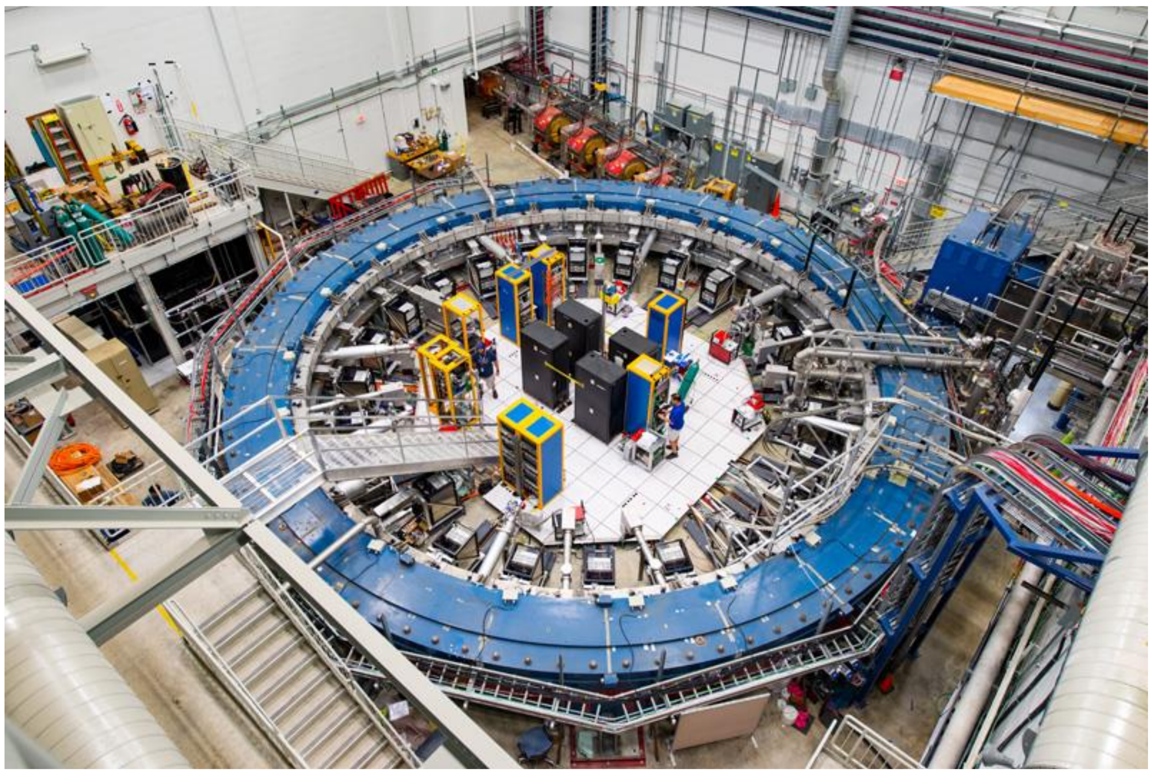
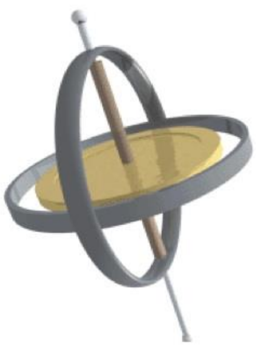
“缪子束加速和对撞技术及应用”科学与技术前沿论坛

Muon g-2实验进展和展望





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

$$a = \frac{g-2}{2}$$

李亮

上海交通大学

Muon g-2 Collaboration

US Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Northern Illinois
- Regis
- Virginia
- Washington

US National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden

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

Korea
- CAPP/ISB
- KAIST

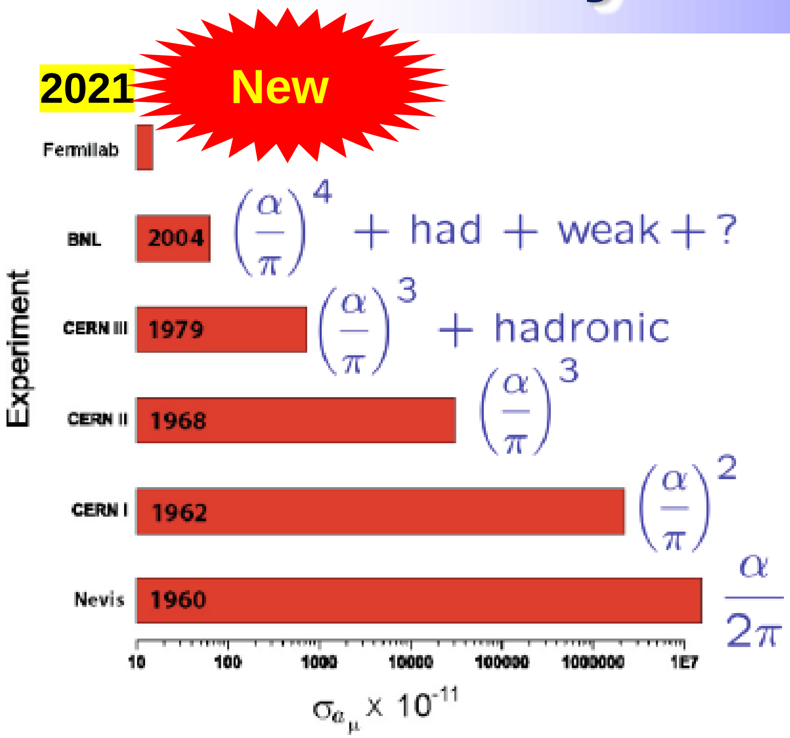
Russia
- Budker/Novosibirsk
- JINR Dubna

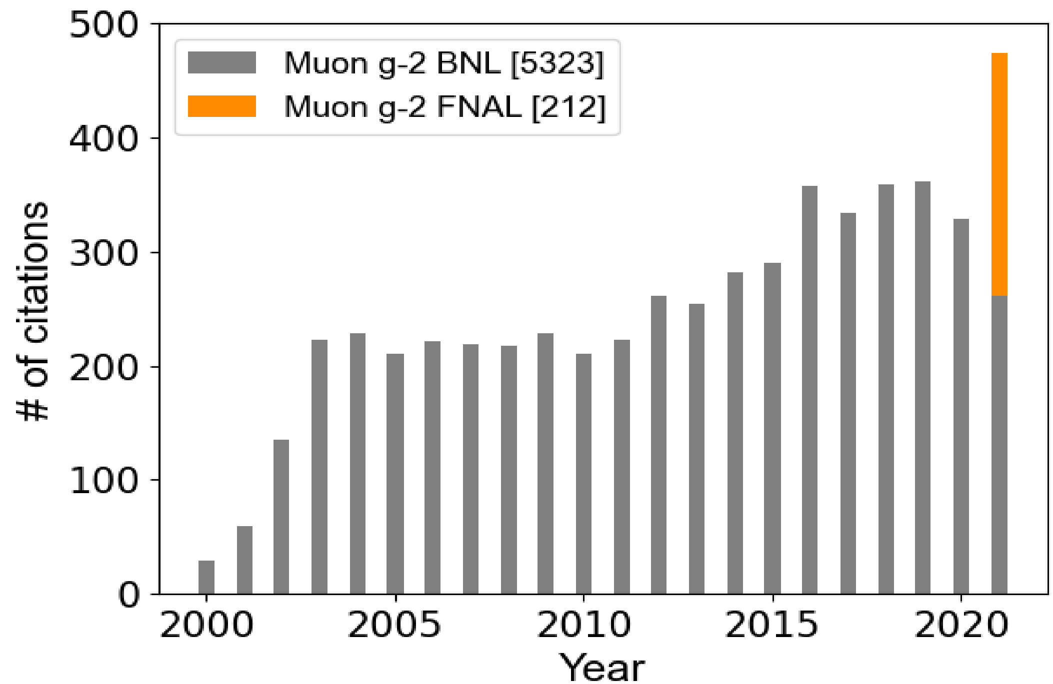
United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

May 27-31, 2019
Elba Collaboration Meeting

上海交大为第三大合作单位
- **7个国家，35个 合作单位**
- **190合作者**

History of Muon g-2 Experiment





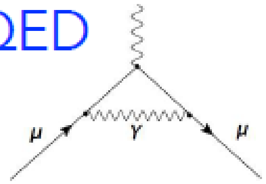
Over 50 years of non-stopping improvement on δa_μ

- **Pushing both theoretical and experimental frontend**
- **Last measurement from BNL E821 (2004) came with 0.54ppm**
- **New muon g-2 experiment at Fermilab aiming at 0.14ppm**
- **Very exciting and highly expected measurement!**

Muon g-2 Theory Initiative

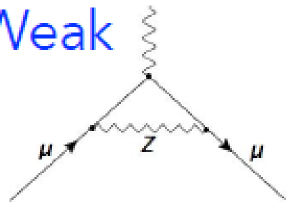
$$a_\mu = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$

QED



$+\ldots$ $116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

Weak

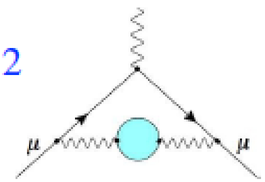


$+\ldots$ $153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

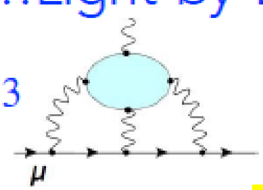
α^2



$+\ldots$ $6845\,(40) \times 10^{-11}$ [0.6%] 0.37 ppm

…Light-by-Light (HLbL)

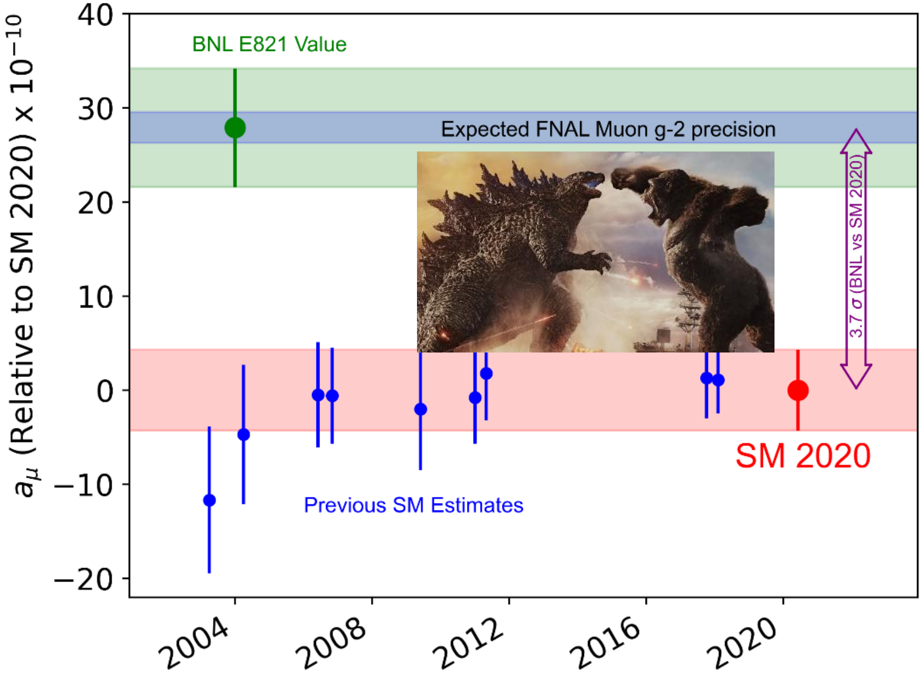
α^3



$+\ldots$ $92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

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

Muon g-2 Experiment vs. Theory



Large difference between theory prediction and experimental value

- **Strong hint of BSM physics**
- **With improvements in theory calculation and experiment measurements, muon g-2 as a fundamental property can serve as a benchmark test for any new physics, such as dark matter, SUSY…**
- **Or even “Unknown Monsters”!**

Experimental Principle

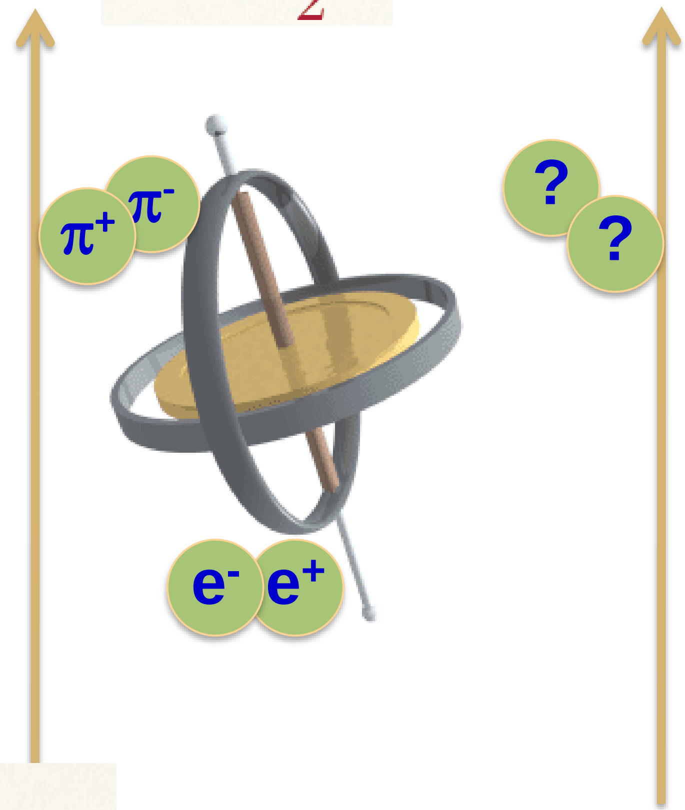
$$a = \frac{g-2}{2}$$

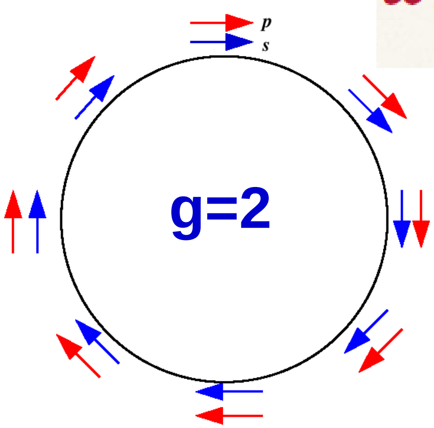
The name of game: a → ω

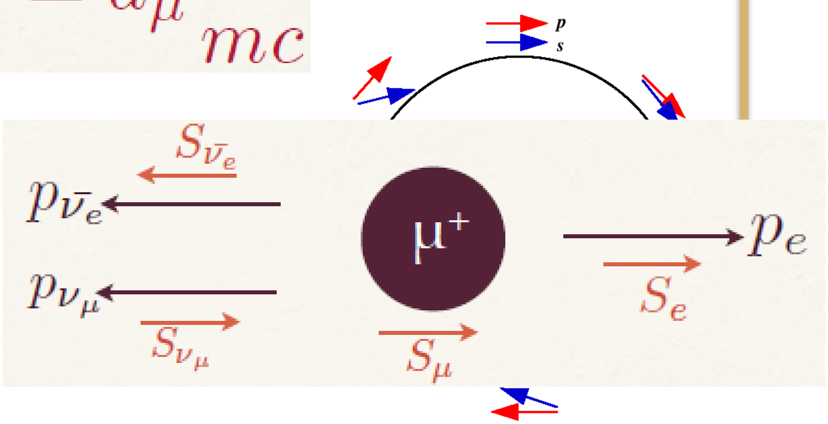
- **Put (polarized) muons in a magnetic field and measure precession f.q.**
- **Get muon spin direction from decayed electrons**
- **a_μ ~ difference between precession frequency and cyclotron frequency**

$$\omega_a = \omega_s - \omega_c$$

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







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

Frequency Measurements

Frequency measurements can be done in very high precision

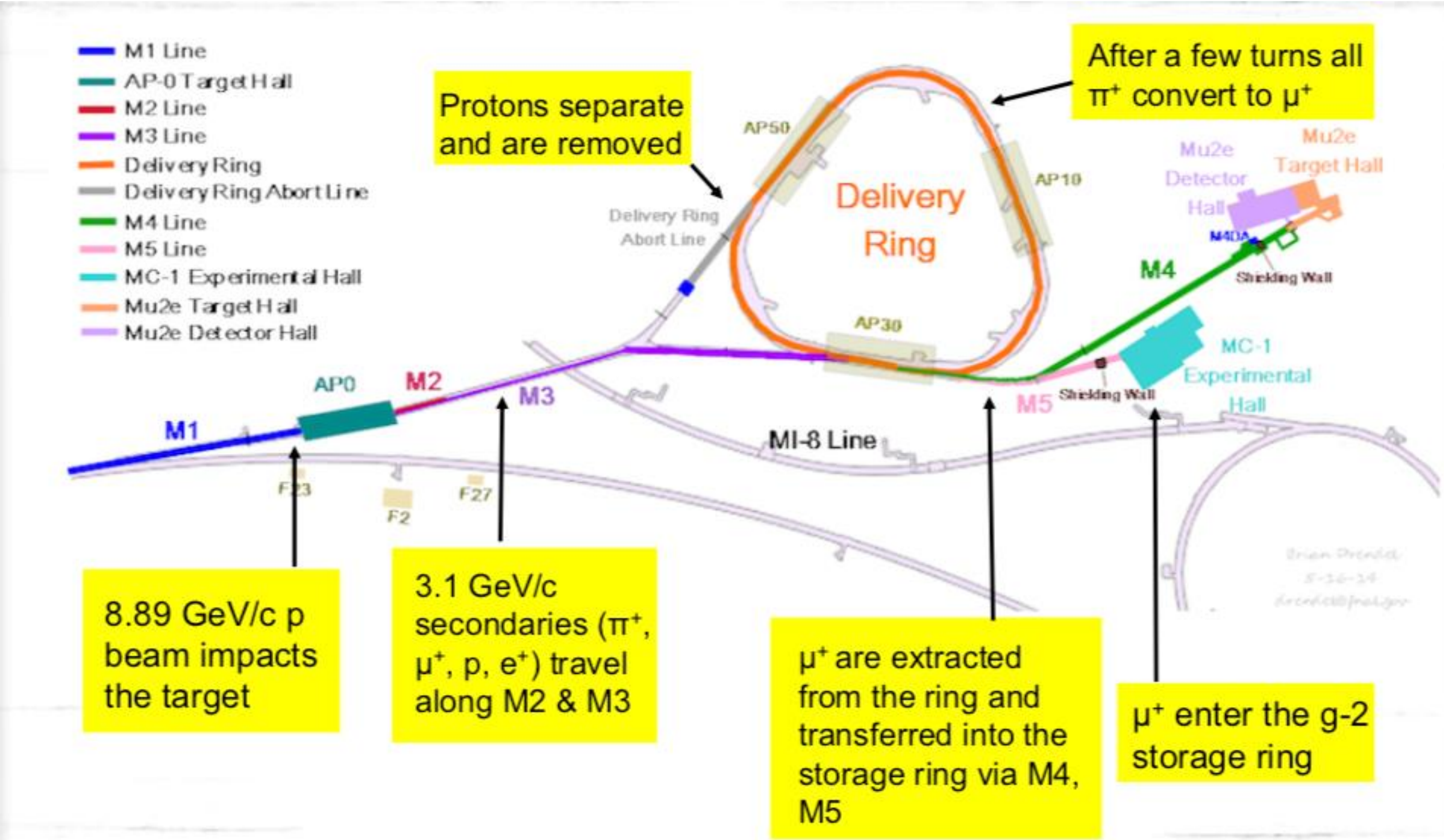
- **Measure frequency ratio and extract from several measurements**

$$a_\mu \sim \frac{\omega_a}{<B>} = \frac{g_e}{2}\frac{\omega_a}{\varpi_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

  - **ω_p is the proton precession frequency (ω_p ~ |B|)**
  - **ϖ_p is the weighted magnetic field folded with muon distribution**
  - **All other values from Committee on Data for Science and Technology (CODATA), uncertainty < 25 ppb**
    - **E.g. muon-to-electron mass ratio by muonium hyperfine structure experiment**
- **Final measurements done in three steps**
  - **Inject muons into a ring with uniform magnetic field**
  - **Measure muon frequency difference ω_a**
  - **Measure proton precession frequency ω_p and muon distribution**
  - **Blind analyses: measurements and correction factors done *before* simultaneously and independently *before* final answer**

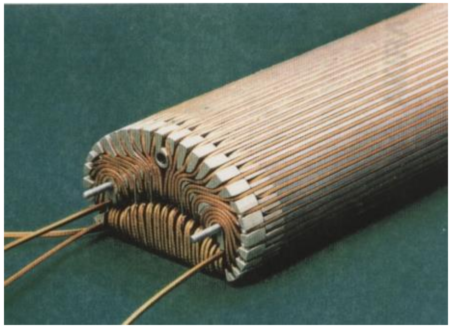
Muon Campus

Muon Campus

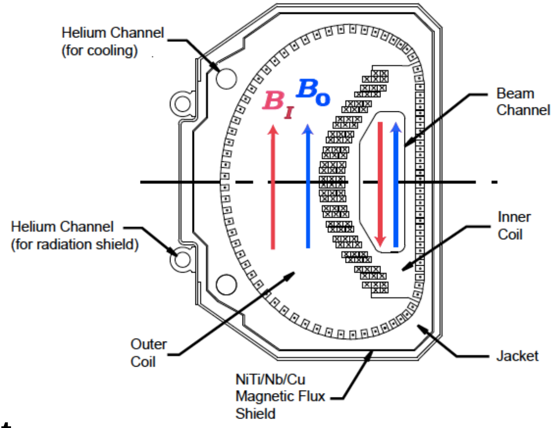


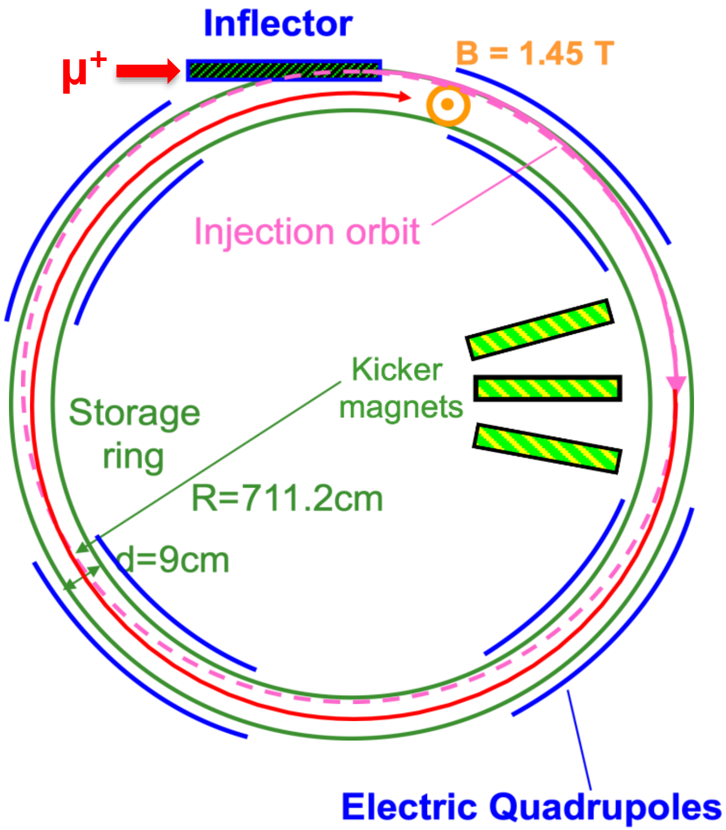
M1 Line
AP-0 Target Hall
M2 Line
M3 Line
Delivery Ring
Delivery Ring Abort Line
M4 Line
M5 Line
MC-1 Experimental Hall
Mu2e Target Hall
Mu2e Detector Hall
Protons separate and are removed
After a few turns all π⁺ convert to μ⁺
Delivery Ring
AP50
AP10
AP30
Delivery Ring Abort Line
Mu2e Detector Hall
Mu2e Target Hall
M4
Shielding Wall
MC-1 Experimental Hall
M5
Shielding Wall
AP0
M2
M3
M1
MI-8 Line
F23
F2
F27
8.89 GeV/c p beam impacts the target
3.1 GeV/c secondaries (π⁺, μ⁺, p, e⁺) travel along M2 & M3
μ⁺ are extracted from the ring and transferred into the storage ring via M4, M5
μ⁺ enter the g-2 storage ring

Muon Injection and Storage System



Truncated double cosine theta superconducting septum magnet

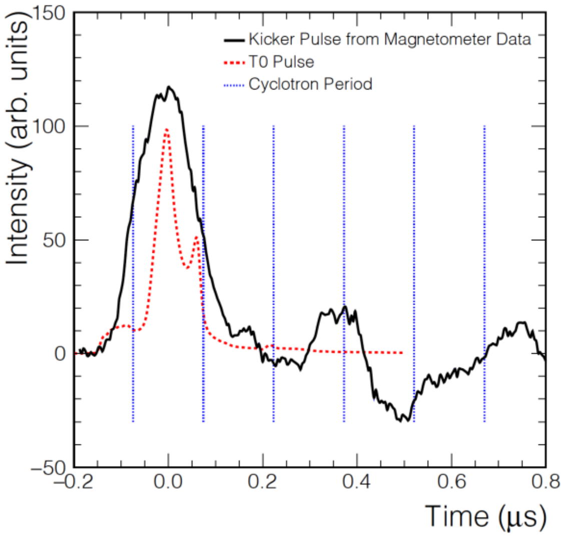


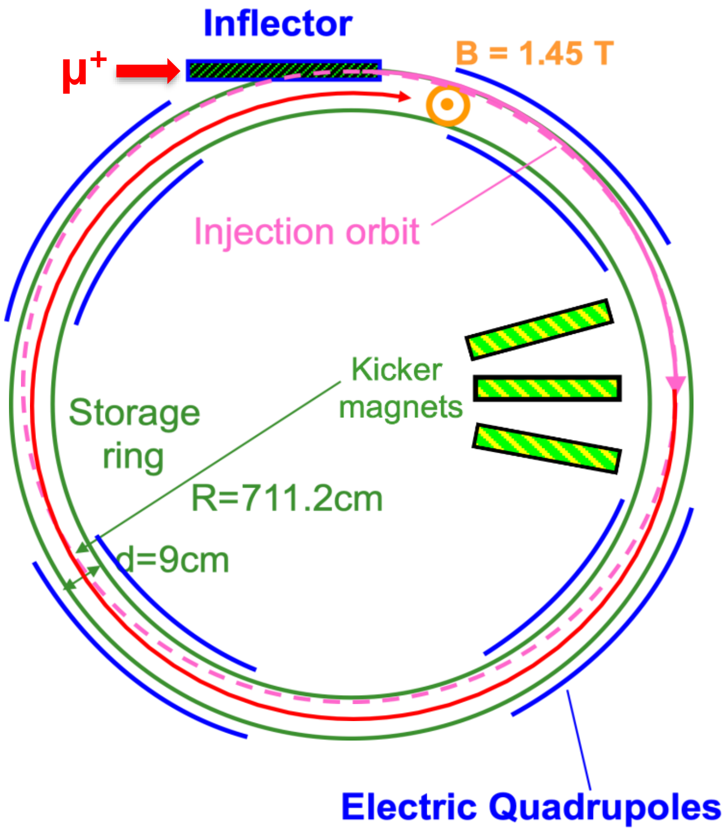


Superconducting inflector

- Provides nearly field free region for muons to enter the ring
- Beam injected through magnet windings
- Does NOT perturb main precision field

Muon Injection and Storage System

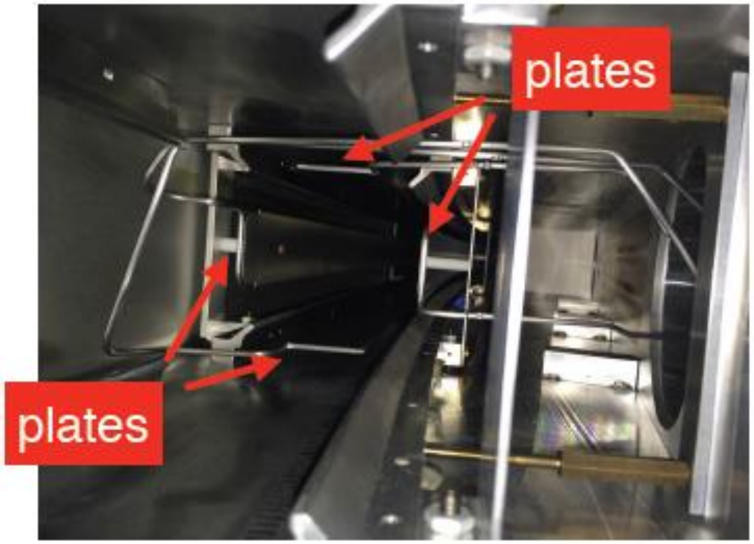


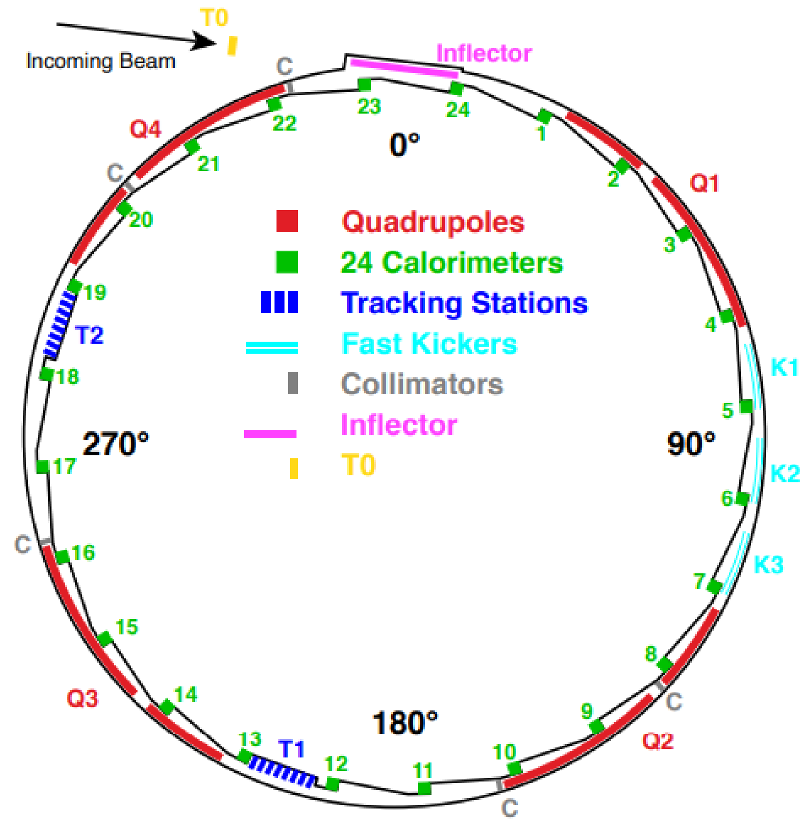


Pulsed fast magnetic kickers

- Direct muons onto storage orbit (~10 mrad)
- 1-turn pulsed magnet (~200 G)

Muon Injection and Storage System

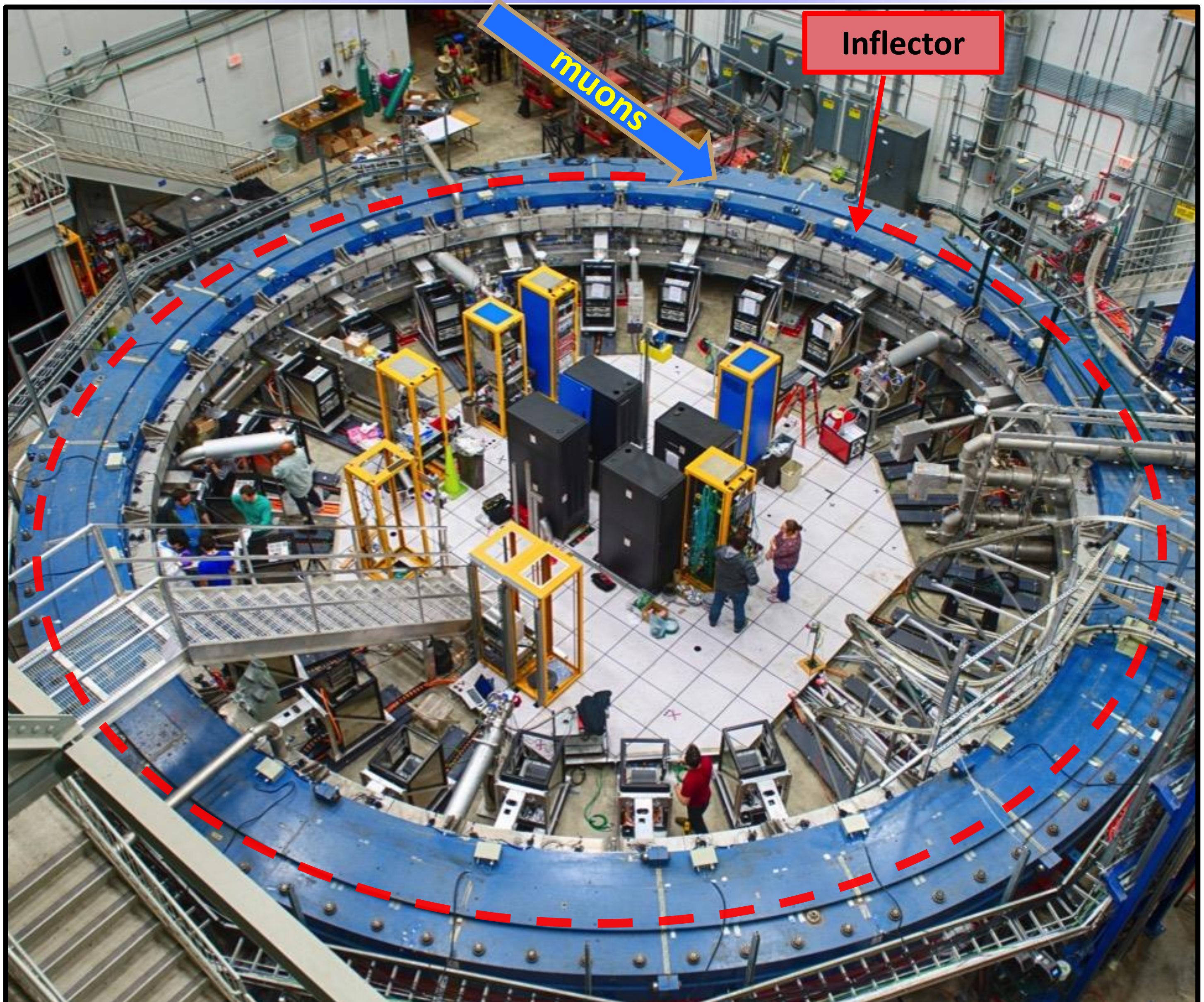




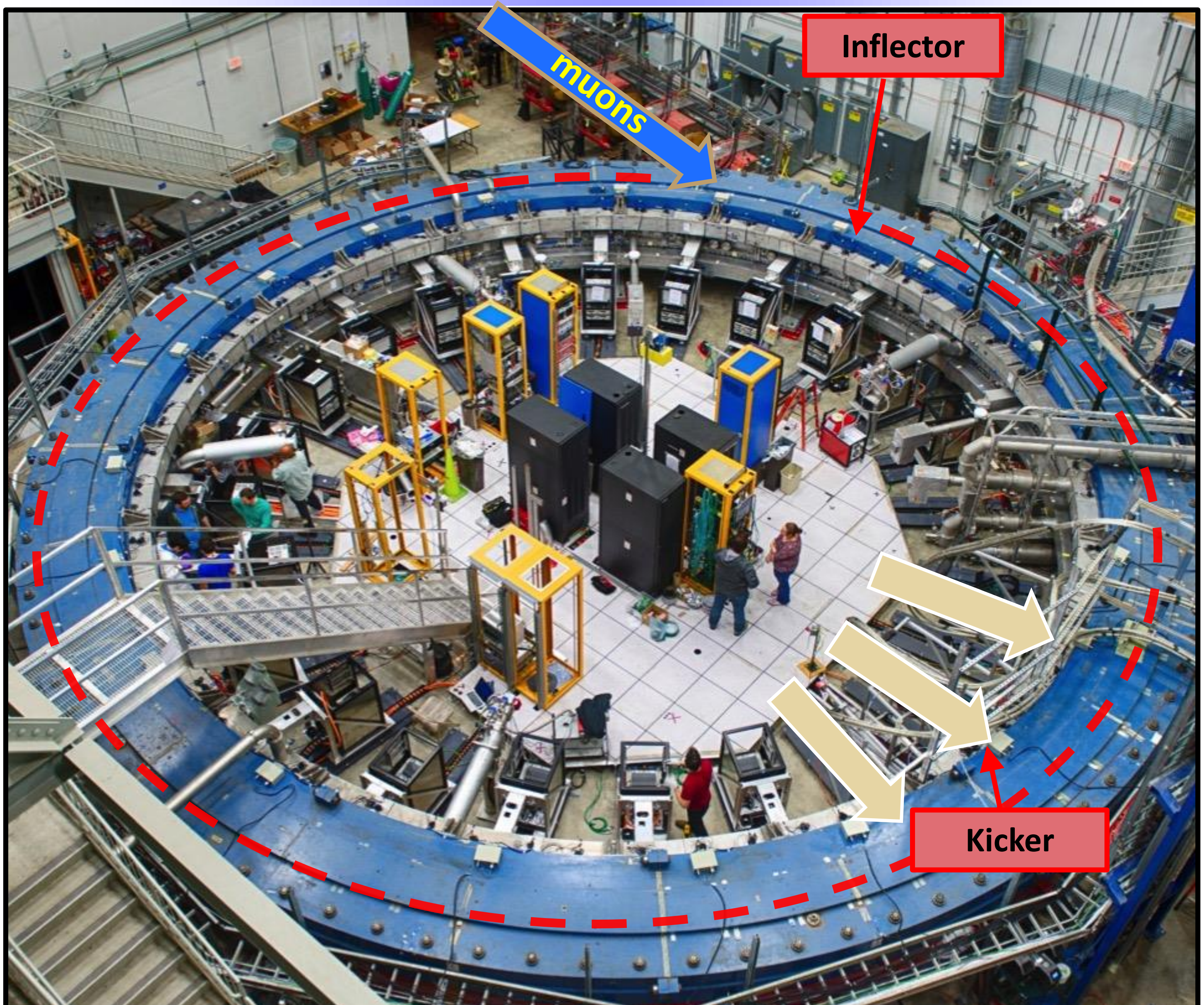
Pulsed electric quadrupoles

- Vertical beam confinement
- Pulsed HV power source
- Operates at ± 18-20 *KV*

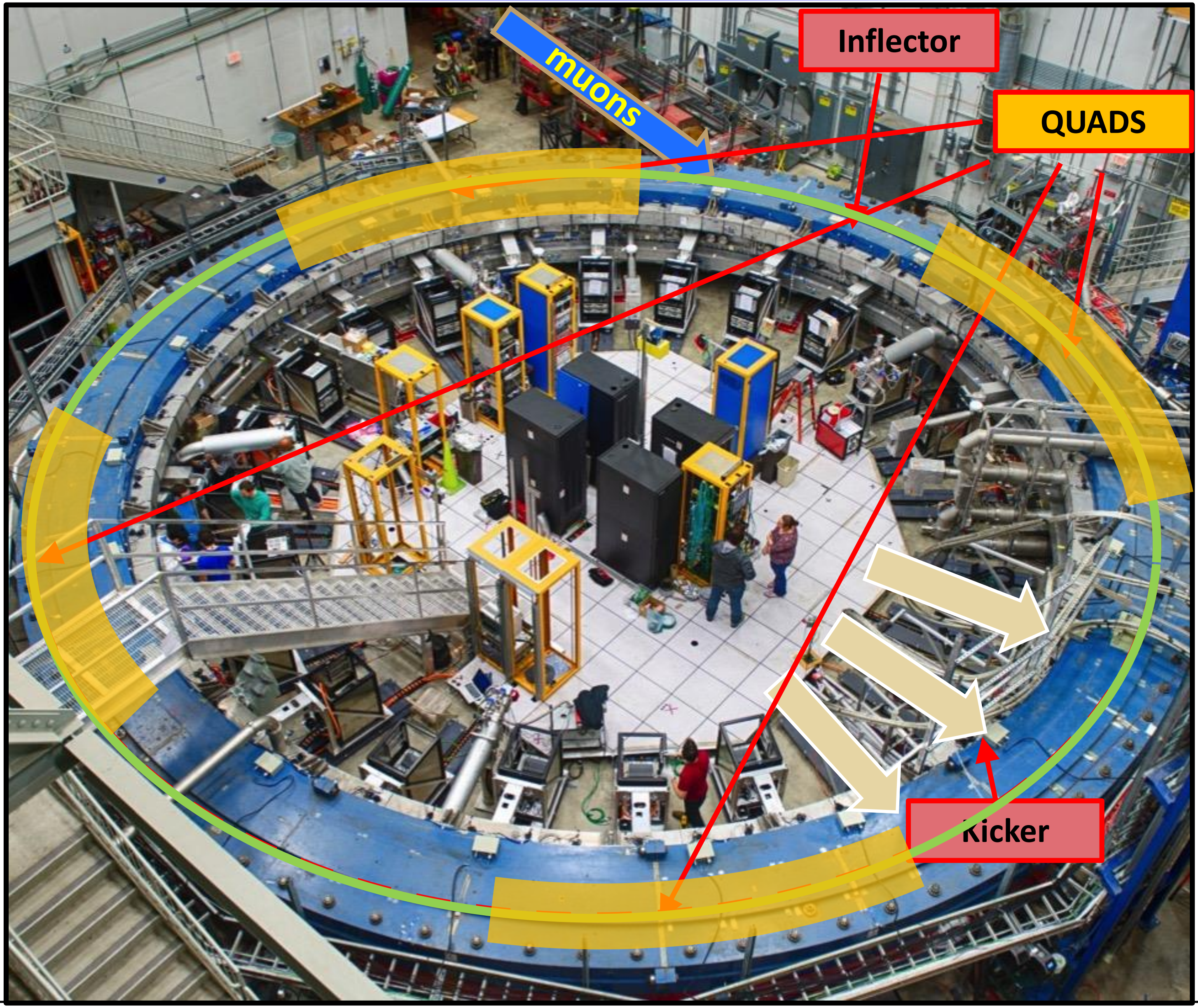
Injection into muon storage ring



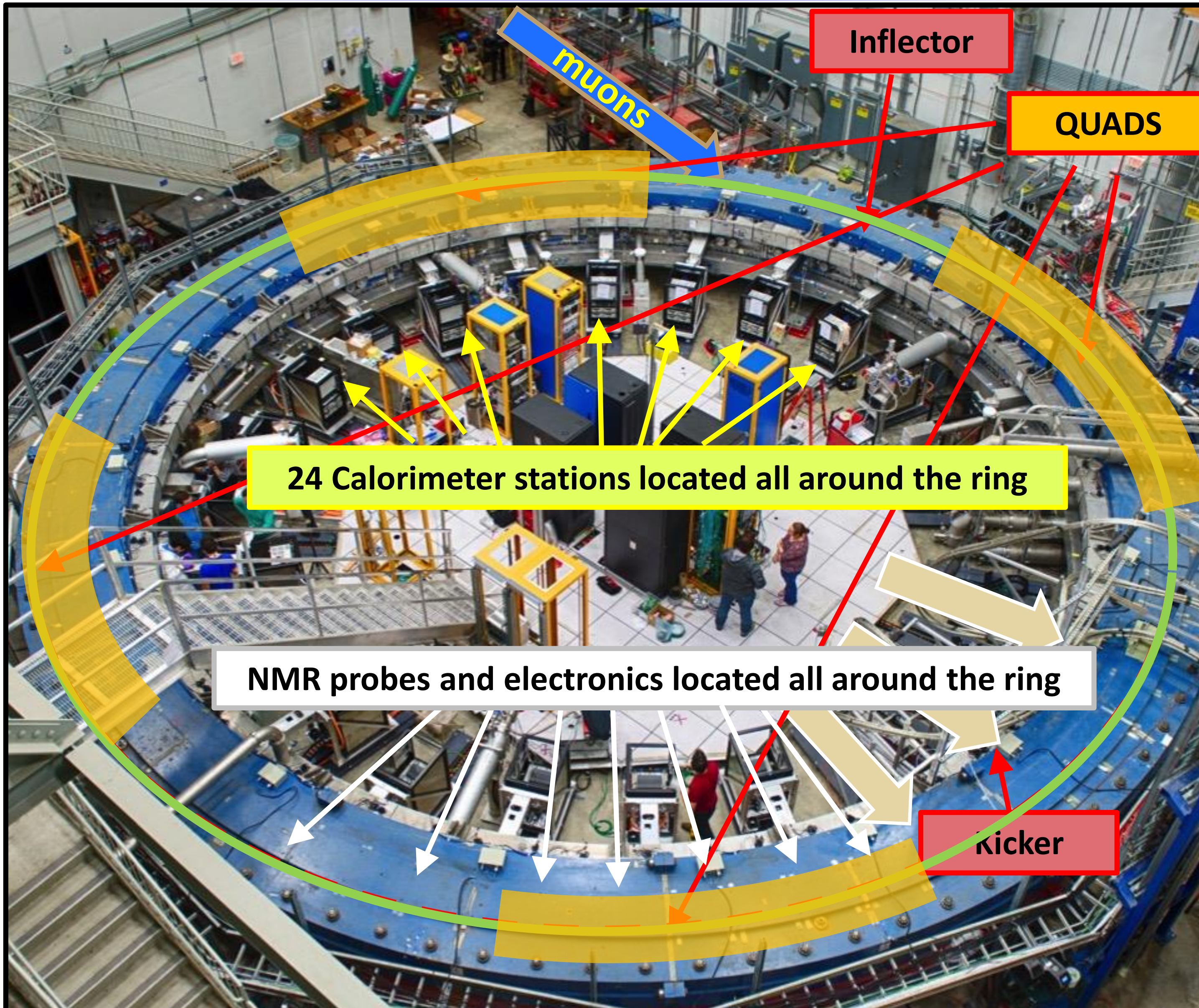
Injection into muon storage ring



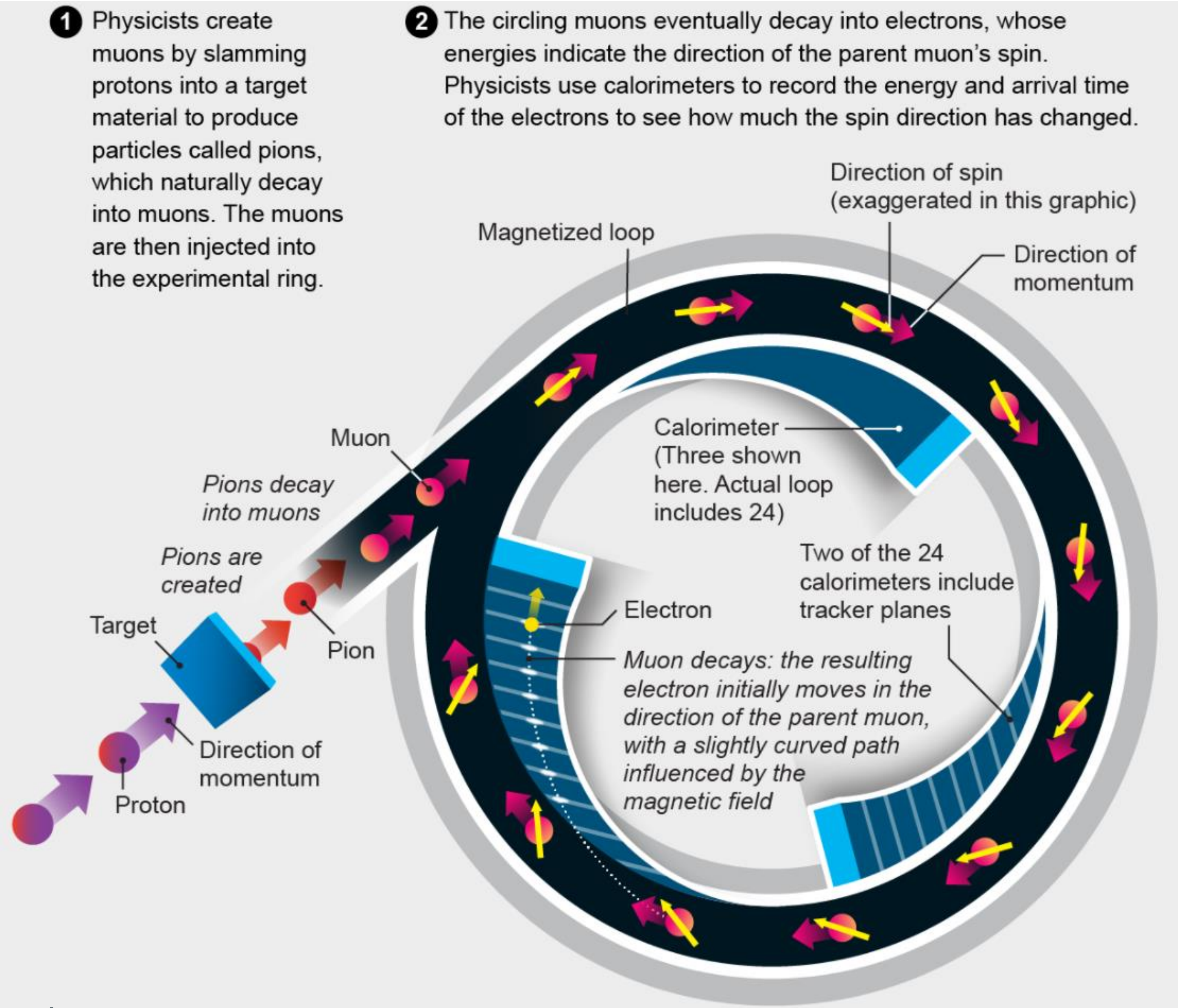
Injection into muon storage ring



Injection into muon storage ring

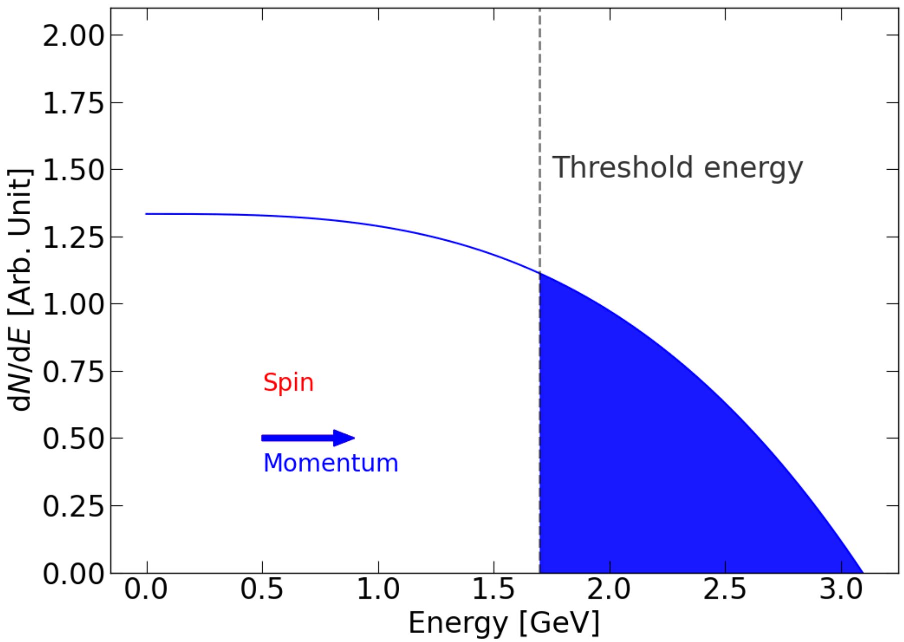


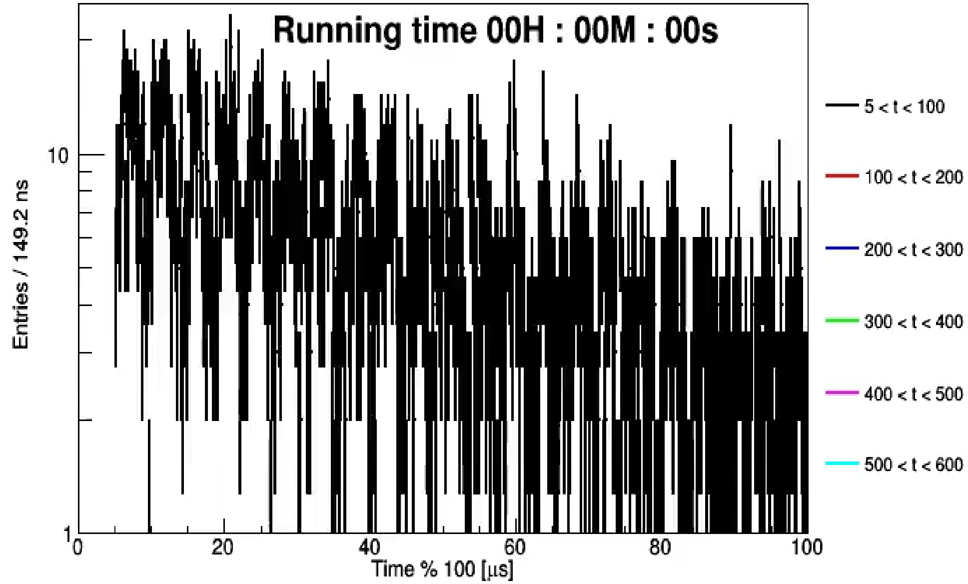
Experimental Setup



Maria Corte

Measuring ω_a



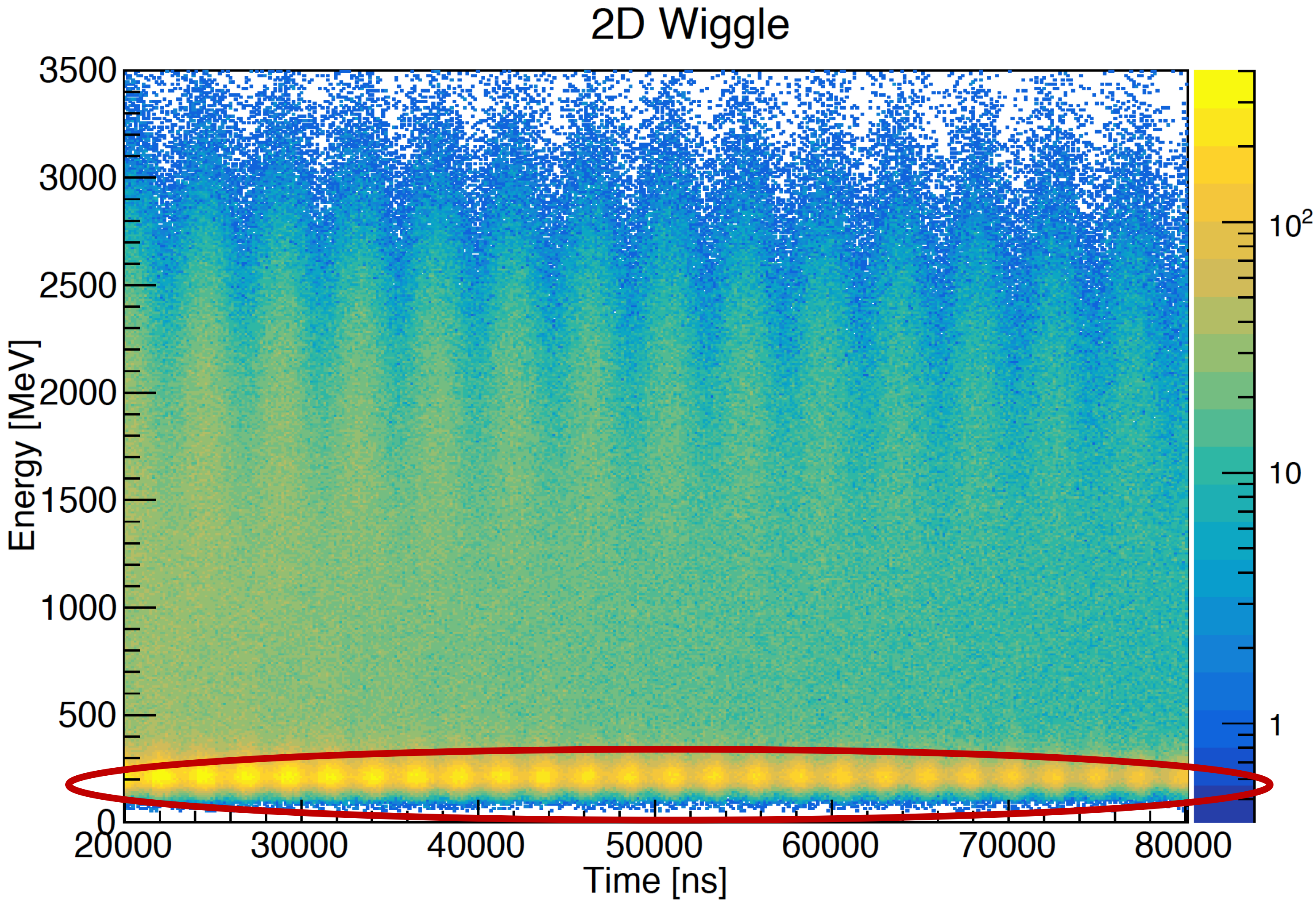


The integrated number of electrons (above E_{th}) modulated at ω_a

- **Angular distribution of decayed electrons correlated to muon spin**
- **(Simplified) five parameter fit to extract ω_a**

$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

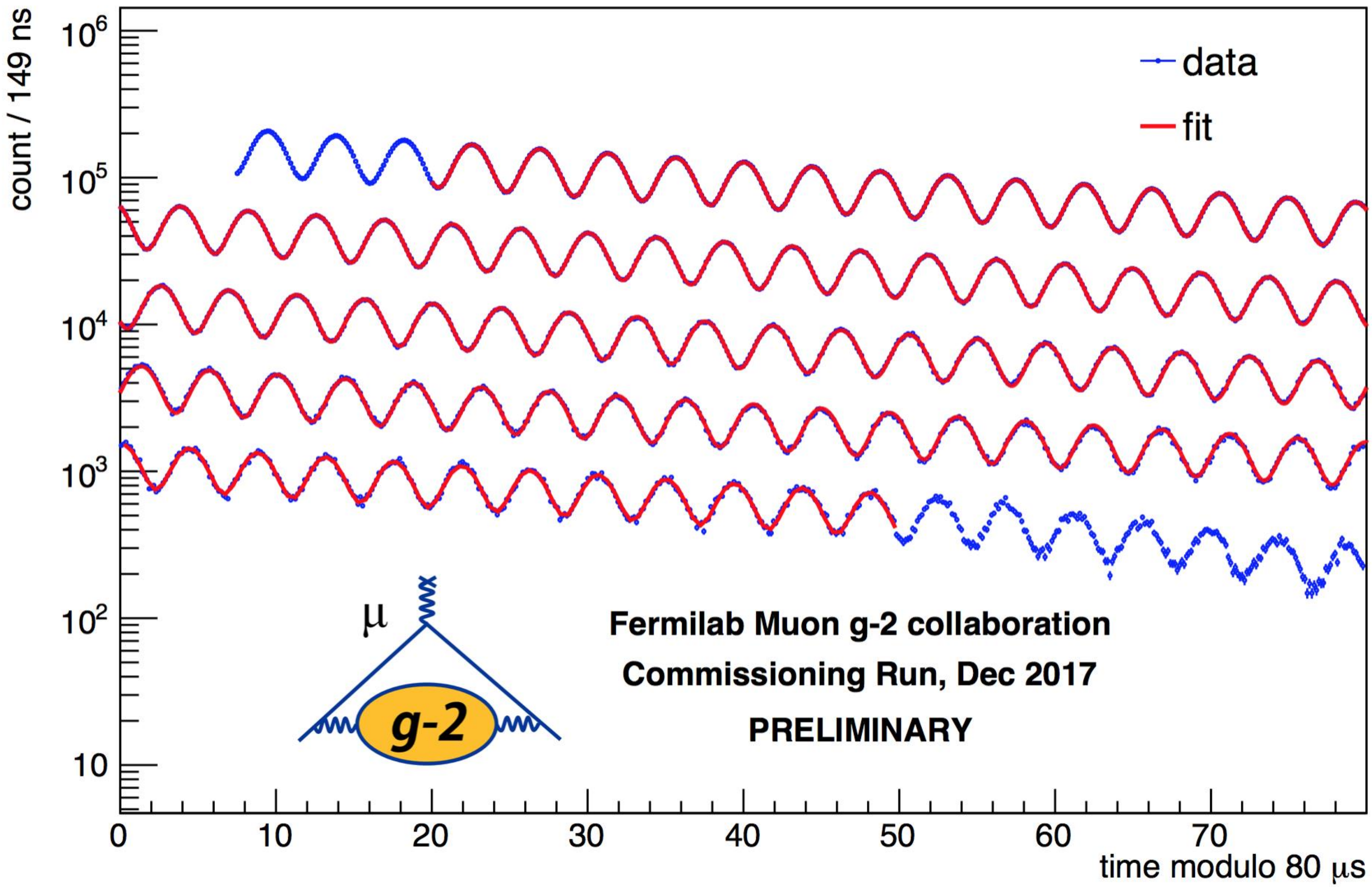
Wiggle, Wiggle, Wiggle…



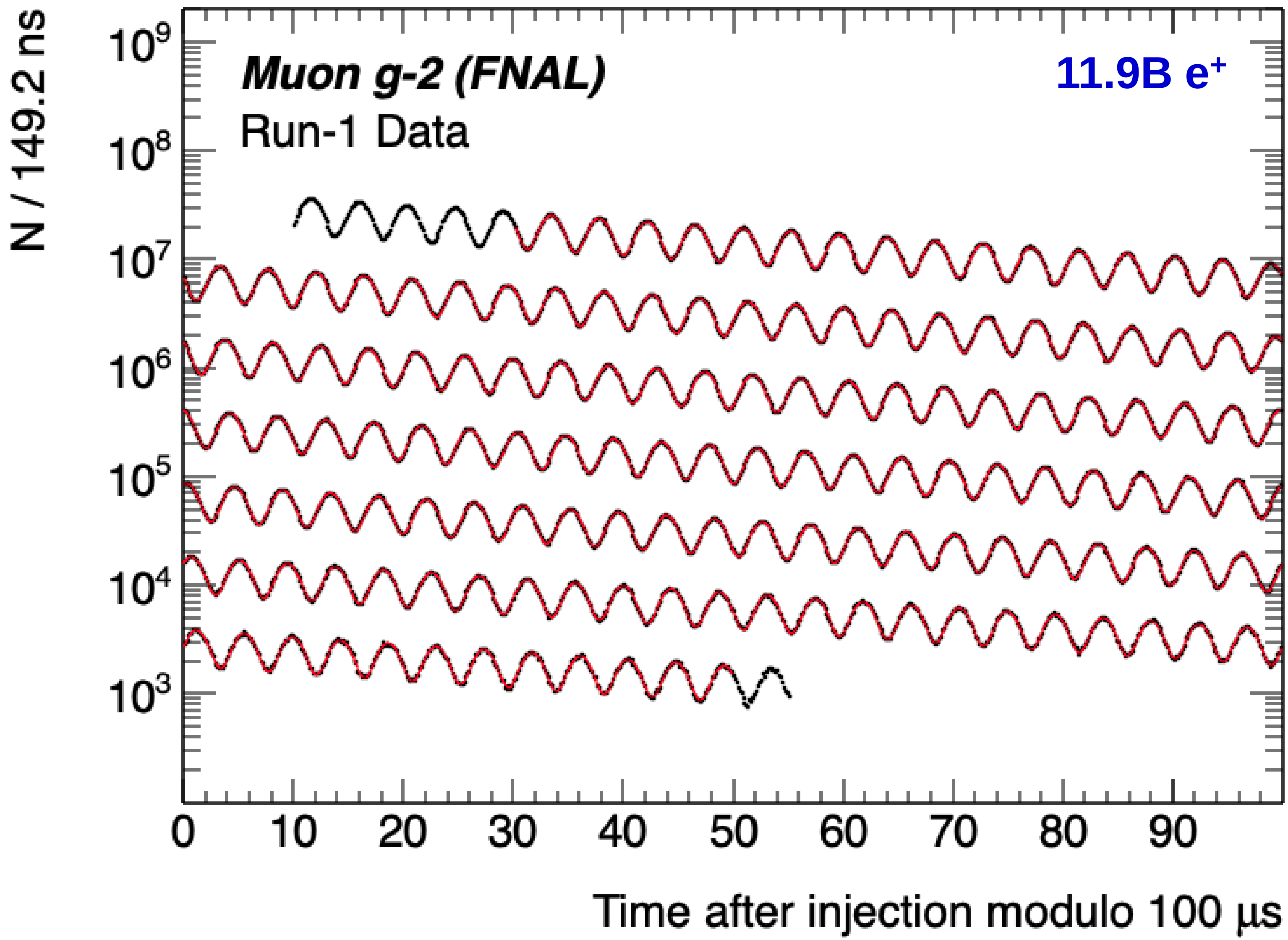
Lost muon background

Energy vs. Time seen by calorimeters

Wiggle, Wiggle, Wiggle…



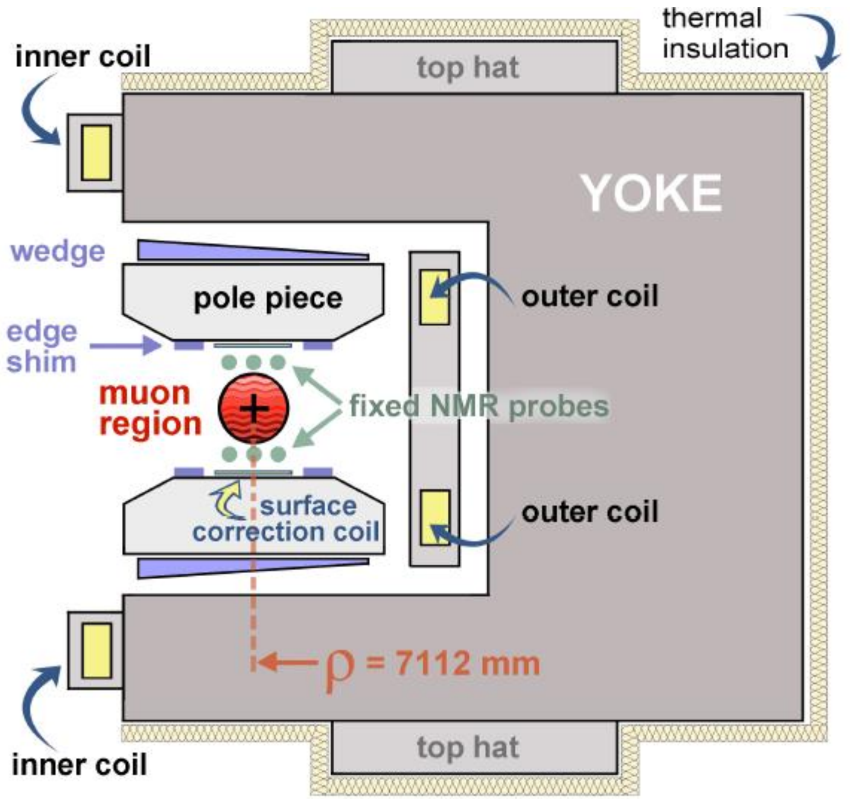
Wiggle, Wiggle, Wiggle…



Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

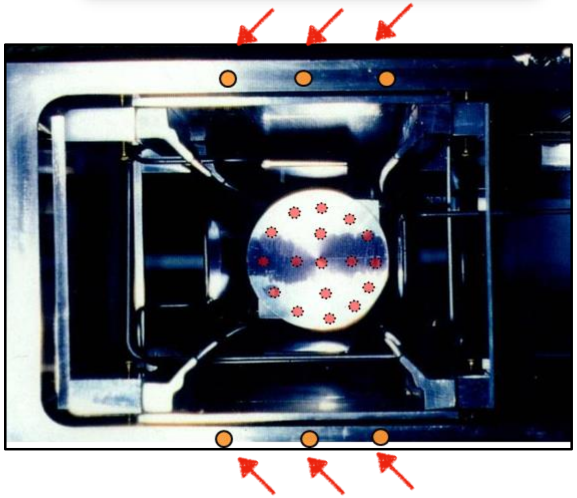
- 1 B field ~ 1.45T
- 12 C shape flux return yokes
- 72 poles
  - Minimizing higher-order multipoles
  - Dipole moment ~ 1.45T
- Field Shimming
  - Passive shim method (geometry)
    - 24 iron top hats
    - 864 wedges: angle quadrupole
    - >1000 edge shims: sextapole
    - >8000 surface iron foils
  - Active shim method (current)
    - Surface correction coil
    - Power supply feedback



g-2 Magnet in Cross Section

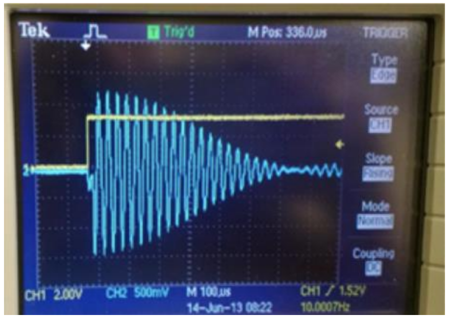
Measuring ω_p, the B field

- 378 **Fixed Probes** above and below the vacuum chamber measure the field continuously throughout the experiment



- A 17-element **NMR Trolley** maps the field where muons live every 2-3 days: beam off

- Digitizing **Free Induction Decay (FID)** signals for more precise frequency determination

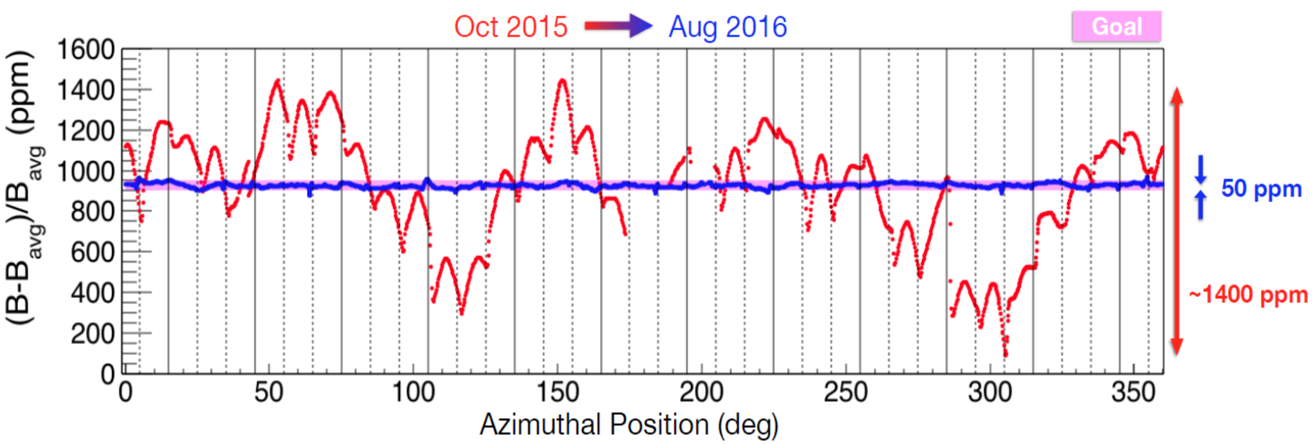


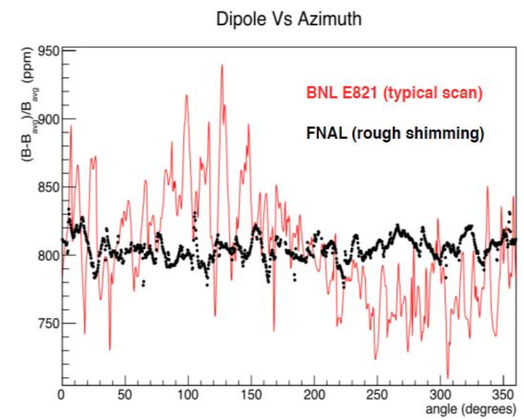
(FID) Waveforms with ~10 ppb resolution

- Monitoring the field and provide feedback to the storage ring power supply during data taking

- Absolute and cross calibration of all probes

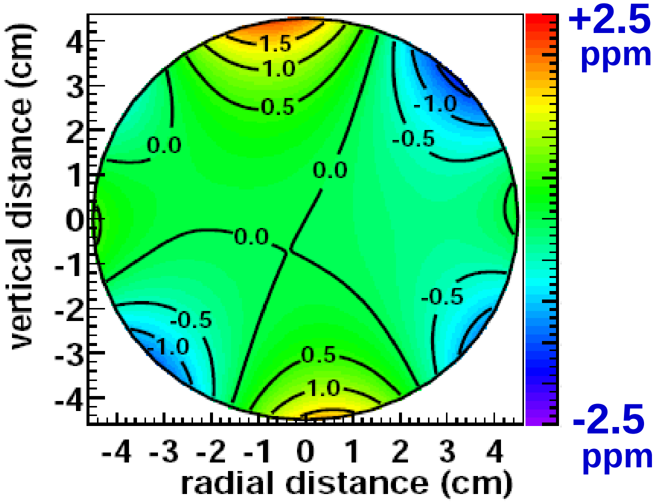
B Field Measurements





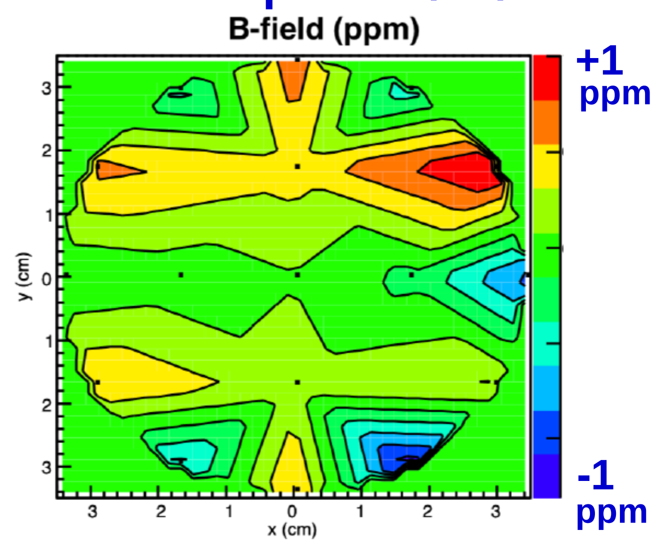
Shim 1.45 T field to high uniformity and measure it vs time

BNL Field Map

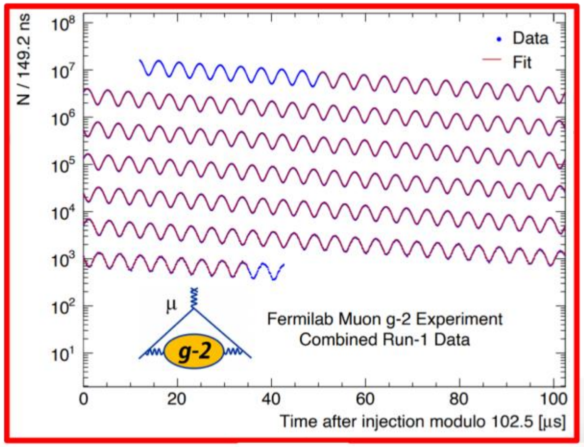


Averaged over azimuth: Shimmed to ±1 ppm level

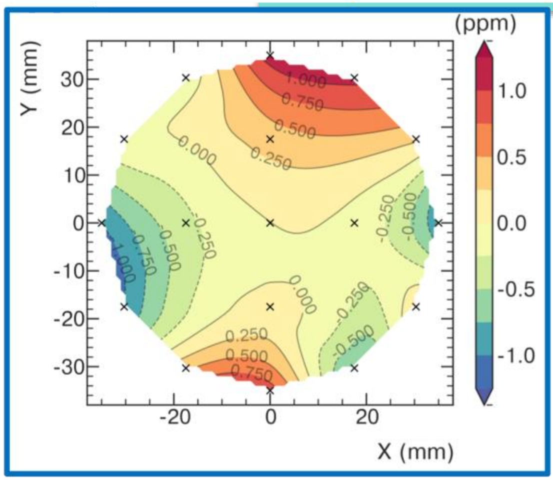
Field Map on 03/17/2018



Final Measurement



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



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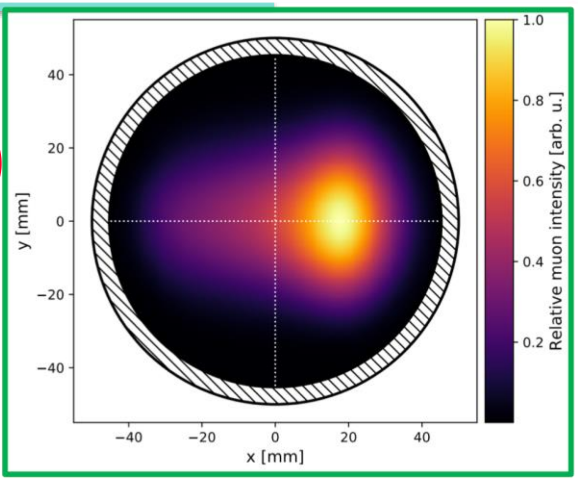

ω_a^m Measurement

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

The ideal and naïve case, 5-parameter function:

$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$

- **Pileup**
- **Gain (energy scale) changes**
- **Coherent Betatron Oscillations**
- **Muon Losses**
- **E-field and pitch corrections**

$$F(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot \left[1 + A_0 \cdot A_x(t) \cdot \cos\left(\omega_a^m t + \phi_0 \cdot \phi_x(t)\right)\right]$$

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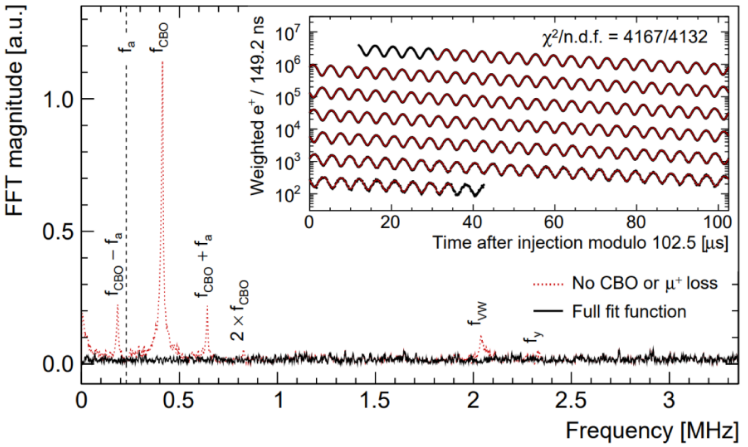


$$N_x(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{N,x,1} \cos(\omega_{\text{CBO}} t + \phi_{N,x,1}) + e^{-2t/\tau_{\text{CBO}}} A_{N,x,2} \cos(2\omega_{\text{CBO}} t + \phi_{N,x,2})$$

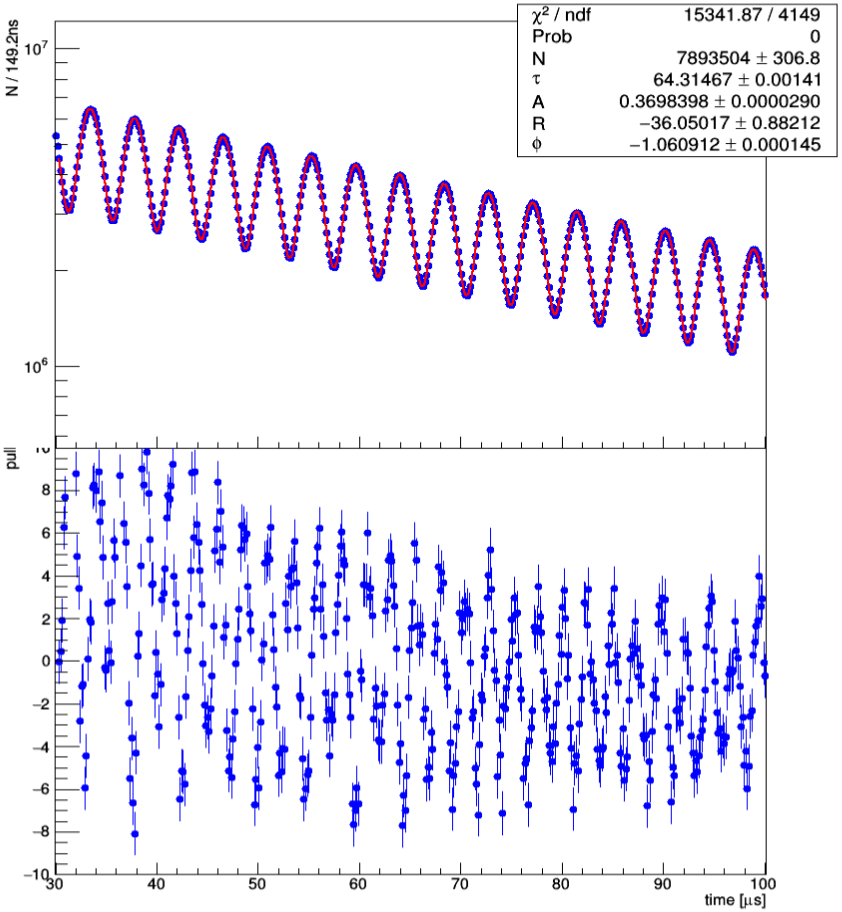
$$N_y(t) = 1 + e^{-t/\tau_y} A_{N,y,1} \cos(\omega_y t + \phi_{N,y,1}) + e^{-2t/\tau_y} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2})$$

$$\Lambda(t) = 1 - K_{\text{loss}} \int_0^t e^{t'/\gamma\tau_\mu} L(t')\,dt'$$

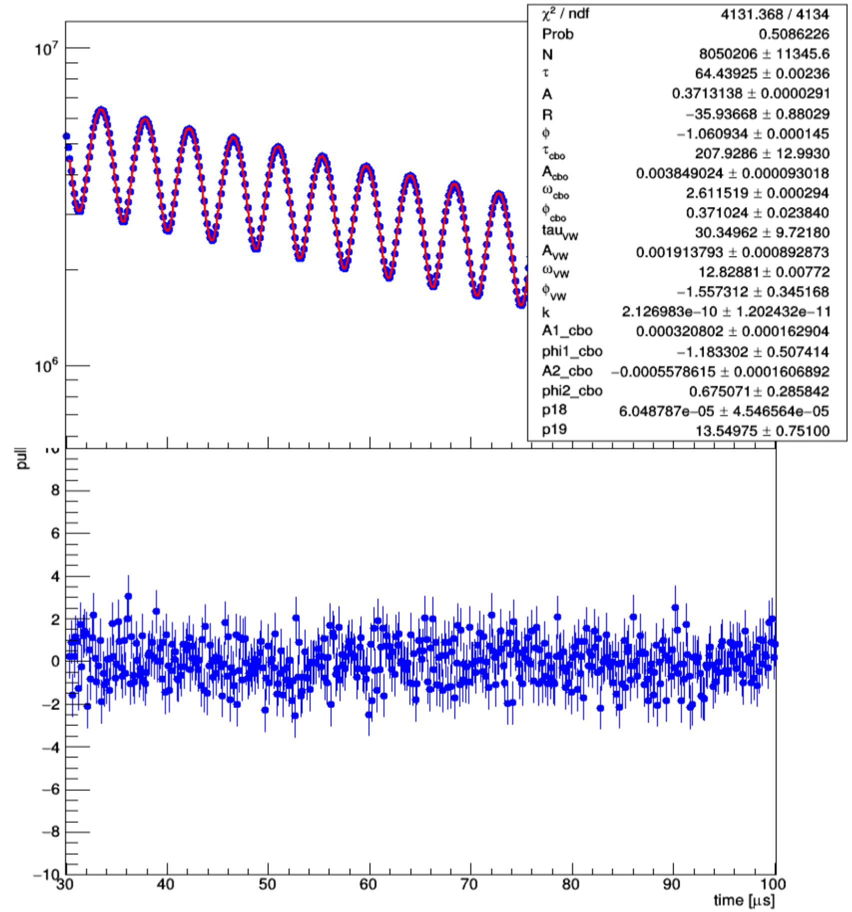
$$A_x(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{A,x,1} \cos(\omega_{\text{CBO}} t + \phi_{A,x,1})$$

$$\phi_x(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{\phi,x,1} \cos(\omega_{\text{CBO}} t + \phi_{\phi,x,1})$$

ω_a^m Measurement: Wiggle Fitting



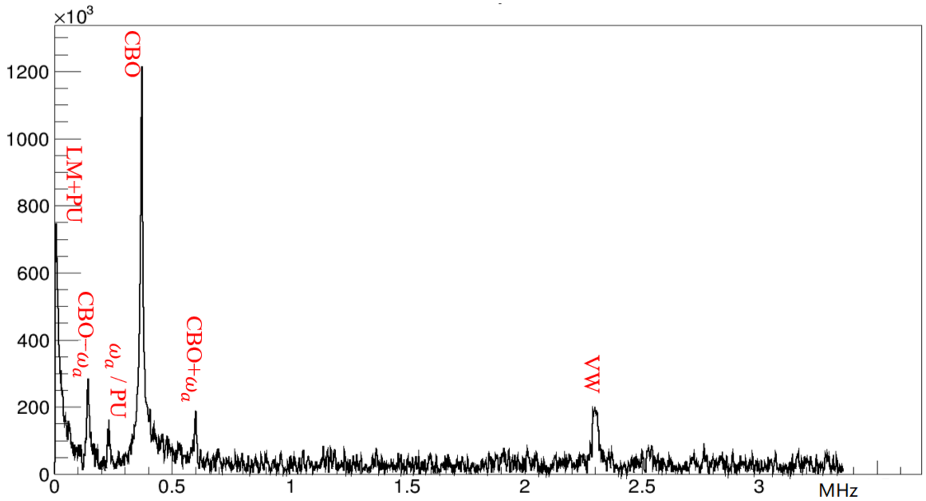
5 parameters



22 parameters

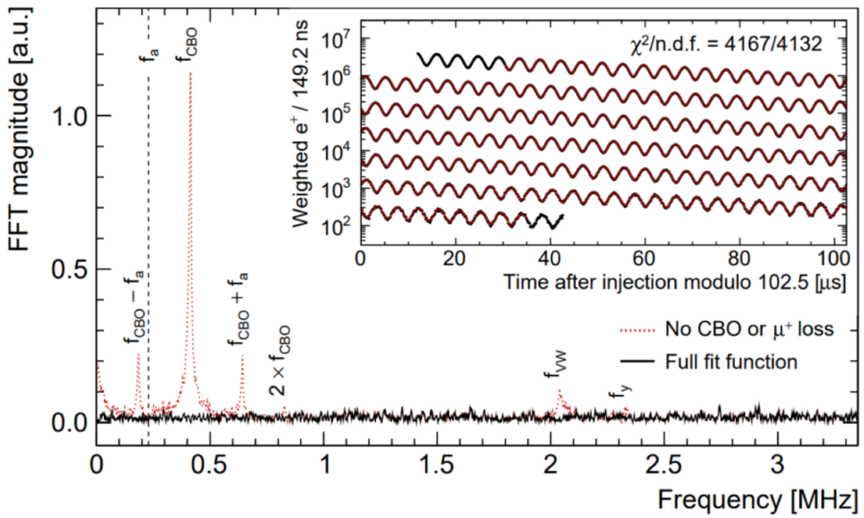
ω_a^m Measurement: FFT Spectrum

Before correction



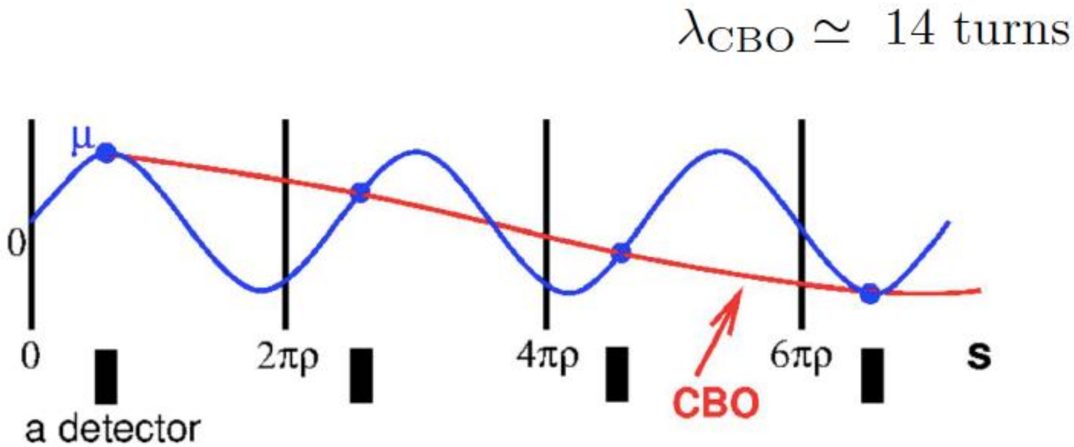
Name	Symbol	Typical value
Cyclotron frequency	f_c	6.71 MHz
Anomalous precession frequency	f_a	0.23 MHz
Coherent betatron frequency	f_{CBO}	0.37 MHz
Vertical betatron frequency	f_y	2.19 MHz
Vertical waist frequency	f_{VW}	2.32 MHz

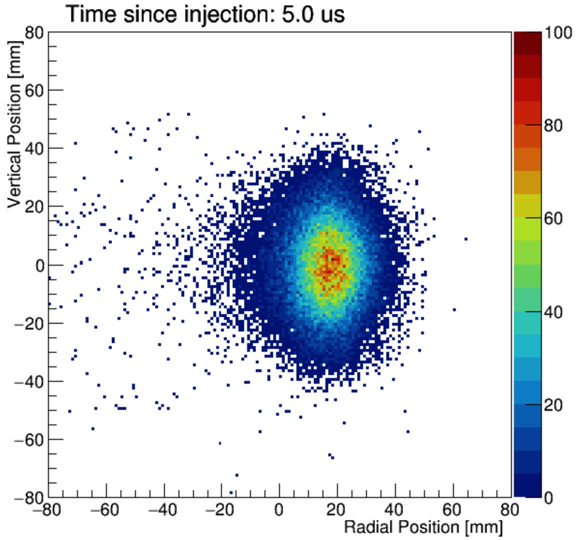
After correction



Coherent Beam Oscillation

- **CBO sampled by each detector at one point around the ring**

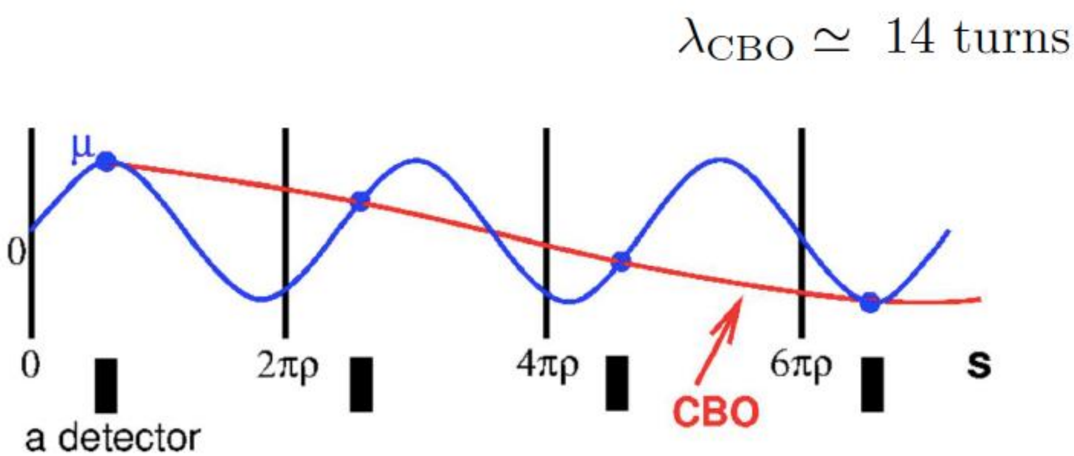


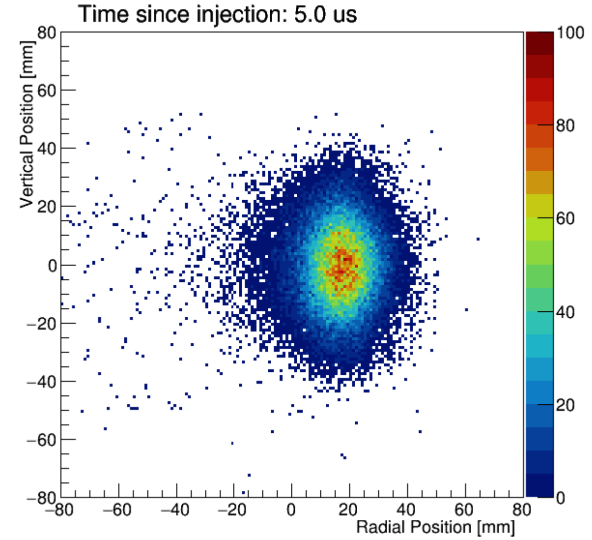


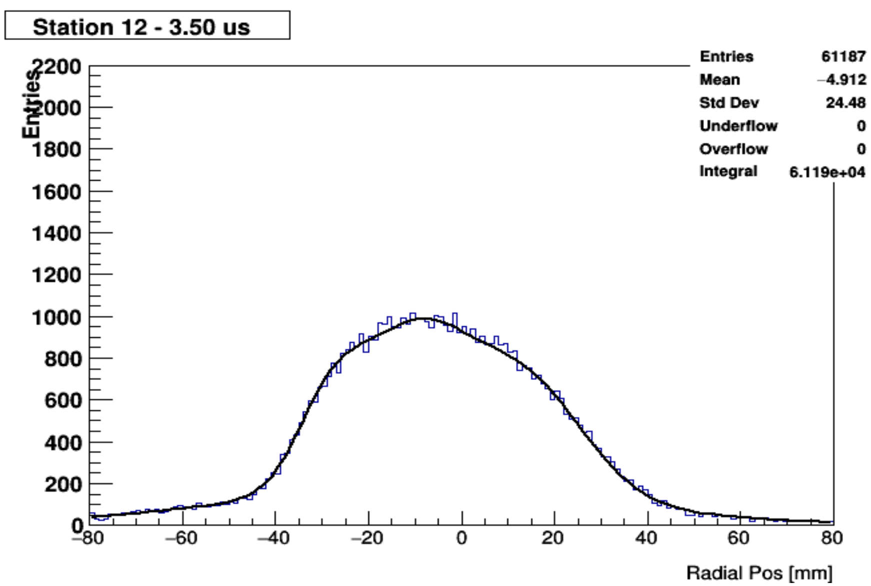
- **Beating effects and additional radial and vertical frequencies**

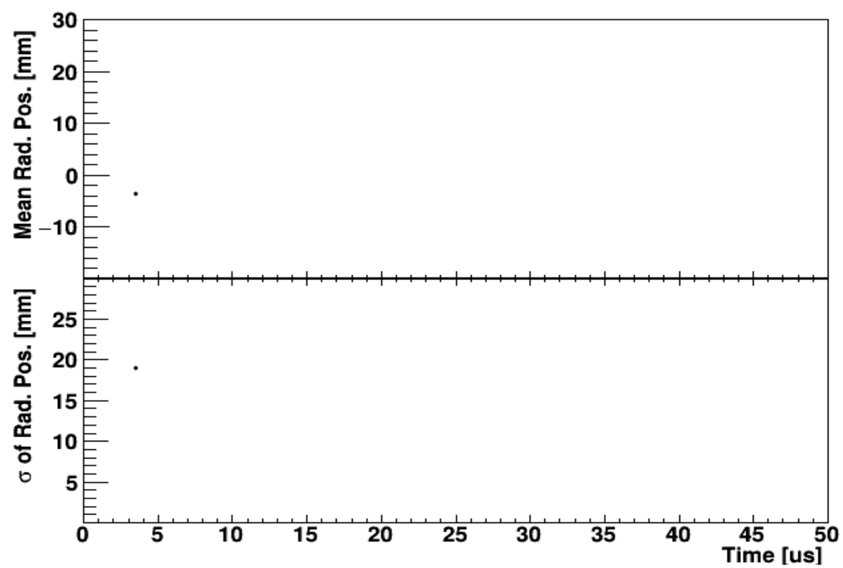
Coherent Beam Oscillation

- **CBO sampled by each detector at one point around the ring**









Classical Electrodynamics

The glory details

- **Muons make horizontal circular movement under influence of magnetic field B, what about vertical movement?**
  - **Need to use electrostatic quadruples to confine muons vertically, this brings additional complication**

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

High order correction

minimized if γ = 29.3

Electric field & pitch correction

- **How to measure this?**
  - **Choose γ = 29.3, p_μ= 3.09 GeV (magic momentum)**
  - **Residual electric field correction**
  - **Muon beam swims and breathes vertically and horizontally**
    - **Coherent betatron oscillations (CBO)**
    - **Presence of electric/magnetic field and betatron motion also leads to pitch and high order corrections**

E-field Correction, C_e

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

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

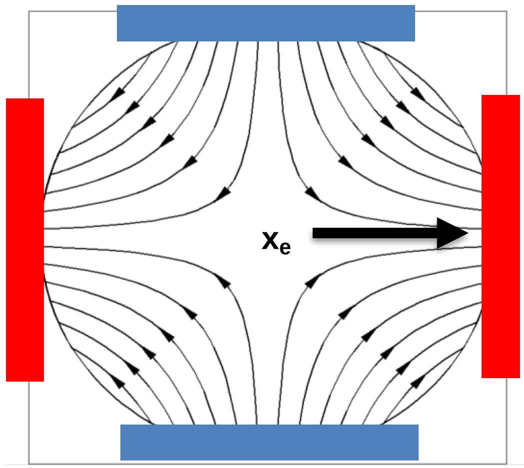
Not all muons are at magic momentum!

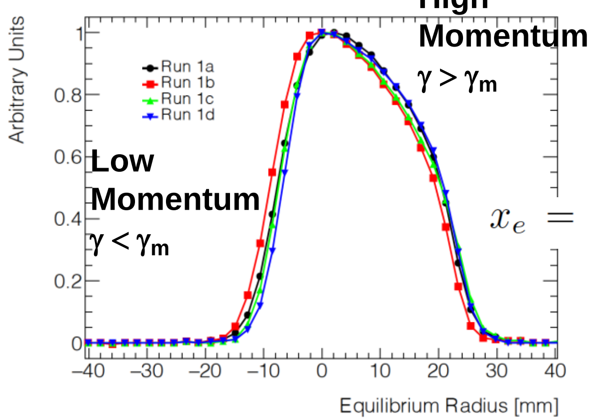
$$C_e = 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

$$\langle x_e^2 \rangle = \sigma_{x_e}^2 + \langle x_e \rangle^2$$

Correction depends on width and mean

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





$$x_e = x - R_0$$

Phys. Rev. Accel. Beams 24, 044002 (2021)

Fourier analysis of early time spectrum

Muon Loss Correction, C_{ml}

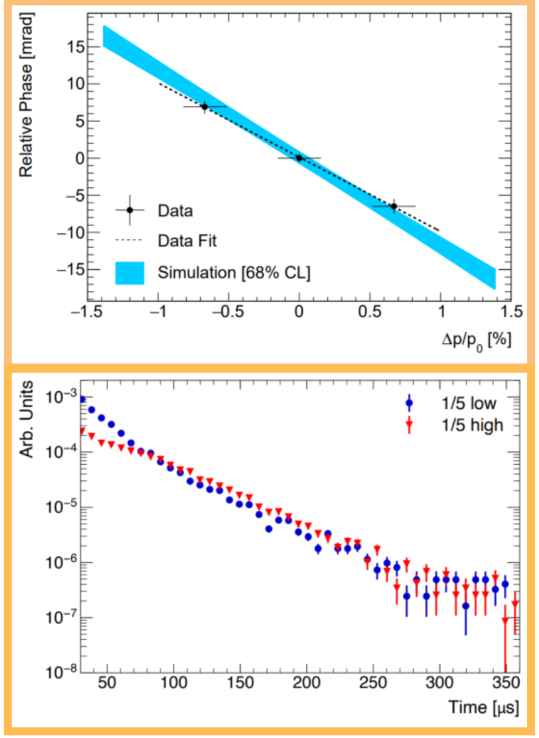
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

Phase-momentum correlation due to dipole bending magnets in upstream beamline

Momentum-dependent muon losses mean different average phase early to late

$$\Delta\omega_a = \frac{d\phi}{dt} = \frac{d\langle\phi\rangle}{d\langle p\rangle} \cdot \frac{d\langle p\rangle}{dt} \neq 0$$

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



Phys. Rev. Accel. Beams 24, 044002 (2021)

Phase-acceptance Correction, C_{pa}

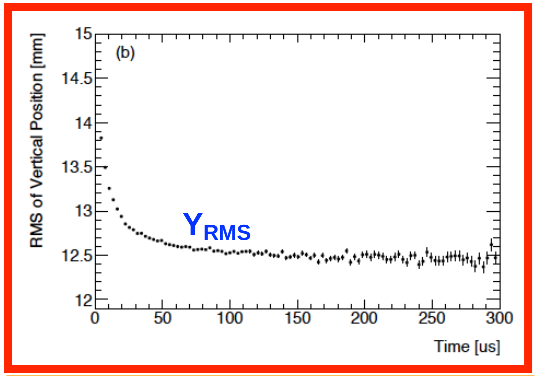
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

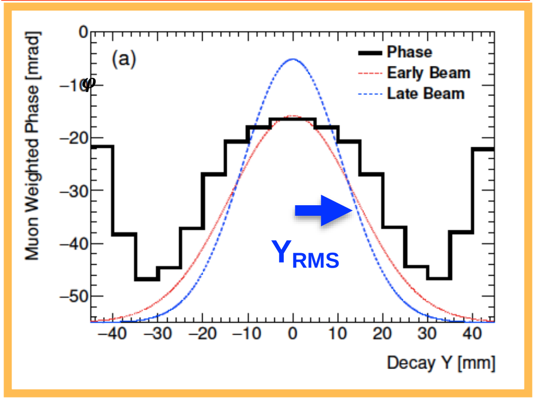
Beam shifting from early-to-late time due to storage ring conditions

Decay-position-dependent phase means different average phase early to late

$$\Delta\omega_a = \frac{d\phi}{dt} = \frac{d\langle Y_{RMS}\rangle}{dt} \cdot \frac{d\langle\phi\rangle}{d\langle Y_{RMS}\rangle} \neq 0$$

$$C_{pa} \sim 150\ ppb, \delta_{C_{pa}} \sim 75\ ppb$$





Phys. Rev. Accel. Beams 24, 044002 (2021)
Phys. Rev. D 103, 072002 (2021)

Magnetic Field Measurement, ω_p

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

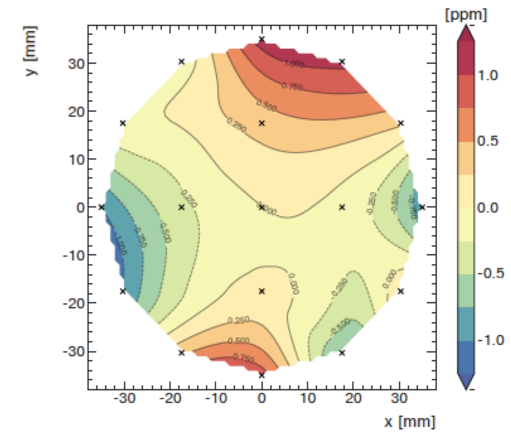
NMR trolley maps magnetic fields at about 9000 locations in azimuth in the storage region every 2-3 days

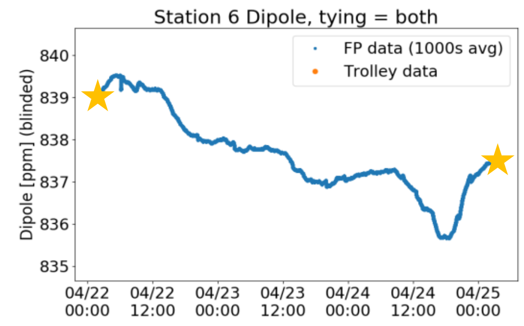
Fixed NMR probes interpolate the field between the trolley runs

Dedicated Plunging Probe to calibrate the NMR trolley probes to the water sample

$$\delta_{\omega_p} \sim 48ppb$$

Phys. Rev. A 103, 042208 (2021)





Muon-weighted Average Field, $\tilde{\omega}_p$

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

The actual field experienced by the muon in the storage region

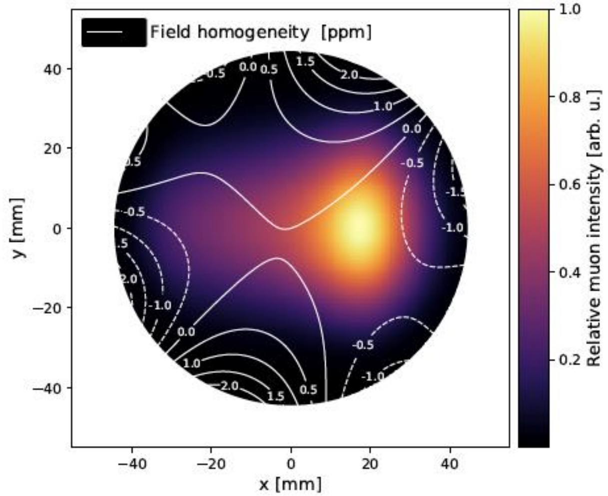
Measure muon beam distribution with straw trackers by extrapolating positron tracks back to the storage region

Use beam dynamics simulations, tuned to the tracker data, to get the muon beam distribution around the ring

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

Phys. Rev. A 103, 042208 (2021)

Muon's view



Kicker Transient Field, B_k

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

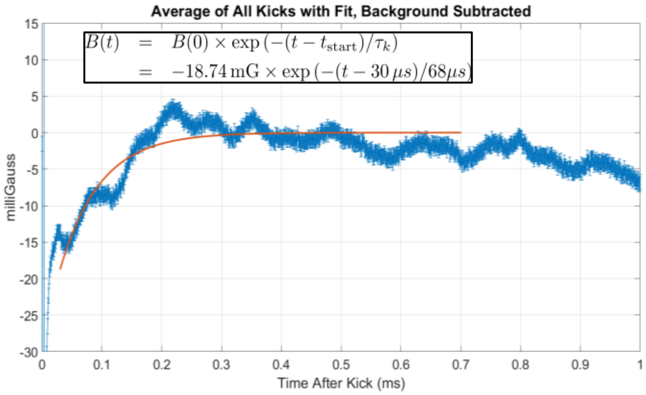
When kicker produces pulsed magnetic field (~ 200G) for 150 ns, eddy currents generated in kicker plates

Faraday magnetometer installed between the plates to measure the rotation of polarized light in a crystal due to the transient field

Signal is fitted with an exponentially decaying function: $\Delta B(t) = \Delta B(0)\exp\left(-t/\tau_k\right)$

$$\boxed{B_k \sim 30\ ppb,\ \delta_{C_{pa}} \sim 40\ ppb}$$

Magnetometer between kicker plates



Phys. Rev. A 103, 042208 (2021)

Electrostatic Quadrupole Transient Field, B_q

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

ESQs are (dis-)charged every muon fill ($700\mu s$)

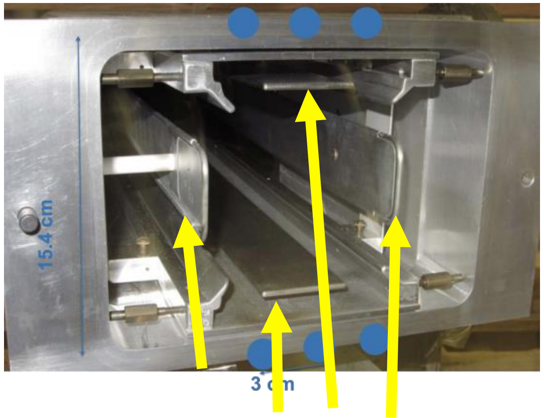
Electric pulse induces mechanical vibrations in ESQ plates and then generates magnetic perturbations

Customized NMR probes measured B_q at several positions in the storage region

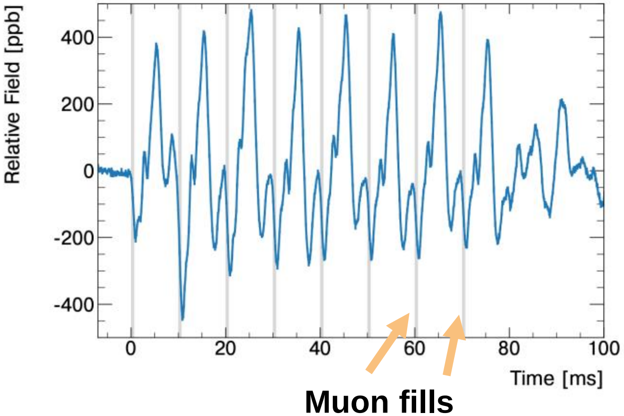
Uncertainty determined by the full width of the measured effect due to limited measurements in Run1 → expect improvement in Run2

$$B_q \sim 20\ ppb, \delta_{B_q} \sim 90\ ppb$$

Phys. Rev. A 103, 042208 (2021)



Quad plates inside vacuum chamber



Systematics: Numerator

Source	Uncertainty
Frequency Standard	1 ppt
Frequency Synthesizers	0.1 ppb
Digitization Frequency	2 ppb
Total Systematic	2 ppb

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

$R(\omega_a)$ with detailed systematics categories [ppb]				
Total systematic uncertainty	65.2	70.5	54.0	48.8
Time randomization	14.8	11.7	9.2	6.9
Time correction	3.9	1.2	1.1	1.0
Gain	12.4	9.4	8.9	4.8
Pileup	39.1	41.7	35.2	30.9
Pileup artificial dead time	3.0	3.0	3.0	3.0
Muon loss	2.2	1.9	5.2	2.4
CBO	42.0	49.5	31.5	35.2
Ad-hoc correction	21.1	21.1	22.1	10.3

***Run 1 ω_a data analyzed in four subsets**

	1a	1b	1c	1d
C_p (ppb)	**176**	**199**	**191**	**166**
Statistical uncertainty	<0.1	<0.1	<0.1	<0.1
Tracker alignment/reco.	11.0	12.3	12.0	10.7
Tracker res. & acc. removal	3.3	3.9	3.7	3.0
Azimuthal avg. & calo. acc.	1.0	1.3	2.2	1.1
Amplitude fit	1.2	0.4	1.0	2.9
Quad alignment/voltage	4.4	4.4	4.4	4.4
Systematic uncertainty	**12.4**	**13.7**	**13.6**	**12.3**

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

	1a	1b	1c	1d
C_e (ppb)	**471**	**464**	**534**	**475**
Statistical uncertainty	0.4	0.5	0.4	0.2
Fourier method	8.4	13.4	14.4	3.9
Momentum-time correlation	52	52	52	52
Quad alignment/voltage	6.4	6.4	6.4	6.4
Field index	1.7	1.5	1.7	4.0
Systematic uncertainty	**53**	**54**	**54**	**53**

Systematics: Denominator

run-1 (substructure)	77.4 ppb
azimuthal shape*	7.6 ppb
skin depth	12.6 ppb
frequency extraction (0.4/1ms)	4.6 ppb
Q3L: fit, position	1.5 ppb
repeatability	13.3 ppb
drift	10.2 ppb
radial dependency	4.4 ppb
2^{nd} 8-pulses	14.0 ppb
total -15.0 ppb	81.7 ppb

Source	Uncertainty (ppb)
Temperature	**15 – 28**
Configuration	**22**
Trolley	**25**
Fixed Probe Production	**<1**
Fixed Probe Baseline	**8**
Tracking Drift	**22 – 43**
Total	**43 – 62**

PROBE	Calibration Coefficients		
	Value (Hz)	Stat (Hz)	Syst (Hz)
1	90.81	0.38	2.02
2	84.21	0.65	1.18
3	95.02	0.53	2.19
4	86.03	0.25	1.28
5	92.96	0.51	1.10
6	106.24	0.46	1.35
7	116.64	0.96	1.61
8	76.39	0.60	1.21
9	83.52	0.23	1.64
10	24.06	1.39	1.26
11	177.55	0.22	1.99
12	110.85	0.44	1.73
13	122.89	2.08	1.93
14	77.11	0.53	1.88
15	74.82	1.06	1.59
16	20.35	0.44	2.94
17	172.12	1.23	1.96
AVG		**0.70**	**1.70**

Run-1 Estimate:
$B_k = -27.4 \pm 37$ ppb

Quantity	Symbol	Value	Unit
Diamagnetic Shielding T dep	$(1/\sigma)d\sigma/dT$	-10.36(30)	ppb/°C
Bulk Susceptibility	δ_b	-1504.6 ± 4.9	ppb
Material Perturbation	δ_s	15.2 ± 13.3	ppb
Paramagnetic Impurities	δ_p	0 ± 2	ppb
Radiation Damping	δ_{RD}	0 ± 3	ppb
Proton Dipolar Fields	δ_d	0 ± 2.3	ppb

	correction [ppb]				uncertainty [ppb]			
Dataset	**1a**	**1b**	**1c**	**1d**	**1a**	**1b**	**1c**	**1d**
1. Tracker and calo effects	-	-	-	-	9.2	13.3	15.6	19.7
2. COD effects	1.6	1.5	1.7	1.4	5.2	4.7	5.2	4.9
3. In-fill time effects	-1.9	-2.3	-1.2	-4.1	-	-	-	-
Total	**-0.3**	**-0.8**	**0.5**	**-2.7**	**10.6**	**14.1**	**16.5**	**20.3**

Blinded Analysis

Avoid possible bias during analysis

- Credibility is the key

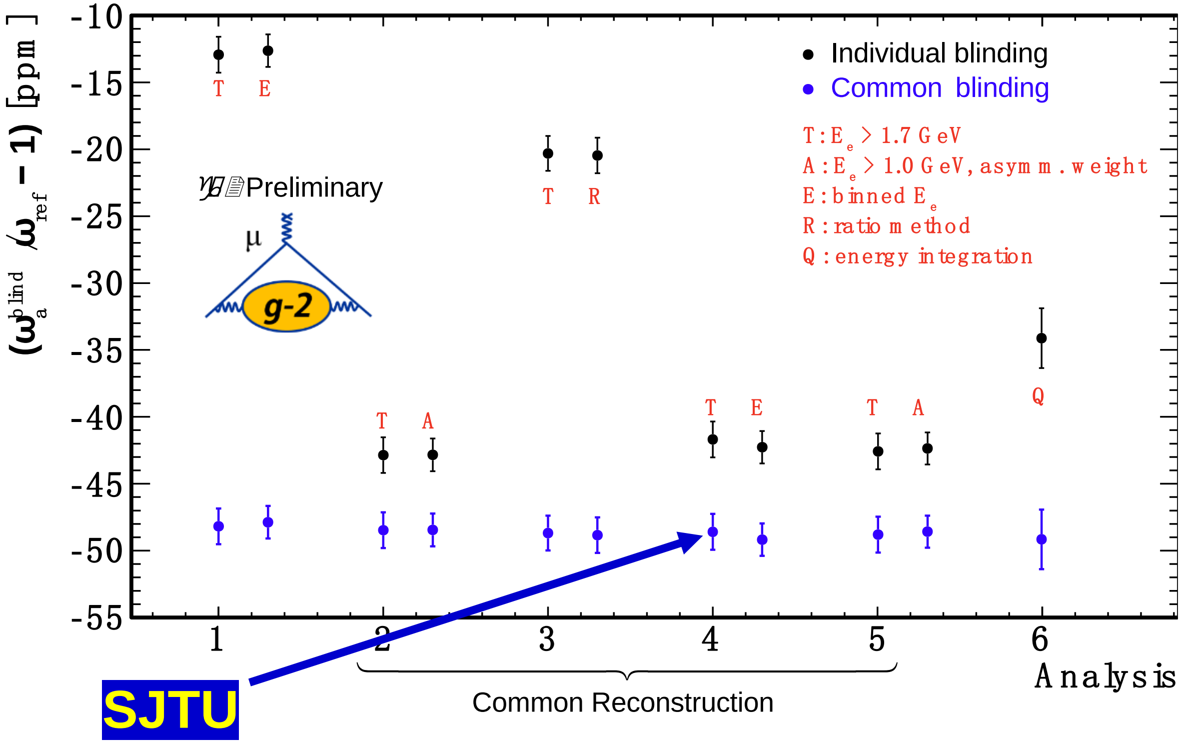
Hardware Blinding

- Perturb the clocks from the nominal frequency of 40 MHz → 39.XX MHz

Software Blinding

- Software package to apply individual offsets to fit results to ensure independence of analyses
- $\omega_a \rightarrow \omega_a \pm \Delta$ ppm
- Unblinding can be done in different stages and cross check

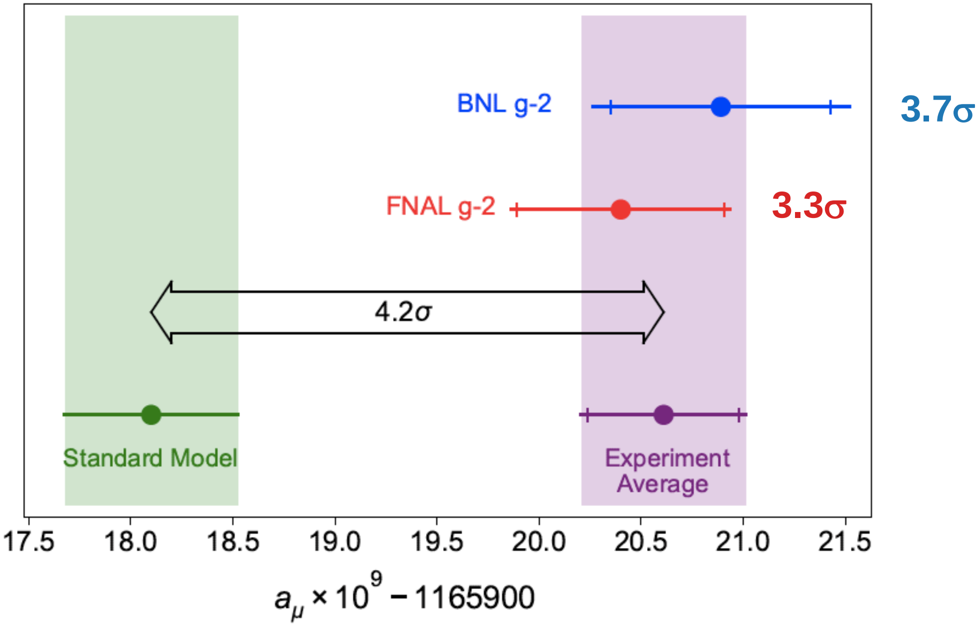
Relative Unblinding



- **6 independent ω_a analysis groups with multiple methods blinded from each other**
- **Relative unblinding performed for analysis consistency check**
- **A-weighted method extract more information from high energy positrons**
- **Statistics uncertainty: δ_{stat} = 0.43 ppm < 0.46 ppm (BNL)**

Final Results and Uncertainties

Phys. Rev. Lett. 126, 141801 (2021)

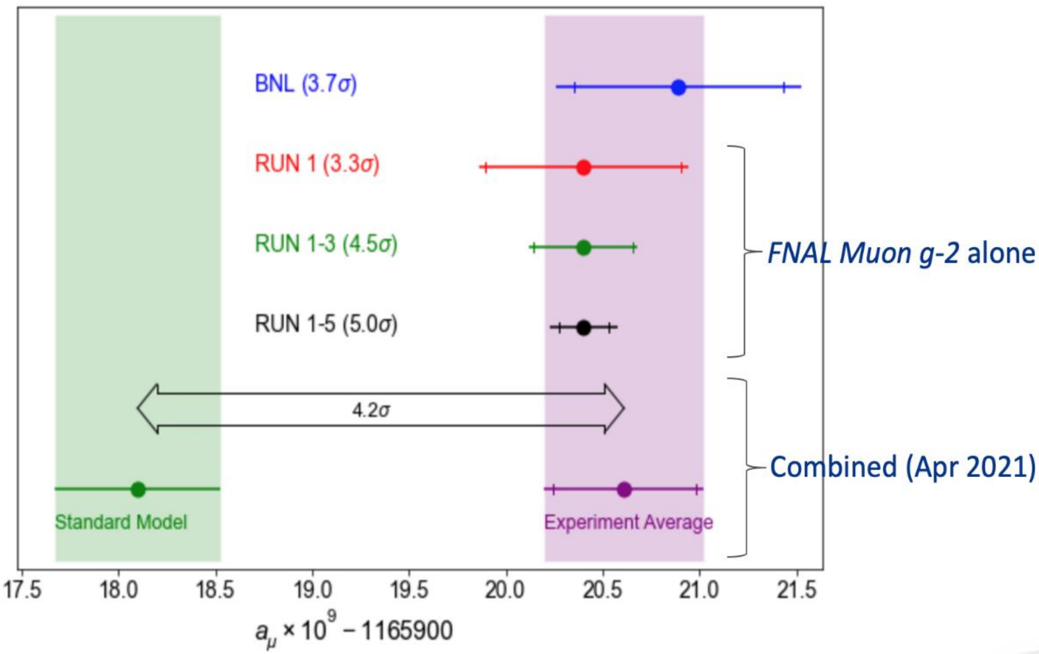


Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	⋯	434
ω_a^m (systematic)	⋯	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\mathrm{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	⋯	56
B_k	−27	37
B_q	−17	92
$\mu_p'(34.7^\circ)/\mu_e$	⋯	10
m_μ/m_e	⋯	22
$g_e/2$	⋯	0
Total systematic	⋯	157
Total fundamental factors	⋯	25
Totals	544	462

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54)\times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

- **Strengthen evidence for BSM physics**
- **Run-1 Results are largely statistically dominated**
  - **15% smaller error than BNL**
  - **Good agreement between two experiments**
  - **Statistically “normal” to see increased significance after combination**

Beyond Run1



- **Analysis of Run2/3 ongoing, expect a factor of two improvement in precision**
- **Run 4 data is expected to bring the statistics to 13x BNL**
- **Run 5 currently running, should bring us to the TDR goal of ~ 20x BNL**
- **Run 6 e^- run under discussion**
  - **CPT and Lorentz Violation Effects**
  - **Sidereal Oscillation**

Run 1 results ~6% of full stats:
434 ppb stat ⊕ 157 ppb syst errors

Improve precision even further

Increase statistics: $\sigma \sim 1/\mathrm{sqrt}(N)$

- High precision frequency measurement with huge statistics
  - ~10^{20} POT -> ~10^{12} 3GeV muon -> ~10^{11} selected e^+ -> ~0.1ppm

Systematics improvement

- Precise beam monitoring
  - CBO reduction and monitoring
  - Muon distribution measurement
- Background mostly under control
  - Pileup effect modelling improved
  - Lost muon largely reduced

} ~0.07ppm

- Highly uniform and stable magnetic field
  - Sub-ppm level uniformity
- Instrumental improvement
  - Kicker
  - Electrostatic Quadrupole Transient Field

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  - **Kicker**
  - **Electrostatic Quadrupole Transient Field**

} **~0.07ppm**

Improve precision even further

W.-L. Zhan

HIAF-μ-Beam in Huizhou

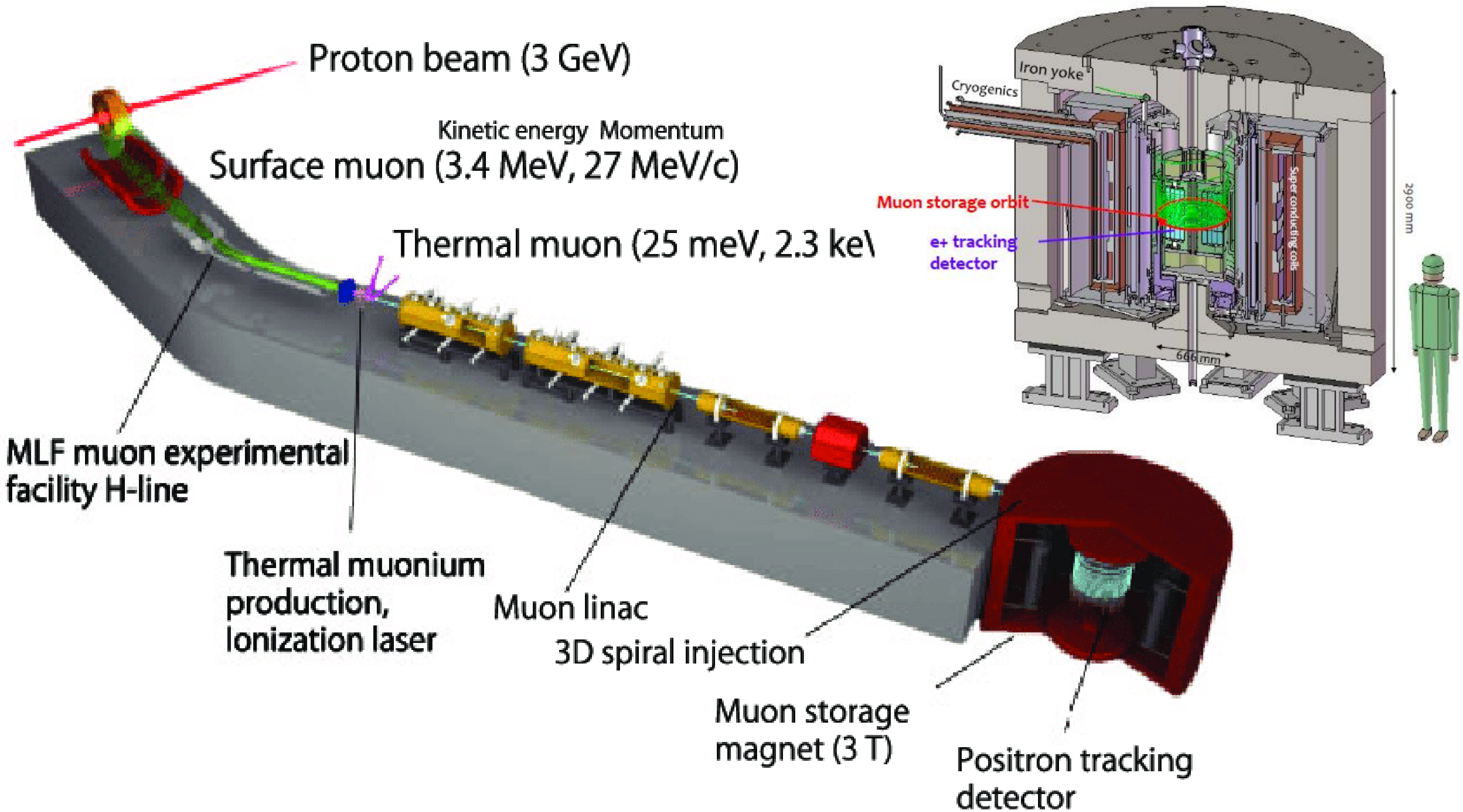
Parameter	1-0 (^{36}Ar)	1-0(^{1}H)	1-1 (^{209}Bi)
Nucleon on target per pulse	$36^{2/3}$*4e^{12}	1e^{14}	209e^{13}
Pulse width (ns)	200~300	200-300	200~300
Number of pulses	≥1	≥1	≥1
Frequency (Hz)	>5 Hz	>5Hz	~3 Hz
Beam momentum (GeV/c)	5.097	10.19	10.23
μ momentum (GeV/c)	>1.5	~3.5	>3.5

μ Campus at Fermilab

Parameter	Value （^{1}H）
Protons on target (POT) per pulse	10^{12}
Pulse width	120 ns
Number of pulses	16
Cycle length	1.4 s
Frequency	12 Hz
Incoming beam momentum	8.89 GeV/c
Selection momentum	3.1 GeV/c

- 统计量可获得数量级的提升
- 期望更小的测量误差
  - 提高π/μ产额
  - 设计和优化π和μ束流的输运和分离
  - 更精确束流模拟
  - 进一步改进测量系统误差

J-PARC g-2/EDM



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

g-2 **E=0** **EDM**

J-PARC g-2/EDM

Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

No magic momentum!

- **No strong focusing**
- **Super-low emittance muon beam**
- **Compact storage ring**
- **Full tracking detector**

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Differential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

Statistical uncertainty dominated

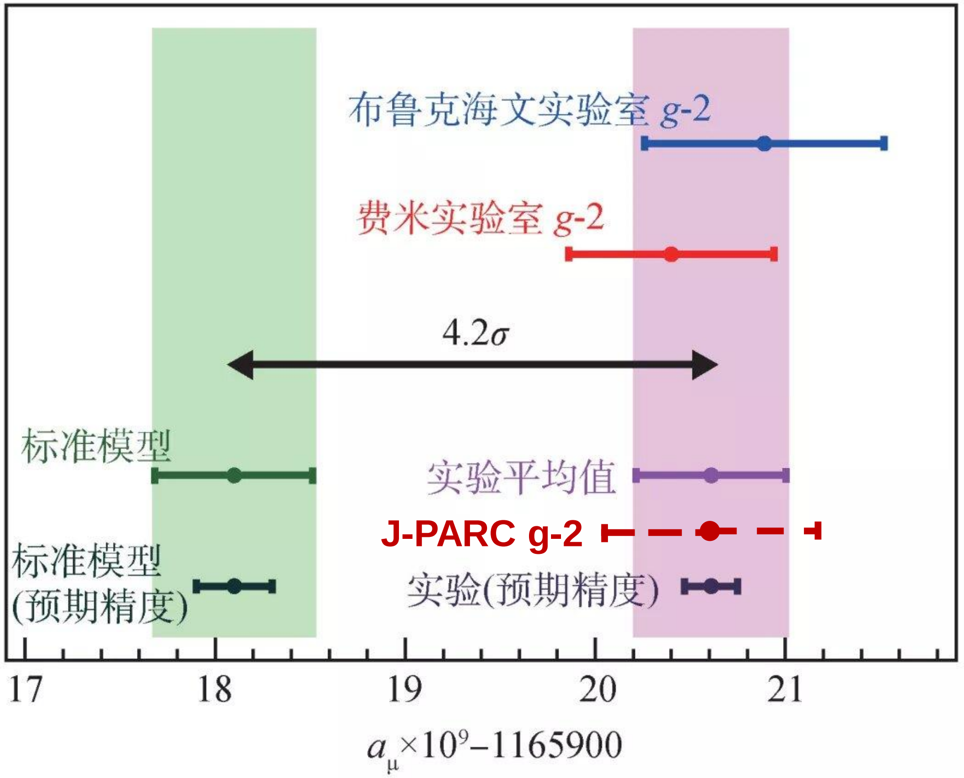
- $\delta\omega_a$ = 0.45 ppm including $\delta\omega_{a\_sys}$ < 0.1ppm
- δEDM = $1.5\cdot10^{-21}$e·cm

TDR: 2017

KEK approval: 2021

Data taking: 2025

Outlook



- ✓ The first results of Fermilab Muon g-2 measurement at 0.46 ppm with μ^+
- ✓ Strengthens significance of discrepancy to 4.2 sigma
- ✓ Expect a factor of two improvement in precision from Muon g-2 Run2-3 data and more from Run4-5
- ✓ Looking forward to J-PARC result and possible Muon g-2 Run6 e^- run!

Backup

E821(BNL) vs. E989(Fermilab)

E821 (BNL) : a_μ^{exp} = 116 592 089 (63) X 10^{-11}
Uncertainty: 0.46 ppm stat., 0.28 ppm syst.

Goal: reduce experimental uncertainty by a factor of 4

New team: >95% new people

New equipment: new beam + new detector + new monitor probes

- **21 times more statistics: powerful Fermilab particle source**
  - δ_{stat} = 0.46 ppm → 0.1 ppm
- **New segmented calorimeters, straw wire tracker, fast muon kicker…**
  - $\delta\omega_a$ = 0.21 ppm → 0.07 ppm
- **Long shimming period, magnet temperature stability, more/better in-situ calibrations, more probes, modern instrumentation…**
  - $\delta_{<B>(\omega_p)}$ = 0.17 ppm → 0.07 ppm

E989 (Fermilab) expected experimental uncertainty:
0.14ppm ~ 16 X 10^{-11}
> 5σ deviation with the same central value

ω_a Systematics

Category	E821 [ppb]	E989 Improvement Plans	E989 [ppb]
Gain changes	120	• Better laser calibration • Low-energy threshold	20
Pileup	80	• Recording low-energy samples • Segmented Calorimeters	40
Lost muons	90	• Better collimation in ring	20
CBO	70	• Higher n value • Better match of beamline to ring	< 30
E and pitch corrections	50	• Improved tracker • High precision storage ring simulation	30
Total	180	Quadrature Sum for $\delta\omega_a$ (syst.)	70

Detector Team

Ring Team

Detector Team

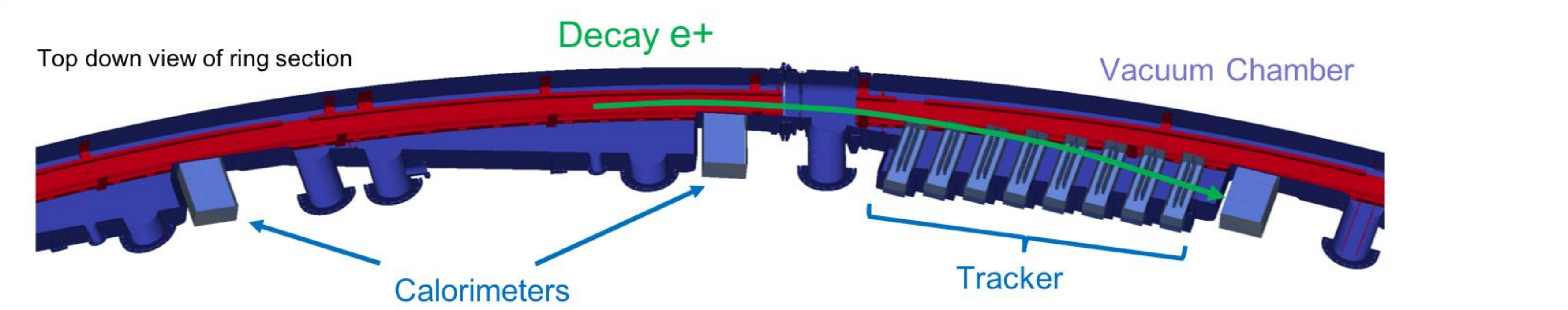
Systematics error < 70 ppb: x 3 improvement !

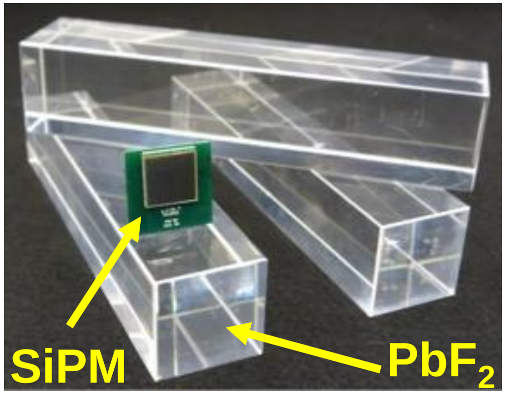
ω_p Systematics

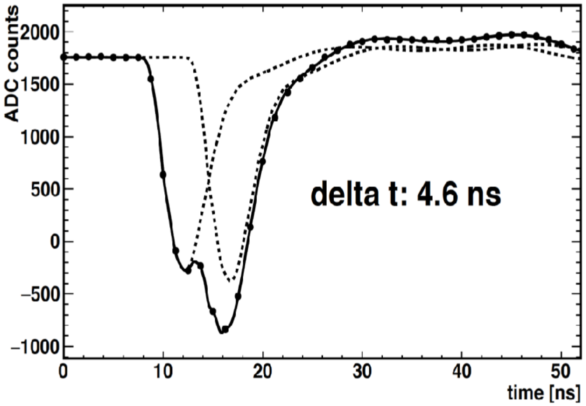
Category	E821 (ppb)	E989 (ppb)	Methods
Absolute probe calibration	50	35	More uniform field for calibration
Trolley probe calibration	90	30	Better alignment between trolley and the plunging probe
Trolley measurement	50	30	More uniform field, less position uncertainty
Fixed probe interpolation	70	30	More stable temperature
Muon distribution	30	10	More uniform field, better understanding of muon distribution
Time dependent external magnetic field	-	5	Direct measurement of external field, active feedback
Others*	100	30	More uniform field, trolley temperature monitor, etc
total	170	70	

Systematics error < 70 ppb: x 2 improvement !

Detector Performance: Calorimeter



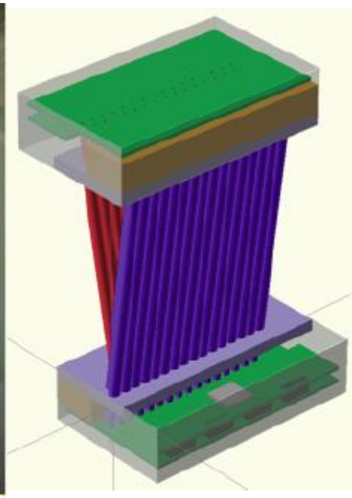


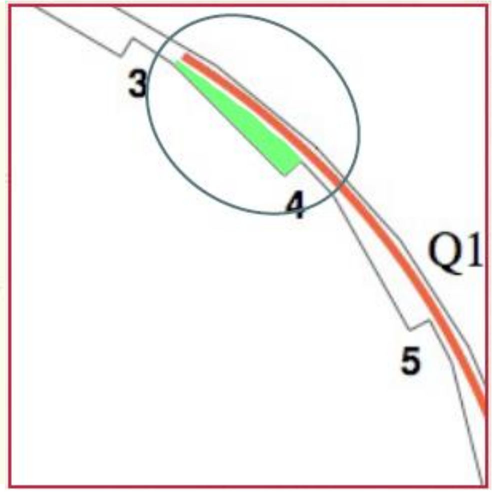


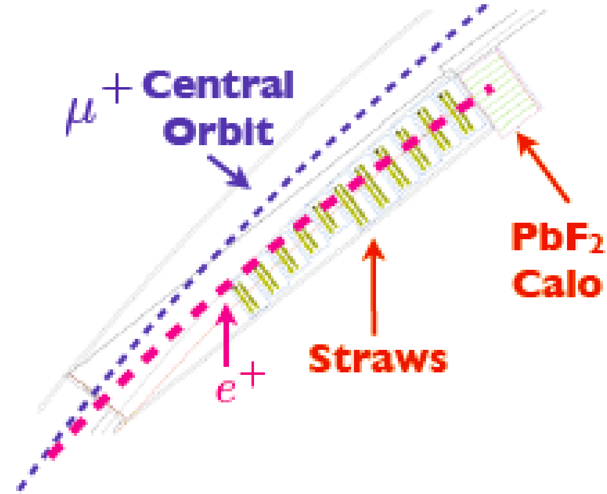
Segmented, fast response, PbF_2 crystal calorimeter (9X6 array)

- **Lead-floride Cherenkov crystal reduces pileup: SICCAS-SJTU-Washington**
  - **Fast separation for pileup backgrounds (>2.5 ns, 100%)**
  - **Resolution (2.3% at 3 GeV) better than requirement (5%)**
- **Silicon photomultiplier (SiPM) directly on back of PbF_2**
  - **No disturbing magnetic field, avoid long light guides**

Detector Performance: Tracker



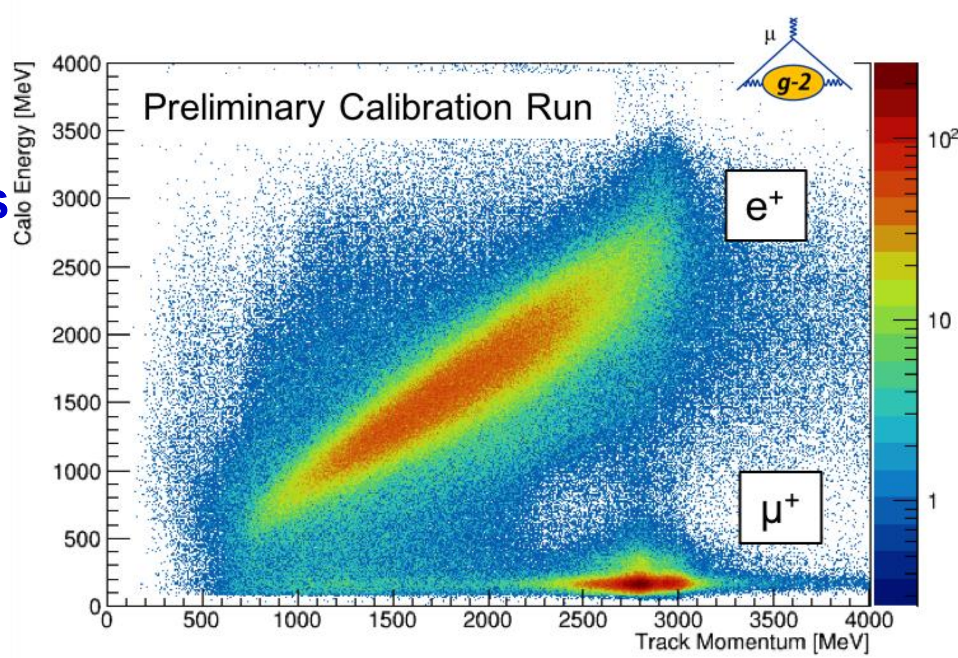




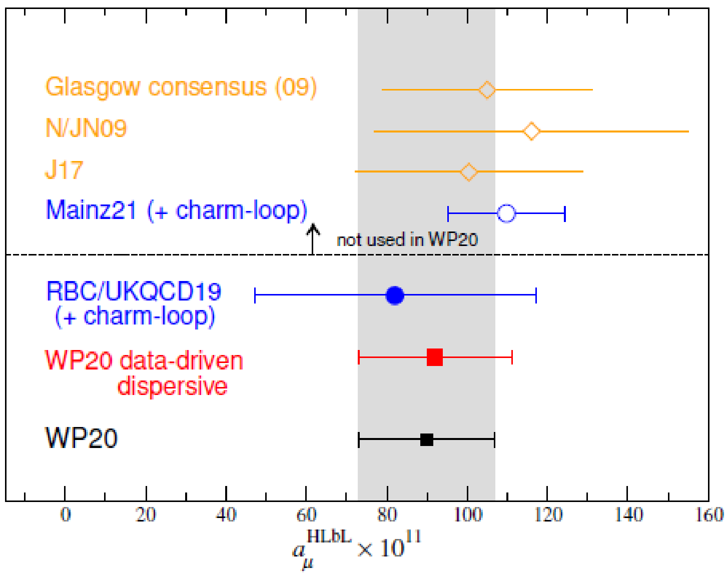
Doublet of UV straw chambers

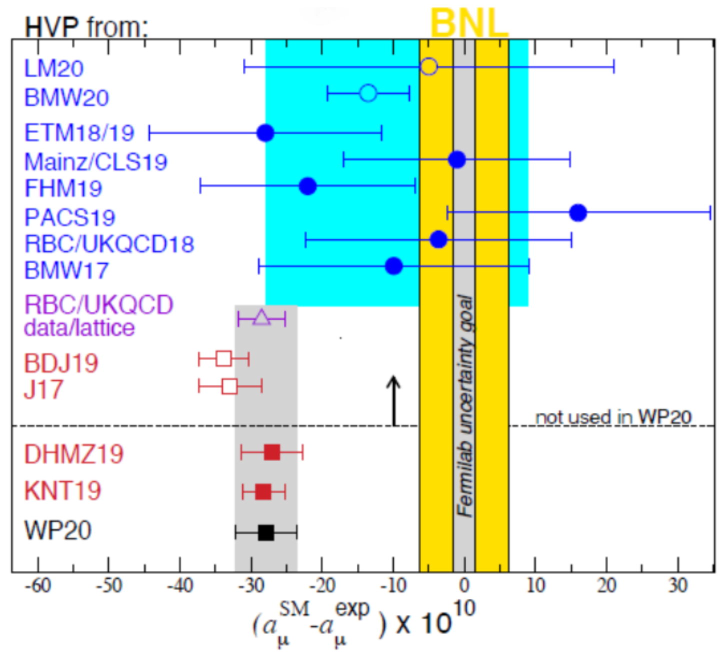
New straw tracking detector

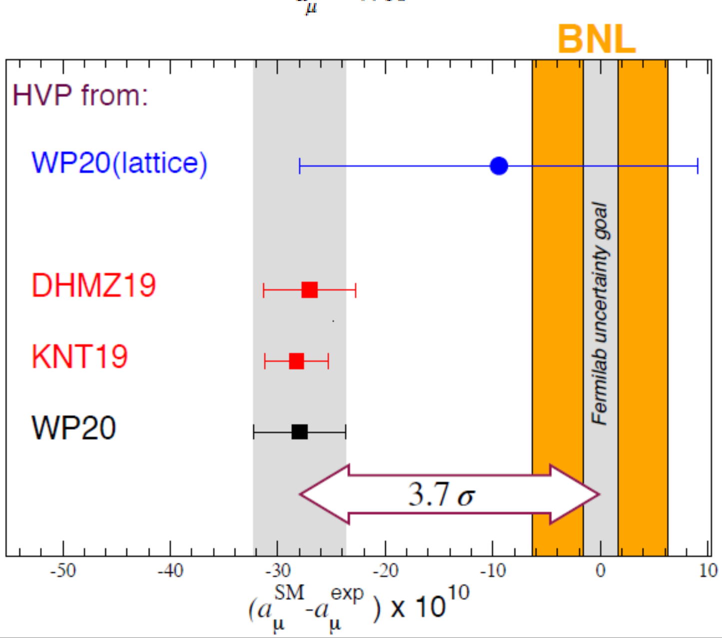
- **Two stations installed, 1024 straws**
- **Measure muon decay vertex and momentum**



Muon g-2 Theory Status







$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{HVP} + a_\mu^{HLbL} = 116591810\,(43) \times 10^{-11}$$

WP20: world average value of SM calc.

- **Strong theory community consensus**
- **"Recent lattice result by BMW with 0.8% error needs further study"**
- **Looking forward to updated conventional and lattice results**