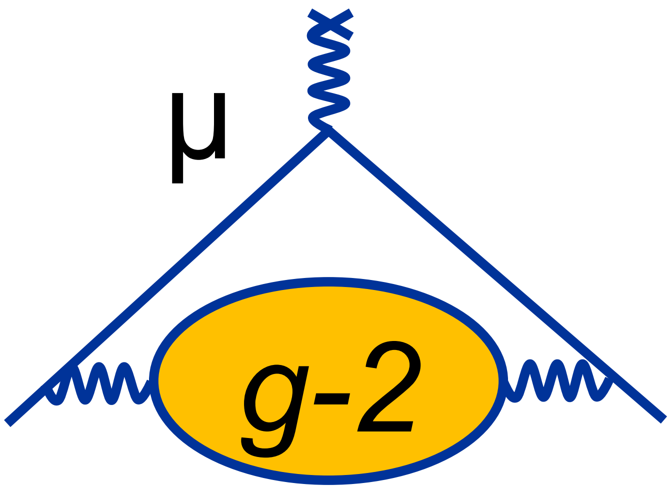
The Muon Program at Fermilab

HEPAP Meeting, Bethesda, MD:
Nov 21-22, 2019

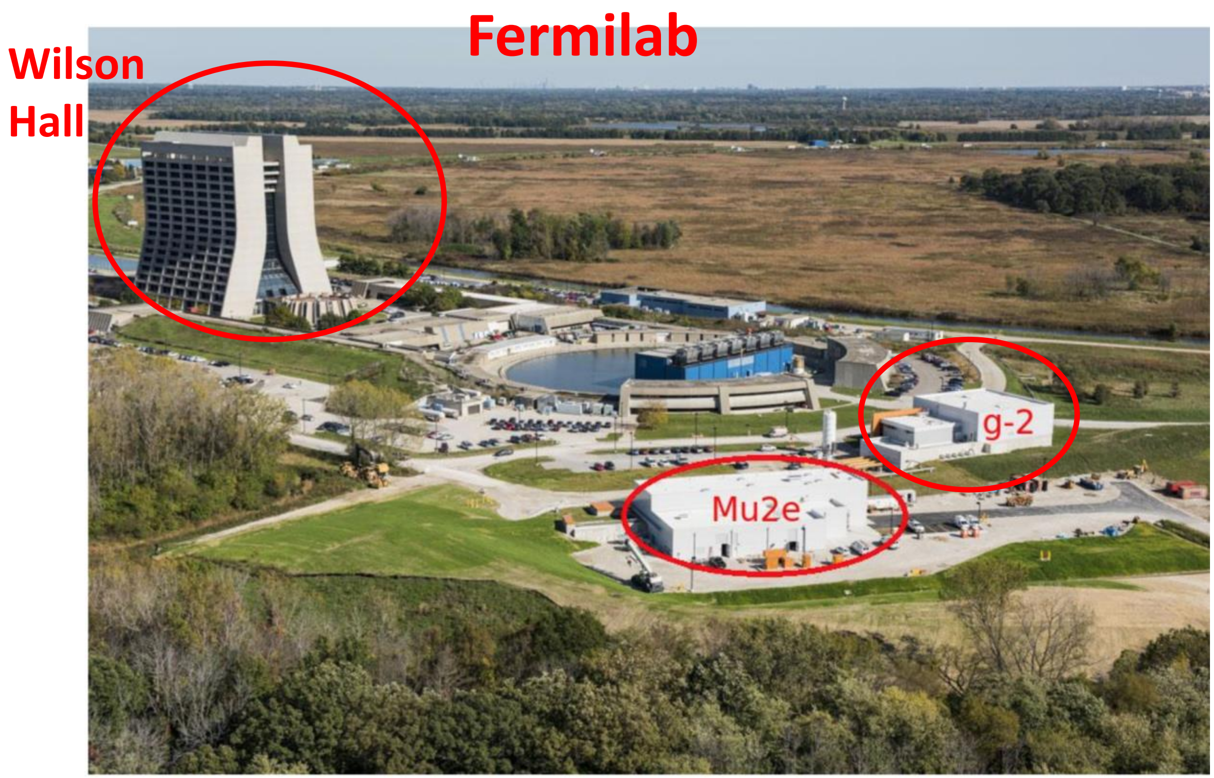
Jim Miller

Boston University



Muon Program: Muon g-2 and Mu2e

- The Muon Program consists of two experiments and the associated beam line development.
- Mu2e and Muon g-2 experiments share common beam-line elements, partly using repurposed Tevatron facilities.
- Both buildings are complete.
- Muon g-2 is taking data now.
- Mu2e is under construction.
- Both need pulsed beams.
- g-2 needs 3.1 GeV/c muons injected into the g-2 storage ring.
- Mu2e needs a large flux of very low energy negative muons that can stop in a thin target.



Completed Muon Campus at Fermilab

P5 Recommendations: Mu2e and g-2

page 15 of
P5 Report

Muons and Kaons

The Mu2e and muon g-2 projects represent a large fraction of the budget in the early years. These are immediate targets of opportunity in the drive to search for new physics, and they will help inform future choices of direction. The science case is undiminished relative to their earlier prioritization. The programmatic impacts of large changes at this point were also discussed and determined to be generally unwise, although the Mu2e profile could be adjusted by a small amount if needed.

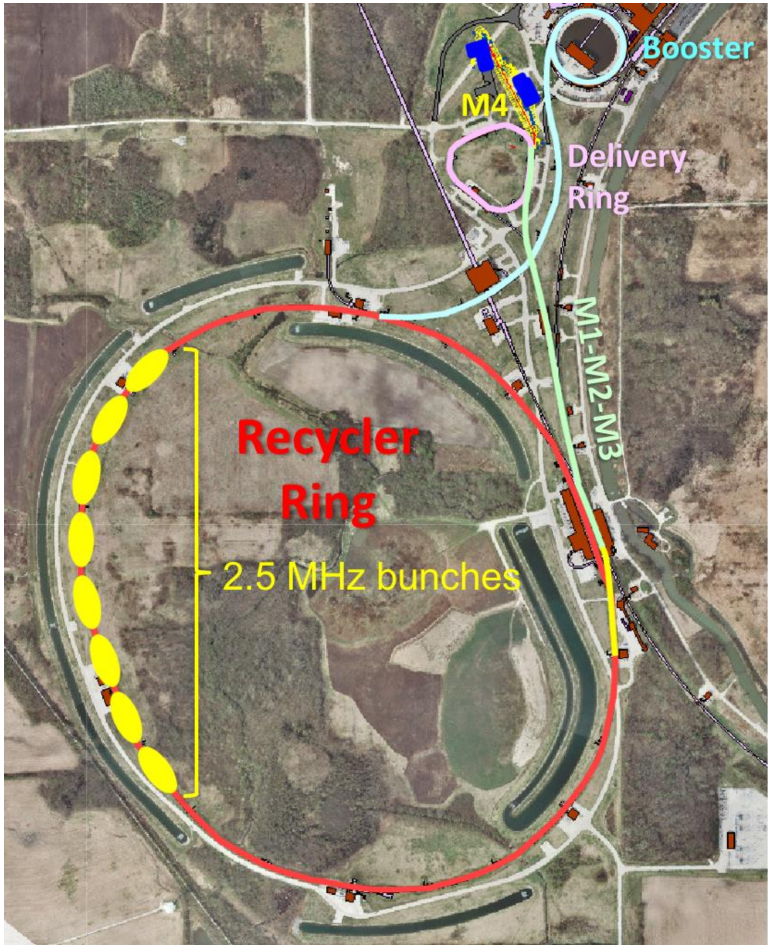
Recommendation 22: Complete the Mu2e and muon g-2 projects.

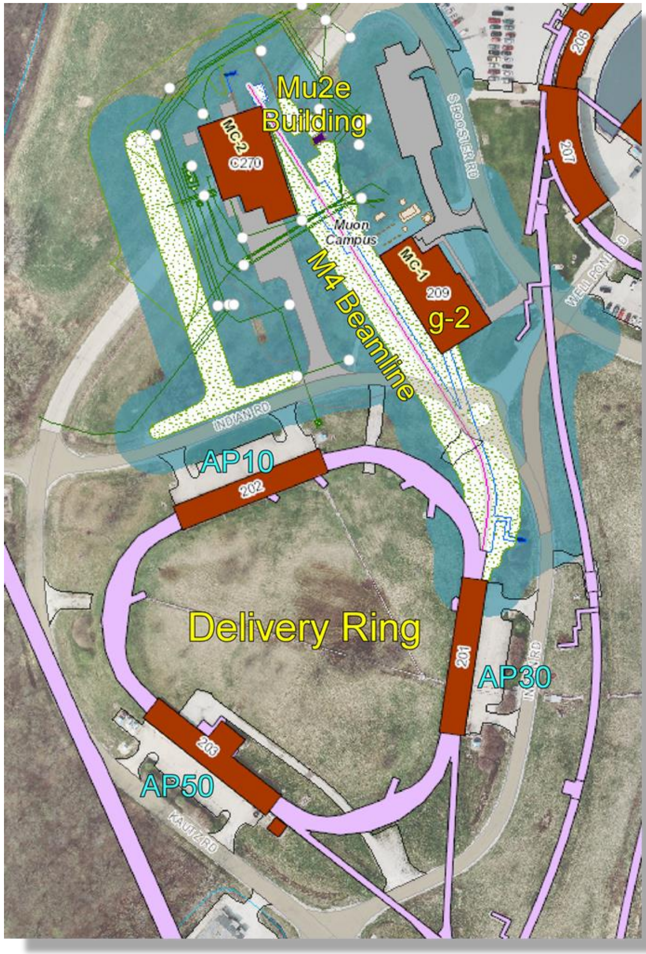
Muon g-2/Mu2e CD Schedules

Milestone	g-2 date	Mu2e date
CD-0	Sep. 2012	Nov. 2009
CD-1	Dec. 2013	Jul. 2012
CD-2	Aug. 2014	Mar. 2015
CD-3	Aug. 2015	Jul. 2016
CD-4	Jan. 2018	~Dec. 2022

Mu2e/g-2 beam lines

- Mu2e or g-2 run concurrently with the neutrino program
- However Mu2e and g-2 cannot run simultaneously
- g-2 beamline complete and delivering muons since 2017
- Mu2e beamline is complete up to final focus region





Muon g-2 Experiment

Goal:

- Measure the muon anomalous magnetic moment to 0.14 ppm
  - 4x smaller uncertainty than the previous experiment at BNL
  - Need 22x BNL Experiment data to achieve its goal
  - Need 3x reduction in BNL Experiment precession frequency systematic error
  - Need 2x reduction in BNL Experiment magnetic field systematic error

Approach:

- Observe the rate of muon spin precession in a known B field

Fermilab Muon g-2 Collaboration …

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

National Labs

- Argonne
- Brookhaven
- Fermilab

34 institutes, 7 countries

China

- Shanghai

Germany

- Dresden

Italy

- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea

- CAPP/IBS
- KAIST

Russia

- Budker/Novosibirsk
- JINR Dubna

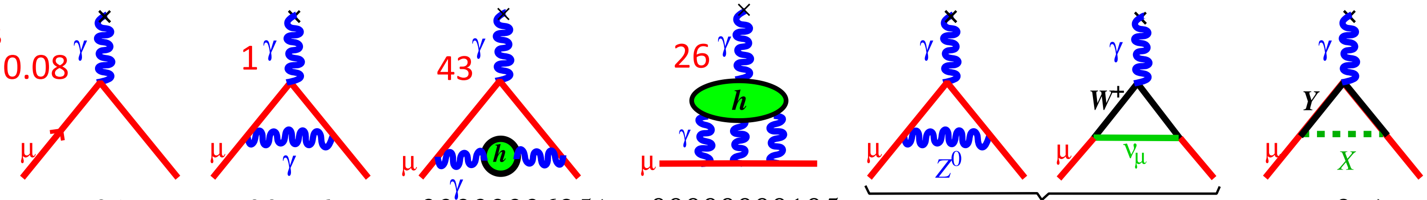
United Kingdom

- Lancaster/Cockcroft
- Liverpool
- University College London
- Manchester

Contribution of virtual particles to the muon anomaly

- Both Standard Model, and perhaps BSM particles can contribute

Uncertainties ($a_\mu x10^{-11}$)



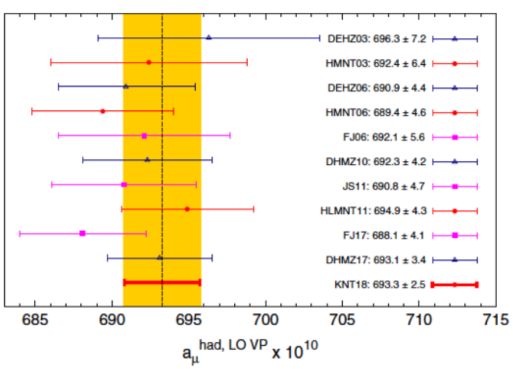
g = 2(1 + .00116. . . + .00000006951 + .00000000105 . . . + .000000001536 +?)

QED Strong (Hadrons) Electroweak

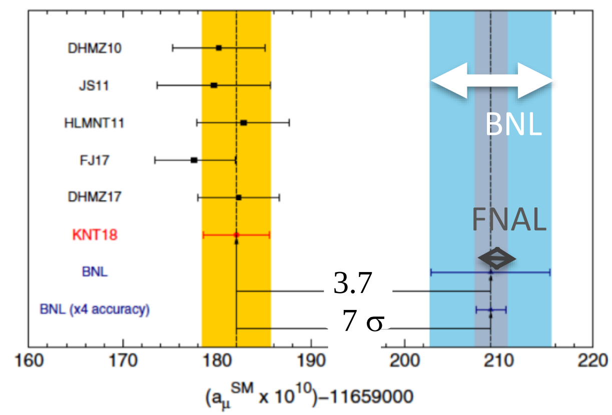
BNL E821 result: $a_\mu^{exp} = 116\,592\,089(54)_{st}(33)_{sy}(63)_{tot} \times 10^{-11}$ 0.54 ppm

KNT. PRD **97**, 114025 (2018) $a_\mu^{SM} = 116\,591\,820.4(35.6) \times 10^{-11}$

$\Delta = (270.6 \pm 72.6) \times 10^{-11} \quad 3.7\sigma$



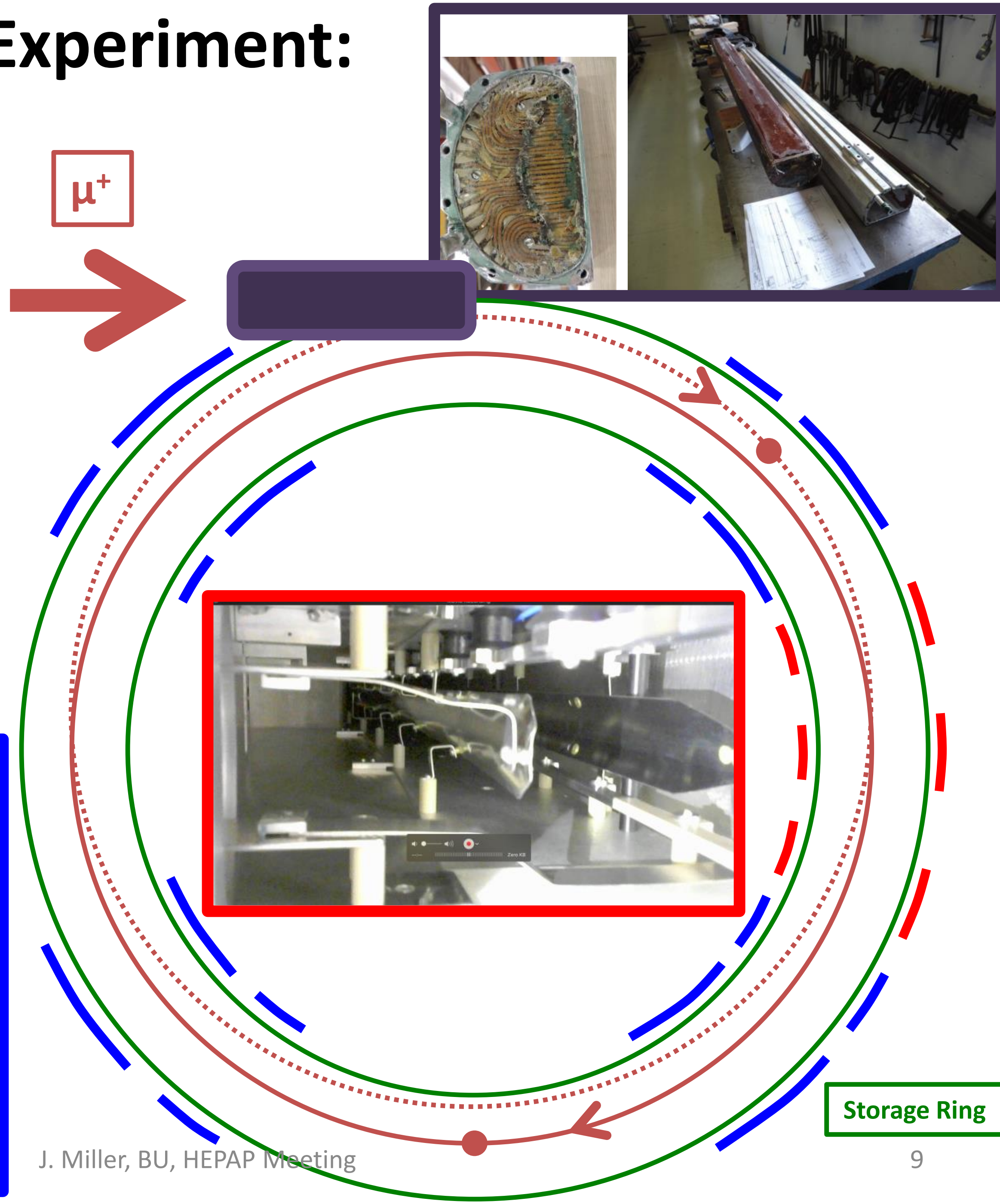
LO hadronic value steady since 2003. As additional data on $e^+e^- \rightarrow$ hadrons have become available, the uncertainly has decreased!

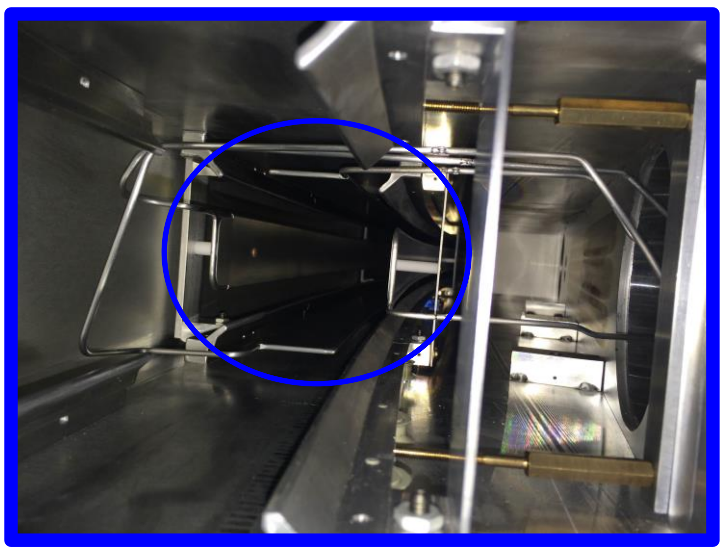


Fermilab Muon g-2 Experiment:

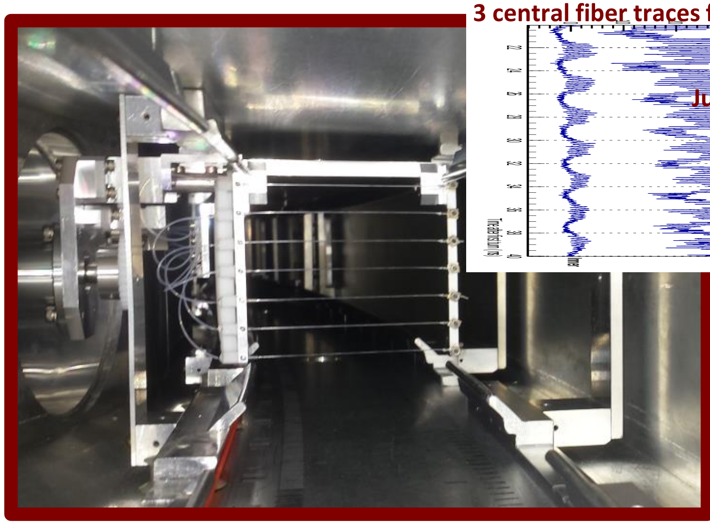
P=3.096 GeV/c
Ring Radius R=7 m
B=1.46 T
9 cm diameter Storage Aperture
Average muon mom=3.094 GeV/c

- **Inflector injects muons into ring while minimizing disturbance to B-field**
- **3 magnetic kickers "kick" the muons onto the storage orbit**
- **4 pairs of electric quads provide vertical focusing**

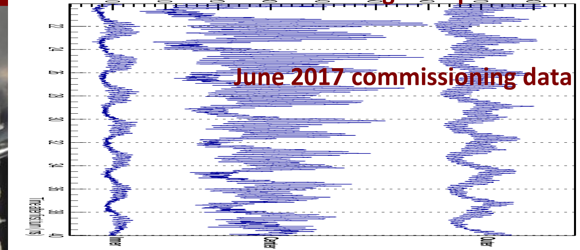




Fermilab Muon g-2 Experiment:



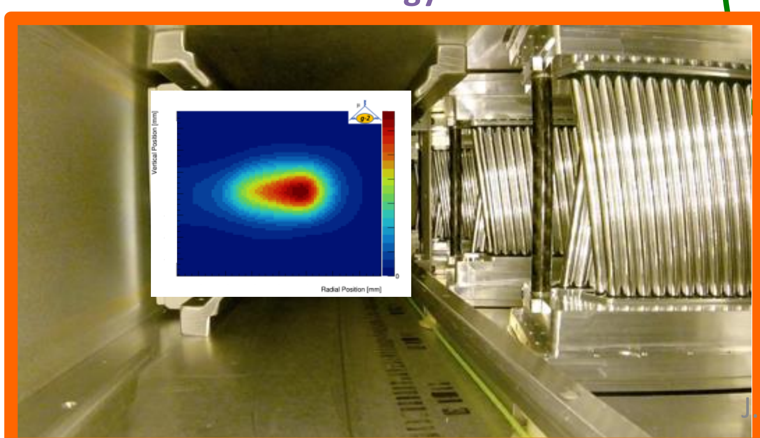
3 central fiber traces from 180 degree x-profile monitor

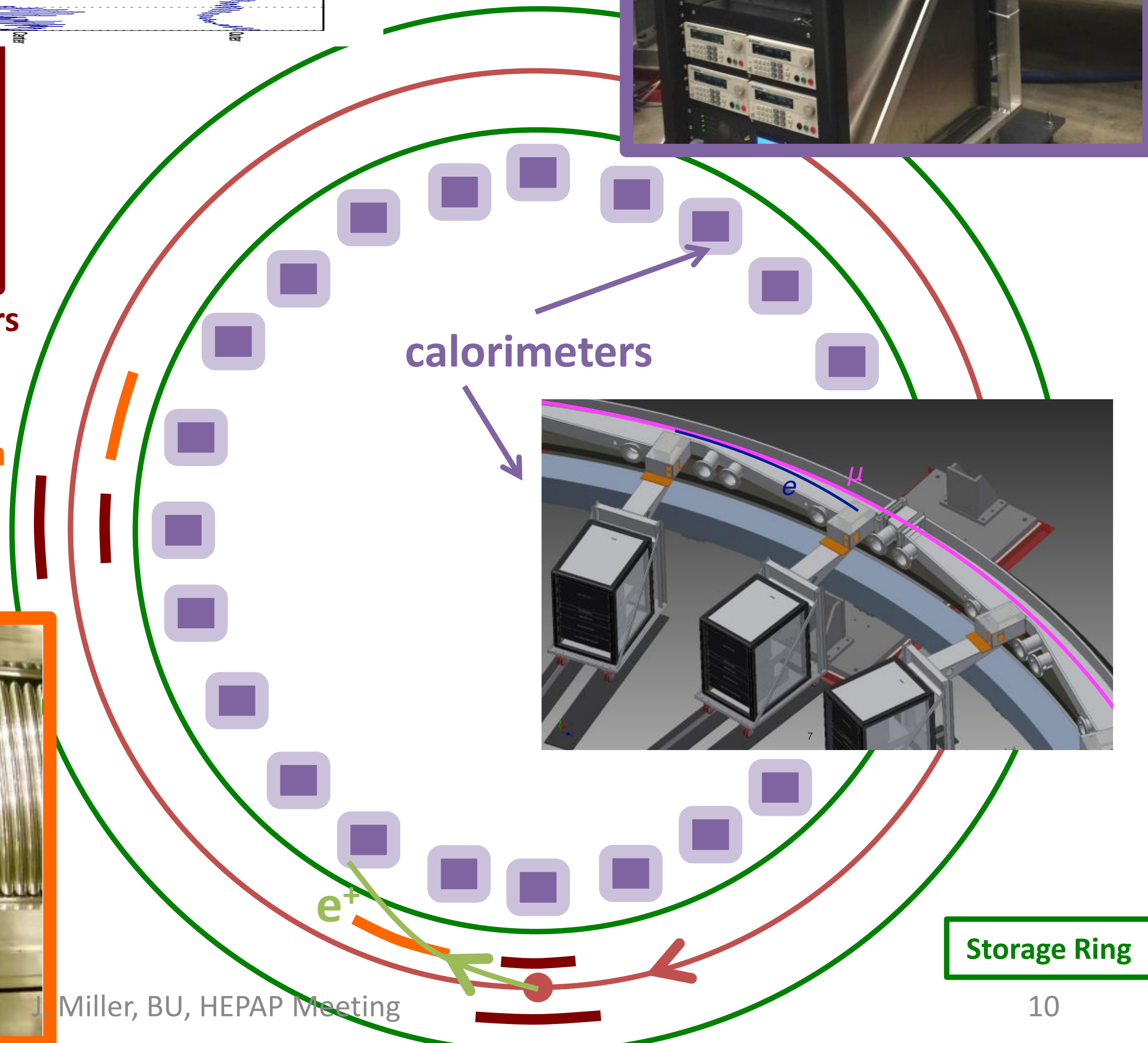


13 mm separation

13 mm separation

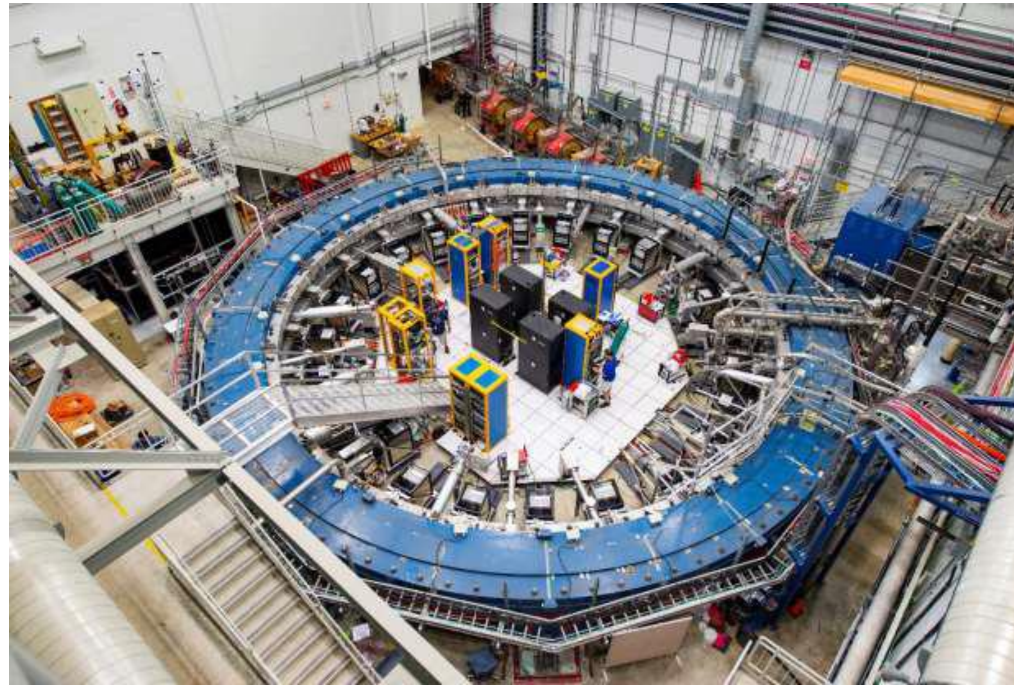
- 180° and 270° fiber profile beam monitors (special runs; degrades beam)
- 2 straw tracker stations measure decay positron trajectory, which provides beam profile reconstruction
- 24 calorimeters detect decay positron arrival time and energy





Muon g-2 Storage Ring

- Move ring from BNL to Fermilab
- Superconducting coils shipped intact by barge and truck from BNL to Fermilab (2013)
- Ring inserted into building July 2014
- First stored muon beam 2017



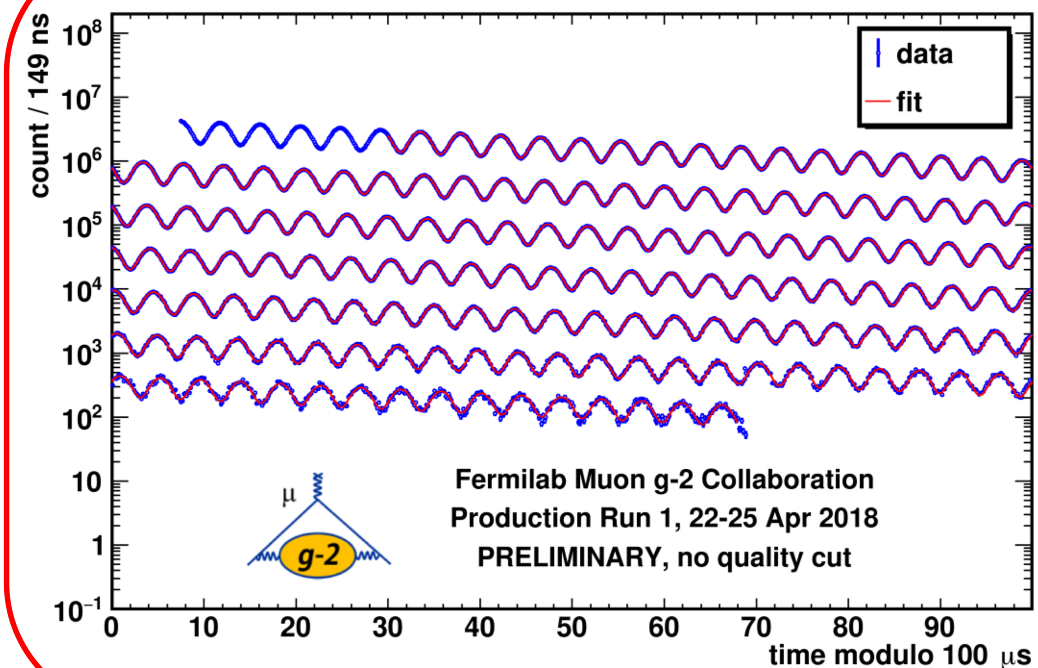
Calorimeter station

Muon anomaly is obtained from 2 measurements.

Anomalous spin precession frequency is extracted from decay positron time spectra

$$N(E,t) = N_0(E,t)e^{-t/(\gamma\tau_\mu)}\left[1 - A(E,t)\cos\left(\omega_a t + \phi(E,t)\right)\right]$$

$$a_\mu = \frac{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\omega_a}{\langle\omega_p\rangle}}{\frac{\mu_e}{\mu_p}}$$



Get from CODATA[1]:

g_e = -2.002 319 304 361 82(52) (0.00026 ppb)

m_μ/m_e = 206.768 2826(46) (22 ppb)

μ_e/μ_p = -658.210 6866(20) (3.0 ppb)

Fermilab Experiment a_μ total error goal is 140 ppb

[1] P. J. Mohr, D. B. Newell and B. N. Taylor, Rev. Mod. Phys. **88**, no. 3, 035009 (2016) doi:10.1103/RevModPhys.88.035009 [arXiv:1507.07956 [physics.atom-ph]].

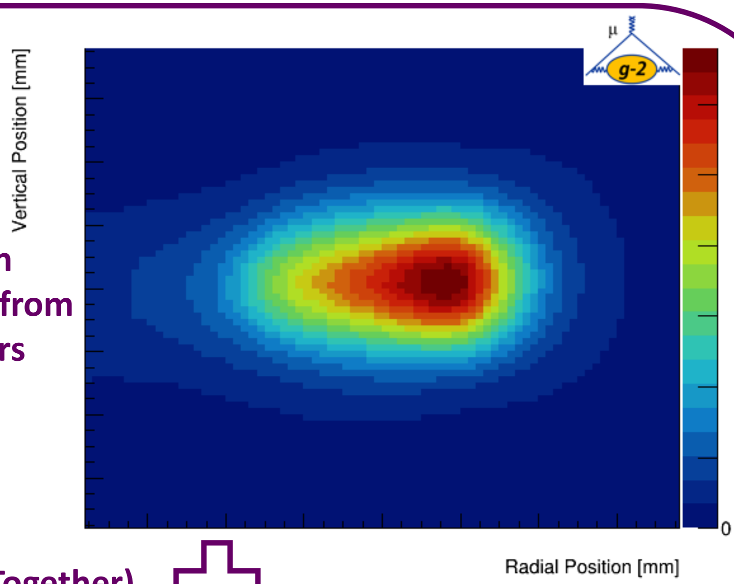
Muon anomaly is obtained from 2 measurements.

Average magnetic field seen by muons is measured with NMR

$$\hbar\omega_p = 2\mu_p\left|\vec{B}\right|$$

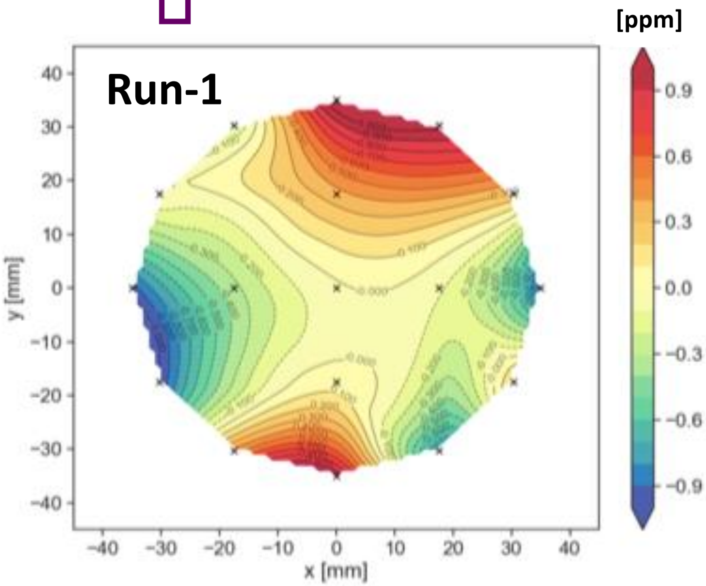
$$a_\mu = \frac{\dfrac{g_e}{2}\,\dfrac{m_\mu}{m_e}\,\dfrac{\omega_a}{\langle\omega_p\rangle}}{\dfrac{\mu_e}{\mu_p}}$$

Obtain muon distribution from straw trackers



(Combine Together) ✚

Obtain B-field from NMR probes



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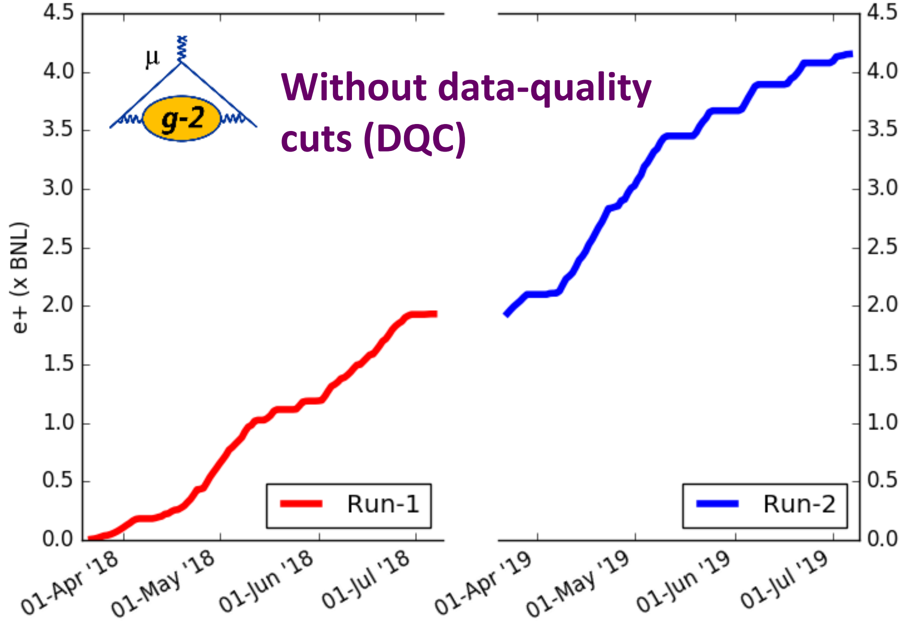
Improvements to Fermilab vs BNL Experiment

- **Highly segmented calorimeters- 6x9 array of PbF_2 crystals**
  - **Reduces pulse pileup**
- **Laser system for improved calorimeter gain monitoring**
- **Improved straw tube trackers to monitor stored muon distribution**
- **B-field shimmed to 3x better uniformity**
- **4 turns in Delivery Ring to eliminate hadronic 'flash' due to pion and proton components in the muon beam during injection**
  - **Eliminates big 'hit' to detectors during injection, improves stability of calorimeters**

Status of the Fermilab Muon g-2 Experiment:

- Finished Run-1 & Run-2; ~3x BNL; looking at data!
- Run-3 just began last week, goal 5-7x BNL
- Goal of publishing Run-1 results in a few months (~1x BNL) data are still blinded)!

Expect ~1.8×BNL Run-2 dataset vs. ~1.4×BNL Run-1 dataset after Data Quality Cuts.

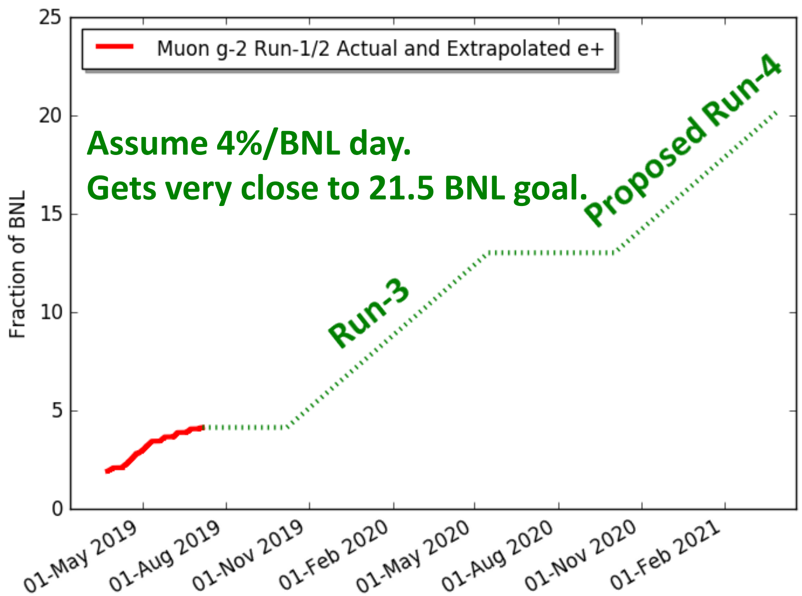


Difficulties encountered in Runs 1 & 2

- Problems with vacuum delayed start of Run 1
- Unable to operate storage ring injection kickers at design voltage. Caused downtime and unstable running.
- HV problems with electric quadrupoles
- Late start for Run-2 due to recovery from safety incident and repairs for HV issues
- Diminished run time in Run 2 due to insufficient lab operating budget.

Stay tuned …

- **Mu2e expects to begin commissioning beamline in FY2022.**
- **Muon g-2 Experiment has finished Run-1 and Run-2 data collection, ~3xBNL statistics**
- **Muon g-2 has the goal of publishing Run-1 physics result (>~1x BNL) by early 2020.**



Run-3 started just started and ends May-15. Expect 5-7x BNL

The proposed Run-4 would share beam time with Mu2e commissioning.
Muon g-2: 6 months
Mu2e: 3 months

1st publication (>1 x BNL statistics)	***2nd publication (3 x BNL statistics)***	***3rd publication (10 x BNL statistics)***	***Final publication***

CY18 → CY19 → CY20 → CY21 → CY22

Mu2e Experiment

Goal:

- Search for muon-to-electron conversion in the field of a nucleus
- Observation would be an example of CLFV and would signal new physics

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N \to e^- + N\right)}{\Gamma\left(\mu^- + N \to \text{all captures}\right)}$$

- Expected sensitivity $R_{\mu e} = 8\text{x}10^{-17}$@ 90% CL, x10,000 better than SINDRUM-II
- Discovery at 5σ: $2\text{x}10^{-16}$

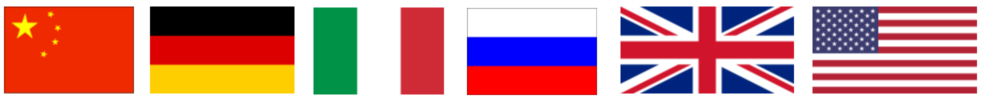
Approach:

- Form muonic atoms by stopping μ- in an aluminum target
- Search for 105 MeV electron from

$$\mu^- + {}^{27}_{13}Al \to e^- + {}^{27}_{13}Al$$

The Mu2e Collaboration

Over 200 scientists from 40 institutions



Argonne National Laboratory ● Boston University
Brookhaven National Laboratory
University of California, Berkeley ● University of California, Davis ● University of California, Irvine
California Institute of Technology ● City University of New York ● Joint Institute for Nuclear Research, Dubna ● Duke University ● Fermi National Accelerator Laboratory ● Laboratori Nazionali di Frascati ● INFN Genova ● Helmholtz-Zentrum Dresden-Rossendorf
University of Houston ● Institute for High Energy Physics, Protvino ● Kansas State University ● Lawrence Berkeley National Laboratory ● INFN Lecce and Università del Salento ● Lewis University ● University of Liverpool ● University College London ● University of Louisville ● University of Manchester ● Laboratori Nazionali di Frascati and Università Marconi Roma
University of Michigan ● University of Minnesota
Institute for Nuclear Research, Moscow ● Muons Inc.
Northern Illinois University ● Northwestern University
Novosibirsk State University/Budker Institute of Nuclear Physics ● INFN Pisa ● Purdue University ● University of South Alabama ● Sun Yat Sen University ● INFN Trieste
University of Virginia ● University of Washington ● Yale University

Mu2e Collaboration

Tracker – ANL, UC Berkeley, CUNY, Duke , FNAL , Houston, LBNL, Michigan, Minnesota

Calorimeter – Caltech, HZDR (Dresden), INFN (Frascati, Lecce, Pisa, Rome, Trieste), JINR Dubna

Cosmic Veto – ANL, JINR Dubna, KSU, NIU, U. South Alabama, Virginia

TDAQ – Caltech, FNAL, KSU, LBNL, Pisa, Yale

Muon & Proton Monitors – Boston, FNAL, Liverpool, Manchester, NIU, Purdue, University College London, Washington

Solenoids and Field Mapping – ANL, Boston, FNAL, INFN Genova, Northwestern

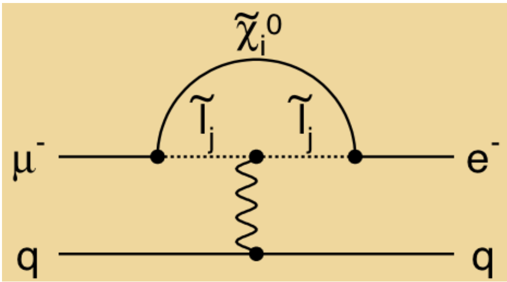
Proton Beam Line – CUNY, UC Davis, FNAL

Simulations & Software – Boston, UC Berkeley, Caltech, CUNY, FNAL, Frascati, LBNL, Louisville, Northwestern, NIU, Sun Yat-Sen, Novosibirsk, Pisa, Virginia, Yale

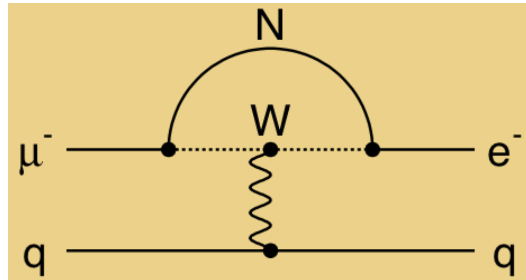
Institutions shown in blue are Research supported by DOE and NSF

New Physics Contributions to μN→eN

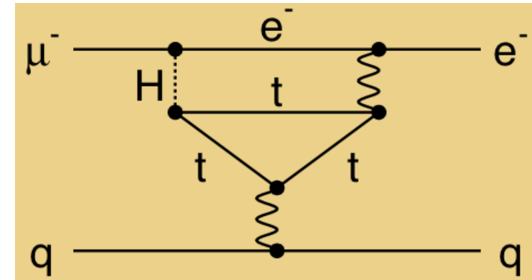
Loops



Supersymmetry

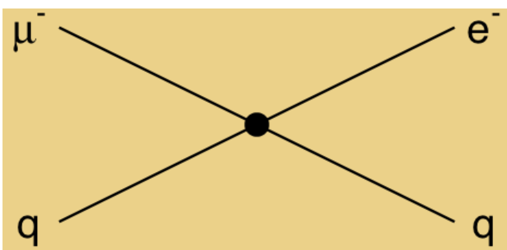


Heavy Neutrinos

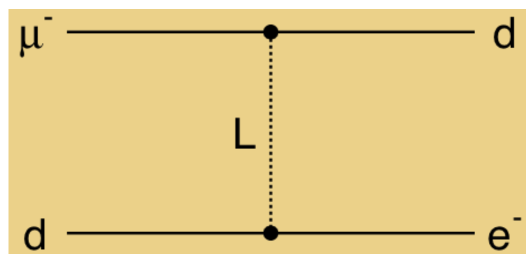


Two Higgs Doublets

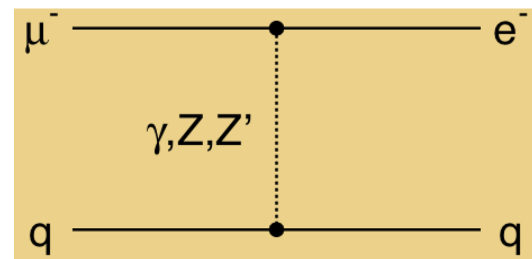
Contact Terms



Compositeness



Leptoquarks



New Heavy Bosons /
Anomalous Couplings

μN→eN sensitive to wide array of New Physics models

Mu2e Sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

★★★ = Discovery Sensitivity

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

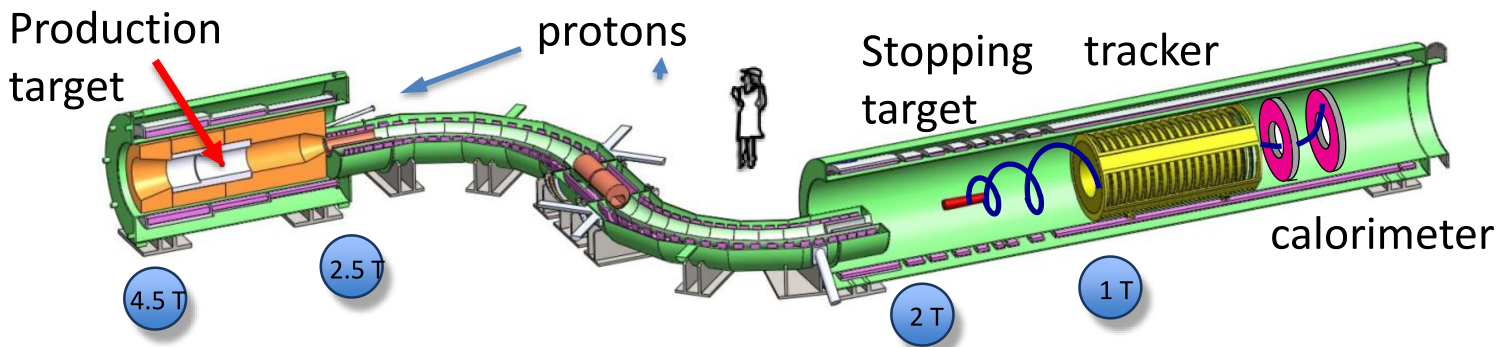
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

- Mu2e sensitive across the board

Mu2e overview

Production Target / Solenoid (PS)

- 8 GeV, 8 kW Proton beam strikes target, producing mostly pions
- Graded magnetic field contains pions/muons and collimate them into transport solenoid



Transport Solenoid (TS)

- Collimator selects low momentum, negative muons
- Antiproton absorber
- The S shape eliminates photons and neutrons

Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field "reflects" downstream conversion electrons emitted upstream, improving efficiency

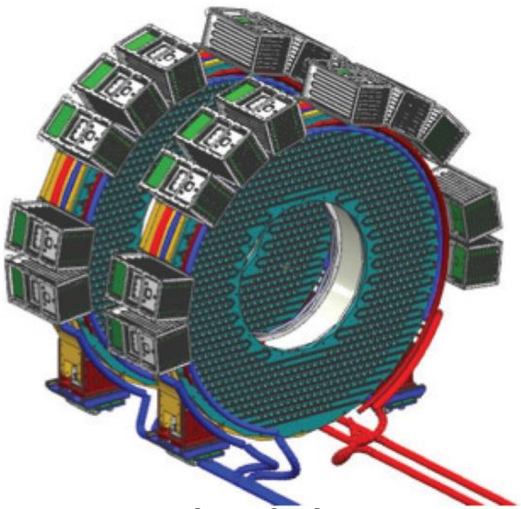
Mu2e Experimental Advances

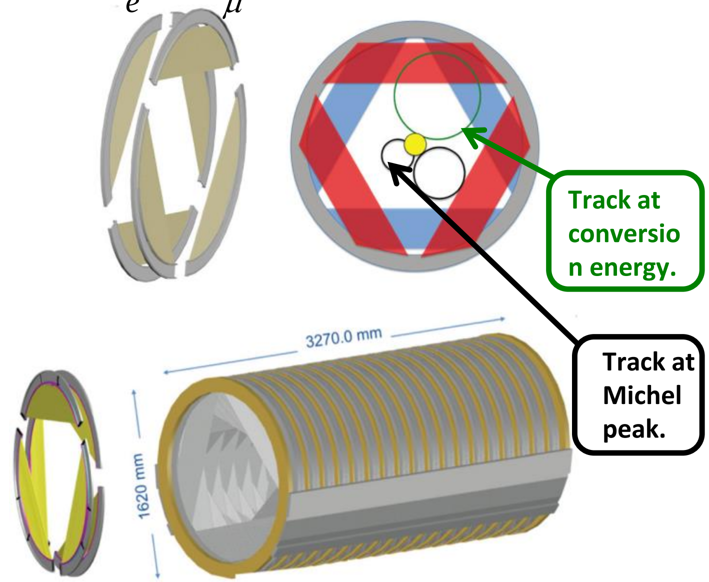
- **Keys to x10,000 better sensitivity**
  - **By placing the production target inside a high-field solenoid, one obtains a highly efficient low-energy muon beam (0.0015 stopped muons/proton)**
    - **This will be the world's hottest stopped-muon source by ~ x100**
    - **10^{10} stopped muons/second**
  - **A pulsed proton beam allows suppression of prompt backgrounds by employing a delayed live gate**
    - **Narrow proton pulses (~250 ns wide) every 1695 ns**
    - **Delay live gate for ~700 ns relative to arrival of protons**
      - **Beam-related 'flash' dissipates early, muonic atoms live long (864 ns)**
    - **Achieves significant suppression of backgrounds from beam electrons and prompt pion interactions in the stopping target**
    - **Time structure is good match to muonic aluminum lifetime (864 ns)**

Trackers and calorimeters are used to reconstruct electron kinematics.

Both nearly blind to all DIO electron background due to hole down the middle

DIO electrons: $\mu^- + {}^{27}_{13}Al \rightarrow {}^{27}_{13}Al + e^- + \bar{\nu}_e + \nu_\mu$





- **2 annular disks separated by half a track wavelength gives ~90% acceptance.**
- **Each disk contains ~674 scintillating CsI crystals with SiPMs readout**
- **Resolution ~5% at 105 MeV and ~1 ns.**

- **5mm diameter straw drift tubes: mylar-epoxy-Au-Al walls and Au-plated W wire.**
- **Operates in a vacuum, Ar/CO2 gas at ~1.45 kV.**
- **Ultra low mass- minimize multiple scattering.**
- **Highly segmented to handle high rates.**
- **Resolution less than 180 keV/c at 105 MeV.**
- **18 stations each having 12 × 120° panels = 216 panels ➔ ~21,000 straws.**

[1] R. H. Bernstein [Mu2e Collaboration], Front. in Phys. **7**, 1 (2019). doi:10.3389/fphy.2019.00001 [arXiv:1901.11099 [physics.ins-det]].

Tracker Progress

TDAQ Test Stand for all detectors

Tracker Panel Construction at University of Minnesota

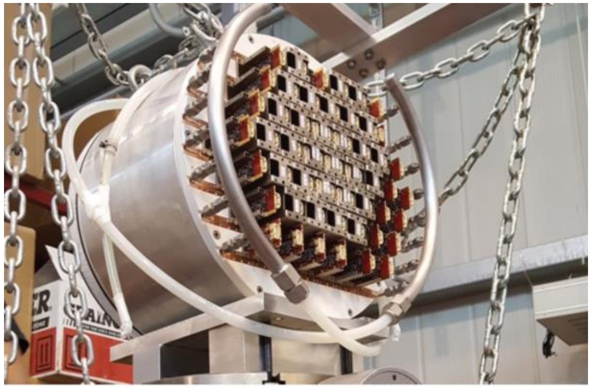
- Panels are being produced at University of Minnesota
- LBNL/UC Berkeley testing electronics
- Panel Component fabrication and QC at Duke and York
- Supports designed at Argonne
- Wires X-rayed at Duke
- Michigan- integration with DAQ
- Houston- panel QC/QA
- Tracker assembled at Fermilab

Half Tracker Plane comprised of 3 panels

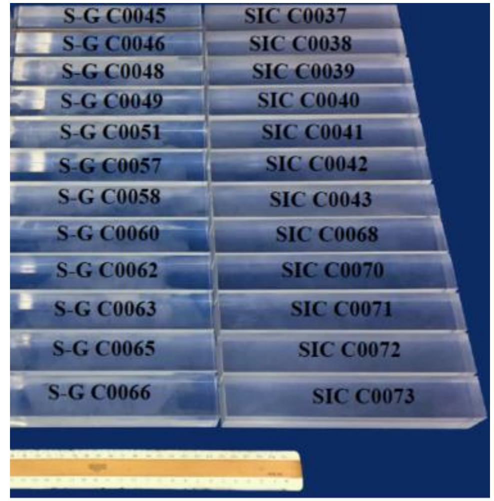
Instrumented Tracker Panel

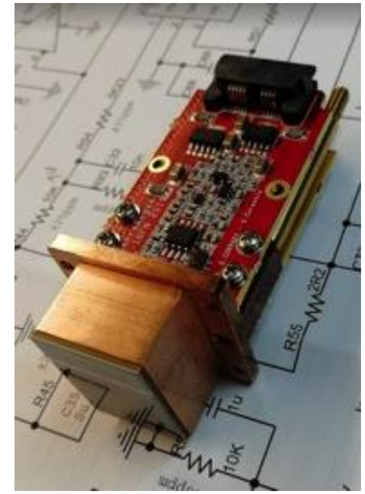
Calorimeter Progress

Prototype Calorimeter crystals



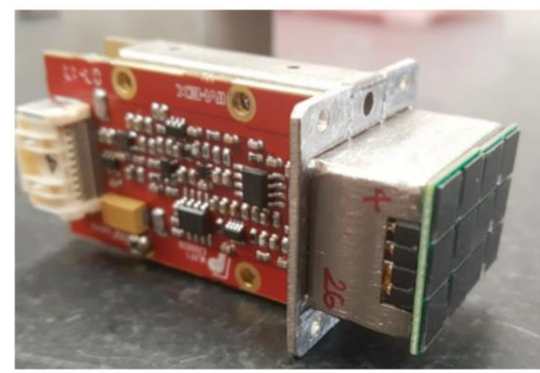
Calorimeter crystals and SiPM (INFN Contribution)





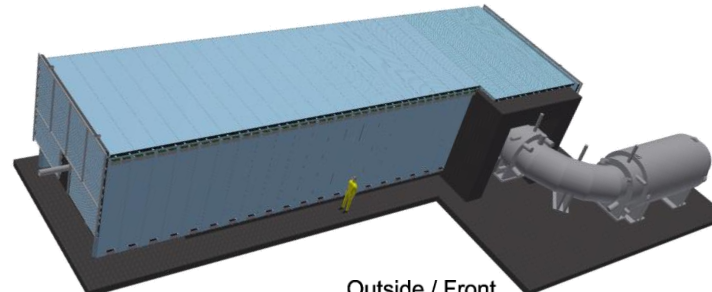
- **75% of the CsI crystals received and tested**
- **All SiPM's received & tested**
- **Completion of DAQ and electronics progressing well**
- **Large INFN contribution**
- **Testing- Dubna,HZDR**
- **QA/QC of crystals, calibration system- Caltech**

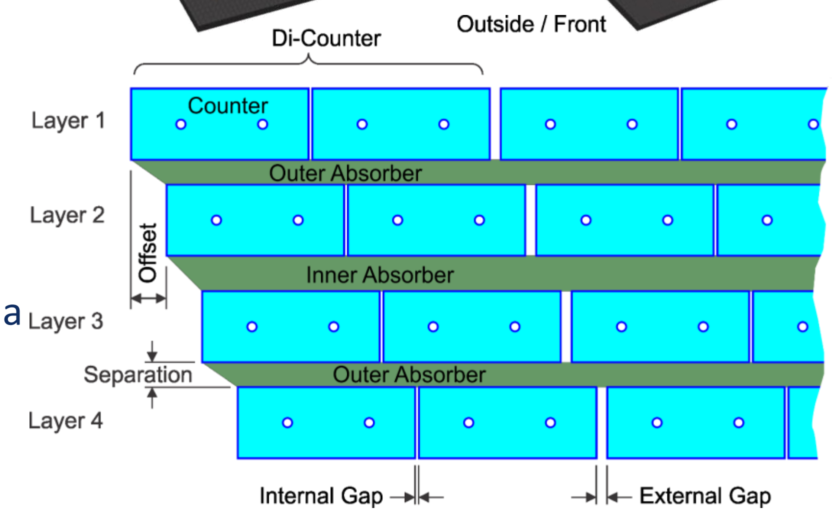
SiPM Array



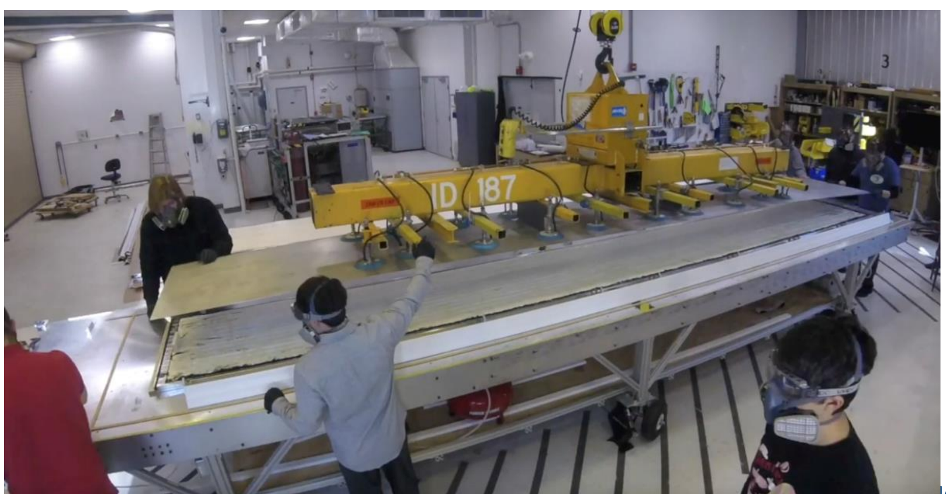
Mu2e Cosmic Ray Veto

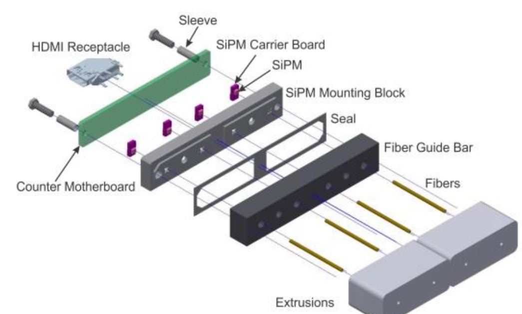
- Covers all of DS, half of TS, better than 10^{-4} inefficiency with 3-fold coincidence
- 4-layers of extruded scintillator bars, wavelength shifting fibers w/SiPM read out
- Scintillator and SiPMs all in hand
- Electronics and DAQ in advanced state
- Virginia, Kansas, Argonne, Dubna





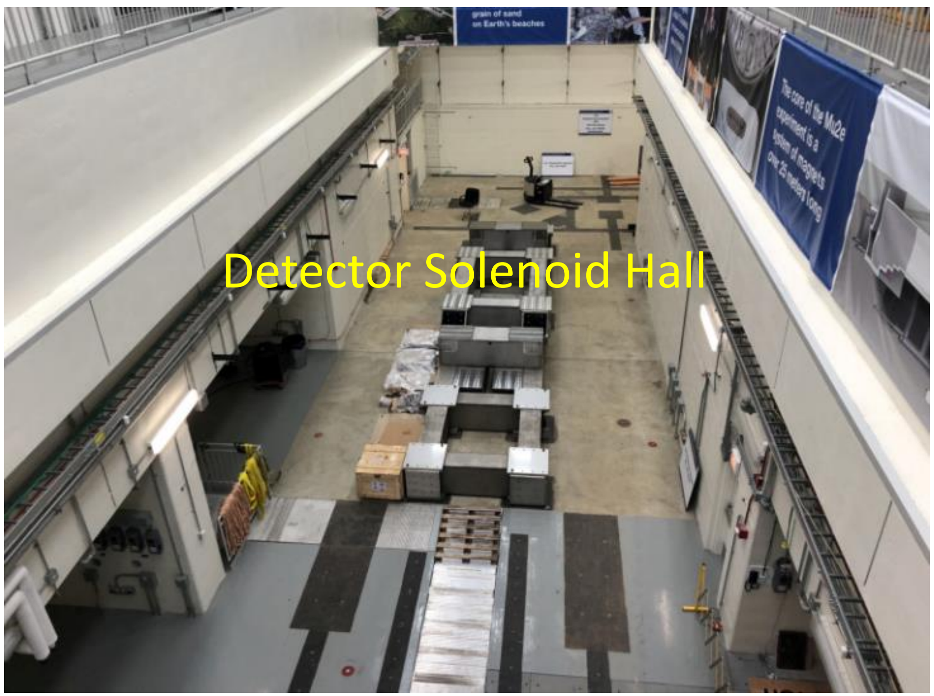
Cosmic Ray Veto Module Construction,University of Virginia

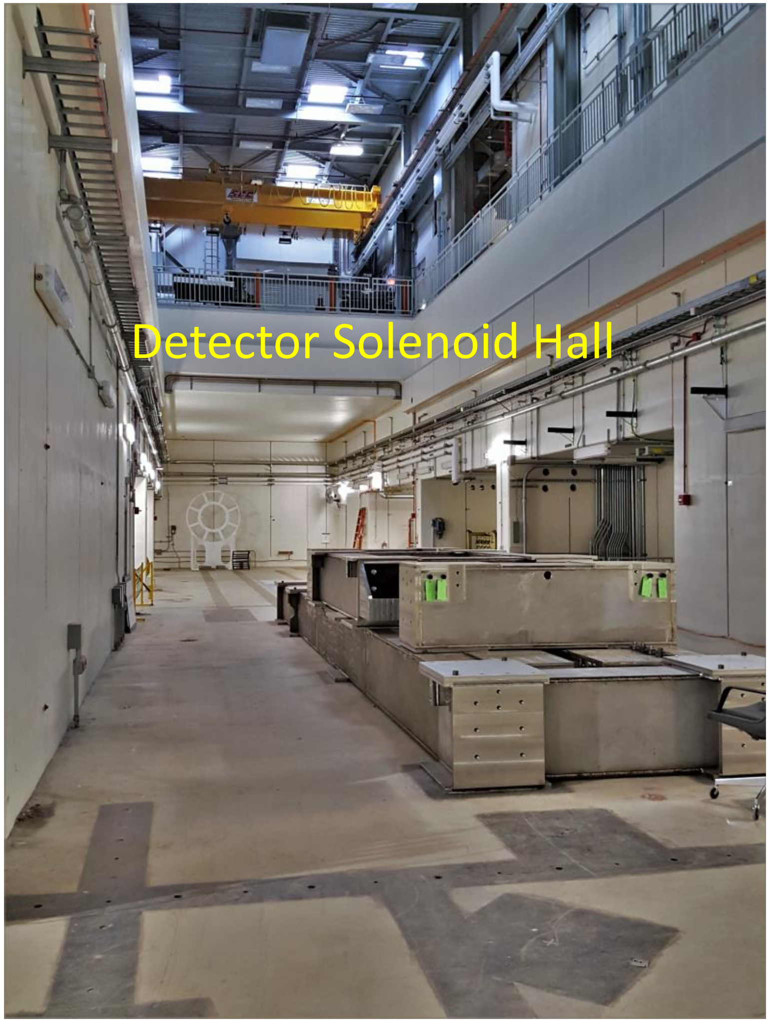




Mu2e Building is Complete

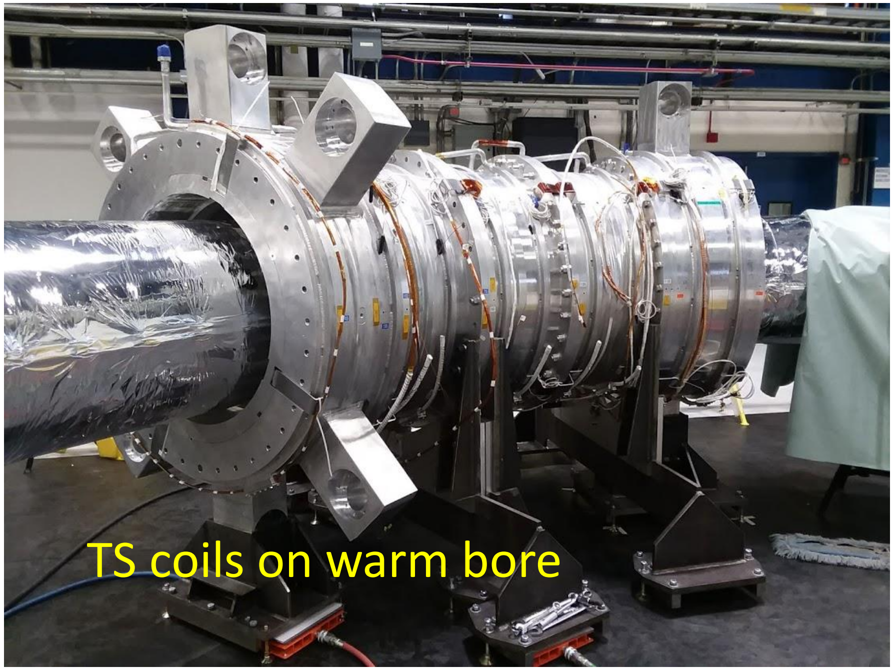
April 2017



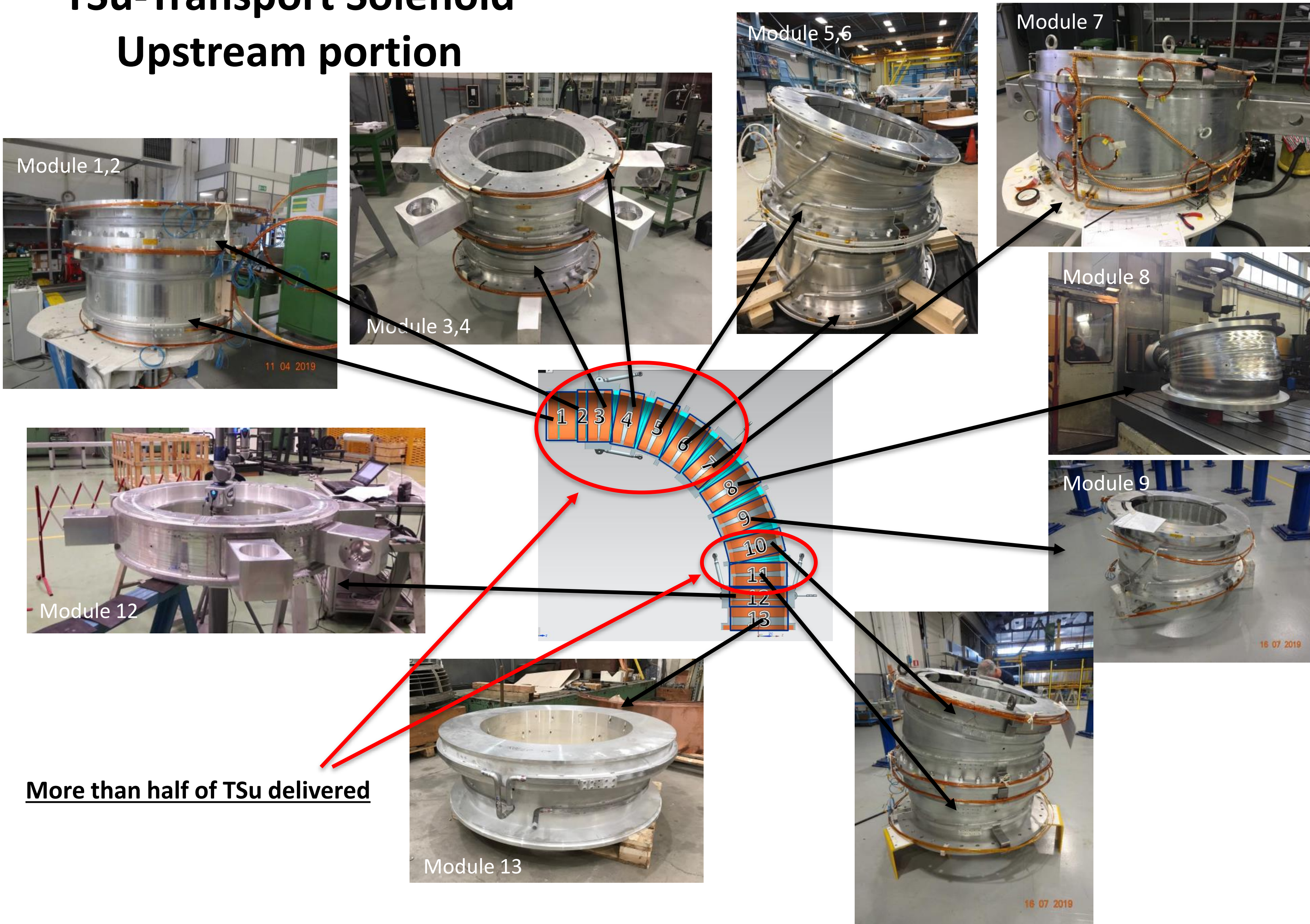


Transport Solenoid Progress

- S-shaped magnet constructed from series of wedge-shaped modules
- Superconducting Coil Modules fabricated in Italian industry
- Delivered modules cooled to Liquid Helium and powered at Fermilab, assembled
- Of 14 total units, 3 units on warm bore, 3 units in house, 2 units ready to ship



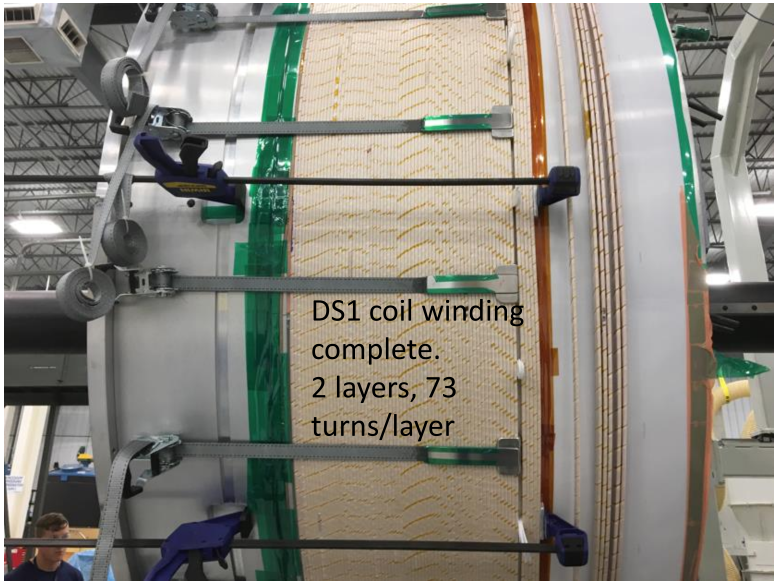
TSu-Transport Solenoid Upstream portion



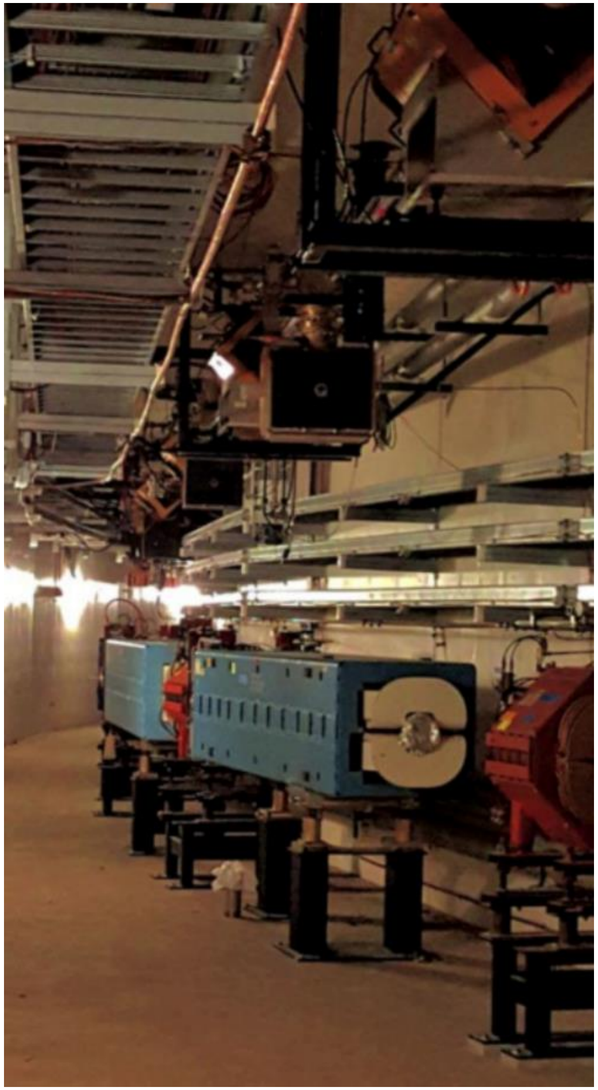
More than half of TSu delivered

Mu2e Status - PS/DS

- Contractor (GA) is manufacturing and assembling Production and Detector Solenoids
- Now successfully winding superconducting coils since early 2019, after initial difficulties which produced delays and cost overruns.
- Working to recover schedule
- 1st of three PS coils on track for completion at end of year
- Completion of solenoids is on the critical path



Mu2e Beamline Installation Making Significant Progress



- Most beamline elements are installed up to final focus
- Resonant extraction sextupoles fabricated
- First beam into beamline 2020

Mu2e Outlook and Schedule

- On track to satisfy P5 recommendation
  - Project is 76% complete
  - Schedule is driven by delivery , installation, commissioning of the Solenoids
  - Projected completion of Project end of 2022
- Begin commissioning the full beamline – Mid 2021
- Begin commissioning detectors – Early 2022
- First physics data taking – Early 2023
- Planned LBNF/PIP-II shutdown interrupts Mu2e running (FY2026-2027 ?)
  - Aim to collect world's best electron conversion limit by shutdown
  - To reach full sensitivity requires running after shutdown
- Mu2e-II: upgrade Mu2e to use PIP-II beam, another x10 sensitivity
  - Depending on Mu2e result, confirm signal, change stopping target, or increase search sensitivity
  - Use as much of the Mu2e apparatus as possible
  - Expression of interest favorably reviewed by Fermilab PAC
    - Several workshops; continued studies under way
    - Requires R&D investments

Muon Program Summary

Muon g-2

- **Project on time and on budget**
  - **DOE 2018 Project Management Achievement Award winner!**
  - **Satisfies P5 recommendation**
- **Successful implementation of beam line**
- **On track to collect necessary statistics for sensitivity goal by 2021**
- **First result ~ 1x BNL expected early 2020**

Mu2e

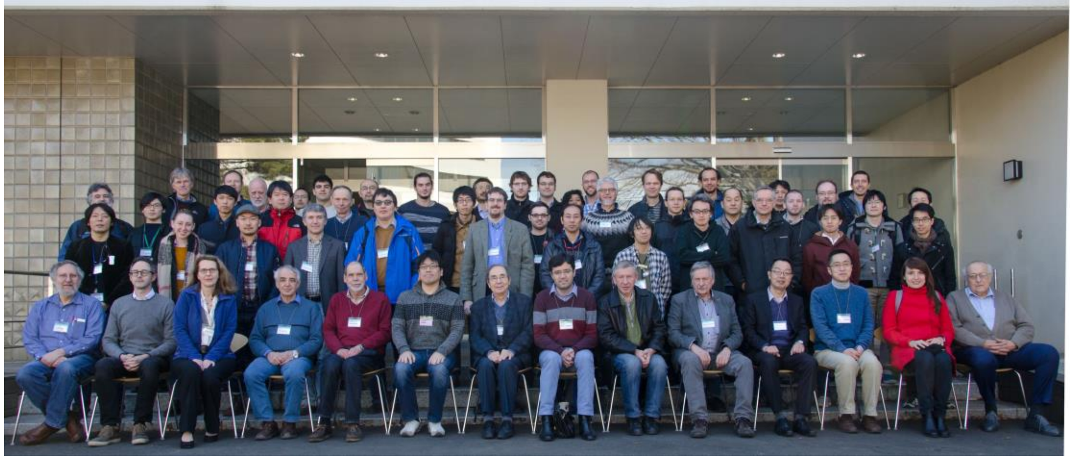
- **Construction of all components under way, building complete**
- **Majority of beam line installed**
- **On track to meet P5 recommendation**
- **First data 2023**

Backup

International Muon g-2 Theory Initiative – approximately 100 active participants

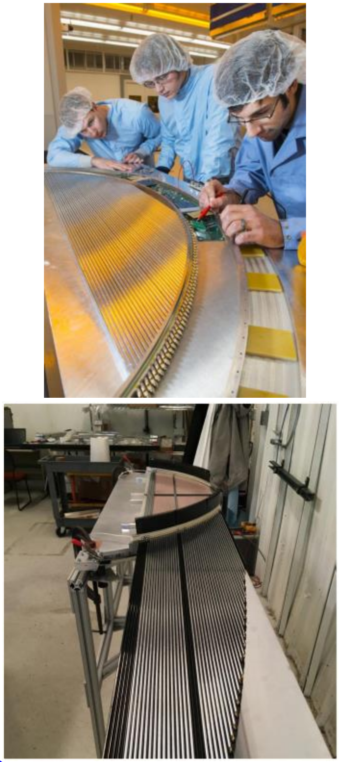
- Goal: Produce a "Whitepaper" on the g-2 theory value by early 2020.
  - Lowest-order hadronic and next order: dispersive and lattice
  - Hadronic Light-by-Light: dispersive and lattice
  - Forthcoming data sets:
    - Novosibirsk (energy scan)
      - CMD3 has a major data set on the $e^+e^- \rightarrow \pi^+\pi^-$ channel that dominates the LOH determination
      - SND also has an additional data set.
    - BESIII at IHEP Beijing is actively accumulating data using initial state radiation to cover the relevant mass region.
    - BESII $\gamma\gamma* \rightarrow \pi^0, \eta$ for the dispersive determination of the Hadronic Light-by-Light contribution.

Participants in the Theory Initiative meeting at KEK in February 2018.
Other meetings: Fermilab June 2017
INT Seattle: September 2019

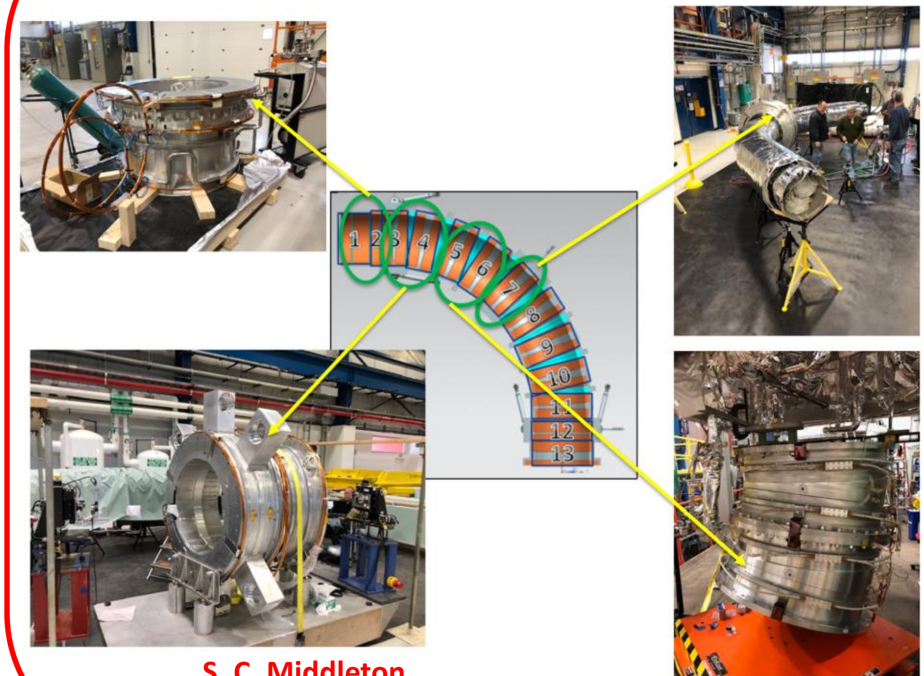


Mu2e Experiment construction underway!

Tracker Construction

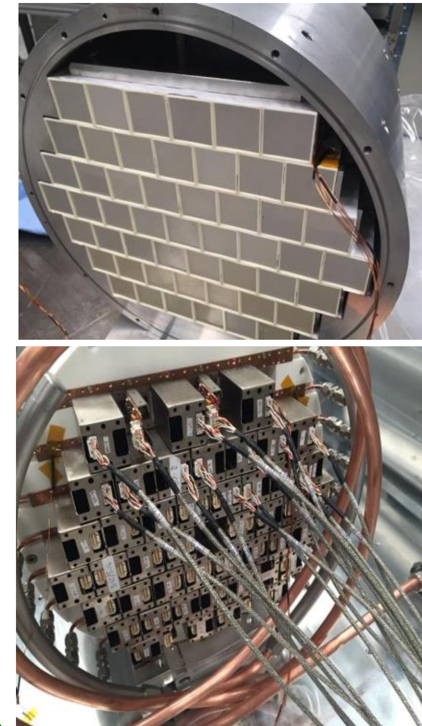


Transport Solenoid

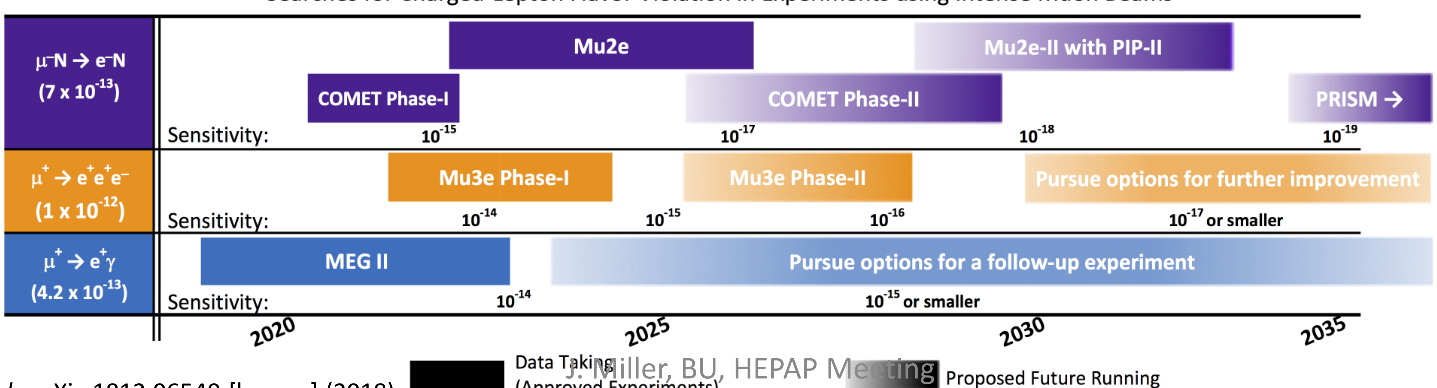


S. C. Middleton

Calorimeter Prototype



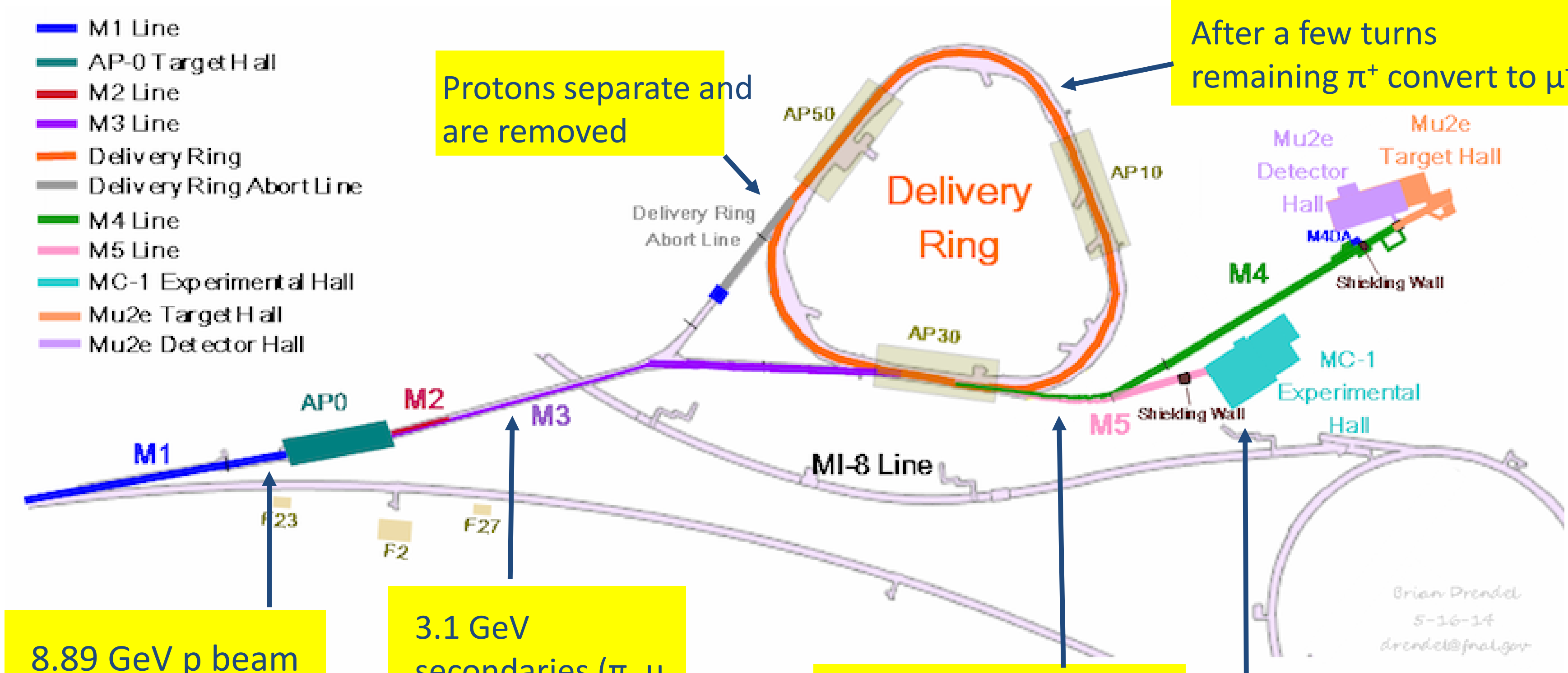
Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams



[1]

[1] A. Baldini *et al.*, arXiv:1812.06540 [hep-ex] (2018).

Fermilab g-2 beamline decays away most of the pions.



Protons separate and are removed

After a few turns remaining π^+ convert to μ^+

8.89 GeV p beam impacts the target

3.1 GeV secondaries (π, μ, p) travel along M2 & M3, where μ^+ are collected from π^+ decays

μ^+ are extracted from the ring and transferred into the storage ring via M5

μ^+ enter the g-2 storage ring

P5 Recommendations: Mu2e and g-2

page v

capability. To meet budget constraints, physics needs, and readiness criteria, large projects are ordered by peak construction time: the Mu2e experiment, the high-luminosity LHC upgrades, and LBNF.

page 15

Muons and Kaons

The Mu2e and muon g-2 projects represent a large fraction of the budget in the early years. These are immediate targets of opportunity in the drive to search for new physics, and they will help inform future choices of direction. The science case is undiminished relative to their earlier prioritization. The programmatic impacts of large changes at this point were also discussed and determined to be generally unwise, although the Mu2e profile could be adjusted by a small amount if needed.

Recommendation 22: Complete the Mu2e and muon g-2 projects.

P5 Recommendations: Mu2e and g-2

page 18

Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context 18

Figure 1
Construction and Physics Timeline

FIGURE 1 Approximate construction (blue; above line) and expected physics (green; below line) profiles for the recommended major projects, grouped by size (Large [>$200M] in the upper section, Medium and Small [<$200M] in the lower section), shown for Scenario B. The LHC: Phase 1 upgrade is a Medium project, but shown next to the HL-LHC for context. The figure does not show the suite of small experiments that will be built and produce new results regularly.

P5 Recommendations: Mu2e and g-2

page 44

- *Muon magnetic moment:* The prediction for the anomalous magnetic moment, g-2, of the muon differs from its measured value by three-and-a-half standard deviations. A new experiment, Muon g-2 at Fermilab, will significantly improve the accuracy of the measurement, and combining this with further improvements in the theoretical prediction for it may sharpen this discrepancy and point the way to new physics. A different approach to measuring g-2, using ultra cold muons, has been proposed at J-PARC.

page 44

Scenario A is much more challenging. The reduction relative to Scenario B, which is approximately $30M per year until FY2018 and then grows over time to $95M in 2024, would have very large impacts:

- A small change in the funding profile of Mu2e would be required.

P5 Recommendation: Muon g-2

page 44

- *Muon magnetic moment:* The prediction for the anomalous magnetic moment, g-2, of the muon differs from its measured value by three-and-a-half standard deviations. A new experiment, Muon g-2 at Fermilab, will significantly improve the accuracy of the measurement, and combining this with further improvements in the theoretical prediction for it may sharpen this discrepancy and point the way to new physics. A different approach to measuring g-2, using ultra cold muons, has been proposed at J-PARC.

P5 Recommendation: Mu2e

page 44

- *Rare Muon decays and processes:* Observation of charged lepton flavor violation (*e.g.*, a muon changing to an electron) would be a signature of new physics. In the muon sector, a dramatic order of magnitude increase in sensitivity to the scale of such new physics should come from experiments on the decays $\mu \rightarrow e\gamma$, $\mu \rightarrow ee^{+}e^{-}$, and muon conversion to an electron in the presence of a nucleus. These experiments will be performed at J-PARC, PSI, and Fermilab.

Of these three processes, muon conversion to an electron in the presence of a nucleus will give the greatest increase in mass reach for new physics. Very ambitious next-generation exper-

page 45

Looking farther into the future, progress in precision physics and rare processes will be shaped partly by what particle physicists learn in the coming decade. Upgrades to the accelerator complex at Fermilab (PIP-II and additional improvements) will offer opportunities to further this program. For example, combined with modest upgrades to Mu2e, improvements in the Fermilab accelerator complex potentially could provide increased sensitivity (by a factor of ten) to muon-to-electron conversion and allow one to search for this very rare process in different nuclei. This will provide crucial clues on the nature of the new physics revealed in the event of an observation in the next-generation experiments.

Muon g-2 Experiment final error goals:

ω_a systematic uncertainty summary[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Gain Changes	120	20
Pileup	80	40
Lost Muons	90	20
CBO	70	< 30
E-field & Pitch Corrections	50	30
Total (Quadrature Sum)	190	70

a_μ uncertainty summary[1,2].

Category	BNL [ppb]	FNAL Goal [ppb]
Total Statistical Uncertainty	460	100
Total Systematic Uncertainty	280*	100
Total (Quadrature Sum)	540*	140

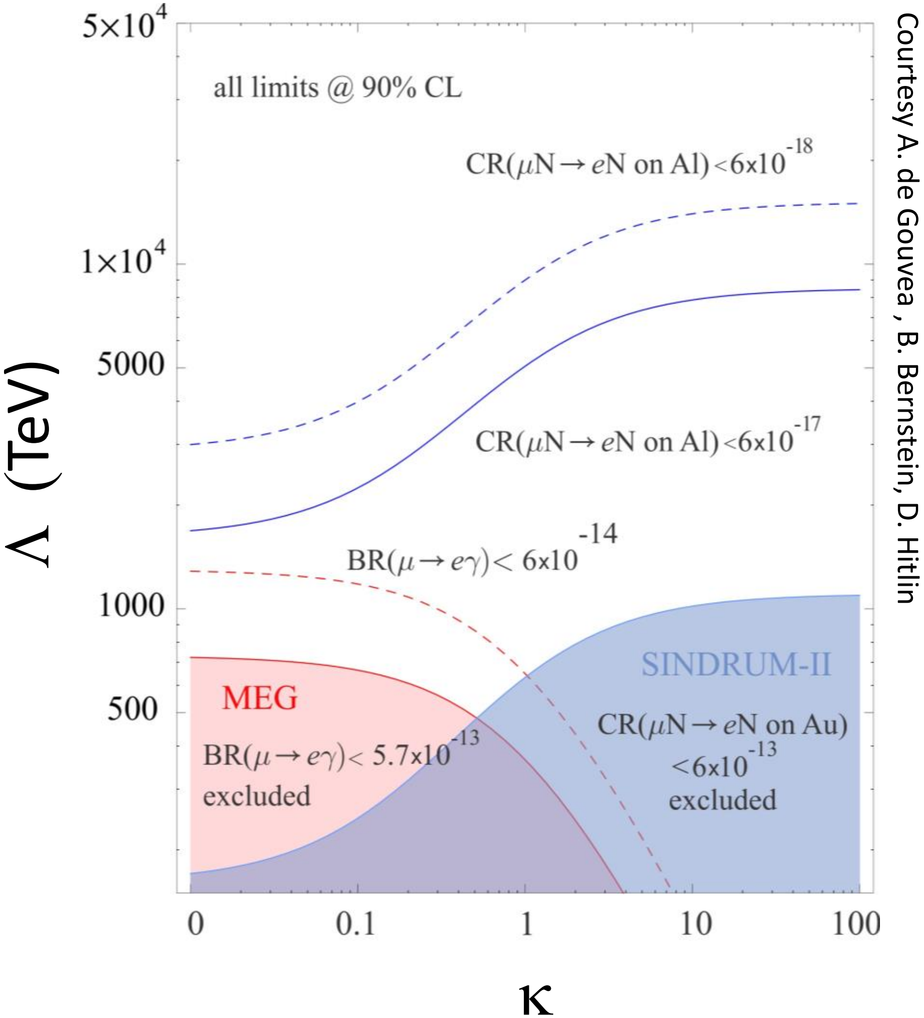
* The net systematic is across 3 running periods.

<ω_p> (B-field) systematic uncertainty summary[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Absolute Field Calibration	50	35
Trolley Probe Calibrations	90	30
Trolley Measurements Of B_0	50	30
Fixed Probe Interpolation	70	30
Muon Distribution	30	10
Time-dependent External Magnetic Fields	-	5
Others (Collective Smaller Effects)	100	30
Total (Quadrature Sum)	170	70

[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].
[2] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

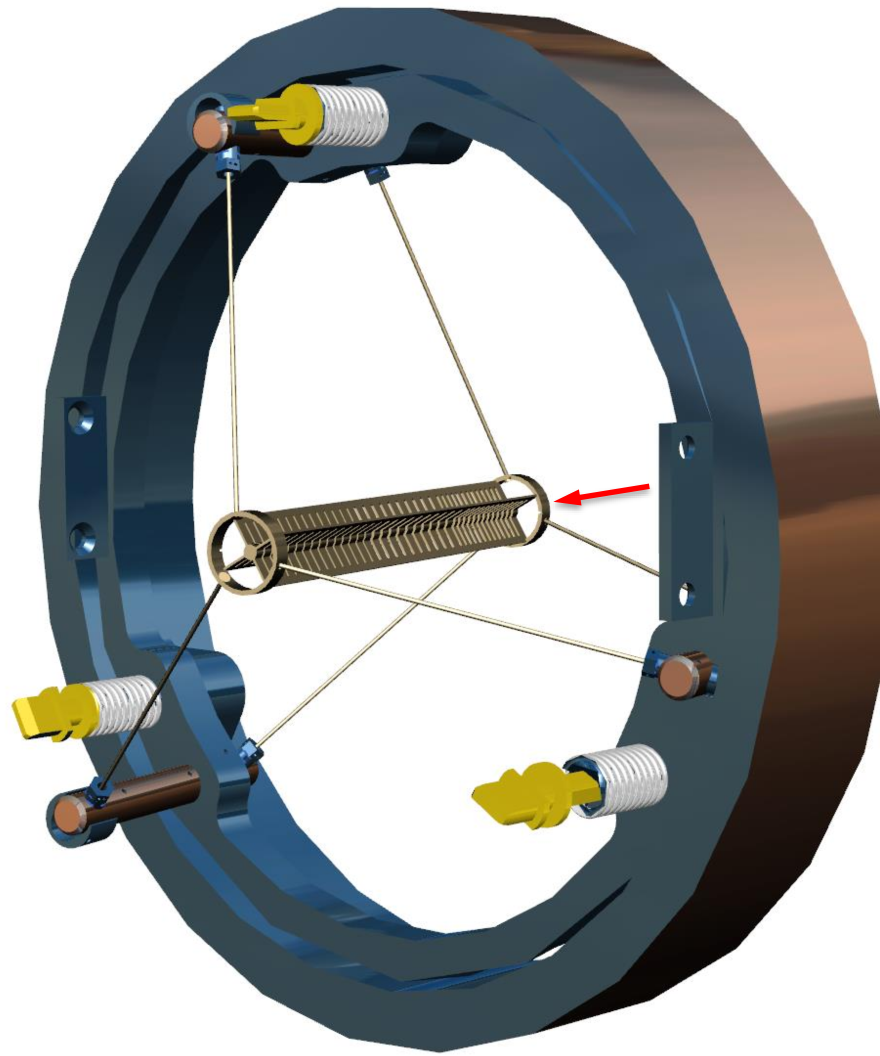
Mu2e Sensitivity



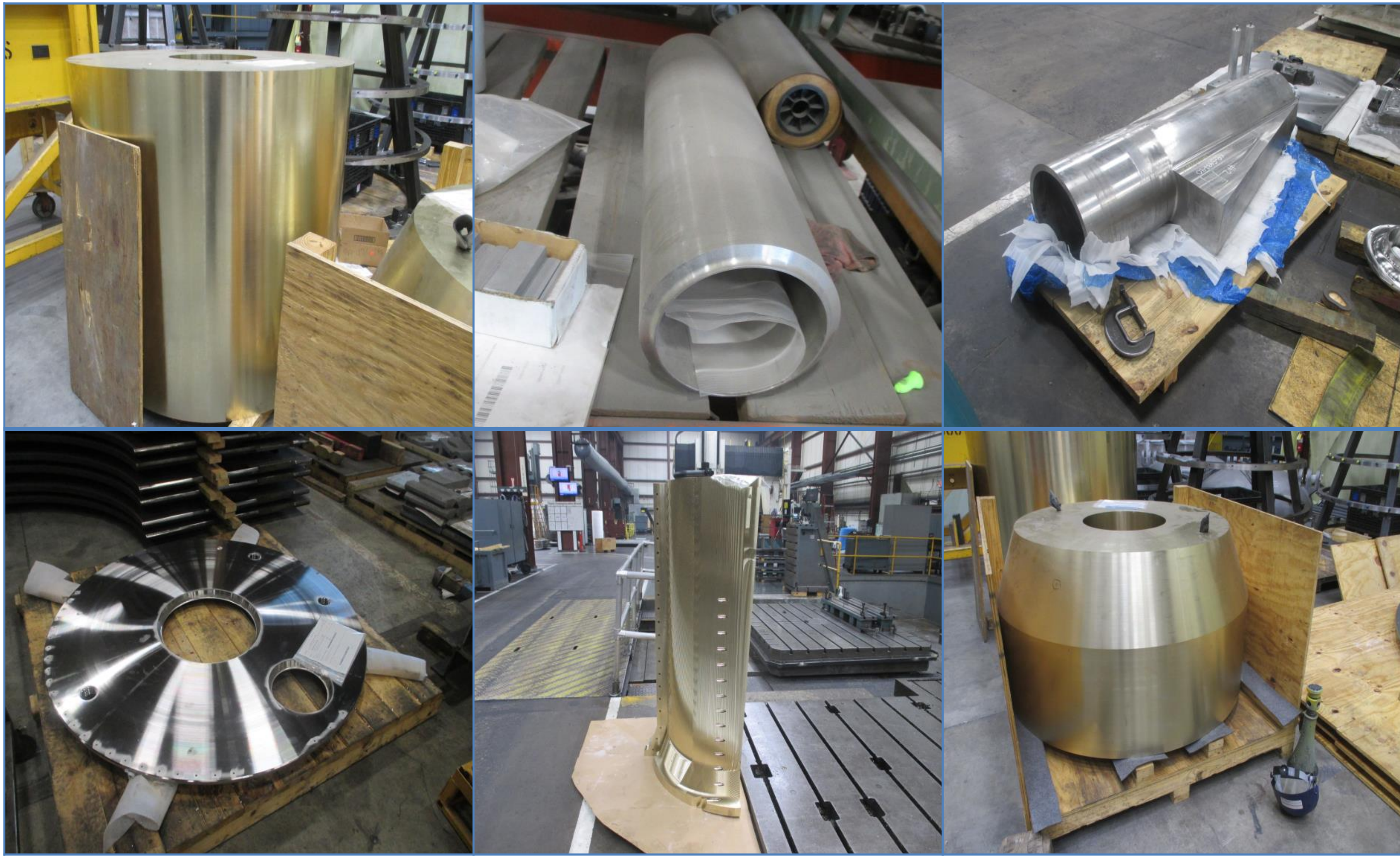
- Mu2e Sensitivity best in all scenarios

Final Target Design

- **Radiatively cooled**
- **Peak temperature = 1130℃**
  (@ 8 kW proton beam power)
- **Variable length segmented core and fins to control longitudinal temperature profile**
- **Four 1mm thick × 13mm tall fins, angled to minimize interference with Extinction Monitor view of target.**
- **Extended mounting bars on outside ring to minimize bending moment on target**
- **Stopped muon yield = 0.0015 m/POT**
- ***Ready to start procurement and fabrication after final reviews***



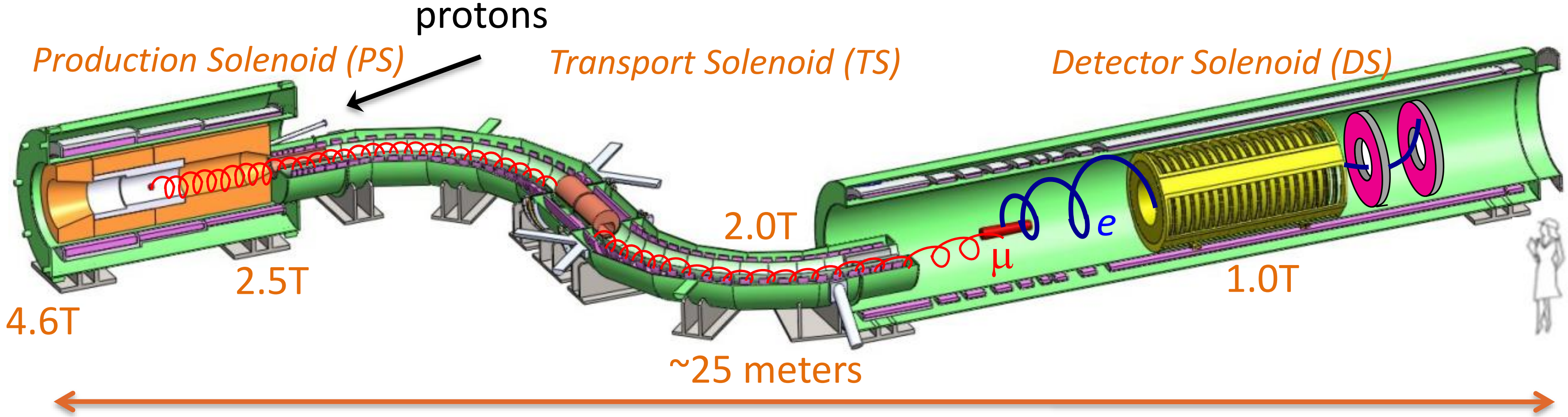
Heat and Radiation Shield Fabrication



Delivery Expected in February 2020 Pictures courtesy of Major Tool & Machine, Indianapolis, IN

The Mu2e Muon Beam Line & Detectors

A System of superconducting solenoids and an intense muon beam

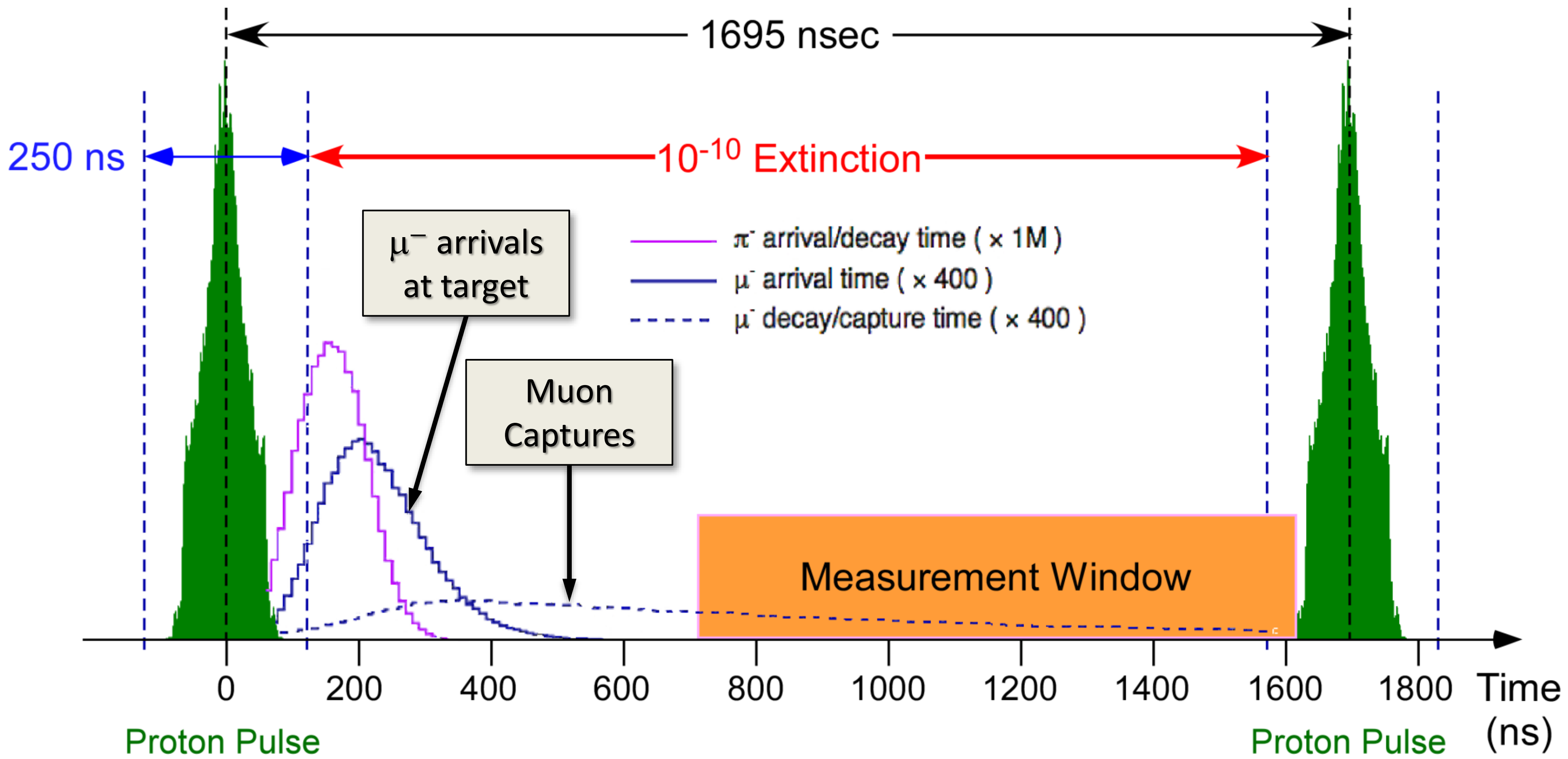


- **A search for Charged Lepton Flavor Violation: $\mu N \rightarrow e N$**
  - **Expected sensitivity of 6x10^{-17}@ 90% CL, x10,000 better than SINDRUM-II**
  - **Probes effective new physics mass scales up to 10^4 TeV/c^2**
  - ***Discovery* sensitivity to broad swath of NP parameter space**

- **Experiment scope includes**
  - **Proton Beam line**
  - **Solenoid systems**
  - **Detector elements**

    (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
  - **Experimental hall**
  - **Commissioning begins in 2020**

Reduction of Prompt Backgrounds



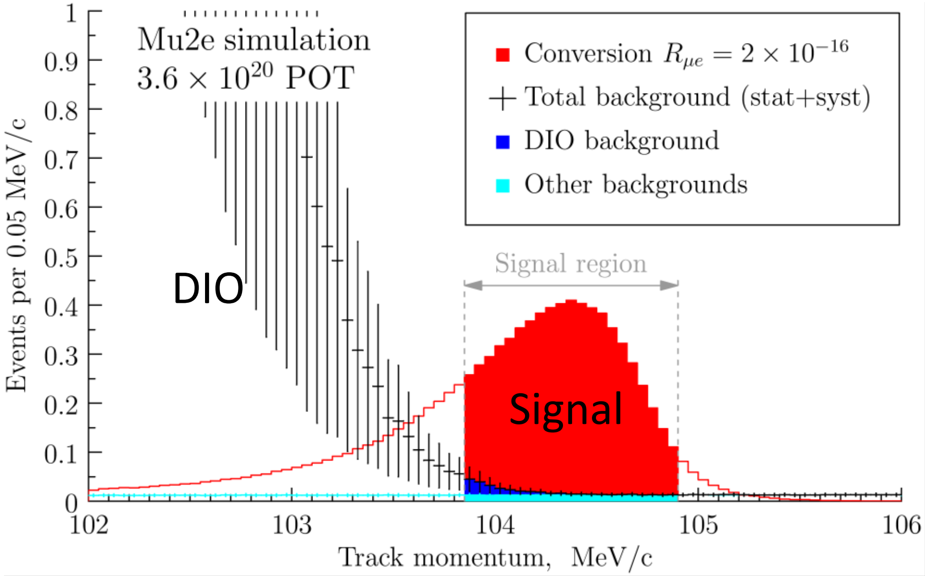
- Beam flash decays within 600 ns
- Live gate begins after prompt signal is gone
- $\tau(\mu^-)$ in Al = 864 ns >> prompt background duration
- Out-of-time backgrounds reduced by 10^{-10} extinction factor

Mu2e:Signal and Background

Simulation: Conversion Signal (Red)
+ Background from electrons in tail of distribution of ordinary muon Decay in Orbit(DIO)

$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + {}^{27}_{13}Al$$

[Simulated signal assumes $R_{\mu e}$=2x10^{-16}]

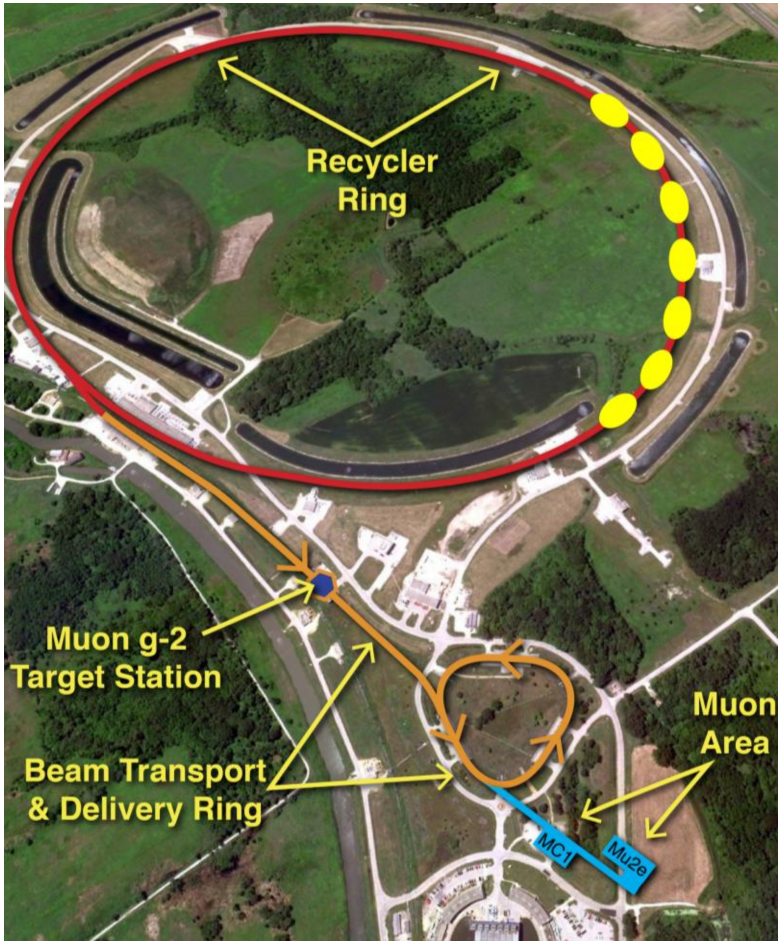


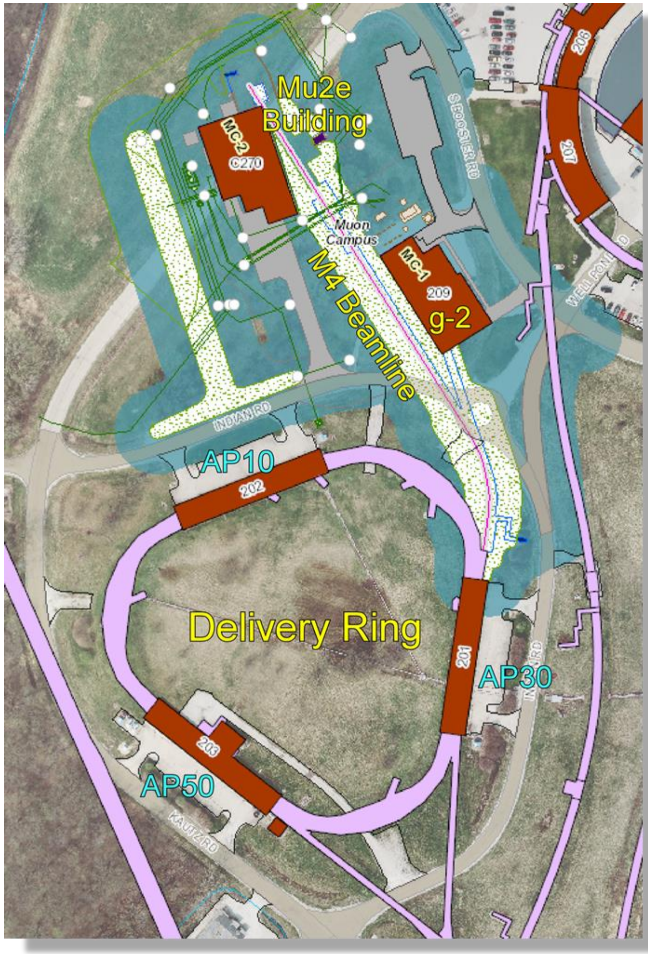
Process	Expected event yield
Cosmic rays	$0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$
DIO	$0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

Assumes 6x10^{7} seconds running at full intensity

Mu2e/g-2 beam lines

- Mu2e or g-2 run concurrently with the neutrino program
- However Mu2e and g-2 cannot run simultaneously
- g-2 beamline complete and delivering muons since 2017
- Mu2e beamline is complete up to final focus region





Muon g-2 Experiment measures the anomalous spin precession frequency.

$$\vec{\omega}_s = -g_\mu \frac{q}{2m}\vec{B} - (1-\gamma)\frac{q}{\gamma m}\vec{B}$$

$\vec{\omega}_s$ = spin precession frequency

$\vec{\omega}_c$ = cyclotron frequency

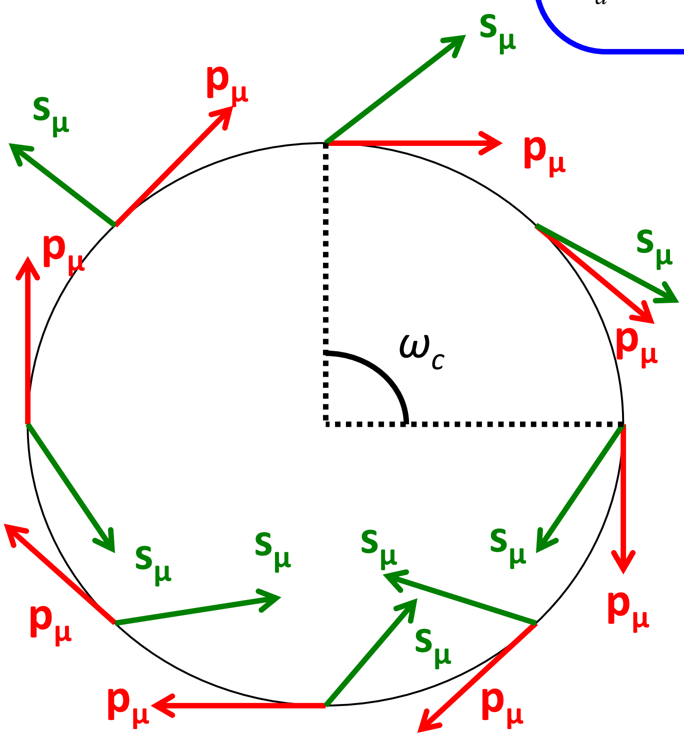
$$\vec{\omega}_c = -\frac{q}{m\gamma}\vec{B}$$

$\vec{\omega}_a$ = anomalous precession frequency

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g_\mu - 2}{2}\right)\frac{q}{m}\vec{B} = -a_\mu \frac{q}{m}\vec{B}$$

Simple case of no E-field, constant B-field, and momentum perpendicular to B-field.

Experiment is sensitive to spin precession relative to momentum.



Want a uniform B field: Then all stored muons precess at same rate regardless of momentum, if E field=0.

$$0 \text{ if } p = p_{\text{magic}} = mc/\sqrt{a_m} = 3.094 \text{ GeV}/c$$

$$\vec{\omega}_a \approx -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

P5 Recommendations: Mu2e and g-2

page 17 of P5 Report

Report of the Particle Physics Project Prioritization Panel 17

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenario B	Scenario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C