Muon g-2 at Fermilab: Current status and outlook

Dominika Vasilkova (on behalf of the Muon g-2 collaboration)

Lake Louise Winter Institute

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The magnetic moment of the muon

- Charged particle in B field interacts via intrinsic magnetic moment:

$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

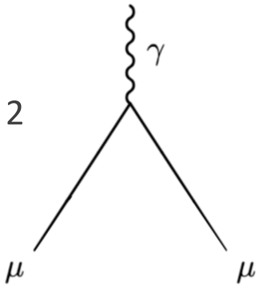
- Dirac equation predicts g = 2 for spin ½ particles, but virtual particles in loops lead to corrections: **g > 2**.

- Unique indirect way to test precision of SM!

  - We define the 'anomalous magnetic moment' and measure that: $a_\mu = \frac{g-2}{2}$

Theoretical predictions

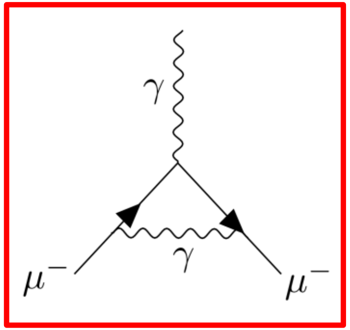
g = 2



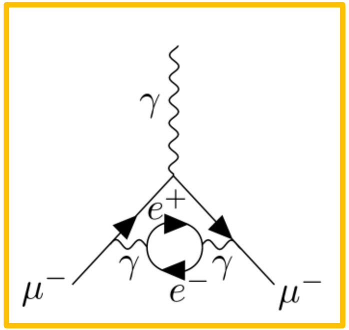
$$a_\mu\ (\mathrm{SM}) = 116591810(43) \times 10^{-11}$$

(Muon g-2 theory initiative: WP2020)

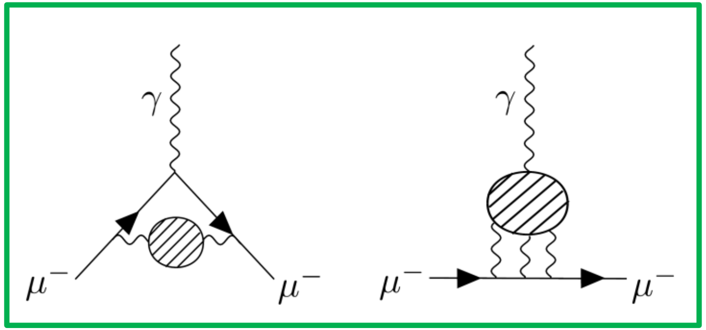
1st Order QED (Schwinger)



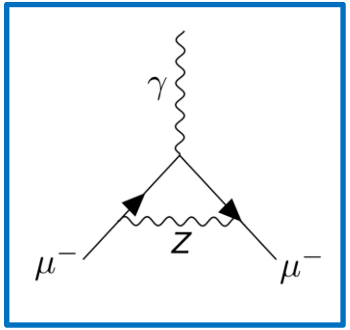
Higher order QED (Vacuum polarization)



Hadronic (HVP or HLBL)



Electroweak



Uncertainties: ~ 0.1×10^{-11}

HVP: ~ 40×10^{-11} HLBL: ~ 19×10^{-11}

~ 1×10^{-11}

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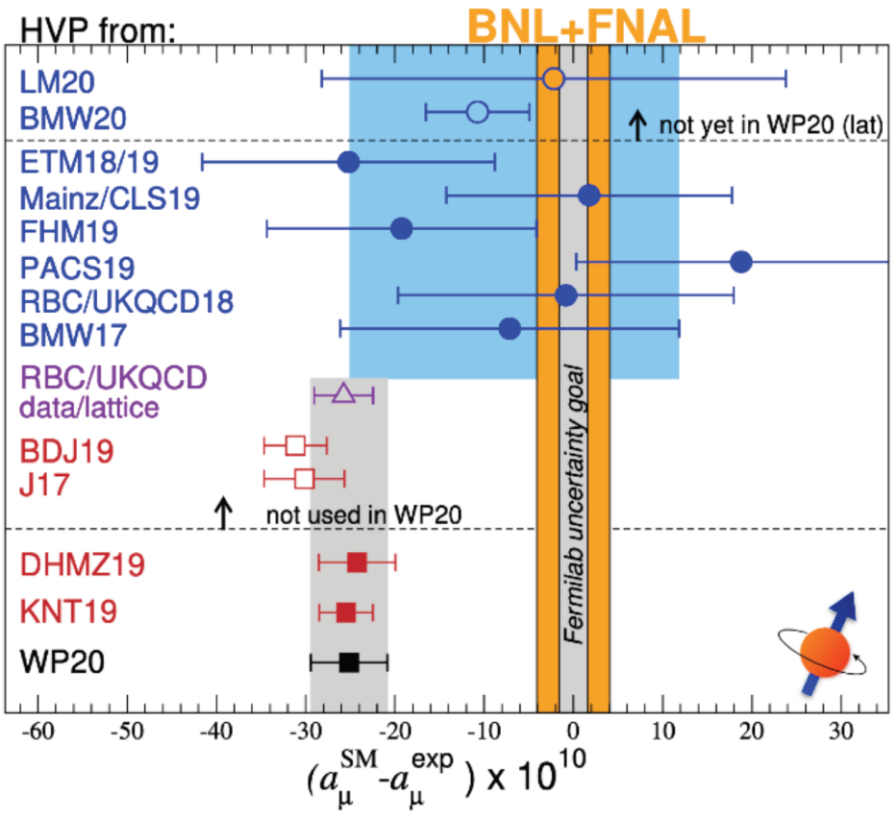
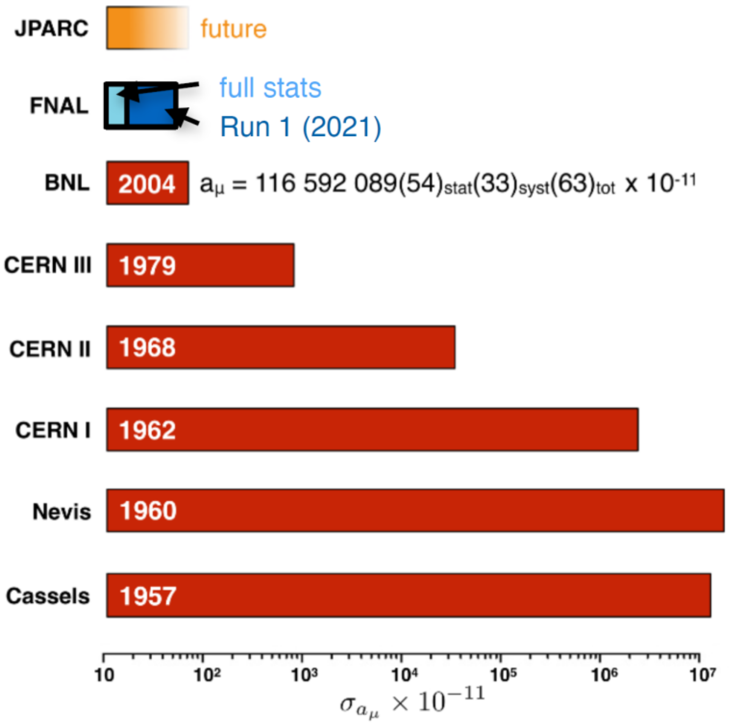
Theoretical predictions

- Uncertainty dominated by HVP.
- Two methods to get this – dispersive methods, and lattice.
- Growing tension between the two – allows for a 3-way comparison.



Experimental measurements

- Previous best measurement at Brookhaven National Laboratory – 3.7σ discrepancy with SM.
- Aim at FNAL is to redo measurement with 4x better precision (140ppb).
- Future measurement also planned at JPARC.



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Measuring a_μ in a storage ring

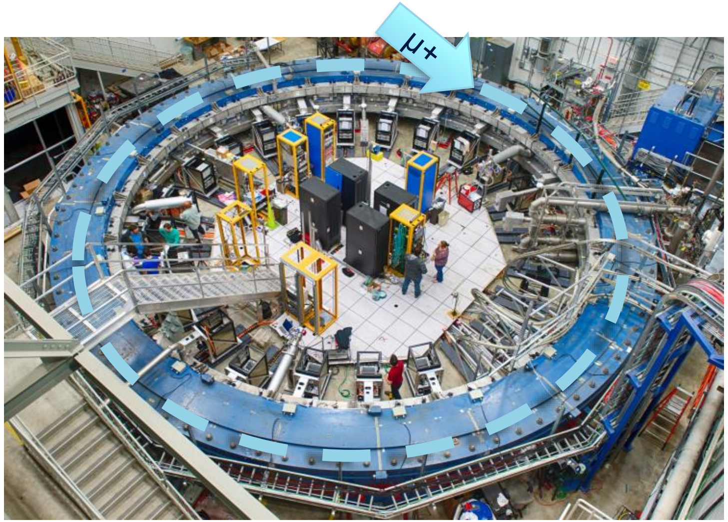
- Beam of polarized muons in a storage ring, 1.45 T vertical B field.
- Two oscillations: cyclotron frequency and spin precession. Measure the difference:

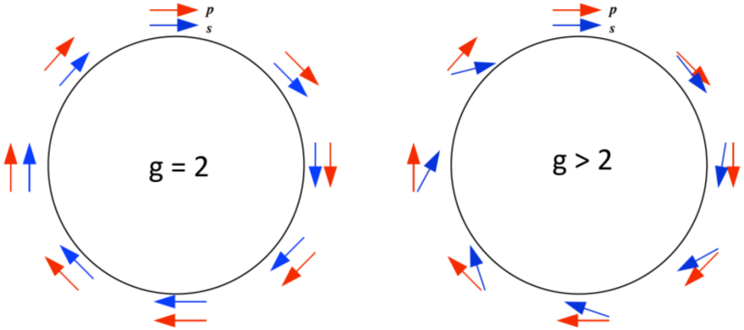
$$\omega_a = \omega_s - \omega_P \cong a_\mu \frac{eB}{m_u}$$

- If we also measure the field to high precision: can extract a_μ.

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

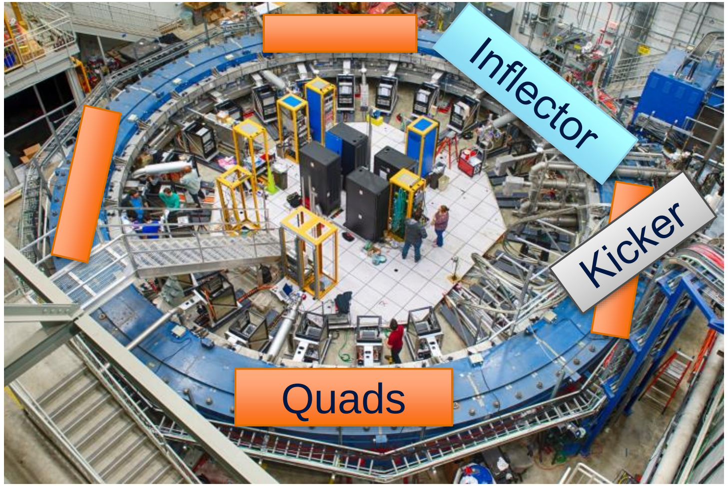
Measured by us | Measured by other experiments

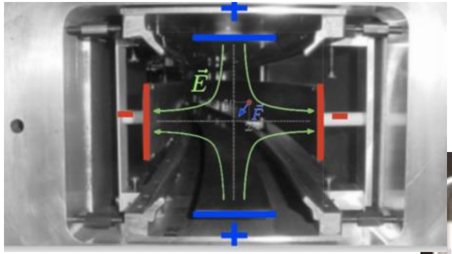


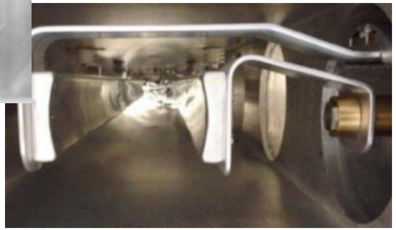


Storage

- Magnet: Radial focusing.
- Inflector: Prevents large beam deflections.
- Kicker: Pushes incoming beam onto equilibrium orbit.
- Electrostatic quadrupoles: vertical focusing.







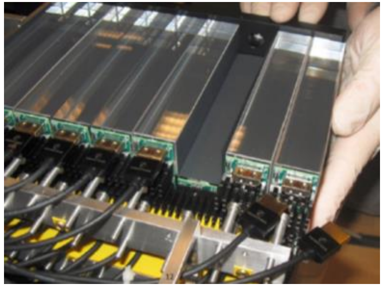
0 when in a flat plane

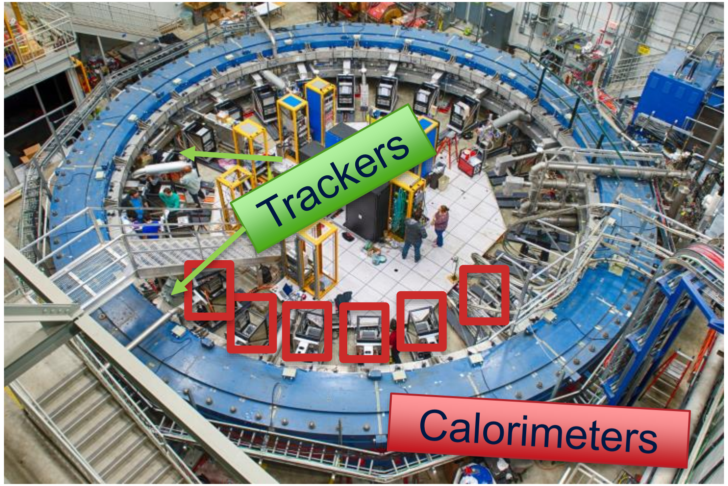
$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

0 at the ‘magic momentum’ = 3.094 GeV

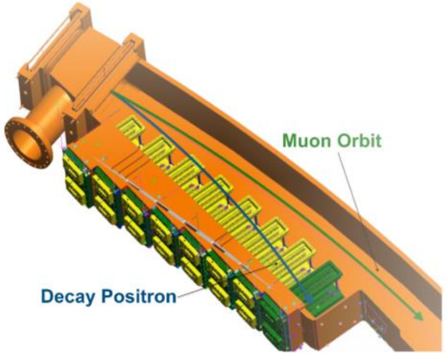
Measurements

- 24 PbF_2 calorimeters around inside of ring
  - 54 crystals read by SiPMs
  - Laser calibration





- 2 straw tracker stations
  - 8 modules per station, 4 x 32 straws Ar:C_2H_6
  - Beam dynamics and muon distribution
  - Bonus analyses: e.g. muon EDM



Our 'master formula'

blinding factor | precession | beam dynamics corrections

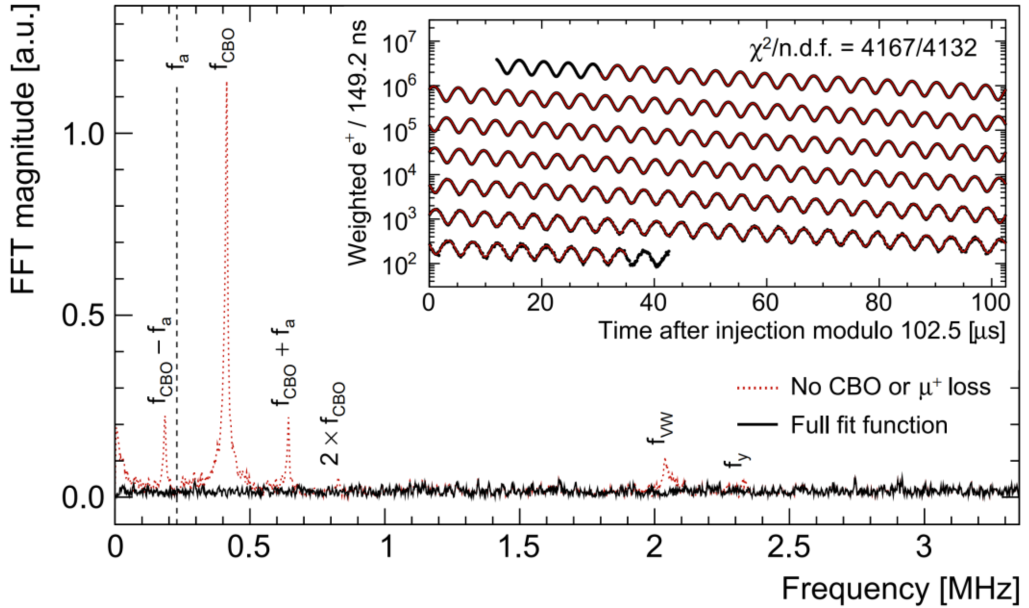
$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_K + B_Q\right)}$$

absolute field calibration | magnetic field sampled by the muon distribution | Magnetic transients corrections

Blinding, extracting ω_a

$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_K + B_Q\right)}$$

- To avoid bias, we blind the frequency at a hardware and software level.
- Parity violating decay – high E e^+ emitted preferentially along spin direction.
- ω_a extracted from the wiggle plot using a 22-parameter fit.



Beam dynamics corrections

$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}}\,\omega_a^{\text{meas}}\left(1+C_e+C_p+C_{ml}+C_{pa}\right)}{f_{\text{calib}}\left\langle \omega'_p(x,y,\phi)\times M(x,y,\phi)\right\rangle\left(1+B_K+B_Q\right)}$$

- E-field correction (C_e) and pitch correction (C_p):

0 when in a flat plane

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

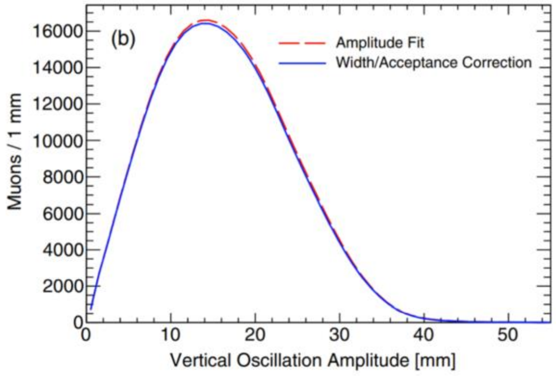
0 at the 'magic momentum' = 3.094 GeV

Spread in muon momentum values, vertical betatron oscillations make these not exactly 0

- Muon loss (C_{ml}) and Phase acceptance (C_{pa}).

  Lost muons have a different phase, any time dependence in phase can bias ω_a

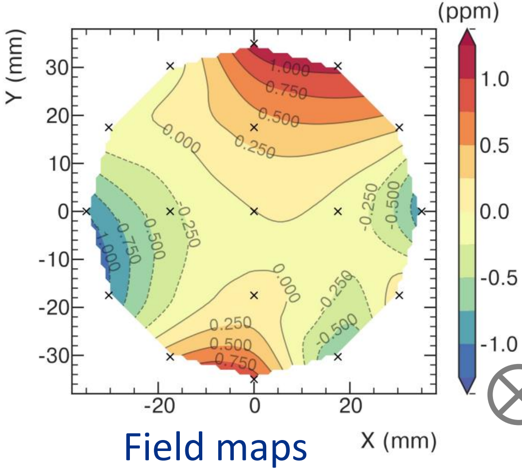
- Quantify these using tracker data/MC simulation.



Field measurements

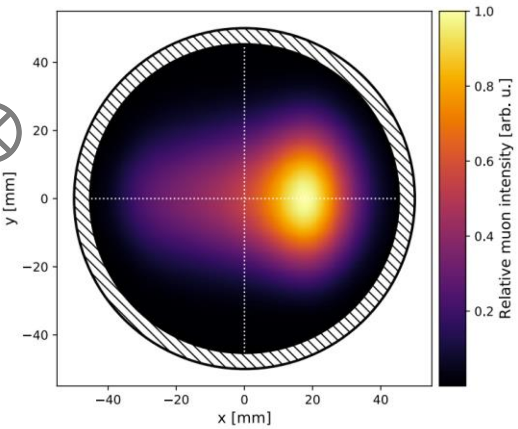
$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_K + B_Q\right)}$$

- Field calibrations with external H_20 probe.
- Trolley measures field maps, then fixed probes monitor in between trolley runs.
- Need to know what field the muon beam sees: so convolute with the muon beam from the trackers.



Field maps

Muon distribution



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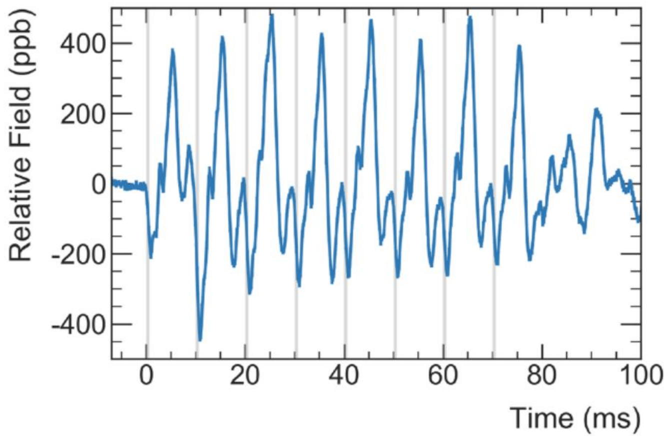
Field transients

$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_K + B_Q\right)}$$

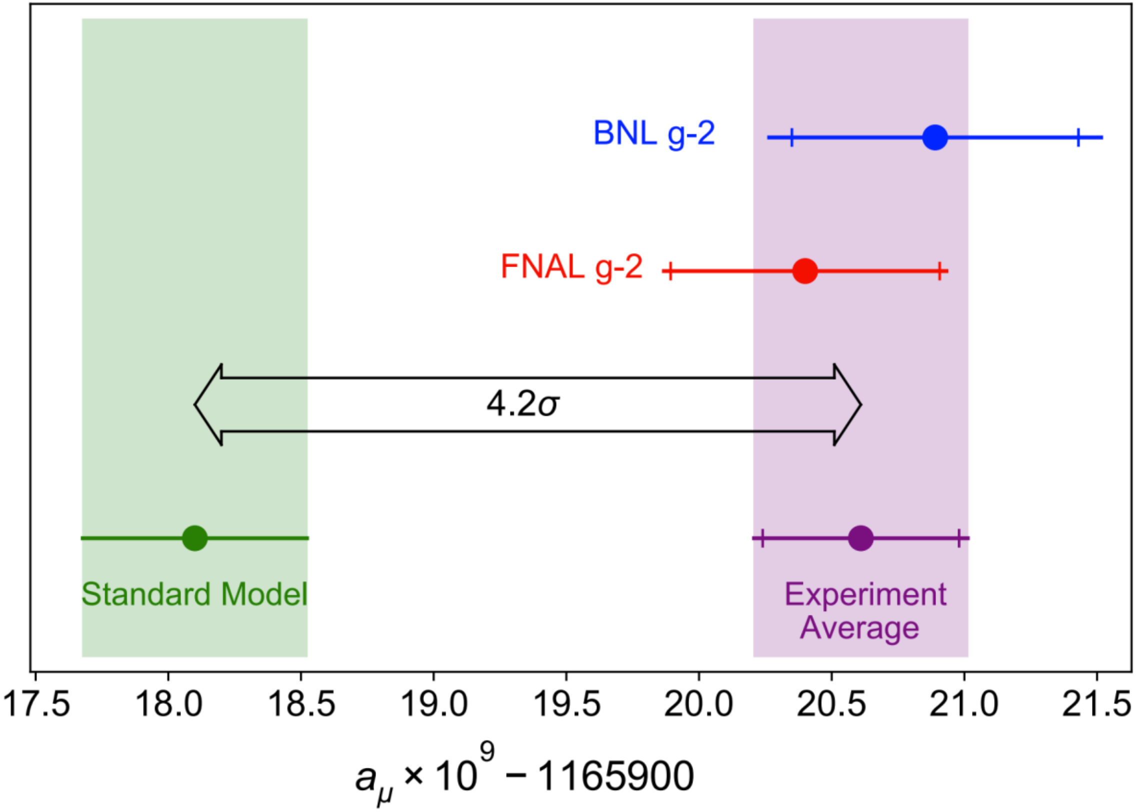
- Kickers and Quadrupoles both perturb the field:
  - Quads introduce a mechanical vibration when charging/discharging
  - Kickers cause eddy currents

- Quad transient very important in Run 1:



The Run 1 result

- First 6% of our data.
- 1st FNAL result is consistent with BNL measurement!
- Discrepancy between SM (WP2020) and experiment rises to 4.2 σ.



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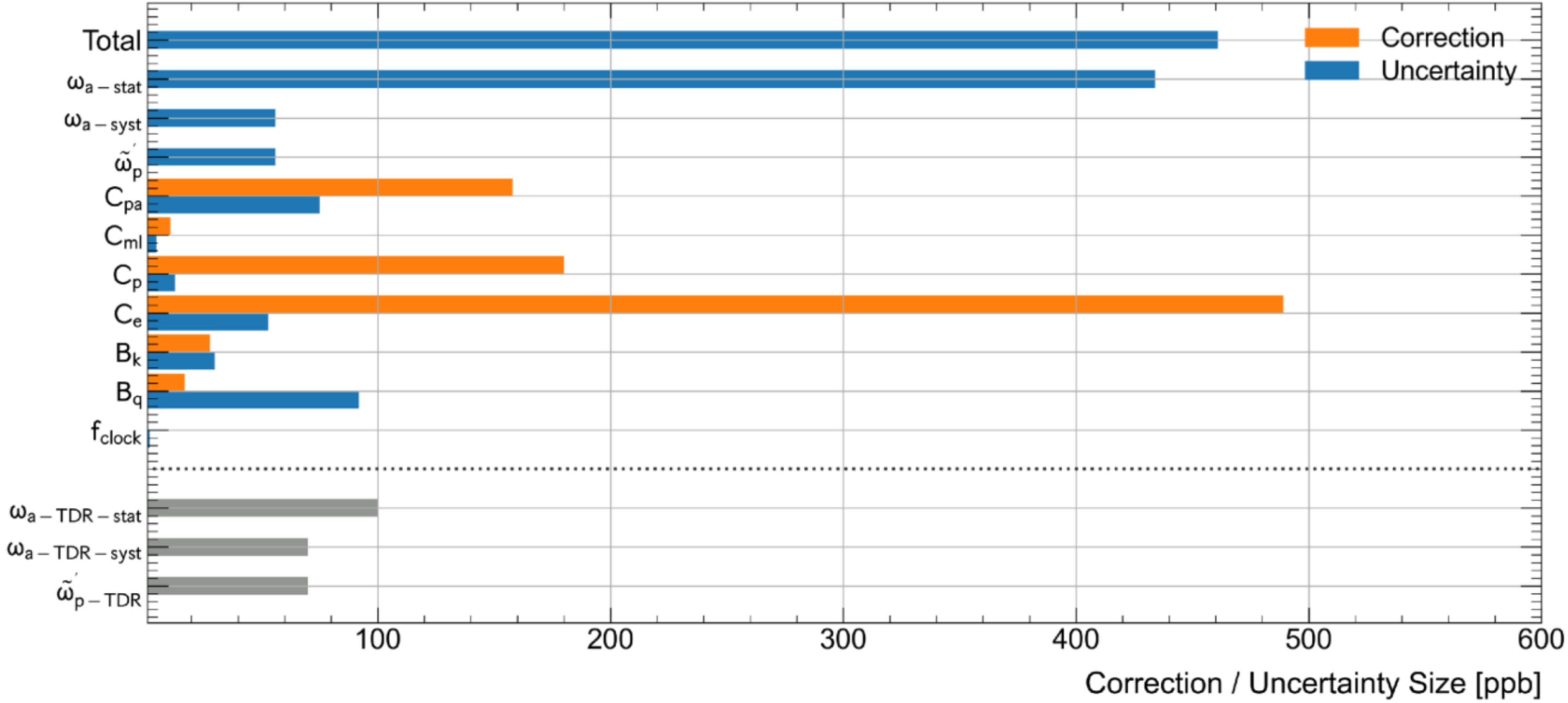
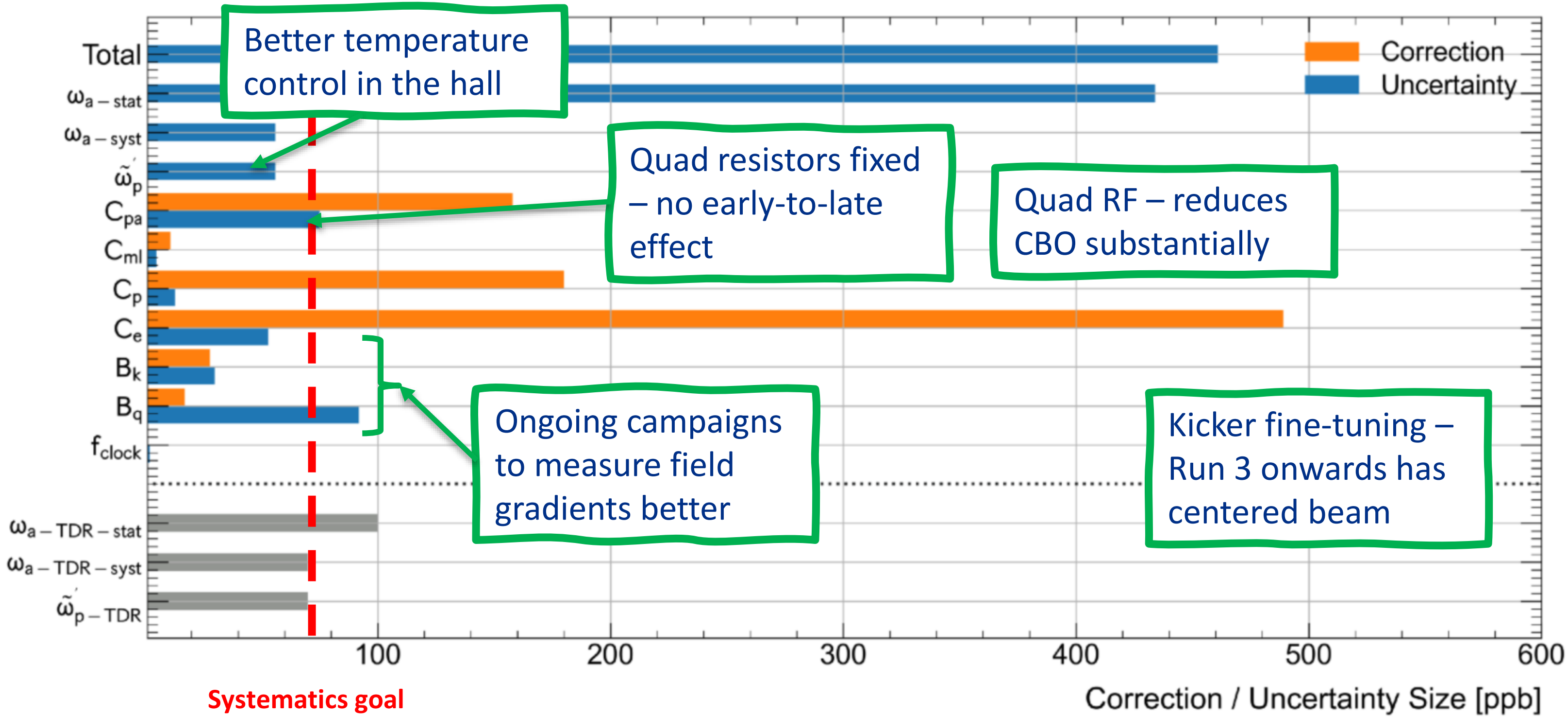
Everything measured to excruciating detail!

- Run 1 is statistically limited, but important to fully understand systematics.

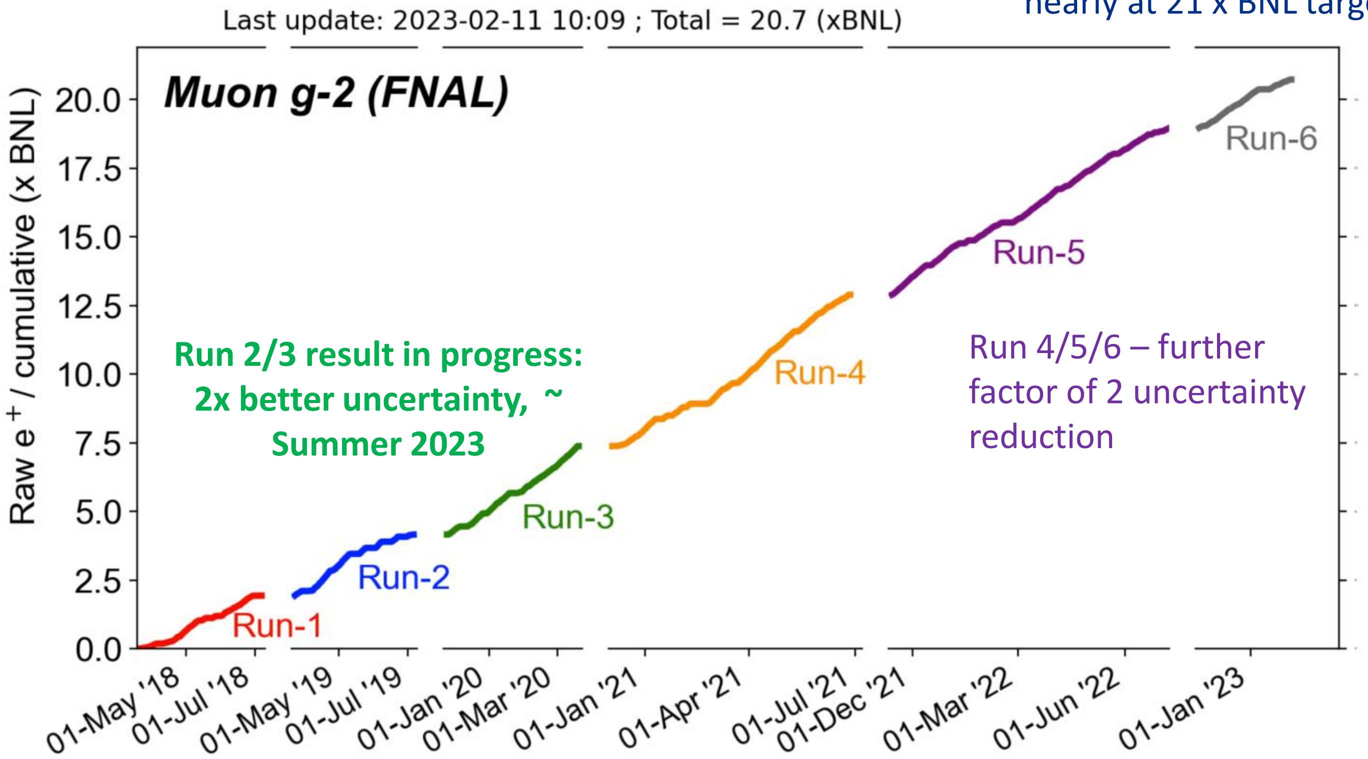


Improvements for Run 2/3 onwards



Looking to the future: Run 2/3 and beyond

Run 6 data collection ongoing: nearly at 21 x BNL target - μ^+



Run 2/3 result in progress: 2x better uncertainty, ~ Summer 2023

Run 4/5/6 – further factor of 2 uncertainty reduction

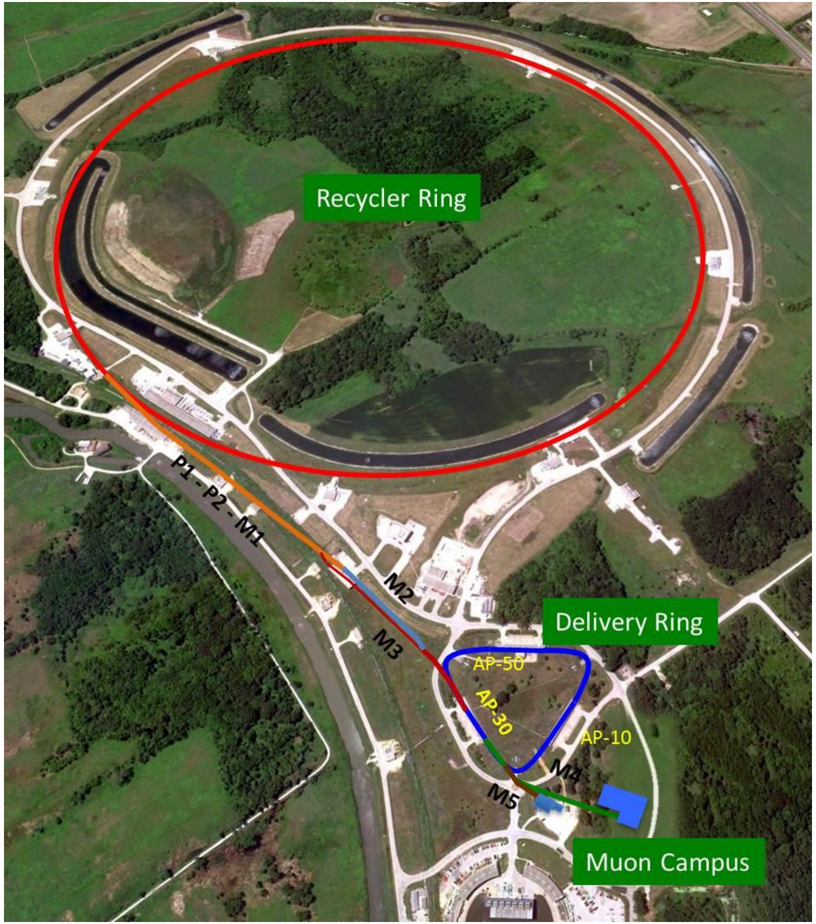
Thank you!

dominika@fnal.gov

Bonus slides

The muon campus beamline

- Protons incident on a target make pions.
- Pions are stored in the delivery ring until they decay into muons.
- Muons injected into our ring.



Where do all the parts come from?

Hydrogen maser measurements (11ppb)

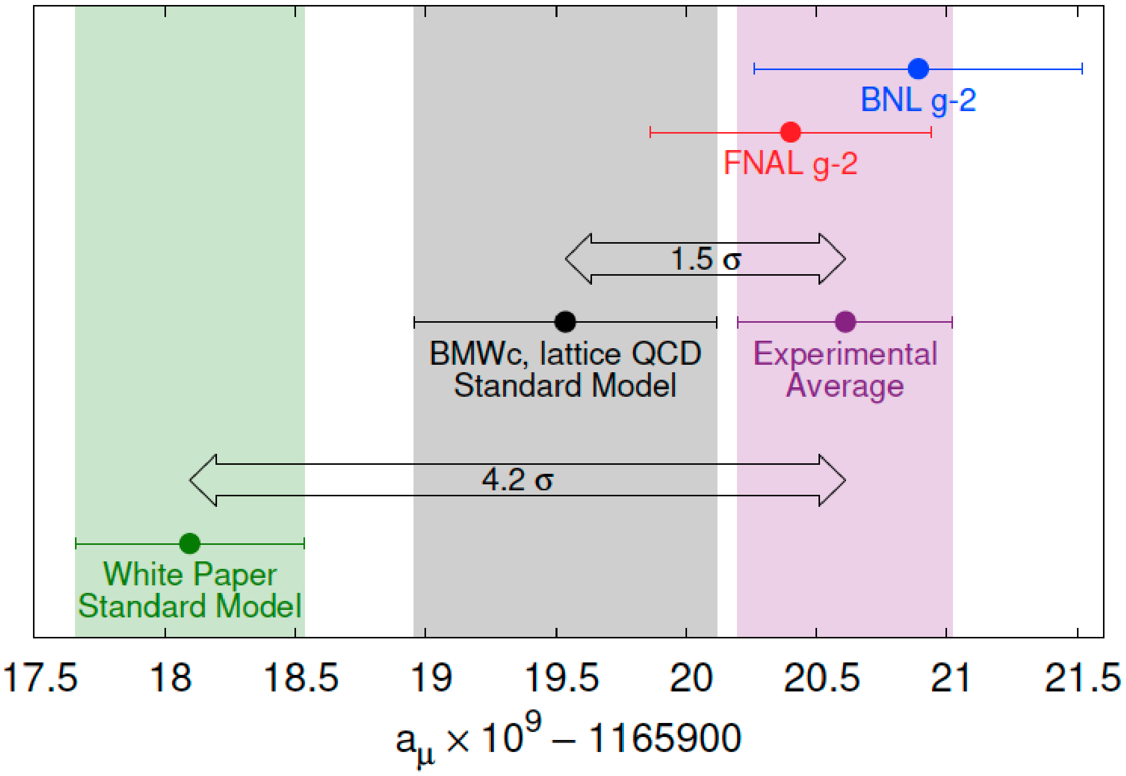
Single trapped electron measurements (0.28ppt)

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

QED calculations (exact)

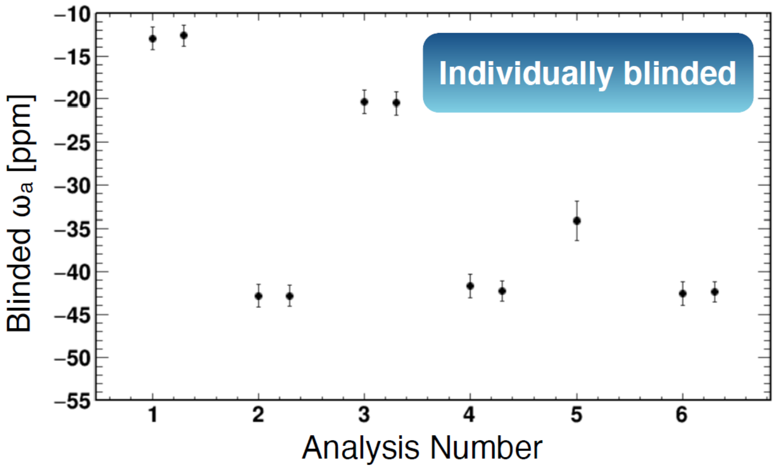
Muonium hyperfine splitting (22ppb)

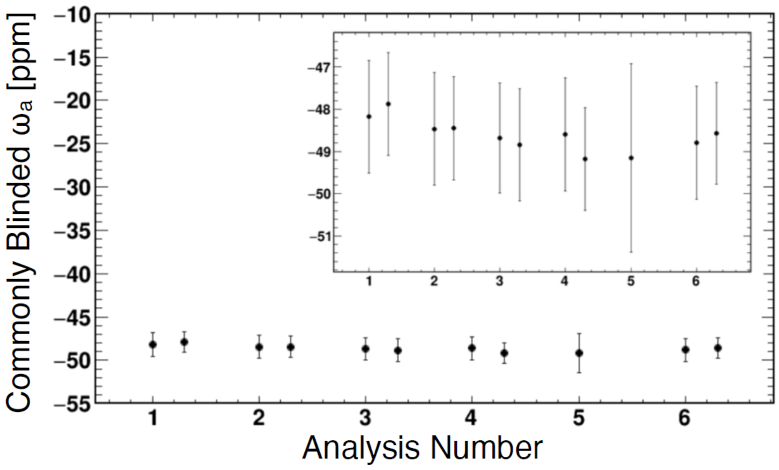
Run 1 with three-way comparison



Blinding

- Both blinding methods shift the frequency by some unknown factor.
- Software blinding can be undone as a consistency check before hardware is unblinded.
- Run 1 example:





The bad resistors

- 2/32 resistors on quad plates faulty – took a longer time to stabilize
- Therefore, they impact things after the start time cut of 30 µs
- Fixed from run 2 onwards