Fundamental Symmetries – III
Muons

R. Tribble

Texas A&M University

All about muons

Topics:

- Lifetime – MuLAN
- Normal decay – TWIST
- Exotic decays – MEGA, MEG, SINDRUM
- Anomalous Moment – (g-2)

Muon Lifetime

- Determines G_F by (two loop QED and SM)

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3m_\mu^2}{5m_W^2}\right)\left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right]$$

where

$$F(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

and

$$\frac{1}{\alpha(m_\mu)} = \frac{1}{\alpha} - \frac{2}{3\pi}\ln\left(\frac{m_\mu}{m_e}\right) + \frac{1}{6\pi} \approx 136$$

- MuLAN collaboration recently completed and published new result for lifetime

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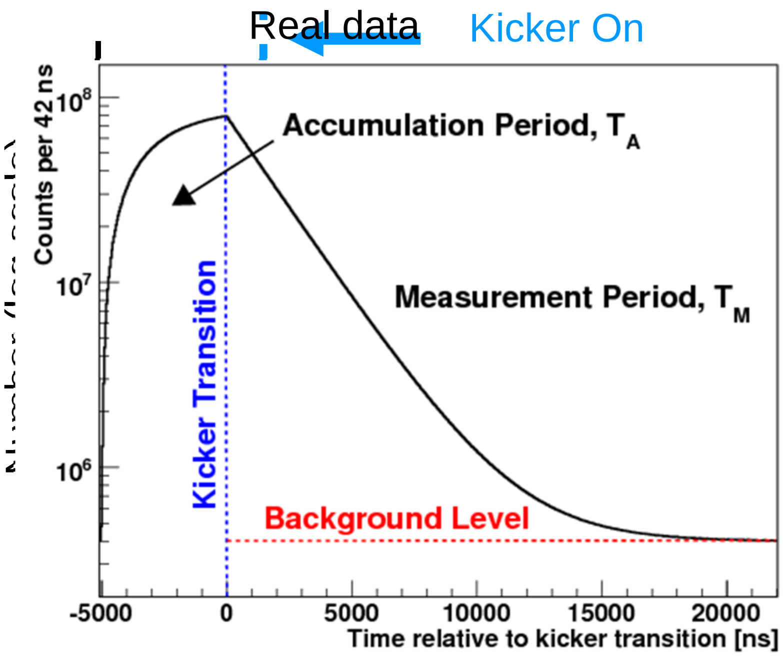
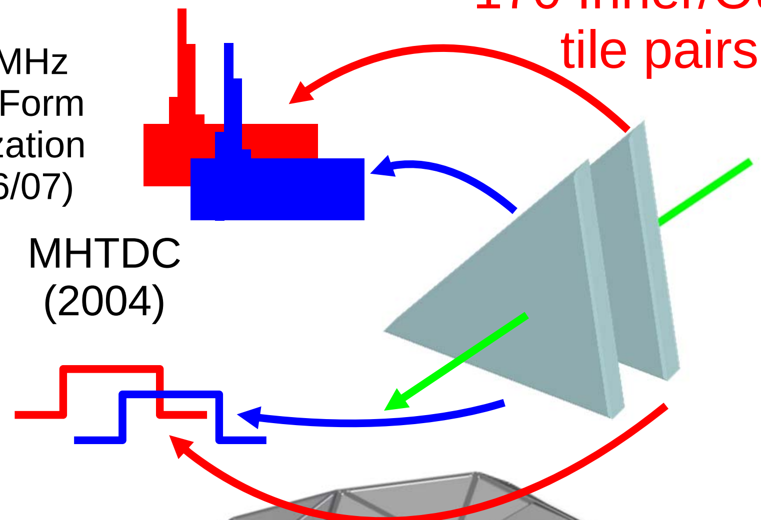
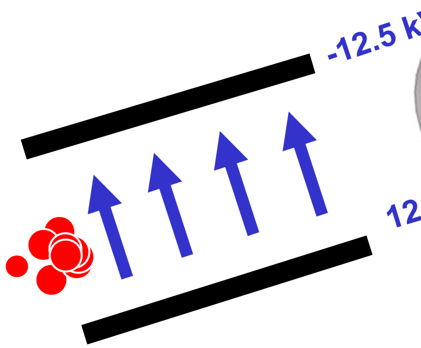
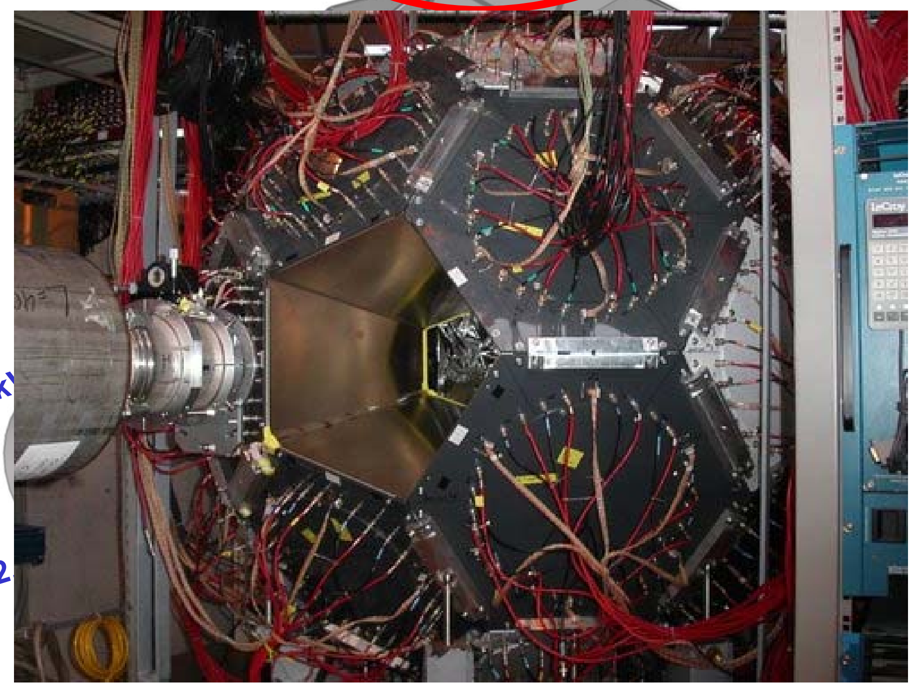
The experimental concept…





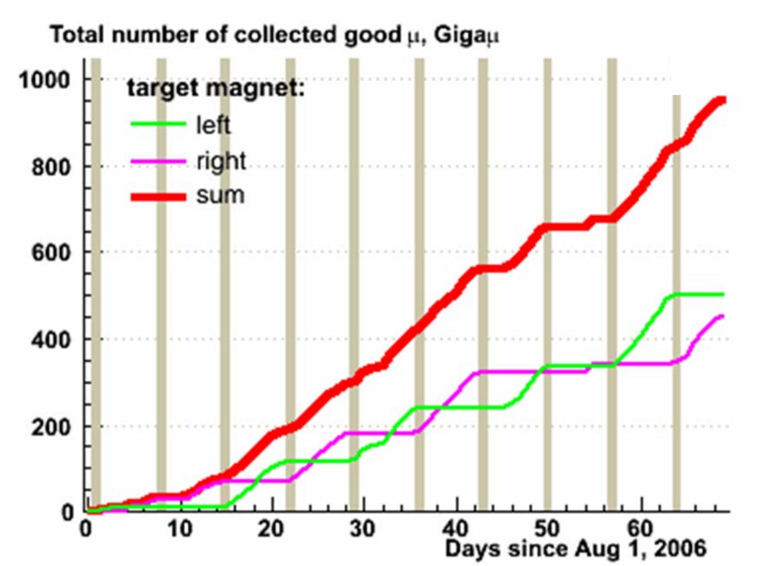




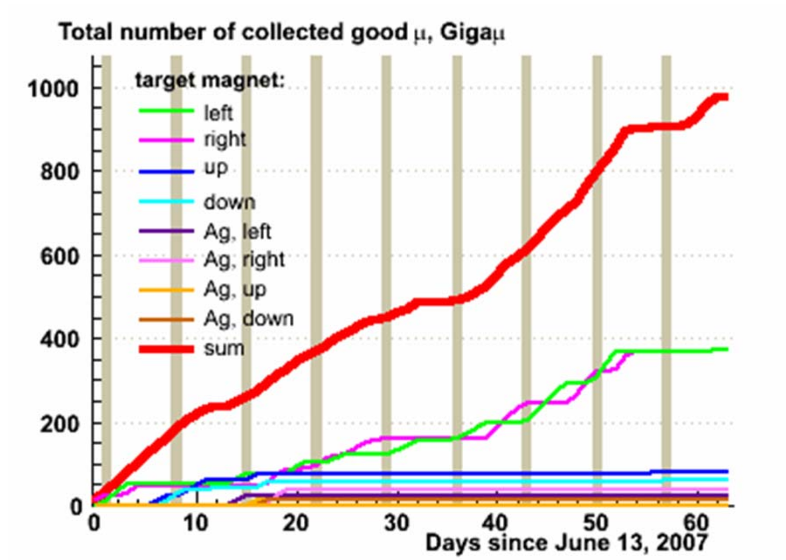
Slide from D. Hertzog

MuLan collected two datasets, each containing 10^{12} muon decays

Ferromagnetic Target, 2006



Quartz Target, 2007



- Two (very different) data sets
  - Different blinded clock frequencies used
  - Revealed only after all analyses of both data sets completed
  - Most systematic errors are common

Slide from D. Hertzog

Final Errors and Numbers

ppm units

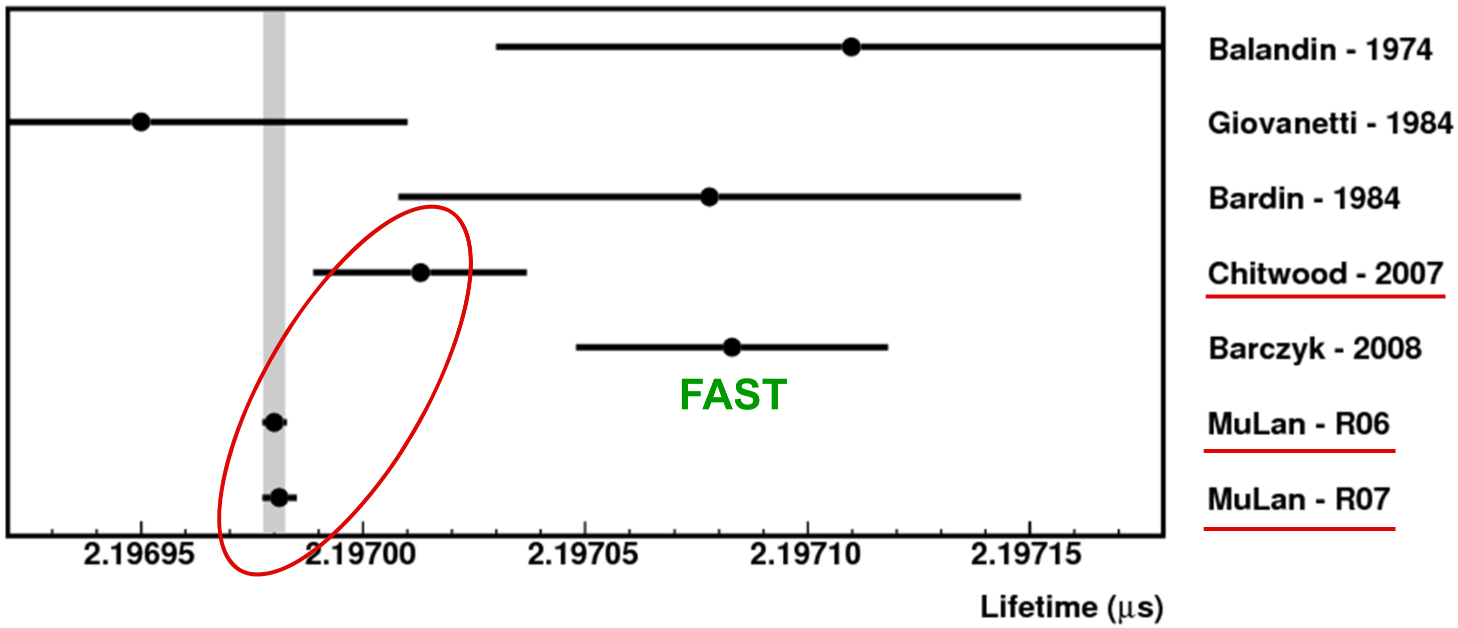
Effect	2006	2007	Comment
Kicker extinction stability	0.20	0.07	Voltage measurements of plates
Upstream muon stops	0.10	0.10	Upper limit from measurements
Overall gain stability:	0.25	0.25	MPV vs time in fill; includes:
Short time; after a pulse			MPVs in next fill & laser studies
Long time; during full fill			Different by PMT type
Electronic ped fluctuation			Bench-test supported
Unseen small pulses			Uncorrected pileup effect → gain
Timing stability	0.12	0.12	Laser with external reference ctr.
Pileup correction	0.20	0.20	Extrapolation to zero ADT
Residual polarization	0.10	0.20	Long relax; quartz spin cancelation
Clock stability	0.03	0.03	Calibration and measurement
Total Systematic	**0.42**	**0.42**	**Highly correlated for 2006/2007**
Total Statistical	**1.14**	**1.68**	

τ(R06) = 2 196 979.9 ± 2.5 ± 0.9 ps

τ(R07) = 2 196 981.2 ± 3.7 ± 0.9 ps

Slide from D. Hertzog

Lifetime "history"



The most precise particle or nuclear or (we believe) atomic lifetime ever measured

New G_F

G_F(MuLan) = 1.166 378 8(7) x 10^{-5} GeV^{-2} (0.6 ppm)

Slide from D. Hertzog

Muon decay spectrum

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

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

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

[Radiative corrections not included]

Muon decay matrix element

- Most general local, derivative-free, lepton-number conserving muon decay matrix element:

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

- In the Standard Model, $g^{V}_{LL} = 1$, all others are zero
- Pre-*TWIST* global fit results (all 90% c.l.):

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

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Muon decay parameters and coupling constants

$$\rho = \frac{3}{4} - \frac{3}{4}[\left|g^V_{RL}\right|^2 + \left|g^V_{LR}\right|^2 + 2\left|g^T_{RL}\right|^2 + 2\left|g^T_{LR}\right|^2 + \mathbb{R}e\left(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR}\right)]$$

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

$$\xi = 1 - \frac{1}{2}\left|g^S_{LR}\right|^2 - \frac{1}{2}\left|g^S_{RR}\right|^2 - 4\left|g^V_{RL}\right|^2 + 2\left|g^V_{LR}\right|^2 - 2\left|g^V_{RR}\right|^2 + 2\left|g^T_{LR}\right|^2 - 8\left|g^T_{RL}\right|^2 + 4\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

$$\xi\delta = \frac{3}{4} - \frac{3}{8}\left|g^S_{RR}\right|^2 - \frac{3}{8}\left|g^S_{LR}\right|^2 - \frac{3}{2}\left|g^V_{RR}\right|^2 - \frac{3}{4}\left|g^V_{RL}\right|^2 - \frac{3}{4}\left|g^V_{LR}\right|^2 - \frac{3}{2}\left|g^T_{RL}\right|^2 - 3\left|g^T_{LR}\right|^2 + \frac{3}{4}\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

Prior to ***TWIST***

	SM
$\rho = 0.7518 \pm 0.0026$	3/4
$\eta = -0.007 \pm 0.013$	0
$P_\mu\xi = 1.0027 \pm 0.0079 \pm 0.0030$	1
$\delta = 0.7486 \pm 0.0026 \pm 0.0028$	3/4
$P_\mu(\xi\delta/\rho) > 0.99682$ (90% c.l.)	1

Goal of *TWIST*

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

Two examples

- Model-independent limit on muon handedness

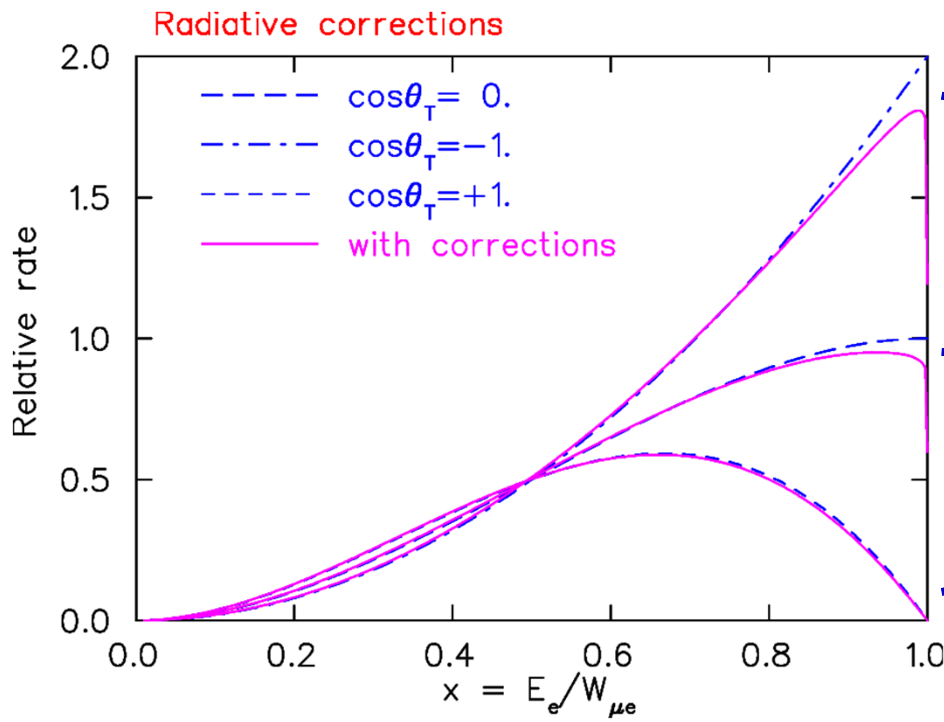
$$Q_R^\mu = \frac{1}{2}\left[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta\right]$$

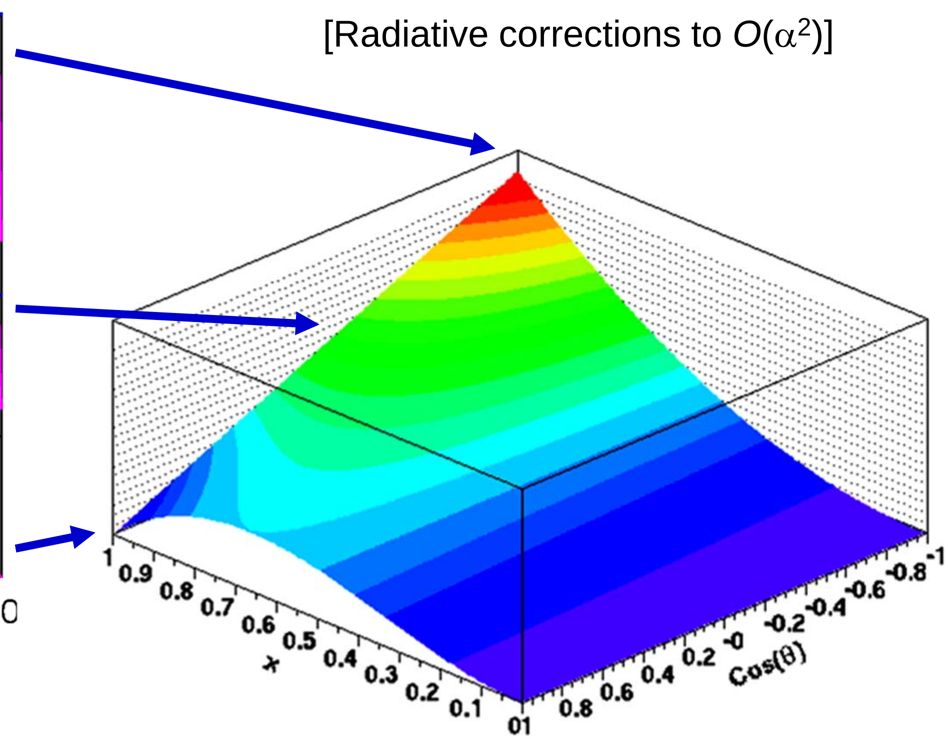
- Left-right symmetric models

$$\frac{3}{4} - \rho = \frac{3}{2}\zeta^2 \qquad 1 - P_\mu\xi = 4\left(\zeta^2 + \zeta\left(\frac{M_L}{M_R}\right)^2 + \left(\frac{M_L}{M_R}\right)^4\right)$$

- …..

What is required?



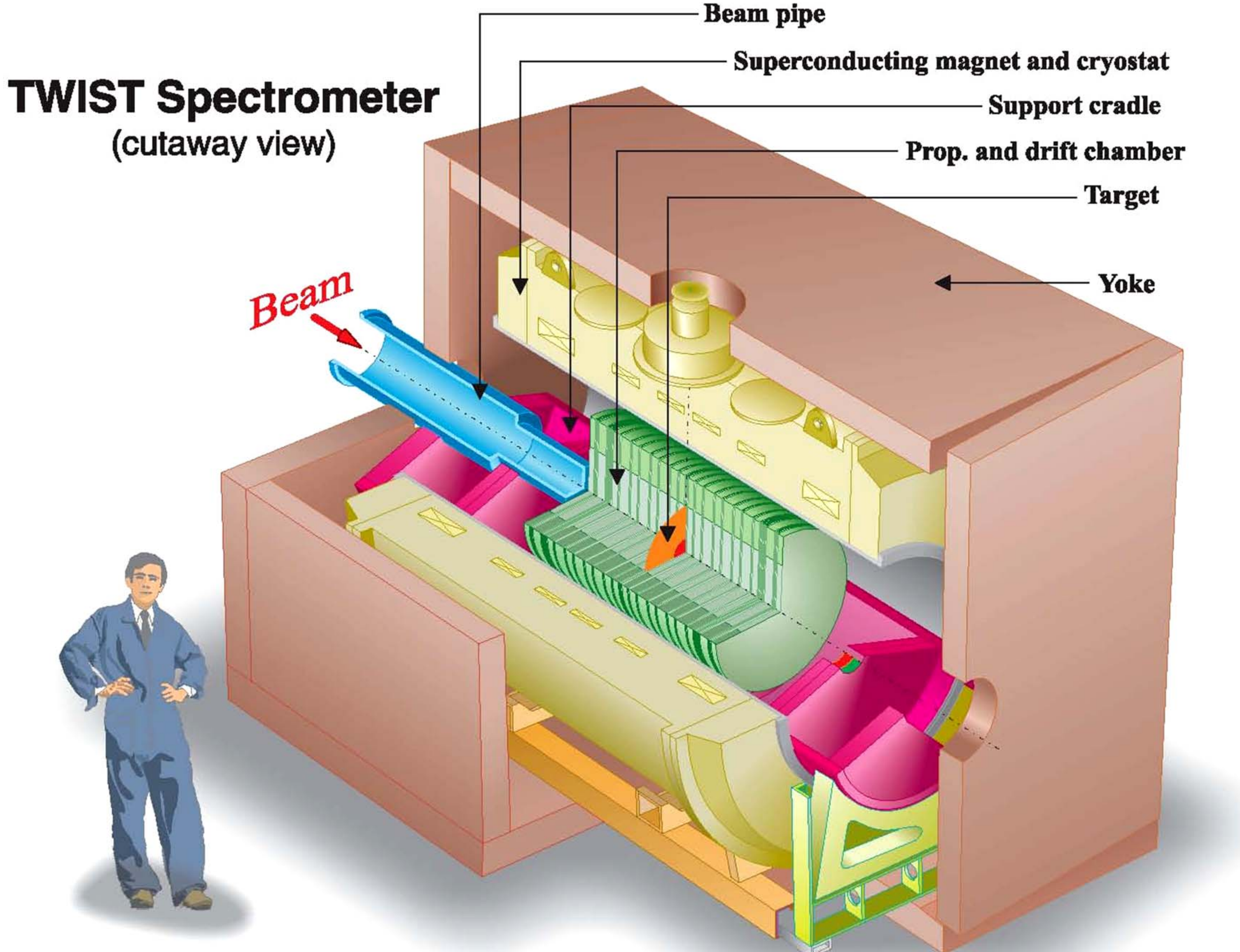


Must:

- Determine spectrum shape
  - -- All three parameters
- Understand sources of muon depolarization
  - -- P_μ and ξ come as a product
- Measure forward-backward asymmetry
  - -- For $P_\mu\xi$ and δ

to within a **few parts in 10^4**

TWIST spectrometer



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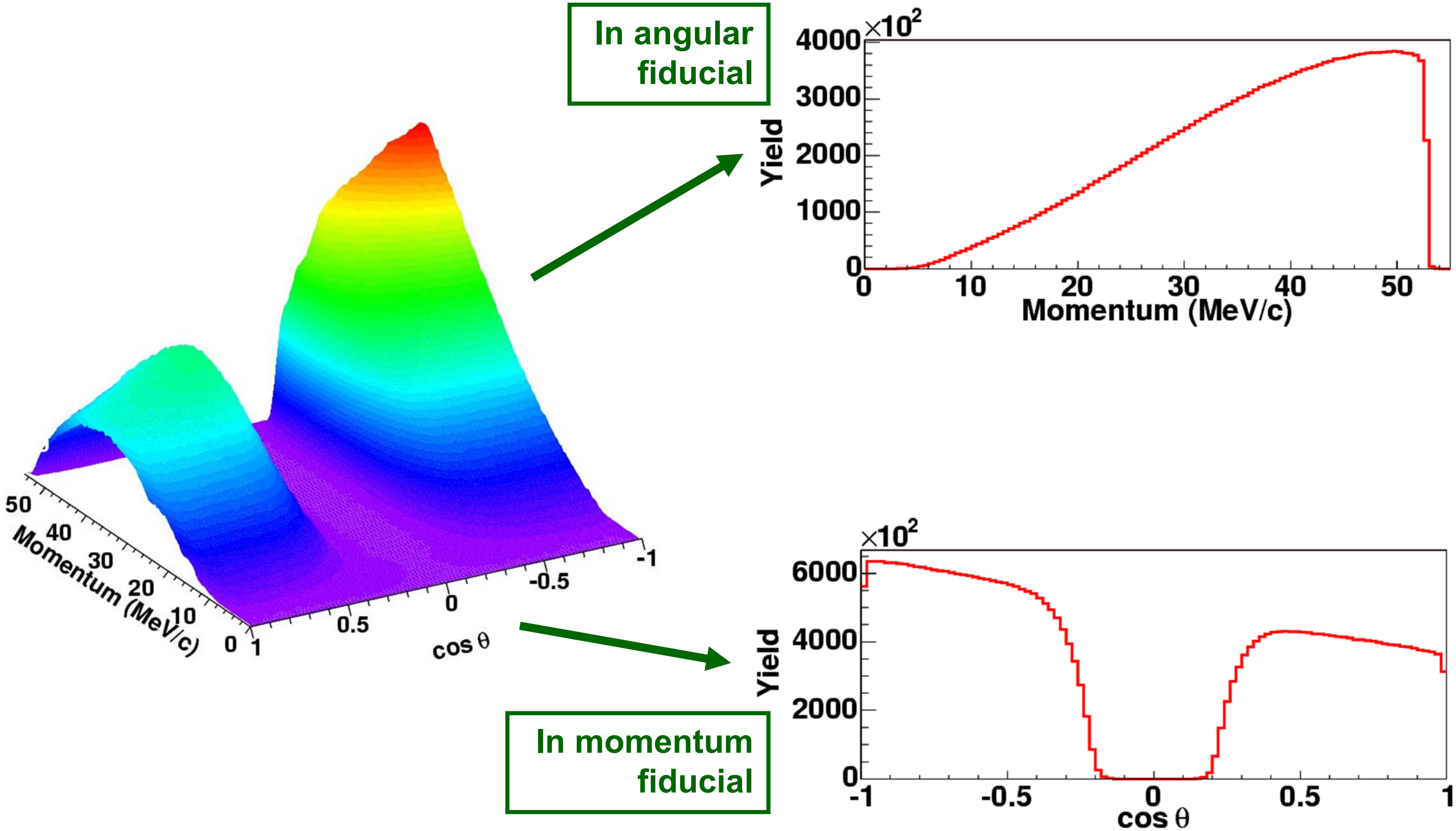
Analysis method

- Extract energy and angle distributions for data:
  - Apply (unbiased) cuts on muon variables.
  - Reject fast decays and backgrounds.
  - Calibrate e^+ energy to kinematic end point at 52.83 MeV.
- Fit to identically derived distributions from simulation:
  - GEANT3 geometry contains virtually all detector components.
  - Simulate chamber response in detail.
  - Realistic, measured beam profile and divergence.
  - Extra muon and beam positron contamination included.
  - Output in digitized format, identical to real data.

2-d momentum-angle spectrum



Acceptance of the **TWIST** spectrometer

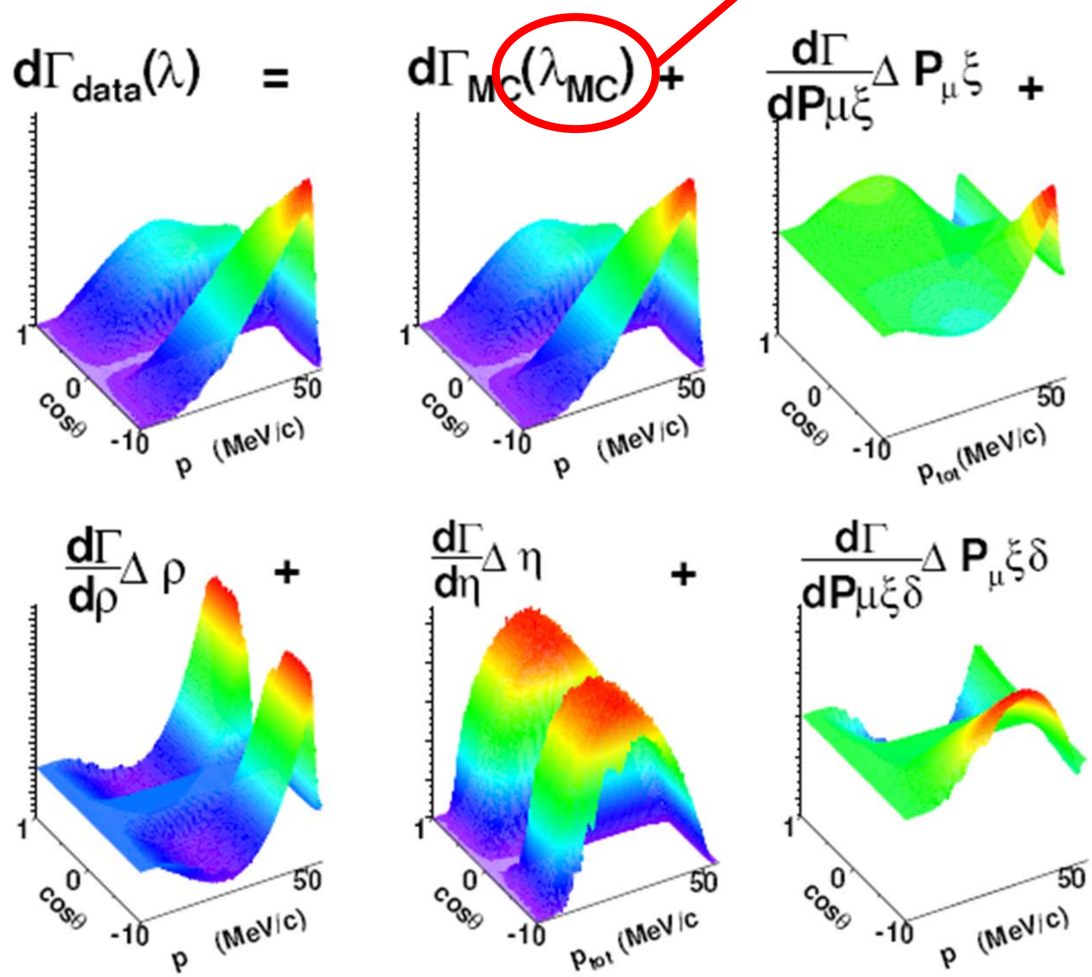
Fitting the data distributions

λ_{MC} **hidden**
➔ **blind analysis**

- Decay distribution is linear in ρ, η, $P_\mu\xi$, and $P_\mu\xi\delta$, so a fit to first order expansion is exact.
- Fit data to simulated (MC) base distribution with *hidden assumed parameters*,

  $\lambda_{MC} = (\rho, \eta, P_\mu\xi_{|P_\mu\xi\delta}, P_\mu\xi\delta)$

  plus MC-generated distributions from analytic derivatives, times fitting parameters ($\Delta\lambda$) representing deviations from base MC. (η is now fixed to global analysis value)

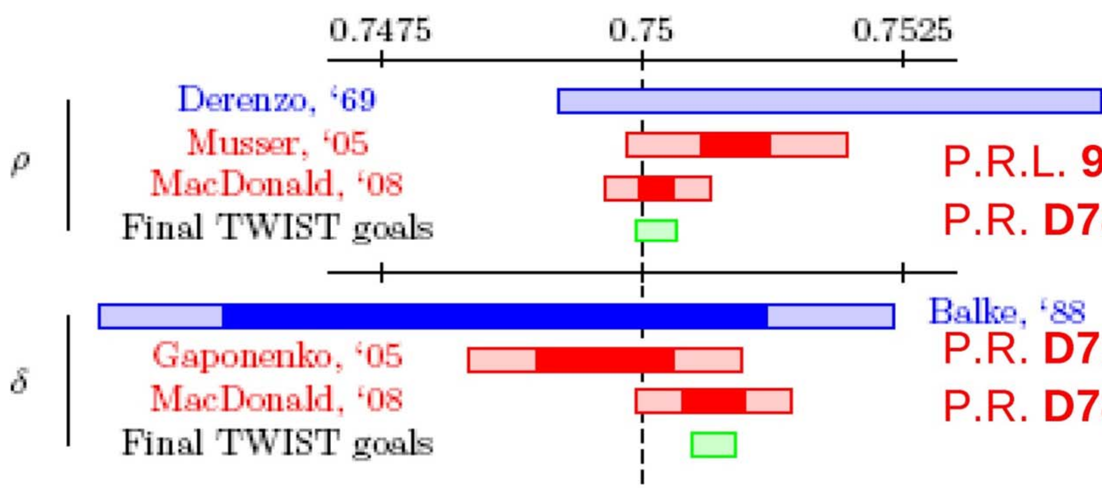


(graphic thanks to Blair Jamieson)

Results from first two data sets

- From Fall, 2002 run:
  - ρ = 0.75080 ± 0.00032 (stat) ± 0.00097 (syst) ± 0.00023 (η)
  - δ = 0.74964 ± 0.00066 (stat) ± 0.00112 (syst)
- From Fall, 2004 run:
  - ρ = 0.75014 ± 0.00017 (stat) ± 0.00044 (syst) ± 0.00011 (η)
  - δ = 0.74964 ± 0.00030 (stat) ± 0.00067 (syst)

R. McDonald et al., PRD **78**, 032010



P.R.L. **94**, 101805(2005)
P.R. **D78**, 032010(2008)

P.R. **D71**, 071171**R**(2005)
P.R. **D78**, 032010(2008)

Global Analysis

Use general form of interaction:

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

- Follow Fetscher, Gerber, Johnson formulation (Phys. Lett. **173B**, 102 (1986))

Global Analysis

$$Q_{RR} = \frac{1}{4}|g^S_{RR}|^2 + |g^V_{RR}|^2,$$

$$Q_{LR} = \frac{1}{4}|g^S_{LR}|^2 + |g^V_{LR}|^2 + 3|g^T_{LR}|^2,$$

$$Q_{RL} = \frac{1}{4}|g^S_{RL}|^2 + |g^V_{RL}|^2 + 3|g^T_{RL}|^2,$$

$$Q_{LL} = \frac{1}{4}|g^S_{LL}|^2 + |g^V_{LL}|^2,$$

$$B_{LR} = \frac{1}{16}|g^S_{LR} + 6g^T_{LR}|^2 + |g^V_{LR}|^2,$$

$$B_{RL} = \frac{1}{16}|g^S_{RL} + 6g^T_{RL}|^2 + |g^V_{RL}|^2,$$

$$I_\alpha = \frac{1}{4}[g^V_{LR}(g^S_{RL} + 6g^T_{RL})^* + (g^V_{RL})^*(g^S_{LR} + 6g^T_{LR})]$$

$$= (\alpha + i\alpha')/2A,$$

$$I_\beta = \frac{1}{2}[g^V_{LL}(g^S_{RR})^* + (g^V_{RR})^* g^S_{LL}] = -2(\beta + i\beta')/A$$

Constraints:

$$0 \le Q_{\epsilon\mu} \le 1, \quad \text{where } \epsilon, \mu = R, L,$$

$$0 \le B_{\epsilon\mu} \le Q_{\epsilon\mu}, \quad \text{where } \epsilon\mu = RL, LR,$$

$$|I_\alpha|^2 \le B_{LR}B_{RL}, \qquad |I_\beta|^2 \le Q_{LL}Q_{RR},$$

Normalization:

$$Q_{RR} + Q_{LR} + Q_{RL} + Q_{LL} = 1$$

Note that $Q_{LL} \approx 1$

(from Phys. Lett. **173B**)

Global Analysis

Relation to muon decay observables:

$$\rho = \frac{3}{4} + \frac{1}{4}(Q_{LR} + Q_{RL}) - (B_{LR} + B_{RL}),$$

$$\xi = 1 - 2Q_{RR} - \frac{10}{3}Q_{LR} + \frac{4}{3}Q_{RL} + \frac{16}{3}(B_{LR} - B_{RL}),$$

$$\xi\delta = \frac{3}{4} - \frac{3}{2}Q_{RR} - \frac{7}{4}Q_{LR} + \frac{1}{4}Q_{RL} + (B_{LR} - B_{RL}),$$

e^+_L {

$$\xi' = 1 - 2Q_{RR} - 2Q_{RL},$$

$$\xi'' = 1 - \frac{10}{3}(Q_{LR} + Q_{RL}) + \frac{16}{3}(B_{LR} + B_{RL}),$$

rad. decay { $\bar{\eta} = \frac{1}{3}(Q_{LR} + Q_{RL}) + \frac{2}{3}(B_{LR} + B_{RL}),$

e^+_T { $\eta = (\alpha - 2\beta)/A, \qquad \eta'' = (3\alpha + 2\beta)/A.$

Global Analysis

2005 Input:

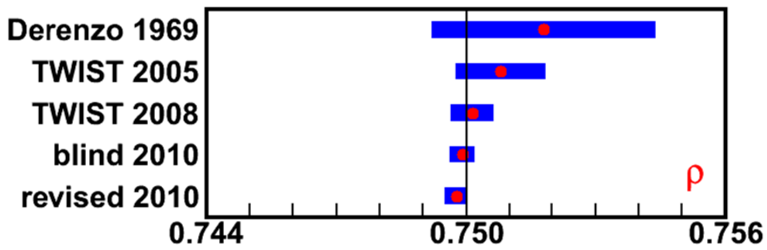
Parameter	Value
ρ	0.7518 ± 0.0026
	$0.75\,080 \pm 0.00\,105$[a]
δ	0.7486 ± 0.0038
	$0.74\,964 \pm 0.00\,130$
$P_\mu \xi$	1.0027 ± 0.0085[b]
$P_\mu \xi \delta / \rho$	$0.99\,787 \pm 0.00\,082$[b]
ξ'	1.00 ± 0.04
ξ''	0.65 ± 0.36
$\bar{\eta}$	0.02 ± 0.08
α/A	0.015 ± 0.052[c]
β/A	0.002 ± 0.018[c]
η	0.071 ± 0.037[d]
η''	0.105 ± 0.052[d]
α'/A	-0.047 ± 0.052[e]
	-0.0034 ± 0.0219[f]
β'/A	0.017 ± 0.018[e]
	-0.0005 ± 0.0080[f]

PRD **72**, 073002

2005 Output:

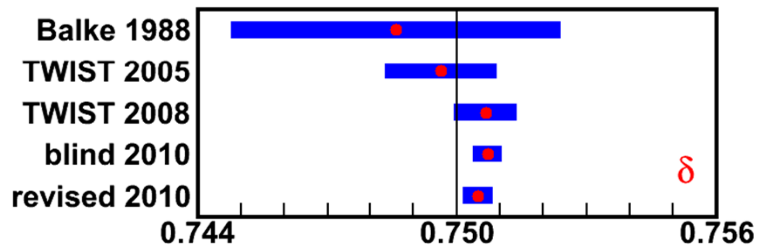
Parameter	Fit Result ($\times 10^3$)
Q_{RR}	$<1.14(0.60 \pm 0.38)$
Q_{LR}	$<1.94(1.22 \pm 0.53)$
B_{LR}	$<1.27(0.72 \pm 0.40)$
Q_{RL}	$<44(26 \pm 13)$
B_{RL}	$<10.9(6.4 \pm 3.3)$
Q_{LL}	$>955(973 \pm 13)$
α/A	0.3 ± 2.1
β/A	2.0 ± 3.1
α'/A	-0.1 ± 2.2
β'/A	-0.8 ± 3.2

Final TWIST Results



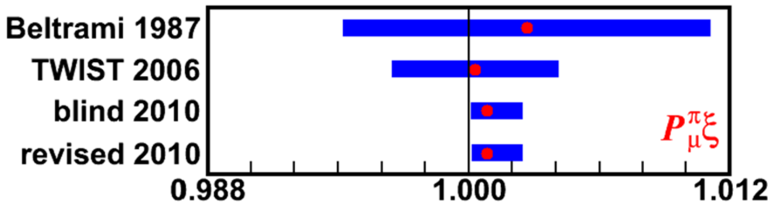
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

(<1σ from SM)



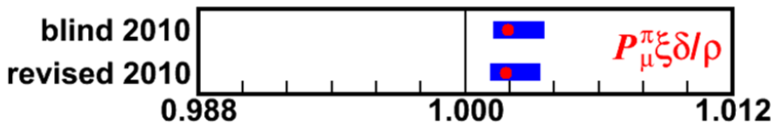
δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

(+1.4σ from SM)



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

(+1.2σ from SM)



$\mathcal{P}_\mu^{\pi}\xi\delta/\rho$ > 0.99909 (90%CL)

from global analysis

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Final Global Analysis Results

- Include new results with other muon decay observables to restrict coupling constants
  - summary of all terms (pre-*TWIST* in parentheses)

$\lvert g^S_{RR}\rvert < 0.035\ (0.066)$	$\lvert g^V_{RR}\rvert < 0.017\ (0.033)$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.050\ (0.125)$	$\lvert g^V_{LR}\rvert < 0.023\ (0.060)$	$\lvert g^T_{LR}\rvert < 0.015\ (0.036)$
$\lvert g^S_{RL}\rvert < 0.420\ (0.424)$	$\lvert g^V_{RL}\rvert < 0.105\ (0.110)$	$\lvert g^T_{RL}\rvert < 0.105\ (0.122)$
$\lvert g^S_{LL}\rvert < 0.550\ (0.550)$	$\lvert g^V_{LL}\rvert > 0.960\ (0.960)$	$\lvert g^T_{LL}\rvert \equiv 0$

  - influences mostly right-handed muon terms

$$
\begin{aligned}
Q^\mu_R &= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \\
&= \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \\
&< 8.2 \times 10^{-4} \quad (90\%\text{C.L.})
\end{aligned}
$$

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Neutrino-less Muon Decays

- Three lepton-flavor violating muon decays are possible:
  - $\mu \rightarrow e + \gamma$
  - $\mu^+ \rightarrow e^+e^+e^-$
  - $\mu \rightarrow e$ conversion
- These decay modes are not allowed with massless neutrinos
- Highly suppressed in SM with known neutrino masses
- SM extensions affect the decay rates differently

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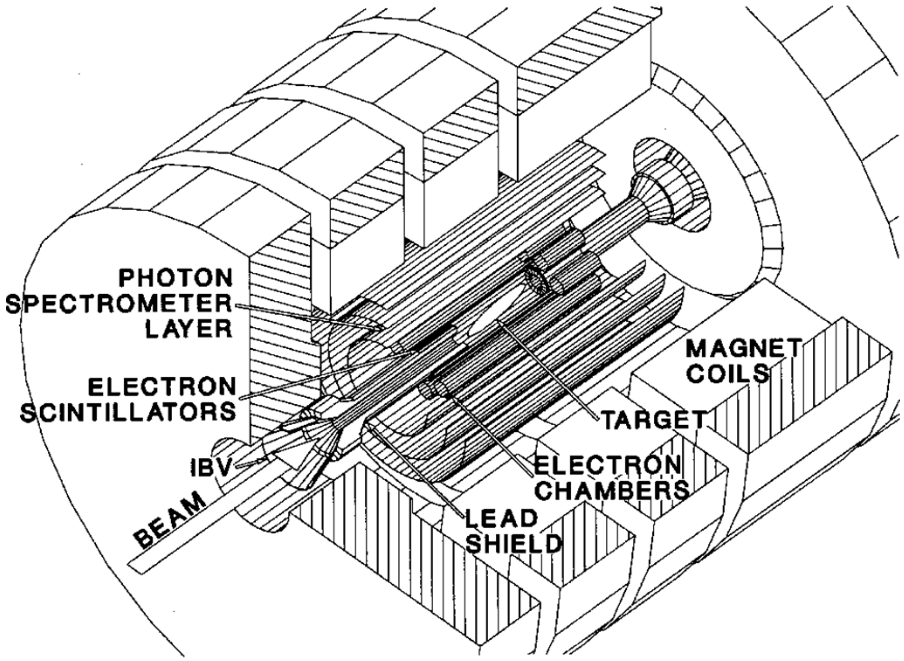
$\mu \rightarrow e + \gamma$ Decay

- History of searches for this decay at LAMPF following preliminary work at TRIUMF and PSI
- Very high flux of muons at LAMPF
- MEGA collaboration most recent $\mu \rightarrow e + \gamma$ experiment (1985-1995)



High energy γ background:

- $\mu \rightarrow e\upsilon\bar{\upsilon}\gamma$
- Annihilation in flight
- External bremsstrahlung

Status of $\mu \rightarrow e + \gamma$

- Last results reported in 1999

Place	Year	ΔE_e	ΔE_γ	$\Delta t_{e\gamma}$	$\Delta\theta_{e\gamma}$	Upper limit	References
TRIUMF	1977	10%	8.7%	6.7 ns		$<3.6\times10^{9}$	Depommier *et al.* (1977)
SIN	1980	8.7%	9.3%	1.4 ns		$<1.0\times10^{-9}$	Van der Schaaf *et al.* (1980)
LANL	1982	8.8%	8%	1.9 ns	37mrad	$<1.7\times10^{10}$	Kinnison *et al.* (1982)
LANL	1988	8%	8%	1.8 ns	87mrad	$<4.9\times10^{-11}$	Bolton *et al.* (1988)
LANL	1999	1.2%[a]	4.5%[a]	1.6 ns	15mrad	$<1.2\times10^{-11}$	Brooks *et al.* (1999)

- New experiment underway at PSI – MEG
- Liquid xenon calorimeter for γ's, solenoid for positrons
- Goal is factor of ≈ 100 below MEGA
- Analysis of results underway – invited talk with new results is scheduled for DNP fall meeting!

Status of $\mu^+ \rightarrow e^+e^+e^-$

- Last results reported in 1991
- SINDRUM at PSI has best limit – solenoid tracking chamber

Place	Year	90%-C.L. upper limit	Reference
JINR	1976	$<1.9\times10^{-9}$	Korenchenko *et al.* (1976)
LANL	1984	$<1.3\times10^{-10}$	Bolton *et al.* (1984)
SIN	1984	$<1.6\times10^{-10}$	Bertl *et al.* (1984)
SIN	1985	$<2.4\times10^{-12}$	Bertl *et al.* (1985)
LANL	1988	$<3.5\times10^{-11}$	Bolton *et al.* (1988)
SIN	1988	$<1.0\times10^{-12}$	Bellgardt *et al.* (1988)
JINR	1991	$<3.6\times10^{-11}$	Baranov *et al.* (1991)

- No new experiments planned that I know
- A non-zero result for $\mu \rightarrow e + \gamma$ would likely change that

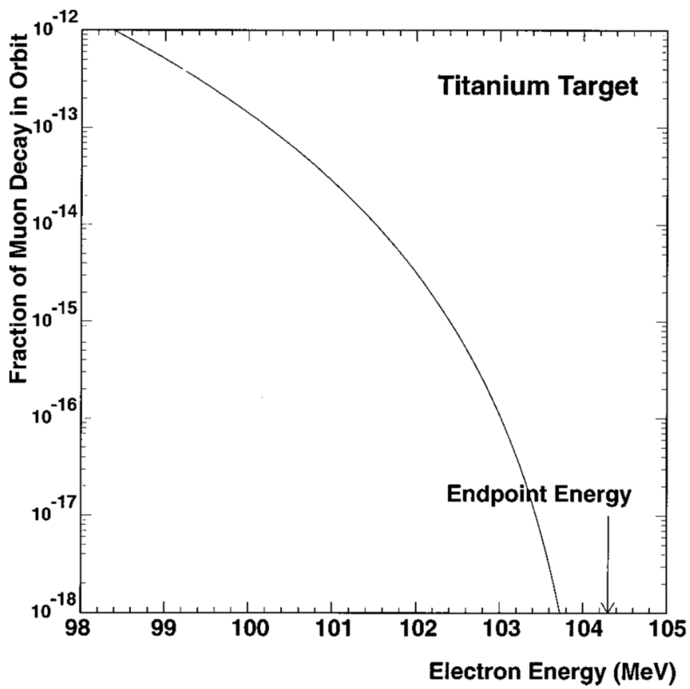
$\mu^- \rightarrow e^-$ Conversion – I

- Searches for this conversion process carried out in several different nuclei (**Cu**, **S**, **Ti**, **Pb**)
- Process involves μ capture by atom and then a cascade to 1s atomic orbital
- After cascade, μ orbit overlaps nucleus then have normal muon decay or
  - $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$ (allowed)
  - $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$ (not allowed)
- Ratio $\Rightarrow$ branching ratio for conversion

$\mu^- \rightarrow e^-$ Conversion – II

- Signal $\Rightarrow$ mono-energetic e^- at end point energy
- Backgrounds: μ decay in orbit, π capture, radiative μ capture with very asymmetric pair creation
- Titanium has high end point so attractive

Predicted signal and background level for μ - e conversion on Ti



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Status of $\mu^- \rightarrow e^-$ Conversion

- Last results reported in 1998

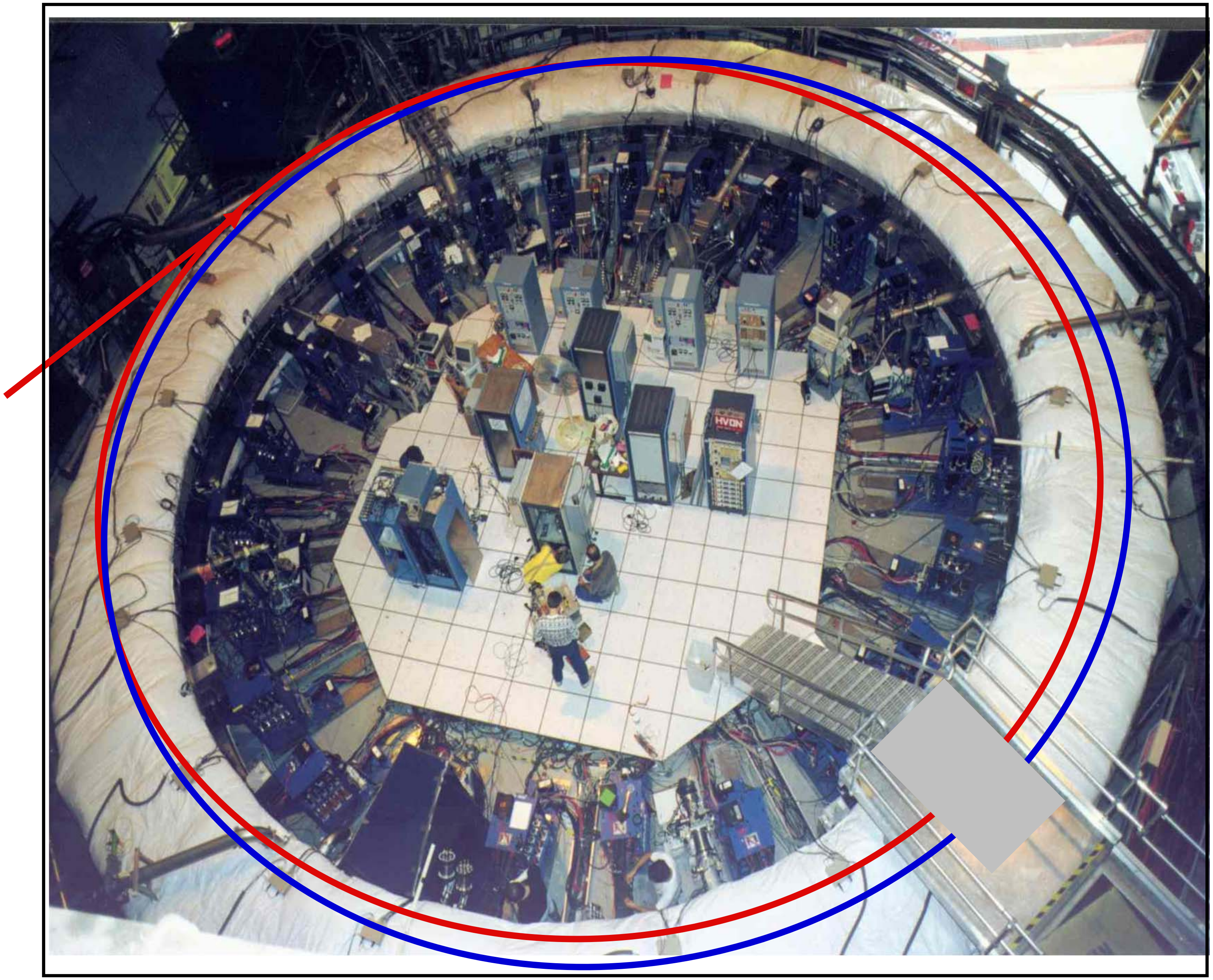
Process	90%-C.L. upper limit	Place	Year	Reference
$\mu^- + \text{Cu} \rightarrow e^- + \text{Cu}$	$<1.6\times10^{-8}$	SREL	1972	Bryman *et al.* (1972)
$\mu^- + {}^{32}\text{S} \rightarrow e^- + {}^{32}\text{S}$	$<7\times10^{-11}$	SIN	1982	Badertscher *et al.* (1982)
$\mu^- + \text{Ti} \rightarrow e^- + \text{Ti}$	$<1.6\times10^{-11}$	TRIUMF	1985	Bryman *et al.* (1985)
$\mu^- + \text{Ti} \rightarrow e^- + \text{Ti}$	$<4.6\times10^{-12}$	TRIUMF	1988	Ahmad *et al.* (1988)
$\mu^- + \text{Pb} \rightarrow e^- + \text{Pb}$	$<4.9\times10^{-10}$	TRIUMF	1988	Ahmad *et al.* (1988)
$\mu^- + \text{Ti} \rightarrow e^- + \text{Ti}$	$<4.3\times10^{-12}$	PSI	1993	Dohmen *et al.* (1993)
$\mu^- + \text{Pb} \rightarrow e^- + \text{Pb}$	$<4.6\times10^{-11}$	PSI	1996	Honecker *et al.* (1996)
$\mu^- + \text{Ti} \rightarrow e^- + \text{Ti}$	$<6.1\times10^{-13}$	PSI	1998	Wintz (1998)

- New experiment proposed in U.S. – **Mu2e** to run at FNAL with accelerator upgrade
- Estimates of background suggest 10^{-16} possible

Measuring the **Muon (g-2)** Factor

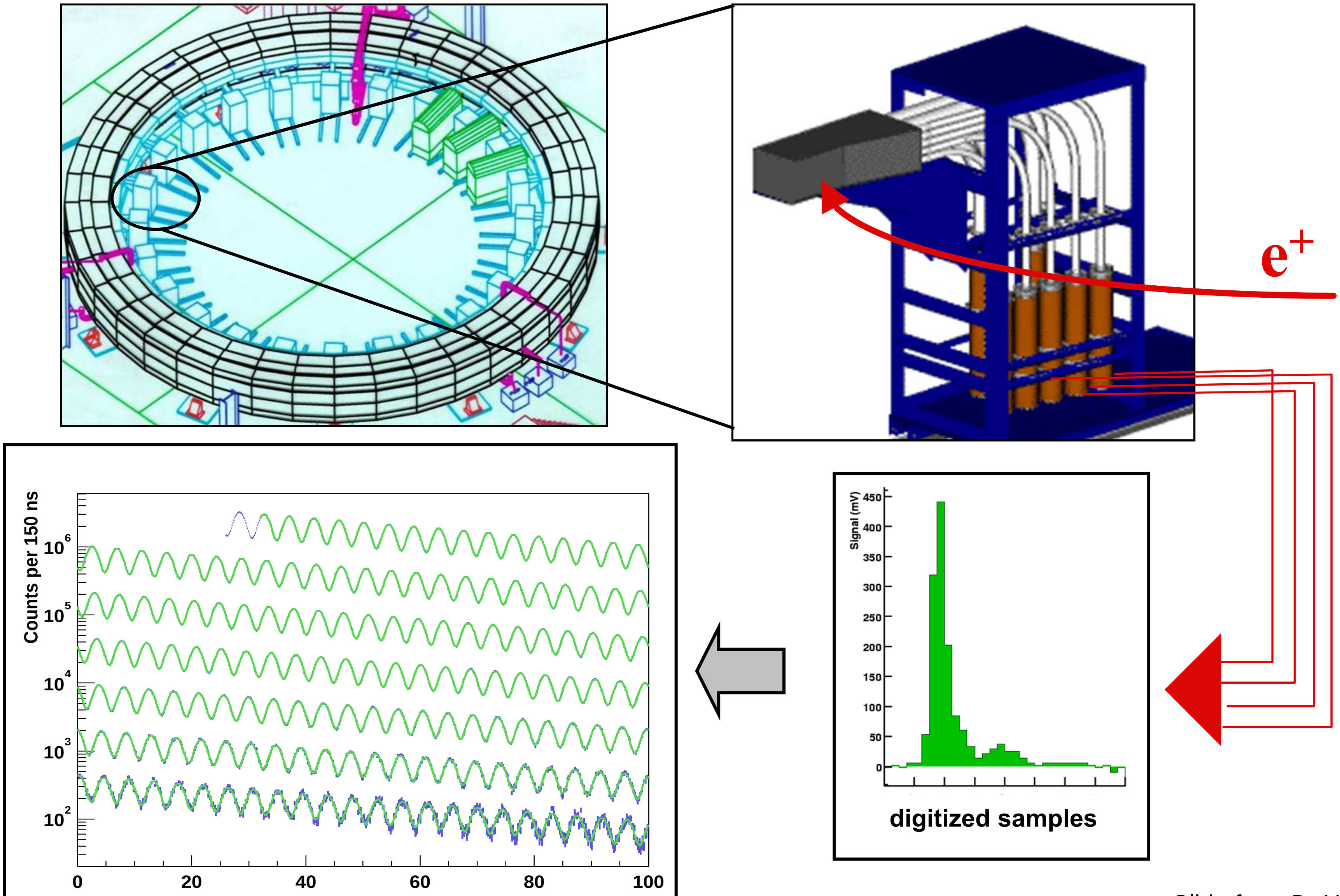
- Like other precision measurements, the determination of **g-2** for the muon has a long history
- Most recent results from **BNL E821**
- Store a polarized muon beam in ring and measure precession frequency as a function of time
- AGS provides muons for ring
- Requires precise knowledge of magnetic
- The SM prediction for a non-zero **g-2** includes several correction factors – higher order loop diagrams

The Storage Ring for E821



Slide from D. Hertzog

An “event” is an isolated positron above a threshold.



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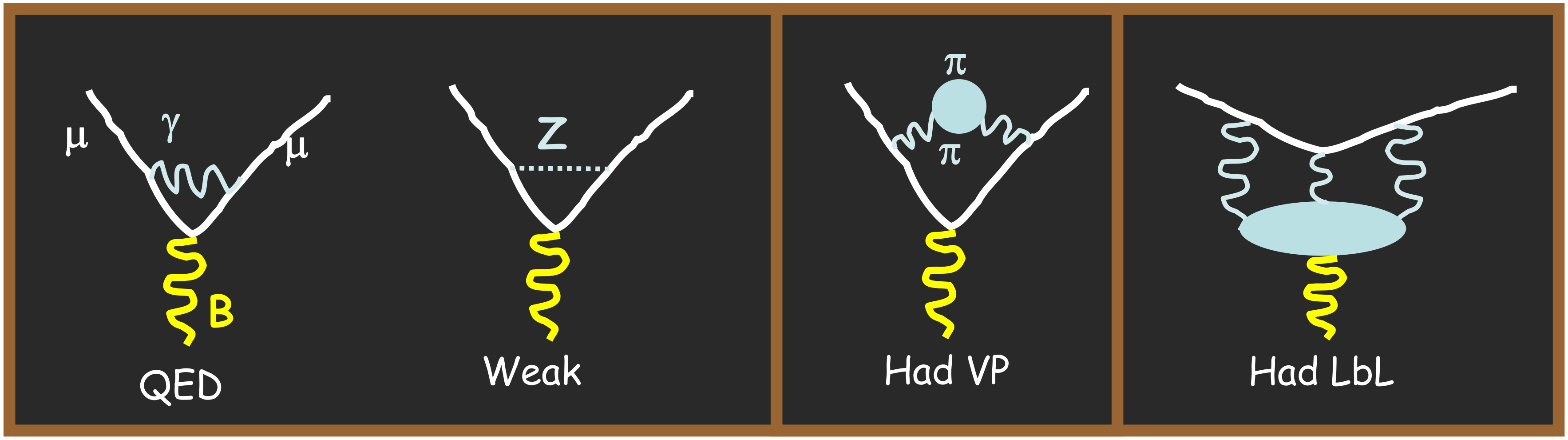
a_μ = (g – 2)/2 is non-zero because of virtual loops, which can be calculated very precisely



Known well **Theoretical work ongoing**

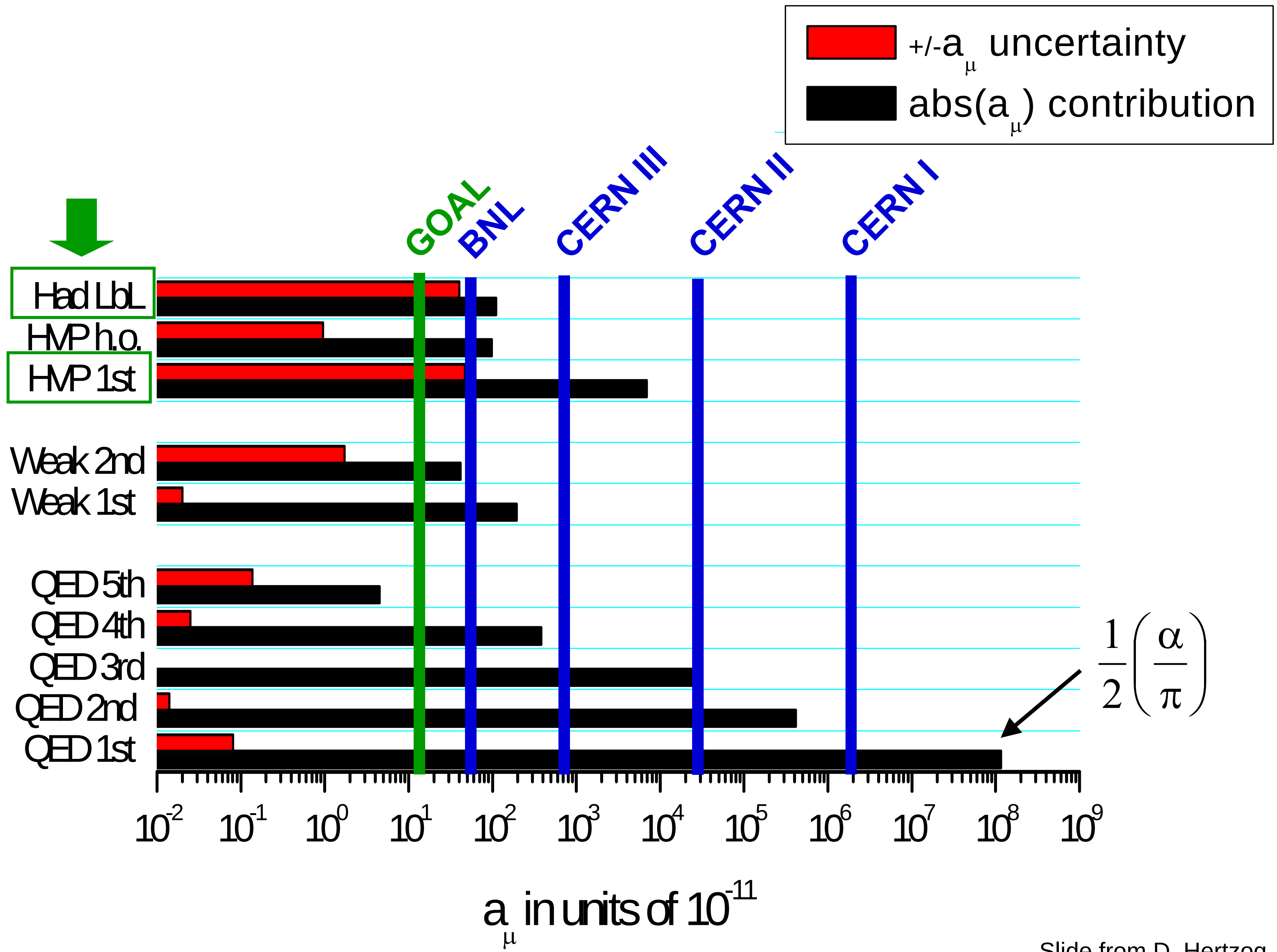
Contribution	Result ($\times 10^{-11}$) units
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 914 \pm 42_{\rm exp} \pm 14_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-98 \pm 1_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 793 \pm 51$

The "g-2 test": Compare experiment to theory. Is SM complete?

$$\delta a_\mu^{NewPhysics} = a_\mu^{Expt.} - a_\mu^{Theory}$$

Slide from D. Hertzog

Historical Evolution



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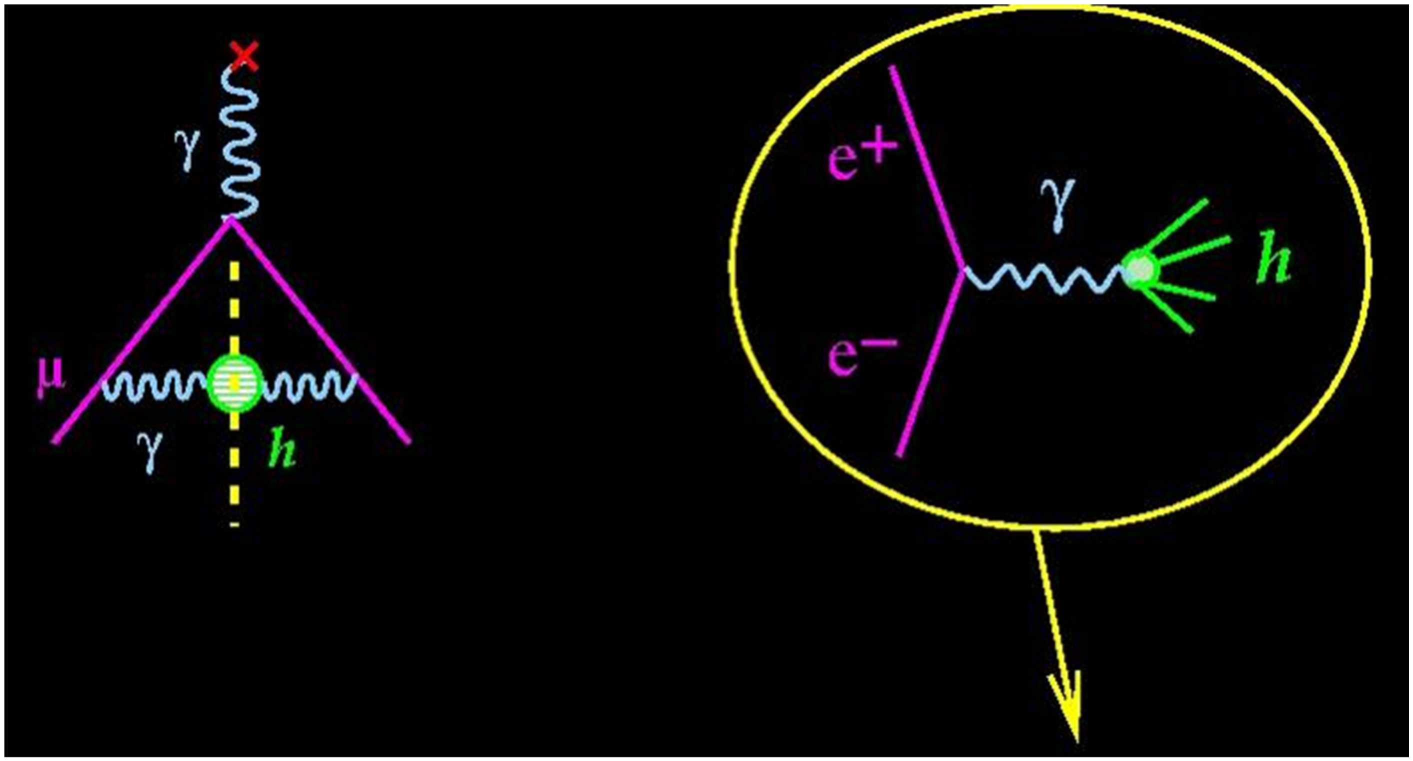
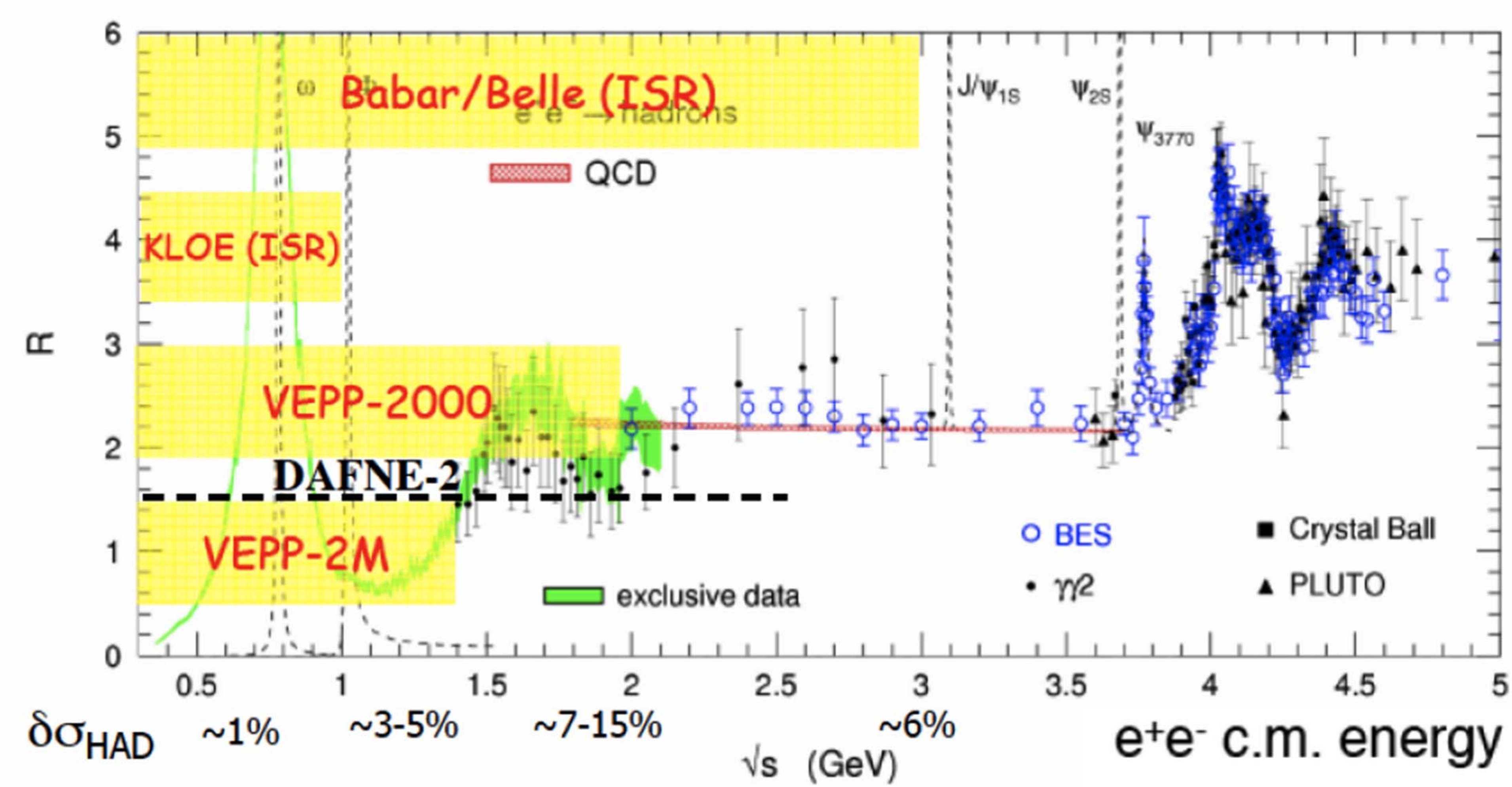
HVP is determined from data



$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$

A world-wide effort exists to measure over full range



$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$

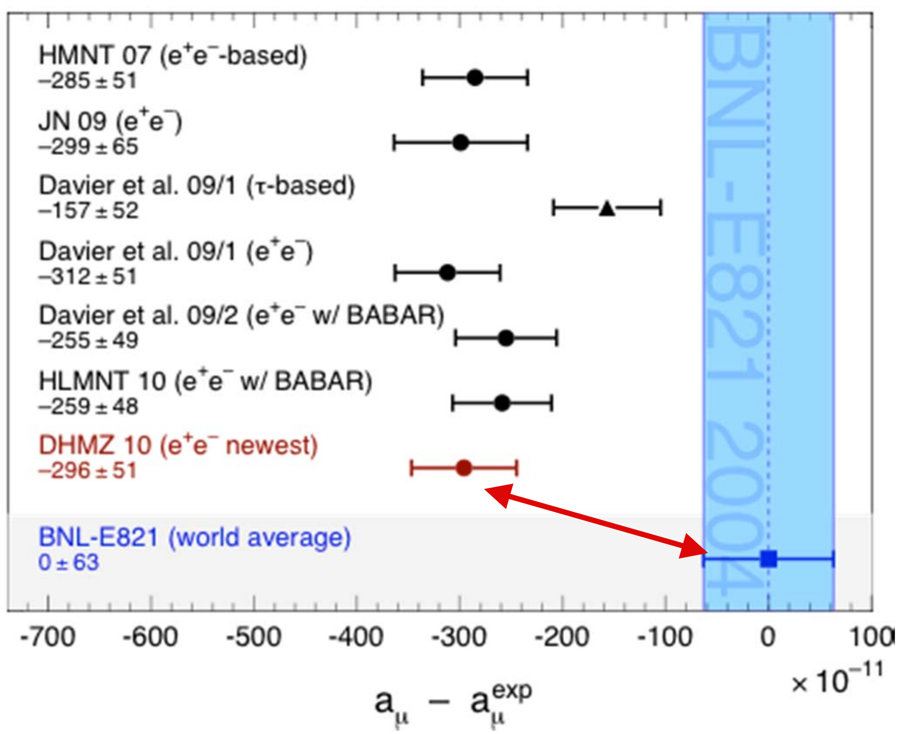
Slide from D. Hertzog

HVP evaluations by 2 groups, updated Tau'10

- Hagiwara, Liao, Martin, Nomura, Teubner (HLMNT)

$$a_\mu^{exp} - a_\mu^{SM} = (259 \pm 81) \times \mathbf{10^{-11}} \rightarrow \mathbf{3.2\ \sigma}$$

- M. Davier, A. Hoecker, B. Malaescu, Z. Zhang (DHMZ)
  - (BaBar team with access to preliminary data)

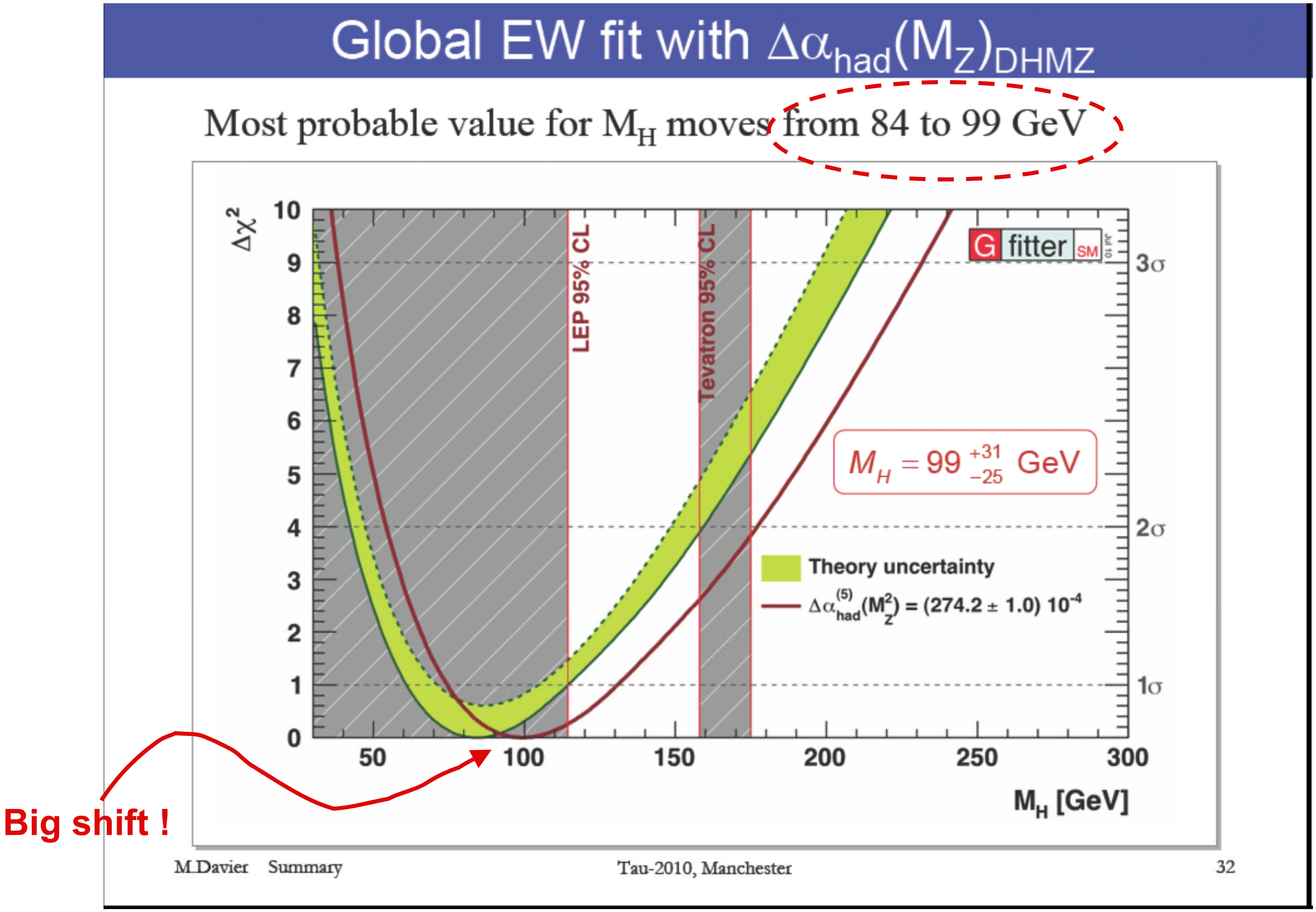


Biggest difference is from high multiplicity states now measured at BaBar; > 1 GeV region
→ Reduces cross sections

$$a_\mu^{exp} - a_\mu^{SM} = (296 \pm 81) \times \mathbf{10^{-11}}$$
$$\Rightarrow \mathbf{3.6\ \sigma}$$

Slide from D. Hertzog

The new HVP evaluations also affect α_{QED} running … and enter the global electroweak fits …



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The values & the new experimental goal

BNL E821

Theory uncertainty = 51 x 10^{-11} (0.44 ppm)

Experimental uncertainty = 63 x 10^{-11} (0.54 ppm)

- **0.46 ppm statistical ← limit was counts**
- **0.21 ppm precession systematic**
- **0.17 ppm field systematic**

$$a_\mu^{Expt} = (116\ 592\ 089\ \pm\ 63) \times 10^{-11}$$

$$a_\mu^{Thy} = (116\ 591\ 793\ \pm\ 51) \times 10^{-11}$$

Leads to Δa_μ(Expt – Thy) = 297 ± 81 x 10^{-11} 3.6 σ

Experimental goal: 63 → 16 x 10^{-11}

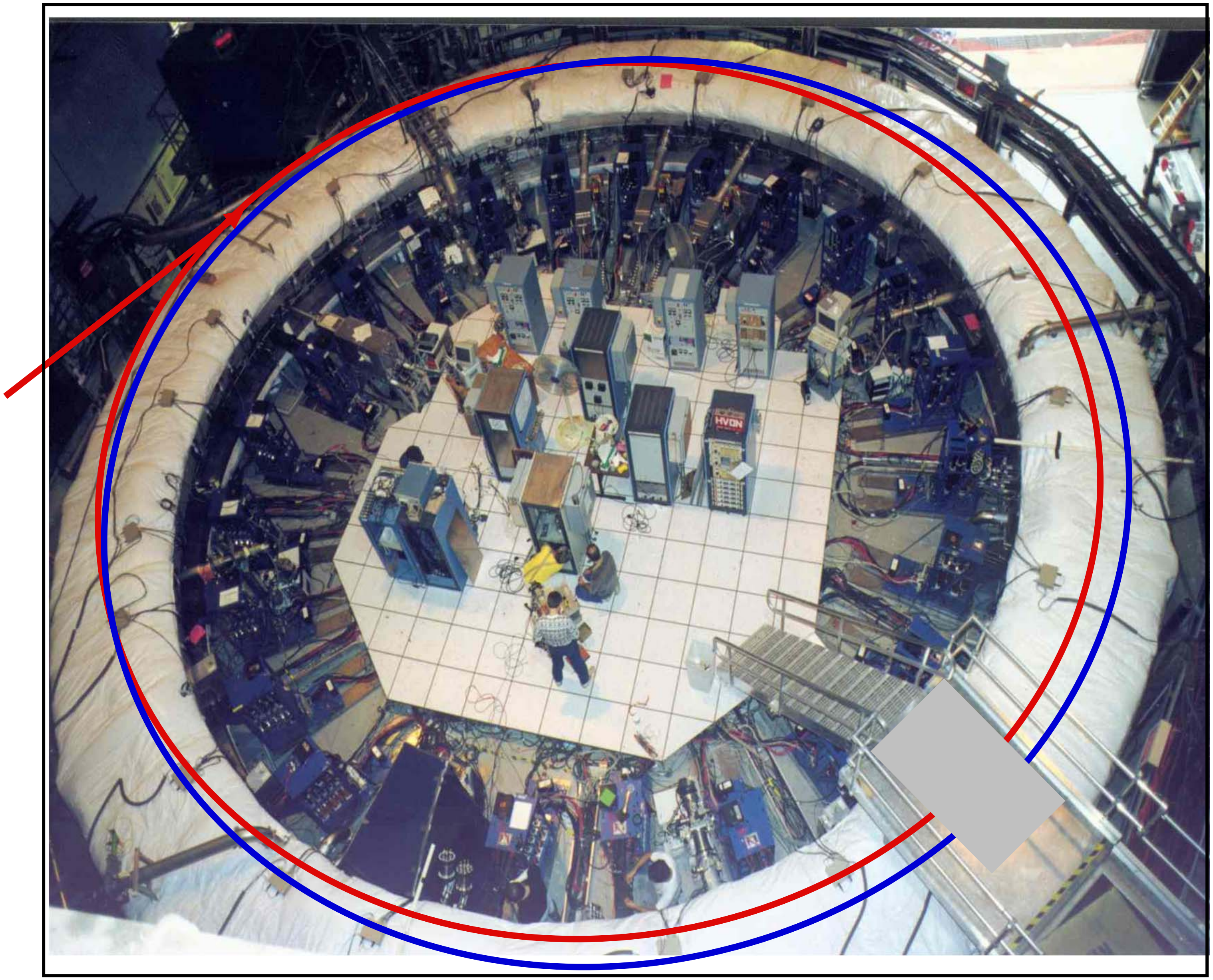
Theory uncertainty expect: 51 → 30 x 10^{-11}

Leads to Δa_μ(Expt – Thy) = XXX ± 34 x 10^{-11}

If central value remained, Δa_μ would exceed 8σ

Slide from D. Hertzog

The Storage Ring exists. It will be <u>moved to FNAL</u>



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- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

Fundamental Symmetries

- Many experimental avenues to explore
- Much to understand about neutrino’s
- Possible signatures for SM deviations from the LHC
- Low-energy SM tests

- A bright future for the field!

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