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# The Muon $g$–2 Experiment

## Validation of the Standard Model by Measuring the Muon Anomalous Magnetic Dipole Moment

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07-Mar-2019 Cockcroft Institute Seminar

μ g-2

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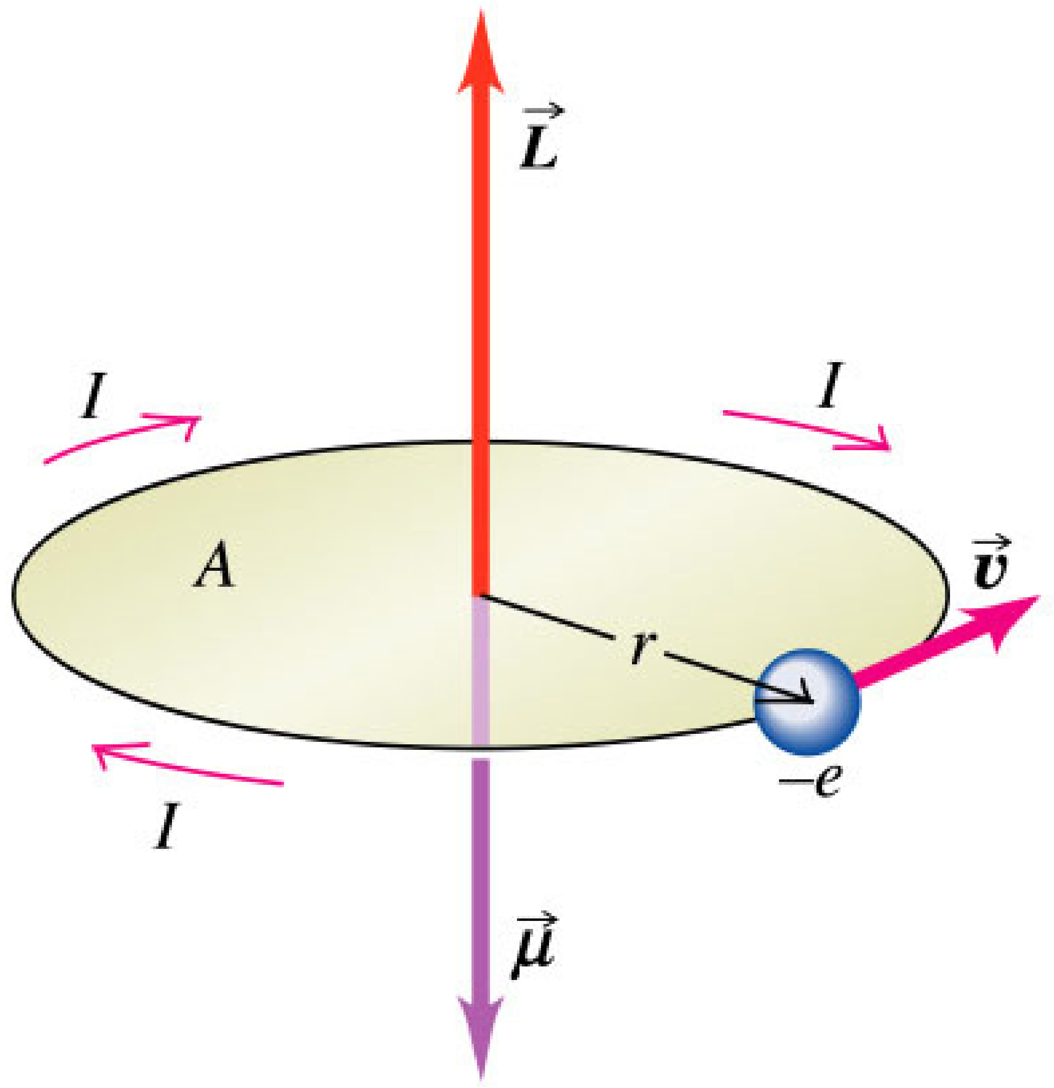
# Magnetic Dipole Moment (MDM)

- MDM $\mu$ is defined by the relation $\tau = \mu \times B$, where $\tau$ is the torque exerted on an object, such as a magnet, by an external magnetic field $B$.
- The spin MDM of a lepton is $\mu = g \frac{e}{2m} s$, where the lepton spin is $s = 1/2$, $m$ is the lepton mass, $e$ is the elementary charge, and $g$ is the $g$-factor (gyromagnetic ratio) of the lepton.



# Anomalous MDM

- The Dirac equation

$$i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)$$

predicts the $g$-factor for elementary particles such as leptons to be $g=2$.

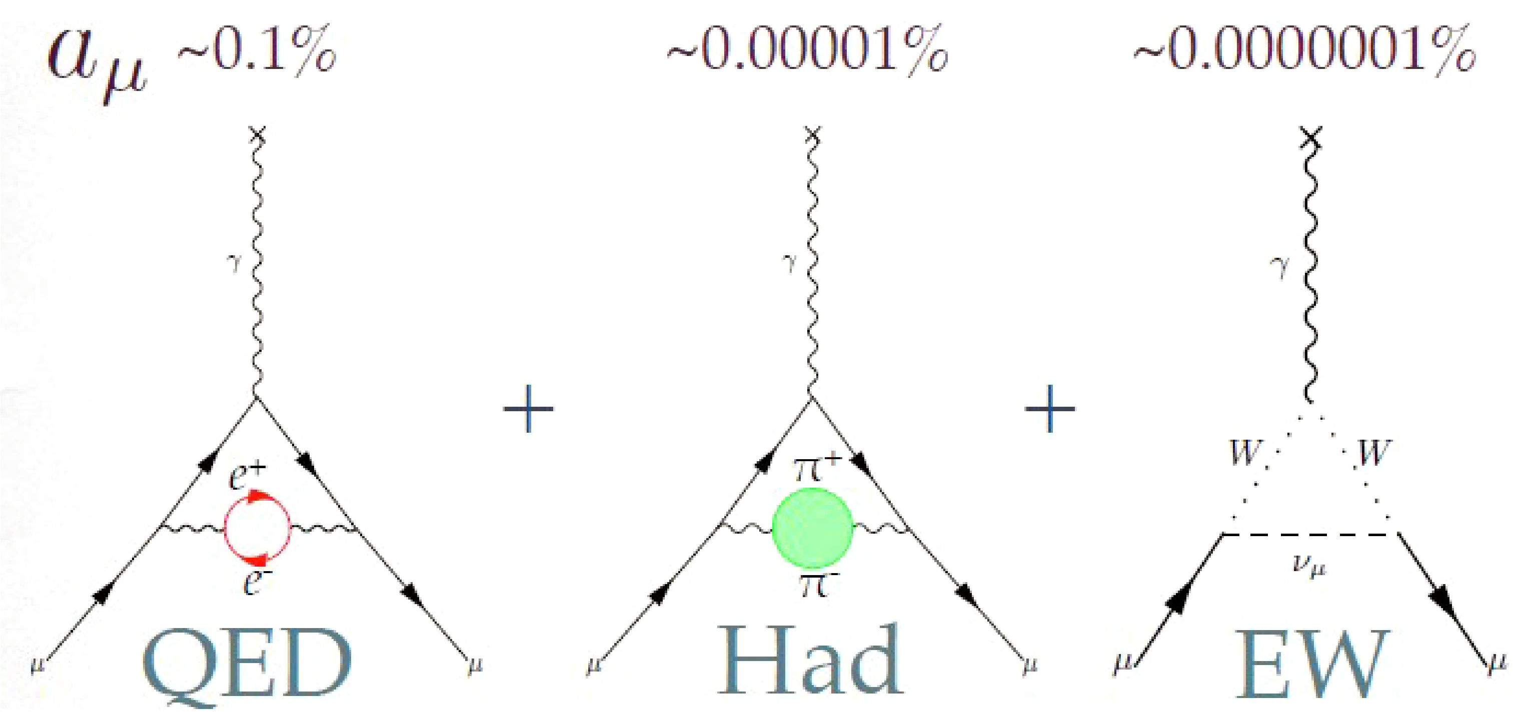
- However, experiments show $g>2$, consistent with adding a Pauli term in Dirac's equation.
- The quantity $a=\frac{g-2}{2}$ is called the ***anomalous MDM*** (or ***MDM anomaly***).

# Muon Anomalous MDM (g-2)

The Standard Model (SM) predicts that the muon anomalous MDM consists of three parts:

$$a^{\mathrm{SM}}{}_{\mu} = a^{\mathrm{QED}}{}_{\mu} + a^{\mathrm{EW}}{}_{\mu} + a^{\mathrm{Had}}{}_{\mu} = \\ = 116591802(49) \times 10^{-11},$$

where QED, EW, and Had denote the QED, electroweak, and hadronic contributions, respectively.



# Beyond–Standard Model Possibilities

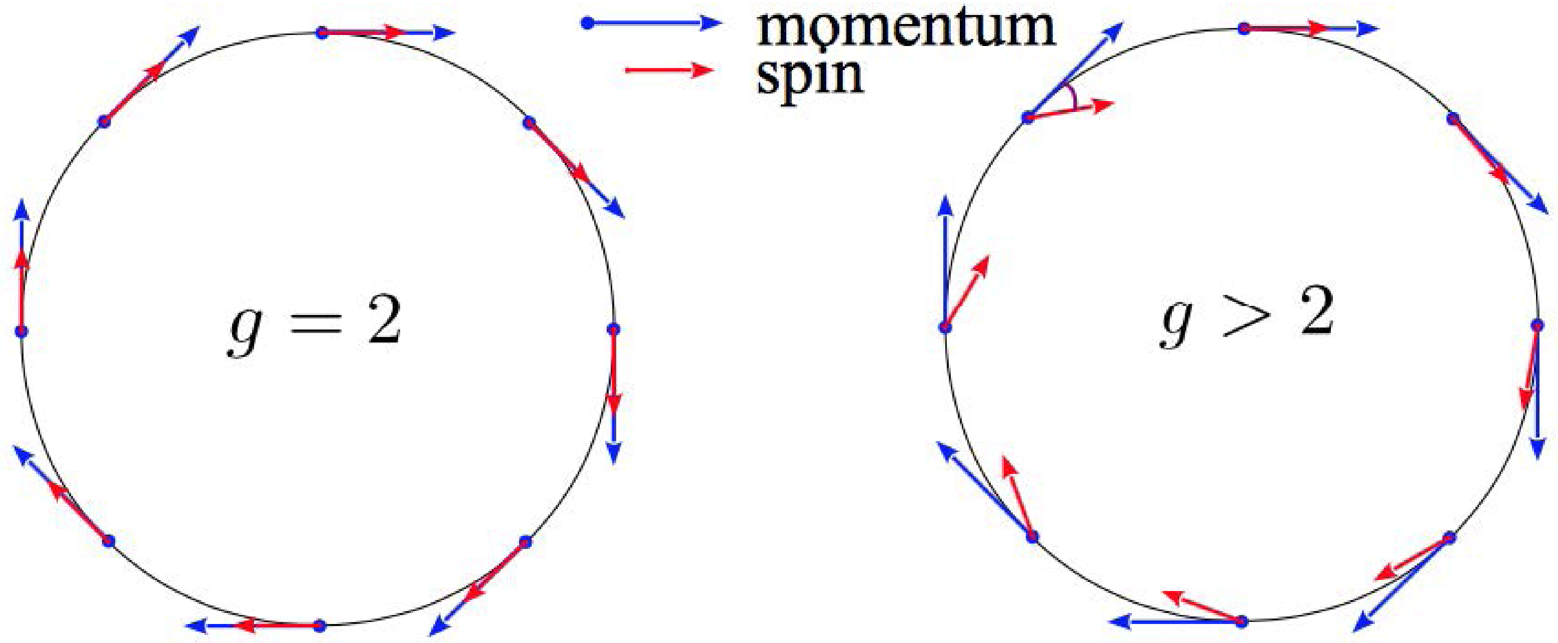
- With the SM's theoretical value of muon $g$–2 known up to 0.41 ppm, muon $g$–2 measurement experiments are are excellent for validation of the SM or discovery of new physics.
- If there is a discrepancy between theoretical and experimental values of muon $g$–2, explanations could include:
  - dark matter
  - supersymmetry (SUSY)
  - extra dimensions
  - additional Higgs bosons

# Previous Muon g-2 Experiments

- Nevis (~1957, ~1959)
- University of Liverpool (~1957)
- CERN I (1961): 4300 ppm
- CERN II (1962–1968), the first to use a storage ring: 270 ppm
- CERN III (1974–1976): 10 ppm
- BNL (1997–2001): 0.7 ppm

# Measurement of Muon g-2 Using a Storage Ring

The idea of muon $g$–2 measurement using a storage ring is as follows:




- Polarized muons are injected at the magic momentum $p = 3.09$ GeV/c, corresponding to $\gamma = 29.3$.
- At this momentum, the electrostatic term in the formula for muon's spin precession becomes zero:

$$\vec{\omega}_\mu = -\frac{Qe}{m}\left[a_\mu \vec{\mathbf{B}} - \cancel{\left(a_\mu - \left(\frac{mc}{p}\right)^2 \frac{\vec{\beta} \times \vec{\mathbf{E}}}{c}\right)}\right].$$

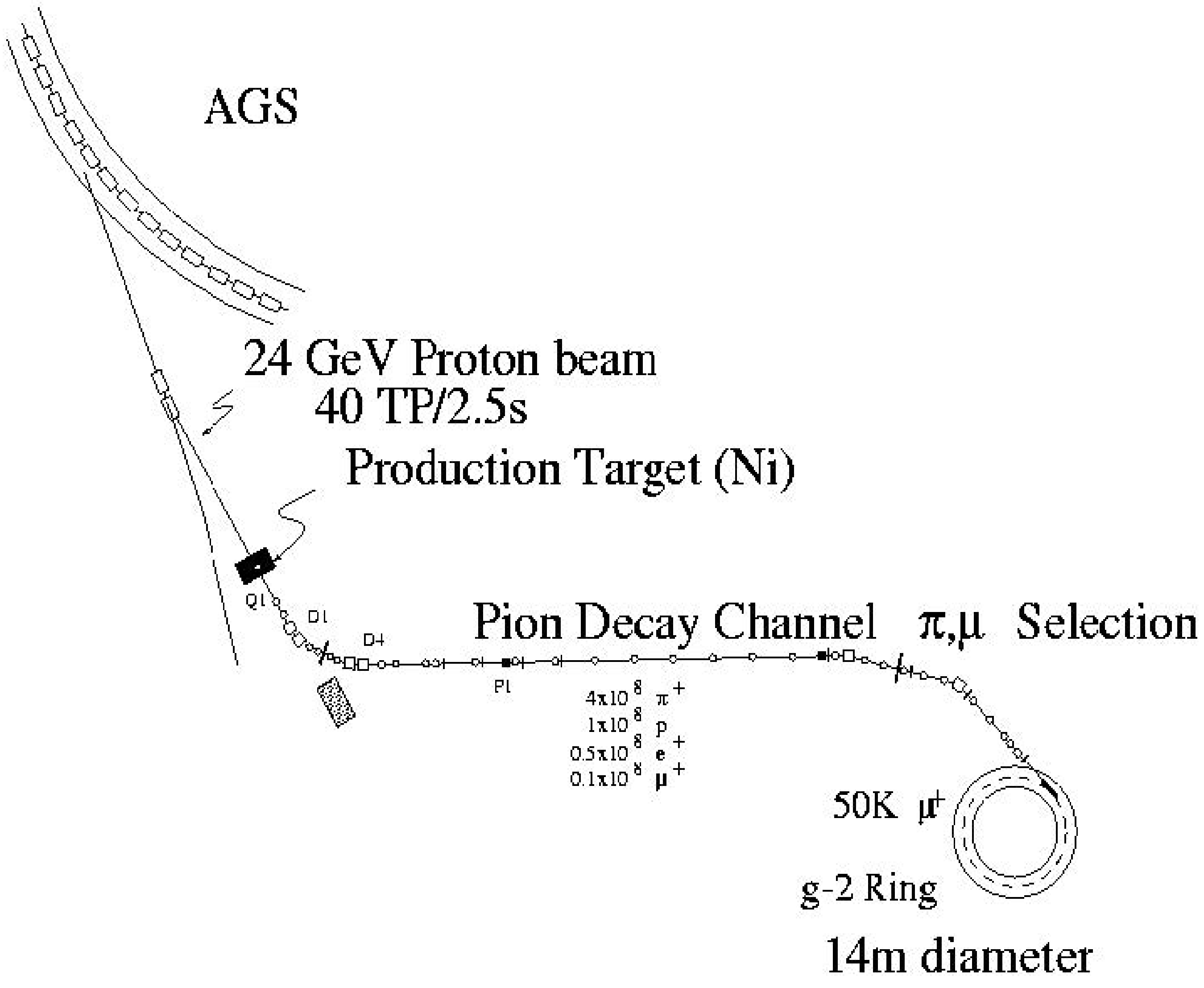
- As a result, the spin precession in the horizontal plane relative to the momentum becomes proportional to muon's anomalous MDM $a_\mu$, which is remarkably convenient.

# E821 Muon g-2 Experiment at BNL

- The Muon $g$–2 Experiment E821 at Brookhaven National Laboratory (BNL), completed in 2001, measured the muon anomalous MDM as

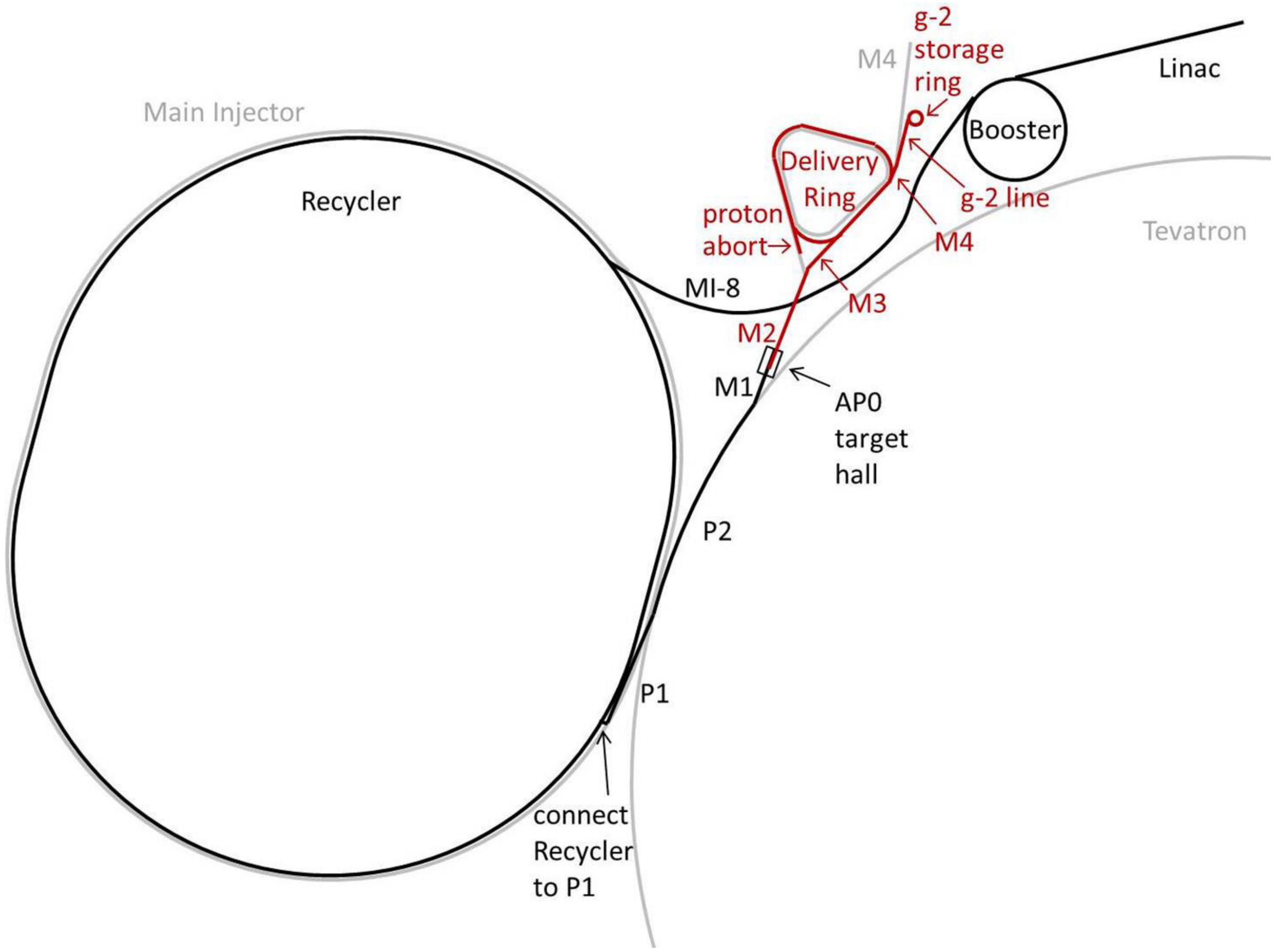
$$a_\mu^{\mathrm{E821}} = 116592089(63) \times 10^{-11}.$$

- The experimental uncertainty was 0.54 ppm — roughly twice the total SM uncertainty.
- The measured value was ~3.3$\sigma$ from the SM prediction.



# E989 Muon g-2 Experiment at Fermilab

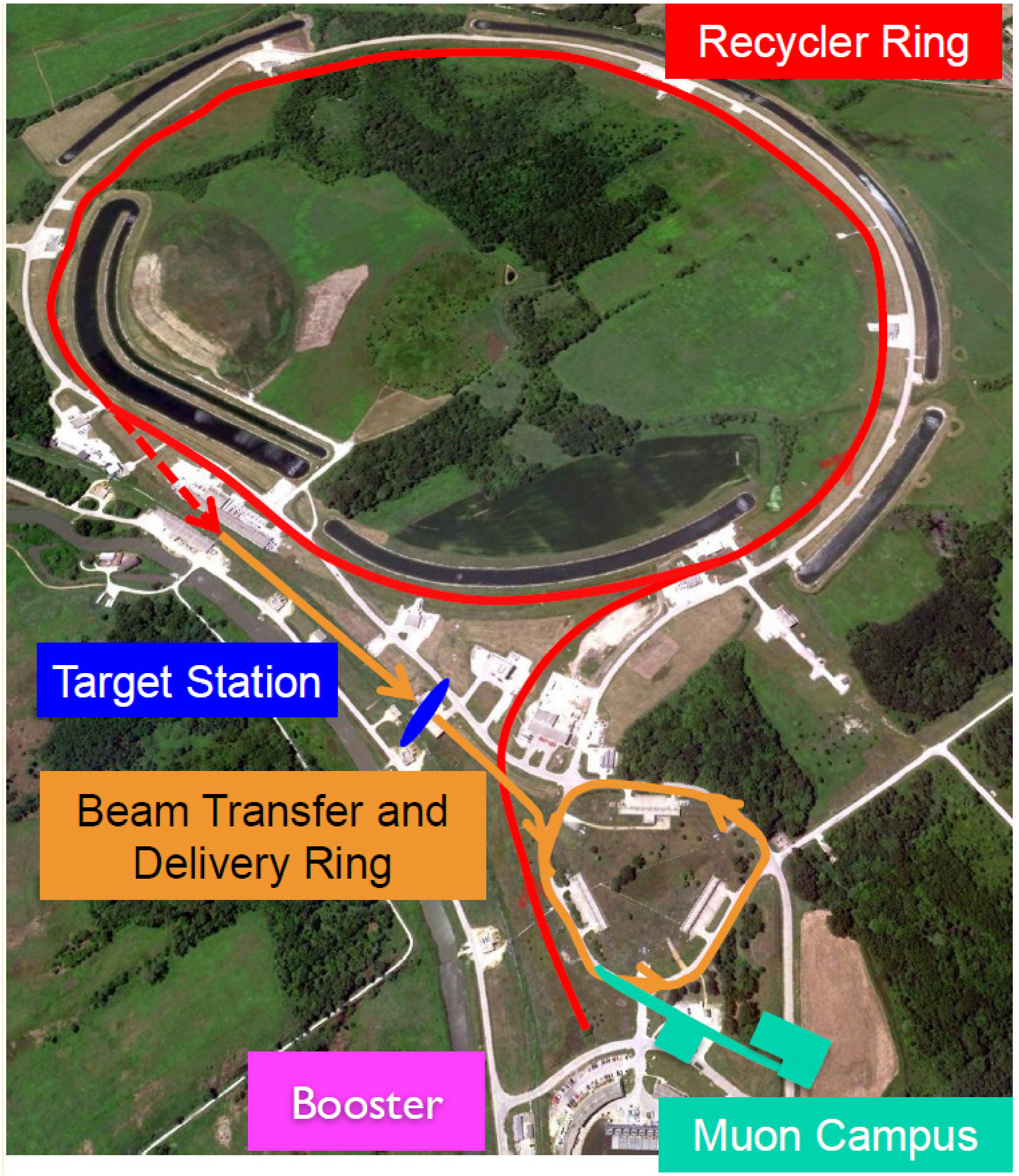
- The new Muon $g$–2 Experiment E989 at Fermilab aims to achieve 0.14 ppm experimental precision by
  - Accumulating 21 times more data than E821
  - Decreasing the systematic errors ~3-fold
- This should exceed the 5$\sigma$ discovery threshold.
- The final results are anticipated in ~2021.



# The Big Move in 2013


- The 15 m, 8 ton cryostat ring was moved in 2013 from BNL on Long Island, NY to Fermilab near Chicago, IL, in one piece by barge and truck.
- The 650 ton magnet iron yoke and pole pieces were disassembled and transported by truck.
- Despite the technical challenges, the move was a success.

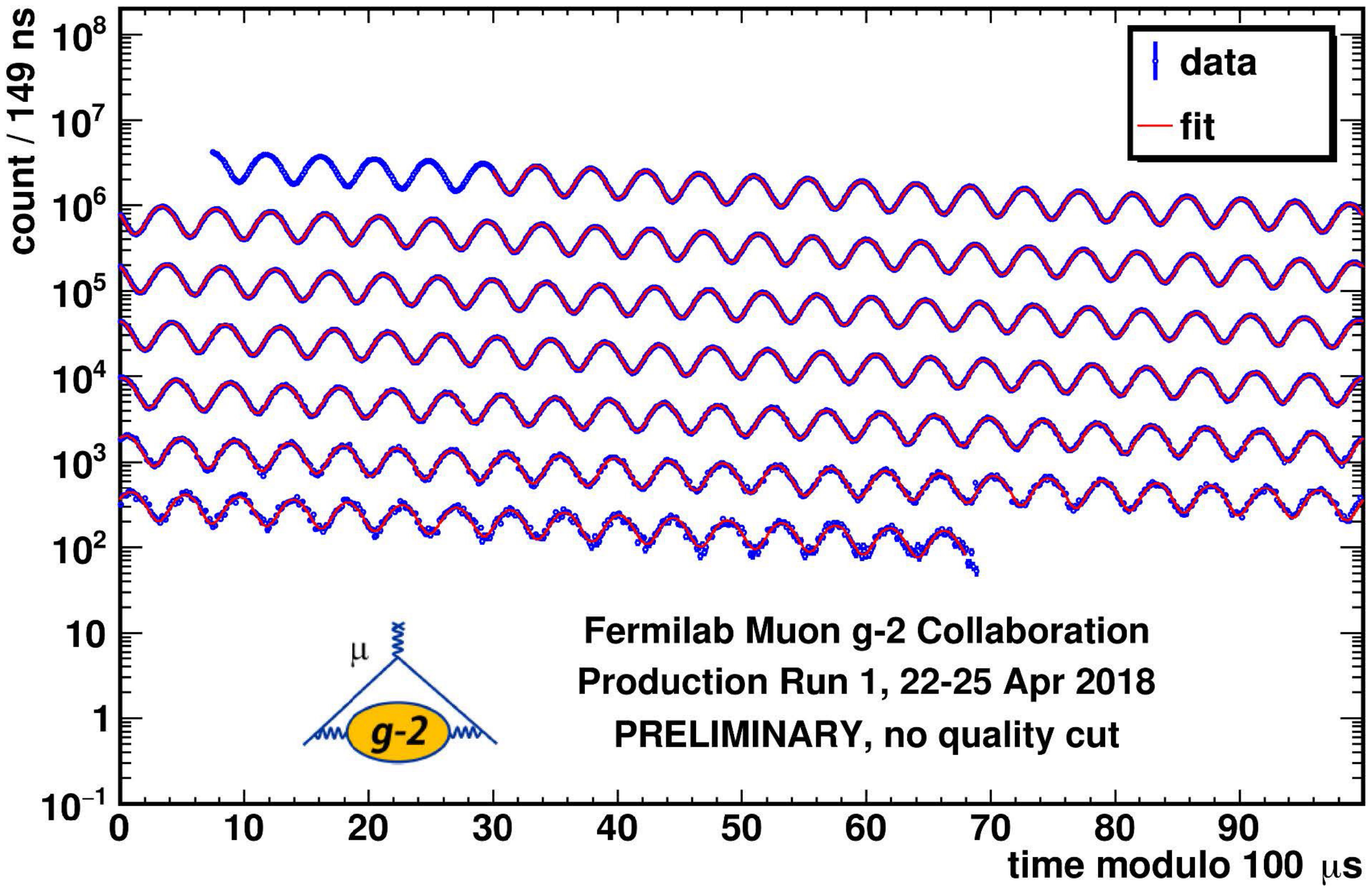
# The Muon g-2 Experiment E989 at Fermilab




1. 8 GeV protons from Booster are re-bunched in the Recycler Ring and are transported to the Muon $g$–2 Target Station.
2. Protons, impinging on an Inconel target, produce pions, which decay into muons in the M2M3 beamline and the Delivery Ring.
3. Protons are separated and removed in the Delivery Ring.
4. Muons are extracted from the Delivery Ring and transferred to the Muon $g$–2 ring via the M4M5 beamline.

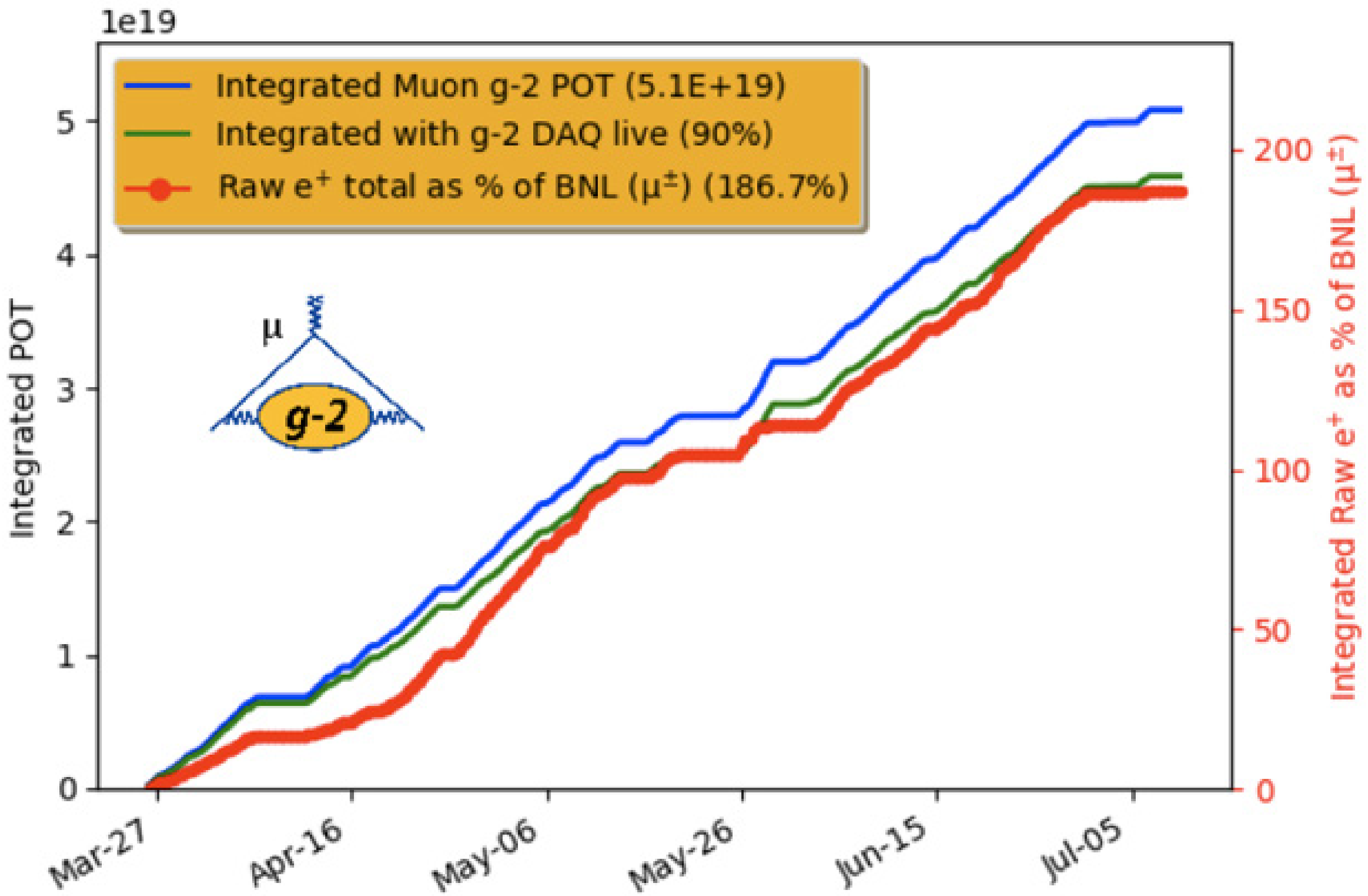
# The Muon g-2 Experiment E989 at Fermilab

5. After circling the Muon $g$–2 ring ~400 times on average, muons spontaneously decay into positrons, as well as neutrinos.
6. Due to the P violation of muon decay, positrons are preferentially emitted in the direction of the muon's spin.
7. The positrons are recorded by straw trackers and 24 calorimeter stations.
8. The so-called Wiggle plot (figure on the right) reflects the time dependence of muon's spin angle.



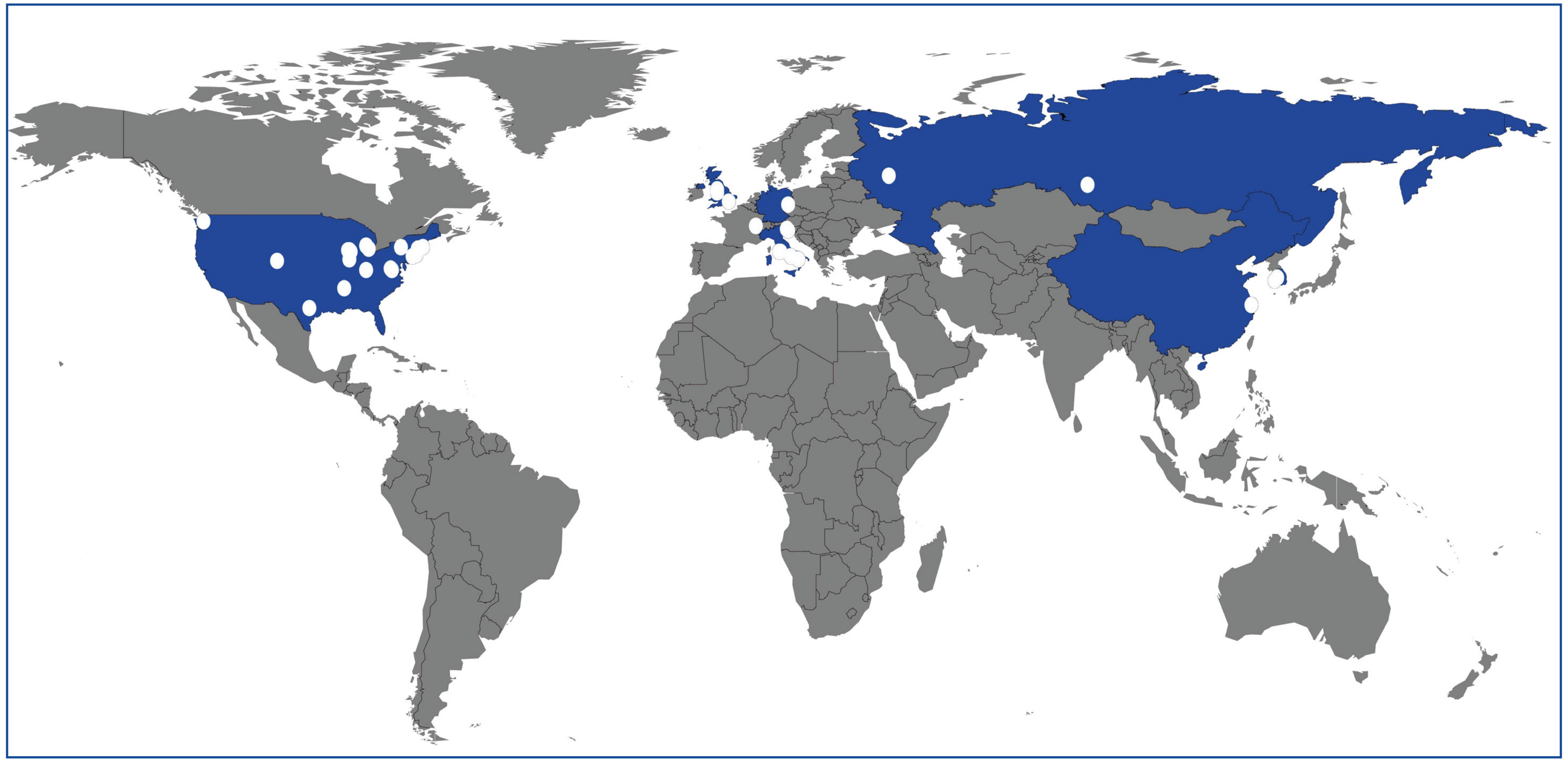
# Run 1 Statistics

- Muon $g$–2 Experiment's Run 1 was completed in 2018.
- About 200% more integrated raw positron data was recorded compared to BNL.
- An accumulated luminosity plot for Run 1 is in the figure on the right.
- Run 2 is currently ongoing, and additional runs are scheduled and discussed for the future.



# The Muon g-2 Collaboration

*7 Countries 33 Institutions 203 Collaborators*



Member institutions representing the UK are:

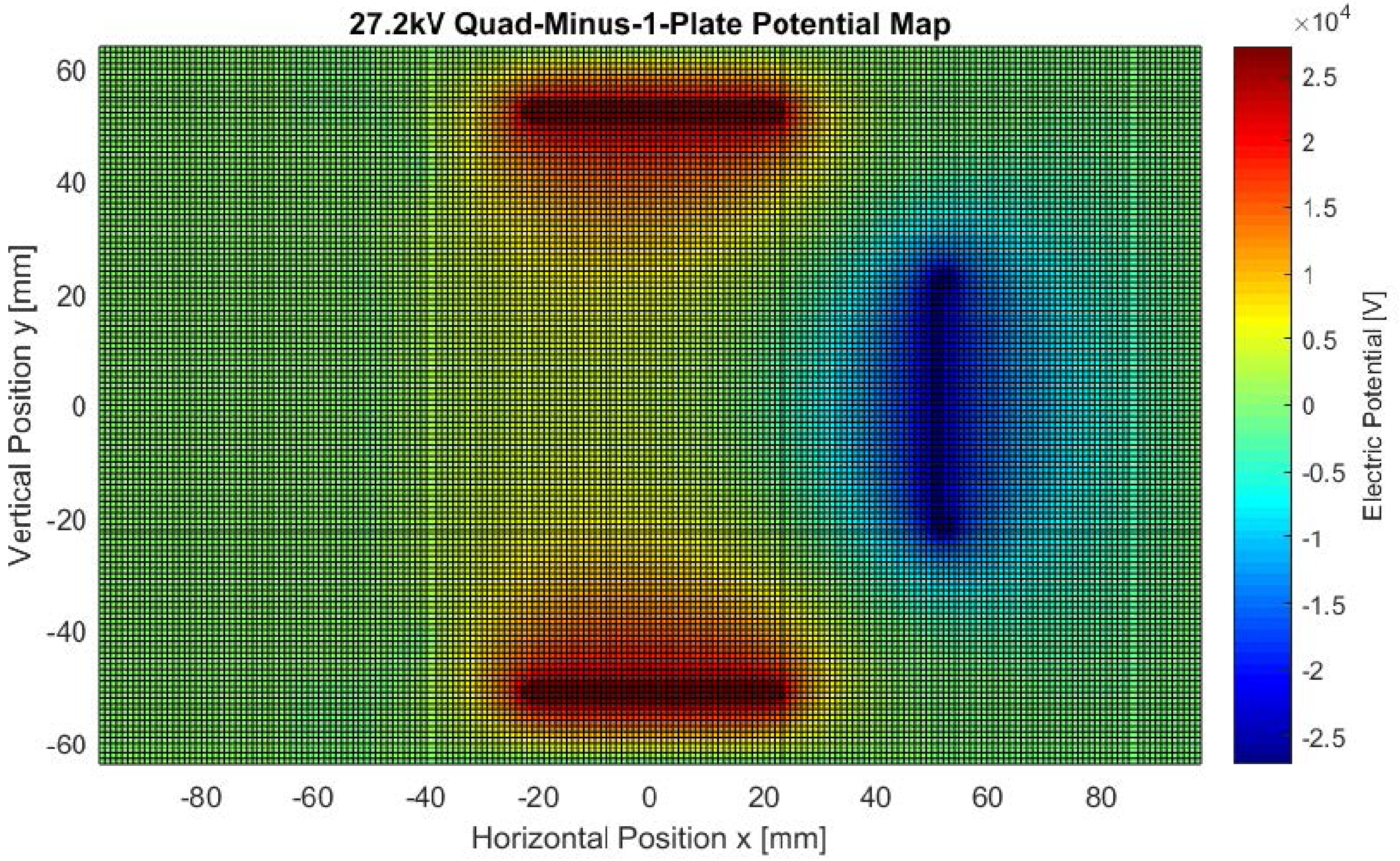
- Lancaster University (**I. Bailey**, **M. Korostelev**, and **E. Valetov**)
- University College London (S. Al-Kilani, R. Chislett, S. Grant, G. Hesketh, M. Lancaster, G. Lukicov, E. Motuk, T. Stuttard, and M. Warren)
- University of Liverpool (T. Albahri, T. Bowcock, J. Carroll, T. Halewood-Leagas, **A.T. Herrod**, B. King, S. Maxfield, J. Price, D. Sim, A. Smith, T. Teubner, K. Thomson, W. Turner, M. Whitley, **A. Wolski**, M. Wormald)

*Authors, including legacy authors, are listed in parentheses.*
*Cockcroft Institute affiliates are in **bold**.*

# Alexander Herrod

## University of Liverpool and the Cockcroft Institute

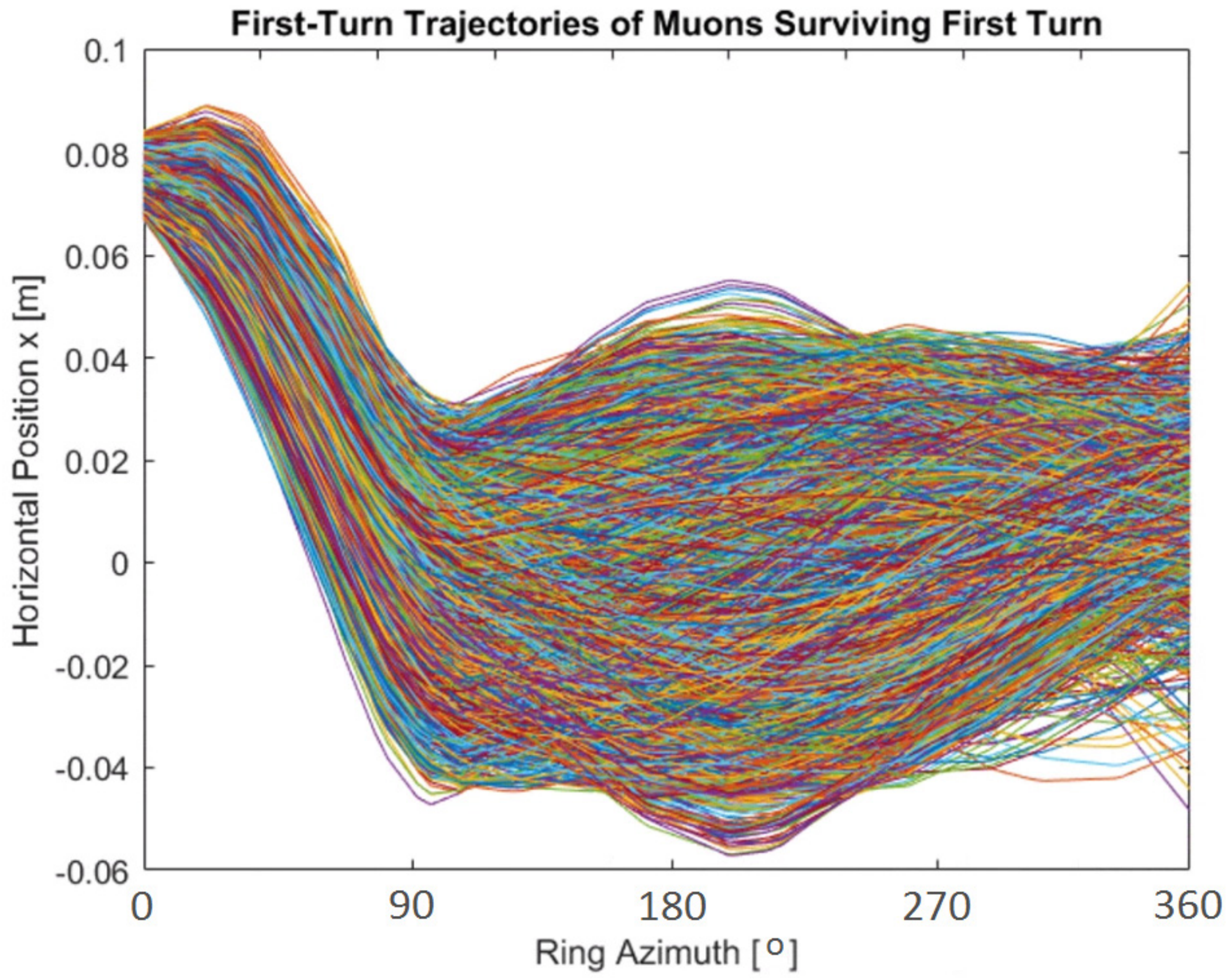
- Together with Andy Wolski, developed an explicit symplectic integrator for tracking in electric and magnetic fields with longitudinal dependence and a curved reference orbit [*Phys. Rev. Accel. Beams* **21**, 084001 (2018)].
- Used Bessel functions and toroidal multipoles to model the fringe field of Muon *g*–2 storage ring's electrostatatic quadrupoles.
- Performed experimentally verified tune calculations for the Muon *g*–2 storage ring using a continuous field representation.



# Alexander Herrod

University of Liverpool and the Cockcroft Institute

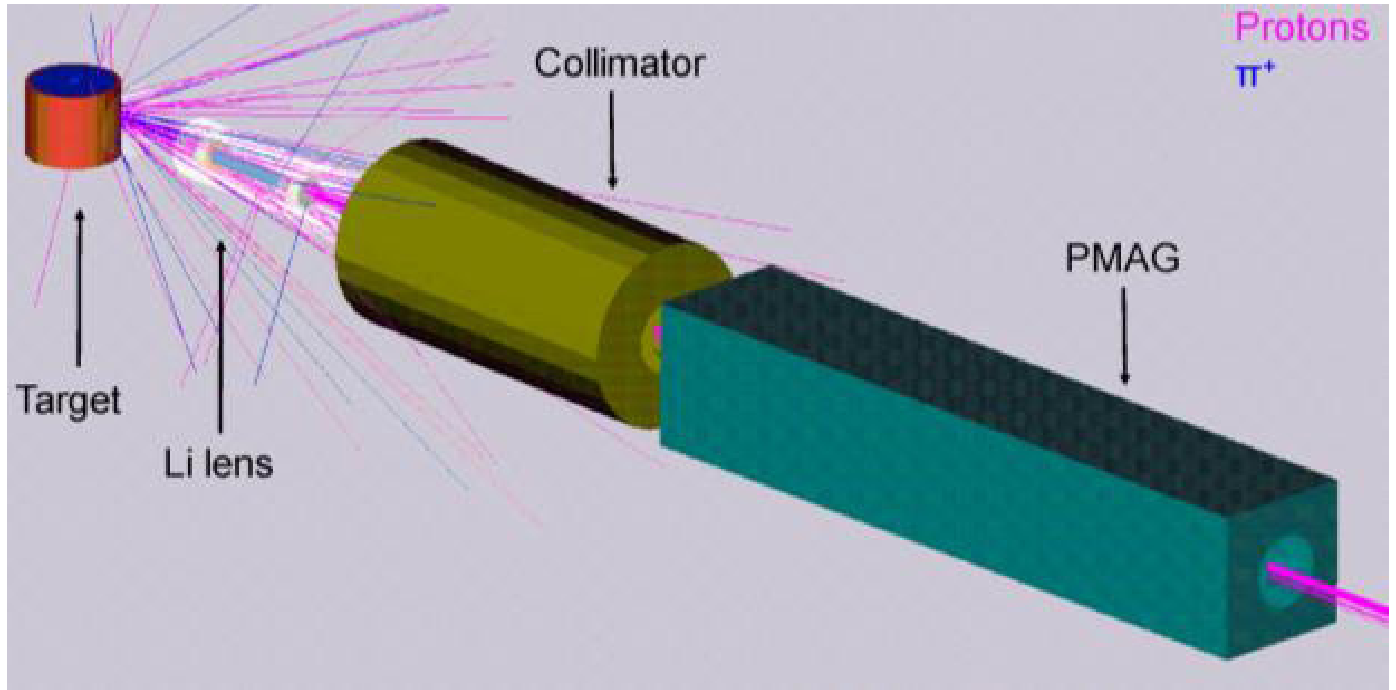
- Developed a BMAD model of the Muon $g$–2 storage ring, with full field maps (including behind quadrupole plates), measured positions of particle optical elements, and time-dependent kickers.
- Performed injection modeling and studied injected muons surviving after $n$ turns in the ring.
- Simulated RF scraping using mispowered quadrupole plates.
- Discussing further studies such as optimizing Twiss parameters at storage ring injection.
- Writing thesis — scheduled submission soon.



# Eremey Valetov

Lancaster University and the Cockcroft Institute*

- Simulated the Muon $g$–2 Target Station, the M2M3 and M4M5 beamlines, and the Delivery Ring (DR) using the codes G4Beamline and BMAD, and analyzed the polarization differences between muon populations born in different beamlines at the entrance of the Muon $g$–2 storage ring.
- Recently implemented several versions of the inflector magnet map to join the beamline simulations toAlex Herrod's BMAD model of the Muon $g$–2 storage ring, for *complete end-to-end* simulations.
- Will study the systematics of muons born at different locations on the experimental result for muon $g$–2.




Muon $g$–2 Target Station (AP0).

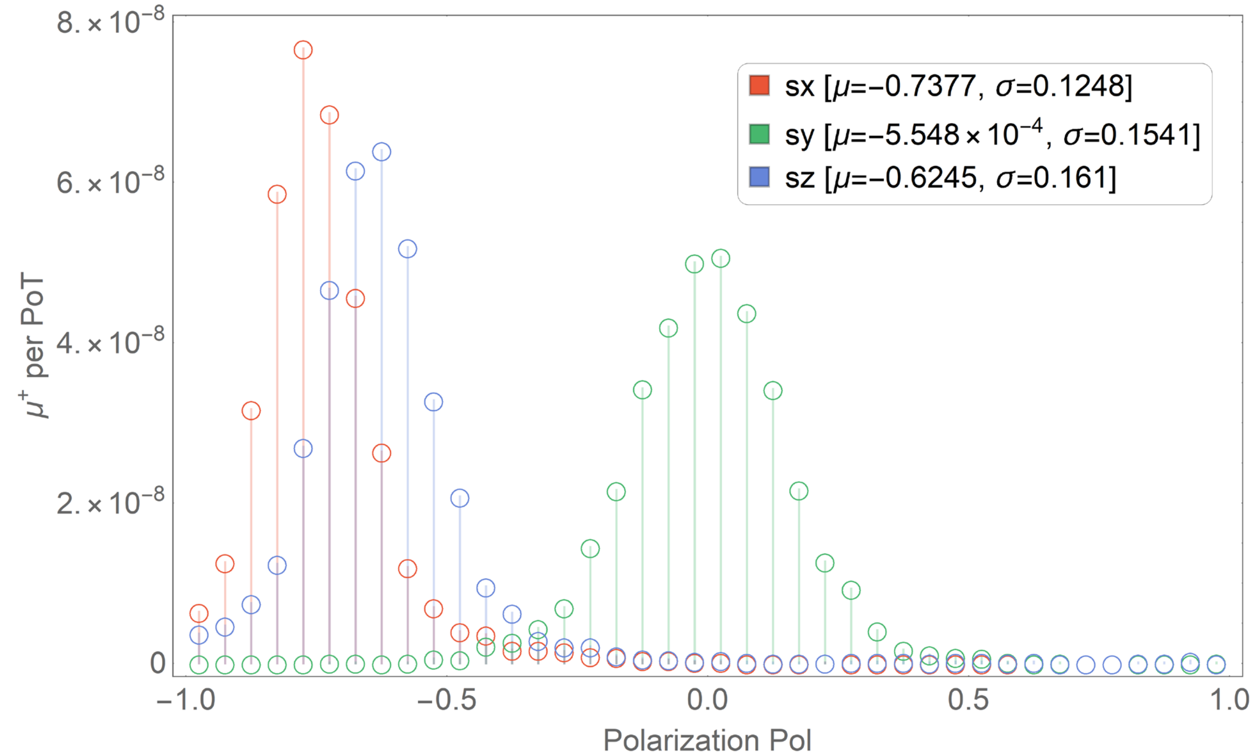
* Joined in September 2018. Prior to that was part of the collaboration through *Michigan State University*.

# Eremey Valetov

## Lancaster University and the Cockcroft Institute

*Recent preliminary result:*

- Most muons are produced in the M2M3 beamline and the first turn through the DR — 69% and 21% after 4 turns in the DR, respectively. The contribution of muons born in the Muon $g$–2 Target Station to the muon polarization statistics is low:
    - G4Beamline: 7% in the DR after 4 turns in the DR
    - BMAD: 8% at the end of the M4M5 beamline after 4 turns in the DR



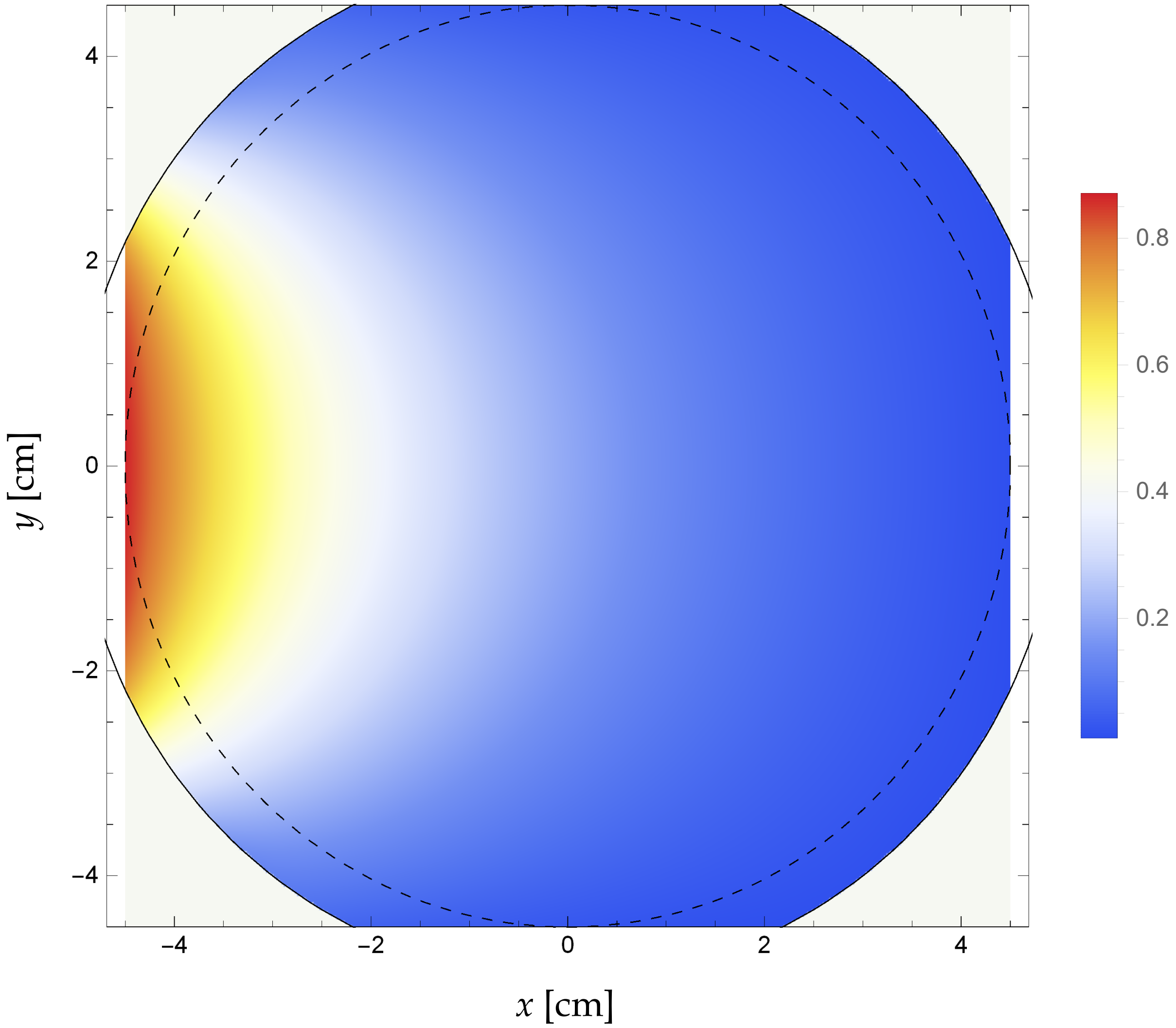

Histogram of x, y, and z polarization components of muons born in the M2M3 beamline recorded at the end of the M4M5 beamline after 4 turns in the Delivery Ring.

- There is a good agreement of muon polarization histograms produced for 1–4 turns through the DR using G4Beamline and BMAD.

# Eremey Valetov

Lancaster University and the Cockcroft Institute

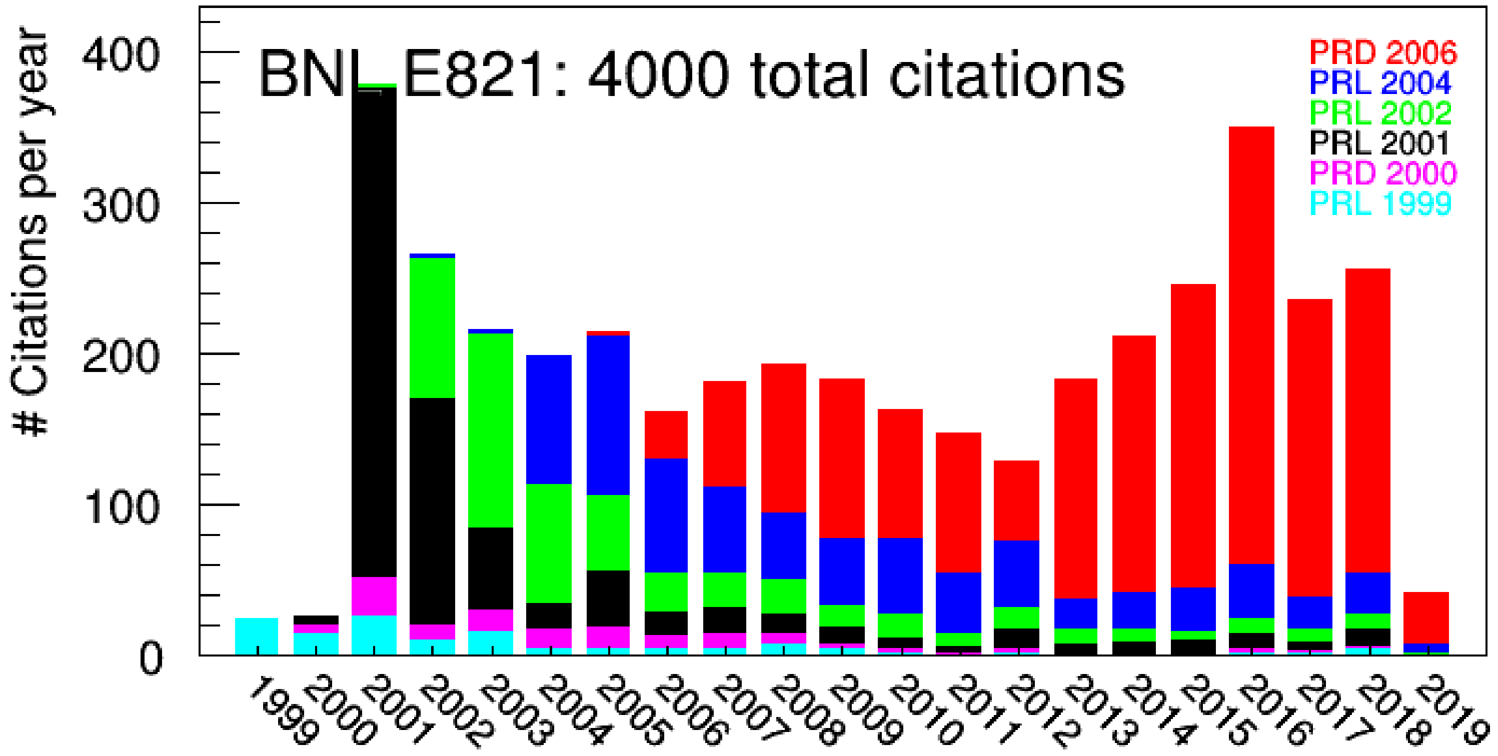
- In the previous years, developed a highly accurate and fully Maxwellian conformal mappings method for calculation of main fields of electrostatic particle optical elements.
- An advantage of this method is the possibility of rapid re-caclulations with geometric asymmetries and mispowered plates.
- Used this method to calculate the multipole terms of the Muon $g$–2 storage ring quadrupole.
- Extracted multipole strength falloffs of the quadrupole, which, together with the so-called oomph effect, resulted in a consistency between calculated and experimentally measured horizontal tunes.




A heatmap plot of the multipole expansion of the electrostatic potential of the Muon $g$–2 quadrupole in case of one plate at 1 V and other plates at 0 V.

# Research Impact

- Alex Herrod's and Eremey Valetov's field models for the Muon $g$–2 collaboration quadrupole, beamline modelling, and tunes calculations contribute to accurate simulations and analysis in the Muon $g$–2 Experiment at Fermilab.
- Eremey Valetov's studies of the correlations between the phase space coordinates of muon creation and its spin, as well as the effect of spin differences between different muon population on the measured muon anomalous MDM are necessary for the error analysis part of the main results of the Experiment.




BNL's E821 Muon $g$–2 Experiment is achieving up to ~400 citations per year.

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# Thank You



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