Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

The Muon Program

Adam L. Lyon (Scientific Computing Division)

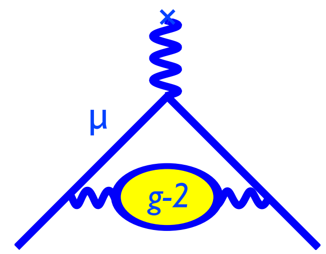
Fermilab 2015 Institutional Review

10-13 February 2015

Look Here

Overview

- Motivation and P5
- The experiments



- Bringing the lab together

Facilities

R&D

Computing

Theory

Community

The Muon program is a high priority in P5

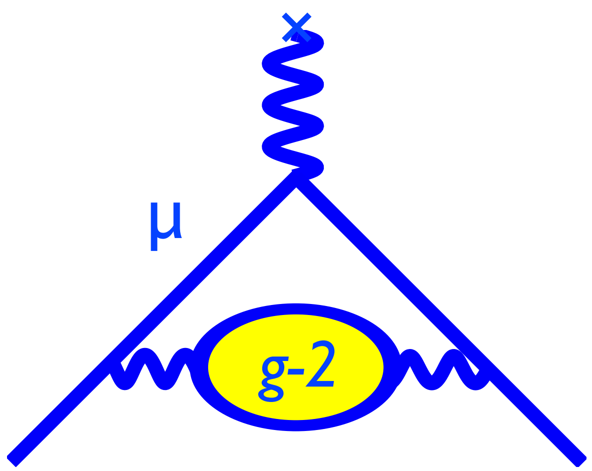
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles.

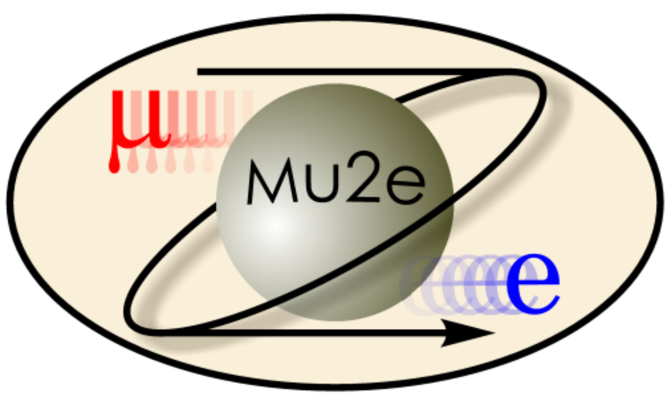
Project/Activity	Scenarios: Scenario A	Scenario B	Scenario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E

Fermilab

Indirect searches offer opportunities for discoveries

The Fermilab Muon Program





Muons offer exciting prospects for discovery

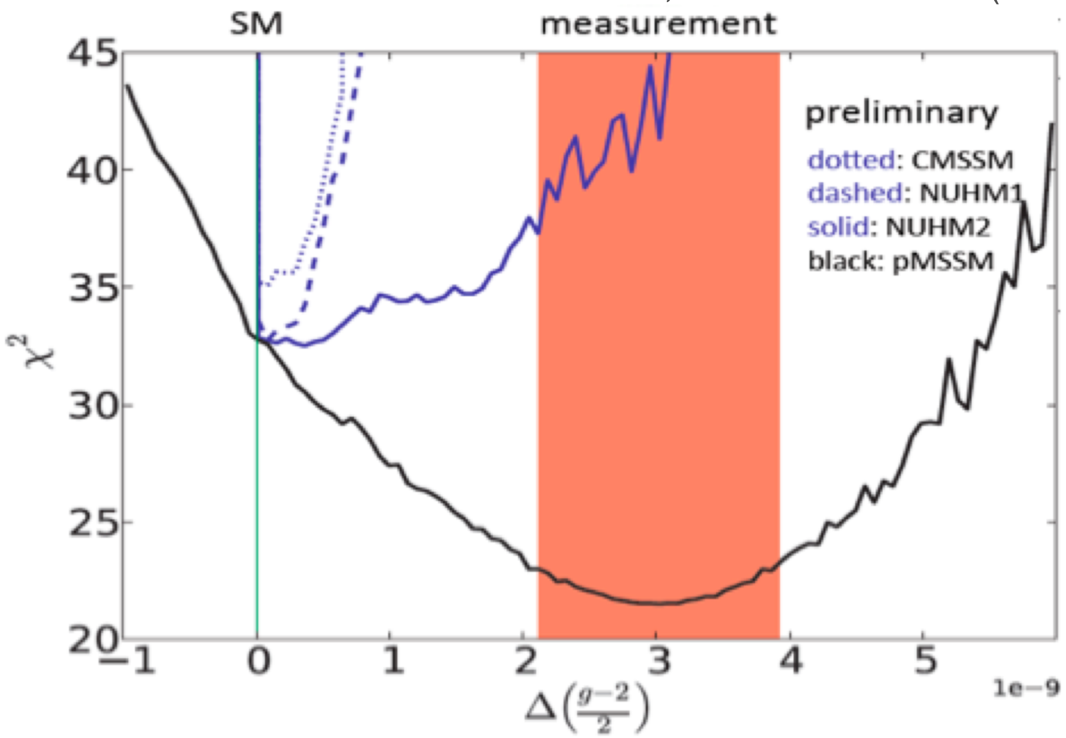
Muon *g-2* probes TeV scale (flavor conserving) physics with the muon anomalous magnetic moment

Mu2e probes effective mass scales of $10^3 – 10^4$ TeV range with charged lepton flavor violation

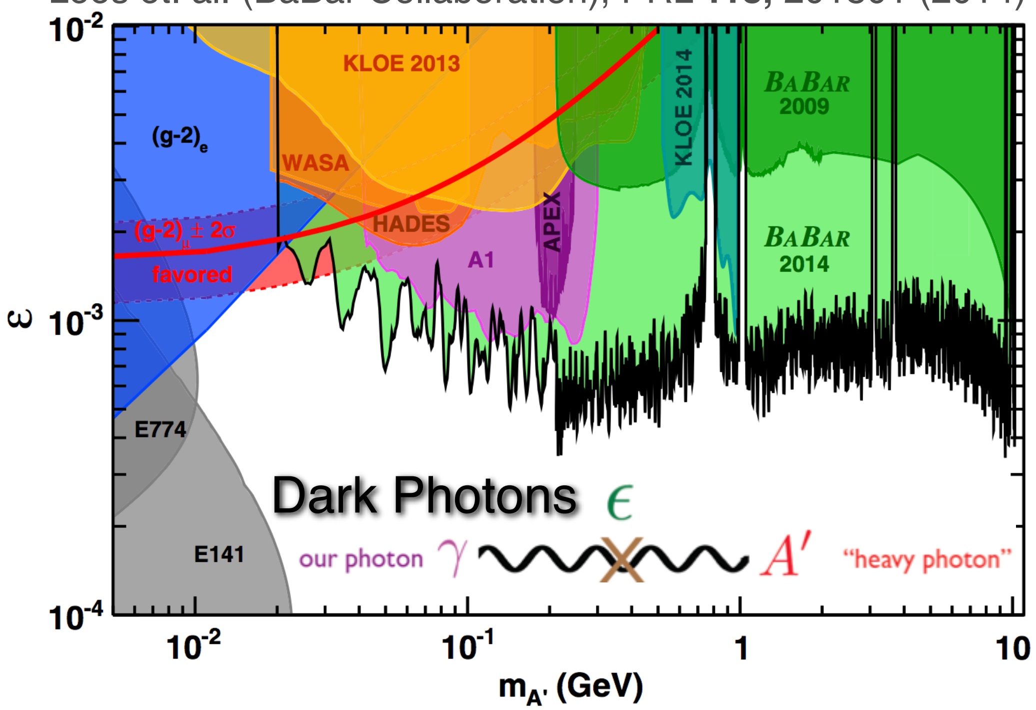
Fermilab supports these experiments with common facilities, infrastructure, and technical and scientific leadership

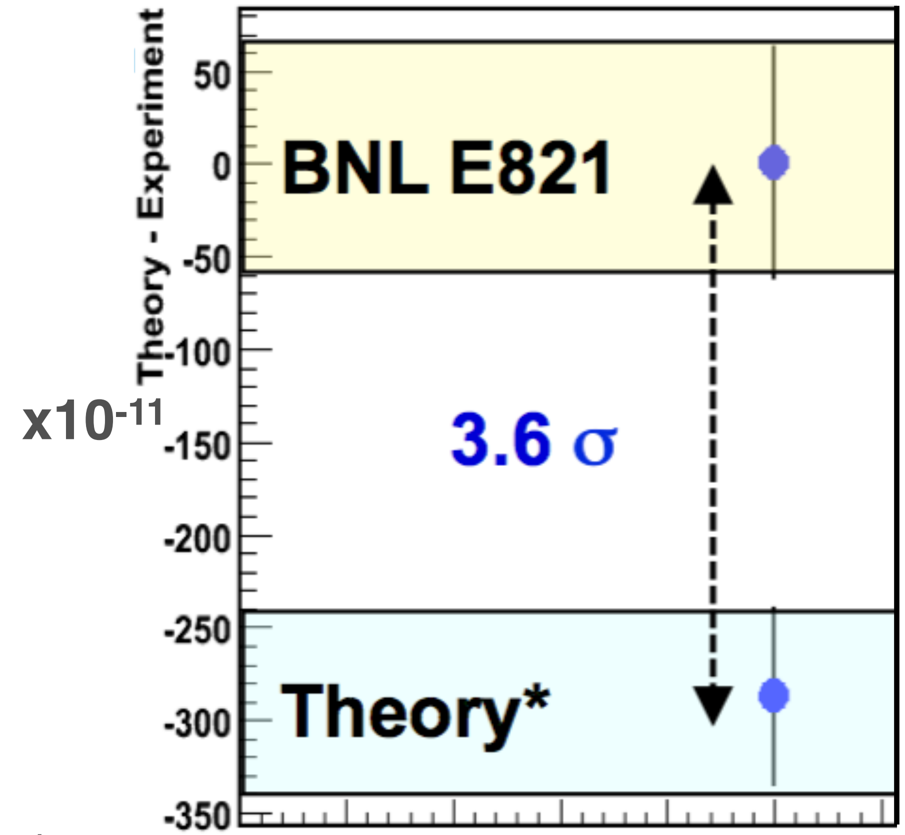
The Muon *g-2* is a unique probe for new physics

Ellis, arXiv:1501.05418 (2015)



Lees et. al. (BaBar Collaboration), PRL **113,** 201801 (2014)





*See Snowmass White Paper arXiv:1311.2198 [hep-ph]

Chirality-flipping while CP and flavor conserving, unlike many other low energy observables

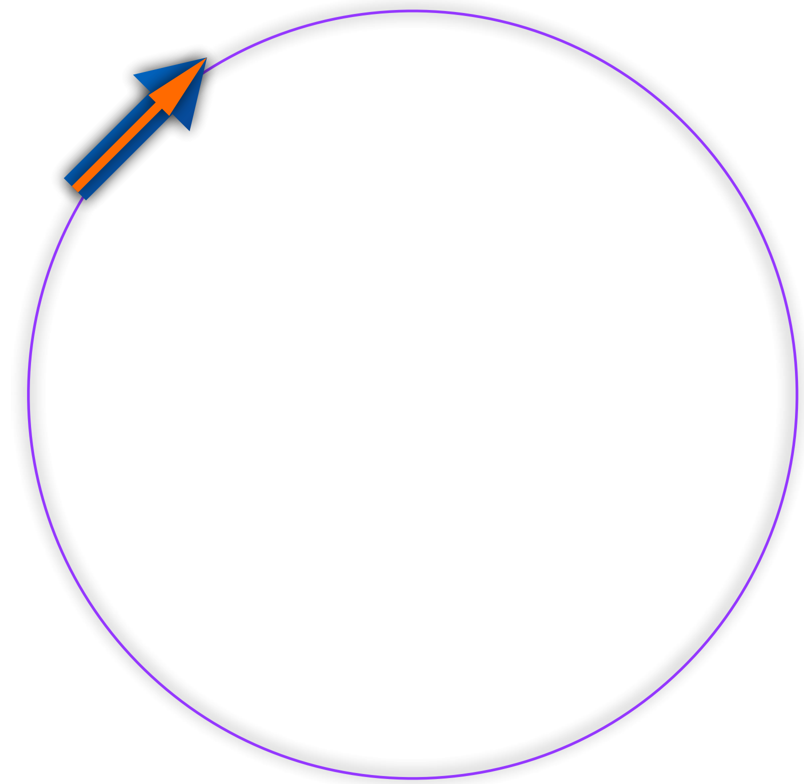
Sensitive to SUSY sleptons and sign(μ), dark matter models

A hint of new physics?!?!?
Complementary to LHC's direct searches

See Polly talk [Project] in Breakout 1D; Kiburg talk [Highlights] in Breakout 6B

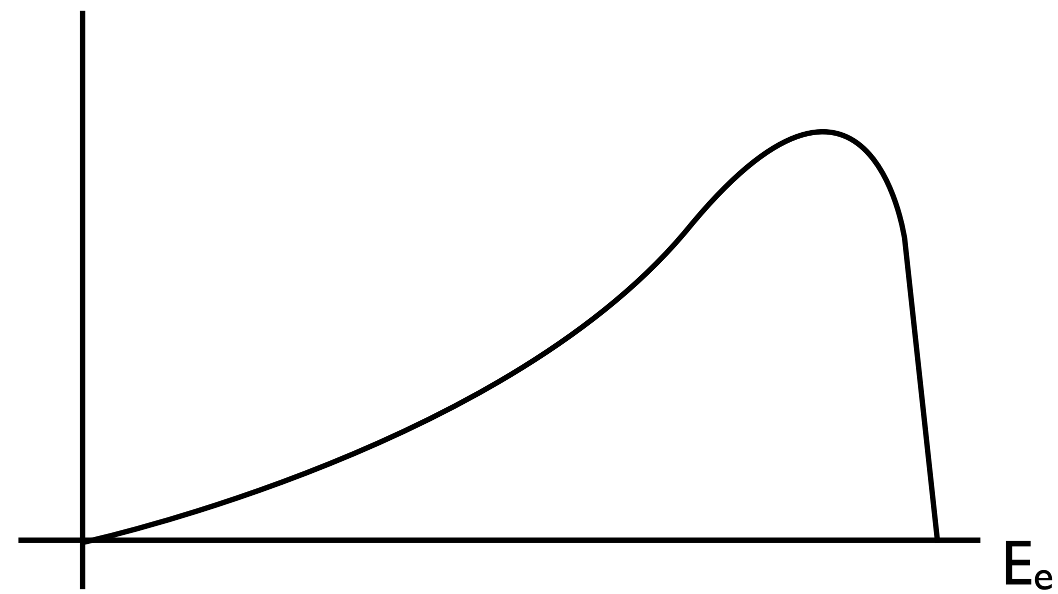
The Muon *g-2* measurement

μ^+ are stored in the ring and decay to positrons, which travel inward hitting detectors



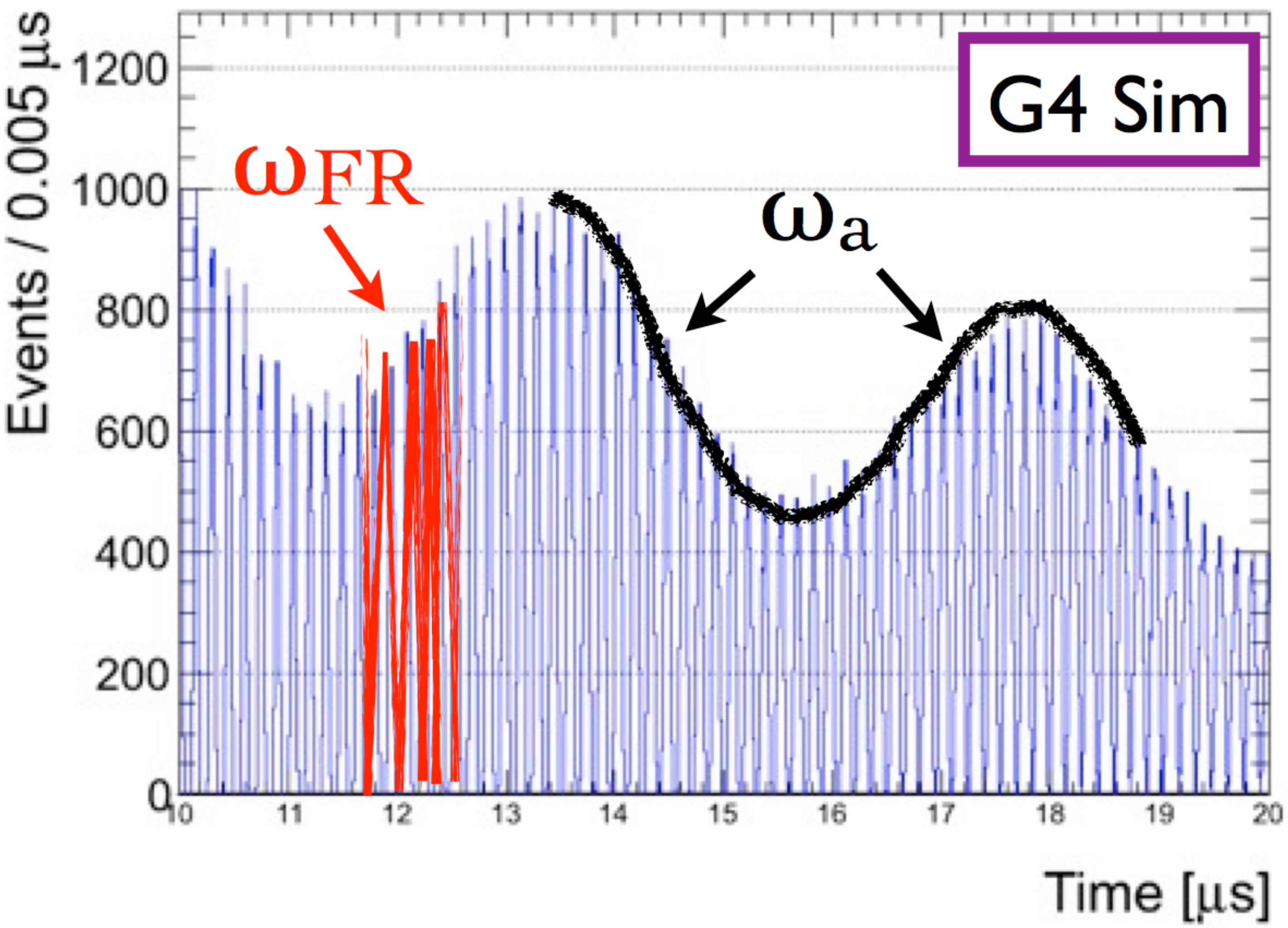
Highest energy positrons are emitted in direction of muon spin

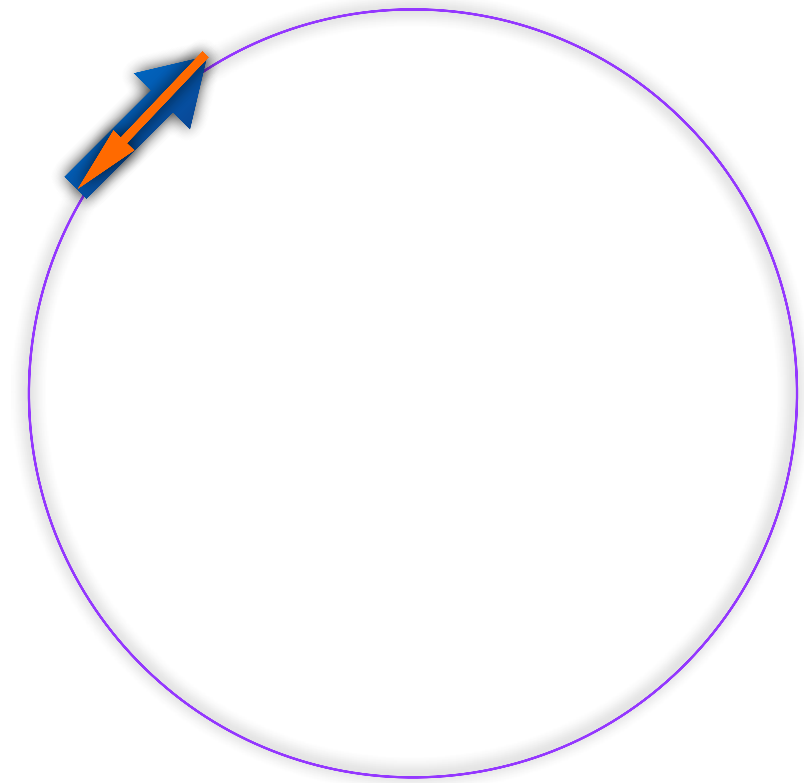
Boost to the lab frame gives *E* a boost

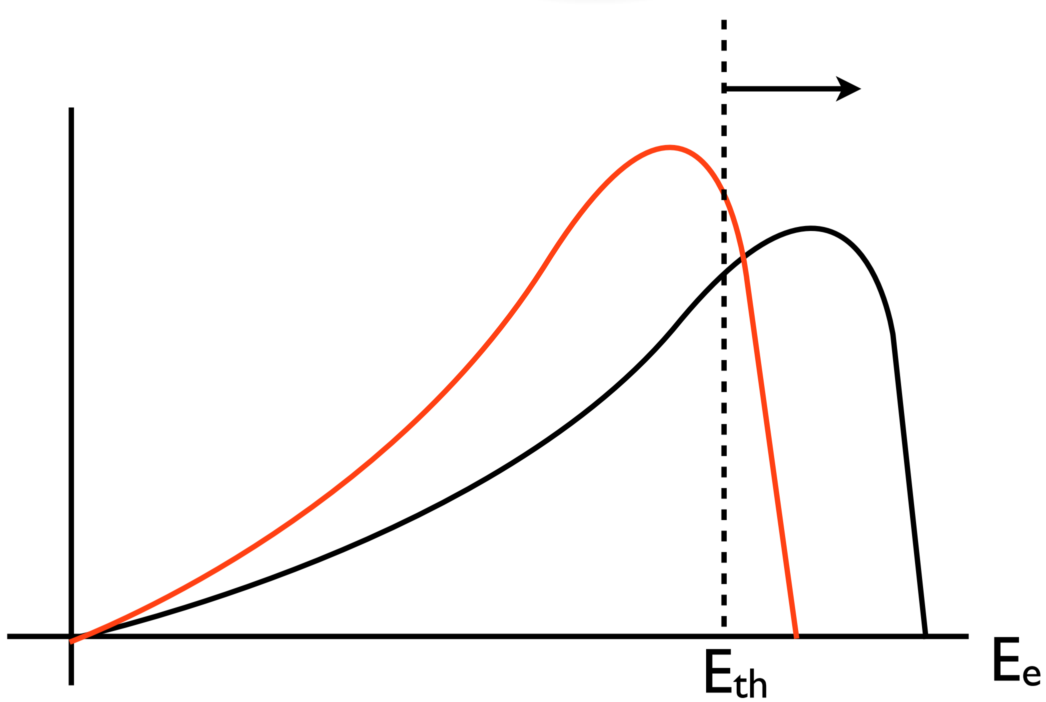


The Muon *g-2* measurement

Maximum *E* oscillates at ω_a







From Lawrence Gibbons

A uniform magnetic field is crucial

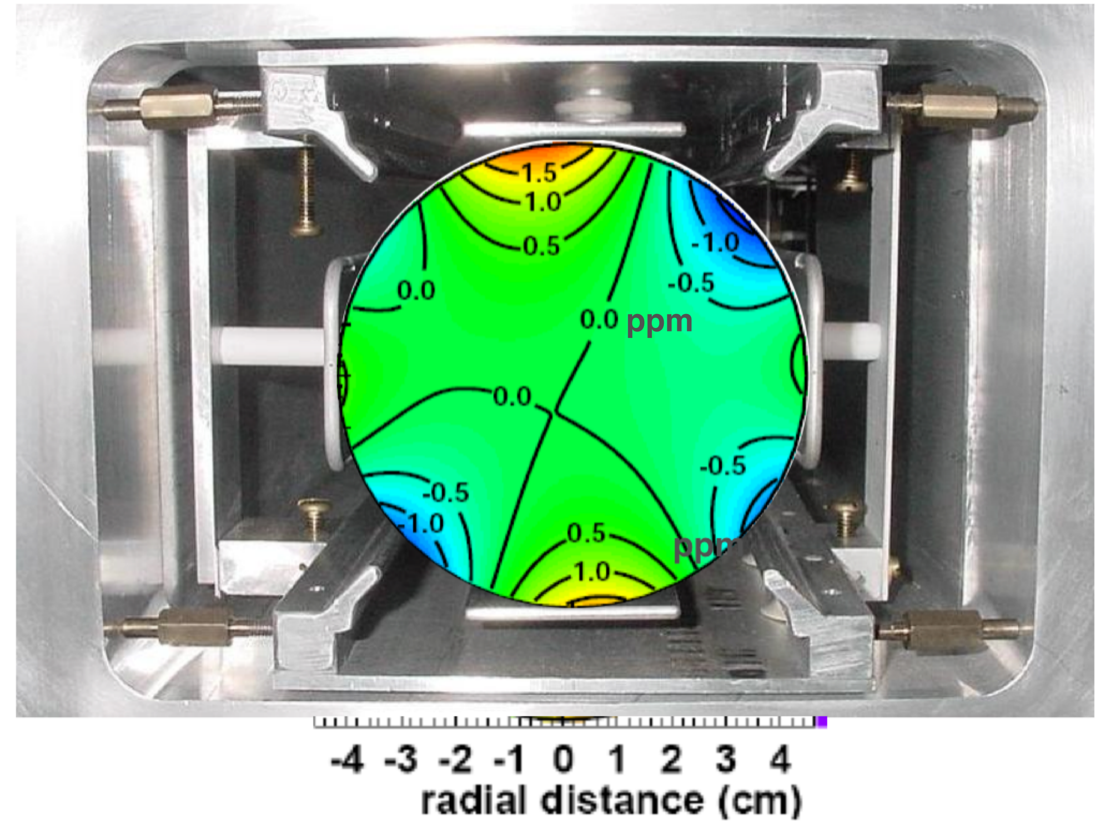
$$\omega_a = a_\mu \frac{eB}{m_\mu c}$$

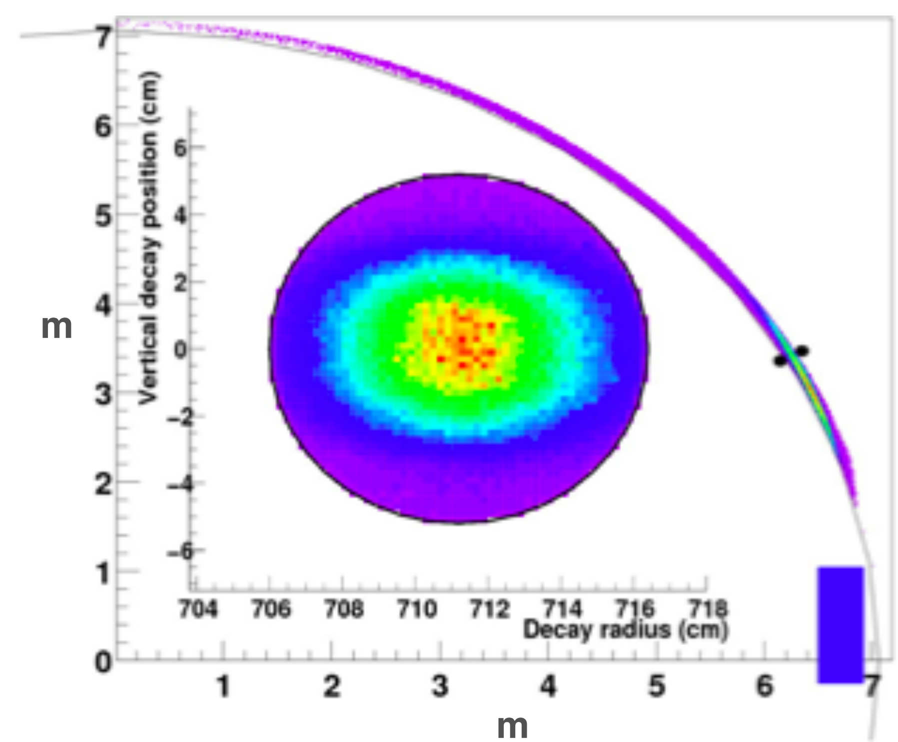
$$a_\mu = \frac{g_e}{2} \frac{\omega_a}{\omega_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e}$$

ω_p is free proton precession frequency (free proton spin rotation rate in ring)

Measure magnetic field in storage region with fixed NMR probes and trolley

Straw trackers are important for measuring beam profile and for systematics





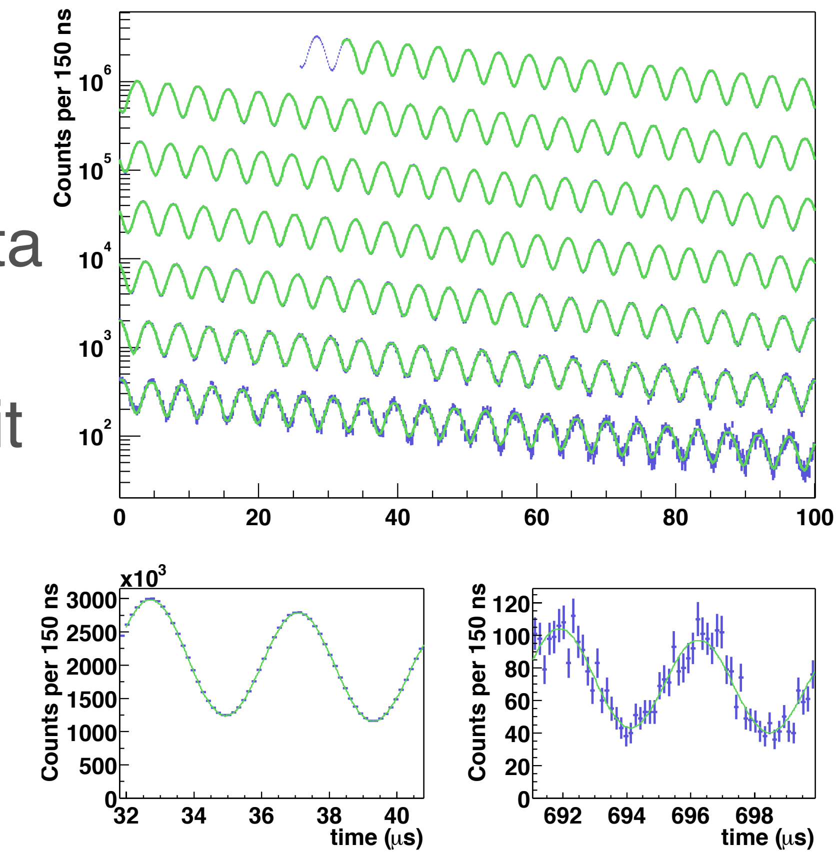
An exciting result - but not a discovery

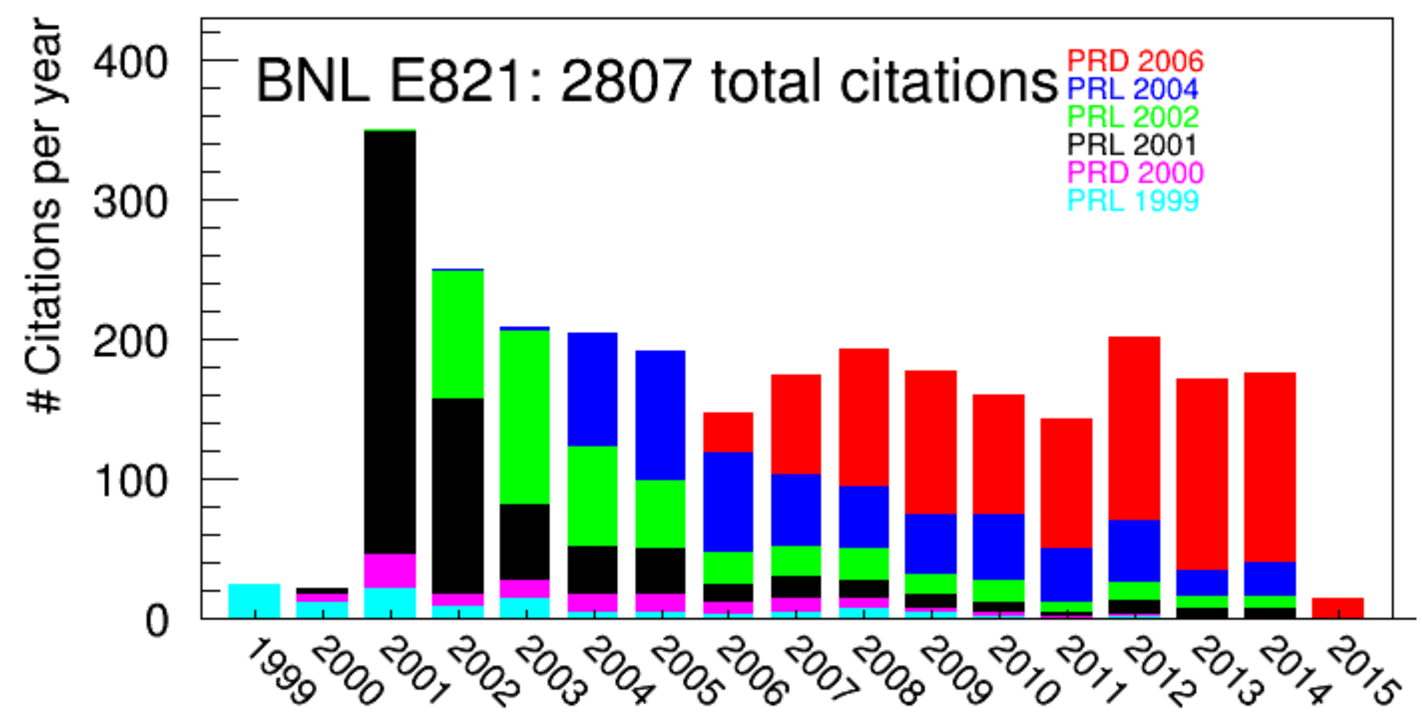
$$a_\mu^{\text{exp}} = 116\,592\,089(63) \times 10^{-11} \;(0.54 \text{ ppm})$$

Year 2000 data

4B decays

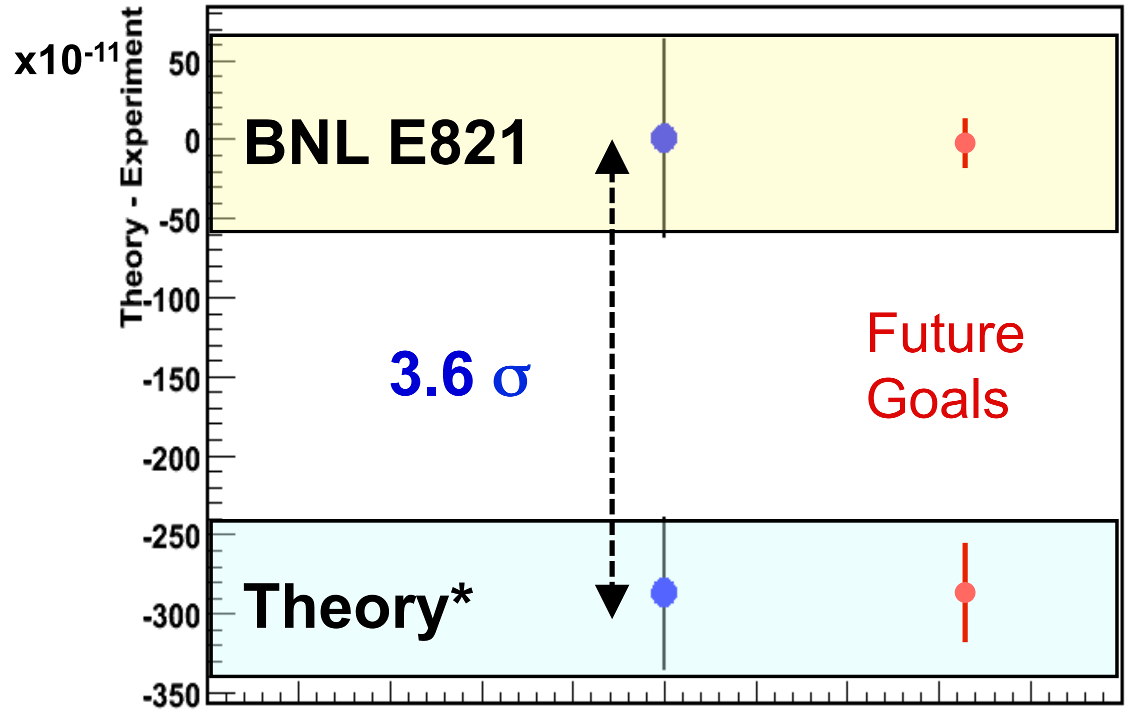
5 parameter fit





Running at Fermilab, with more 20x statistics and improved systematics, for the definitive *g-2* experiment

Getting from 540 ppb to 140 ppb…



Goal: 140 ppb

7.5 σ if same central values

Expected 330 ppb

E989 Experimental Scope

Positive muons will be used to measure the muon anomaly to an absolute precision of $\delta a_{\mu} = 16 \times 10^{-11}$ (140 ppb). The error budget is distributed as follows:

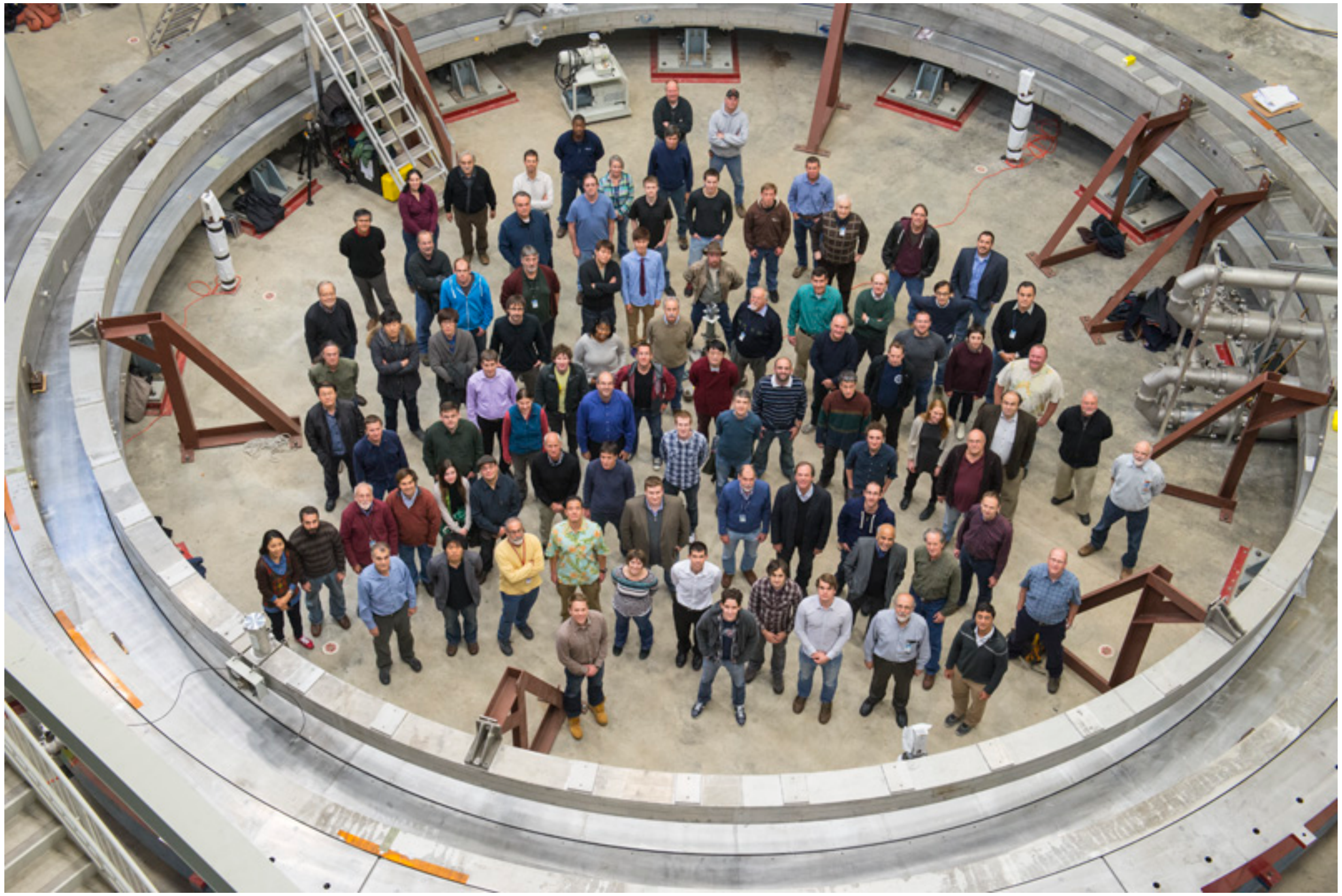
Category	Error (ppb)	vs BNL E821
Statistical	100	x20 events
Field Systematics	70	x2 better
Precession Systematics	70	x3 better

*See Snowmass White Paper arXiv:1311.2198 [hep-ph]

The Muon *g-2* collaboration 34 institutions 155 members

US Universities
- Boston
- Cornell
- Illinois
- James Mason
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Northwestern
- Regis
- Virginia
- Washington
- York College

US National Labs
- Argonne
- Brookhaven
- Fermilab



Italy
- Frascati
- Roma 2
- Udine
- Pisa
- Naples
- Trieste

China
- Shanghai

The Netherlands
- Groningen

Germany
- Dresden

Russia
- Dubna
- Novosibirsk

United Kingdom
- University College London
- Liverpool
- Oxford

Republic of Korea
- KAIST

Reuse the ring…

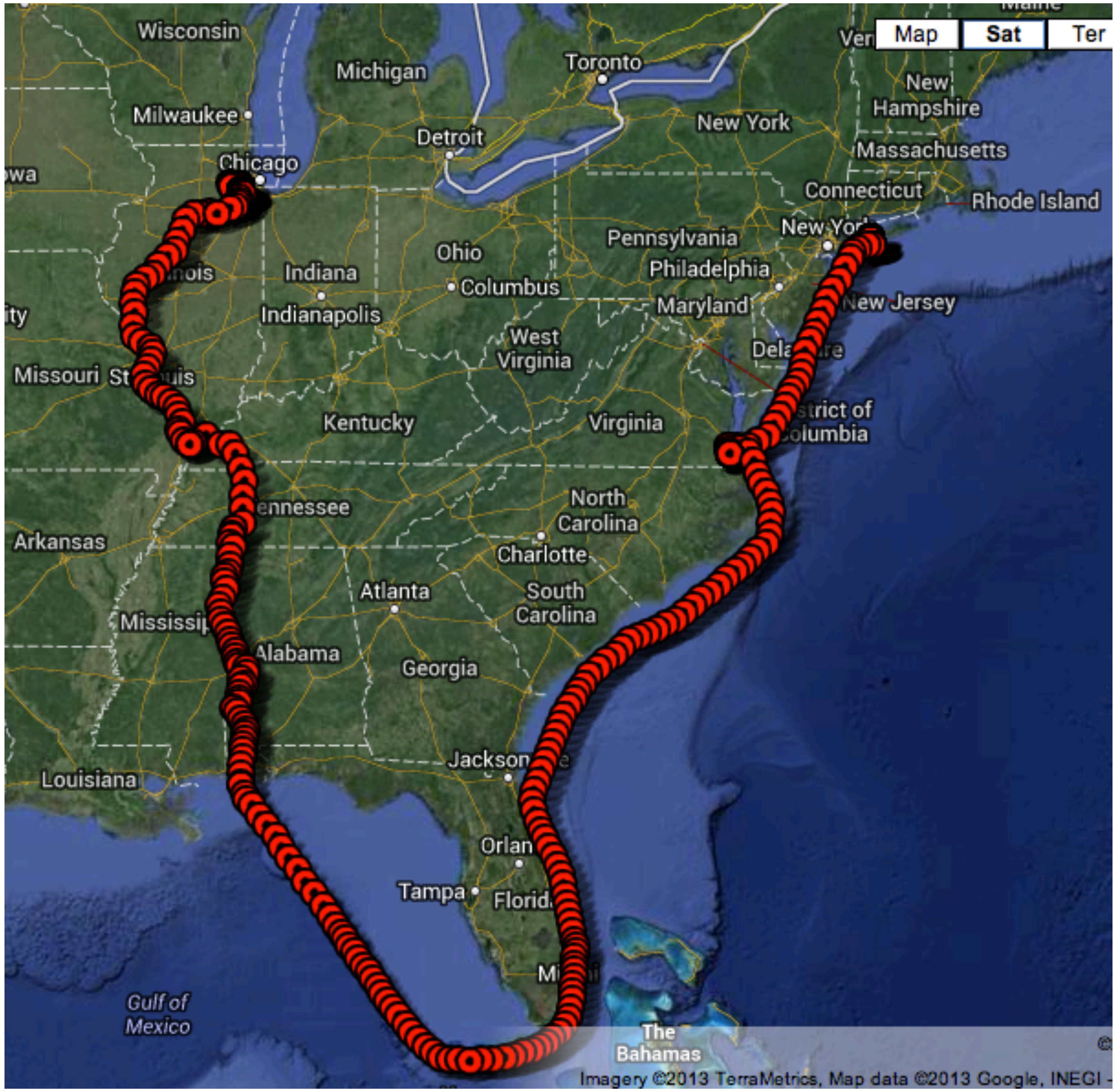
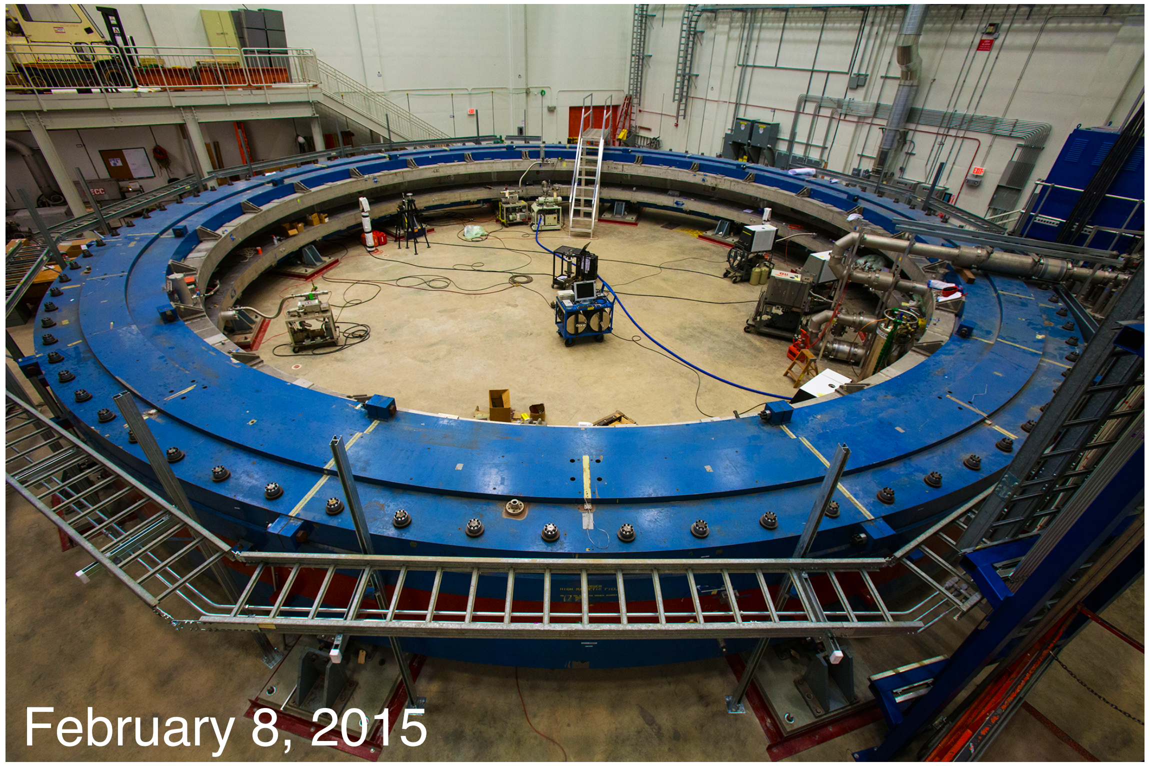


Photo: Fermilab

More fun pictures



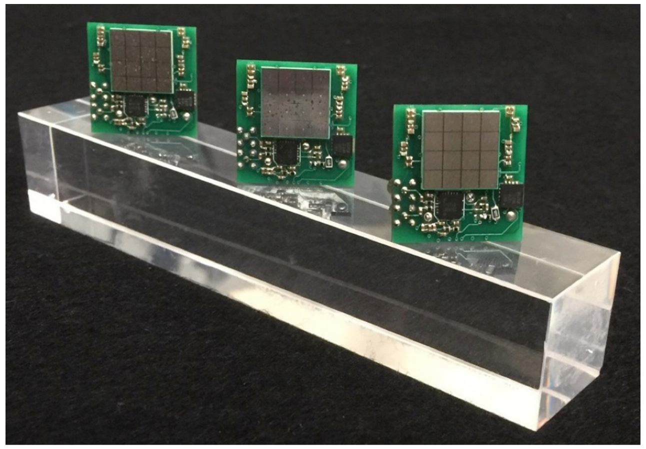
New detectors: Calorimeters and Straws

- Calorimeters 24 9x6 PbF_2 crystal arrays with SiPM readout
- New electronics and DAQ
- 3x 1024 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons
- Auxiliary detectors

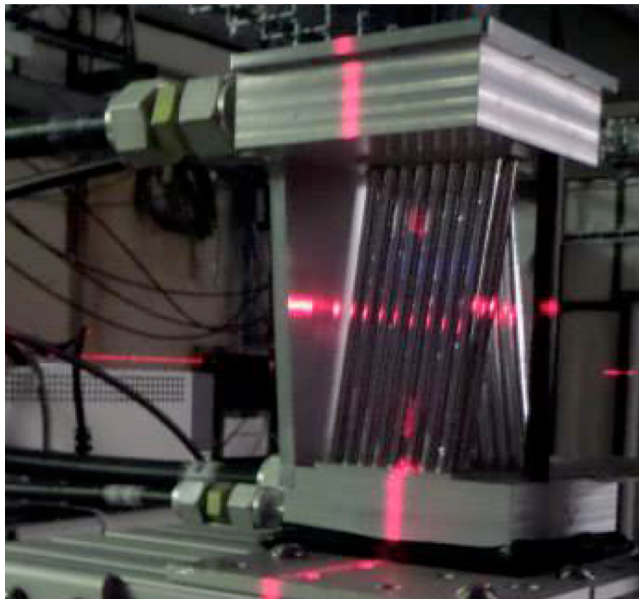
Additional funding sources

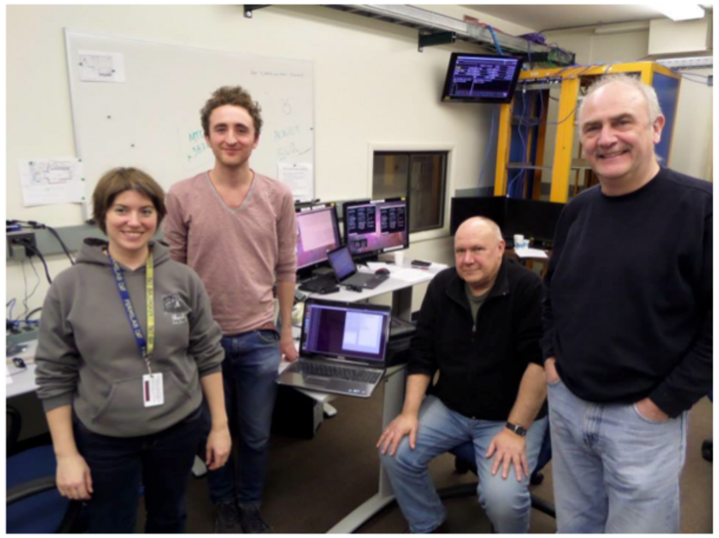
- NSF MRI, INFN: Calorimeters, DAQ and electronics
- DOE Early Career, STFC: Straw Tracker
- IF Fellowships
- URA Visiting Scholar Fellowships
- DOE Office of Science Graduate Student Research Awards

Calorimeters; SLAC Test Beam



Straw Trackers; Fermilab (PPD) Test Beam





Muon g-2 highlights of 2014

MC-1 Completed and Ring arrives!
Test beam for calorimeter at SLAC
Test beam for tracker at FNAL
TDR Complete and CD-2/3 review

2015 –
March: Cool down and test magnet
July: Test beam for tracker at FNAL
July: Analysis Workshop at U. Washington
Ongoing: Ring reassembly, shimming

Plan is first muons in early 2017!

Muon $g-2$ Technical Design Report
July, 2014
Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov
Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359

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D. Hertzog – Co-Spokesperson (hertzog@uw.edu)
B. L. Roberts – Co-Spokesperson (roberts@bu.edu)

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Fermilab

The Mu2e Experiment

Neutral lepton flavor violation happens (a whole cross-cut devoted to that!)

Charged Lepton Flavor Violation (CLFV):

$$\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$$

Suppressed in SM to **$< 10^{-50}$**

But, BSM models may contribute at level just out of reach of current experiments

A signal is a clear sign of new physics!

See Ray talk [Project] in Breakout 1D; Knoepfel talk [Highlights] in Breakout 6B

What is measured in Mu2e?

Ratio of CLFV conversions to number of captures:

$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)]}{\Gamma[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)]}$$

(BSM)
(SM)

Mu2e goals for $R_{\mu e}$

- Single-event-sensitivity: 2.5×10^{-17}
- Upper limit 90% C.L. 6×10^{-17}
- Probing mass scales $10^3 – 10^4$ TeV
- Background goal < 1 event

Need > 10^{18} muons

- Previous best limits

$R_{\mu e} < 7 \times 10^{-13}$ SINDRUM-II 2006
$Br(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$ MEG 2013
$Br(\mu \rightarrow 3e) < 1 \times 10^{-12}$ SINDRUM-I 1988

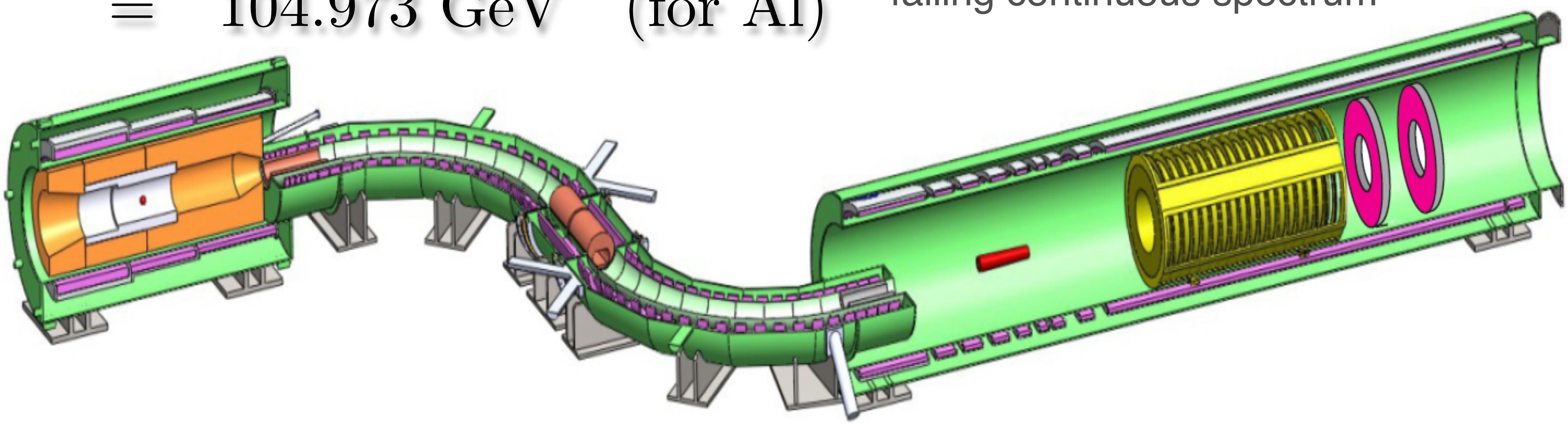
Mu2e is factor of ~10^4 more sensitive

How does Mu2e measure *R* ?

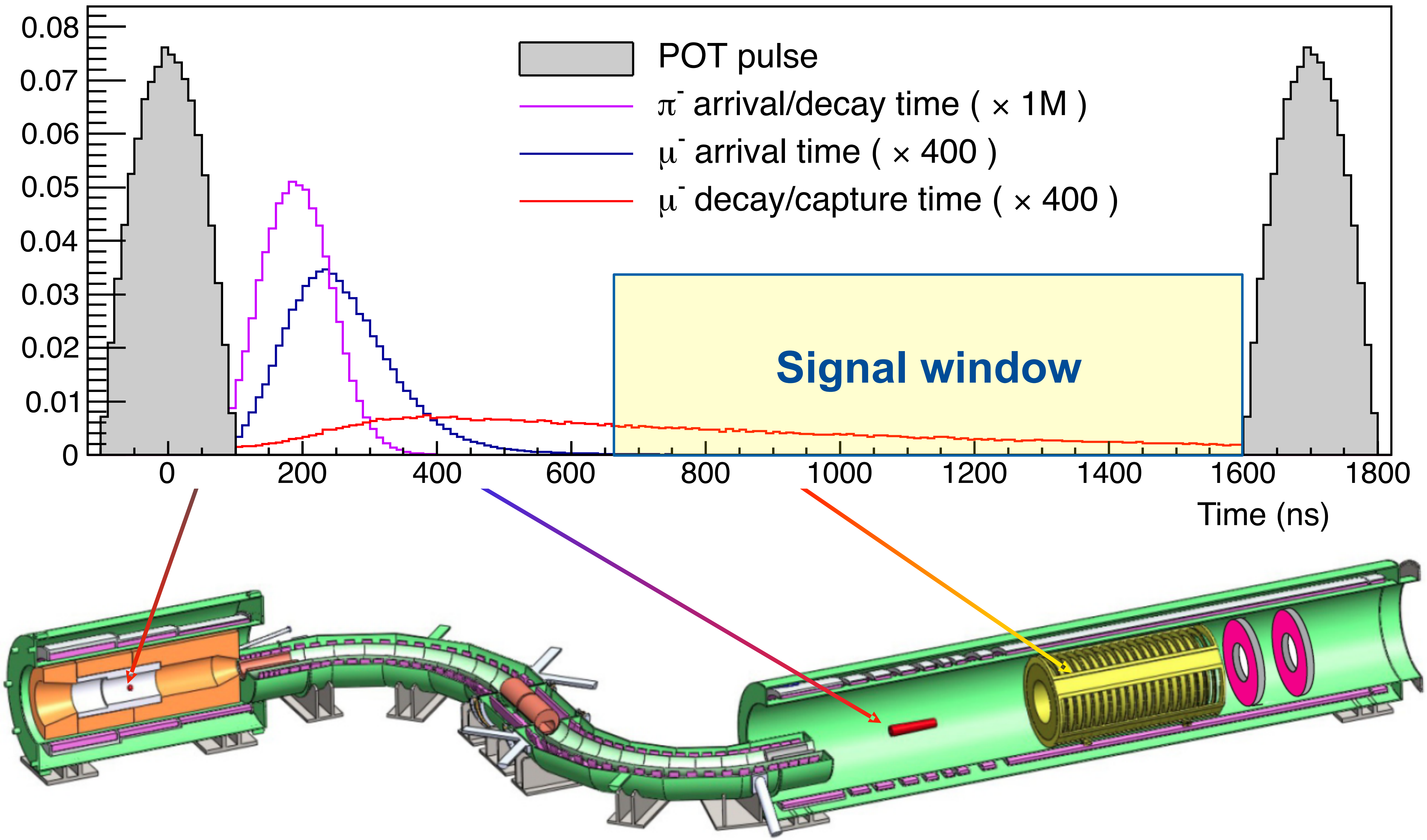
Generate low momentum muons from 8 GeV proton beam
Stop muons to orbit around an Al nucleus
Time constant for muons bound to Al nucleus = 864 ns
Electrons spiral into tracker and calorimeter

$$\begin{aligned} E_e &= m_\mu c^2 - E_b - E_{\text{recoil}} \\ &= 104.973 \text{ GeV} \quad (\text{for Al}) \end{aligned}$$

Signal is excess at endpoint of rapidly falling continuous spectrum



Proton timing is crucial



Plan on beam commissioning in late 2020; 3 year run

The Mu2e collaboration 32 institutions 170 members

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Lewis University
University of Louisville
University of Massachusetts, Amherst
University of Minnesota
Muons Inc.
Northern Illinois University
Northwestern University
Purdue University
Rice University
University of South Alabama
University of Virginia
University of Washington
Yale University

Significant growth of collaboration since 2013 S&T Review

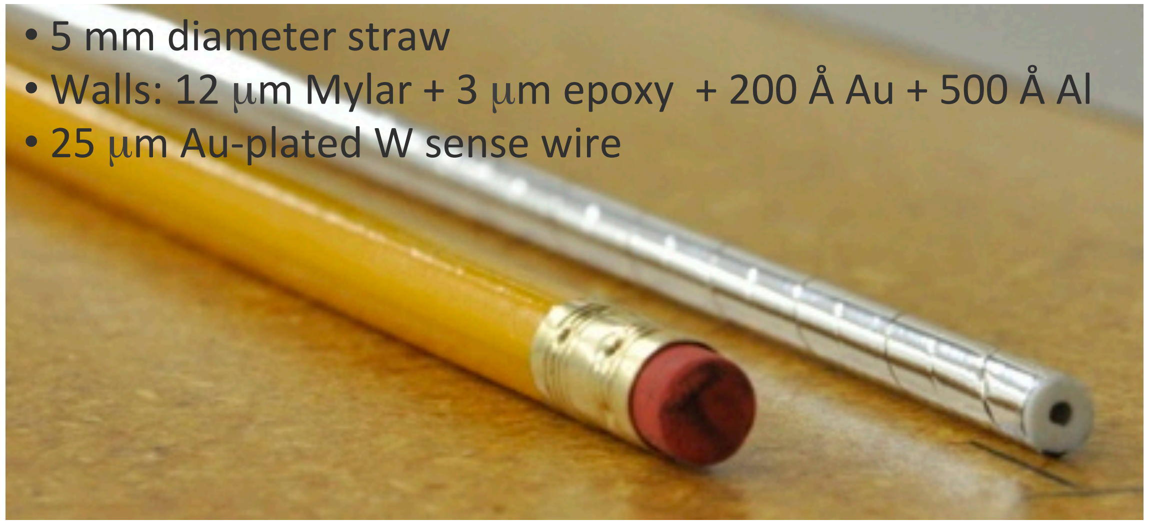
7 new institutions; 20% more collaborators

Laboratori Nazionali di Frascati
INFN Genova
INFN Lecce and Università del Salento
Laboratori Nazionali di Frascati and Università Marconi Roma
INFN Pisa

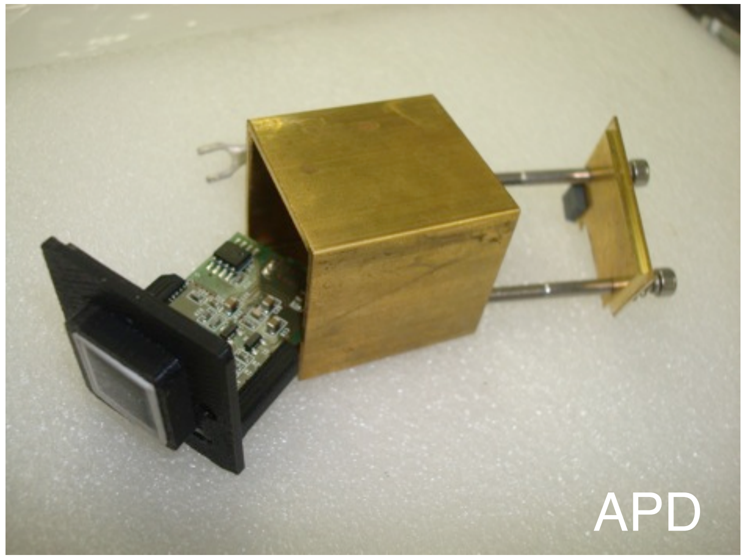
Joint Institute for Nuclear Research, Dubna
Novosibirsk State University/Budker Institute of Nuclear Physics
Institute for Nuclear Research, Moscow

Mu2e is pushing detector technology

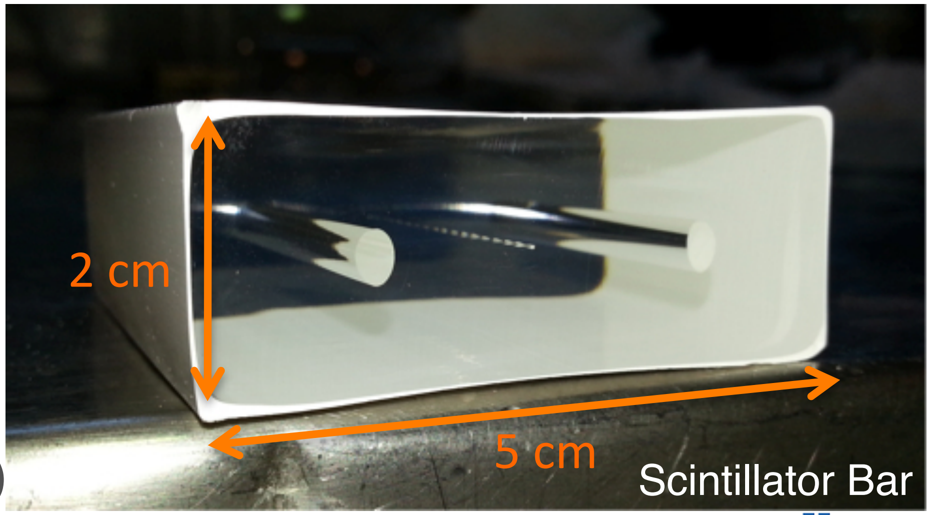
Tracker: 20k straw tubes, 15 um thick walls, in vacuum (led by FNAL)



Calorimeter (led by Caltech and Frascati): 1800 BaF_2 crystals (1ns decay time), Novel APDs



Cosmic-veto: 300 m^2 scintillator bar, WLS fiber, SiPM read-out – 99.99% efficient (led by U.Virginia)



Extruded at NICADD facility (PPD)

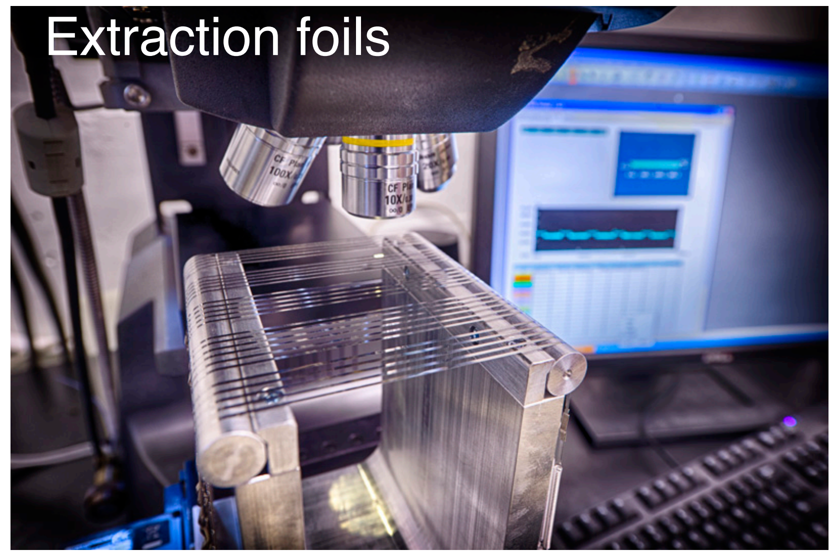
<u>Additional funding sources</u>

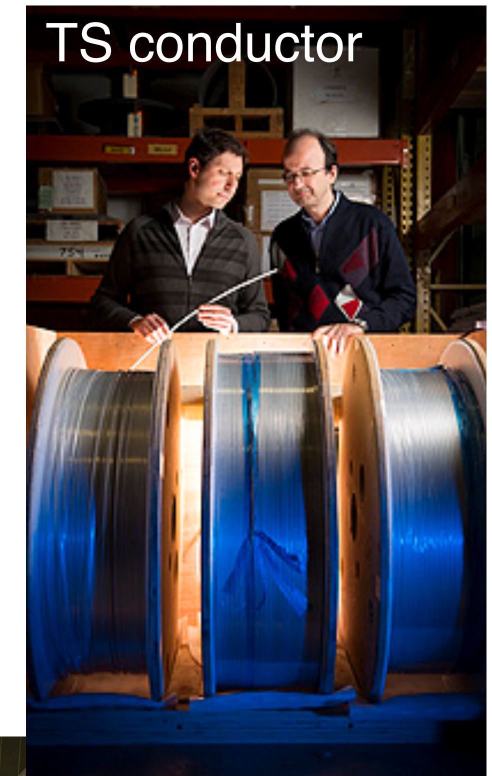
- INFN: Calorimeters, Solenoids
- SBIR: UV Sensitive solar blind APDs
- Joint appointment: C. Group (U.Va.)
- IF Fellowships
- URA Visiting Scholar Fellowships

Mu2e leads active R&D, test beams, and prototyping programs

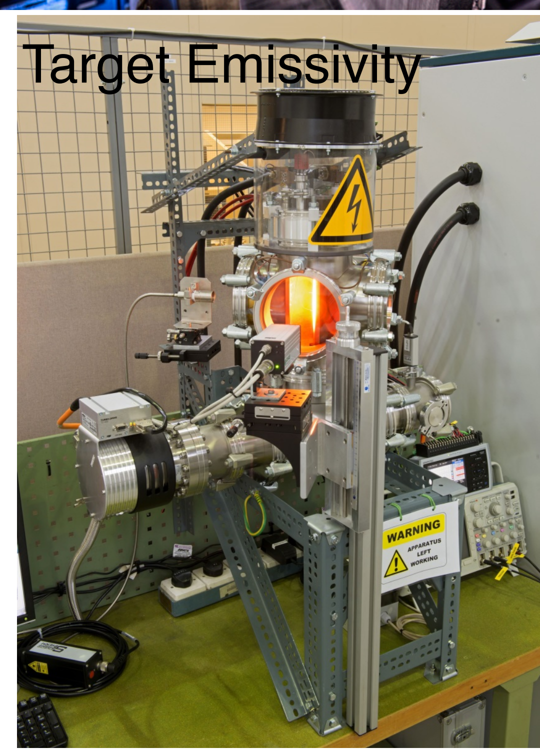
Significant progress across the project, including test beam efforts at Fermilab (PPD), PSI and Frascati


Cosmic ray veto


Extraction foils


TS conductor


Tracker Prototype


Target Emissivity

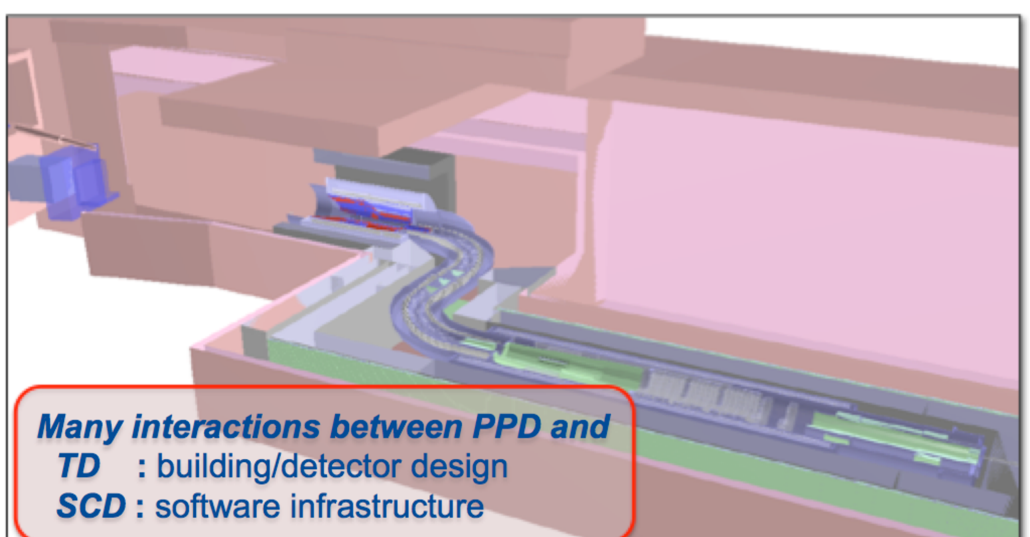

ALCAP
Test Beam/PSI

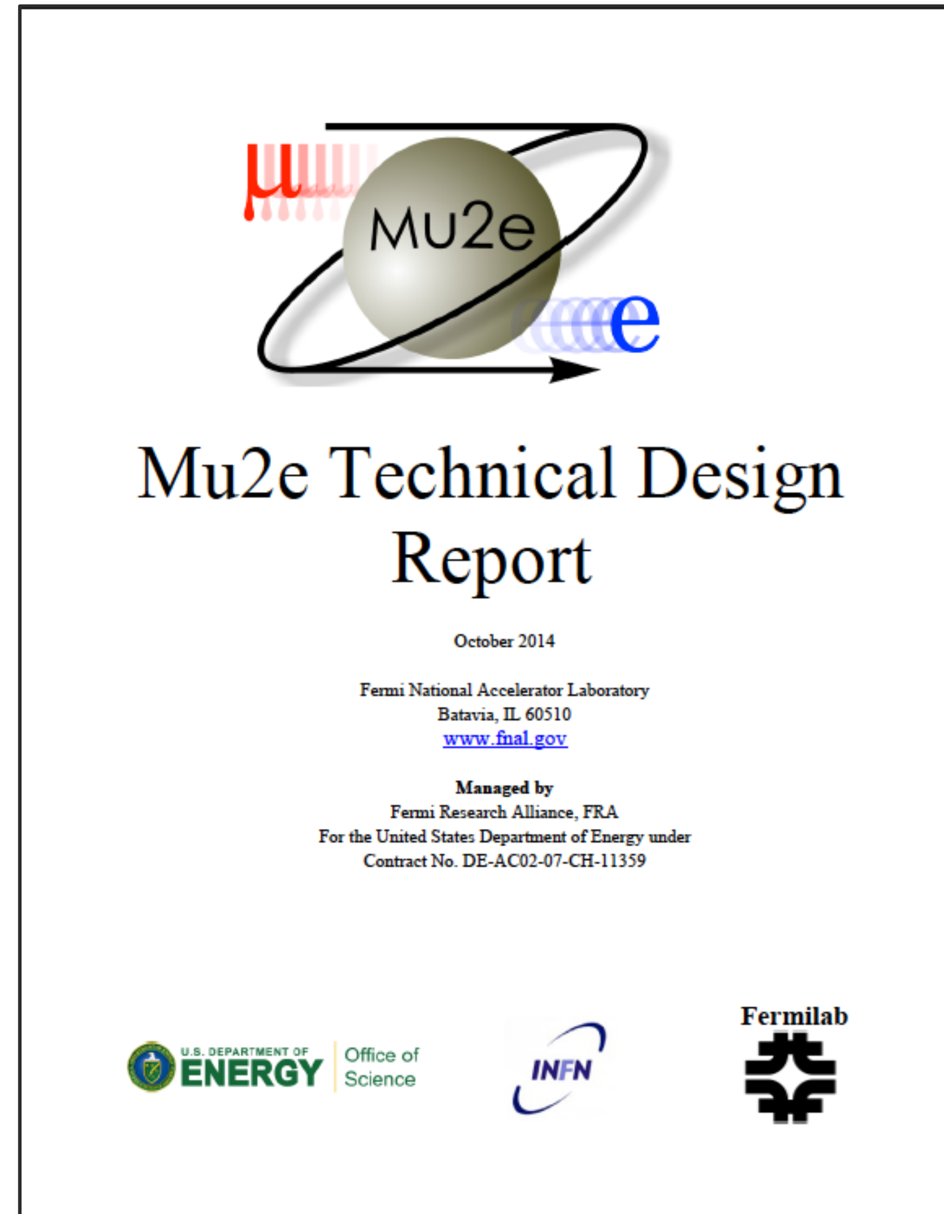
Mu2e highlights from the past year

Technical Design Report for CD2/3b

- Contributions from collaborators, universities, institutes, industry, and all parts of Fermilab
- Background task force
  Simulated 100B events!
  FNAL, Novosibirsk, Virginia, LBNL, UC Irvine
- Geant4 Geometry

FNAL	**California Institute of Technology**	**U. Virginia**	**U. Louisville**
LBNL	**Northern Illinois University**	**UC, Irvine**	**Boston University**




Mu2e Technical Design Report

October 2014

Fermi National Accelerator Laboratory
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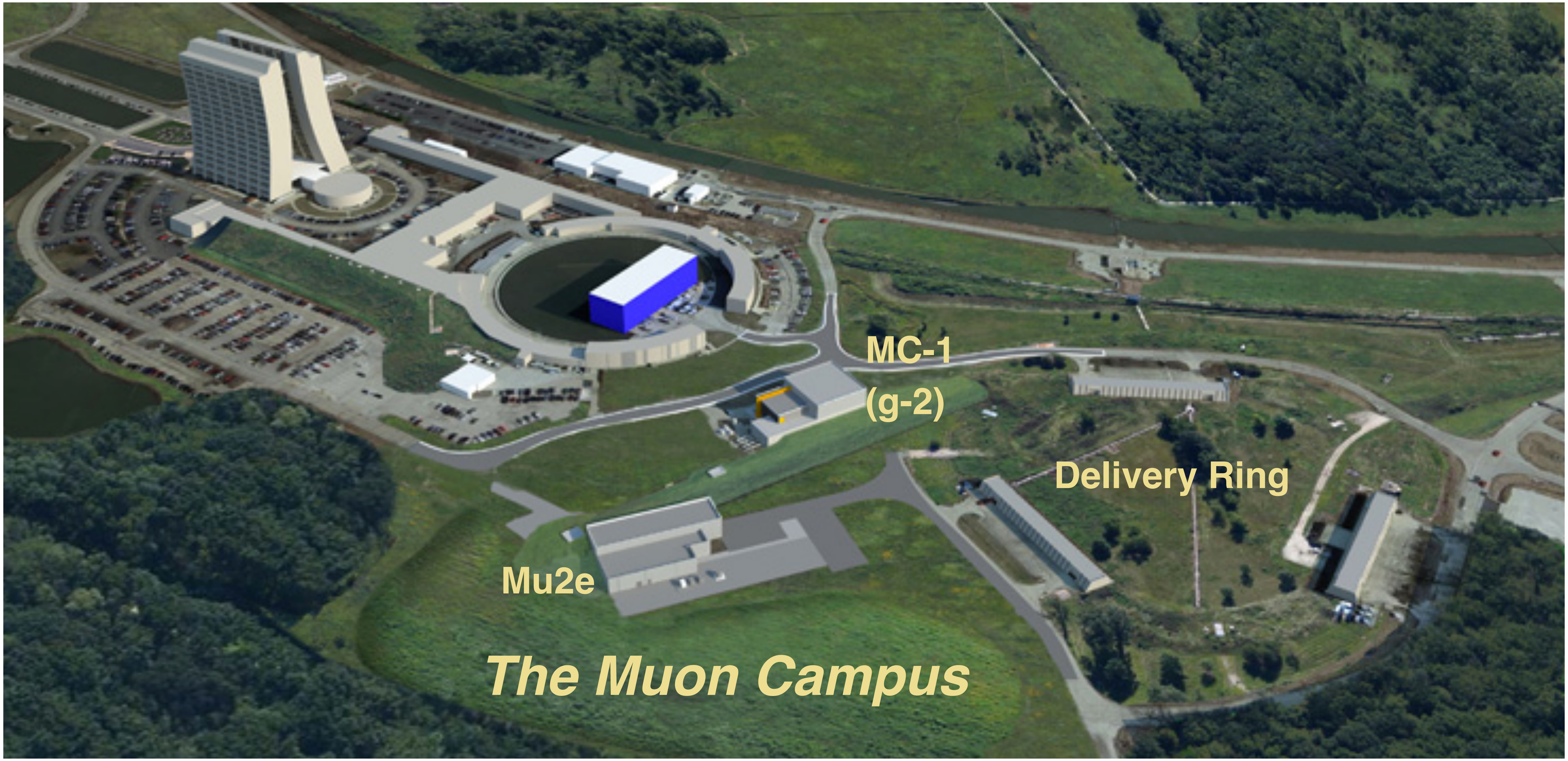
The Muon Campus optimizes the global muon program

Minimizes cost, meets combined needs of experiments, accommodates build time scales, versatile, creates options for future experiments

Common solutions and shared infrastructure saved **~$100M** compared to each experiment making its own solution



See Convery talk in Breakout 1D

Muon campus is shared infrastructure and funding (Accelerator Division)

Optimized plan presented to OHEP in Jan 2012 by Annala, Glenzinski, Polly, and Ray

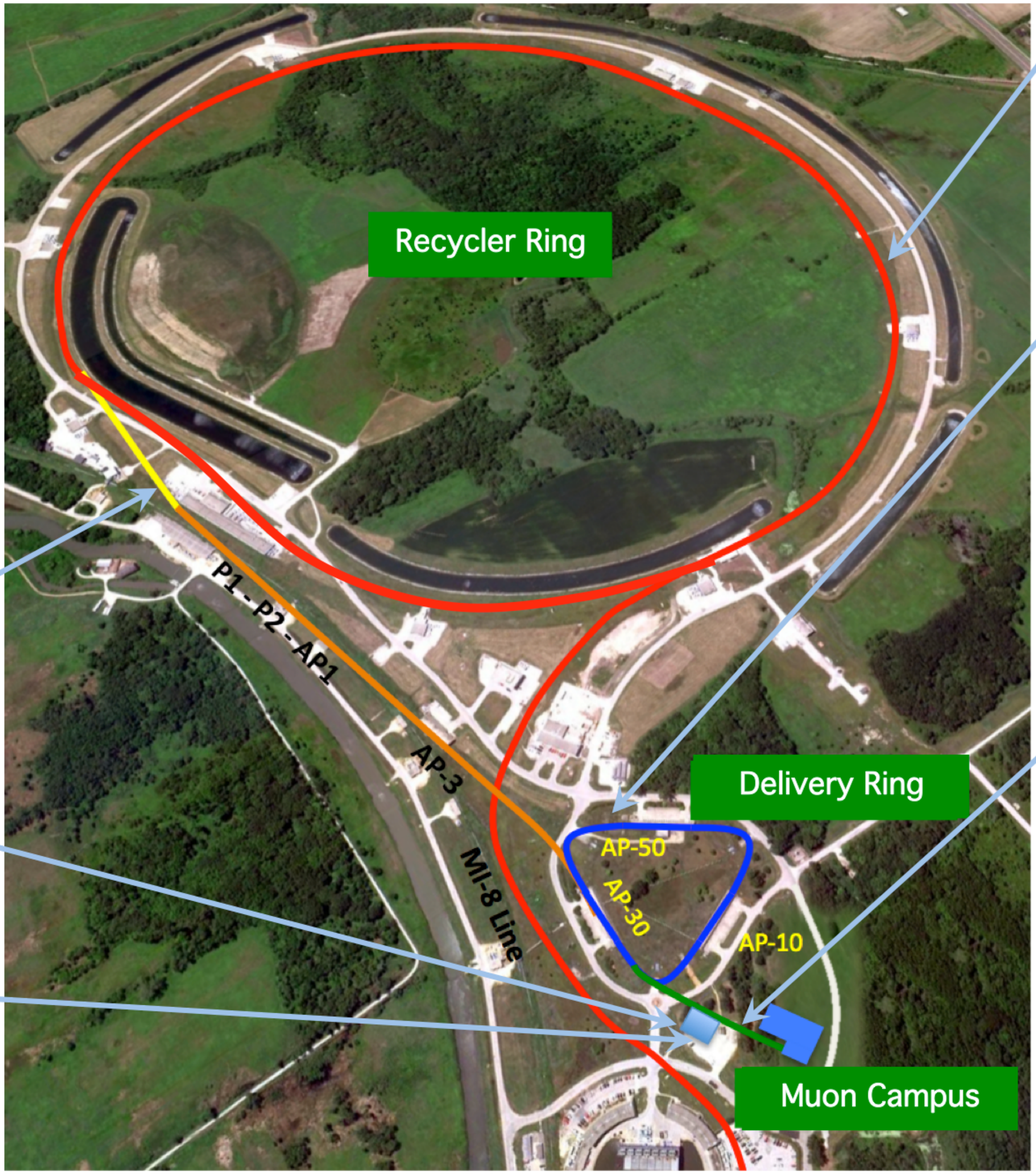
Common upgrades managed as AIP/GPP packages in order to meet the combined specs and timelines of both expts.

Managed by Mary Convery who is also the L2 for the accelerator g-2 work.

Beam Transport AIP:
New connection from Recycler to Delivery Ring, improve apertures

MC-1 Building GPP:
Houses cryo plant, power supplies for beams, g-2

Cryo Plant AIP:
Cryogenics to both experimental halls



Recycler RF AIP:
Adds RF capability to Recycler meeting g-2/Mu2e specifications

Delivery Ring AIP:
Modify Delivery Ring to deliver custom beams to the muon experiments

Beamline Enclosure GPP:
New tunnel to Muon Campus

Infrastructure Upgrades GPP:
Cooling for A0 compressors, MI-52 building extension, added feeder if needed

Fermilab

Holes in the ground == Progress

Organized to bring muon expertise together

Muon department in AD

MUON DEPARTMENT

G. ANNALA, HEAD
S. WERKEMA , DEPUTY

(N. SELLS, ADMIN SUP-PORT)

J. BUDLONG
M. CONVERY
B. DRENDEL
P. KASPER
A. LEVELING
J. MORGAN
V. NAGASLAEV
A. SONDGEROTH
D. STILL
D. VANDER MEULEN

Muons department in PPD

MUONS
B. Casey, Head
D. Glenzinski, Deputy Head

ADMIN. SUPPORT
(B. Hehner)
(C. Kennedy)

Mu2e PROJECT OFFICE
(R. Ray, PM)
H. Brown
M. Gardner
(D. Knapp)
(F. Leavell, DO)
(D. Leeb, DO)

Mu2e GROUP
(D. Glenzinski, Ldr)
R. Bernstein
R. Culbertson
A. Gaponenko, WF
C. Group, JA
(K. Knoepfel, SC)
(R. Kutchke, SC)
(E. James)
A. Mukherjee
P. Murat
(R. Ray)
V. Rusu
(K. Vellidis, G)
R. Wagner
J. Whitmore

MUON g-2 PROJECT OFFICE
(C. Polly, PM)
C. Y. Yoshikawa
(C. Vendetta)

MUON (g-2) GROUP
(B. Casey, Ldr)
B. Kiburg, LF
(A. Lyon, SC)
W. Merritt
H. Nguyen
(C. Polly)
M. Rominsky, RA
(E. Ramberg)
(M. A. Soha)
T. Walton, RA

(Scientists from other divisions matrixed in)

Scientific Programs in SCD

Division is organized in **functional** departments, with scientists matrixed into a cross-cutting Scientific Programs Quadrant

Scientific Programs
Robert Harris — Associate Head

Intensity Frontier
(Robert Kutschke) — Department Head

(Michael Diesburg)
(Pengfei Ding)
(Stuart Fuess)
(Michael Kirby)
(Art Kreymer)
(Qizhong Li)
(Adam Lyon)
(Leo Michelotti)
(Andrew Norman)
(Adam Para)
(Gabriel Perdue)
(Erica Snider)
(Michael Wang)
(Stephen Wolbers)

Both Mu2e and *g-2* benefit from TD's expertise

Mu2e *production [PS]* and *detector [DS]* solenoids built by industry from reference designs

Transport solenoid (S-curved) *[TS]* is collaboration between Fermilab TD, INFN Genova, Industry

Prototype TS coil module delivered January 2015 (need 27 modules total)

	PS	TS	DS
Length (m)	4	13	11
Diameter (m)	1.7	0.8	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	52	11
Conductor (km)	10	44	15
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

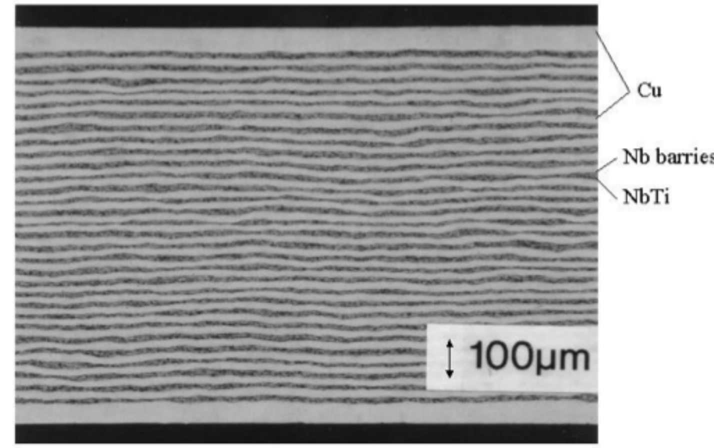
Both Mu2e and *g-2* benefit from TD's expertise

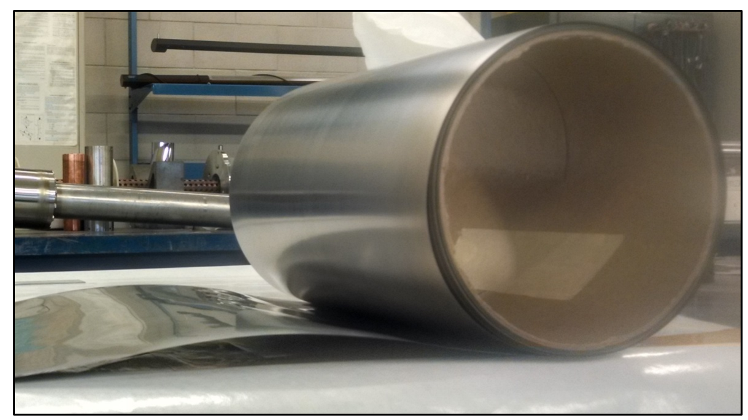
How do muons enter a continuous magnet?

Inflector cancels fringe field near injection region so muons are not deflected

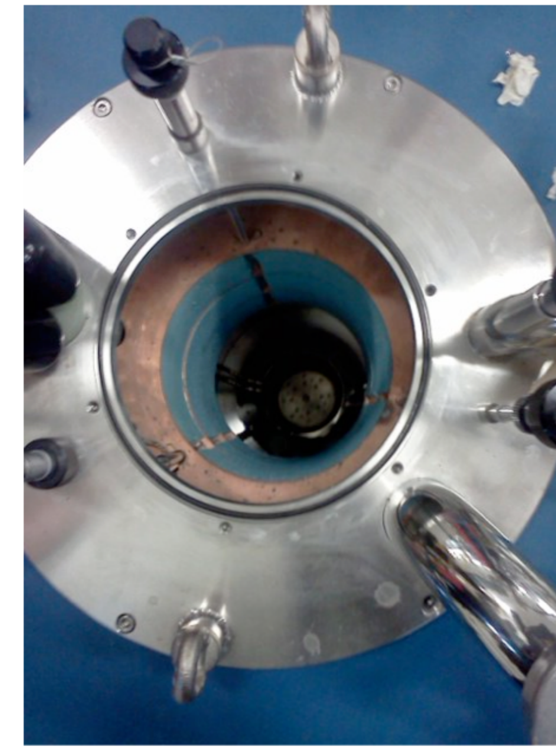
Superconducting shield upgrade under study by TD

- Construction of the multilayer NbTi shield is very unique
- Production technology may no longer exist
- TD is studying the shield for feasibility





100 µm thick, 46' long, 10" wide NbTi foil purchased this year from Luvata



TD "Teslatron" for shield testing

1995 Spare g-2 shield material

Fermilab

SCD Common Software, Tools and Services are used broadly

Application software frameworks help Physicists be efficient and effective; infrastructure is critical

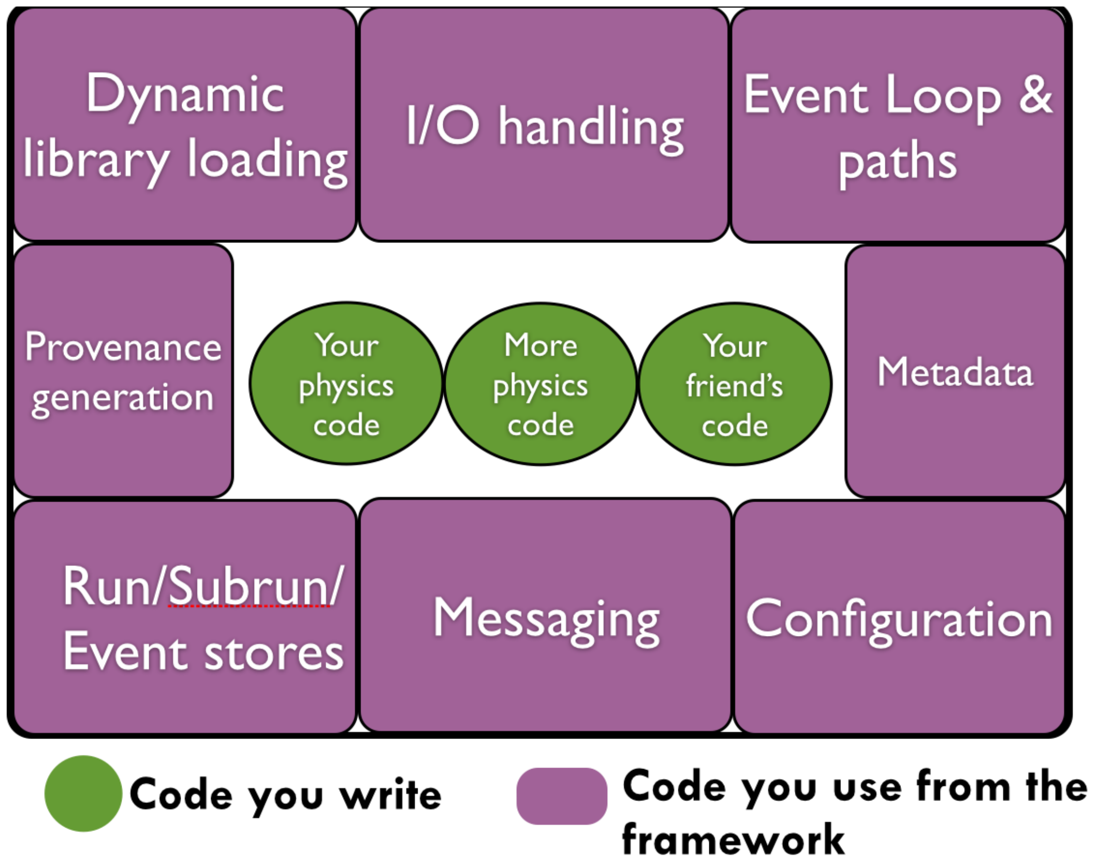
A framework surrounds physics code with infrastructure services

Mu2e instigated the "art" framework

Forked from CMSSW and tailored for neutrino/muon experiments

Used by Mu2e, Muon *g-2*, NOvA, MicroBoone, LAriAT, LBNF, Darkside-50

See Spentzouris Plenary Talk and Roser talk in Breakout 2C



Experiments use art as-is as an external

New features and direction decided among stakeholders by consensus

SCD is working to identify common functionality, principles, and goals between *CMSSW* and *art* to leverage new architectures, tools, and effort for the future

There are many benefits to having a shared framework

Main support team is from SCD, but computing experts from experiments help answer questions

Experiments help each other with common computing problems and can easily share their solutions
("Hey NOvA, how did you do …?")

Advances to the framework (event mixing, multithreading, ease of use), benefit many experiments simultaneously

Common training (classes & workshops) and documentation (art-workbook) benefit many experiments

FNAL Software School 2014

Mu2e will use SCD's "artdaq" for online/offline integration

artdaq is a toolkit for creating DAQ systems

Provides common reusable components. Based on event streaming architecture with software event filtering

Integrated with art framework, so offline modules can run online

Used by Darkside-50 [first production use], LBNE (35t), Mu2e [pilot system under development], LArIAT [used on top of original DAQ code]

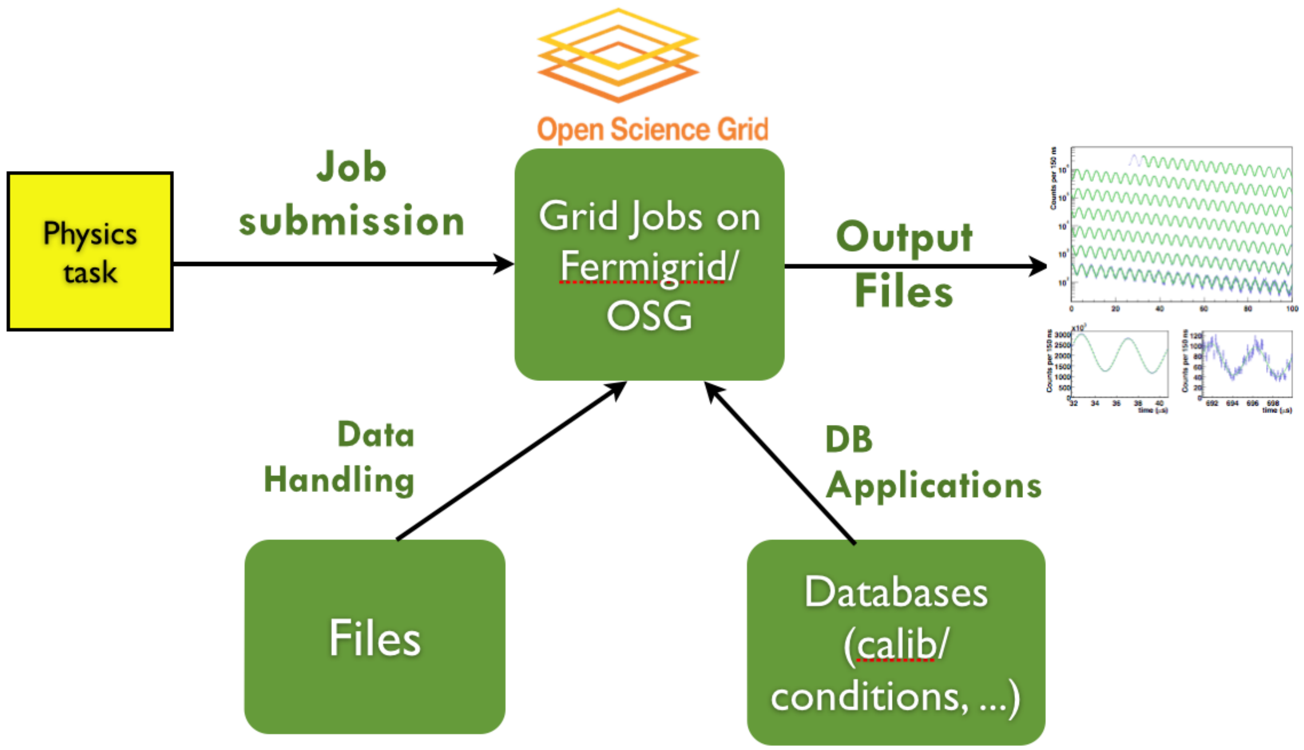
Some artdaq components are used by NOvA & uBooNE

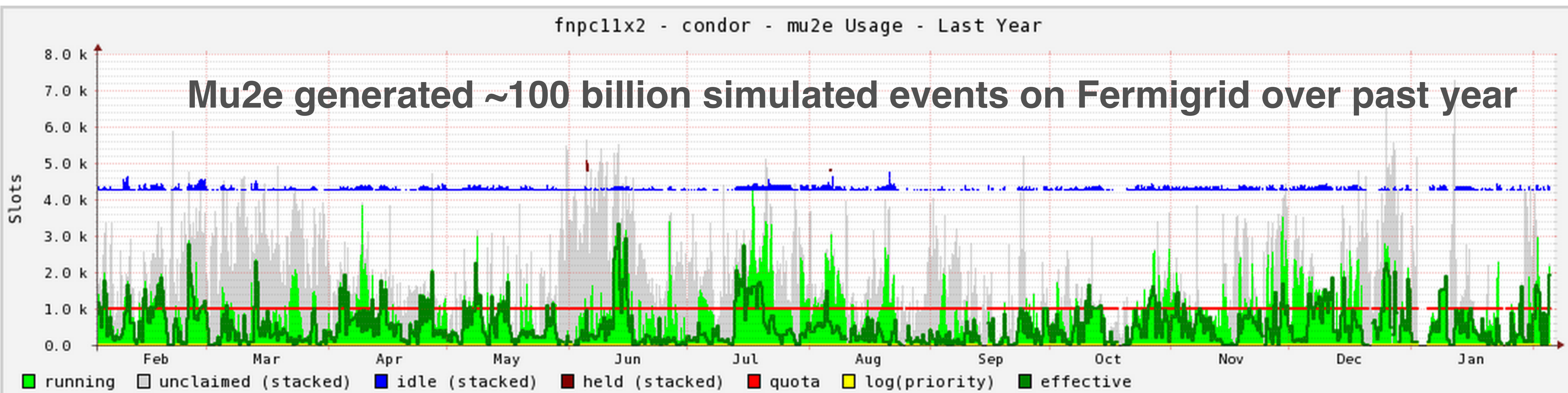
Data are processed with the Fermilab Facility and Tools

Fabric for Frontier Experiments (FIFE)

A comprehensive set of services and tools for MC generation, reconstruction, and analysis processing on Fermilab and offsite OSG opportunistic resources [used by all neutrino/ muon experiments at FNAL]

A new SCD Production Team was established to run production jobs for experiments [will be very beneficial for Mu2e and *g-2*]





See Gutsche talk in Breakout 5C

Both Muon *g-2* and Mu2e benefit from computing expertise and leadership

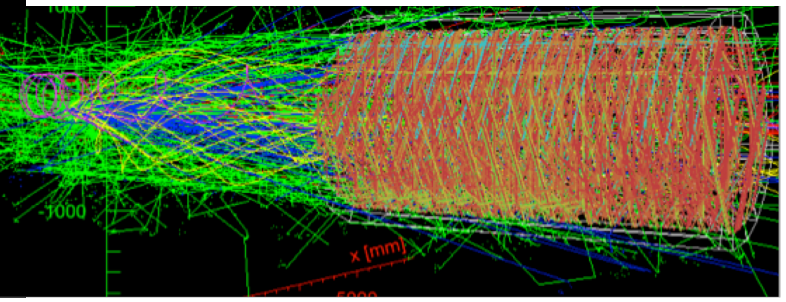
Already mentioned Frameworks, DAQ, Processing

Both experiments leverage FNAL's expertise with Geant4
- Interaction model
- Geometry building

See Perdue talk in Breakout 5C

g-2

Mu2e



Behind the scenes support from SCD & CCD:
- Redmine and code repositories,
- Networking in MC-1 (SCD/CCD/AD),
- Desktop/Laptop support,
- Databases,
- IT management,
- web pages,
- E-mail, …

In the past, some user interactions with computing were bumpy; e.g. requesting new accounts…

… now much smoother and streamlined - lots of behind the scenes tracking of requests

Synergies with Theory are crucial

Fermilab theorists engaged with muon program in numerous ways including:

- Organized academic lecture series "The Allure of UltraSensitive Experiments." including 4 talks on *g-2*, 4 on LFV, ...
- Hosted & organized 2014 "Lattice Meets Experiment" workshop addressing role of lattice–QCD calculations for *g-2*, Mu2e, ...

g-2 theory uncertainties need to improve!

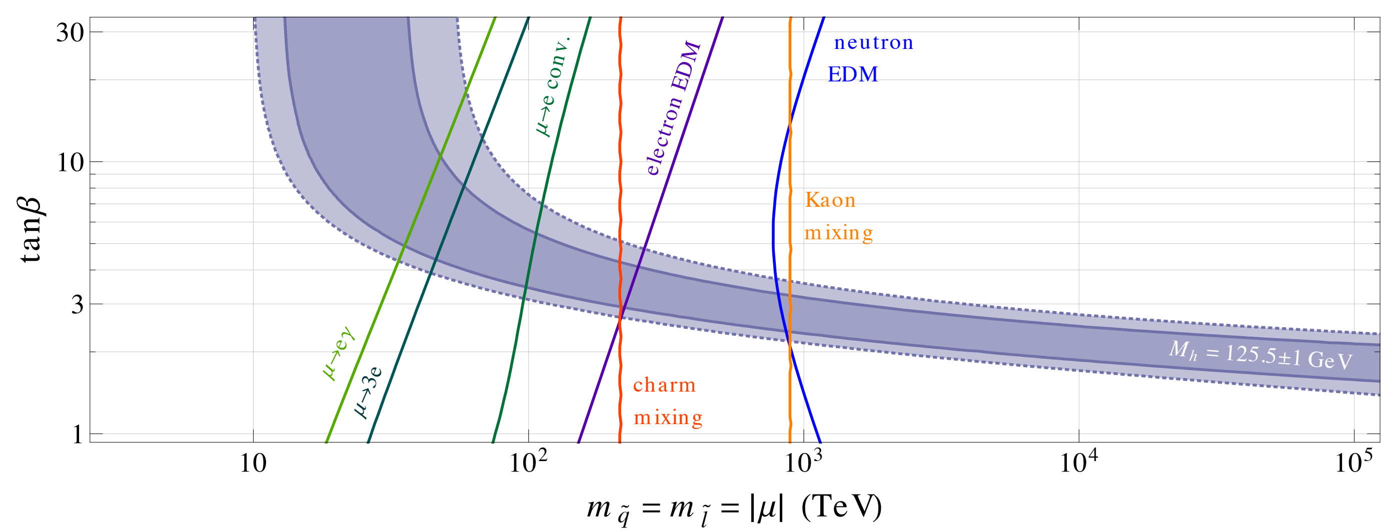
Fermilab lattice theorists undertaking calculations of hadronic contributions

- Implementing recent improvements for vacuum polarization
- Developing & testing methods for light-by-light
- RA Zhou leading effort on dynamical QCD +QED gauge-field ensembles needed for HLbL
- Scientists Kronfeld, Mackenzie, and Van de Water pursuing these topics

See Campbell Plenary and Parke talk in Breakout 4C

Fermilab BSM theorists studying new-physics reach of Mu2e:

- 4 orders of magnitude better on muon-e-Higgs flavor violation than the LHC!
- Probes sleptons at 100 TeV scale



[Altmannshofer, Harnik, Zupan, JHEP 1311 (2013) 202]

Muon program personnel engage the future of the field (Snowmass 2013)

IF/Charged lepton group co-led by Brendan Casey, David Hitlin, Yuval Grossman

Significant engagement from FNAL scientists, including convening working groups and break-out sessions and writing and editing significant portions of the final report.

	Ongoing / planned	Future	Study group
$\mu \to e\gamma$	MEG upgrade plans to get to 5 x 10^{-14} based on 10^{8} μ/s DC	What can be done with 10^{9}-10^{10} μ/s?	Yury Kolomensky, Doug Glenzinski, David Hitlin, Yuval Grossman, Chih-hsiang Cheng, Bertrand Echenard, Jim Miller, Craig Group, Kyle Knoepfel
$\mu \to eee$	μ3e plans on 10^{-15} based on 10^{8} μ/s DC and 10-16 based on 10^{9} μ/s DC from spallation target	What can be done with 10^{10} μ/s?	
		Can something be done with mu2e solenoid?	
		What do we get from a Dalitz plot analysis?	
$\mu N \to eN$	COMET and Mu2e plan on 6 x10^{-17} based on 10^{11} μ/s pulsed	What can be done with 10^{13} μ/s pulsed?	
		Can we do different nuclei?	
$\mu^- N \to \mu^+ N'$		How far can we get with the mu2e solenoid?	
$\mu^- N \to e^+ N'$		How far can we get with the mu2e solenoid?	
μ EDM	g-2 expects 10^{-21}	What can we do with continued running?	Mandy Rominsky, Leah Welty-Reiger
		Can we get to m^2 scaling with the electron with a dedicated experiment?	
g-2	FNAL and J-PARC plan on 140 ppb for μ+	Can μ- be done to this level?	
		How will the SM value evolve?	
		Can systematics be reduced with a significant increase in beam power?	Thomas Gadfort
Muonium mixing		Is there motivation for factor 100 improvement?	
		What would the experiment look like?	
Muon decay parameters		Can we get significant improvement beyond TWIST?	Andrei Gaponenko
Surface muons	PSI has 10^{8} μ/s	What are the possibilities with a next generation source?	Brendan Keiberg, Peter Winter
τ LFV EDM, τ g-2	New limits based on several ab-1 from super B factories and several fb-1 from LHCb	Comparison of sensitivity with longitudinally polarized and unpolarized electron beams at luminosities of 10^{36} and beyond	
Tau decay paremeters		How well can these be done at a Super B factory?	

Fermilab Contribution

Fermilab

Muon program personnel in the community

We participate in reviews, organize conferences, members on HEPAP and DPF Executive Committee, and members are APS Fellows, Snowmass Leadership

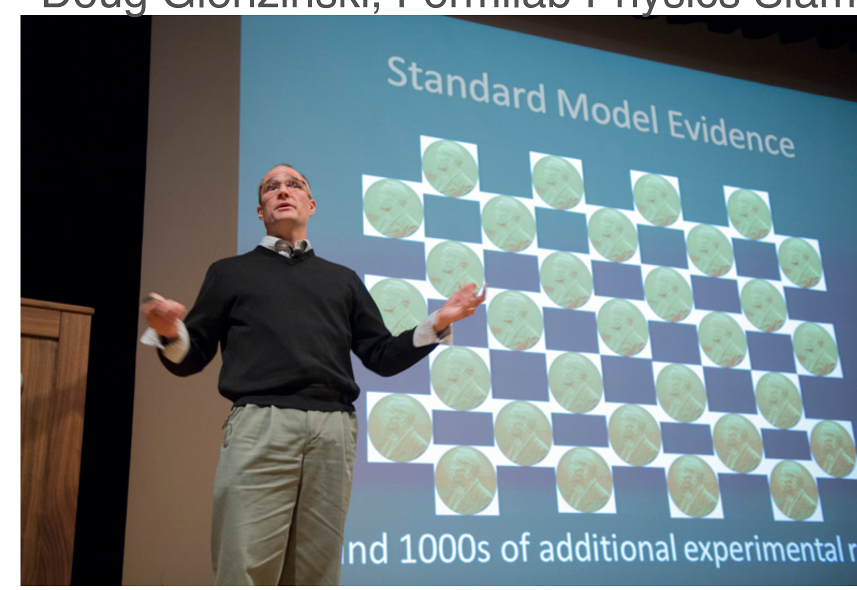
We give colloquia, seminars, public talks, and tours

Brendan Kiburg, Lederman Fellow

TEDx Naperville
x = independently organized TED event

Science display at Indian Prairie Public Library in honor of Adam Lyon's talk

Doug Glenzinski, Fermilab Physics Slam



Strategic plans

Muon *g-2* and Mu2e drive the immediate future

- *g-2* sees first muons in early 2017
- Mu2e starts commissioning in 2020

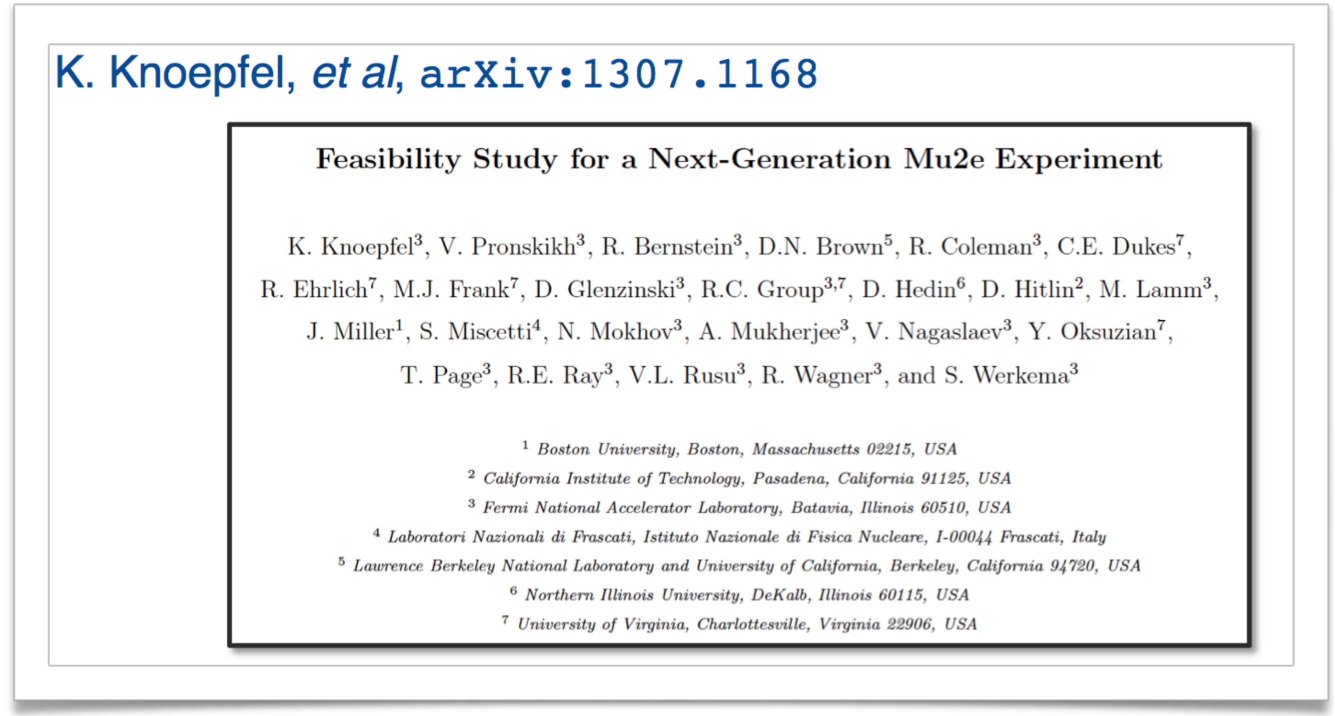
Leveraging these experiments:

- Mu2e II (PIP-II; Ti target)
- μ^- running for *g-2*

New concepts:

- Dedicated storage ring for proton EDM
- $\mu \to eee$
- $\mu \to e\gamma$

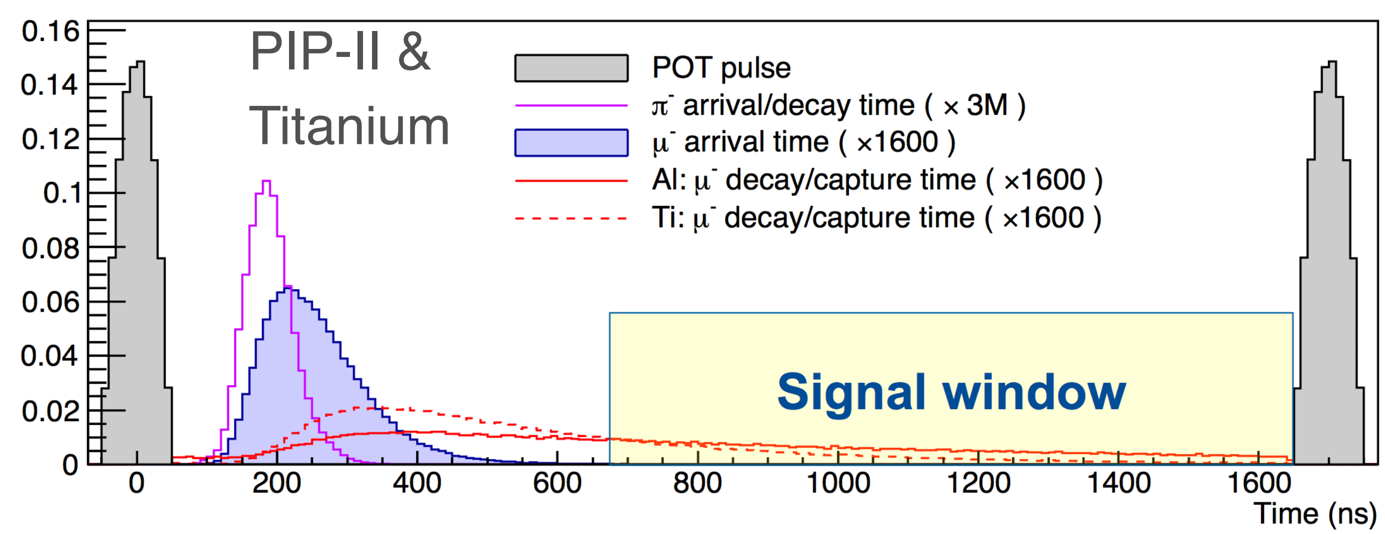
K. Knoepfel, *et al*, arXiv:1307.1168



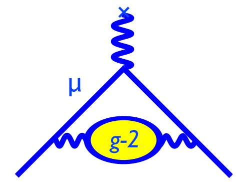
Feasibility Study for a Next-Generation Mu2e Experiment

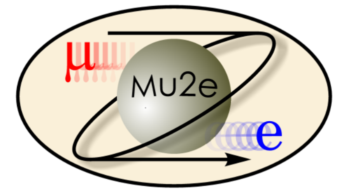
K. Knoepfel[3], V. Pronskikh[3], R. Bernstein[3], D.N. Brown[5], R. Coleman[3], C.E. Dukes[7], R. Ehrlich[7], M.J. Frank[7], D. Glenzinski[3], R.C. Group[3,7], D. Hedin[6], D. Hitlin[2], M. Lamm[3], J. Miller[1], S. Miscetti[4], N. Mokhov[3], A. Mukherjee[3], V. Nagaslaev[3], Y. Oksuzian[7], T. Page[3], R.E. Ray[3], V.L. Rusu[3], R. Wagner[3], and S. Werkema[3]

[1] *Boston University, Boston, Massachusetts 02215, USA*
[2] *California Institute of Technology, Pasadena, California 91125, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[5] *Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6] *Northern Illinois University, DeKalb, Illinois 60115, USA*
[7] *University of Virginia, Charlottesville, Virginia 22906, USA*



Summary

The Muon program… 

+ 

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brings together all parts of the lab

and collaborators from institutions world-wide

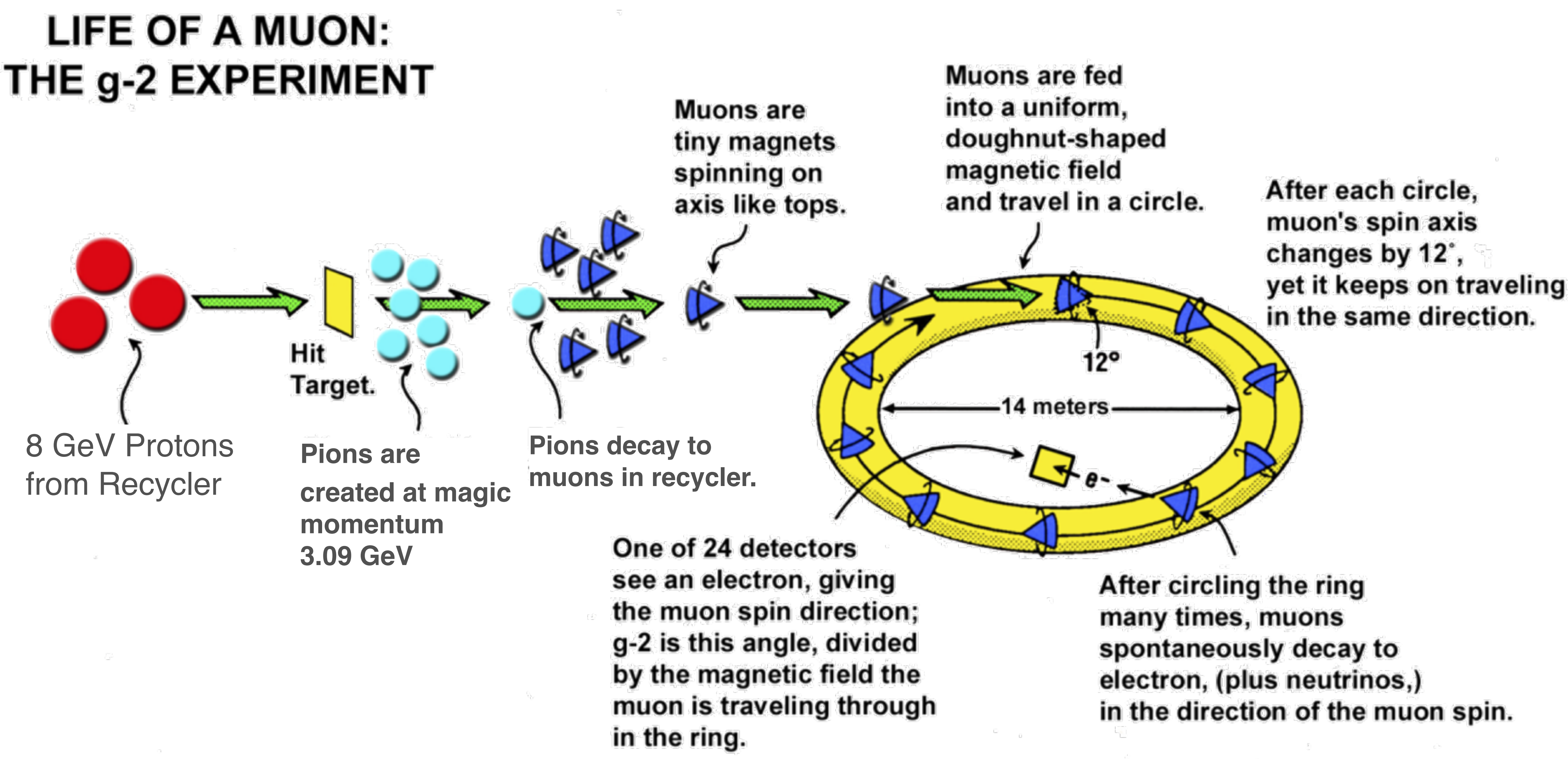
to make a program more than the sum of its parts

to do precision physics that may lead

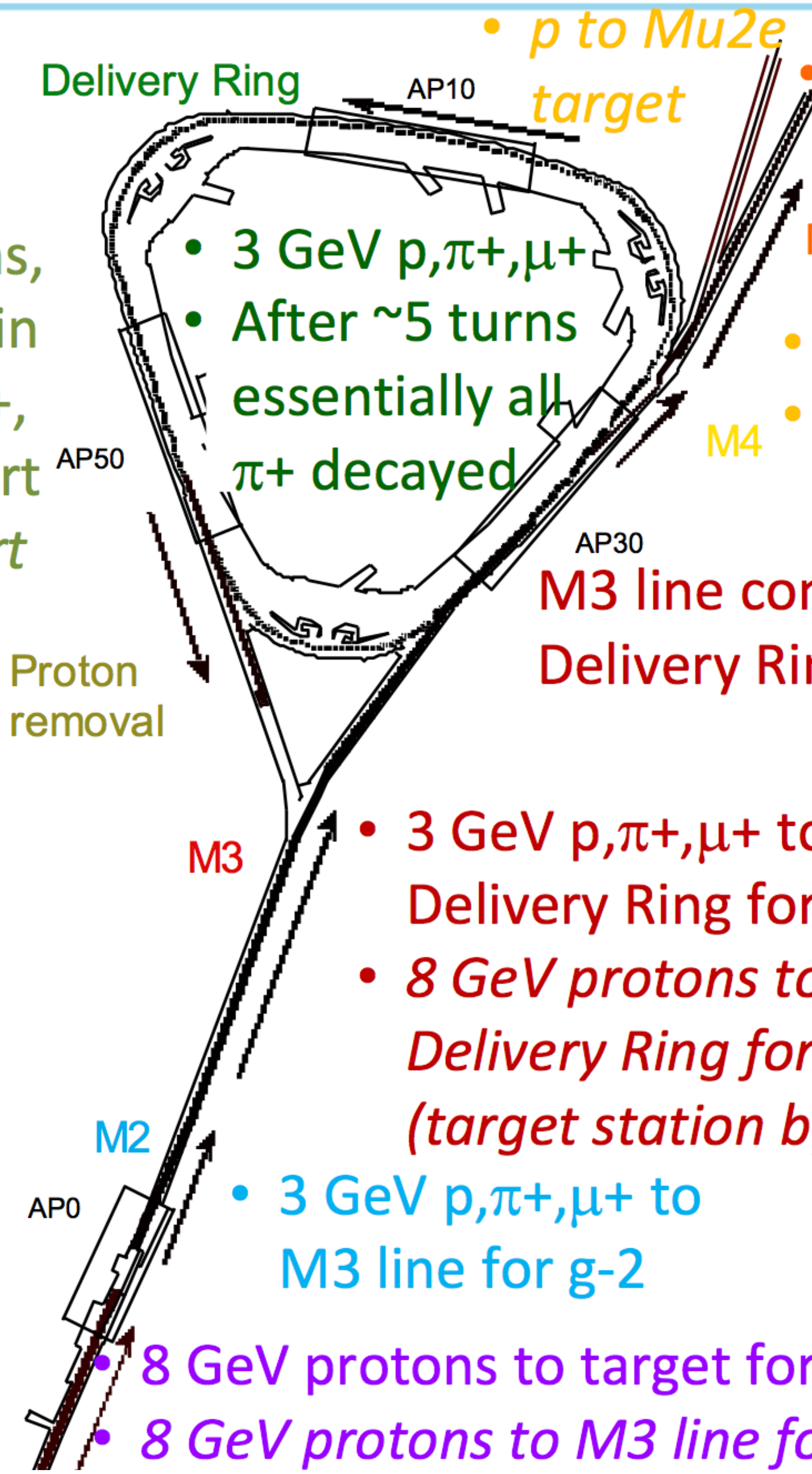
to vital discoveries beyond the Standard Model

See breakout talks for many more details!

Muon *g-2* in a nutshell



Muon Campus



- *p to Mu2e target*

- μ+ to g-2 ring

- Extract μ+ for g-2
- *Resonant extraction for Mu2e*

- After ~5 turns, p separated in time from μ+, kick into abort
- *Primary abort for Mu2e*

- 3 GeV p,π+,μ+
- After ~5 turns essentially all π+ decayed

M3 line connects to Delivery Ring (Debuncher)

- 3 GeV p,π+,μ+ to Delivery Ring for g-2
- *8 GeV protons to Delivery Ring for Mu2e (target station bypass)*

- 3 GeV p,π+,μ+ to M3 line for g-2

- 8 GeV protons to target for g-2
- *8 GeV protons to M3 line for Mu2e*

The Muon Campus supports both experiments

1D

Reuse existing infrastructure of the “pbar" source to deliver muons (target, lens, magnets, …)

Funded by Accelerator Improvement Projects (AIP)

- Recycler RF: For rebunching
- Beam transport: To deliver beam to campus
- Delivery Ring: To converting debuncher ring
- Cryogenics: For Mu2e solenoids and *g-2* ring

and General Plant Projects (GPP)

- MC-1 Building: Houses *g-2*, cryo refrigerators, beam line power supplies
- Beam line enclosure: New tunnels
- Muon Campus Infrastructure: e.g. cooling for cryo compressors, extension of MI-52 building

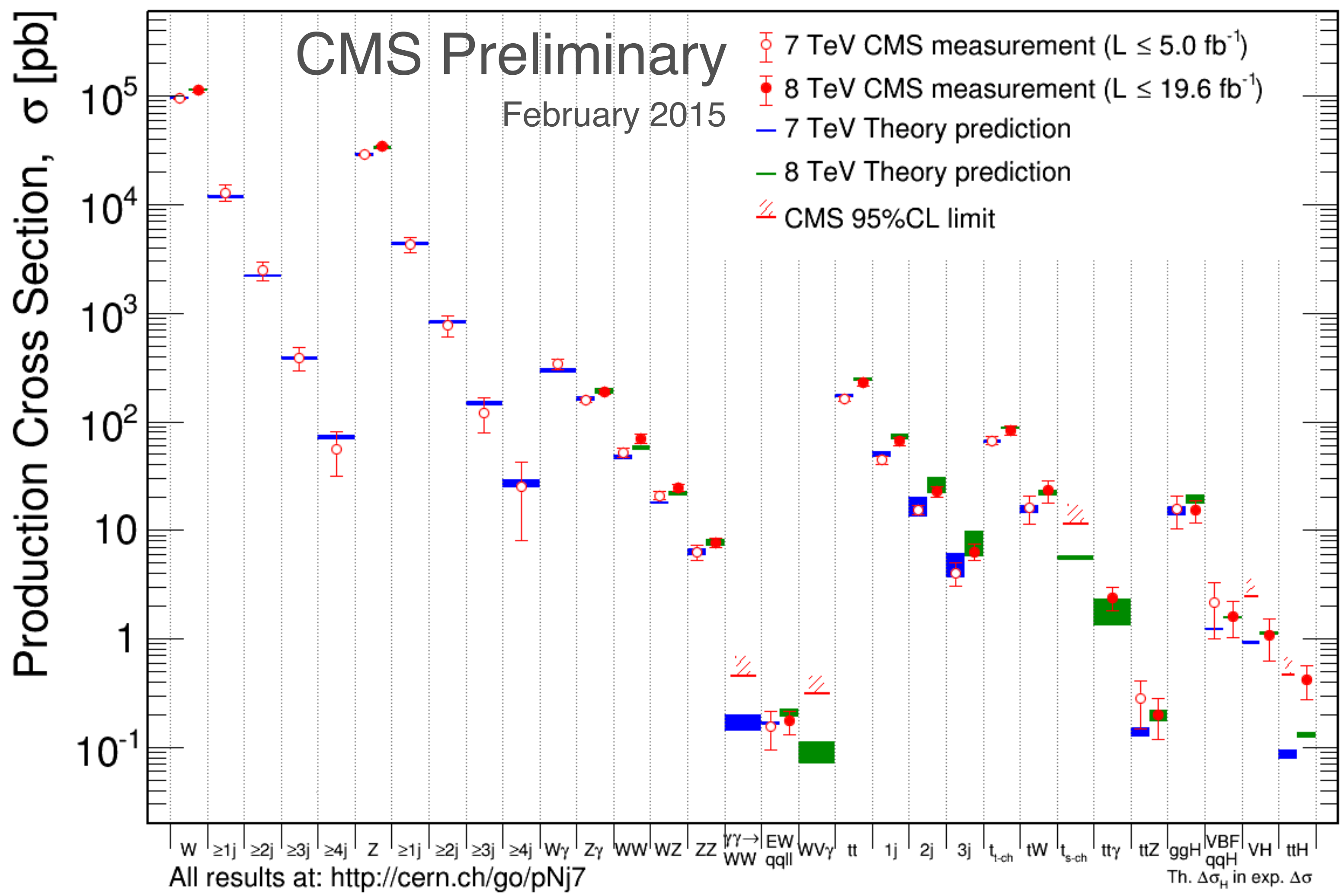
Managed by Muon Campus Program Coordinator (Mary Convery)

Expertise collected in one AD Department (Muon Dept)

Common solutions and shared infrastructure for *g-2* and *Mu2e* have saved **~$100M** compared to each experiment making its own solution

We do great science by exploring the unknown

While the Standard Model is incredibly successful,

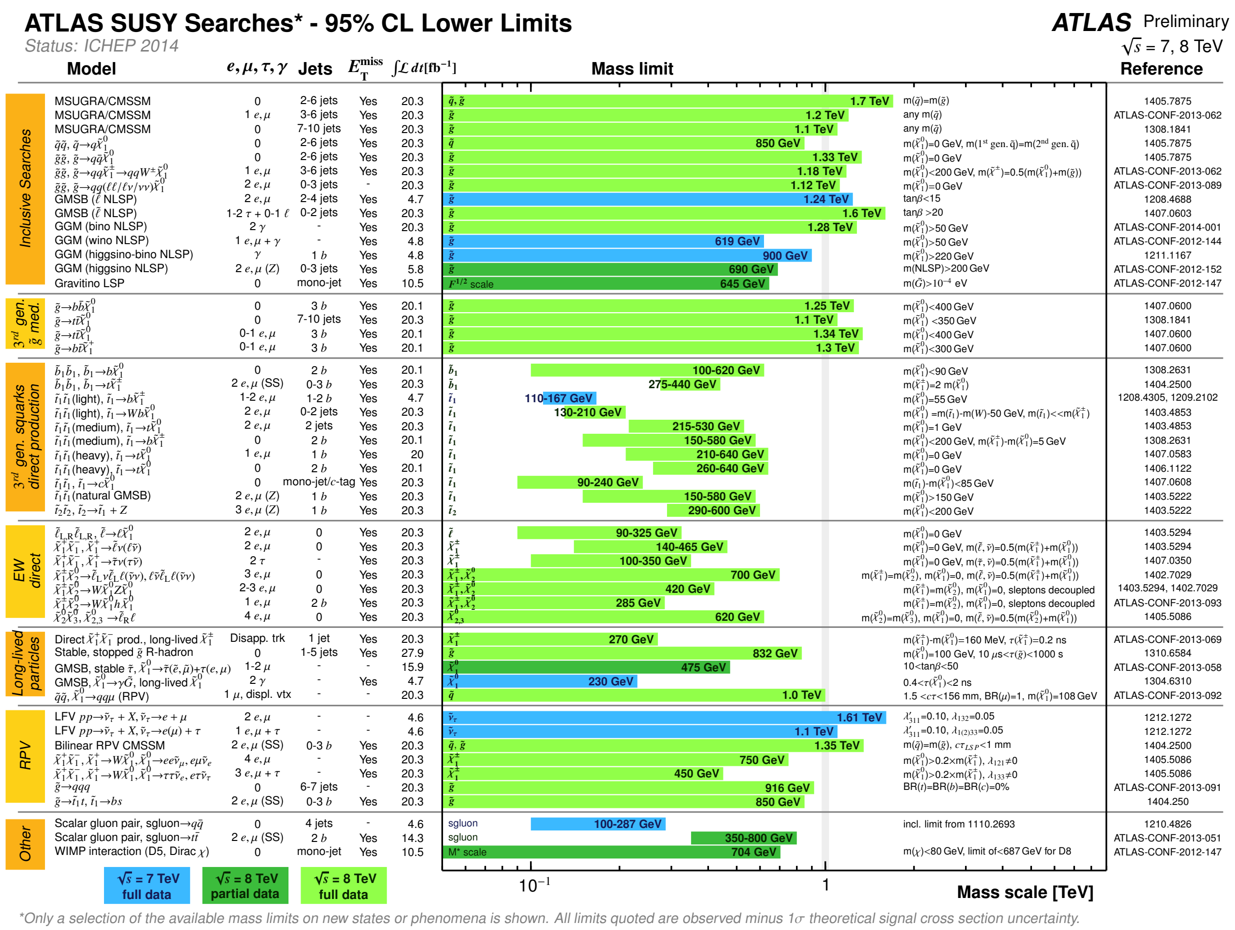


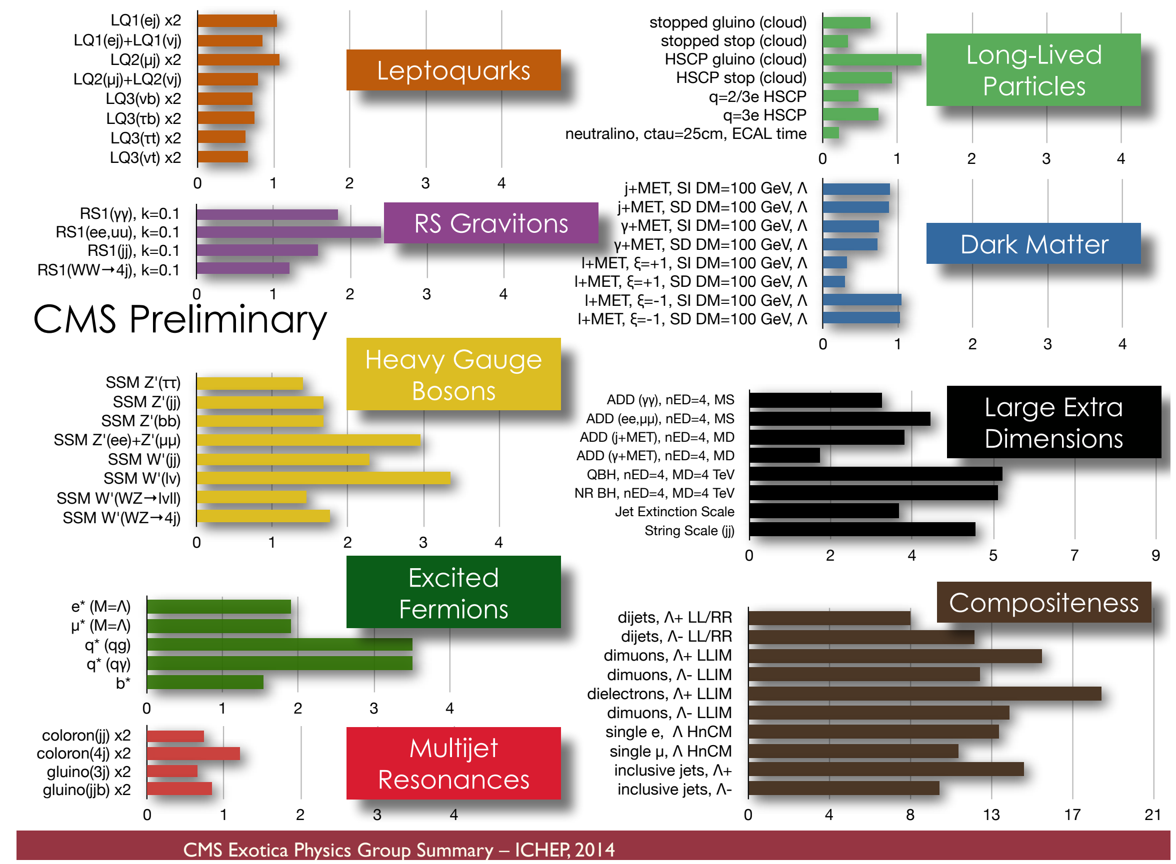
it gives an incomplete picture of nature:

Gravity? Matter/antimatter asymmetry? Dark Matter? SUSY?

Search for new phenomena beyond the SM…

No SUSY, Leptoquarks, Dark Matter, … has been seen directly





Not for lack of trying!

What will LHC Run II bring?

Fermilab