Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

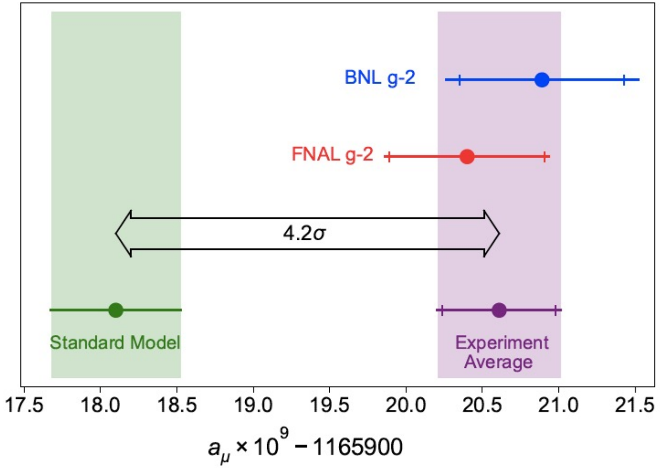
Upgraded Muon EDM and Negative Muon g-2 Measurements

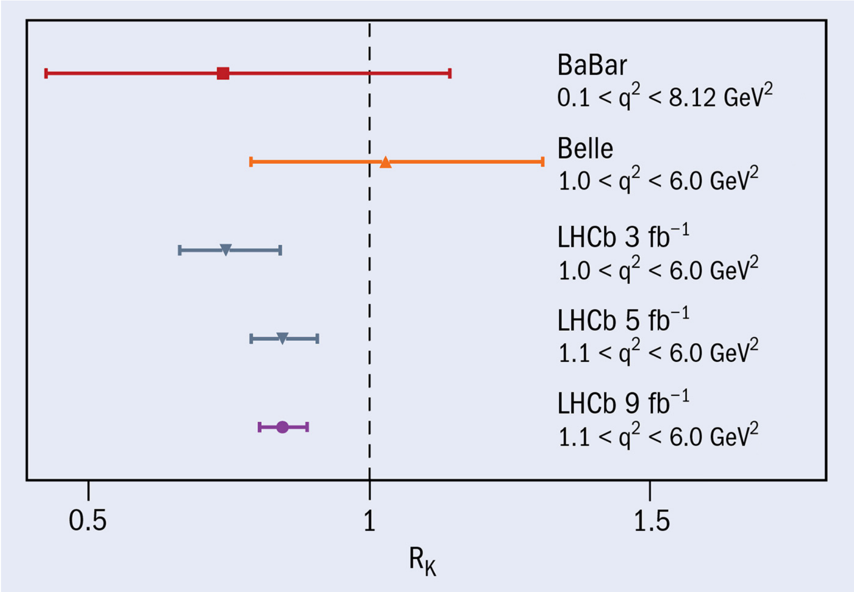
Brendan Kiburg

Muon Properties and Related Topics III

04 Feb 2022

2021 saw enhanced anomalies popping up in the flavor sector





https://cerncourier.com/a/new-data-strengthens-rk-flavour-anomaly/

Muon g-2

LHCB, Belle

Several other anomalies at the 2^+ σ level

Maybe NP couples differently to muons …

R_K probes the ratio of B-meson decays to muons vs electrons: $R_K = BR(B^+ \to K^+\mu^+\mu^-) / BR(B^+ \to K^+e^+e^-)$

$R_K = 0.846^{+0.044}_{-0.041}$, 3.1σ

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LHCB: arXiv:2103.11769v1

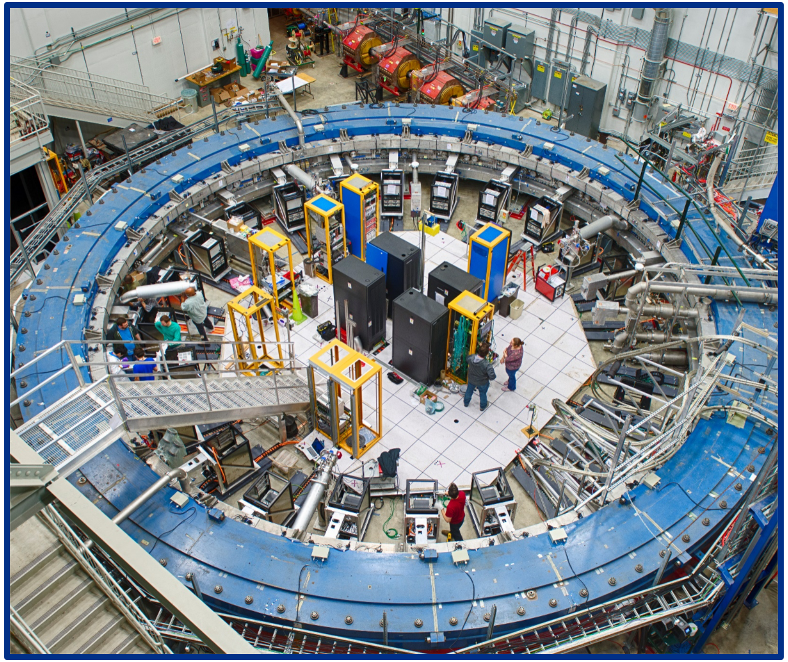
Outline

Summarize FNAL Muon g-2 Status

Negative Muon Running

Opportunistic Muon EDM

Future Efforts



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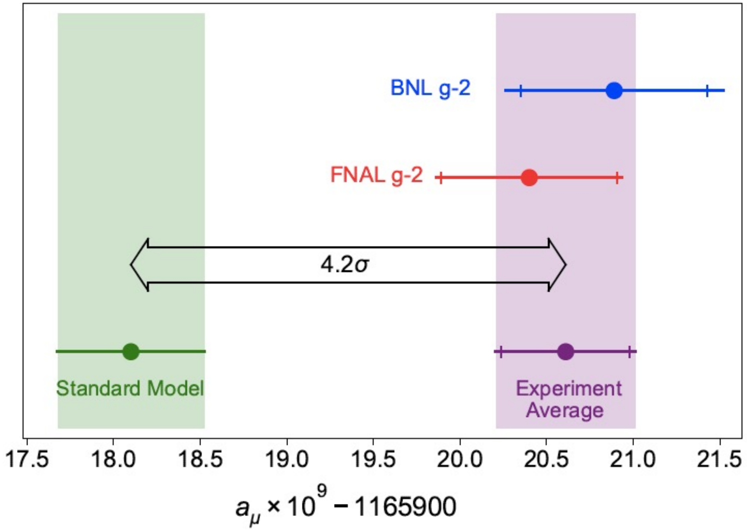
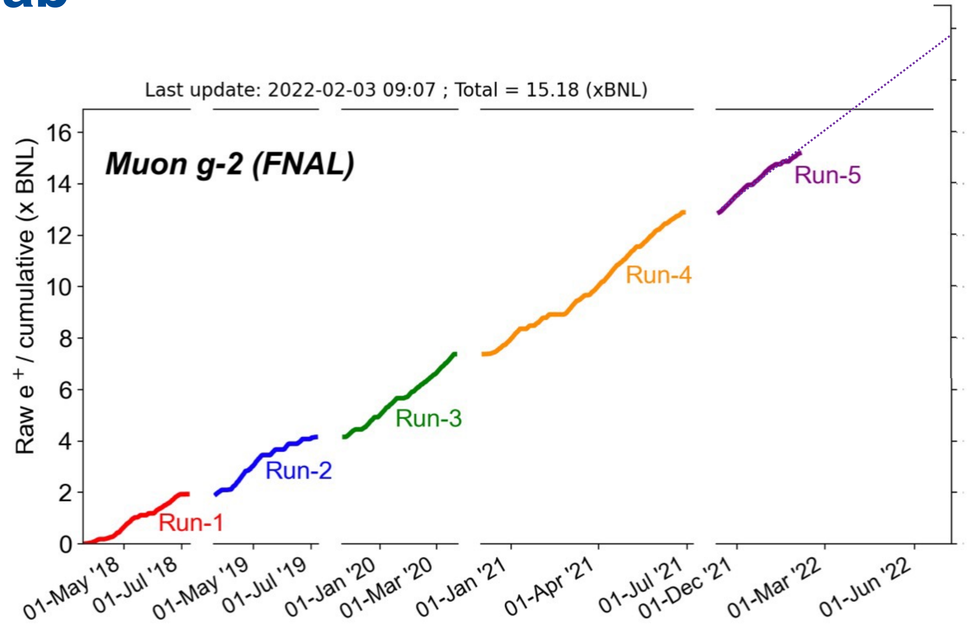
Muon g-2 Experiment at Fermilab





- 2021 – First Result from Run-1 data
- Increases tension with theory to 4.2σ
- $a_\mu \propto \frac{\omega_a}{\omega_p} \frac{\text{muon precession frequency}}{\text{magnetic field strength}}$

- Analysis of Run2+3 data making good progress
- Run-5 ongoing → expecting ~19x BNL

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BNL Measurement

- BNL collected
  - Total precision of 540 ppb, statistically limited
  - Ran μ^- in 2001 (~ 40% total stats)
- FNAL goals
  - 21x total BNL stats, 140 ppb goal
  - Balance 100 ppb syst + stat

Run Period	Polarity	Electrons [millions]	Systematic ω_p [ppm]	Systematic ω_a [ppm]	Final Relative Precision [ppm]
R97	μ^+	0.8	1.4	2.5	13
R98	μ^+	84	0.5	0.8	5
R99	μ^+	950	0.4	0.3	1.3
R00	μ^+	4000	0.24	0.31	0.73
R01	μ^-	3600	0.17	0.21	0.72

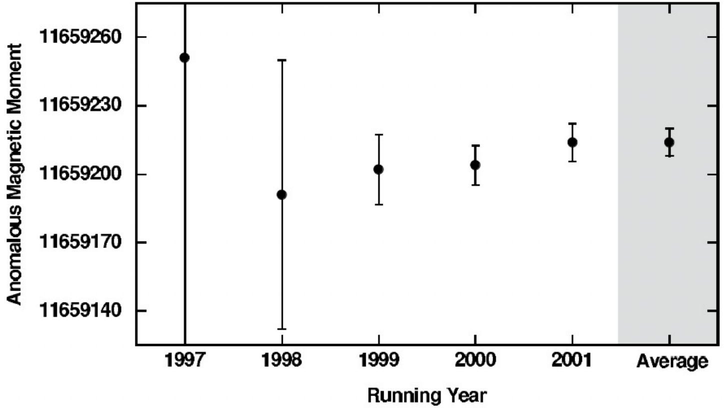

FIG. 40: Results for the E821 individual measurements of a_μ by running year, together with the final average.

Bennett, et al https://doi.org/10.1103/PhysRevD.73.072003

Run 6 Plan: μ^- configuration

- Goal
  - Measure a_{μ^-} to 350 ppb precision (factor two improvement on BNL μ^- result)
- Physics Motivation
  - World's most precise measurement of a_{μ^-} , which can't be done in future efforts at J-PARC or PSI that utilize μ^+
  - CPT- and Lorentz- violation at highest sensitivity in muon sector
  - Reach proposal goal of 21x BNL statistics (~140 ppb uncertainty)
- Notes
  - Requires ~2x BNL total statistics (4x BNL μ- statistics)
  - Roughly 1 accelerator season needed

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CPT/Lorentz Physics Motivation

Data Tables for Lorentz and CPT Violation

V. Alan Kostelecký[a] and Neil Russell[b]
[a] *Physics Department, Indiana University, Bloomington, IN 47405*
[b] *Physics Department, Northern Michigan University, Marquette, MI 49855*

January 2022 update of *Reviews of Modern Physics* **83**, 11 (2011) [arXiv:0801.0287]

This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, neutrino, and gravity sectors. Tables presenting definitions and properties are also compiled.

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

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

  - All these terms violate Lorentz invariance, CPT is broken for a and b terms
  - Best limits on these coefficients in the muon sector come from the BNL experiment
- Predicts two CPT- / Lorentz violating signatures in Muon g-2
  - Sidereal (or annual) variations in precession frequency (will be done w/ μ^+ as well) → b_T
  - Difference in muon precession frequency between μ^+/ μ^- → b_Z, H_{XY}, d_{Z0}
  - Sensitivity scales with precision of muon precession frequency

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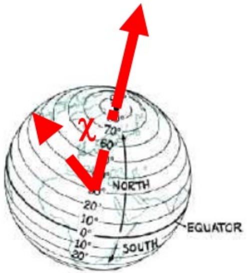
CPT / LV Tests

Measurements within one experiment



- Examine shift in precession frequency $\Delta\omega_a$ for μ^+,μ^- at colatitude χ

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

- Normalize to B-field ($\mathcal{R} = \frac{\omega_a}{\omega_p}$)
- BNL Results (2008)

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

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

- Improve by 2.5x with μ^- run at FNAL

Measurements across different experiments

- Perform comparison between experiments at different colatitudes χ_1 , χ_2

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

- Combining BNL w/ CERN

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

- Improvements only possible w/ FNAL μ^-
- Improve by 15x w/ future JPARC μ^+ result

Bennett et al, https://doi.org/10.1103/PhysRevLett.100.091602

Experimental Requirements

- Flip all field polarities

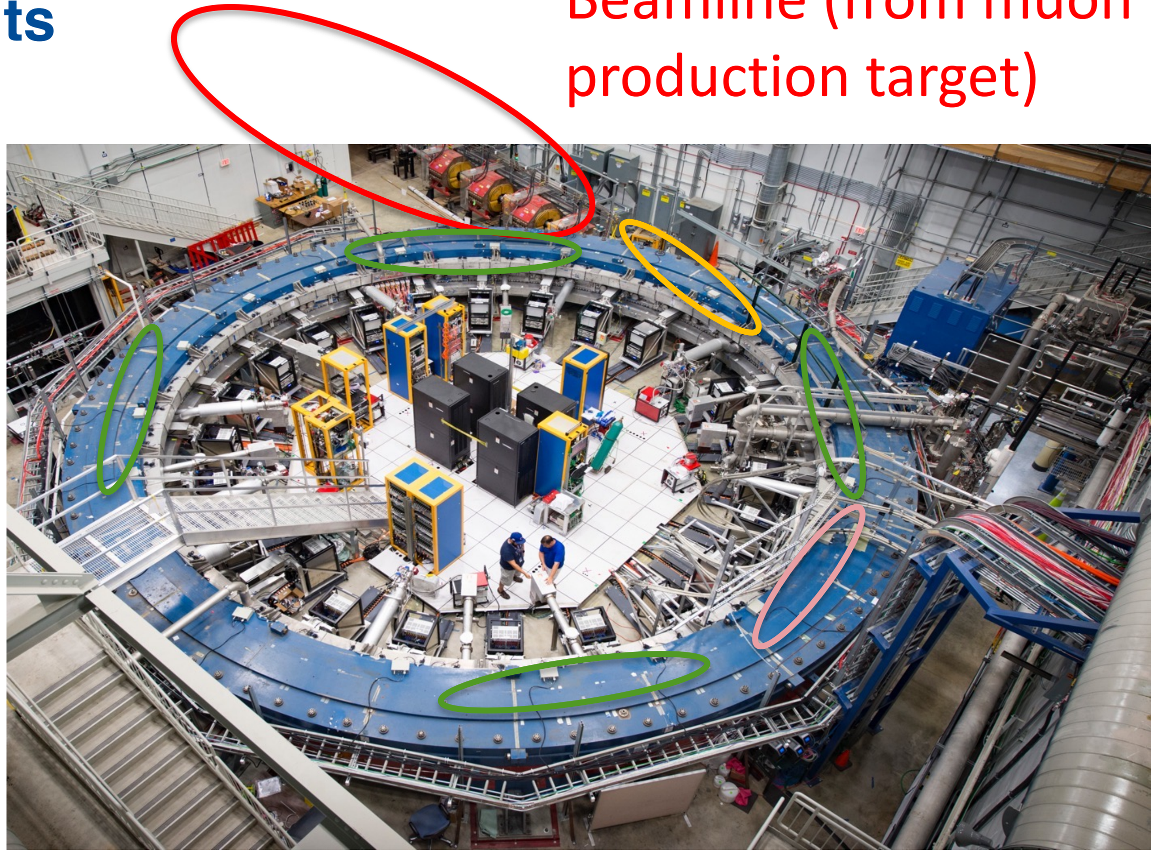
  Beamline, Inflector, Main Magnet,

  Focusing Quadrupoles

  Kicker

- Kicker refurbishment to allow injection pulse to flow in opposite direction
- Improve storage ring vacuum for focusing quad operation

Beamline (from muon production target)



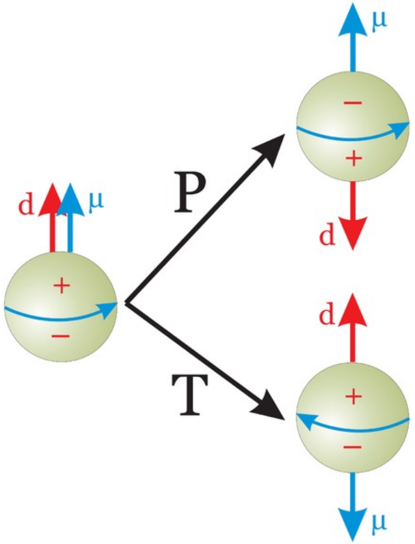
Potential Future Running

- Current proposed timeline
  - Flip polarity during summer 22
  - Run during FY23 and complete beam operations
- Muon Campus will source Mu2e in the near future (in the positive beam polarity)
- If future μ^- running is merited down the road and fits with the program …
  - Production rates of μ^- are suppressed by a factor of ~2 wrt μ^+
  - Would install new inflector magnet (used to inject beam into storage ring)
    - Device is built, currently ready as a spare
    - Reduce scattering of incoming beam
    - Expect 20-40% flux gains

EDM Basics

- Motivation: Baryon Asymmetry & new CPV sources
- Permanent Electric Dipole Moments

  T- & P-Violating
  - → CP-Violating (Assuming CPT)
  - good candidates



- Types of EDMs
  - Nucleon EDM (n,p)
  - Bare lepton (e, μ)
  - Paramagnetic Atoms/Molecules → Electron EDM, nuclear-spin independent coupling
  - Diamagnetic Atoms → Nuclear Shiff moment, nucleon EDM, or nuclear-spin-dependent electron-nucleon interaction

Theory must interpret

- ANY detection of an EDM would be very significant
  - So far, experiments have set impressive limits

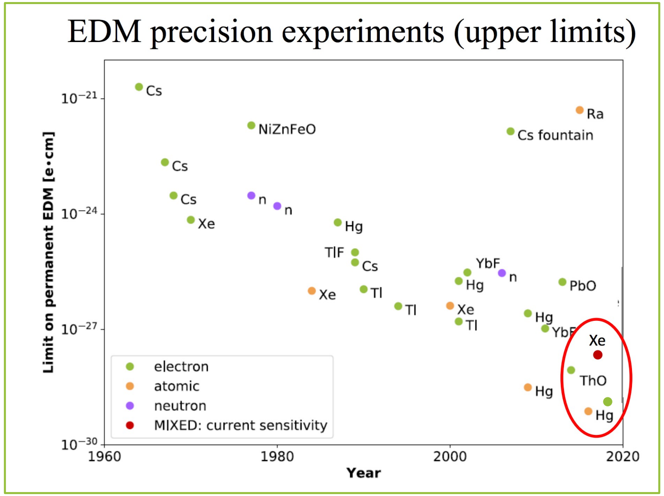
References: Theory: Engel, Musolf arXiv:1303.2371. Exp: Chupp 10.1103/RevModPhys.91.015001

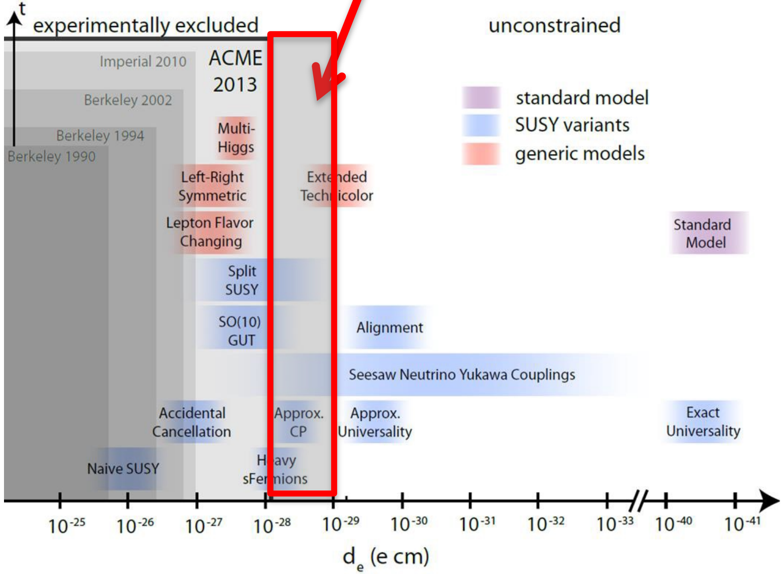
ACME-II Results for e EDM in ThO system

Impressive new limit:

$$|d_e| < 1.1 \times 10^{-29} e\mathrm{cm}$$

Nature, 2018 ACME collaboration
https://doi.org/10.1038/s41586-018-0599-8





- EDMs challenge various BSM models
- Under naïve scaling ($d_\mu \sim (m_\mu/m_e).d_e$) implies limit of ~10^{-27} *e* cm for muon EDM

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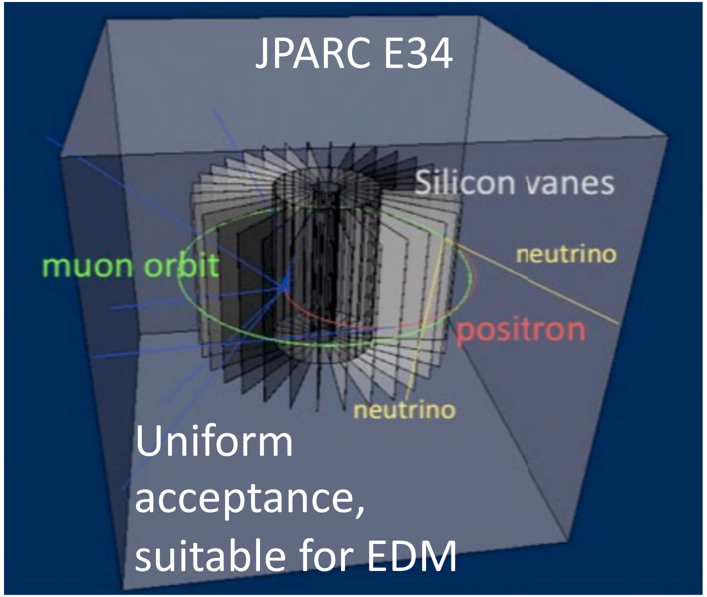
FNAL and JPARC Muon g-2 efforts will look for muon EDM



Source	d_μ Limit (e-cm)	Note
CERN III	$< 1.05 \times 10^{-18}$	Bailey (1978)
BNL	$< 1.8 \times 10^{-19}$	Bennett (2009)
FNAL	$< 2 \times 10^{-21}$	Projection Runs 1-6
JPARC	$< \sim 10^{-21}$	Projection
muEDM	$\sim 6 \times 10^{-23}$	Proposal @ PSI
eEDM	$< \sim 10^{-27}$	Naïve SM scaling* from ACME-II

*However, NP models that address flavor puzzles can couple differently to the muon and electron sectors , relaxing this naïve scaling constraint. Could be as large as $\sim 10^{-19}$ e cm

Crivellin, Hoferichter, https://doi.org/10.1103/PhysRevD.98.113002

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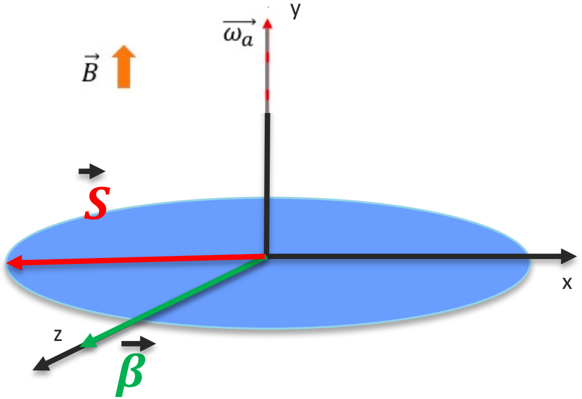
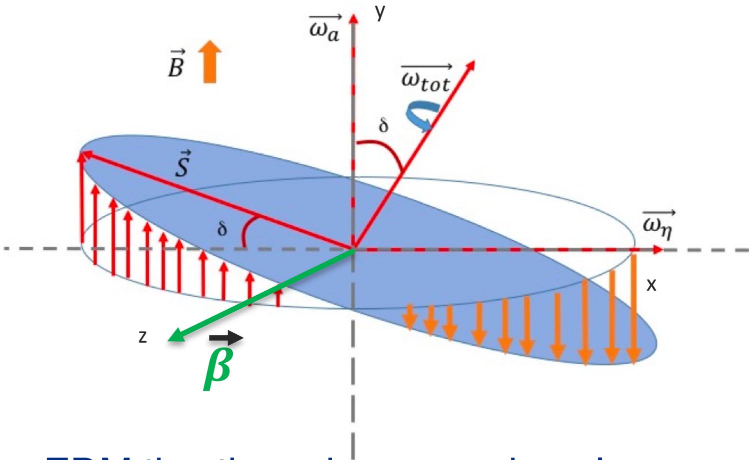
A Muon EDM modifies the muon g-2 precession

$$\boldsymbol{\omega}_{tot} = \boldsymbol{\omega}_a + \boldsymbol{\omega}_\eta = \frac{e}{mc} a_\mu \boldsymbol{B} + \eta \frac{e}{2m} (\boldsymbol{\beta} \times \boldsymbol{B})$$

$$\boldsymbol{d}_{\boldsymbol{\mu}} = \frac{\eta}{2} \frac{e\,\hbar}{2m_\mu c} \boldsymbol{S}$$

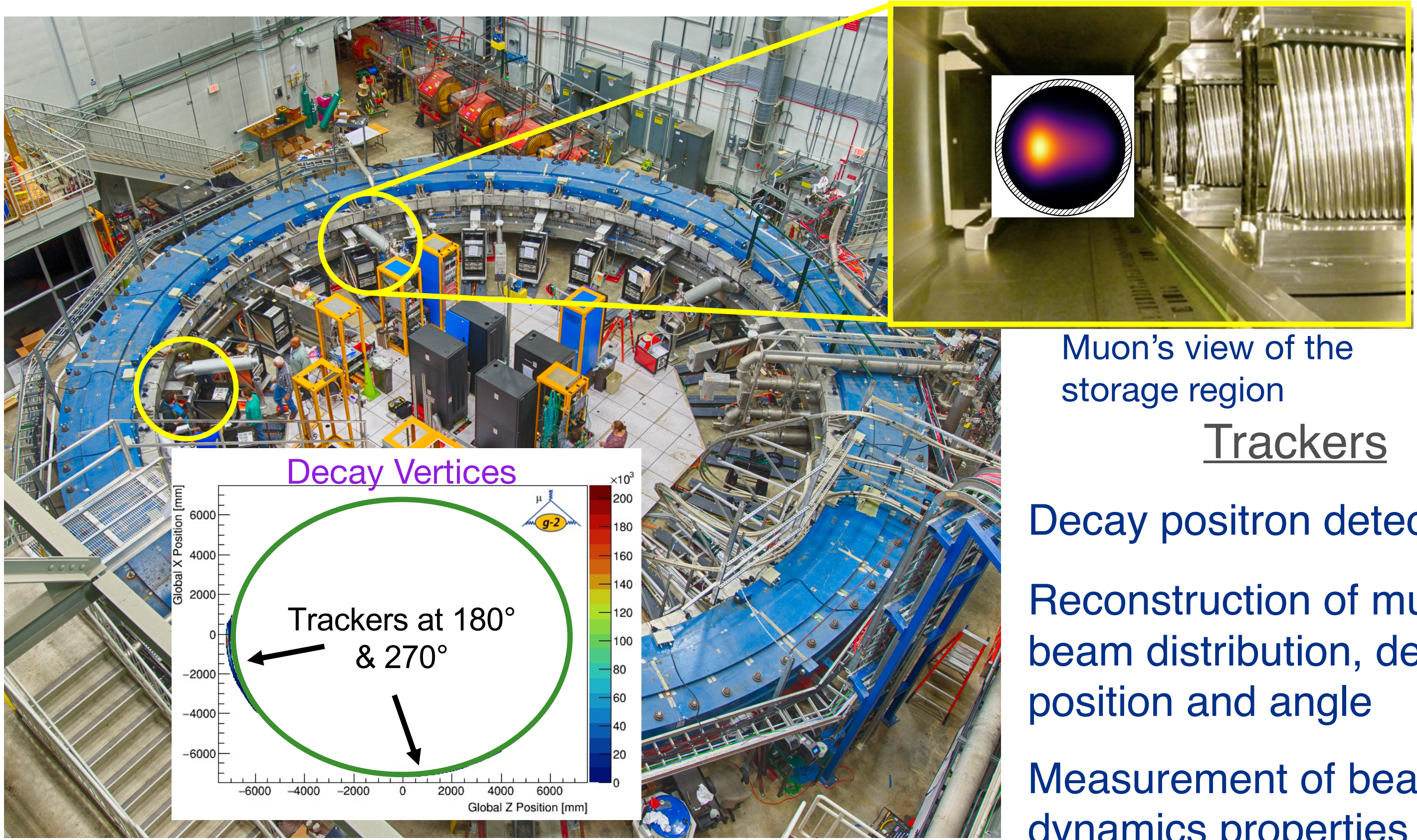




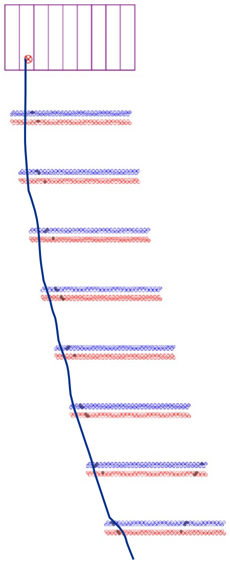
- Only MDM, Uniform B-Field
- An EDM tips the spin precession plane, modifies $\boldsymbol{\omega}_{tot}$

- Positrons at high energy tend to be emitted in direction of muon's spin
- Look for vertical oscillations at same frequency, but out of phase from muon g-2 signal
- Backgrounds come from anything that can generate this signal (e.g. B_r)

Trackers used to image beam and study decay properties



Muon's view of the storage region



Trackers

Decay positron detected

Reconstruction of muon beam distribution, decay position and angle

Measurement of beam dynamics properties

EDM Analysis Options

1. Look for an asymmetry in the phase of muon precession frequency as a function of vertical position
   - Geometric effect that couples decay positron pathlength to the average fitted phase as a function of vertical position
   - An EDM tilts the precession plane, leading to an asymmetric phase in the vertical distribution
   - Dominated by detector misalignment if an EDM is present
   - BNL-style calorimeter-based analysis, systematically limited (current best limit)

2. Directly measure the variation in the vertical decay angle over time with the trackers
   - Fit for an oscillation $\pi/2$ out of phase with g-2 signal
   - Sensitive to couplings with beam oscillations, vertical angle-detector acceptance couplings

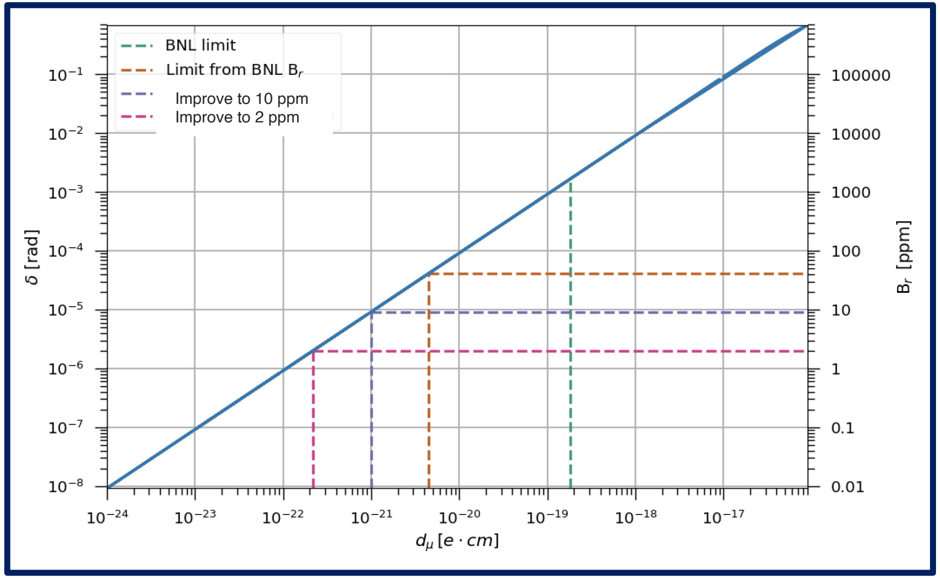
$$\langle\theta_y\rangle(t) = A_{g-2}\cos(\omega_a t + \phi) + A_{\mathrm{EDM}}\sin(\omega_a t + \phi) + c$$

   - Was performed at BNL, statistically limited, main path to improvements at FNAL

Uncertainties

- BNL tracking EDM result was statistically limited (~9.4M tracks)
- FNAL trackers closer to beam and have better vertical angle acceptance, project several Billion high quality tracks
- Unavoidable “background” from the Radial Field
    - Tilts precession plane, net average radial field would fake an EDM
    - Largest expected uncertainty
    - Novel systematic beam technique for scanning $< B_r >$ and tuning it close to 0
    - Developing additional instrumentation to measure $B_r(\theta)$

False EDM from radial field



S. Charity

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Dedicated Frozen Spin EDM effort @PSI

muEDM: Towards a search for the muon electric dipole moment at PSI using the frozen-spin technique, Sakurai et al., https://arxiv.org/pdf/2201.06561.pdf

- Muon spin precession in presence of EDM

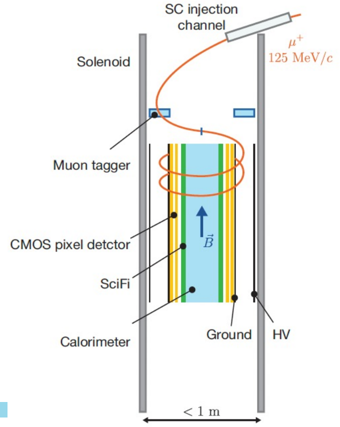
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_e = -\frac{e}{m_\mu}\left[\left\{a_\mu \vec{B} - \left(a_\mu + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right\} + \frac{\eta}{2}\left\{\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right\}\right],$$

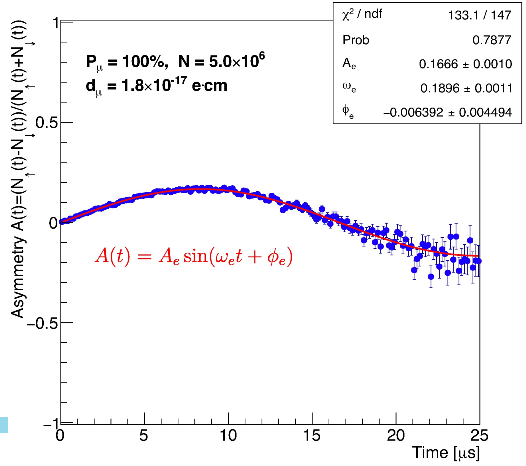
- Apply radial electric field to "freeze" muon spin to its momentum vector

$$E_\mathrm{f} \approx a_\mu B c \beta \gamma^2 \longrightarrow \vec{\omega} = \vec{\omega}_e = -\frac{e\eta}{2m_\mu}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}_\mathrm{f}}{c}\right]$$

- A muon EDM would result in a vertical counting asymmetry of decay positrons as a function of time

- Goal 6 x 10^{-23} e cm in ~1 year





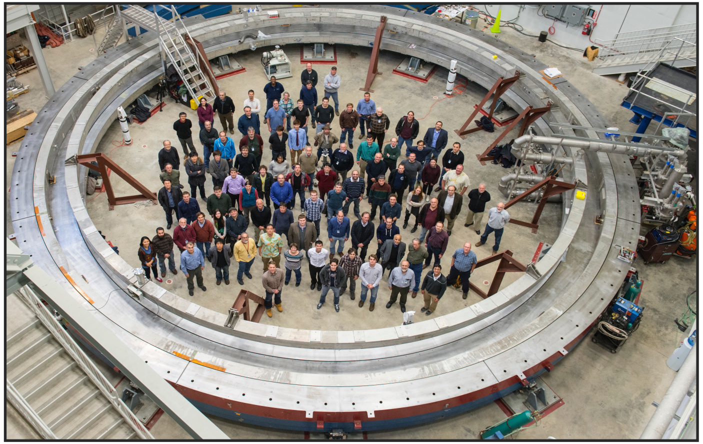
Potential Future EDM Efforts at Fermilab

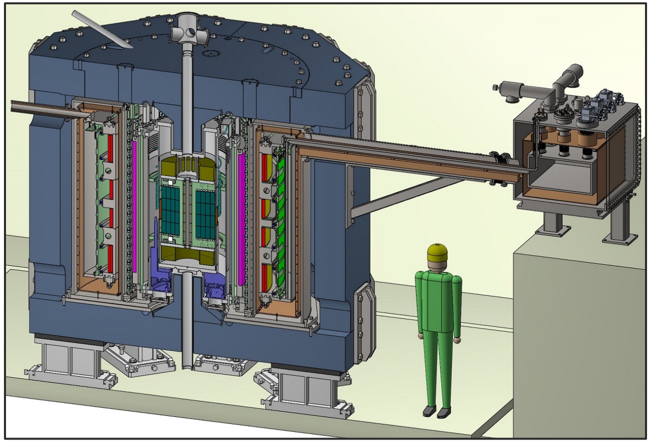
- Maximize Physics Output of FNAL Muon g-2 Experiment
  - Get the most out of the existing Runs 1-6 data
  - Add additional tracker(s) to increase electron statistics,
  - Improve detector acceptance for tracks near the top/bottom of detectors by improving lower momentum track fitting
  - Minimize the net radial field and improve its knowledge
  - Improve focusing quadrupole alignment / coupling between BD and detectors
- Workshop planning for later this year to discuss the possibility of future upgrades of this equipment

Summary

- Muon g-2
  - Nearing its statistics goals
  - Planning to convert the polarity to μ^- this summer and produce the best measurement for μ^- and constrain SME CPT-violating parameters
- Muon EDM
  - Analyzing Runs 1-3 of FNAL data
  - Considering additional methods for improvements → Workshop 2022
  - Additional efforts underway and proposed at other facilities
    - JPARC EDM from g-2
    - Dedicated Frozen-spin EDM @PSI

JPARC g-2 offers novel approach, systematics





- Fermilab (E989)
  - High-rate 3.09 GeV/c muon beam
  - Highly polarized (97%)
  - 1.45 Tesla, 7-meter-radius storage ring
  - Run from 2018-2023
  - 140 ppb goal

- JPARC (E34)
  - Surface muon beam → muonium → 0.3 GeV/c muon beam
  - Polarization ~ 50%
  - 3 Tesla, 0.33-meter-radius storage ring
  - Run mid 2020s
  - 400 ppb goal