Polarized muon decay asymmetry measurement: status and challenges

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Muon Physics in the LHC Era
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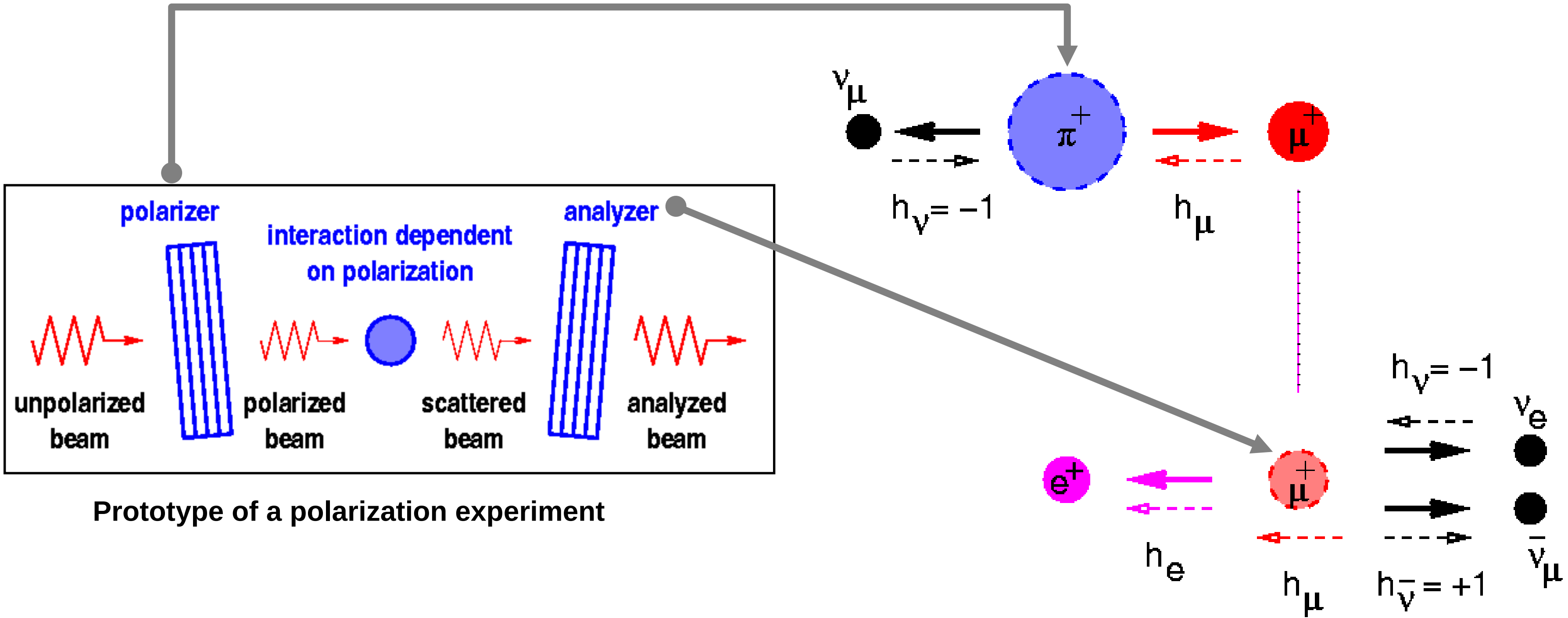
Outline

- Origin of the asymmetry
- Prior results, *TWIST* and other experiments
- Depolarization and asymmetry
  - experimental features important for $\mathcal{P}_\mu\xi$ measurement
  - simulation methods and tests
  - fringe field depolarization and beam characterization
  - stopping target depolarization
  - other issues: detector response and symmetry
  - expectations for final precision
- Application of decay asymmetry for SM tests
- Summary: what are the limitations for *TWIST*?

Pion decay: the “polarizer”



Prototype of a polarization experiment

- For SM with massless ν:
  - RH anti-ν (LH ν) and μ^- (μ^+) result when π^- (π^+) decay.
  - μ^+ created with $\mathcal{P}_\mu \equiv \mathcal{P}_\mu^\pi$ = -1.0 *with respect to muon momentum.*

Asymmetric decay: the “analyzer”

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

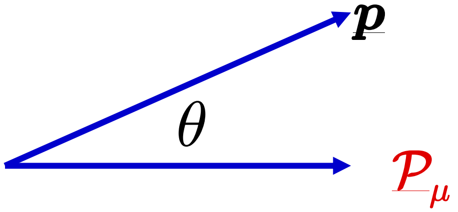
$$\frac{d^2\Gamma}{dx\; d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2}\,\cdot$$
$$\left\{\mathcal{F}_{IS}(x,\rho,\eta) + \cos\theta \left(\boxed{\mathcal{P}_\mu \mathcal{F}_{AS}(x,\xi,\delta)}\right)\right\} + R.C.$$

  - where

$$\mathcal{F}_{IS}(x,\rho,\eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\sqrt{x^2 - x_0^2}\left[\xi\{1-x\} + \frac{2}{3}\xi\delta\left\{4x - 3 + \left(\sqrt{1-x_0^2} - 1\right)\right\}\right]$$

  - and

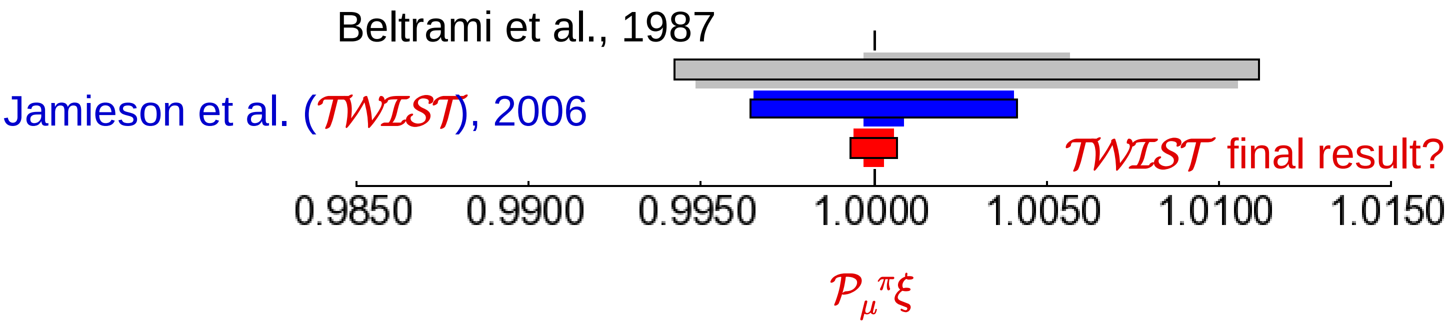
$$W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu},\; x = \frac{E_e}{W_{\mu e}},\; x_0 = \frac{m_e}{W_{\mu e}}.$$



Results to date

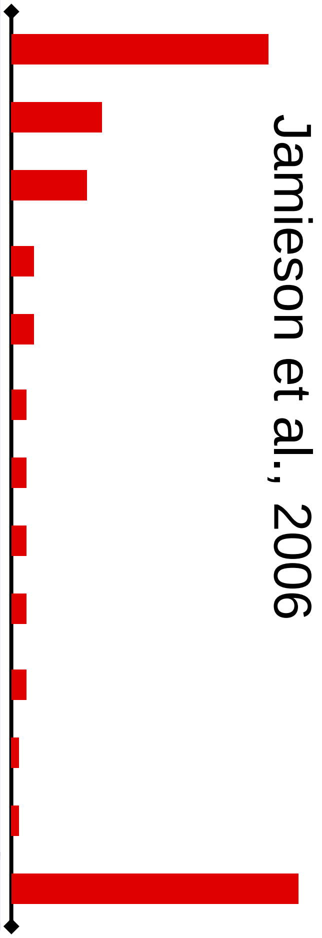
- “Direct” measurements:
  - $\mathcal{P}_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$ (Beltrami *et al.*, 1987)
  - $\mathcal{P}_\mu\xi = 1.0003 \pm 0.0006(\text{stat}) \pm 0.0038(\text{sys})$ (TWIST, Jamieson et al., 2006)

    (TWIST precision goal: <0.0008)
- “Indirect” from $\mathcal{P}_\mu(\xi\delta/\rho) > 0.99682$ (Jodidio *et al.*, 1986)
  - $0.9960 < \mathcal{P}_\mu\xi < 1.0040$ (TWIST, Gaponenko et al., 2006)
  - $0.99524 < \mathcal{P}_\mu\xi < 1.00091$ (TWIST, MacDonald et al., 2006)

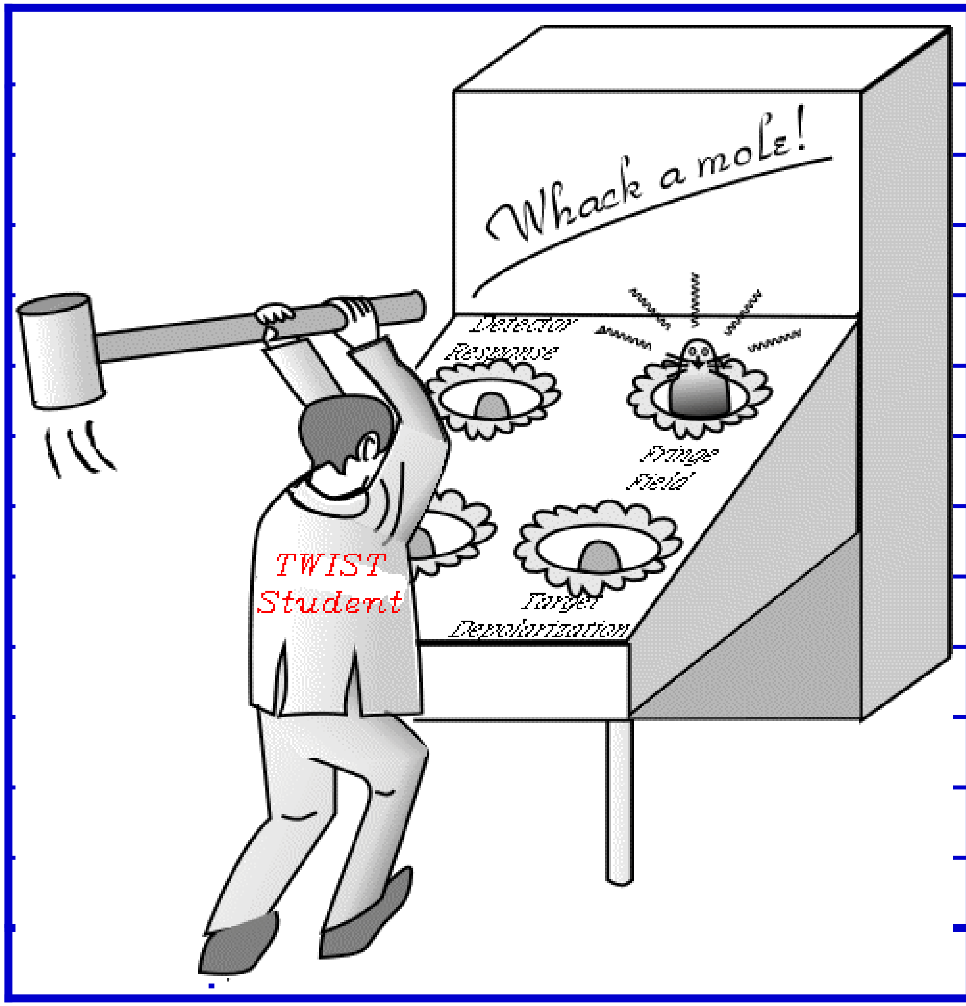


Systematics for *TWIST* result

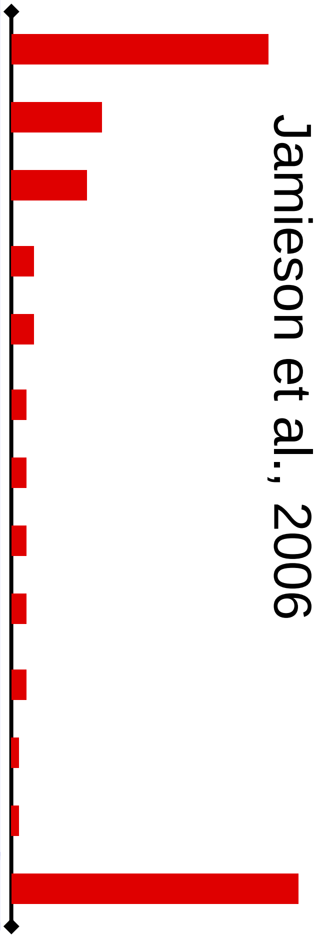
Systematic uncertainties	$\mathcal{P}_\mu \xi$ (× 10^{-4})
Depolarization in fringe field (ave)	34
Depolarization in muon stopping material (ave)	12
Chamber response (ave)	10
Spectrometer alignment	3
Positron interactions (ave)	3
Depolarization in muon production target	2
Momentum calibration	2
Upstream-downstream efficiency	2
Background muon contamination (ave)	2
Beam intensity (ave)	2
Decay η parameter	1
Theoretical radiative correction	1
Total in quadrature	**38**



Systematics for *TWIST* result



$\mathcal{P}_\mu\xi$ (× 10^{-4})
34
12
10
3
3
2
2
2
2
2
1
1
38



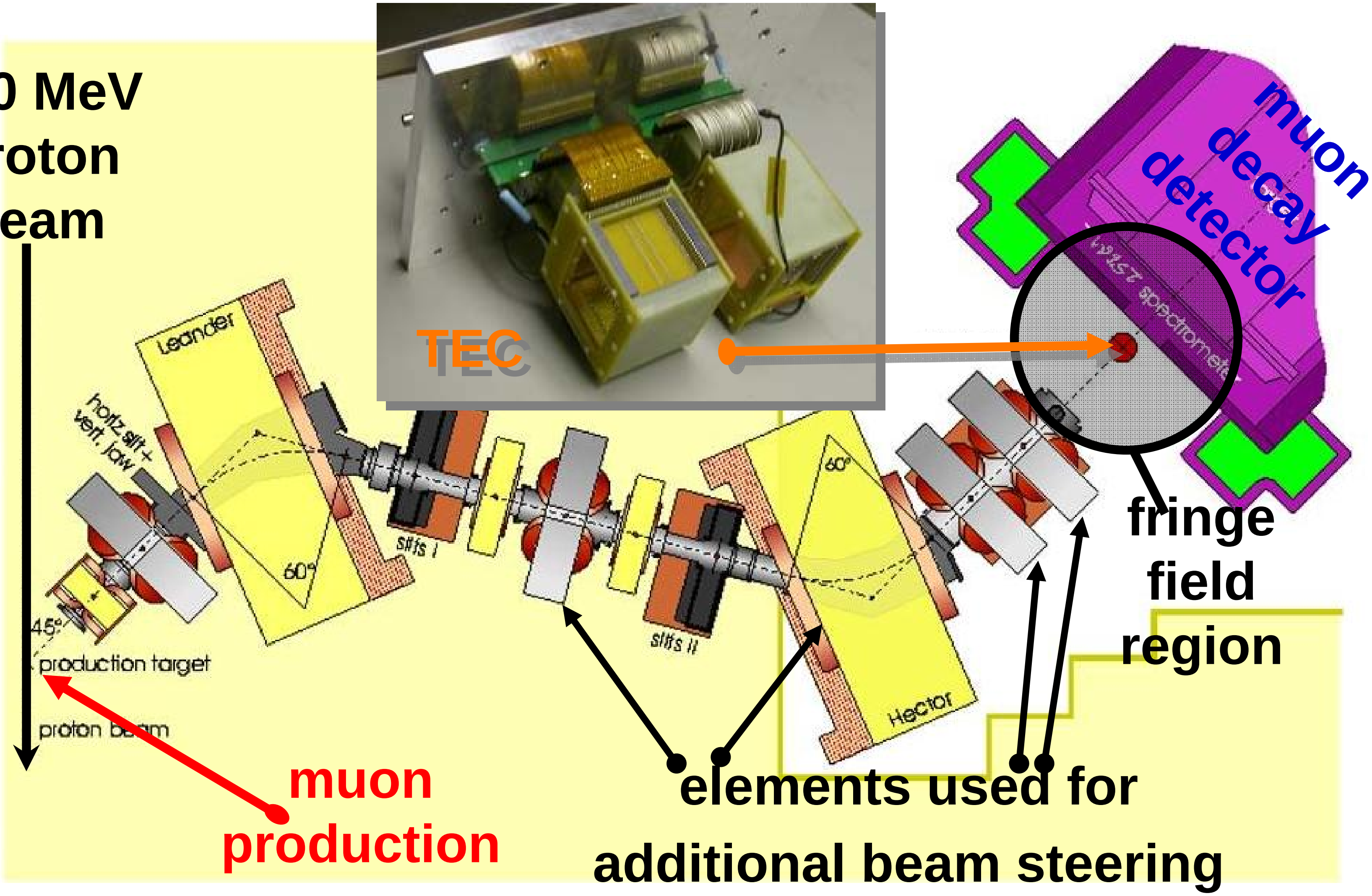
Jamieson et al., 2006

Depolarization and asymmetry

Two classes of systematic uncertainty:

- Depolarization: relate $\mathcal{P}_\mu$ at decay to $\mathcal{P}_\mu^\pi$ at production
  - $\mathcal{P}_\mu$ impossible to measure via decay, independent of ξ .
    - “polarizer” and “analyzer” depend on weak interaction.
  - Two main sources
    - fringe field – requires ***accurate field model*** and ***simulation*** of beam characteristics, motion: $\mathcal{P}_\mu < \mathcal{P}_\mu^\pi$
    - stopping target – spin interactions with high-purity metal (Al, Ag) lead to small time-dependence and ***extrapolation***: $\mathcal{P}_\mu = \mathcal{P}_\mu^\circ \, e^{-\lambda t}$.
- Asymmetry
  - Detector asymmetries (chamber response and efficiency, material interactions, alignment).

Muon production and transport



500 MeV proton beam

TEC

muon decay detector

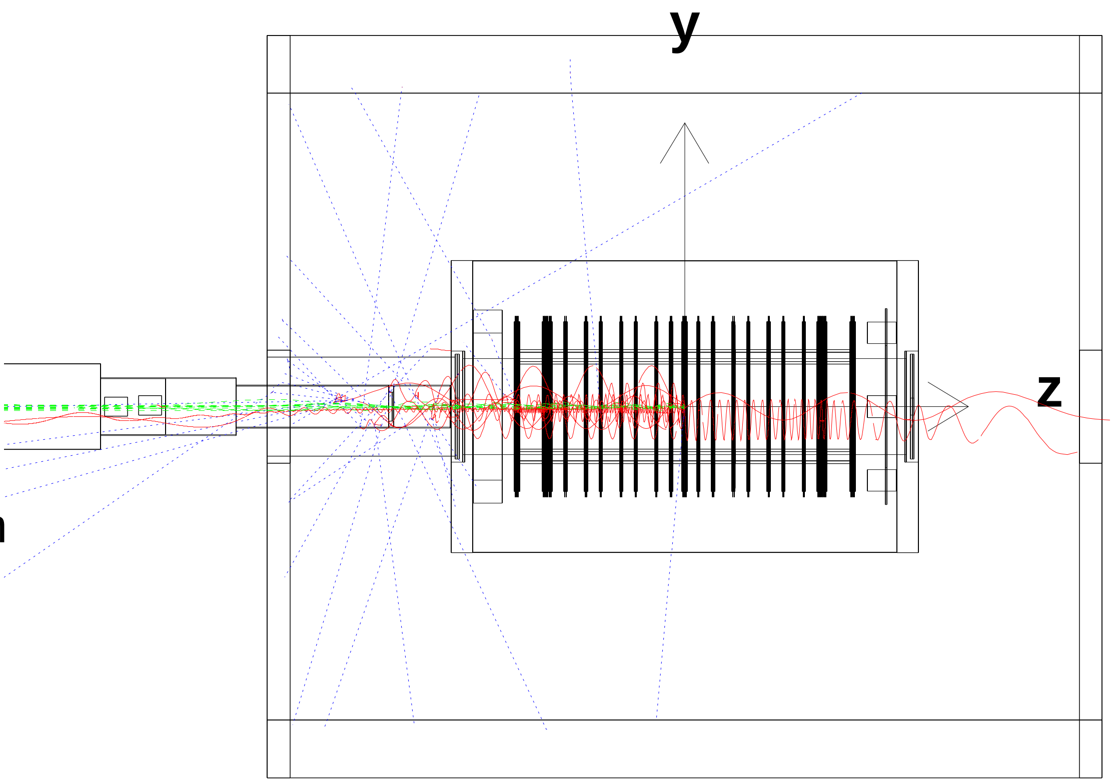
fringe field region

muon production

elements used for additional beam steering

Simulation quality is essential

- Simulation based on GEANT3
- contains:
    - precise geometry
    - output format same as data
    - Thomas-BMT spin tracking
    - muons sampled from data distributions
- verified via:
    - special data sets
    - special analyses of standard sets
    - comparison to G4



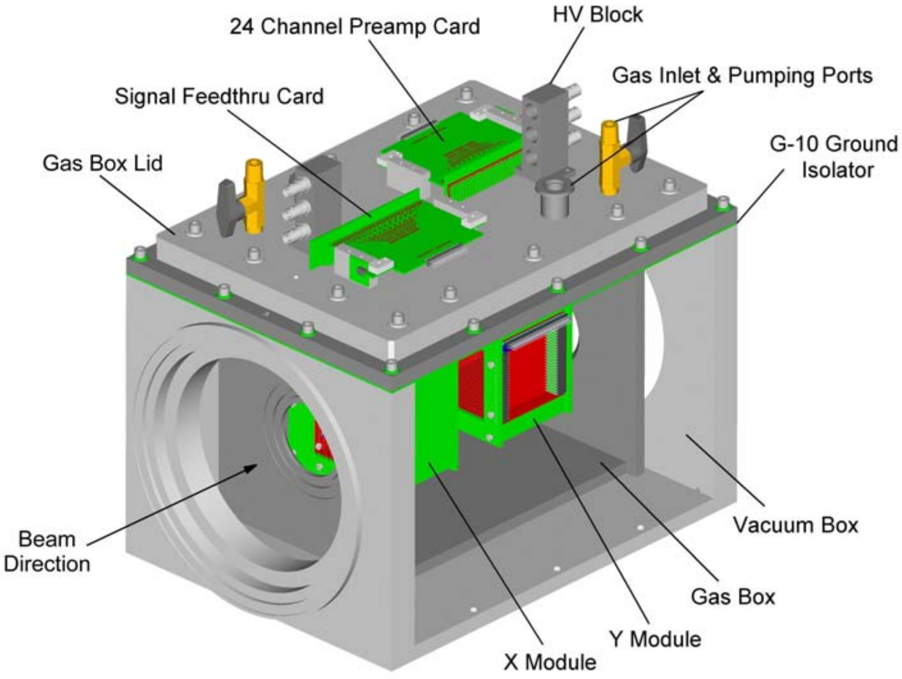
Ten muon decay events *simulated* in the *TWIST* detector.

Fringe field depolarization

- The problem:
  - For SM with massless ν, μ^+ produced with $|\mathcal{P}_\mu| \equiv |\mathcal{P}_\mu^\pi| = 1$ *with respect to muon momentum.*
  - $\langle\mathcal{P}_\mu\rangle$ *with respect to physical axis* (beam direction, magnetic field) is less, due to finite beam acceptance (angular divergence).
  - effective $\langle\mathcal{P}_\mu\rangle$ of a muon beam changes as beam divergence changes, e.g. due to $\mathcal{B}$ field in a beam line or detector.
- The *TWIST* solution:
  - *Simulate* μ^+ with $|\mathcal{P}_\mu^\pi| = 1$, in realistic $\mathcal{B}$ field, sampling from “measured” beam characteristics (position, divergence, momentum).
  - Apply Thomas equation (BMT) for spin evolution, GEANT3 physics processes (scattering, energy loss, *etc.*).
  - Carefully assess systematic effects due to limitations in field map, detector stability, beam size and stability, simulation precision, ...

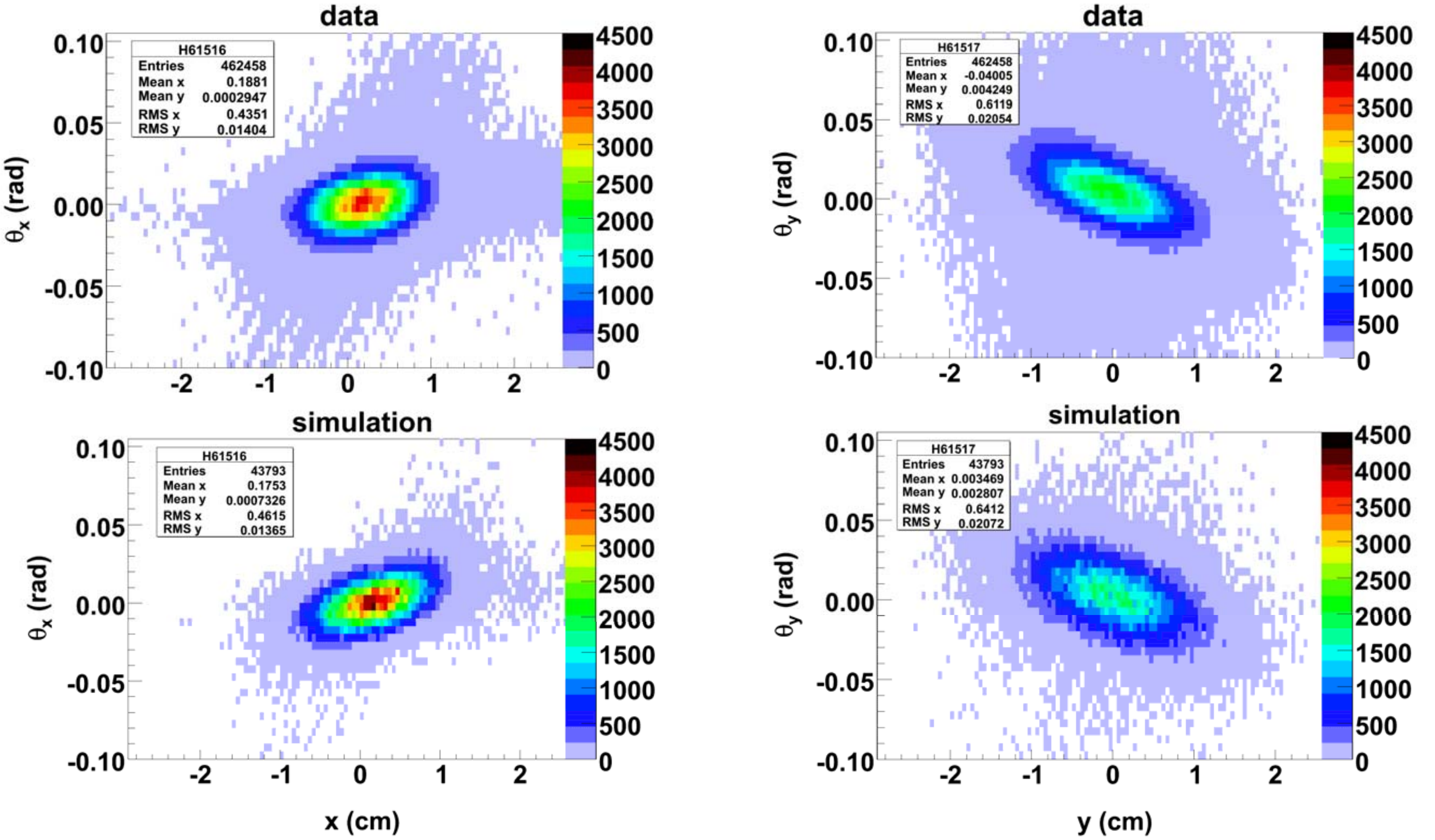
Measuring beam characteristics

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



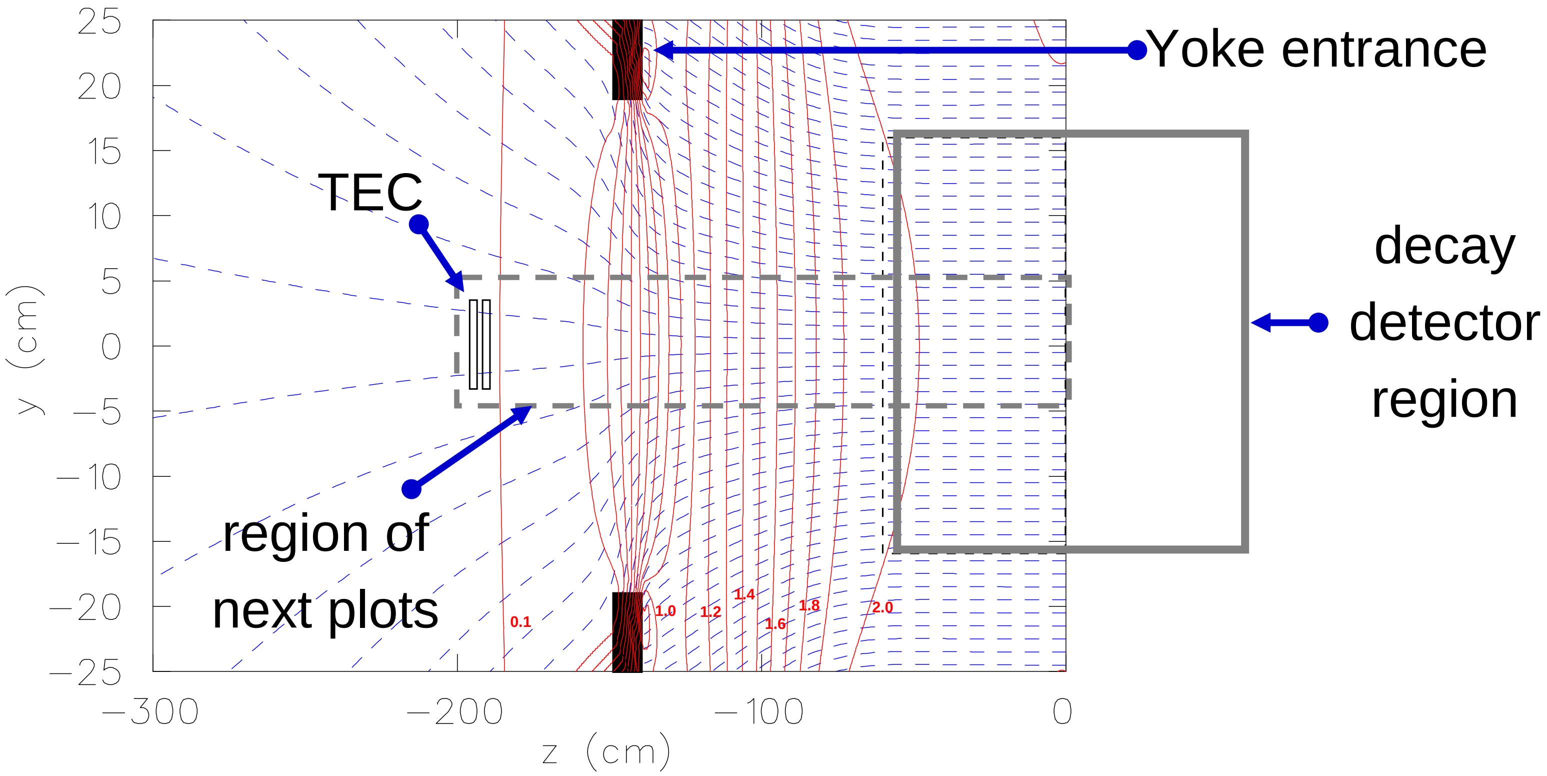
J. Hu et al., NIM A566 (2006) 563-574

Simulating the muon beam



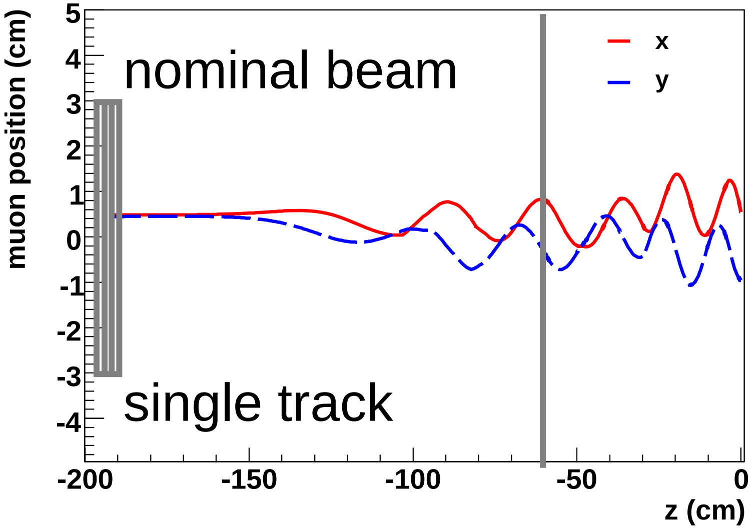
Comparison of TEC data and corresponding simulation of beam profiles

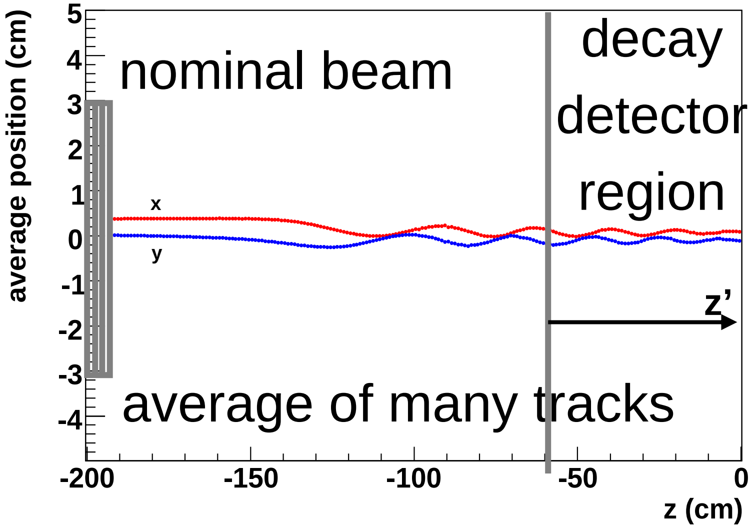
Fringe field, solenoid entrance

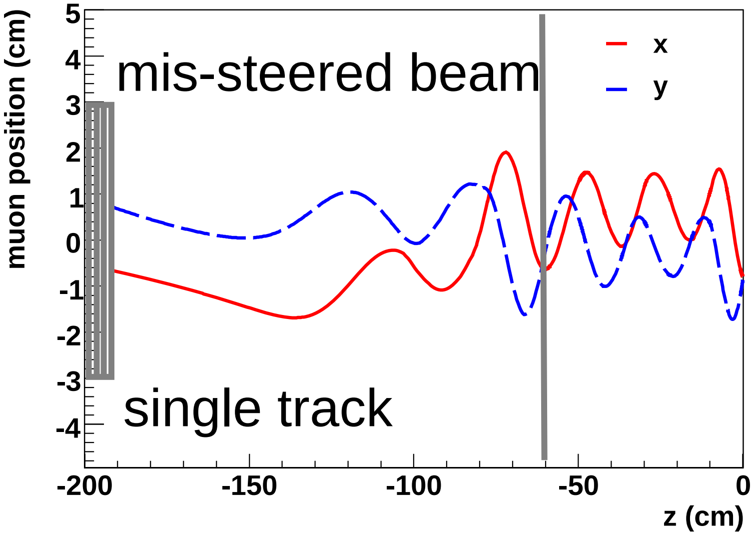


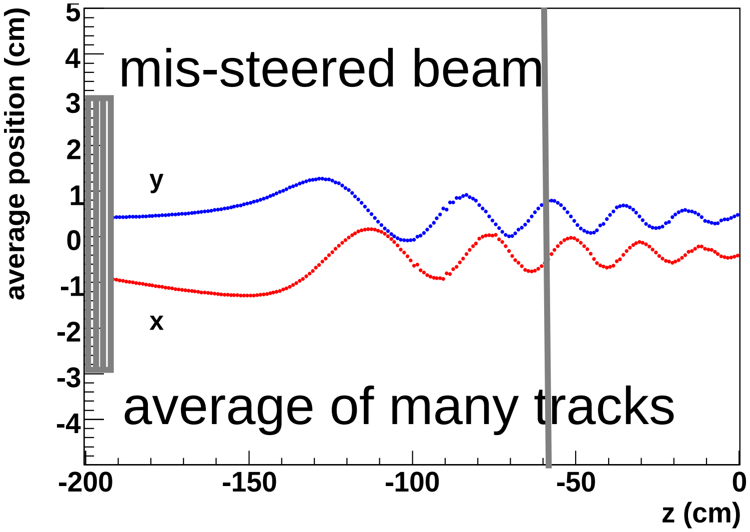
The central field is 2 T, with a strong gradient near the solenoid yoke entrance.
Muon tracks are measured by the TEC, to establish incident beam parameters.
Muons are also tracked in the upstream part of the decay detector

Muon entrance paths



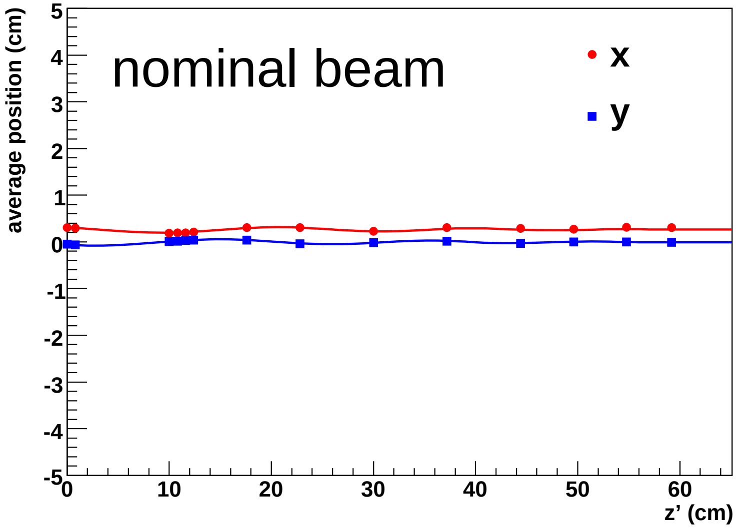


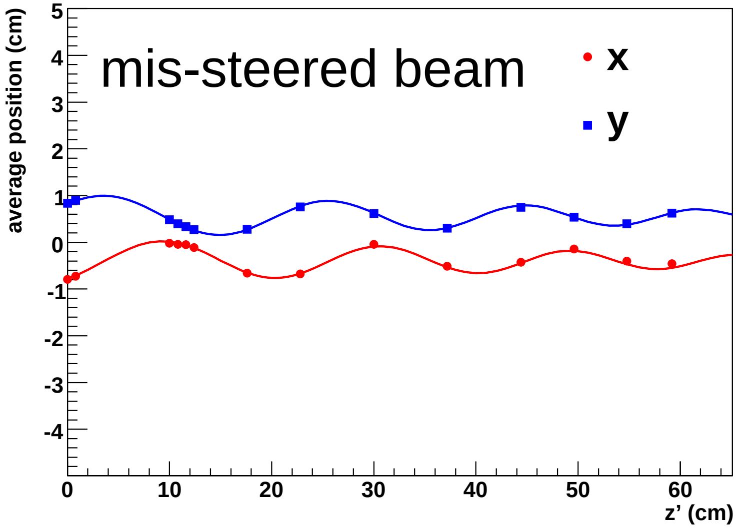




Measured average muon positions

plots courtesy of J. Bueno



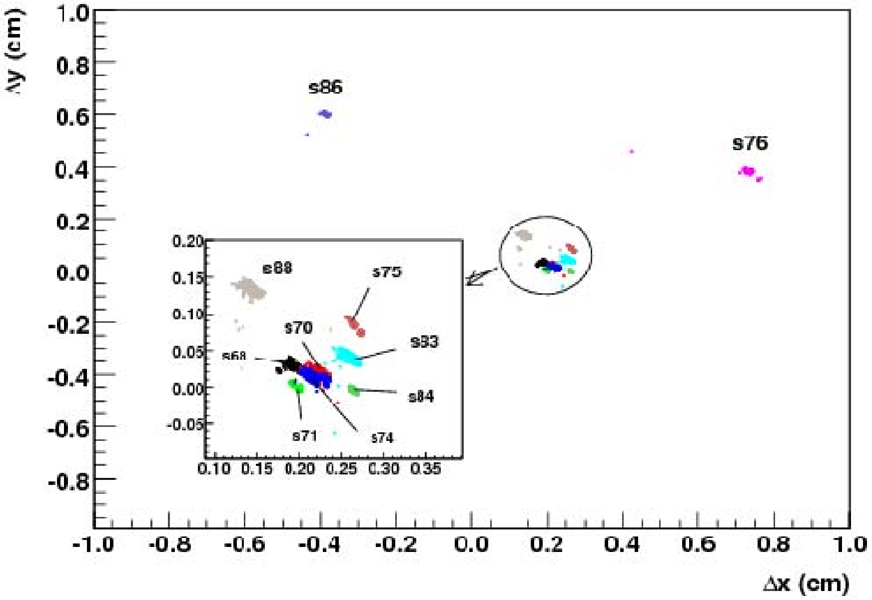


- Each point represents the average muon beam position at a detector plane.
- Simulated data can be analyzed in the same way.
- Fit both to "shrinking helix".
- Comparison of fits of data and simulation is a powerful way to verify the simulation, *e.g.* , influence of fringe field on muon beam, detector-field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

- ➔ Use "internal beam" to test fringe field depolarization limitations.

Muon beam in decay detector

- Average muon beam:
  - position (run-by-run) shows beam (in)stability.
  - Typical sets stable to ±0.03 cm. Outliers discarded.
- Internal beam parameters (position, amplitude, *etc.*) compared with simulation to verify effect of fringe field.
  - systematic uncertainties derived, especially from mis-steered sets.
- Data taken under different conditions: beam steering, stopping target material, solenoid field (± 2%), muon stop position, material in detector (symmetry), initial muon momentum.



Average position of helix, with respect to detector axis, for internal muon beam for all runs in each of ten data sets.
Set 76 and set 86 are intentionally mis-steered.

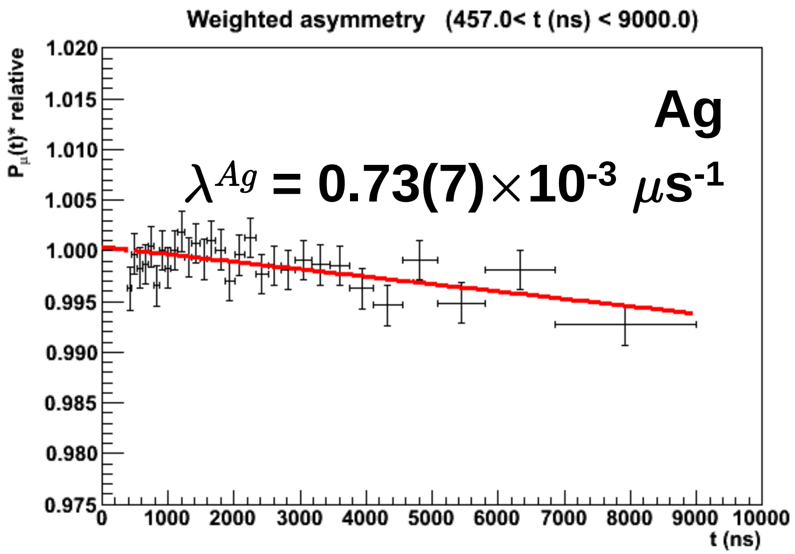
Depolarization in stopping target

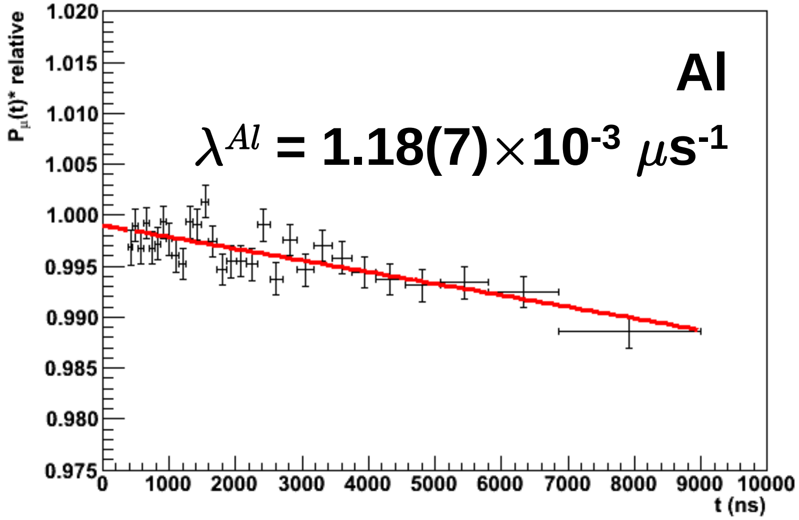
- " $\mu\mathcal{SR}$ " effect -- minimize by use of high-purity metal targets:
  - main mechanism at room temperature is via interaction with conduction electrons (Korringa relaxation), studied in $\mu\mathcal{SR}$ experiments.
  - asymmetry is a function of time: $\mathcal{P}_\mu(t) = \mathcal{P}_\mu^\circ\, exp(-\lambda t)$.
  - different targets, Al (76 μm) and Ag (28 μm) provide test of possible systematic bias.

- Stopping target forms anode of adjacent MWPC detectors:
  - energy loss (ionization charge) information discriminates against muons stopping in other detector materials, to reduce depolarization from
    - ($\mu^+ e^-$) formation (*e.g.* in MWPC gas, He), which depolarizes muons (depolarization also reduced by high longitudinal field).
    - chemical reactions (analogous to hydrogen atom).

Systematic correction for relaxation

- *TWIST* detector is a very powerful $\mu\mathcal{SR}$ device:
  - uniform field, excellent background rejection.
  - e^+ momentum available for weighting the asymmetry.
  - ... but not very versatile...
- Observed relaxation rate is included in the simulation:
  - accounts realistically for relaxation.
  - statistical uncertainty in λ is a source of target depolarization systematic uncertainty in $\mathcal{P}_\mu^\pi\xi$.





Other depolarization mechanisms?

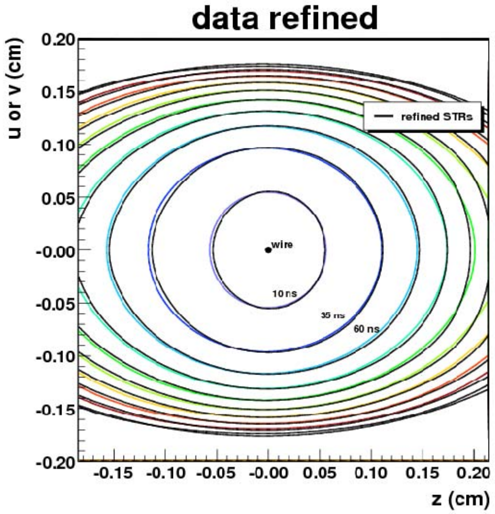
- Multiple muon scattering at exit of production target:
  - use narrow momentum range (29.4 – 29.8 MeV/c); small energy loss quantifies possible depolarization ($\sim 1\times10^{-4}$ systematic correction).
- Radiative processes in pion decay
  - calculated to be negligible for our kinematics.
- In-flight interactions with magnetic moments
  - “magnetic scattering”, estimated to be negligible.
- (g–2), laboratory $\underline{\mathcal{E}}$ fields, relativistic $\underline{\mathcal{E}}$ fields, non-zero neutrino mass
  - all estimated to be negligible.

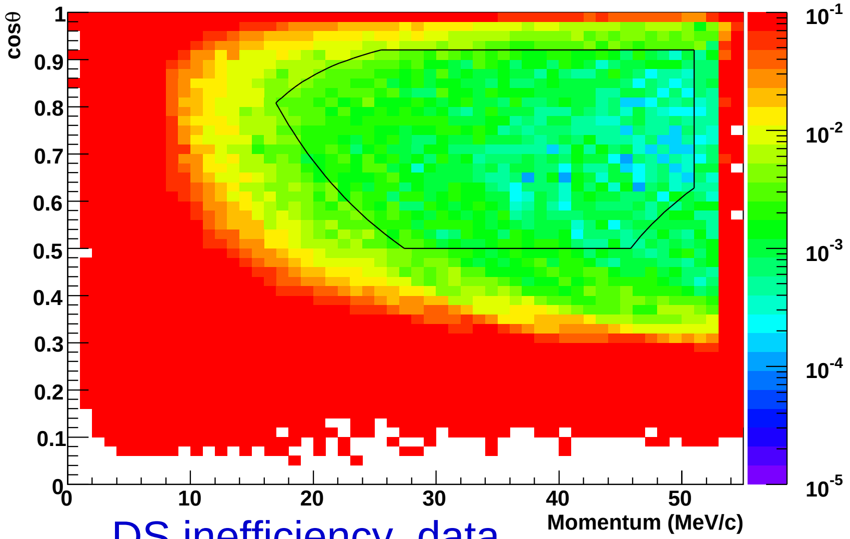
Chamber response

- Improvements benefit three parameters, ρ, δ, and $\mathcal{P}_\mu\xi$.
- Detector position response:
  - use drift chamber Space Time Relationships as determined from data, individually for each plane. Use same procedure with simulated data to reduce bias in fit of data to simulation.
- Upstream/Downstream tracking inefficiency differences:
  - Test with positrons from “Upstream stops”
  - tracking inefficiency difference between simulation and data:

$\sim 0.6(2)\times10^{-4}$ US

$\sim 0.3(2)\times10^{-4}$ DS.

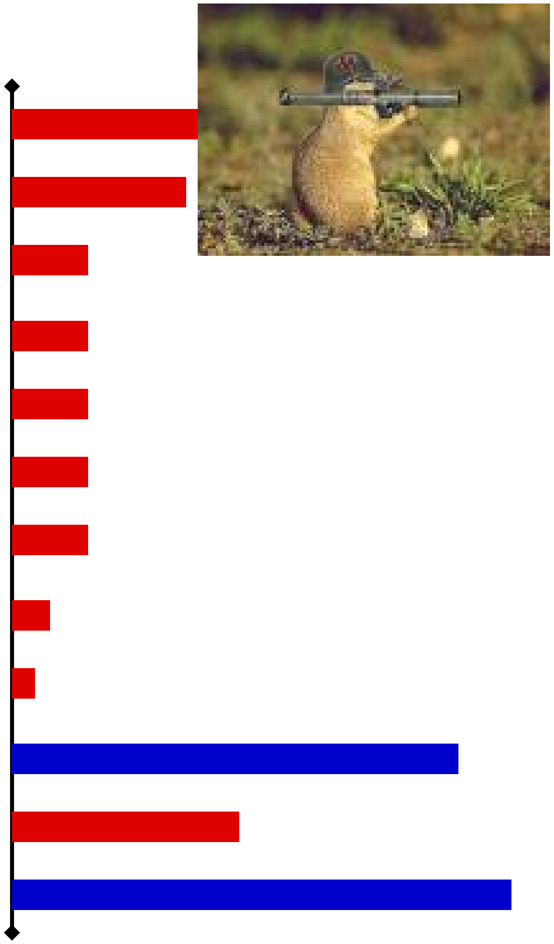




DS inefficiency, data

Preliminary estimates: final uncertainties

Systematic uncertainties	$\mathcal{P}_\mu \xi$ ($\times 10^4$)
Depolarization in fringe field (ave)	5.0
Depolarization in muon stopping material (ave)	2.3
Chamber response (ave)	1
Momentum calibration	1
Decay η parameter	1
Theoretical radiative correction	1
Positron interactions (ave)	1
Depolarization in muon production target	0.5
Upstream-downstream efficiency	0.3
Total systematic in quadrature	**6.0**
Statistical uncertainty	3.0
Total uncertainty in quadrature	***6.7***



Several of the previous systematic uncertainties are now too small to be included.

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. Use notation: $t = \frac{g_R^2 m_1^2}{g_L^2 m_2^2}$, $t_\theta = t\frac{|V^R_{ud}|}{|V^L_{ud}|}$, $\zeta_g^2 = \frac{g_R^2}{g_L^2}\zeta^2$

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

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

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

  - “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.

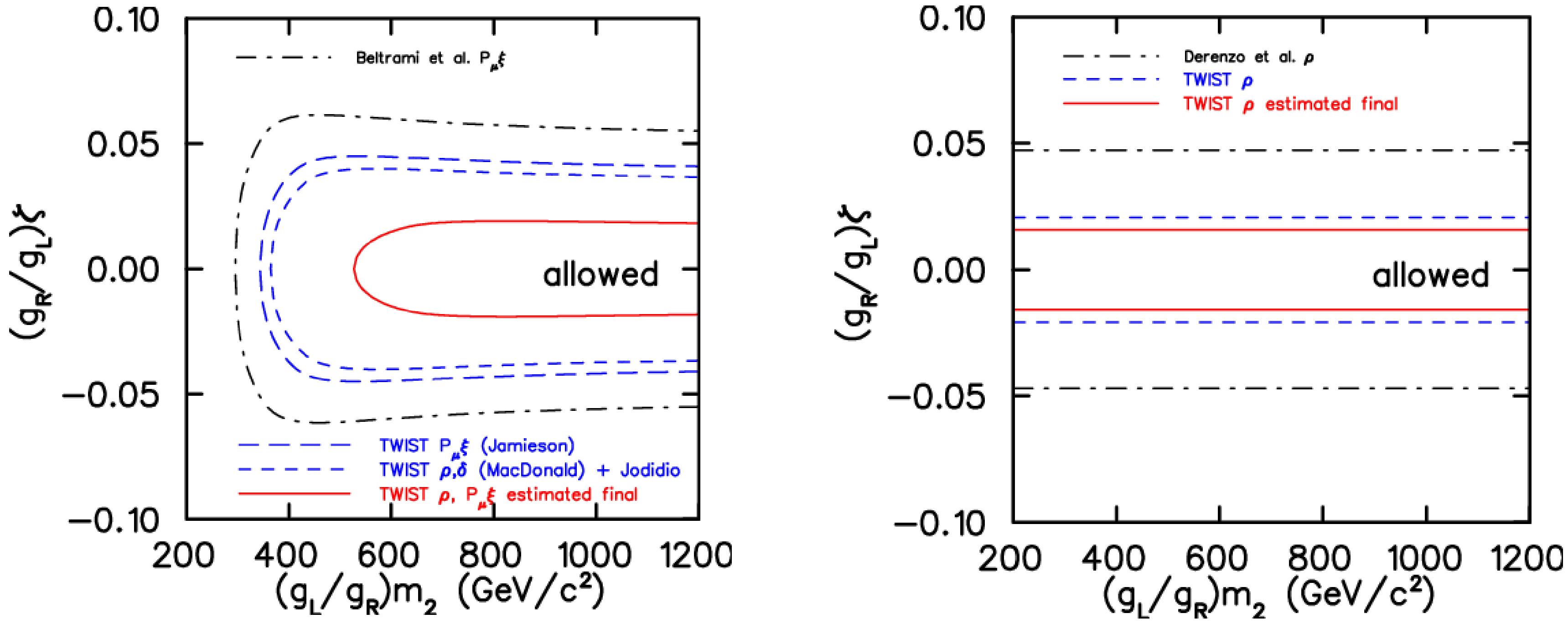
- ***Many experiments must make assumptions about LRS models!***

Limits on LRS parameters: PDG08

Observable	m_2 (GeV/c_2)	$\|\zeta\|$	👍	👎
$m(K_L{}^0)$- $m(K_S{}^0)$	>700		reach	(P)MLRS
Direct W_R searches	>1000 (D0) >788 (CDF)		clear signal	(P)MLRS decay model
Electro- weak fit		<0.013	fit	(P)MLRS
β decay	>310	<0.040	both parameters	(P)MLRS light ν_R
μ decay*, *TWIST*	>475 (>530)	<0.021 (<0.016)	model independence	light ν_R

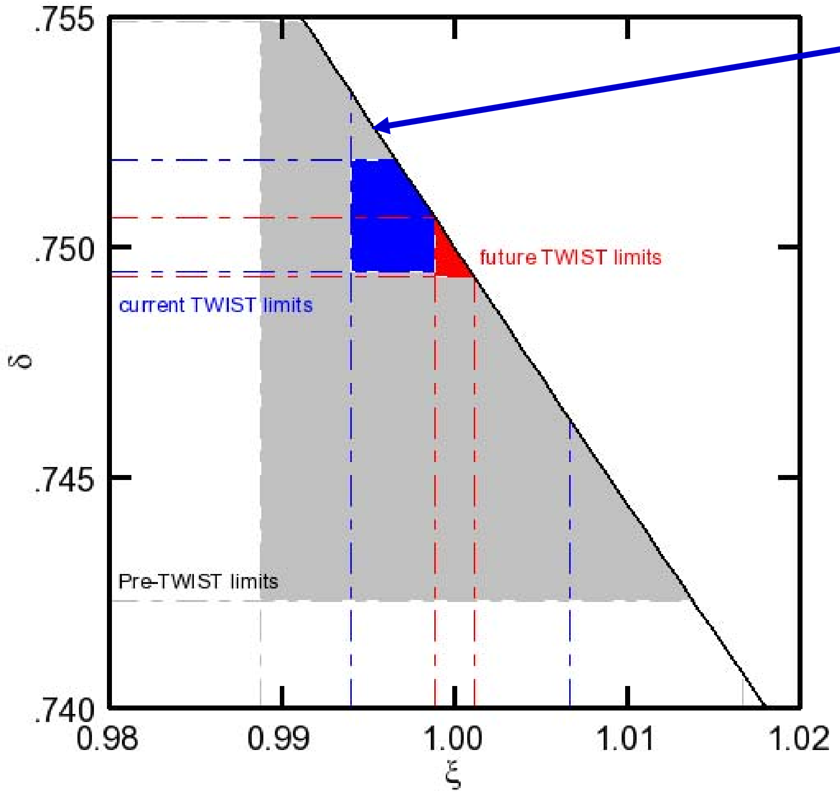
*** in generalized LRS model; to be interpreted as $m_2(g_L/g_R)$, $\zeta(g_R/g_L)$.**

Muon decay LRS limits



- Exclusion (90% cl) plots for left-right symmetric model mixing angle ζ and W_2 mass m_2.
- “Generalized LRS” model; no assumptions on RH CKM matrix elements.

Handedness of the muon



Diagonal represents exactly left-handed muon decay.

Shaded regions represent comparison of current and proposed *TWIST* limits, compared to previous PDG limits.

$$\begin{aligned} Q_R^{\mu} &= \frac{1}{2}\left[1+\frac{1}{3}\xi-\frac{16}{9}\xi\delta\right] \\ &\geq 0 \\ &< 0.0024(90\%CL) \end{aligned}$$

(Global analysis; R.P. MacDonald *et al.*, 2008)

Final *TWIST* result with global analysis could reduce the limit to <0.0015.

Summary

- *TWIST* has completed data taking; analysis well underway.
  - Systematic and statistical precision should meet or exceed initial expectations.
- The polarization measurement has unique challenges;
  - Depolarization systematics especially.
- *TWIST* was successful, but could be improved upon:
  - higher luminosity beams, better field characterization, higher precision detectors (beam and decay).
  - or some better ideas?

Thank you to:

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- our support agencies: NSERC, DOE, TRIUMF
- WestGrid, for lots of CPU power
- the audience, for your attention