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Contacts: C. Polly – Project Manager (polly@fnal.gov)
M.E. Convery – Deputy Project Manager (convery@fnal.gov)
D. Hertzog – Co-Spokesperson (hertzog@uw.edu)
B. L. Roberts – Co-Spokesperson (roberts@bu.edu)

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Muon $(g-2)$ Technical Design Report

E989 Collaboration

J. Grange, V. Guarino, P. Winter, K. Wood, and H. Zhao
Argonne National Laboratory, Lemont, IL, USA

R.M. Carey, D. Gastler, E. Hazen, N. Kinnaird, J.P. Miller, J. Mott, A. Palladino, and B.L. Roberts[1]
Boston University, Boston, MA, USA

J. Benante, J. Crnkovic, W.M. Morse, H. Sayed, and V. Tishchenko
Brookhaven National Laboratory, Upton, NY, USA

V.P. Druzhinin, B.I. Khazin, I.A. Koop, I. Logashenko, Y.M. Shatunov, and E. Solodov
Budker Institute of Nuclear Physics, Novosibirsk, Russia

M. Korostelev, D. Newton, and A. Wolski
The Cockcroft Institute, Daresbury and University of Liverpool, Liverpool, United Kingdom

R. Bjorkquist, A. Chapelain, N. Eggert, A. Frankenthal, L. Gibbons, S. Kim, A. Mikhailichenko, Y. Orlov, D. Rubin, and D. Sweigart
Cornell University, Ithaca, NY, USA

D. Allspach, G. Annala, E. Barzi, K. Bourland, G. Brown, B.C.K. Casey, S. Chappa, M.E. Convery, B. Drendel, H. Friedsam, T. Gadfort, K. Hardin, S. Hawke, S. Hayes, W. Jaskierny, C. Johnstone, J. Johnstone, V. Kashikhin, C. Kendziora, B. Kiburg, A. Klebaner, I. Kourbanis, J. Kyle, N. Larson, A. Leveling, A.L. Lyon, D. Markley, D. McArthur, K.W. Merritt, N. Mokhov, J.P. Morgan, H. Nguyen, J-F. Ostiguy, A. Para, C.C. Polly[2], M. Popovic, E. Ramberg, M. Rominsky, D. Schoo, R. Schultz, D. Still, A.K. Soha, S. Strigonov, G. Tassotto, D. Turrioni, E. Villegas, E. Voirin, G. Velev, L. Welty-Rieger, D. Wolff, C. Worel, J-Y. Wu, and R. Zifko
Fermi National Accelerator Laboratory, Batavia, IL, USA

K. Jungmann and C.J.G. Onderwater
University of Groningen, Groningen, The Netherlands

P.T. Debevec, S. Ganguly, M. Kasten, S. Leo, K. Pitts, and C. Schlesier
University of Illinois at Urbana-Champaign, Urbana, IL, USA

K. Giovanetti
James Madison University, Harrisonburg, VA, USA

V.A. Baranov, V.N. Duginov, N.V. Khomutov, V.A. Krylov, N.A. Kuchinskiy, and V.P. Volnykh
Joint Institute for Nuclear Research, Dubna, Russia

M. Gaisser, S. Haciomeroglu, Y-I. Kim, S. Lee, M-J Lee, and Y.K. Semertzidis
Institute for Basic Science and KAIST, Daejeon, Republic of Korea

E. Won
KAIST and Korea University, Seoul, Republic of Korea

C. Crawford, R. Fatemi, W.P. Gohn, T.P. Gorringe, W. Korsch, and B. Plaster
University of Kentucky, Lexington, KY, USA

A. Anastasi[3], D. Babusci, S. Dabagov[4], C. Ferrari[5], A. Fioretti[5], C. Gabbanini[5], D. Hampai, A. Palladino, and G. Venanzoni
Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy

T. Bowcock, J. Carroll, S. Charity, B. King, S. Maxfield, K. McCormick, J. Price, D. Sim, A. Smith, T. Teubner, W. Turner, M. Whitley, and M. Wormald
University of Liverpool, Liverpool, United Kingdom

R. Chislett, S. Kilani, M. Lancaster, E. Motuk, T. Stuttard, and M. Warren
University College London, London, United Kingdom

D. Flay, D. Kawall, and Z. Meadows
University of Massachusetts, Amherst, MA, USA

T. Chupp, R. Raymond, and A. Tewlsey-Booth
University of Michigan, Ann Arbor, MI, USA

M.J. Syphers and D. Tarazona
Michigan State University, East Lansing, MI, USA

J. Holzbauer, B. Quinn, and W. Wu
University of Mississippi

S. Catalonotti[6], R. Di Stefano[7], M. Iacovacci[6], and S. Mastroianni
INFN, Sezione di Napoli, Napoli, Italy

S. Chattopadhyay, M. Eads, M. Fortner, D. Hedin, and N. Pohlman
Northern Illinois University, DeKalb, IL, USA

A. de Gouvea
Northwestern University, Evanston, IL, USA

B. Abi, F. Azfar, and S. Henry
University of Oxford, Oxford, United Kingdom

F. Gray
Regis University, Denver, CO, USA

G. Di Sciascio and D. Moricciani
INFN, Sezione di Roma Tor Vergata, Roma, Italy

C. Fu, X. Ji, L. Li, and H. Yang
Shanghai Jiao Tong University, Shanghai, China

D. Stöckinger
Technische Universität Dresden, Dresden, Germany

J. Ritchie
University of Texas, Austin

G. Cantatore[8], D. Cauz[9], M. Karuza[10], G. Pauletta[9], and L. Santi[9]
INFN, Sezione di Trieste e G.C. di Udine, Italy

S. Baeßler, M. Bychkov, E. Frlez, and D. Pocanic
University of Virginia, Charlottesville, VA, USA

L.P. Alonzi, M. Fertl, A. Fienberg, N. Froemming, A. Garcia, D.W. Hertzog[1], J. Kaspar, P. Kammel, R. Osofsky, M. Smith, E. Swanson, and T. van Wechel
University of Washington, Seattle, WA, USA

K. Lynch
York College, CUNY, Jamaica, NY, USA

Friday 12th June, 2015

[1]Co-spokesperson
[2]Project Manager
[3]Dipartimento di Fisica e di Scienze della Terra dell'Università di Messina, Messina, Italy
[4]Lebedev Physical Institute and NRNU MEPhI, Moscow, Russia
[5]Istituto Nazionale di Ottica, UOS Pisa, Consiglio Nazionale delle Ricerche, Italy
[6]Università di Napoli, Napoli, Italy
[7]Università di Cassino, Cassino, Italy
[8]Università di Trieste, Trieste, Italy
[9]Università di Udine, Udine, Italy
[10]University of Rijeka, Rijeka, Croatia

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Executive Summary

The Muon $g-2$ Experiment, E989 at Fermilab, will measure the muon anomalous magnetic moment, $a_\mu \equiv (g-2)/2$, to unprecedented precision: the goal is 0.14 parts per million (ppm). The worth of such an undertaking is coupled to the fact that the Standard Model (SM) prediction for a_μ can also be determined to similar precision. As such, the comparison between experiment and theory provides one of the most sensitive tests of the completeness of the model. The Brookhaven-based E821 experiment, which completed data taking in 2001, determined a_μ(Expt) to 0.54 ppm. Steady improvements in theory since that time have resulted in a present SM uncertainty on a_μ(SM) of 0.42 ppm. The experimental measurement and SM predictions differ by 3.3 to 3.6 standard deviations, depending on which evaluation of the lowest-order hadronic contribution in the SM is used:

$$\Delta a_\mu(\text{Expt} - \text{SM}) = (286 \pm 80) \times 10^{-11} \quad (1)$$

$$= (260 \pm 78) \times 10^{-11} \quad (2)$$

(see Chapter 2 for details). This is a highly cited result, owing in part to the many natural SM extensions, from supersymmetry to dark photons, that could cause such an effect. The planned four-fold improvement in experimental precision compared to E821, could establish beyond doubt a signal for new physics—if the central value of the measurement remains unchanged. During the time it will require to mount, run and analyze the data, the SM hadronic predictions are expected to become even more precise; thus the comparison of experiment to theory will be quite powerful, no matter what final values are found. The Motivation for the new experiment and a detailed exposition on the SM theory is provided in Chapter 2 of this document.

The original E989 Proposal, and the additional design work now completed in preparation of this Technical Design Report (TDR), outline a credible plan to achieve the experimental goal in a timely and cost-efficient manner. The approach is anchored by the re-use of the existing precision muon storage ring, an efficient and parasitic deployment of the Fermilab proton complex and beamlines, and strategic upgrades or replacements of outdated or under-performing components from E821. The experiment will be carried out by a collaboration of accelerator, atomic, nuclear and particle physicists, drawing from domestic and international universities and national laboratories. The collaboration retains a strong core of experienced participants from BNL E821, augmented by many new groups selected for their expertise in areas that are required to mount a next-generation experiment.

In many ways, E989 is a unique, large-scale Project. Several core aspects involve proven elements from E821 that will be retained in whole or with minor upgrades. This is especially true for the storage ring elements and the magnetic field measuring tools, which will be relocated, re-assembled and restored to operation. Many of these items are well beyond a normal TDR stage in terms of design; indeed, they exist and often require no more than testing and minor repair. In contrast, several items have been identified as requiring a new approach to meet the demands of a higher rate experiment with lower systematic uncertainties. Chief among them is a new storage ring kicker and, possibly, a new inflector magnet. The storage-ring electrostatic quadrupoles will undergo an operational upgrade and one set will be redesigned to better allow for the beam passage through them as it enters the storage

ring. The beam position mapping will employ a unique in-vacuum tracking system and the instrumentation for the precession frequency measurement—calorimeters, fast digitizers and modern data acquisition—will all be new. Naturally, the entire pion-to-muon beam path from target to storage ring is unique at Fermilab.

The BNL experiment was statistics limited. With a persistent and tantalizing hint of new physics, it has been recognized for many years that a next-generation effort is required to lead to a true discovery. A number of informal studies led to the realization that relocation of the storage ring to Fermilab would provide the ideal environment for the next generation experiment. The Booster, the Recycler, and the existing antiproton target station can be used to acquire a 20-fold increase in statistics in a timely manner. One can take direct advantage of the experience with the unique and well-understood storage ring developed for E821. The proposed beam environment and relatively modest experimental upgrades would provide a better measurement environment that will lead to reduced systematic uncertainties. The E989 Proposal was presented to the Fermilab PAC in March 2009. Cost evaluations by an independent committee followed, and beam delivery studies were initiated. Following the completion of the Proton Improvement Plan, Fermilab can service the NOνA experiment fully and provide excess proton cycles to adequately meet the unique needs of the $g-2$ experiment. The experimental technical approach described in this TDR is conservative. It is built on the foundation and lessons learned from several generations of $g-2$ experiments at CERN and then Brookhaven, and we retain key personnel that provide necessary overlap with the most recent effort.

The beam-use plan has evolved further such that it now largely overlaps with the needs of the Mu2e Experiment. Together, $g-2$ and Mu2e have become the first tenants of the new Muon Campus, which involves several buildings, beamlines and infrastructure support. A new general purpose building, MC-1, has been designed with specific attention to the needs of the $g-2$ experiment—e.g., stable floor, temperature control to $\pm 2^\circ$ F, and the necessary services. Ground-breaking for MC-1 occurred in May, 2013 and beneficial occupancy occured in May 2014.

Following the Project Overview, the TDR is organized as follows. We begin with chapters on the physics motivation—including the discussion standard-model and non-standard-model physics—and the experimental strategy. The measurement involves ambitious statistical and systematic uncertainty goals. Chapter 5 then provides a road map that summarizes our plans to meet the statistical and systematic uncertainty targets. The factors contributing to these estimates are distributed throughout the document, as they fall into different WBS categories, so this chapter also provides both short descriptions of the factors that underlie the uncertainty targets, and pointers to the specific sections that discuss the topics in detail. The bulk of the TDR then describes the experimental design that can reach those targets, from production and delivery of the muon beam through to the slow controls and monitoring of the data taking process.

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