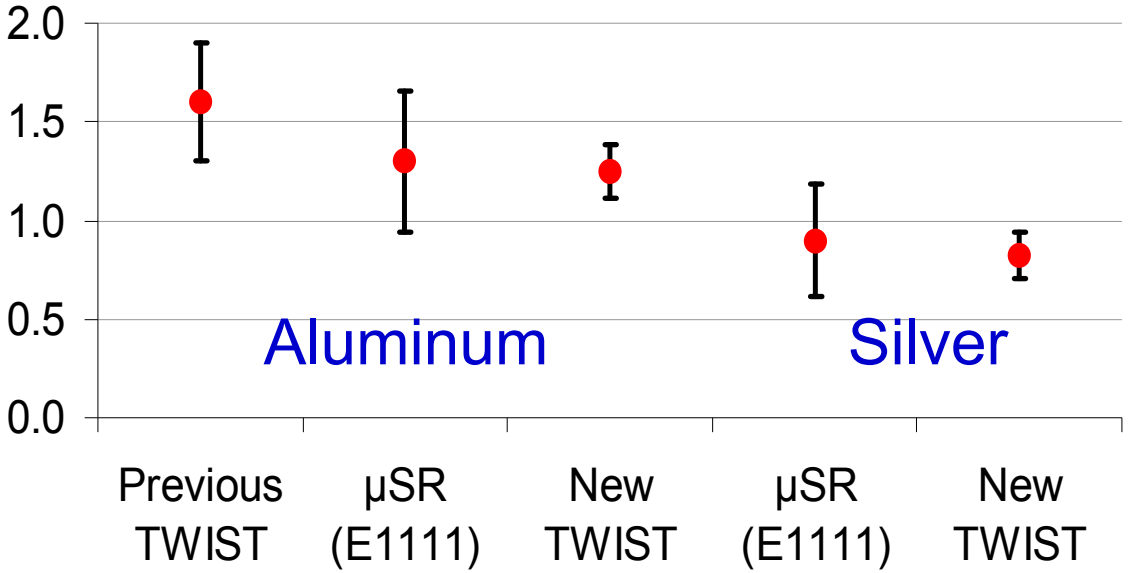
Estimating field component effects



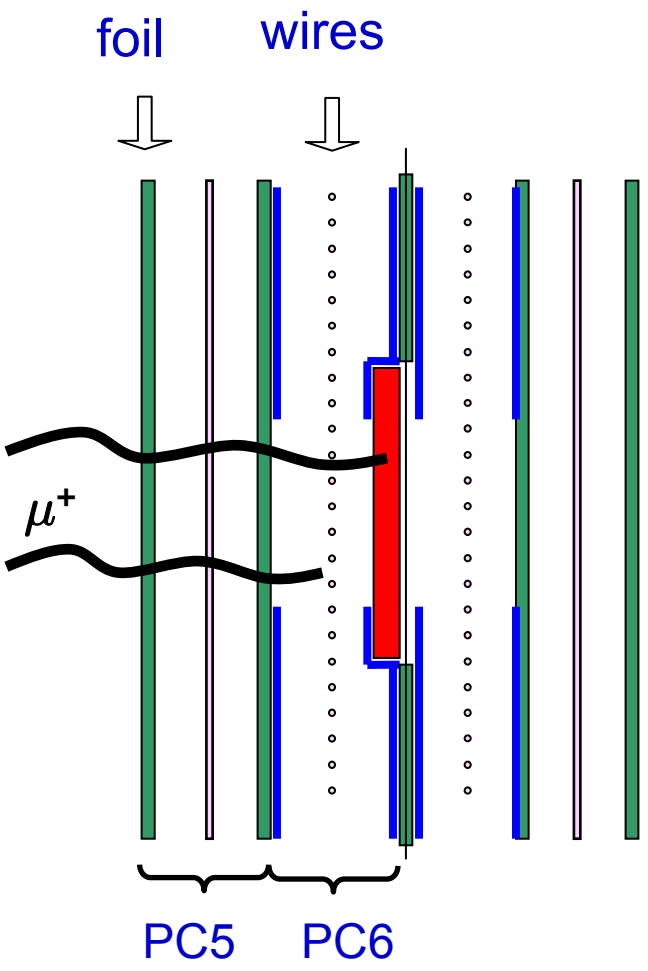
Depolarization in target material

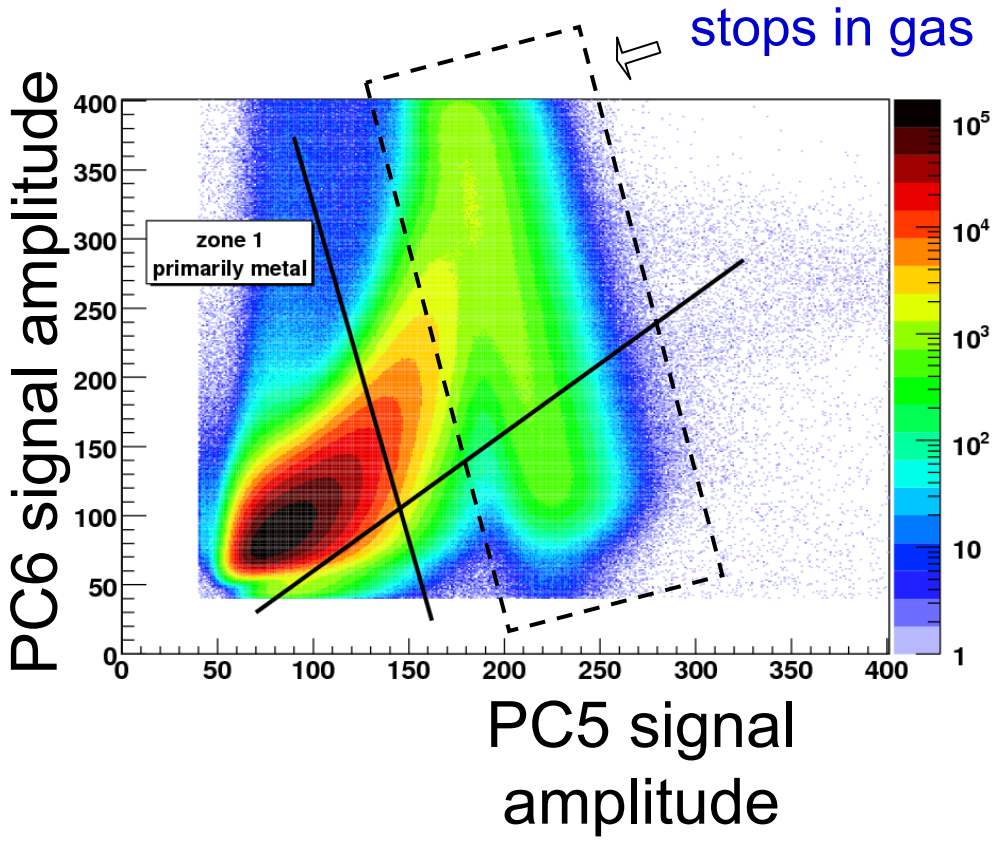


- Estimate of relaxation is included in simulation; small correction is made to polarization parameter.
- μSR experiment establishes no fast relaxation.
- Statistical uncertainty in λ is included in decay parameter statistical uncertainty.



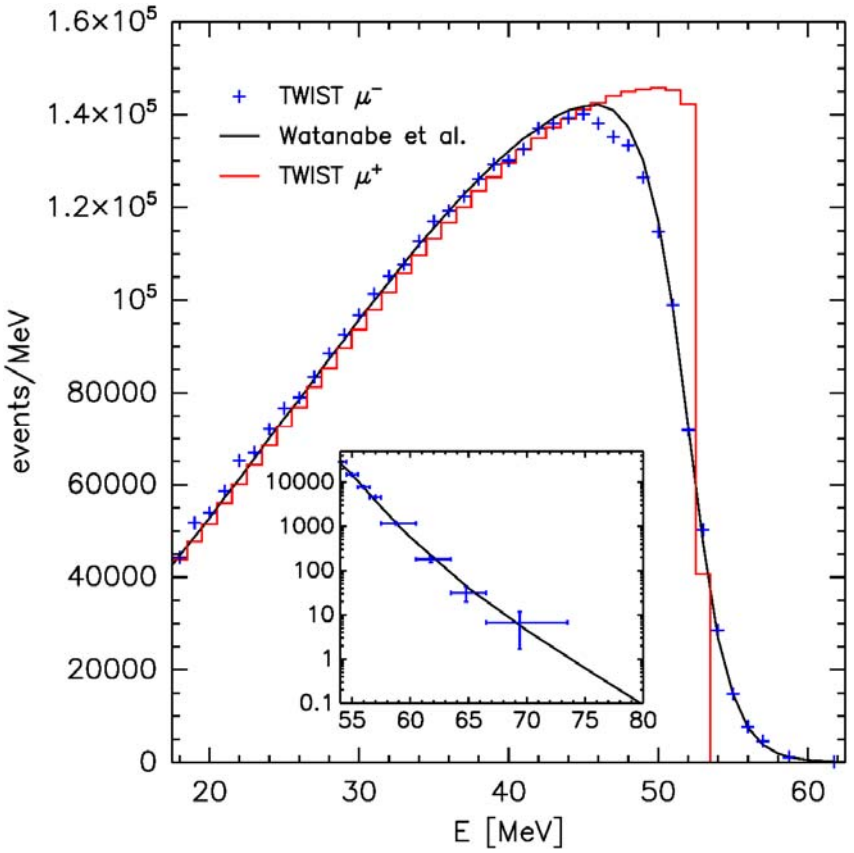
Selecting muons in metal target





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

Aside: electron spectrum from μ^-Al



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

- 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 μe conversion signal)
  - mismatch near peak and excess events at lower energies
  - O(α) corrections explain shape