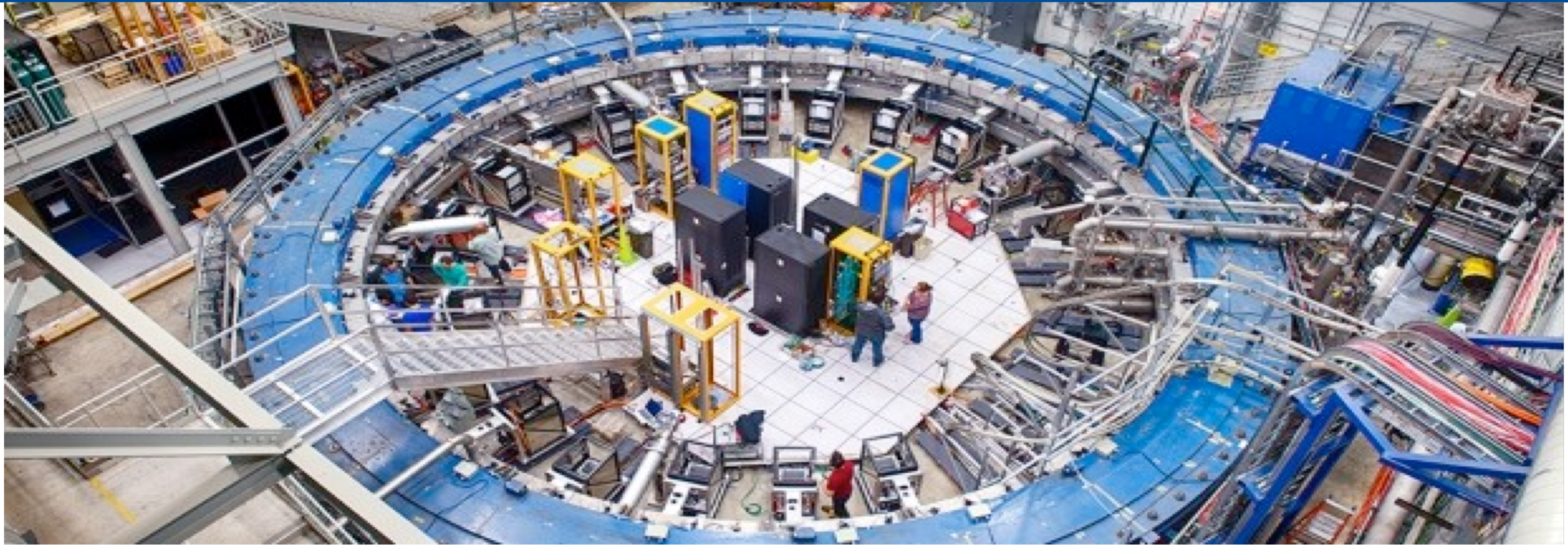


Status and plans of the Muon g-2 experiment

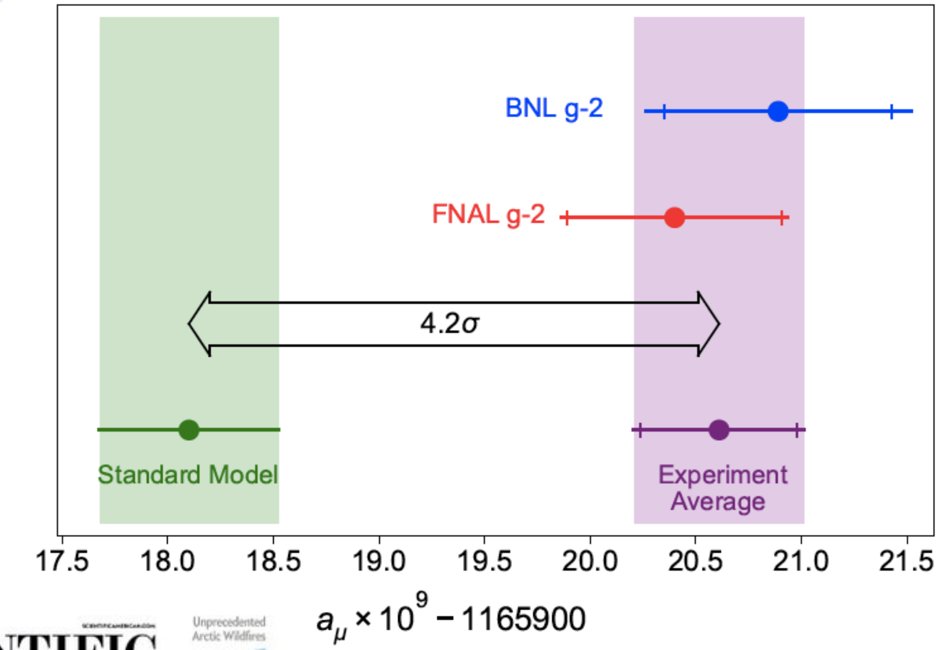
Brendan Casey & Graziano Venanzoni
(on behalf of the Muon g-2 Experiment)

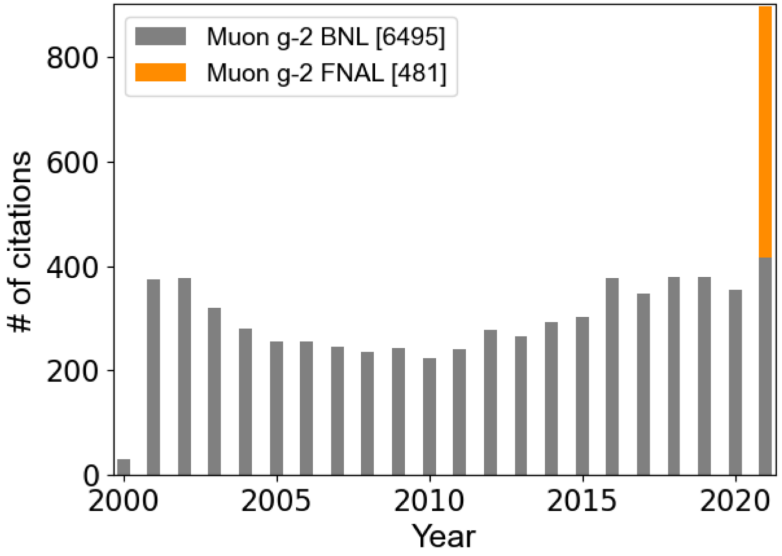
Fermilab PAC 17/Nov/2021

Muon g-2 first result

PRL 126 (2021) 14, 141801

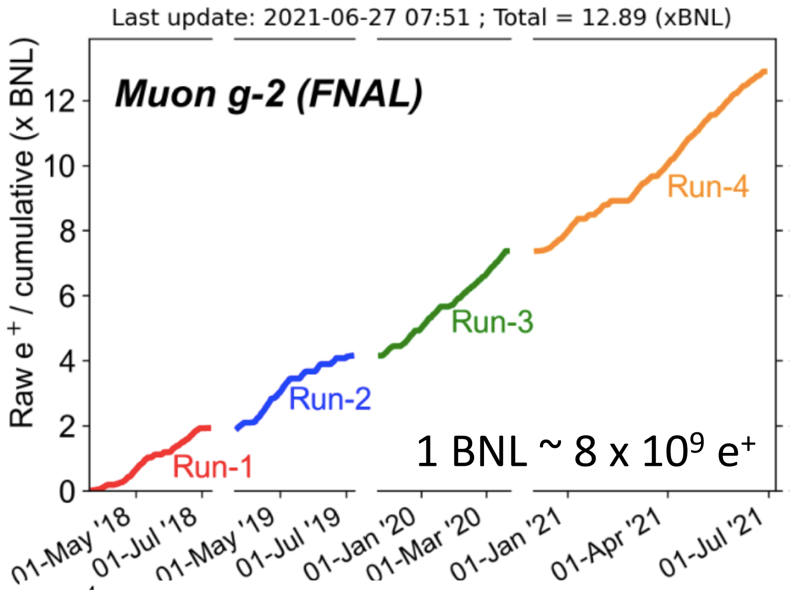
- **First result released April 2021**
  - Muon g-2 measured to 460 ppb (based on 2018 data)
  - It strengthens the tension with the SM [wp21] to 4.2σ
  - New Lattice calculation [BMW21] differs from experimental average by ~1.5 σ
- **Four publications**
  - PRL (a_μ), PRD (precession frequency), PRA (magnetic field), PR-AB (beam dynamics)
- **Enormous reach**
  - 480 citations so far (probably the most cited paper in 2021)
  - Invited lecture by the Nobel Committee for Physics
  - Huge public engagement (3 billions views in the 24h following the release)

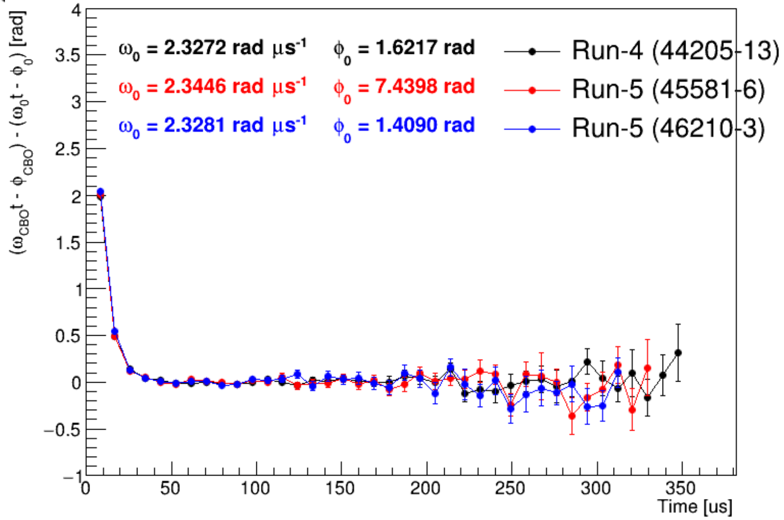




Status of the operations

- About 13 × BNL collected so far (Run1-4)
- Each dataset campaign brought an incremental improvement in data quality
- Run 4 was largest dataset collected to date: collected 5.5 × BNL. Successful remote-shift model implemented.
- Run 5: stored first beam on November 2, data taking began on November 13.
- Expect 5-6 × BNL in Run5 → 18-19 x BNL total
- First look at data shows good agreement with Run-4

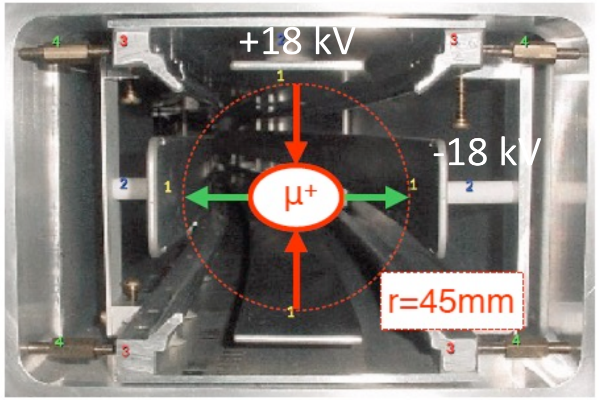


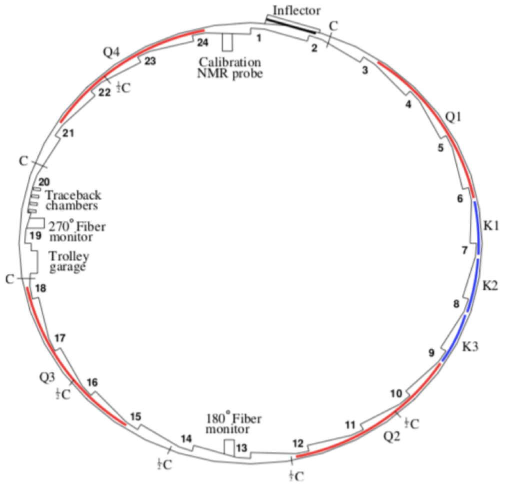


Summer shutdown 2021 accomplishments

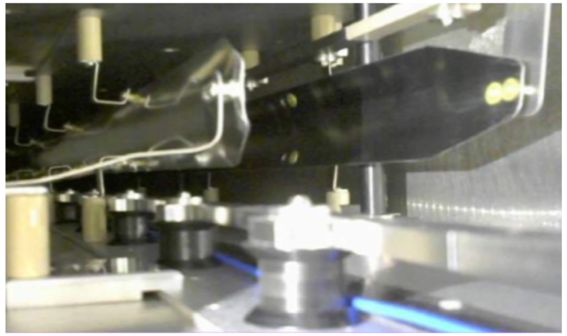
- Mapped Electrostatic Quadrupole (ESQ) transient field $B_q(t, \varphi)$ around entire storage ring
  - Main systematic effect in Run1
- Tested new ESQ pulsing configuration
  - Extended time of voltage pulse on top plate
  - Up to a factor of ~2 reduction in vibration of ESQ
- Measured of the residual magnetic field of the kicker in Run3-4 configuration
  - Needed to determine $B_k(t)$ systematic
  - Important input to Monte Carlo simulation

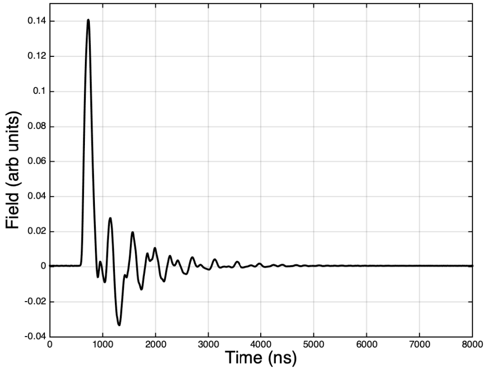
Front view of an ESQ





Kicker plates





ESQ RF in Run5

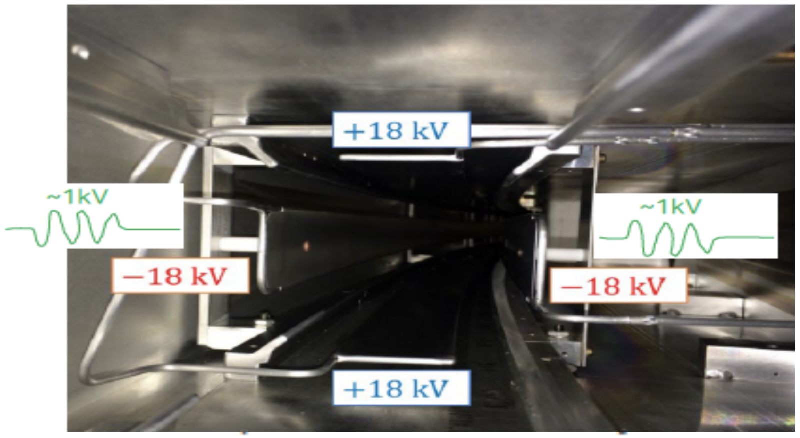
- The beam undergo betatron oscillations (stable oscillations about the equilibrium orbit):
  - They produce a time modulation of Asymmetry and phase.
  - Must be included in the fitting function of $N(e^+)$

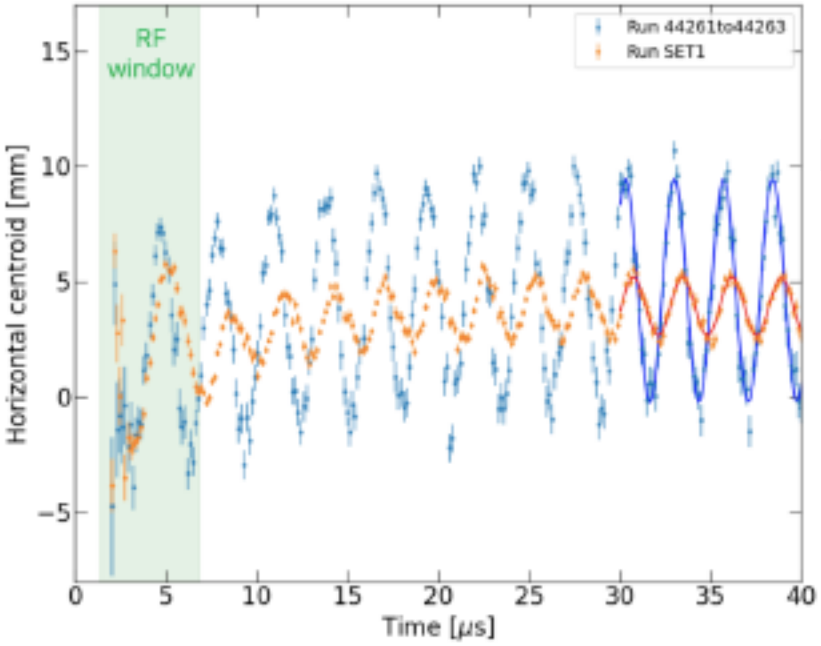
- The coherent betatron oscillations (CBO) is the predominant one:
  - Large uncertainty to ω_a (~40ppb) in Run1

- A ~1kV RF signal to the Quad plates at < 30 μs reduces significantly the CBO amplitude
  - It reduces also the Muon loss (by a 3.5 factor)

[On Kim *et al,* New J. Phys. **22** (2020) 063002]

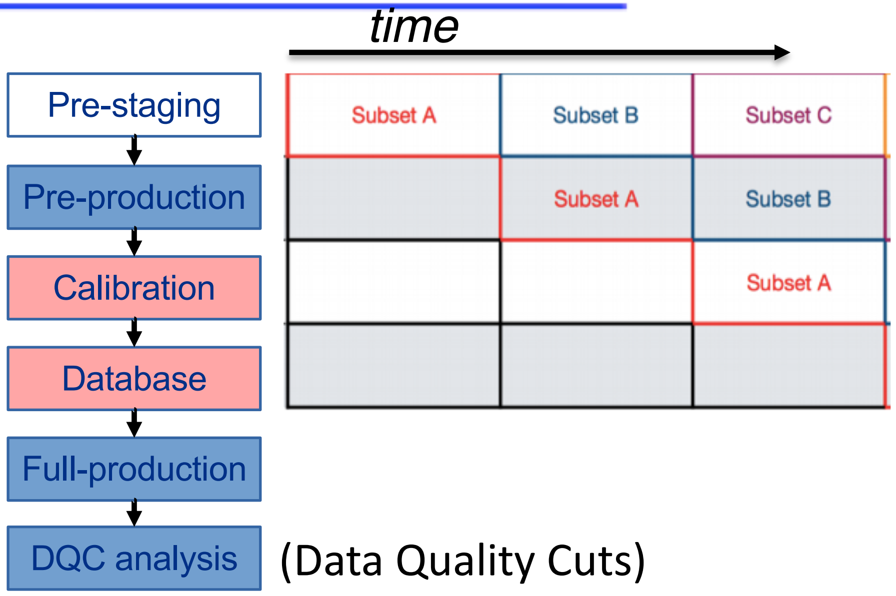
- RF was successfully tested at the end of Run4 (x5 reduction). Larger effect expected after optimization
- We are going to implement this technique in Run5!





Offline production

- Datasets are produced in a parallel way to optimize production efficiency
- Significant effort to improve the production process
- For the next release, Run2-3 (~3 x BNL after DCQ) will be analyzed together.
- Run2 (2.2 x BNL) reconstruction has been completed; Run3 (3.3 x BNL) 25% fully reconstructed; Run4 (5.5 x BNL raw) at early stages
- Full data set is expected to be available early in calendar year 2022
- Estimated time for release of Run2-3 result: Sep – Dec 2022



	Run2	Run3	Run4
Preproduction	**100%**	**96%**	**9%**
Calibration	**100%**	**91%**	**6%**
Full production	**100%**	**28%**	**0%**
DQC analysis	**100%**	**25%**	**0%**
Total Files	294,207	571,247	1,121,603

Systematic errors from Run1 analysis

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

(simplified, see backup slides)

PRL 126 (2021) 14, 141801

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	⋯	434
ω_a^m (systematic)	⋯	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	⋯	56
B_k	−27	37
B_q	−17	92
$\mu_p'(34.7^\circ)/\mu_e$	⋯	10
m_μ/m_e	⋯	22
$g_e/2$	⋯	0
Total systematic	⋯	157
Total fundamental factors	⋯	25
Totals	544	462

Electric field correction to ω_a

Phase-Acceptance correction to ω_a

Quad transient field correction to ω_p

Main systematic uncertainties

Precession frequency (ω_a)

Field (ω_p)

External inputs

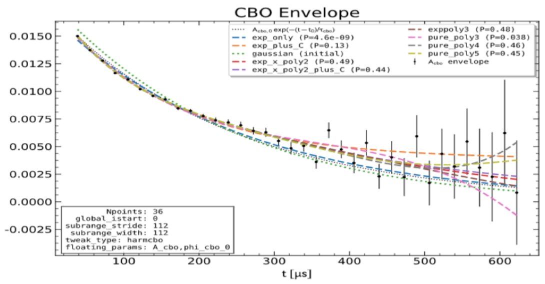
Expected to be significantly reduced in Run2-3

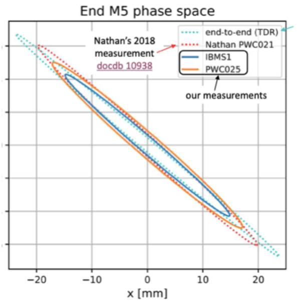
Overview on Run2/3 analysis

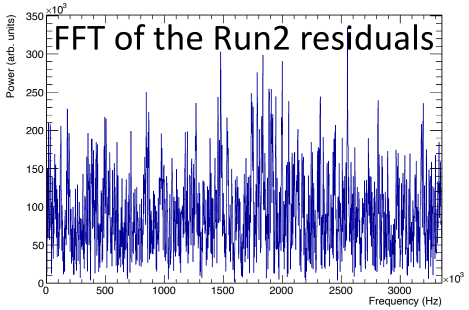
- Mostly new analysis teams, building on experience and success of Run-1 analyzers.
- Large statistical improvement – expect reduction from 434 (Run-1) to ~200 ppb (Runs-1,2,3).
- Large improvement on the main systematic uncertainty of Run1 (Electric Field correction, Phase acceptance, Quad transient)
- Many other improvements to improve on Run-1 analysis, streamline process and to reduce smaller systematics further
- Total systematic error goal: ~100 ppb

Precession frequency (ω_a) and Beam Dynamics corrections in Run2-3

- Many systematics explored in greater depth than for Run 1
  - Refinement of pileup techniques
  - Data-driven investigation of CBO envelope models
  - Identified a solution to mystery of Residual Early to Late effect
- Beam dynamic corrections (C_e, C_p, C_{pa}, C_{ml}) well in progress:
  - Optimized analysis methods and dedicated measurements
- Analysis of full Run 2 dataset is maturing
- Expect to apply same methods to Run 3 dataset



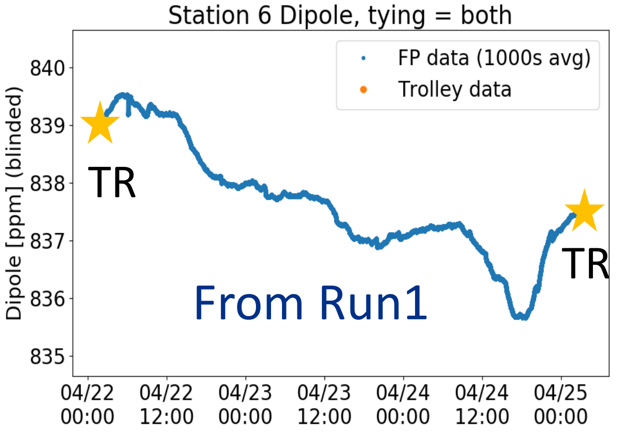


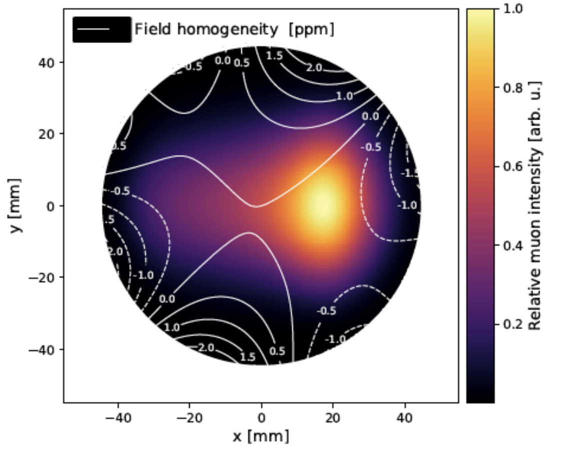


ω_a Uncertainty	Run 1	Improvement	Run 2+3 Est.
Statistics	434		220
Electric Field correction	53	Better Kick + correction	30
Phase-acceptance	75	Quad resistors	30
CBO Model	38	Stats + Quad resistors	15
Pileup	35	Algorithm changes	10
Early to Late Effect	17	Maybe?	(<) 17
Other	21	Varies	17
Total	443 = 434 + 90		228 = 220 + 60

Reminder on B Field (ω_p) analysis

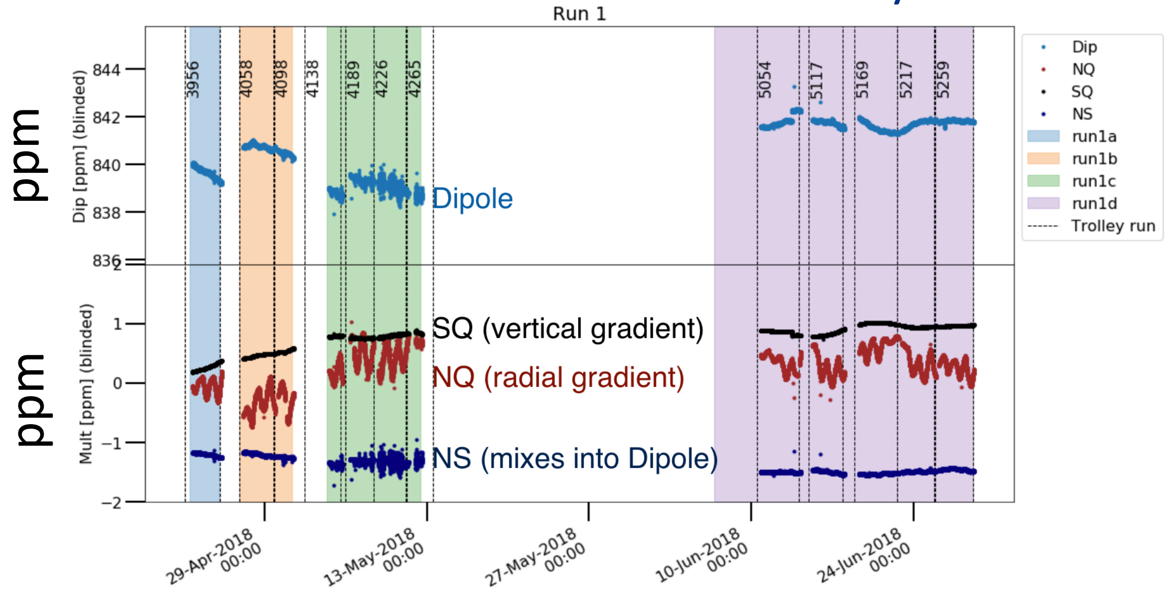
- Measurement of B field:
  - Combination of fixed NMR probes +trolley run
  - Interpolation of the fixed probe measurements to the trolley ones + calibration to get field map
  - Use of tracker information (+simulation) to convolute the field map with the muon distribution





- Dominant uncertainty (Run1):
  - Transient magnetic field corrections (kicker and quad transients) → Dedicated measurement campaigns in 2021 shutdown (Run2-3)
  - Field tracking uncertainty → Run2-3: Reduced by improving field stability (magnet termal insulation), higher statistics (more trolley runs)

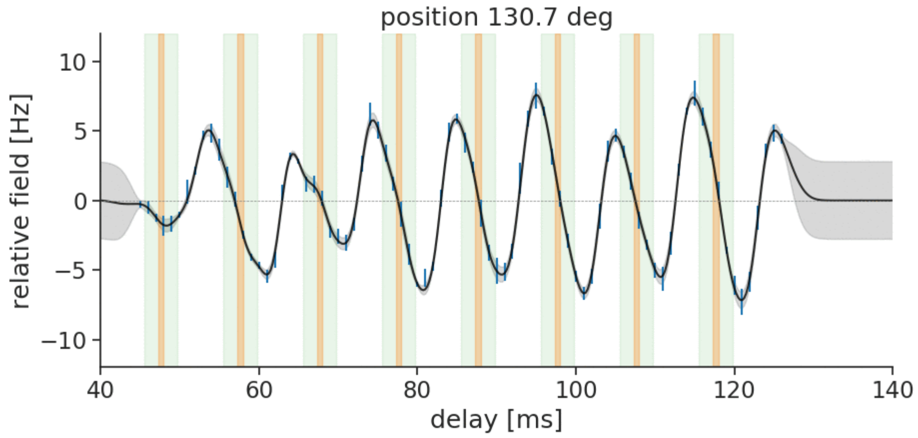
Field stability



Transient Field studies in Run2-3

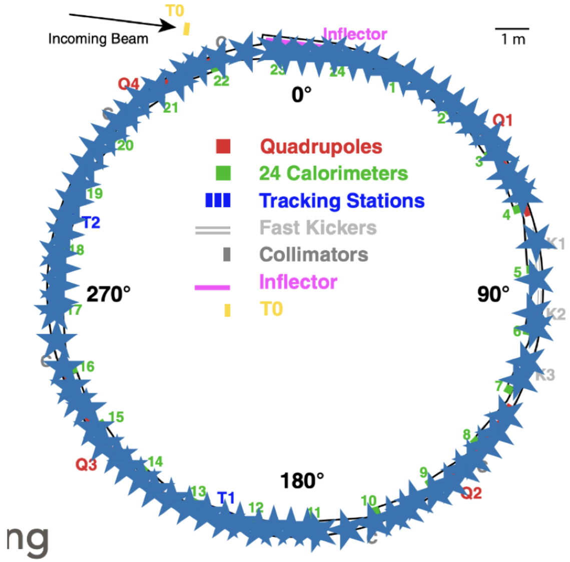
Quad transient field

- Largest field uncertainty in Run-1: only measured at one position in each ESQ, with a fine-granularity measurement in one location
- For Run2-3: multiple measurements of effect all around the ring
- On track for significant improvement in this term for the next analysis



Kicker transient field

- Dedicated measurements over the shutdown
- Two independent magnetometers to measure shape of kicker pulse and duration of eddy current tail
- Reduced noise and improved background measurements
- On track for improvement in the kicker transient term in the next analysis

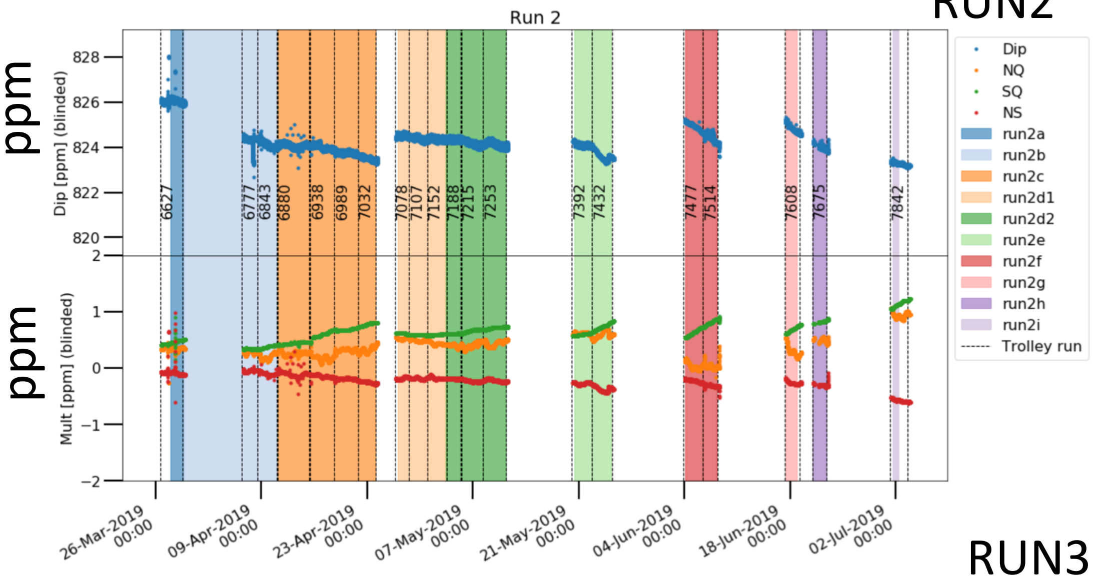


Run-2/3 measurement locations

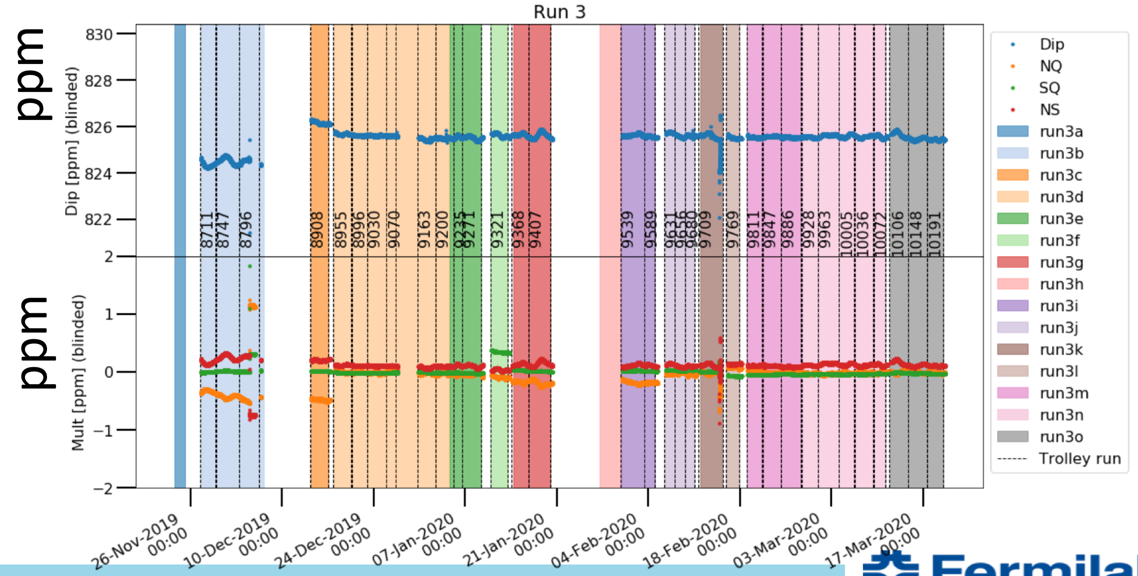
Interpolation field analysis status in Run2-3

- Two independent analysis teams, separately blinded.
- Preliminary “full-chain” analysis has been performed for Run-2 and Run-3.
- Field stability much improved in Run-3 (with the added magnet insulation).
- Relative unblinding for the interpolation analysis ~Dec 2021

RUN2



RUN3



Run6 μ^- : Overview

- **Goal:**
  - Measure $a_{\mu-}$ to 350 ppb → A factor 2 improvement on BNL μ^- (700ppb)
  - It requires 4x BNL μ^-
- **Physics Motivation:**
  - World most precise measurement of $a_{\mu-}$ (and $a_{\mu+}$). No other laboratory has plans to do that (J-PARC and PSI will use μ^+)
  - CPT and Lorentz Violation at the highest sensitivity in the muon sector
- **Additional motivations:**
  - Experimental validation of the robustness of the storage ring technique
  - It will add 2 x BNL reaching the TDR goal (21 x BNL)
- **Schedule:**
  - 3 Months of shutdown: July 2022 – September 2022
  - 9 Months of run (including beam re-commissioning, data taking, contingency): October 2022 – June 2023

Run6 μ^- : Physics case

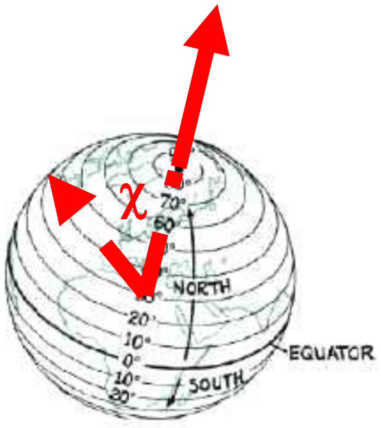
- (Minimal) Standard Model Extension (SME) Lagrangian (Kostelecký et.al.) for the muon sector:

$$\mathcal{L}' = -a_\kappa \bar{\psi}\gamma^\kappa\psi - b_\kappa\bar{\psi}\gamma_5\gamma^\kappa\psi - \frac{1}{2}H_{\kappa\lambda}\bar{\psi}\sigma^{\kappa\lambda}\psi + \frac{1}{2}ic_{\kappa\lambda}\bar{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda\psi + \frac{1}{2}id_{\kappa\lambda}\bar{\psi}\gamma_5\gamma^\kappa \overleftrightarrow{D}^\lambda\psi$$

- Difference with the SM is the vacuum solution of the SME which violates CPT and Lorentz invariance spontaneously
- All terms violate Lorentz invariance, and CPT is broken for terms involving *a* and *b* coefficients
- The coefficients are expected to be suppressed by m_μ/M_P (~10^{-20}). Best limits on these coefficients in the muon sector come from BNL
- Predicts two CPT/Lorentz violating signatures for muon g-2:
  - Sidereal (or annual) variation in ω_a (with μ^+ *or* μ^-) → b_T *Best limit from BNL (1.4x10^{-24})* → *~5x10^{-25} at FNAL*
  - Difference in ω_a between μ^+ / μ^- → b_Z, H_{XY}, d_{Z0} *(see next slides)*
- Sensitivity scales (roughly) with ω_a uncertainty

CPT and Lorenz Violation (LV) tests μ^+/μ^- (I)

- ω_a difference can be expressed in terms of the colatitude χ of the experiment



$$\Delta\omega_a \equiv \langle \omega_a^{\mu^+} \rangle - \langle \omega_a^{\mu^-} \rangle = \frac{4b_Z}{\gamma} \cos\chi$$

- Experimentally it is convenient to perform the analysis of the ratio $\mathcal{R} = \omega_a / \omega_p$

- BNL E821 Results (2008)

$$\Delta\mathcal{R} = -(3.6 \pm 3.7) \times 10^{-9}$$

$$b_Z = -(1.0 \pm 1.1) \times 10^{-23}\ \mathrm{GeV}$$

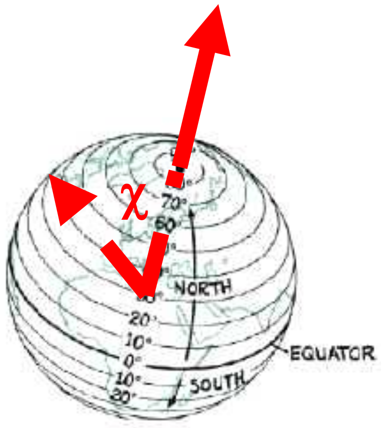
- A μ^- run at FNAL would allow to improve the uncertainty by x 2.5 ($\sim \frac{\sqrt{2}\delta\omega_a^-(BNL)}{\delta\omega_a^-(FNAL)}$)

at BNL $\delta\omega_a^- \cong \delta\omega_a^-$ ~700ppb

CPT and Lorenz Violation (LV) tests μ^+/μ^- (II)

- By performing this comparison between two experiments at different colatitudes:

$$\Delta\mathcal{R} = \frac{2b_Z}{\gamma}\left(\frac{\cos\chi_1}{\omega_{p1}} + \frac{\cos\chi_2}{\omega_{p2}}\right) + 2(m_\mu d_{Z0} + H_{XY})\left(\frac{\cos\chi_1}{\omega_{p1}} - \frac{\cos\chi_2}{\omega_{p2}}\right)$$



- BNL E821 & CERN:

$$(m_\mu d_{Z0} + H_{XY}) = (1.6 \pm 5.6 \times 10^{-23})\ \text{GeV}$$

- In future we can compare Fermilab with JPARC, but JPARC can't do μ^-. This test can be done only if Fermilab does μ^- !

- A μ^- run at FNAL with future μ^+ at JPARC would allow to improve by x 15

Prospects on CPTV and LV tests with μ⁻ Run at Fermilab

- A μ^- run will give us **new** experimental results:

- What we have:
  - BNL μ^+/μ^- (700 ppb each) & CERN μ^+/μ^- (10000 ppb each)

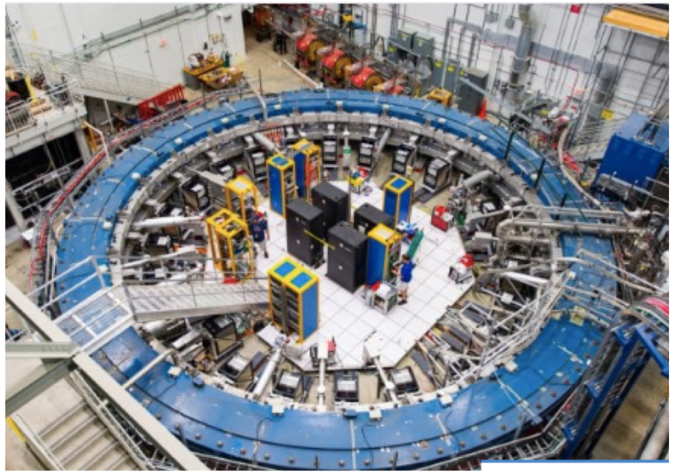
- What we would get:
- CPTV: b_Z
  - FNAL μ^- (350 ppb) & FNAL μ^+ (150 ppb)
  - x 2.5 improvement
- LV: d_{Z0}, H_{XY}
  - FNAL μ^- (350 ppb) & J-PARC μ^+ (450 ppb)
  - Potentially about x 15 improvement

	SME coefficients	Current limit	Expected improvement from FNAL μ^-
CPTV	b_Z	(-1.0±1.1) x 10^{-23} GeV	2.5
LV	$(m_\mu d_{Z0} + H_{XY})$	(1.6±5.6) x 10^{-23} GeV	15 (with JPARC μ^+)

- Improvements in many other CTP and LV parameters in non minimal SME
- Improvement of x 15 will allow us to reach the sensitivity to LV required to explain muon g-2

Run6 μ- preparatory work

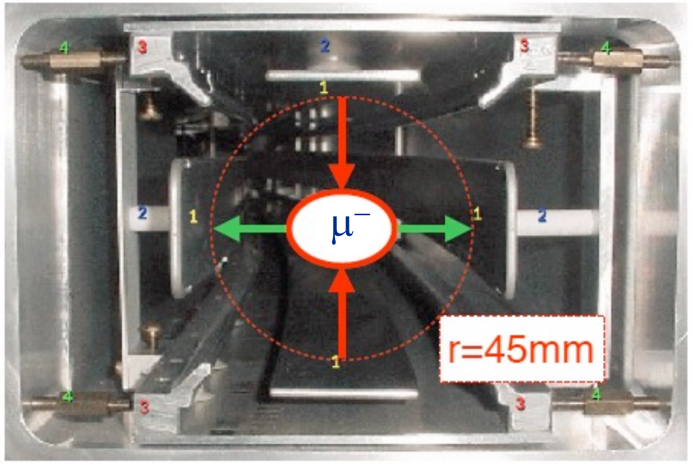
- **Flip polarities in Muon Campus**
  - Switching the polarities of all target and beamline components from the AP0 target station through the injection into the storage ring
  - Estimate 1-2 weeks to complete polarity change *plus* few weeks for recommissioning
  - No major risks expected, although the lower yield from the target could reduce the sensitivity of some of the instrumentation.
- **Flip polarity in MC-1**
  - Main magnet leads (BNL experience indicates no major reshimming expected)
  - Inflector leads
  - Electrostatic Quadrupoles (ESQ) plates
  - Kicker plates
  - No major risk associated but technical work and mitigation in case of surprises
  - Work expected to be done in 3 months (July-Sep 22)



ESQ and kicker switching polarity considerations

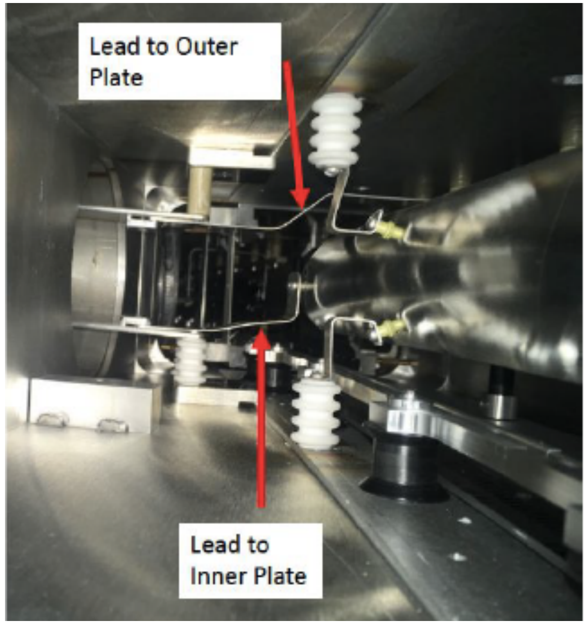
- Reversing the polarity of **ESQ** for μ^- increases the probability of e^- trapping and sparks (limited in μ^+)
- We will flip the polarity of the quads and measure the spark rate
- If the current vacuum is not sufficient a cryo pump will be added

-18 kV



+18 kV

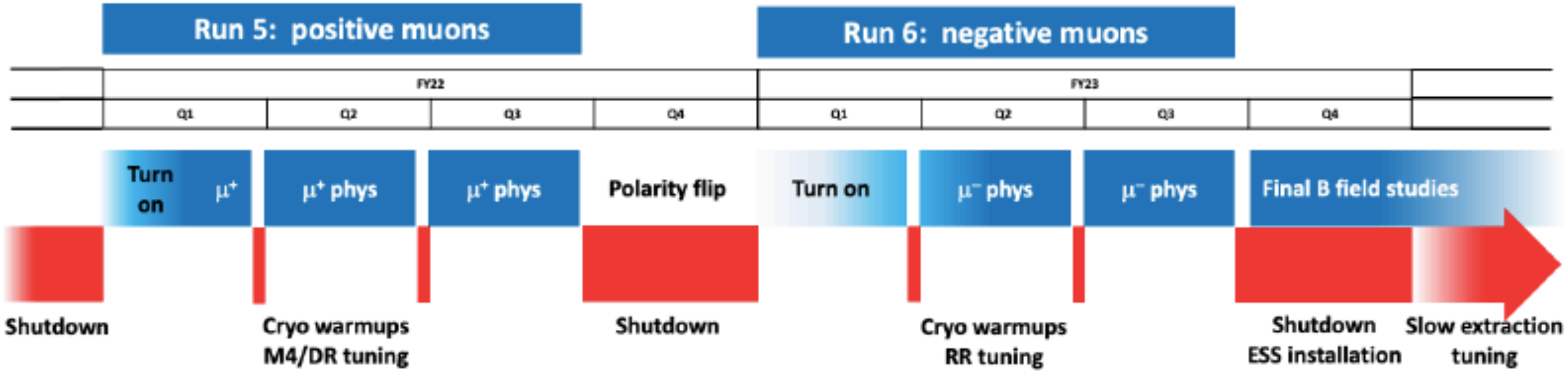
- Reversing the polarity of the **Kicker** likely requires the extraction of the kicker chambers to access back plate standoffs and refurbish
- Has been successfully been carried out in BNL
- It will be done as first step of summer shutdown



more details in the backup slides

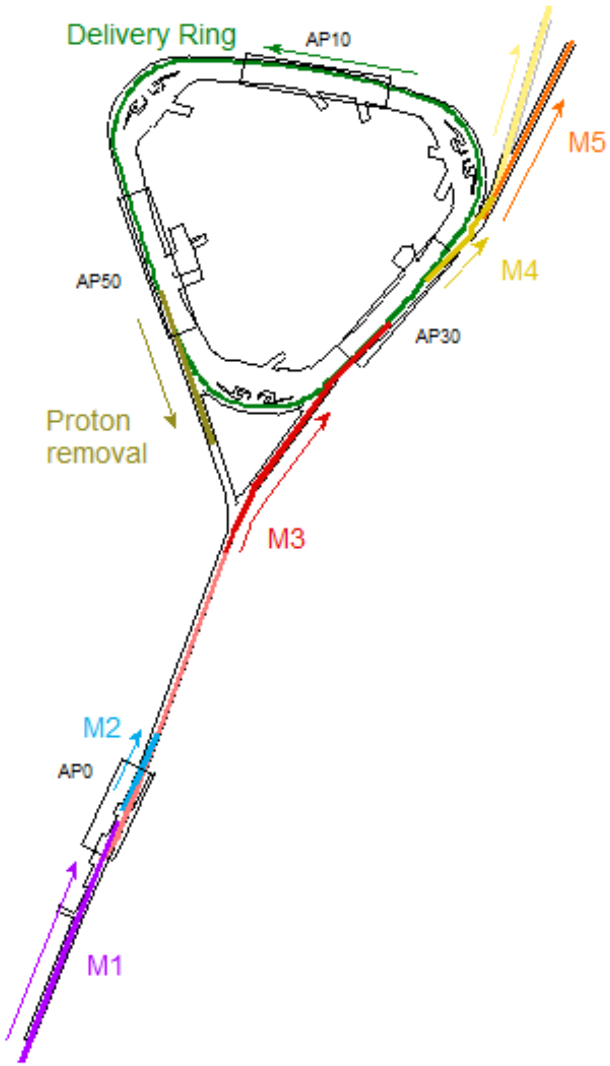
Run6 μ- run plan and time schedule

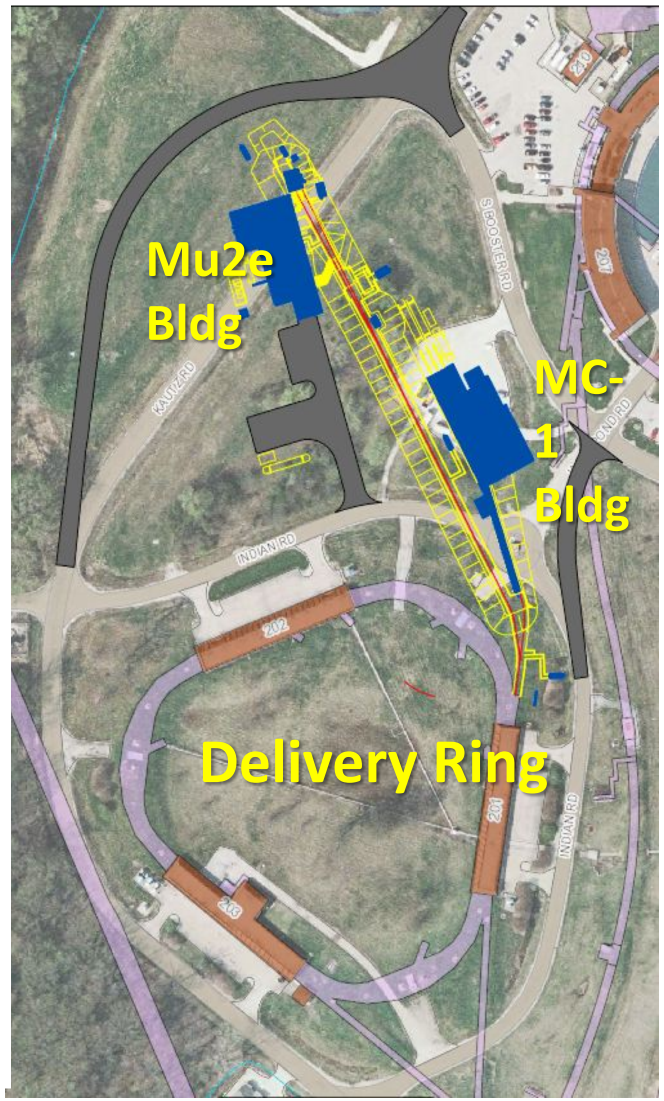
- **Shutdown work (July-September 2022):**
  - kicker and ESQ polarity flip
  - Additional installation of at least one cryo pump if needed
  - Routine maintenance summer shutdown work (field mapping, etc..)
- **Running time + turn on (October 2022 - June 2023)**
  - Turn on of the accelerator
  - Production data: 4 x μ^- BNL ($1\mu^-$ BNL per month) at full uptime
  - 3 months for contingency
- **July 2023:**
  - Beam to Mu2e
  - Keep the g-2 magnet cold for final field studies



g-2 & Mu2e interaction

- g-2 and Mu2e share the delivery ring and part of the elements downstream AP0
- Mu2e electrostatic septa will be located where Extraction Kicker is now
- Running with μ- would preclude Mu2e studies downstream AP0
- The g-2 collaboration is accommodating beam studies in the downtime periods of RUN5





Conclusion I

- Enormous impact (interest) of the Run1 result
- Run5 operations started last week: turn on was extremely smooth
  - Expected statistics 5-6 BNL → 18-19 BNL after Run 5
  - Plan to use RF quad to reduce CBO effects
- Analysis of Run2-3 ongoing:
  - Large statistical improvement (460 R1 →~220 ppb)
  - Many systematics explored in greater depth than for Run 1
  - Data production expected to be completed in early 2022
  - Planned to publish result in Run2-3 Sep – Dec 2022 with a precision goal of 240 ppb tot error (~1/2 of Run1)

Conclusion II

- Proposed μ^- run in Run6 in FY23 to perform the most precise measurement of the negative muon g-2 (a factor 2 improvement respect to BNL) and reach our goal on the total error for the combined negative and positive muon g-2 values

- The technical aspects has been studied:
  - It involves flipping the polarities of a lot of Muon Campus and MC1 components
  - No major risk associated but technical work and mitigation in case of surprises
  - 9 months run would bring us on a safe ground on reaching the goal

- The collaboration strongly support this proposal

- After FY23 three years of data processing and analysis which puts us on a schedule to submit our final publication in roughly 5 years.

The Muon g-2 Collaboration

Thanks!

END

BACKUP SLIDES

Reminder on Run1 analysis

Corrections due to beam dynamics

$$R'_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Corrections due to transient magnetic fields

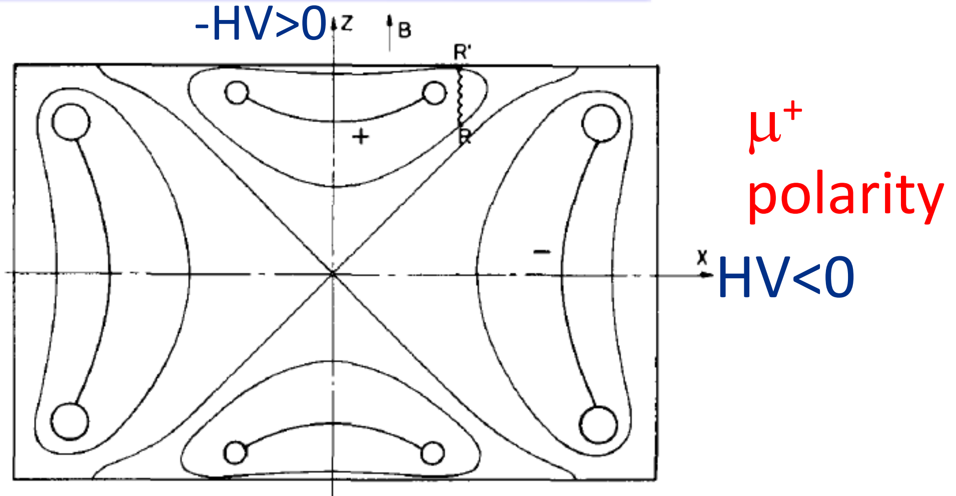
$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

What we measure

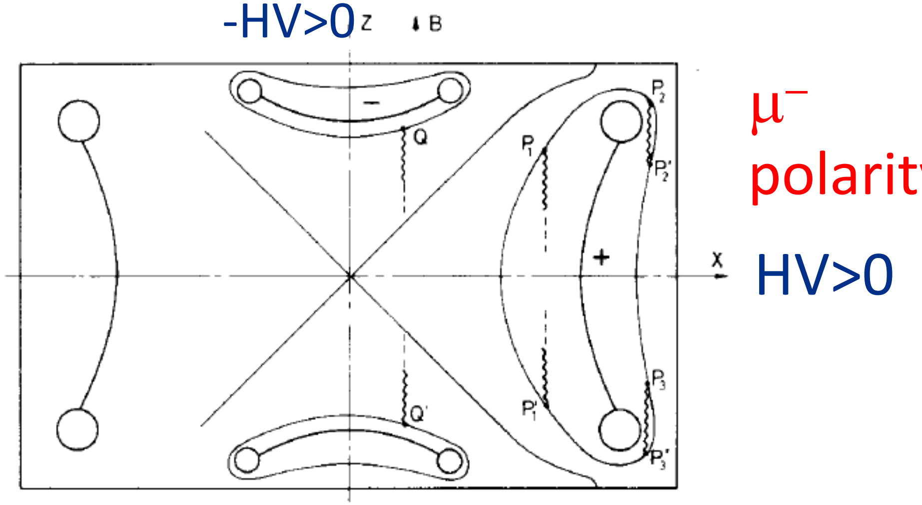
External inputs(known at 24 ppb)

ESQ switching polarity considerations

- Limited number of sparks (caused by trapped e^- emitted interacting with the residual gas) for μ^+ runs
- Reversing the polarity for μ^- increases the probability of trapping and therefore of sparks
- At BNL the quads were successfully operated at 25 kV for BNL's μ^- run
- Our vacuum is ~ 10 times worse (6-9 10^{-7}), however HV is lower (18.2 kV vs 25 kV)
- We will flip the polarity of the quads and measure the spark rate
- If the current vacuum is not sufficient a cryo pump will be added



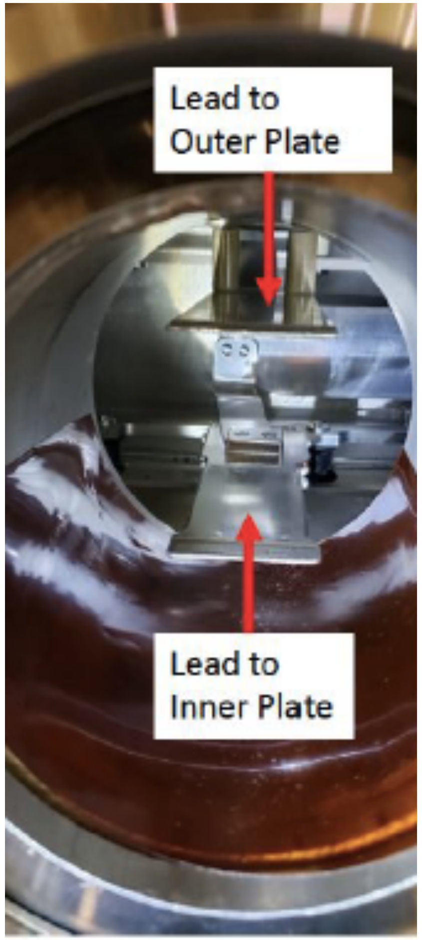
Trapping of e^- for μ^+ run (negative HV)

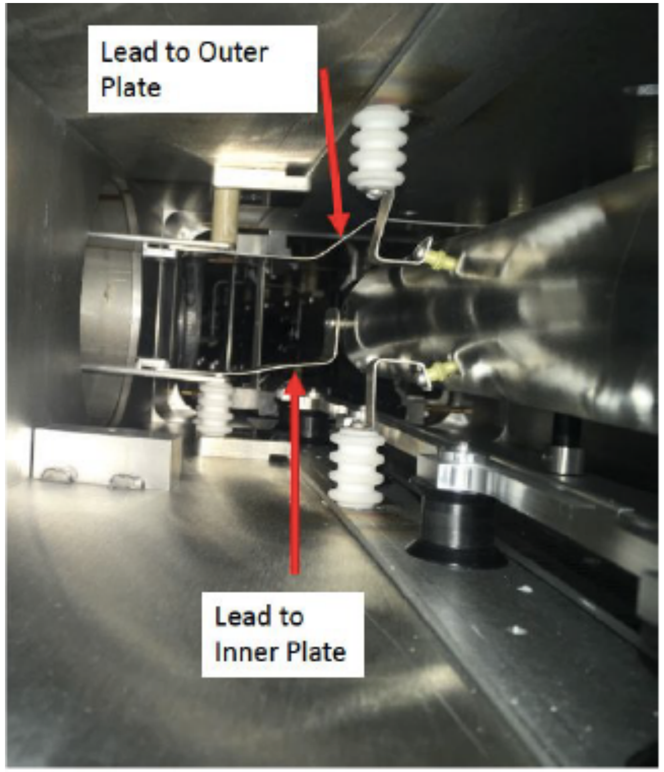


Trapping of e^- for μ^- run (positive HV)

Kicker switching polarity considerations

- 3 kicker units to produce a narrow pulsed magnetic field which put muons in the stored orbit
- During Run1 we replaced the HV standoff that support the Kicker plates
- To store μ^- the current should flow in the opposite direction
- Back plate ceramic standoffs have not been replaced with fluted insulators → Likely need to pull kicker chambers to access back plate standoffs and refurbish
- Has been successfully been carried out in BNL
- It will be done as first step of summer shutdown





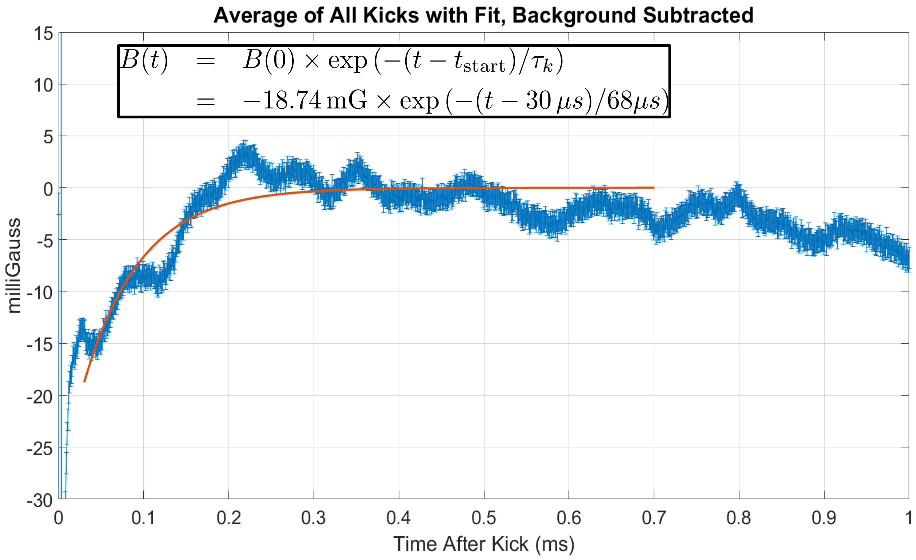
Kicker transient field B_k

- The kicker pulse (~ 200G) produces a transient magnetic field for 150ns in the storage volume → eddy currents
- **A Faraday magnetometer** installed between the kicker plates measured the rotation of polarized light in a crystal due to the transient field
- Signal was fitted with an exponential function

$$\Delta B(t) = \Delta B(0) \exp\left(-t/\tau_k\right)$$

$$B_k \sim 30\ ppb, \delta_{C_{pa}} \sim 40\ ppb$$

Magnetometer between kicker plates



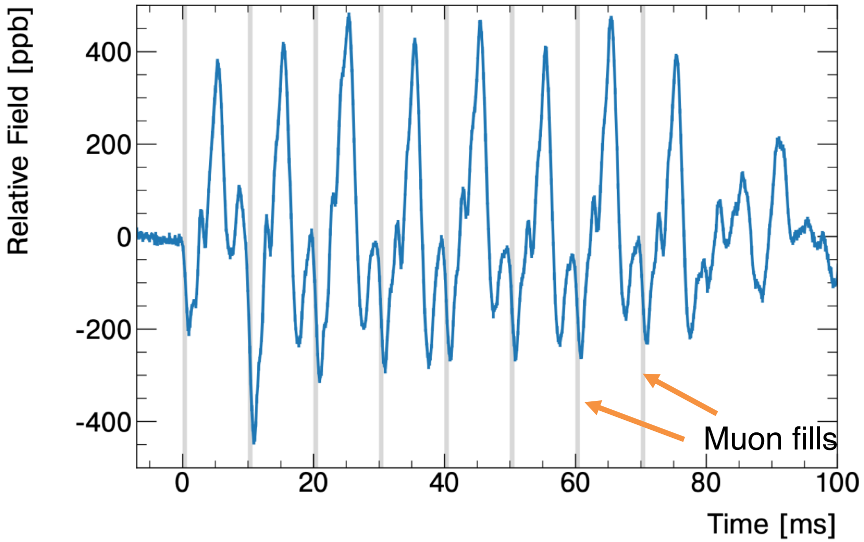
ESQ transient field B_q

- The ESQ are charged/discharged every muon fill (700μs)
- The electric pulse induces mechanical vibrations in the plates which generate magnetic perturbations
- Customized NMR probes measured B_q at several positions

$$B_q \sim 20\ ppb, \delta_{B_q} \sim 90\ ppb$$

The uncertainty is determined by the full width of the measured effect due to the lack of measurements in run-1. (To be reduced in RUN2 by more measurement)

Quad Plates inside Vacuum Chamber



CPTLV: Sidereal Results

- BNL E821 Results (2008)

Amplitude of sidereal oscillation: $A^{\mu} = 2b_T^{\mu} \sin\chi$

$\boldsymbol{A^{\mu^-} < 4.2\ \mathrm{ppm}}$

$\boldsymbol{A^{\mu^+} < 2.2\ \mathrm{ppm}}$

Preliminary Muon g-2 result (2xBNL):

$\boldsymbol{A^{\mu^+} < 2.0\ \mathrm{ppm}}$

$$b_T^{\mu^+} = \sqrt{(\check{b}_X^{\mu^+})^2 + (\check{b}_Y^{\mu^+})^2} \leq 1.4 \times 10^{-24}\ \mathrm{GeV}$$

$$\check{b}_T^{\mu^-} = \sqrt{(\check{b}_X^{\mu^-})^2 + (\check{b}_Y^{\mu^-})^2} \leq 2.6 \times 10^{-24}\ \mathrm{GeV}$$

SME Muon Sector Current Limits (Kostelecký et.al.)

With μ^+

Table D21. Muon sector, $d = 3$

Combination	Result	System	Ref.
$\lvert \mathrm{Re}\, H_{011}^{\mathrm{NR}(0B)} \rvert$, $\lvert \mathrm{Im}\, H_{011}^{\mathrm{NR}(0B)} \rvert$, $\lvert \mathrm{Re}\, g_{011}^{\mathrm{NR}(0B)} \rvert$, $\lvert \mathrm{Im}\, g_{011}^{\mathrm{NR}(0B)} \rvert$	$< 2 \times 10^{-22}$ GeV	Muonium spectroscopy	[20]*
$\lvert \mathrm{Re}\, H_{011}^{\mathrm{NR}(1B)} \rvert$, $\lvert \mathrm{Im}\, H_{011}^{\mathrm{NR}(1B)} \rvert$, $\lvert \mathrm{Re}\, g_{011}^{\mathrm{NR}(1B)} \rvert$, $\lvert \mathrm{Im}\, g_{011}^{\mathrm{NR}(1B)} \rvert$	$< 7 \times 10^{-23}$ GeV	"	[20]*
b^T / m_μ	$(7.3 \pm 5.0) \times 10^{-7}$	Muon decay	[184]*
b_Z	$-(1.0 \pm 1.1) \times 10^{-23}$ GeV	BNL $g_\mu - 2$	[185]
$\sqrt{(\check{b}_X^{\mu^+})^2 + (\check{b}_Y^{\mu^+})^2}$	$< 1.4 \times 10^{-24}$ GeV	"	[185]
$\sqrt{(\check{b}_X^{\mu^-})^2 + (\check{b}_Y^{\mu^-})^2}$	$< 2.6 \times 10^{-24}$ GeV	"	[185]
$\sqrt{(\tilde{b}_X)^2 + (\tilde{b}_Y)^2}$	$< 2 \times 10^{-23}$ GeV	Muonium spectroscopy	[186]
$b_Z - 1.19(m_\mu d_{Z0} + H_{XY})$	$(-1.4 \pm 1.0) \times 10^{-22}$ GeV	BNL, CERN $g_\mu - 2$ data	[187]
b_Z	$(-2.3 \pm 1.4) \times 10^{-22}$ GeV	CERN $g_\mu - 2$ data	[187], [188]*
$\lvert \mathrm{Re}\, H_{011}^{(3)(0B)} \rvert$, $\lvert \mathrm{Im}\, H_{011}^{(3)(0B)} \rvert$	$< 5 \times 10^{-23}$ GeV	"	[20]*
$\check{H}_{010}^{(3)}$	$(-1.6 \pm 1.7) \times 10^{-22}$ GeV	BNL, CERN $g_\mu - 2$ data	[20]*
$\lvert \mathrm{Re}\, \check{H}_{011}^{(3)} \rvert$, $\lvert \mathrm{Im}\, \check{H}_{011}^{(3)} \rvert$	$< 2.0 \times 10^{-24}$ GeV	BNL $g_\mu - 2$	[20]*
$m_\mu d_{Z0} + H_{XY}$	$(1.8 \pm 6.0) \times 10^{-23}$ GeV	"	[185]

SME Muon Sector Current Limits

With μ^+

With μ^-

Table D21. Muon sector, $d = 3$

Combination	Result	System	Ref.
$\lvert\mathrm{Re}\, H_{011}^{\mathrm{NR}(0B)}\rvert$, $\lvert\mathrm{Im}\, H_{011}^{\mathrm{NR}(0B)}\rvert$, $\lvert\mathrm{Re}\, g_{011}^{\mathrm{NR}(0B)}\rvert$, $\lvert\mathrm{Im}\, g_{011}^{\mathrm{NR}(0B)}\rvert$	$< 2 \times 10^{-22}$ GeV	Muonium spectroscopy	[20]*
$\lvert\mathrm{Re}\, H_{011}^{\mathrm{NR}(1B)}\rvert$, $\lvert\mathrm{Im}\, H_{011}^{\mathrm{NR}(1B)}\rvert$, $\lvert\mathrm{Re}\, g_{011}^{\mathrm{NR}(1B)}\rvert$, $\lvert\mathrm{Im}\, g_{011}^{\mathrm{NR}(1B)}\rvert$	$< 7 \times 10^{-23}$ GeV	"	[20]*
b^T/m_μ	$(7.3 \pm 5.0) \times 10^{-7}$	Muon decay	[184]*
b_Z	$-(1.0 \pm 1.1) \times 10^{-23}$ GeV	BNL $g_\mu - 2$	[185]
$\sqrt{(\check{b}_X^{\mu^+})^2 + (\check{b}_Y^{\mu^+})^2}$	$< 1.4 \times 10^{-24}$ GeV	"	[185]
$\sqrt{(\check{b}_X^{\mu^-})^2 + (\check{b}_Y^{\mu^-})^2}$	$< 2.6 \times 10^{-24}$ GeV	"	[185]
$\sqrt{(\tilde{b}_X)^2 + (\tilde{b}_Y)^2}$	$< 2 \times 10^{-23}$ GeV	Muonium spectroscopy	[186]
$b_Z - 1.19(m_\mu d_{Z0} + H_{XY})$	$(-1.4 \pm 1.0) \times 10^{-22}$ GeV	BNL, CERN $g_\mu - 2$ data	[187]
b_Z	$(-2.3 \pm 1.4) \times 10^{-22}$ GeV	CERN $g_\mu - 2$ data	[187], [188]*
$\lvert\mathrm{Re}\, H_{011}^{(3)(0B)}\rvert$, $\lvert\mathrm{Im}\, H_{011}^{(3)(0B)}\rvert$	$< 5 \times 10^{-23}$ GeV	"	[20]*
$\check{H}_{010}^{(3)}$	$(-1.6 \pm 1.7) \times 10^{-22}$ GeV	BNL, CERN $g_\mu - 2$ data	[20]*
$\lvert\mathrm{Re}\, \check{H}_{011}^{(3)}\rvert$, $\lvert\mathrm{Im}\, \check{H}_{011}^{(3)}\rvert$	$< 2.0 \times 10^{-24}$ GeV	BNL $g_\mu - 2$	[20]*
$m_\mu d_{Z0} + H_{XY}$	$(1.8 \pm 6.0) \times 10^{-23}$ GeV	"	[185]

Fermilab

SME Muon Sector Current Limits

With μ^+

With μ^-

Table D22. Muon sector, $d = 4$

Combination	Result	System	Ref.
$c_{TT} + 0.35(c_{XX} + c_{YY}) + 0.28c_{ZZ}$	$< 8.5 \times 10^{-11}$	BNL $g_\mu - 2$	[189]*
$\lvert c_\mu - c_\gamma \rvert$	$< 3 \times 10^{-11}$	Astrophysics	[48]*
$c^{TT} - 0.05c^{ZZ}$	$(4.9 \pm 1.1) \times 10^{-8}$	Muon decay	[184]*
$\lvert c \rvert$	$< 10^{-11}$	Astrophysics	[68]*
$\lvert \mathrm{Re}\, g_{011}^{(4)(0B)} \rvert,\ \lvert \mathrm{Im}\, g_{011}^{(4)(0B)} \rvert$	$< 5 \times 10^{-22}$	Muonium spectroscopy	[20]*
$\lvert \mathrm{Re}\, \breve{g}_{011}^{(4)} \rvert,\ \lvert \mathrm{Im}\, \breve{g}_{011}^{(4)} \rvert$	$< 6.6 \times 10^{-25}$	BNL $g_\mu - 2$	[20]*
$\breve{g}_{010}^{(4)}$	$(-2.3 \pm 2.4) \times 10^{-25}$	"	[20]*
$m_\mu g_{XYT}^{(M)}$	$-(7.8 \pm 8.5) \times 10^{-27}$ GeV	"	[20]*
$m_\mu \sqrt{(g_{XZT}^{(M)})^2 + (g_{YZT}^{(M)})^2}$	$< 1.1 \times 10^{-27}$ GeV	"	[20]*