Muon g-2 Science, Management, & Publication Plan

Chris Polly

2 Oct 2017

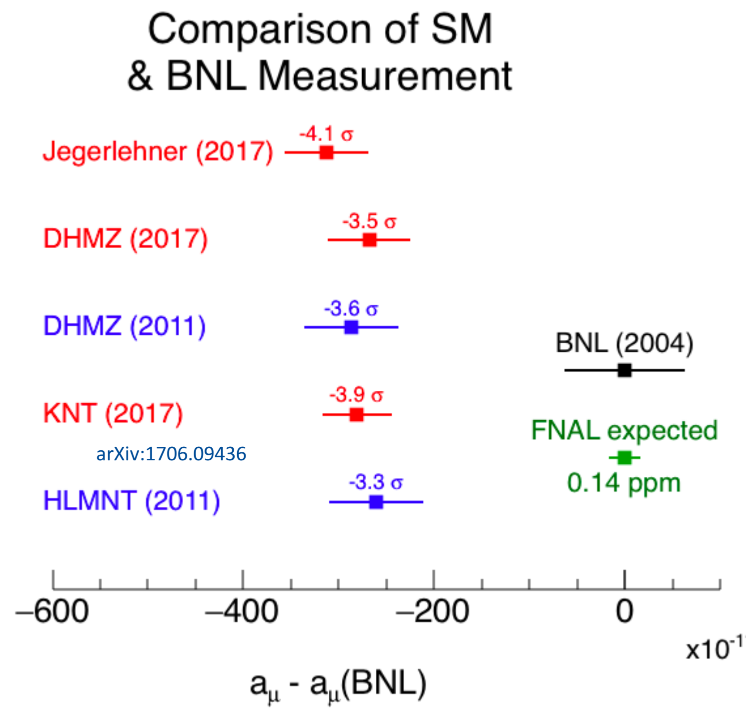
Muon g-2 scientific goals

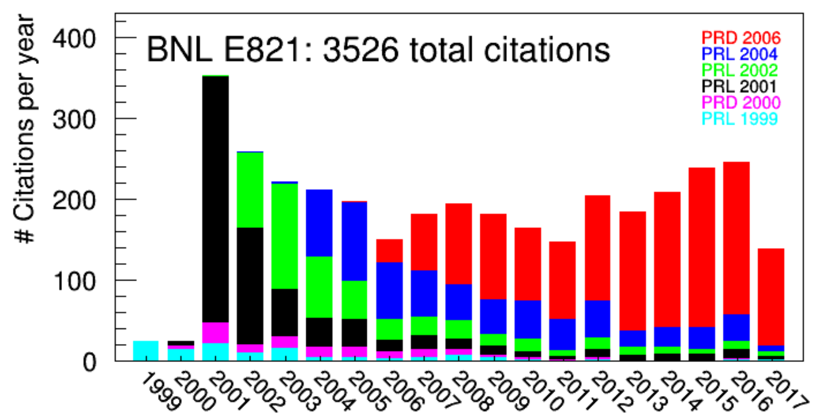
- To provide a definitive test of the muon g-2 anomaly
- The discrepancy has stood the test of time as theory improved to current ~3.5σ discrepancy
- Goal: Collect > 20 x the BNL statistics & control systematics to achieve 140 ppb exp. error

If Δa_μ(exp-thy) = 280×10^{-11} persists

→ anomaly > 5σ with current theory

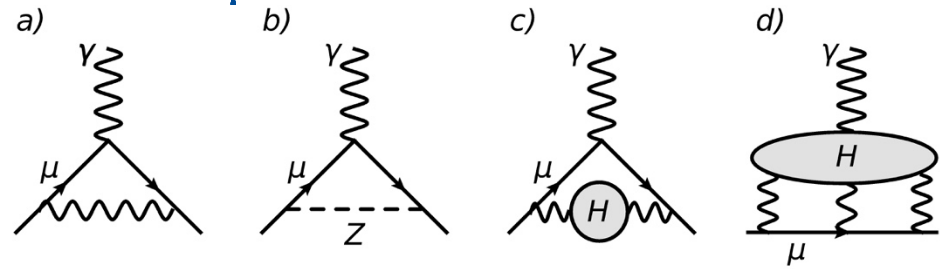
→ anomaly > 7σ with future theory



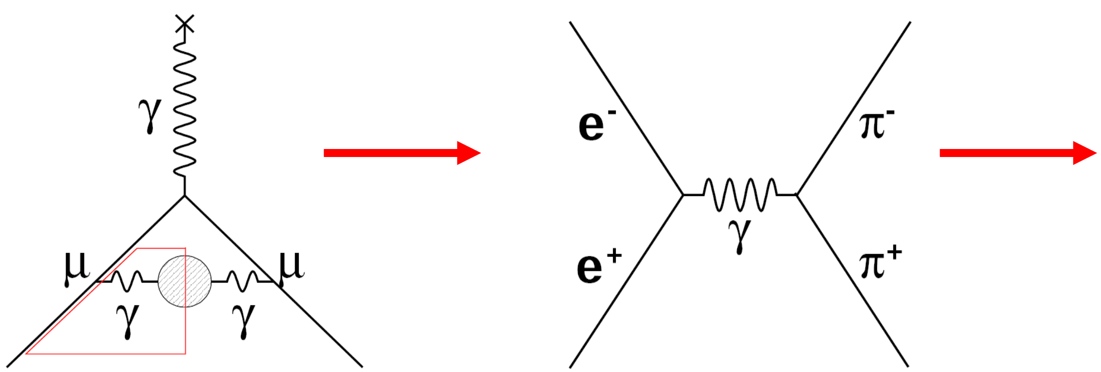


Status of theoretical progress on a_μ

- Theory requires precise calculation of a_μ
- Error dominated by quark loops
  - HVP extracted from data $e^+e^- \rightarrow$ hadrons
  - HLBL based on model-dependent calculation
  - Many improvement to e^+e^- and HLBL model crosschecks
  - Lattice on track to provide independent determination



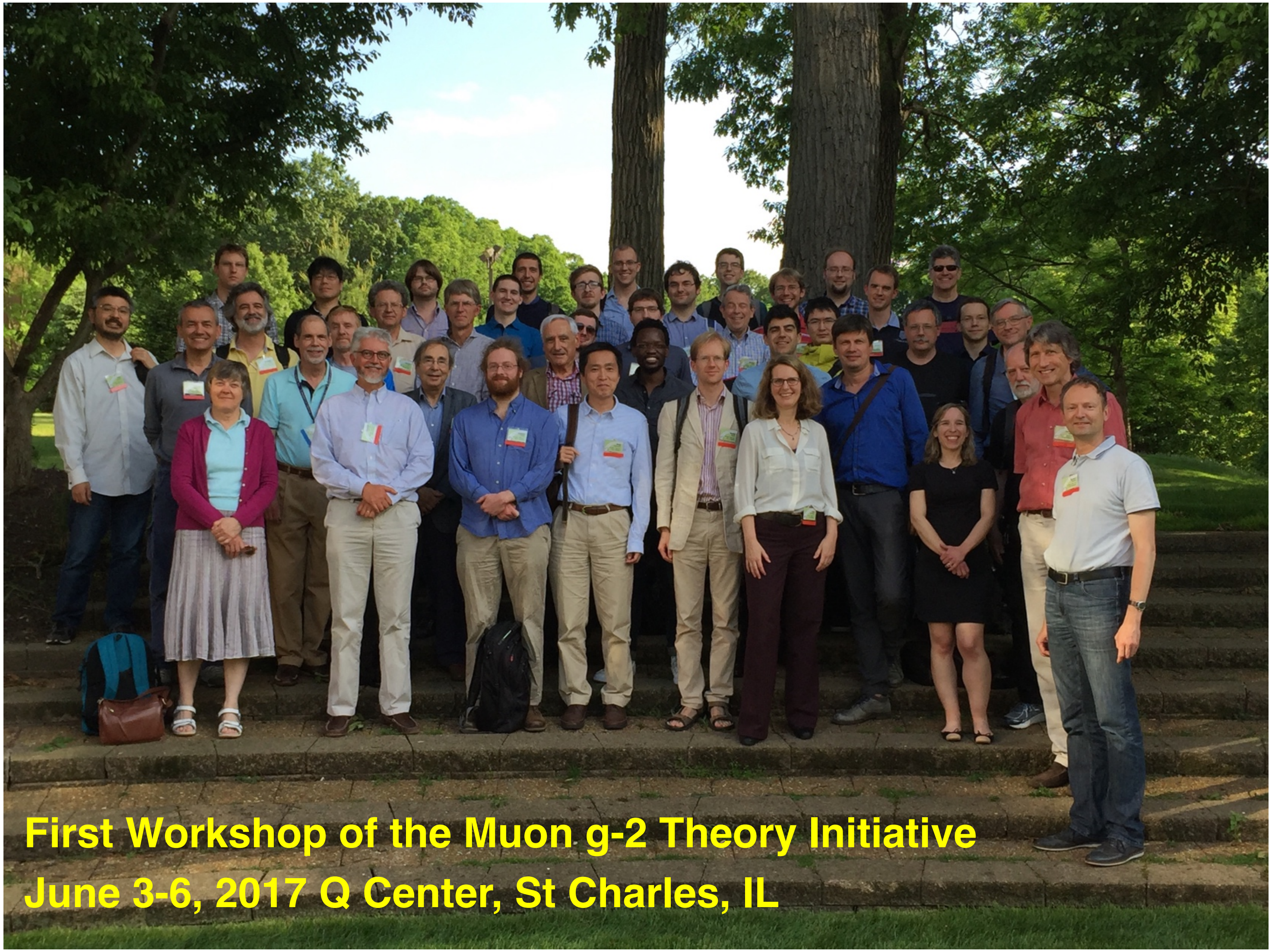
Source	Value (a_μ x 10^{-11})	Error
a) QED	116 584 718.95	0.08
b) EW	154	1
c) HVP	6850.6	43
d) HLBL	105	26



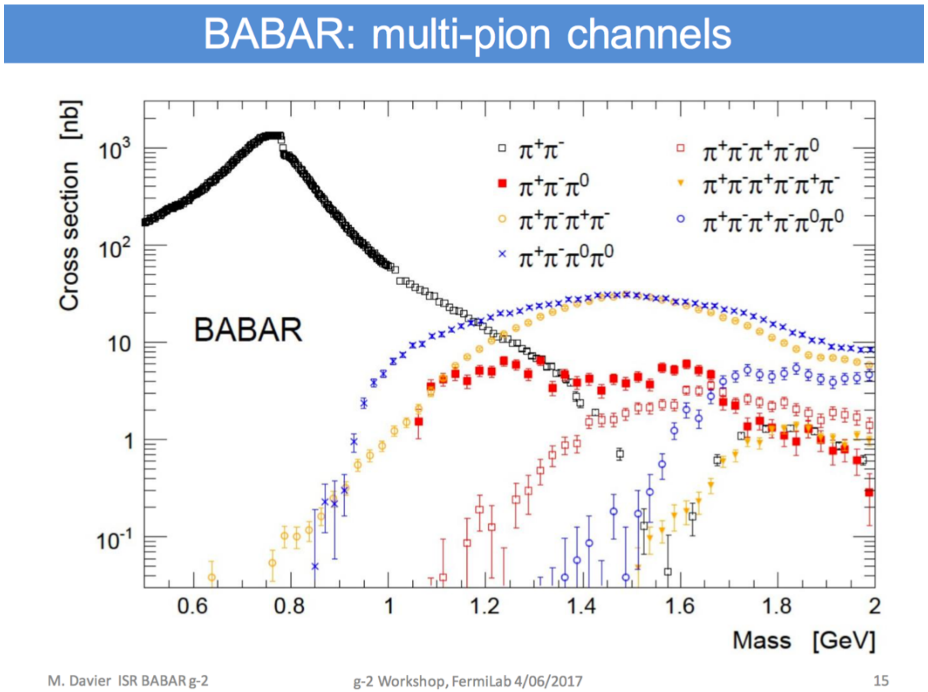
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

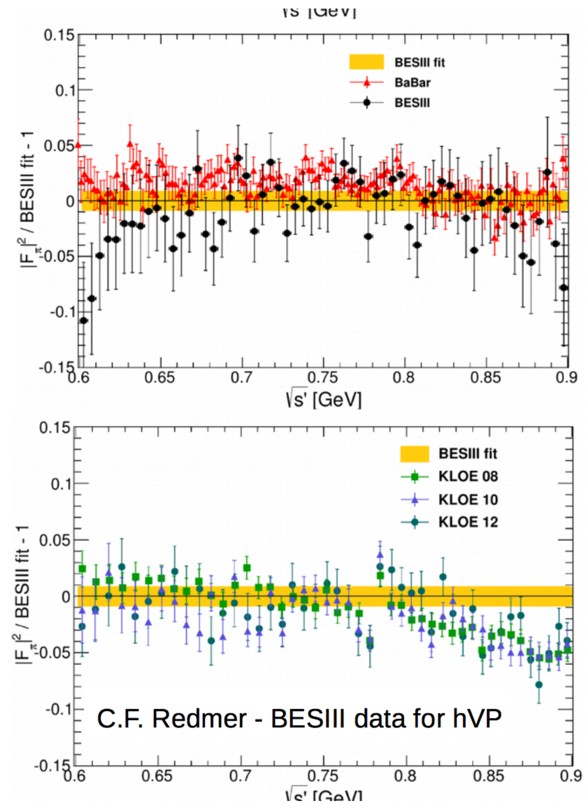
$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \text{muons})}$$

Highly active theory community…



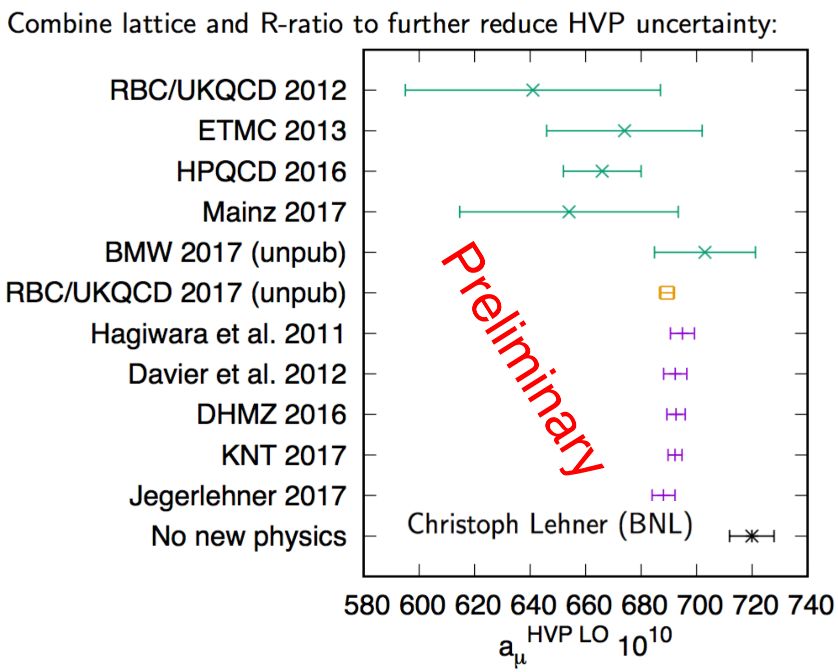
HVP e+e- Improvements





- 2π channel…72% of a_μ(LOHVP)
  - BABAR updating analysis with improved systematic approach and 2x statistics
  - BES-III newest player
  - Novosibirsk high stats w/ CMD-3 upgrades & VEPP 2000 upgraded to sqrt(s) = 2 GeV
  - KLOE working on rigorous data combinations…generally true across expts as well
- Phi- and B-factories determining many higher multiplicity exclusive channels

Lattice Outlook



- HLBL on the Lattice
  - Preliminary result for a_μ about 50% of model calculation (needs to be 300% to fix discrepancy)
  - Two systematics need more work for meaningful error bar

- LOHVP on the Lattice
  - Solved problem! Just a matter of processing time to bring error down and perform systematic checks

Conclusions and future plans 37/38

Using the recently developed methods, we have computed the connected hadronic light-by-light contribution with physical pion mass. We use a $48^3 \times 96$ lattice where $L = 5.5\mathrm{fm}$, $m_\pi = 139\mathrm{MeV}$, $m_\mu = 106\mathrm{MeV}$. 65 configurations are used in the calculation.

$$\left.\frac{g_\mu - 2}{2}\right|_{\mathrm{cHLbL}} = (0.0926 \pm 0.0077)\left(\frac{\alpha}{\pi}\right)^3 = (11.60 \pm 0.96) \times 10^{-10} \qquad (27)$$

We have extended the methods to cover the leading disconnected diagrams.

$$\left.\frac{g_\mu - 2}{2}\right|_{\mathrm{dHLbL}} = (-0.0498 \pm 0.0064)\left(\frac{\alpha}{\pi}\right)^3 = (-6.25 \pm 0.80) \times 10^{-10} \qquad (28)$$

The sum of these two contributions is (significant cancellation between them):

$$\left.\frac{g_\mu - 2}{2}\right|_{\mathrm{HLbL}} = (0.0427 \pm 0.0108)\left(\frac{\alpha}{\pi}\right)^3 = (5.35 \pm 1.35) \times 10^{-10} \qquad (29)$$

- We expect rather large finite volume and finite lattice spacing corrections.
- The finite lattice spacing errors can be corrected by performing the same calculation on a finer $64^3 \times 128$ lattice.
- Most of the finite volume errors come from the QED part of the calcutions. They can be corrected by perform only the QED part of the calculation in infinite volume with a semi-analytical way.

T. Blum HLBL Summary

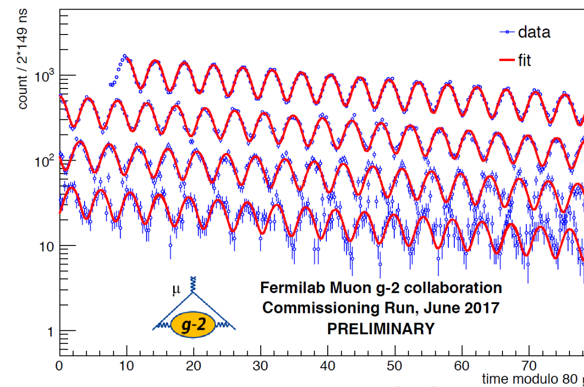
Storage Ring Experimental Timeline

Ring Arrived

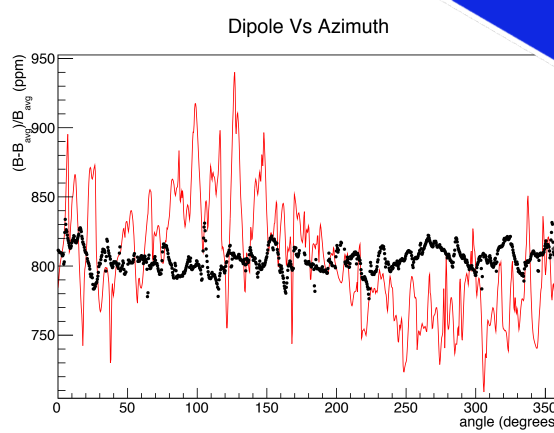
2013 → 2014 → 2015 → 2016 → 2017

Coils In MC-1

Full Power



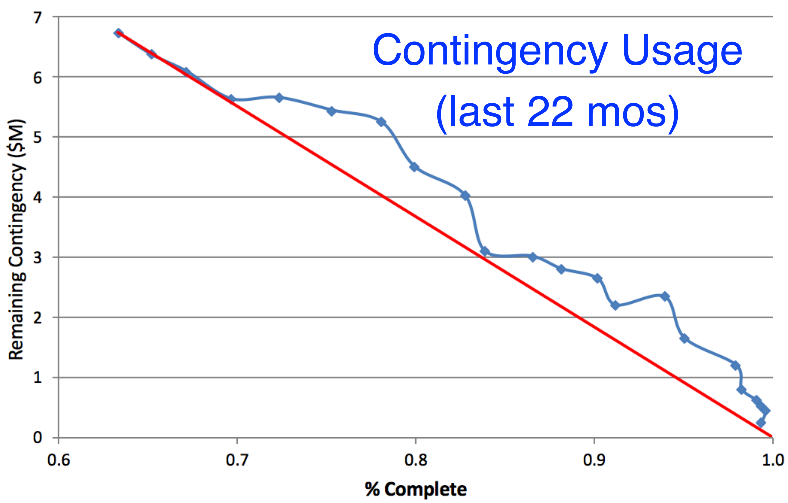
Muons Stored!

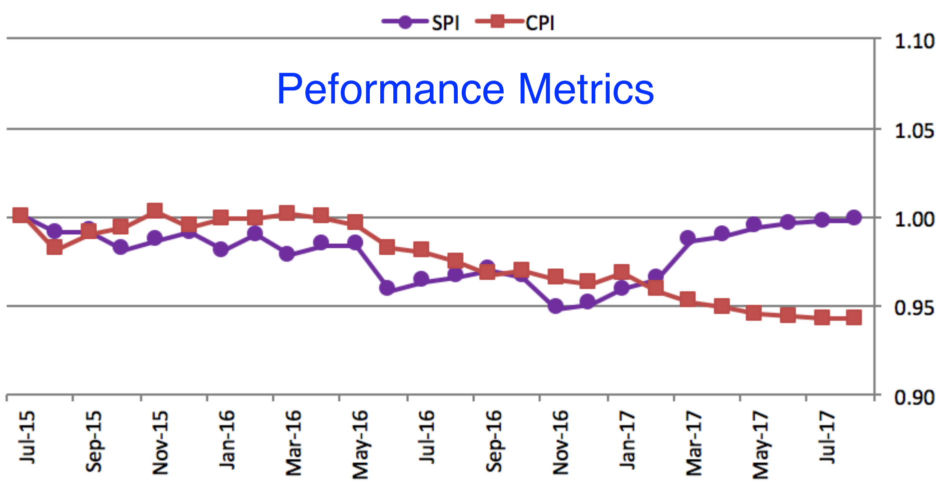


Rough Shimming Complete

Status of Muon g-2 Project

- Project is basically done…and out of money ☺
  - Spending last ~$200k of contingency on construction of new inflector (30-40% flux increase)
  - Need to install 2nd tracker to satisfy last Objective KPP
  - Scheduling CD-4 Review for Nov 13 or 14, 2017





Scientific collaboration

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- UT Austin
- Virginia
- Washington
- York College

National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

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

China

- Shanghai

Germany

- Dresden

Russia

- Budker
- JINR/Dubna
- PNPI
- Novosibirsk

England

- Lancaster
- Liverpool
- University College London

Korea

- CAPP/IBS
- KAIST

7 countries

36 institutions

- 18 domestic
- 18 international

~192 authors w/

~138 actively taking shifts in FY18

Domestic Responsibilities/FTEs by institution

~60 "research FTEs"

U.S. University Groups

- **Boston University;** FTEs: 4.1; Responsibilities: Tracker electronics, Tracker analysis, $\omega_a$ratio analysis; Beam dynamics, Machining
- **Cornell University;** FTEs: 5.8; Responsibilities: Blumlein kicker development, Beam dynamics, Storage ring modeling, Waveform digitizers, Clock and controls, $\omega_a$analysis, Fiber harp hardware support and analysis
- **University of Illinois at Urbana-Champaign;** FTEs: 1.85; Responsibilities: Muon loss analysis, $\omega_a$analysis
- **James Madison University;** FTEs: 0.25; Responsibilities: Power management system
- **University of Kentucky;** FTEs: 4.5; Responsibilities: Fast DAQ, Simulations, ω_aQ-method
- **University of Massachusetts;** FTEs: 2.5; Responsibilities: Absolute water probe; Plunging probes, $\omega_p$analysis
- **University of Michigan;** FTEs: 2.67; Responsibilities: Absolute He-3 probe, External magnetic fields
- **Michigan State University;** FTEs: 3.6; Responsibilities: Beam dynamics, COSY beamline model
- **University of Mississippi;** FTEs: 1.5; Responsibilities: Fast rotation analysis, Quadrupole assistance, Lorentz violation analysis
- **North Central College;** FTEs: 0.25; Responsibilities: local university students to help with various tasks
- **Northern Illinois University;** FTEs: 1.5; Responsibilities: Slow control system, Tracker hardware support
- **Regis University;** FTEs: 1.0; Responsibilities: Fiber Harp hardware and analysis, T0 detector
- **University of Texas at Austin;** FTEs: 2.8; Responsibilities: Kicker support software, Fixed probes, $\omega_p$analysis
- **University of Virginia;** FTEs: 0.7; Responsibilities: Muon loss analysis
- **University of Washington;** FTEs: 10.0; Responsibilities: Beam dynamics, Calorimeters hardware, Calorimeter low-level analysis, Data quality monitor, $\omega_a$analysis, NMR probes and multiplexors, Radial field, Surface coil DAQ and modeling, IBMS detectors

National Laboratories

- **Argonne National Laboratory**; FTEs: 3.0; Responsibilities: Collimators, NMR Trolley, Field DAQ, $\omega_p$analysis, Test site for NMR calibrations
- **Brookhaven National Laboratory;** FTEs: 3.0; Responsibilities: Beam dynamics, Beamline simulations, Quadrupole system, CBO analysis
- **Fermi National Accelerator Laboratory;** FTEs: 9.2; Responsibilities: Host institution, Inflector, Storage ring magnet, Surface coils, Vacuum chambers, Kicker operations, Tracker gas, Tracker analysis, Computing support

1 research FTE = 100% of research fraction spent on g-2

Responsibilities/FTEs by institution

~40 "research FTEs"

International Groups by Country

- **CHINA: Shanghai Jiao Tong University;** FTEs: 2.6; Responsibilities: Database development, Offline production
- **GERMANY: Technische Universitt Dresden;** FTEs: 0.25; Responsibilities: $g-2$ BSM theory
- **ITALY: Laboratori Nazionali di Frascati, INFN: Sezione di Napoli, Sezione di Pisa, Sezione di Roma Tor Vergata, Sezione di Trieste, Universit'à del Molise, Università di Udine;** FTE: 16.2; Responsibilities: Laser calibration system, including laser, optics, monitors, DAQ, flight simulator, analysis, systematic gain studies
- **KOREA: Korea Advanced Institute of Science and Technology (KAIST);** FTEs: 3.0; Responsibilities: RF phase-space damping, Beam dynamics
- **RUSSIA: Novosibirsk Budker Institute of Nuclear Physics and Dubna Joint Institute for Nuclear Research;** FTEs: 3.0; Responsibilities: Paraview event display, Alarm system, MIDAS ODB support (Note: group presently subject to Fermilab site accessibility restrictions)
- **UNITED KINGDOM: Cockcroft Institute, Lancaster University, University of Liverpool, University College London;** FTEs: 13.0; Responsibilities: Tracker hardware, tracker analysis, EDM analysis, tracker DAQ, Beamline modeling, Beam Dynamics, $g-2$ SM theory

October 2017 Muon g-2 Org Chart

Fermilab
Program Planning: Geer
Muon Dept Head: Casey
Accelerator Liaison: Convery
Computing Liaison: Lyon
Safety Liaison: Hahn

Spokespersons
Hertzog (UW), Polly (FNAL)

Institution Board
Chair: Lancaster (UCL)

Talks Committee
Chair: Winter (ANL)

Publications Committee
Chair: Venanzoni (INFN)

Scientific Secretary
Liang Li (Shanghai)

Managers

Coordinators

Run Coordinator
Kiburg (FNAL)
Kaspar (UW)

Ring Ops
Nguyen (FNAL)
Crnkovic (BNL)

Field Ops
Flay (UMass)
Hong (ANL)

Detector Ops
Price (LIV)
Mott (BU)

DAQ/Online Ops
Gohn (UKy)
Chislett (UCL)

Analysis Coordinator
(Spokes for now)

Beam Dynamics
Stratakis (FNAL)
Morse (BNL)

Field Analysis
Kawall (UMass)
Winter (ANL)

Muon Precession
Khaw (UW)
Lancaster (UCL)

Offline Computing & Simulations
Fatemi (UKy)
Casey (FNAL)

Run Coordinators
Kiburg (FNAL), Kaspar (UW)

- **Ring Ops** – Nguyen (FNAL), Crnkovic (BNL)
  - **Magnet** – Allspach (FNAL)
  - **Inflector** – Nguyen (FNAL)
  - **Kicker** – Stoughton (FNAL)
  - **Quads** – Crnkovic (BNL)
- **Field Ops** – Flay (UMass), Hong (ANL)
  - **Trolley** – Hong (ANL)
  - **Plunging probe** – Flay (UMass)
  - **Fixed probes** – George (UT)
  - **Surface Coils** – Osofsky (UW)
  - **Flux gate** – Tewsley-Booth (UMich)
  - **Calib. Probes** – Flay (UMass)
- **Detector Ops** – Price (Liverpool), Mott (BU)
  - **Calorimeters** – Hempstead (UW)
  - **WFD5 & CCC** – Sweigart (Cornell)
  - **Laser** – Incagli (INFN)
  - **Trackers** – Price (Liverpool)
  - **Aux Detectors** – Gray (Regis)
  - **Slow Controls** – Eads (NIU)
- **DAQ/Online Ops** – Gohn (UKy), Chislett (UCL)
  - **Fast DAQ** – Gohn (UKy)
  - **DQM** – Fienberg (UW)
  - **Field DAQ** – Hong (ANL)
  - **Tracker DAQ** – Chislett (UCL)
  - **Laser Hut DAQ** – Driutti (INFN)

Analysis Coordinator (Spokes for now)

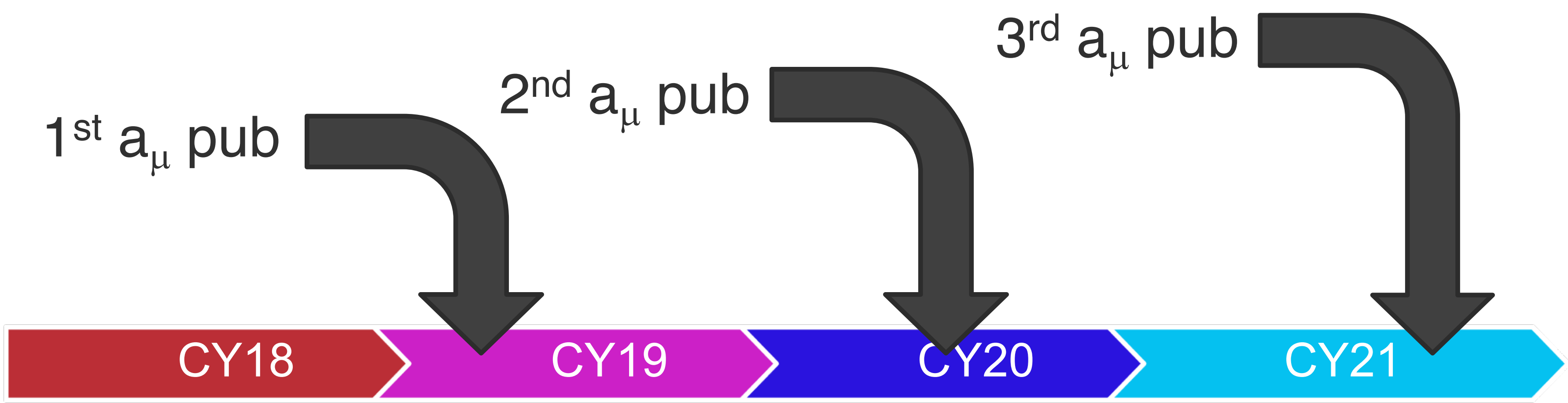
- **Muon Precession** – Khaw (UW), Lancaster (UCL)
  - **Recon West** – Hertzog (UW), Fienberg (UW)
  - **Recon East** – Polly (FNAL), Sweigart (Cornell)
  - **Laser Cal** – Venanzoni (INFN)
  - **Tracking Algos** – Mott (BU)
  - **Aux Det Algos** – Gray (Regis), Chapelain (CNL)
  - **R method** – Roberts (BU), Chislett (UCL)
  - **Q method** – Gohn (UKy)
  - **Muon Distribution** – Tran (BU)
  - **EDM** – Price (Liverpool)
  - **Muon losses** – Ganguly (UIUC)
  - **CPT/LV** – Quinn (UMiss)
- **Field** – Kawall (UMass), Winter (ANL)
  - **Frequency Extraction** – Chupp (UMich)
  - **Interpolation** – Swanson (UW)
  - **Field Map** – Hong (ANL)
  - **Absolute Calibration** – Flay (UMass))
  - **Muon Convolution** – Grange (ANL)
- **Beam Dynamics** – Stratakis(FNAL), Morse (BNL)
  - **Beamline Simulations** – Stratakis (FNAL)
  - **Muon BD** – Tishchenko (BNL), Rubin (Cornell)
  - **Fast Rotation E-field & Pitch** – Carey (BU)
  - **CBO** – Crnkovic (BNL)
- **Offline & Simulations** – Fatemi (UKy), Casey (FNAL)
  - **Release Mgr** – Stapleton (FNAL)
  - **Database Mgr** – LI (Shanghai)
  - **Simulation Mgr** – Fatemi (UKy)
  - **Nearline Mgr** – Khaw (UW)
  - **Prodn Mgr** – Li (Shanghai)

Publication Plan (Charge Question #5)

- Active talks committee to equitably distributes talks
  - Numerous talks over the the last few years
  - Variety of venues including accelerator, computing, detector, nuclear, and high energy physics conferences
- Upcoming publications
  - Series of NIM-style articles on major subsystems as they are fully-commissioned and operating reliably over the next year
- Targeting two PRD-style major publications by the end of 2018 to facilitate later publication of physics results
  - Field shimming and analysis
  - Muon beam dynamics

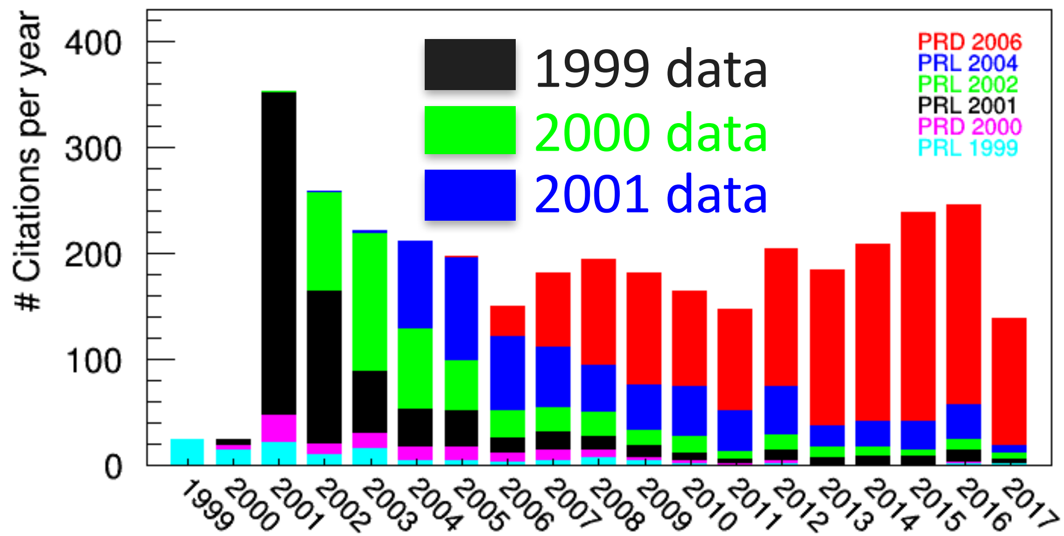
Publication Plan (Charge Question #5)

- Planning on three generations of a_μ publications
  - 2-3 x BNL (~400 ppb) to be collected in FY18 and aiming for publication by Winter 2019 conferences
  - 5-10 x BNL (~200 ppb) collected over FY18+FY19 with publication by Summer 2020…caveat that we now enter unknown regime
  - 20+ x BNL (~140 ppb) collected by end of FY20 with final publications in 2021
- Muon EDM and CPT/LV physics results in at least two generations



Two caveats to publications plan

- BNL publications lagged 2-3 yrs behind acquiring stats
  - Understanding systematics and fixing for next run takes priority
- However, we benefit from BNL experience and analysis tools much more advanced



Fermilab Accelerator Experiments' Run Schedule

		FY 2017 (Q1–Q4)	FY 2018 (Q1–Q4)	FY 2019 (Q1–Q4)	FY 2020 (Q1–Q4)	
NuMI	MI	MINERvA	MINERvA	MINERvA ?	OPEN	
		NOvA	NOvA	NOvA	NOvA	
BNB	B	MicroBooNE	MicroBooNE ?	SBN: MicroBooNE	SBN: MicroBooNE	ν
		SBN: ICARUS	SBN: ICARUS	SBN: ICARUS SBN:ICARUS	SBN: ICARUS	
		SBN: SBND	SBN: SBND	SBN: SBND	SBN: SBND	
Muon Campus		g-2	g-2	g-2	OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	
SY 120	MT	FTBF - MTEST	FTBF - MTEST	FTBF - MTEST	FTBF - MTEST	p
	MC	OPEN LArIAT	FTBF - MC	FTBF - MC	FTBF - MC	
	NM4	SeaQuest	OPEN	OPEN	OPEN	

- Likely 2020 running will be required to complete $\mu+$ stats

EOP a) outline of science goals

Quantity	Present Uncertainty ppb	E989 Goal ppb
Total ω_a Statistical	460	100
Final ω_a Systematic	210	70
Final $\tilde{\omega}_p$ Systematic	170	70
CODATA m_μ/m_e	22	–
CODATA μ_p/μ_e	3.0	NA
Electron g factor, g_e	0.000035	NA
Final E821	630	–
Goal Fermilab E989	–	140

EOP pg 10

- a_μ to 140 ppb for μ+
- x 10-30 improvement in EDM sensitivity
- Improved limits on CPT/LV

EOP b) description of operational tasks

- Maintaining and operating equipment outlined in EOP pgs 11-14
- Executing the plan to get to physics quality data taking EOP pgs 14-17

EOP c) ES&H

- EOP pg 37 and reference to SAD therein

EOP d) org charts

- Shown in this talk and EOP pg 29-31

EOP e) Fermilab roles and resources by division

- Shown in this talk and EOP pg 35-37

X. FERMILAB ROLES AND RESOURCES

The Muon $g-2$ experiment receives support from the Accelerator Division (AD), Scientific Computing Division (SCD), Technical Division (TD), and Particle Physics Division (PPD).

EOP f) data processing/analysis model

- See EOP pg 18-26 sections
  - IV: Overview of Computing
  - V: Data Production
  - VI: Simulation Requirements and Tools
  - VII: Simulation Workflow

EOP f cont.) computing budget

Table IV: FY18 Computing Cost Estimates

SCPMT FY18 Request	Amount	Units	Cost in thousands of dollars
Data Processing CPU	18,000,000	Core-hours	180,000
Simulation CPU (offsite)	9,000,000	Core-hours	0
dCache Tape Backed	400	TB	50,000
dCache Scratch	300	TB	37,500
dCache Persistent	200	TB	25,000
dCache Write Pool	100	TB	12,500
NAS Storage	60	TB	15,000
DAQ Data Tape (2 copies)	4400	TB	264,000
Reco Tape	1800	TB	108,000
Simulation Tape	1000	TB	60,000
TOTAL			752,000
SCD Support Services	10	FTE	1,500,000

EOP pg 27

EOP g) identified resources

- Section X: Fermilab Roles and Resources EOP pg 35-37
- Section XI: Budget and Resources EOP pg 38

EOP h) responsibilities by institution

- This talk slides 10-11
- Collaboration FTEs EOP pg 33-35

Addressing the charge

2. Has it been demonstrated that the experiment is ready for physics-quality data taking? If not, what actions are required to make it ready? Is there a clear plan for monitoring (the beam and) the data quality and has the associated infrastructure been tested? If not, what actions are required to adequately monitor the data quality? Hertzog-Experimental Overview, Convery-Beam, Nguyen-Storage Ring, Rubin-Muon Storage, Kaspar-Detectors, Gohn-DAQ/DQM, Flay-Field

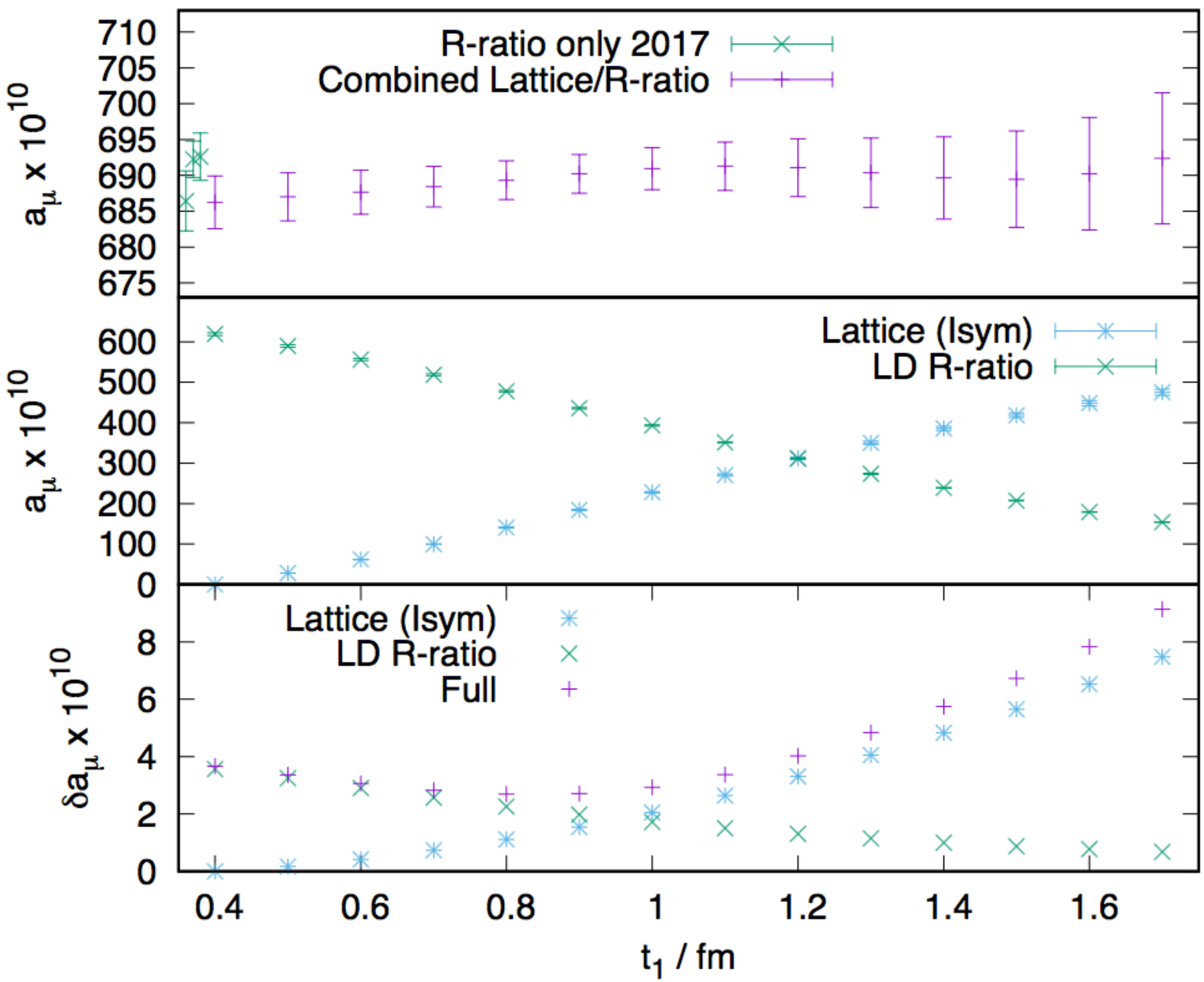
3. Is there a well-understood run plan for FY18, consistent with accelerator schedule and performance? Have adequate resources from the laboratory and the collaboration been identified for an efficient and safe running of the experiment and for maintenance of the detector, and is it clear who is responsible for what? Convery-Beam, Kiburg-FY18 Run Plan

4. Are there robust plans for data processing and data analysis? Have adequate resources from the laboratory and the collaboration been identified for data analysis to meet these goals? Fatemi-Simulations, Khaw-Precession Frequency Analysis, Hong-Field Analysis, Lyon-Data Processing

5. Are there clear goals set for reporting and publishing the results from the experiment in a timely fashion? Polly-Intro

6. Does the committee recommend further actions to ensure full exploitation of the muon g-2 experimental program? Closing remarks for our perspective

Backup



New result by RBC/UKQCD, to be published next month 13 /