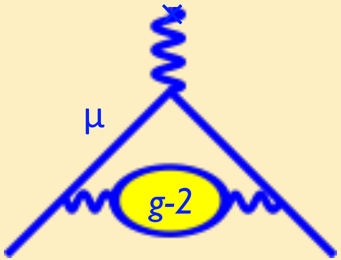

# First Results from the Muon g-2 Experiment at Fermilab

Adam Lyon (Fermilab) on behalf of the Muon g-2 Collaboration

University of Maryland/Johns Hopkins University HEP Seminar

14 April 2021

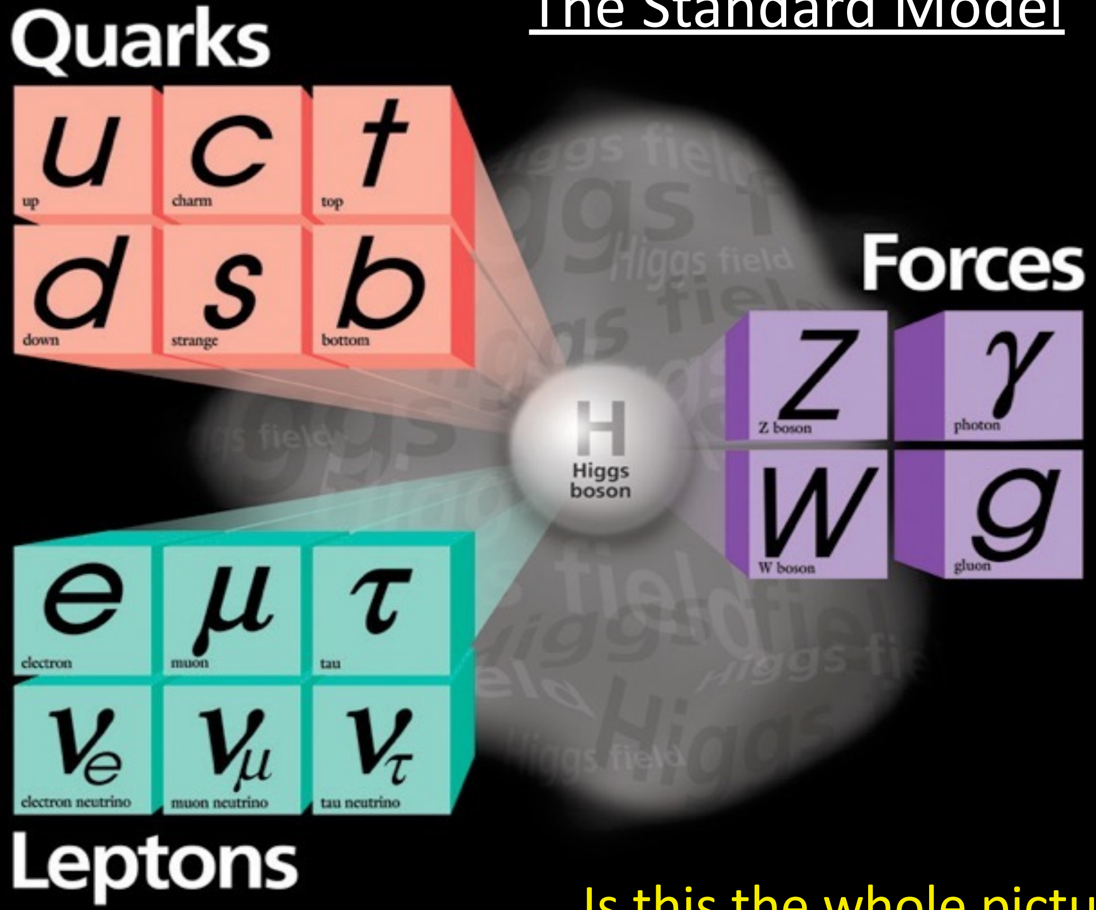



# The New Muon g-2 Experiment at Fermilab

Adam Lyon
(Fermilab/Scientific Computing Division)

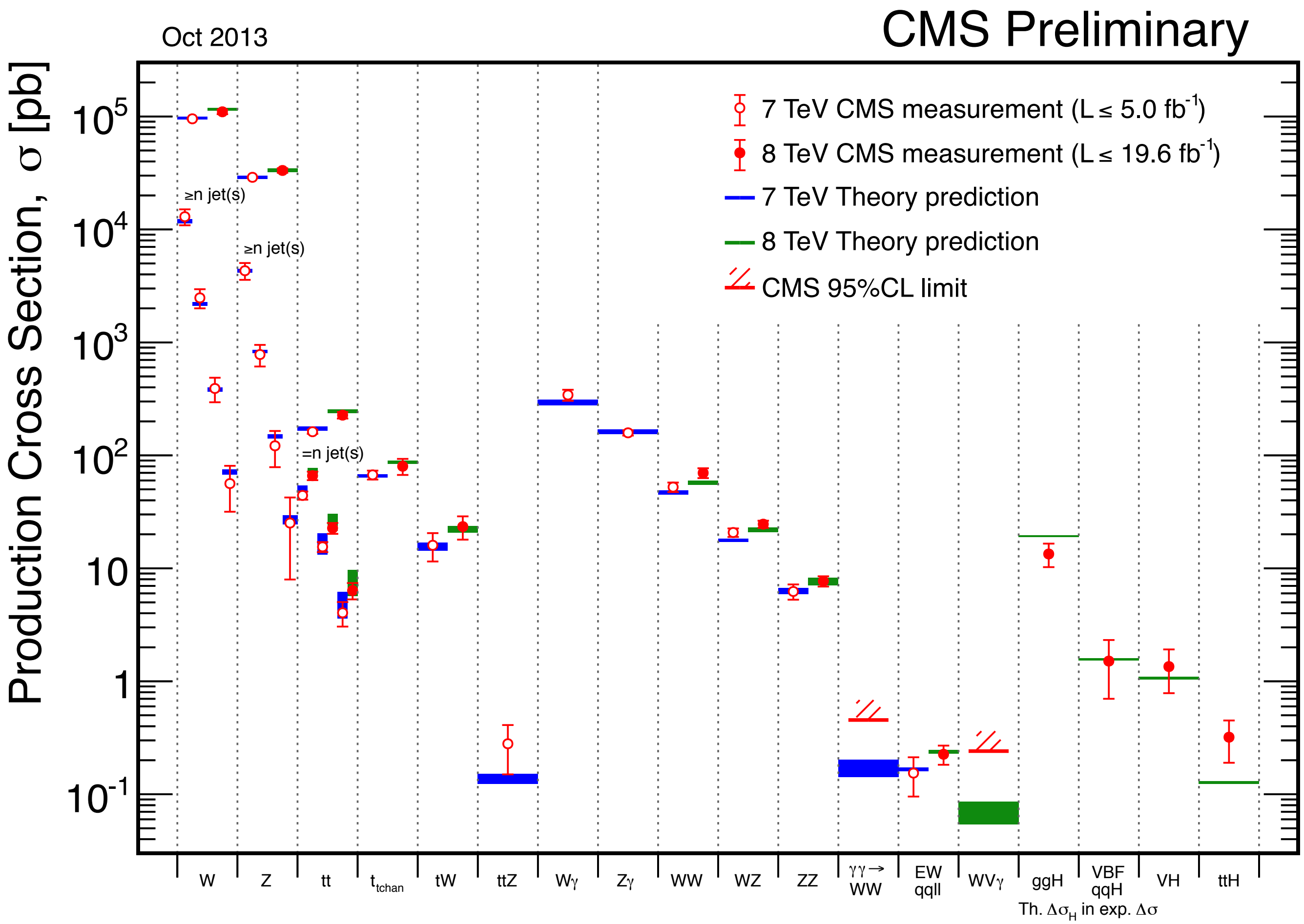
University of Maryland HEP Seminar
May 1, 2013

# The Standard Model

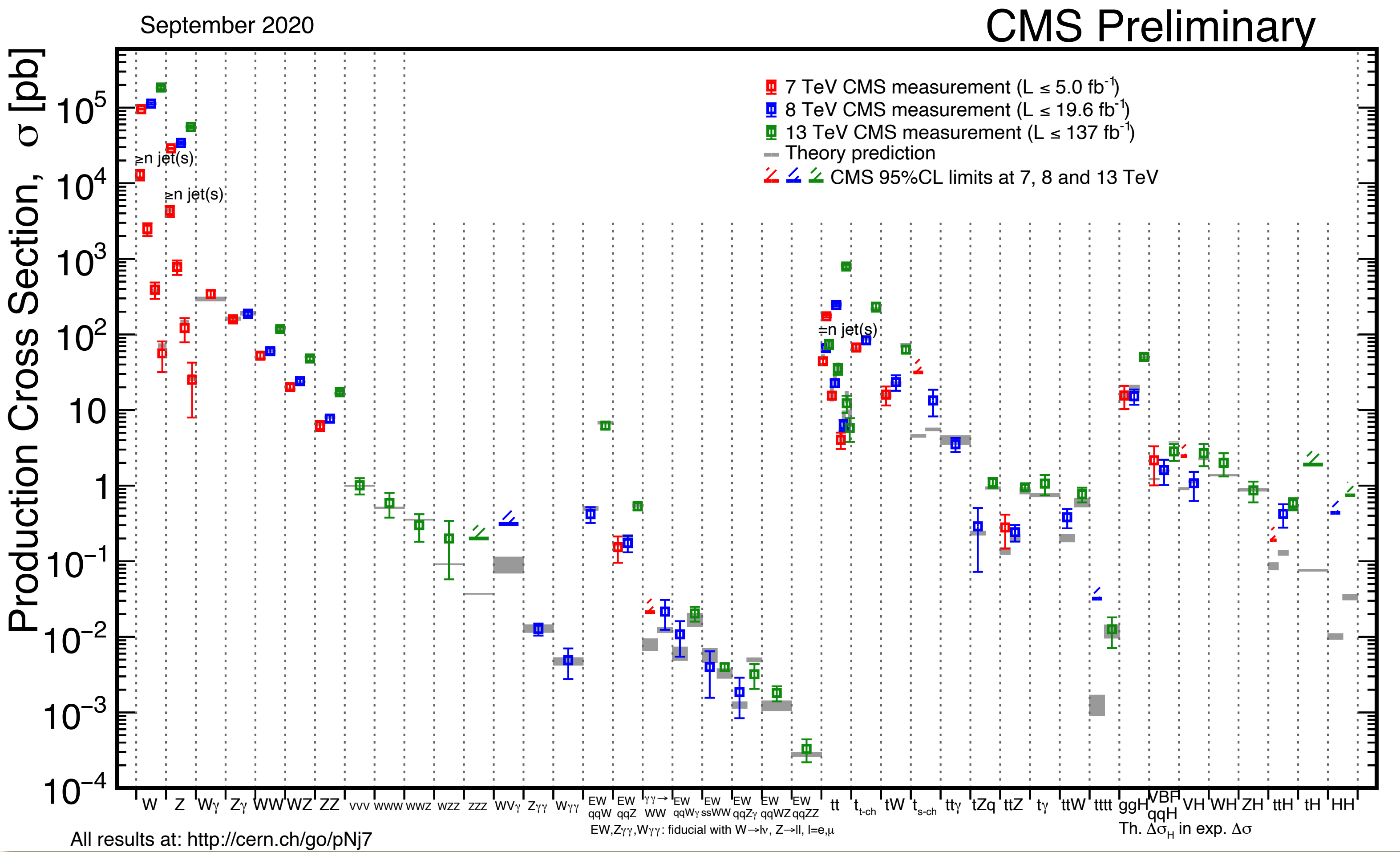



Is this the whole picture?

# Remarkable Success!



# Remarkable Success!





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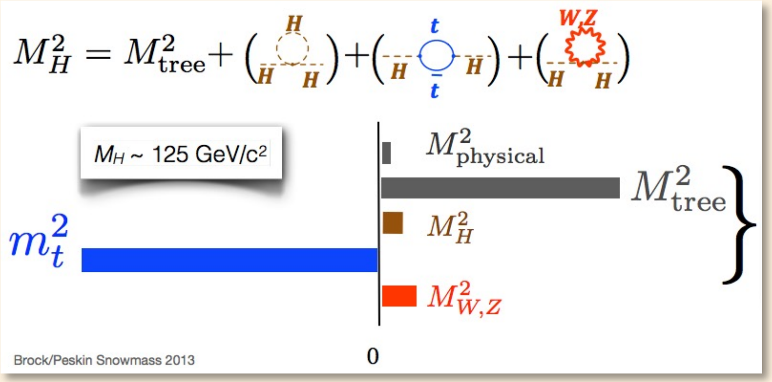
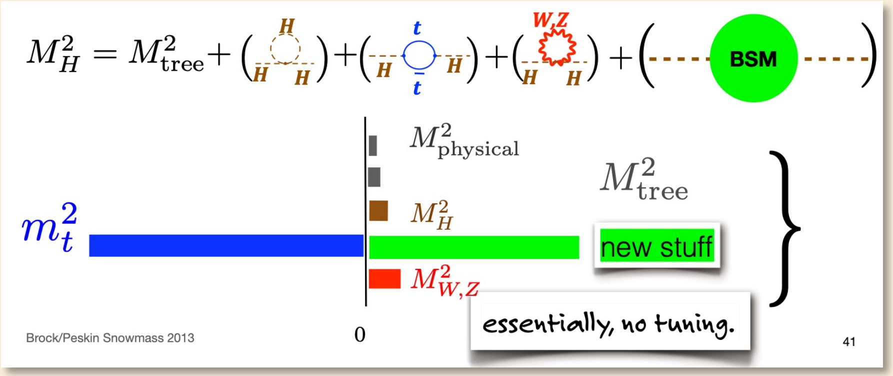
# Why do we look beyond the SM?

… it doesn't predict everything we want:

- Gravity? Dark Matter? Dark Energy? Neutrino masses? Matter/antimatter asymmetry?

… and the SM contains some headaches that Beyond the SM may fix



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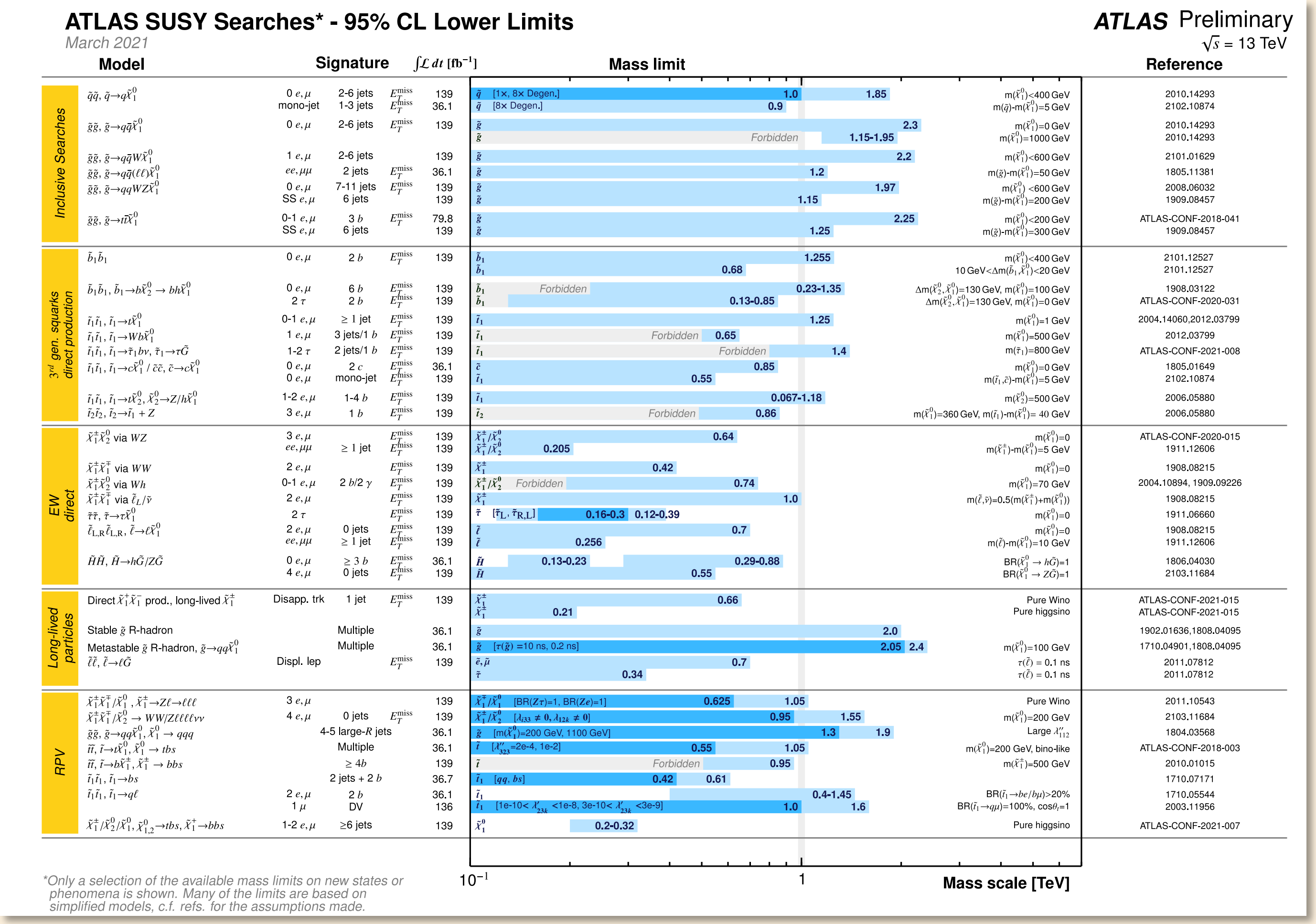
# And we've looked for BSM

# Supersymmetry



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# And looked…

Contact Interactions

Dark Matter

*R* parity violating

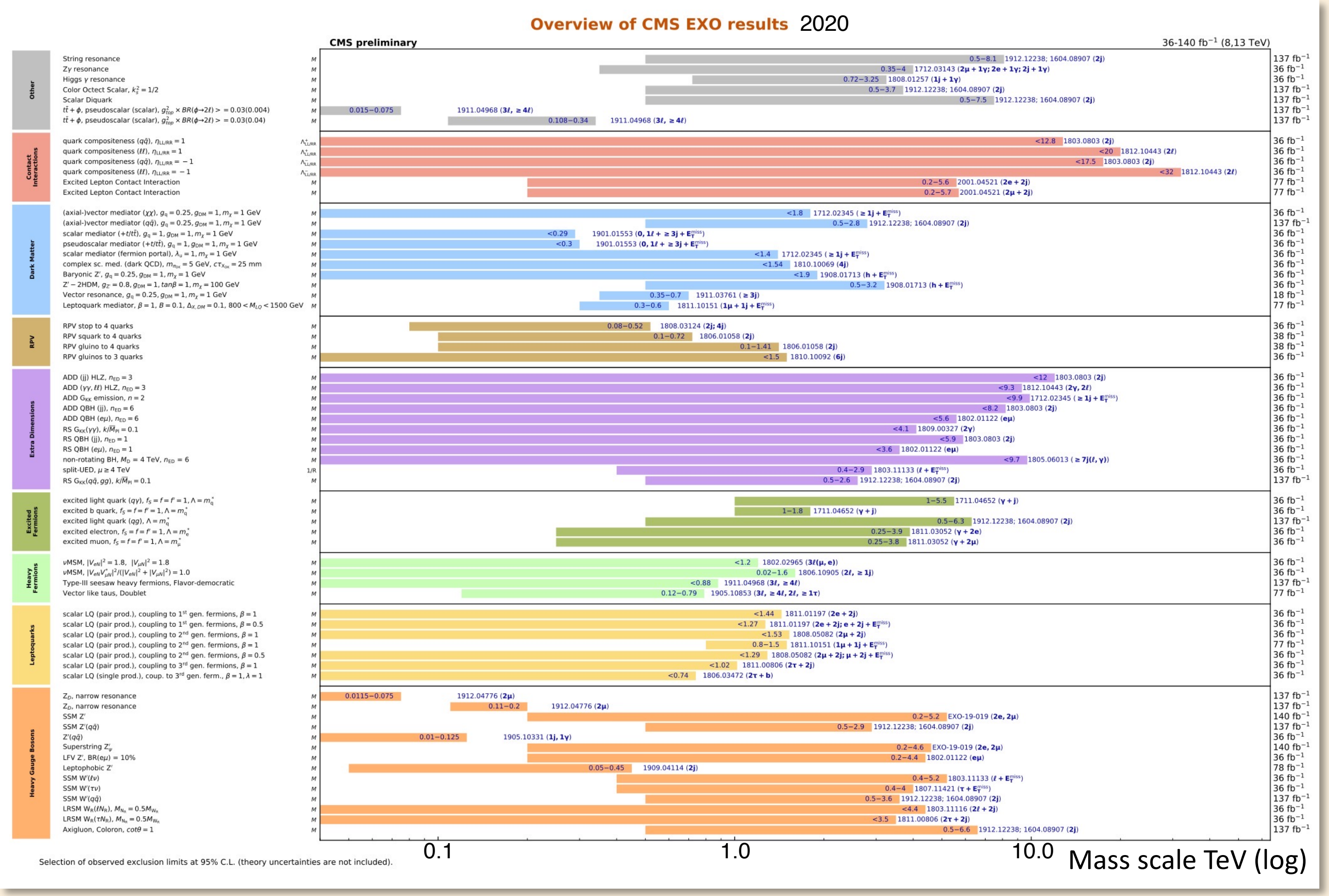
Extra dimensions

Excited Fermions

Heavy Fermions

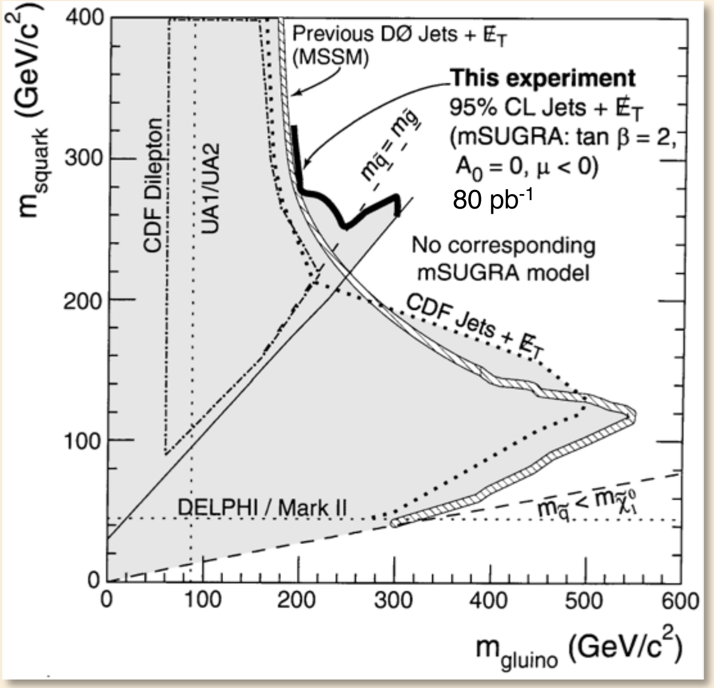
Leptoquarks

Heavy Gauge Bosons

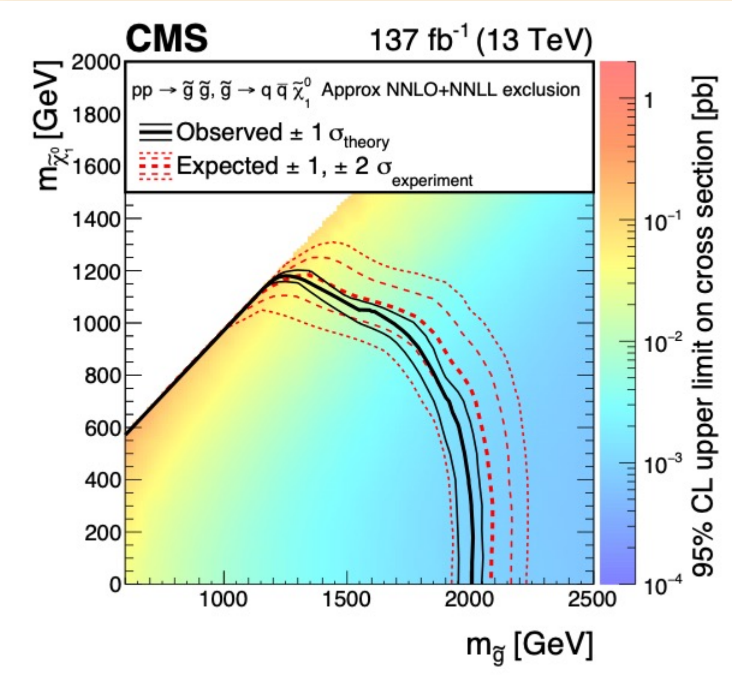


# I've looked too…

My Run 1 D0 Thesis result (1999)




Latest CMS result (2020)



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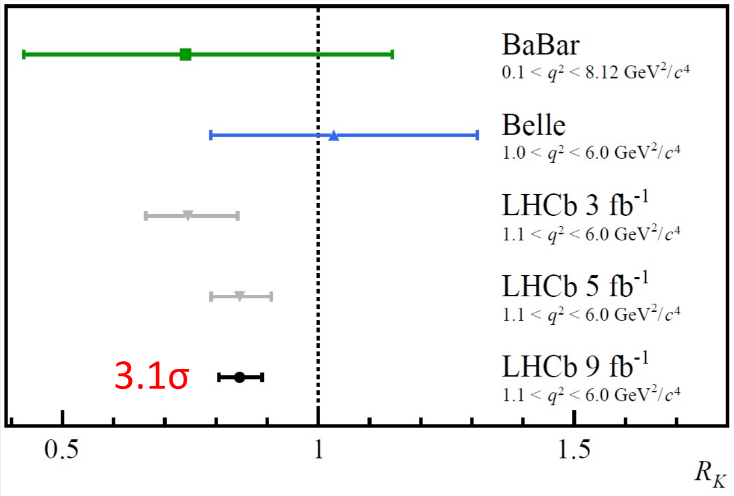
# Still looking…

No direct confirmation of a Beyond the Standard Model theory and precious few experimental hints to guide us. Here are maybe two…

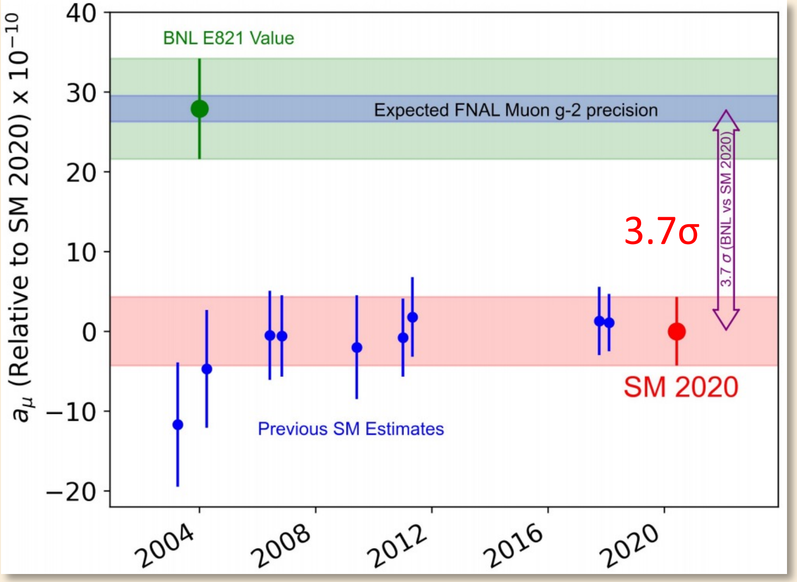
1) LHCb test of lepton flavor universality

(March 2021)

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \overset{\text{SM}}{=} 1$$

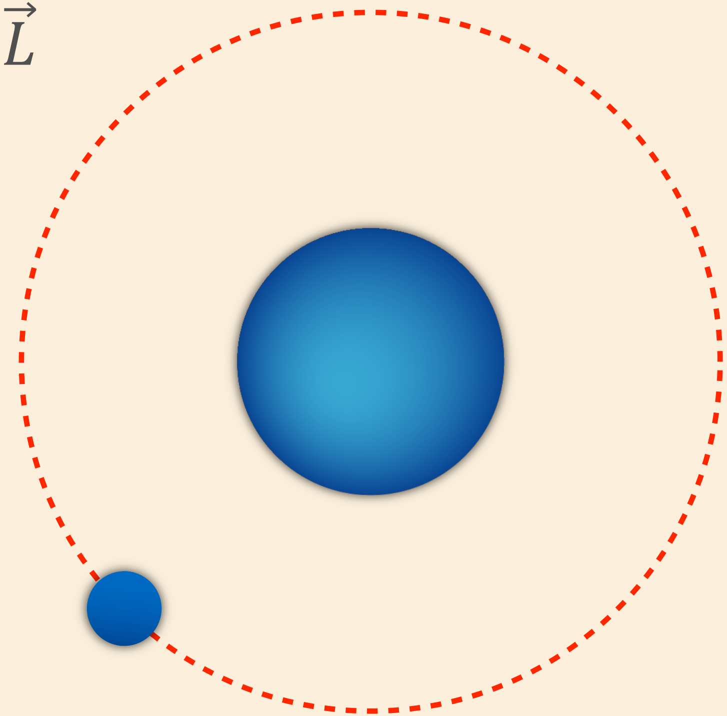



2) Muon *g-2*



# The "g-factor" basics

Orbiting charged particle: $\overrightarrow{\mu_L} = \vec{I}A = \frac{q}{2m}\vec{L}$



Spin ½ particle has an intrinsic magnetic moment:

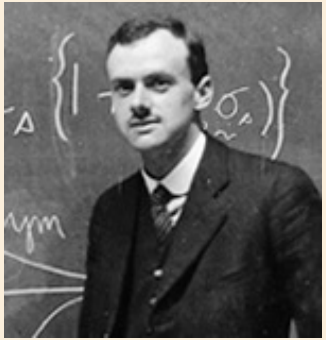
$$\overrightarrow{\mu_S} = g\,\frac{q}{2m}\vec{S}$$

For classical systems, $g = 1$

For the electron, $g = 2$ was known from Stern-Gerlach and spectroscopy experiments

# Why does $g = 2$?

Predicted theoretically by Dirac in 1928



Paul Dirac

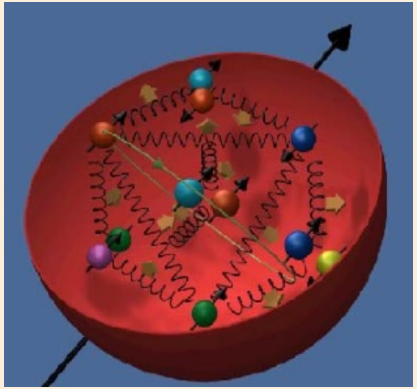
$$\left(\gamma^{\nu}\left(p_{\nu} - \frac{e}{c}A_{\nu}\right) - mc\right)\psi = 0$$

$$i\frac{\partial\psi}{\partial t} = \left[\frac{1}{2m}\left(\vec{p} - e\vec{A}\right)^{2} - 2\frac{e}{2m}\vec{S}\cdot\vec{B}\right]\psi$$

An aside: in 1933, for protons g = 5.6,

neutron g = –3.8

Protons and neutrons are not like electrons!



For the <u>electron</u>, *g* remained = 2 for twenty years

# Why is g > 2?

1948: Foley & Kusch in spectroscopy measure $g_e = 2.00238(10)$ 0.12%

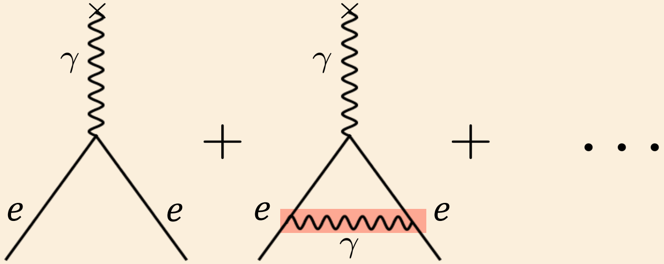
Write as the **anomalous magnetic moment** $a \equiv \frac{g-2}{2}$, $a_e = 0.00119(5)$

Soon after this, Schwinger calculates first order QED correction

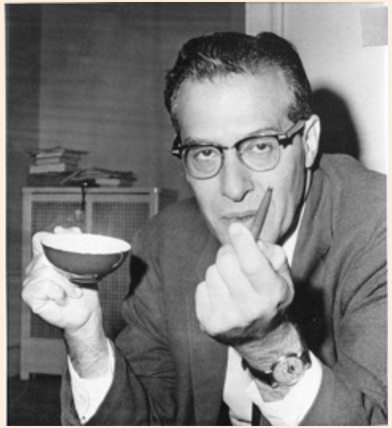
$$a_e = \frac{\alpha}{2\pi} = 0.00116$$

Quantum Corrections

$g =$




2 + 0.00236 + . . .



Julian Schwinger
"His laboratory is his ballpoint pen"

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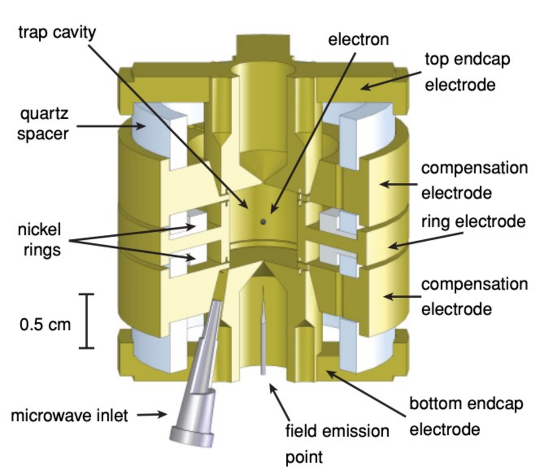
# Electrons vs. Muons

Currently: $a_e = 0.001\,159\,652\,180\,73(28)$ ... a 0.28 ppt result! Hanneke et. al., PRA **83**, 052122 (2011)




Difference from QED prediction is $|\delta a_e| < 9 \times 10^{-13}$
Excellent agreement

But hadronic and weak contributions to $a_e$ are tiny
$a_{e,\mathrm{hadronic}} = 1.671(19)\times 10^{-12}$ $a_{\mathrm{e,weak}} = 0.030(01)\times 10^{-12}$
Gabrielse et. al., PRL 97, 030802 (2006)

Sensitivity goes as $(m_\mu / m_e)^2 \approx 43\,000$
So, look to Muons...



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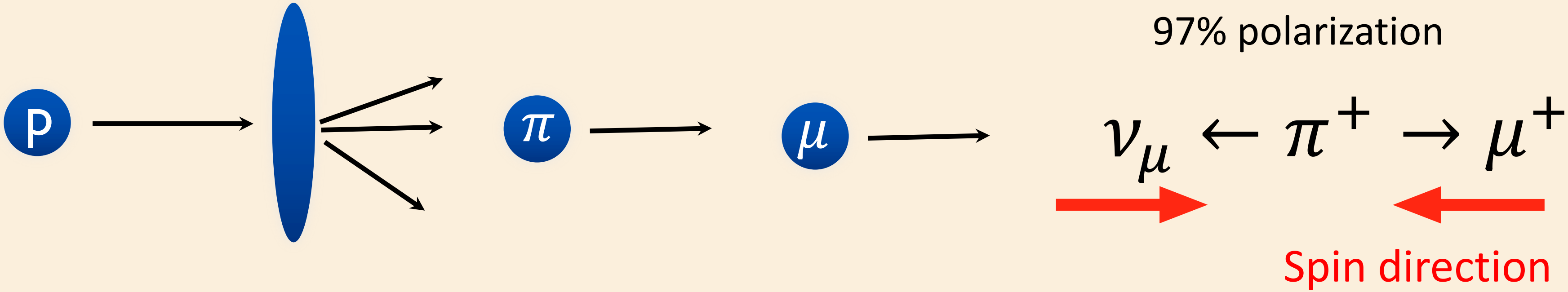
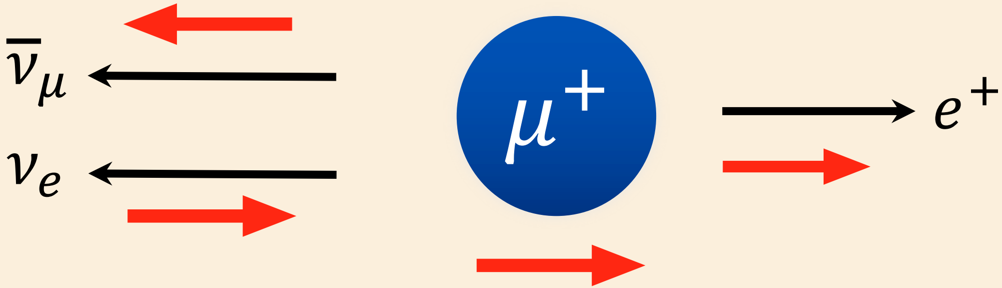
# Controlling and measuring the muon spin

Production: Muons from $\pi^+ \rightarrow \mu^+\nu_\mu$ are polarized

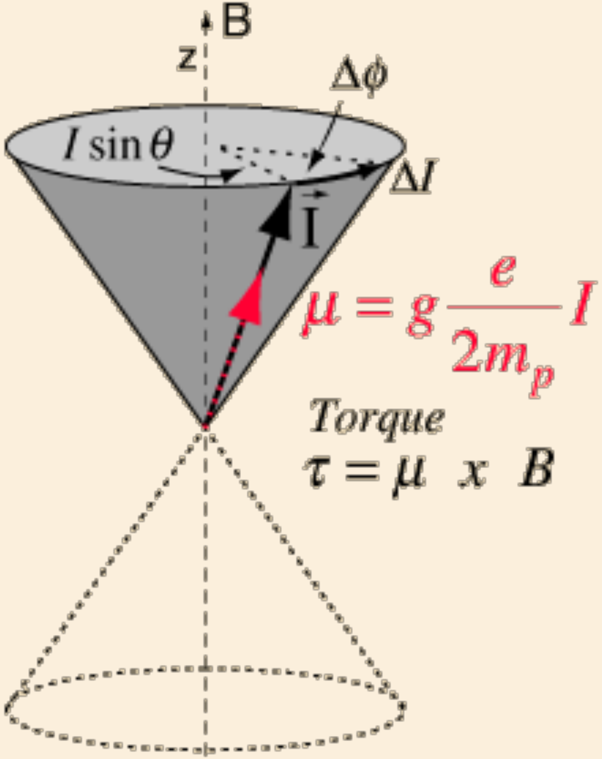



Decay: "Self analyzing" $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$

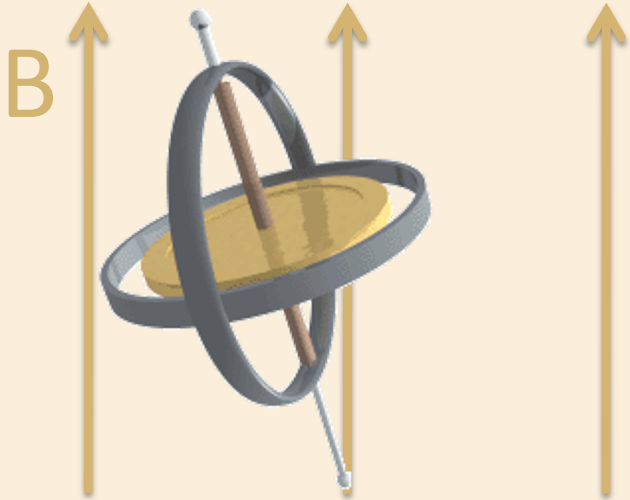



Highest energy positrons emitted along muon's **spin** direction

# Muons at rest in a magnetic field – Larmor Precession




$$\omega_s = g\frac{eB}{2mc}$$




http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/larmor.html

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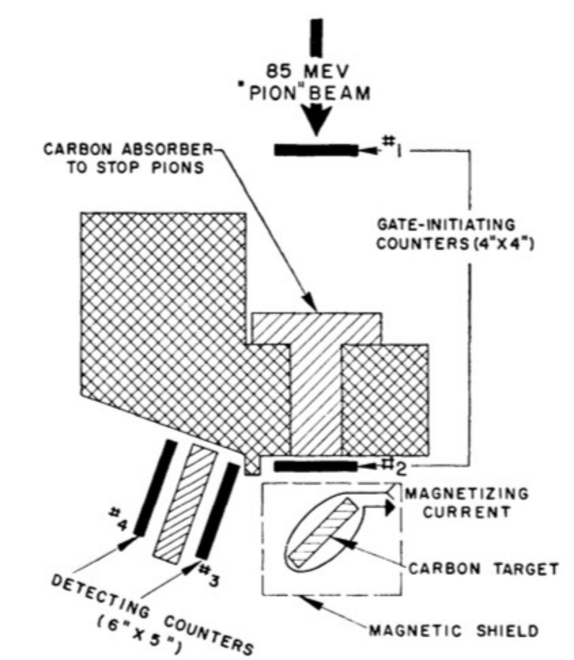
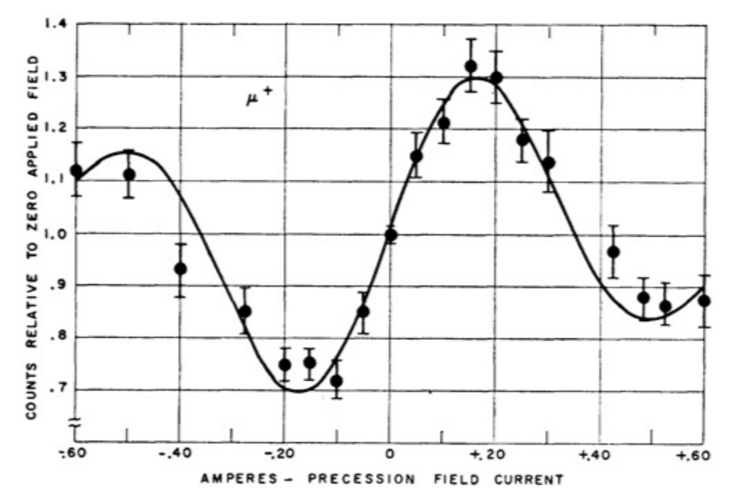
# First experiment for muon magnetic moment

B. Lee Roberts, SciPost Phys. Proc. 1, 032 (2019)

1957: Garwin, Lederman, Weinrich at Nevis (confirmed Yang & Lee parity violation)




Direct measurement of g (asymmetry vs field)




$g_\mu = 2.00 \pm 0.10$ 5% uncertainty
Muons behave like electrons

$g_\mu = 2.004 \pm 0.014$ Cassels et. al. (Liverpool)

# Subsequent Experiments

CERN I (1965) $a_\mu = 0.001\,162(5)\ \pm 4300\ \text{ppm}$ (Non-relativistic)

CERN II (1968) $a_\mu = 0.001\,166\,16(31)\ \pm 270\ \text{ppm}$ (storage ring)

$p_\pi = 1.27\ \text{GeV}/c$

$B = 1.7\ \text{T}$

CERN III (1969-79) $a_\mu = 0.001\,165\,924(8.5)\ \pm 7.3\ \text{ppm}$ (storage ring)

$p_\pi = 3.1\ \text{GeV}/c$ $B = 1.47\ \text{T}$ Large systematic due to magnet edges

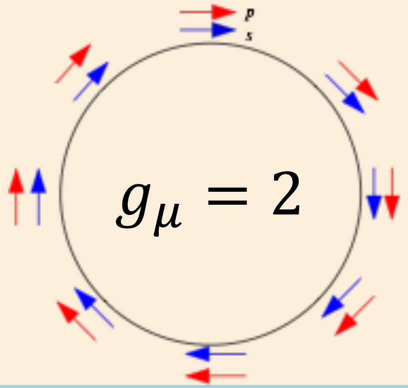
BNL E821 (2001) $a_\mu = 0.001\,165\,920\,89(63)\ \pm 0.54\ \text{ppm}$ $B = 1.45\ \text{T}$

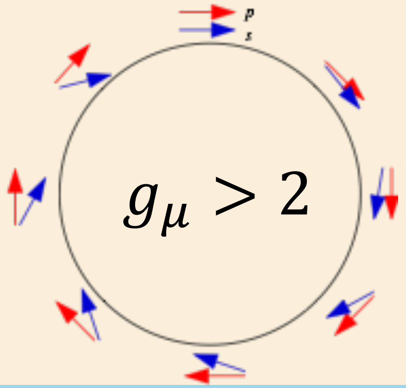
# Muons moving in a magnetic field

Thomas (spin) precession $\omega_s = \frac{g_\mu eB}{2m_\mu c} + (1-\gamma)\frac{eB}{m_\mu c\gamma}$

Cyclotron Frequency
(Momentum precession) $\omega_c = \frac{eB}{m_\mu c\gamma}$

A nice simplification $\omega_a \equiv \omega_s - \omega_c = \frac{g_\mu - 2}{2}\frac{eB}{m_\mu c} = a_\mu \frac{eB}{m_\mu c}$



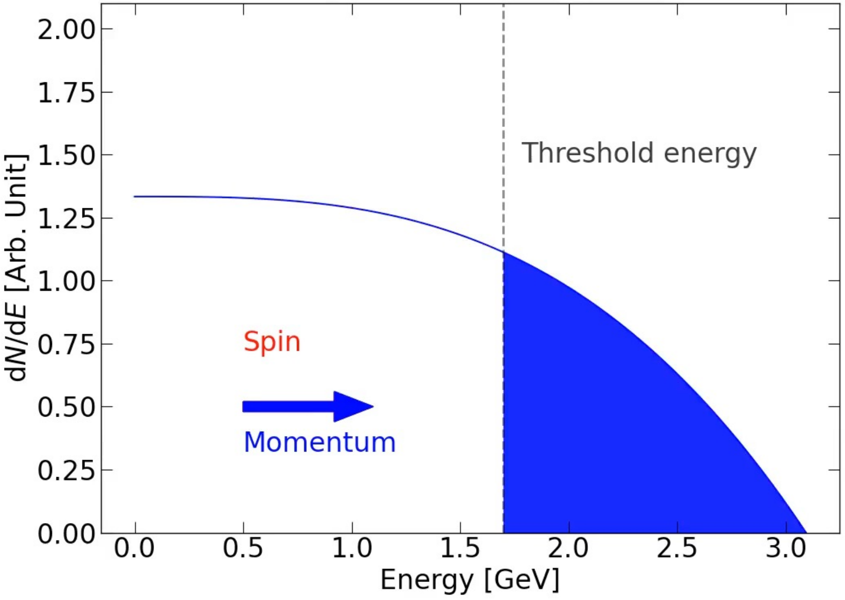



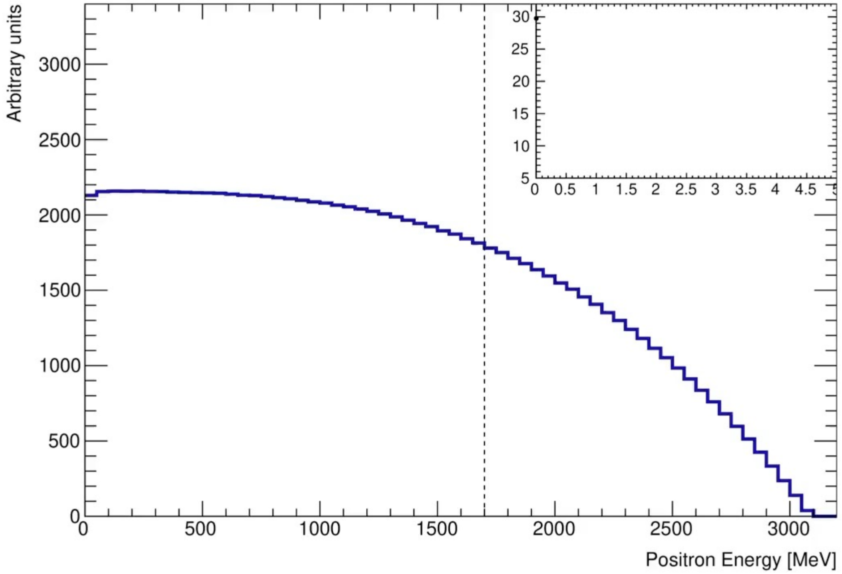

True for any ring
and any muon momentum

# Spin and Momentum

# What do we measure?

Remember, $\mu^+ \rightarrow e^+ \nu_\mu \overline{\nu}_e$ and highest energy positrons are in spin direction



# Improvements and a miracle

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$$

Since $a_\mu \approx g_\mu/800$, measuring $\omega_a$ gives big improvement in precision than for muons at rest measuring $g_\mu$

But a problem – how do we vertically confine the beam of muons in the ring? Introduce electrostatic quadrupoles. That leads to…

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

Can mostly cancel last term if we choose $\gamma = 29.3\ (0.9994c)$  $p_\mu = 3.09\ \mathrm{GeV}/c$

Vertical beam oscillation leads to muon decays out-of-plane (pitch correction)

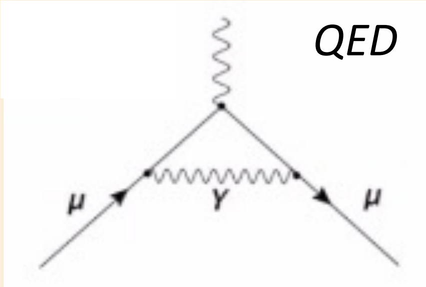
# Theoretical interlude

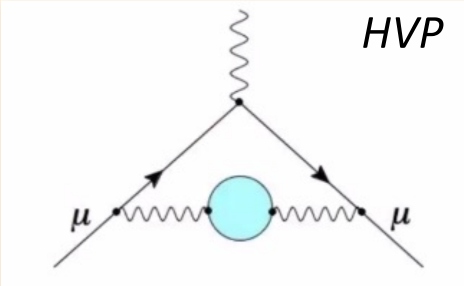
Muon g-2 Theory Initiative White Paper Phys. Rept. 887 (2020) 1-166

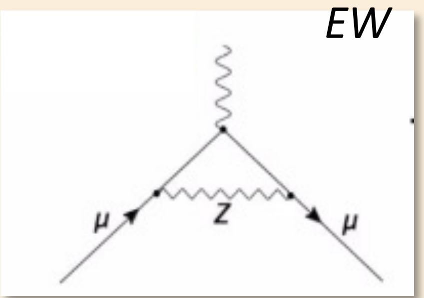
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL}$$

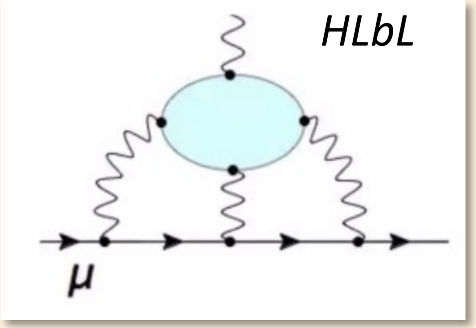
$$a_\mu^{SM} = 116\,591\,810(43)\times 10^{-11}$$

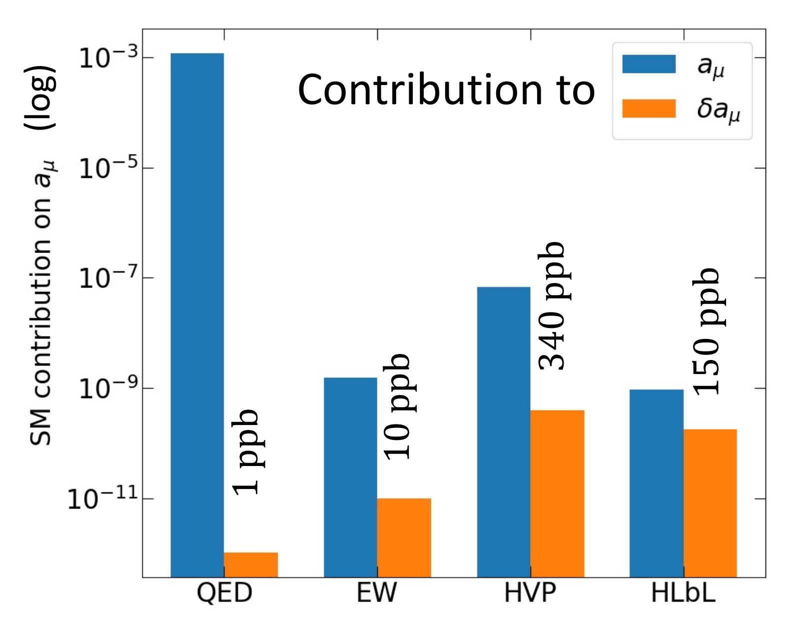
370 ppb



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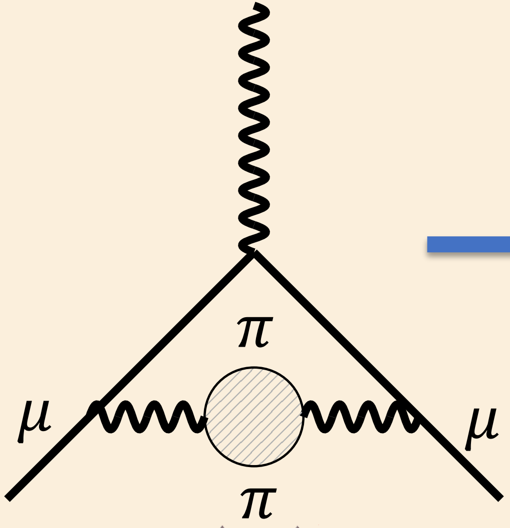
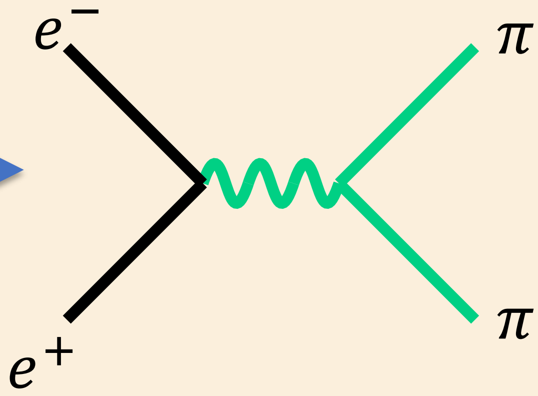
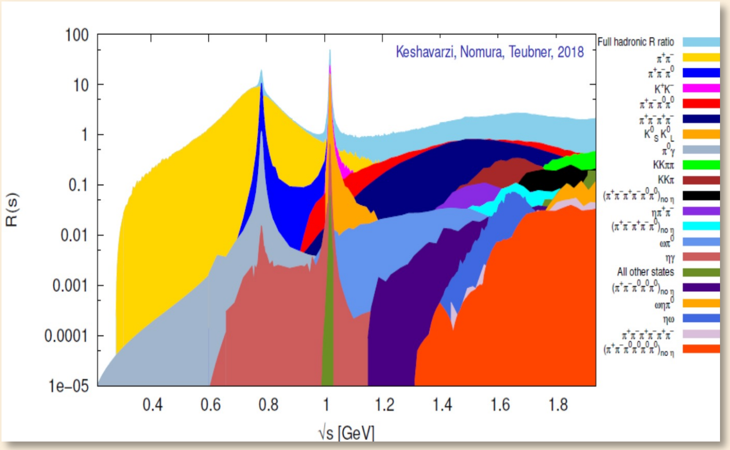
# Data Driven HVP Calculation    340 ppb uncertainty (dominates)




Phys. Rev. D **97**, 114025 (2018)

+ decades of $e^+e^- \rightarrow$ hadrons data

+ dispersion relation with $R(s) = \dfrac{\sigma(e^+e^-\rightarrow\text{hadrons})}{\sigma(e^+e^-\rightarrow\text{muons})}$

New Lattice QCD efforts are interesting and looking promising

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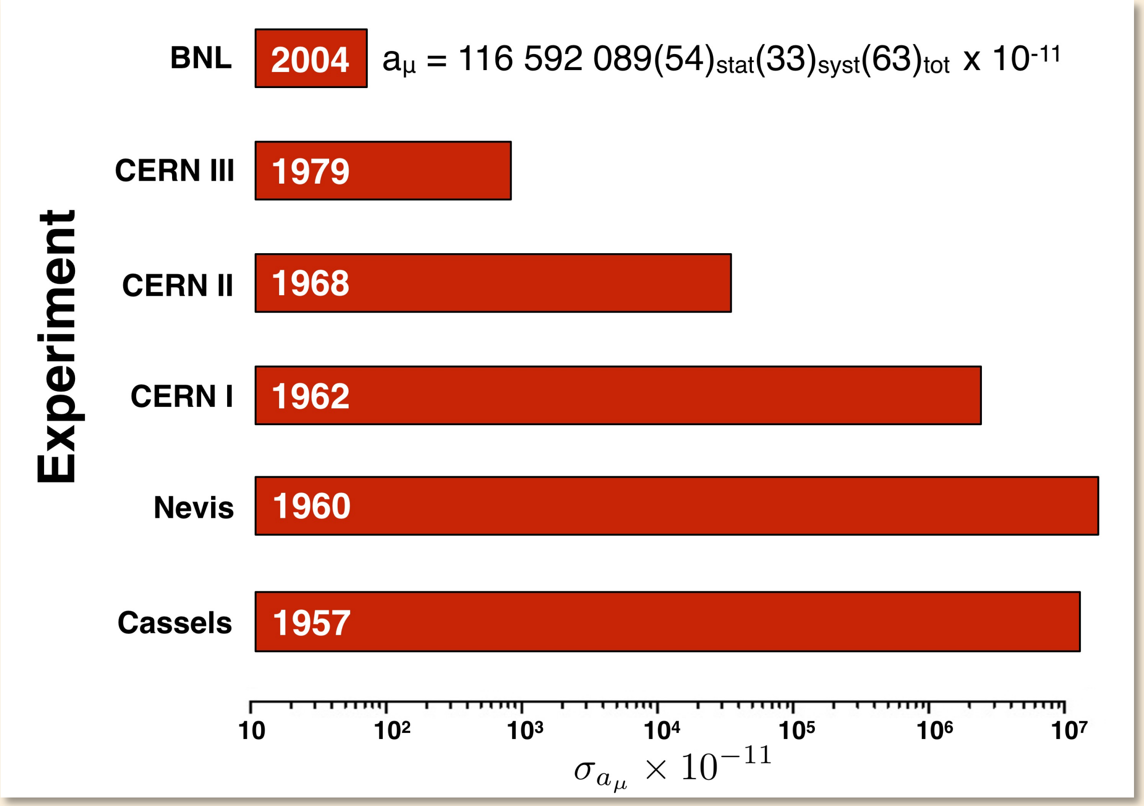
# History




## New Sensitivity

5 loops QED, EW

Hadronic

3 loops QED

2 loops QED



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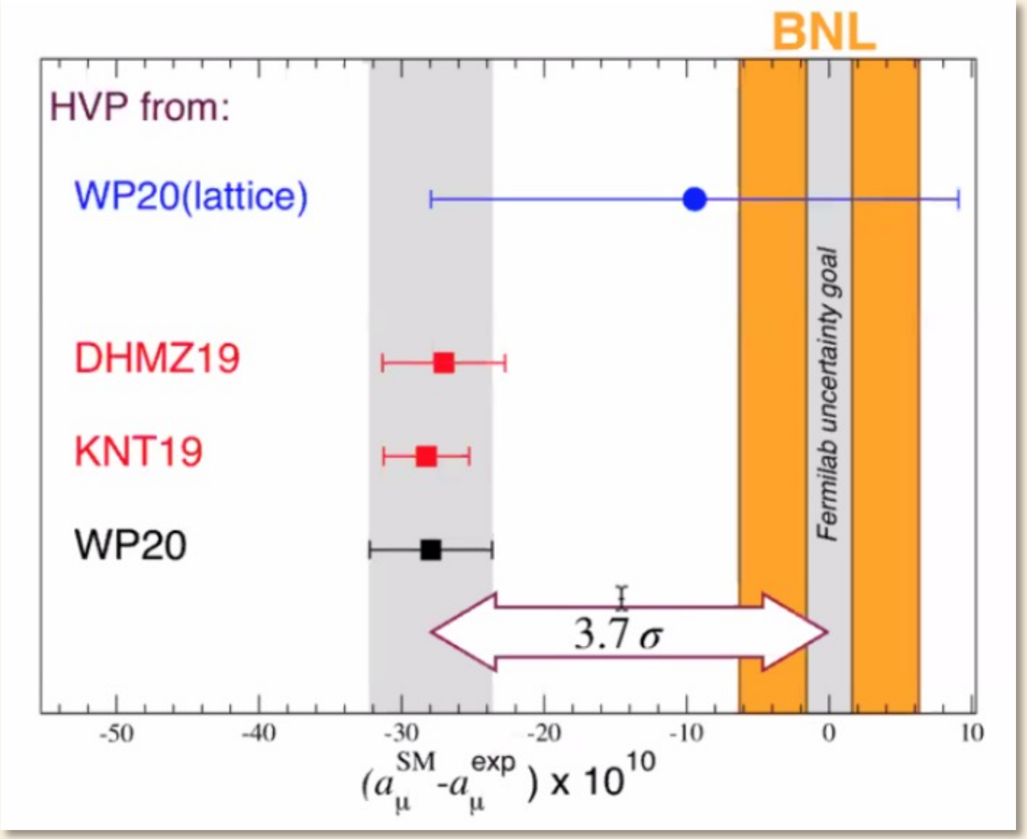
# Situation prior to 4/7/2021



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# Goals of the Fermilab Experiment

Do the experiment at Fermilab with more powerful and cleaner muon beam

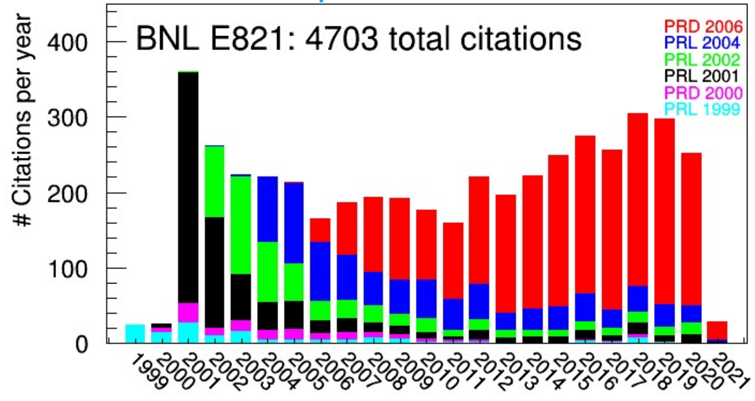
Reduce the overall error by a factor of ~4
$540 \text{ ppb} \rightarrow 140 \text{ ppb}$

With 20x more muons, reduce the statistical uncertainty $460 \text{ ppb} \rightarrow 100 \text{ ppb}$

With many improvements, control systematics ~3x better $280 \text{ ppb} \rightarrow 100 \text{ ppb}$

Reuse the BNL ring (and recycle lots of other parts)

BNL result sparked lots of interest!




# Muon g-2 collaboration

## USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

## USA National Labs
- Argonne
- Brookhaven
- Fermilab

## China
- Shanghai Jiao Tong

## Germany
- Dresden
- Mainz

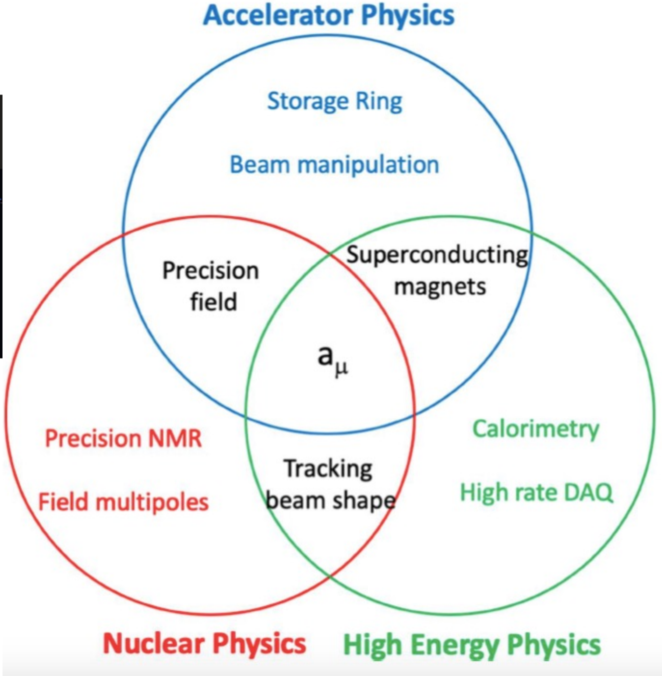
## Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

## Korea
- CAPP/IBS
- KAIST

## Russia
- Budker/Novosibirsk
- JINR Dubna

## United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London


>200 collaborators
35 institutions
7 countries



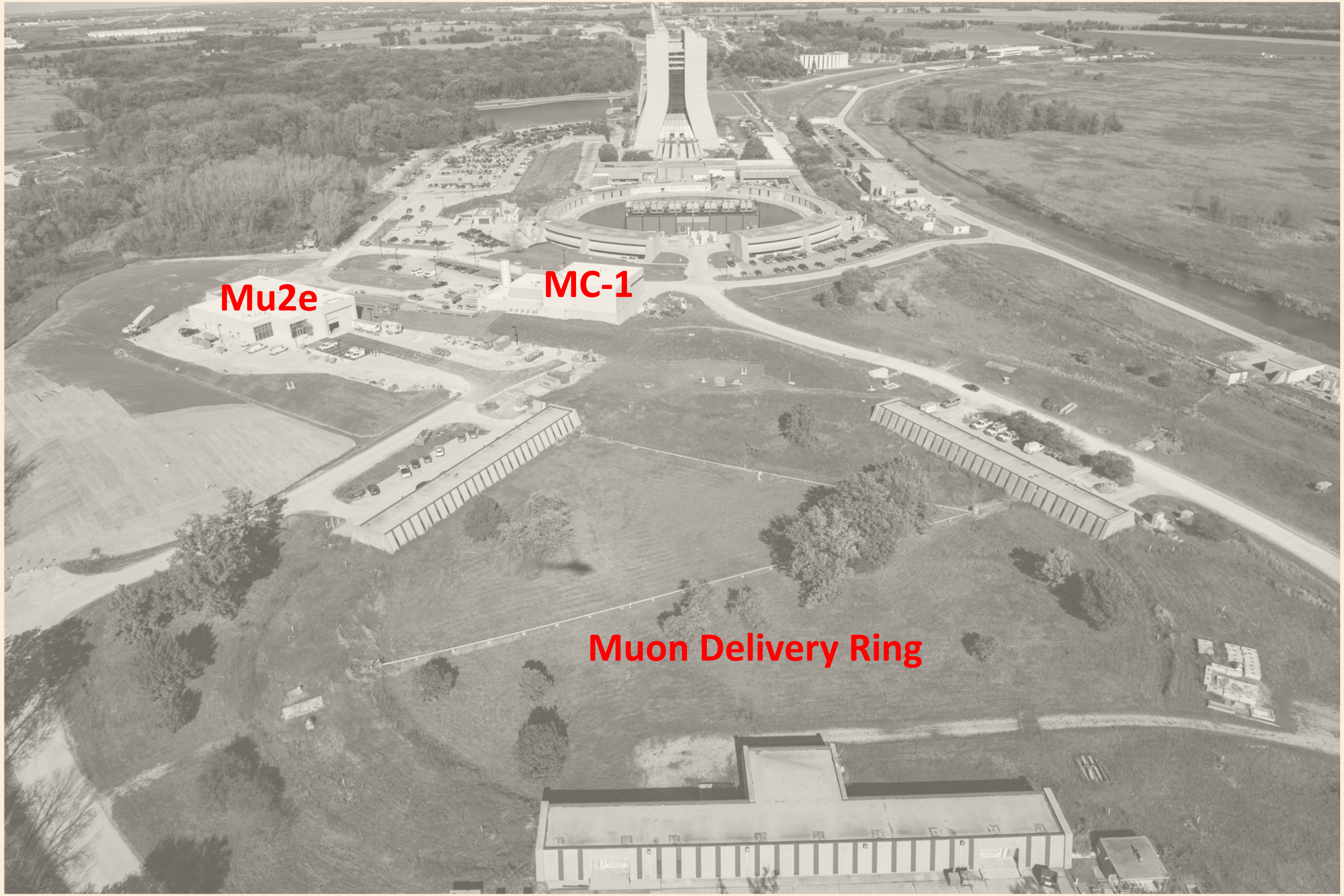

10 collaborators from BNL E821

# The Big Move of the 50’ diameter magnet (2013, 3000 mi, 3 months)



# The Fermilab Muon Campus

# The Fermilab Muon Campus



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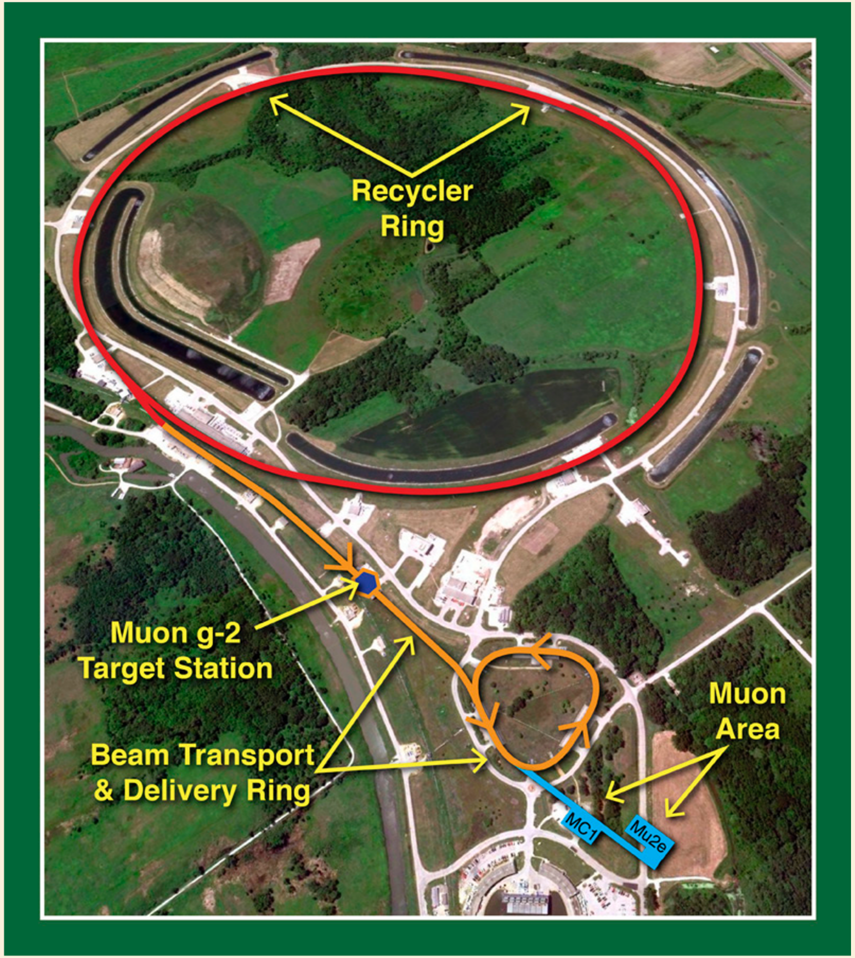
# Delivering Muons

Protons accelerated in Linac, Booster and into the Recycler

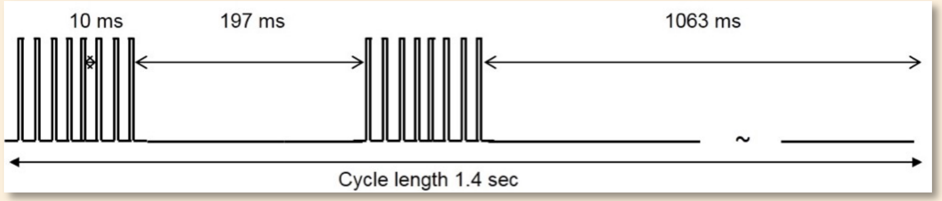
Repurposing the Tevatron anti-proton source



# Delivering Muons

8 GeV protons from the Booster enter the Recycler Ring for re-bunching

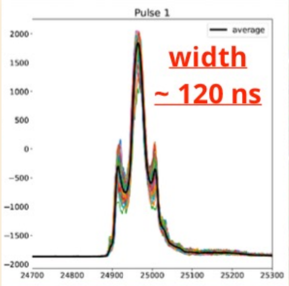
16 bunches per 1.4 s cycle



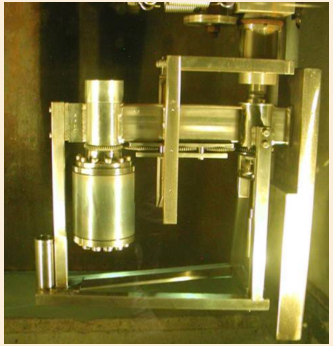

Recycler is a permanent magnet ring that was used to retain the Tevatron anti-proton "stash" after a Tevatron shot to be "recycled" into the next shot

# Delivering Muons

Repurposing the Tevatron anti-proton target



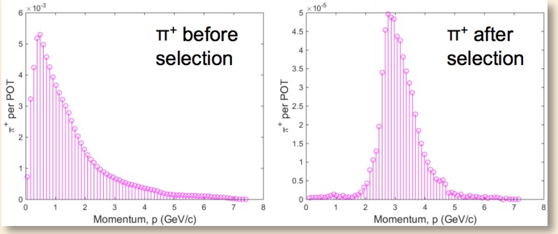

120 ns wide 8 GeV proton bunch



Inconel (nickel alloy) target

Avg $9.84\times10^{11}$ protons on target

Lithium lens & pulsed magnet for $3.11\ \mathrm{GeV}\ \pi^+$




# Delivering Muons

280 m transfer line for $\pi^+ \rightarrow \mu^+$

High quadrupole density

Accepts $\Delta p/p \approx \pm 4\%$ collecting $3.09\ \mathrm{GeV}$ muons from forward decays (longitudinally polarized)

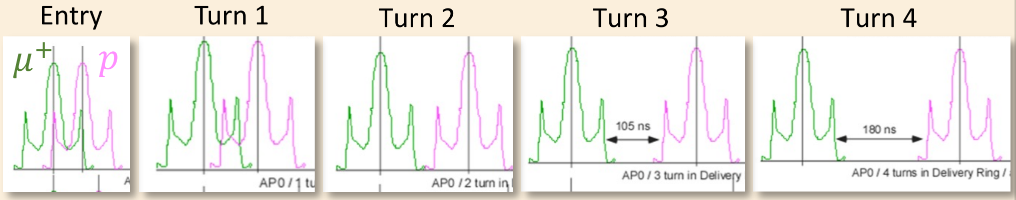
~ 80% of pions decay in the transfer line
95% polarized

# Delivering Muons

Delivery ring

Repurposing the anti-proton debuncher

4 turns around the 505 m circumference separate muons from hadrons




Protons are kicked out of the beam

Muons go to MC-1 and into the g-2 storage ring

# Muon g-2 ring

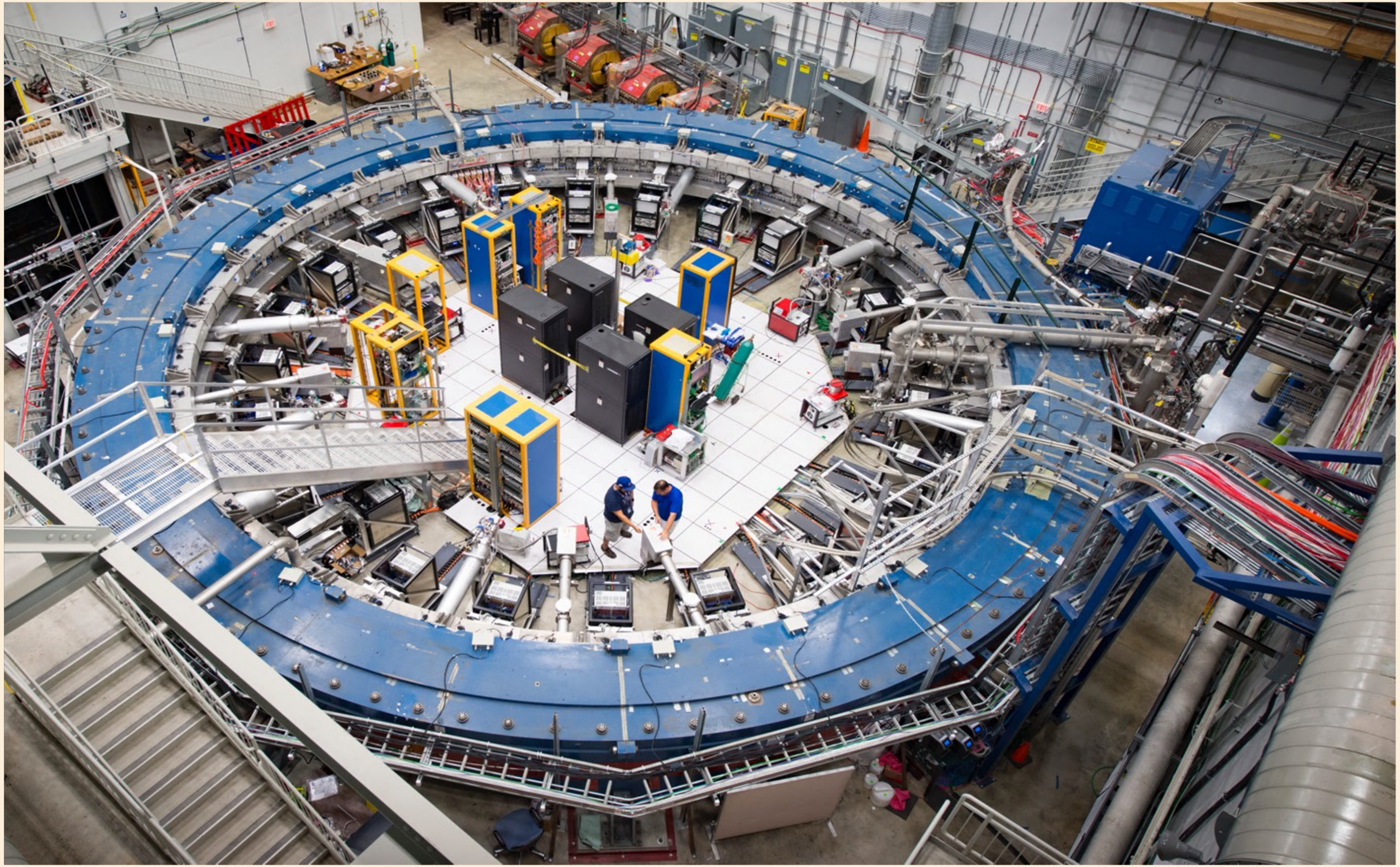
5 000 $\mu$/fill stored
(2% of injected)

$\mu$ lifetime is ~ 64 $\mu s$

Fill is 700 $\mu s$
(about 10 muon lifetimes)

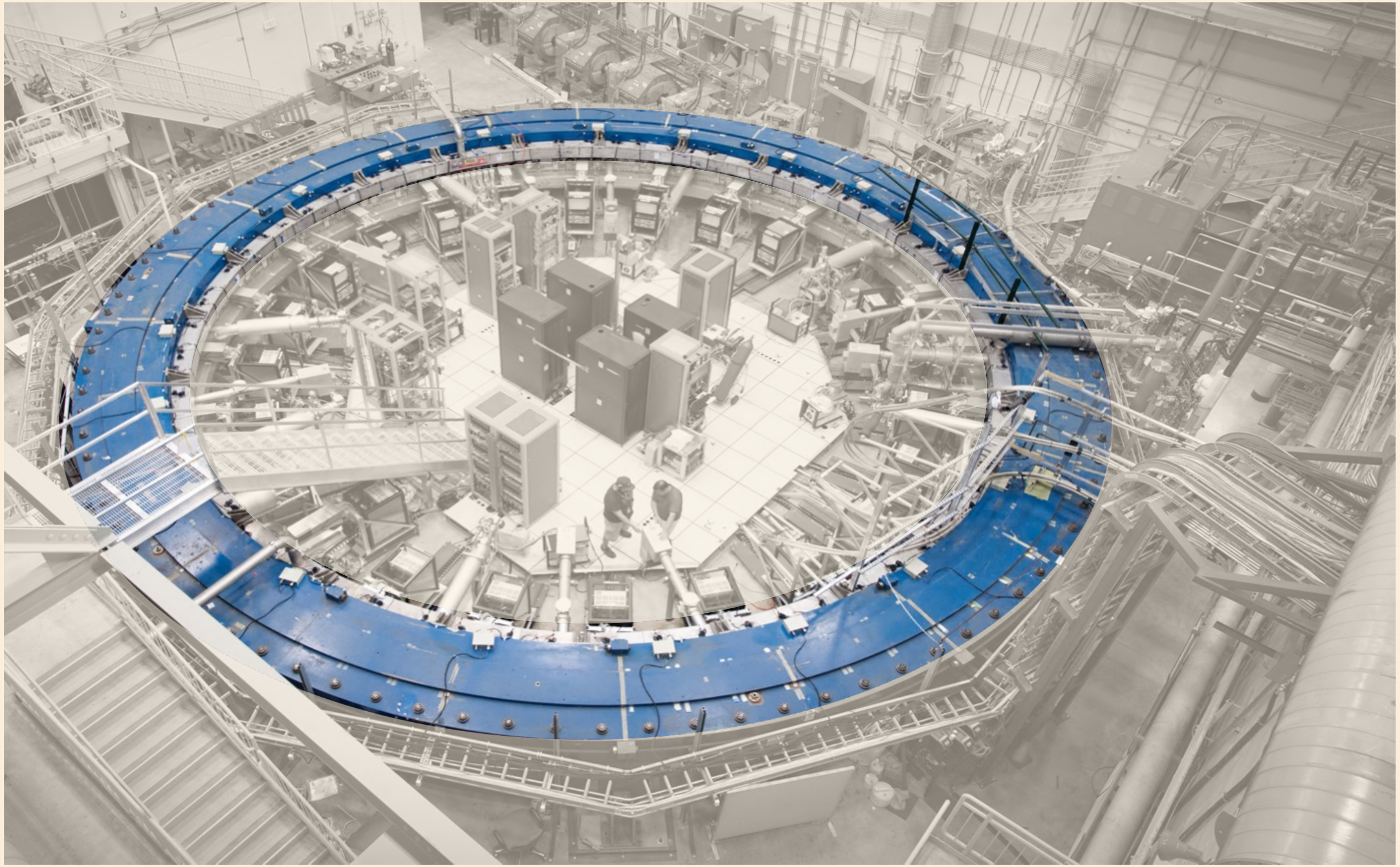
Cyclotron period
$149.2 \text{ ns}$

$R_0 = 7.112 \text{ m}$



# The Magnet

1.45 T
Superferric
magnet



# Storage Ring Magnet

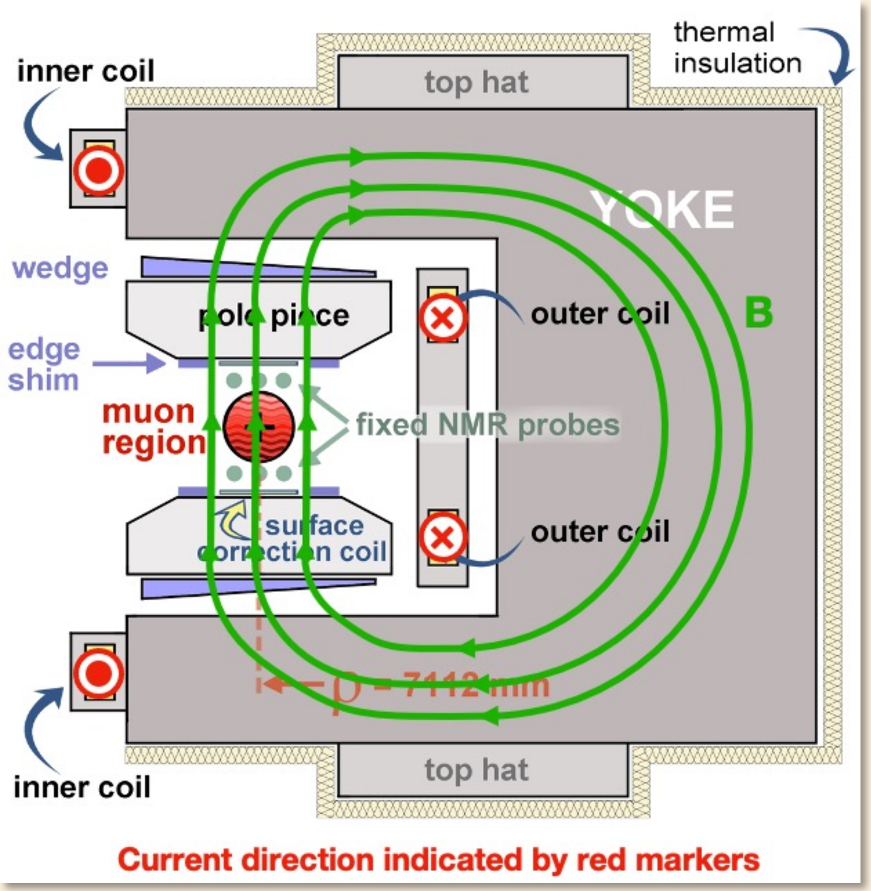
Iron yoke excited by superconducting coils

Pieces of asymmetric iron including wedges, laminations, and shims for shaping the filed

Storage region radius 4.5 cm

Magnet radius 7.112 m

Shimmed to better than 50 ppm (3x better than Brookhaven)



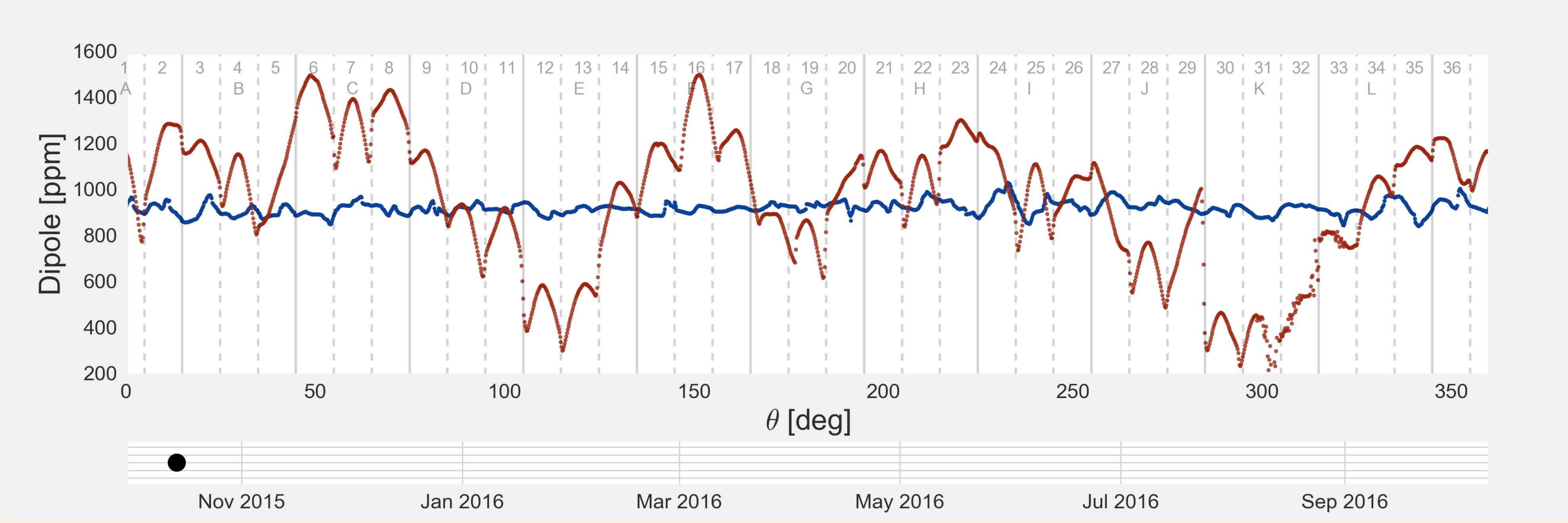



Fermilab

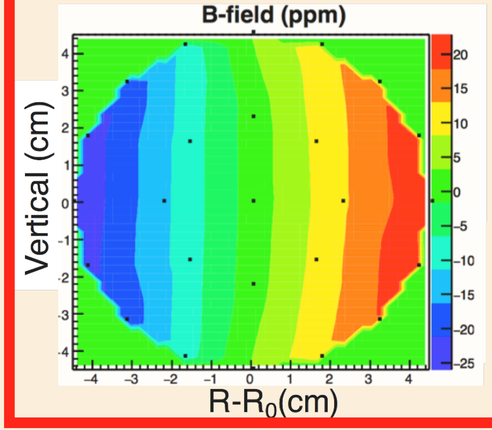
# Shimming the magnet

Took a year to interactively map, simulate, and adjust top hats, 864 wedges, 366 pole feet attached to 72 poles to $\pm 6\ \mu\text{m}$ and **8424 foil shims**

BNL Shim FNAL Shim

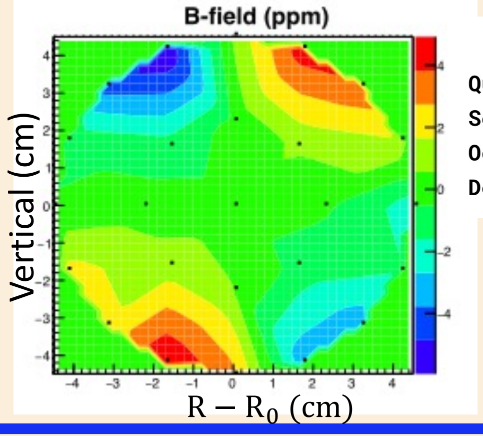


# Shimming the magnet




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

Oct 2015

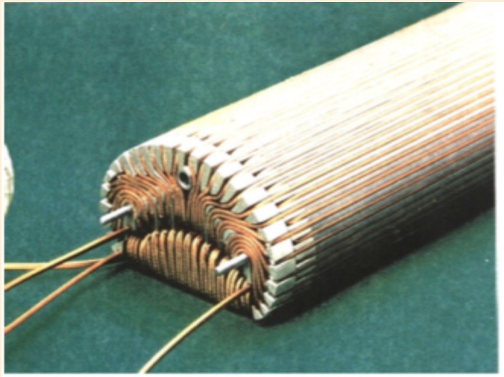


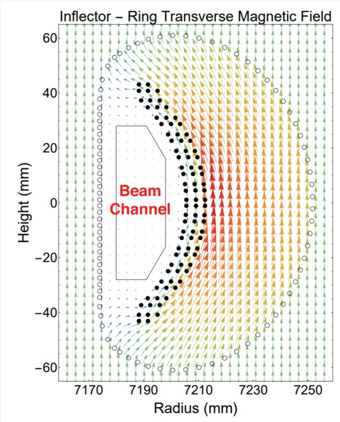

| | Norm | Skew |
|---|---|---|
| Quad | -0.02 | -0.57 |
| Sext | -0.70 | 3.84 |
| Octu | -0.76 | 0.56 |
| Decu | 0.44 | -1.61 |

Aug 2016

# Inflector

# Entry & Inflector magnet






Muons need a field free section to enter the storage ring

Superconducting Inflector magnet cancels the 1.45 T field. Surrounded by superconducting sheet to avoid perturbing main magnet

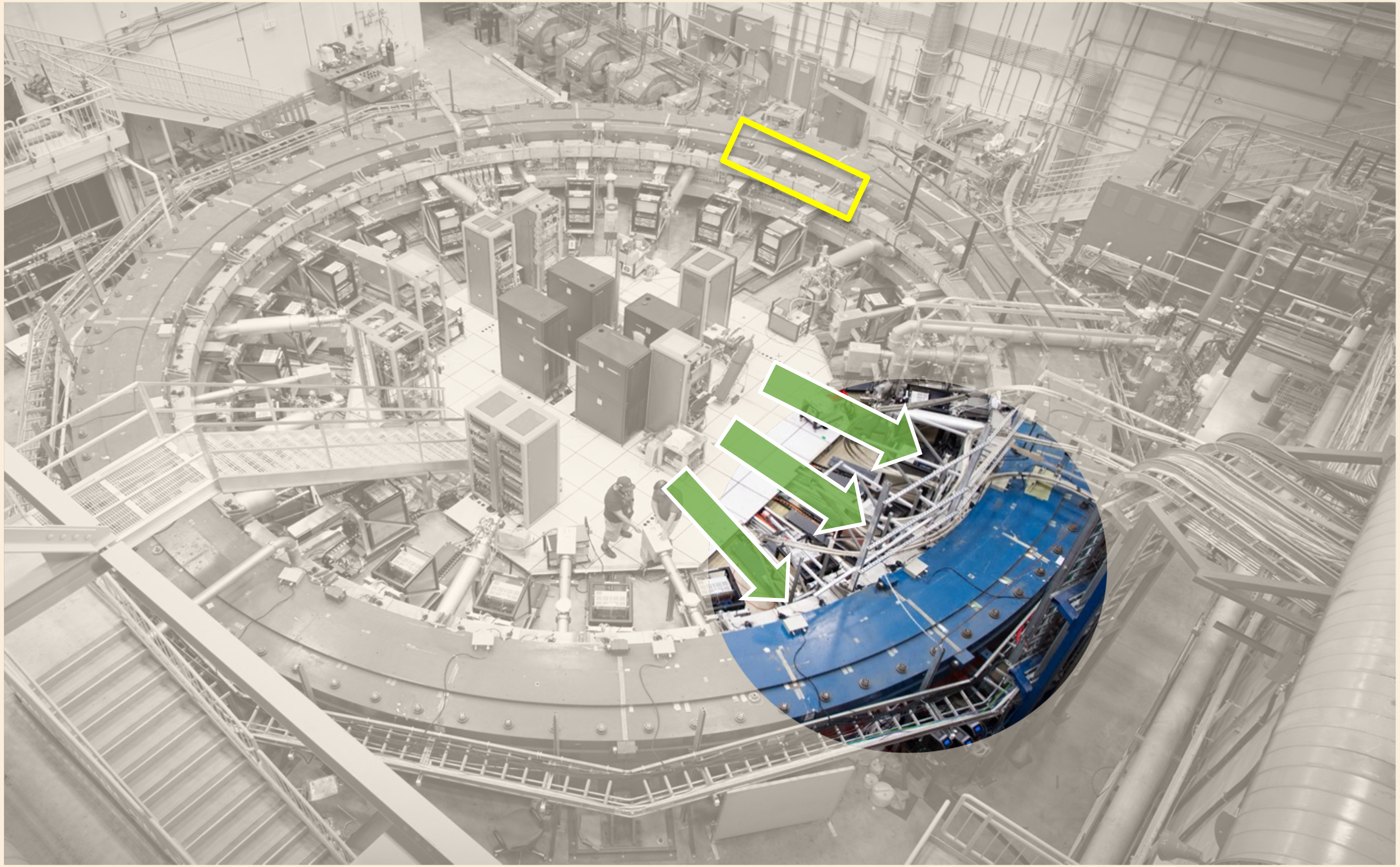
# Kickers

Beam must be kicked 10 mrad

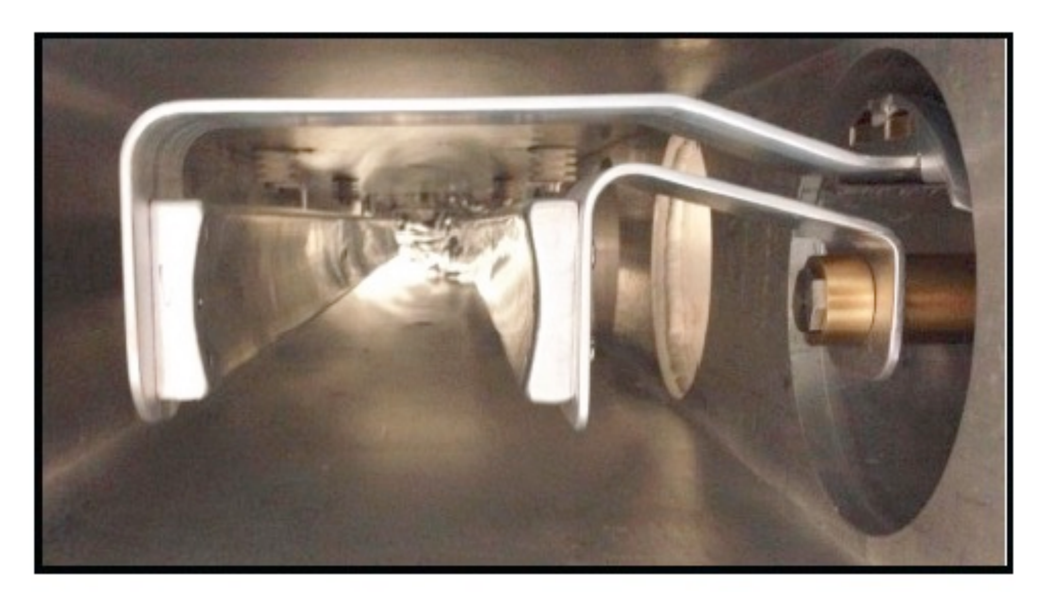
125 – 137 kV

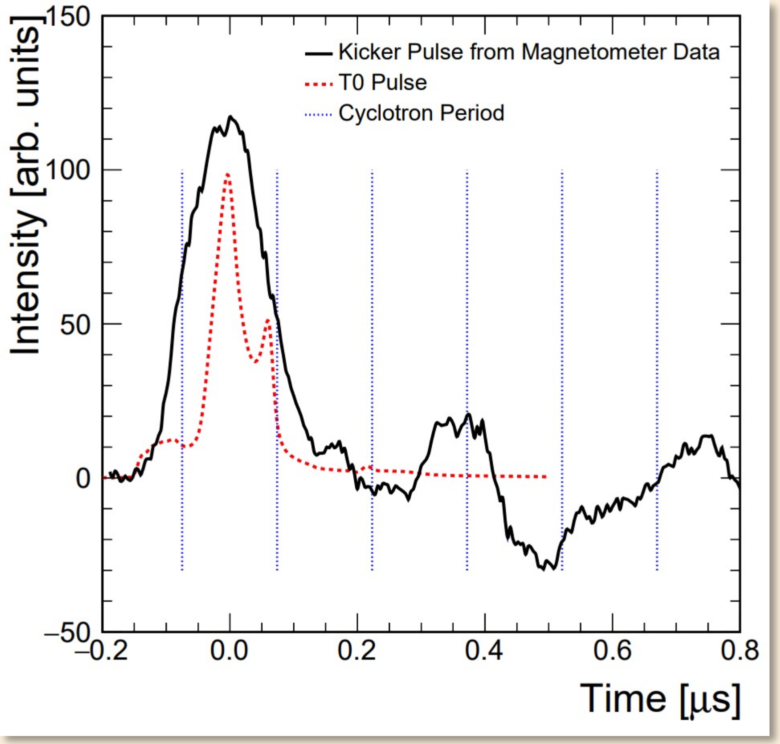
~ 200 G field

Must turn off within 149 ns (first turn)



# Kickers




Kicker Pulse from Magnetometer Data
T0 Pulse
Cyclotron Period
Intensity [arb. units]
150
100
50
0
−50
−0.2
0.0
0.2
0.4
0.6
0.8
Time [μs]

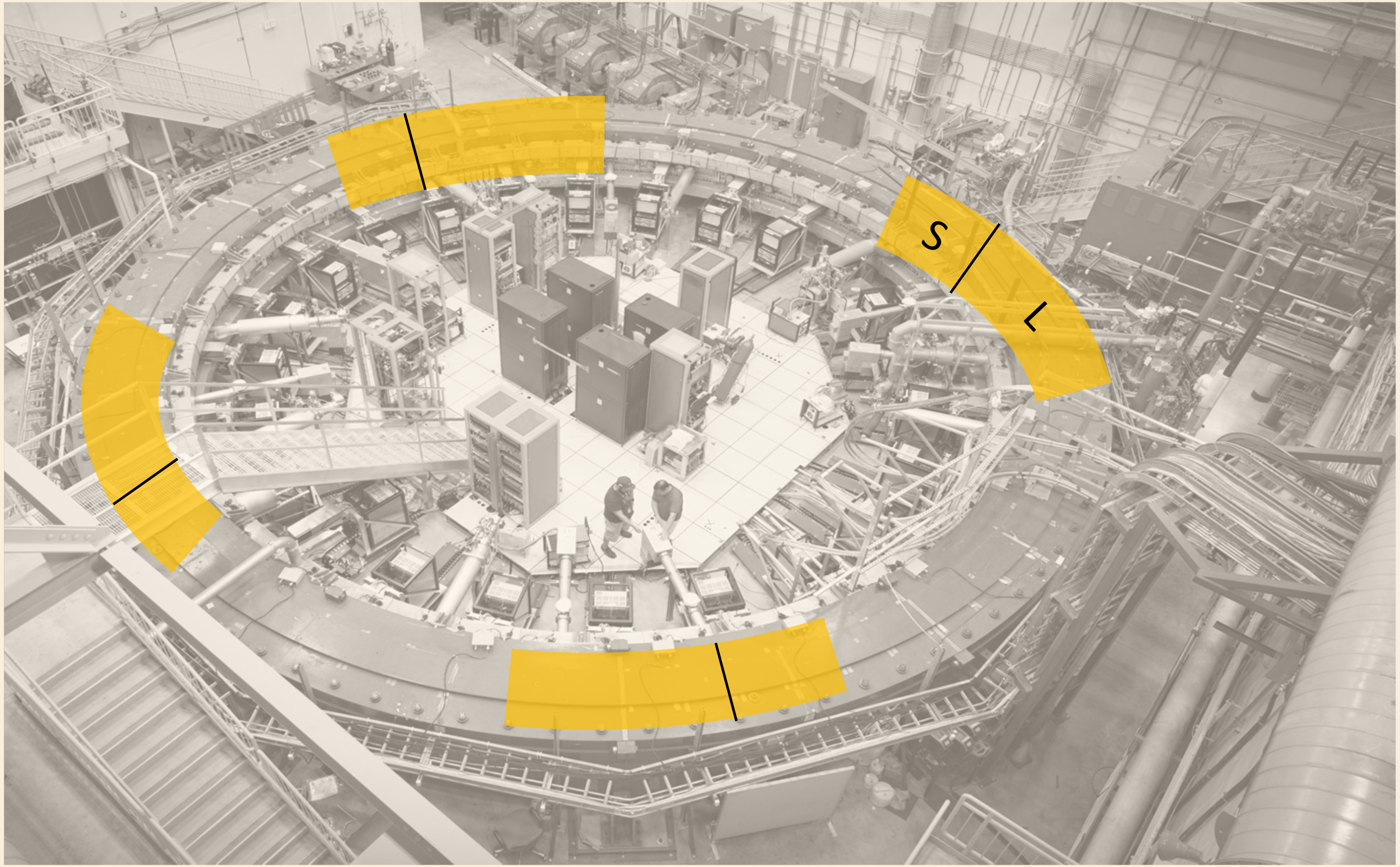
# Quadrupoles

Electrostatic Quadrupoles (ESQ)

Vertical focusing

4 sections each with short & long

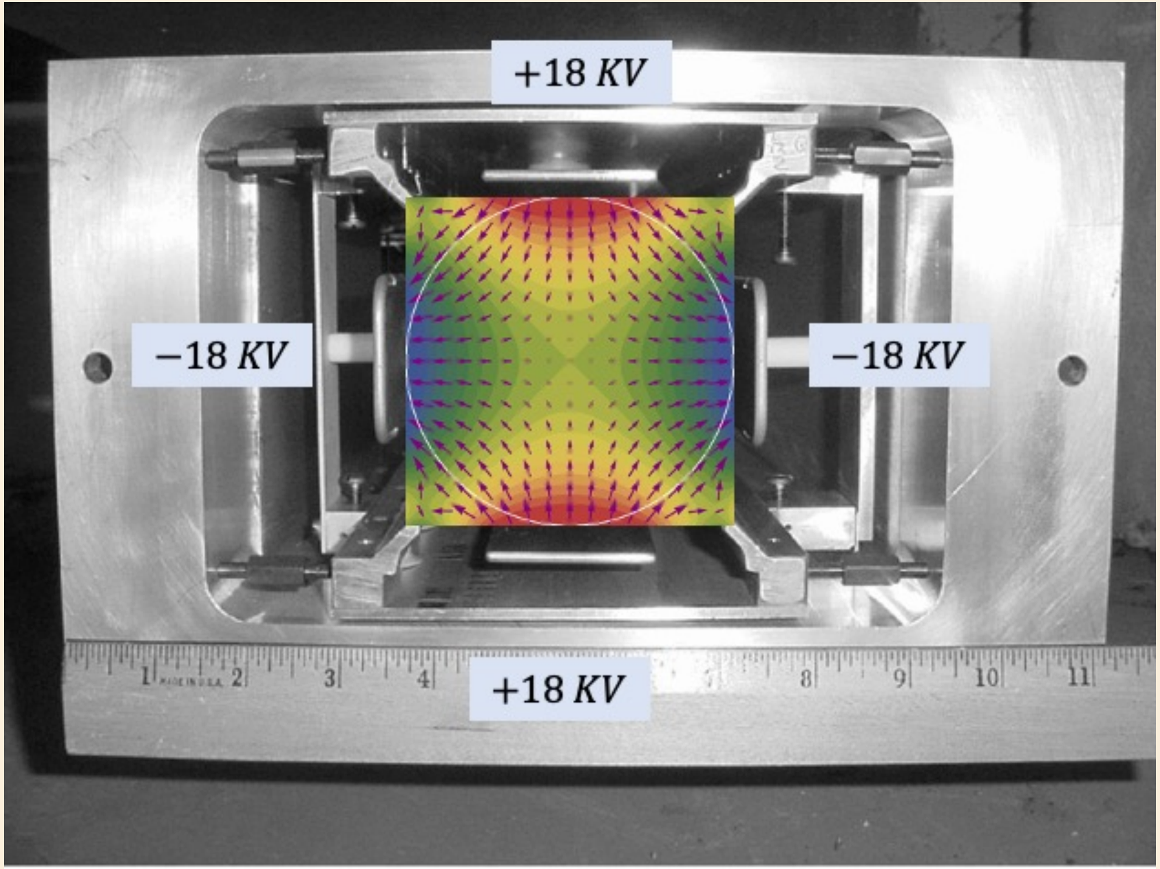
43% of circumference






Fermilab

# ESQ




Picture credit: Hogan Nguyen

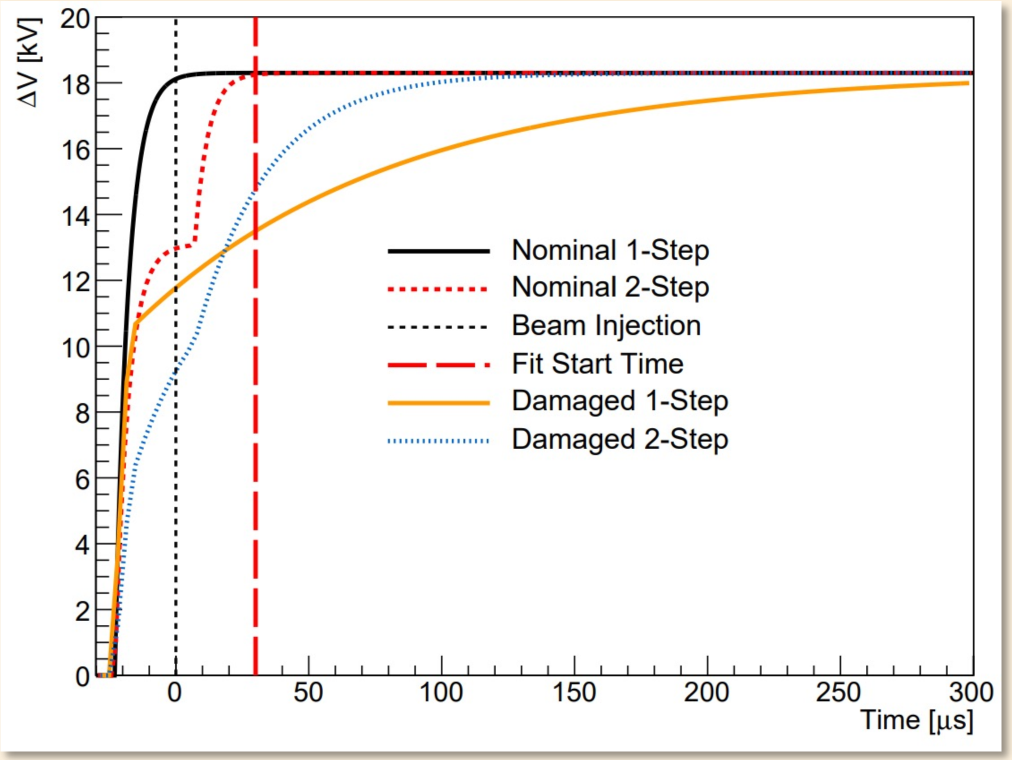
# ESQ – Challenge in Run 1

Quadrupole plates are pulsed at 18.3 kV or 20.4 kV
On for $700\ \mu s$ fill then off

RC time constant designed to charge Quads in $\sim 5\ \mu s$

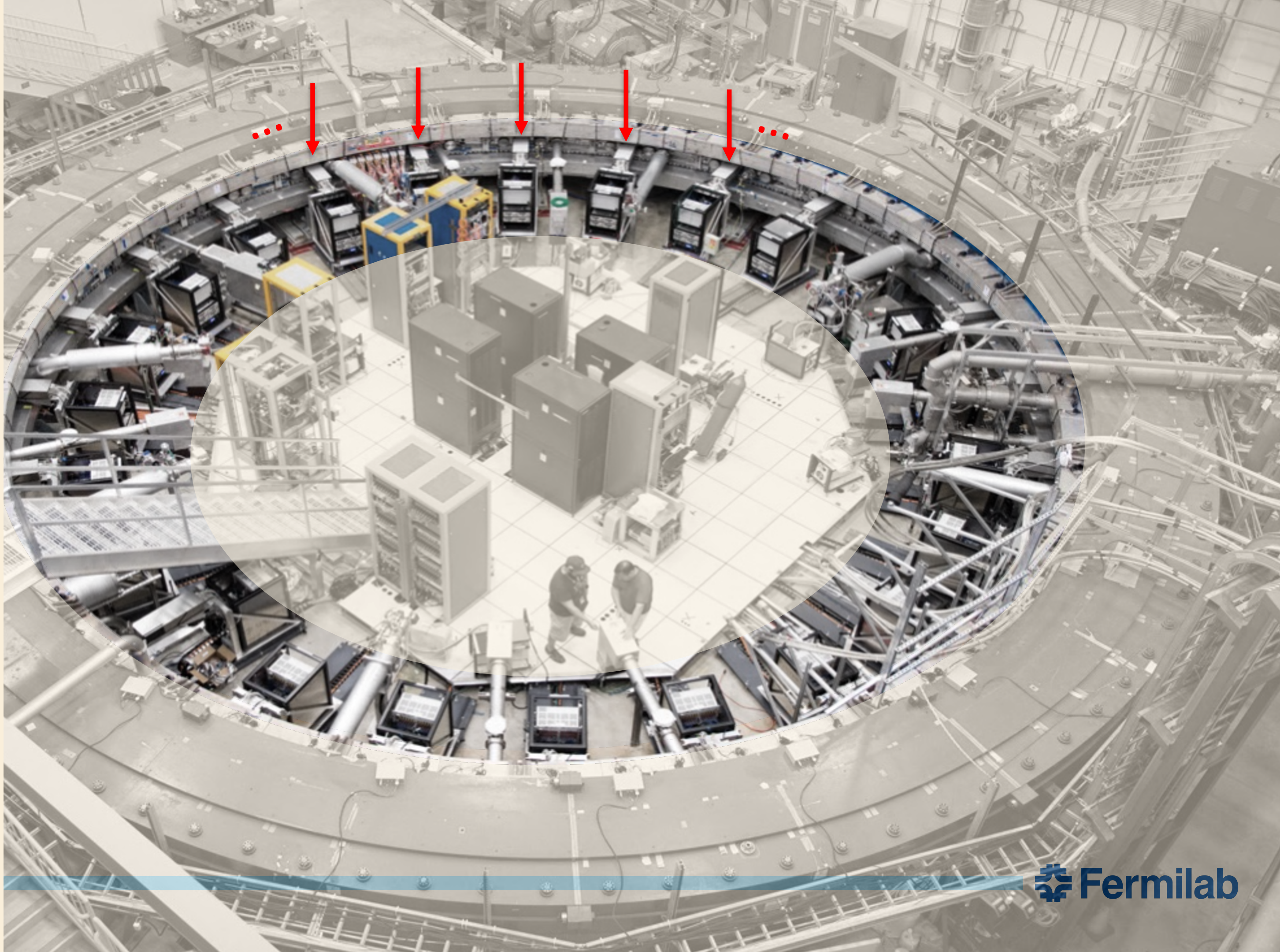
But HV two resistors (of 32) were damaged and prolonged the turn on

Implications for beam dynamics
[Fixed after Run 1]



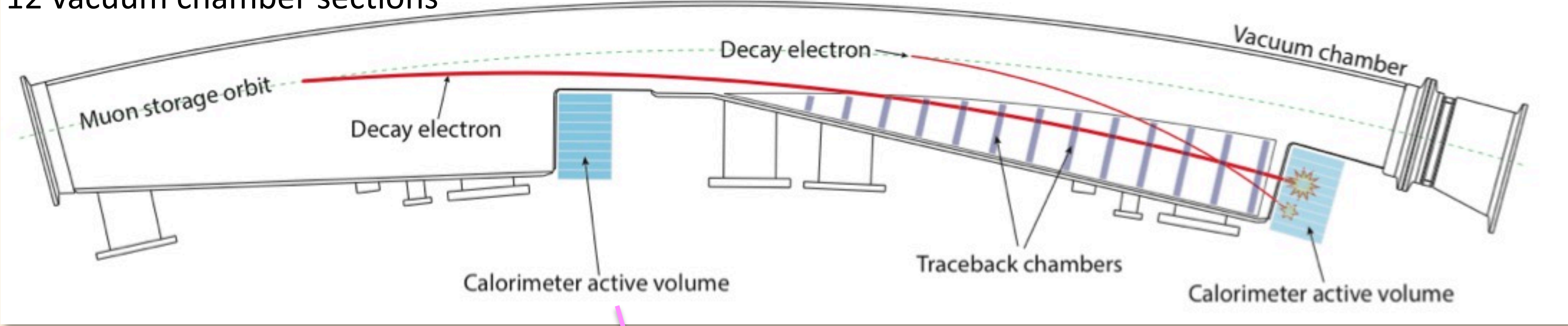
# Calorimeters

24 Calorimeters for measuring positron energy



# 24 Calorimeters

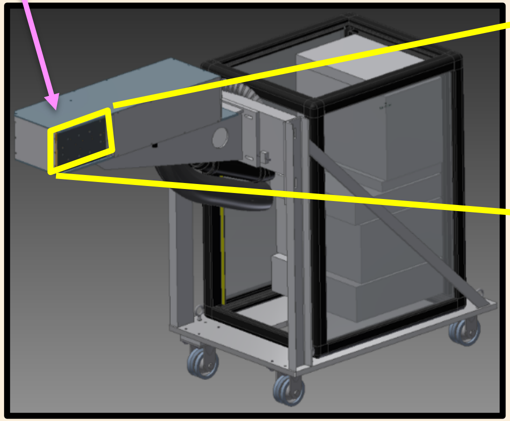
12 vacuum chamber sections

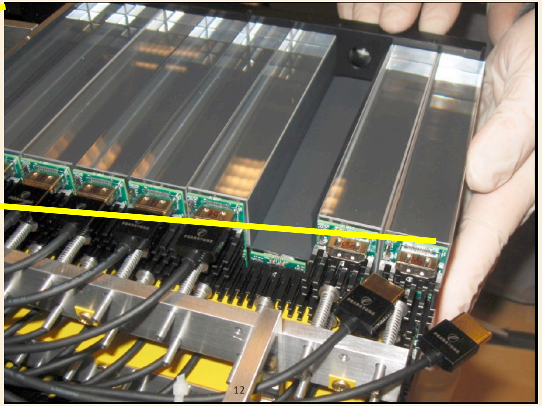



9x6 array of $PbF_2$ crystals

Fast SiPM readout

800 Msamples/s
waveform digitizers





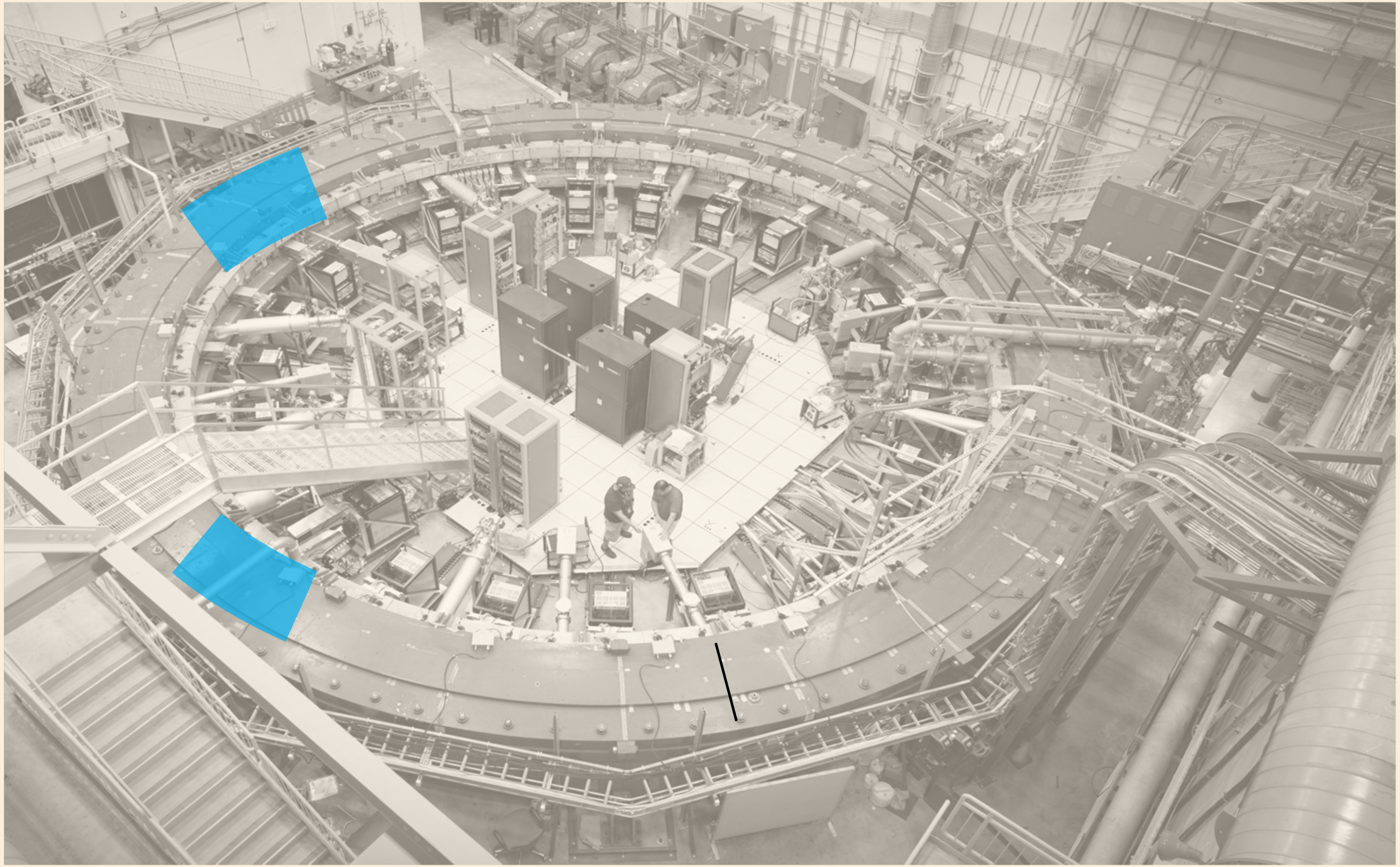
# Trackers

2 stations of straw trackers *in vacuo*

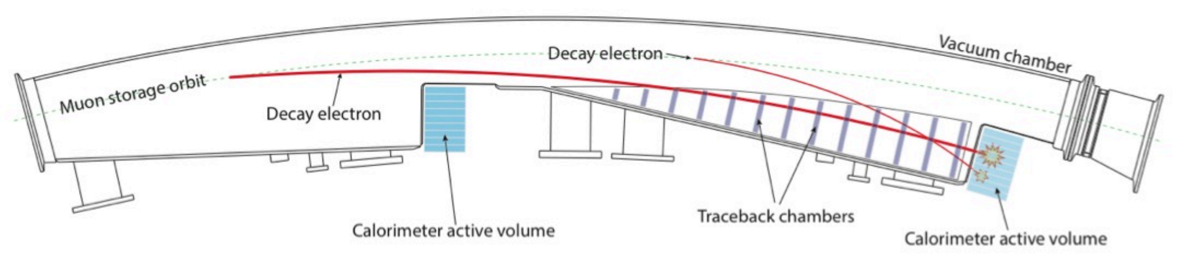
Argon-Ethane

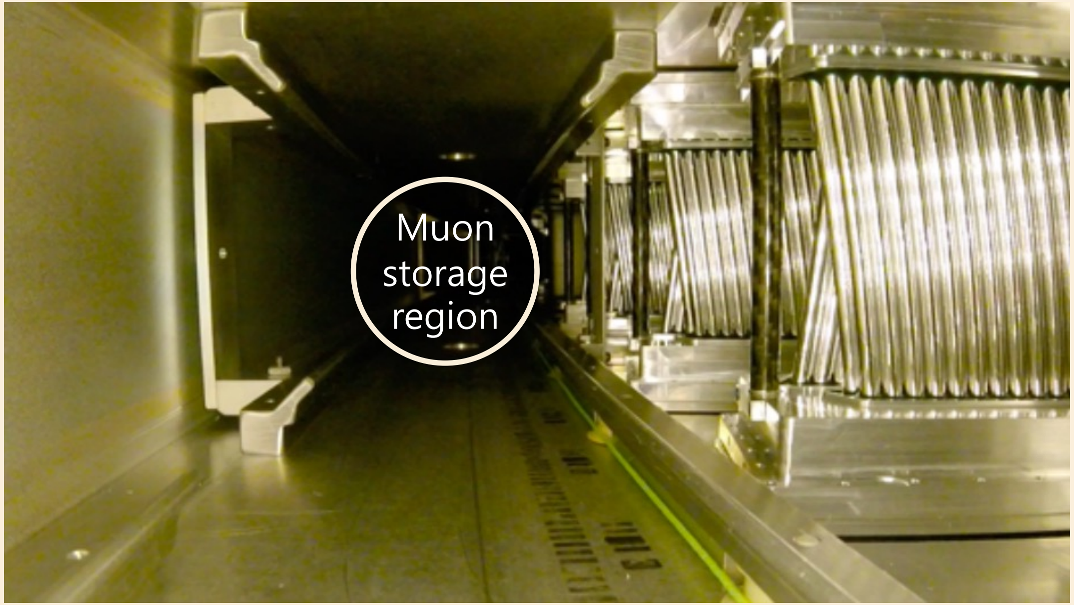
1500 channels

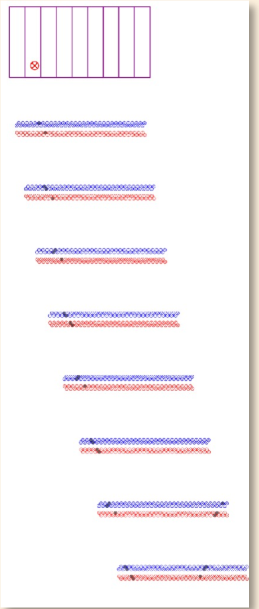
Gives spatial distribution and $\mu$ beam properties



# Straw tube trackers



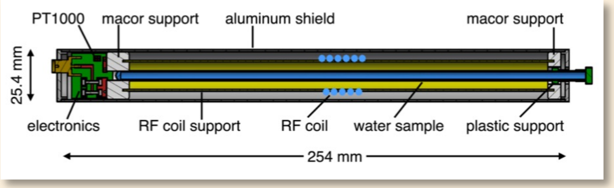
# Measuring the Field

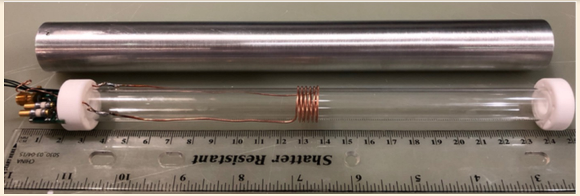
$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$$

We need to determine $B$ to < 100 ppb

Use NMR probes to measure $B$ in terms of proton precession frequency $\omega_p$

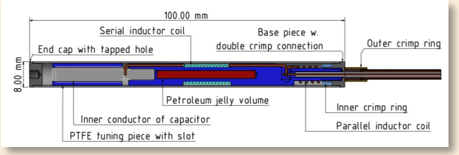
Trolley cross-calibrated to absolute probes
Absolute probes all cross-calibrated in a 1.45 T MRI magnet at Argonne National Laboratory



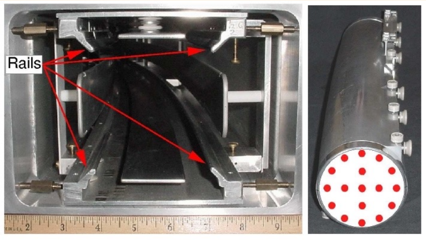



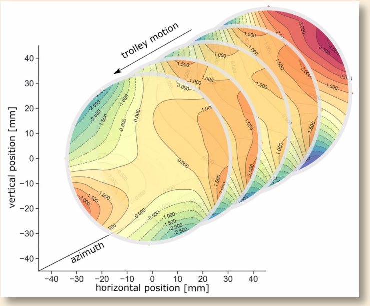


378 fixed probes monitored 24/7




Trolley maps field every 3 days



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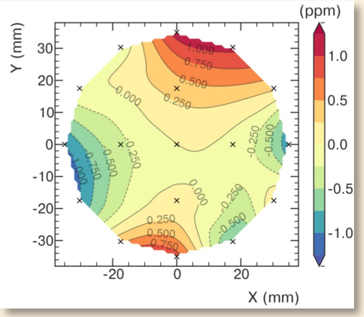
# Measuring $a_\mu$

us | others (total known to ~ 24 ppb)

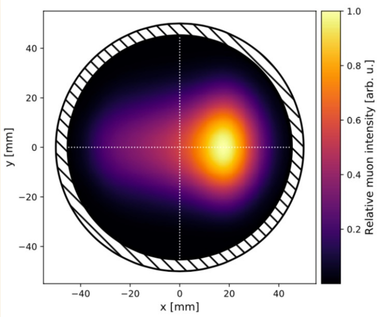
$$a_\mu = \frac{\omega_a}{B}\frac{m_\mu}{e} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)}\frac{\mu'_p(T_r)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$\omega_a$: Muon spin precession frequency

$\tilde{\omega}'_p(T_r)$: Precession of protons in shielded water sample at 34.7 °C mapping the field and weighted by the muon spatial distribution




$\otimes$




$\tilde{\omega}'_p(T)$: Proton Larmor precession frequency in a spherical water sample (temp dependence known to $< 1$ ppb/°C)
Metroligia **13**, 179 (1977); **51**, 54 (2014); **20**, 81 (1984)

$\mu_e(H)/\mu'_p(T_r)$: Measured to 10.5 ppb at $T_r = 34.7$ °C
Metrologia **13**, 179 (1977)

$\mu_e/\mu_e(H)$: Bound-state QED (exact)
Rev. Mod. Phys. 88 035009 (2016)

$m_\mu/m_e$: From muon hyperfine splitting (22 ppb)
Phys. Rev. Lett. **82,** 711 (1999)

$g_e/2$: Measured to 0.28 ppt
Phys. Rev. A **83**, 052122 (2011)

# Measuring $a_\mu$

The quantities we measure:

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

| Dataset | # Days (Apr-Jun 2018) | Tune (n) | Kicker (kV) | # fills $(10^4)$ | # positrons $(10^9)$ |
|---|---|---|---|---|---|
| 1a | 3 | 0.108 | 130 | 151 | 0.92 |
| 1b | 7 | 0.120 | 137 | 196 | 1.28 |
| 1c | 9 | 0.120 | 132 | 333 | 1.98 |
| 1d | 24 | 0.107 | 125 | 733 | 4.00 |

Total 8.2B positrons ( ~ 1.2x BNL) 6% of our target statistics

# Reconstructing positrons

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

SiPM voltages → reconstructed positron energy in time

Find waveform islands with hits over threshold (50 MeV)

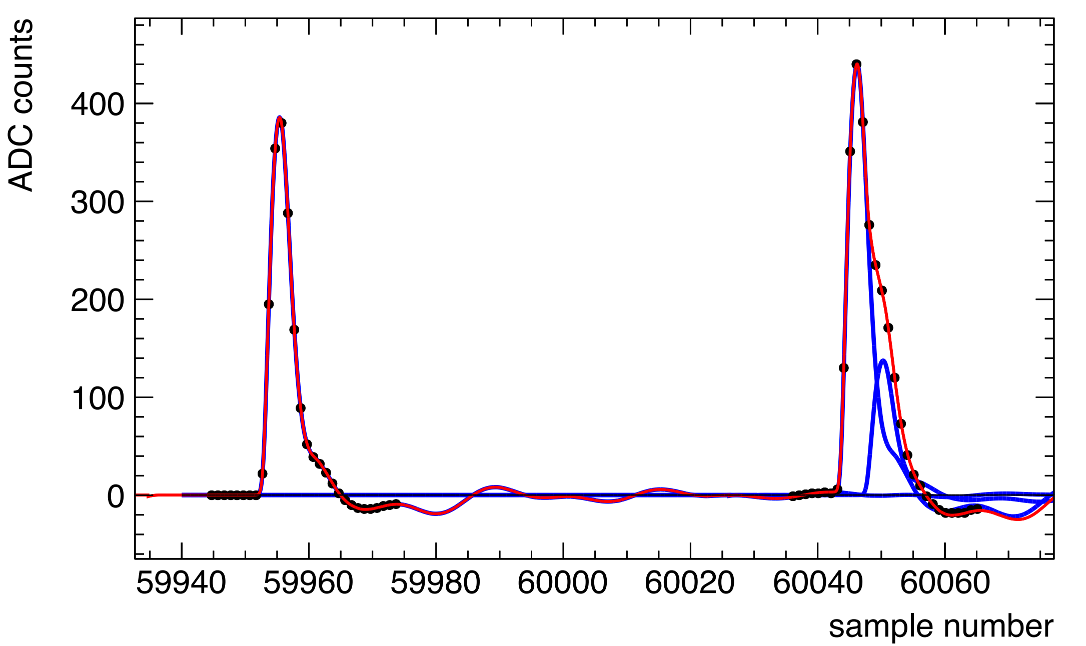
Fit waveforms from WFD to templates (template unique to each crystal)

Cluster across crystals to form positrons

Two algorithms…

Local: individual crystals are fit & combined

Global fit across multiple crystals




From Kevin Labe



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# Fitting wiggles

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

Fit to exponential decay and anomalous precession oscillation

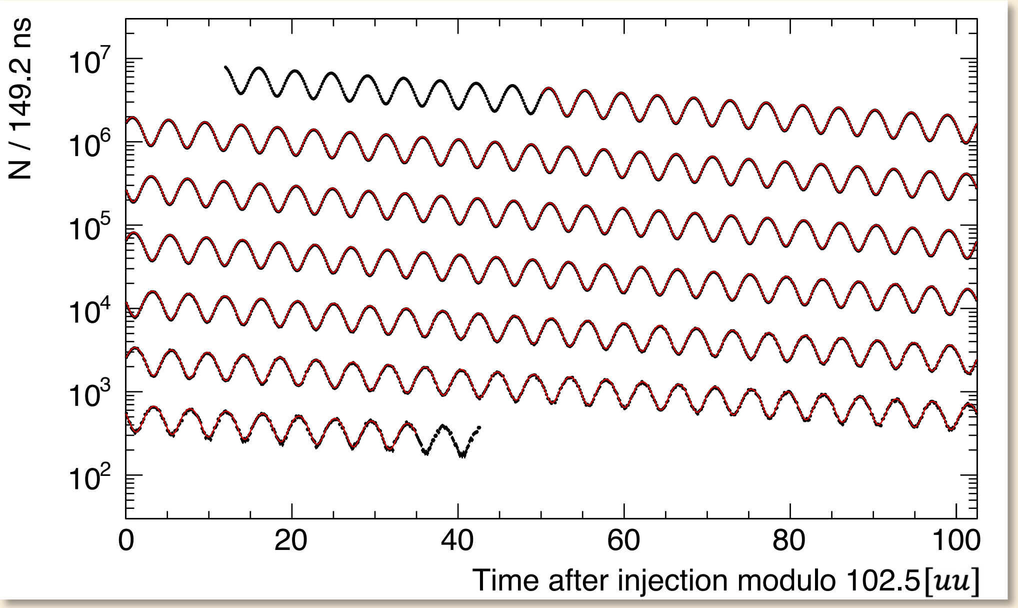
$$N(t) = N_0 e^{-t/\tau_\mu}\left[1 + A(E_{\text{th}})\cos(\omega_a t + \phi_0)\right]$$

Wiggle plot from counting positrons over threshold

Note that clock frequency is blinded (25 ppm) $[uu]$ = unknown time unit

The fit $\chi^2/ndf = 9500/4150$

Why is the fit not good?

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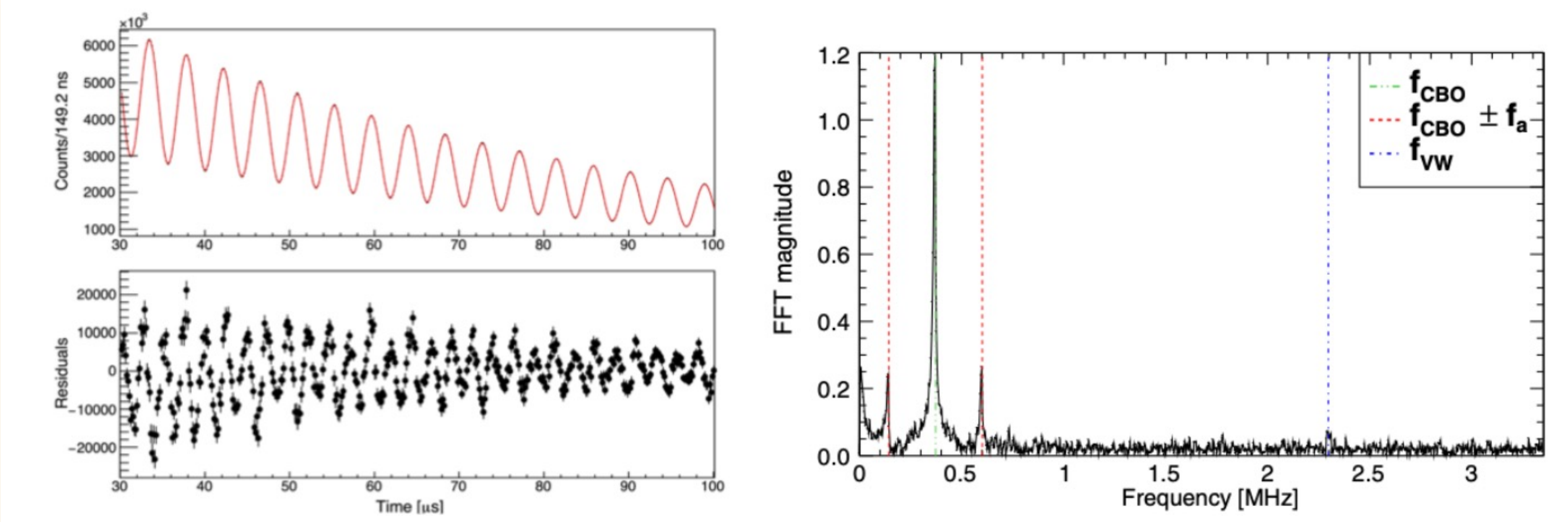
# Other frequencies

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

$\chi^2/\text{ndf} = 9500/4150$



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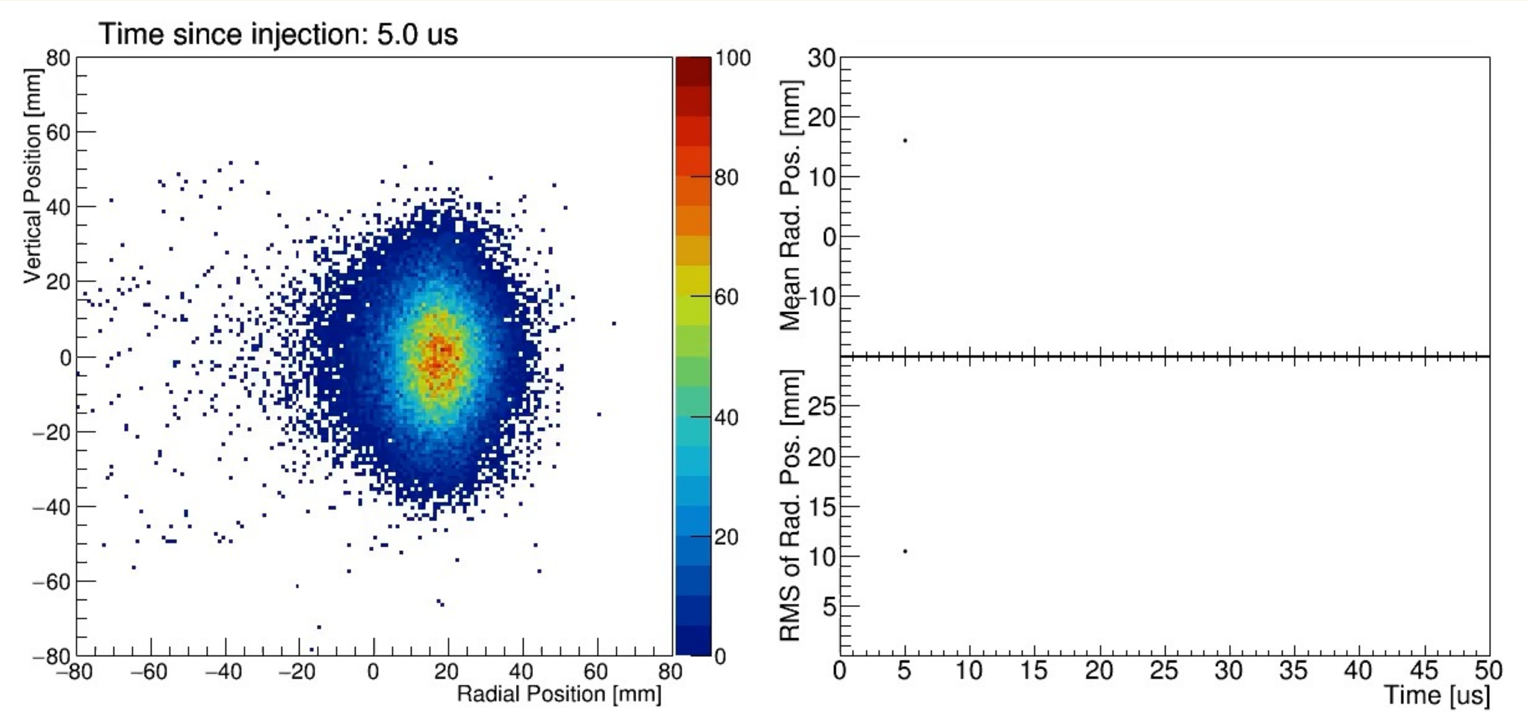
# Coherent Betatron Oscillation (CBO)

The muon beam “swims” and “breathes”

Measured by trackers



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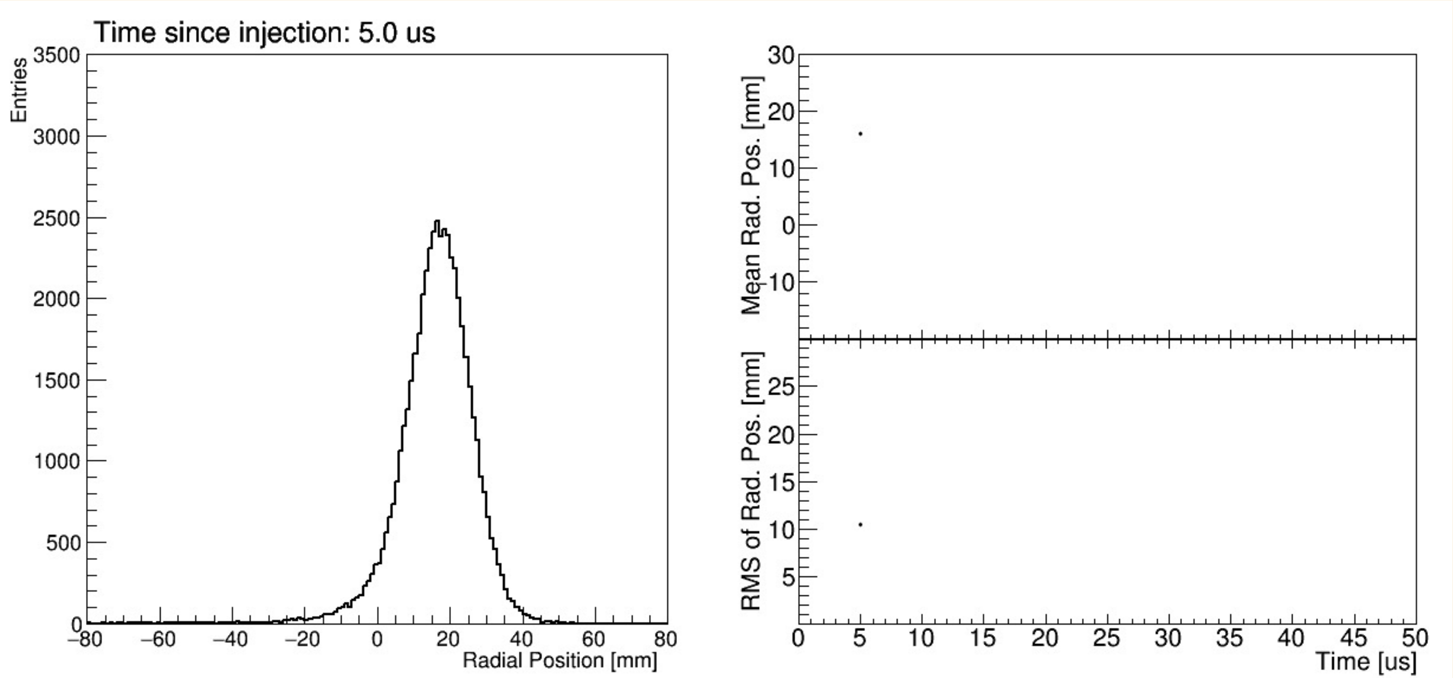
# Coherent Betatron Oscillation (CBO)

The muon beam "swims" and "breathes"     Measured by trackers



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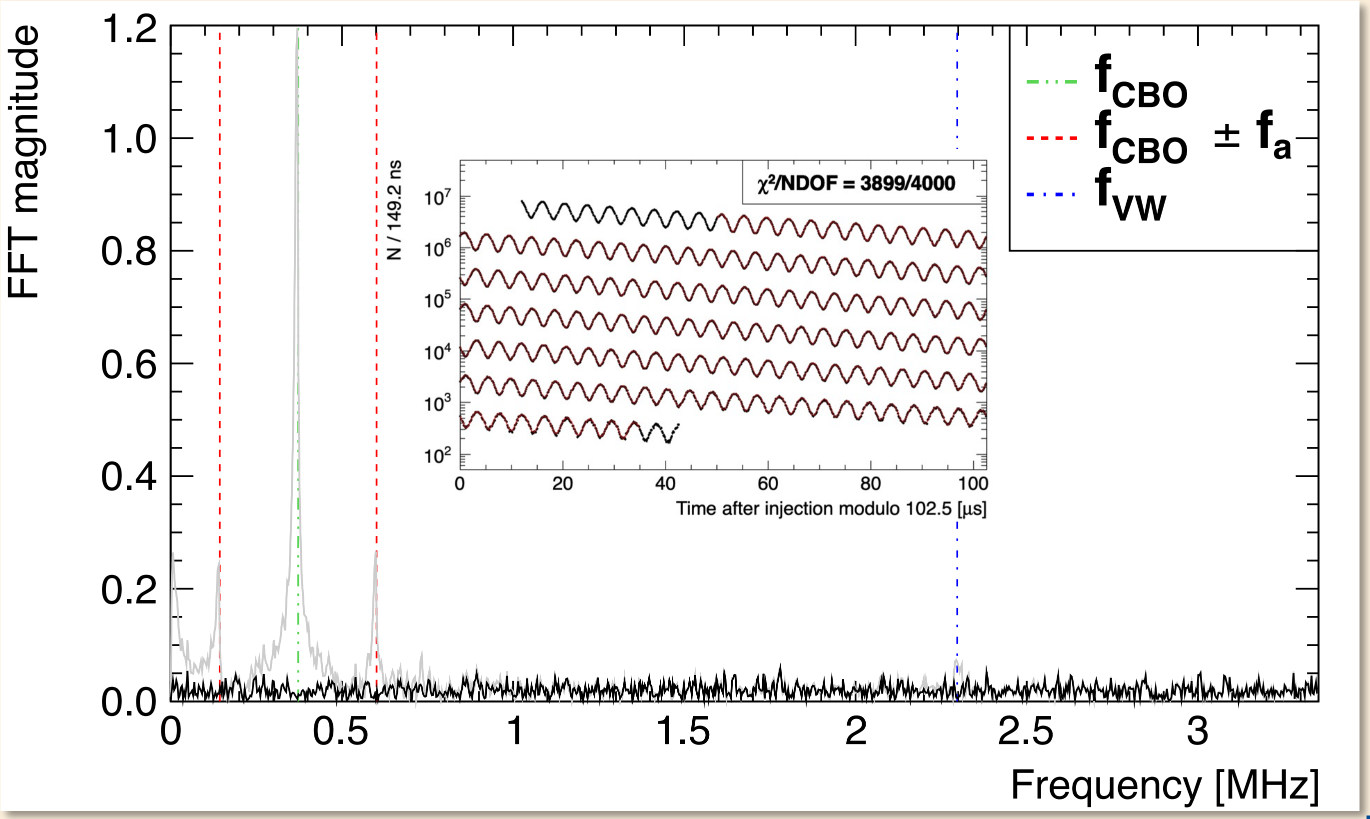
# 21 parameter fit

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



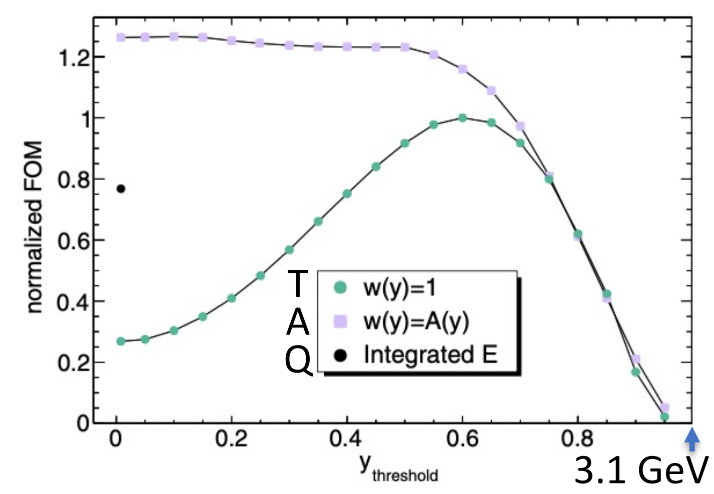
# Four analysis techniques

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

Multiple analyses (with added software blinding)

$$\sigma^2 \propto 1/N\langle A^2 \rangle_{E_{\text{th}}}$$

- T: $\sum N(E_{\mathrm{e}^+})$ $E_{\mathrm{e}^+} > 1.7\ \mathrm{GeV}$
- **A**: $\sum A(E_{\mathrm{e}^+})N(E_{\mathrm{e}^+})$ $E_{\mathrm{e}^+} > 1.0\ \mathrm{GeV}$
- R: Ratio Method splits data into two time shifted sets and divide. Removes slow $t$ dependence (exponential decay)
- Q: $\sum N(E_{\mathrm{e}^+})$ No threshold (histograms from DAQ)




$$y = E_{e^+}/E_{\max}$$

Two clustering algorithms; three pileup algorithms

4 **A** analyses were combined for result. Other 7 analyses were cross checks
All 11 (highly correlated) analyses consistent

# An important complication: Early-to-late effects

There is a potential problem in $N(t) = N_0 e^{-t/\tau_\mu} \cos(\omega_a t + \phi_0)$

Systematic effects sensitive to particle flux change from early in the fill to late
Introduce an effective $\phi(t)$

$$\cos(\omega t + \phi_0) \rightarrow \cos\big(\omega t + \phi(t)\big) = \cos(\omega t + \phi_0 + \phi' t + \cdots) = \cos((\omega + \phi')t + \phi_o + \cdots)$$

Failing to account for these effects would lead to a biased $\omega_a$ !!

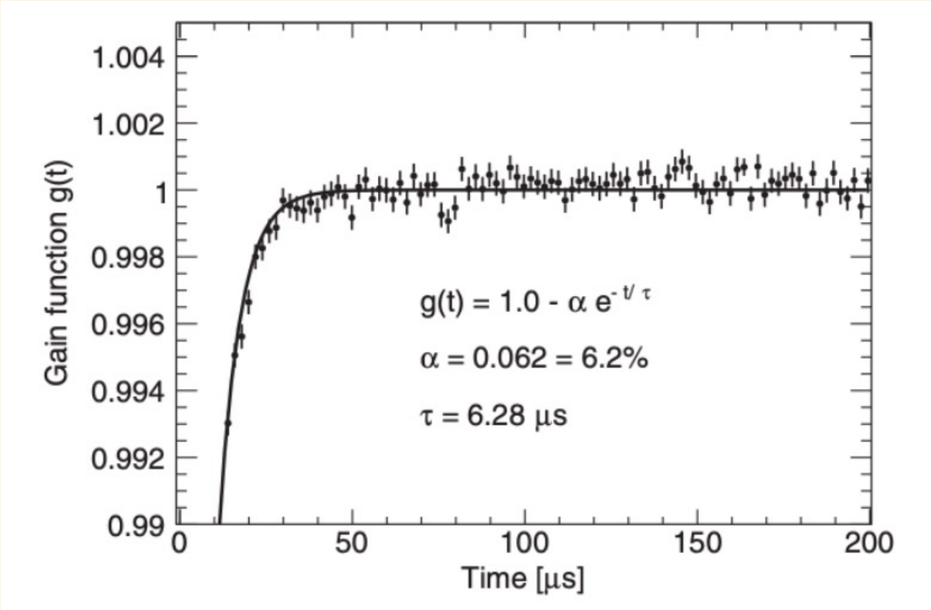
Possibilities: detector gain, pileup, lost muons, beam distortion

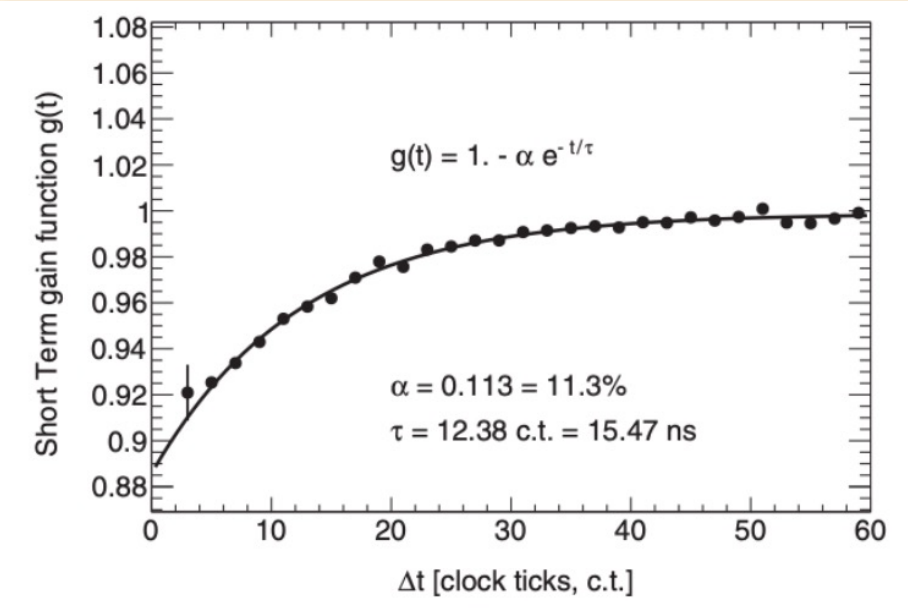
# Early-to-late effects - Gain

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

Temperature changes; Injection splash; SiPM recovery time

Use Laser calibration system (in fill and between fills) to track and **correct**

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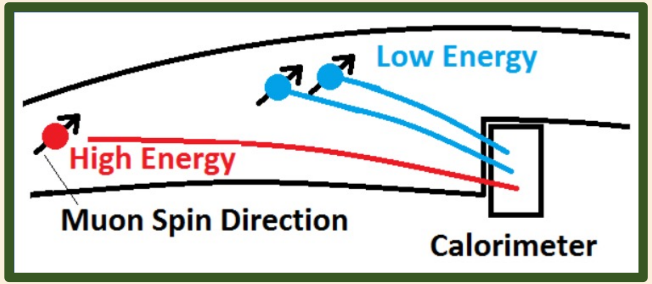
# Early-to-late effects - Pileup

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



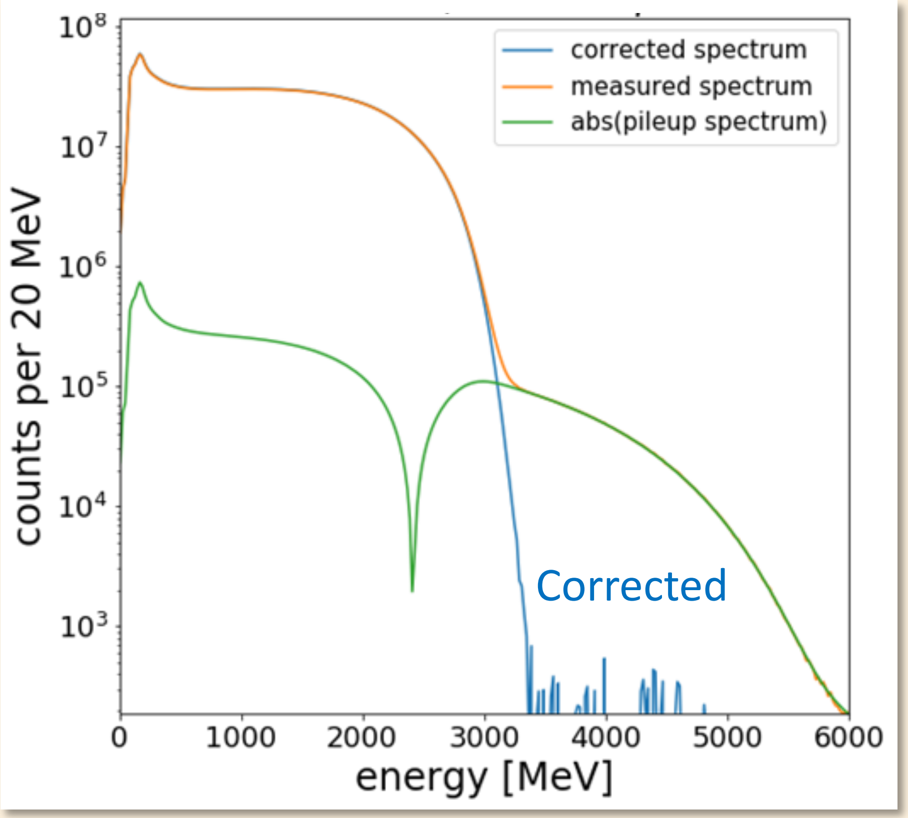

Deduce and subtract
pileup spectrum for each dataset

<u>Three methods:</u>

Model based approach (Shadow)

Empirical approach

PDF approach



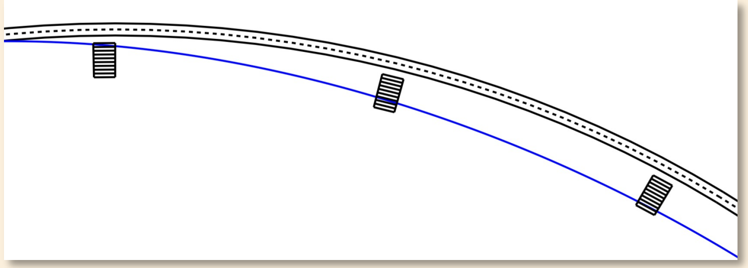
# Early-to-late effects - Lost muons

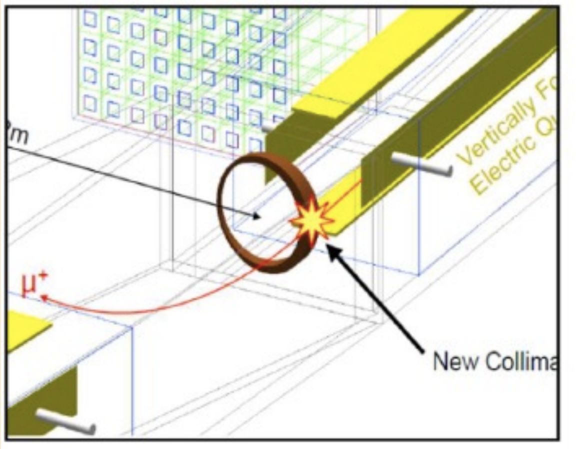
$$\mathcal{R}'_\mu \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \frac{\boldsymbol{\omega_a^{\text{meas}}}}{\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle} \frac{(1 + C_e + C_p + C_{ml} + C_{pa})}{(1 + B_k + B_q)}$$

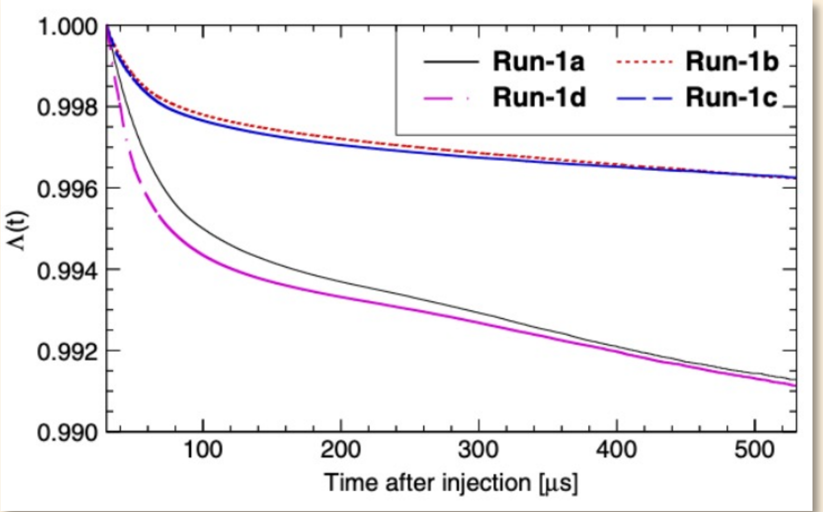
Muon losses lead to time dependence of $N$

Muon loss term $\Lambda(t) = 1 - K_{\text{loss}} \int_0^t e^{t'/\gamma\tau} L(t') dt'$

Loss spectrum $L(t)$ measured from detecting MIP traces in calorimeters and verified by identifying muons with $E/p$ in stations with tracker and calorimeter

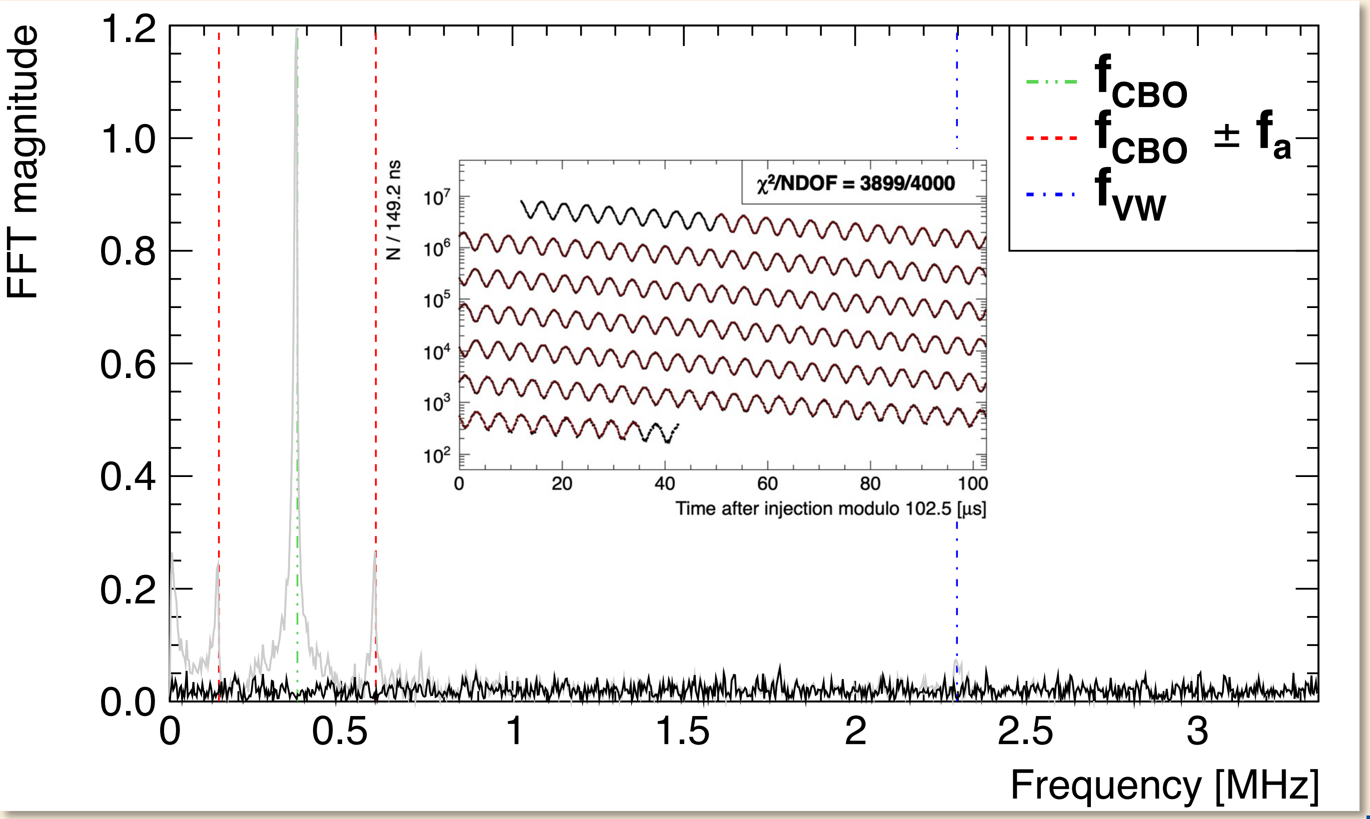




# 21 parameter fit (again)

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





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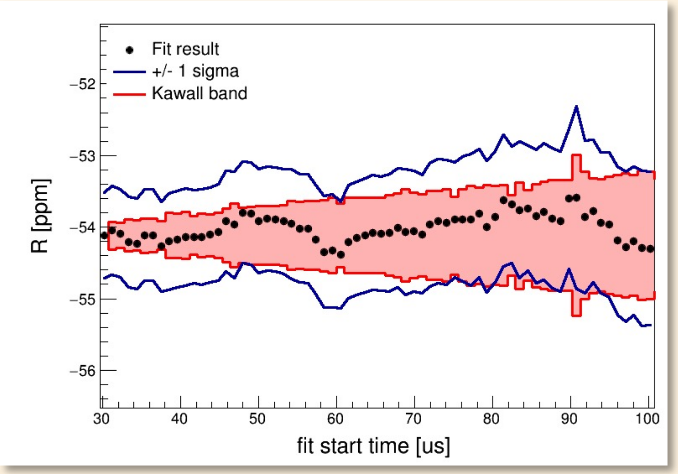
# Checks

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

Fit results should be stable against fit start time

Would show improper modeling of slow effects (e.g. gain)

Excellent stability is observed




Also checked fit is independent of

Calorimeter station

Bunch number

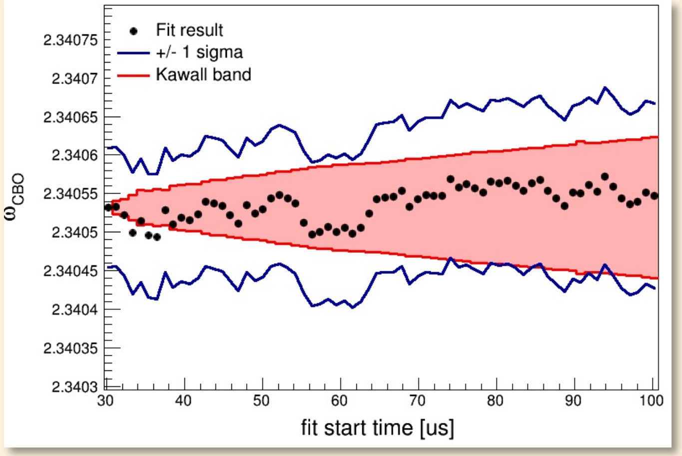
Run number

Time of day

Energy bin

Position within calorimeter

…



# Systematics on $\omega_a^{\text{meas}}$

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

| Dataset | Run-1a | Run-1b | Run-1c | Run-1d |
|---|---|---|---|---|
| Gain (ppb) | 12 | 9 | 9 | 5 |
| Pileup (ppb) | 39 | 42 | 35 | 31 |
| CBO (ppb) | 42 | 49 | 32 | 35 |
| Randomization (ppb) | 15 | 12 | 9 | 7 |
| Early-to-late effect (ppb) | 21 | 21 | 22 | 10 |
| TOTAL (ppb) | 64 | 70 | 54 | 49 |

# Clock blinding

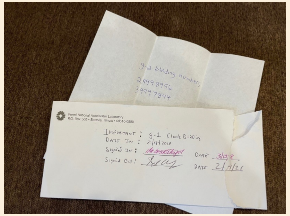
$$\mathcal{R}'_\mu \approx \frac{f_{\text{clock}}\ \omega_a^{\text{meas}}(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Clock detuned $(40 - \epsilon)$ MHz $\pm 25$ ppm

Blinding factor known to only two people outside of collaboration

Checked weekly

Each run is separately blinded



blinding the clock in 2018

Locked Clock Panel

# Beam dynamics corrections

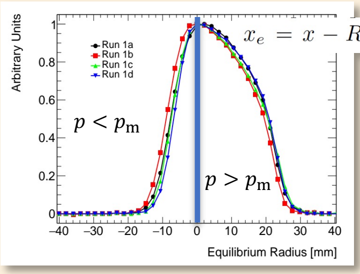
$$\mathcal{R}'_\mu \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

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

## $C_e$ Electric field correction

Muon beam momentum distribution

$$\Delta p/p = (1-n)\frac{x_e}{R_0} \qquad C_e = 2n(1-n)\beta^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$




Mean $x_e$ and width determined by Fourier analysis of the decoherence rate of incoming bunched beam (6mm, 9mm)

$$C_e \sim 450 \text{ ppb}, \delta_{C_e} \sim 50 \text{ ppb}$$

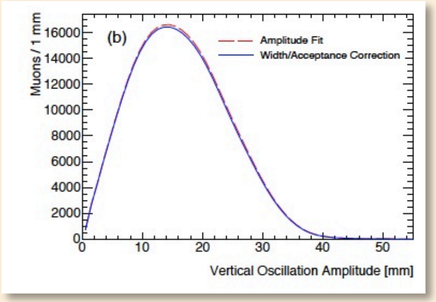
## $C_p$ Pitch correction

From vertical beam oscillations

$$C_p = \frac{n}{4}\frac{\langle A^2 \rangle}{R_0^2}$$

$A$ is vertical oscillation amplitude

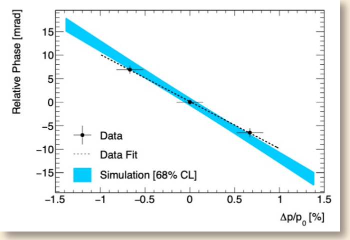
Measure with trackers and average over $\phi$




$$C_p \sim 200 \text{ ppb}, \delta_{C_e} \sim 20 \text{ ppb}$$

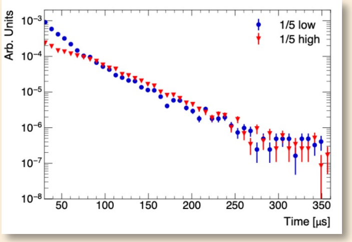
## $C_{ml}$ Muon loss correction

(Muon momentum-phase correlation) + (loss rate depends on momentum) lead to tiny phase shift




Verify phase-$p$ relation with simulation and changing magnet field

DR collimators used to bias $p_\mu$ distribution




$$C_{ml} < 20 \text{ ppb}, \delta_{C_{ml}} \sim 5 \text{ ppb}$$

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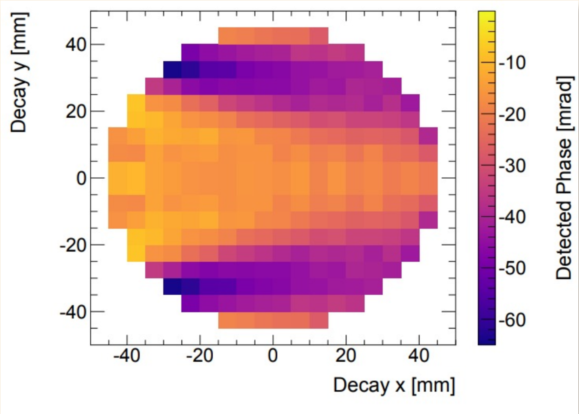
# Phase acceptance correction

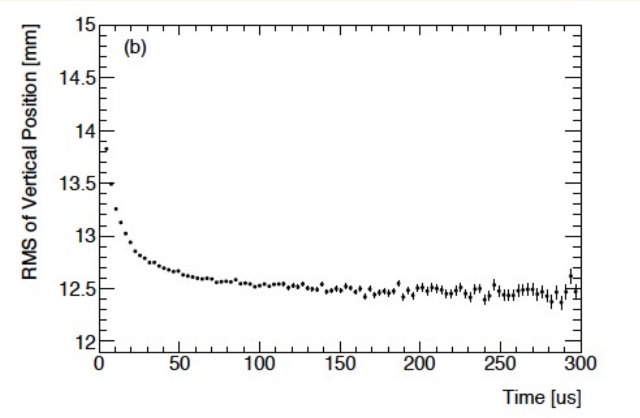
$$\mathcal{R}'_\mu \approx \frac{f_{\text{clock}}\,\omega_a^{\text{meas}}(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\,\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

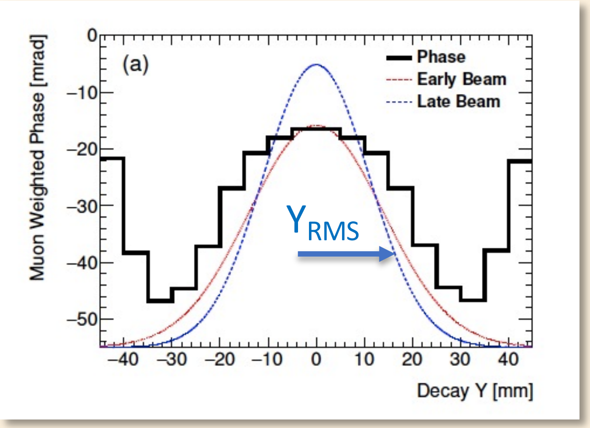
(Beam changing early to late) + (measured phase depending on decay coordinates) lead to...

$$\Delta\omega_a = \frac{d\phi}{dt} = \frac{dY_{\text{rms}}}{dt}\frac{d\phi}{dY_{\text{rms}}} \neq 0$$

Damaged ESQ resistors exacerbated stability of beam distribution




Extensive use of several simulations (Geant, BMAD, COSY) tuned to data from trackers and calorimeters

$\boldsymbol{C_{pa} \sim 200\ \text{ppb},\ \delta_{C_{pa}} \sim 80\ \text{ppb}}$

Fixing resistors for Run 2 should make $C_{pa} < 50$ ppb

# Phase acceptance correction

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

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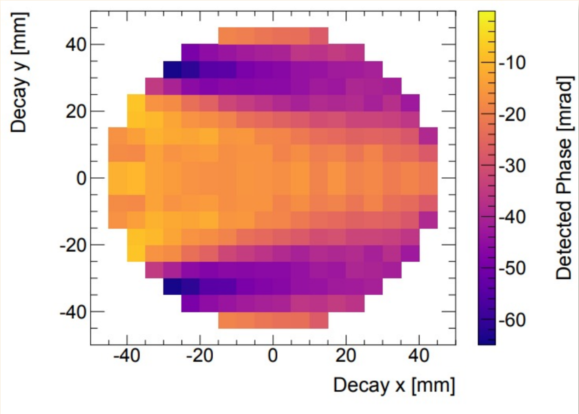


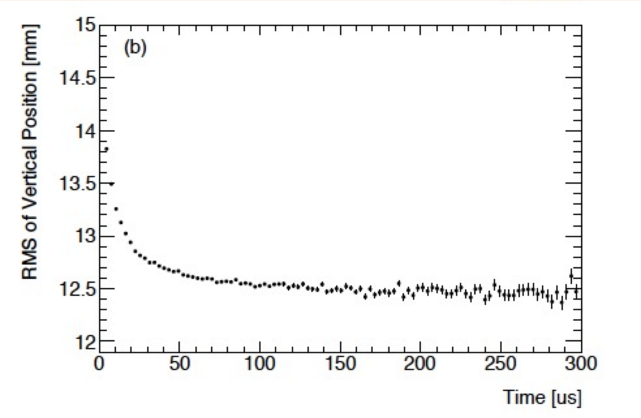


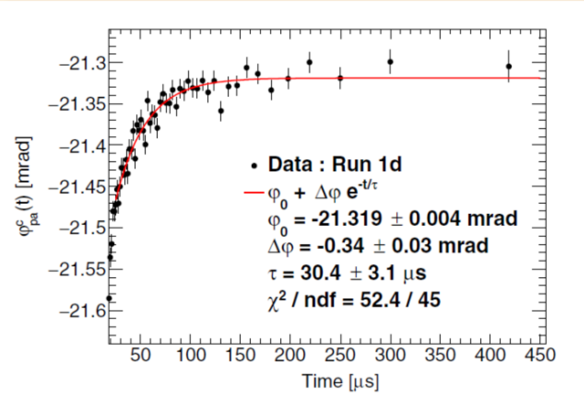


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Fixing resistors for Run 2 should make $C_{pa} < 50$ ppb

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# Measuring the Field (again)

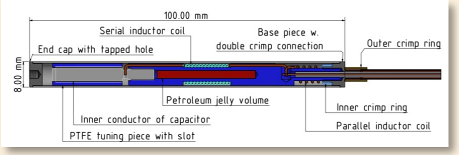
$$\mathcal{R}'_\mu \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib}\, \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

We need to determine $B$ to < 100 ppb

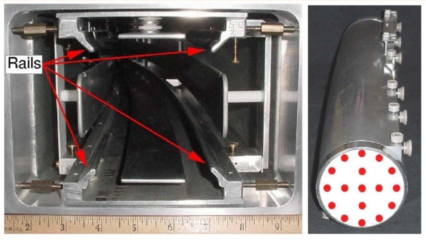
Use NMR probes to measure $B$ in terms of proton precession frequency $\omega_p$

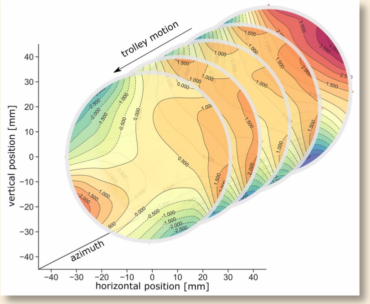
Trolley cross-calibrated to absolute probes
Absolute probes all cross-calibrated in a 1.45 T MRI magnet at Argonne National Laboratory

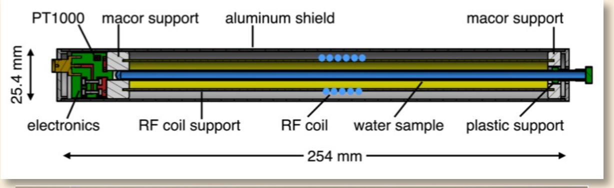
378 fixed probes monitored 24/7

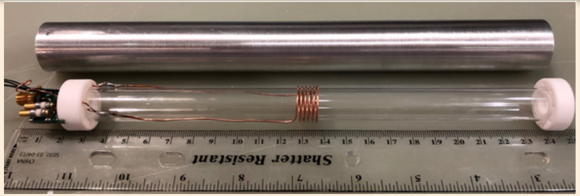



Trolley maps field every 3 days







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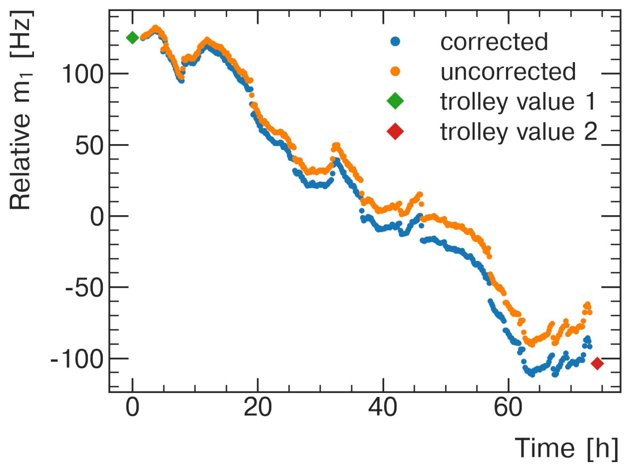
# Field Measurement

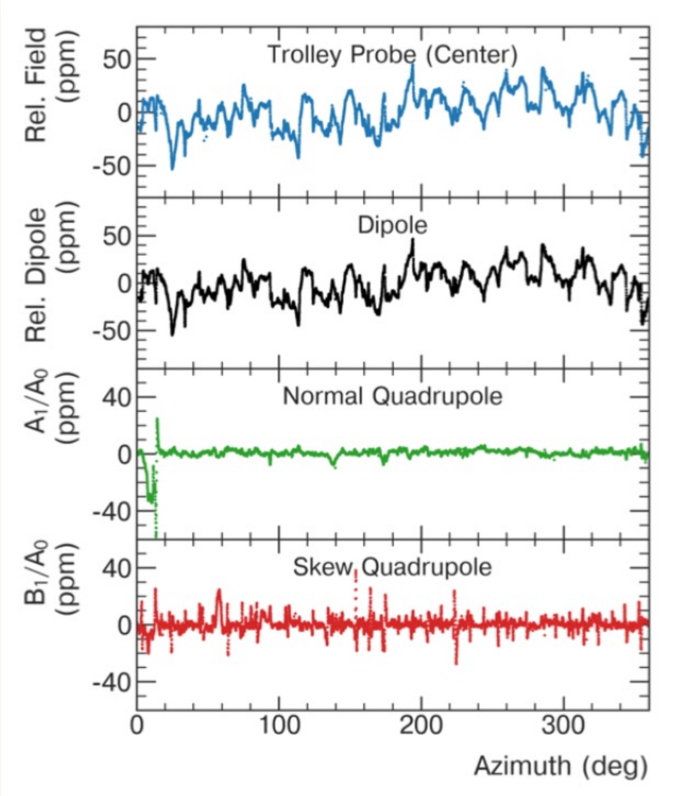
$$\mathcal{R}'_\mu \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} (1 + C_e + C_p + C_{ml} + C_{pa})}{\boldsymbol{f_{calib}} \,\langle \boldsymbol{\omega'_p(x,y,\phi) \times M(x,y,\phi)} \rangle (1 + B_k + B_q)}$$

Trolley maps magnetic field in storage region at about 9000 locations over the entire azimuth every 3 days

Fixed probes track field in between trolley runs

Correct with random walk (Brownian bridge) model



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# Muon weighting

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

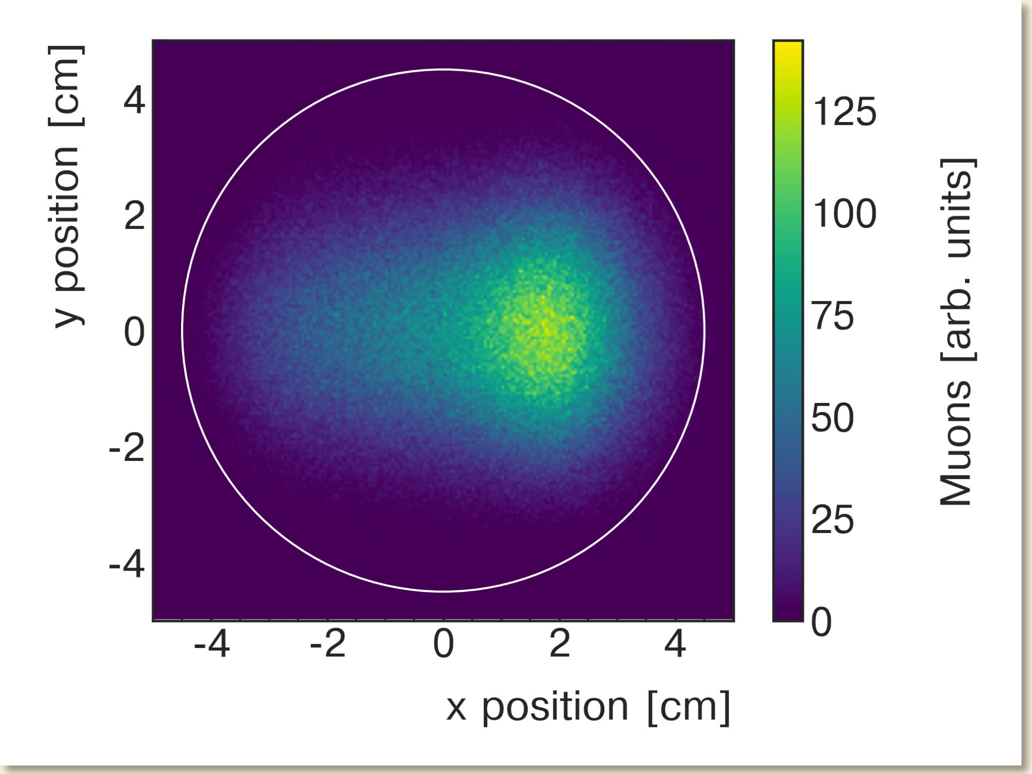
Beam moments are estimated with the trackers

Interpolated field maps averaged over 10s periods and weighted by number of detected positrons

Field and beam moments folded on scale of three hours

Uncertainties from probe calibrations, field maps, tracker alignment and acceptance, calorimeter acceptance, and beam dynamics modeling

$$\delta_{\tilde{\omega}'_p} \sim 56 \text{ ppb}$$

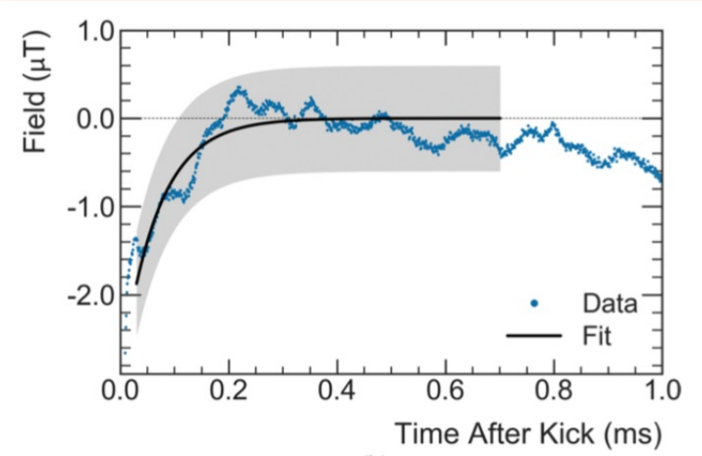


# Kicker transient field

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

150 ns ~ 200 G kicker pulse produces eddy currents; NMR probes shielded by vacuum chamber wall; Kicker off for trolley runs

Installed a Faraday magnetometer to measure field




Fit to exponential for fill fit time

$$B_K \sim 30\ \text{ppb}, \delta_{B_K} \sim 40\ \text{ppb}$$

# ESQ transient field

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

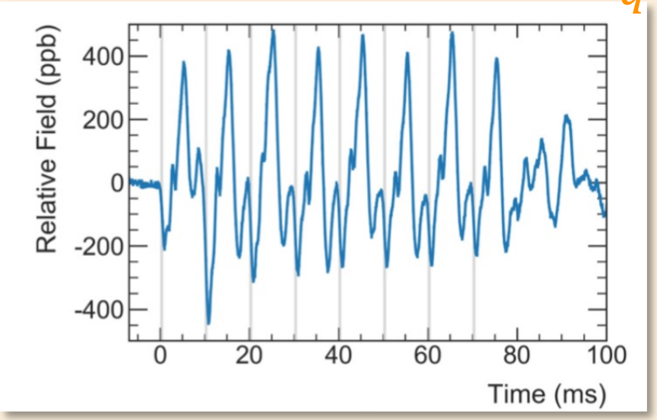
Pulsing quads introduces mechanical vibrations
Oscillating conductor perturbs field

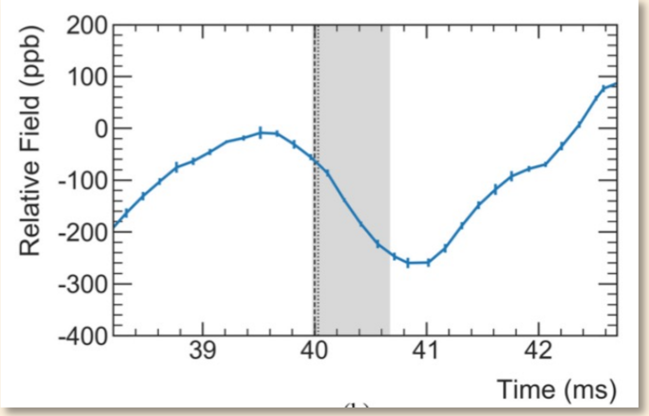
Built special NMR probes to map the effect

Averaged over 8 bunches and over 43% of ring with Quad coverage

$$B_q \sim 17\ \text{ppb}, \delta_{B_K} \sim 92\ \text{ppb}$$

Uncertainty dominated by incomplete map
Expect to reduce x2-3 for Run 2 and after



# Corrections & Uncertainties

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

| Quantity | Correction terms (ppb) | Uncertainty (ppb) |
| --- | --- | --- |
| $\omega_a^m$ (statistical) | ⋯ | 434 |
| $\omega_a^m$ (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 |
| $\mu'_p(34.7°)/\mu_e$ | ⋯ | 10 |
| $m_\mu/m_e$ | ⋯ | 22 |
| $g_e/2$ | ⋯ | 0 |
| Total systematic | ⋯ | 157 |
| Total fundamental factors | ⋯ | 25 |
| Totals | 544 | 462 |

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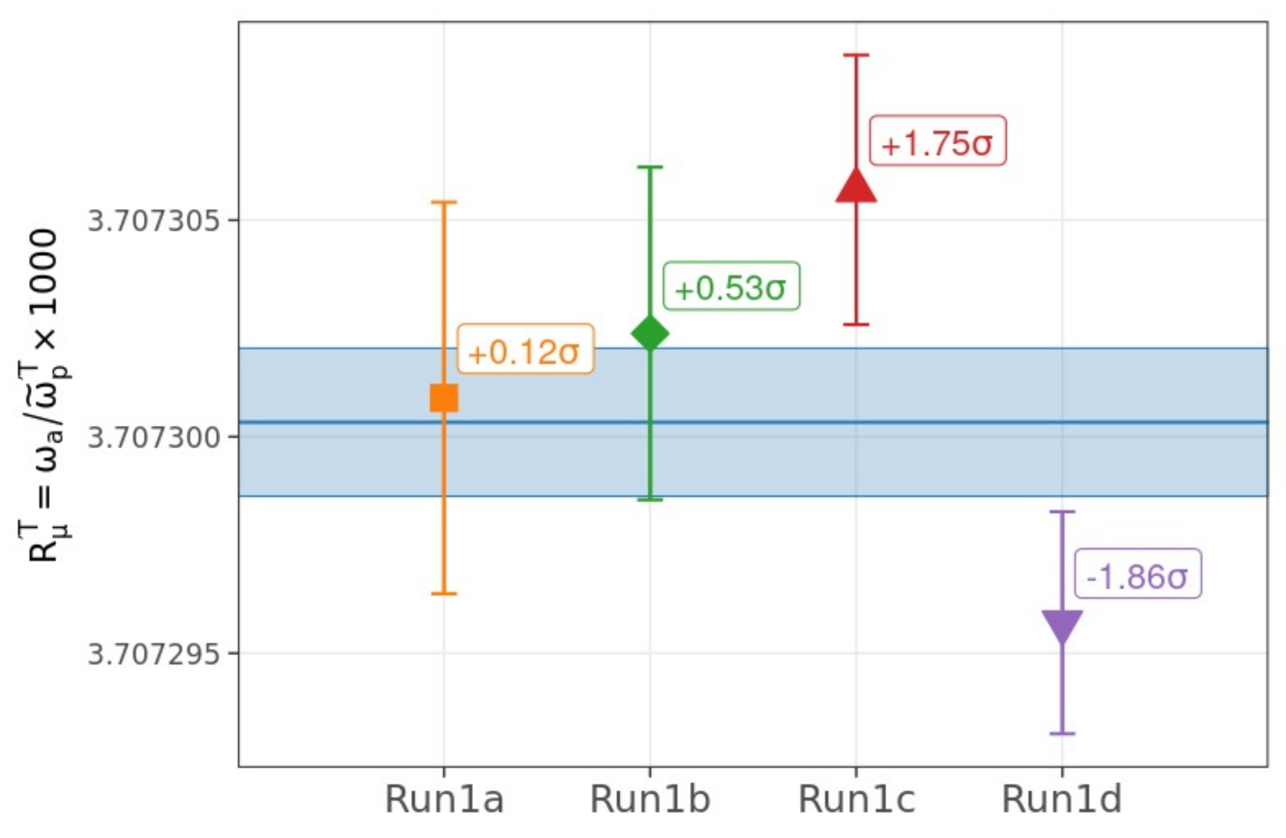
# Blinded results

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




$\chi^2$/ndf=6.8/3

P($\chi^2$)=7.8%

Statistical uncertainties dominate, so measurements are largely uncorrelated



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# Are we ready to unblind (February 25, 2021)?

# Like landing successfully on Mars



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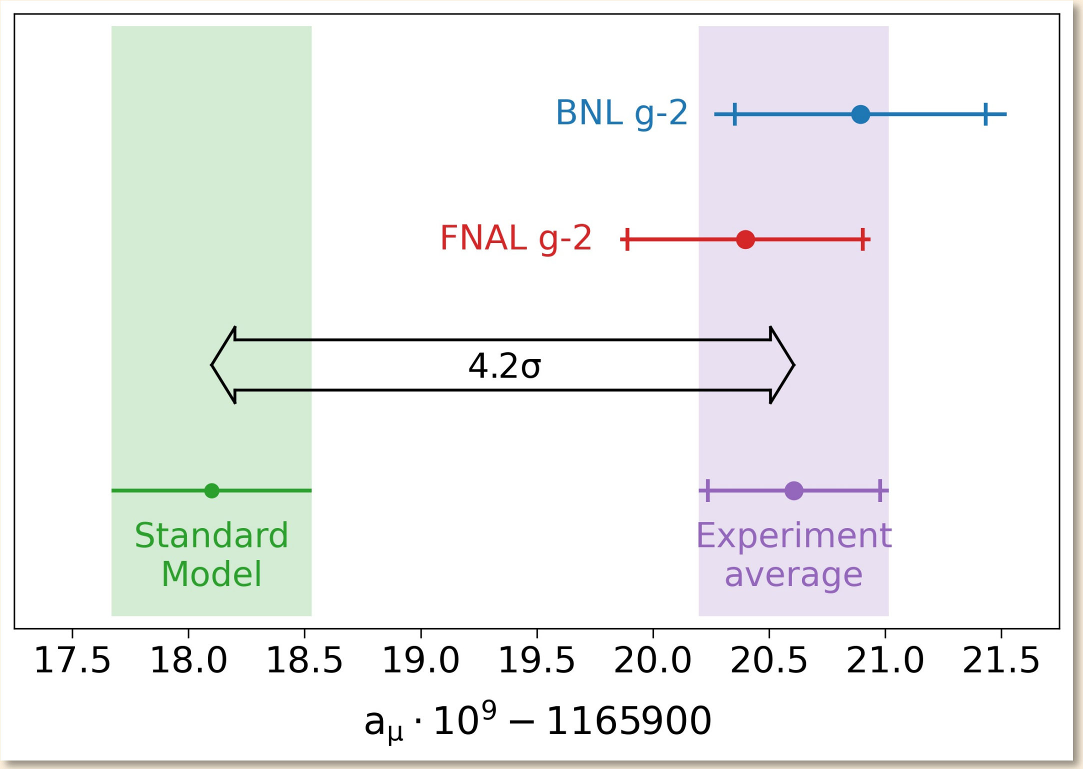
# The result and comparison to SM (Announced April 7, 2021)




BNL: 540 ppb

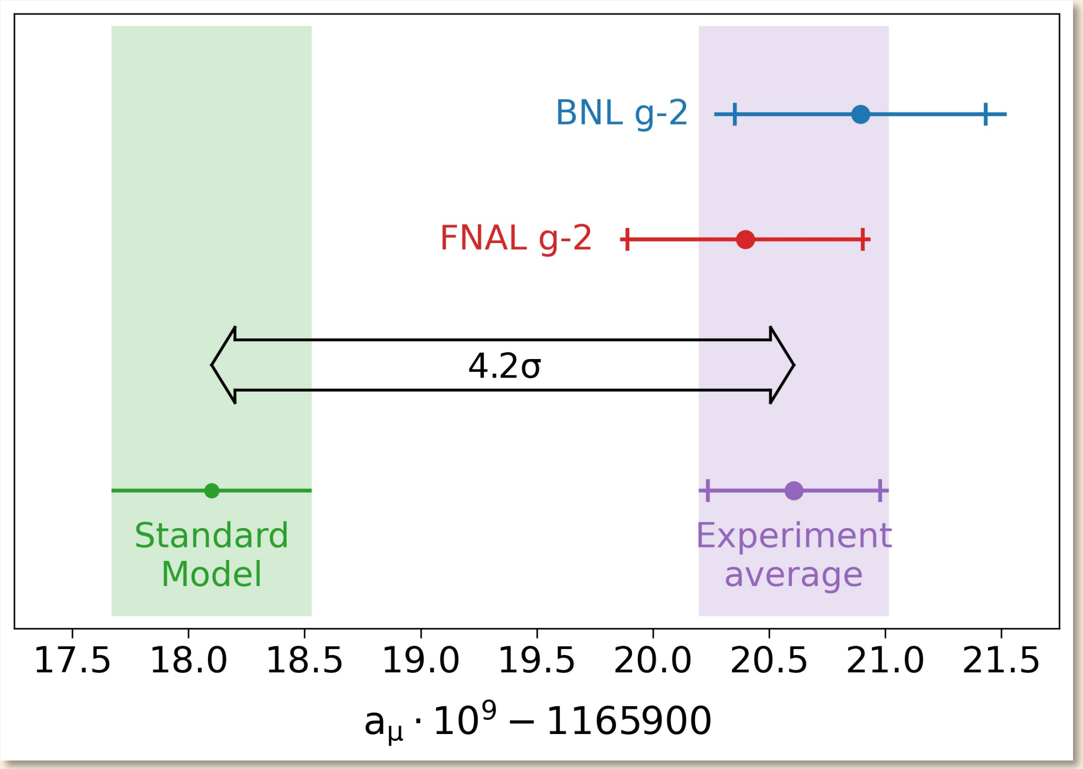
Couldn't find anything needing change

Are we independent?

- New beamline (higher purity)
- New calorimeters (segmented)
- Better shimmed field
- New trackers
- New kickers
- New field metrology
- More powerful simulations
- New people

Analyses are like BNL, but no problems found in past 20 years

# The result and comparison to SM




## FNAL Run 1

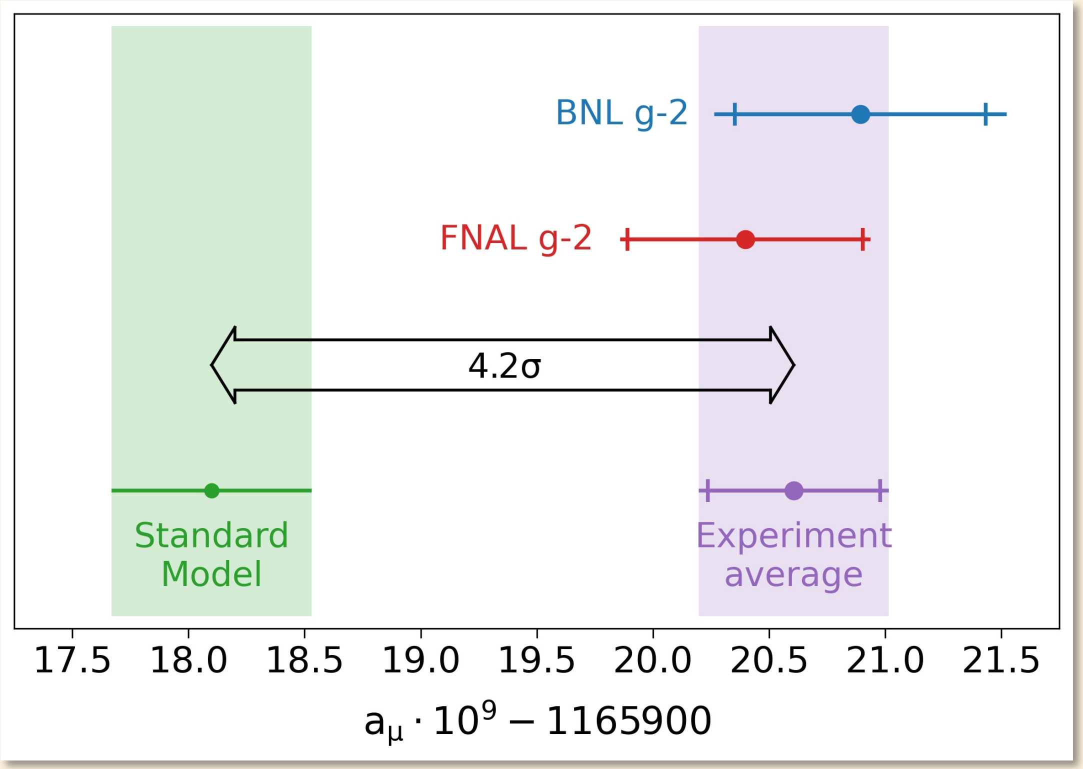
$a_\mu = 116\,592\,040(54)\times10^{-11}$ (462 ppb)

Statistical: 434 ppb

Systematic: 157 ppb

Good agreement with BNL
(FNAL 15% smaller uncertainty)

# The result and comparison to SM




## Combined Experiment

$a_\mu = 116\,592\,061(41)\times10^{-11}$ (350 ppb)

$a_\mu(\text{exp}) - a_\mu(\text{SM}) = 0.000\,000\,002\,51(59)$

## Significance of tension is $4.2\sigma$

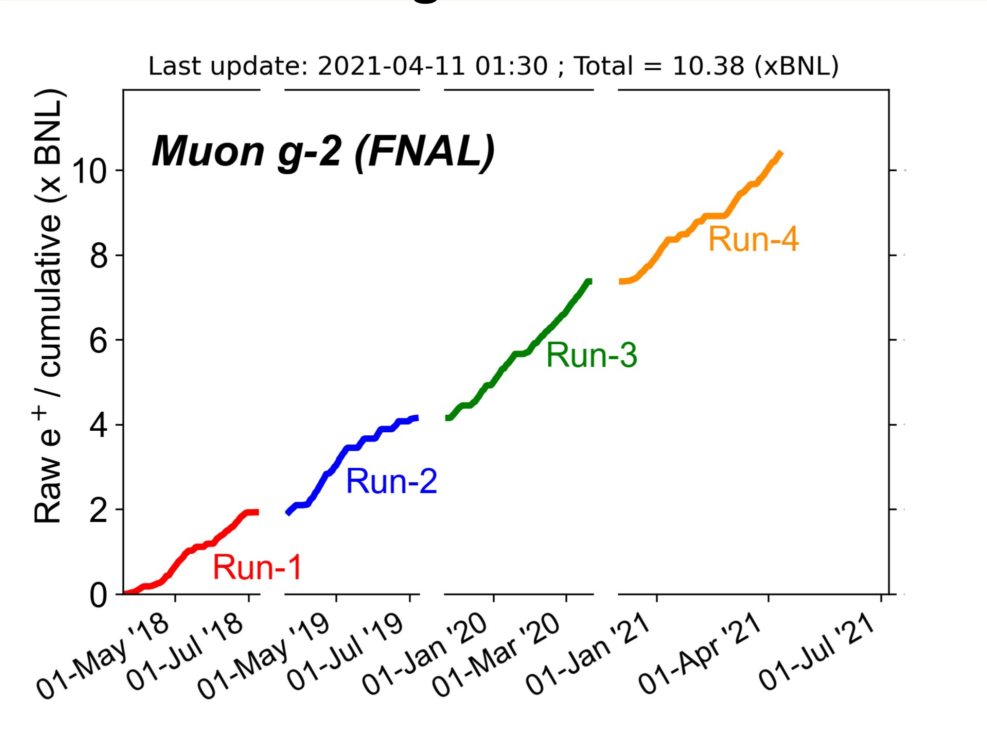
Individual tensions with SM

BNL: $3.7\sigma$

FNAL: $3.3\sigma$

# Outlook

## Data we have right now




Run 1 is 6% of full dataset

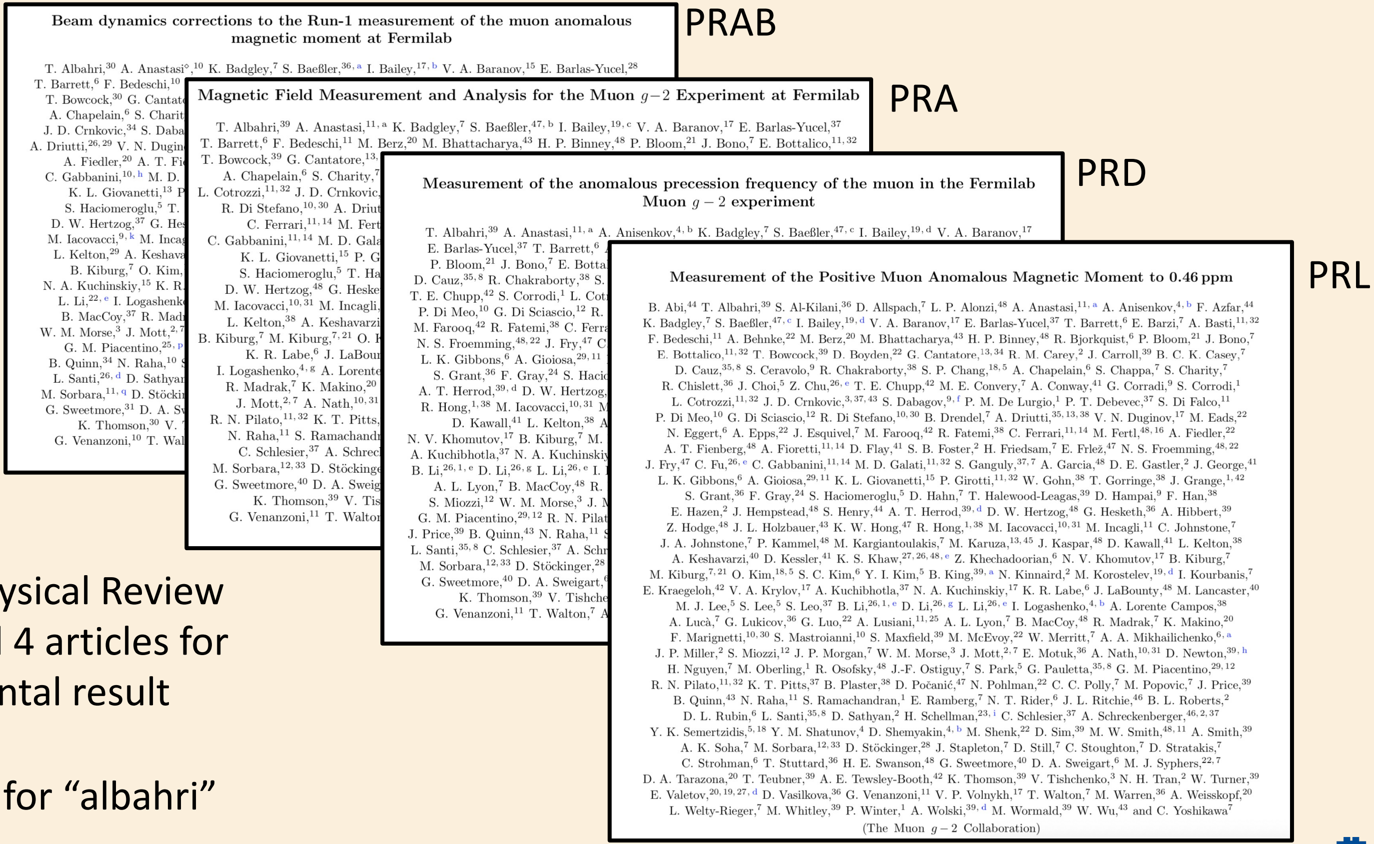
Plan to publish Runs 2+3 Summer 2022
Reduce uncertainty x2
Systematics on track < 100 ppb
Lots of Run 1 problems fixed

We're taking Run 4 now

Planning to reach 20xBNL and yet another 2x reduction in uncertainty

Expect a lot of activity in the Muon g-2 theory initiative too

# Read all about it!




First time Physical Review co-published 4 articles for an experimental result

Search arXiv for “albahri”

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