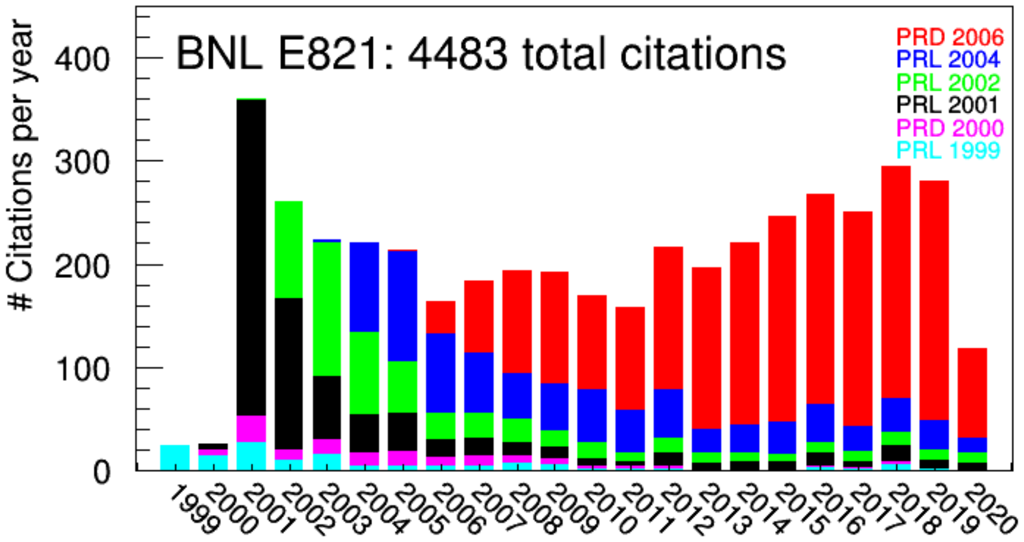
Muon g-2 PAC Update

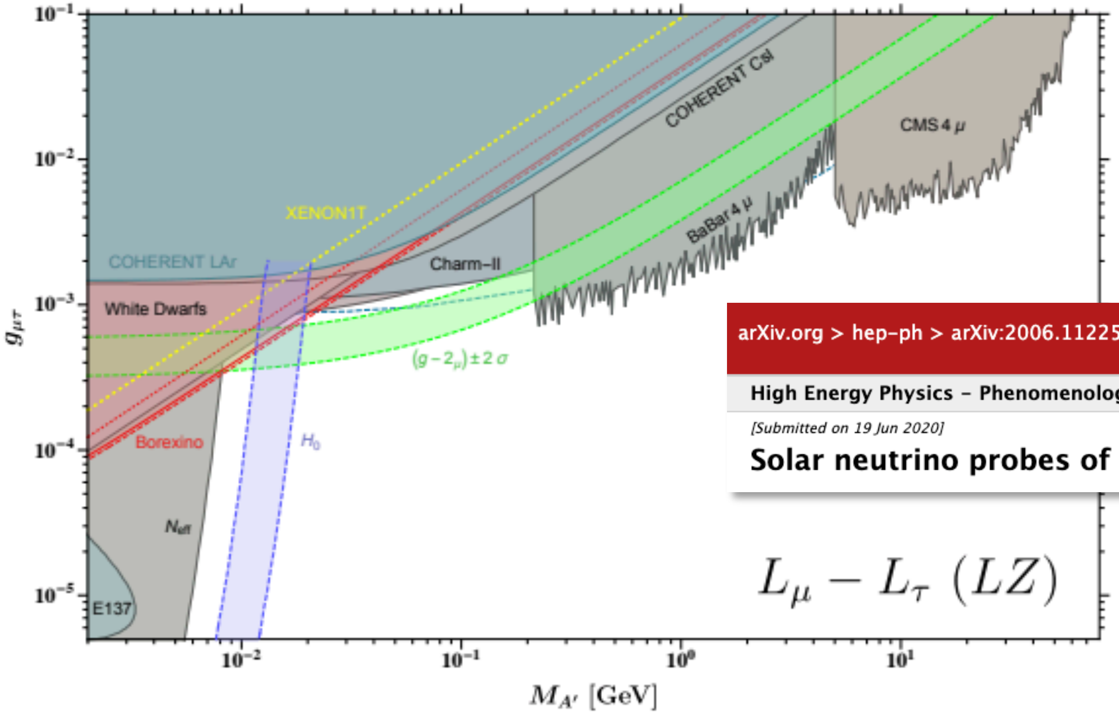
Mark Lancaster (U. Manchester) & Chris Polly (FNAL)

30 Jun 2020

Introduction

Interest in the muon g-2 measurement remains strong both to refute or confirm BSM physics





arXiv.org > hep-ph > arXiv:2006.11225

High Energy Physics – Phenomenology

[Submitted on 19 Jun 2020]

Solar neutrino probes of the muon anomalous magnetic moment in the gauged $U(1)_{L_\mu - L_\tau}$

Five-year initiative for consensus SM value

Physicists publish worldwide consensus of muon magnetic moment calculation

June 11, 2020 | Jerald Pinson

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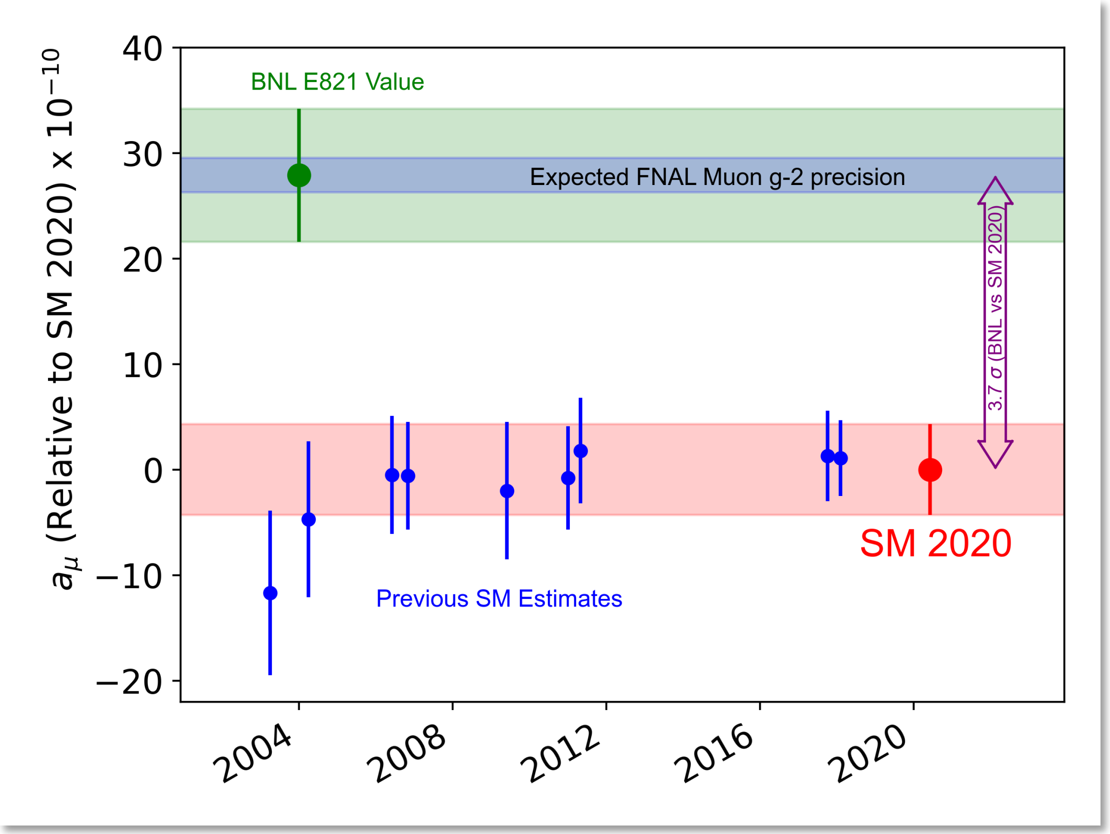
For decades, scientists studying the muon have been puzzled by a strange pattern in the way muons rotate in magnetic fields, one that left physicists wondering if it can be explained by the Standard Model — the best tool physicists have to understand the universe.

This week, an international team of more than 170 physicists published the most reliable prediction so far for the theoretical value of the muon's anomalous magnetic moment, which would account for its particular rotation, or precession. The magnetic moment of



- No surprises: BNL value 3.7σ from SM 2020
- With hoped-for FNAL precision → 6.1σ
- Requires: 100 ppb (stat.) + 100 ppb (syst.) and thus a dataset ~ x 21 that of BNL

arXiv.org > hep-ph > arXiv:2006.04822

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High Energy Physics – Phenomenology

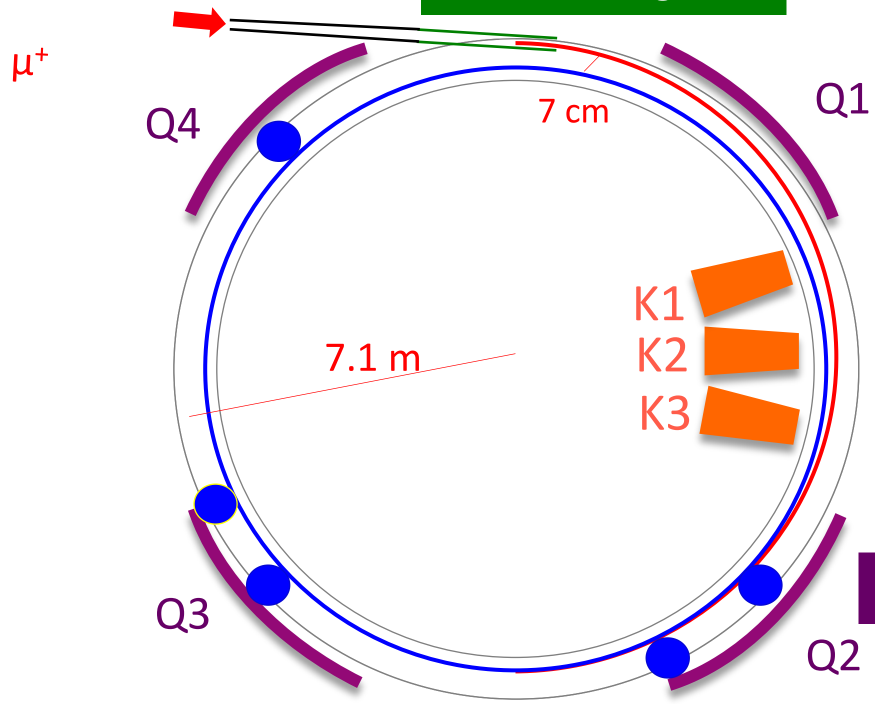
[Submitted on 8 Jun 2020]

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama, N. Asmussen, M. Benayoun, J. Bijnens, T. Blum, M. Bruno, I. Caprini, C. M. Carloni Calame, M. Cè, G. Colangelo, F. Curciarello, H. Czyż, I. Danilkin, M. Davier, C. T. H. Davies, M. Della Morte, S. I. Eidelman, A. X. El-Khadra, A. Gérardin, D. Giusti, M. Golterman, Steven Gottlieb, V. Gülpers, F. Hagelstein, M. Hayakawa, G. Herdoíza, D. W. Hertzog, A. Hoecker, M. Hoferichter, B.-L. Hoid, R. J. Hudspith, F. Ignatov, T. Izubuchi, F. Jegerlehner, L. Jin, A. Keshavarzi, T. Kinoshita, B. Kubis, A. Kupich, A. Kupść, L. Laub, C. Lehner, L. Lellouch, I. Logashenko, B. Malaescu, K. Maltman, M. K. Marinković, P. Masjuan, A. S. Meyer, H. B. Meyer, T. Mibe, K. Miura, S. E. Müller, M. Nio, D. Nomura, A. Nyffeler, V. Pascalutsa, M. Passera, E. Perez del Rio, S. Peris, A. Portelli, M. Procura, C. F. Redmer, B. L. Roberts, P. Sánchez-Puertas, S. Serednyakov, B. Shwartz, S. Simula, D. Stöckinger, H. Stöckinger-Kim, P. Stoffer, T. Teubner, R. Van de Water, M. Vanderhaeghen, G. Venanzoni, G. von Hippel, H. Wittig, Z. Zhang, M. N. Achasov, A. Bashir, N. Cardoso, B. Chakraborty, E.-H. Chao, J. Charles, A. Crivellin, O. Deineka, A. Denig, C. DeTar, C. A. Dominguez, A. E. Dorokhov, V. P. Druzhinin, G. Eichmann, M. Fael, C. S. Fischer, E. Gámiz, Z. Gelzer, J. R. Green, S. Guellati-Khelifa, D. Hatton, N. Hermansson-Truedsson et al. (32 additional authors not shown)

This time last year

Just completed Run-2 adding another x 2 BNL to our dataset but we had not yet achieved ideal operating conditions

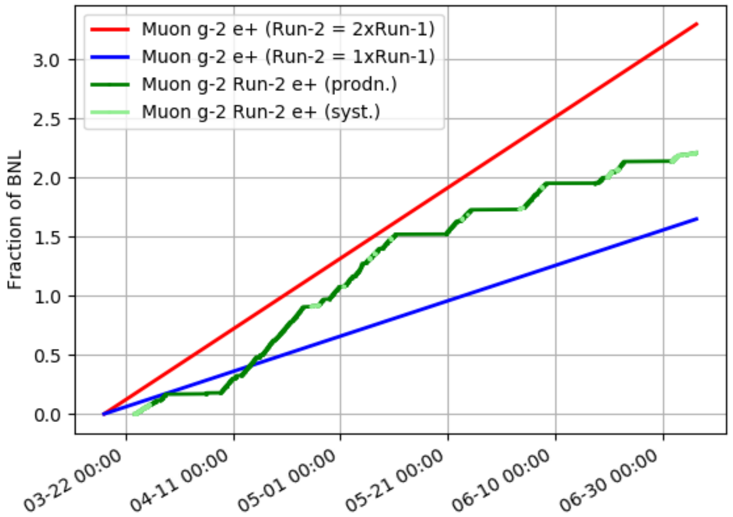


Inflector Magnet **cancels 1.45 T main field**

Kicker magnets **x3 (40-55 kV)**
radially centers beam

Focusing quadrupoles **15-28 kV**
vertically focuses beam

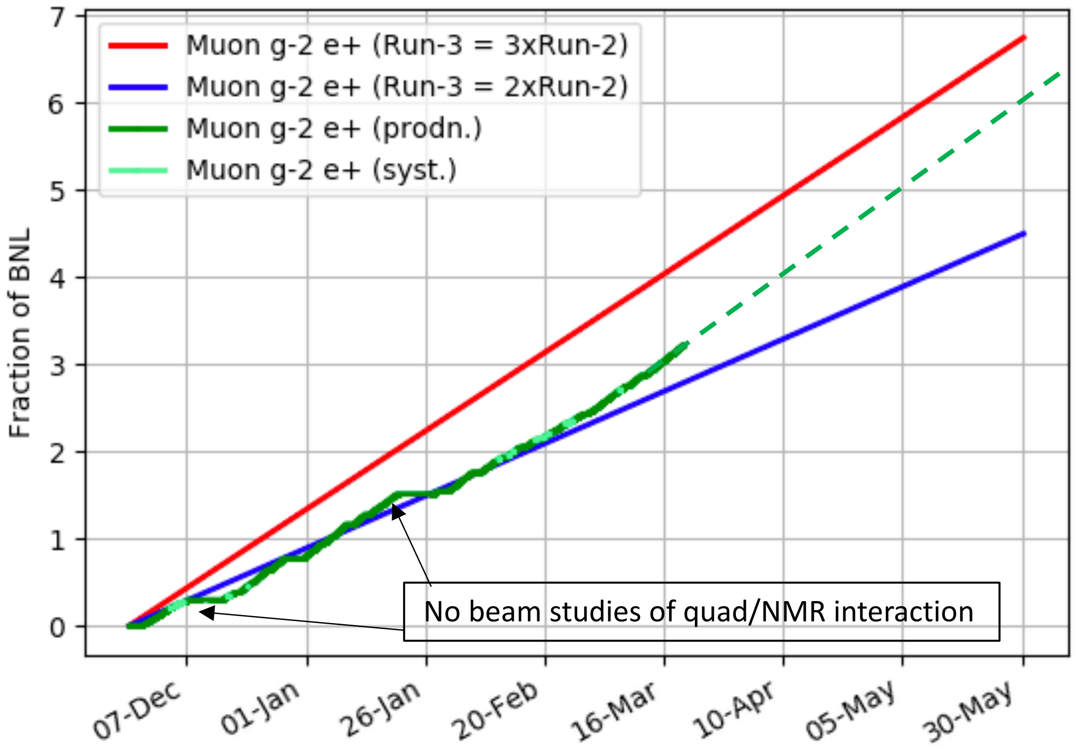
Collimators



1. Temperature fluctuations in hall too large
2. Kicker while stable was (3x) 6 kV below par

This year (Run-3)

- We reached our operating goals and accumulated another x 3.3 BNL prior to the CV19 shutdown
- We were on track to meet statistical goals (POT, muons) for the run
  and likely would have doubled the Run-1/2 dataset.

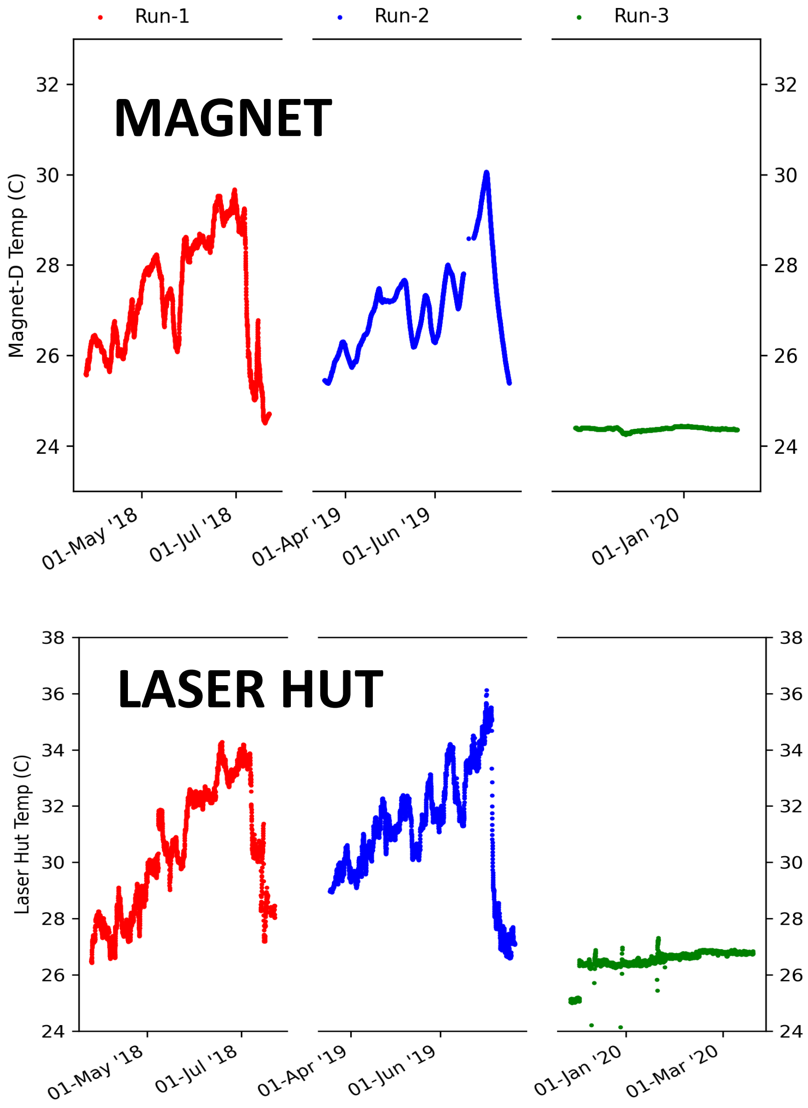


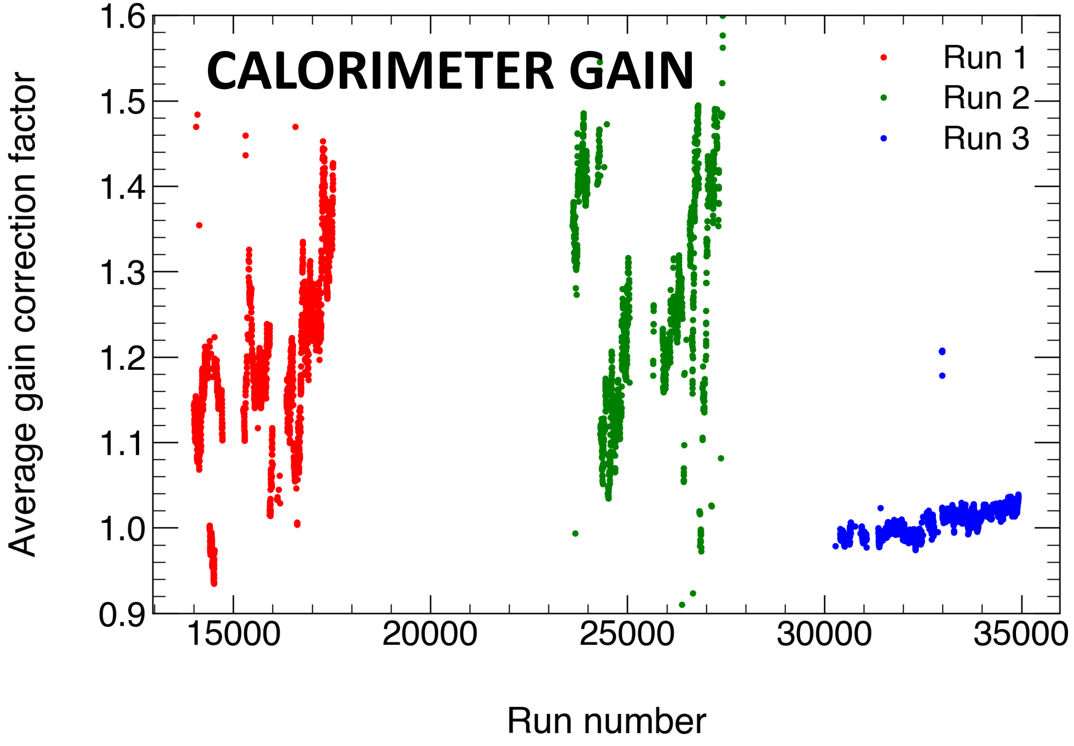
1. Temperature fluctuations under-control
2. Kicker achieved 161 kV (total) and beam centred

Operational improvements in cryo, DAQ, field.

Temperature Variations in Run-3

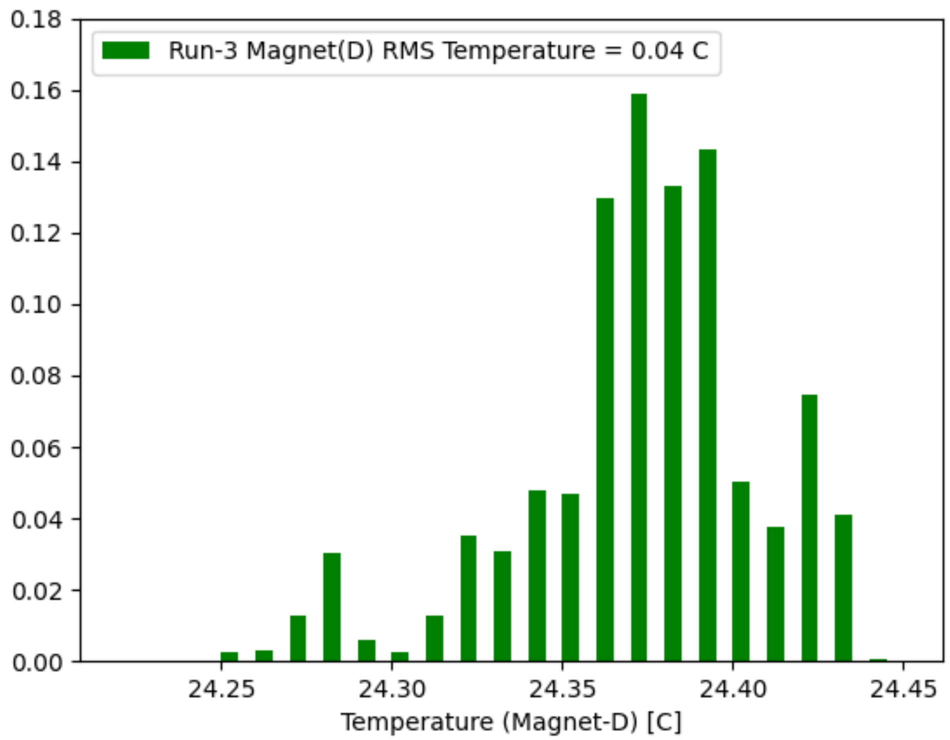
Very stable due to completion of the cooling system prior to the run.

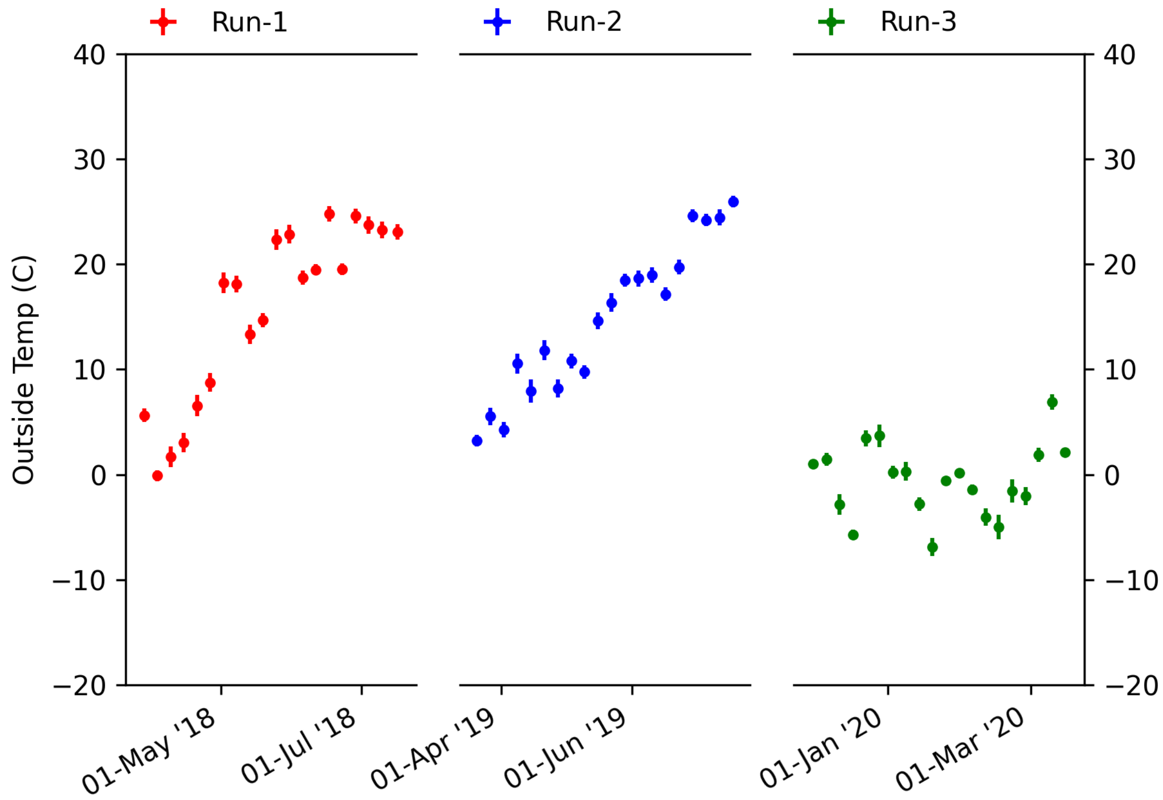




Temperature Variations

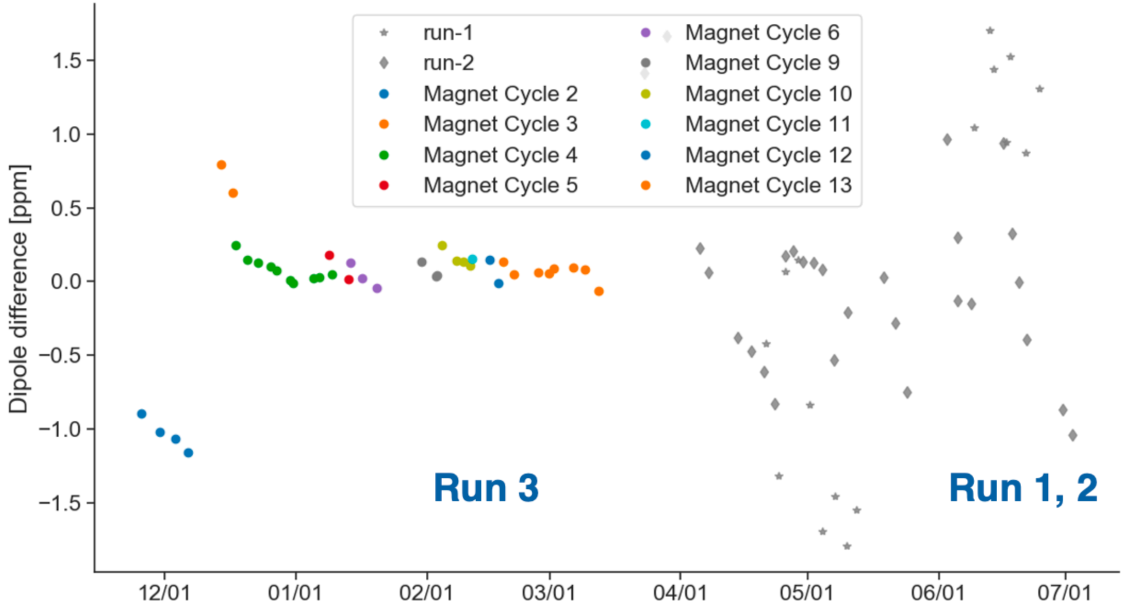
Magnet RMS: 0.04C vs 1C (1.3C) in Run-2 (1) albeit with a somewhat smaller outside temperature variance

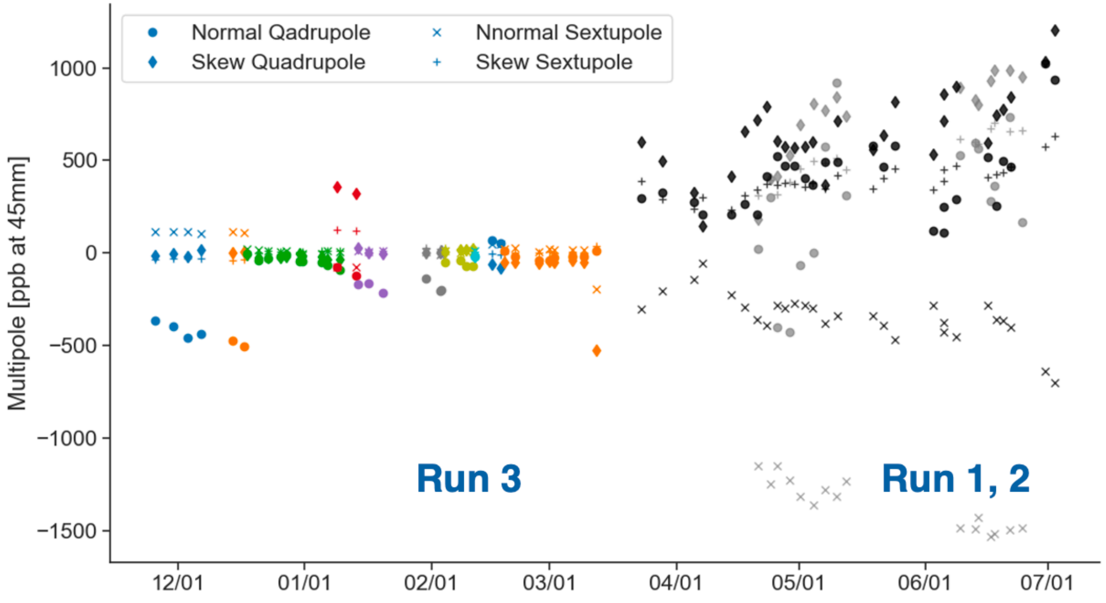




B-field much more stable

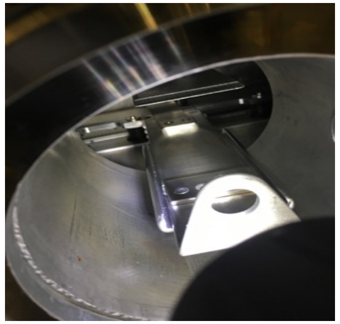
Trolley runs mapping the field now can be done remotely and routinely done every 2-3 days (4 hour process)



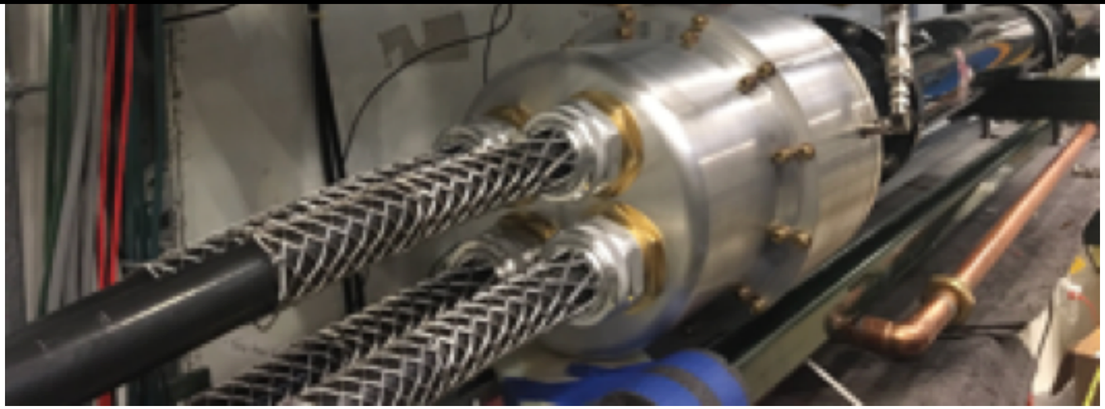


Kicker Improvements

New feedthrough on K2



New connectors to allow quick cable replacement



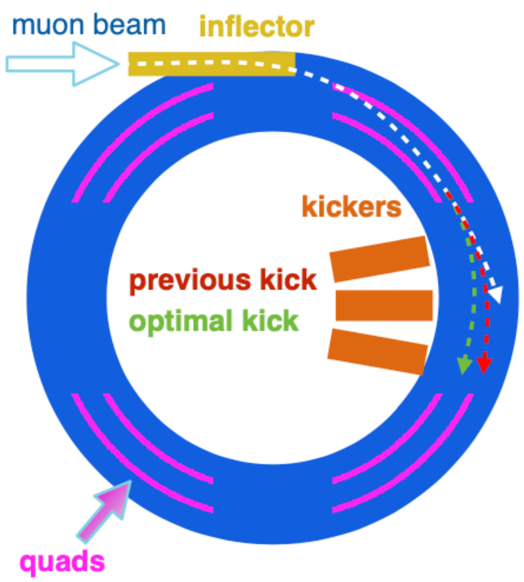
New cables rated to higher voltage

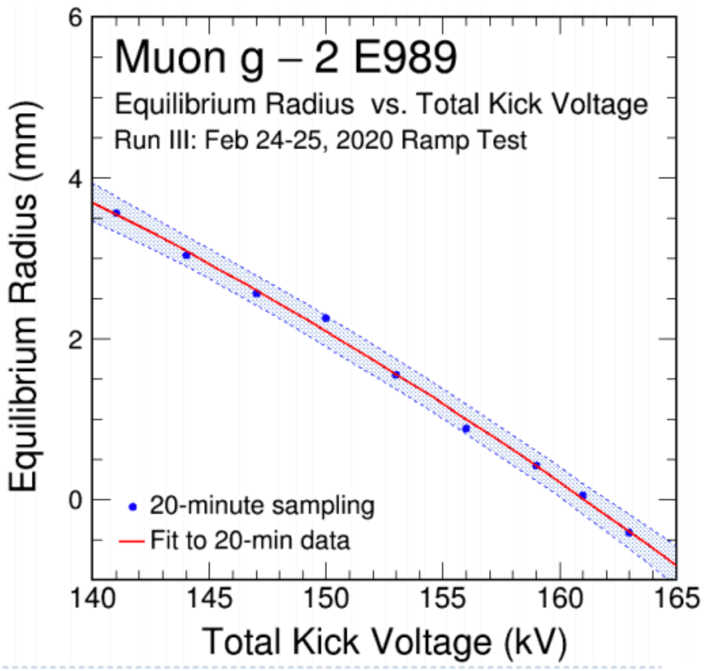
Going from 142 kV to 161 kV
- more stored muons
- a beam at the magic momentum and centered

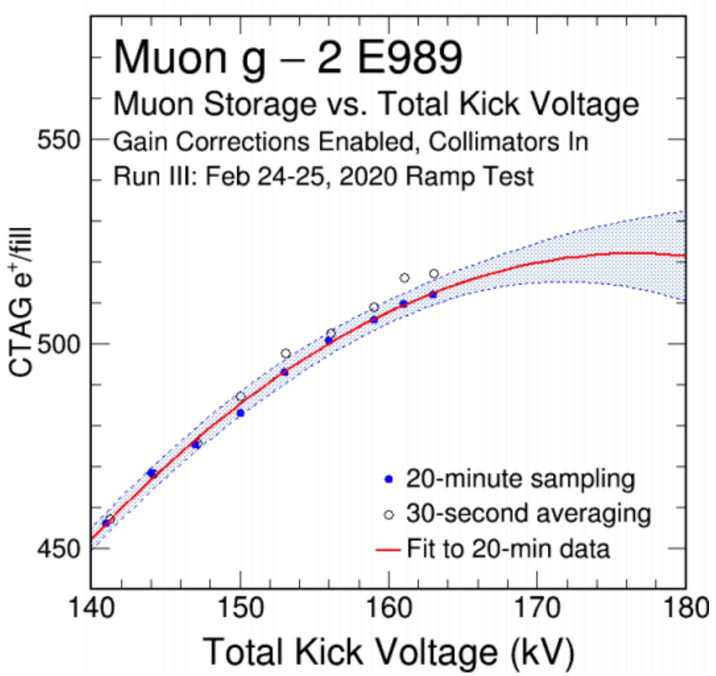
If the mean beam position is not at the magic radius, a correction must be applied.

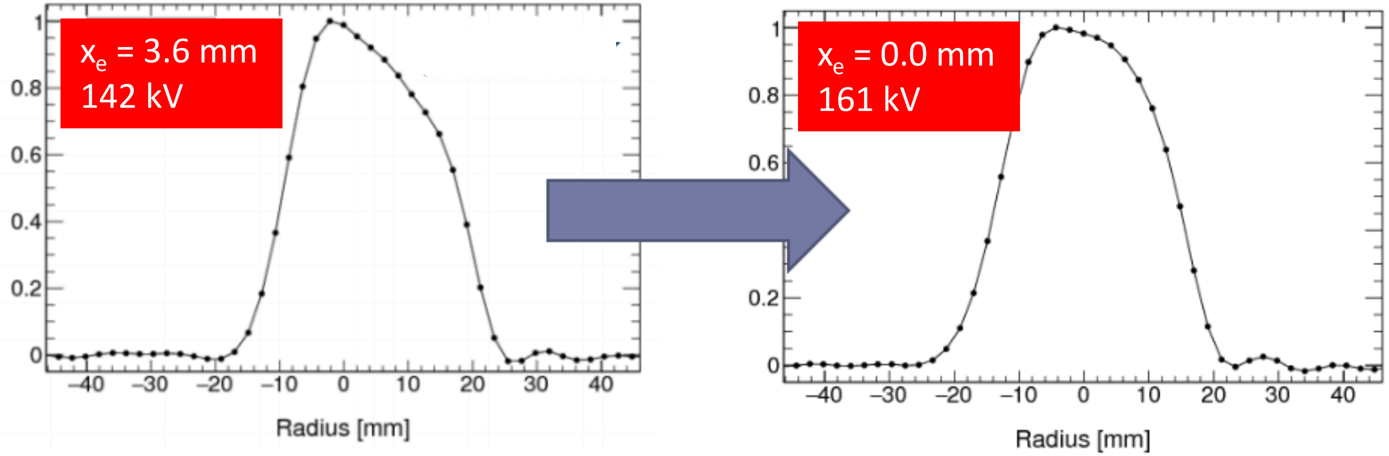
Correction is larger and more uncertain the less-centered the beam is → systematic in g-2.

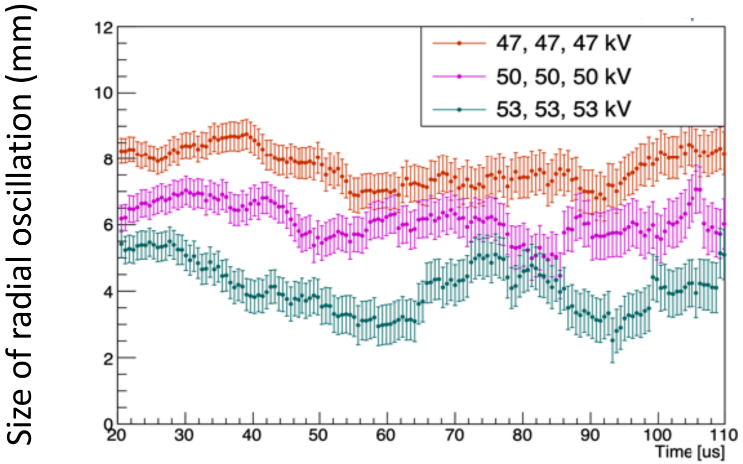
A centered beam at 161 kV





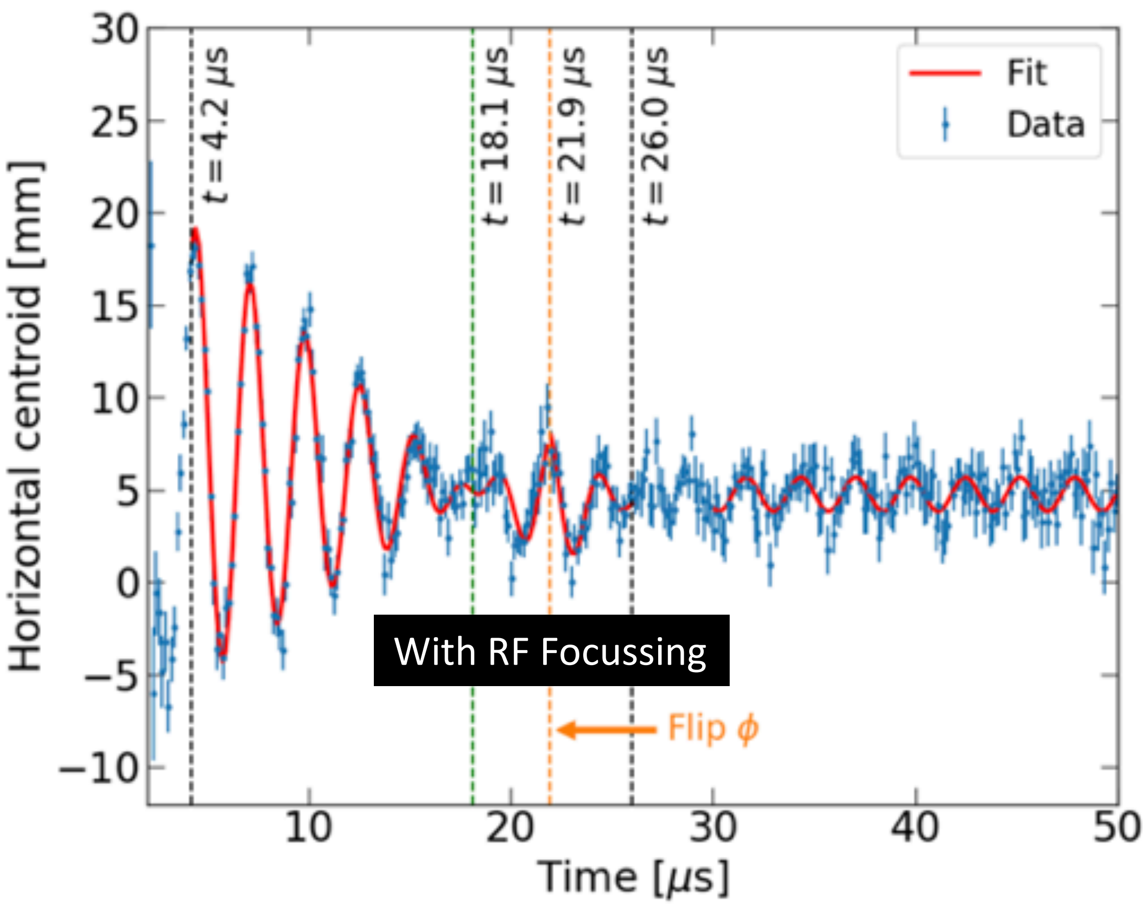


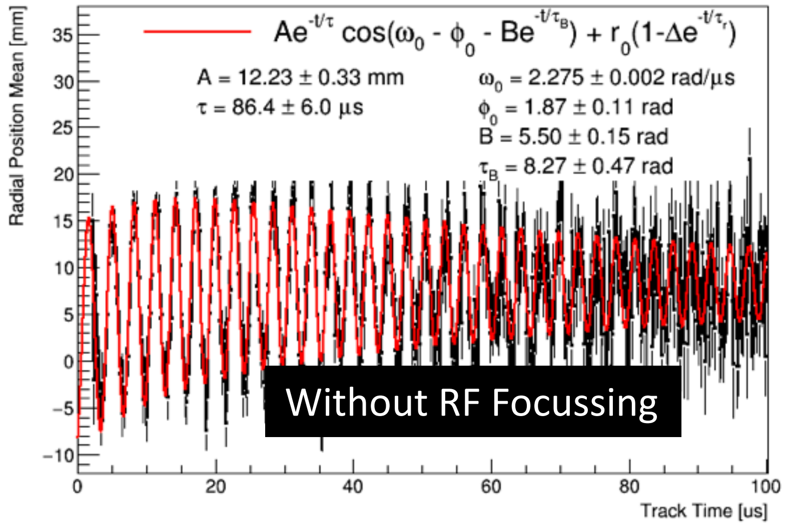




Tested novel RF Focussing

We also demonstrated the efficacy of RF focussing augmenting the electrostatic quadrupoles that we will likely deploy in Run-4.

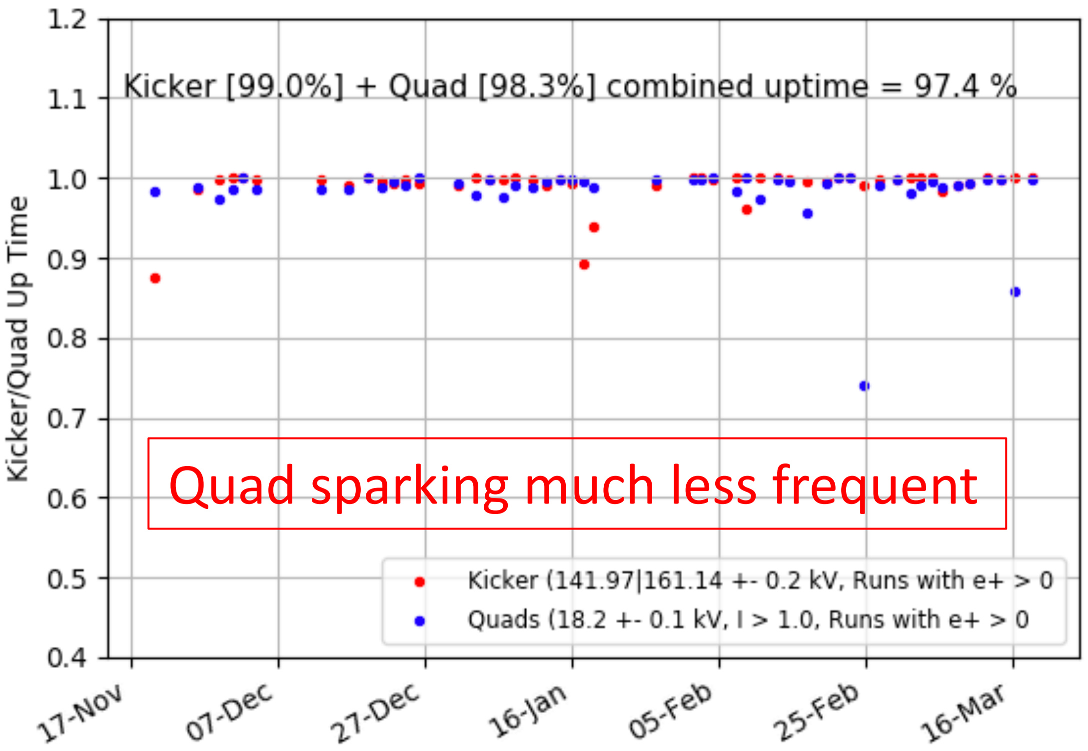


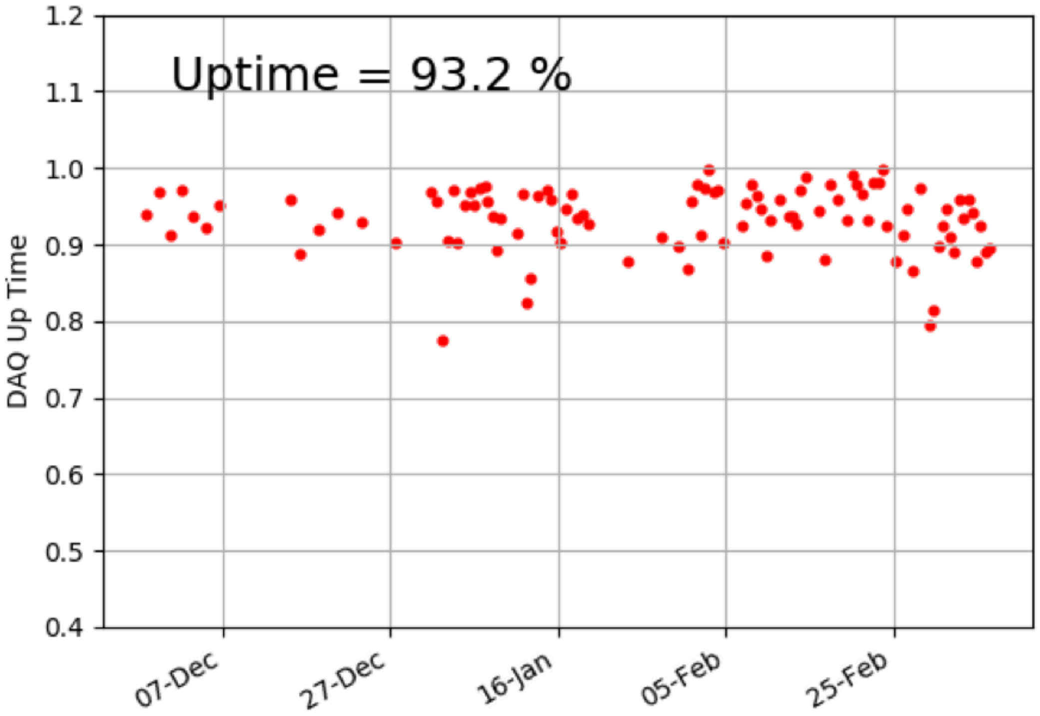


Reduces the amplitude of the beam oscillations from O(± 10mm) to O (± 2mm)

Operational Up-Time

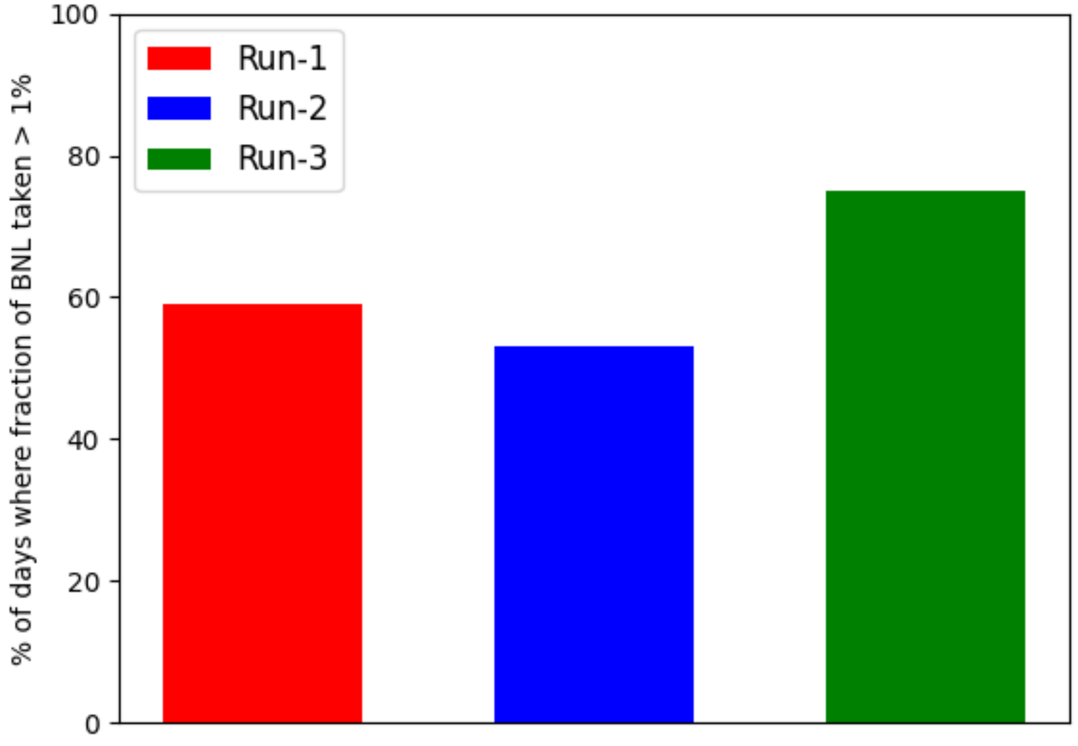
Run-2 : 90% (Quads/Kickers) & 92% DAQ
Run-3 : 97% (Quads/Kickers) & 93% DAQ

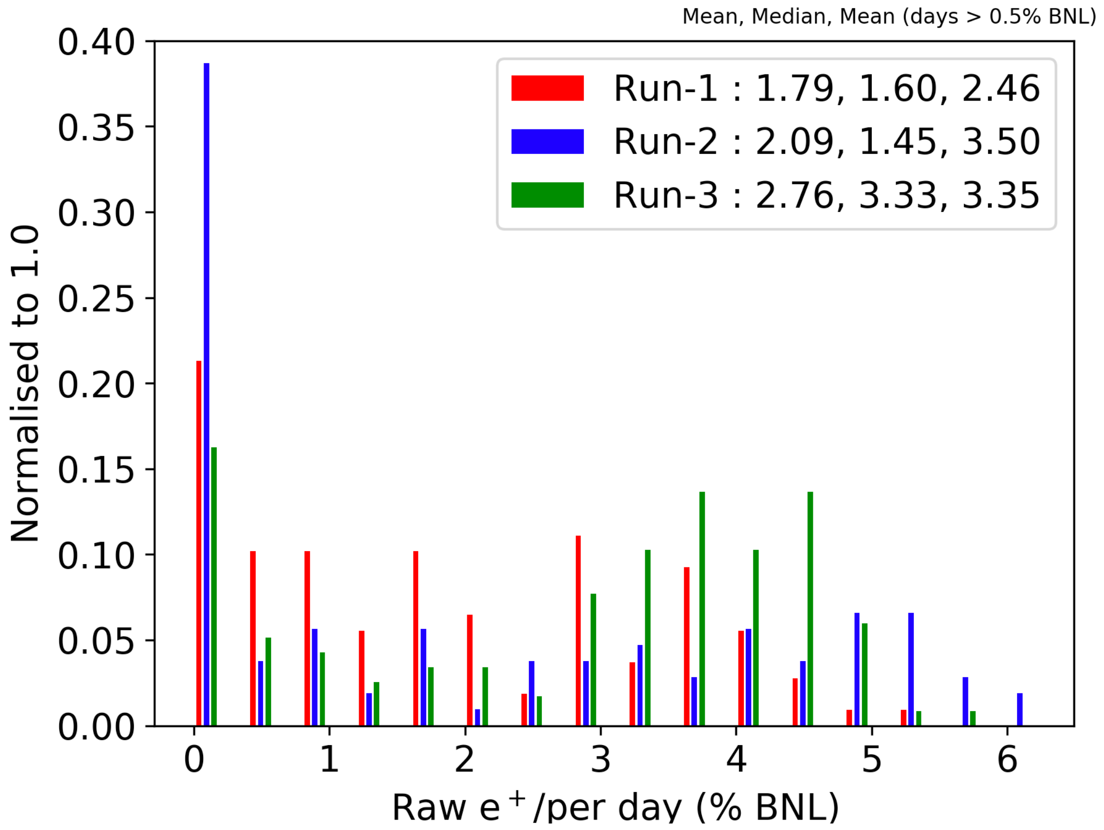




This and opportunistic cryo interventions resulted in our most efficient run to date.

Overall Uptime





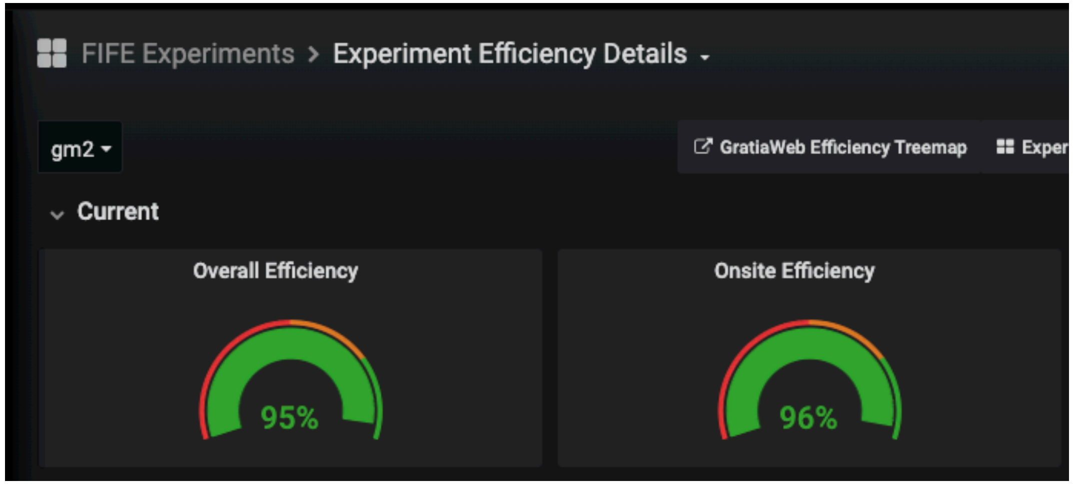
40% more days in Run-3 vs Run-2 where we took appreciable data (> 1% BNL/day)

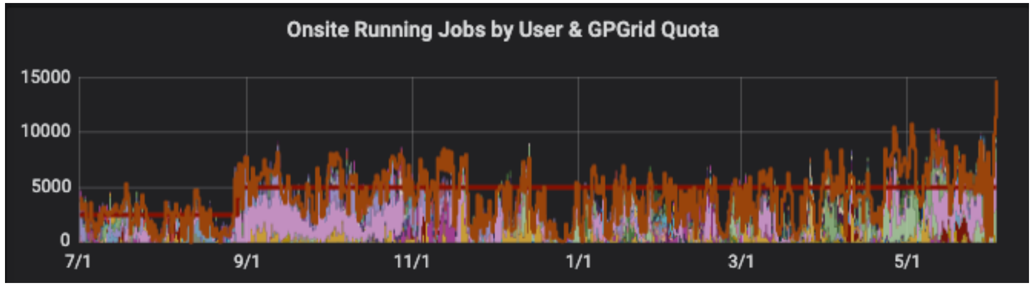
75% of days had > 1% BNL/day
- downtime split equally between experiment and AD

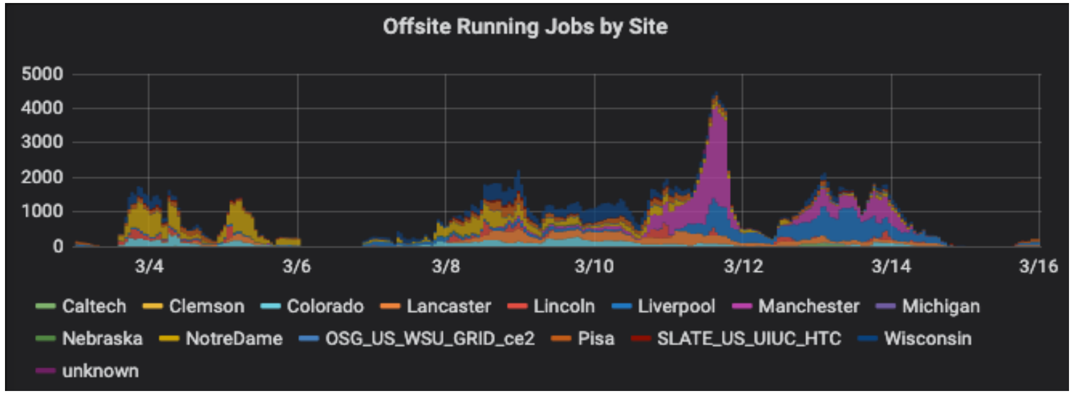
In steady-state taking 1 BNL dataset per month

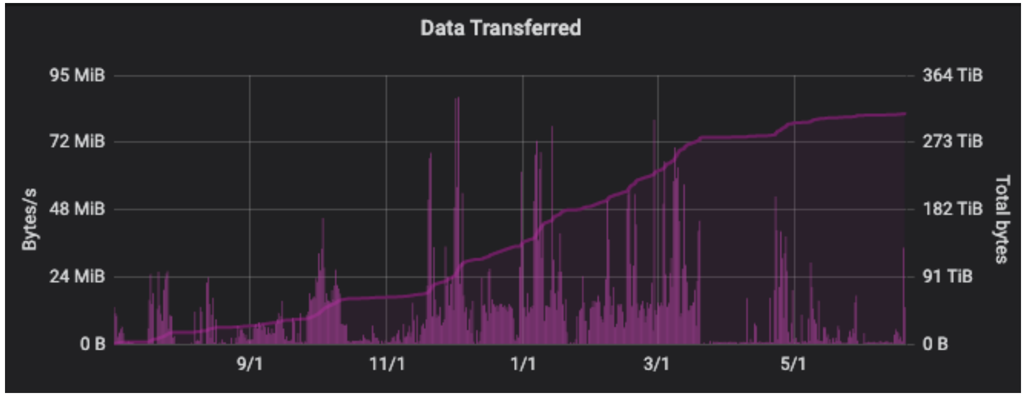
Computing Summary

Added considerable automation into our data processing
- much more extensive use of SCD database products
- embedded Data-Quality infrastructure
- calibrations in real time
- dedicated “shift” teams for data processing
- more use of outside resources eg in UK



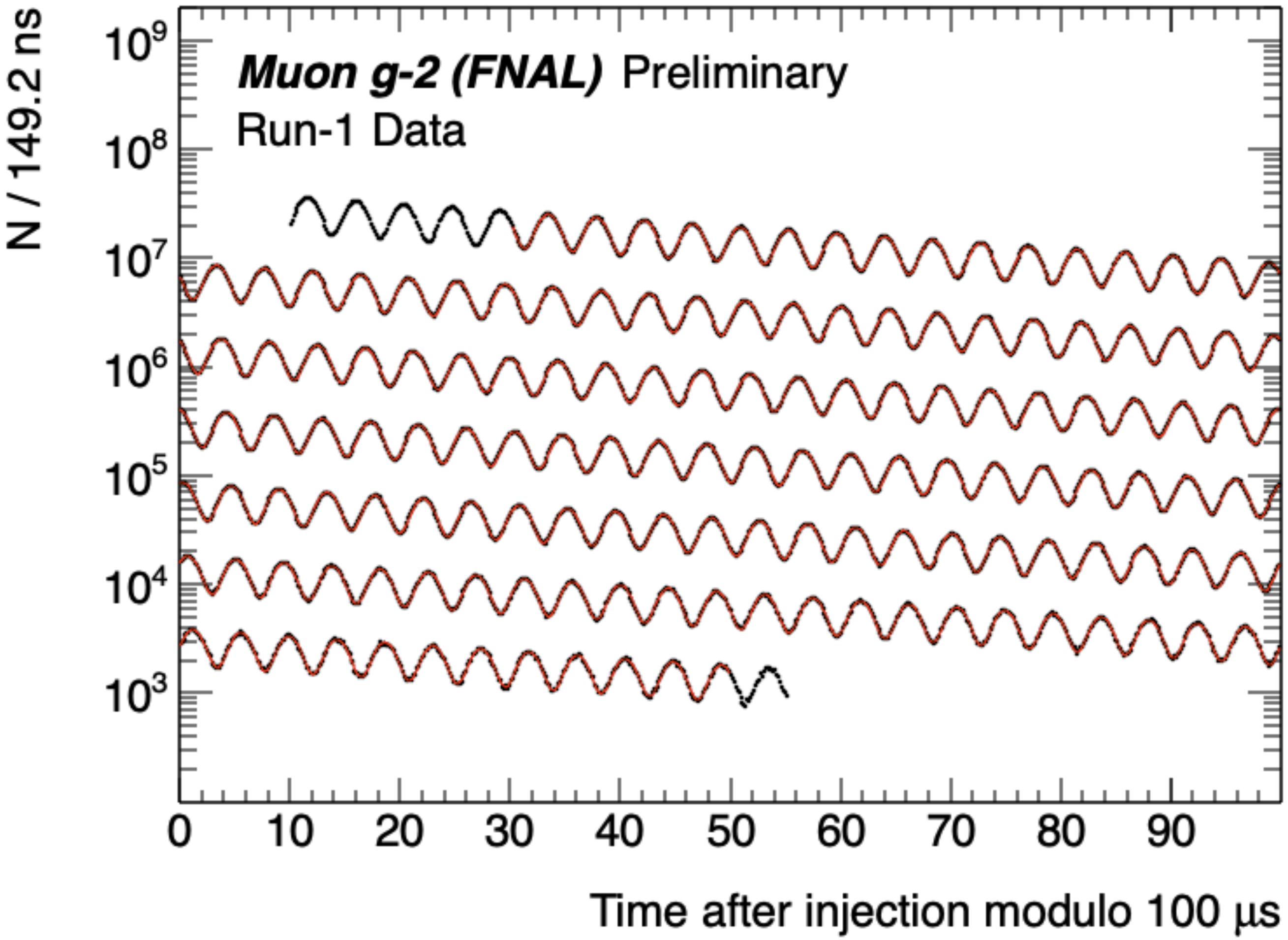






Run-2 data is now 90% processed
Run-3 data processing beginning to inform Run-4.

Run-1 Analysis Status



Run-1 data is 11.6B muon decays

Split into 4 separate datasets defined by their kicker and quadrupole voltages and magnet cycles.

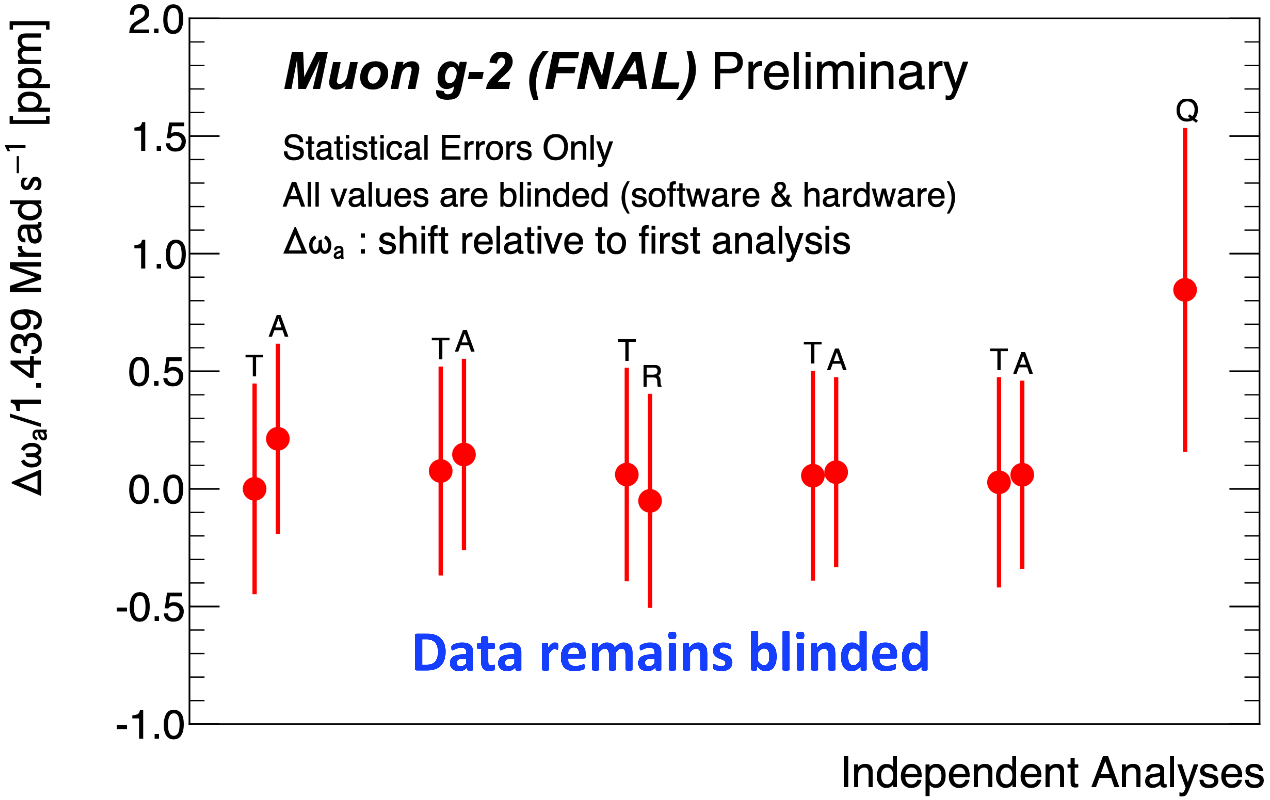
Statistical precision: 435 ppb (*cf* BNL: 460 ppb)
Systematic precision: approx ½ statistical

The Run-1 measurement is statistically dominated but it has highlighted systematics that need better mitigation to reach ultimate systematic goal

The SM-BNL discrepancy is 2790 ppb

Omega-a Analysis

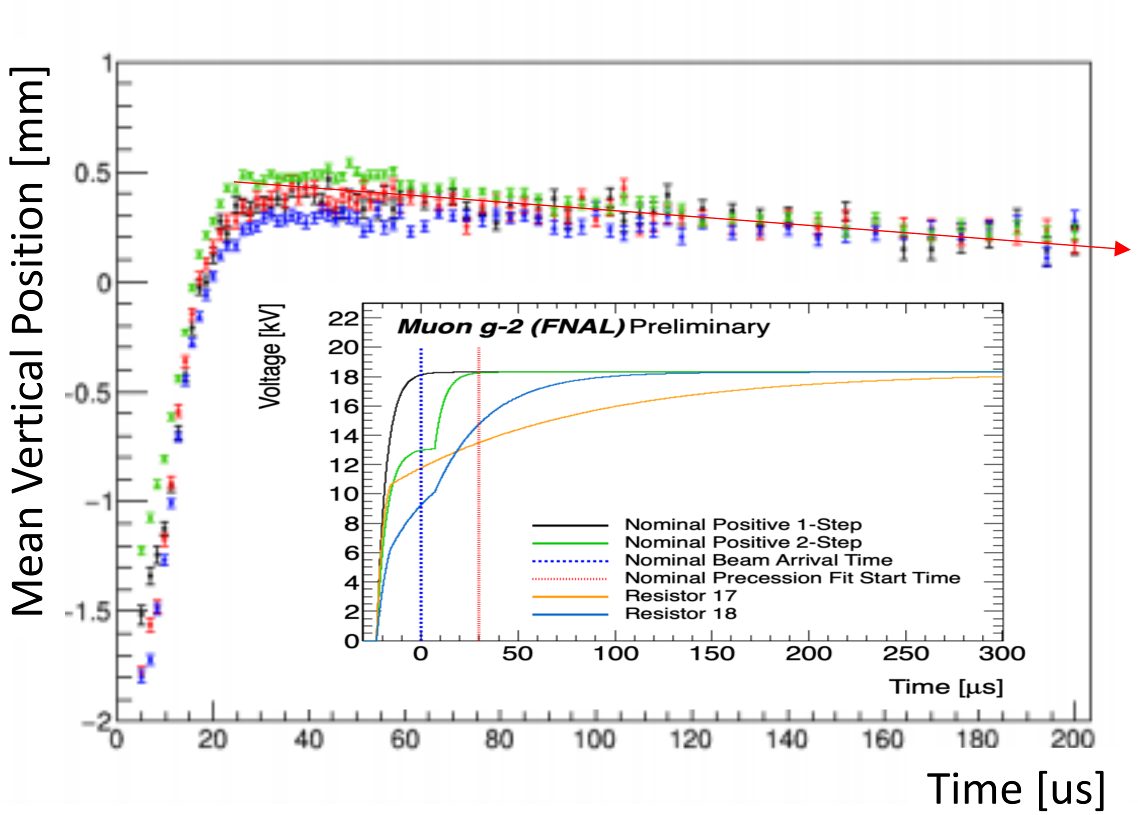
Relative software unblinding of the different omega-a analyses undertaken in Feb. 2020 : no surprises.

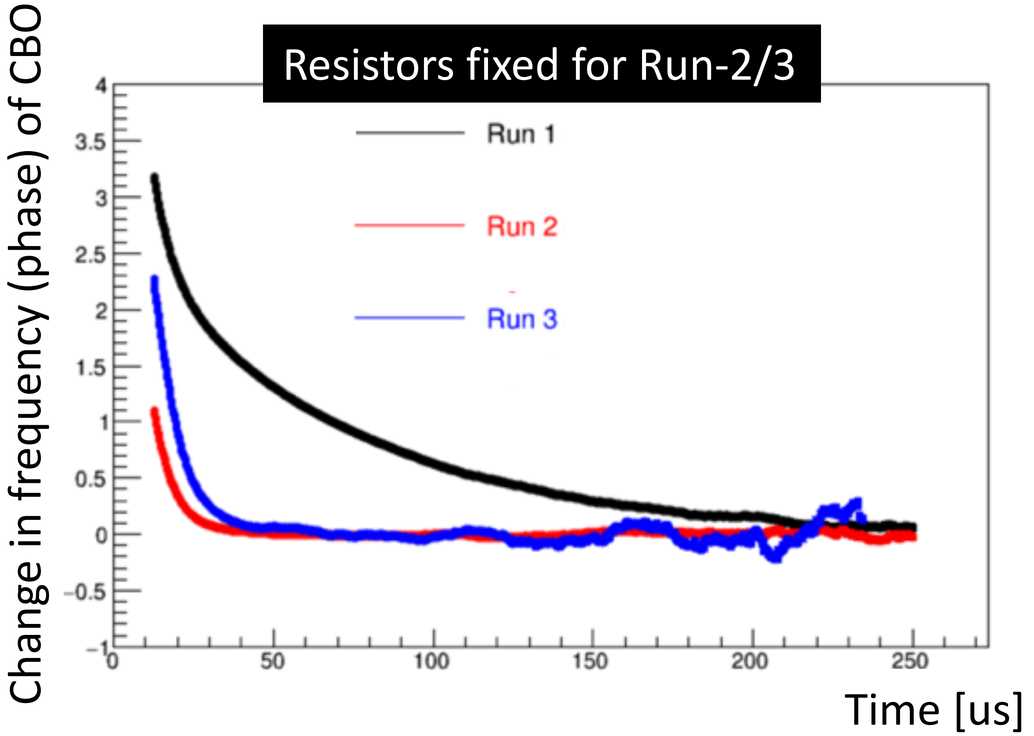


Beam Dynamics Analysis

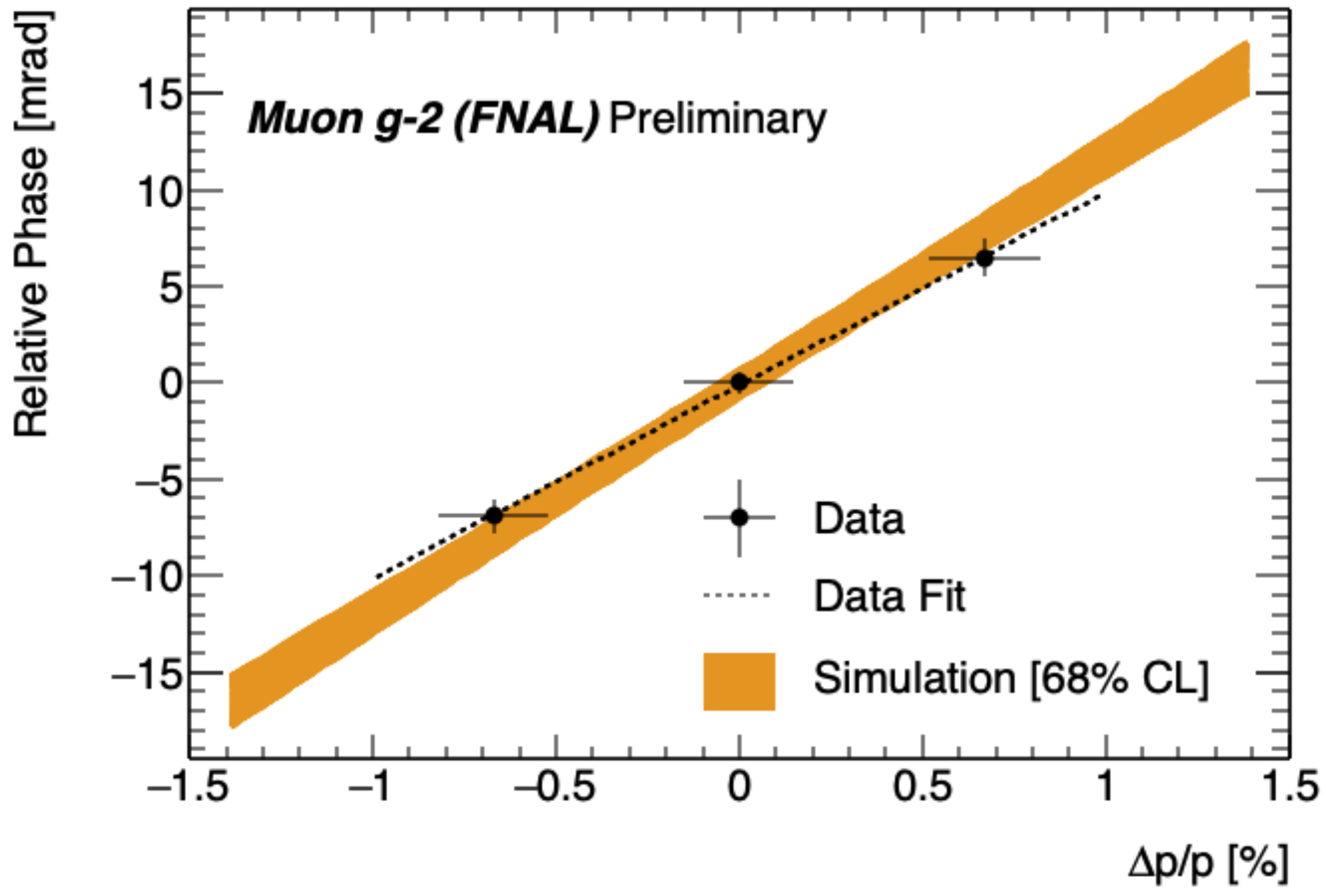
Made somewhat more protracted due to failure of 2 (of 32) resistors in the quadrupole system that caused the beam to move downwards ~ 0.6mm during a fill, the beam width to develop an azimuthal dependence and rate of muon losses to increase.

Required a very detailed evaluation over many months and verification with dedicated systematic runs





Beam Dynamics Analysis



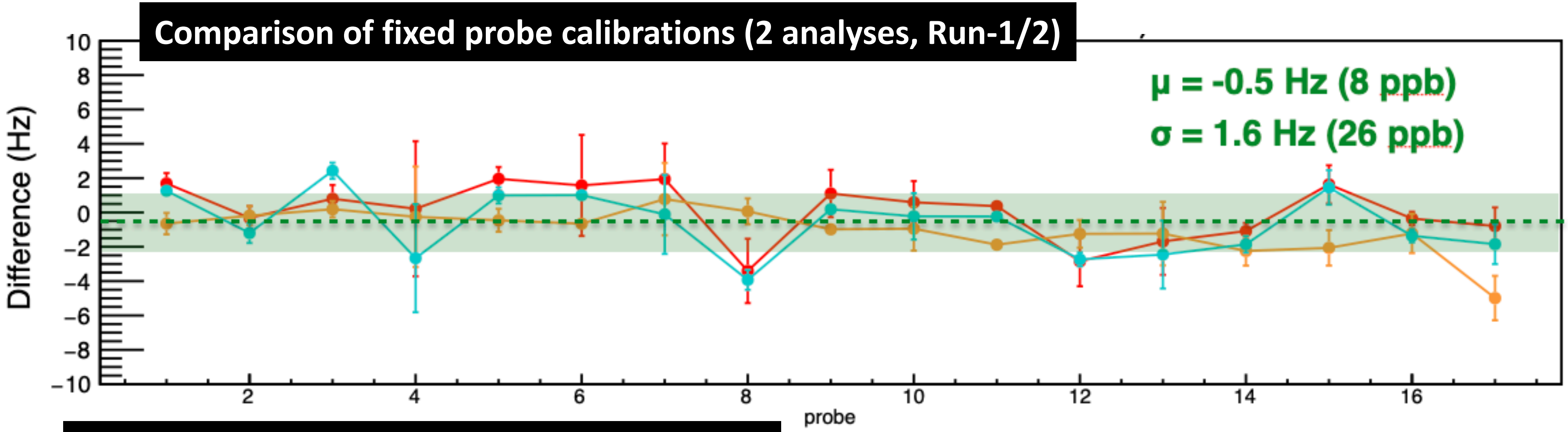
Dedicated data taken

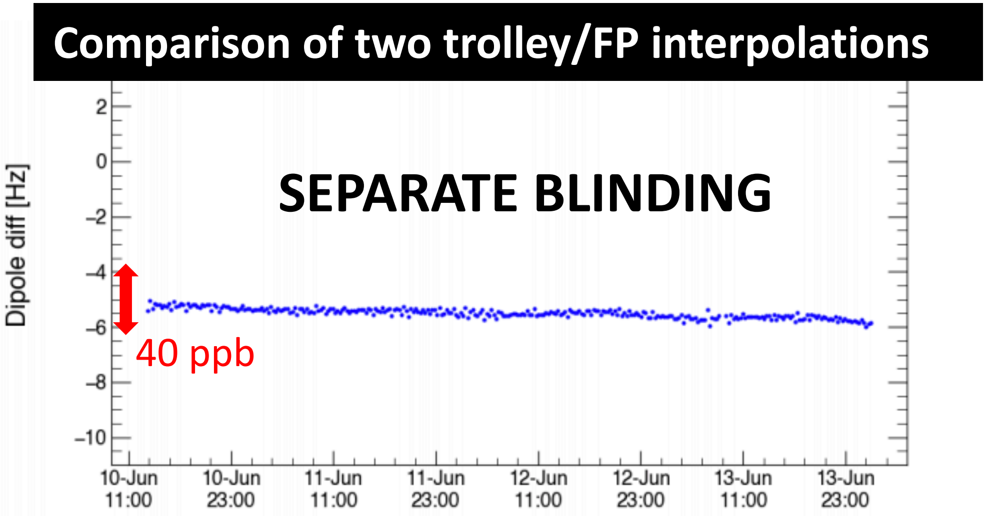
- different delivery-ring collimator settings
- different storage ring B-fields

to introduce beams with different momenta in the g-2 ring.

B-Field Analysis

In some areas we have already done better than TDR target e.g. calibration of plunging and trolley probes

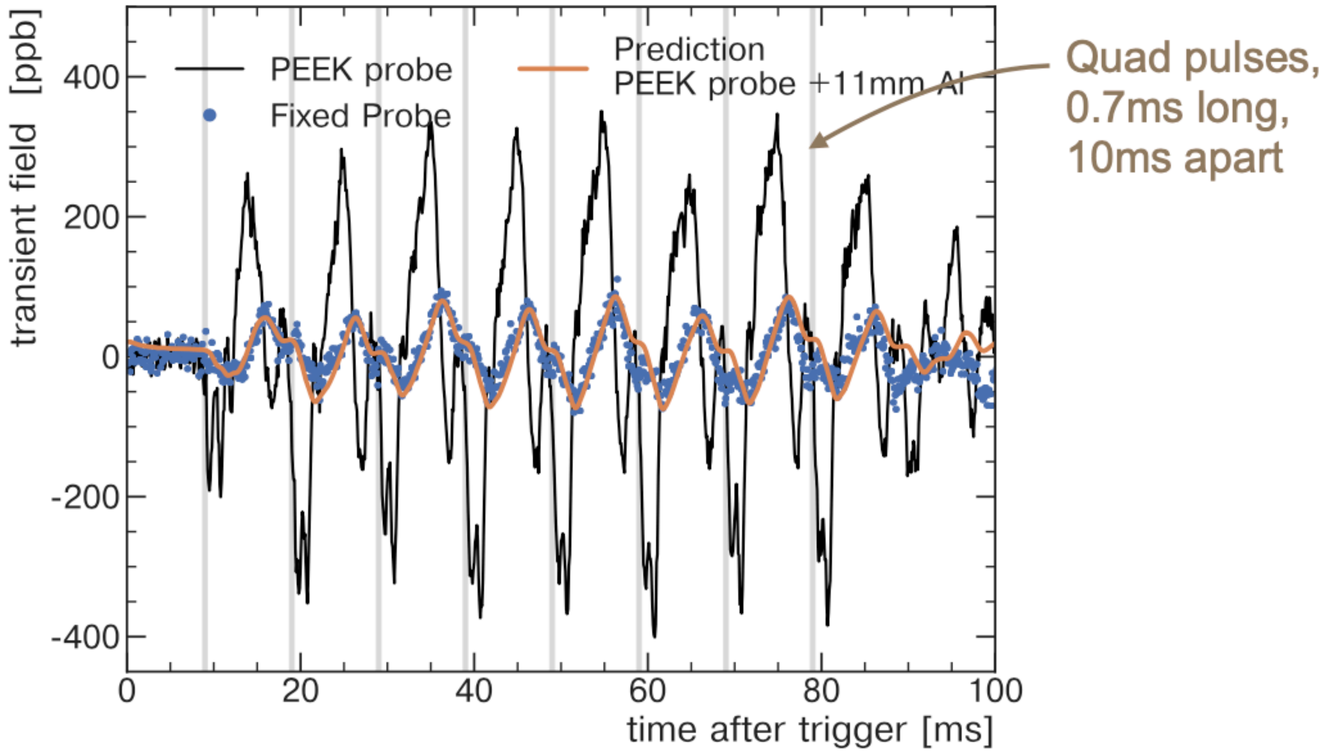


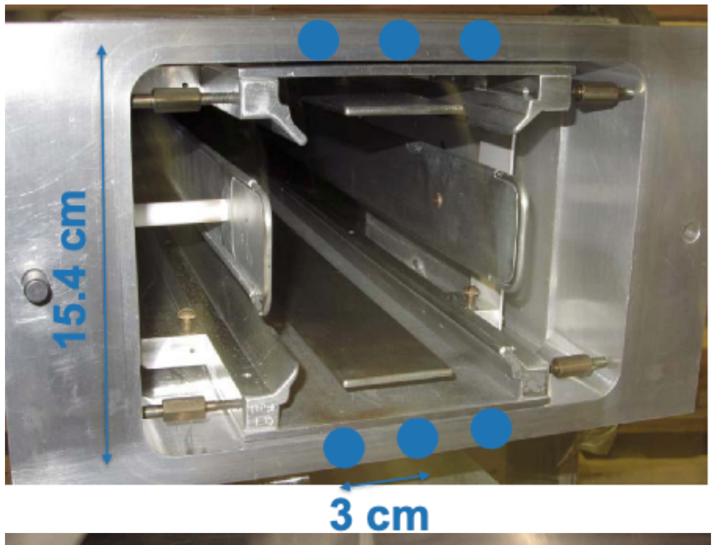


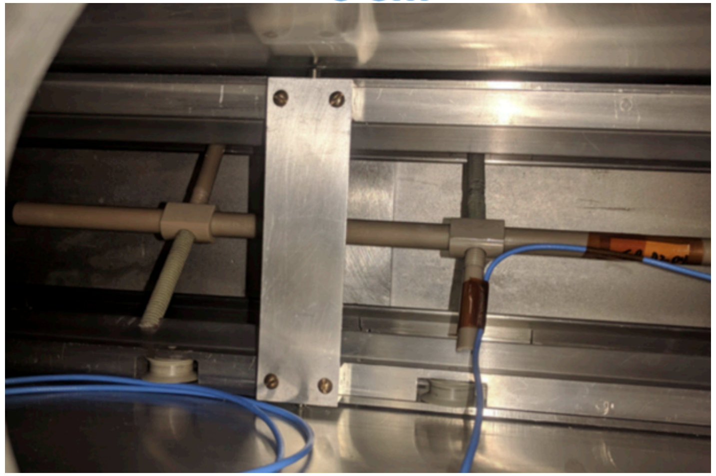
Averaged over all magnet cycles the two independent (blinded) determinations are consistent to better than 40 ppb.

Larger Transient Field Effect

The NMR fixed probes measure B-field continuously but those near the quads are perturbed by the quad plates vibrating when they are pulsed in sync with beam (100 Hz).

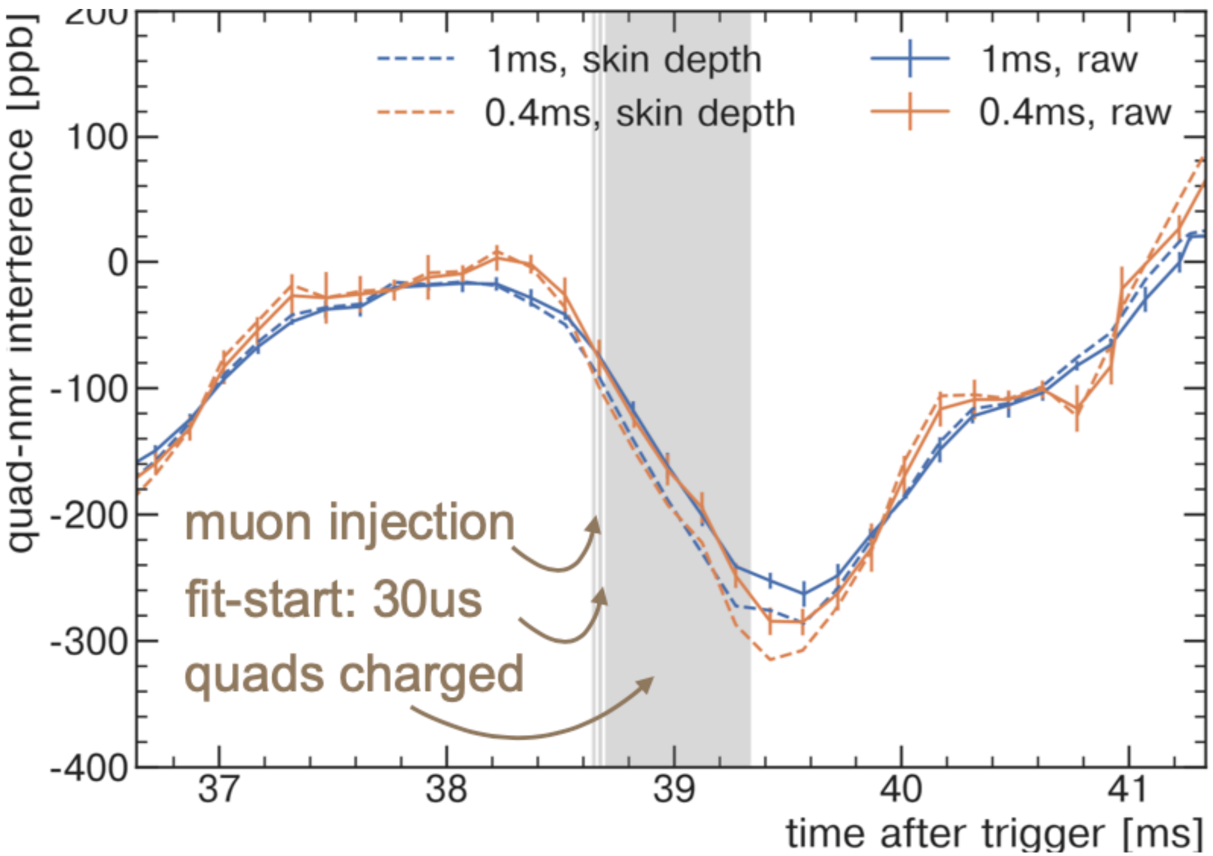






Dedicated (no-beam) studies of this with "PEEK" probes installed inside the vacuum chamber

Larger Transient Field Effect



Only 43% of ring covered by quads.

Effect is now well quantified and further studies are presently being undertaken to mitigate the effect in Run-4/5

Systematics

Evaluation largely complete
Three main papers being prepared and reviewed : presently at 135 pages. Plus supporting technical JINST papers

ω_a	**Beam Dynamics Corrections**	ω_P
Pileup	Pitch	Absolute Calibration
Gain	E-Field	Fixed Probe Calibration
Radial/Vert Oscillations		Trolley Probe Calibration
Lost Muons		Field Interpolation
Other		Muon Convolution
		Quad/ Fixed Probe
	Phase-Acceptance / Quad Resistors	Kicker Residual Field

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

→ Measured elsewhere to 26 ppb

Quad/ Fixed Probe → Larger effect at FNAL than BNL due to higher spill frequency

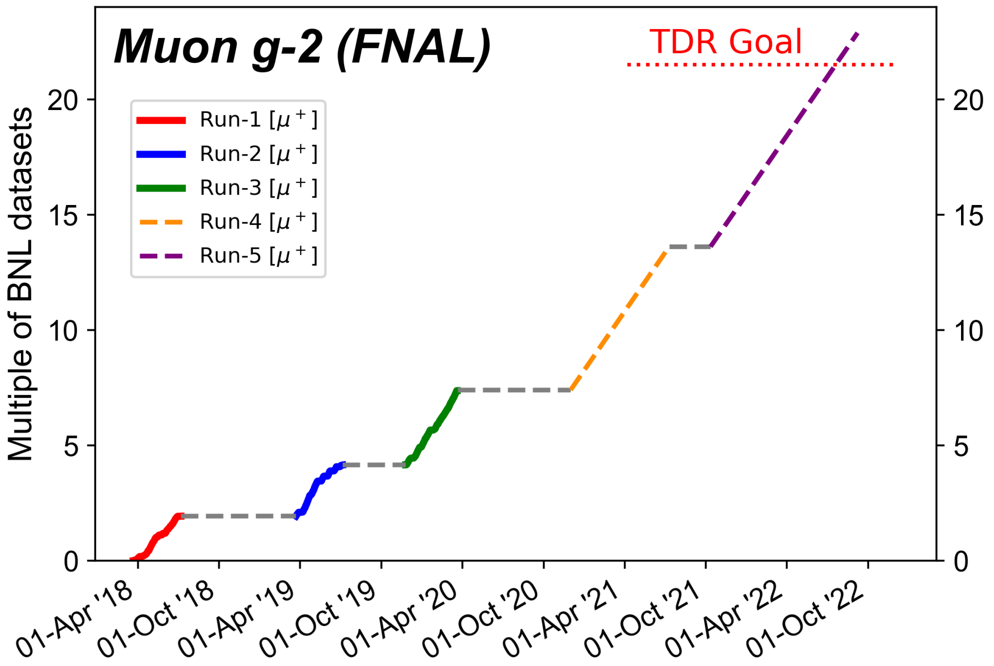
Kicker Residual Field → With no beam recently took and now analyzing data to determine kicker residual field [was 20 ppb at BNL]

Future Running

Due to CV19 we will now not install the new inflector in this summer shutdown. It remains available as a spare.

The shutdown is being used to further analyse and mitigate the quad/FP and improve the instrumentation measuring the kicker eddy current.

Inflector would have provided a 20% increase in flux and so effects somewhat our extrapolations



To reach TDR stats. goal requires full 9 month Run-5 (FY22)

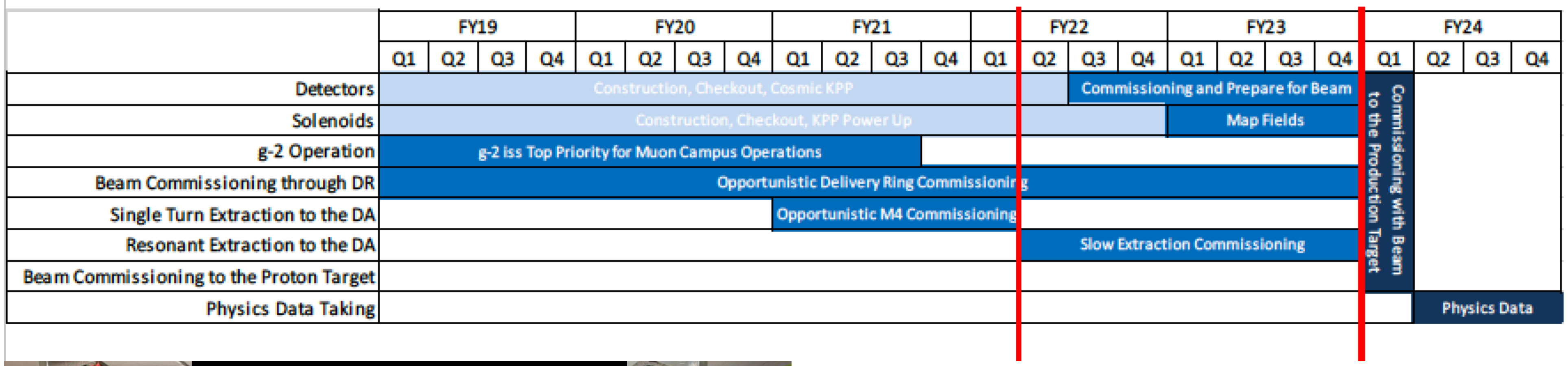
Installation of Mu2e electrostatic septum (ESS) scheduled for Jan-2022 would reduce Run-5 to 3 months and leave g-2 15% short in statistical precision

We have worked with Mu2e spokespersons and the lab to build flexibility into the g-2/Mu2e beam sharing so that g-2 can reach its goal.

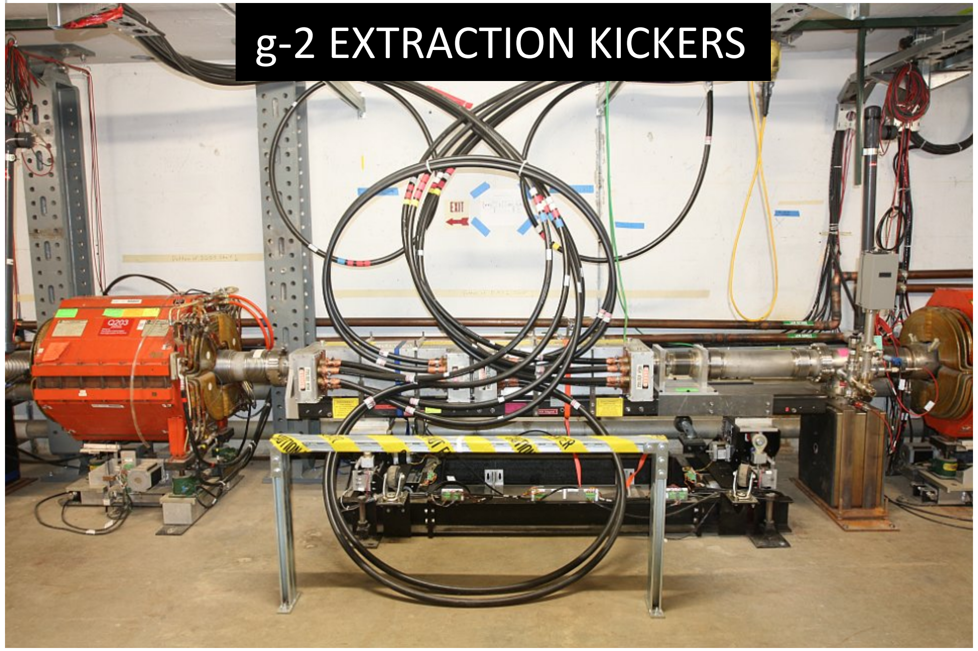
Co-operation with Mu2e

ESS Ready
To Install

Start Commissioning
Beam to Target



In FY25 the long LBNF shutdown begins



Mu2e ESS would replace g-2 extraction kickers

Preliminary design has begun for a new (smaller) g-2 extraction kicker that could be located upstream and allow switching between g-2 and Mu2e beam

Completing the design & installing this kicker would give the Muon progamme the flexibility to maximise the physics output

Observations / Recommendations from last PAC

Operation of kickers at reduced voltage

Now resolved. We accumulated ~ 1 BNL at the end of Run-3 at the nominal kicker voltage (161 kV) with no issues.

Mitigate potential Li lens failures through installation of new inflector to reduce # beam pulses required

We had no Li lens failures in Run-3. Since April 2019 we have deliberately run at a lower lens current

Unfortunately the impact of CV19 both in terms of resource availability and safe-working has meant it is not possible to install the new inflector this shutdown.

Plan with SCD resources required for data storage and reconstruction

SCD have kindly increased our Grid-Job quota. This along with improvements (with help from SCD DB) in our calibration and data-quality procedures mean we will have processed both the Run-2 and Run-3 data prior to Run-4.

Conclusions

We've had a productive year and now have x 7 BNL on tape.
The combined Run-2/3 dataset will have an uncertainty ½ that of Run-1.

We're now running at the design kick in a hall of uniform temperature

We hope to ~ double our dataset in the next year and achieve our design systematic uncertainty

We look forward to showing you the Run-1 result next year !

Backup

Lattice BMW Result (arXiv:2002.12347)

- Came too late to be included in the SM 2020 consensus but predicts (g-2) 1.1σ below BNL value
- Still the subject of much scrutiny within the lattice community
- Has implications to the Global EWK fits

Result implies there must be large, non-measured contributions to the hadronic e^+e^- cross section at low $\sqrt{s}$

arXiv.org > hep-ph > arXiv:2006.12666

High Energy Physics – Phenomenology

[Submitted on 22 Jun 2020]

The muon g-2 and $\Delta\alpha$ connection

Alexander Keshavarzi, William J. Marciano, Massimo Passera, Alberto Sirlin

The discrepancy between the Standard Model prediction and experimental measurement of the muon magnetic moment anomaly, $a_\mu = (g_\mu - 2)/2$, is connected to precision electroweak (EW) measurements via their common dependence on hadronic vacuum polarization effects. The same data for the total $e^+e^- \to$ hadrons cross section, $\sigma_{had}(s)$, are used as input into dispersion relations to estimate the hadronic vacuum polarization contributions, $a_\mu^{had,\,VP}$, as well as the five-flavor hadronic

arXiv.org > hep-ph > arXiv:2003.04886

High Energy Physics – Phenomenology

[Submitted on 10 Mar 2020 (v1), last revised 7 May 2020 (this version, v2)]

Hadronic vacuum polarization: $(g-2)_\mu$ versus global electroweak fits

Andreas Crivellin, Martin Hoferichter, Claudio Andrea Manzari, Marc Montull

Hadronic vacuum polarization (HVP) is not only a critical part of the Standard Model (SM) prediction for the anomalous magnetic moment of the muon $(g-2)_\mu$, but also a crucial ingredient for global fits to electroweak (EW) precision observables due to its contribution to the running of the fine-structure constant encoded in