# Precison muon physics 1

## Muon basics and flavor diagonal measurements


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Fermilab


CTEQ 2018

# The “Standard Model” in early 1930s

$e^{\pm}$

$\gamma$

$p$

$\nu$

Postulated to preserve conservation laws in beta decay.
Pauli: “I created a monster.”

$n$

Recently observed.
Now nuclei make sense.

# New physics in 1930s — theory

*How can protons in nuclei stay together despite electric repulsion?*

## Hideki Yukawa, 1935

New particle (“meson”) to explain nuclear force:

1935] *On the Interaction of Elementary Particles. I.*

Assuming $\lambda = 5\times10^{12}\text{cm}^{-1}$., we obtain for $m_U$ a value $2\times10^2$ times as large as the electron mass. As such a quantum with large mass and positive or negative charge has never been found by the experiment, the above theory seems to be on a wrong line. We can show, however, that, in the ordinary nuclear transformation, such a qnantum can not be emitted into outer space.

*History overview per “Muon physics” edited by Vernon W. Hughes and C.S. Wu*

# New physics in 1930s — experiment

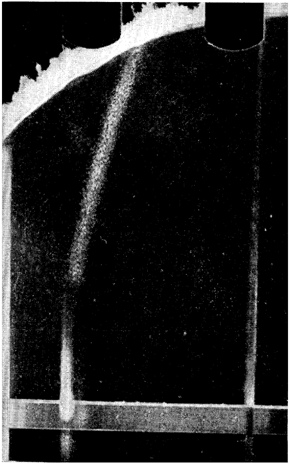
## "Penetrating particle"

- Several groups report charged particle not consistent with electron or proton in cosmic rays.

## J.C. Street and E.C. Stevenson (1937)

**New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron**

to permit an accurate ion count) and an $H\rho$ value of $9.6\times10^4$ gauss cm. If it is assumed, as seems reasonable, that the particle entered from above, the sign is negative. If it is taken that the ionization density varies inversely as the velocity squared, the rest mass of the particle in question is found to be approximately 130 times the rest mass of the electron. Because of uncertainty in the ion count this determination has a probable error of some 25 percent. In any case it does not seem possible to explain this track as due to a proton traveling up, for the observed



# Yukawa meson = mu-meson?

For some time

- Looks like Yukawa meson = mu-meson
- Well done?

10 years later: Conclusive experiment by M. Conversi, E. Pancini, and O. Piccioni

- Selected negative cosmic ray “mesons”
- Stopped in carbon
- Theory: should be absorbed by nuclei via strong force
- Observation: large yield of decay electrons

$\Longrightarrow$ Decay and capture times comparable ($\approx 10^{-6}$ s)

  - Strong interaction timescale $10^{-18}$ s
  - Muons do not interact strongly!

# Who ordered that?


*Image by Roni Harnik*

## Why are there flavor and generations?

*See R. H. Bernstein and P. S. Cooper, Phys. Rept.* **532**, *27 (2013)*

*for a backstory on the Rabi's quote.*

# Another puzzle

If muons are weekly interacting, how so many of them can be produced by cosmic rays?

# Another puzzle

If muons are weekly interacting, how so many of them can be produced by cosmic rays?

- Model builders: two kinds of mesons, one with strong, and one with weak interaction
- The “strong” one can be copiously produced, then decays into the “weak” one
  - Why not into electron?
  - Does not this sound contrived?

# 1947: discovery of the pion and its decay to muon

PROCESSES INVOLVING CHARGED MESONS

By Dr. C. M. G. LATTES, H. MUIRHEAD,
Dr. G. P. S. OCCHIALINI and
Dr. C. F. POWELL
H. H. Wills Physical Laboratory, University of Bristol

between that of a proton and an electron. In continuing our experiments we have found evidence of mesons which, at the end of their range, produce secondary mesons. We have also observed transmutations in

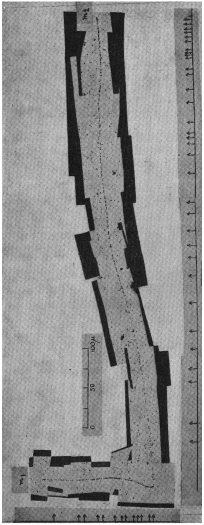



Fig. 1. Observation by Mrs. I. Roberts. Photomicrograph with Cooke × 45 'fluorite' objective. Ilford 'Nuclear Research', boron-loaded C2 emulsion. $m_1$ is the primary and $m_2$ the secondary meson. The arrows, in this and the following photographs, indicate points where changes in direction greater than 2° occur, as observed under the microscope. All the photographs are completely unretouched

# The “contrived” explanation

The quirk of Nature with muon production via strongly interacting pions and long life time weak decay

- Explained cosmic muons
- Also enabled all modern muon experiments:
  intense, clean muon beams are practical to create at accelerators

# Some things we learned from muons

- Similarity of muon decay, muon nuclear capture, and nuclear beta decay coupling constants: new fundamental "weak interaction"
- Together with beta decay, parity violation
- First $\mu \to e\gamma$ searches. Hincks and Pontecorvo (1948): *"each decay electron is not accompanied by a photon of about 50 MeV"*. Sard, Althaus (1948)

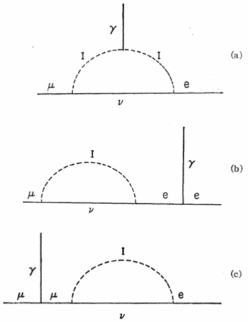
> photon-decay hypothesis. Another way of describing the result is to say that less than 5 percent or so of the mesons decaying in the brass could give rise to a high energy photon.

$\Longrightarrow$ muon is not an excited electron, *generations*

- $\mu \to e\nu\bar{\nu}$

# Beginning of *precision* muon physics

- Four-fermion point interaction non-renormalizable
- Intermediate vector boson to fix that
- Feinberg (1958): then $Br(\mu \to e\gamma) \approx 10^{-4}$
  - 5 times the experimental limit
  - Need 2 types of neutrinos



Feynman diagrams for $\mu \to e + \gamma$ through an intermediate boson. $I$ labels the intermediate boson field.

Enough history!

# The rest of the material

## Today

Muon basics and some “allowed” interactions

- Search for New Physics with normal muon decay ($\mathcal{TWIST}$)
- Muon magnetic moment (g-2), anomaly and the follow up

## Tomorrow

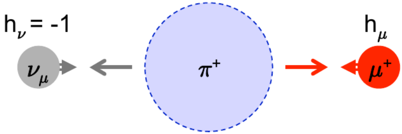
Searches for Charged Lepton Flavor Violation (CLFV) with muons.

# Muon basics

- Charged, spin=1/2, does not interact via strong force
- $m_\mu \approx 106$ MeV $\approx 207 \times m_e$
- Long lifetime: $\tau_\mu = 2.2 \times 10^{-6}$ s
  - can have muon beams
  - $\mu^+$ forms hydrogen-like atoms with $e^-$ (muonium)
  - $\mu^-$ forms hydrogen-like atoms with nuclei: atomic capture
- Atomic capture transitions: $207 \times 13.6$ eV (keV X-rays)
- 1S state radius 207 times smaller $\Longrightarrow$ wavefunction overlap with the nucleus is $(207)^3 = \mathcal{O}(10^7)$ that of electron
- $\mu^-$ nuclear capture: $W$-boson exchange with the nucleus
  $\mu^- + (A, Z) \rightarrow \nu_{mu} + (A', Z') +$ some $\gamma, n, p,$ deuterons, $\ldots$
  Energy scale $= m_\mu$: nuclear physics on steroids.

# Muon production

SM pion decay




In the pion rest frame

- $\pi^+ \rightarrow \mu^+ \nu_\mu$
- $\vec{p}_\mu = -\vec{p}_\nu$
- The neutrino is left-handed (spin opposite momentum)

$\Longrightarrow$ Muon spin must be opposite the muon momentum
100% polarized!

- Two-body decay $\Longrightarrow |\vec{p}_\mu| = 29.8$ MeV/c
N.B. Kinetic energy $T_\mu = 4.1$ MeV
*(Can't be sloppy with E vs p here!)*

# Muon beams: “cloud”

- Protons from an accelerator hit a target
- Pions are produced and fly away
- Pions decay in flight produce muons.
  Boost to the lab frame

  $\Longrightarrow$ “Random” muon momenta

  $\Longrightarrow$ No perfect polarization in the lab frame

# Muon beams: “surface”

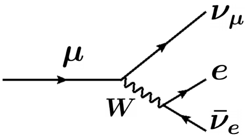
- Most pions stop in the target—use their decay at rest!
- Range of 4.1 MeV muon in material $\approx$ 1 mm

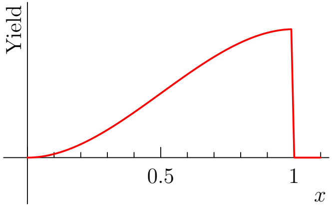
$\Rightarrow$ Secondary beamline with acceptance $\Delta p/p \approx 1\%$ will select muons from a dozen micron thick layer of the target: “surface” beam

- Large phase space density of muons
- Tune to $\approx 29.8$ MeV$/$c
  - Muon pass through minimal amount of material in the target
  - Do not depolarize!

*A.E. Pifer, T. Bowen, K.R. Kendall, NIM **135** (1976) 39*

# Muon decay: the SM



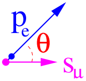




$$\frac{d^2\Gamma}{x^2\,dx\,d\cos(\theta)} \propto 1 - x + \frac{2}{9}\cdot\frac{3}{4}(4x-3)$$

$$+\frac{1}{3}P_\mu\cdot 1\,\cos(\theta)\left[(1-x)+\frac{2}{3}\cdot\frac{3}{4}(4x-3)\right]$$

$$+\,1\,\mathcal{O}(m_e/m_\mu) + \text{Rad. Corrections}$$

$$x = E_e/E_{\text{max}},\ E_{max} = (m_\mu^2 + m_e^2)/(2m_\mu) = 52.8\text{ MeV}$$



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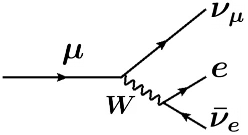


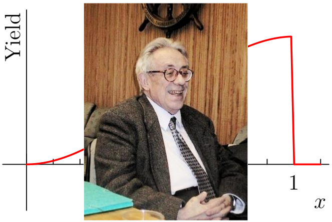

L. Michel

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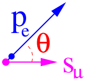

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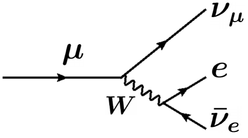


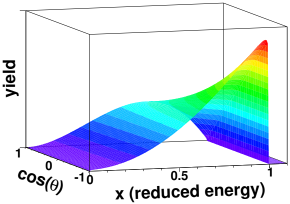


"self-analyzing" decay

$$\frac{d^2\Gamma}{x^2\,dx\,d\cos(\theta)} \propto 1 - x + \frac{2}{9}\cdot\frac{3}{4}(4x-3)$$

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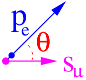

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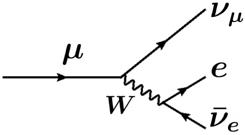


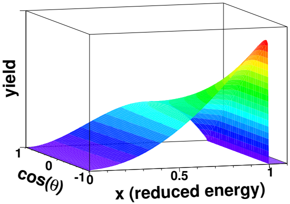


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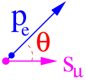


# Muon decay: SM radiative corrections

## Hadronic are small (for experimental precision $\mathcal{O}(10^{-4})$)

$0.07 \times (\alpha/\pi)^2 \approx 0.4 \times 10^{-6}$

*A. I. Davydychev, K. Schilcher and H. Spiesberger, Eur. Phys. J. C* **19**, *99 (2001)*

## Electromagnetic are important

Recent progress motivated by $\mathcal{TWIST}$ measurements:
full $\mathcal{O}(\alpha)$ with exact $m_e$ dependence, leading $\mathcal{O}(\alpha^2\mathcal{L}^2)$ and next-to-leading $\mathcal{O}(\alpha^2\mathcal{L})$, leading $\mathcal{O}(\alpha^3\mathcal{L}^3)$. ($\mathcal{L} = \ln(m_\mu^2/m_e^2)$)

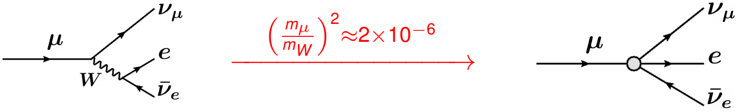
*C. Anastasiou, K. Melnikov and F. Petriello, JHEP* **0709**, *014 (2007)*
*A. Arbuzov, JHEP* **0303**, *063 (2003)*
*A. Arbuzov and K. Melnikov, Phys. Rev. D* **66**, *093003 (2002)*
*A. Arbuzov, A. Czarnecki and A. Gaponenko, Phys. Rev. D* **65**, *113006 (2002)*
*A. B. Arbuzov, Phys. Lett. B* **524**, *99 (2002) Erratum: [Phys. Lett. B* **535**, *378 (2002)]*

# *TWIST*

- SM: precise and unambiguous prediction for electron spectrum from muon decay
- Does it agree with the experiment?
- Let's measure! *Any* deviation would be New Physics!
- Tree level effects in
  - Left-Right symmetric models
  - R-parity violating SUSY
  - Composite leptons
  - Some extra dimensions models
  - Nonlocal tensor interactions
  - ...

To parameterize possible deviations from the SM, *TWIST* uses the effective theory framework:

# Muon decay effective theory




Most general local, derivative free 4-fermion matrix element:

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

$$\Gamma^S = 1, \qquad \Gamma^V = \gamma^\alpha, \qquad \Gamma^T = \frac{i}{\sqrt{2}} \sigma^{\alpha\beta}.$$

*W. Fetscher, H. J. Gerber and K. F. Johnson, Phys. Lett. B* **173**, *102 (1986).*

*“General”? Includes decay to photini, but not scalar neutrini. Extensions with derivatives: M. Chizhov hep-ph/9612399, hep-ph/0405073*

# General 4-fermion continued

- Scalar, vector and tensor interactions.
- Left and right-handed particles.
- 10 complex coupling constants ($g^T_{LL} = g^T_{RR} \equiv 0$)
  - minus overall phase

  $\Longrightarrow$ 19 independent real parameters
- Overall strength: $G_F$, from muon lifetime
- 18 remaining "weak interaction shape" parameters:
  - 16 determined from muon decay
  - 2 from inverse muon decay $\nu_\mu + e^- \to \mu^- + \nu_\mu$
- The Standard Model: $g^V_{LL} = 1$, the rest are zero.

# Michel parameters and the couplings

(Just 4 observables relevant to $\mathcal{TWIST}$ out of 10 total.)

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

$$\eta = 0 + \frac{1}{2}\mathrm{Re}[g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})]$$

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

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

# Aside: positive semidefinite forms

- How can 4 shape (Michel 1950, Bouchiat and Michel 1957) + 6 electron polarization observables (Kinoshita and Sirlin, 1957) constrain 16 parameters without more assumptions?
- Fetscher, Gerber, Johnson above:

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

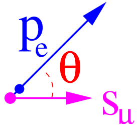
$$0 \le Q_{\varepsilon\mu} \le 1, \quad \text{and} \quad \sum_{\varepsilon\mu} Q_{\varepsilon\mu} = 1 \quad (2)$$

$(\varepsilon, \mu = R, L)$ are relative the probabilities for a $\mu$-handed muon to decay into $\varepsilon$-handed electron.

- Experiment: $Q_{LL} \approx 1$, other $Q_{\varepsilon\mu} \approx 0$

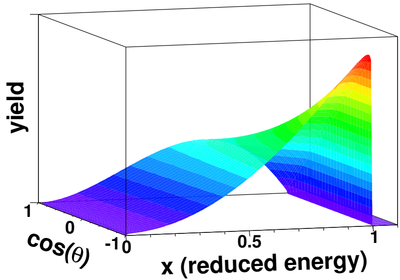
# $\mathcal{TWIST}$ view of muon decay spectrum

$$\frac{d^2\Gamma}{x^2\,dx\,d\cos(\theta)} \propto 1 - x + \frac{2}{9}\rho\,(4x-3)$$
$$+\frac{1}{3}P_\mu\xi\,\cos(\theta)\,\left[(1-x)+\frac{2}{3}\,\delta\,(4x-3)\right]$$
$$+\,\eta\,\mathcal{O}(m_e/m_\mu) + \text{Rad. Corrections}$$

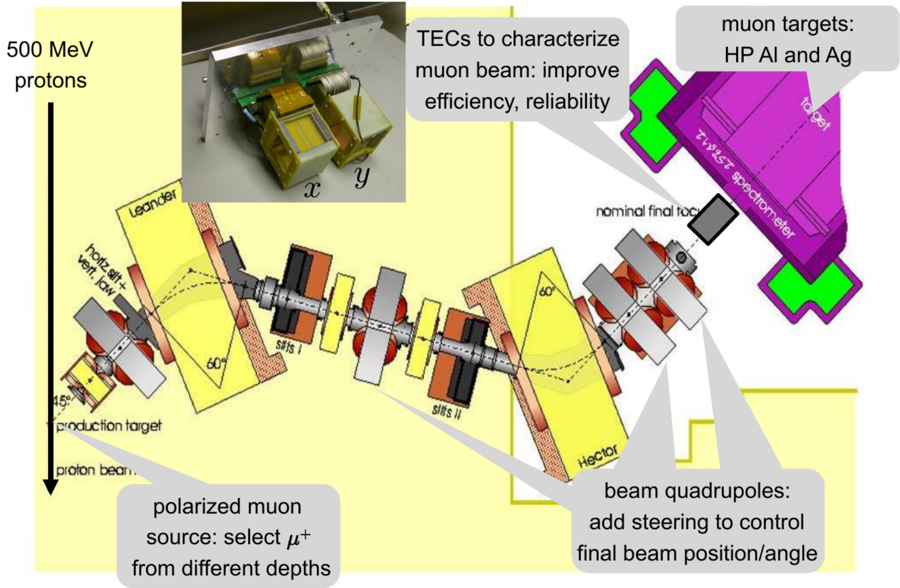



$x = E_e/E_{\max}$

- $\mathcal{TWIST}$ directly measures $\rho$, $P_\mu\xi$, $\delta$.
- Improves constraints on $\eta$ via a global fit of muon decay measurements



# TWIST: muon production and transport



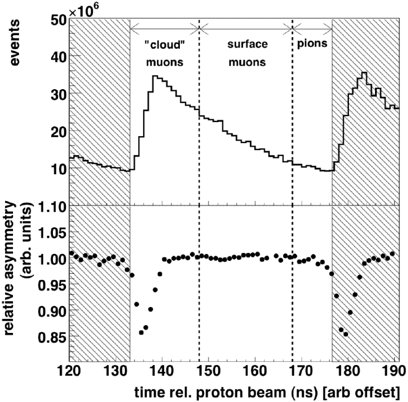
# Surface muon beam

## Recall

- Muons perfectly polarized at production

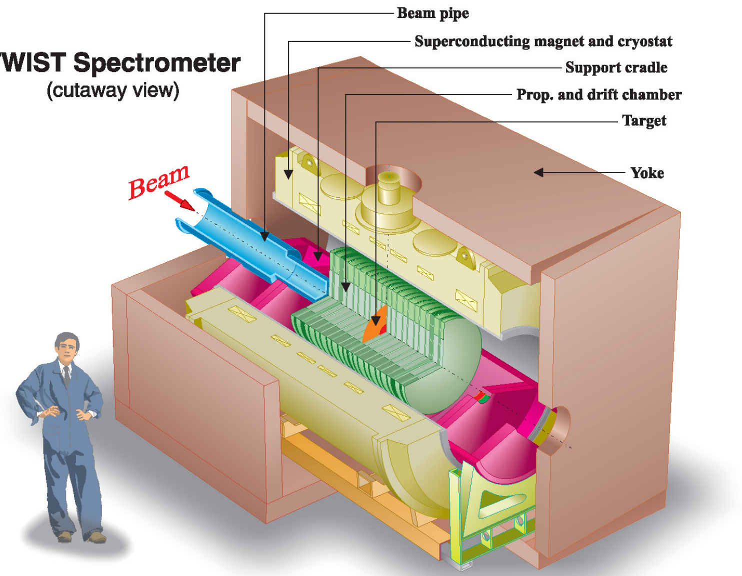
## Control loss of polarization:

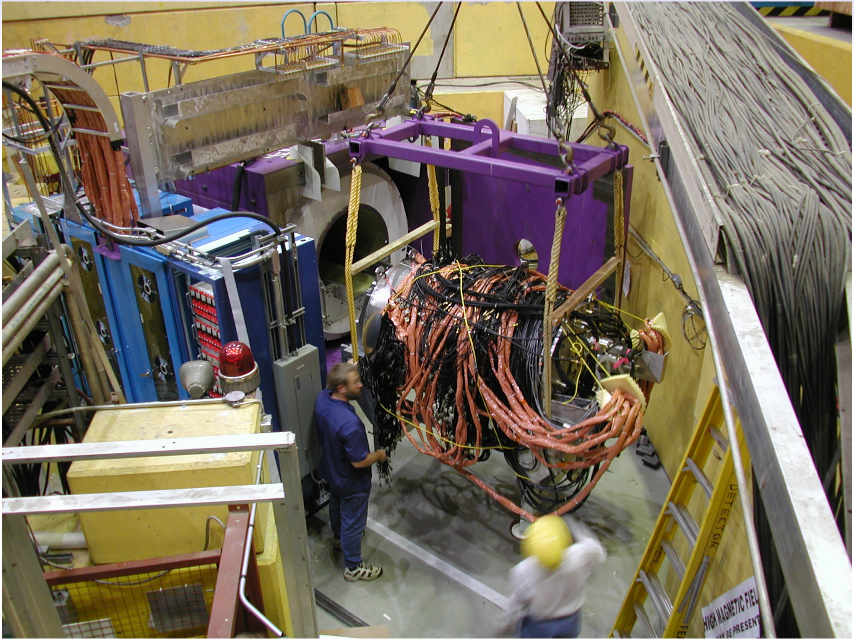
- narrow momentum acceptance near 29.8  MeV/c
- TOF selection for DAR
- small solid angle



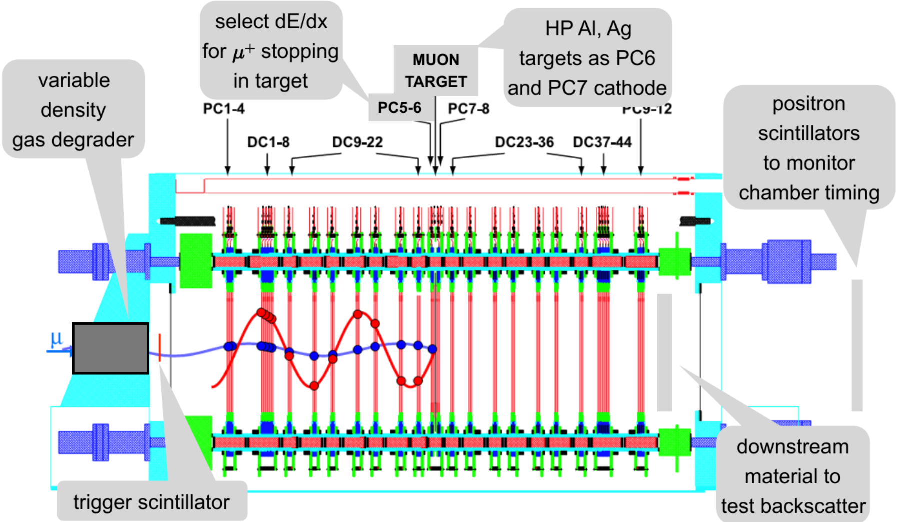

*J. Bueno et al., Phys. Rev. D* **84**, *032005 (2011)*

# TWIST Spectrometer
(cutaway view)




DETECTOR

# TWIST detector close-up



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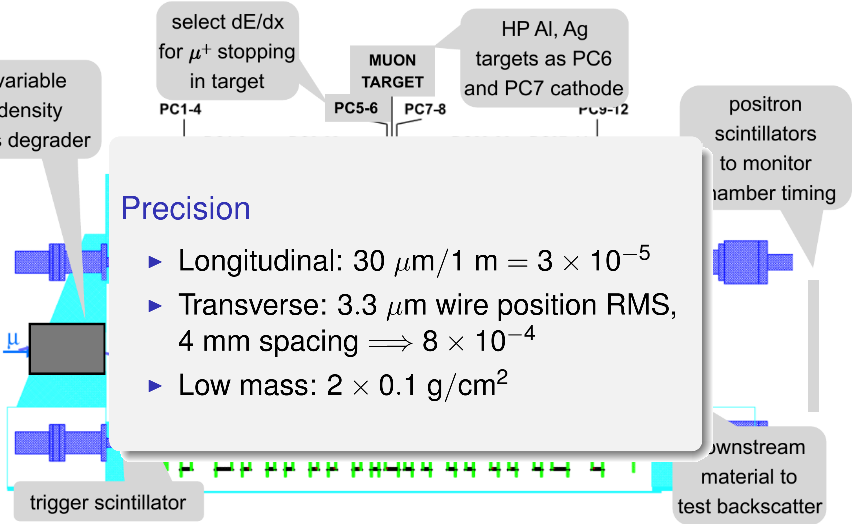
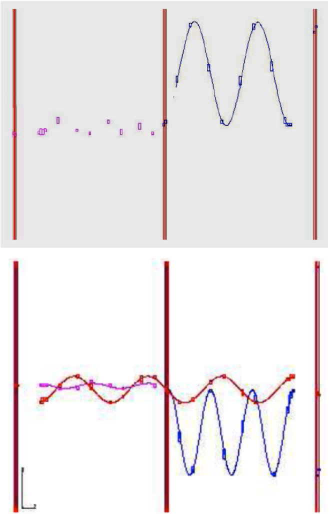



## Precision

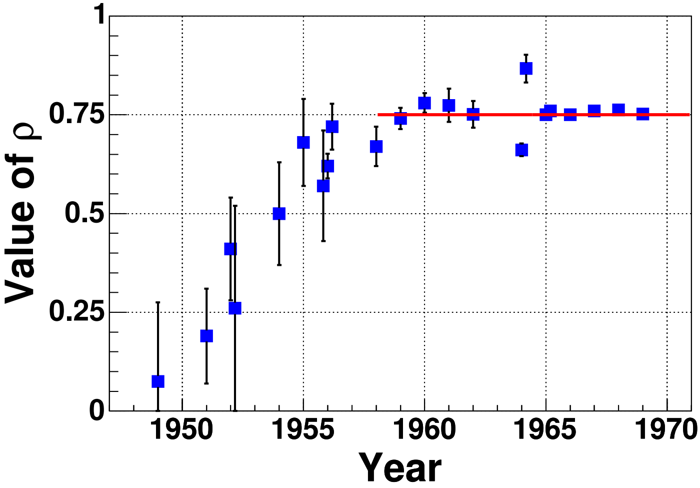
- Longitudinal: 30 $\mu$m$/$1 m $= 3 \times 10^{-5}$
- Transverse: 3.3 $\mu$m wire position RMS, 4 mm spacing $\Longrightarrow 8 \times 10^{-4}$
- Low mass: $2 \times 0.1$ g$/$cm$^2$

# TWIST events

- Beam rate (2–5) $\times$ $10^3$ $\mu^+$/s:
  one muon at a time!
- Unbiased trigger on incoming muon (thin scintillator)
- Read out all detector activity from 6 $\mu$s before to 10 $\mu$s after trigger ($\tau_\mu = 2.2$ $\mu$s)



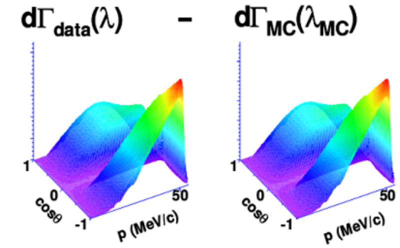
# Measurement history of Michel parameter $\rho$

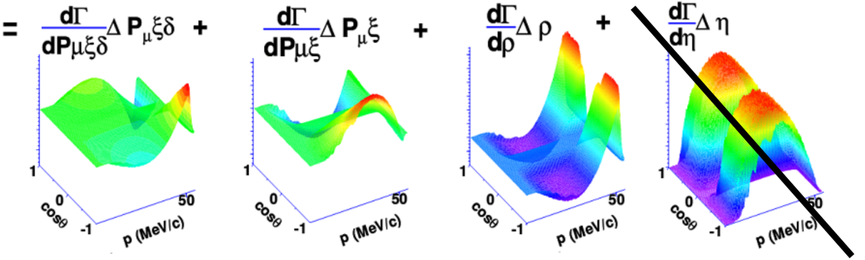



We performed a blind analysis…

# TWIST: blind fit of 2D spectrum

- fit data to normalized GEANT3 simulation
- use linearity in $\mathcal{P}_\mu\xi$, $\mathcal{P}_\mu\xi\delta$, $\rho$, $\eta$
- measure ***differences*** from hidden parameters $\lambda_{MC}$ .



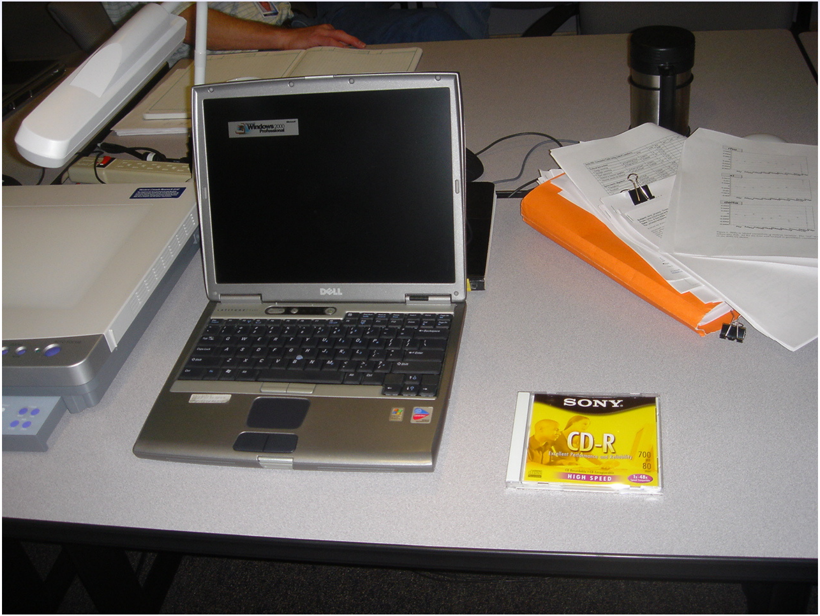




*A.Gaponenko, arXiv:1104.2914*

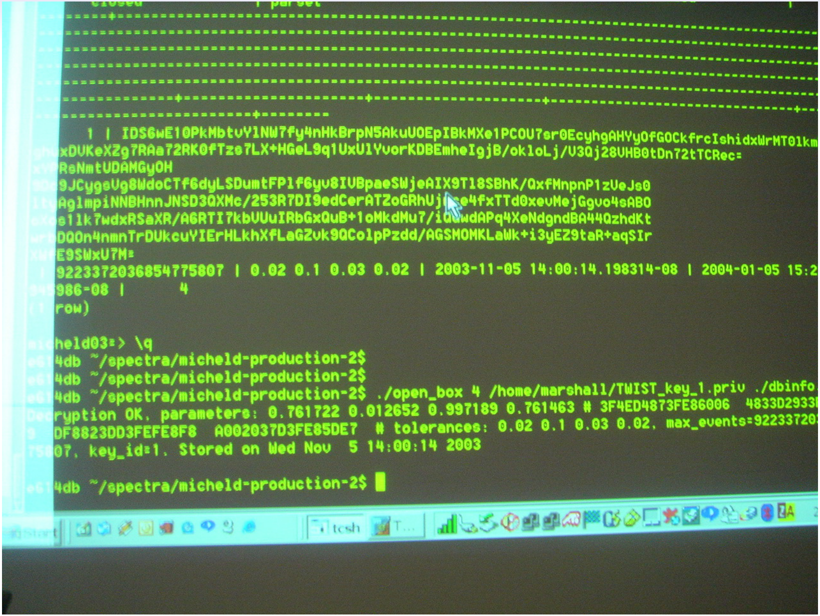
# Datasets and systematics

- About 1 week to take a dataset of $\mathcal{O}(10^9)$ triggers
- Dozens of datasets with modified conditions to measure systematics from data
  - solenoid field
  - muon beam tune
  - muon stopping position
  - ...
- Years of analysis
  - First results: released in 2004 from data taken in 2002
  - Final results: released in 2010 from 2006, 2007 data.
- Ready to open the box!

# The first $\mathcal{TWIST}$ black box opening story


SONY
CD-R
HIGH SPEED
DELL


TWIST Day 1
CD-R
Copy 2


1 | IDS6wE10PkMbtvY1NW7fy4nHkBrpN5AkuUOEpIBkMXe1PCOU7sr0EcyhgAHYy0fGOCkfrcIshidxWrMT01km
xDUKeXZg7RAa72RK0fTzs7LX+HGeL9q1UxUlYvorKDBEmheIgjB/okloLj/V3Qj28UHB0tDn72tTCRec=
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e4fxTTd0xevMejGgvo4sABO
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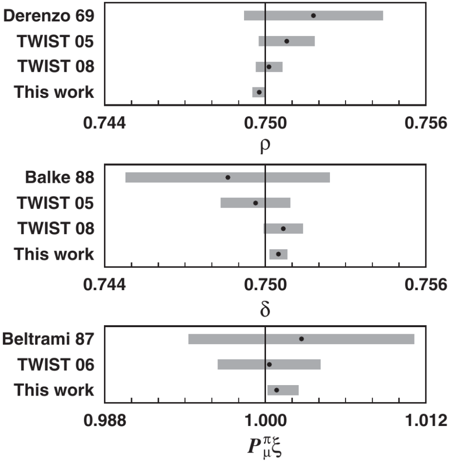
DQOn4nmnTrDUkcuYIErHLkhXfLaGZvk9QColpPzdd/AGSMOMKLaWk+i3yEZ9taR+aqSIr
E9SWxU7M=
9223372036854775807 | 0.02 0.1 0.03 0.02 | 2003-11-05 14:00:14.198314-08 | 2004-01-05 15:2
986-08 | 4
row)
held03=> \q
4db ~/spectra/micheld-production-2$
4db ~/spectra/micheld-production-2$
4db ~/spectra/micheld-production-2$ ./open_box 4 /home/marshall/TWIST_key_1.priv ./dbinfo
ryption OK, parameters: 0.761722 0.012652 0.997189 0.761463 # 3F4ED4873FE86006 4833D2933
DF8823DD3FEFE8F8 A002037D3FE85DE7 # tolerances: 0.02 0.1 0.03 0.02, max_events=92233720
07, key_id=1, Stored on Wed Nov 5 14:00:14 2003
4db ~/spectra/micheld-production-2$
tcsh

# Final TWIST results




$$\rho = 0.74977 \pm 0.00012(\text{stat}) \pm 0.00023(\text{syst})$$

$$\delta = 0.75049 \pm 0.00021(\text{stat}) \pm 0.00027(\text{syst})$$

$$P_\mu \xi = 1.00084 \pm 0.00029(\text{stat}) {}^{+0.00165}_{-0.00063}(\text{syst})$$

*R. Bayes et al., PRL* **106**, *041804 (2011)*

# TWIST results: global fit

## Effective theory couplings

(Pre-$\mathcal{TWIST}$ values in parentheses)

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

## New constraint on right-handed muon interactions

$$
Q^{\mu}_{R} \equiv Q_{LR} + Q_{RR} = \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2
$$

$$
< 8.2 \times 10^{-4} \quad 90\%\text{C.L.}
$$

*A. Hillairet et al., Phys. Rev. D* **85**, *092013 (2012)*

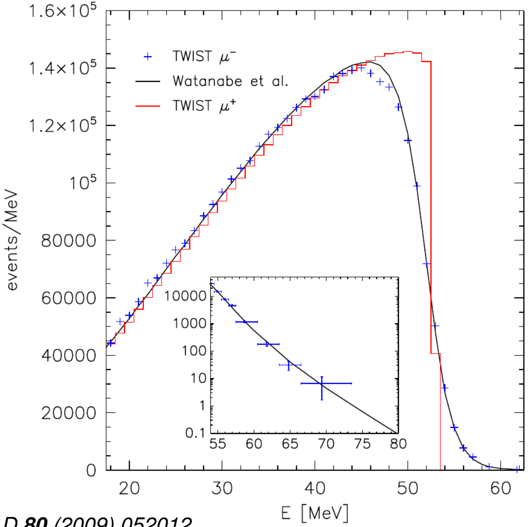
# What about $\mu^-$?

- The results above are for $\mu^+$
- Can we just flip beamline magnet polarity and measure $\mu^-$ decay?
- Should not it be “the same” by CPT?

# $\mathcal{TWIST}$ $\mu^-$ measurement

Cloud beam. Expect $\mu^-$ spectrum to differ from $\mu^+$.

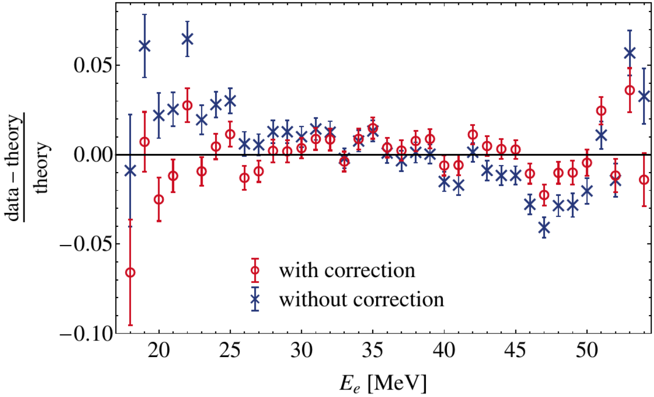
Still data $\neq$ theory.




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

# Theory fixed in 2014

The spectrum of electrons from muons decaying in an atomic bound state is significantly modified by their interaction with the nucleus. Somewhat unexpectedly, its first measurement, at the Canadian laboratory TRIUMF, differed from basic theory. We show, using a combination of techniques developed in atomic, nuclear, and high-energy physics, that radiative corrections eliminate the discrepancy. In addition to




*A. Czarnecki, M. Dowling, X. Garcia i Tormo, W. J. Marciano and R. Szafron, Phys. Rev. D* ***90****, no. 9, 093002 (2014)*

# $g-2$

# What is “g”?

- Magnetic moment for a classical system of point charges

$$\vec{\mu} = \sum_i \frac{q_i}{2m_i c} \vec{L}_i$$

- Quantum

$$\vec{\mu} = g \frac{q}{2mc} \vec{S}$$

Dirac particles: $g = 2$

# What is "g"?

- Magnetic moment for a classical system of point charges

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Dirac particles: $g = 2$

## But real life is messier

constant magnetic field. The ratios of the $g_J$ values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L = 1$ and $g_S = 2(1.00119 \pm 0.00005)$. The possibility that the observed effects

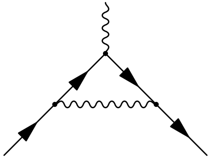
P. Kusch and H. M. Foley, Phys. Rev. **74**, no. 3, 250 (1948).

# Radiative corrections

## Schwinger

$$g_e = 2\,(1 + \frac{\alpha}{2\pi}) \approx 2(1 + 0.00116)$$

(Usual notation: $a = (g - 2)/2$)



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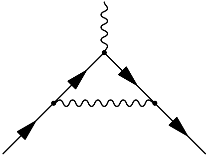
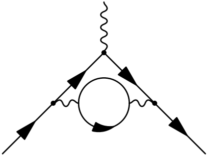
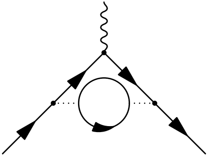


## But there is more





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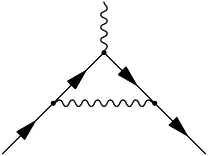
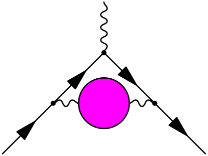
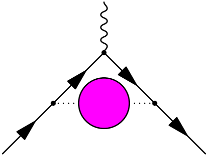


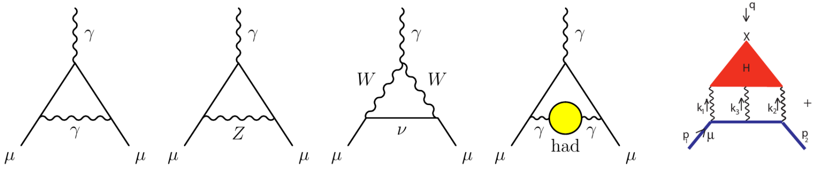
## But there is more





What else is in the loops? *Just* the particles we know about?

# Need to understand the SM




QED Electroweak HVP LBL

Many thousands of diagrams have been computed, then…

# BNL E821 result

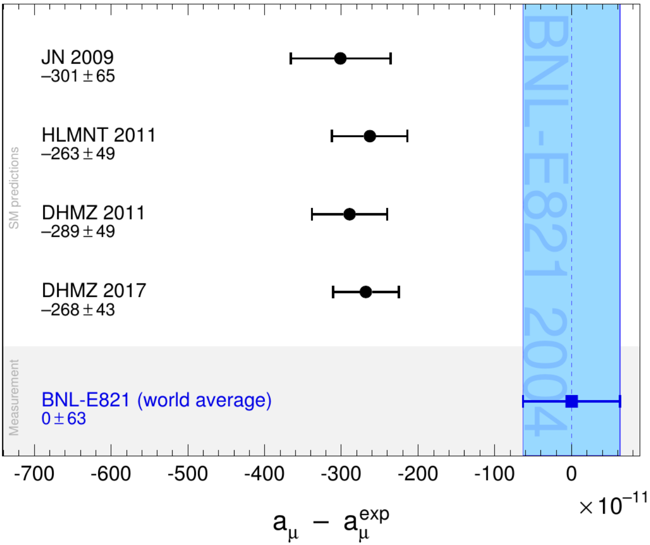



*Figure from PDG 2018 review*

G. W. Bennett *et al.* [Muon g-2 Collaboration], Phys. Rev. D **73**, 072003 (2006)

# What's next?

- The discrepancy

$$\Delta a_\mu = a_\mu^{\text{expt}} - a_\mu^{\text{SM}}$$
$$= (268 \pm 63(\text{expt}) \pm 43(\text{theory})) \times 10^{-11}$$

  is $3.5\sigma$: large, but not conclusive [PDG 2018]
- Need to better understand the SM
- Need a better measurement

# Thanks!

A lot of material here was borrowed from, or inspired by

- Bob Bernstein
- Jason Bono
- Glen Marshall
- Brendan Kiburg
- Chris Polly
- The history overview is mostly per "Muon physics", vol 1, ed. Vernon W. Hughes and C.S. Wu, New York, 1977