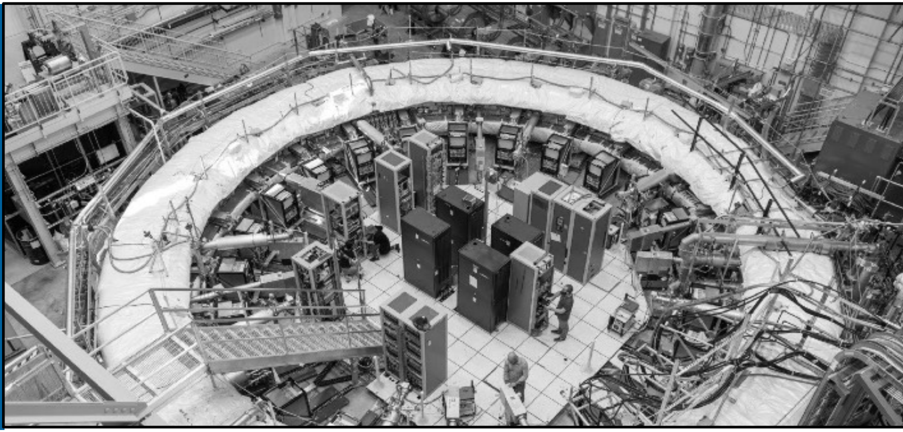
Argonne NATIONAL LABORATORY

OVERVIEW OF THE MUON G-2 EXPERIMENT AT FERMILAB



SIMON CORRODI
Argonne National Laboratory

on behalf of the Muon g-2 collaboration
II Workshop on Muon Precision Physics (MPP2023)
November 8th 2023

μ g-2

INTRINSIC MAGNETIC MOMENT

Magnetic moment $\overrightarrow{\mu}$ is connected to spin $\vec{s}$ via dimensionless factor g

"gyromagnetic ratio"

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

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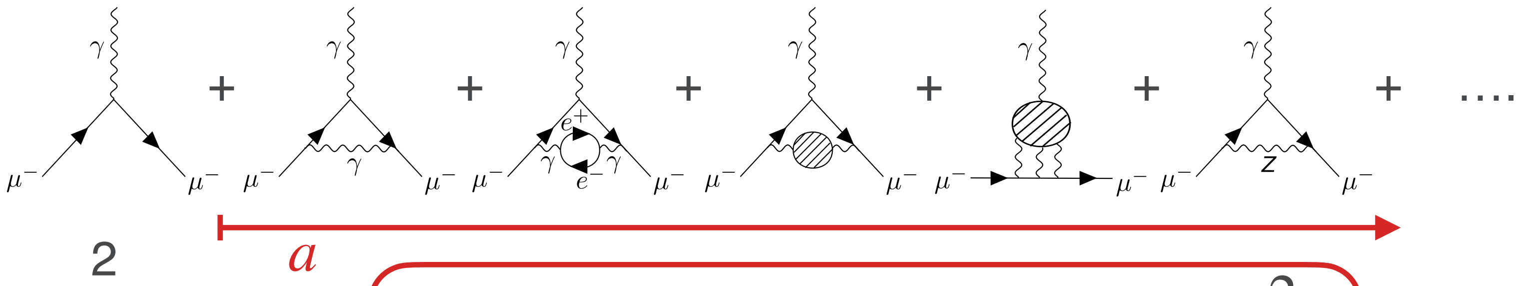


anomalous magnetic moment: $a \equiv \frac{g-2}{2}$

THE MAGNETIC MOMENT OF THE MUON: HISTORY

Storage Ring

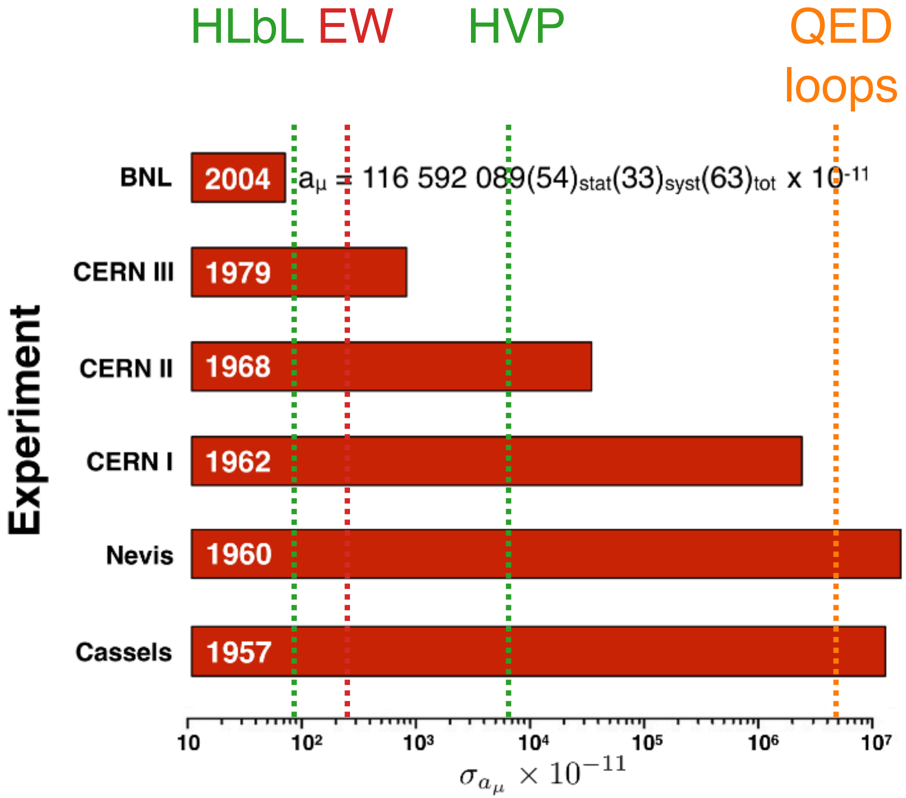
Dilated lifetime

measurement of a_μ, more precise

Stopped Muons

Stop muons in a magnetic field

measurement of g_μ directly



THE MAGNETIC MOMENT OF THE MUON: HISTORY

~3.5σ sigma between a_μ^{exp} and a_μ^{SM}

Storage Ring

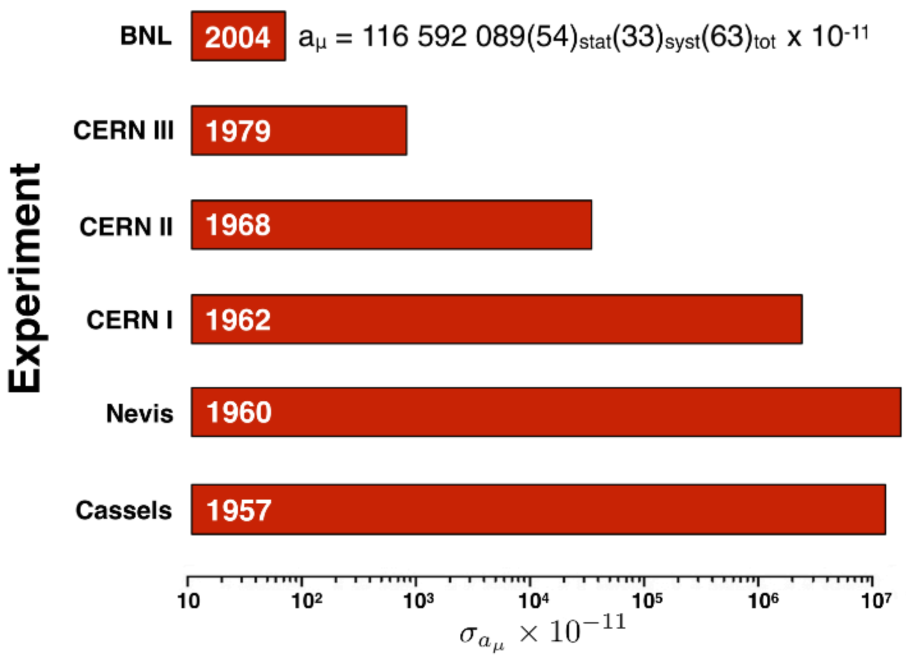
Dilated lifetime

measurement of a_μ, more precise

Stopped Muons

Stop muons in a magnetic field

measurement of g_μ directly



THE MAGNETIC MOMENT OF THE MUON: HISTORY

FNAL **goal**: 4 x improvement

Storage Ring

Dilated lifetime

measurement of a_μ, more precise

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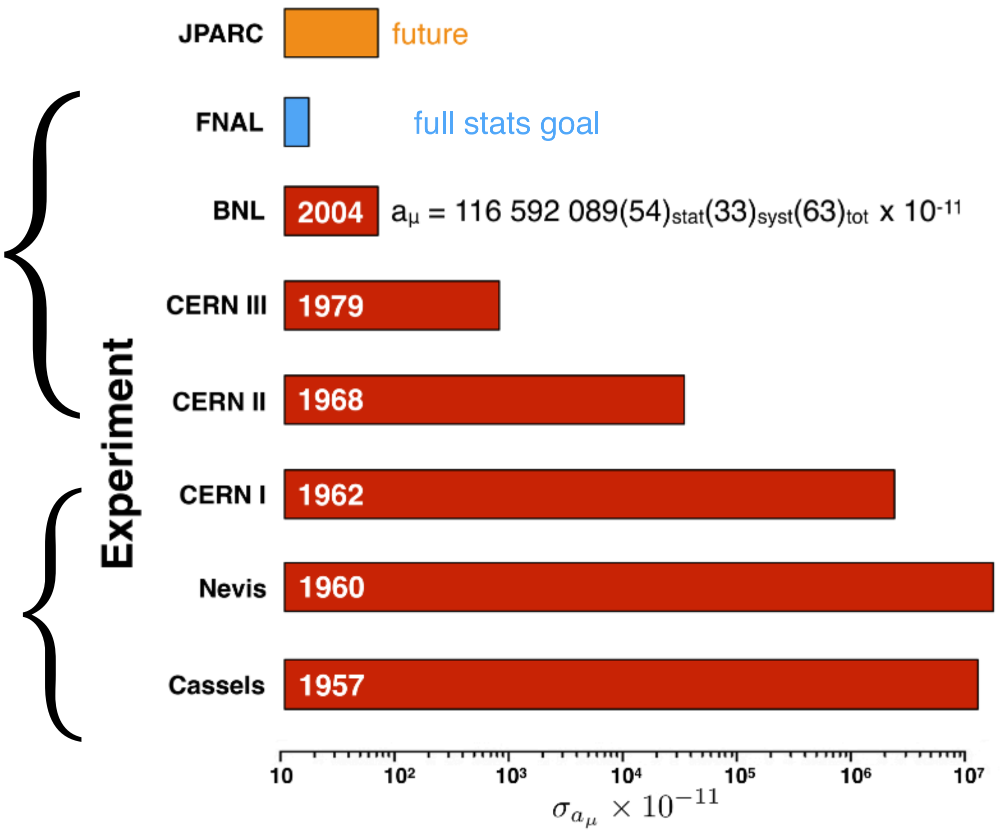
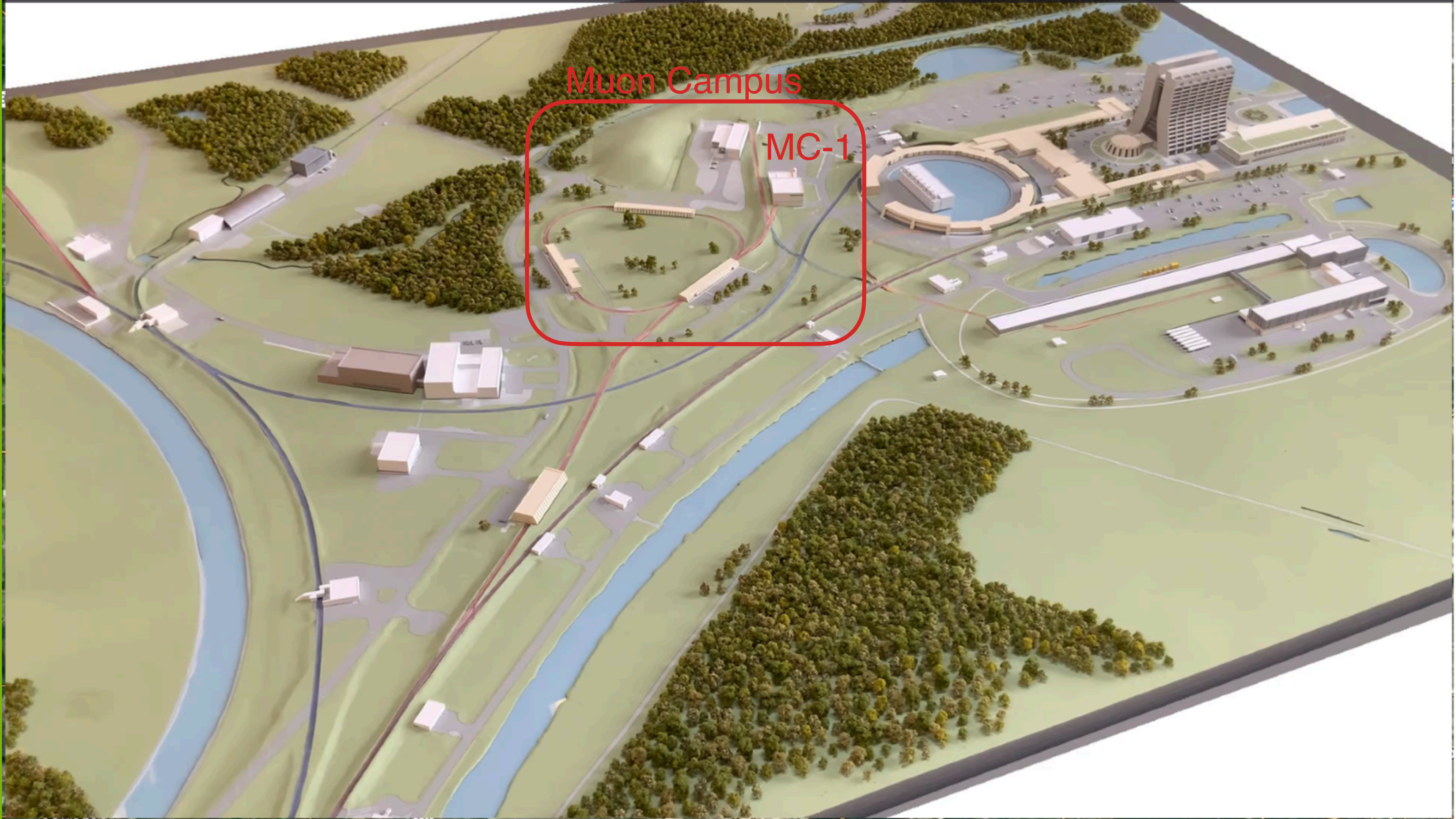
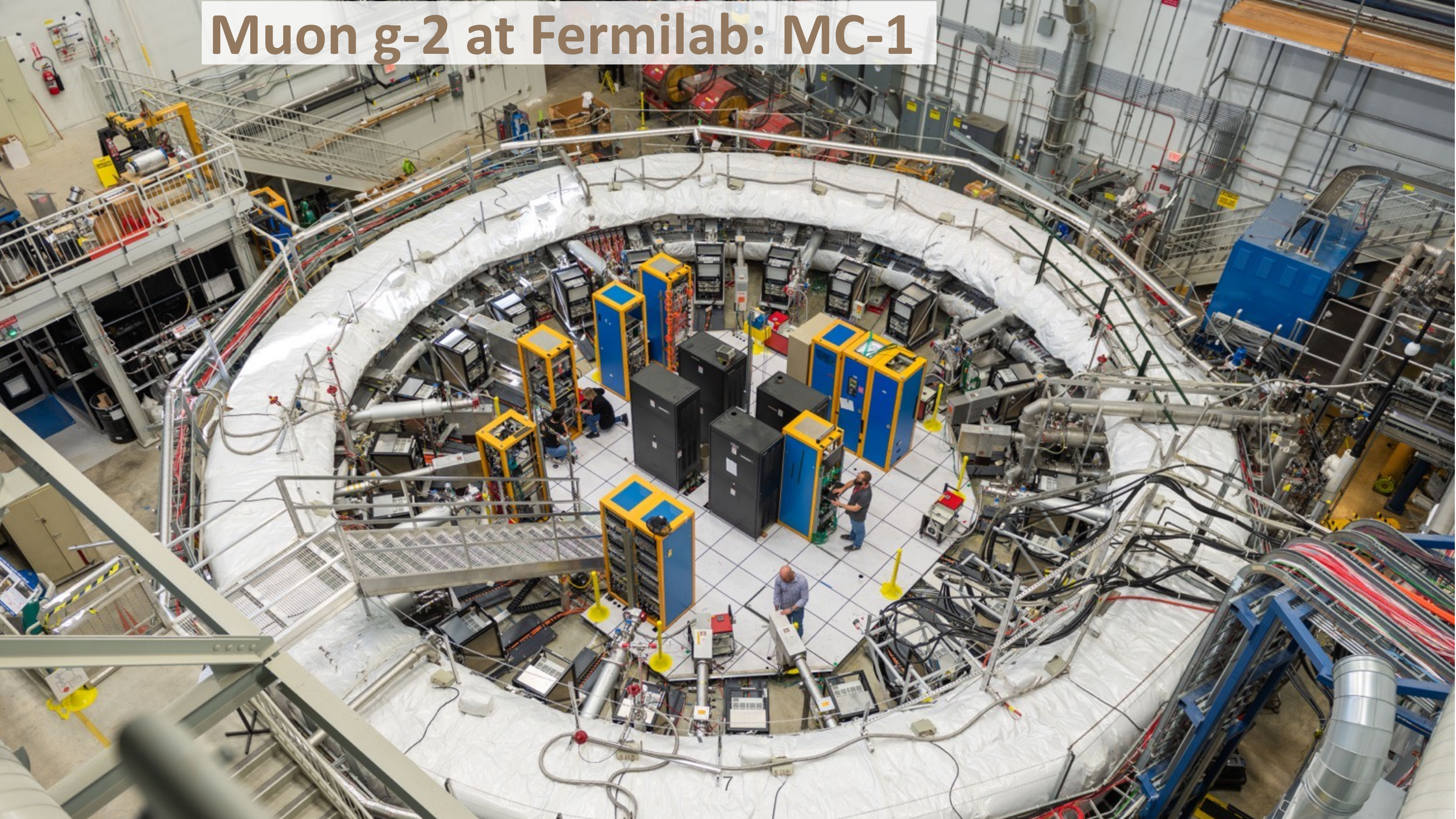
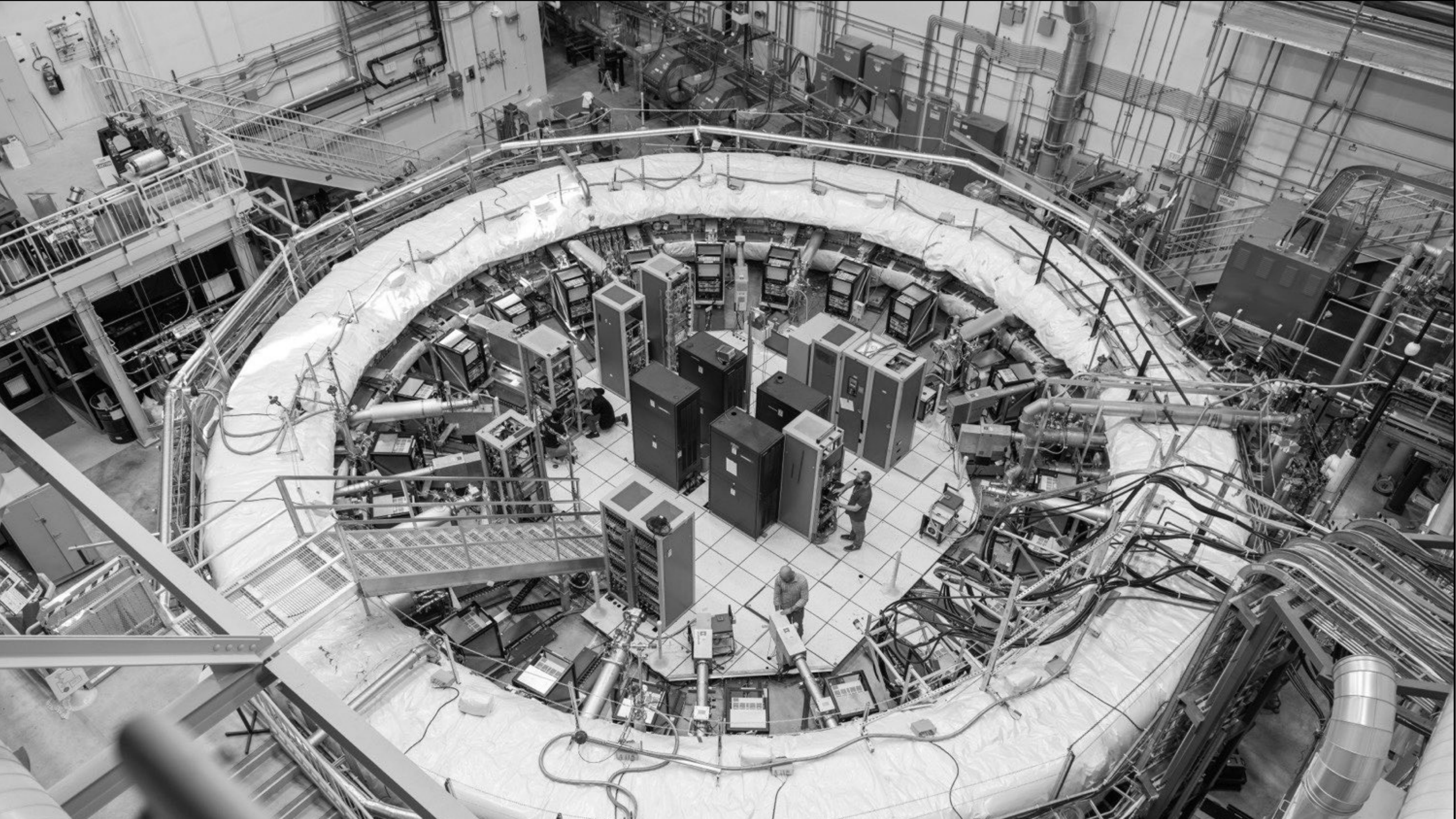
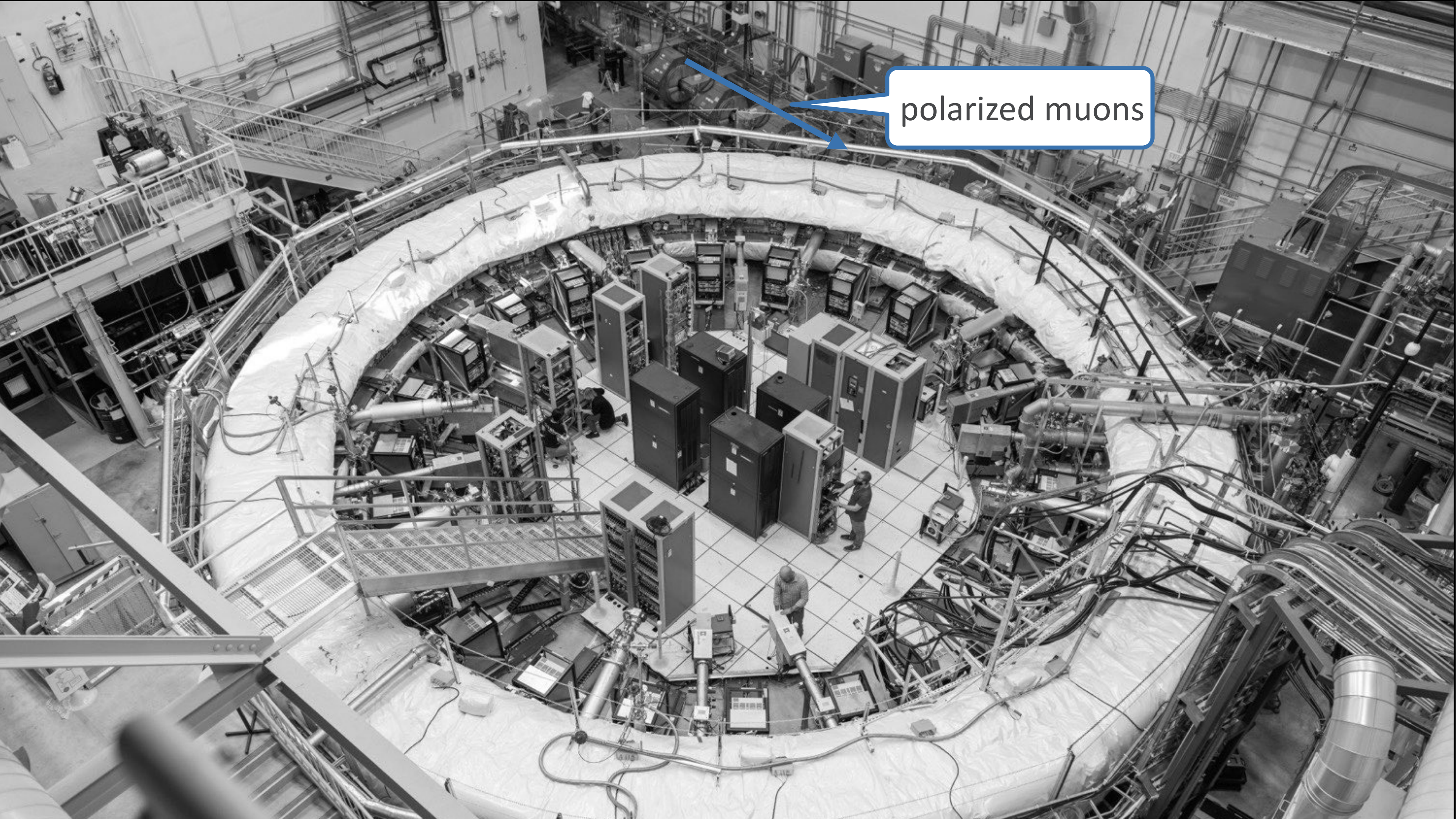


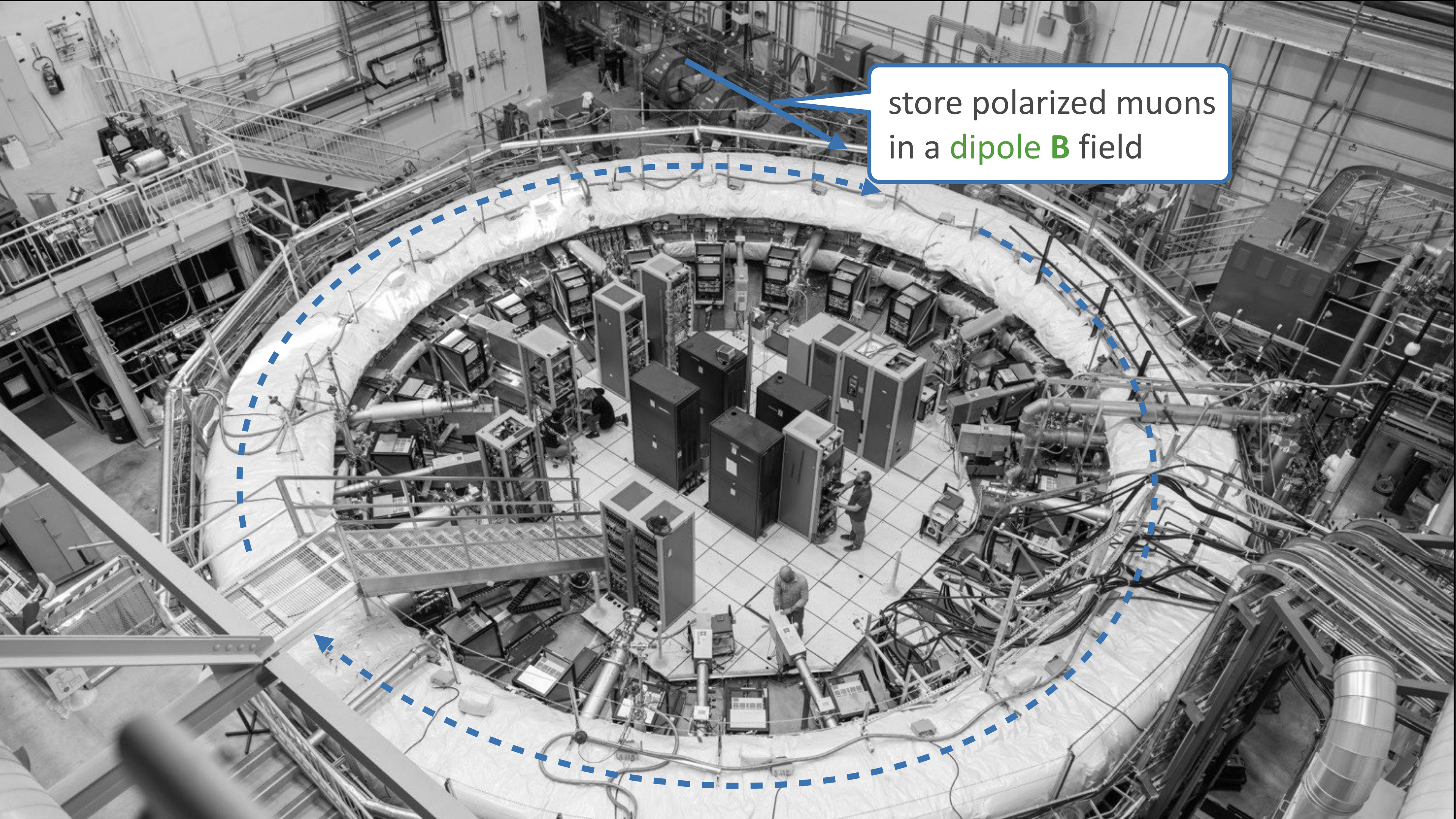

Muon Campus
MC-1

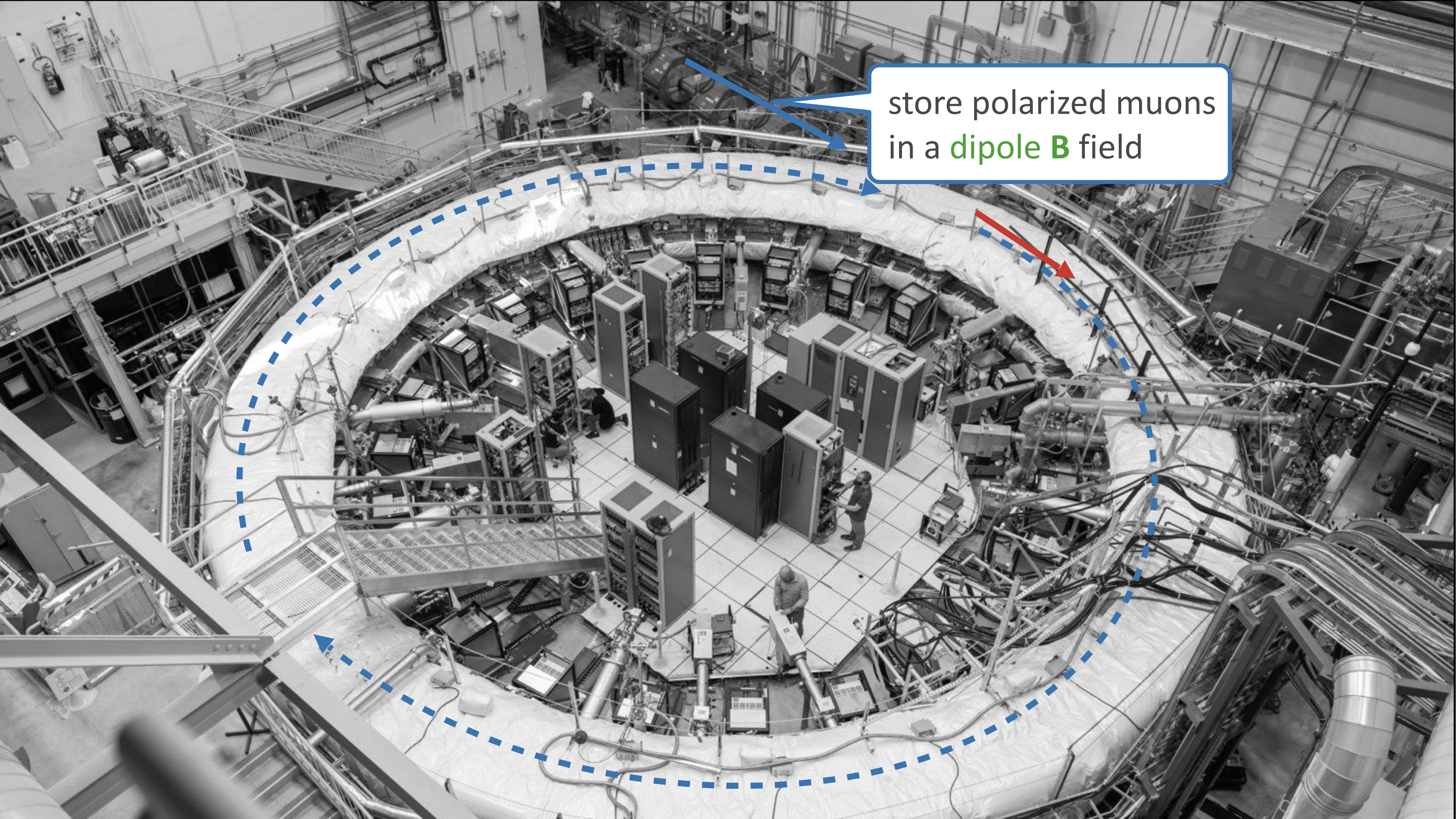
Muon g-2 at Fermilab: MC-1






polarized muons


store polarized muons
in a dipole B field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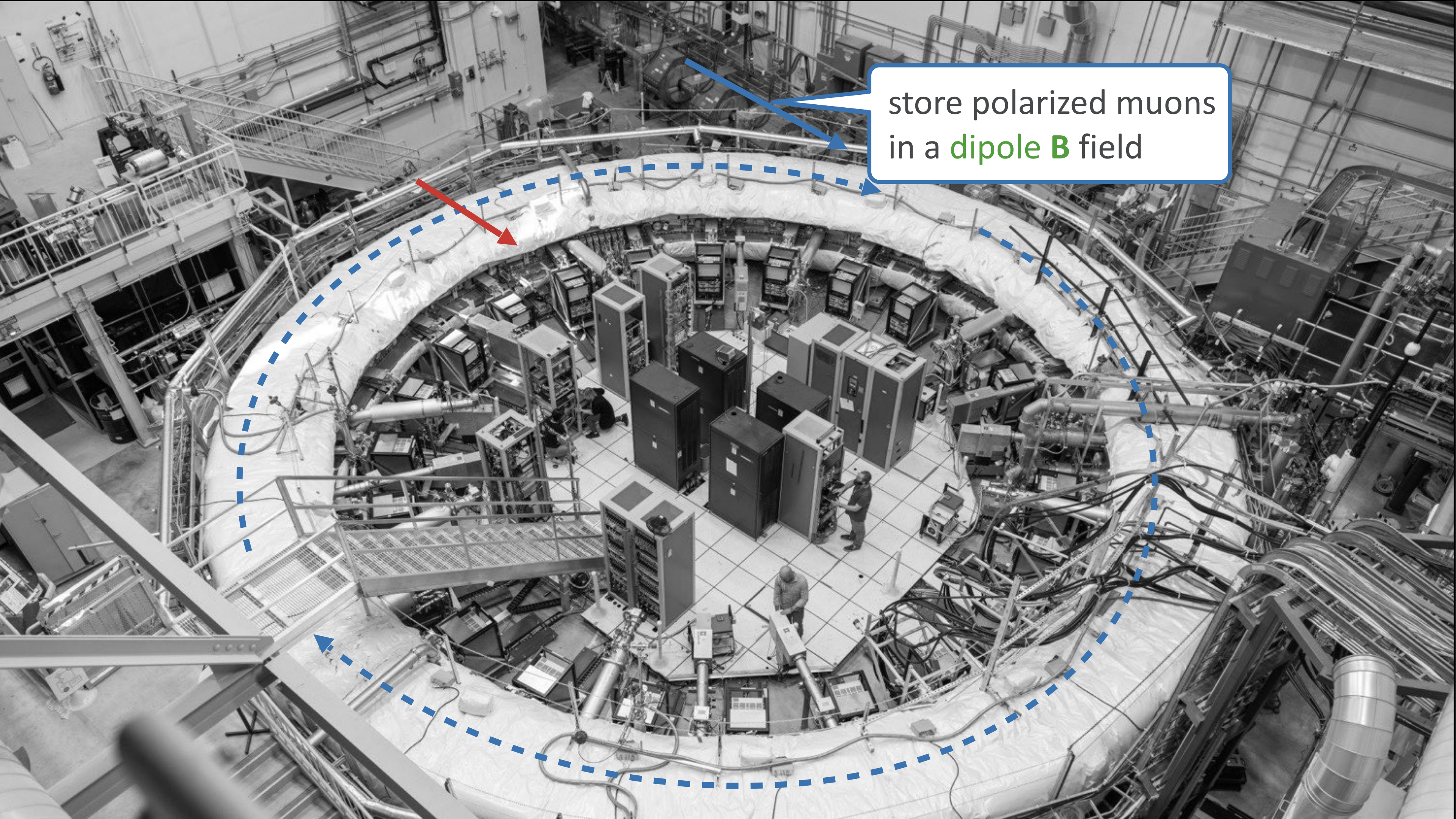
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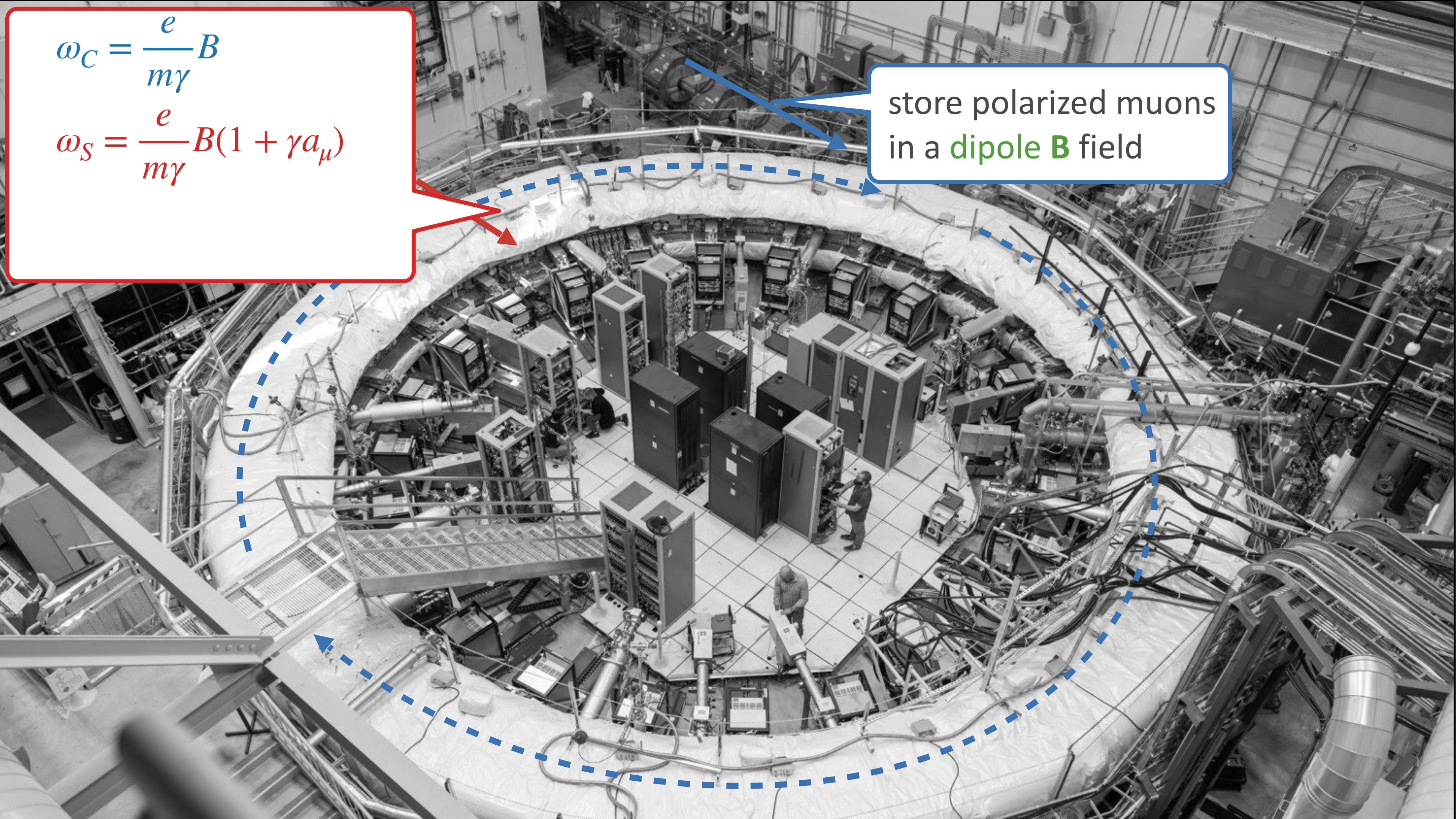
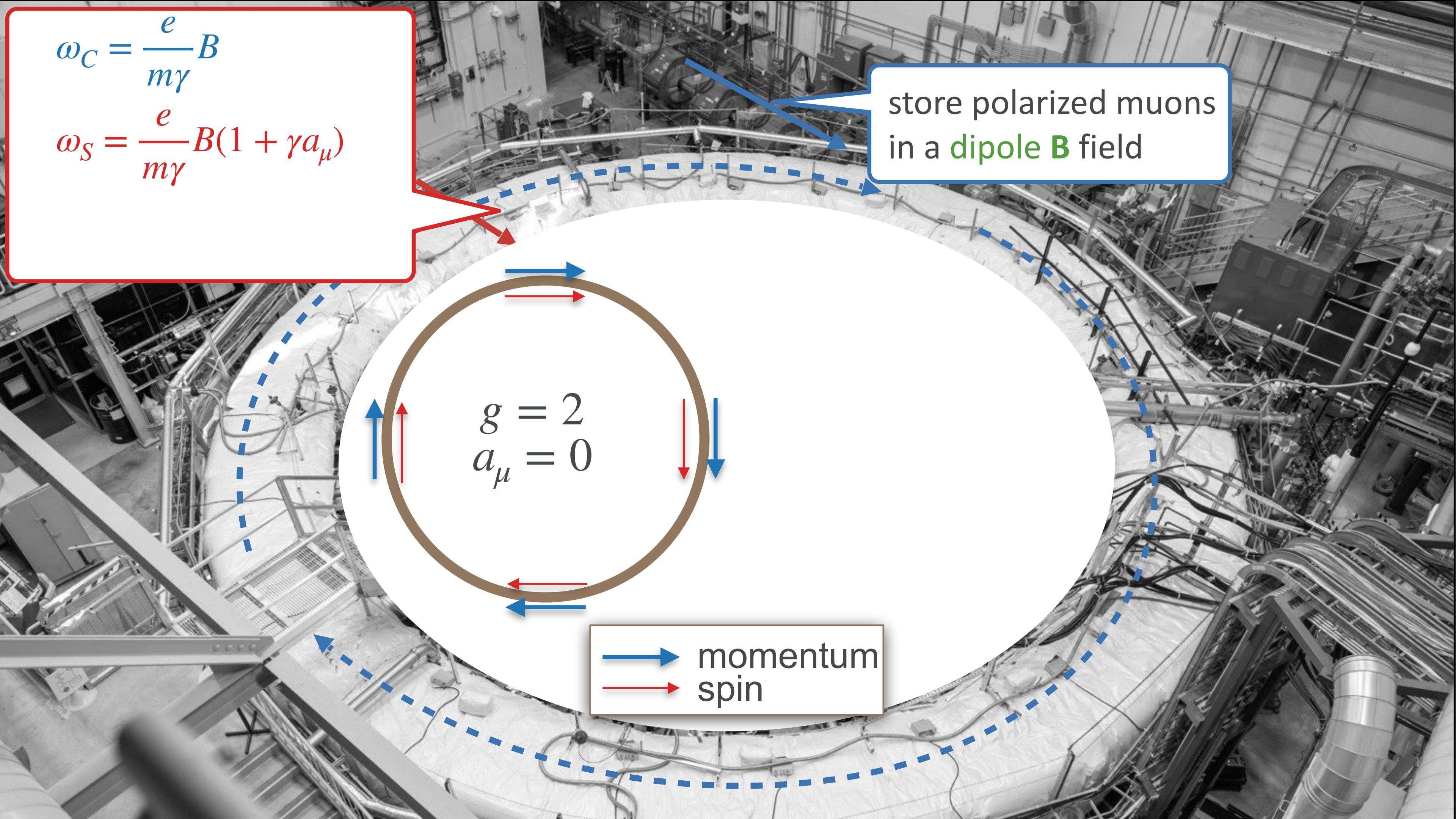
$$\omega_C = \frac{e}{m\gamma} B$$

$$\omega_S = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$





$\omega_C = \frac{e}{m\gamma} B$
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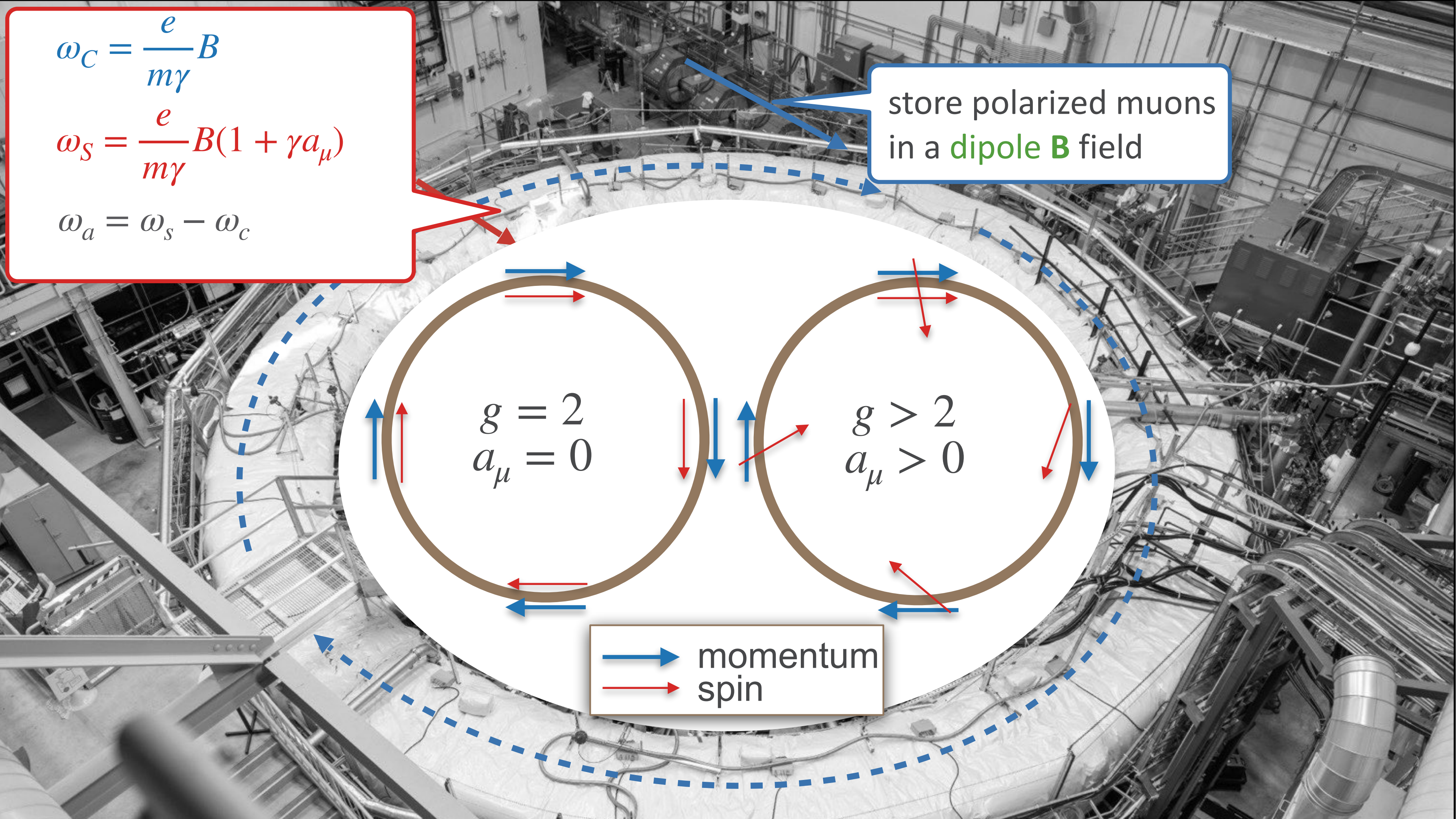
store polarized muons
in a dipole **B** field
$g = 2$
$a_\mu = 0$
momentum
spin



$\omega_C = \frac{e}{m\gamma} B$
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$\omega_a = \omega_s - \omega_c$
store polarized muons
in a dipole **B** field
$g = 2$
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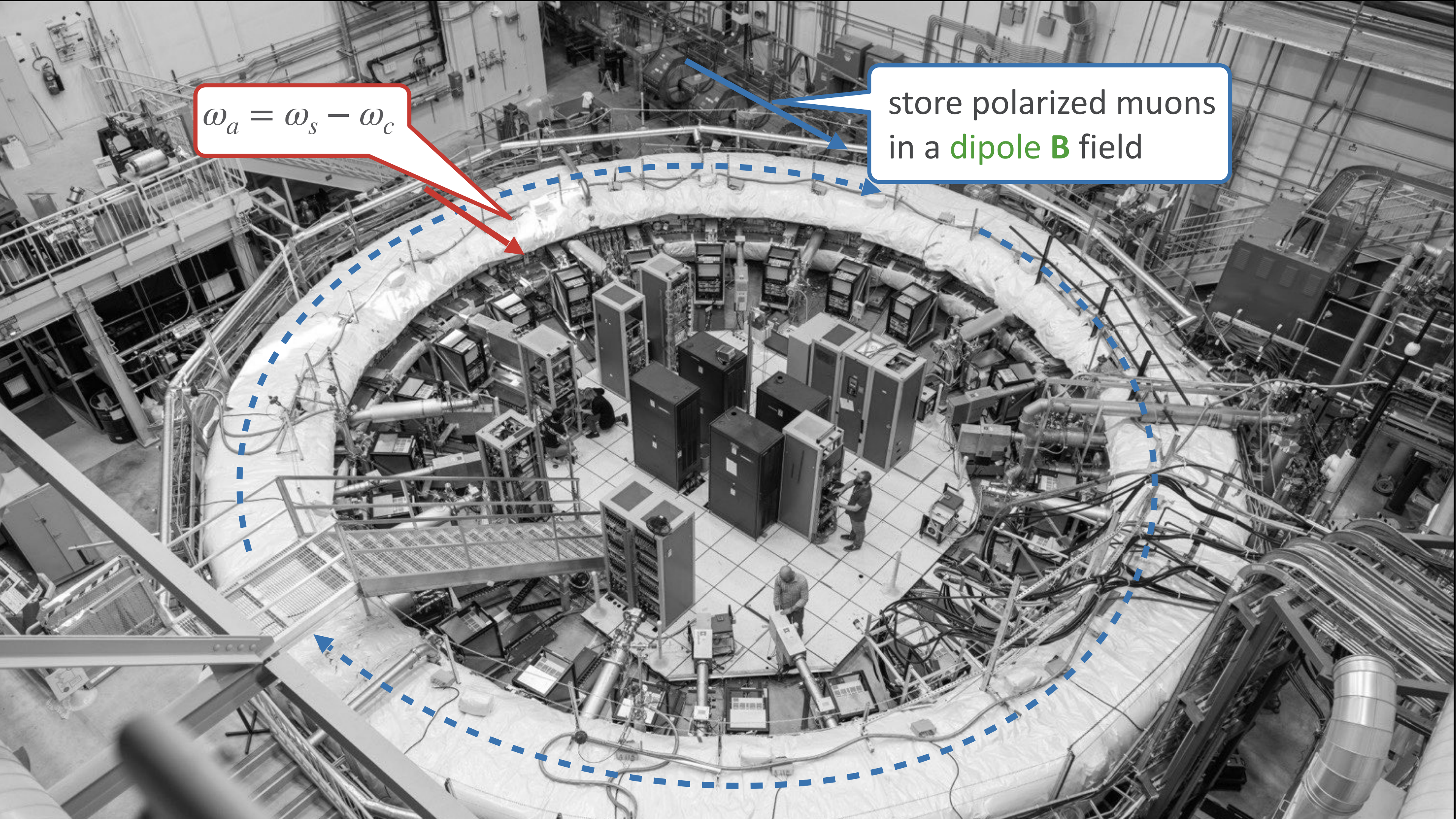
$g > 2$
$a_\mu > 0$
momentum
spin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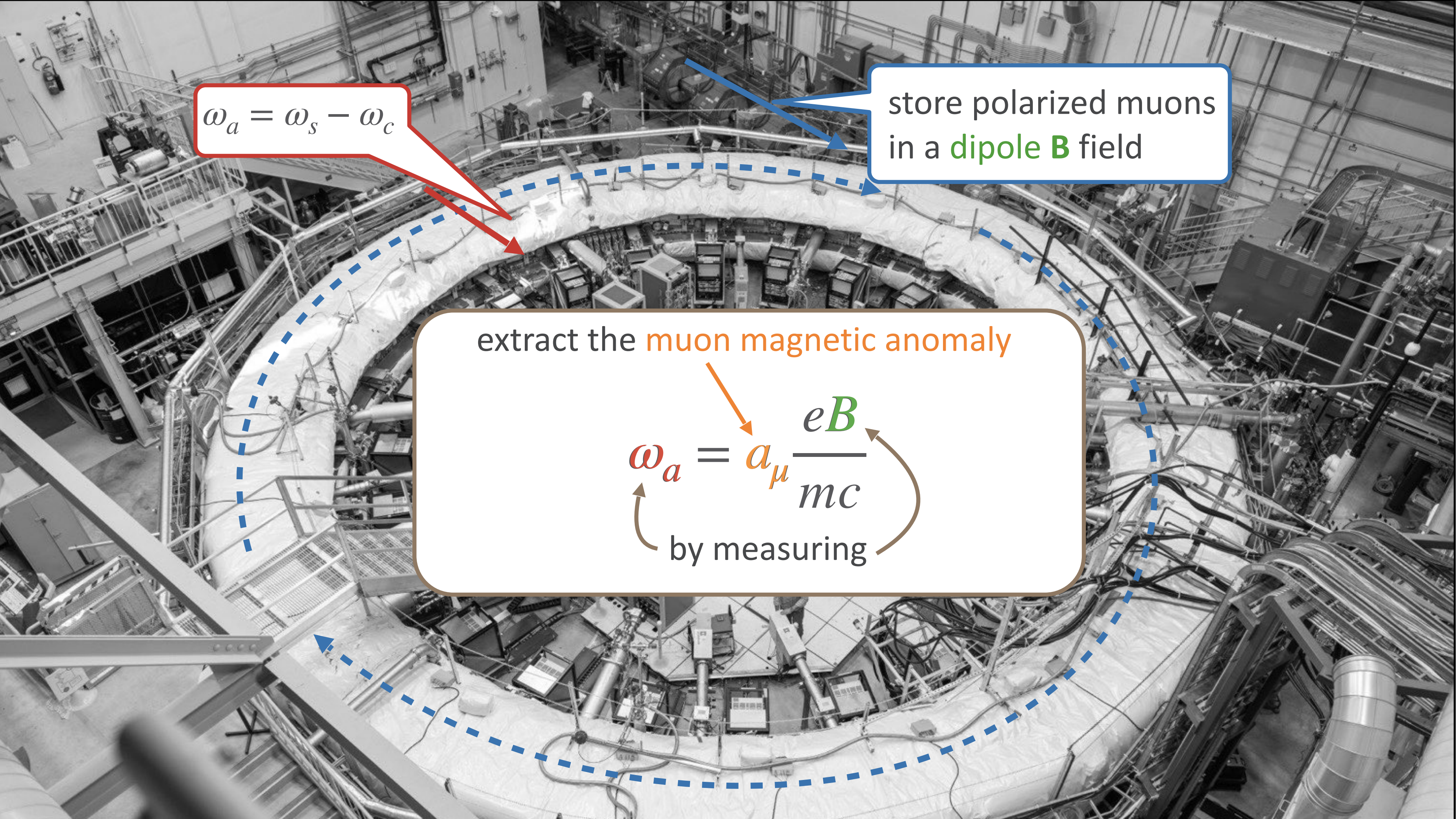

$\omega_a = \omega_s - \omega_c$
store polarized muons in a dipole B field
extract the muon magnetic anomaly
$\omega_a = a_\mu \frac{eB}{mc}$
by measuring

WHAT IS THE MAGIC MOMENTUM?

extract the muon magnetic anomaly

$$\vec{\omega}_a = -\frac{q}{m} a_\mu \vec{B}$$

by measuring

WHAT IS THE MAGIC MOMENTUM?

extract the muon magnetic anomaly

$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} + \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta} x \vec{E}}{c}\right)$$

by measuring

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~0

$$p = p_{\text{magic}} = \frac{mc}{\sqrt{a_\mu}} = 3.094\,\text{GeV/c}$$

WHAT IS THE MAGIC MOMENTUM?

extract the muon magnetic anomaly

pitch corrections: C_p E-field corrections: C_e

$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} + \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta} x \vec{E}}{c}\right)$$

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~0 ~0

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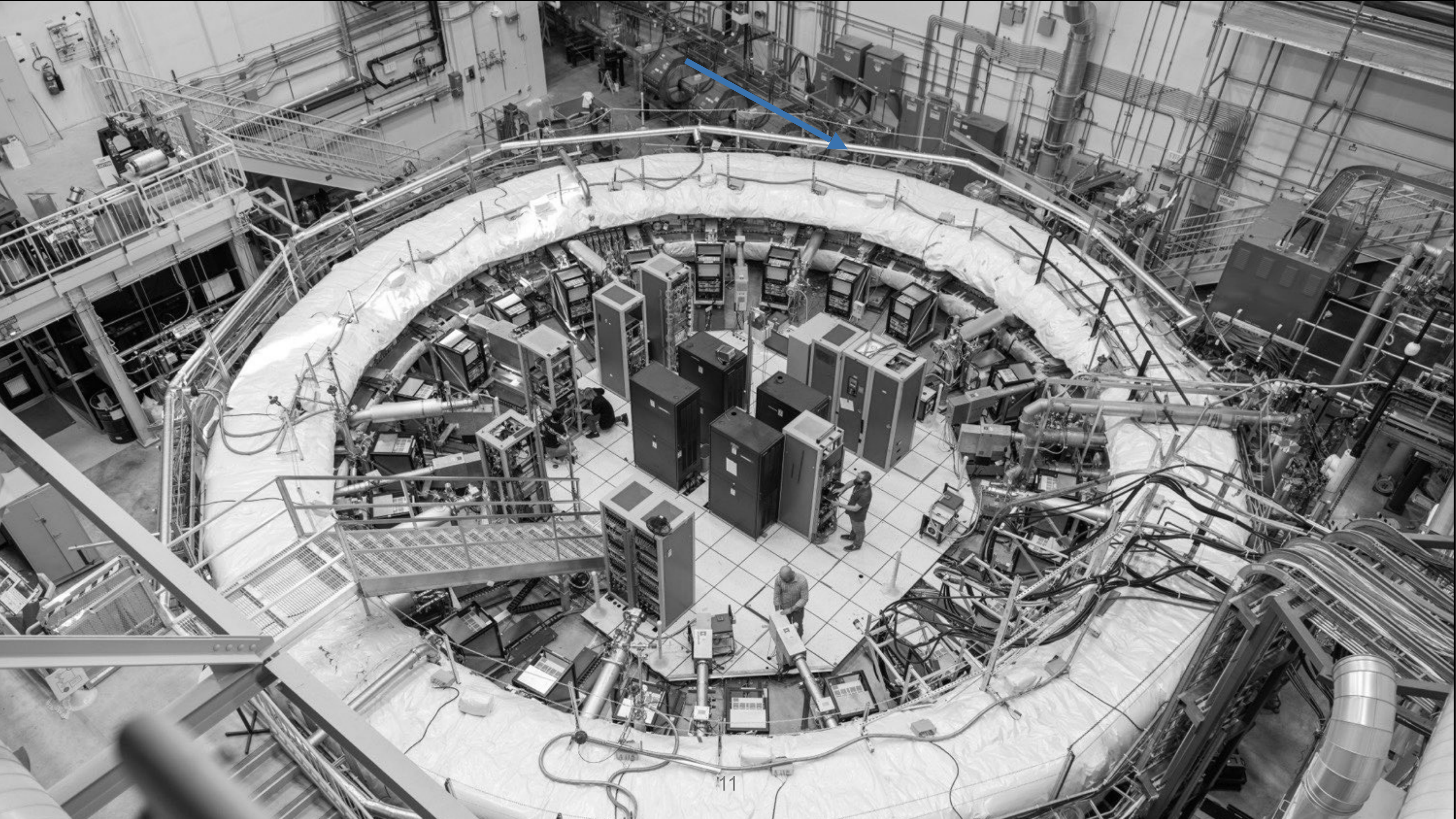
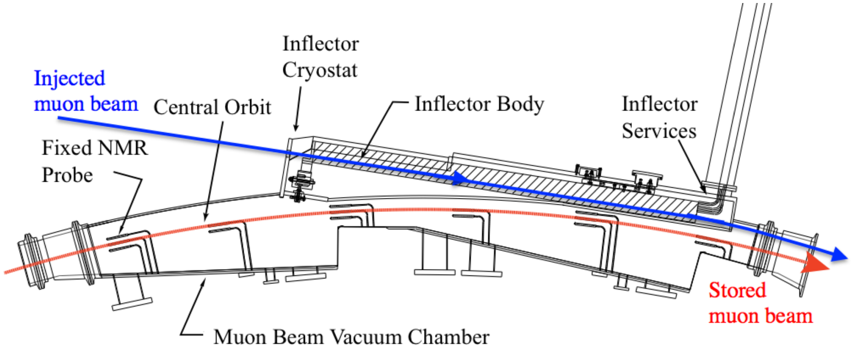
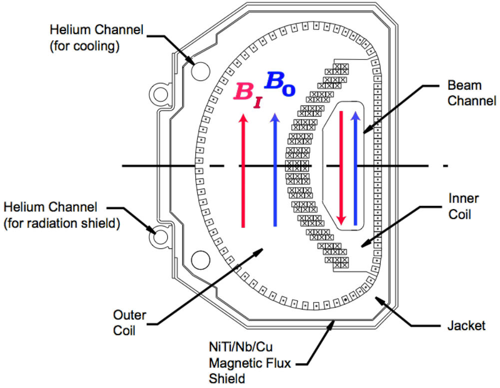
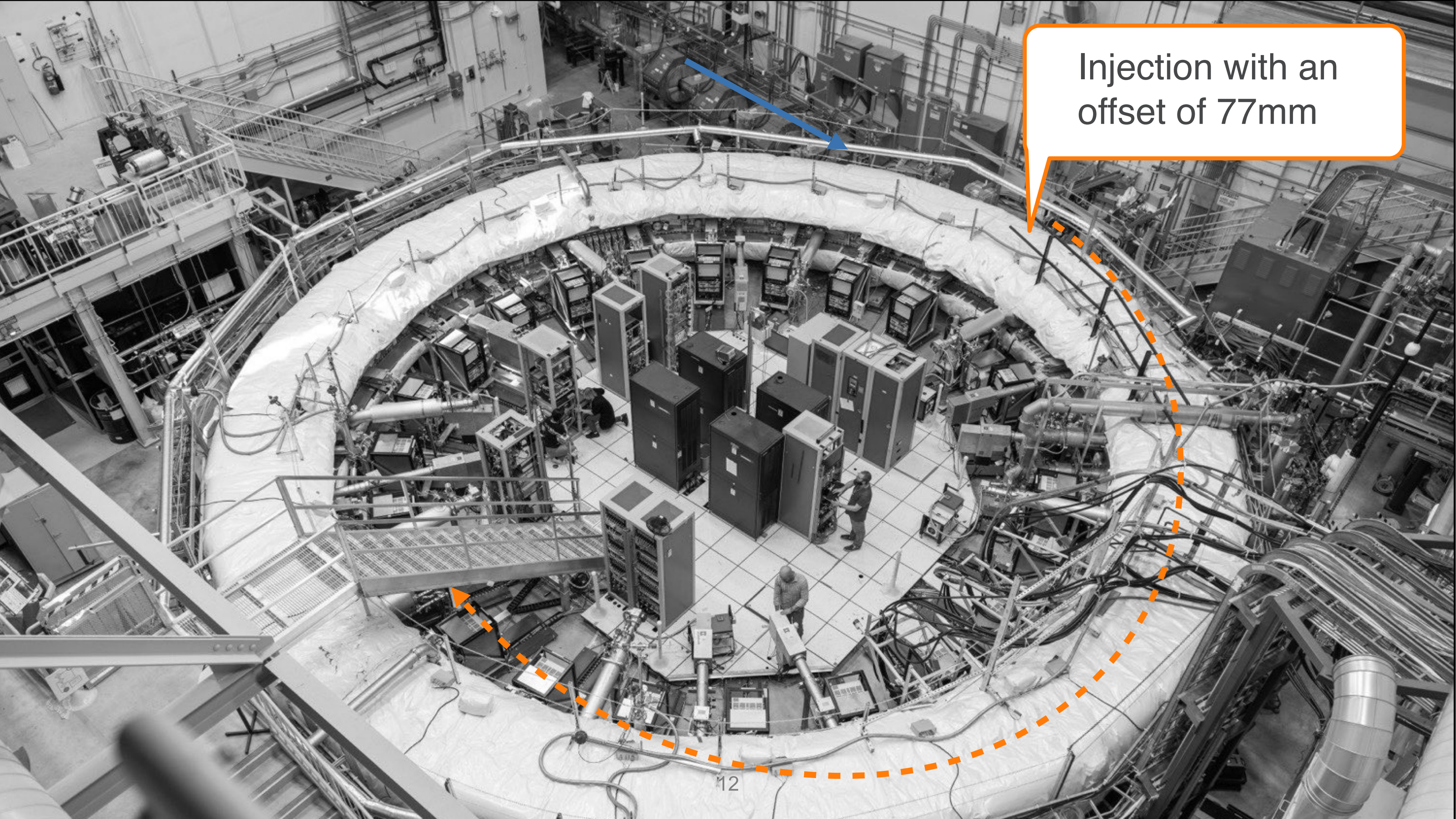


Injection with an offset of 77mm

“Inflector” magnet: provides field free injection path






Injection with an
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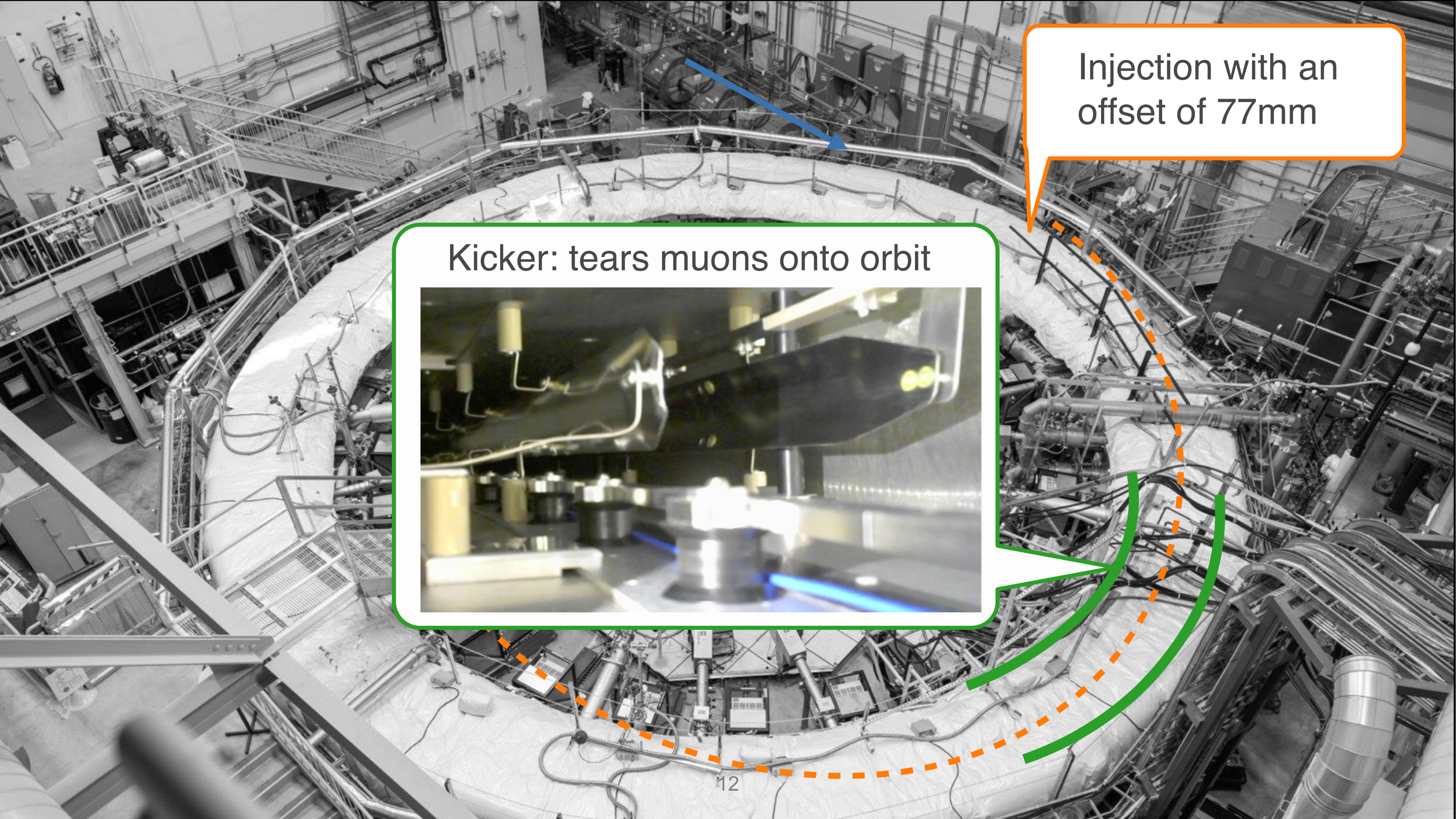
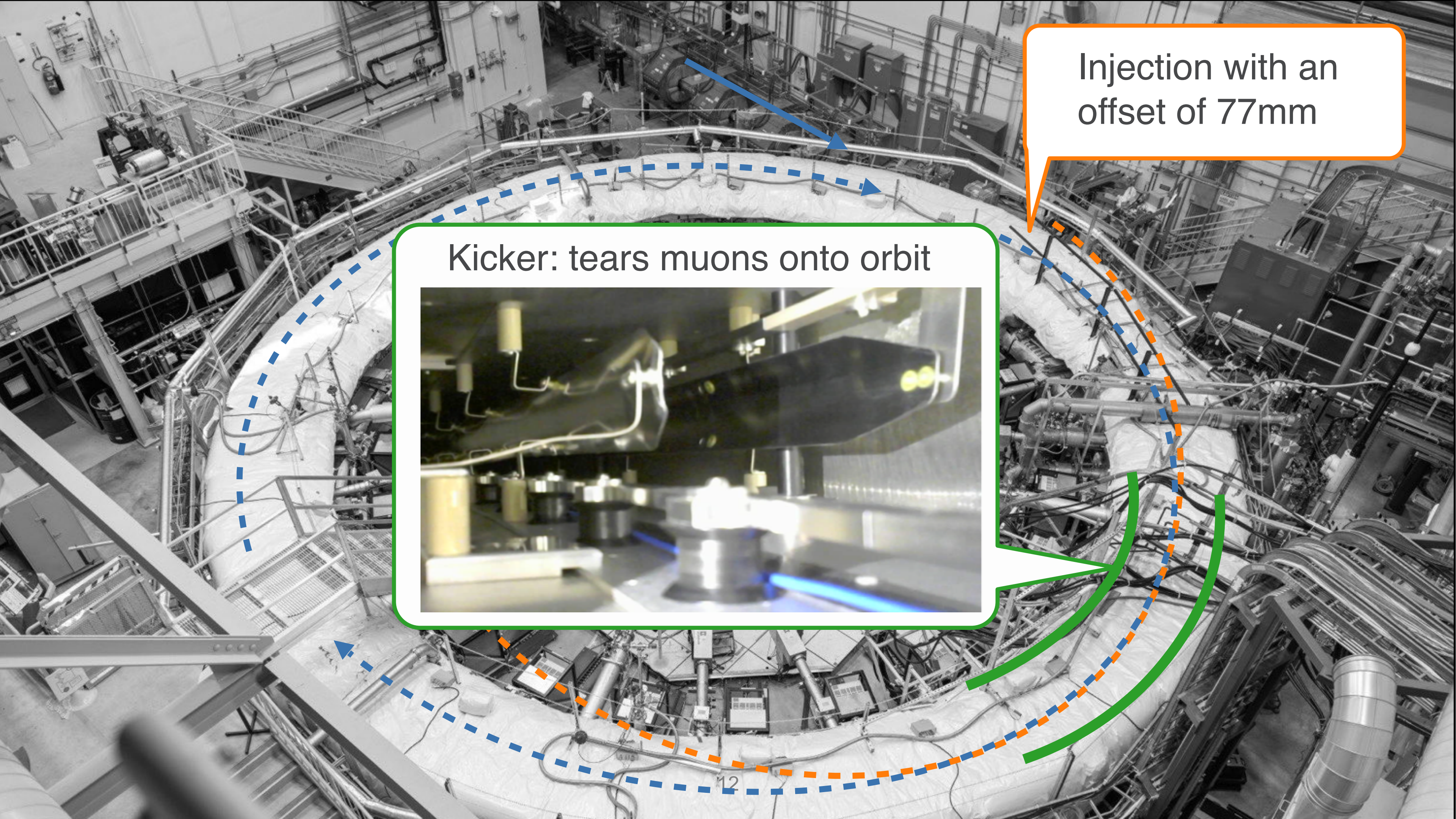

Injection with an offset of 77mm
Kicker: tears muons onto orbit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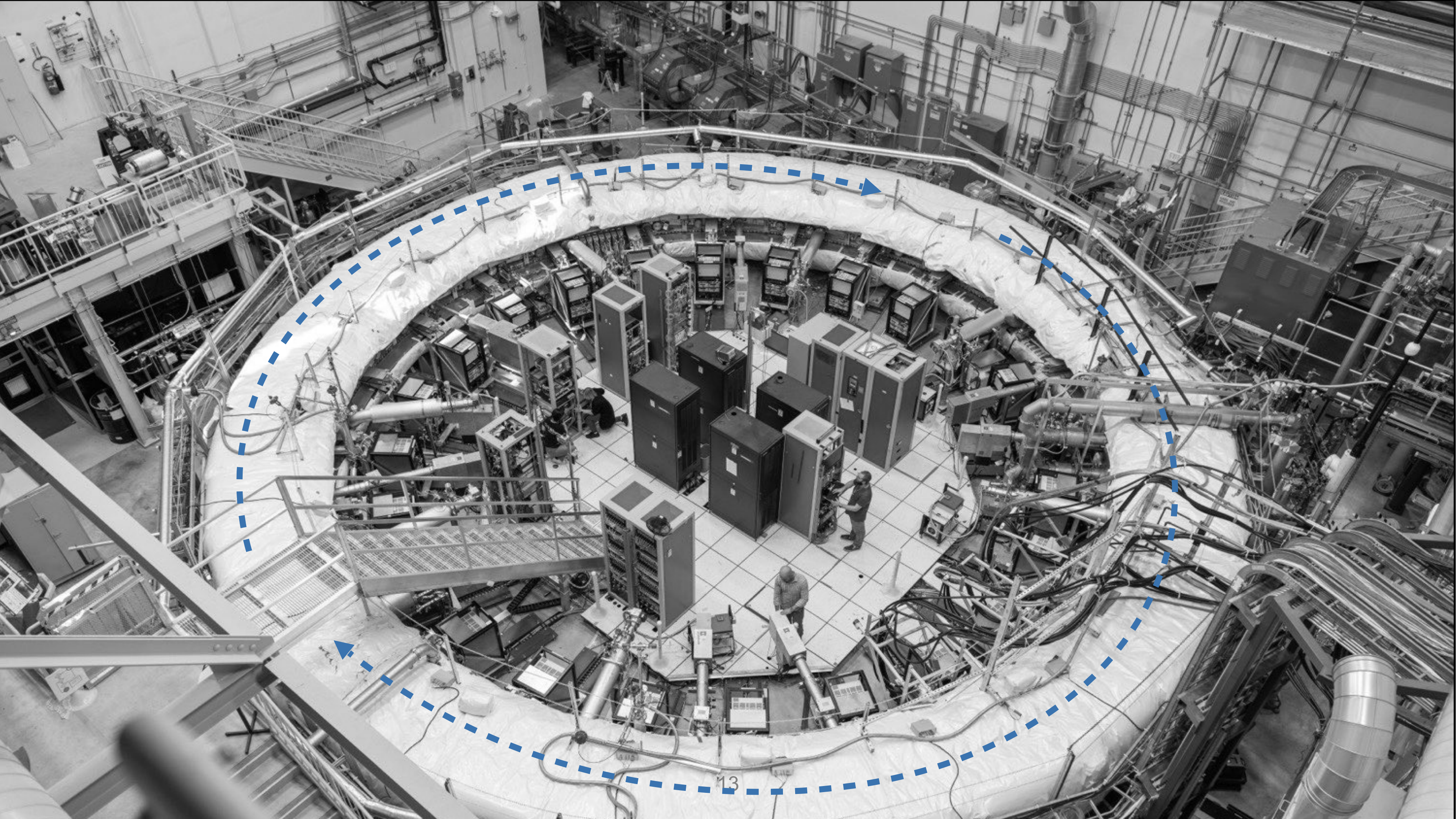
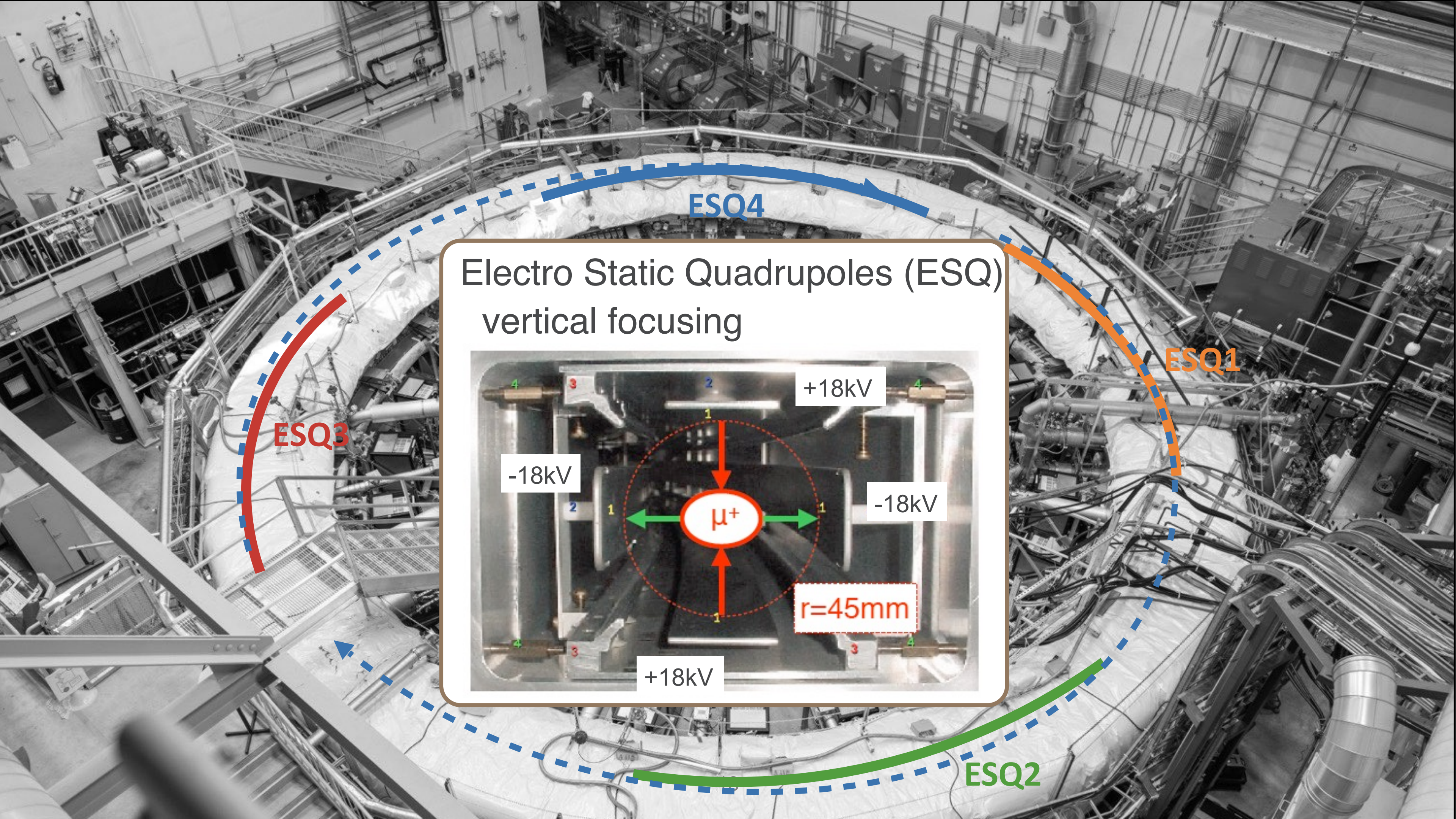
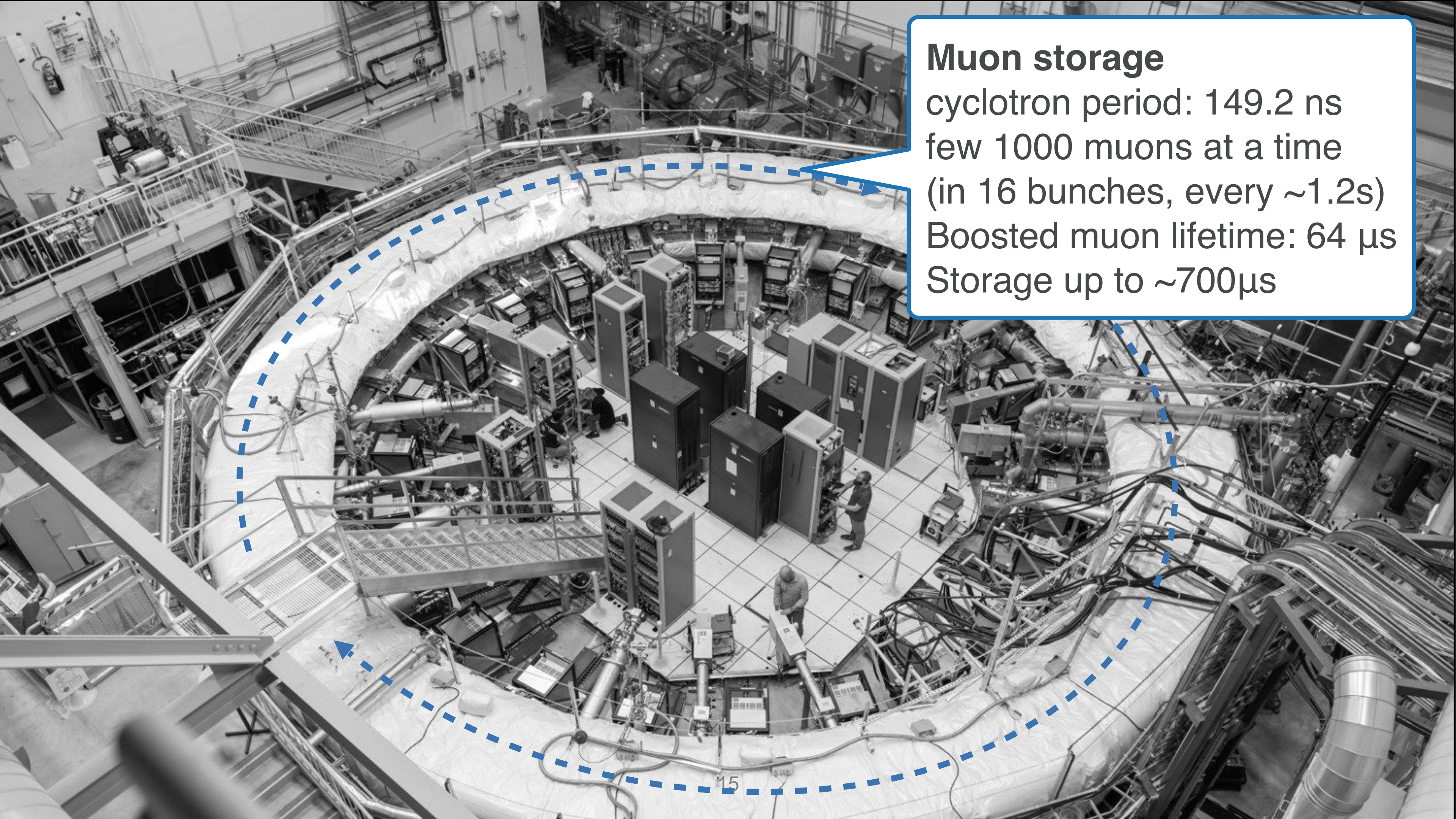
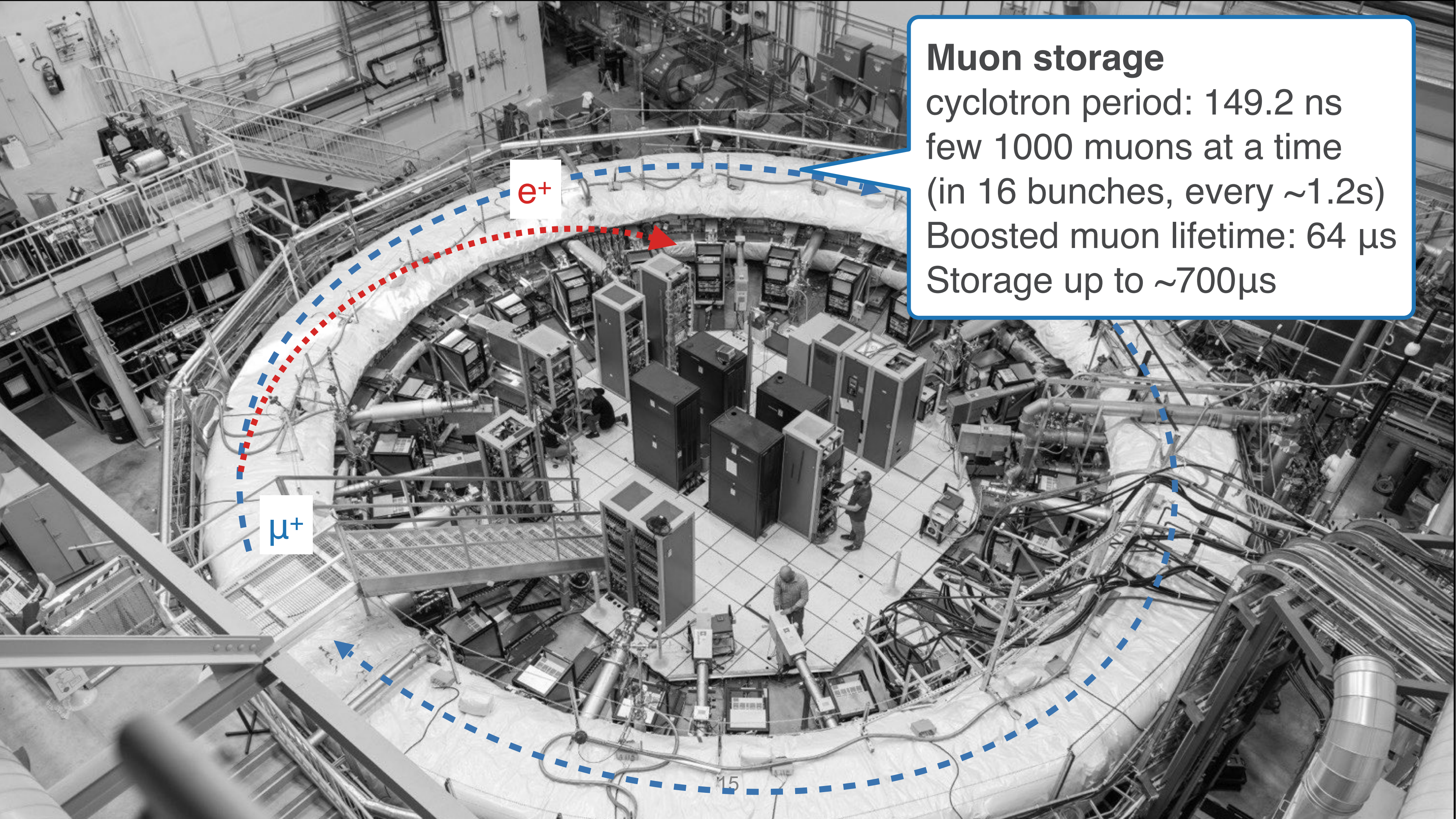



Electro Static Quadrupoles (ESQ)
vertical focusing
ESQ4
ESQ1
ESQ3
ESQ2
+18kV
-18kV
-18kV
+18kV
μ+
r=45mm


speed 8x


speed 8x


Muon storage
cyclotron period: 149.2 ns
few 1000 muons at a time
(in 16 bunches, every ~1.2s)
Boosted muon lifetime: 64 μs
Storage up to ~700μs


e+
μ+
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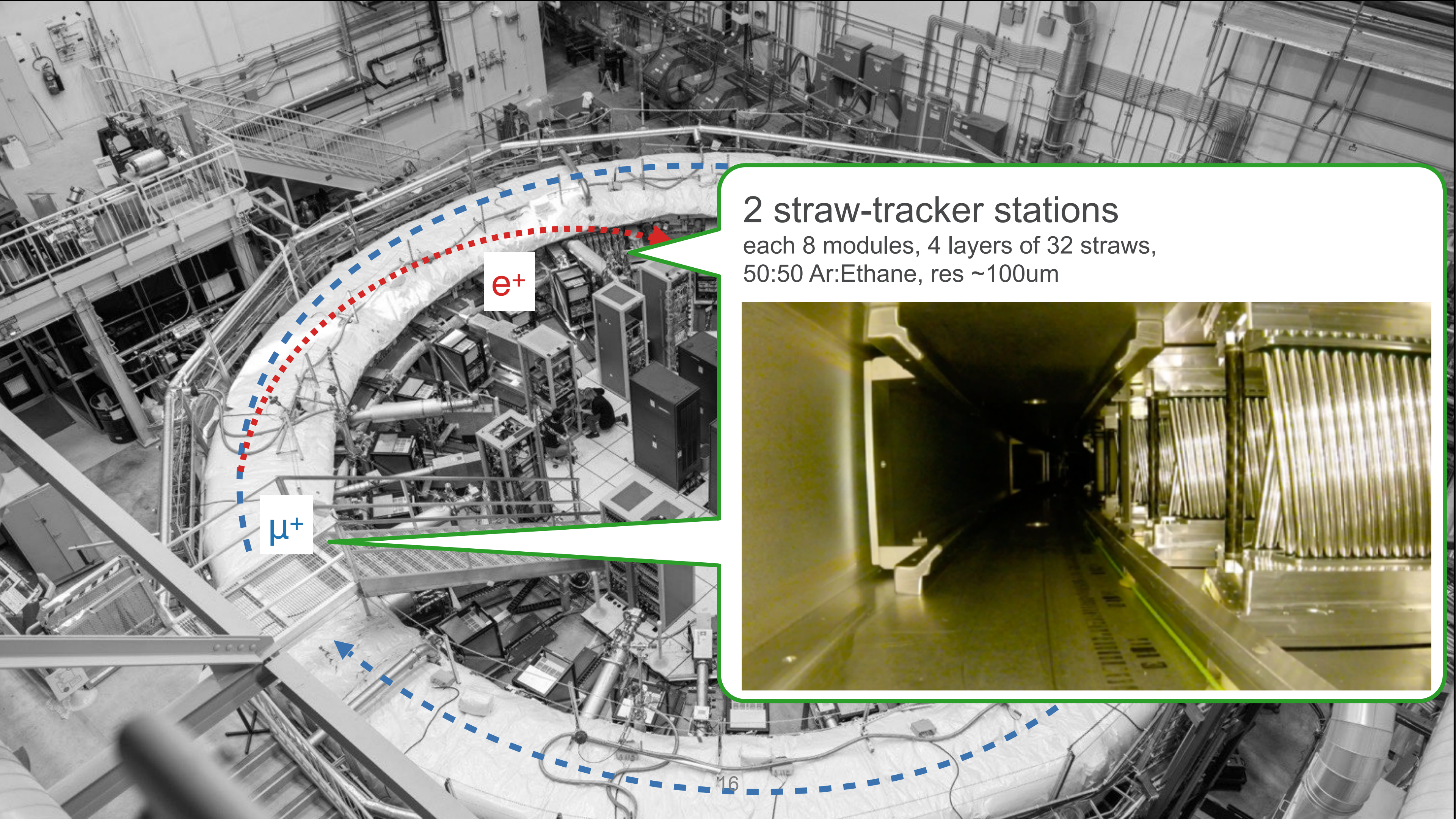
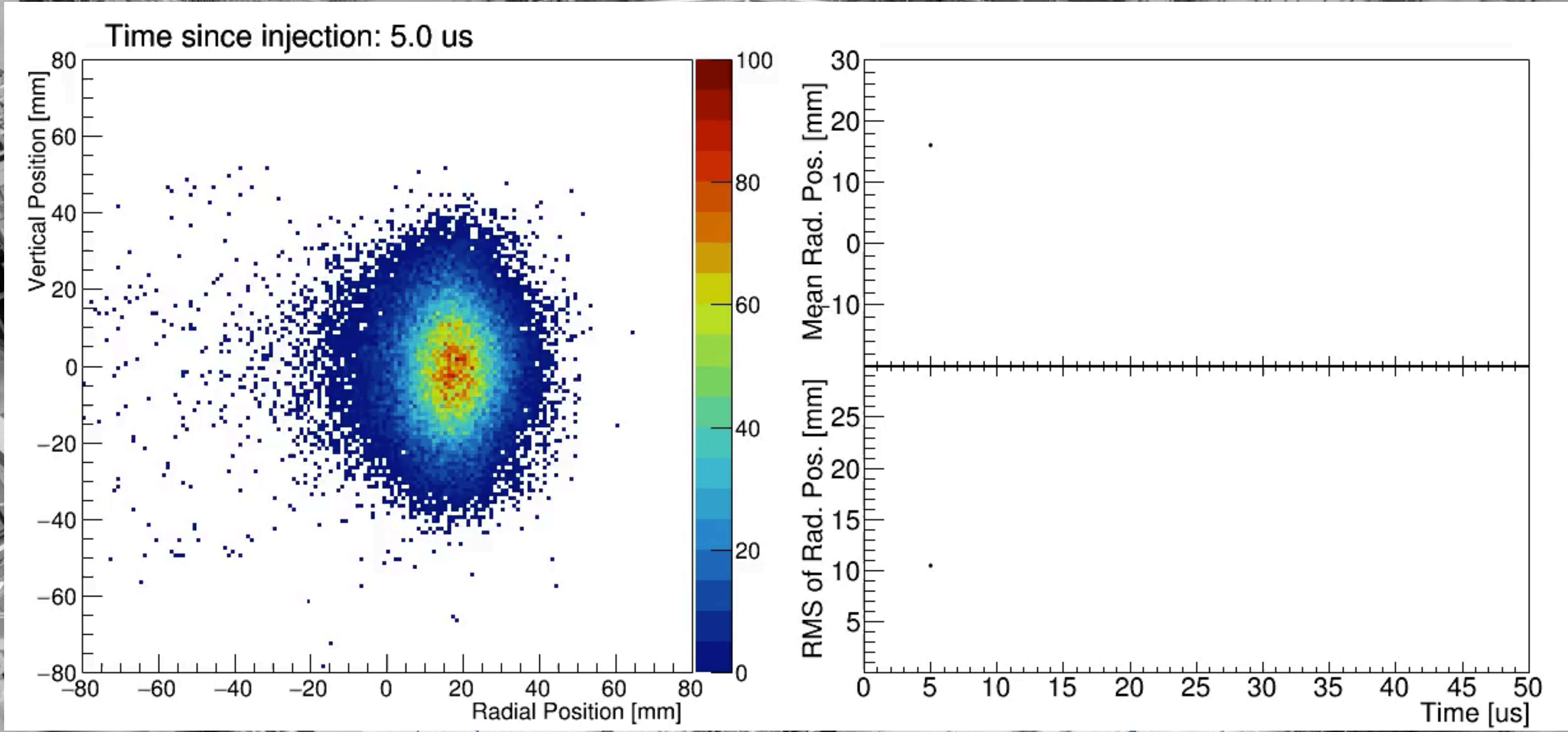
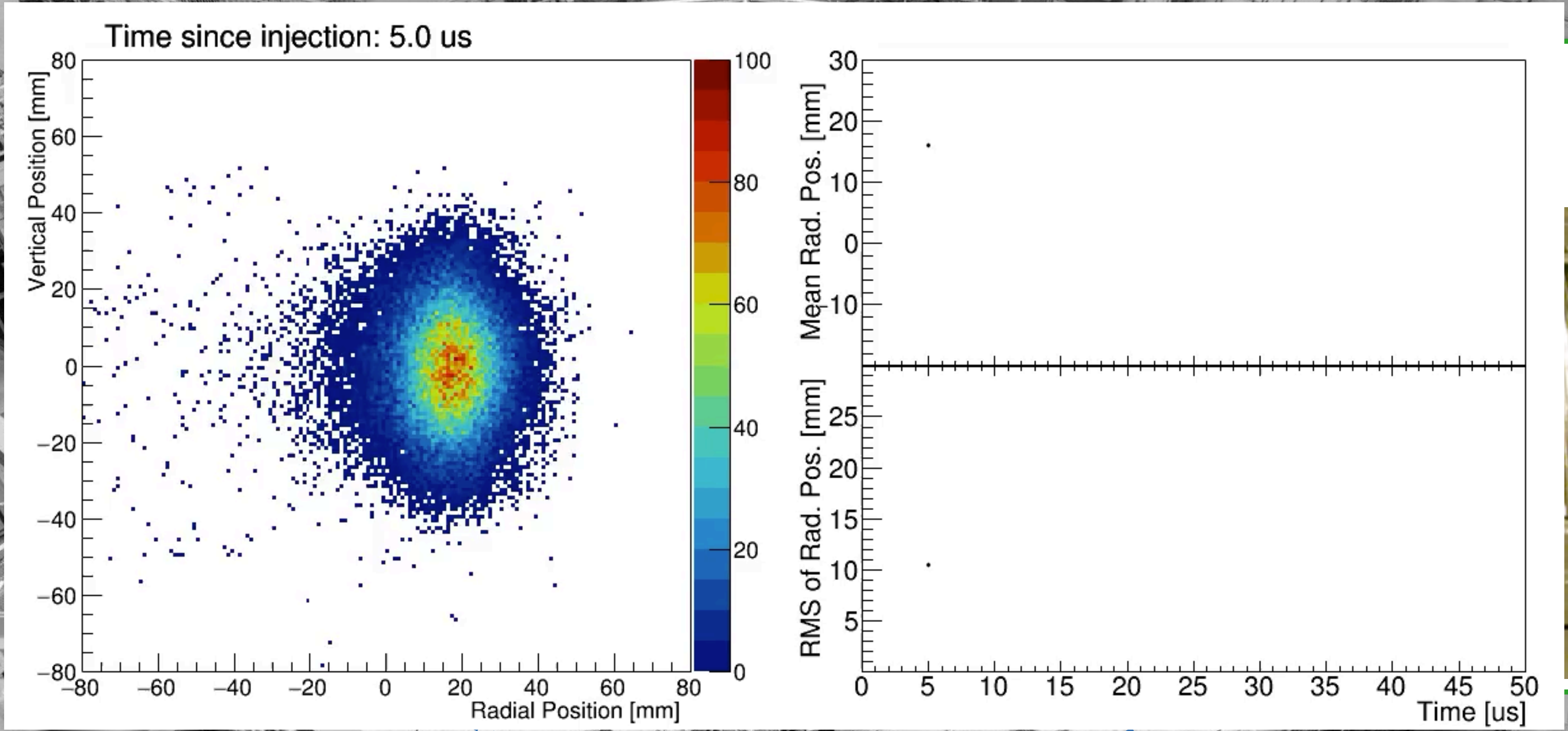


2 straw-tracker stations

each 8 modules, 4 layers of 32 straws,
50:50 Ar:Ethane, res ~100um



Time since injection: 5.0 us
Vertical Position [mm]
Radial Position [mm]
Mean Rad. Pos. [mm]
RMS of Rad. Pos. [mm]
Time [us]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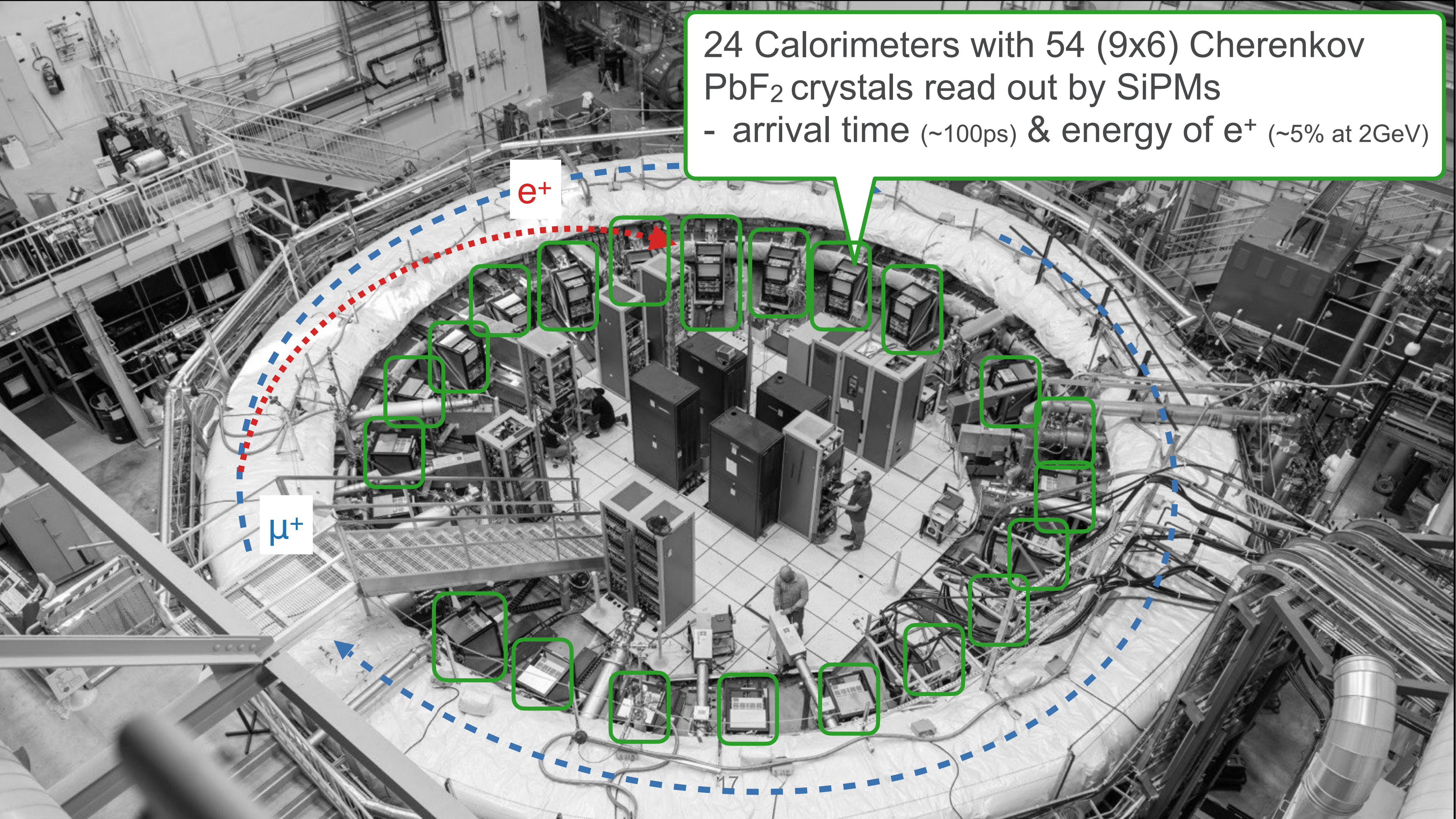
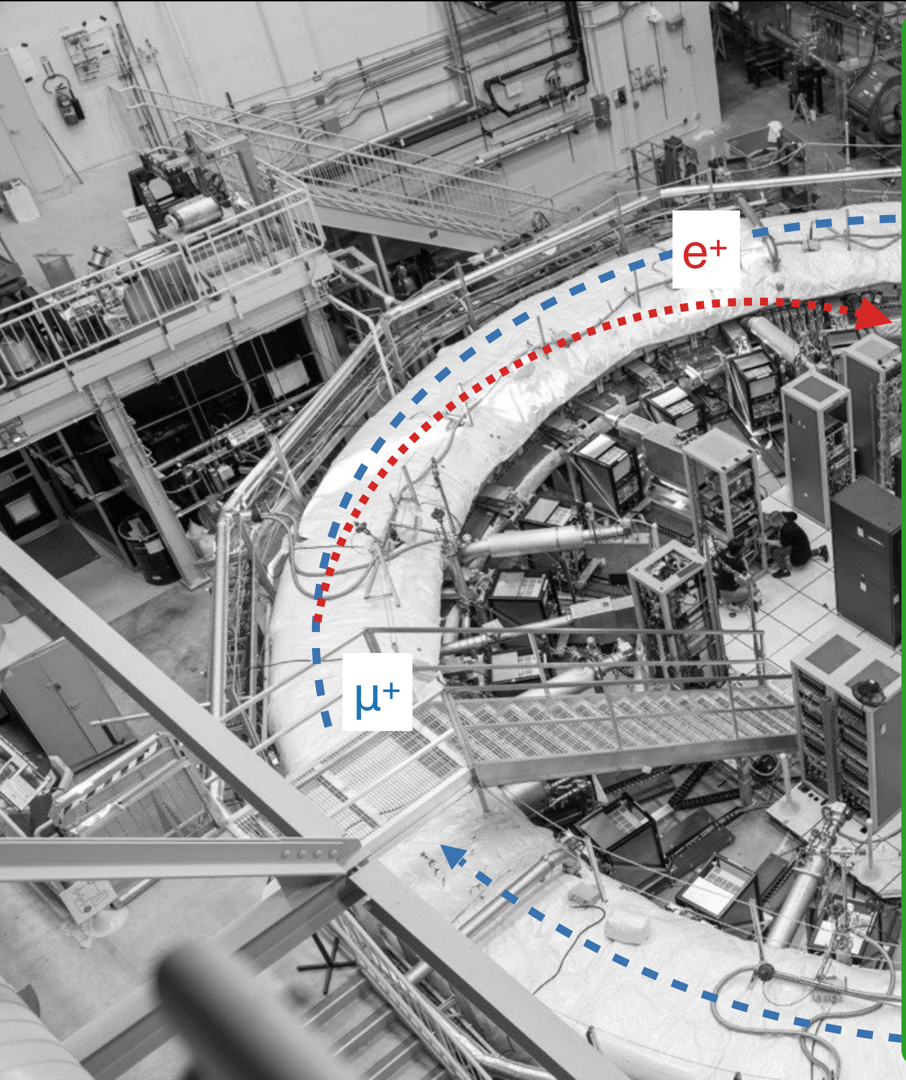

24 Calorimeters with 54 (9x6) Cherenkov
PbF2 crystals read out by SiPMs
- arrival time (~100ps) & energy of e+ (~5% at 2GeV)
e+
μ+



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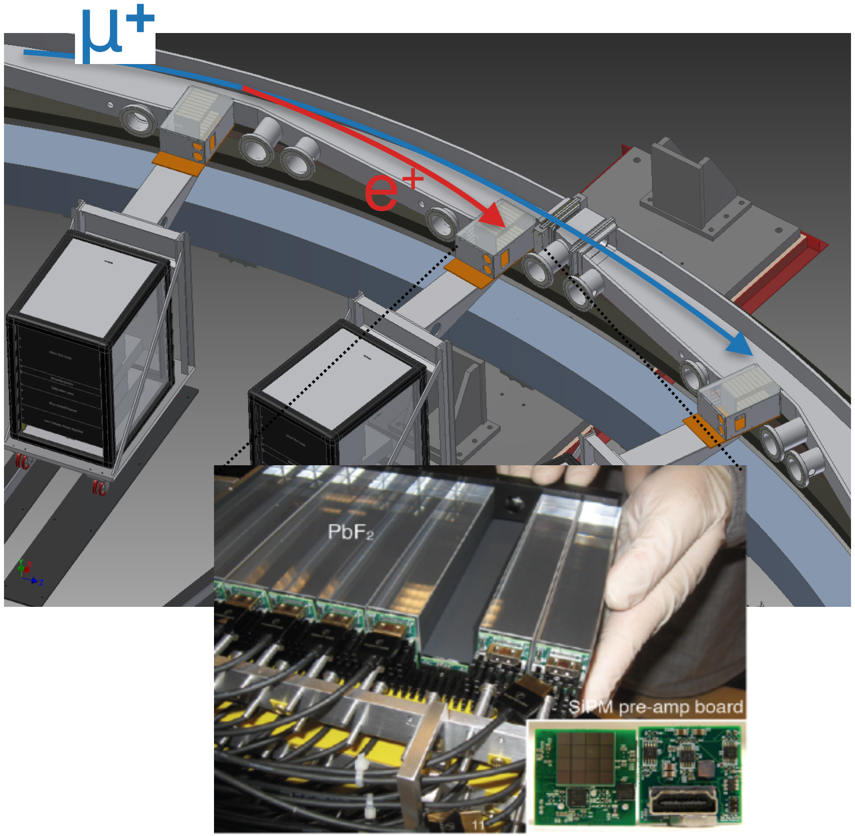
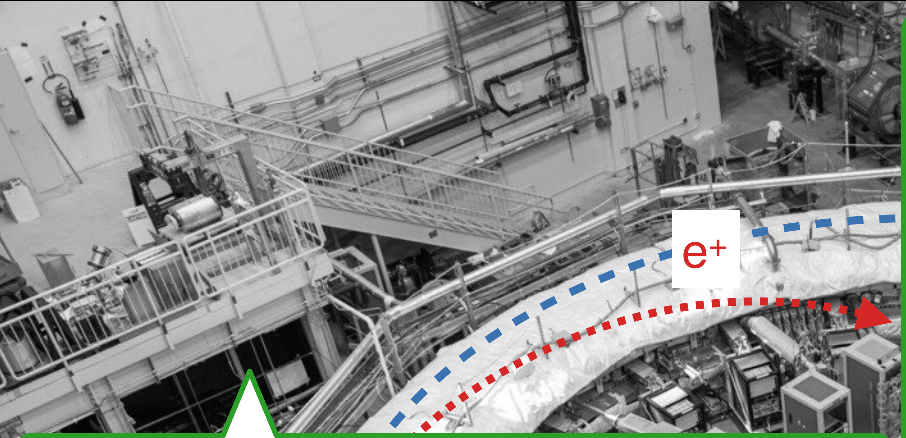


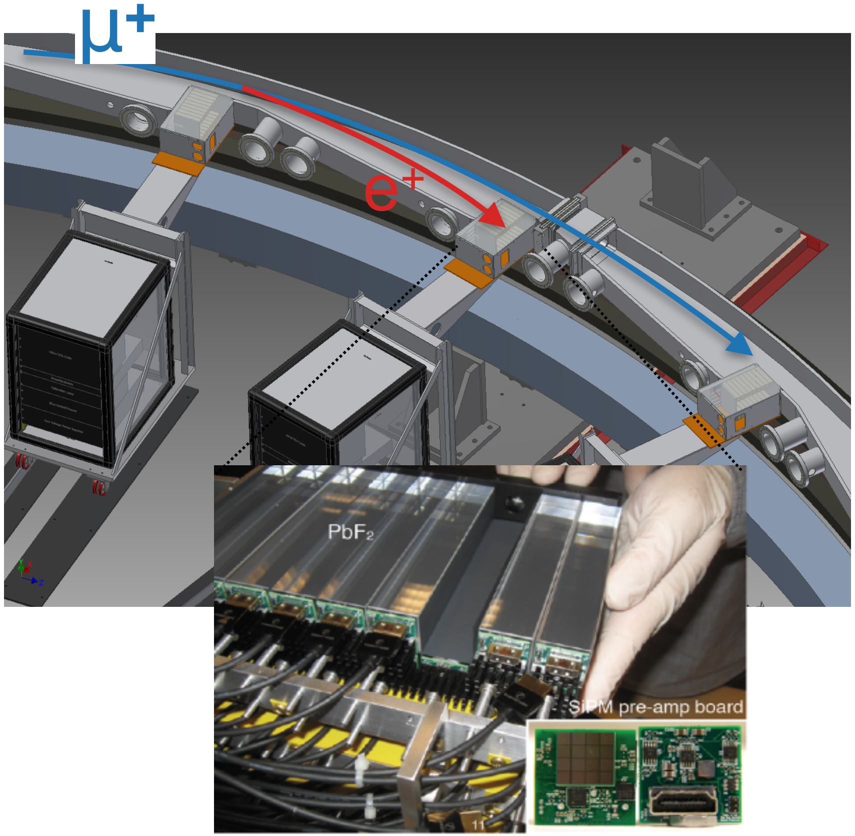


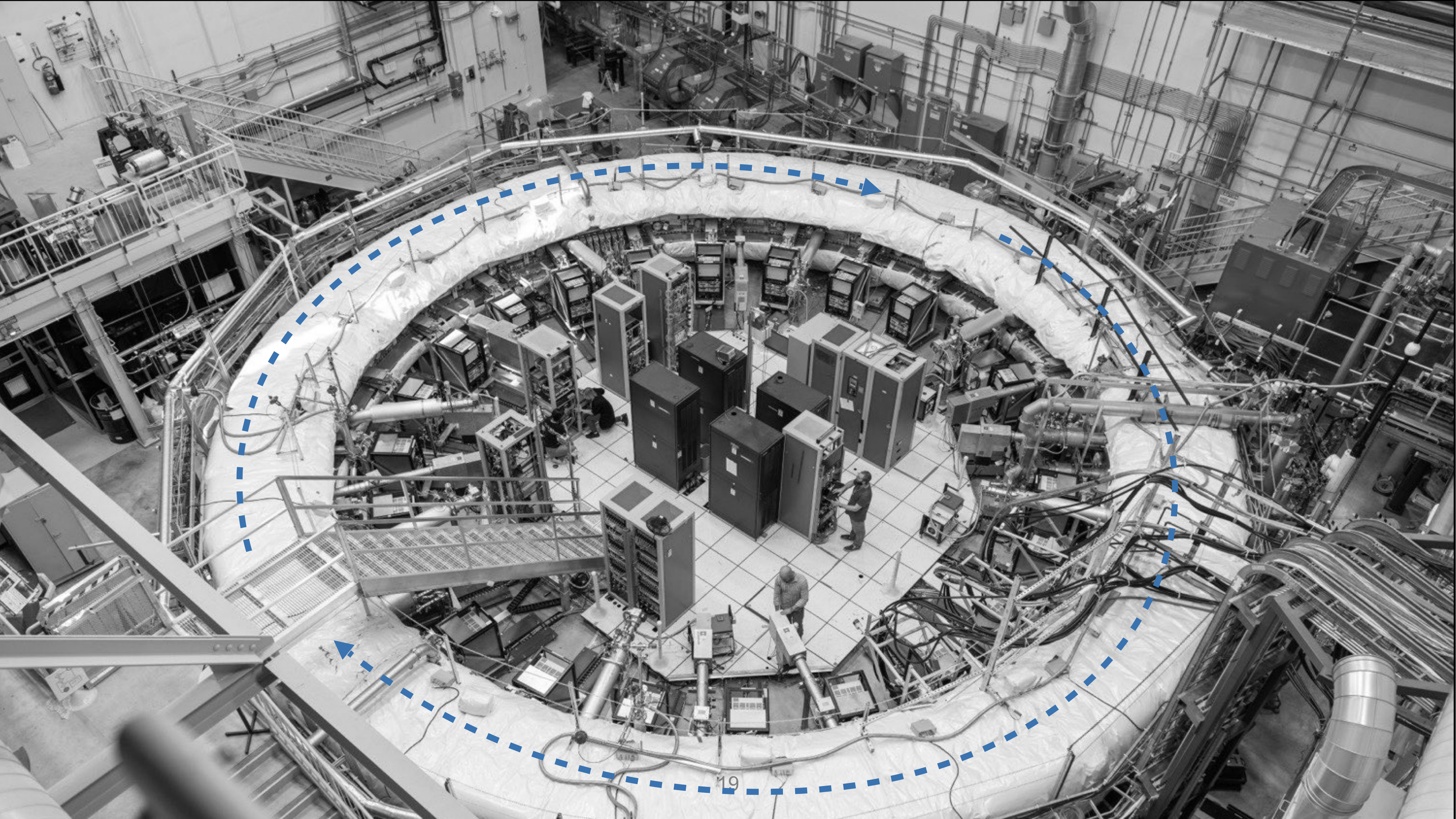
Laser system for gain response calibration throughout data taking

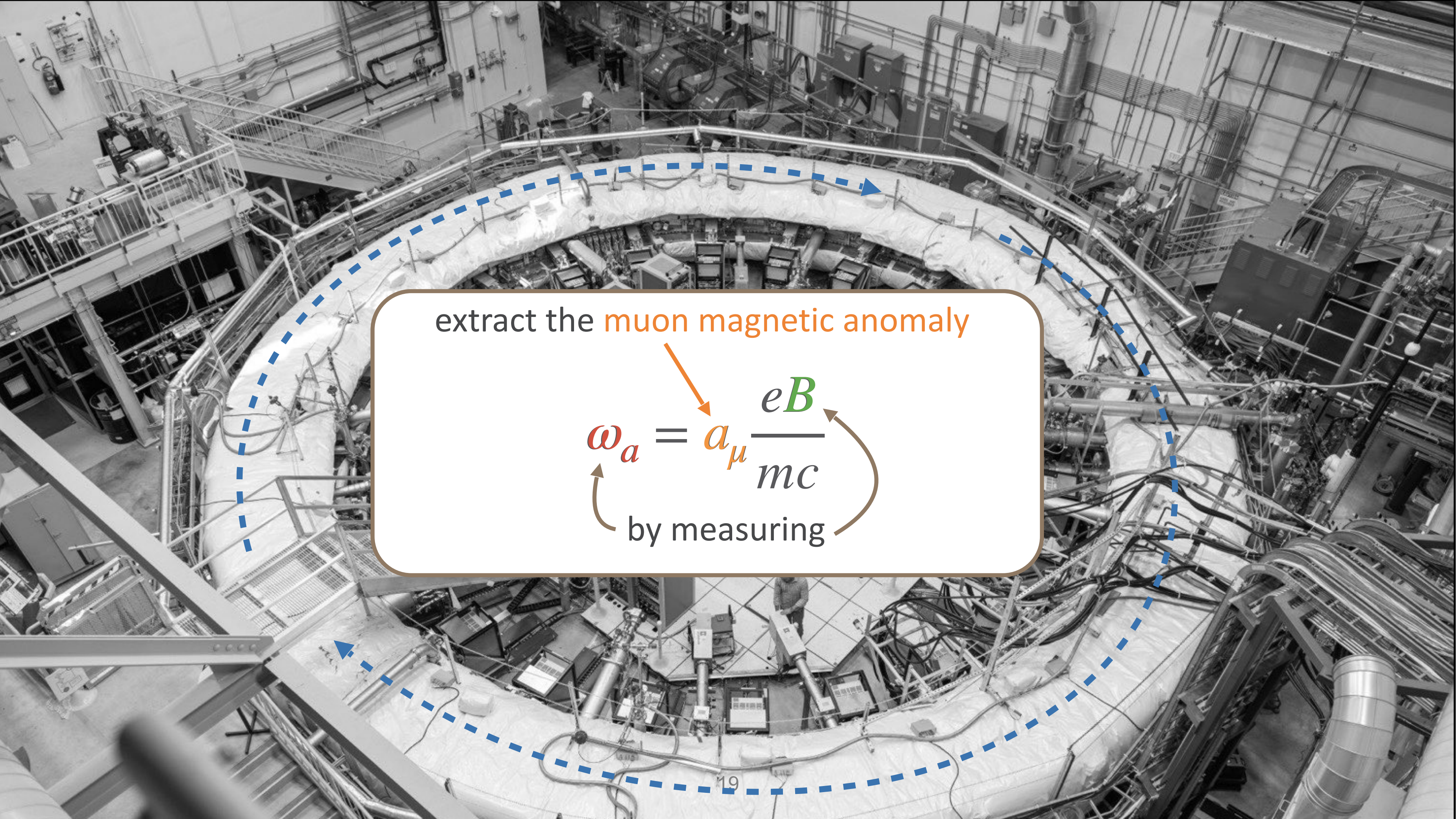
stability 10^{-3}, rate difference 10^4

24 Calorimeters with 54 (9x6) Cherenkov PbF_2 crystals read out by SiPMs

- arrival time (~100ps) & energy of e^+ (~5% at 2GeV)







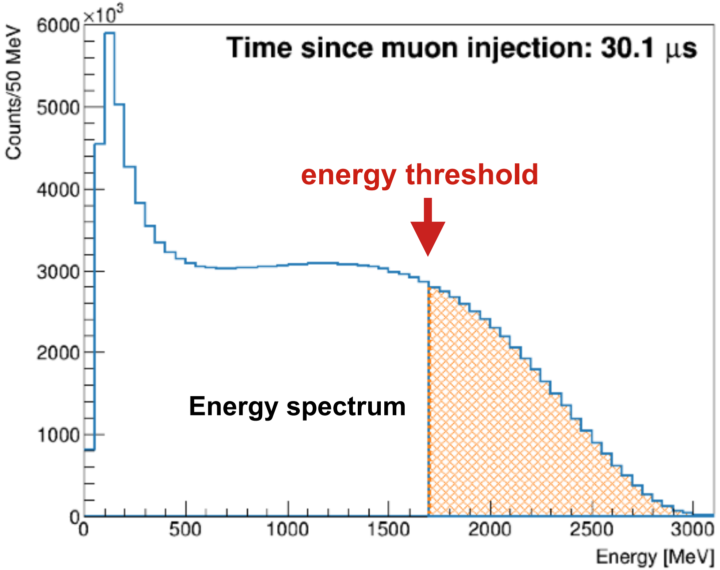
extract the muon magnetic anomaly

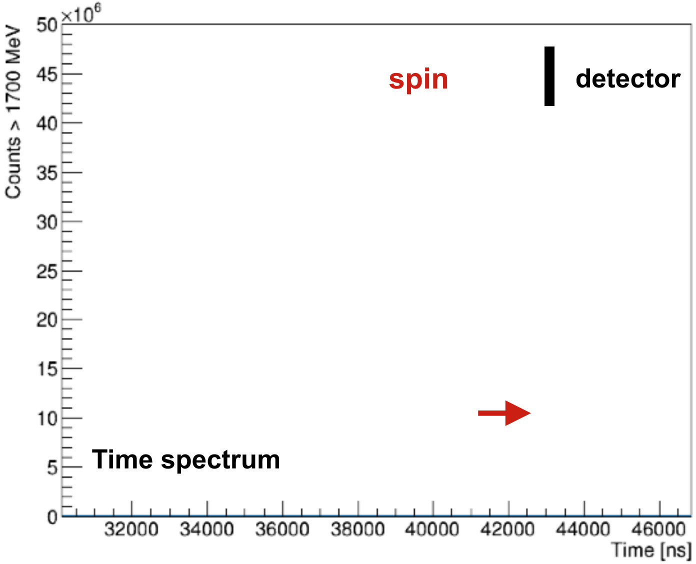
$$\omega_a = a_\mu \frac{eB}{mc}$$

by measuring

MEASURE: ω_a

Due to **parity violation** in muon decay, number of detected **high energy positrons** oscillates as muon **spin** points towards/away from detectors





Count positrons above an energy threshold

Counts **oscillate** at ω_a; extract frequency from time spectrum

*for the final analysis we use an asymmetry weighted analysis

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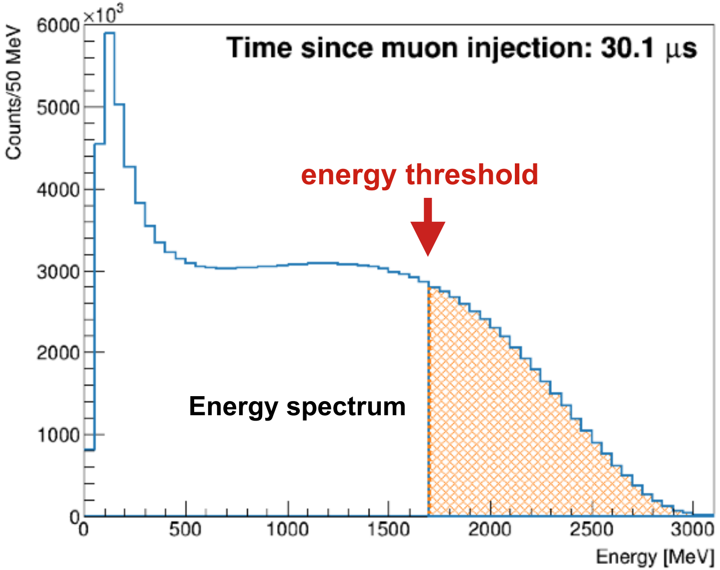

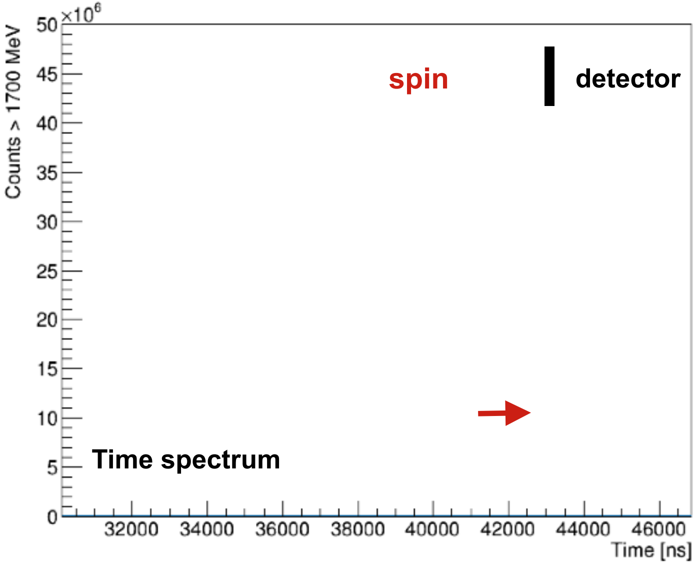

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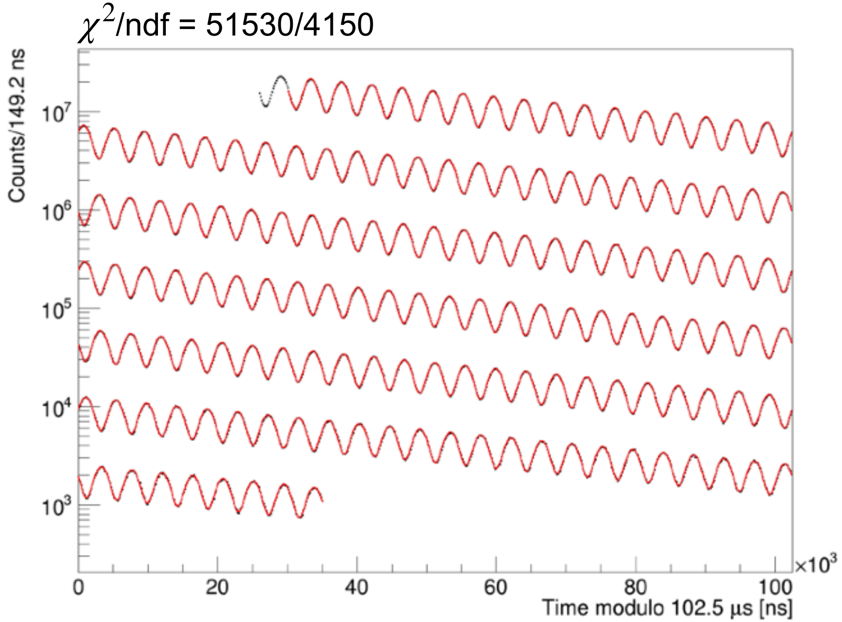
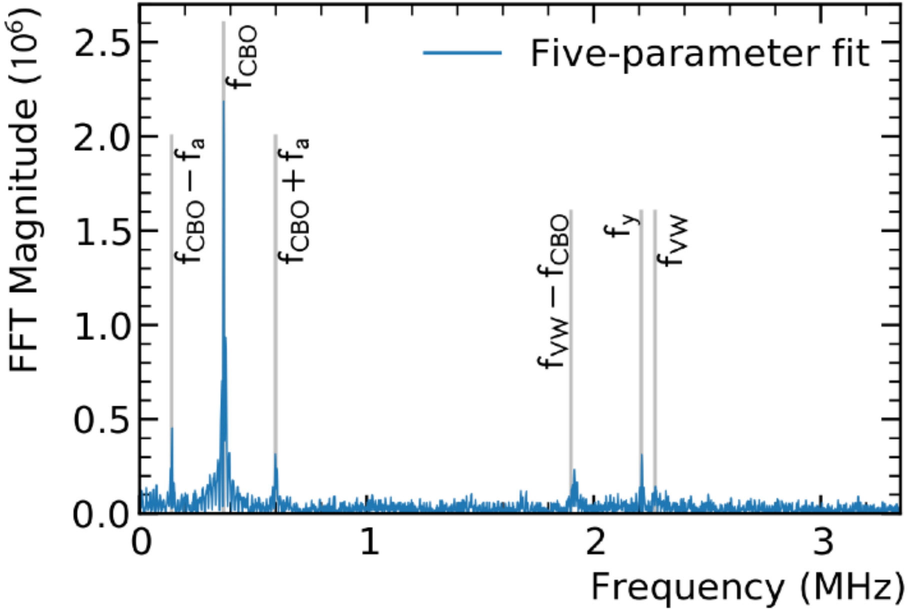
MEASURE: ω_a

Simplest model captures **exponential decay** & **g-2 oscillation**

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



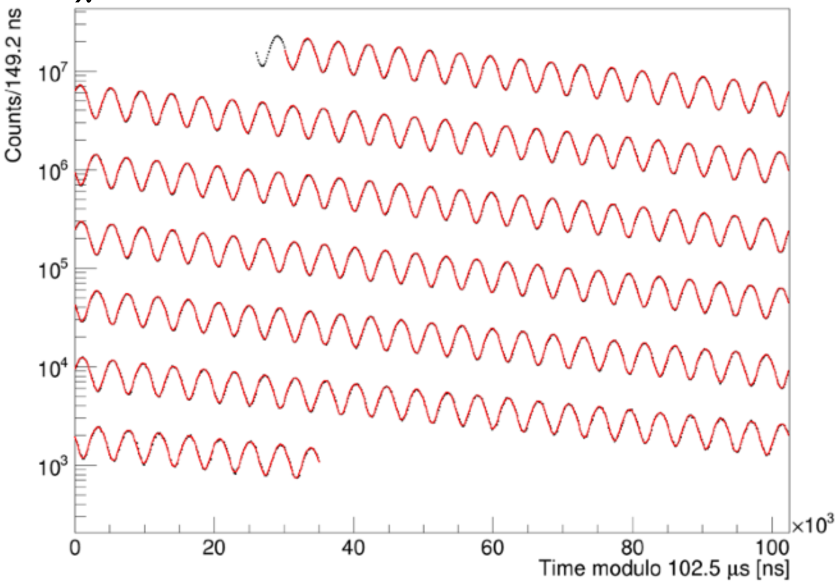


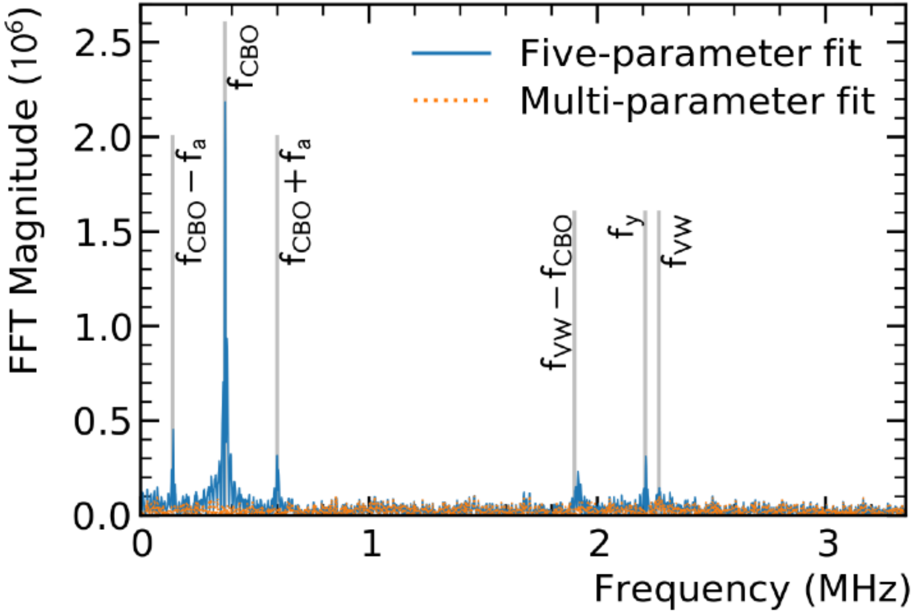
MEASURE: ω_a

Simplest model captures **exponential decay** & **g-2 oscillation**

must account for **beam oscillations**, **muons losses**, and **detector effects** (~1.6ppm shift in ω_a)

χ^2/ndf = 4086/4138





MEASURE: ω_a CORRECTIONS

$$\omega_a = \omega_a^m \left(1 + C_{\mathrm{e}} + C_{\mathrm{p}} + C_{\mathrm{pa}} + C_{\mathrm{dd}} + C_{\mathrm{ml}}\right)$$

Total correction is **622 ppb** (Run-2/3), dominated by **E-field & Pitch**

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E-field & Up/Down motion:
Spin precesses slower than
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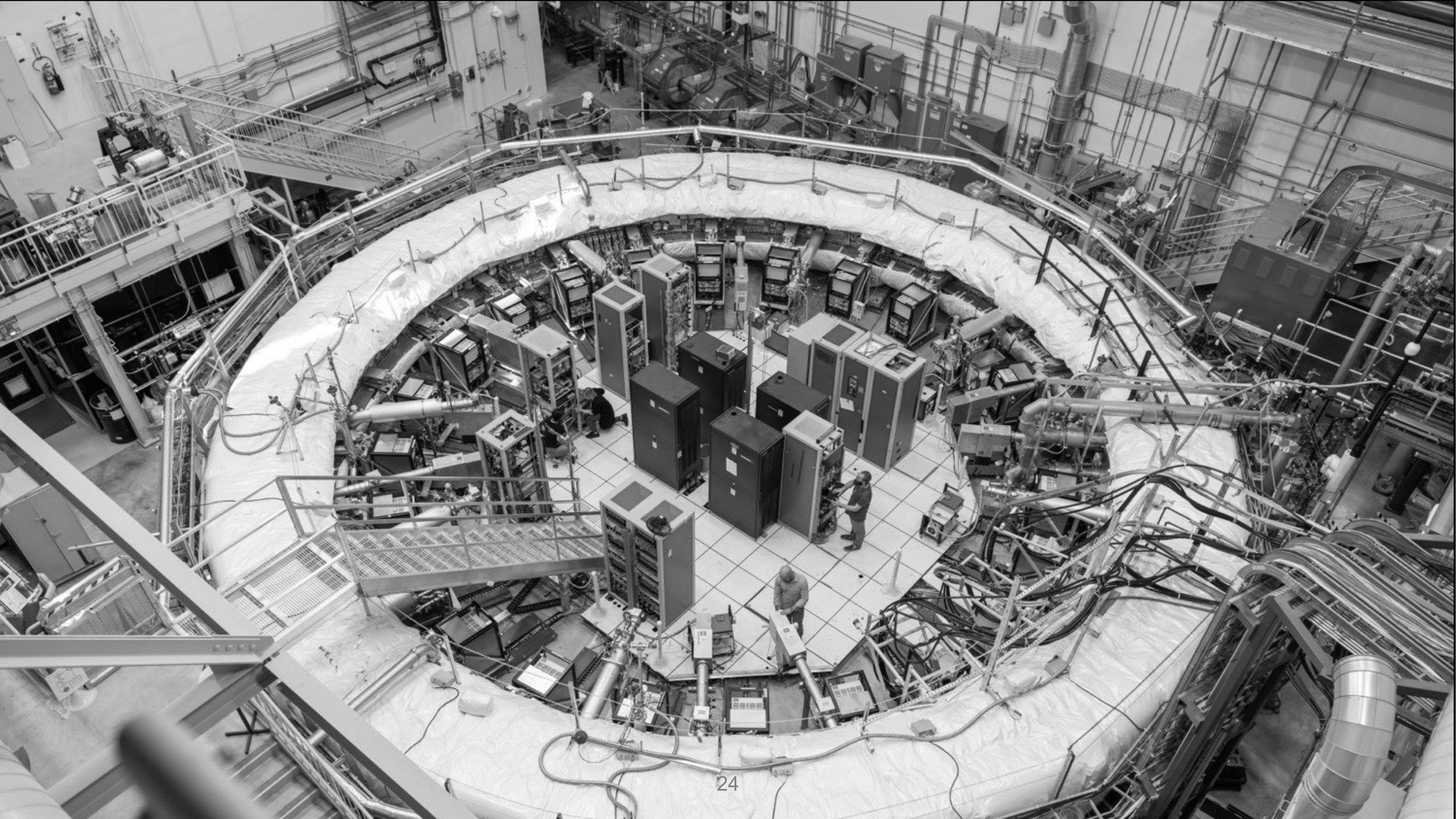
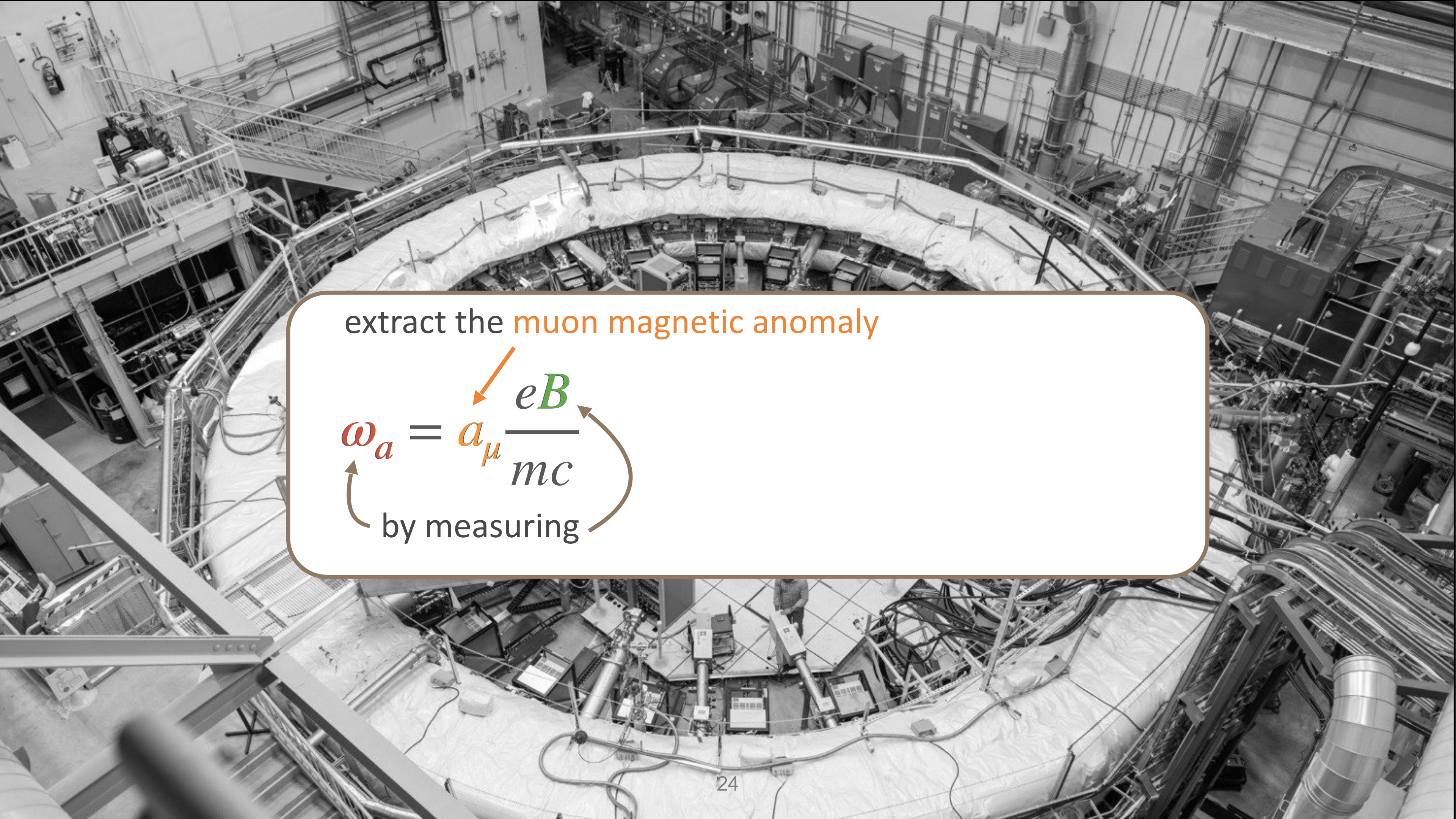
E-field & Up/Down motion: Spin precesses slower than in basic equation

Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses

Total correction is **622 ppb** (Run-2/3), dominated by **E-field & Pitch**





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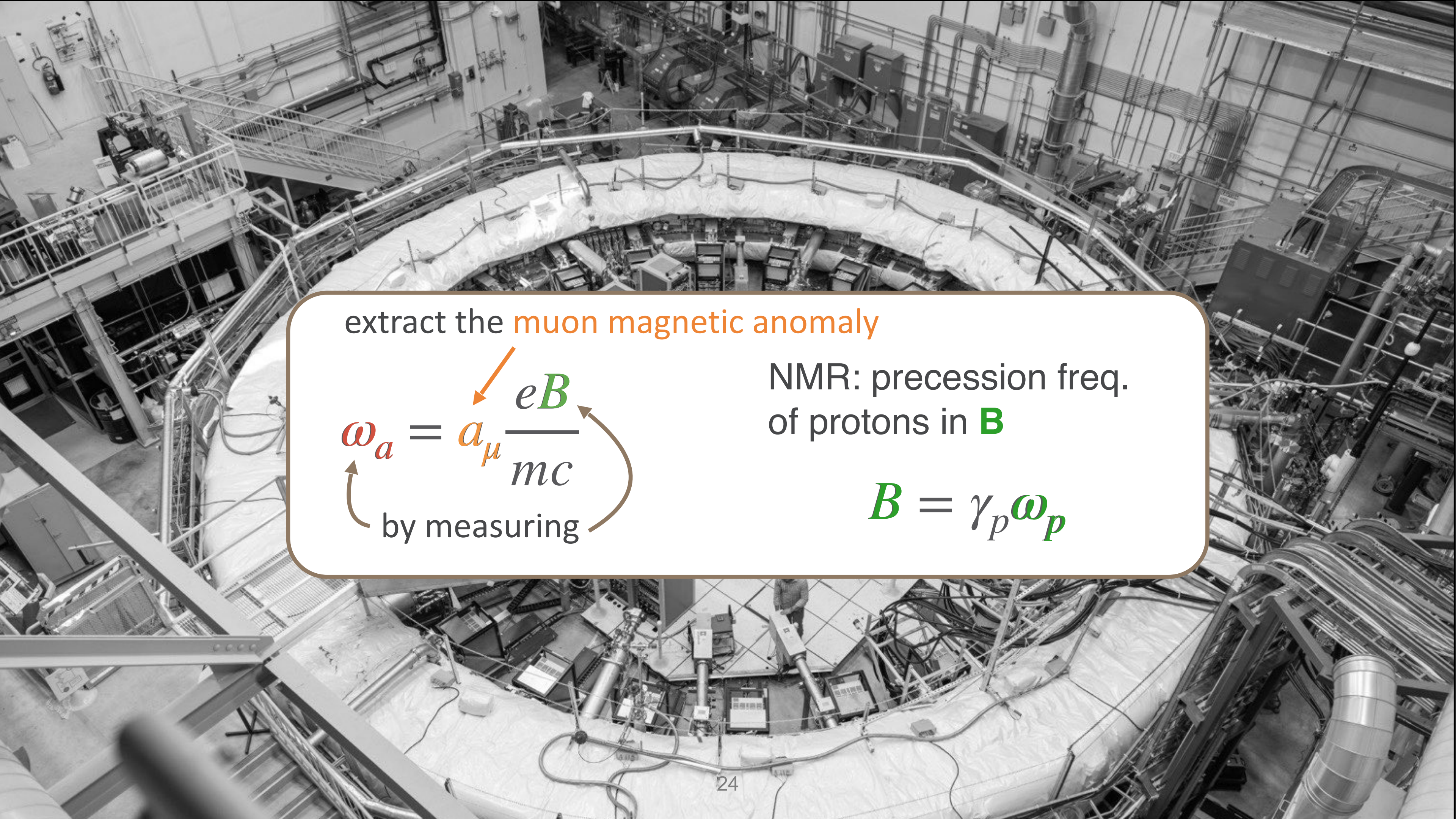

extract the muon magnetic anomaly

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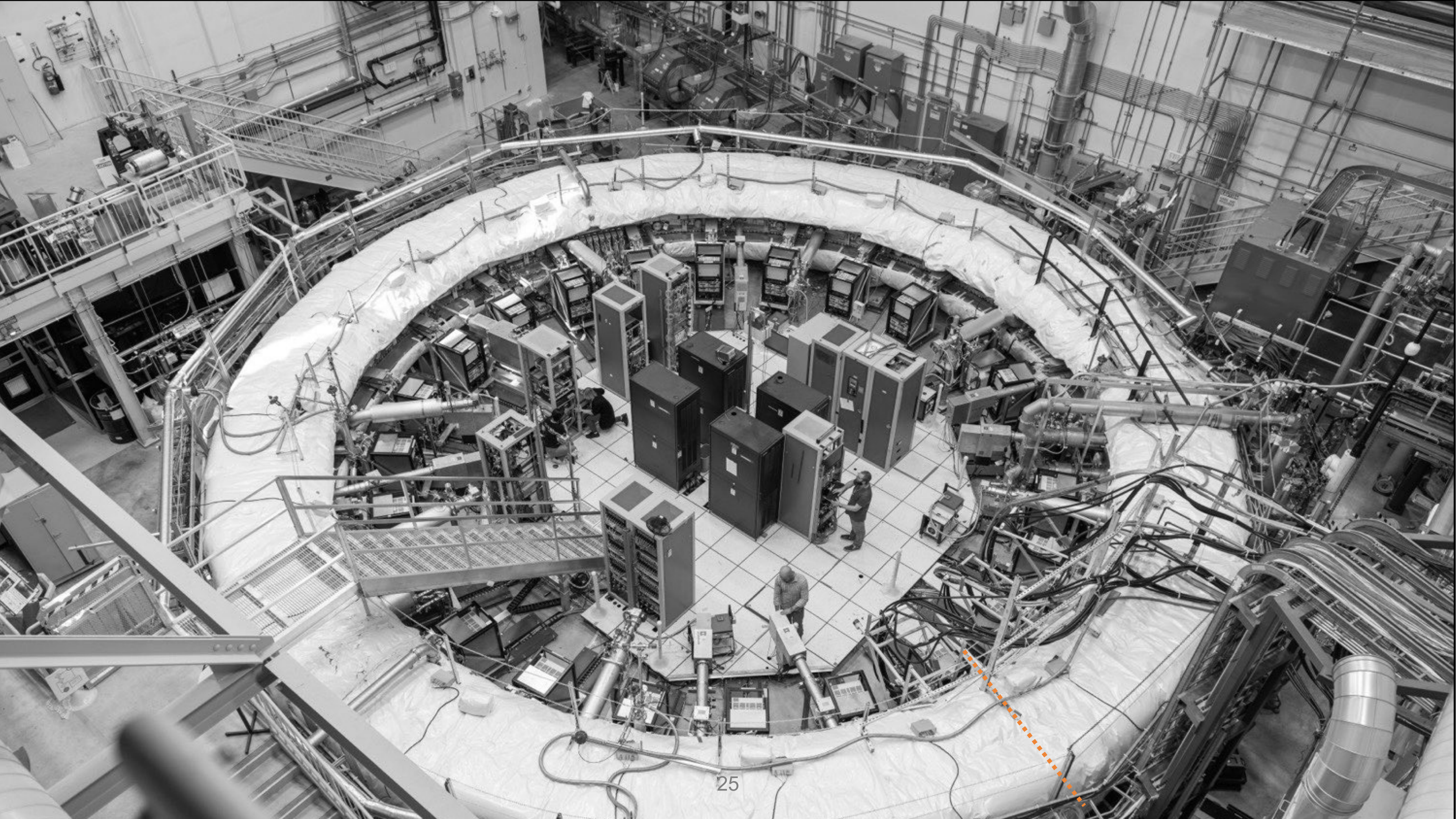
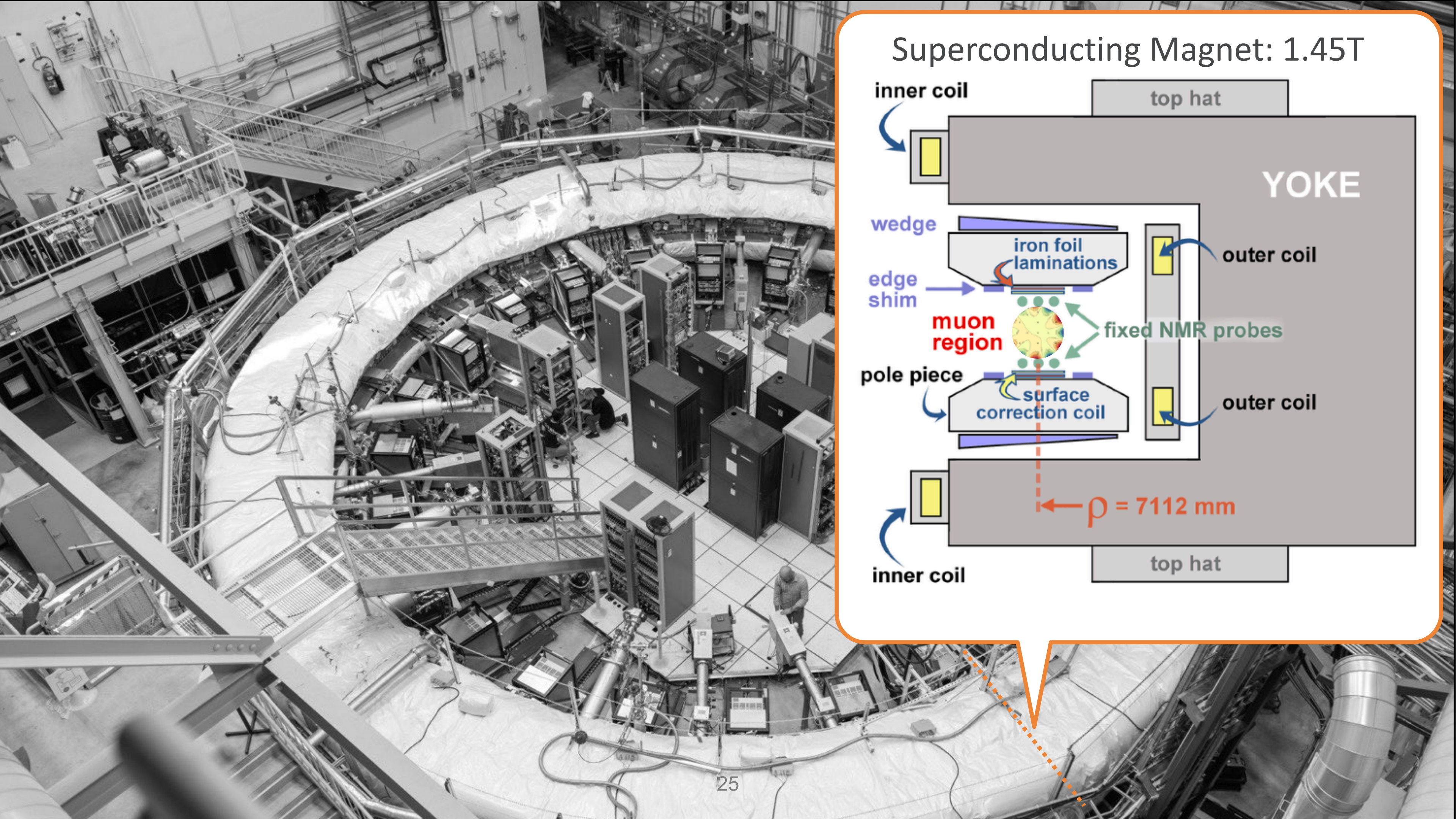
NMR: precession freq. of protons in **B**

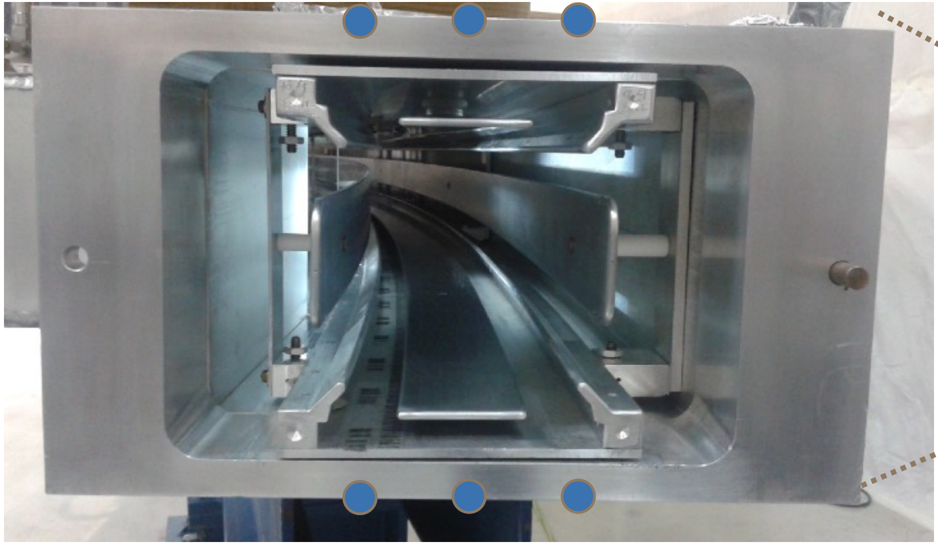
$$B = \gamma_p \omega_p$$



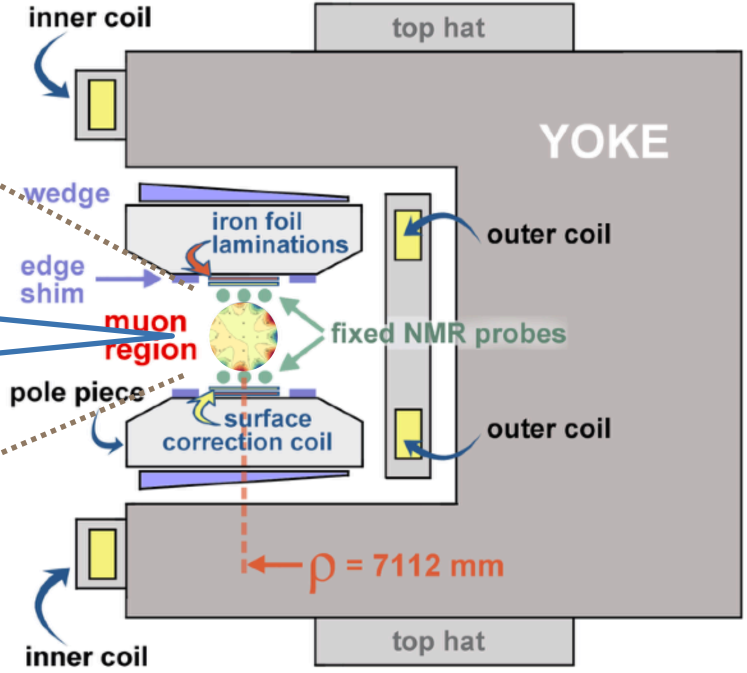
Superconducting Magnet: 1.45T



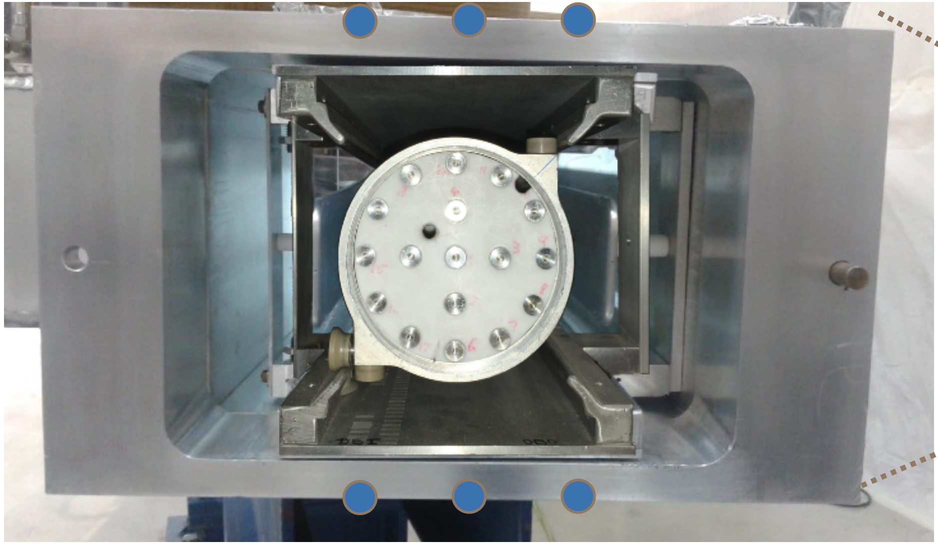
Filed Monitor: Fixed NMR Probes



Superconducting Magnet: 1.45T

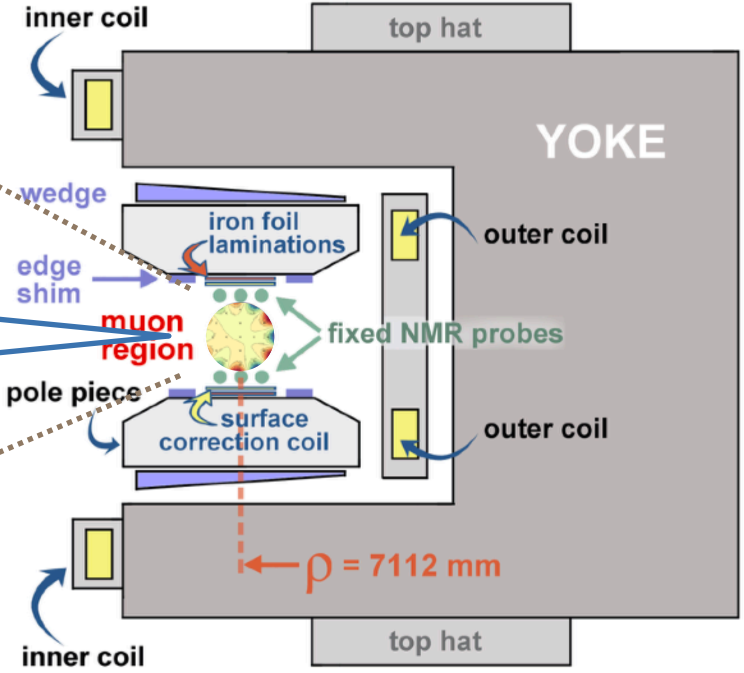


Filed Monitor: Fixed NMR Probes

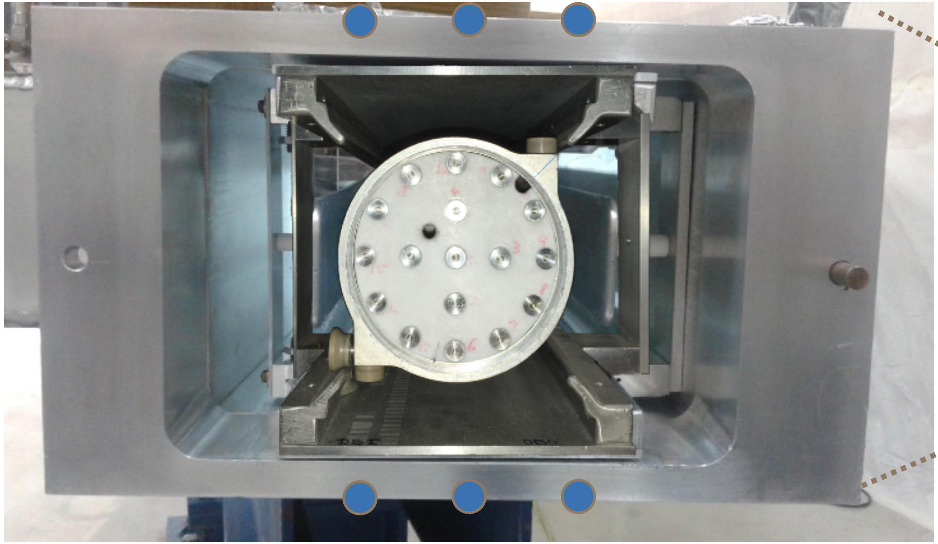


Trolley: Field Mapper

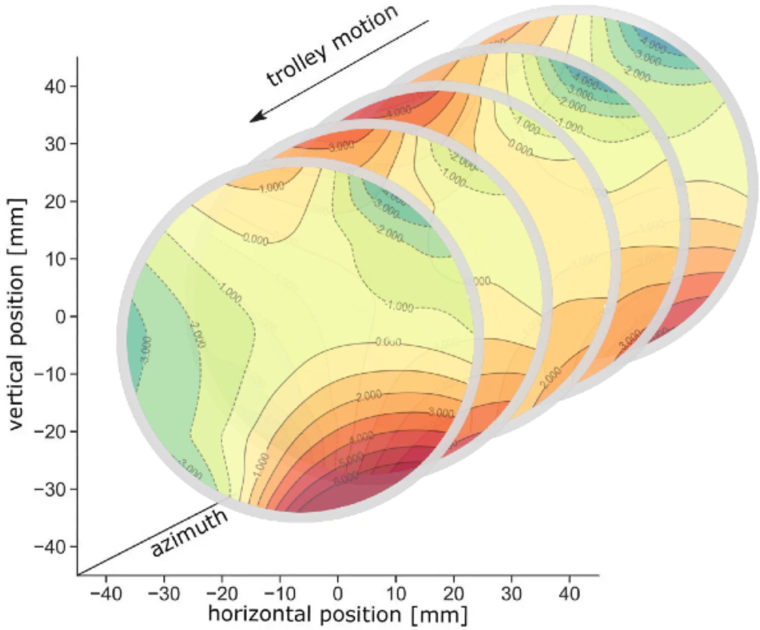
Superconducting Magnet: 1.45T



Filed Monitor: Fixed NMR Probes



Trolley: Field Mapper

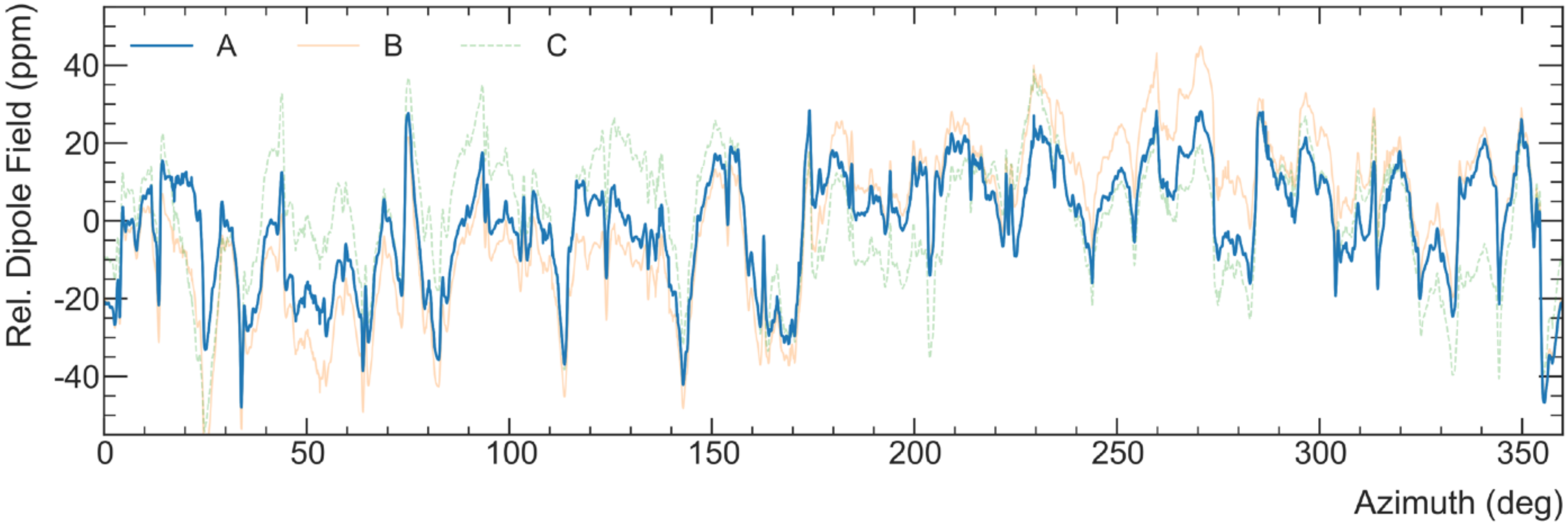


~9000 2D field maps around the ring

FIELD MAPS

RMS around the ring <20 ppm

take field maps every 3-5 days

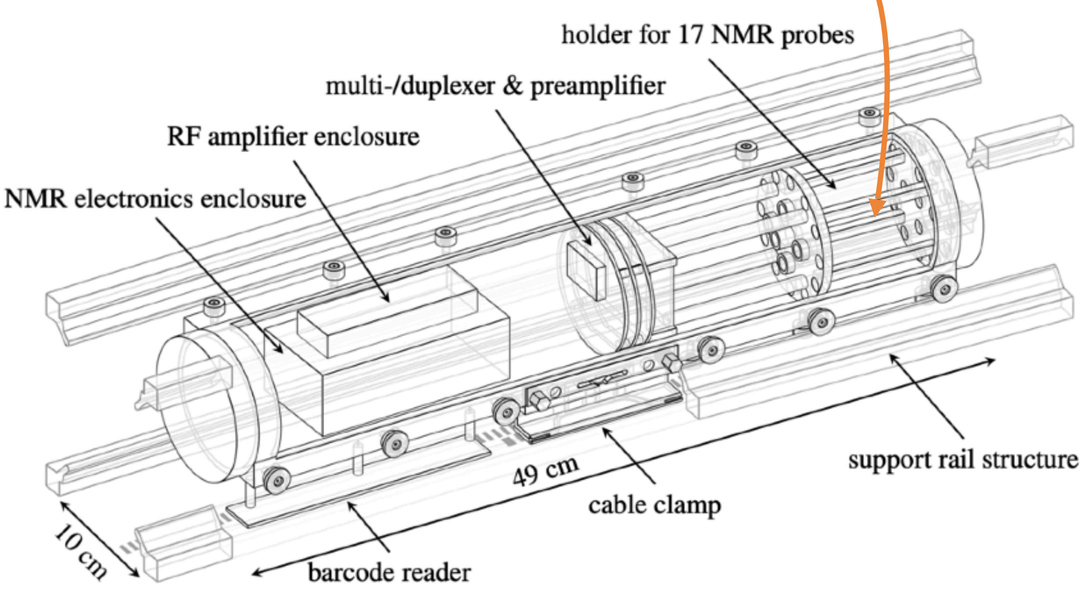


The field between field maps (trolley runs) is tracked by the fixed NMR probes.

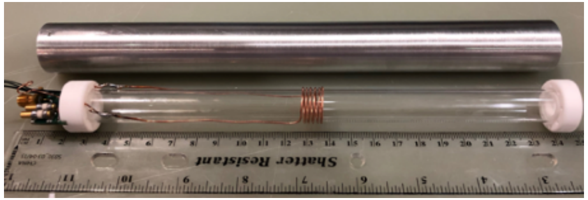
CALIBRATION

Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω_p'

NMR probes are in the "trolley's magnetic environment"



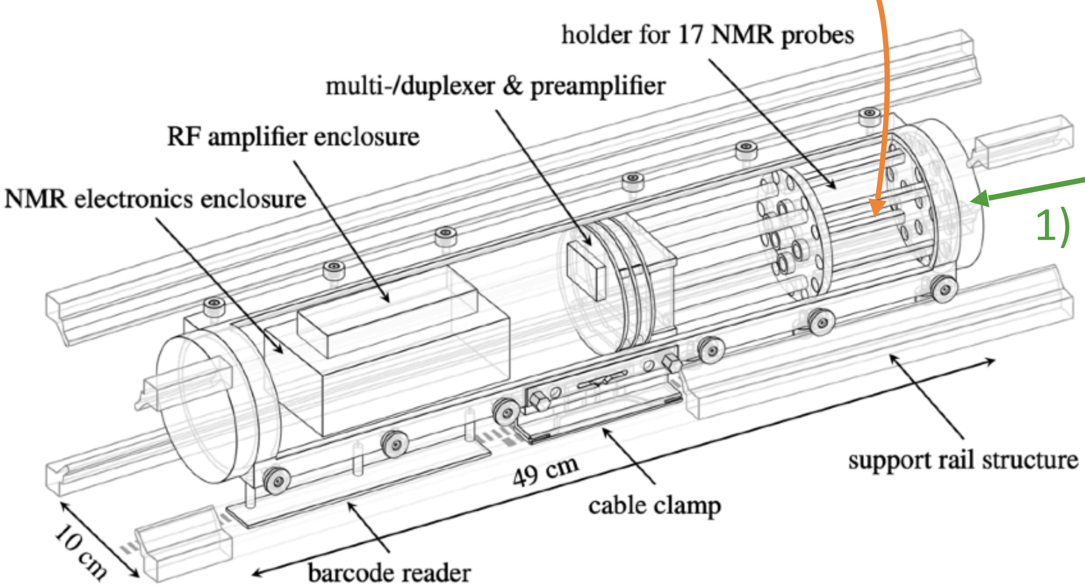
water based calibration probe



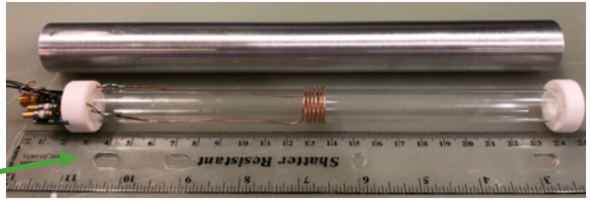
CALIBRATION

Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω'_p

NMR probes are in the
"trolley's magnetic environment"



water based calibration probe



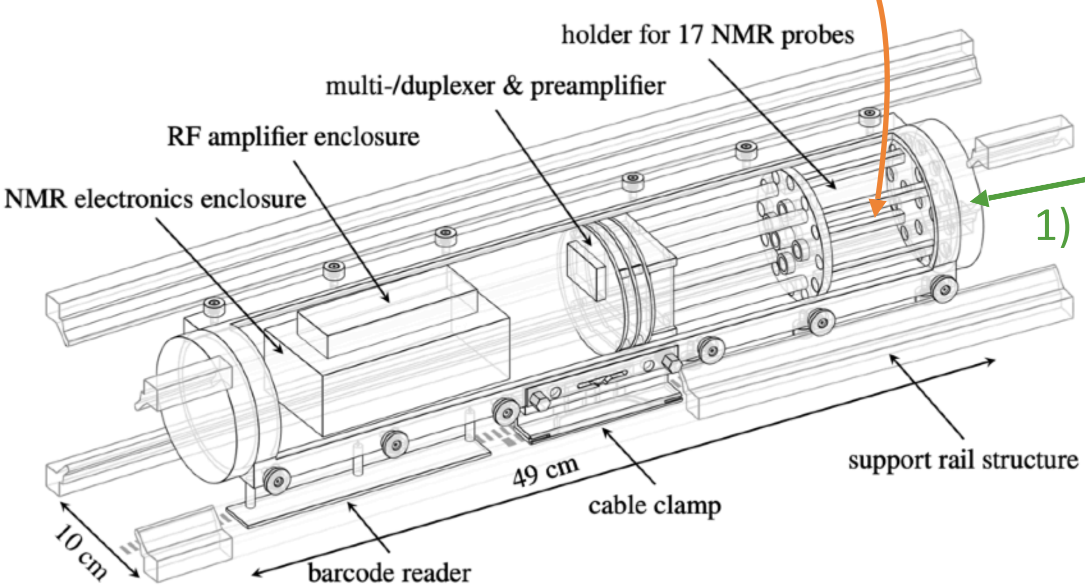
1) swap place in situ

uncertainty: 17 ppb

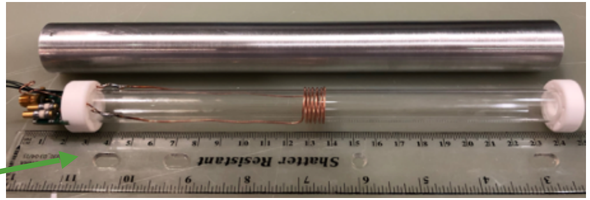
CALIBRATION

Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω_p'

NMR probes are in the
"trolley's magnetic environment"



water based calibration probe



1) swap place in situ *uncertainty: 17 ppb*

2) correct for material effects

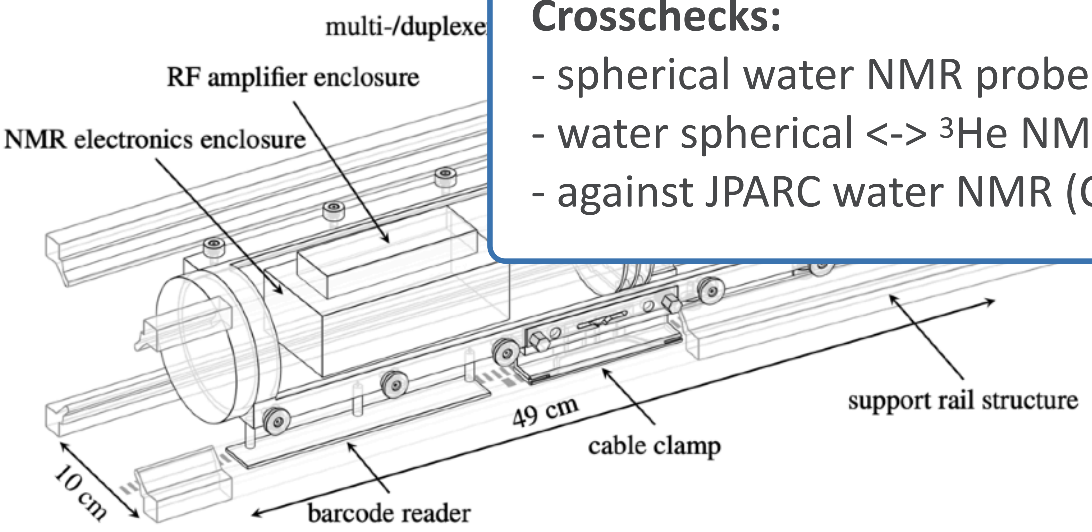
3) correct from cylinder -> sphere

uncertainty: 9 ppb

CALIBRATION

Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω_p'

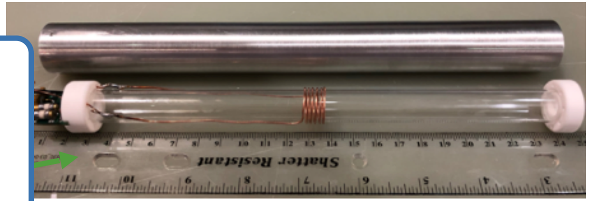
NMR probes are in the "trolley's magnetic environment"



Crosschecks:

- spherical water NMR probe (BNL)
- water spherical <-> ^{3}He NMR
- against JPARC water NMR (CW)

water based calibration probe



ce in situ *uncertainty: 17 ppb*

2) correct for material effects

3) correct from cylinder -> sphere

uncertainty: 9 ppb

CALIBRATION

Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω_p'

10.5 ppb uncertainty (hydrogen maser)
Metrologia **13**, 179 (1977)

bound state QED calc., exact

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

0.13 ppt uncertainty
PDG, dominated by
Phys. Rev. Lett. **130**, 071801 (2023)

22 ppb uncertainty
(Muonium hyper fine split.)

Phys. Rev. Lett. **82**, 711 (1999)

CALIBRATION

Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω'_p

10.5 ppb uncertainty (hydrogen maser)
Metrologia **13**, 179 (1977)

bound state QED calc., exact

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

0.13 ppt uncertainty
PDG, dominated by
Phys. Rev. Lett. **130**, 071801 (2023)

magnetic field
seen by the muons

22 ppb uncertainty
(Muonium hyper fine split.)

Phys. Rev. Lett. **82**, 711 (1999)

CALIBRATION

Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω'_p

10.5 ppb uncertainty (hydrogen maser)
Metrologia **13**, 179 (1977)

bound state QED calc., exact

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

0.13 ppt uncertainty
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Phys. Rev. Lett. **130**, 071801 (2023)

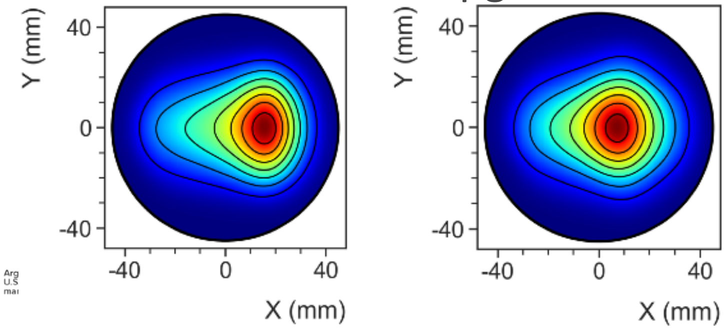
magnetic field
seen by the muons

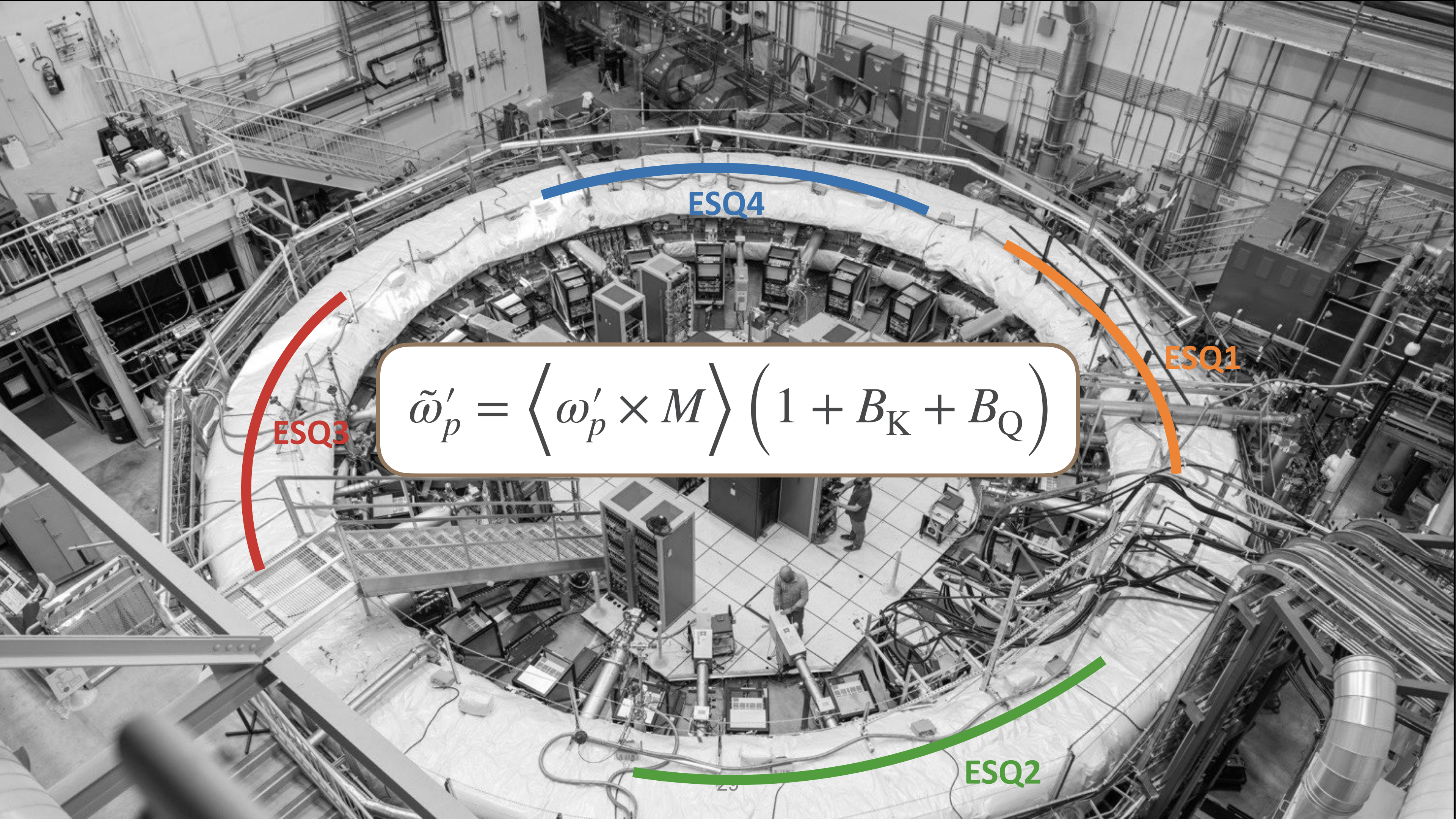
22 ppb uncertainty
(Muonium hyper fine split.)

Phys. Rev. Lett. **82**, 711 (1999)

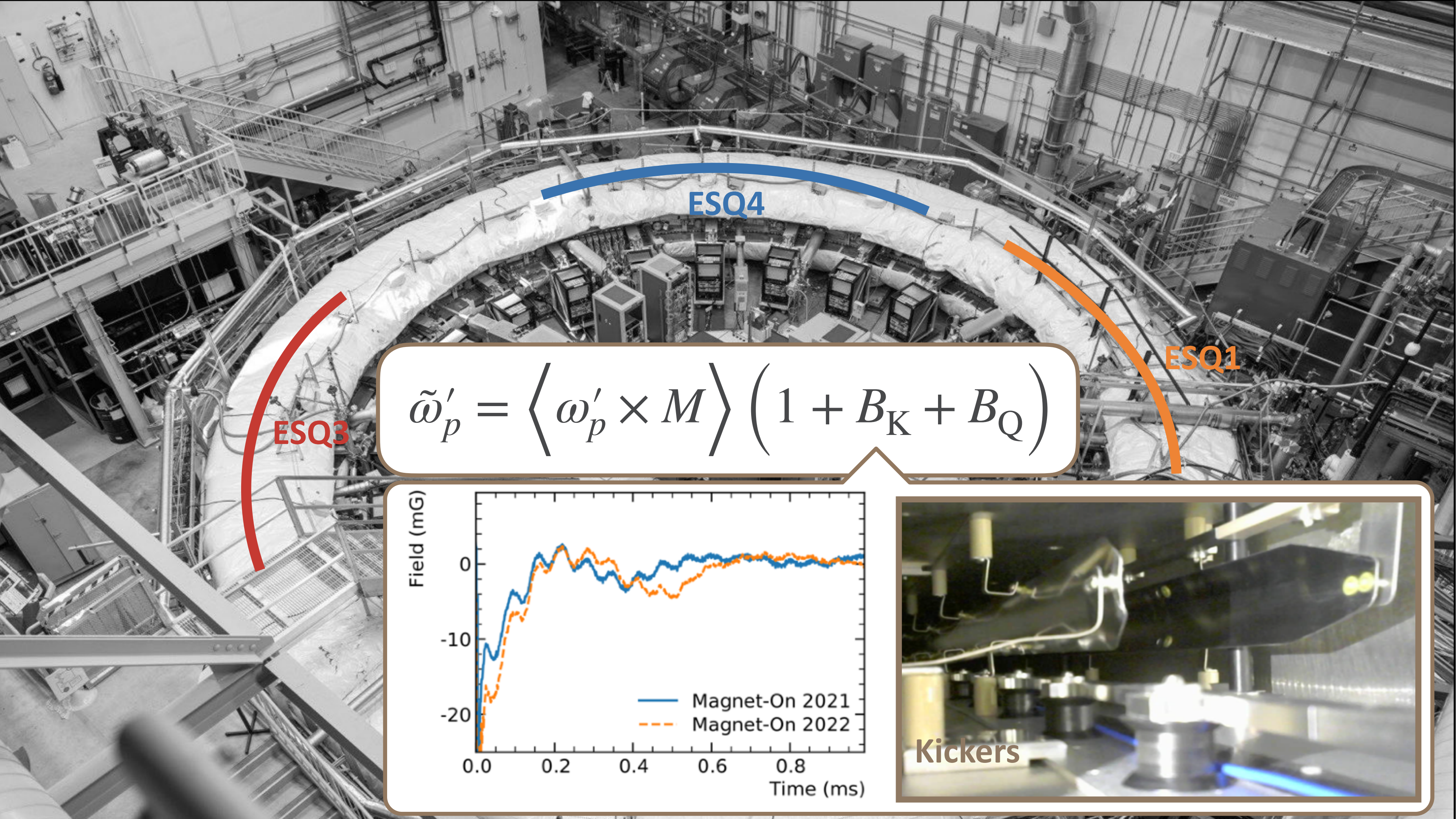
Run-2 and 3a

Run-3b:
upgraded kickers

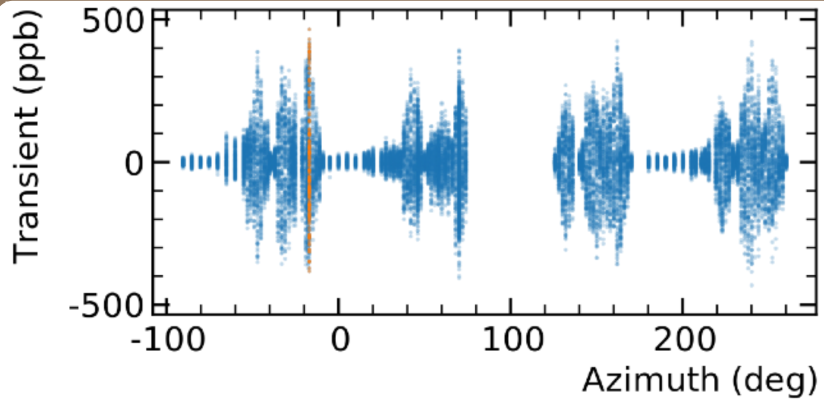


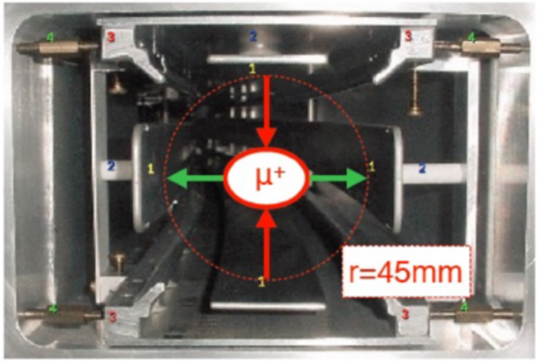


$$\tilde{\omega}'_p = \left\langle \omega'_p \times M \right\rangle \left(1 + B_{\mathrm{K}} + B_{\mathrm{Q}}\right)$$

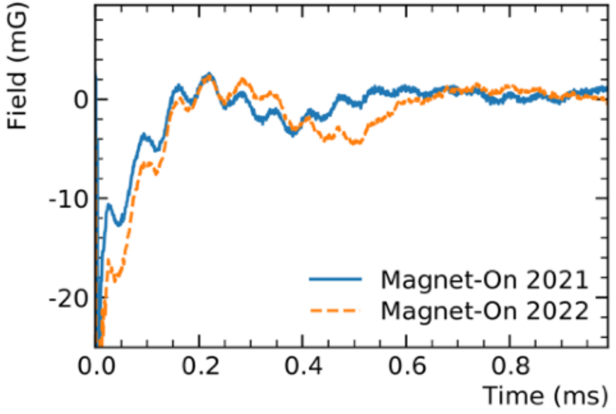


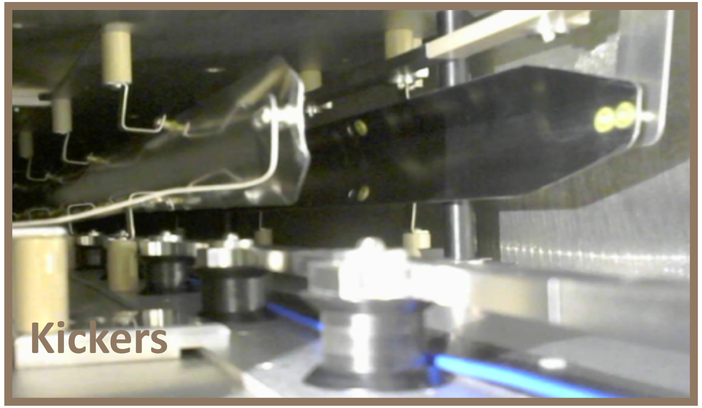
$$\tilde{\omega}'_p = \left\langle \omega'_p \times M \right\rangle \left(1 + B_{\mathrm{K}} + B_{\mathrm{Q}} \right)$$

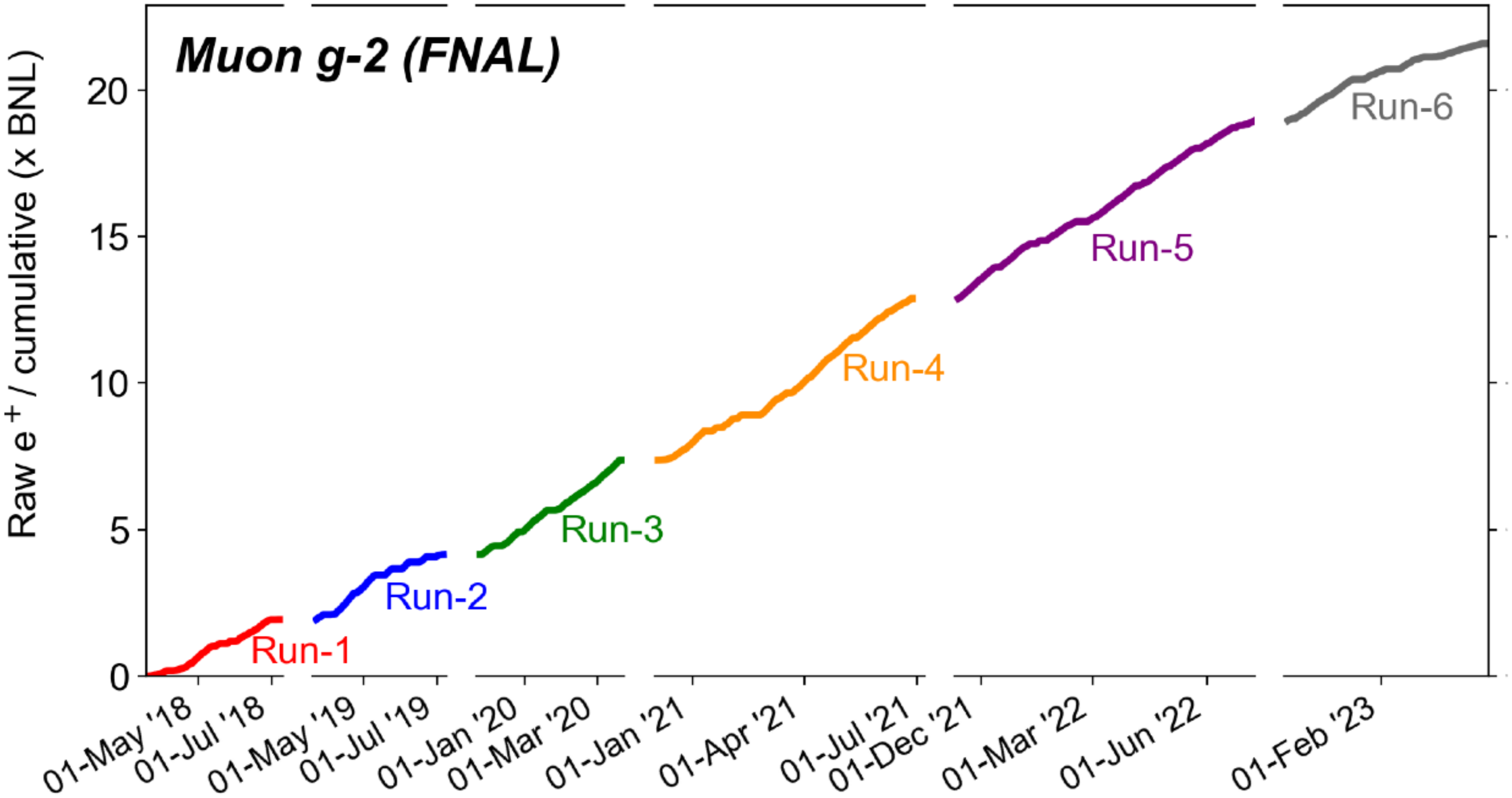




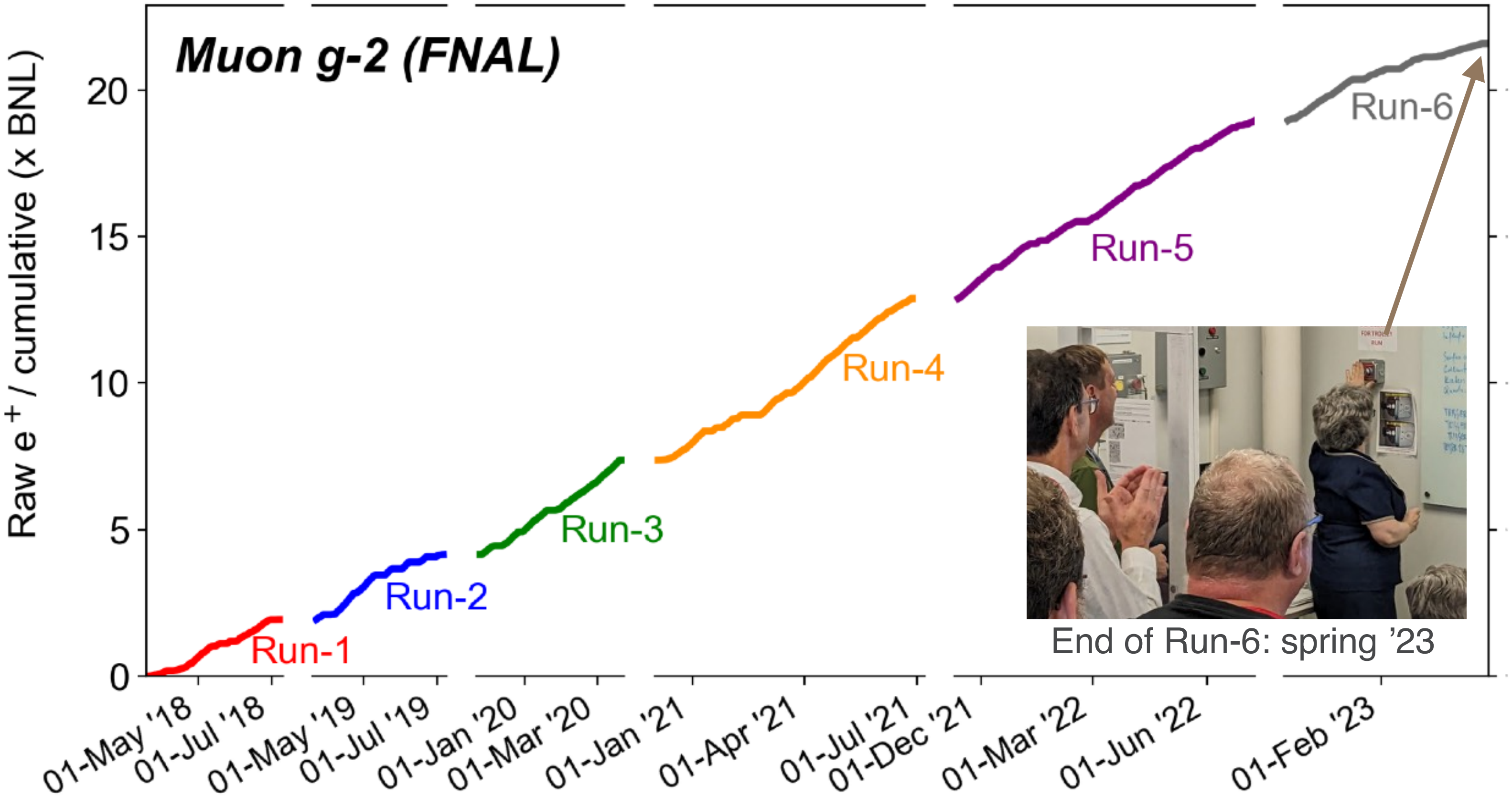
$$\tilde{\omega}'_p = \left\langle \omega'_p \times M \right\rangle \left(1 + B_{\mathrm{K}} + B_{\mathrm{Q}}\right)$$

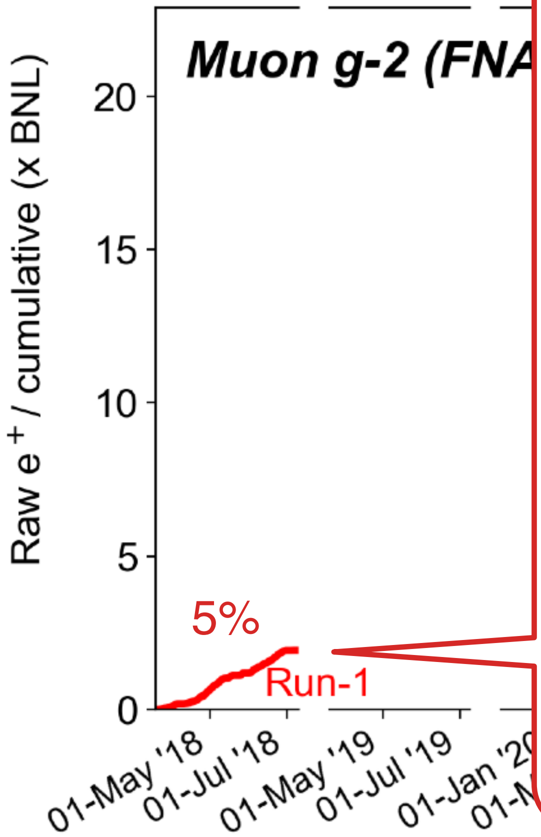




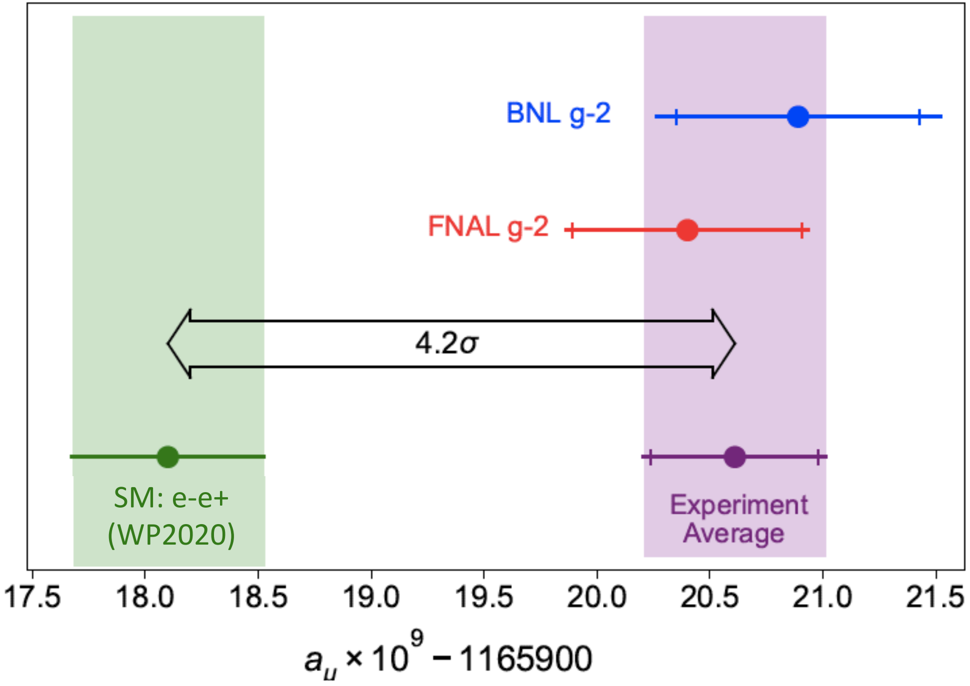


Muon g-2 (FNAL)
Raw e + / cumulative (x BNL)
20
15
10
5
0
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
01-Mar '22
01-Jun '22
01-Feb '23

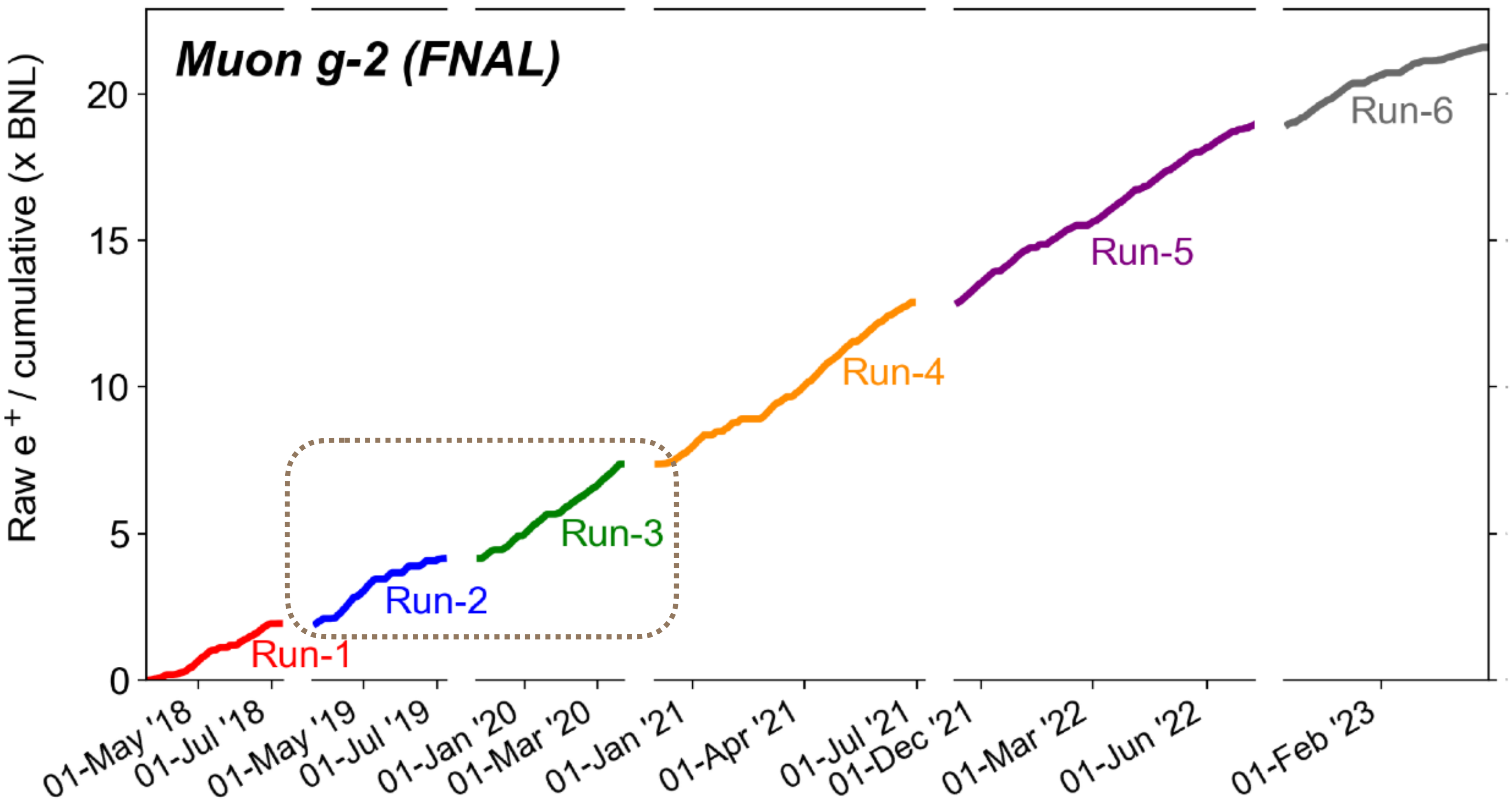

Muon g-2 (FNAL)
Raw e+ / cumulative (x BNL)
0
5
10
15
20
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
01-Mar '22
01-Jun '22
01-Feb '23
End of Run-6: spring '23



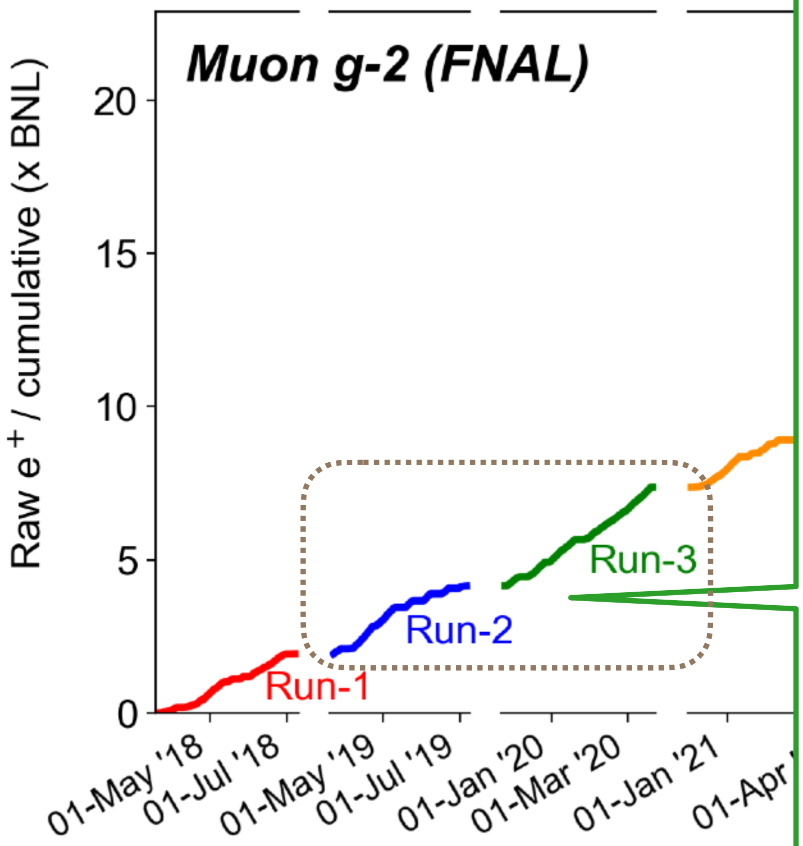
Run-1 Result: 2021 :: 0.46 ppm



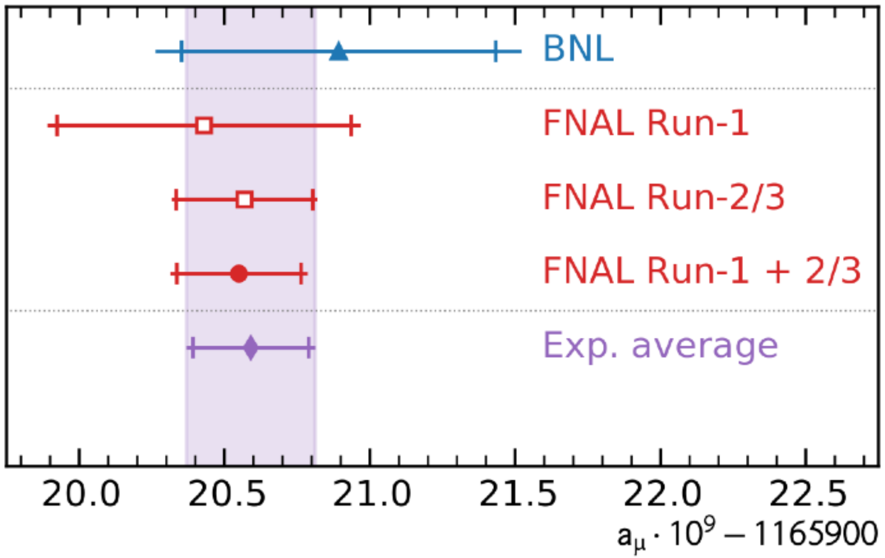
$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$



Muon g-2 (FNAL)
Raw e + / cumulative (x BNL)
0
5
10
15
20
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
01-Mar '22
01-Jun '22
01-Feb '23



Run-2/3 Result: 2023 :: 0.2 ppm

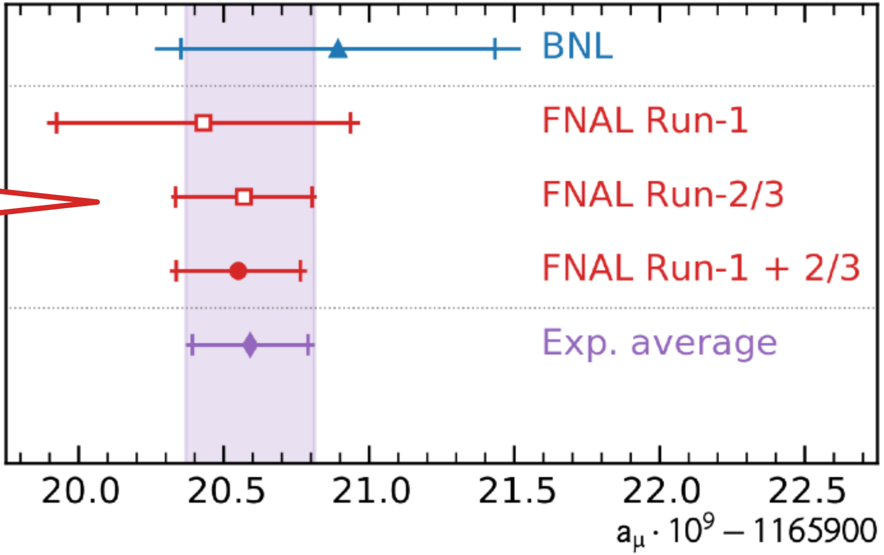


a_μ(Exp) = 116 592 059(22) x 10^{-11} [190 ppb]

Statistics dominated: 4.7 x data

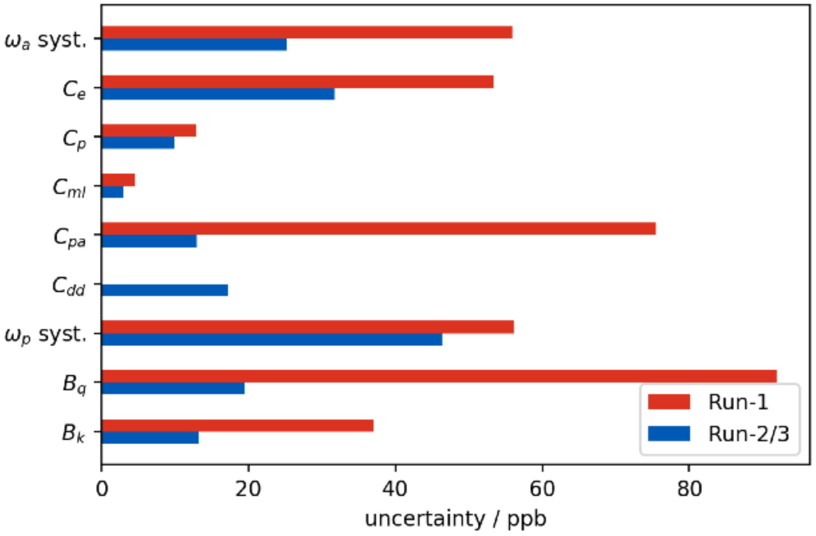
Run-1	434 ppb	2.2 x
Run-2/3	201 ppb	
Run1 + Run+2/3	185 ppb	

Run-2/3 Result: 2023 :: 0.2 ppm



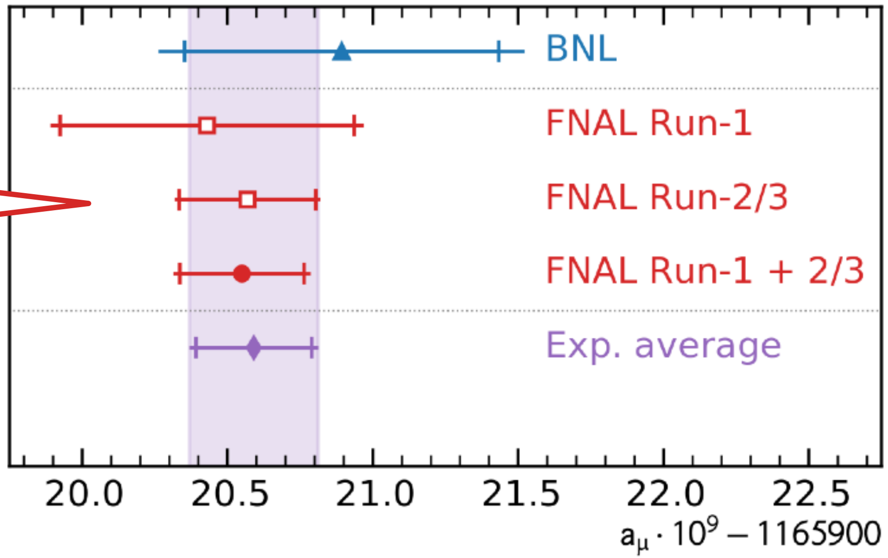
a_μ(Exp) = 116 592 059(22) x 10^{-11} [190 ppb]

Systematics: also 2.2 x improved



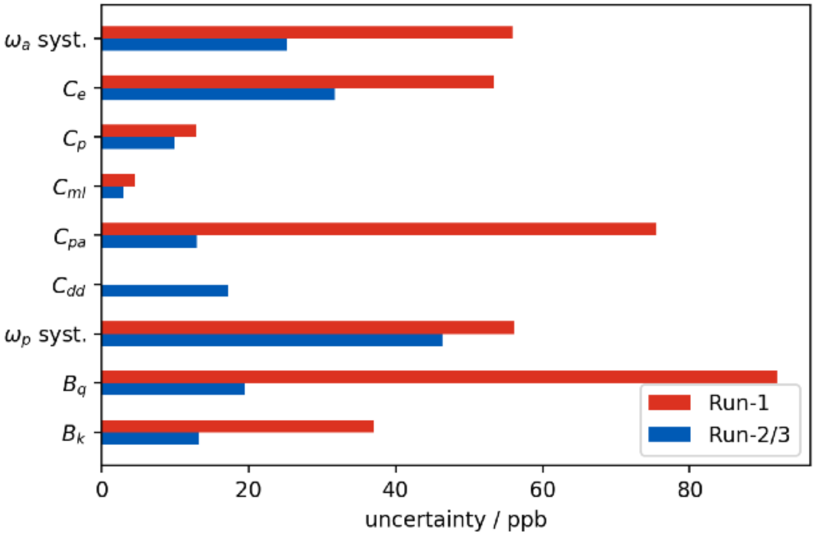
Total syst. Run-1: 157 ppb
Total syst. Run-2/3: 70 ppb
TDR goal: 100 ppb

Run-2/3 Result: 2023 :: 0.2 ppm



a_μ(Exp) = 116 592 059(22) x 10^{-11} [190 ppb]

SYSTEMATIC UNCERTAINTY - WHAT TO EXPECT

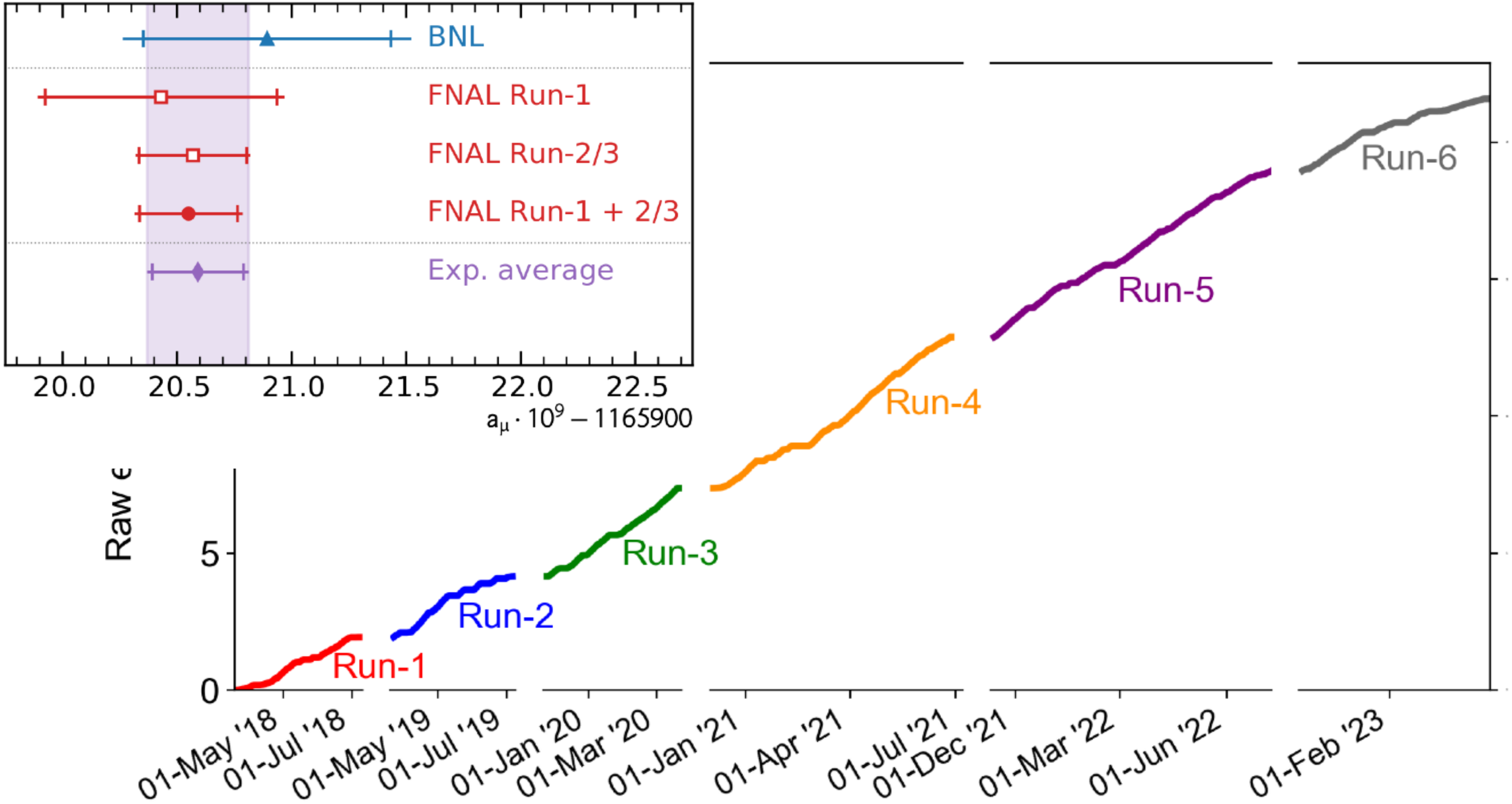


Total syst. Run-1: 157 ppb
Total syst. Run-2/3: 70 ppb
TDR goal: 100 ppb

Run-1: a few "large" systematics
B_q: new measuemrents
C_{pa}: fixed broken hardware
improved running conditions

Run-2/3: many individual systematics
on a very similar level
(~20 to 30 ppb)

Run-4/5/6: very similar conditions
added RF system to the ESQ
-> reducing beam oscillations


BNL
FNAL Run-1
FNAL Run-2/3
FNAL Run-1 + 2/3
Exp. average
20.0
20.5
21.0
21.5
22.0
22.5
$a_\mu \cdot 10^9 - 1165900$
Raw ϵ
5
0
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
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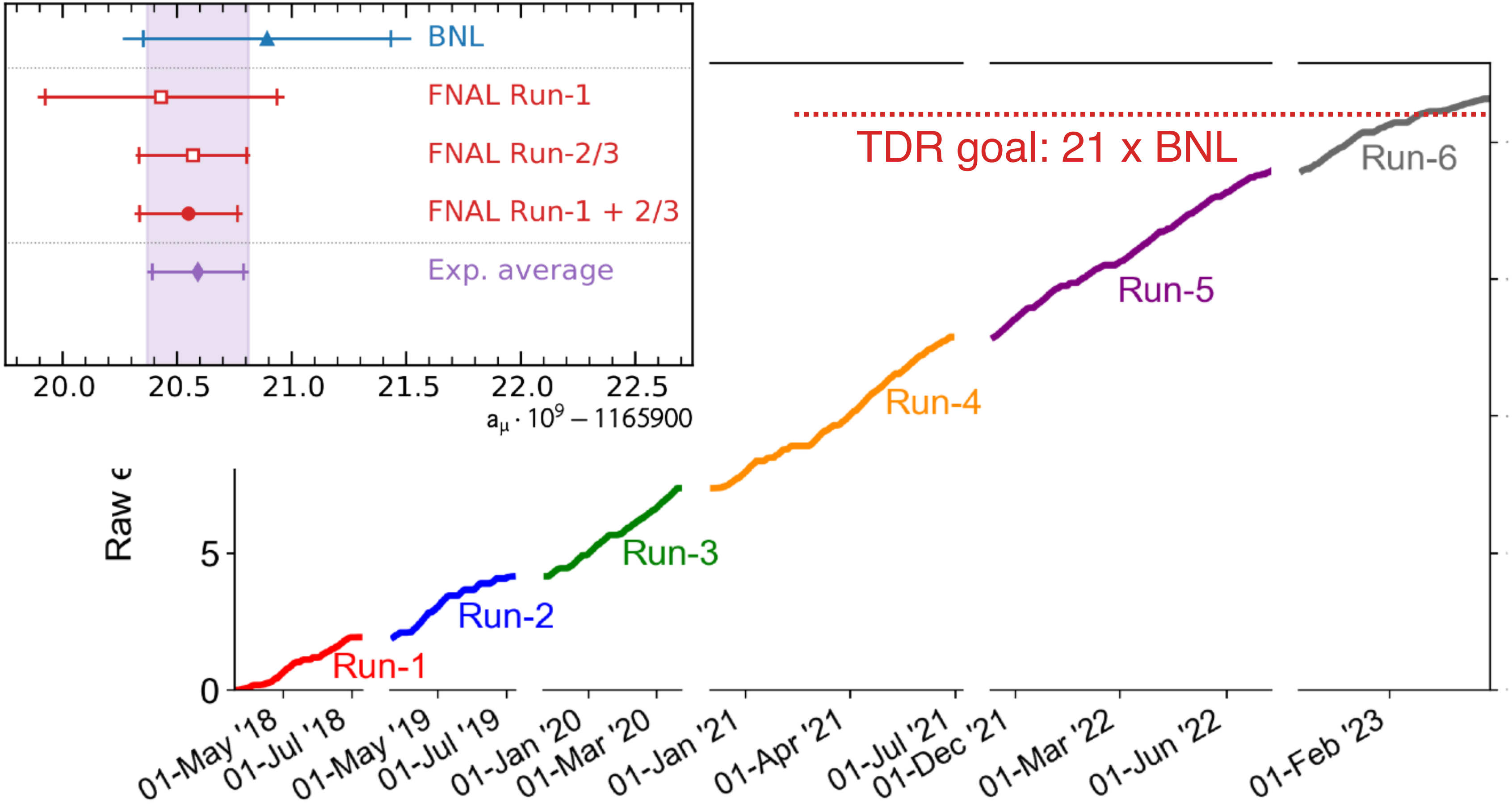
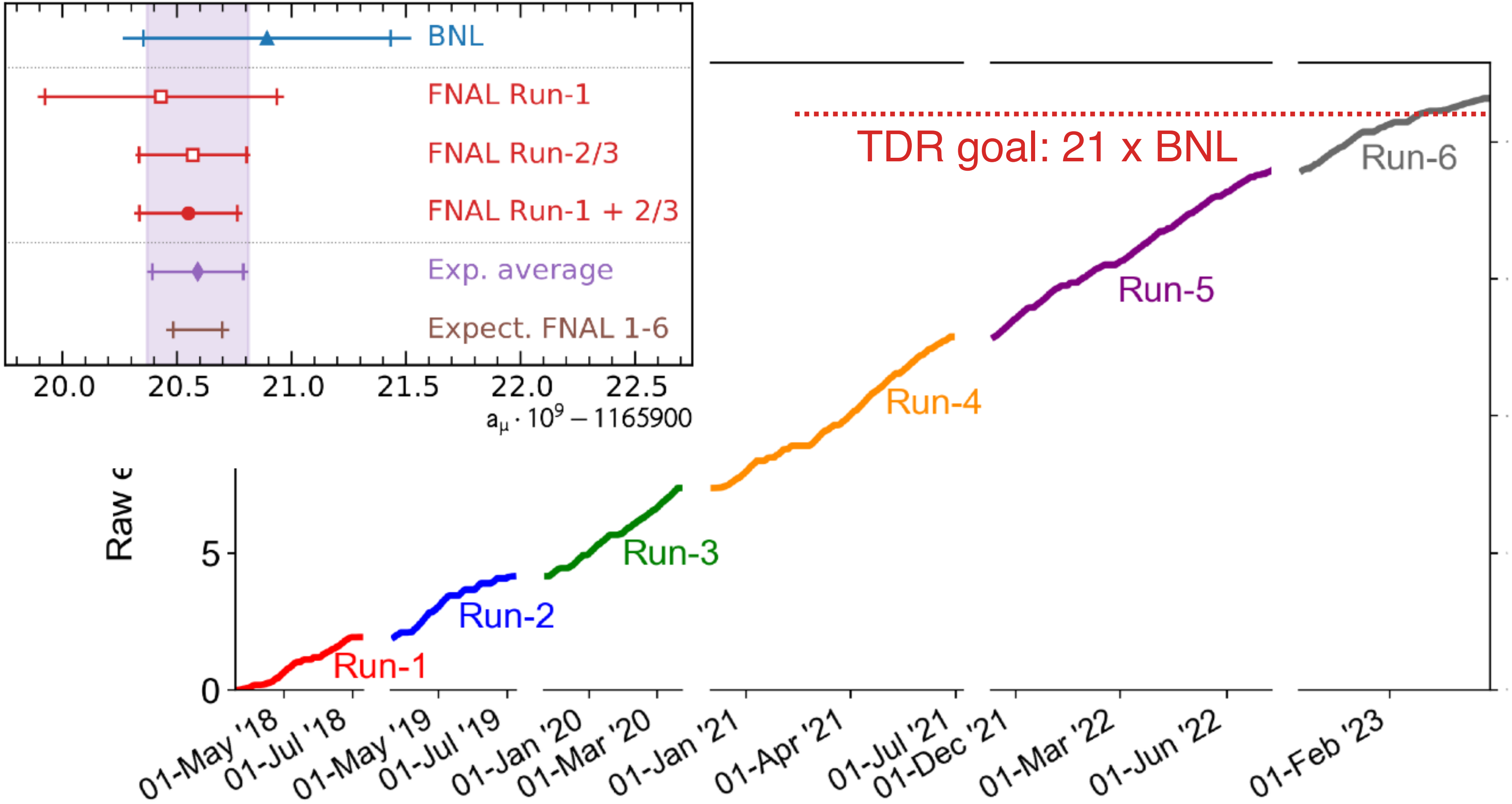
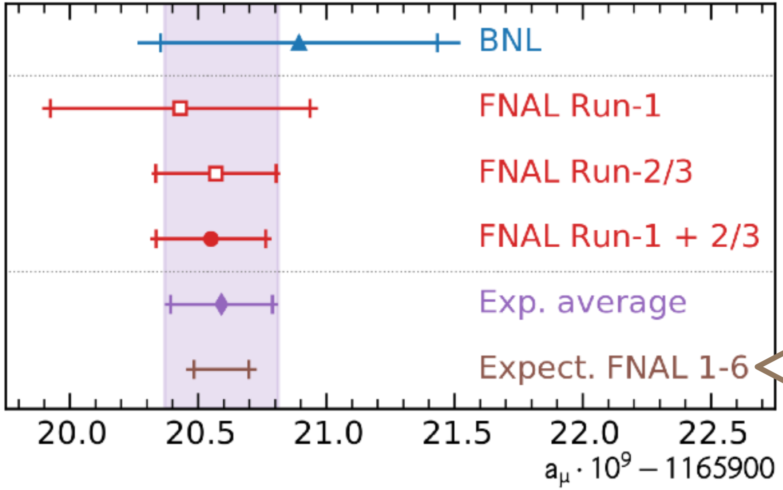
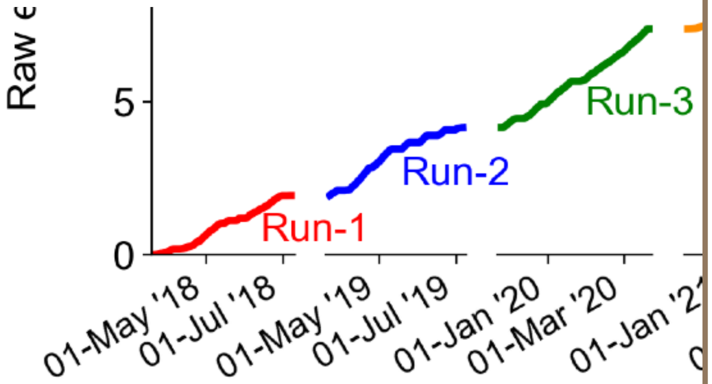
01-Feb '23



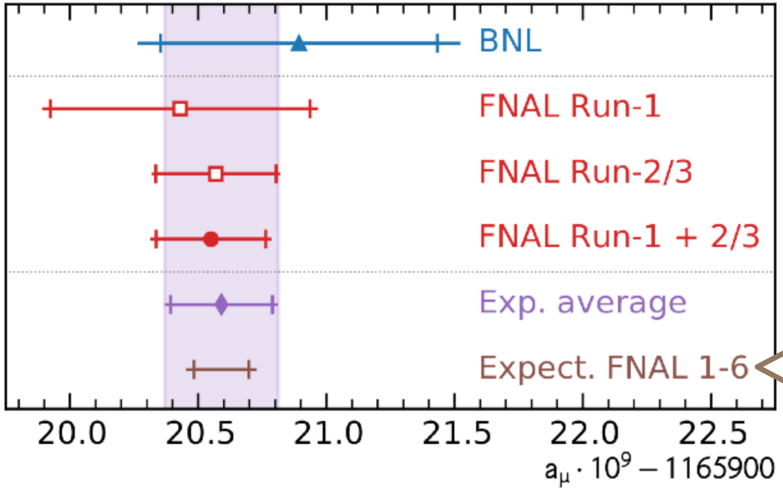
BNL
FNAL Run-1
FNAL Run-2/3
FNAL Run-1 + 2/3
Exp. average
20.0
20.5
21.0
21.5
22.0
22.5
$a_\mu \cdot 10^9 - 1165900$
TDR goal: 21 x BNL
Raw ϵ
0
5
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
01-Mar '22
01-Jun '22
01-Feb '23

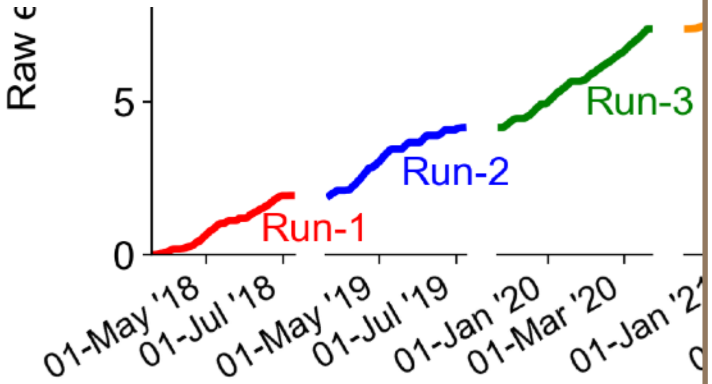

BNL
FNAL Run-1
FNAL Run-2/3
FNAL Run-1 + 2/3
Exp. average
Expect. FNAL 1-6
20.0
20.5
21.0
21.5
22.0
22.5
$a_\mu \cdot 10^9 - 1165900$
TDR goal: 21 x BNL
Raw ϵ
0
5
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
01-Mar '22
01-Jun '22
01-Feb '23





Expect to publish the full dataset 2025
~ 2x improved precision
likely still statistics limited





Expect to publish the full dataset 2025
~ 2x improved precision
likely still statistics limited

Other Analysis:
Muon EDM:
Current best limit from BNL Muon g-2:
$|d_\mu| < 1.8 \times 10^{-19} e\,\mathrm{cm}\ (95\,\%\ \mathrm{CL})$

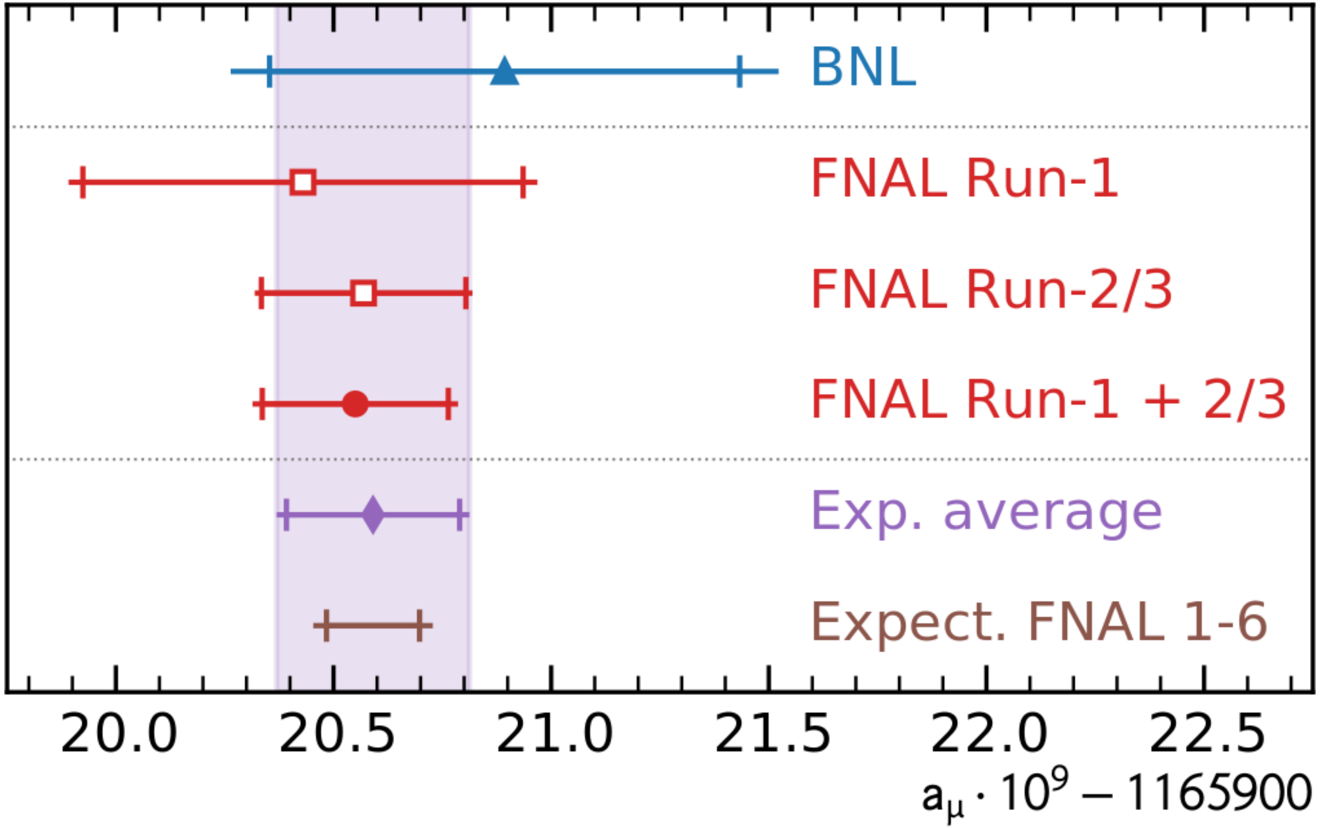
we aim to improve to $\sim 10^{-21} e\,\mathrm{cm}$
-> Dominika's talk on Friday

BSM searches:
CPT/LV & Dark Matter

THE COLLABORATION

Summer Collaboration meeting at University of Liverpool July 24-28,

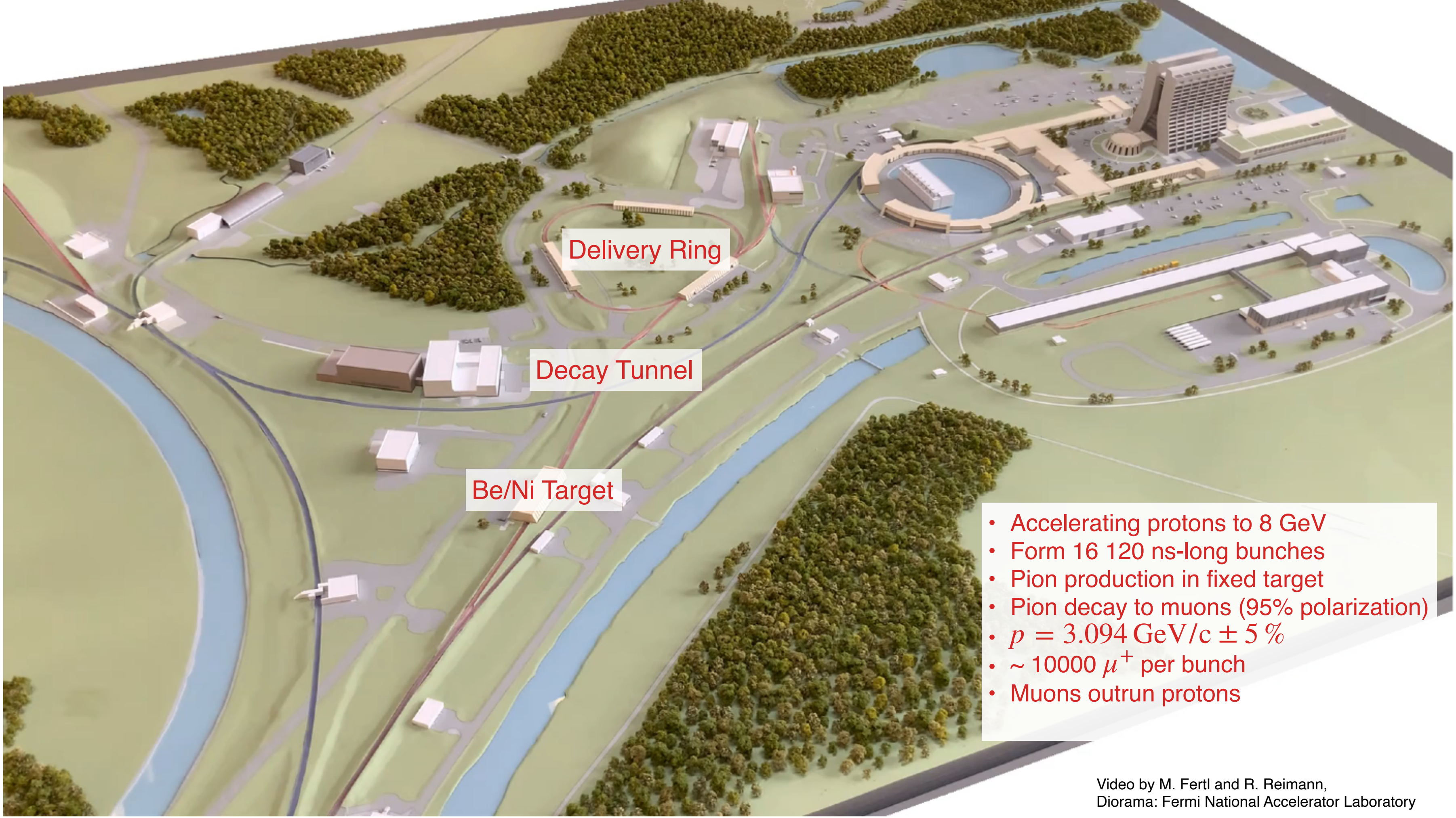
SUMMARY



BNL
FNAL Run-1
FNAL Run-2/3
FNAL Run-1 + 2/3
Exp. average
Expect. FNAL 1-6
20.0
20.5
21.0
21.5
22.0
22.5
$a_\mu \cdot 10^9 - 1165900$

The Muon g – 2 Experiment was performed at the 326 Fermi National Accelerator Laboratory, a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, 329 LLC (FRA), acting under Contract No. DE-AC02- 330 07CH11359. Additional support for the experiment was provided by the Department of Energy offices of HEP and NP (USA), the National Science Foundation (USA), the Istituto Nazionale di Fisica Nucleare (Italy), the Science and Technology Facilities Council (UK), the Royal Society (UK), the National Natural Science Foundation of China (Grant No. 11975153, 12075151), MSIP, NRF and IBS-R017-D1 (Republic of Korea), the German Research Foundation (DFG) through the Cluster of Excellence PRISMA+ (EXC 2118/1, Project ID 39083149), 340 the European Union Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements No. 101006726, No. 734303, European Union STRONG 2020 project under grant agreement No. 824093 and the Leverhulme Trust, LIP-2021-01.

Video by M. Fertl and R. Reimann,
Diorama: Fermi National Accelerator Laboratory



- Accelerating protons to 8 GeV
- Form 16 120 ns-long bunches
- Pion production in fixed target
- Pion decay to muons (95% polarization)
- $p = 3.094\,\mathrm{GeV/c} \pm 5\,\%$
- ~ 10000 μ^+ per bunch
- Muons outrun protons

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Diorama: Fermi National Accelerator Laboratory

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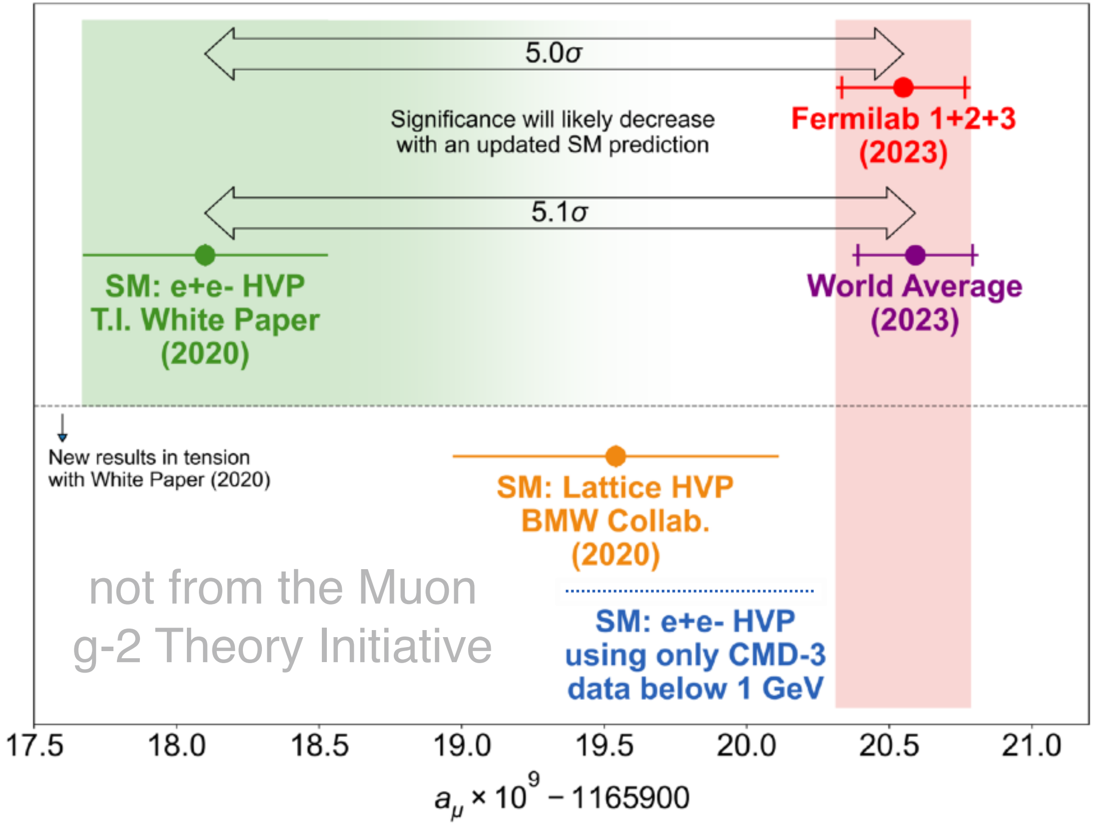
- Muons outrun protons
- Muon g-2 experimental hall

Video by M. Fertl and R. Reimann,
Diorama: Fermi National Accelerator Laboratory

Theory prediction is less clear now then in 2021, but we can still compare



Following A. Keshavarzi at Lattice 2023…

Substitute **CMD-3** data for HVP below 1 GeV

Cherry-picking one experiment but gives a bounding case

SND2k cannot be processed in this way, but would fall closer to WP (2020)

Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

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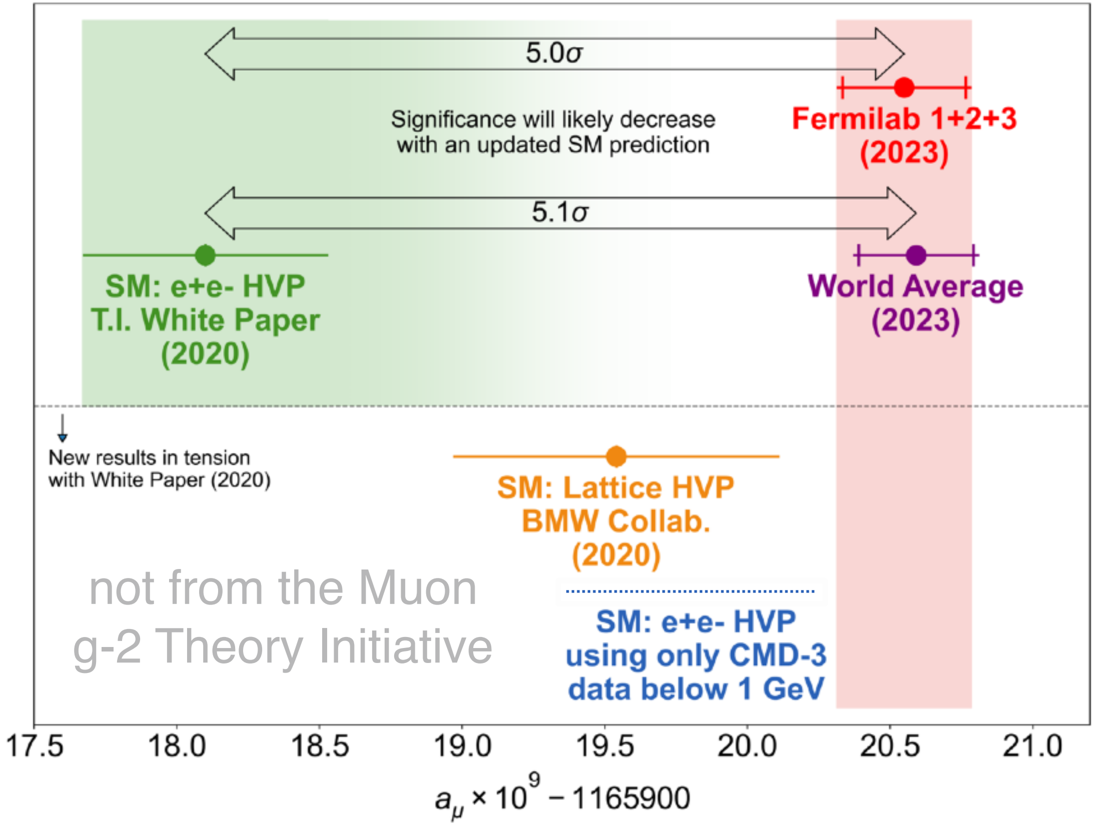

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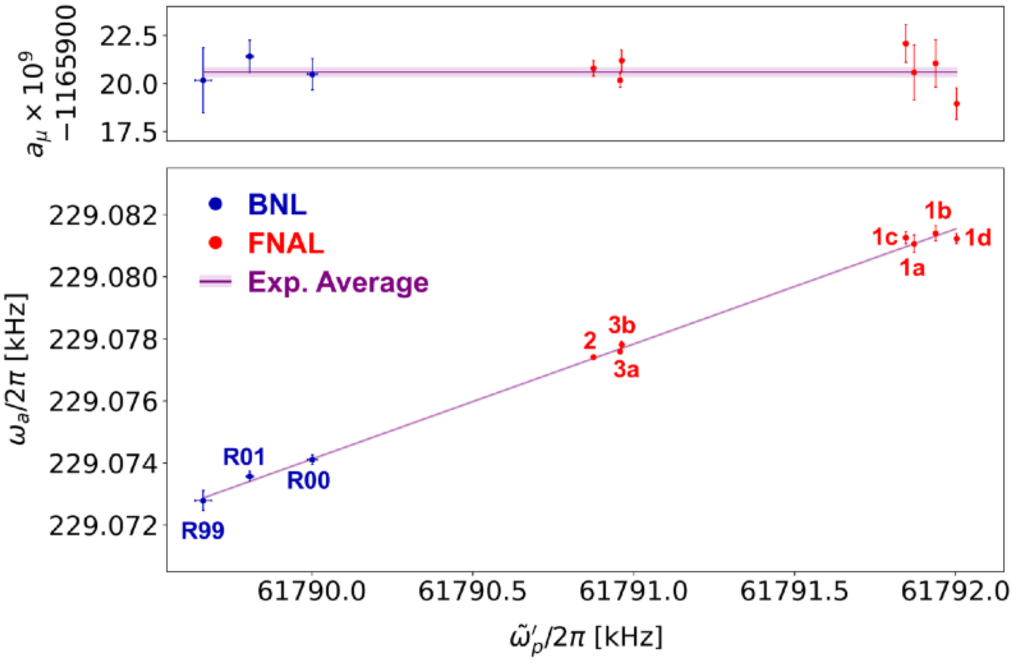
COMPARING DATASETS: CROSSCHECKS

Datasets were taken at slightly different field settings



Example of one of the most basic “handles”:
other checks against day/night, temperature, …