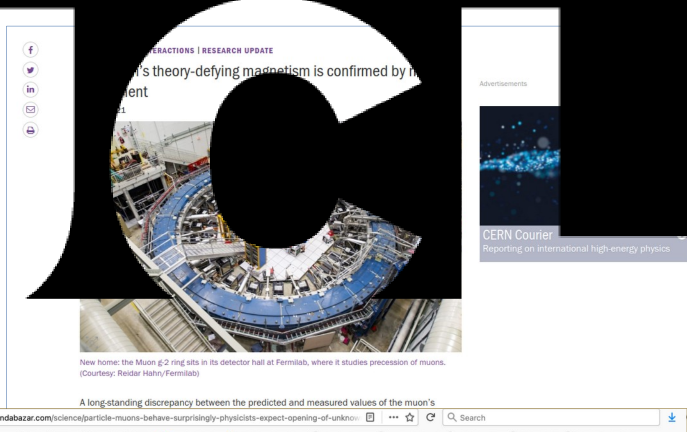
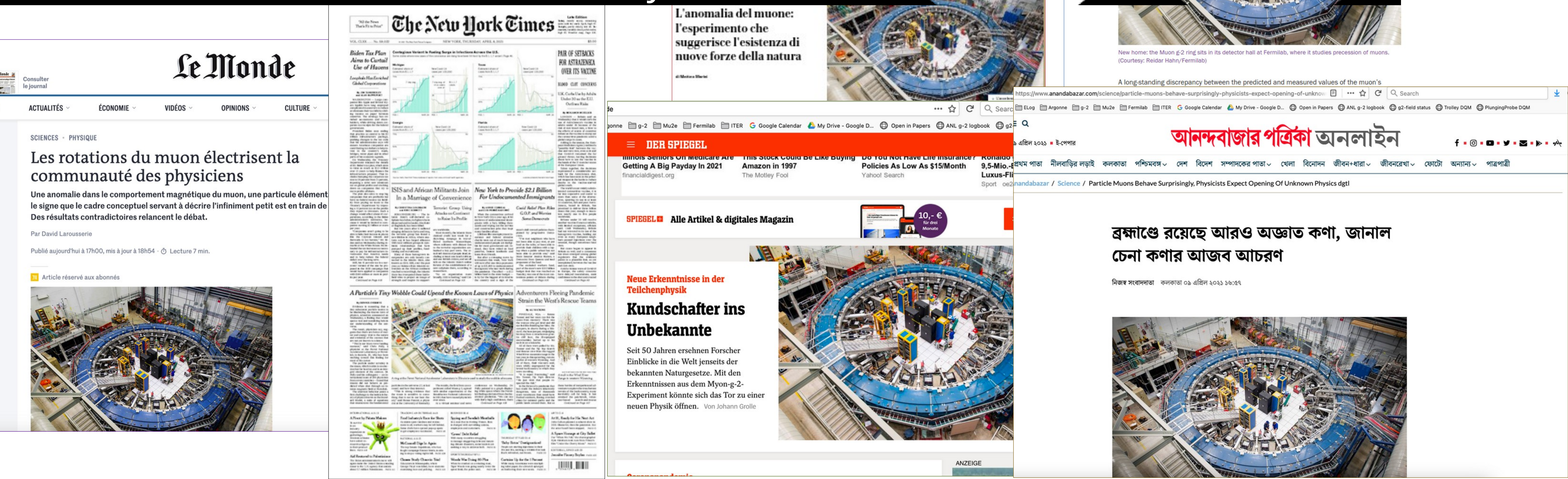
First result from FNAL Muon g-2

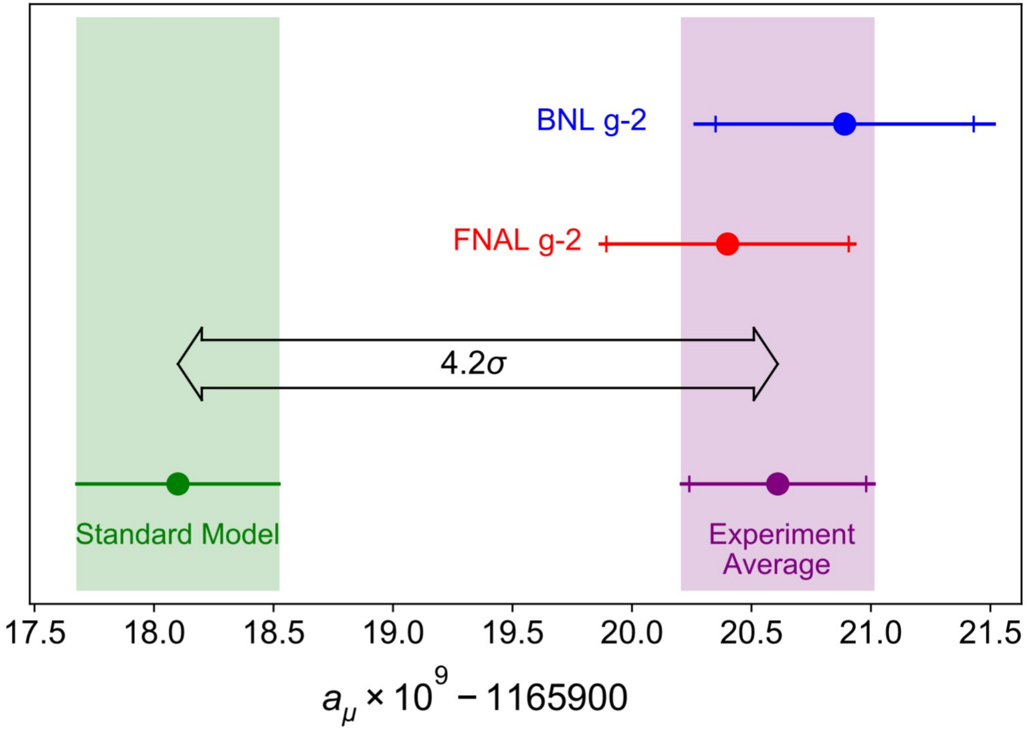
Gavin Hesketh, 12th May 2021

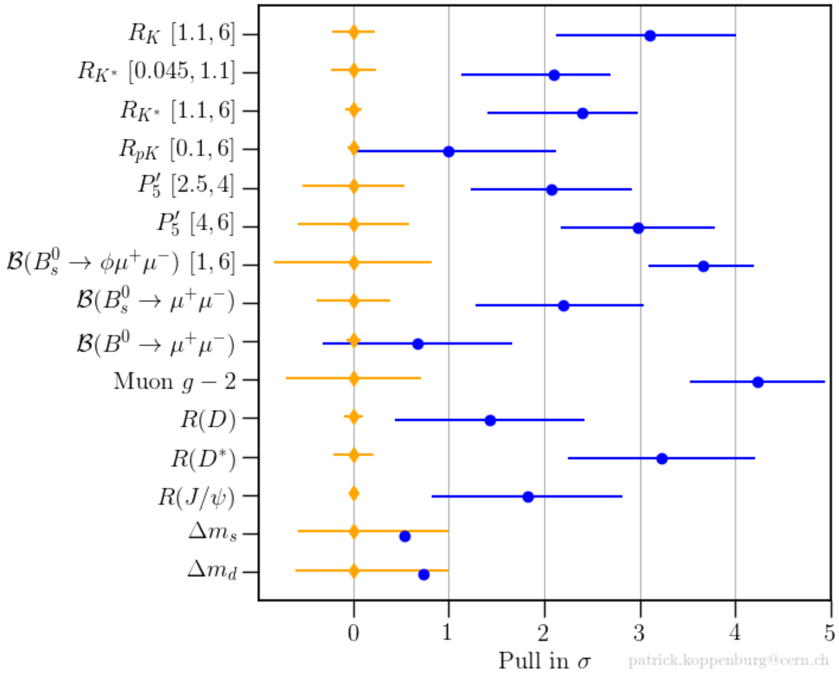




Fermilab Muon g-2 (E989) confirms the Brookhaven (E821) results

- measured a_μ to 0.46 ppm
- 4.2σ tension with consensus theory prediction





Some background

The g-factor

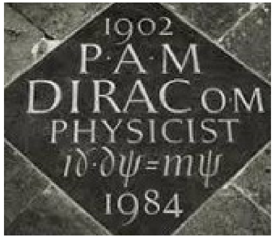
All fermions have an intrinsic magnetic moment:

- spin + g-factor

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

For all fundamental fermions:

g = 2 **(Dirac, 1927)**



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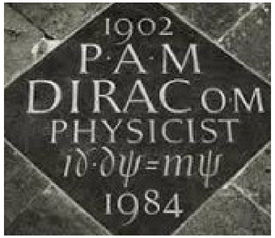

Electron anomaly!

g = 2.00238 ± 6 **(Kusch & Foley, 1948)**

The g-factor

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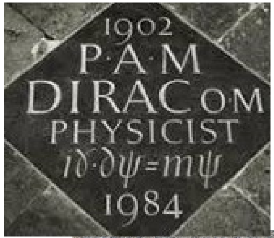
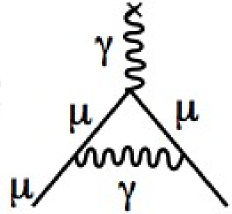
For all fundamental fermions:

g = 2.00232



(Schwinger, 1948)

$$\frac{\alpha}{2\pi} = 0.00232$$



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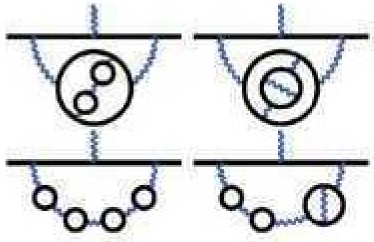
Electrons today:

g = 2.00231930436328 ± 153



Phys. Rev. D **97,** 036001 (2018)

g = 2.00231930436146 ± 56

Phys. Rev. A **83**, 052122 (2011)

"the most precisely determined quantity in physics"

Muon g-factor

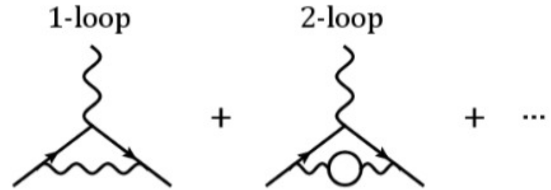
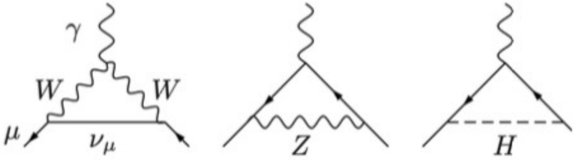
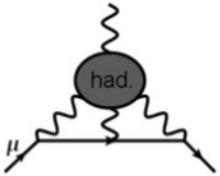
“Anomalous” term: $a = \frac{g - 2}{2}$

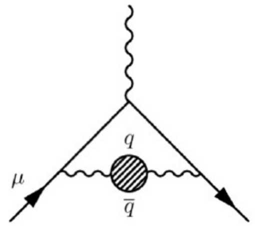
- all the loop corrections
- contributions scale as $(m_l / M)^2 \rightarrow$ muons x43,000 more sensitive to higher mass effects

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}}$$

Muon g-factor

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}}$$

			a_μ^{SM} portion	δa_μ^{SM} portion
QED		Perturbative (Known to five-loop)	$\sim 99.99\%$	$\sim 0.001\%$
EW		Perturbative (Known to two-loop)	~ 1 ppm	$\sim 0.2\%$
HVP		Non-perturbative (Data-driven & lattice)	~ 59 ppm	**$\sim 84\%$**
HLbL		Non-perturbative (Data-driven & lattice)	~ 1 ppm	**$\sim 16\%$**

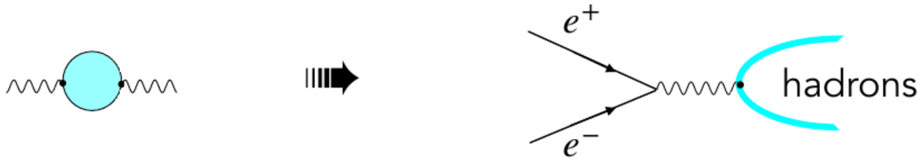


g-2 Theory Initiative determination of SM value

T. Aoyama et al, arXiv:2006.04822, Phys. Repts. 887 (2020) 1-166

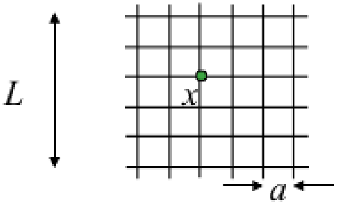
Consensus approach to HVP:

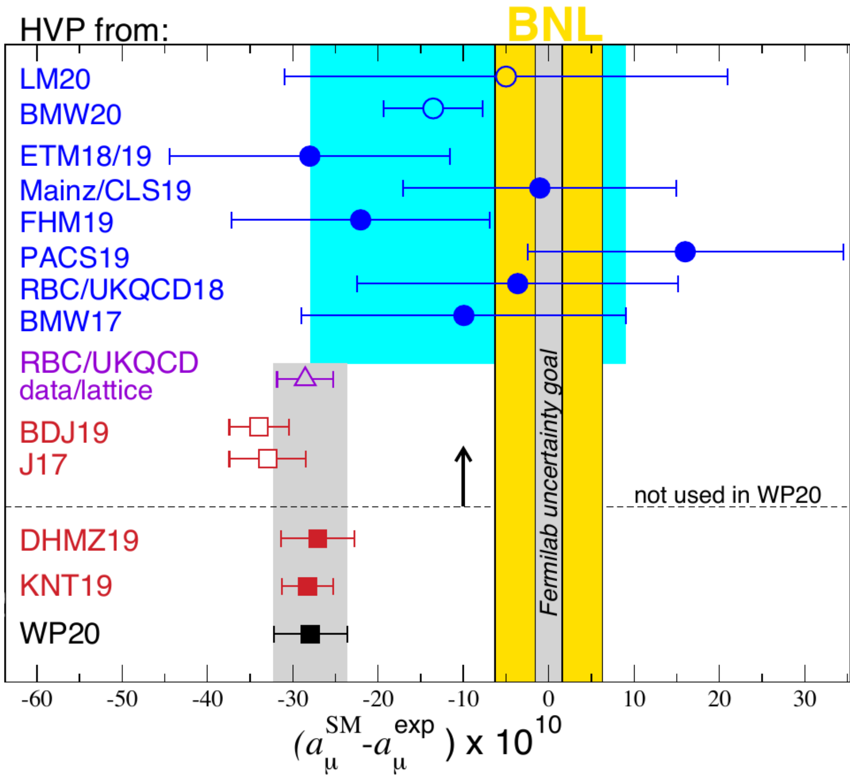
- $e^+e^- \rightarrow$ hadrons data + dispersion theory
- many data-sets + analyses, long-standing approach



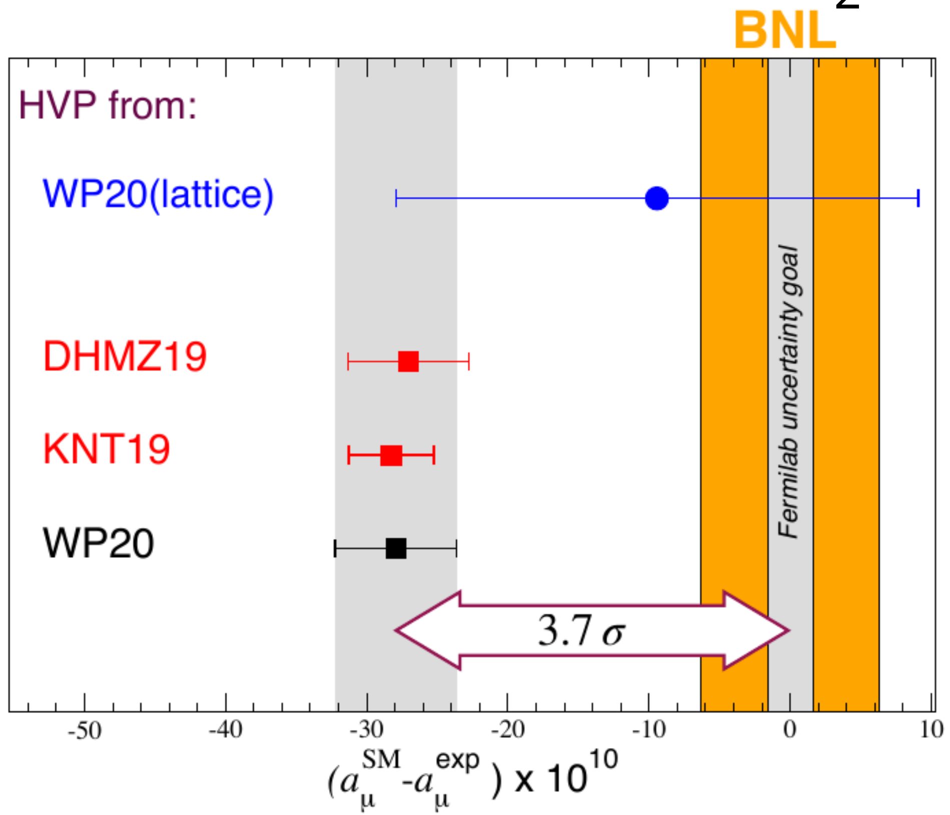
Lattice QCD:

- theory-based evaluation on super-computers
- huge recent progress, several groups





Results for anomalous term: $a = \frac{g-2}{2}$



a_μ^{SM} = 0.00116591810 (43) Theory Initiative

a_μ^{Exp} = 0.00116592089 (63) BNL E821 (2004)

Brookhaven Experiment (E821)
- 540 ppm precision
- 3.7σ from Standard Model

Fermilab Experiment (E989)
- 540ppb → 140 ppb
- better muon beam
  - lower inst rate, higher int rate
  - higher purity
- new detectors

BNL → FNAL

[50 (stat) + 33 (syst) → 11 (stat) + 11 (syst)] x 10^{-11}

Measuring g-2

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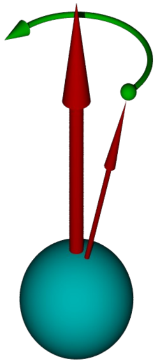
Spin precession in a magnetic field:

$$\omega_s = g\frac{eB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$
$$= a_\mu \frac{eB}{m} + \frac{eB}{\gamma m}$$



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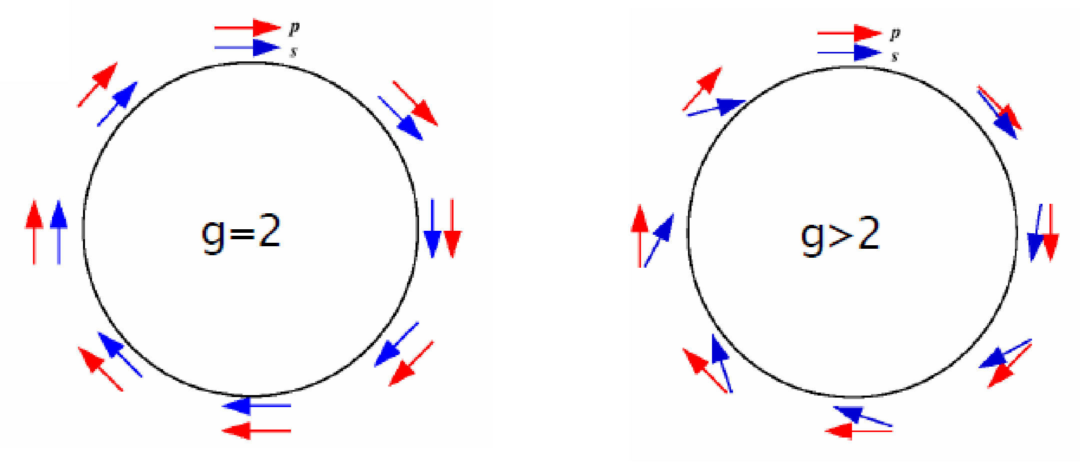
$$\omega_s - \omega_c \equiv \omega_a = a_\mu \frac{eB}{m}$$



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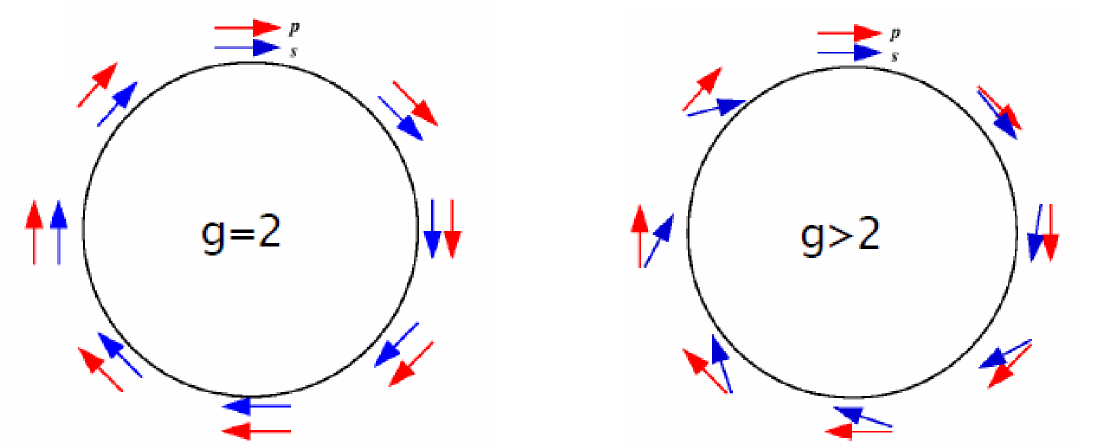
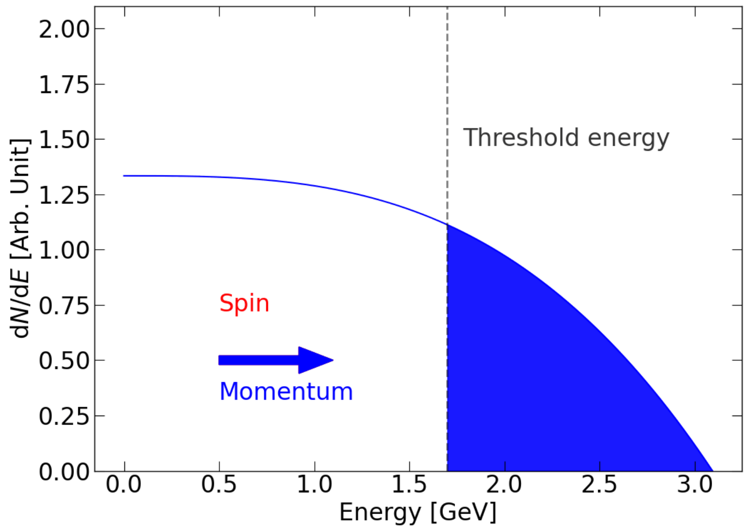
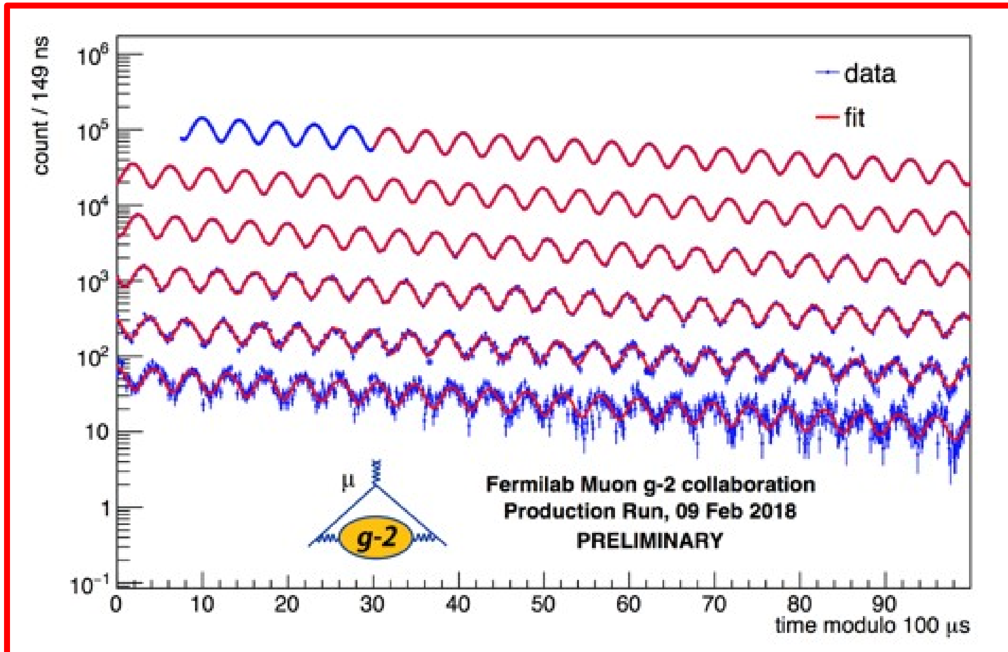
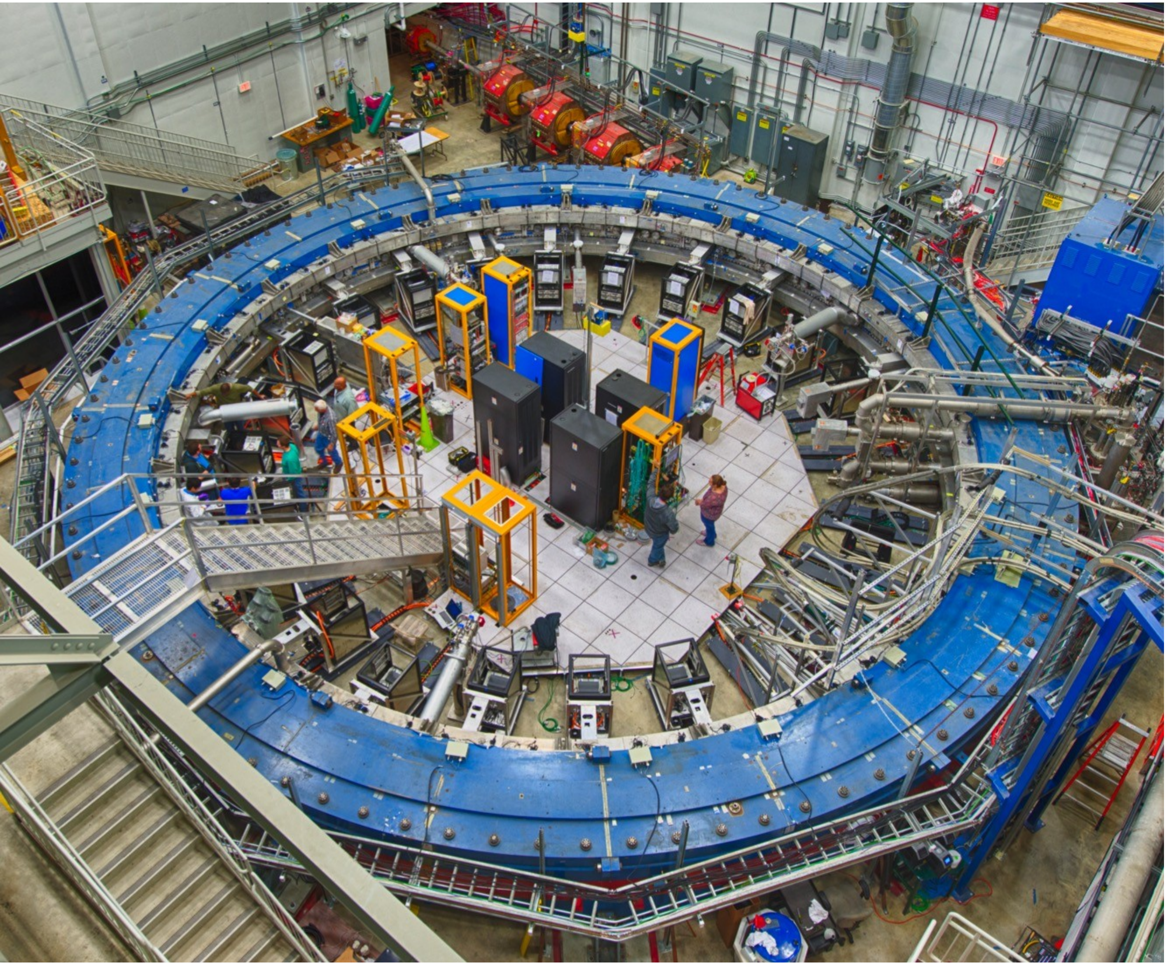


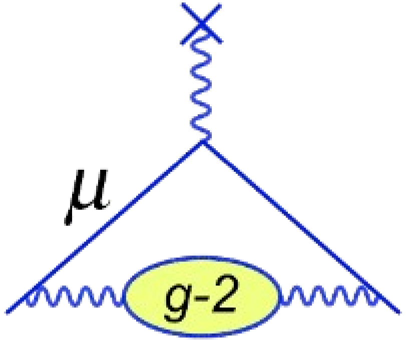




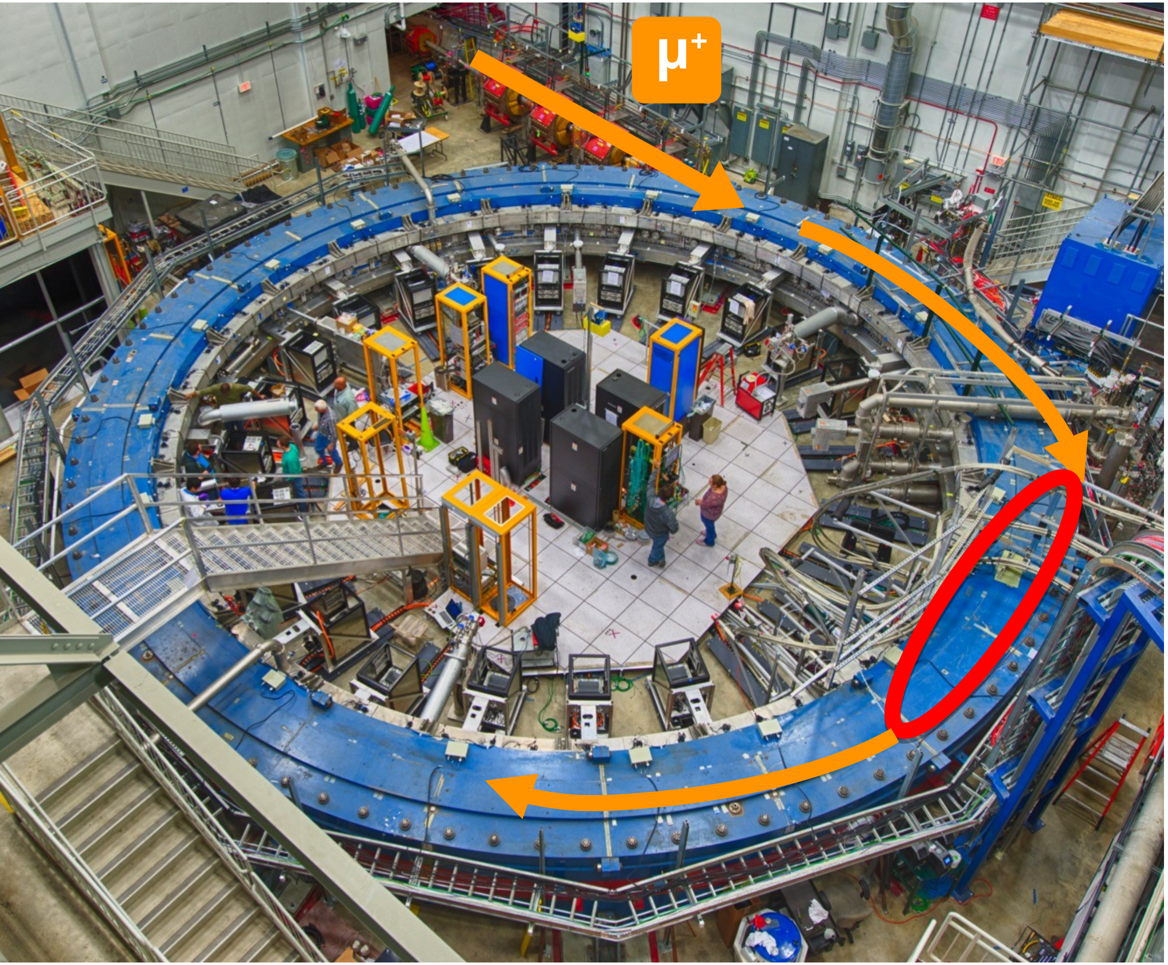
The Big Move, 2013

Fermilab Muon g-2



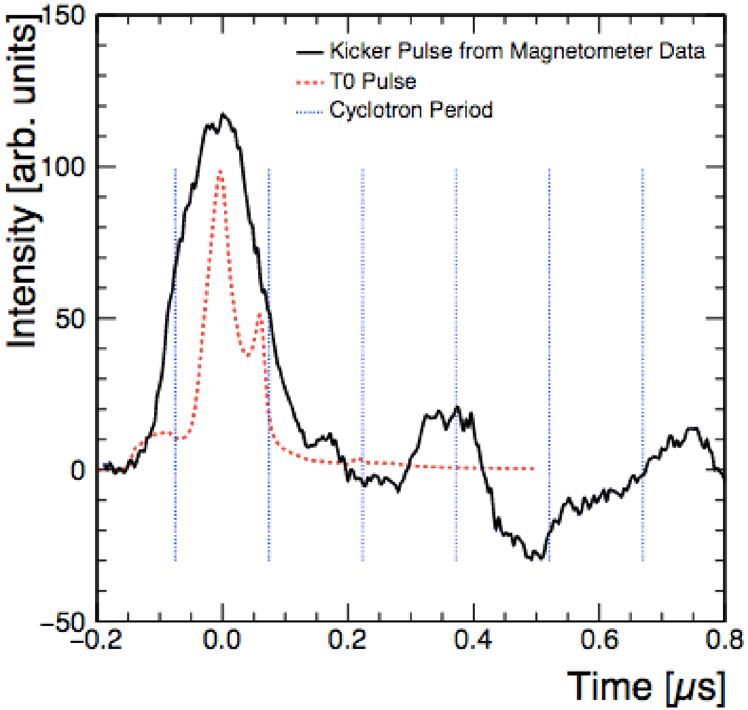


Injection and kick



Beam pulse ~ 125 ns wide

Muons ~77 mm away from ideal radius
- “kick” them into right orbit



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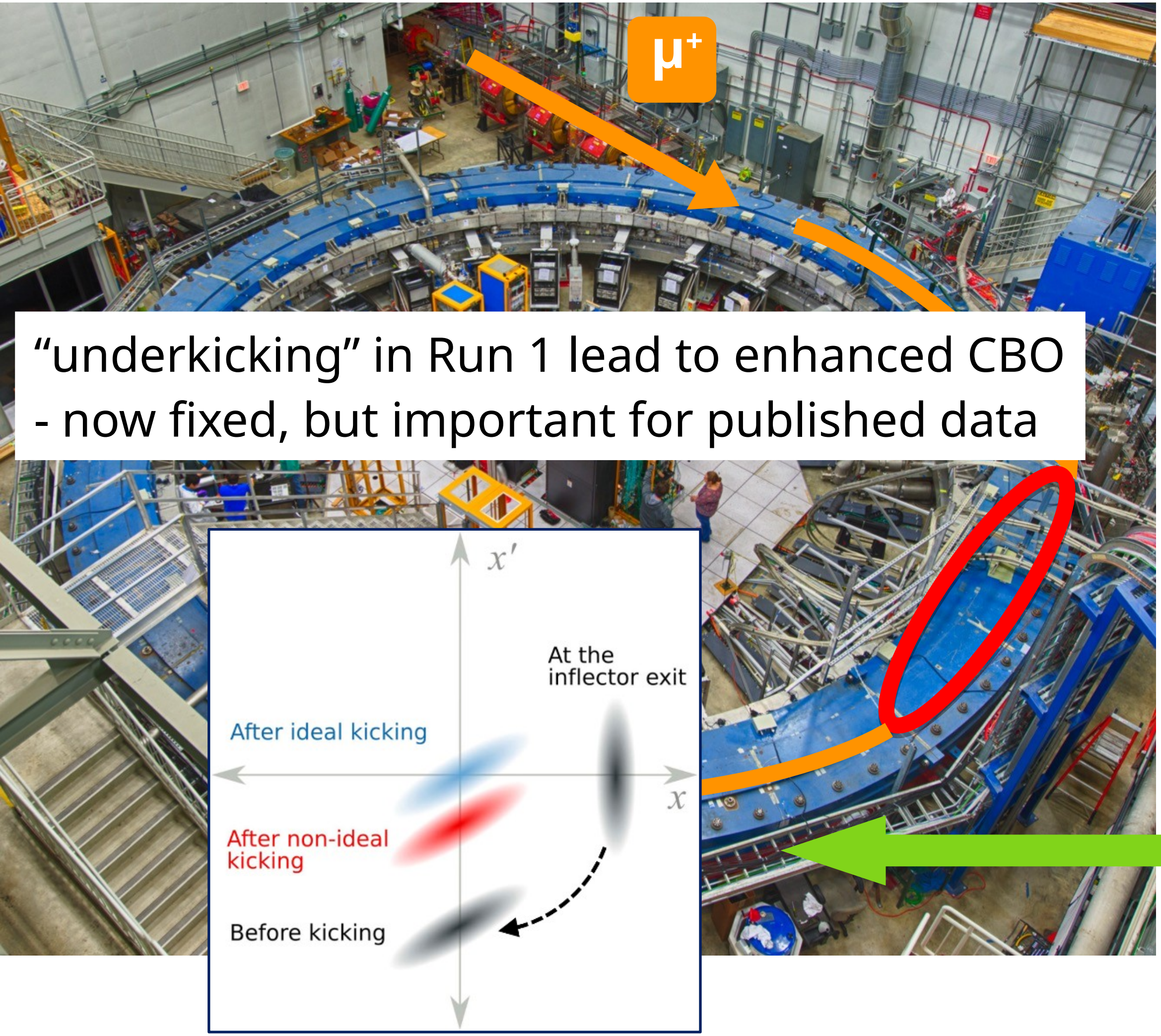

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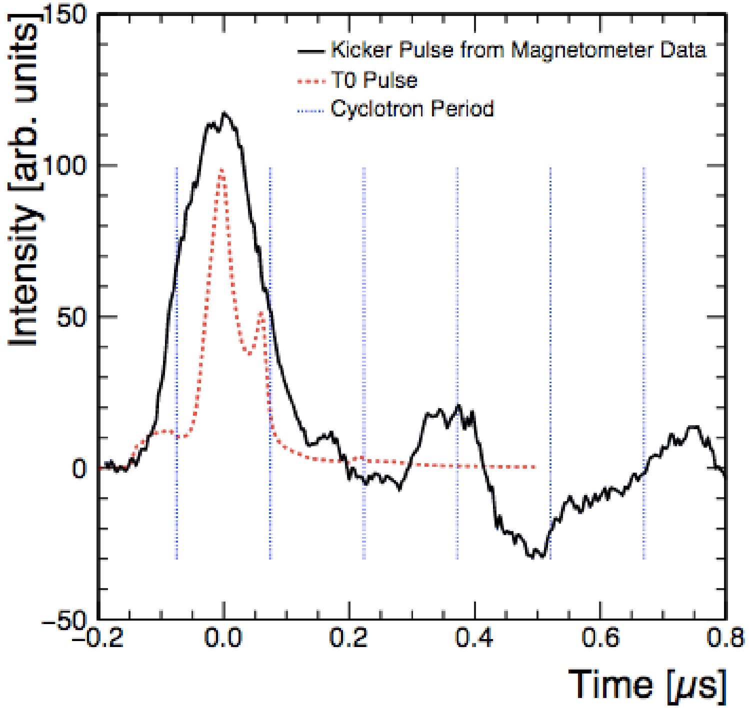
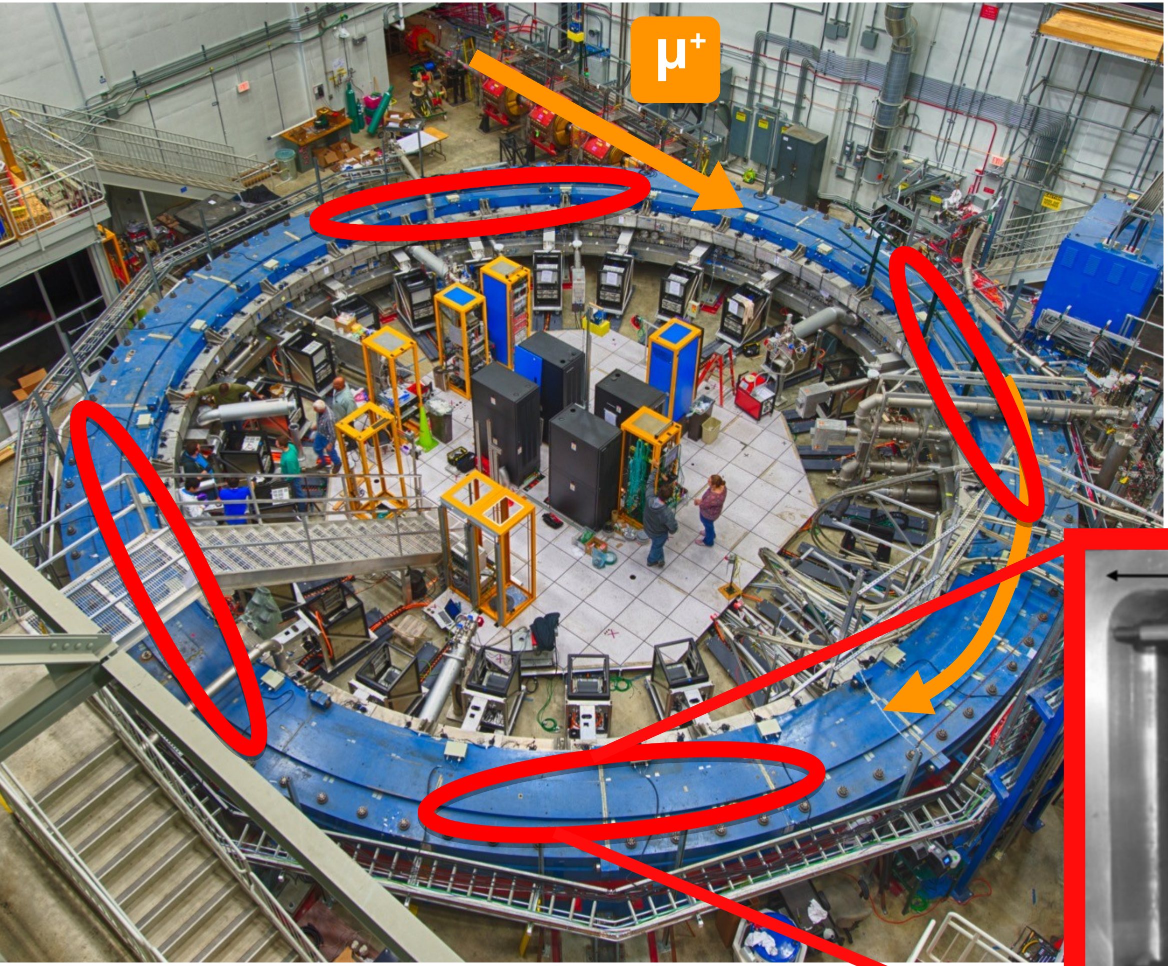


Focus and scrape

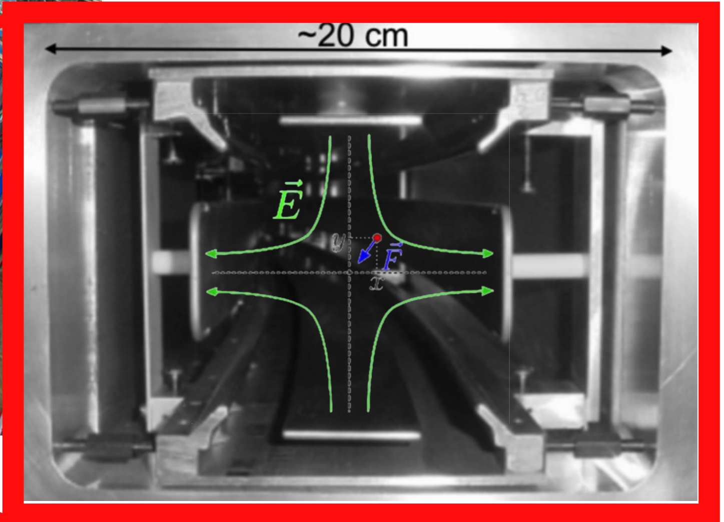


Scraping at the start of each fill:

- beam is moved to collimators
- momentum spread 0.15% → 0.1%

Electric quadrupoles:

- focus the beam vertically



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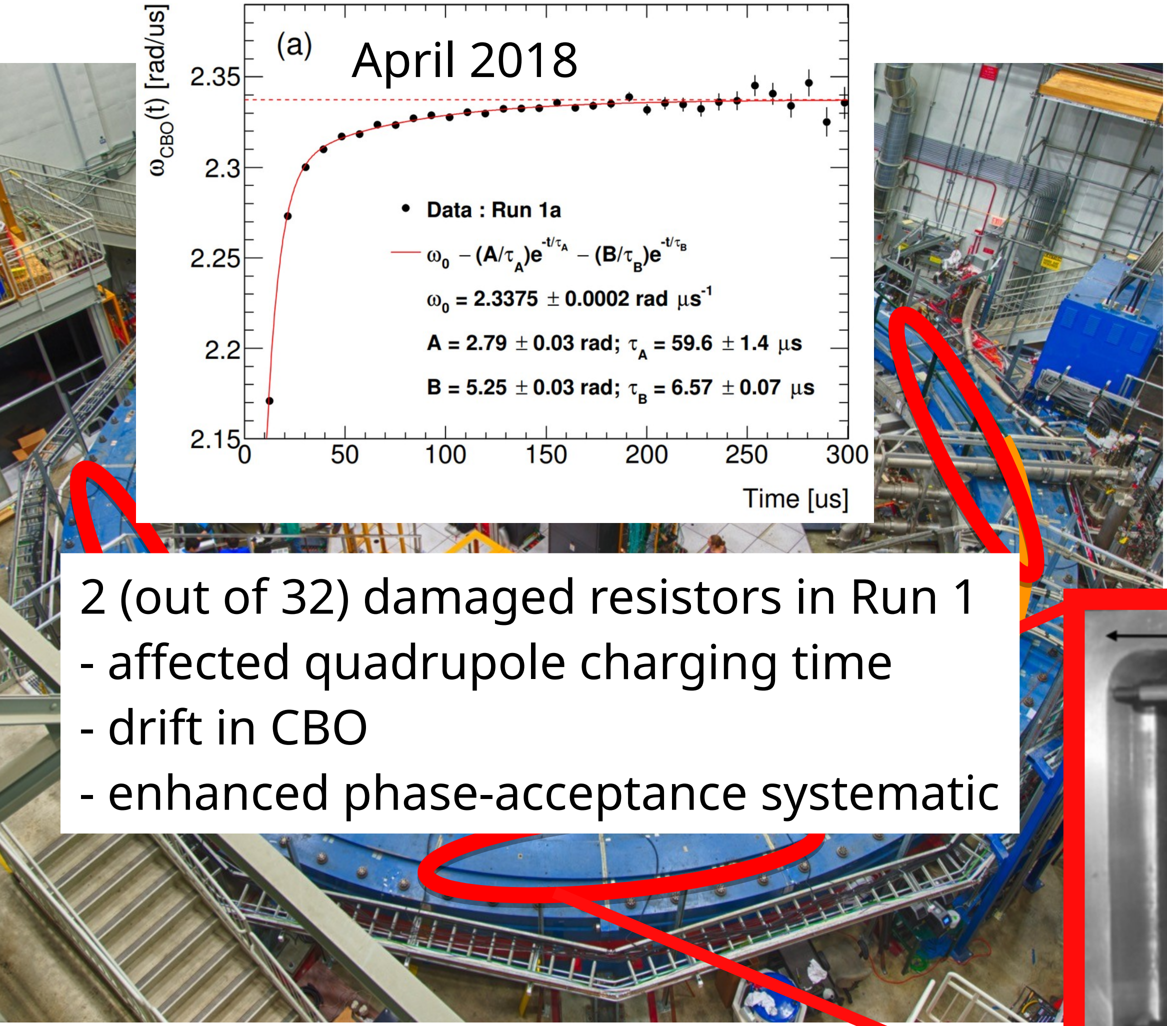

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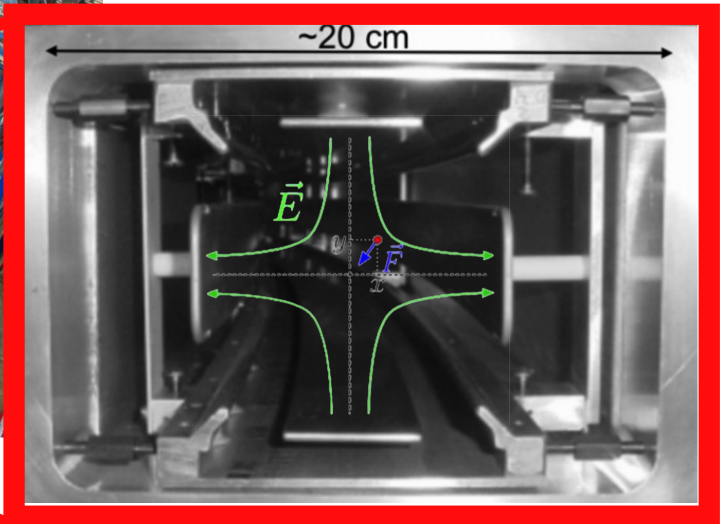
2 (out of 32) damaged resistors in Run 1
- affected quadrupole charging time
- drift in CBO
- enhanced phase-acceptance systematic



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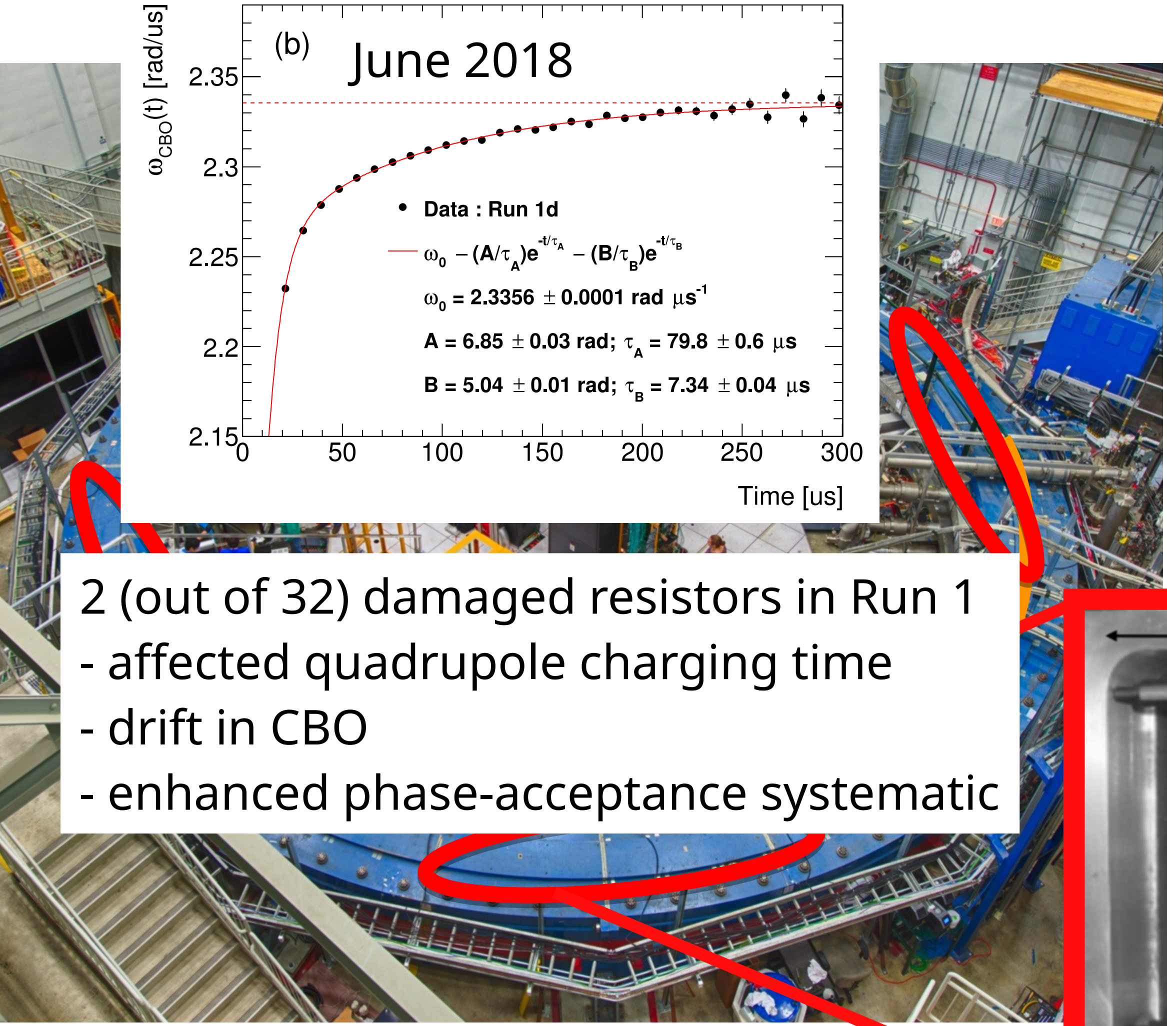

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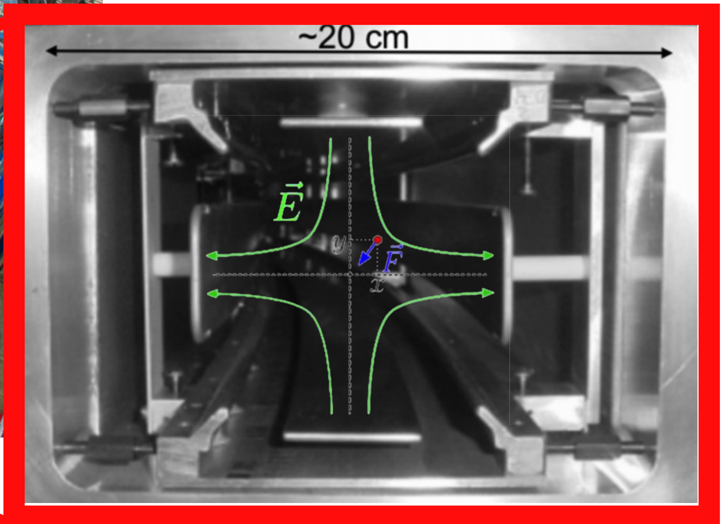
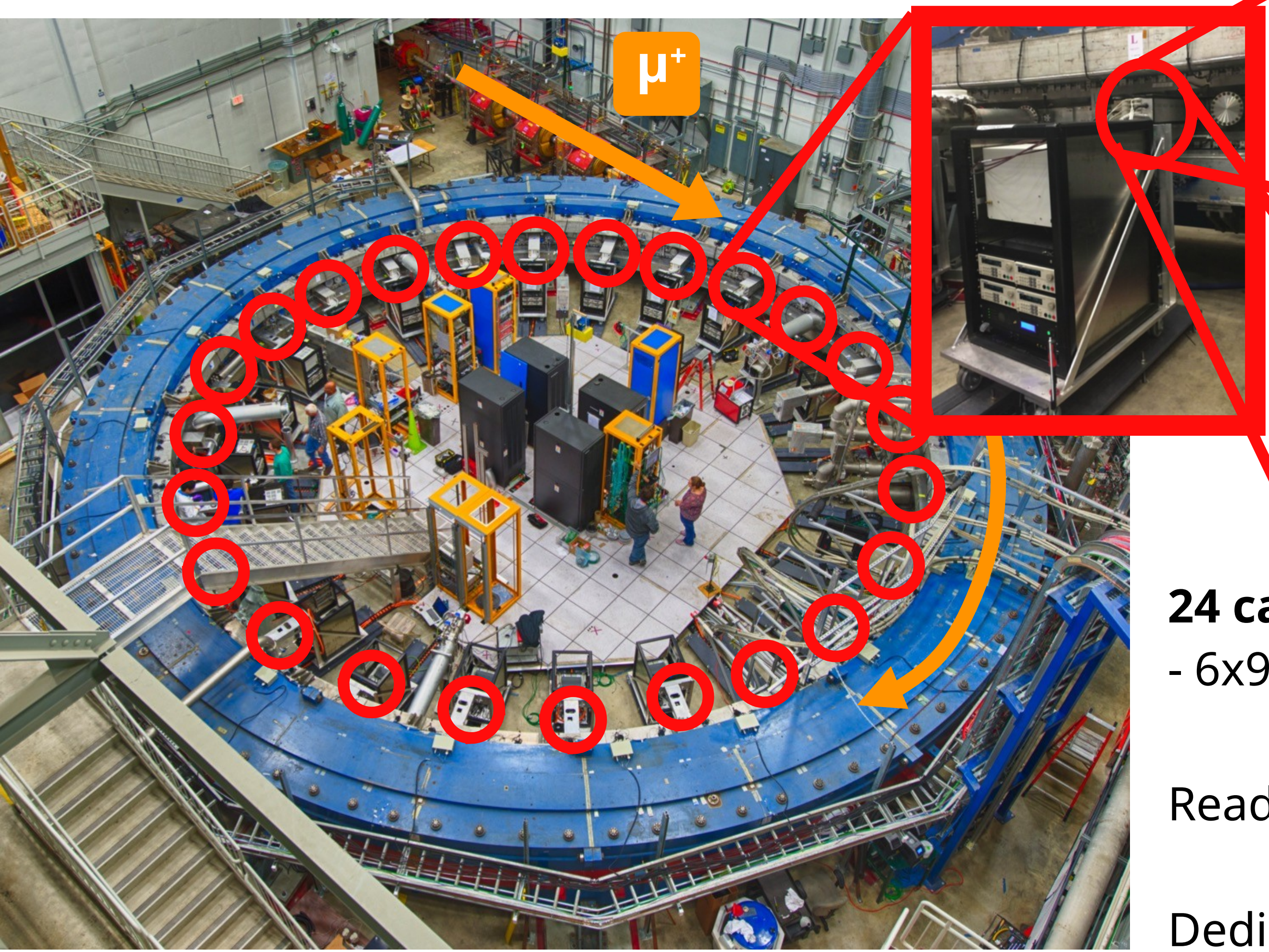
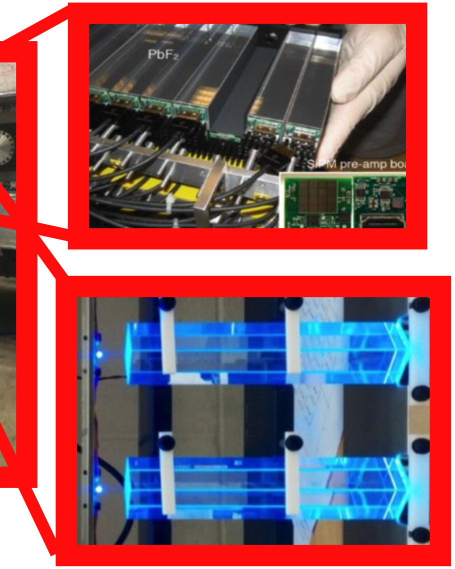


Calorimeters





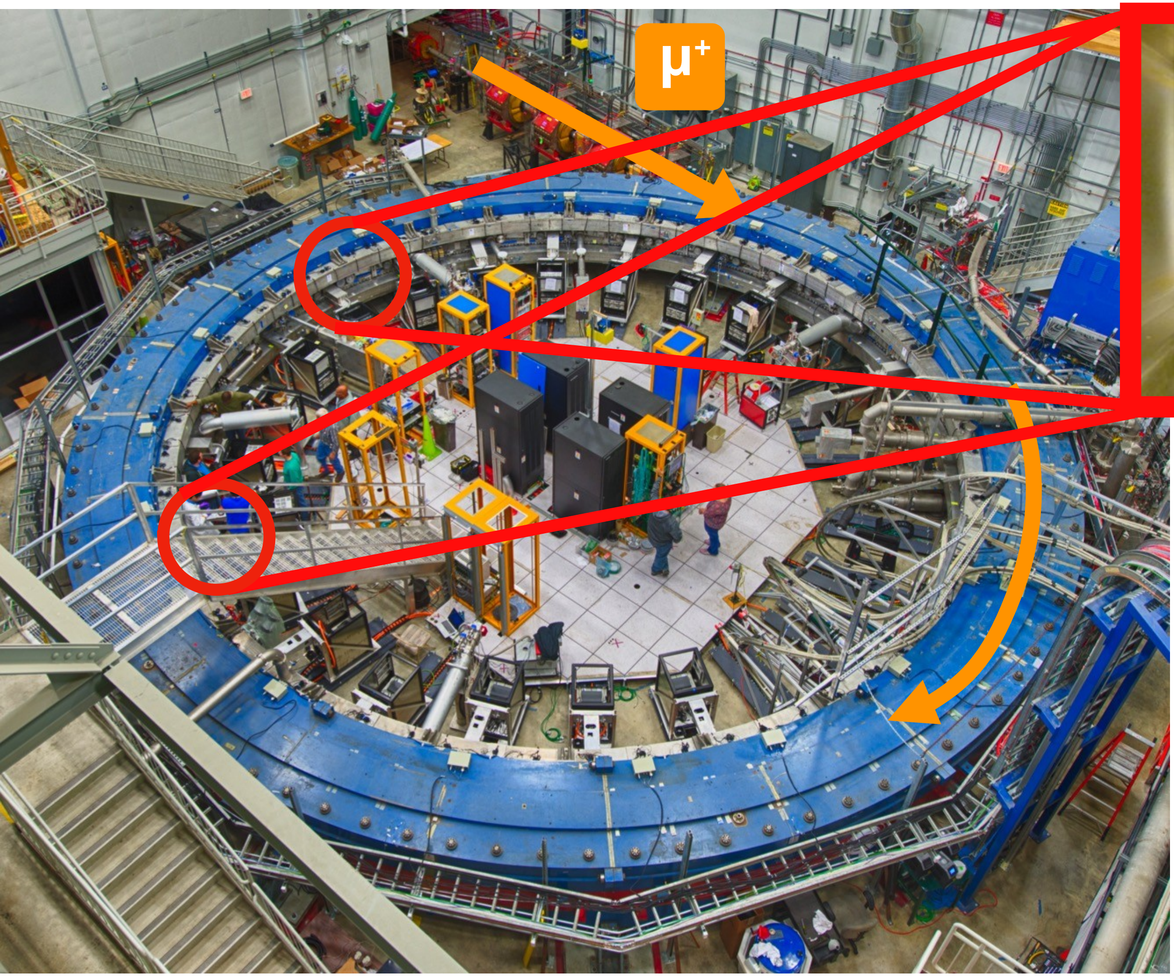
24 calorimeters:

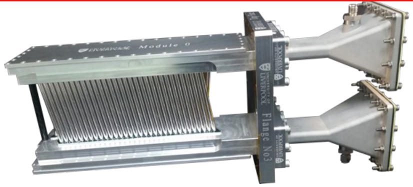
- 6x9 PbF_2 crystals (2.5x2.5x14cm, $15X_0$)

Read out by SiPMs, 1296 total channels

Dedicated laser calibration system

Trackers

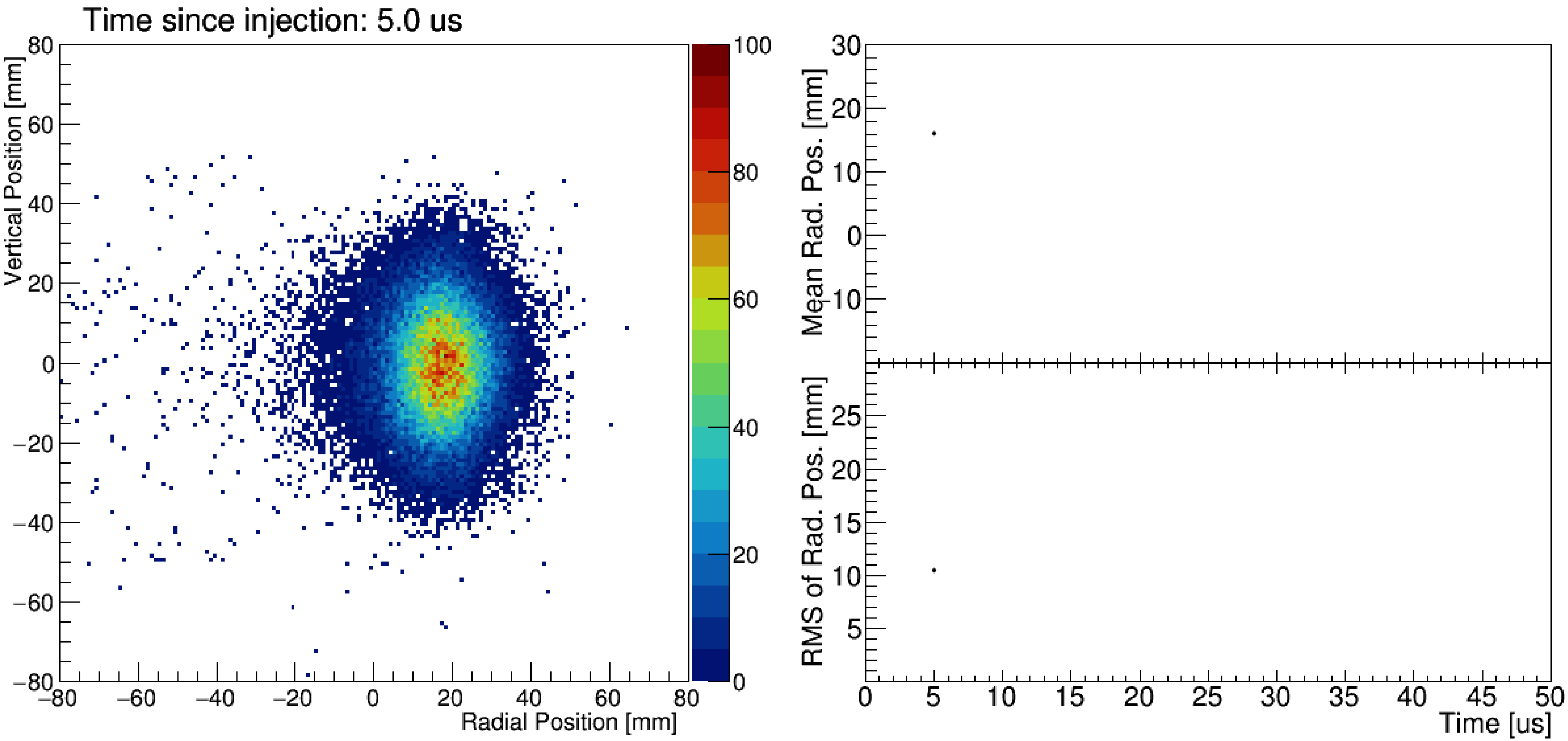




Two tracking stations:

- 8 modules, 128 straws in each
- stereo angle for vertical position
- trace positrons back to decay point
- UK built

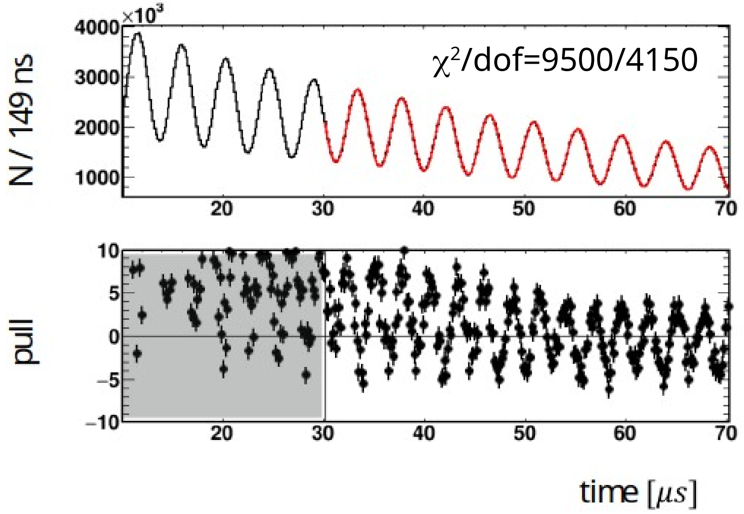
Beam position



The basic method:

- count positrons over threshold
- 5-parameter fit to determine ω_a

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



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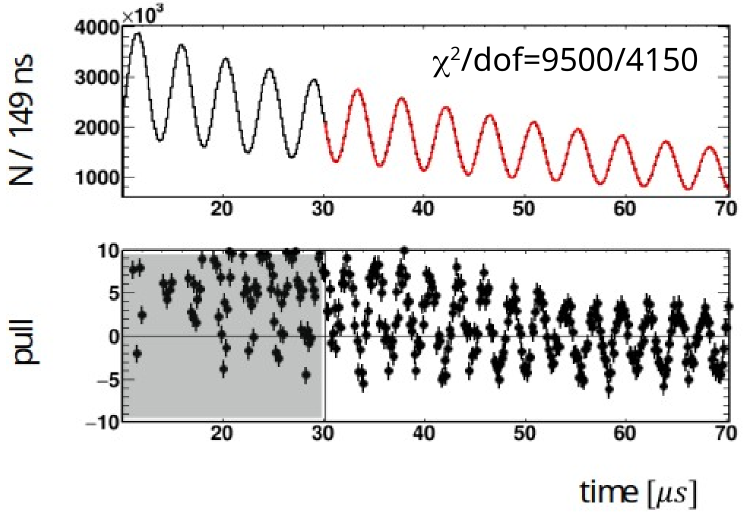
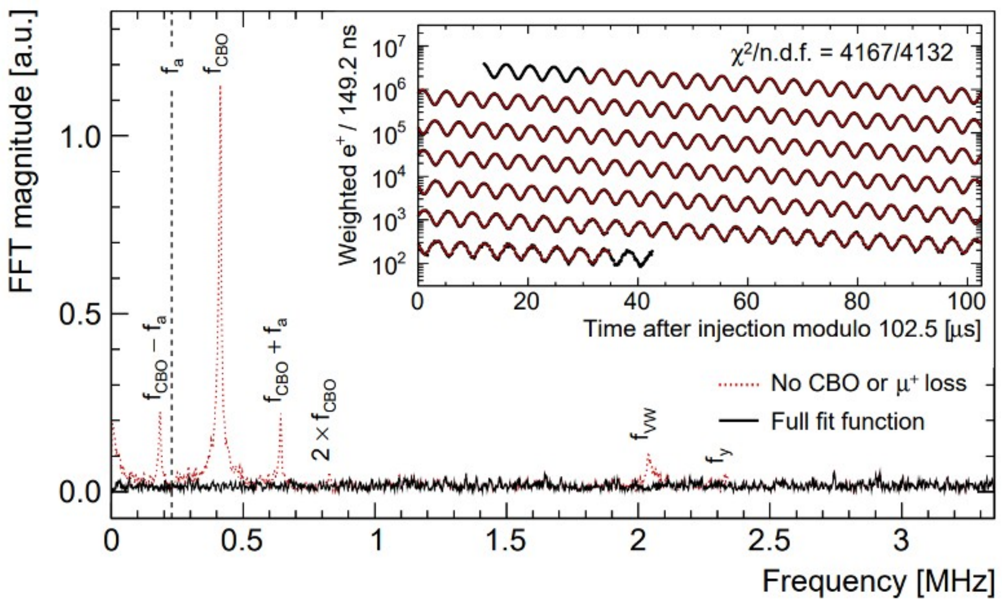
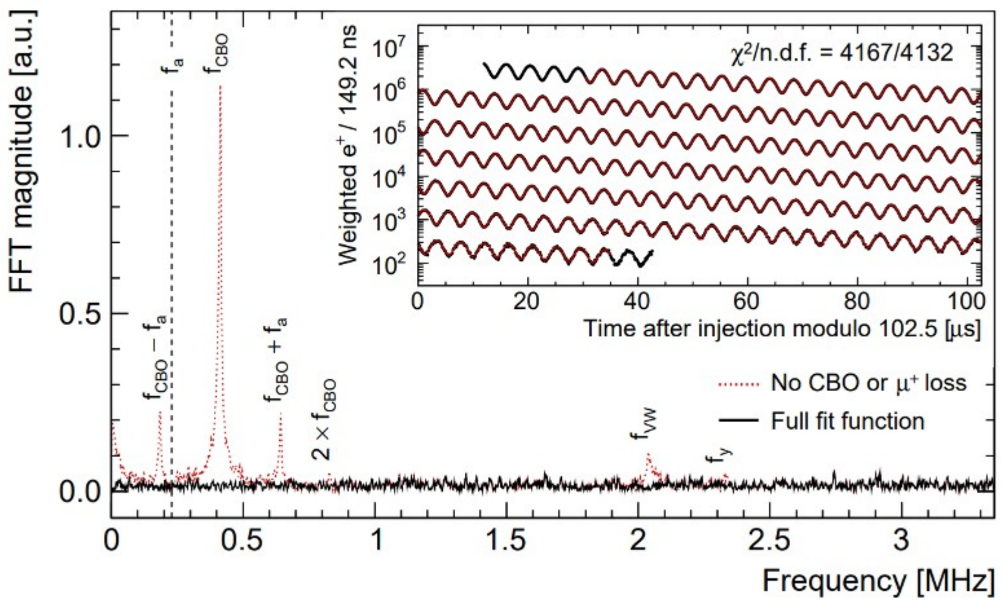




Real fit function includes:

- calorimeter gain change (from laser data)
- positron pileup
- Muon losses
- Coherent betatron oscillations

$$
\begin{aligned}
N_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{N,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{N,x,1}) \\
&\quad + e^{-2t/\tau_{\mathrm{CBO}}} A_{N,x,2} \cos(2\omega_{\mathrm{CBO}} t + \phi_{N,x,2}) \\
N_y(t) &= 1 + e^{-t/\tau_y} A_{N,y,1} \cos(\omega_y t + \phi_{N,y,1}) \\
&\quad + e^{-2t/\tau_y} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2}) \\
\Lambda(t) &= 1 - K_{\mathrm{loss}} \int_0^t e^{t'/\gamma\tau_\mu} L(t')\, \mathrm{d}t' \\
A_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{A,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{A,x,1}) \\
\phi_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{\phi,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{\phi,x,1})
\end{aligned}
$$



- 2 positron reconstruction methods
- 4 different analysis methods (T,A,R,Q)
- 6 independent analysis teams,
  using different combinations
- Many cross-checks performed,
  varying sensitivities to systematics

Just a few details

What is actually measured…

$$a_\mu = \omega_a \frac{m}{eB}$$

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$$a_\mu = \omega_a \frac{m}{eB} \longrightarrow a_\mu = \frac{\omega_a}{\tilde{\omega}_p(\mathrm{Tr})} \frac{\mu_p(\mathrm{Tr})}{\mu_e(\mathrm{H})} \frac{\mu_e(\mathrm{H})}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Total uncertainty from external inputs: 24 ppb

We determine the ratio:

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}_p(\mathrm{Tr})}$$

$\frac{\mu'_p(T_r)}{\mu_e(H)}$	10.5 ppb uncertainty at T_r = 34.7°C Metrologia 13, 179 (1977)
$\frac{\mu_e(H)}{\mu_e}$	Bound state QED calculation, exact Rev. Mod. Phys. 88, 035009 (2016)
$\frac{m_\mu}{m_e}$	Muonium hyperfine splitting 22 ppb uncertainty Phys. Rev. Lett. 82, 11 (1999)
$\frac{g_e}{2}$	0.28 ppt uncertainty Phys. Rev. A 83, 052122 (2011)

What is actually measured...

$$a_\mu = \omega_a \frac{m}{eB} \longrightarrow a_\mu = \frac{\omega_a}{\tilde{\omega}_p(\mathrm{Tr})} \frac{\mu_p(\mathrm{Tr})}{\mu_e(\mathrm{H})} \frac{\mu_e(\mathrm{H})}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Unblinding conversion factor (f_{clock})

Measured precession frequency (ω_a^m)

Corrections from beam dynamics systematic effects ($C_e + C_p + C_{ml} + C_{pa}$)

NMR probe calibration factor (f_{calib})

Proton precession frequency ($\omega_p(x,y,\phi)$)

Magnetic field weighted over the muon distribution and azimuthally averaged ($M(x,y,\phi)\rangle$)

Corrections from the transient magnetic field ($B_k + B_q$)

$$\omega_a = a_\mu \frac{eB}{m}$$

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

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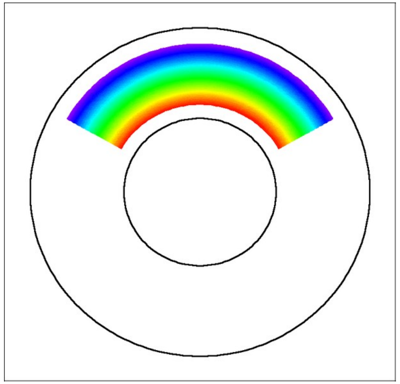
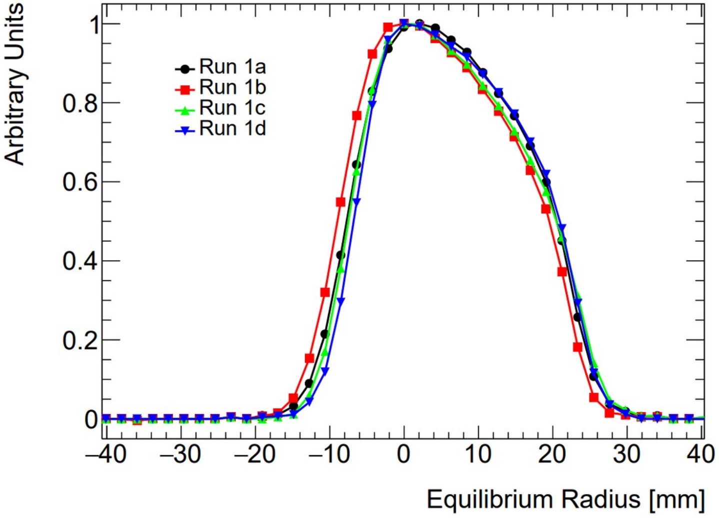
Coupling to electrostatic quadrupoles:

- use "magic momentum" of 3.1 GeV, but momentum spread ~0.10%
  - → "E-field correction"
  - - from Fourier analysis of "fast-rotation"





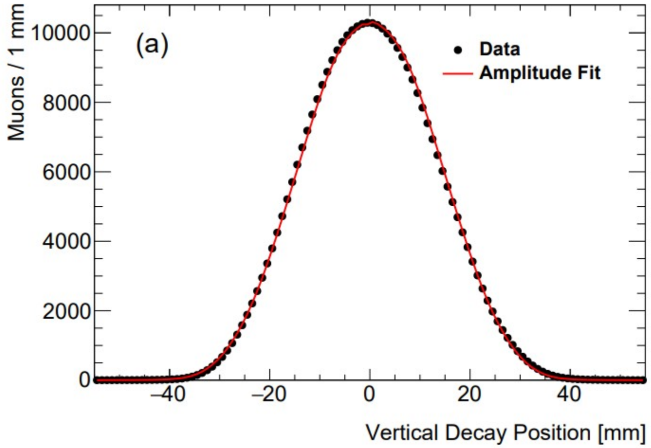
Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_e	471	464	534	475
Stat. uncertainty	< 1	1	< 1	< 1
Fourier method	8	13	14	4
Momentum-time	52	52	52	52
Quadrupole calibration	6	6	6	6
Field index	2	2	2	4
Syst. uncertainty	53	54	54	53

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

Small vertical momentum component:

→ "Pitch correction"

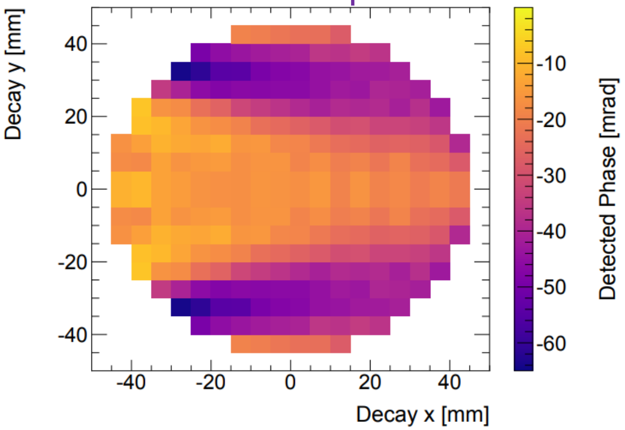
- use tracking detectors to measure vertical width of beam

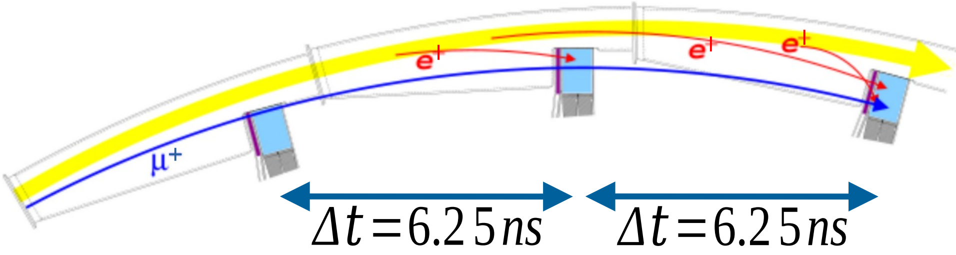


Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_p (ppb)	176	199	191	166
Stat. uncertainty	< 1	< 1	< 1	< 1
Tracker reco.	11	12	12	11
Tracker res. & acc	3	4	4	3
$\beta_y(\phi)$ & calo. acc.	1	1	2	1
Amplitude fit	1	< 1	1	3
Quad calibration	4	4	4	4
Syst. uncertainty	12	14	14	12

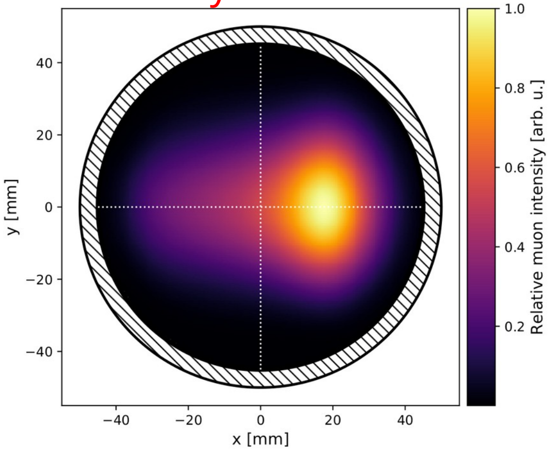
Beam Dynamics

Phase map



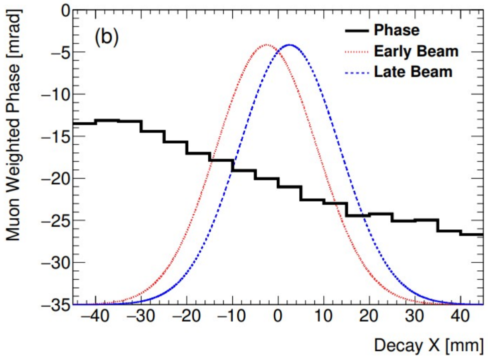


Decay distribution



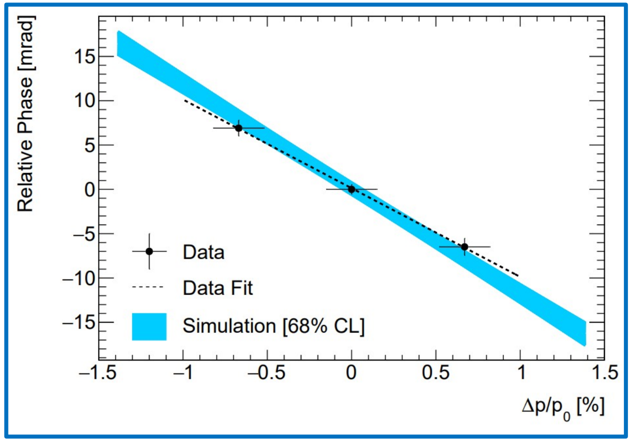
“Phase/Acceptance” correction:

- changes in beam distribution during fill
  → time-dependent phase
- enhanced by damaged resistors in Run-1



Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{pa}	-184	-165	-117	-164
Stat. uncertainty	23	20	15	14
Tracker & CBO	73	43	41	44
Phase maps	52	49	35	46
Beam dynamics	27	30	22	45
Total uncertainty	96	74	60	80

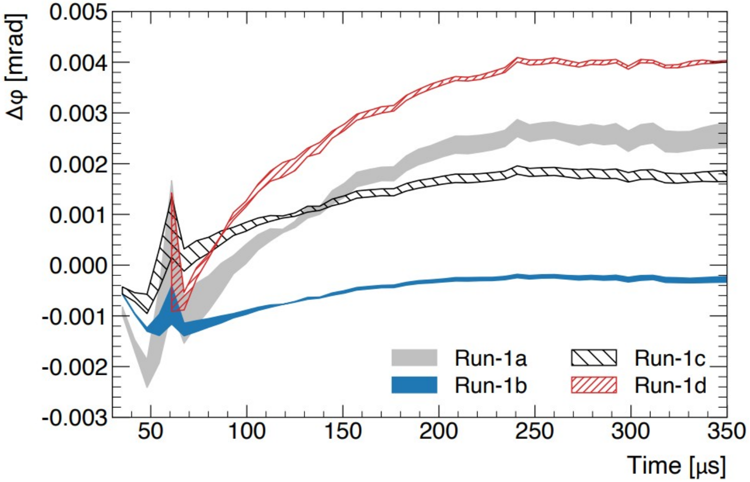
Beam Dynamics



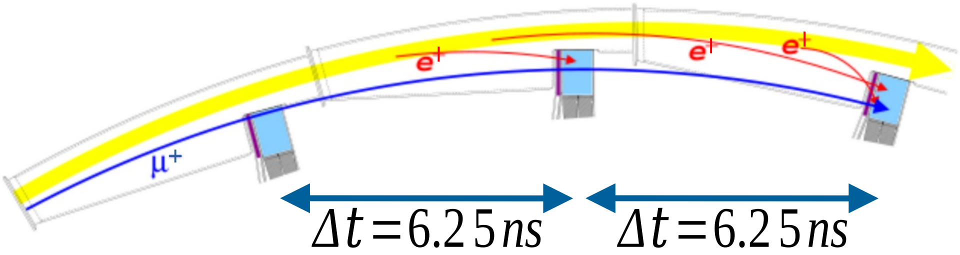
Lost Muons:

- low momentum muons are lost more quickly than high
- slightly different phase to ensemble
- causes change in overall phase vs time

$$\frac{d\varphi_0}{dt} = \frac{d\varphi_0}{d\langle p\rangle}\frac{d\langle p\rangle}{dt}$$



Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{ml}	-14	-3	-7	-17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum ($\sigma_{C_{ml}}$)	6	2	4	6



What is actually measured...

$$a_\mu = \omega_a \frac{m}{eB} \longrightarrow a_\mu = \frac{\omega_a}{\tilde{\omega}_p(\mathrm{Tr})} \frac{\mu_p(\mathrm{Tr})}{\mu_e(\mathrm{H})} \frac{\mu_e(\mathrm{H})}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Unblinding conversion factor

Measured precession frequency

Corrections from beam dynamics systematic effects

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\mathrm{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\mathrm{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

NMR probe calibration factor

Proton precession frequency

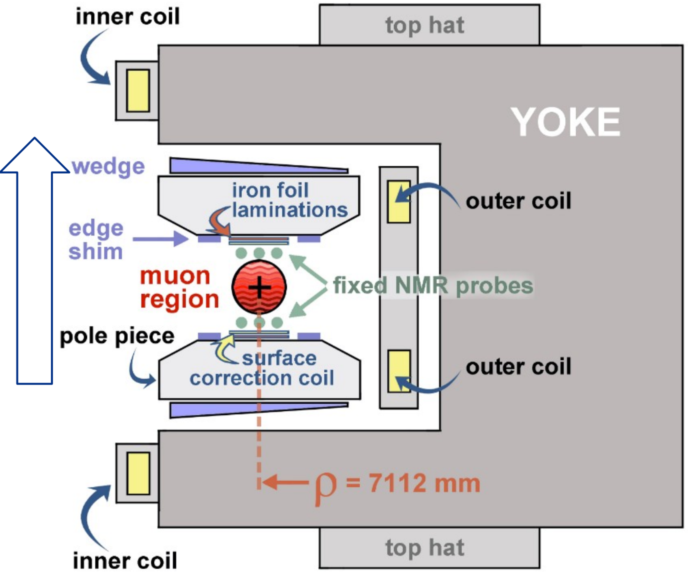
Magnetic field weighted over the muon distribution and azimuthally averaged

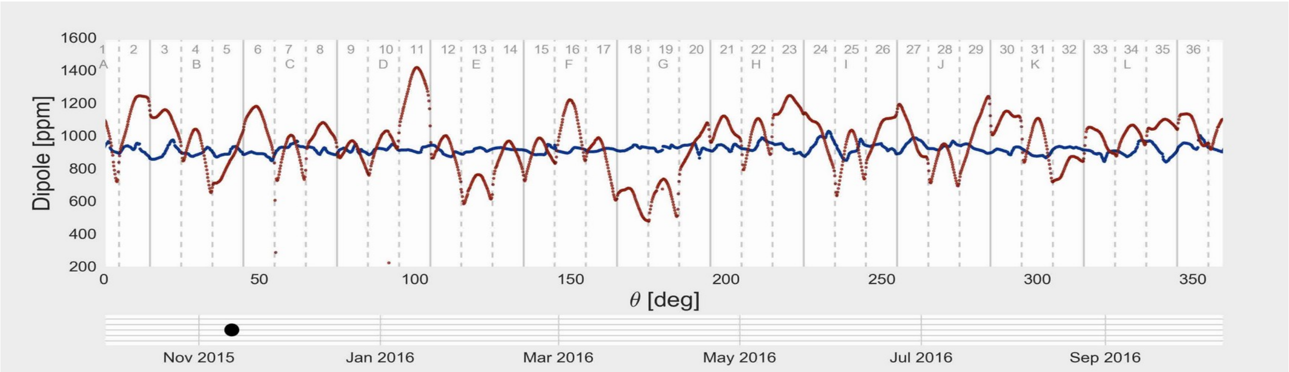
Corrections from the transient magnetic field

Magnetic Field

7.112 m radius ‘C’-shape magnet with vertically-aligned field B = 1.45 T, ppm-level uniformity

Magnet cross-section





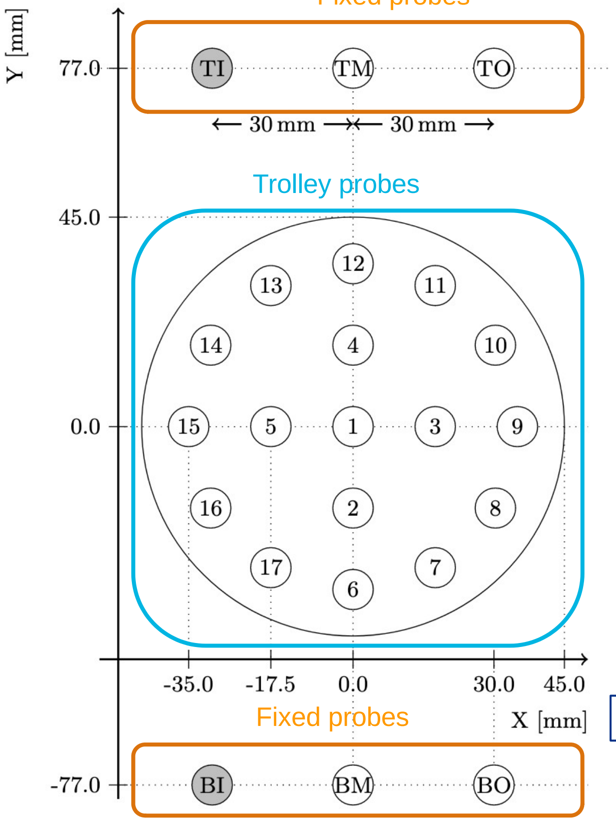
Temperature variations → ppm changes in magnet geometry, and drift in the field

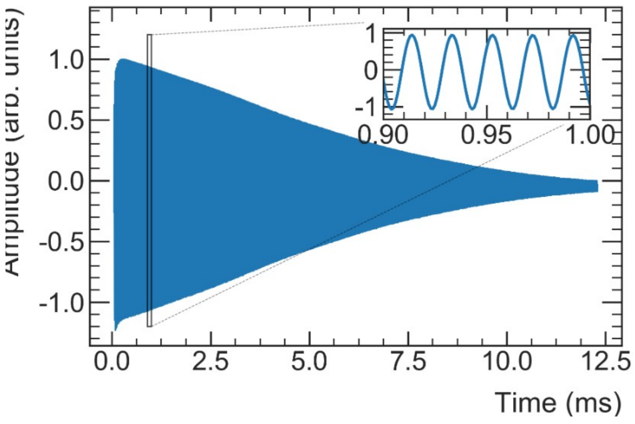
378 ‘fixed’ NMR probes around the ring measure the drift continuously
→ feedback to the magnet power supply to keep the dipole (vertical) term constant

The NMR Trolley

An in-vacuum trolley drives around the ring every ~3 days

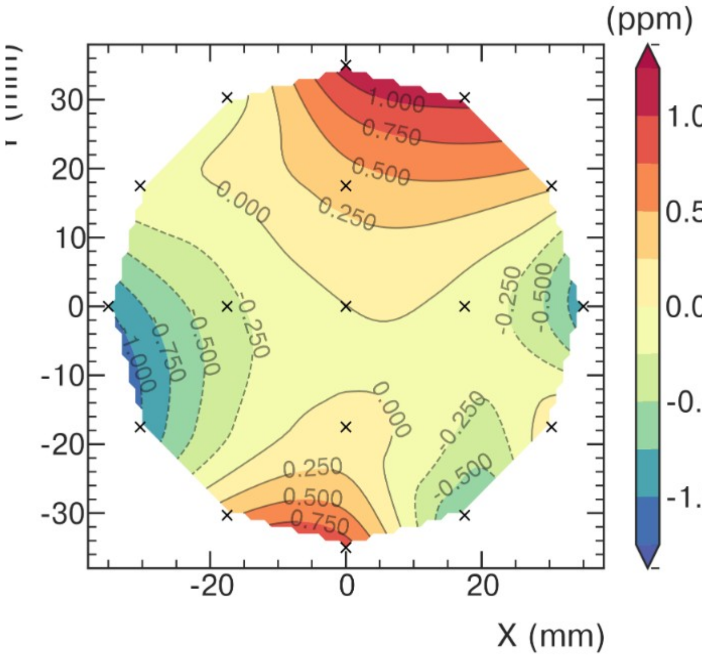
- 17 NMR probes x 9000 measurements, mapping out the field components





Field measured by extracting frequency from a Free Induction Decay (FID) spectrum

Field gradients in an azimuthal "slice"



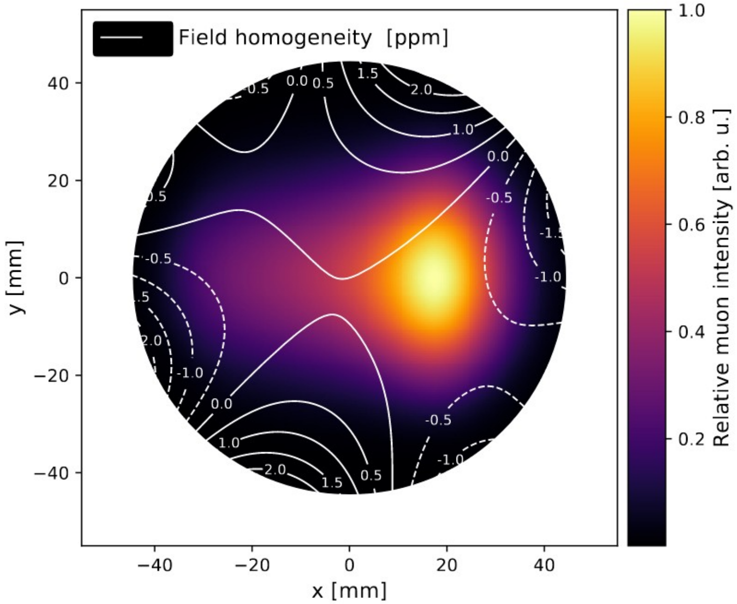
Field contour plot from the 17 probes

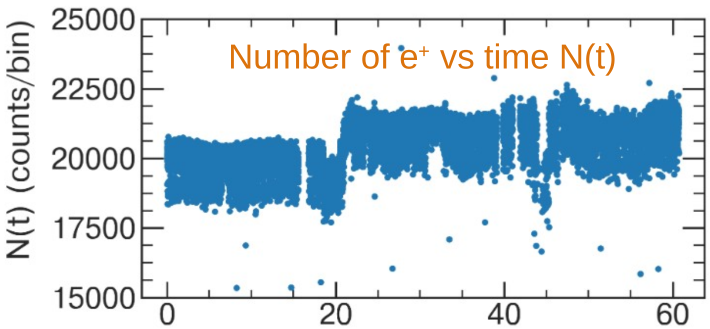
Muon-weighted field

Frequency maps from trolley and fixed probe data need to be weighted by the muon distribution

$$\tilde{\omega}_p = \left\langle \frac{\int \omega_p(x,y,\phi)\ M(x,y,\phi)\ \mathrm{d}x\ \mathrm{d}y}{\int M(x,y,\phi)\ \mathrm{d}x\ \mathrm{d}y} \right\rangle$$

2D beam distribution obtained from the straw trackers
- includes beam dynamics information
- and detector acceptances

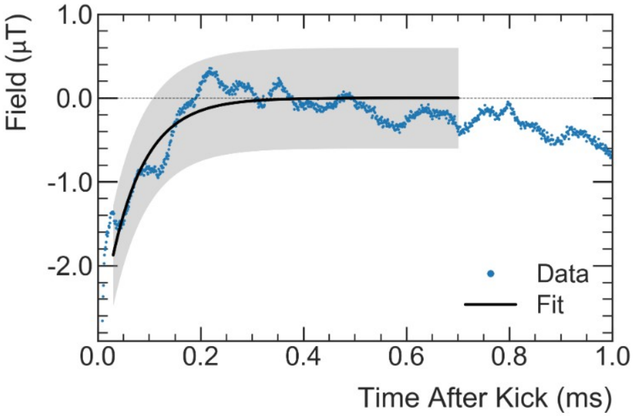




Transients

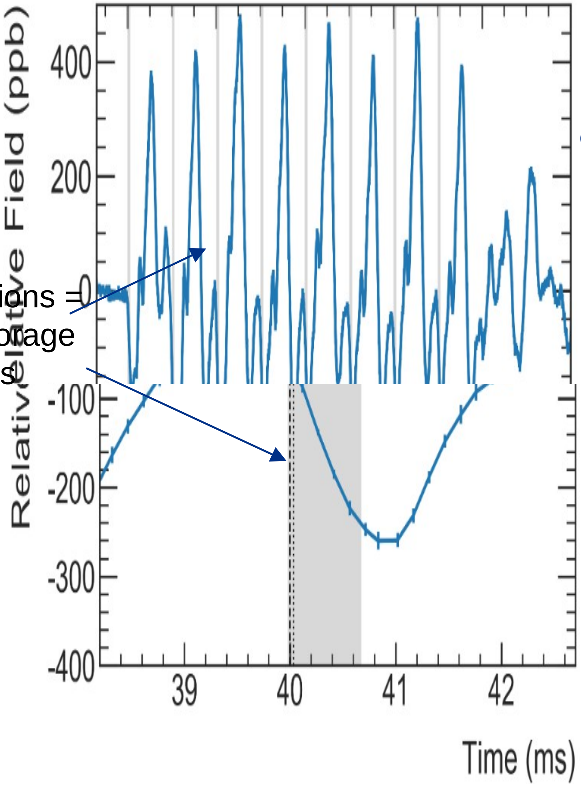
Muons experience “fast transient” fields from the pulsed kickers & quadrupoles
→ invisible to fixed probes due to shielding

Measured during dedicated campaigns



Kicker: B_k

- Kicker pulse of 22 mT for 150 ns just after muon injection.
- Field change caused by residual field after kicker pulse. Muons present from 30μs to 700μs after the kick (fit region)
- Kicker correction: -27 (37) ppb

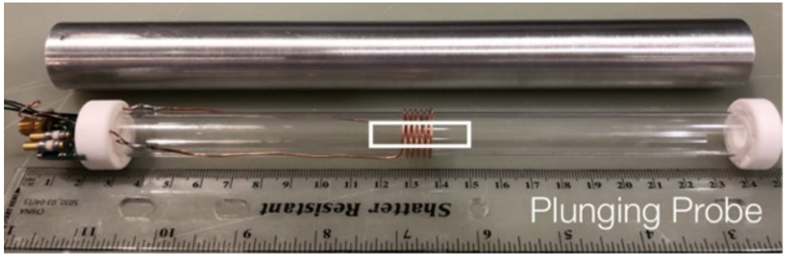


Grey regions = muon storage times

Quad B_q

- Measured with a dedicated in-vacuum NMR probe located between quad plates during pulsing
- Quad correction: -17 (92) ppb

Absolute calibration



Specially designed "plunging probe":

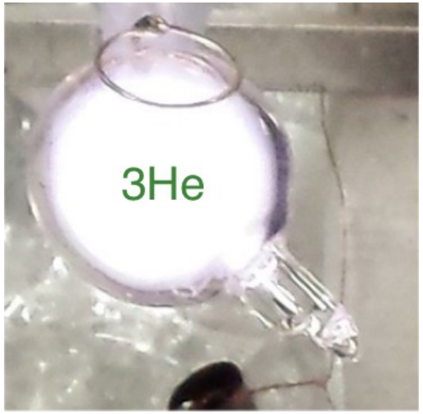
- characterised in very stable, homogenous solenoid
  → accuracy of 15 ppb
- used to calibrate trolley probes in-situ

Calibrated against spherical, water-based probe from BNL to 6ppb

A novel 3He NMR probe also developed (different systematics)

→ provides cross-check to 38 ppb (PRL 124, 223001 (2020))

Ongoing effort to cross-calibrate E989 probe with J-PARC Muon g-2/EDM probe



Quantity	Symbol	Value (ppb)	Uncertainty (ppb)
Diamagnetic Shielding T dep	δ^T	-99.1 to -86.0	5
Bulk Magnetic Susceptibility	δ^b	-1505.9 to -1505.6	6
Material Perturbation	δ^s	15.2	12
Water Sample and Sample Holder	δ^w	0	2
Radiation Damping	δ^{RD}	0	3
Proton Dipolar Fields	δ^d	0	2
TOTAL		-1589.8 to -1576.4	15

...just one more thing

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

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

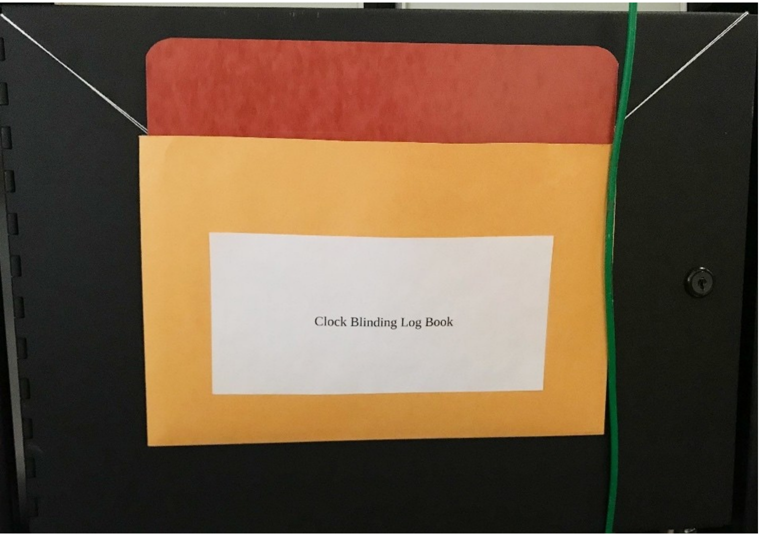
- f_{clock}: Unblinding conversion factor
- ω_a^m: Measured precession frequency
- C_e, C_p, C_{ml}, C_{pa}: Corrections from beam dynamics systematic effects
- f_{calib}: NMR probe calibration factor
- ω_p: Proton precession frequency
- $\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle$: Magnetic field weighted over the muon distribution and azimuthally averaged
- B_k, B_q: Corrections from the transient magnetic field

Clock blinding

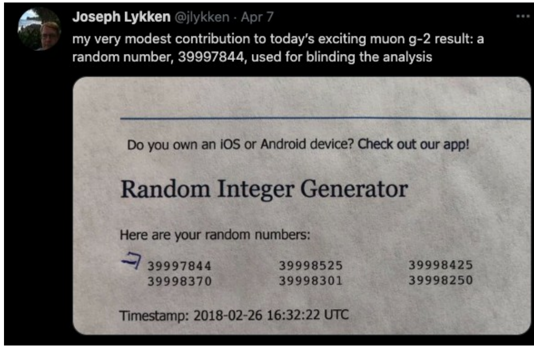
Hardware-blinded clock with frequency (40 + x) MHz
- offset was ~25ppm (approx 10x the BNL-SM difference)

Set by two people outside the collaboration, stored in locked cabinet!

Locked cabinet



Greg Bock and Joe Lykken (2018)



1st April

*"The code was picked by the Fermilab theorist,
and he is the only person to know it.*

*This theorist now refuses to give away the code.
It is not clear why.*

*One time he said he had forgotten the envelope with the code
on a train, another time he said the dog had eaten it."*

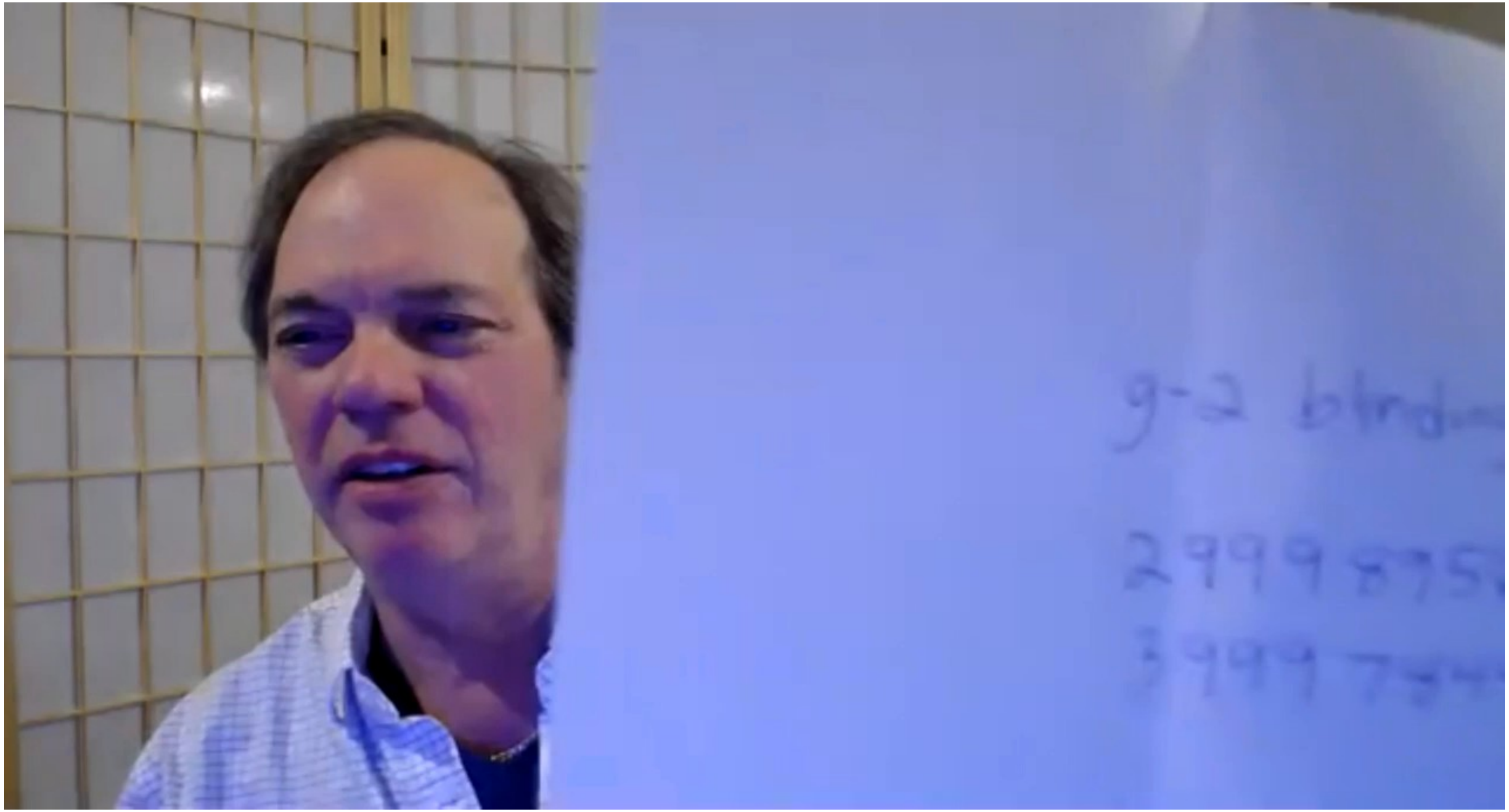
https://resonaances.blogspot.com/2021/04/trouble-with-g-2.html

"Are we ready to unblind?"

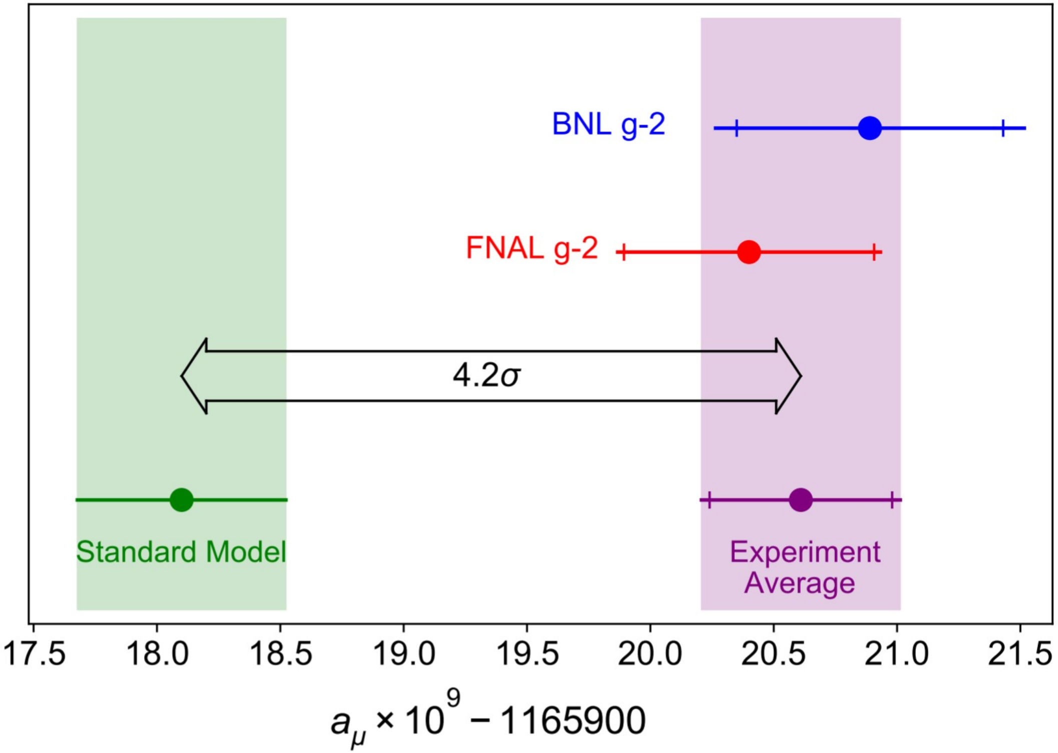
Unblinding meeting 25th Feb 2021

After all corrections uncertainties were finalized, the collaboration unanimously vote to unblind.

No changes to the result were made since then



The Result



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

$$a_\mu(\text{FNAL}) = 116592040(54) \times 10^{-11}$$
$$a_\mu(\text{Exp}) = 116592061(41) \times 10^{-11}$$
$$a_\mu(\text{SM}) = 116591810(43) \times 10^{-11}$$

Beyond the Standard Model?

Discrepancy is ~2.5 ppm

- x2 the size of the electroweak contribution, x1/30 the size of QCD

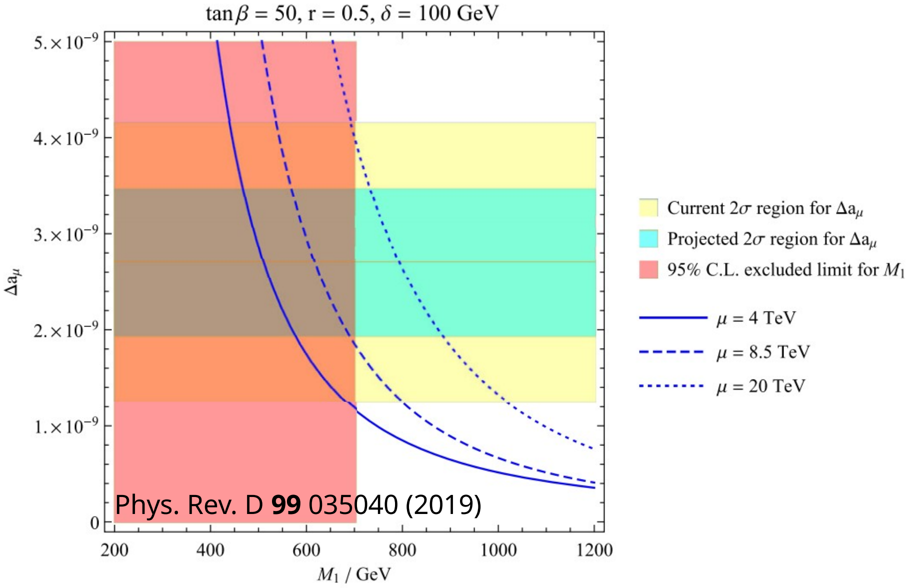
Many models can explain the anomaly and evade other constraints (dark matter, LHC limits, ...)

- TeV leptoquarks, Z’, ALPs, SUSY, 2-Higgs doublets, ...

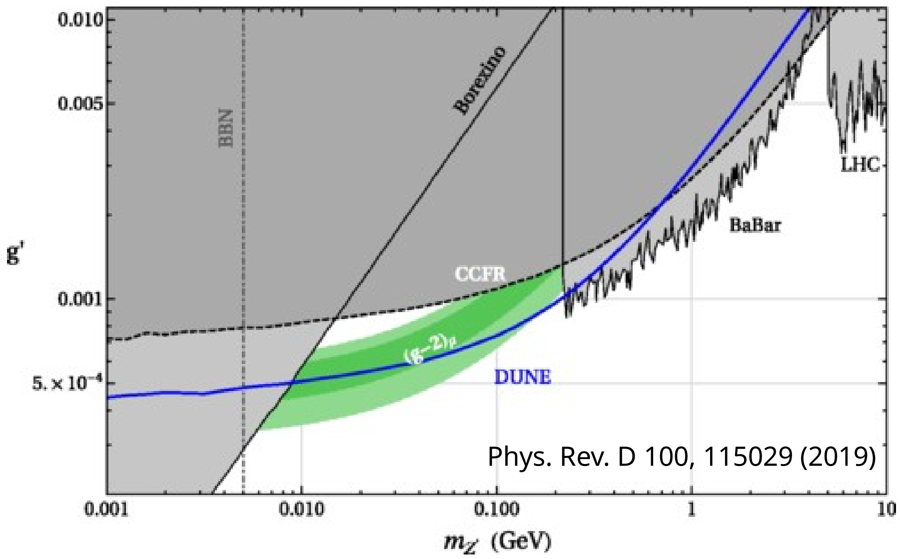
Chirality-flipping, flavour conserving

$$\Delta a_\mu^{\mathrm{BSM}} = C_{\mathrm{BSM}} \left(\frac{m_\mu}{M_{\mathrm{BSM}}} \right)^2$$

arXiv:2104.03691



Phys. Rev. D **99** 035040 (2019)



Phys. Rev. D 100, 115029 (2019)

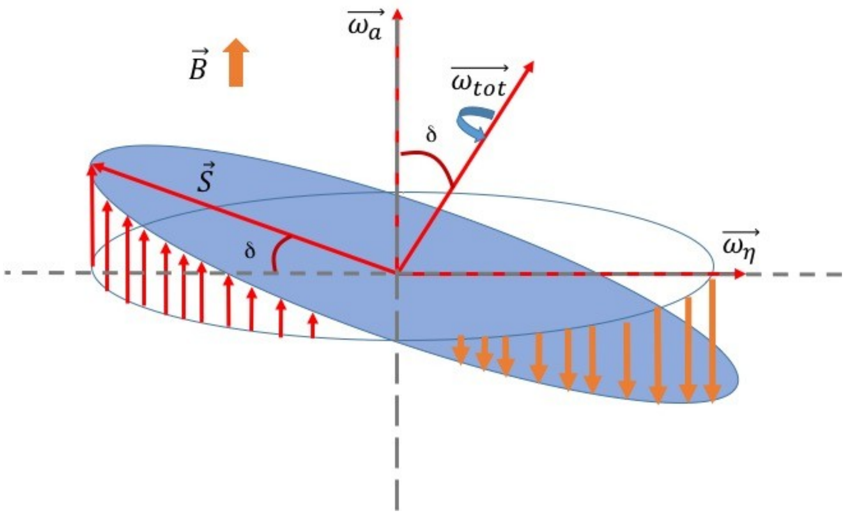
EDM

Search for a muon electric dipole moment:

~zero in the Standard Model

- possible source of CP-violation

$$\vec{d} = \eta \left(\frac{Qe}{2mc} \right) \vec{s}$$

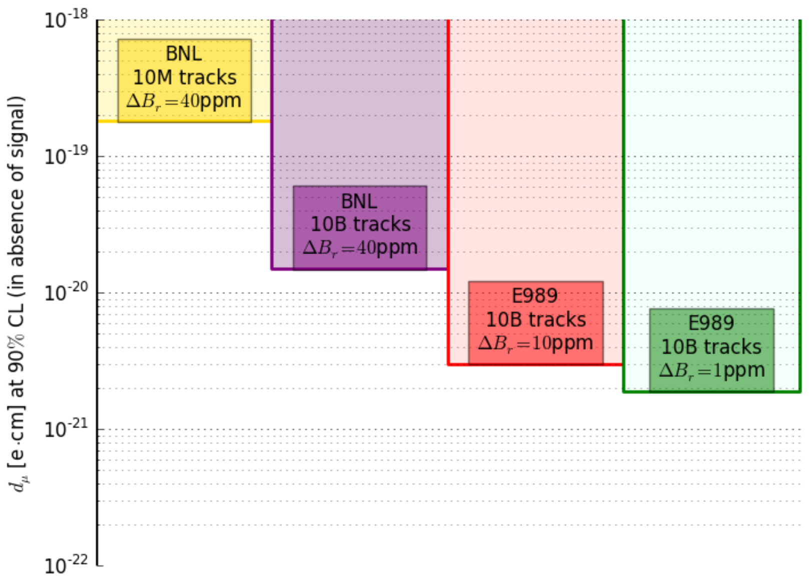


World's best limit:

$|d_\mu| > 1.9 \times 10^{-19}$ e.cm (BNL)

Target:

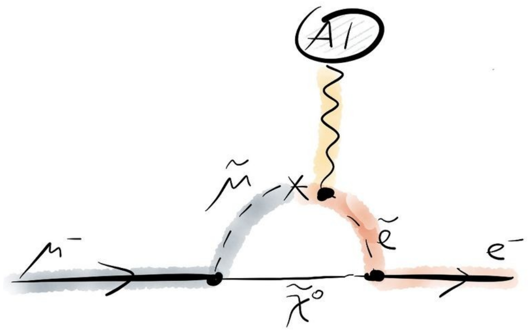
$|d_\mu| \approx 1.9 \times 10^{-21}$ e.cm



Tilts precession plane towards center of ring

- vertical oscillation, 90° out of phase with a_μ
- tracking detectors key to sensitivity

cLFV

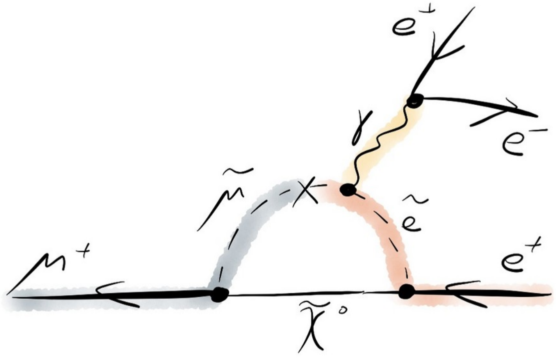


Charged lepton flavour violation:

- again, ~zero in the Standard Model
- predicted by many BSM models (particularly leptogenesis)

Mu2e:

- follows g-2 at Fermilab
- decay of captured muons



Mu3e:

- data taking in 2023 @ PSI
- full reconstruct $\mu \rightarrow eee$ final state

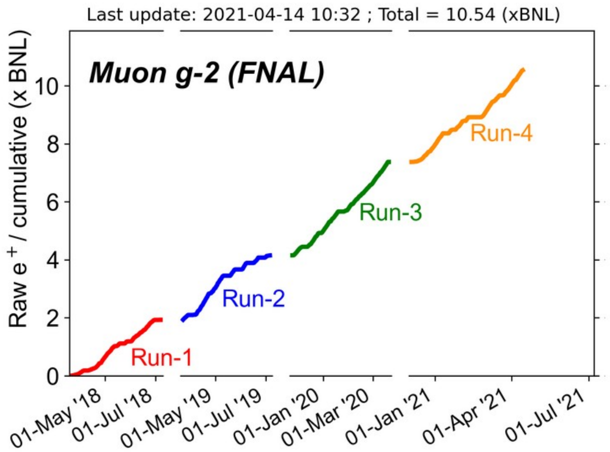
Aim to push limits on Br to 10^{-17} (factor x 10^4)

- mass scales up to 10,000 TeV

Future

The FNAL Muon g-2 experiment measured a_μ to 0.46 ppm

- result consistent with BNL
- combined result differs from SM by 4.2σ
- statistics limited, based on 6% of target stats

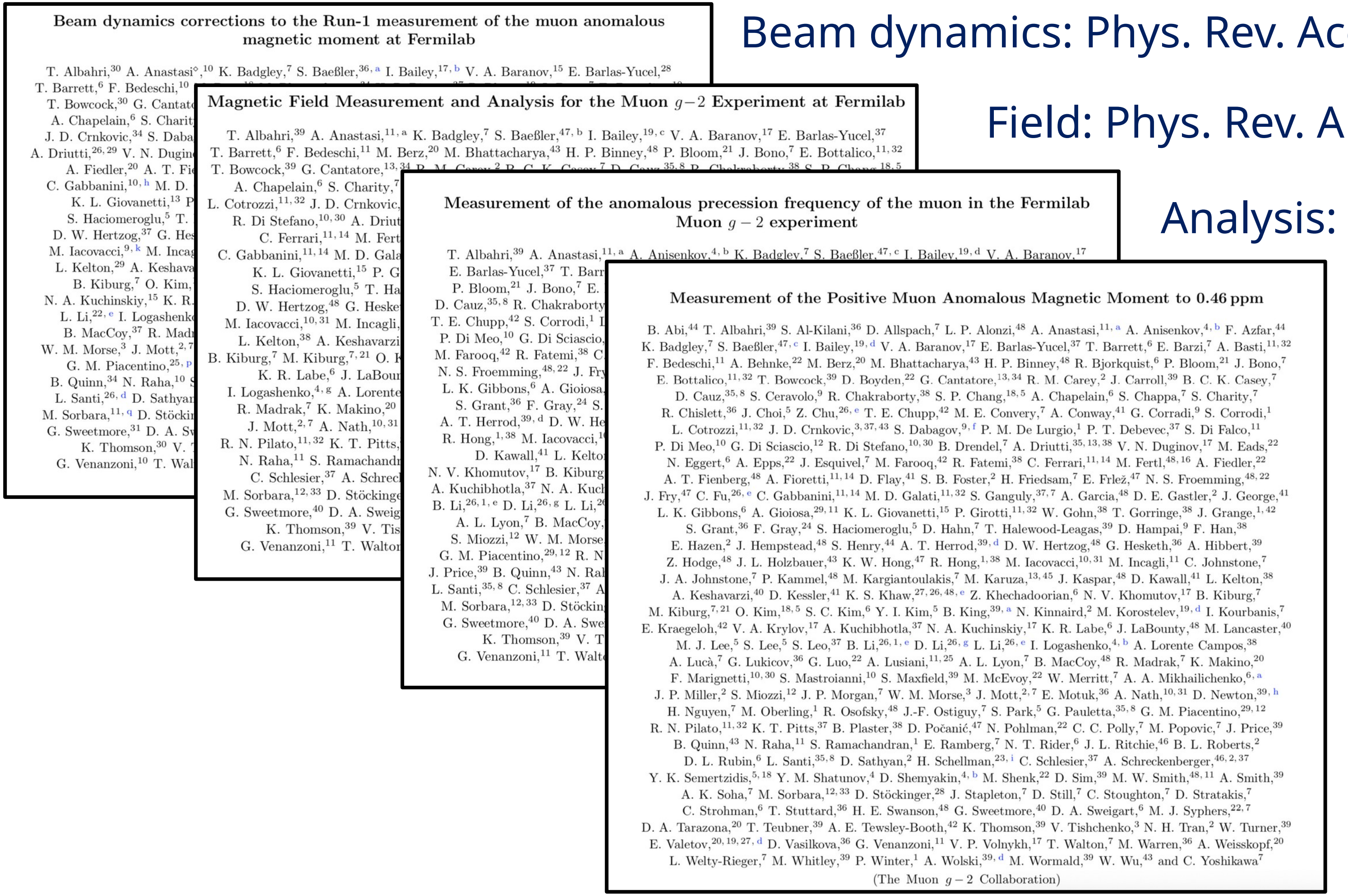


Upgrades since Run-1:

- Replaced damaged resistors, reducing C_{pa}
- Higher kicker voltage to center beam radially
- Thermal magnet insulation & hall cooling improve field stability

EDM search & CLFV: complementary information on any BSM scenario

Further reading



Beam dynamics: Phys. Rev. Accel. Beams **24**, 044002

Field: Phys. Rev. A **103**, 042208

Analysis: Phys. Rev. D **103**, 072002

Phys. Rev. Lett. **126**, 141801