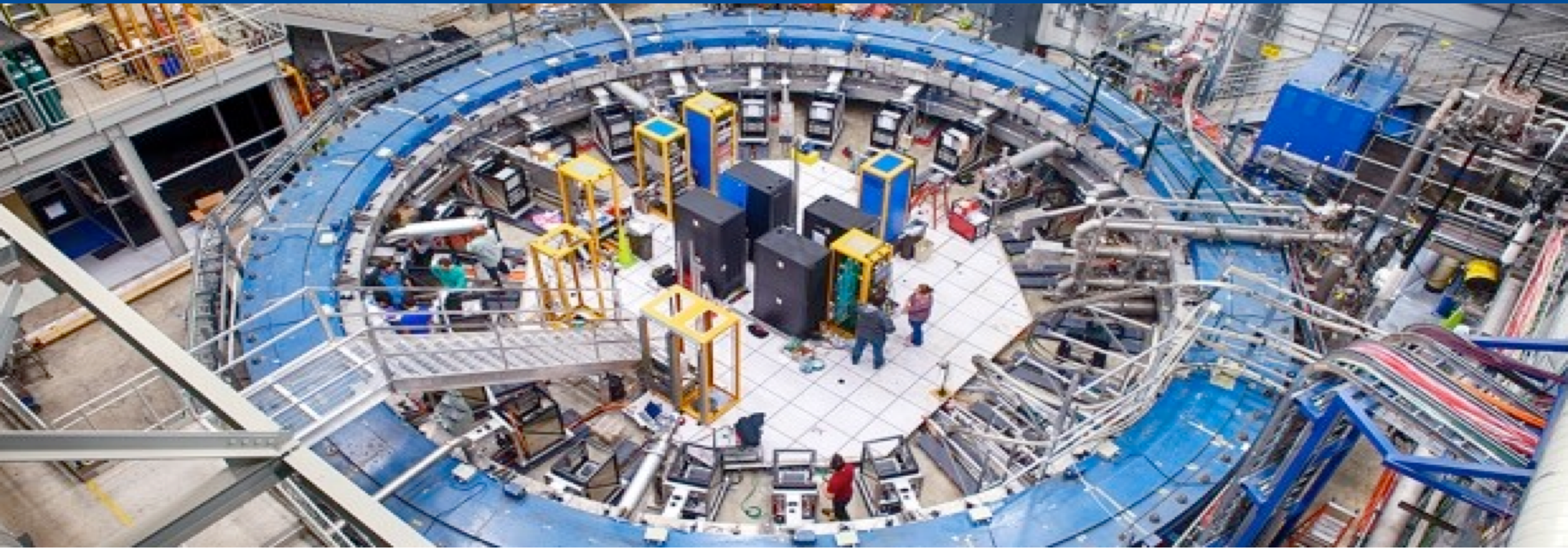


Status of the Muon g-2 experiment at Fermilab

Graziano Venanzoni– INFN Pisa

SIF 16/Sep/2020

Outline

- Status of the Muon g-2 test of the Standard Model
- The Muon g-2 experiment at Fermilab
- Status of the analysis
- Conclusions

Muon g-2: Status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad \text{(0.54 ppm)}$$

- Tantalizing ~3.5 σ deviation with SM (persistent since ~20 years):

$$a_\mu^{SM} = 11659181.0(4.3)\times 10^{-10}$$

T. Aoyama «**The anomalous magnetic moment of the muon in the Standard Model**», June 8, 2020, 194 pages, e-print: 2006.04822 [hep-ph] (>40 citations)

$$a_\mu^{E821} - a_\mu^{SM} = (27.9 \pm 7.6)\times 10^{-10} = 3.7\sigma$$

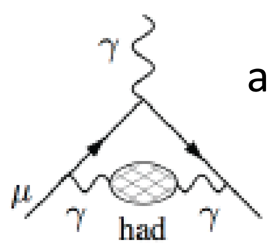
$$(\Delta a_\mu \sim 2300\text{ppb})$$

- Current discrepancy limited by:
  - Experimental uncertainty→ New experiments at FNAL and J-PARC x4 accuracy
  - Theoretical uncertanty→ limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

MUonE (see Marconi's talk)

Hadronic Vacuum polarization (HLO)

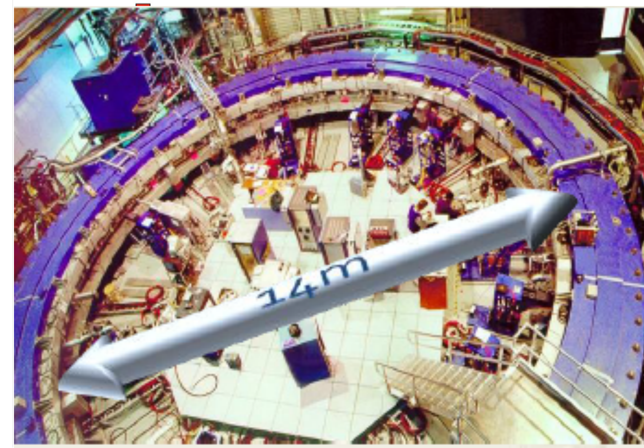


$a_\mu^{HLO} = (692.3 \pm 4.0)10^{-10}$

$\delta a_\mu / a_\mu \sim 0.6\%$

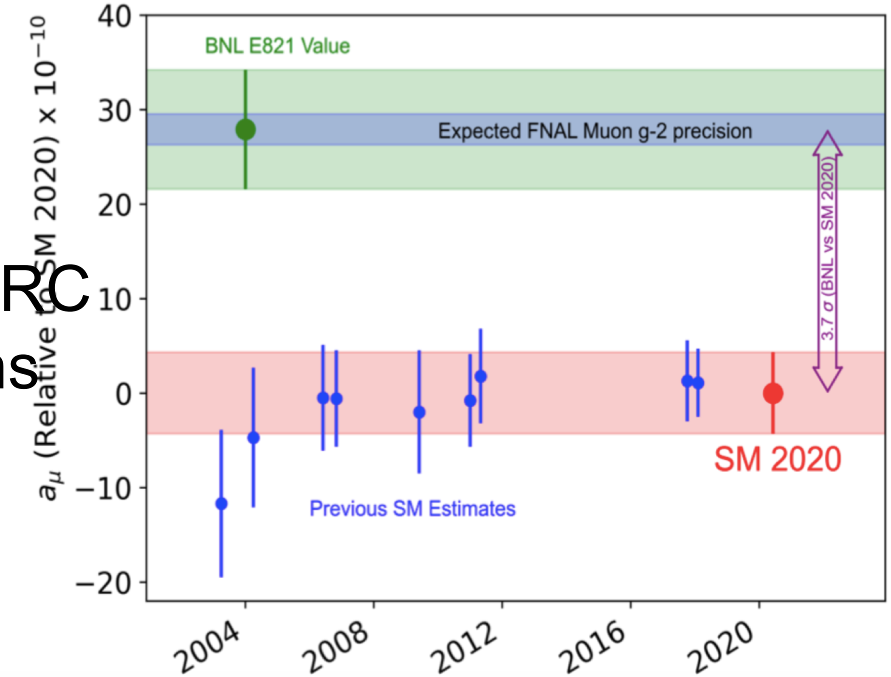
$(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat**. w.r.t. E821. Relocate the BNL storage ring to FNAL.

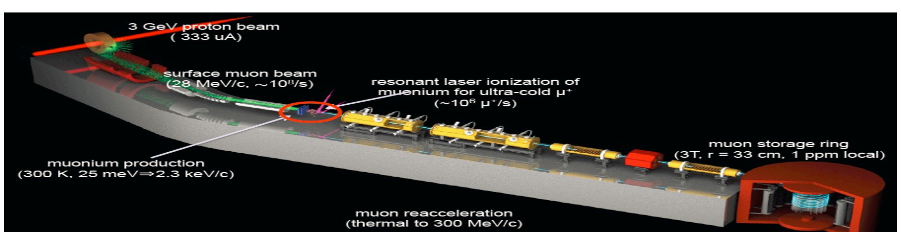


$\rightarrow \delta a_\mu$x4 improvement (0.14ppm)

If the central value remains the same > 5σ from SM (enough to claim discovery of New Physics!)

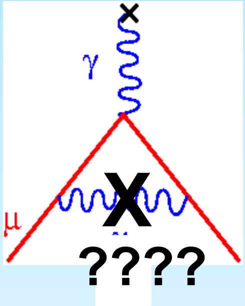


Complementary proposal at J-PARC in progress using ultra-cold muons



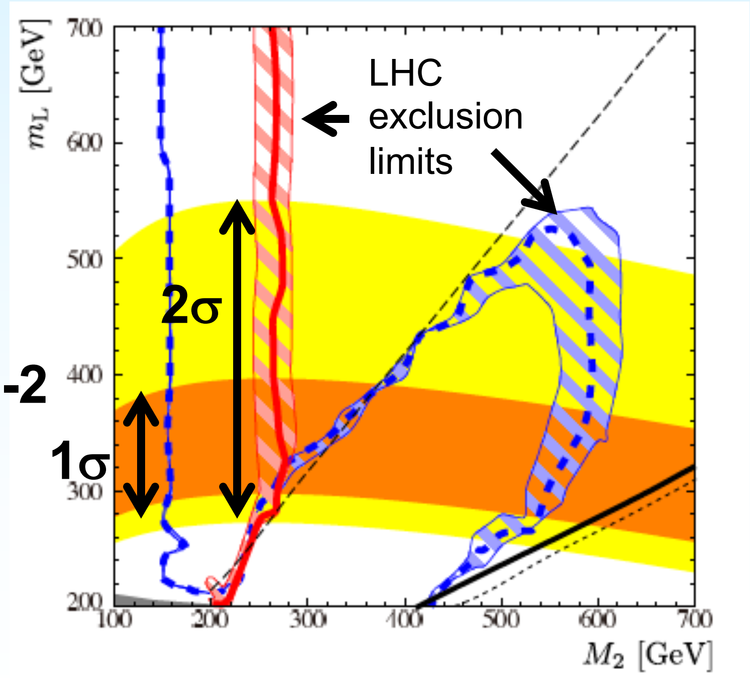
New Physics?

$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} + a_\mu^{???}$$



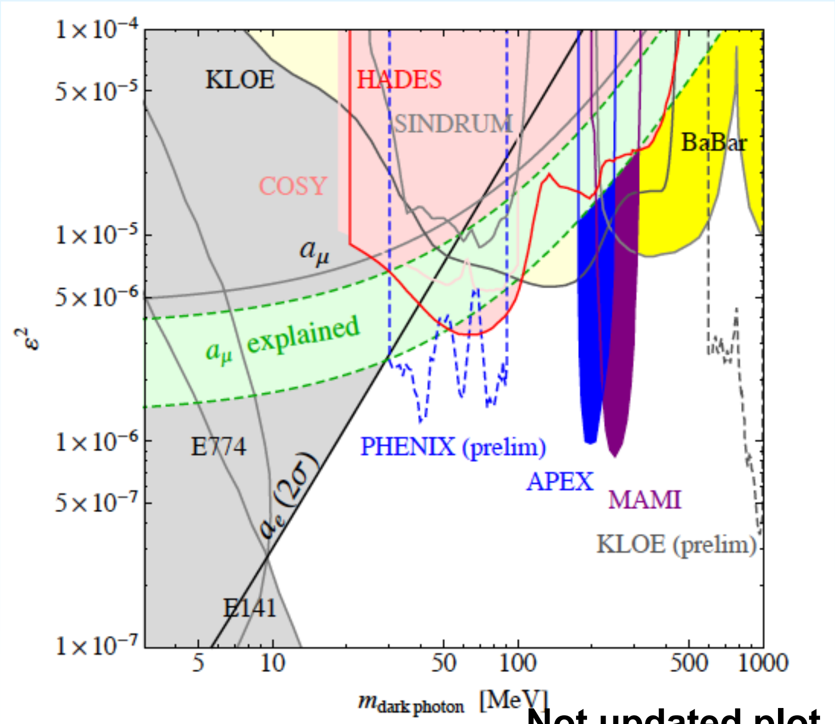
(BNL) (SM)

SUSY?



[Endo,Hamaguchi,Iwamoto,Yoshinaga '13]

Dark Photons?



Not updated plot

New Physics?

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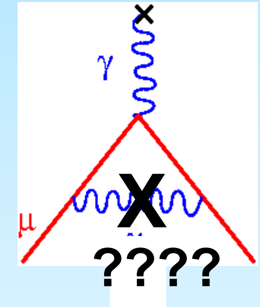
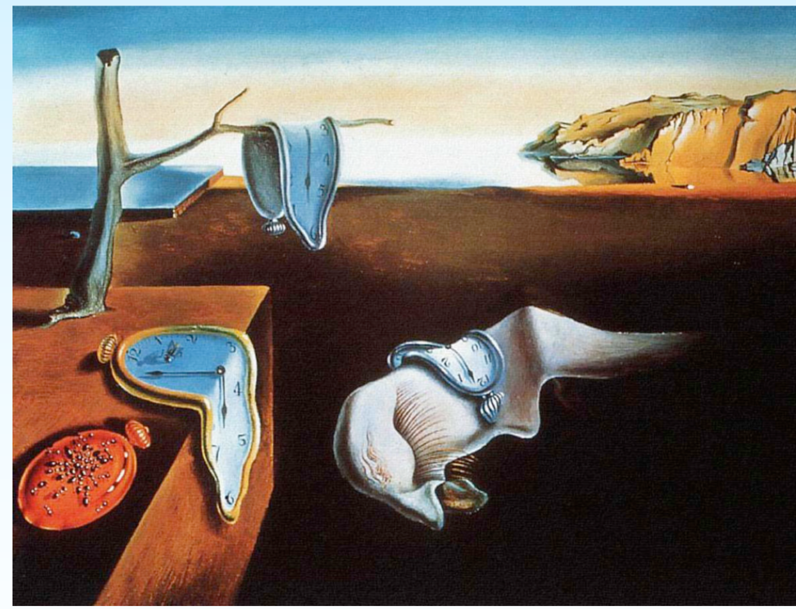


Maybe an unknow "unknown" ?

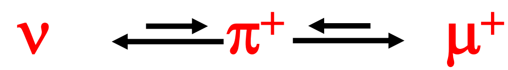


In any case 3σ are not enough to claim a discovery.

We need a new (possible more) experiment with better precision!

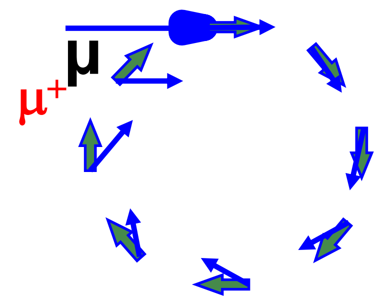
How to measure g-2 in a storage ring

(1) Polarized muons



~97% polarized for forward decays

(2) Precession proportional to (*g*-2)



$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

$a_\mu=(g-2)/2$

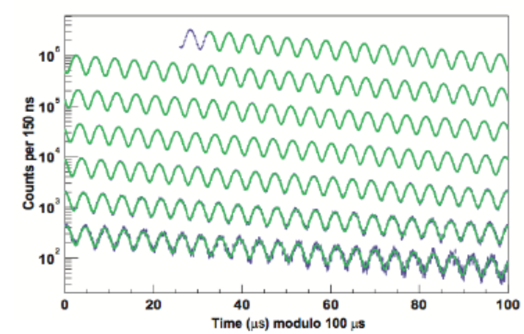
(3) P_μ magic momentum = 3.094 GeV/c

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

E field doesn't affect muon spin when γ = 29.3

(4) Parity violation in the decay gives average spin direction

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



How to measure g-2 in a storage ring

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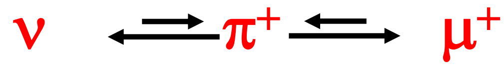

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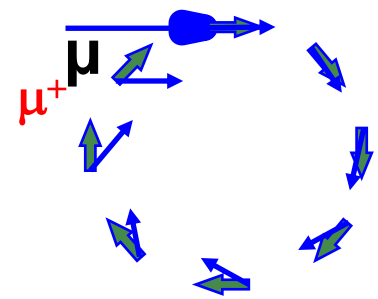
$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

$a_\mu=(g-2)/2$

Measure 2 quantities



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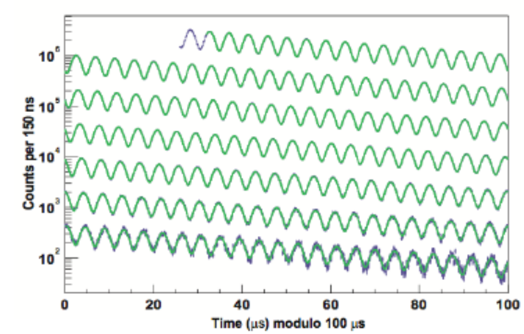


Effect of Beam Dynamics

- The *full equation* is more complex and corrections due to radial (x_e) and vertical (y) beam amplitude and shape are needed

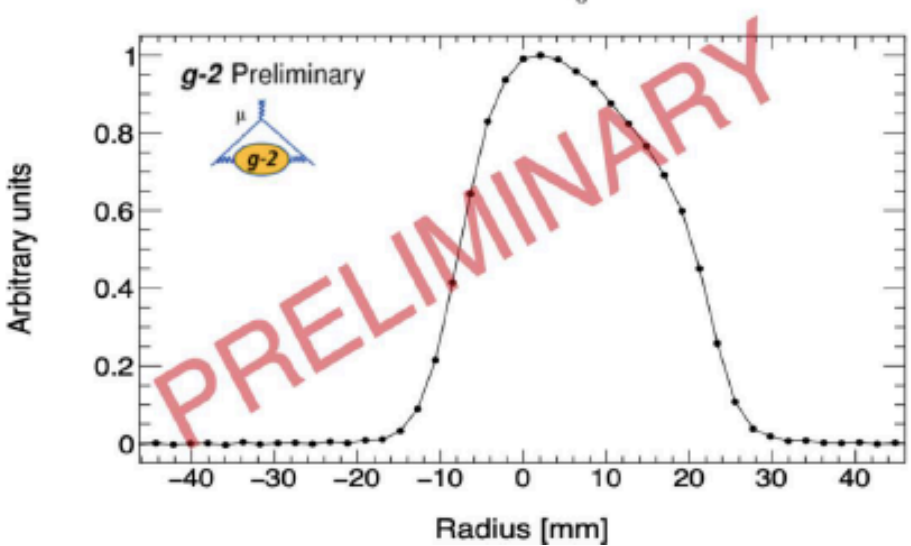
$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}\right]$$

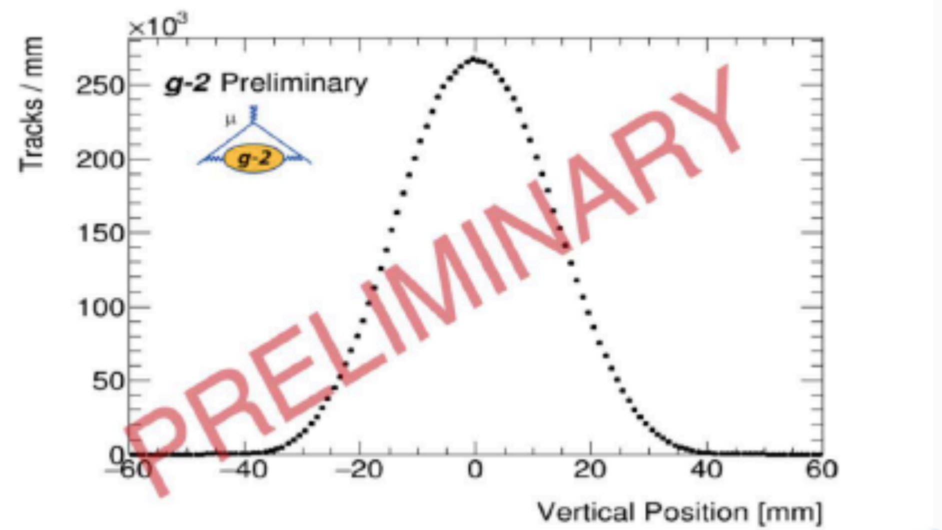
- Running at γ_{magic}=29.3 (p_μ=3.094 GeV/c) this coefficient is null
- Because of beam spread → E-field Correction

- Vertical beam oscillations, field felt by the muons is reduced → Pitch Correction

$$C_E = -2n(1-n)\beta^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

$$C_P = \frac{\Delta\omega_a}{\omega_a} = -\frac{n}{2R_0^2}\langle y^2 \rangle$$





Extracting a_μ

2017 CODATA

FNAL Projected Errors:
140 ppb (total) =
100 (stat)⊕ 100 (syst)

-0.001 519 270 380(5) [3 ppb] Hydrogen Maser

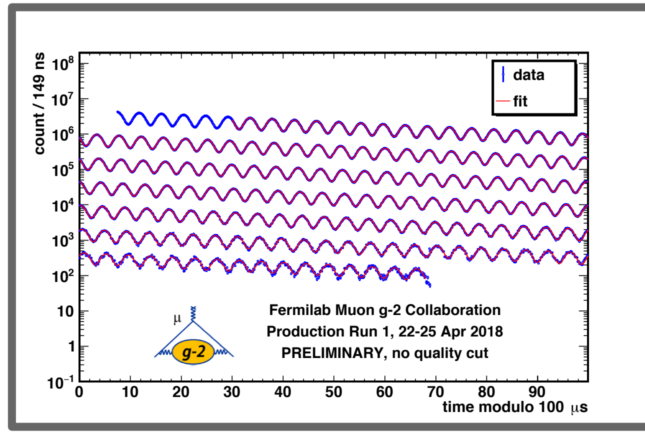
206.768 2826(46) [22 ppb] Muonium Hyperfine

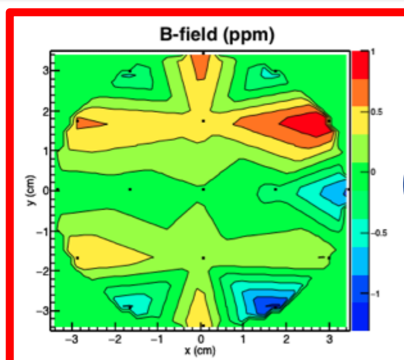
-2.002 319 304 361 82(52) [0.26 ppt] Electron g-2/QED

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

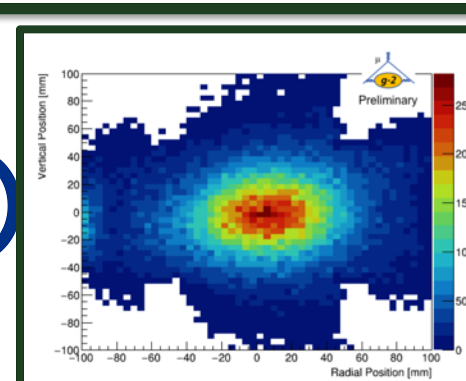
$$\Downarrow$$

$$\frac{\omega_a}{\omega_p \otimes \rho(r)} \Rightarrow$$





$\otimes$



4 key elements for E989 at FNAL

- Consolidated method
- More muons (x20)
- Reduced systematics (ring and detector)
- New crew

- **E821 at Brookhaven**

$$\left.\begin{aligned}\sigma_{\text{stat}} &= \pm 0.46 \text{ ppm} \\ \sigma_{\text{syst}} &= \pm 0.28 \text{ ppm}\end{aligned}\right\} \sigma = \pm 0.54 \text{ ppm}$$

$\hookrightarrow 0.2\omega_a \oplus 0.17\omega_p$

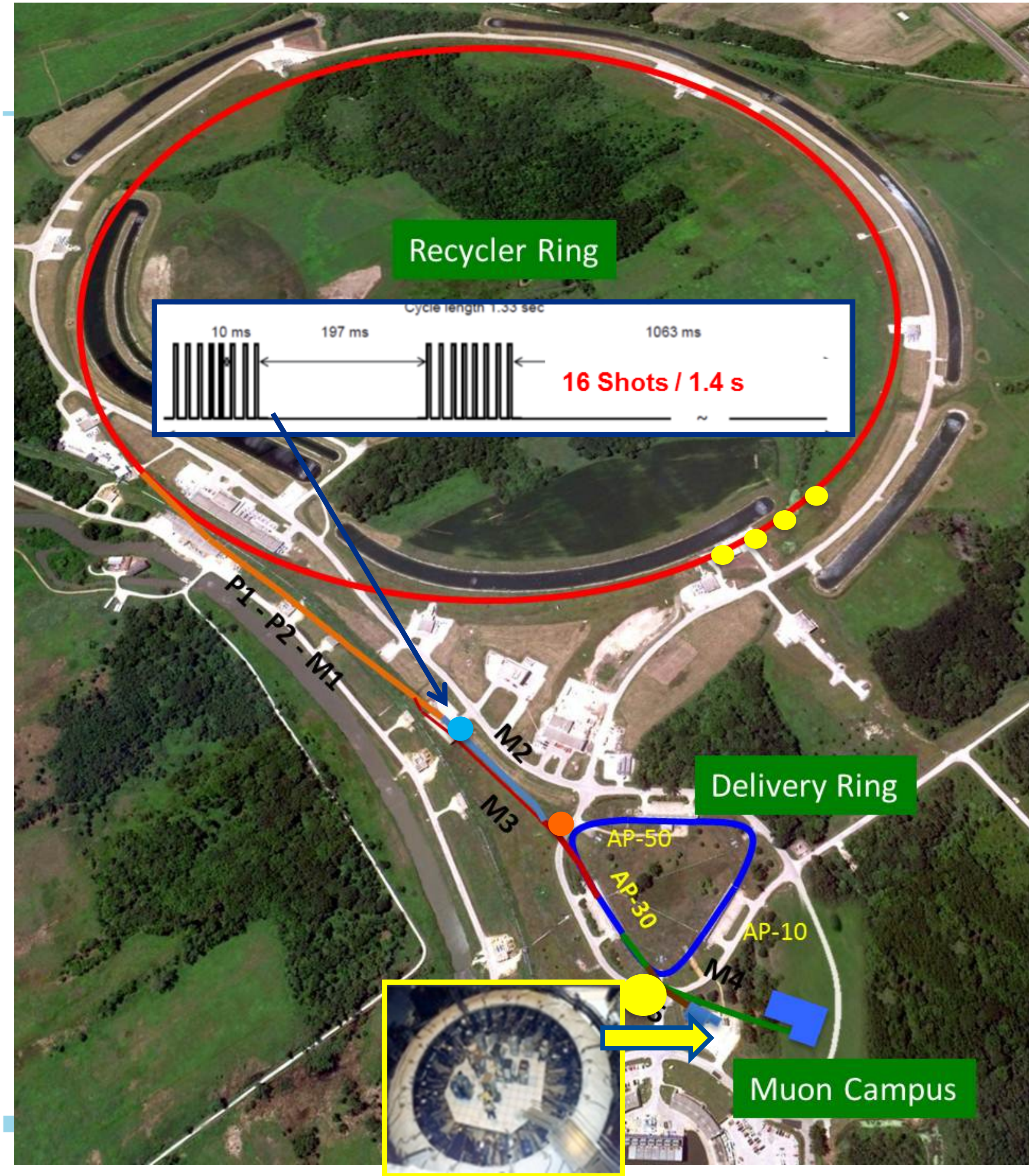
- **E989 at Fermilab**

$$\left.\begin{aligned}\sigma_{\text{stat}} &= \pm 0.1 \text{ ppm} \\ \sigma_{\text{syst}} &= \pm 0.1 \text{ ppm}\end{aligned}\right\} \sigma = \pm 0.14 \text{ ppm}$$

$\hookrightarrow 0.07\omega_a \oplus 0.07\omega_p$

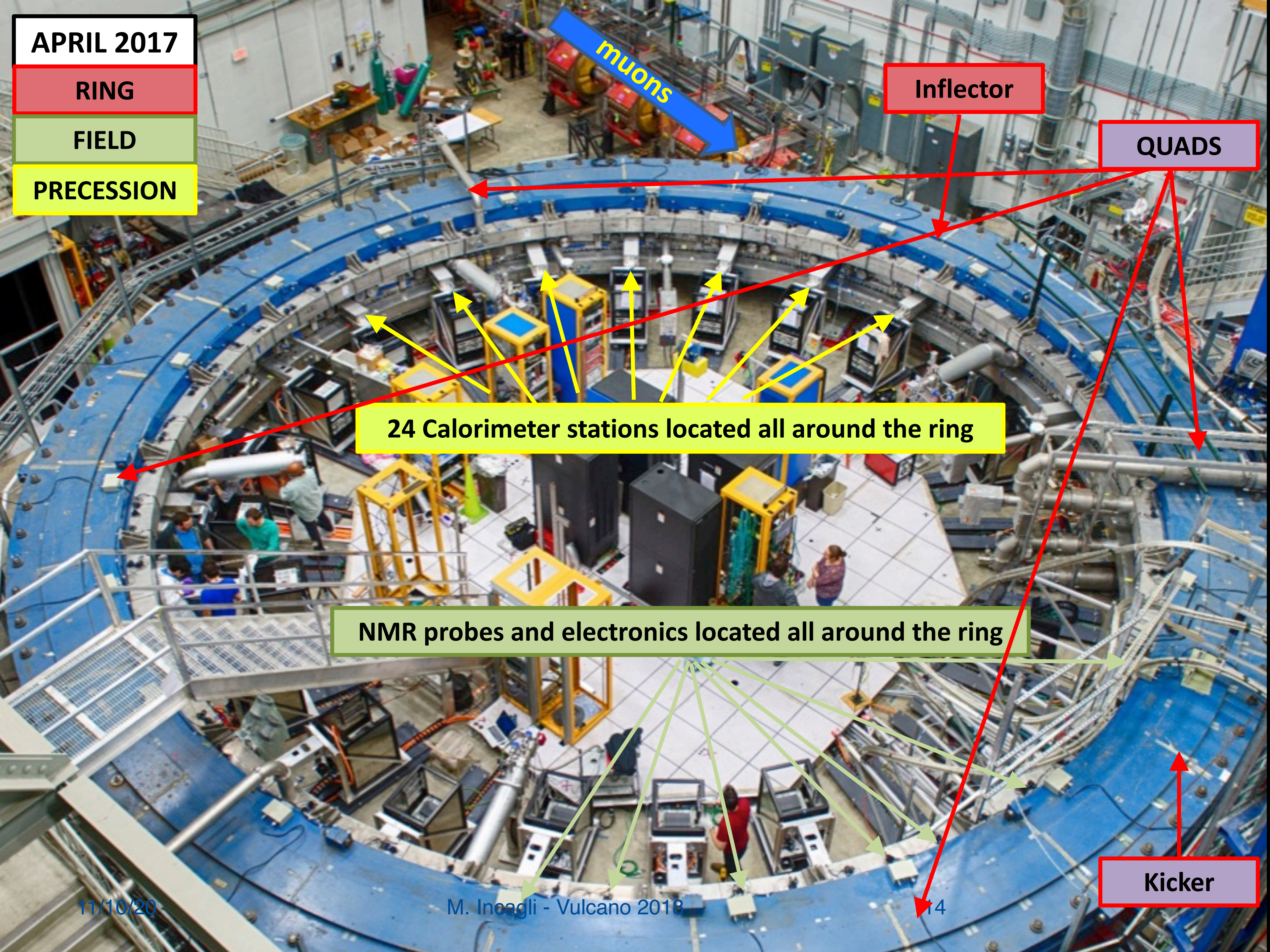
Towards 140ppb

δa_μ	BNL (ppb)	FNAL goal (ppb)	
ω_a statistic	480	100	**20 × BNL statistics**: more muons/sec, higher quality beam, less beam background
ω_a systematic	180	70	**new instrumentation for ω_a measurement**: segmented and fast EM calorimeters with laser calibration system
$\overline{\omega}_p$ systematics	170	70	**improved ω_p measurement:** new precise NMR probes and tracker system for beam distribution
Total	**540**	**140**	

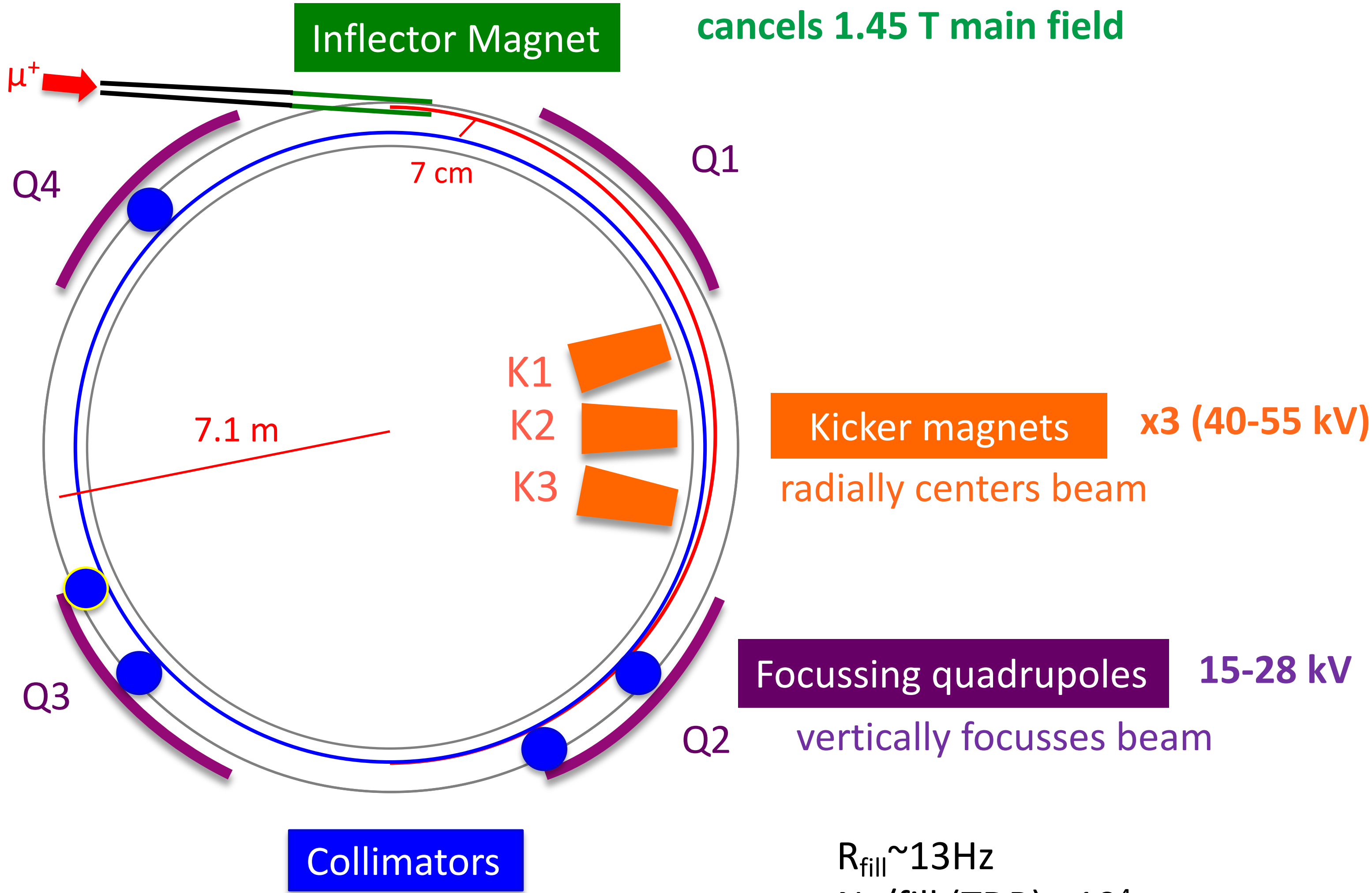


Creating the Muon Beam for g-2

- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- μ enter storage ring

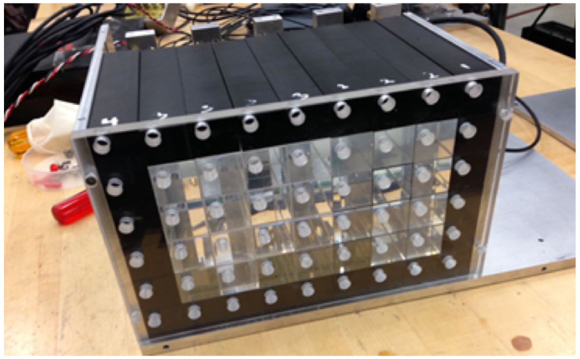

APRIL 2017
RING
FIELD
PRECESSION
muons
Inflector
QUADS
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring
Kicker

Injection / storage

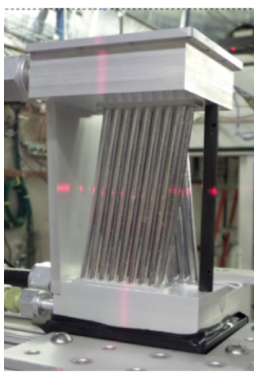


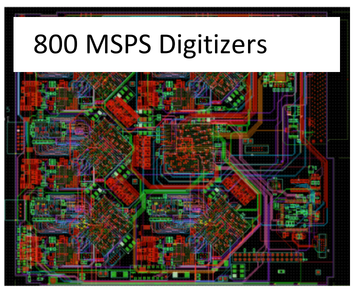
R_{fill}~13Hz
N_{μ}/fill (TDR)~ 10^4
N_{μ}/sec(TDR)~ 1.3×10^5
$N_{e+\ E>1.8\ GeV}$/fill (TDR)~ 10^3

New detector systems

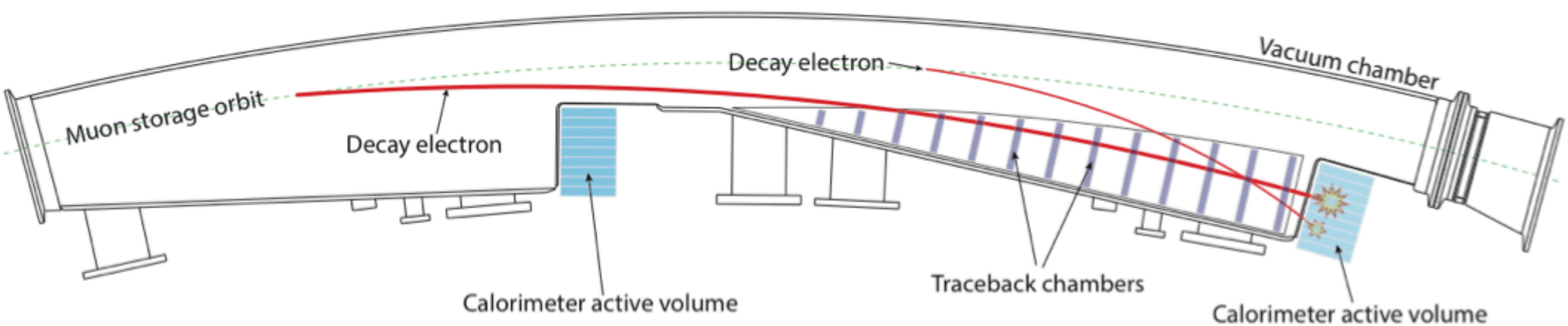


- Calorimeters 24 6x9 PbF_2 crystal arrays with SiPM readout, segmentation to reduce pileup
- New electronics and DAQ, 800MHz WFDs and a greatly reduced threshold
- Two 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons, significant UK contributions
- New laser calibration system from INFN crucial for untangling gain from other systematics



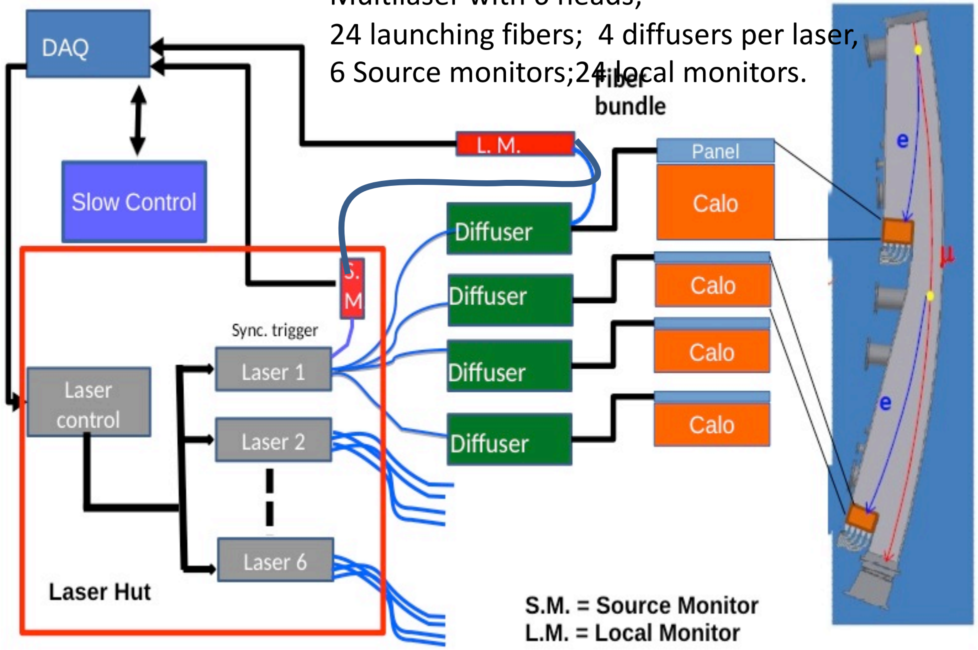


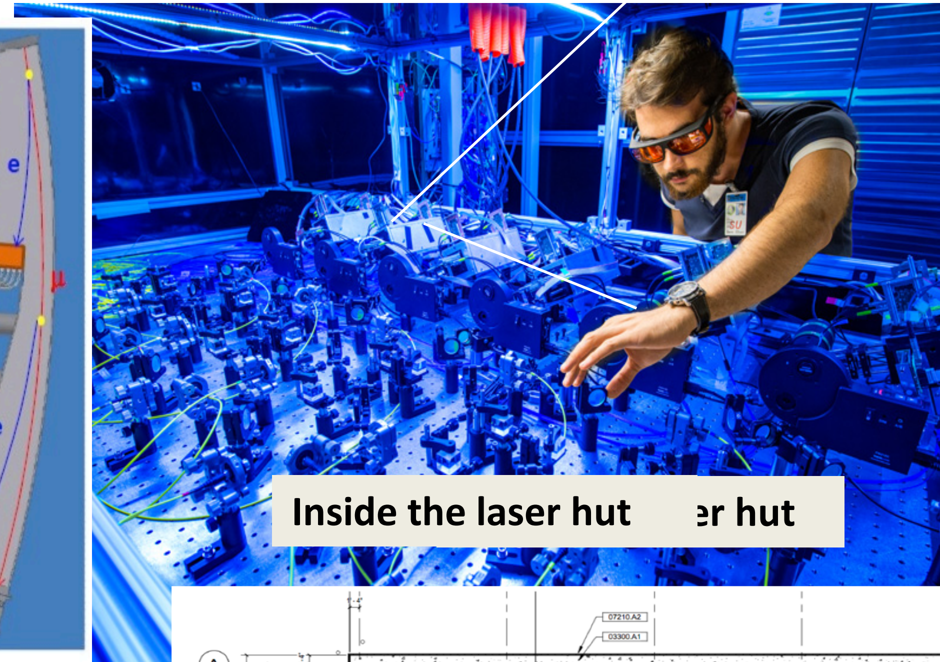
Top view of 1 of 12 vacuum chambers

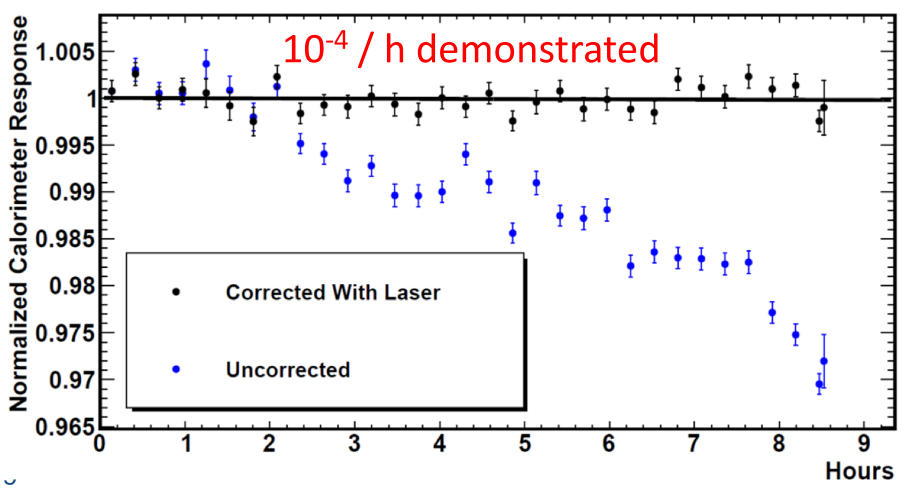


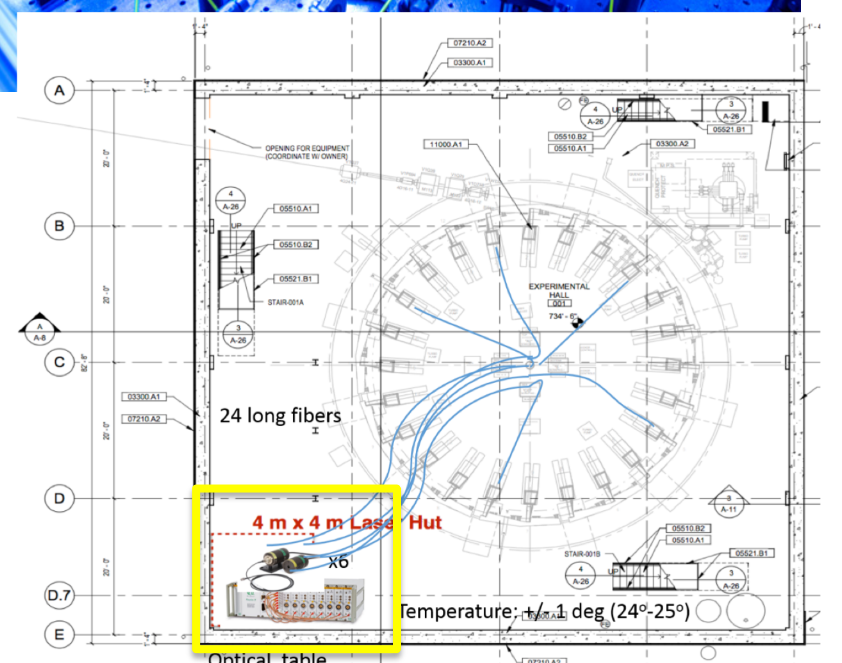
The g-2 laser calibration system

Multilaser with 6 heads;
24 launching fibers; 4 diffusers per laser,
6 Source monitors;24 local monitors.

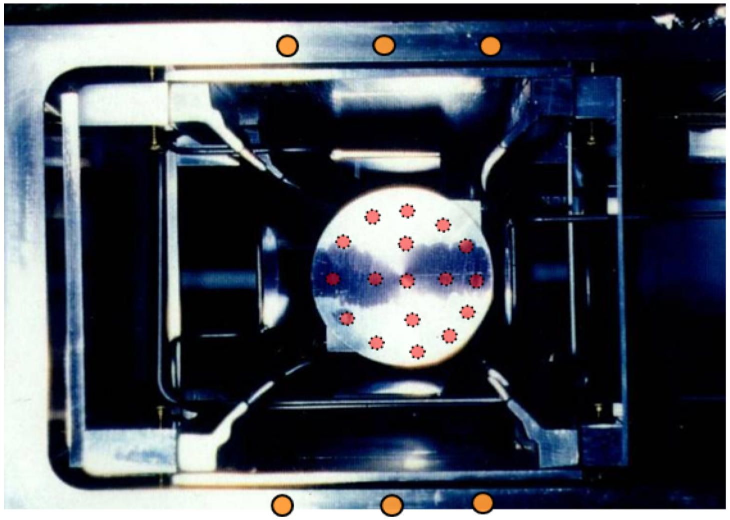






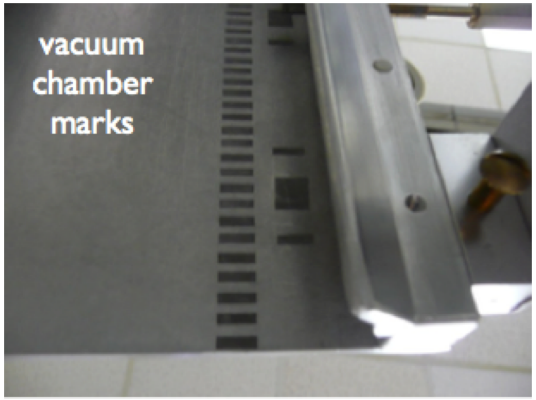


Monitoring the magnetic field

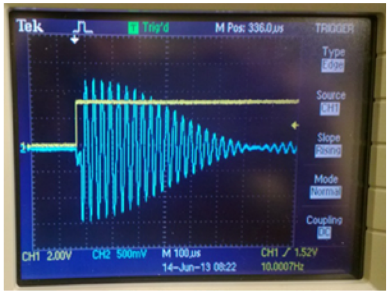


- Fixed probes track field at top/bottom of vacuum chamber monitor field 24/7
  - Only half of 400 were used in BNL (primarily due to being in gradients that were too large) → building better NMR probes and in some case adjusting positions

- NMR trolley pulls out of garage every 2-3 days and maps field where muons live
  - More frequent trolley runs (every 2-3 days) to reduce extrapolation error
  - Optical encoders for better position resolution



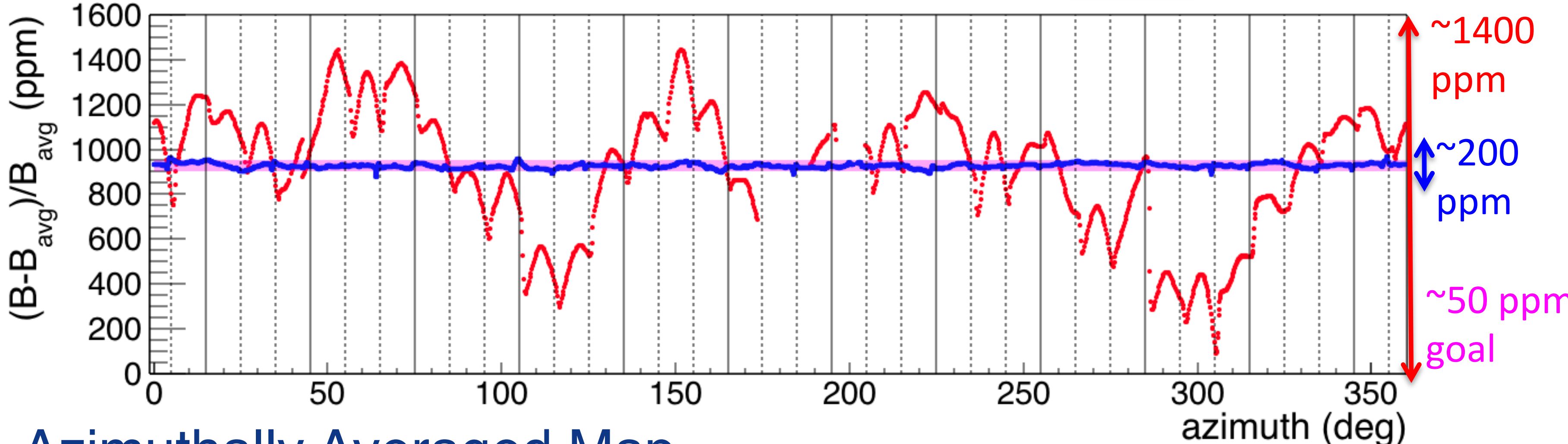
- Digitizing FID signals



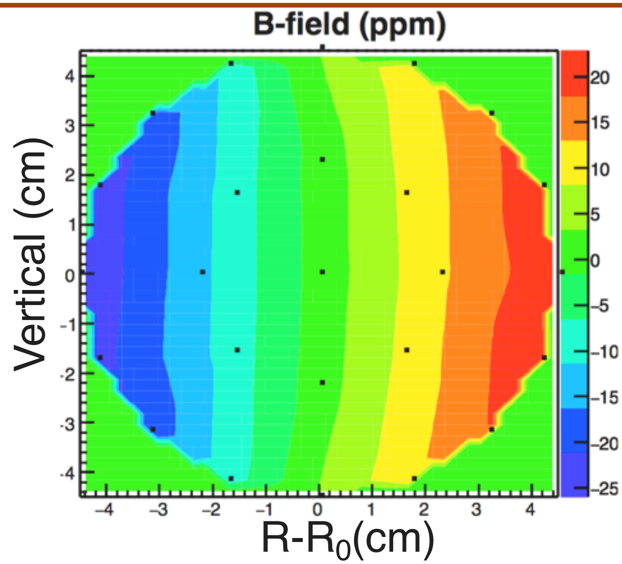
Progress on Field

Oct 2015 → Aug 2016

Goal

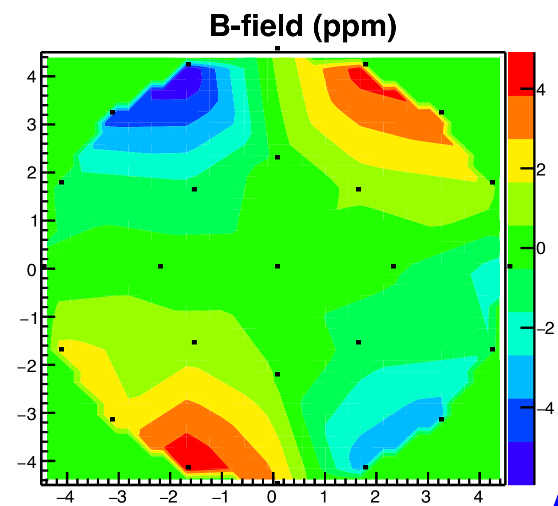


Azimuthally Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

Oct 2015

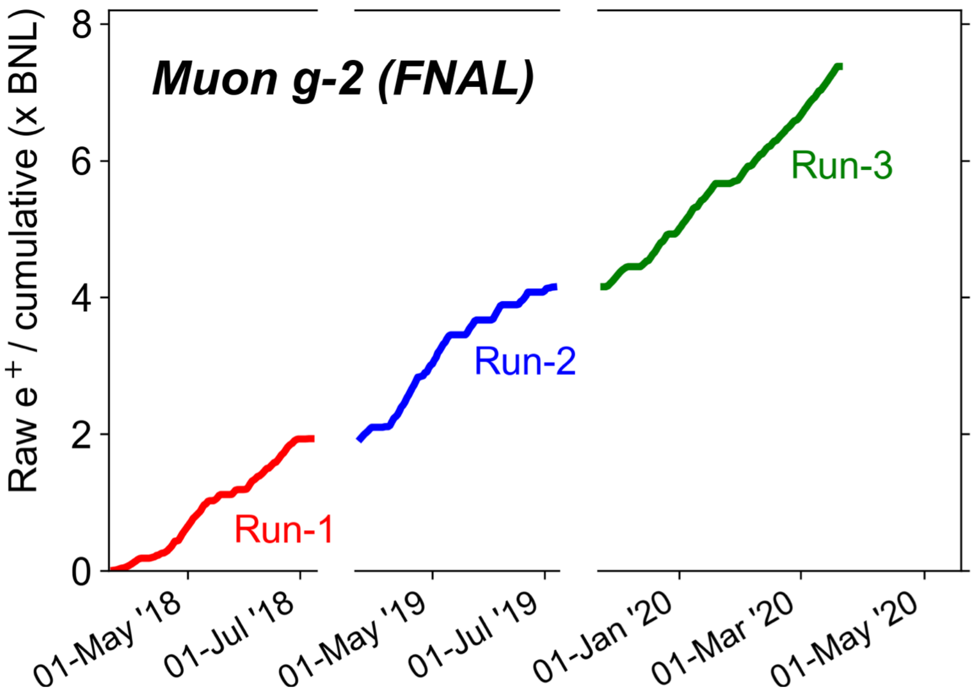


	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

Data accumulated so far

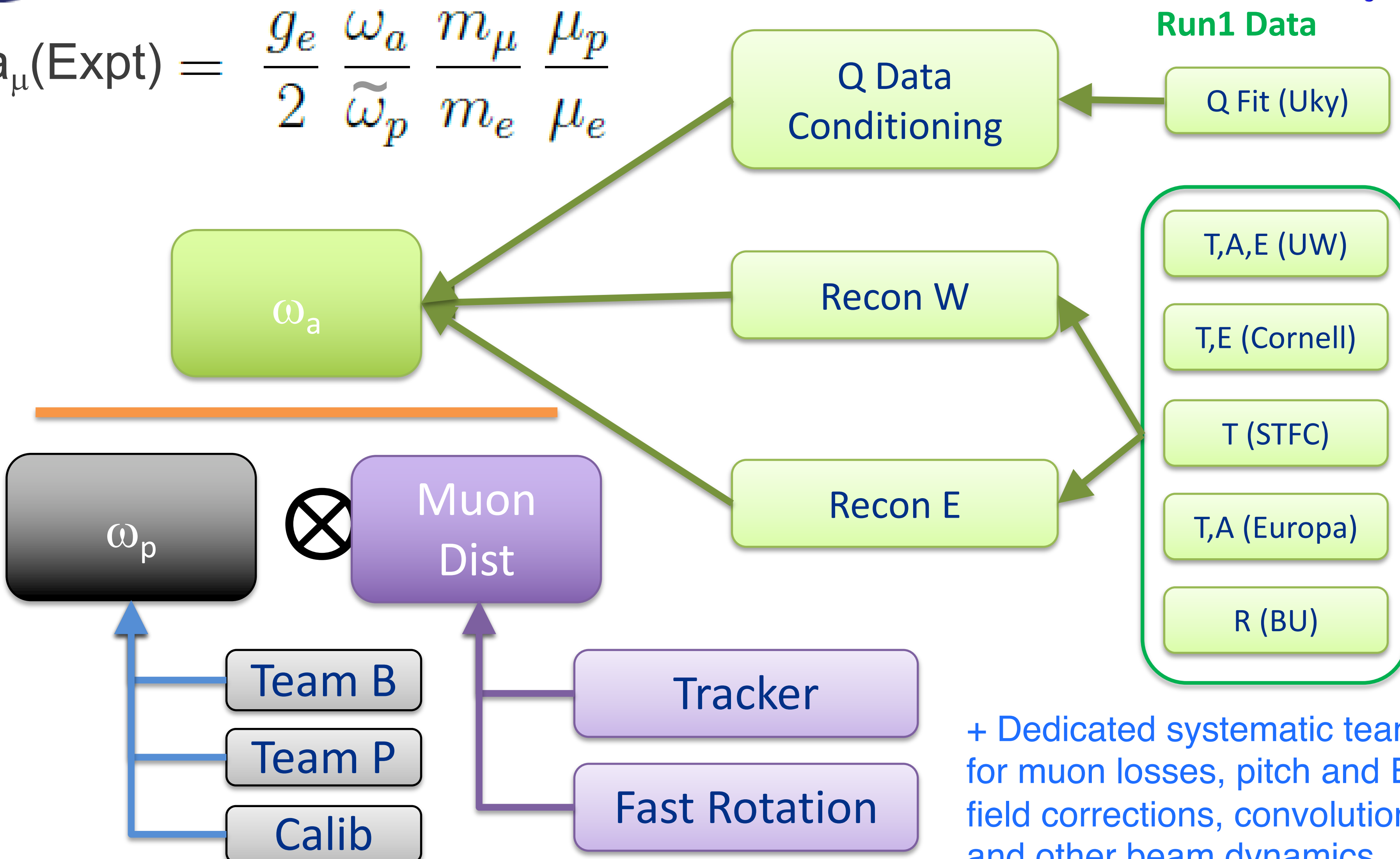
- Accumulated 7.4xBNL through run 3
- Full run 1 has ~1.2xBNL after Data Quality Cuts
- Improvements between run1 and run 2/3 for:
  - Better beam dynamics
  - Reduced muon loss
  - More stable temperature



RUN1: March-July 2018, ~2x BNL (→ 1.2 xBNL after data quality)
RUN2: March 2019 – July 2019 ~2x BNL
RUN3: Nov 2019 – March 2020 ~3.2 x BNL

Overview of analysis structure

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



+ Dedicated systematic teams for muon losses, pitch and E-field corrections, convolution, and other beam dynamics

Run 1 Datasets

Run 1 collected in spring 2018. Identified 4 datasets based on the storage parameters (quadrupoles field index, kickers voltage)

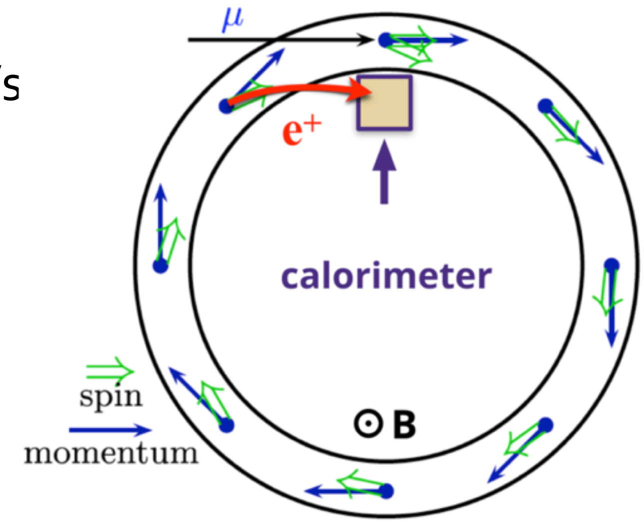
Dataset	Nickname	Acquisition	Quad n	Kicker [kV]	Positrons
1a	60 hour	22 – 25 Apr	0.108	128-132	1.0B
1b	High Kick	26 Apr – 2 May	0.120	136-138	1.2B
1c	9 day	4 – 12 May	0.120	128-132	2.4B
1d	End Game	6 – 29 Jun	0.108	122-127	4.0B

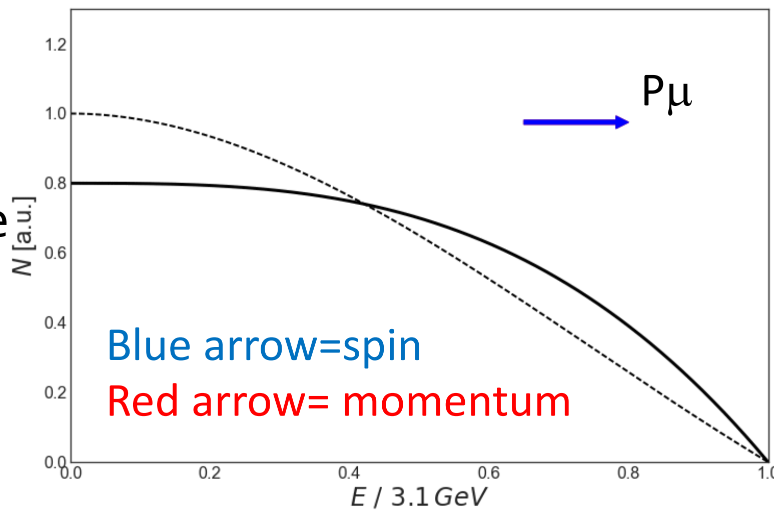
ω_a Measure

- Muon's spin is correlated to high energy positron's momentum
- The number of positrons is modulated by the anomalous precession frequency

$$N_0 e^{-t/\tau}[1 - A\,cos(\omega_a t + \phi)]$$

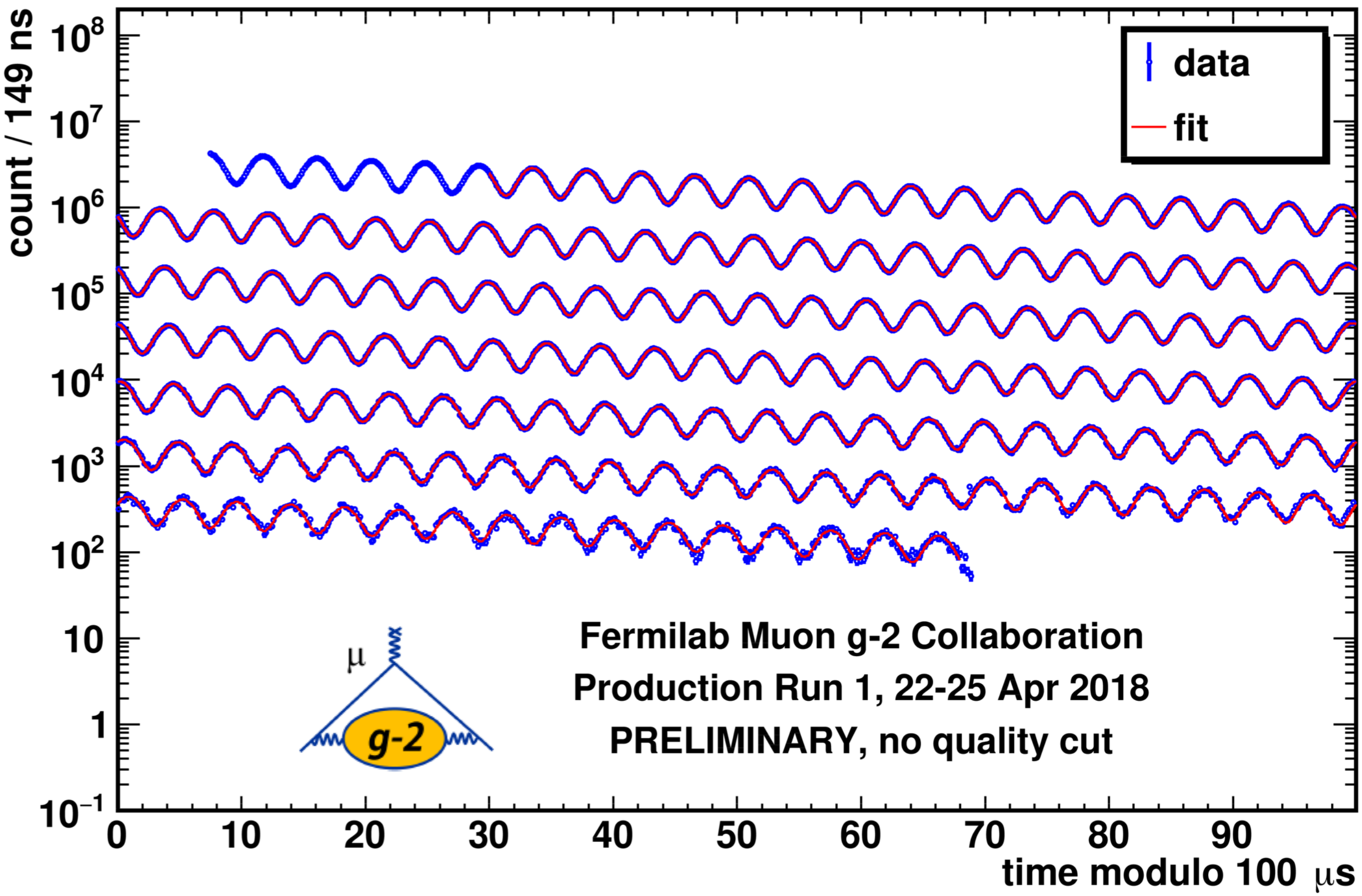
- 4 different analysis methods:
  - T: integrate all positrons above 1.7 GeV
  - A: weight the positrons with A(E) function and integrate above 1.1 GeV
  - R: randomly split dataset in 2 subsets shifted by ±half a g-2 period, build combinations of the 2 subsets to remove slow terms (exponential, gain…)
  - Q: No clustering: just integrate energy above threshold (in theory no threshold should be applied) for each crystal





E and t are the measured observables.

T-method Wiggle Plot

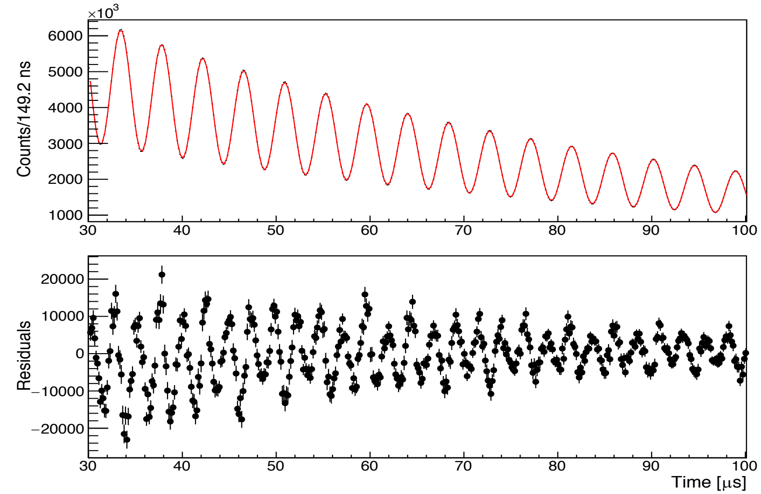


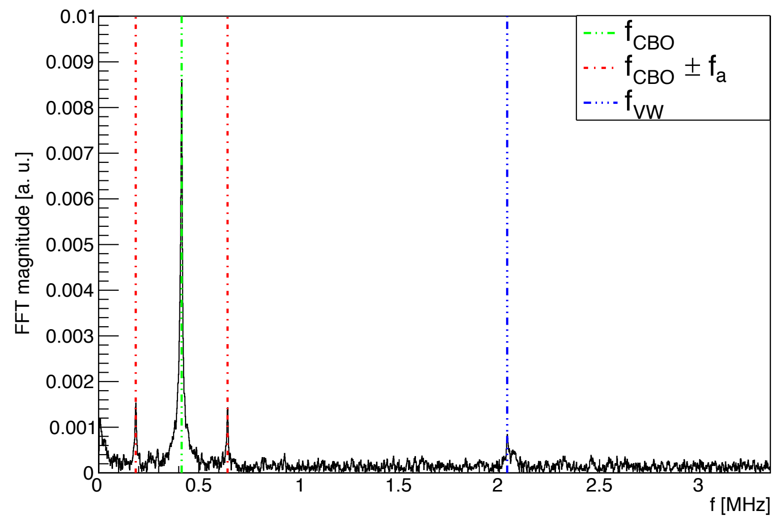
The ω_a fit

- The wiggle plot is fitted with a decay exponential modulated by the precession frequency:

$$f_5(t) = N_0 e^{-t/\tau}[1 - A\,cos(\omega_a t + \phi)]$$

- The 5 parameters function presents peaks in the residuals FFT due to beam dynamics effects
- Increasing the number of corrections in order to remove peaks from the FFT residuals





The fit equation

$$N_0\, e^{-\frac{t}{\gamma\tau}} \left(1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot J(t)$$

$$A_{\mathrm{BO}}(t) = 1 + A_A \cos(\omega_{\mathrm{CBO}}(t) + \phi_A) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$\phi_{\mathrm{BO}}(t) = 1 + A_\phi \cos(\omega_{\mathrm{CBO}}(t) + \phi_\phi) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{CBO}}(t) = 1 + A_{\mathrm{CBO}} \cos(\omega_{\mathrm{CBO}}(t) + \phi_{\mathrm{CBO}}) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{2\mathrm{CBO}}(t) = 1 + A_{2\mathrm{CBO}} \cos(2\omega_{\mathrm{CBO}}(t) + \phi_{2\mathrm{CBO}}) e^{-\frac{t}{2\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{VW}}(t) = 1 + A_{\mathrm{VW}} \cos(\omega_{\mathrm{VW}}(t)t + \phi_{\mathrm{VW}}) e^{-\frac{t}{\tau_{\mathrm{VW}}}}$$

$$N_y(t) = 1 + A_y \cos(\omega_y(t)t + \phi_y) e^{-\frac{t}{\tau_y}}$$

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$ Muon Loss term

$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

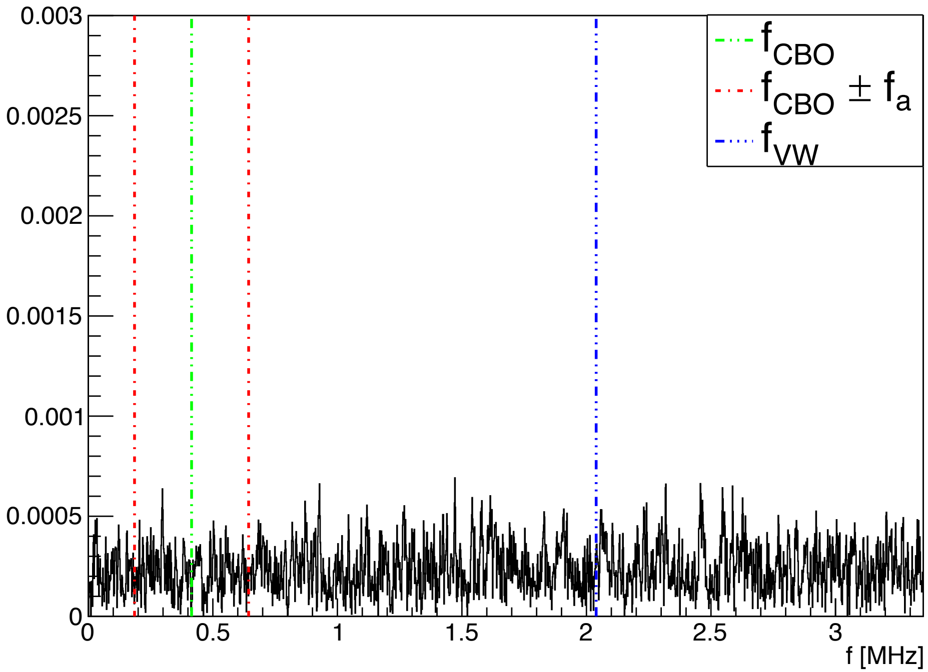
$$\omega_y(t) = F \omega_{\mathrm{CBO}(t)} \sqrt{2\omega_c / F \omega_{\mathrm{CBO}}(t) - 1}$$

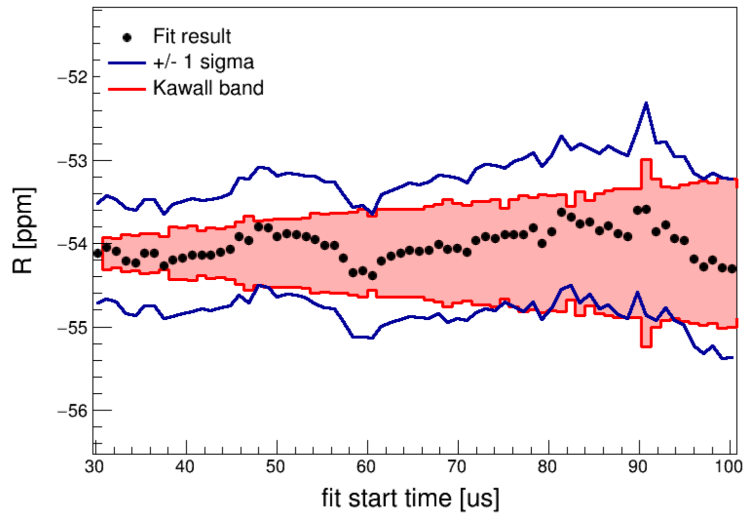
$$\omega_{\mathrm{VW}}(t) = \omega_c - 2\omega_y(t)$$

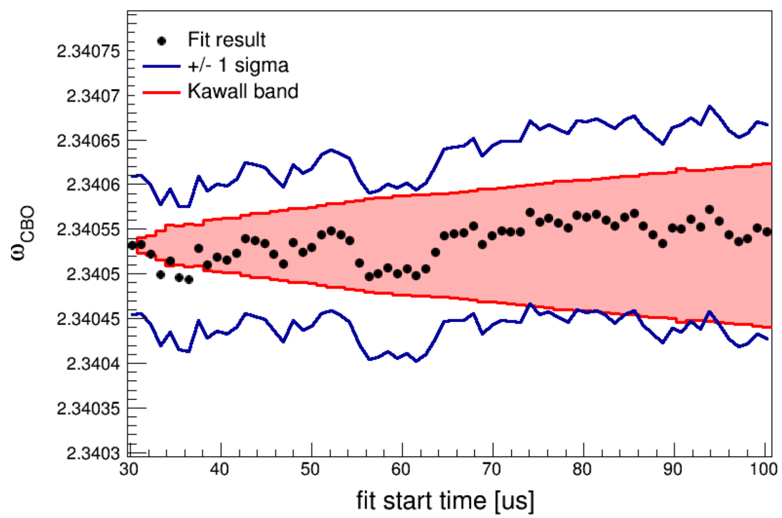
Final Fit

$R = (\omega_{blind} / \omega_{ref} - 1)$ [ppm]

Fourier transformation of residuals



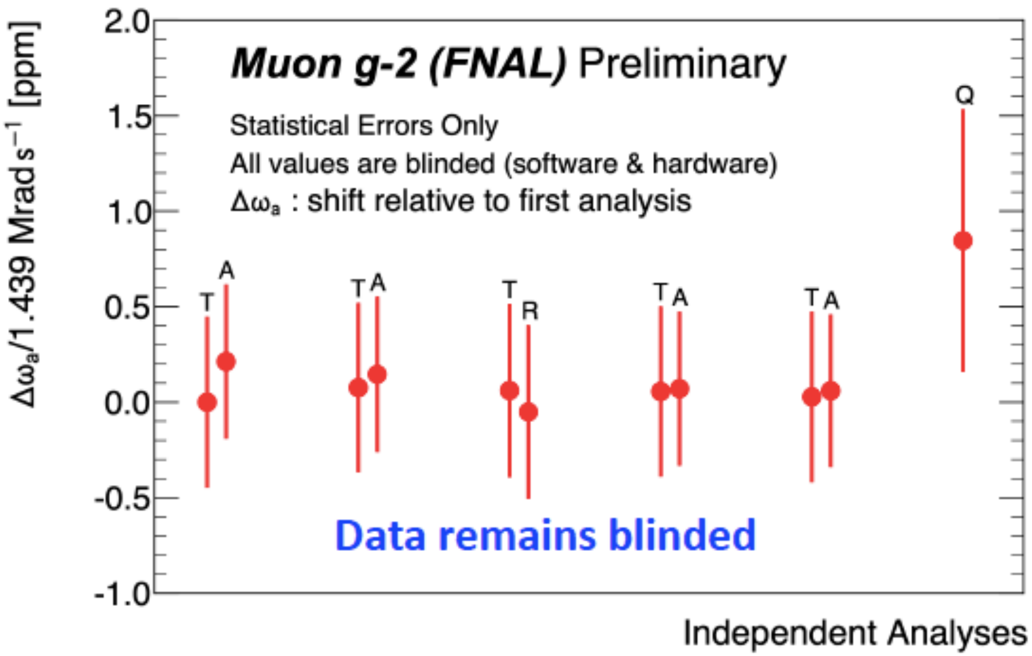




Run 1 Unblinding and Combination

- 6 different analysis groups with 4 different analysis methods: Boston (T, R), Cornell (T, A), Europa (T, A), Kentucky (Q), Shanghai (T, A), Washington (T, A)
- 2 different algorithm to reconstruct positrons: reconWest and reconEast
- Analyzers provided the final blinded ω_a value, one for each different method
- A combination of these values is in progress

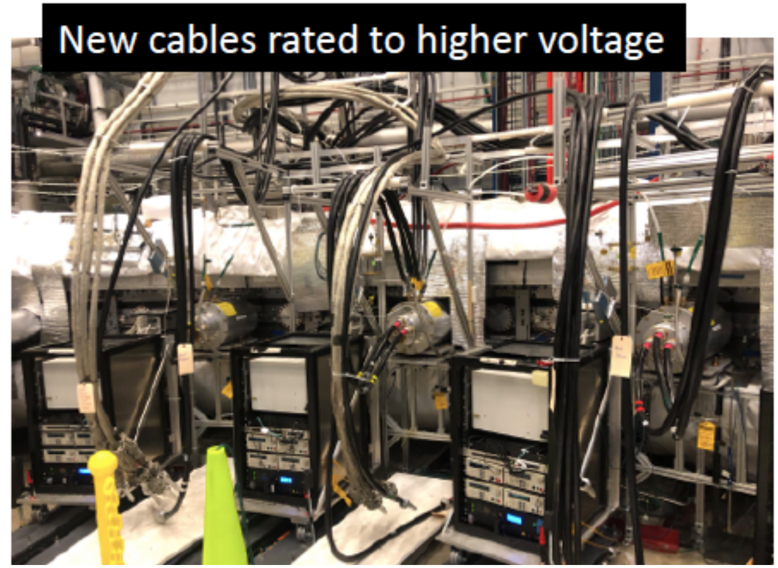
Note: R is the blinded value for ω_a



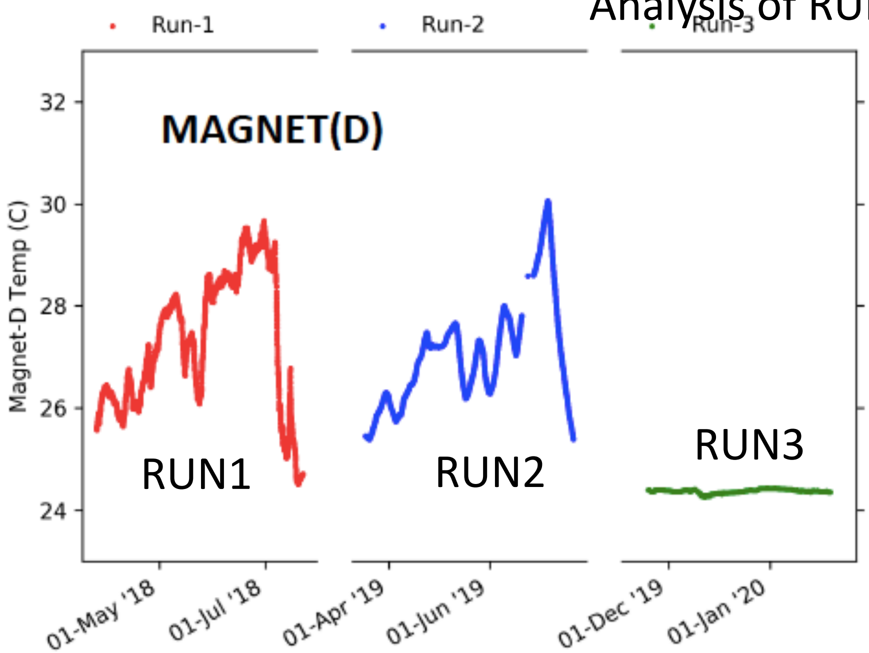
- expect **430 ppb** statistical uncertainty (compare to 460 ppb for BNL)

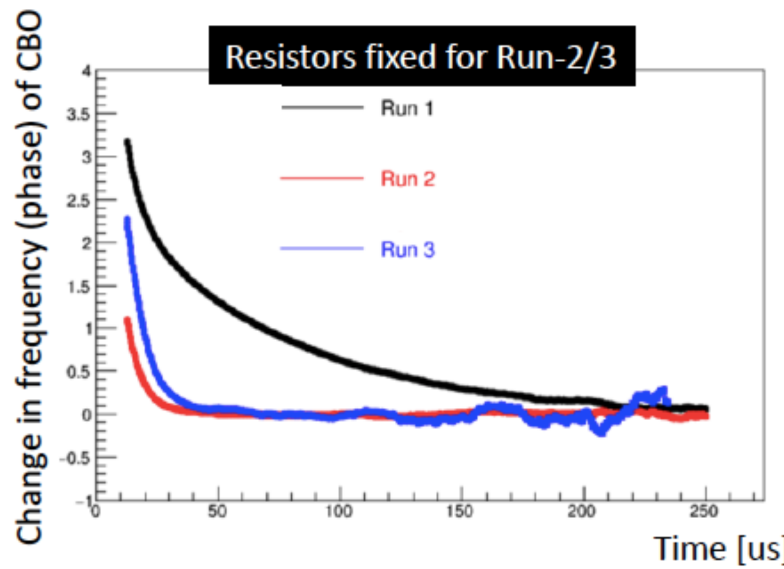
Improvements Run1-Run2-Run3

- Solved the faulty resistors issue that was causing problems to the beam vertical motion
- Better beam storage with kickers at full power (55 kV each)
- Improved temperature stability of the ring with an air conditioning system in the hall (more stable magnetic field)



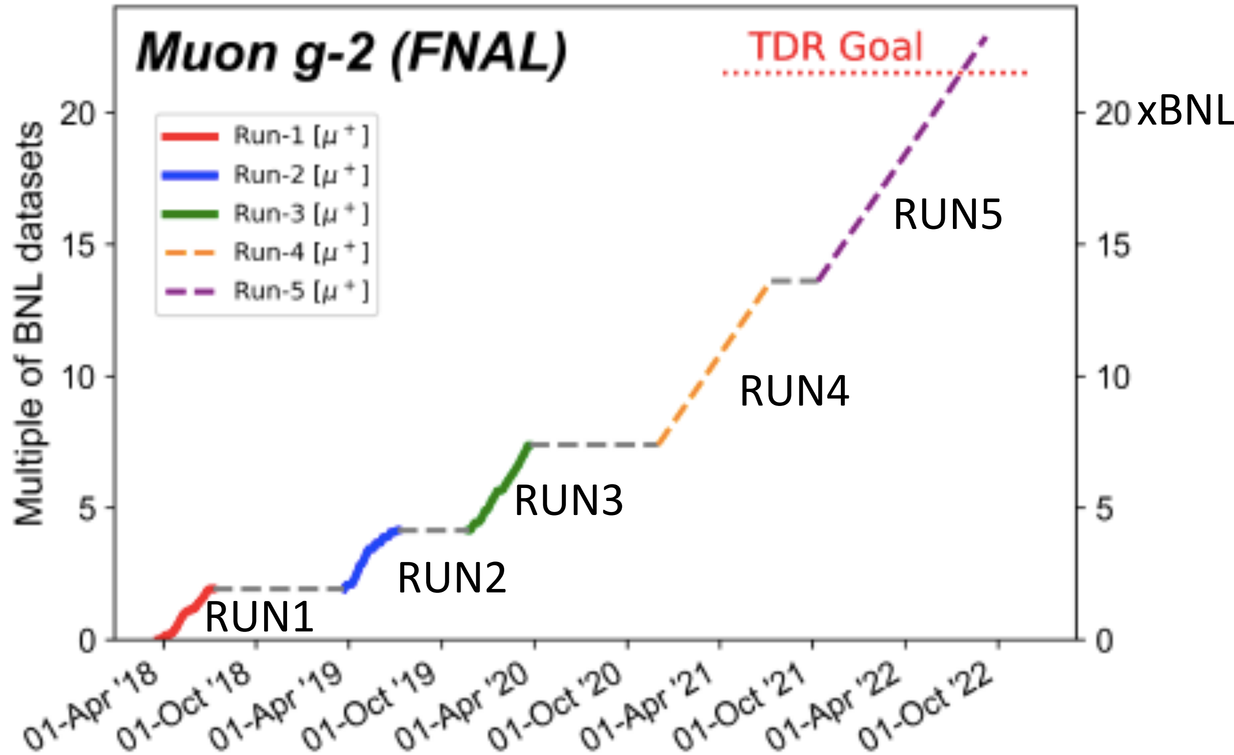
Analysis of RUN2-3 in progress





Future

- RUN4 (November 2020-July 2021) is exptected to double the statistics taken so far (~14 BNL)
- RUN5 in 2021-2022 should allow to achieve the x20 BNL project goal
- Work is in progress with Mu2e to build flexibility into the g-2/Mu2e beam sharing



Conclusions

- Exciting period for g-2!
- A four-year effort from the Theory Initiative produced in June 2020 a value of a_μ which confirms the ~3.5 σ discrepancy from the experimental value measured at BNL
- FNAL Muon g-2 experiment has started data taking in 2018 with the ultimate goal to measure a_μ with a precision of 140 ppb (4xBNL precision)
- Run 3 just finished: ~7.4 x BNL total statistics collected
- Run 1 measurements of ω_a and ω_p almost completed: goal of releasing the a_μ result within this year
- Run 4 will start in November through July 2021
- Run 5 in 2022 should allow to reach the x20 BNL TDR goal

Stay tuned!