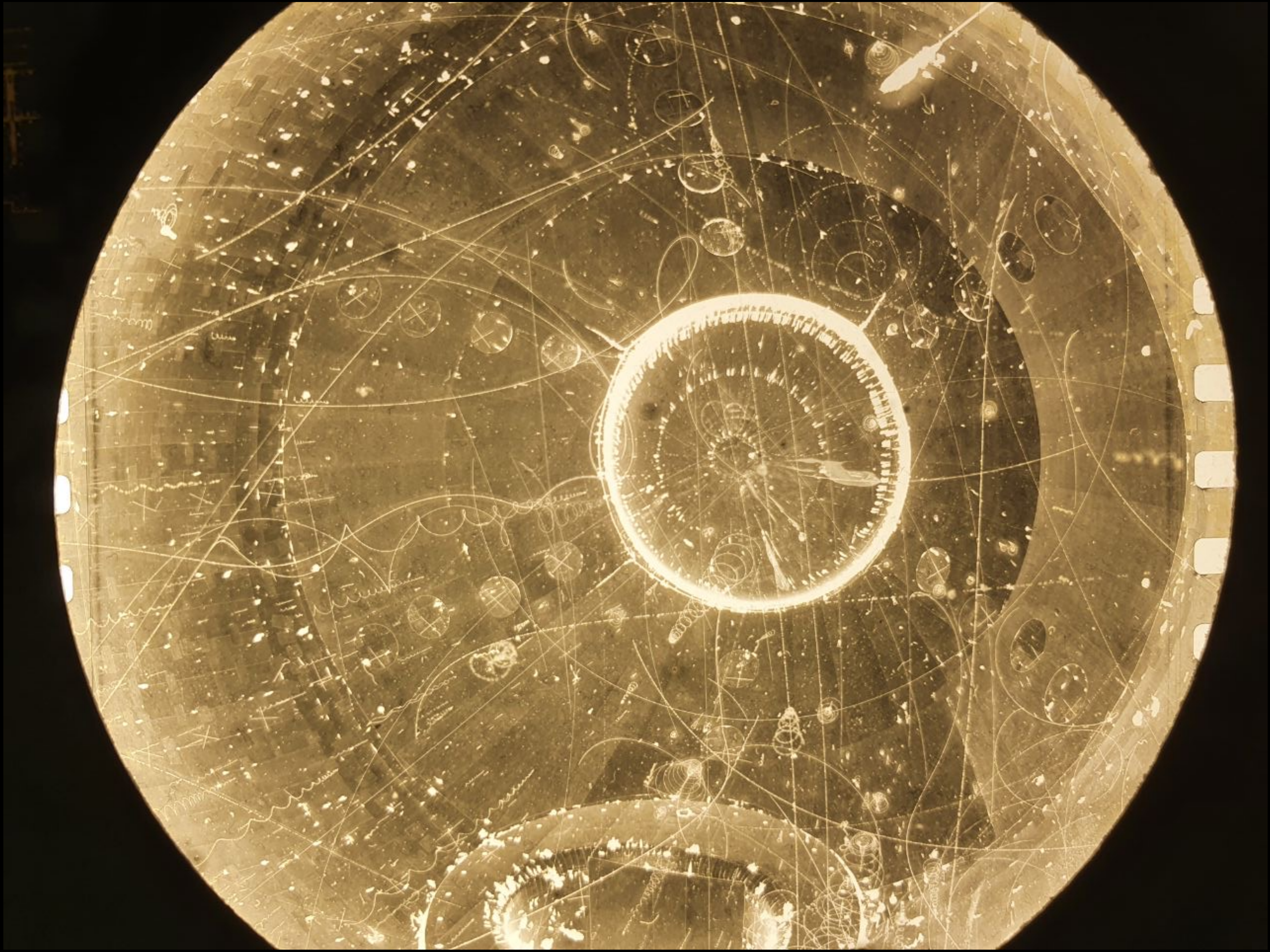
MUON g-2 EXPERIMENT

Matteo Sorbara

Università e INFN sezione Roma Tor Vergata

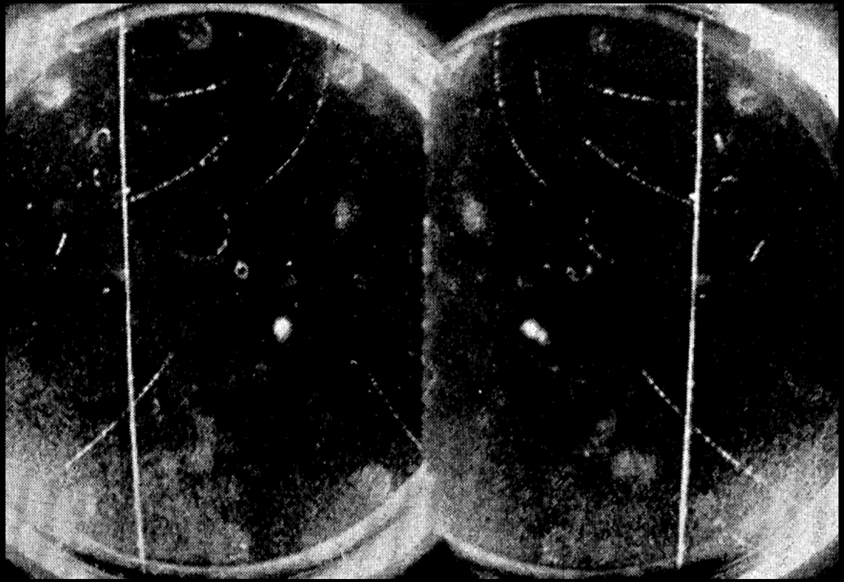
2024 Summer Students Program at FNAL

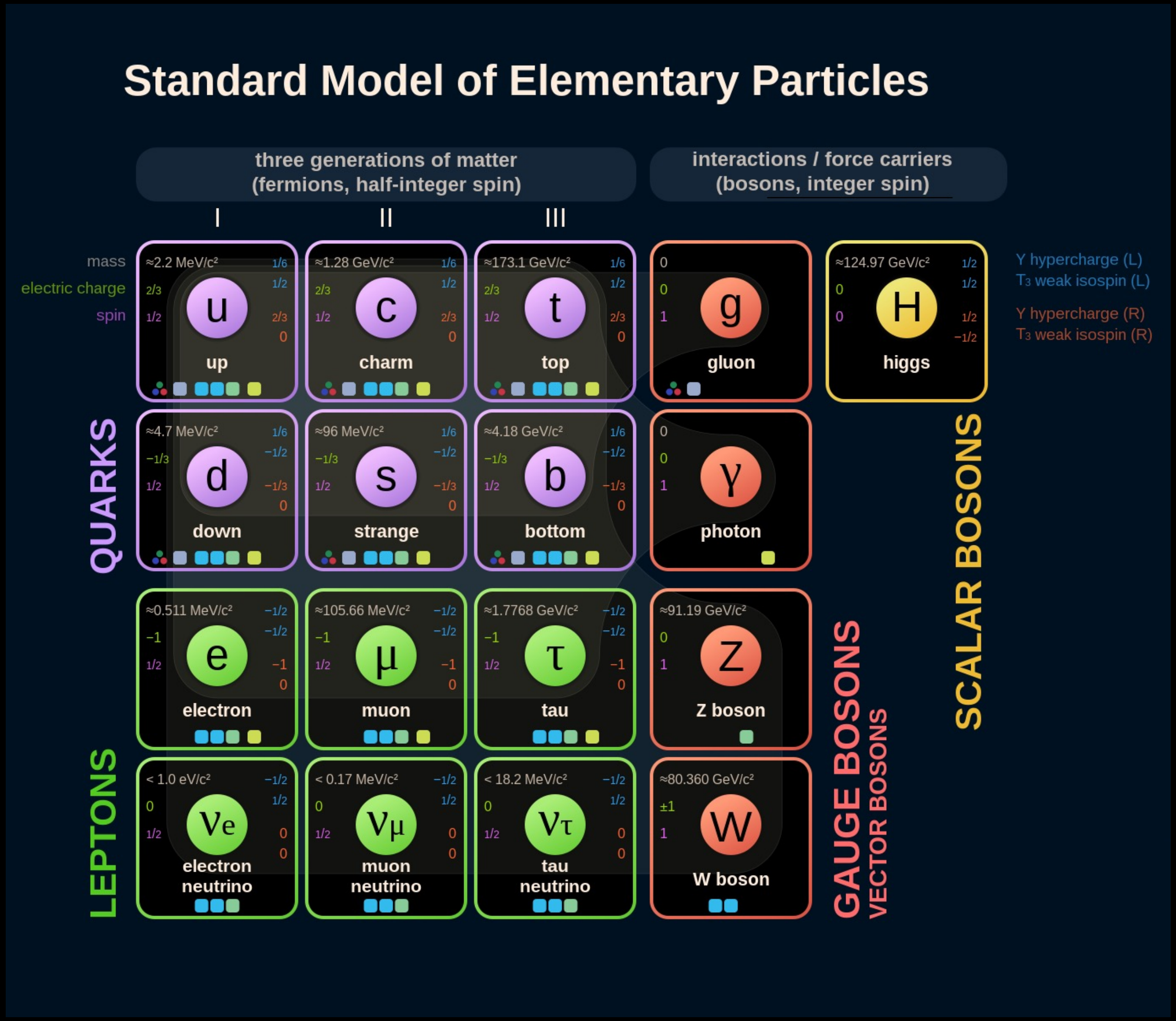
24 - 07 - 2024



Muons

- Discovered in 1936 by C. Anderson and S. Neddermeyer
- Charge: -1; Spin ½
- Lifetime at rest: 2.2 μs
- Mass: 105.65 MeV





Spin Precession

- A particle in a magnetic field experience a torque proportional to the magnetic moment:

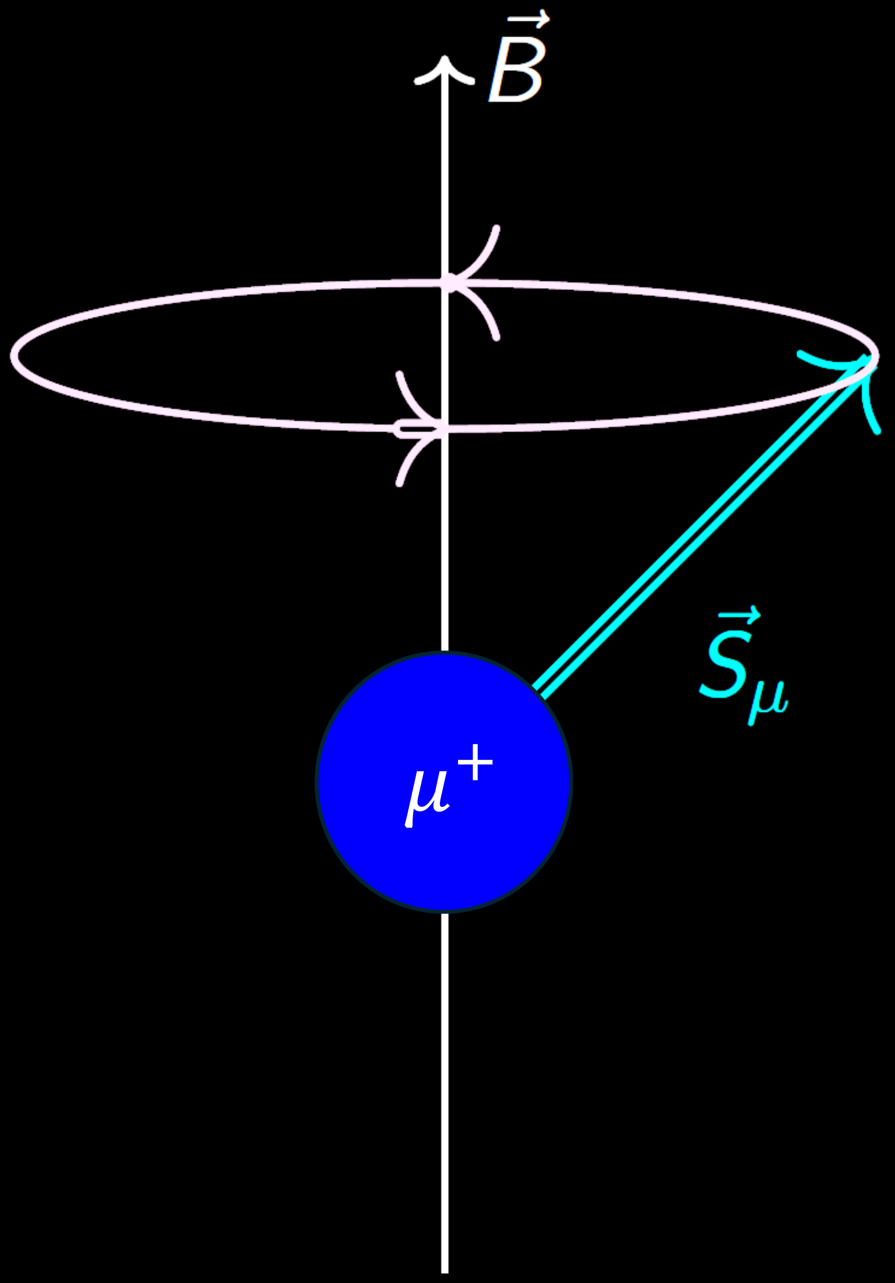
$$\vec{\mu} = g \frac{e}{2m} \vec{S}$$

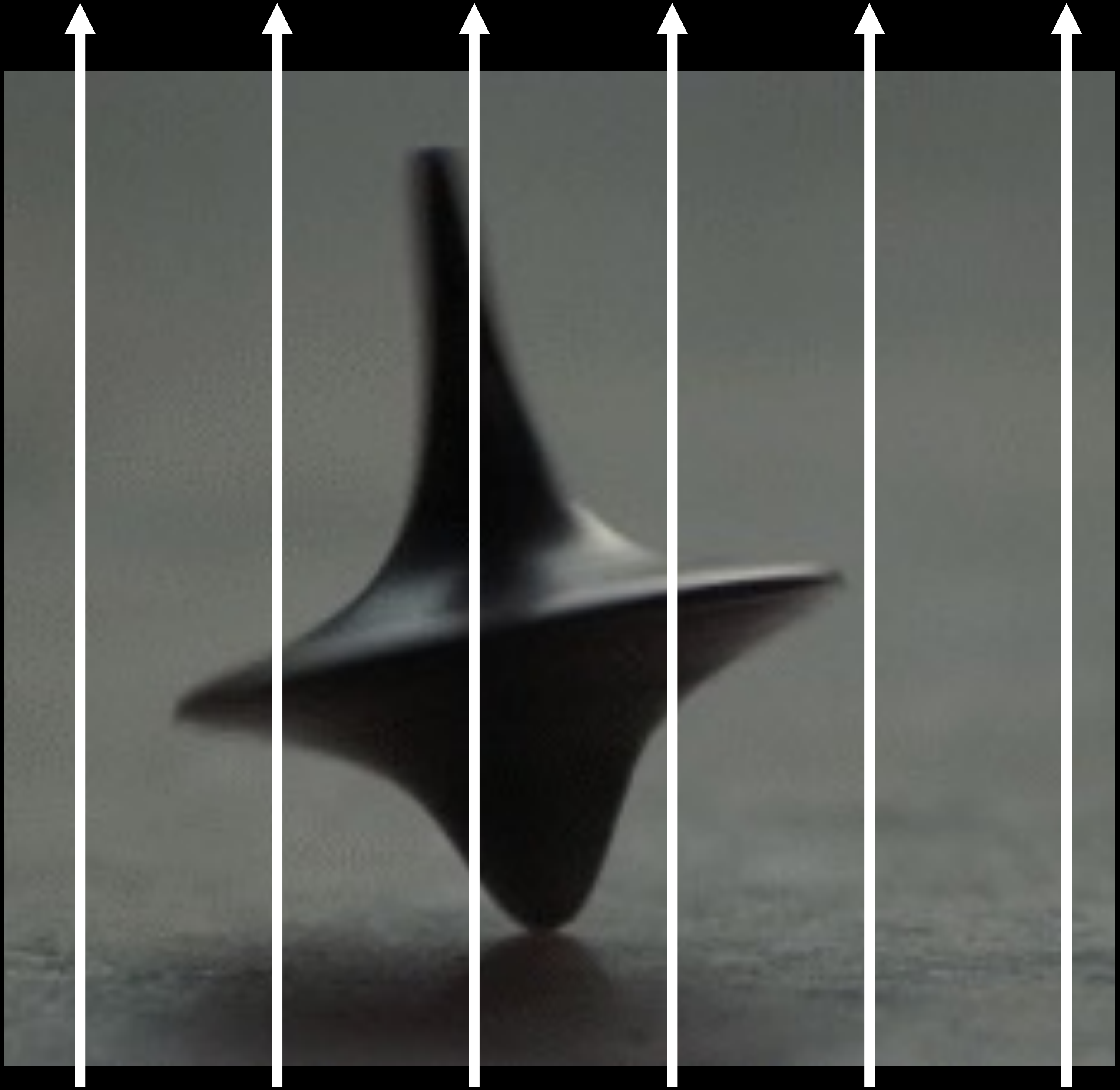
- The spin precession frequency is defined as:

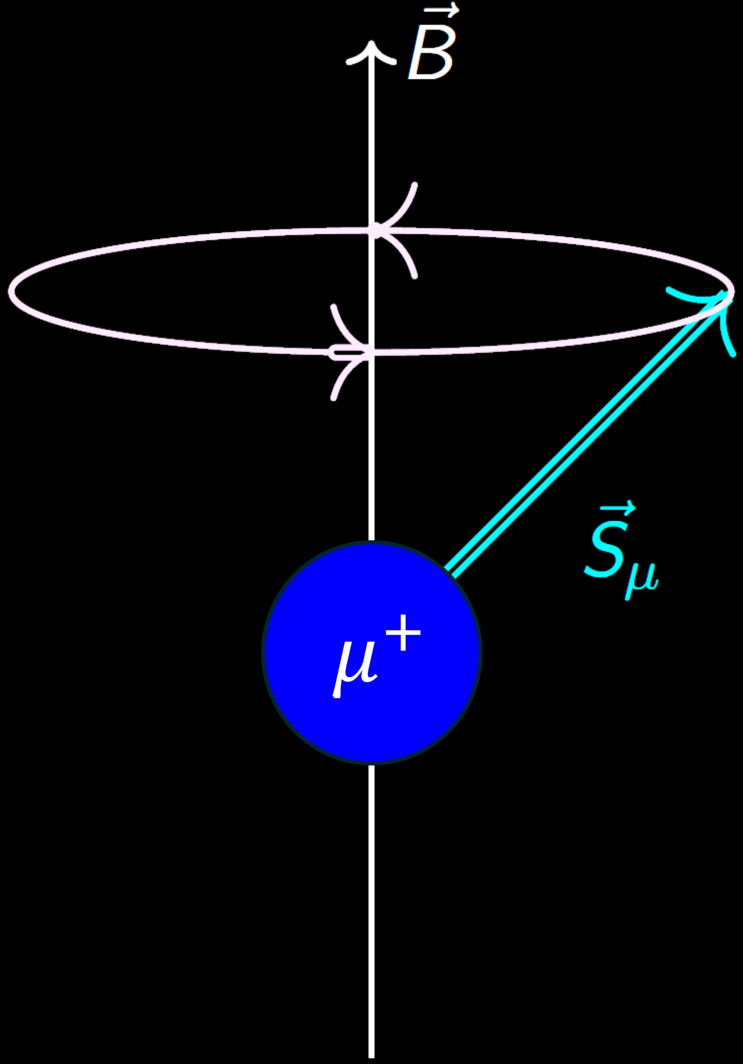
$$\omega_s = g \frac{e}{2m} B$$

- From Dirac's equation g=2 for an elementary particle

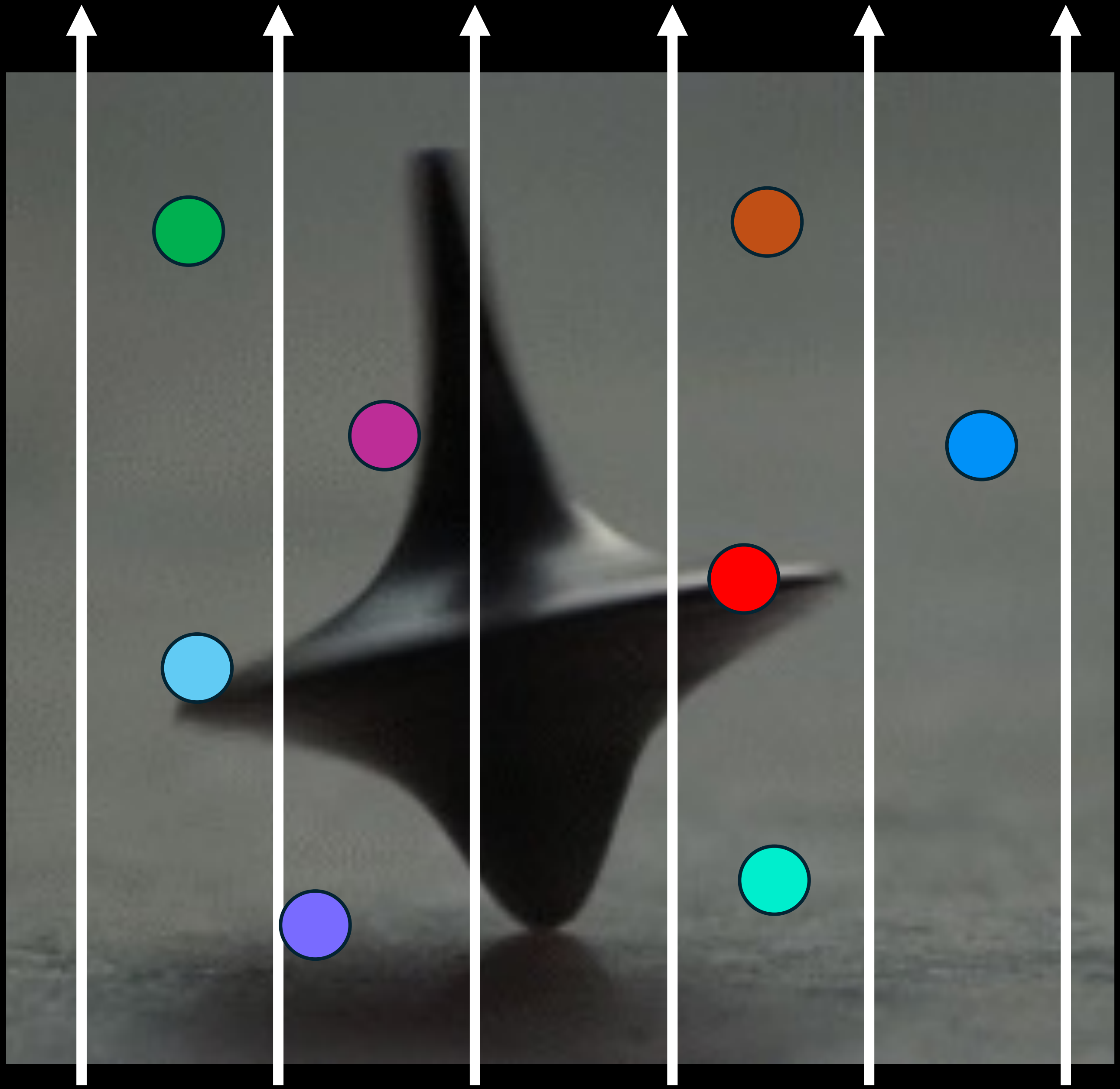
- Define the anomaly $a_\mu = \frac{g-2}{2}$

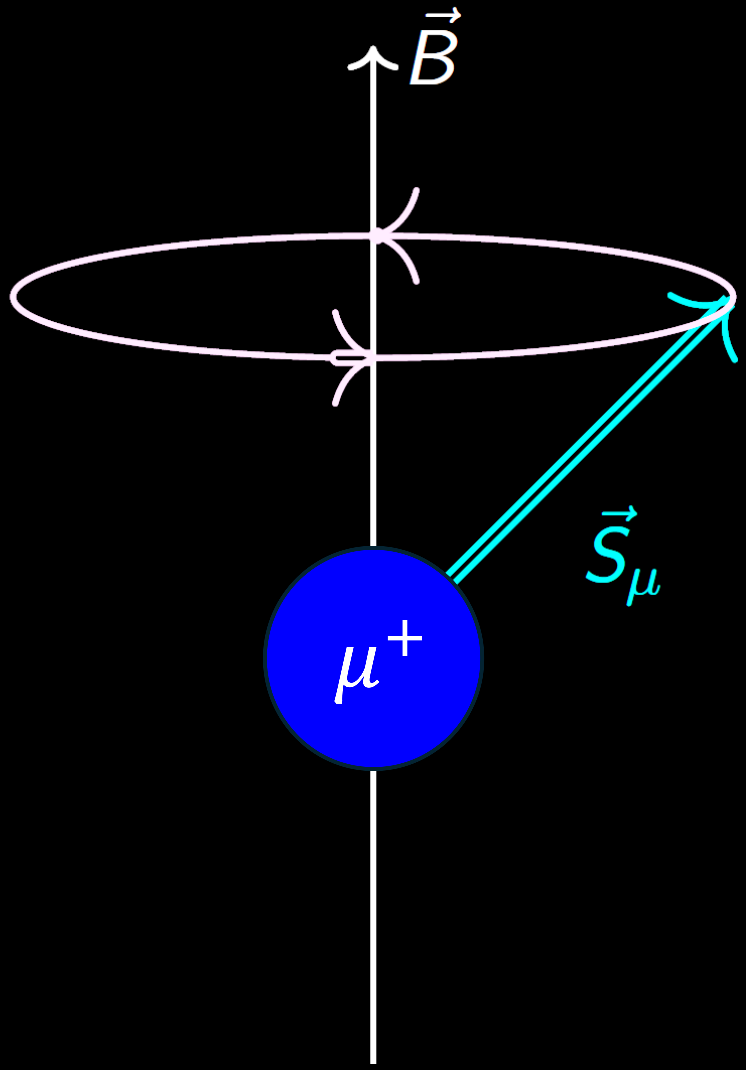






$$\omega_s = g\,\frac{e}{2m}\,B$$



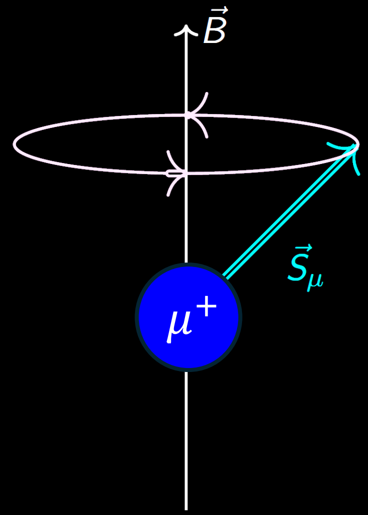


$$\omega_s = g' \frac{e}{2m} B$$

Muon g-2 Value

Theory VS Experiment

$a_\mu = 0$



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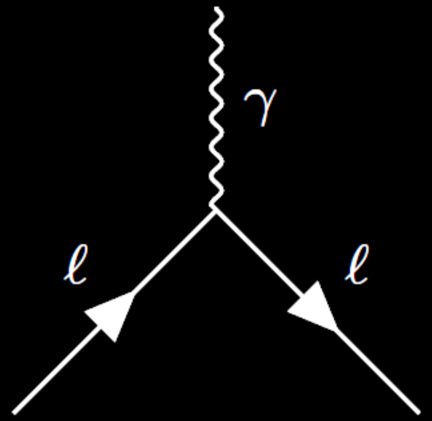
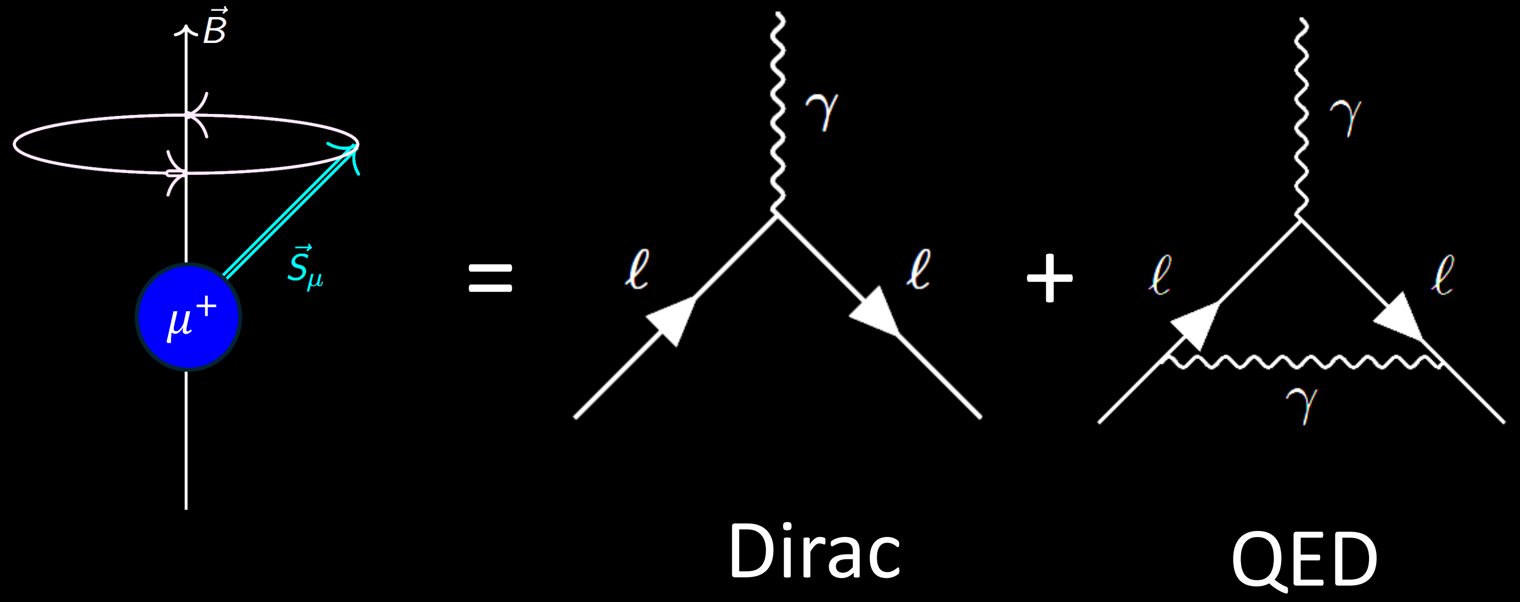
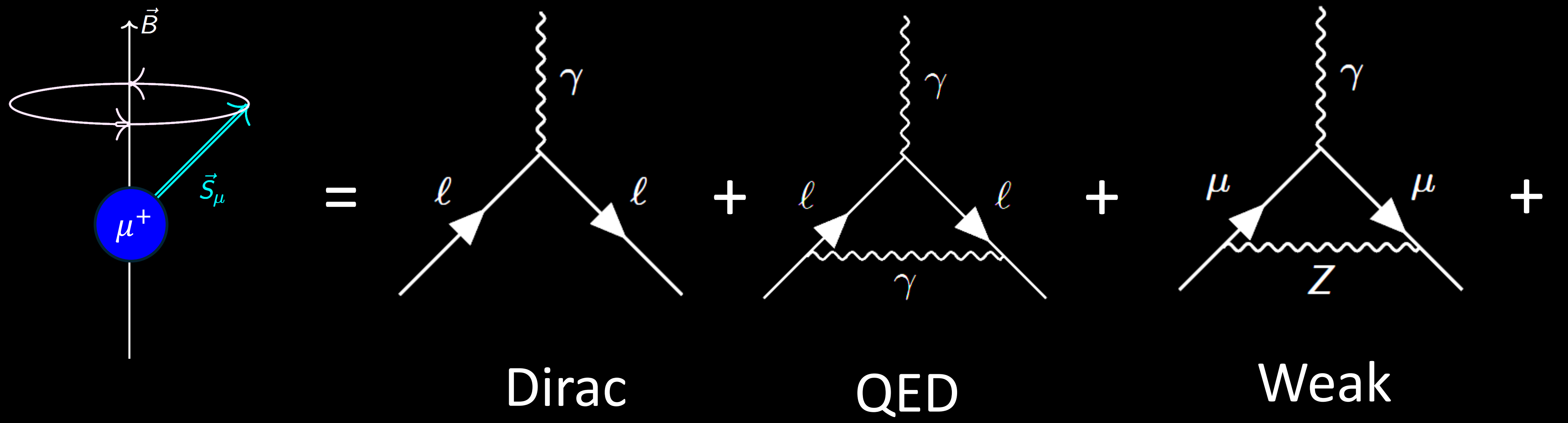


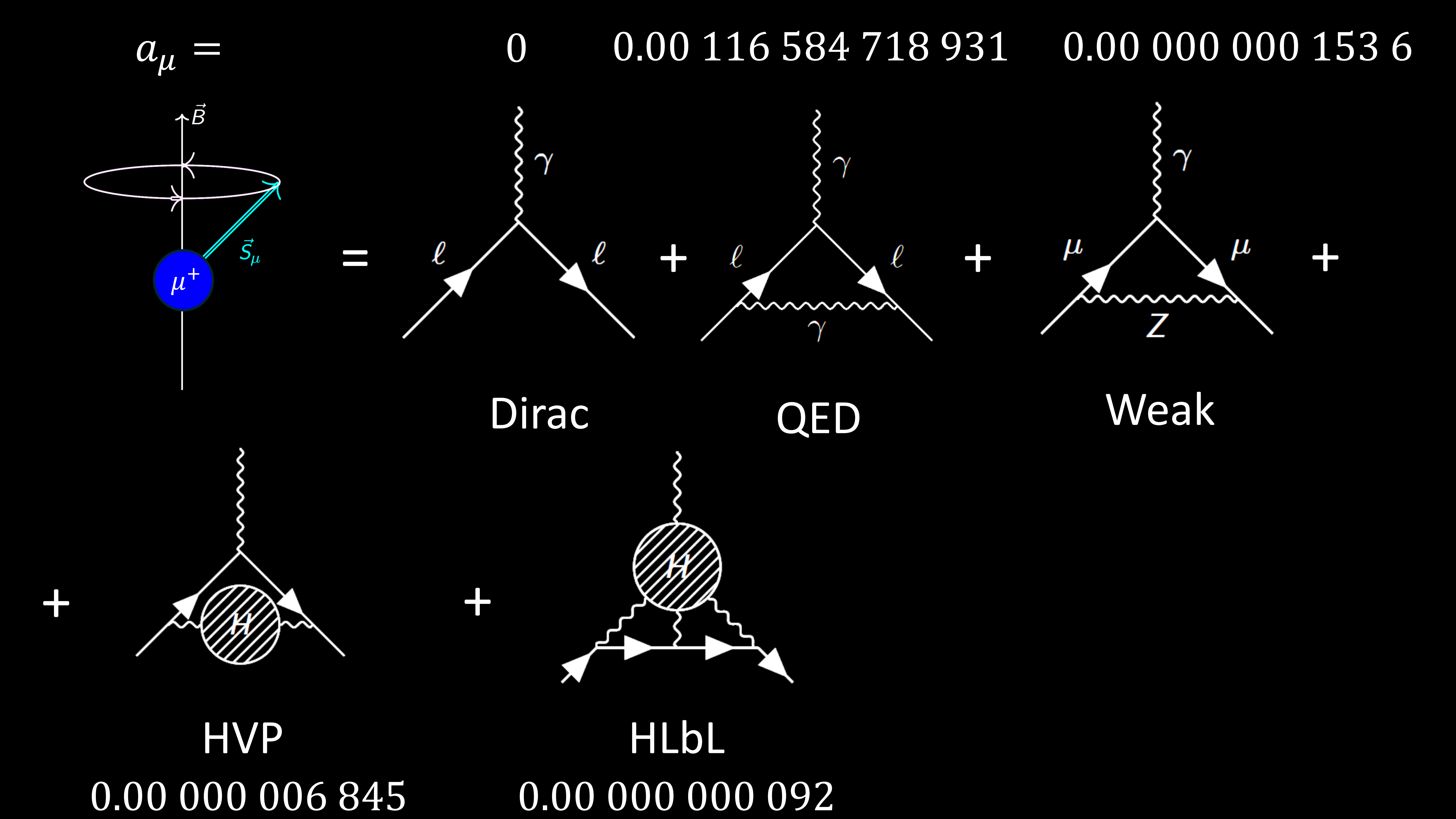
Dirac

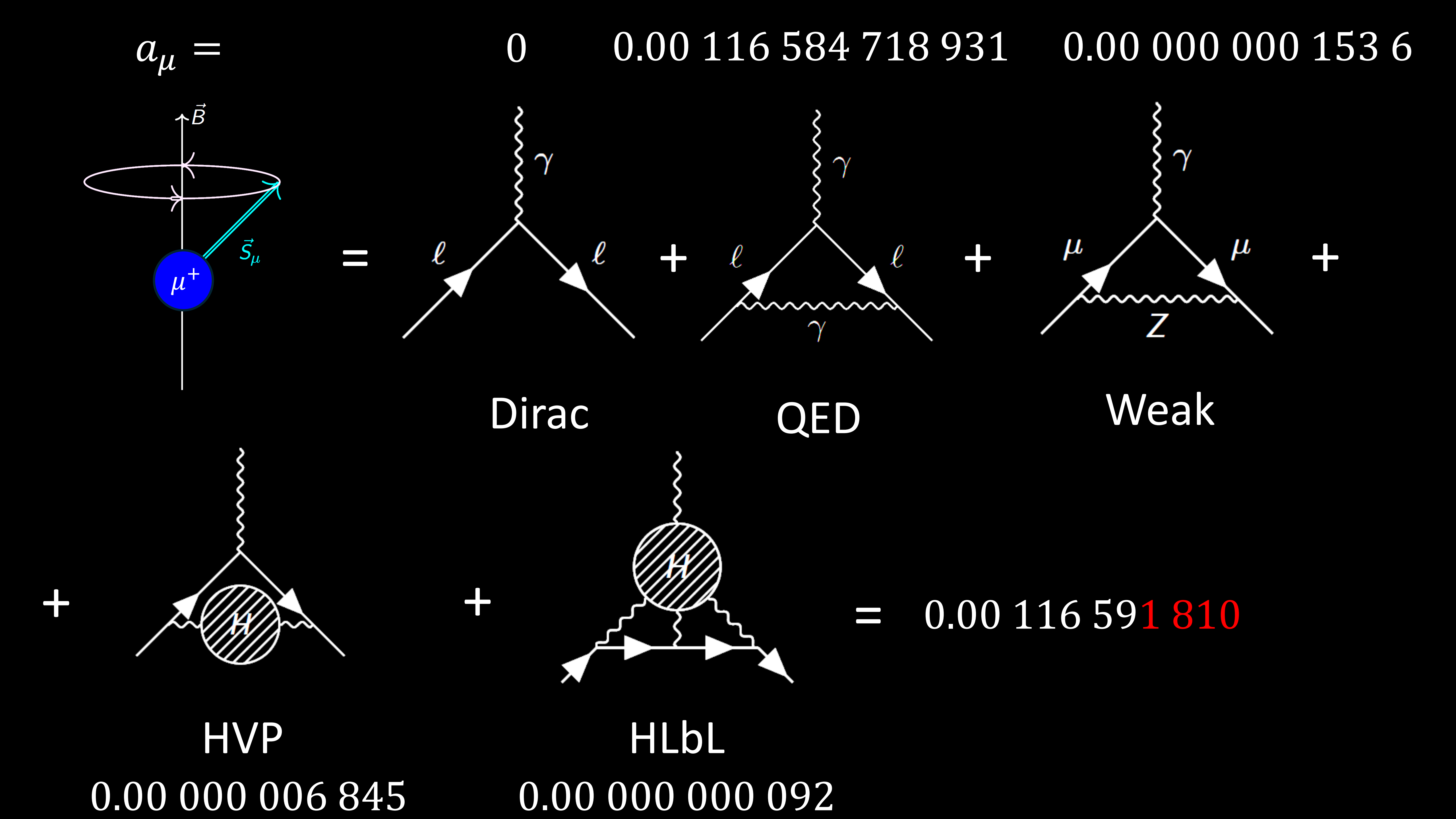
$a_\mu = \quad 0 \quad 0.00\,116\,584\,718\,931$



$$a_\mu = \quad 0 \quad 0.00\,116\,584\,718\,931 \quad 0.00\,000\,000\,153\,6$$

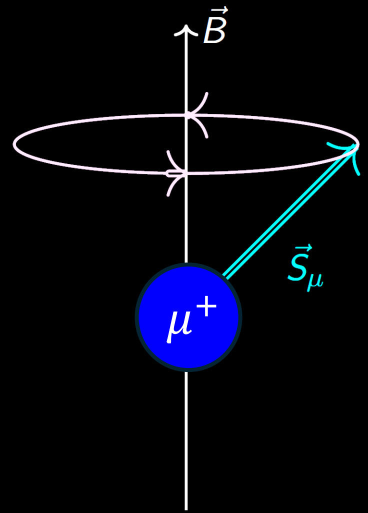



$a_\mu =$ 0 0.00 116 584 718 931 0.00 000 000 153 6
$\vec{B}$
$\vec{s}_\mu$
μ^+
γ
ℓ
μ
Z
Dirac
QED
Weak
H
HVP
0.00 000 006 845
HLbL
0.00 000 000 092



$a_\mu =$
0
0.00 116 584 718 931
0.00 000 000 153 6
$\vec{B}$
$\vec{s}_\mu$
μ^+
=
γ
ℓ
μ
Z
+
Dirac
QED
Weak
H
=
0.00 116 591 810
HVP
0.00 000 006 845
HLbL
0.00 000 000 092

$a_\mu =$ 0 0.00 116 584 718 931 0.00 000 000 153 6



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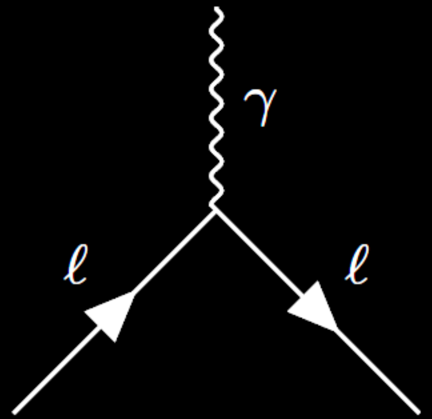
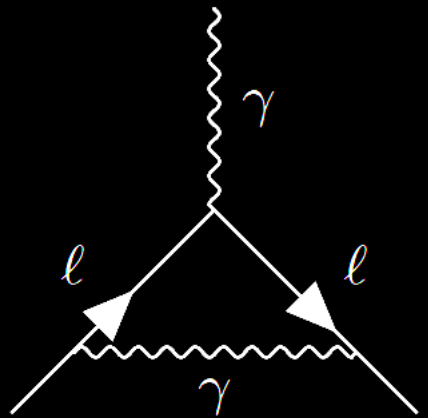


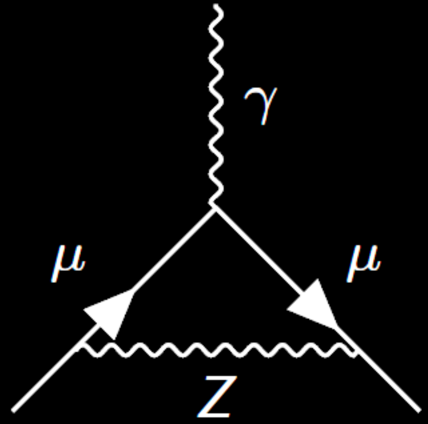
Dirac

+



QED

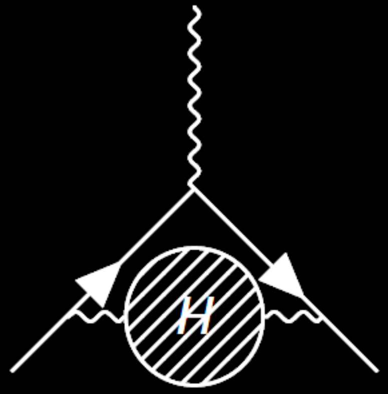
+



Weak

+

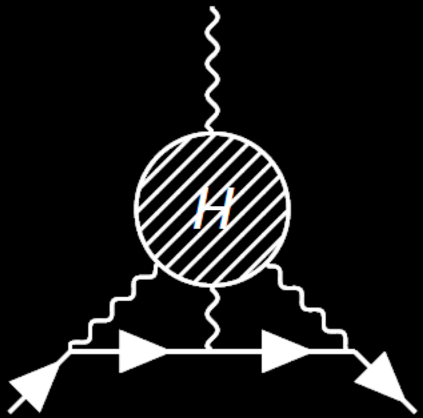
+



HVP

0.00 000 006 845

+



HLbL

0.00 000 000 092

= 0.00 116 591 810

0.00 116 592 059

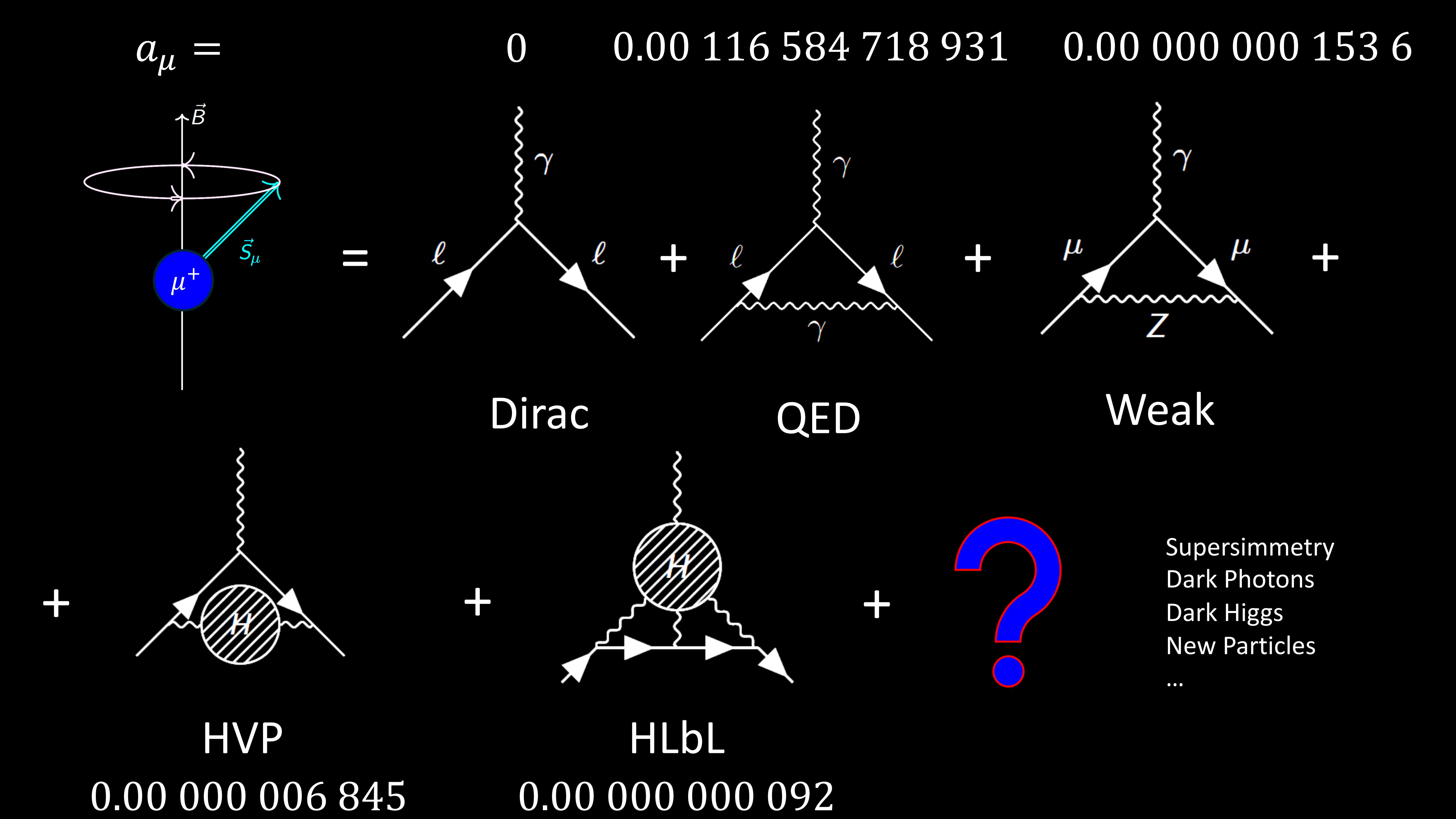
EXPERIMENTAL RESULT

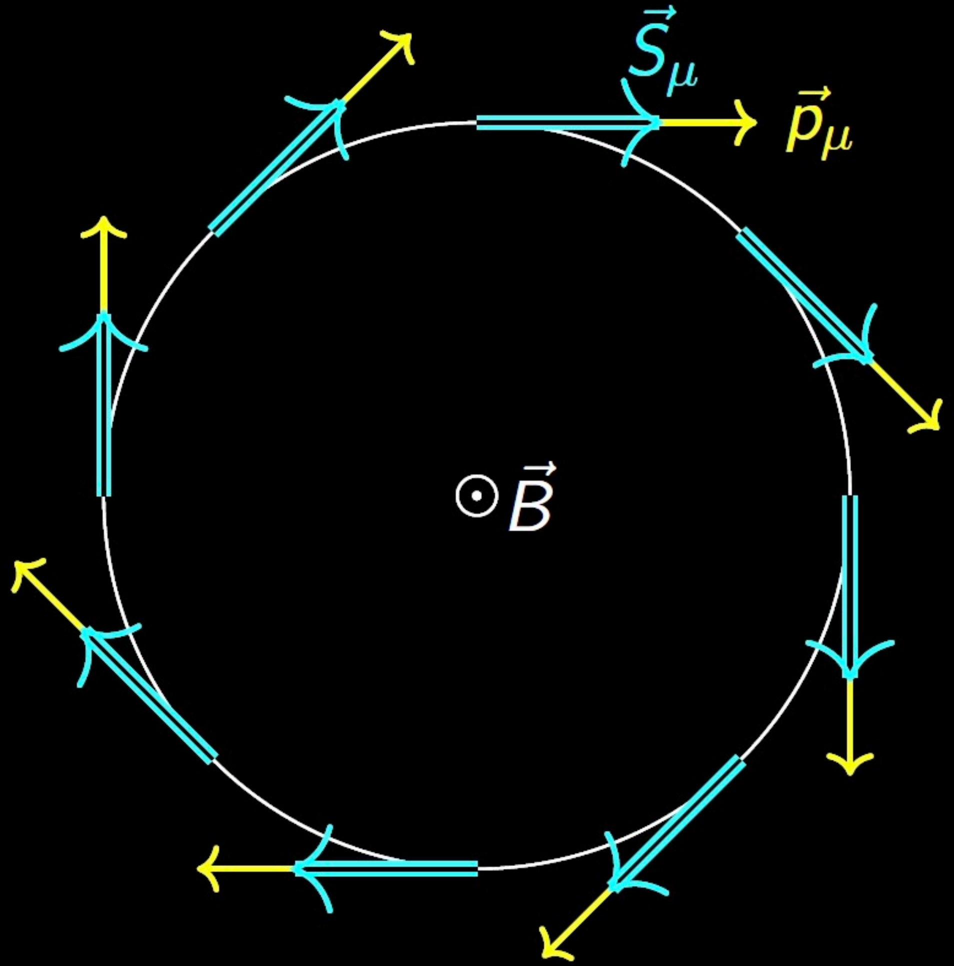
The Muon g-2 Theory Initiative

T. Aoyama et al. - The anomalous magnetic moment of the muon in the Standard Model - Phys. Rept. 887 (2020) 1-166

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	Sec. 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	Sec. 2.3.8	Eq. (2.34)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	Sec. 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, $udsc$)	Sec. 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Sec. 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Sec. 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, uds)	Sec. 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Sec. 8	Eq. (8.10)	90(17)	Refs. [18–30, 32]
QED	Sec. 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33, 34]
Electroweak	Sec. 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35, 36]
HVP (e^+e^-, LO + NLO + NNLO)	Sec. 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Sec. 8	Eq. (8.11)	92(18)	Refs. [18–32]
Total SM Value	Sec. 8	Eq. (8.12)	116 591 810(43)	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	Sec. 8	Eq. (8.14)	279(76)	

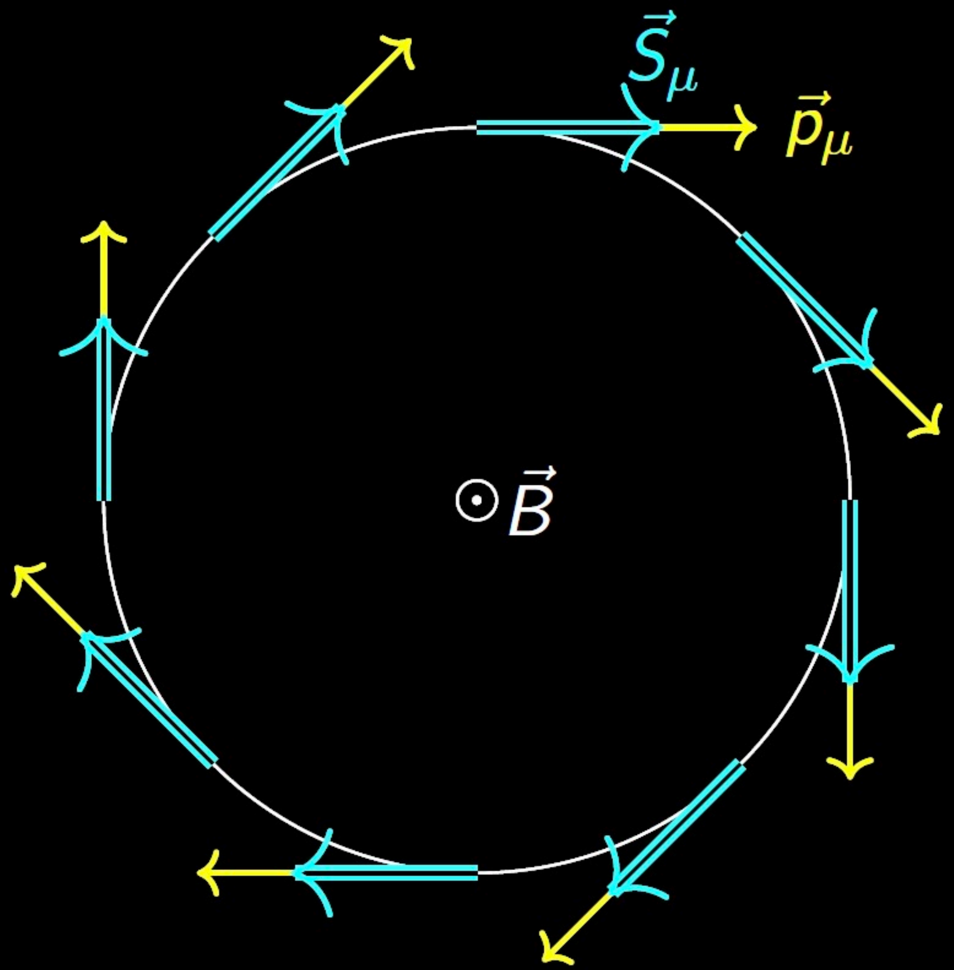
Table 1: Summary of the contributions to a_μ^{SM}. After the experimental number from E821, the first block gives the main results for the hadronic contributions from Secs. 2 to 5 as well as the combined result for HLbL scattering from phenomenology and lattice QCD constructed in Sec. 8. The second block summarizes the quantities entering our recommended SM value, in particular, the total HVP contribution, evaluated from e^+e^- data, and the total HLbL number. The construction of the total HVP and HLbL contributions takes into account correlations among the terms at different orders, and the final rounding includes subleading digits at intermediate stages. The HVP evaluation is mainly based on the experimental Refs. [37–89]. In addition, the HLbL evaluation uses experimental input from Refs. [90–109]. The lattice QCD calculation of the HLbL contribution builds on crucial methodological advances from Refs. [110–116]. Finally, the QED value uses the fine-structure constant obtained from atom-interferometry measurements of the Cs atom [117].


$a_\mu =$
0
0.00 116 584 718 931
0.00 000 000 153 6
$\vec{B}$
$\vec{s}_\mu$
μ^+
=
γ
ℓ
ℓ
Dirac
+
γ
ℓ
ℓ
γ
QED
+
γ
μ
μ
Z
Weak
+
+
H
HVP
0.00 000 006 845
+
H
HLbL
0.00 000 000 092
+
?
Supersimmetry
Dark Photons
Dark Higgs
New Particles
…

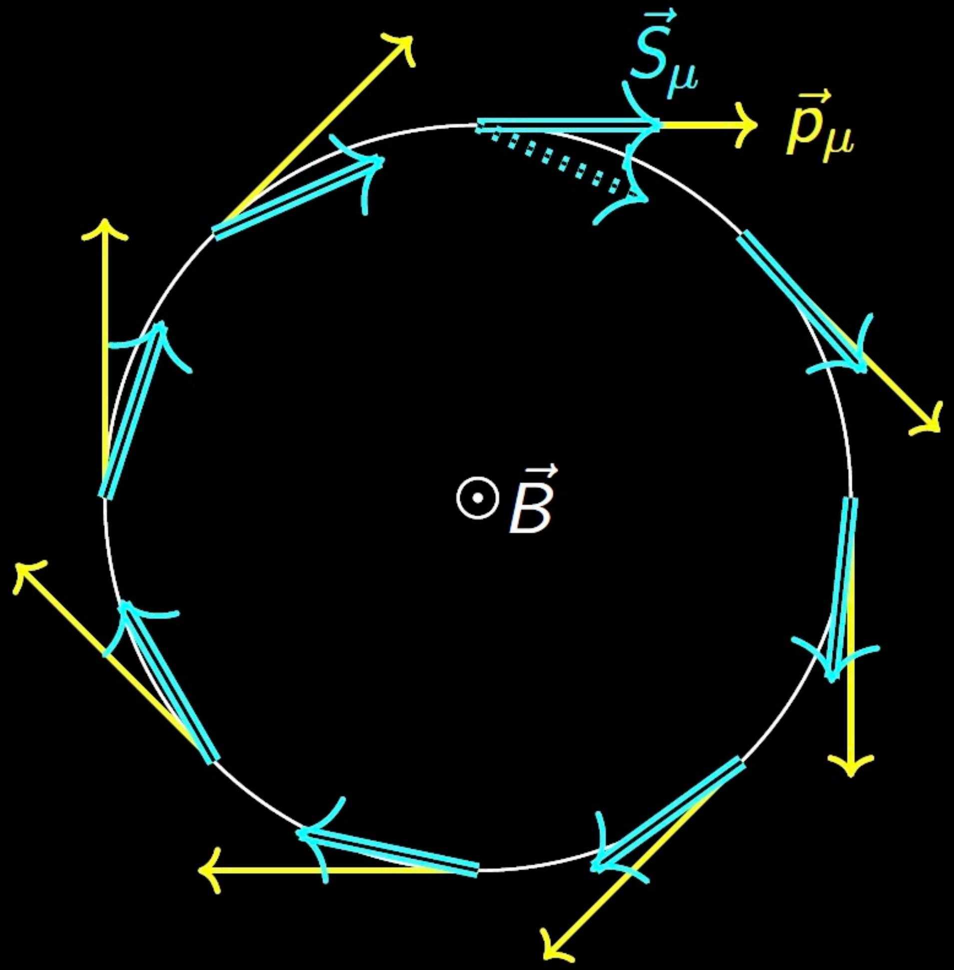


$$g = 2$$

$$\omega_a = \omega_s - \omega_c = \frac{g-2}{2}\frac{e}{2m}B$$

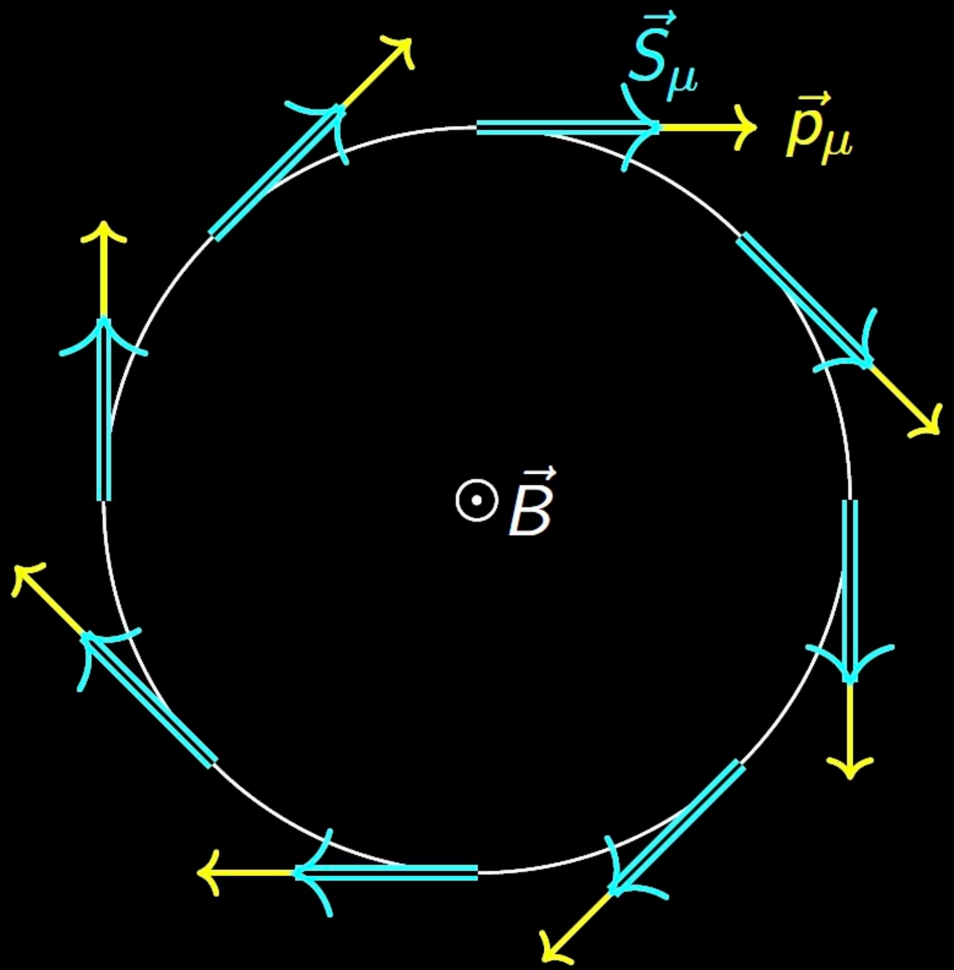


$g = 2\,;\ a_\mu = 0$

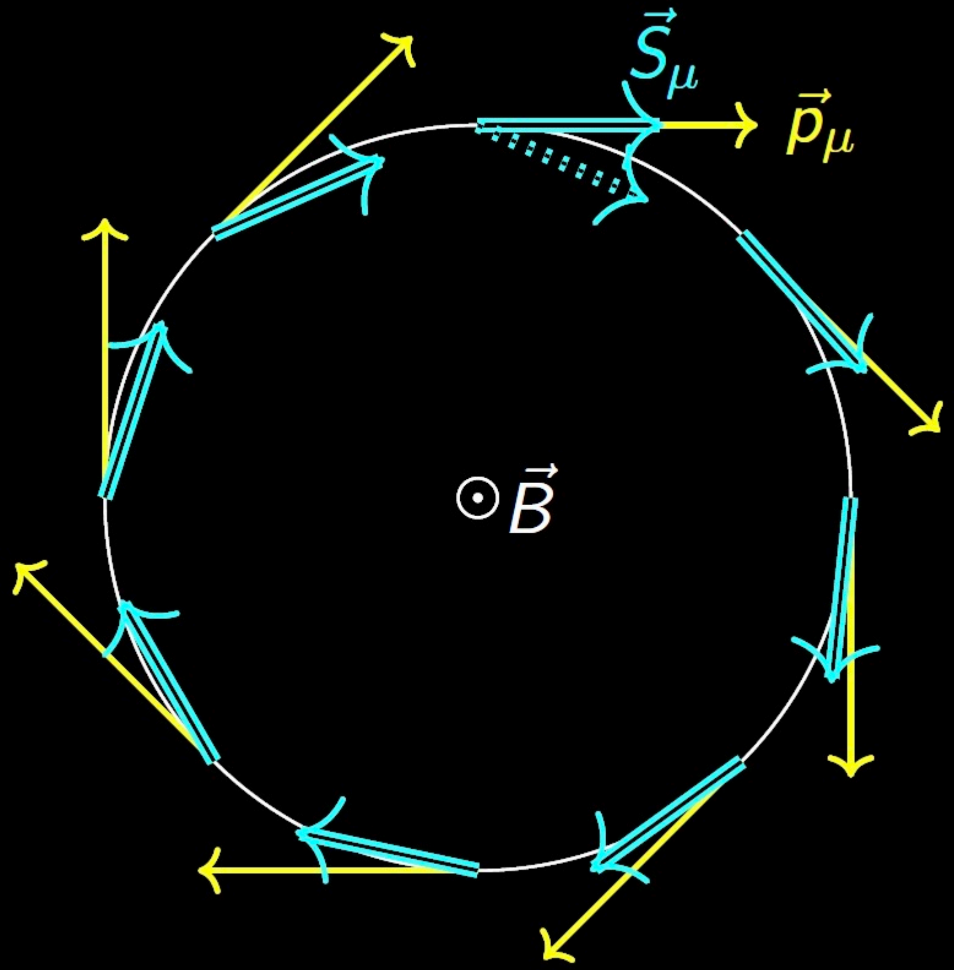


$g > 2\,; a_\mu > 0$

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e}{2m} B$$

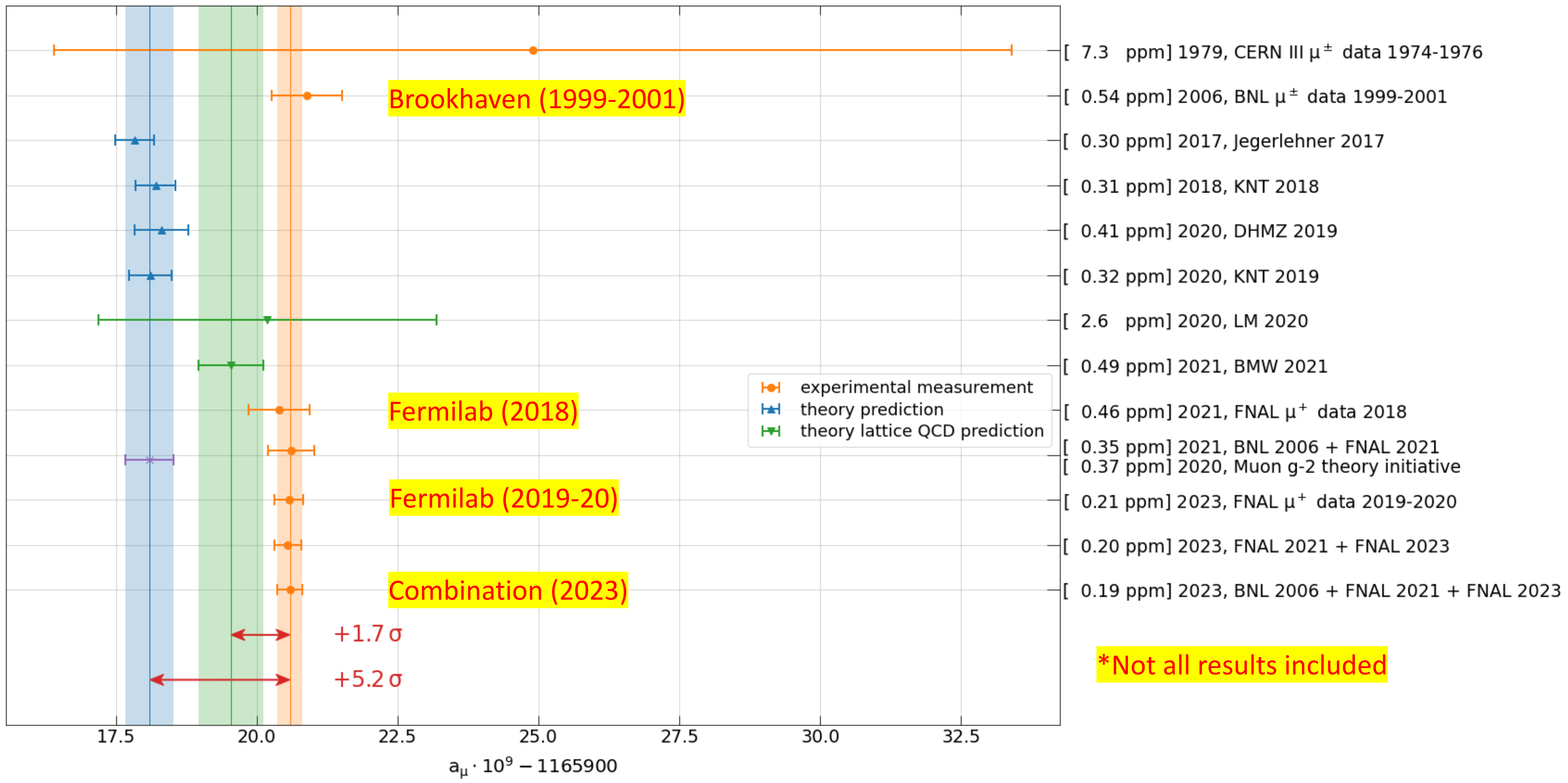


$g = 2\,;\ a_\mu = 0$



$g > 2\,;\ a_\mu > 0$

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e}{2m} B$$



*Not all results included


Lake Michigan
Lake Ontario
Lake Erie
Appalachian Mountains
Washington
Mississippi
Alabama
Georgia
Florida
The Bahamas


© Fermilab, 2013
Illinois Tollway
OVERSIZE LOAD
EMMERT

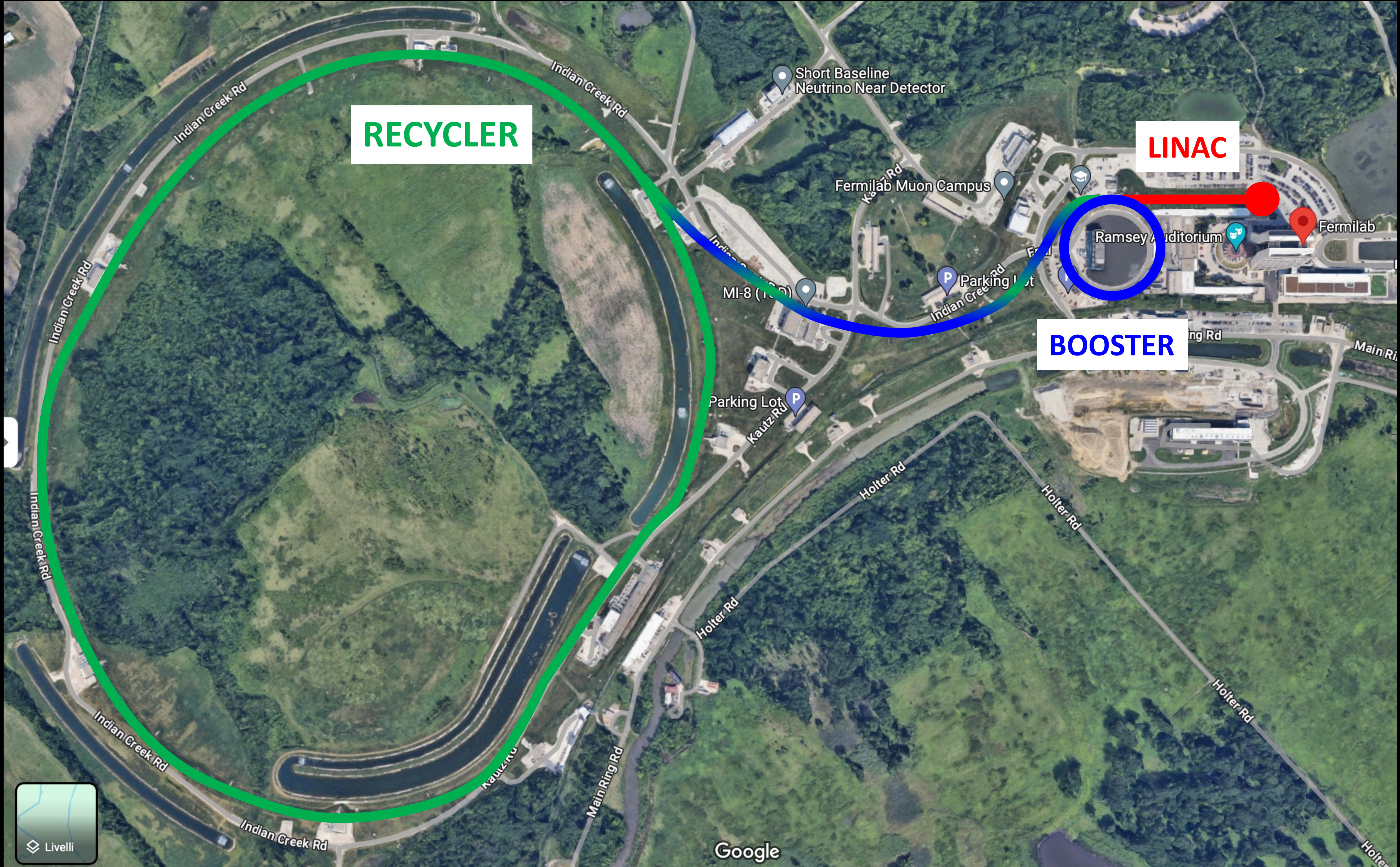

EMMERT

Beam Injection and Storage

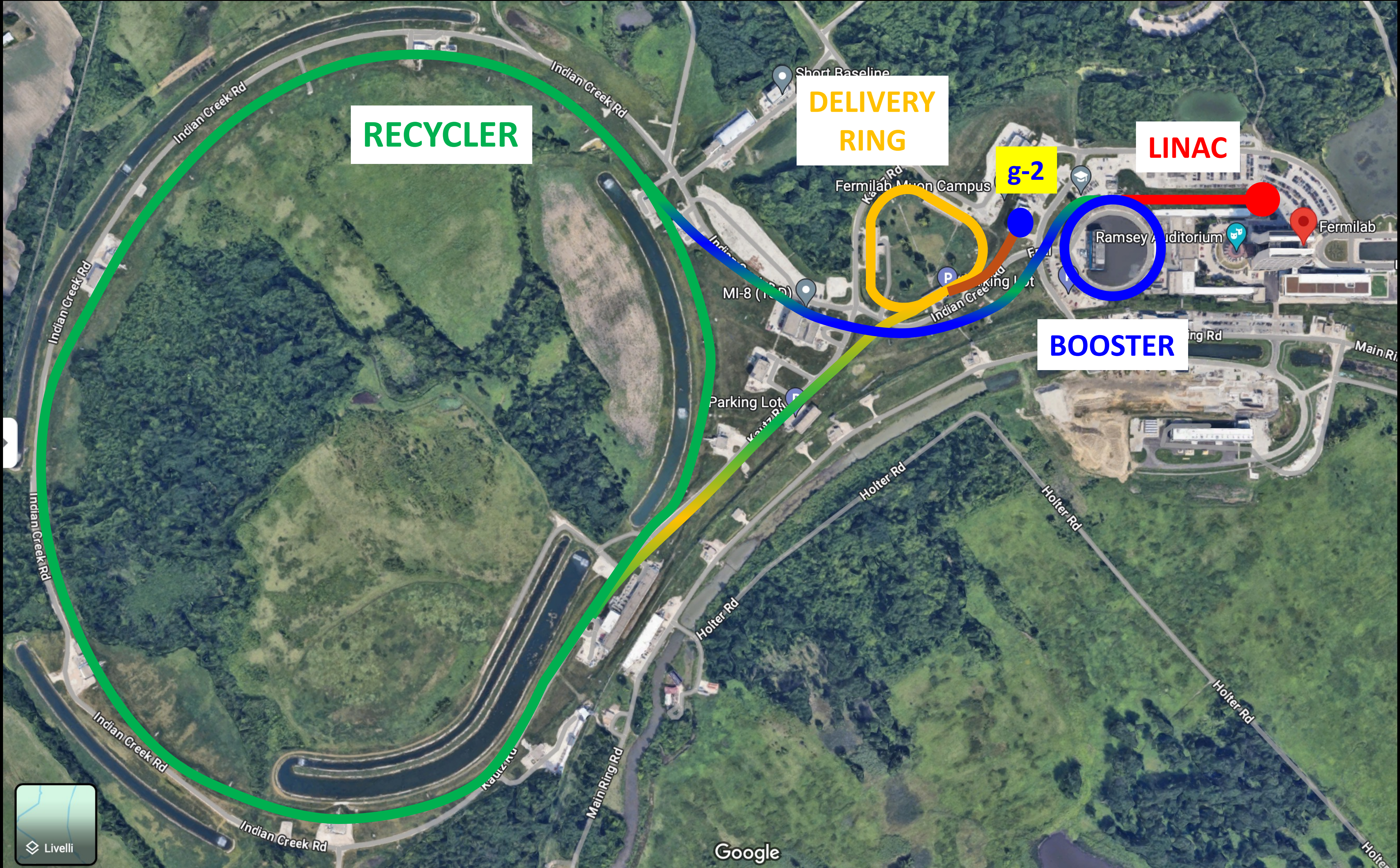
How we produce and store a 95% polarized muon beam


Short Baseline
Neutrino Near Detector
Indian Creek Rd
Kautz Rd
Fermilab Muon Campus
Ramsey Auditorium
Fermilab
Fnal
Parking Lot
MI-8 (TSD)
Main Ring Rd
Holter Rd
Livelli
Google

LINAC
BOOSTER
Short Baseline
Neutrino Near Detector
Fermilab Muon Campus
Ramsey Auditorium
Fermilab
MI-8 (TSD)
Parking Lot
Parking Lot
Indian Creek Rd
Kautz Rd
Holter Rd
Main Ring Rd
Google
Livelli



RECYCLER
LINAC
BOOSTER
Short Baseline
Neutrino Near Detector
Fermilab Muon Campus
Ramsey Auditorium
Fermilab
Parking Lot
Parking Lot
Indian Creek Rd
Kautz Rd
Holter Rd
Main Ring Rd
Livelli
Google


RECYCLER
DELIVERY RING
g-2
LINAC
BOOSTER
Short Baseline
Fermilab Muon Campus
Ramsey Auditorium
Fermilab
MI-8
Parking Lot
Indian Creek Rd
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Main Ring Rd
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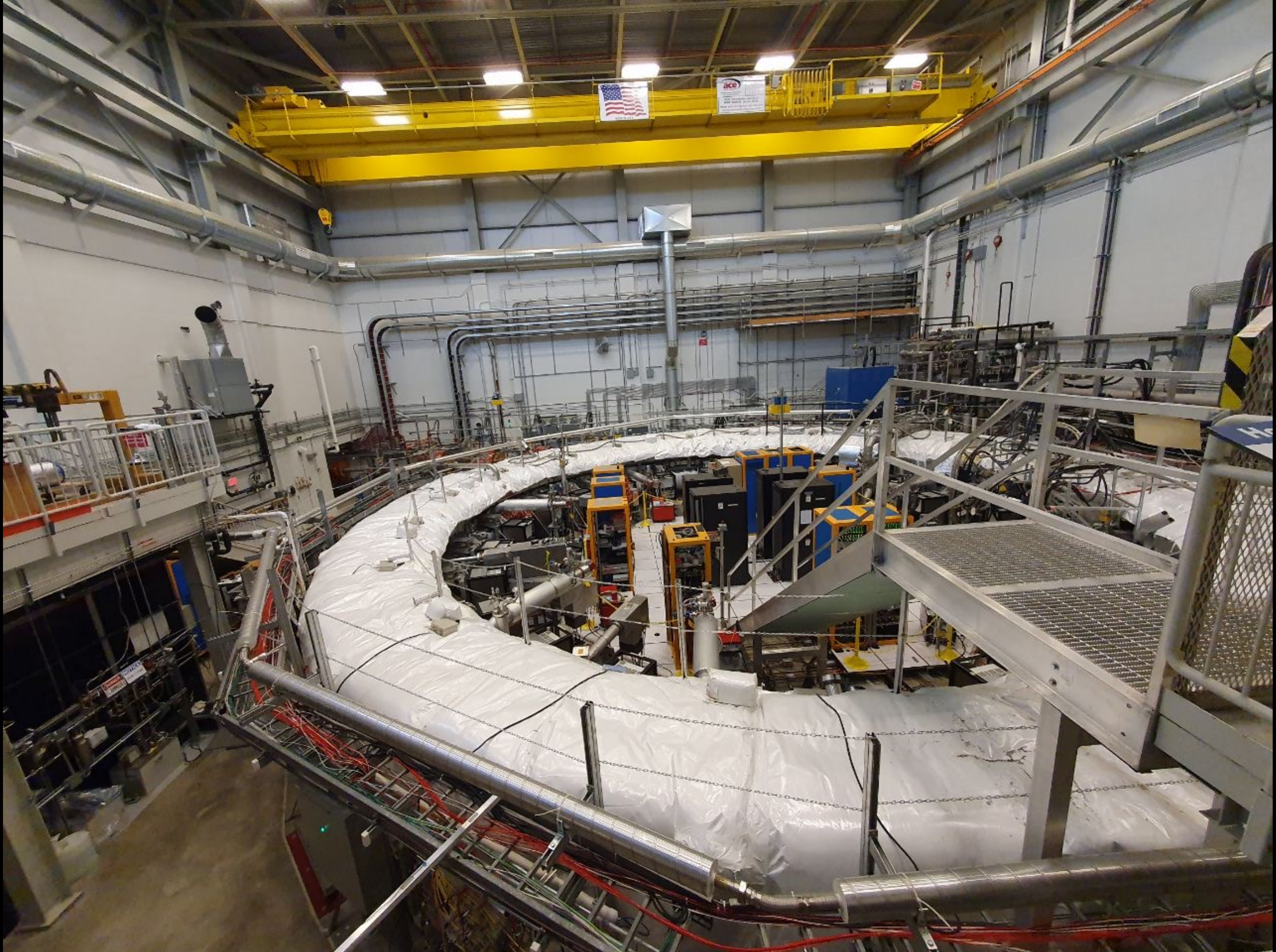
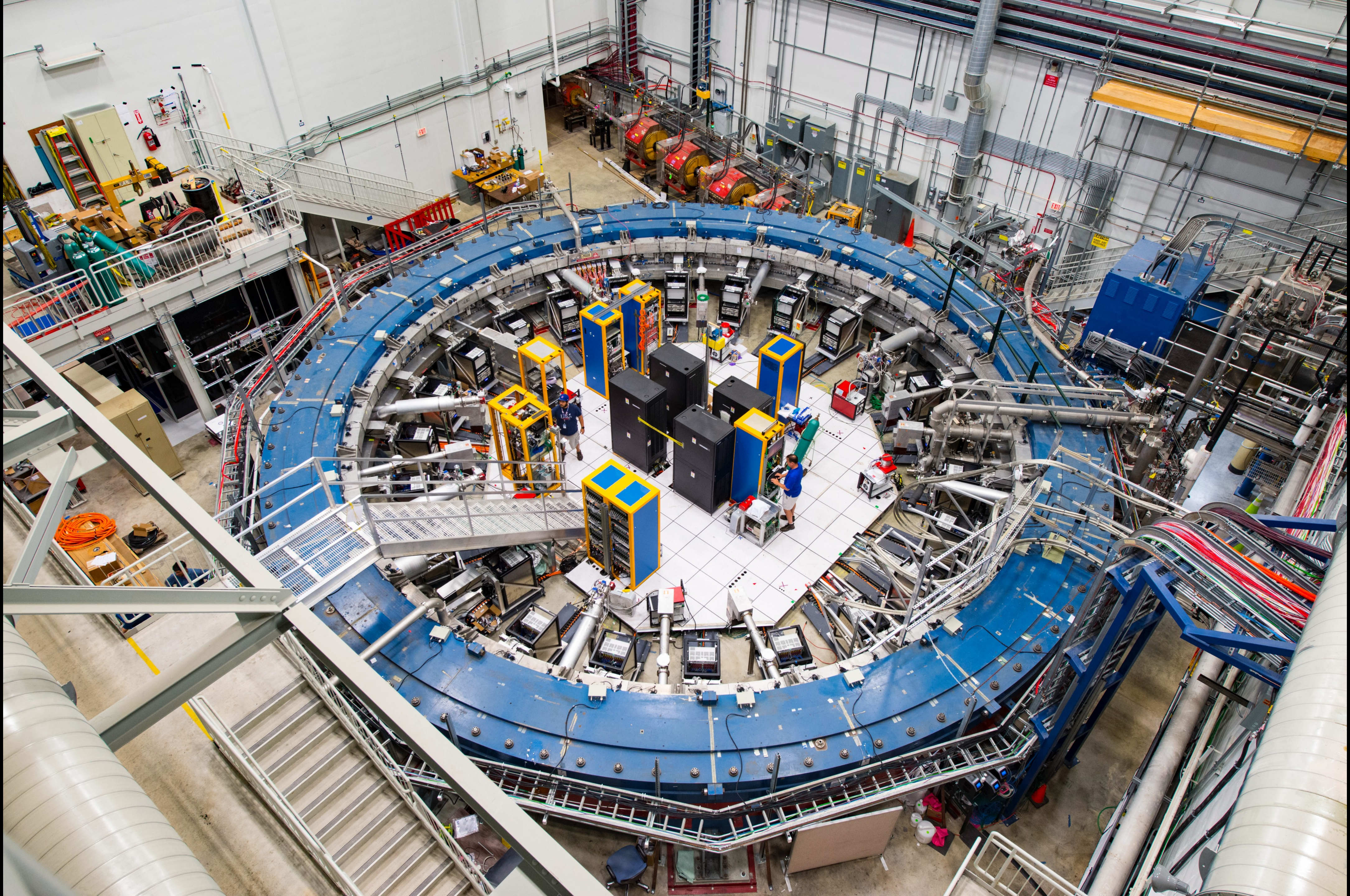
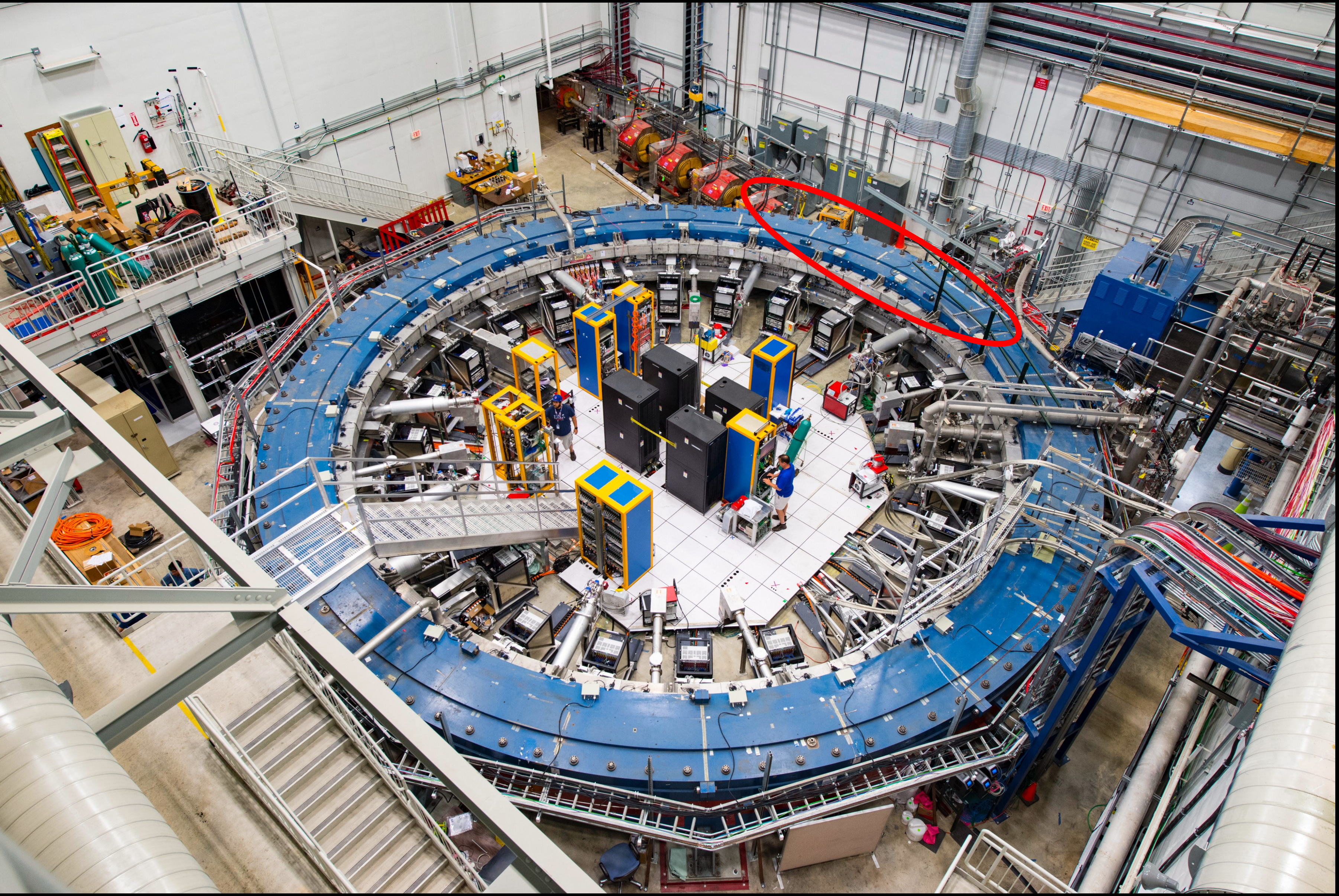
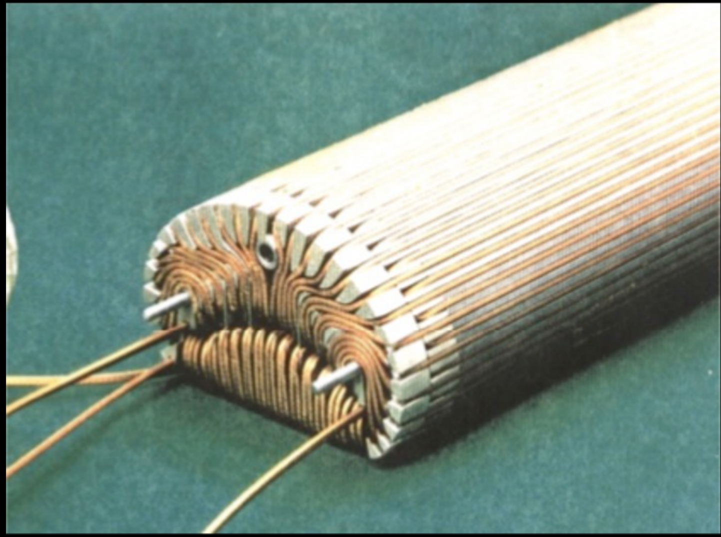
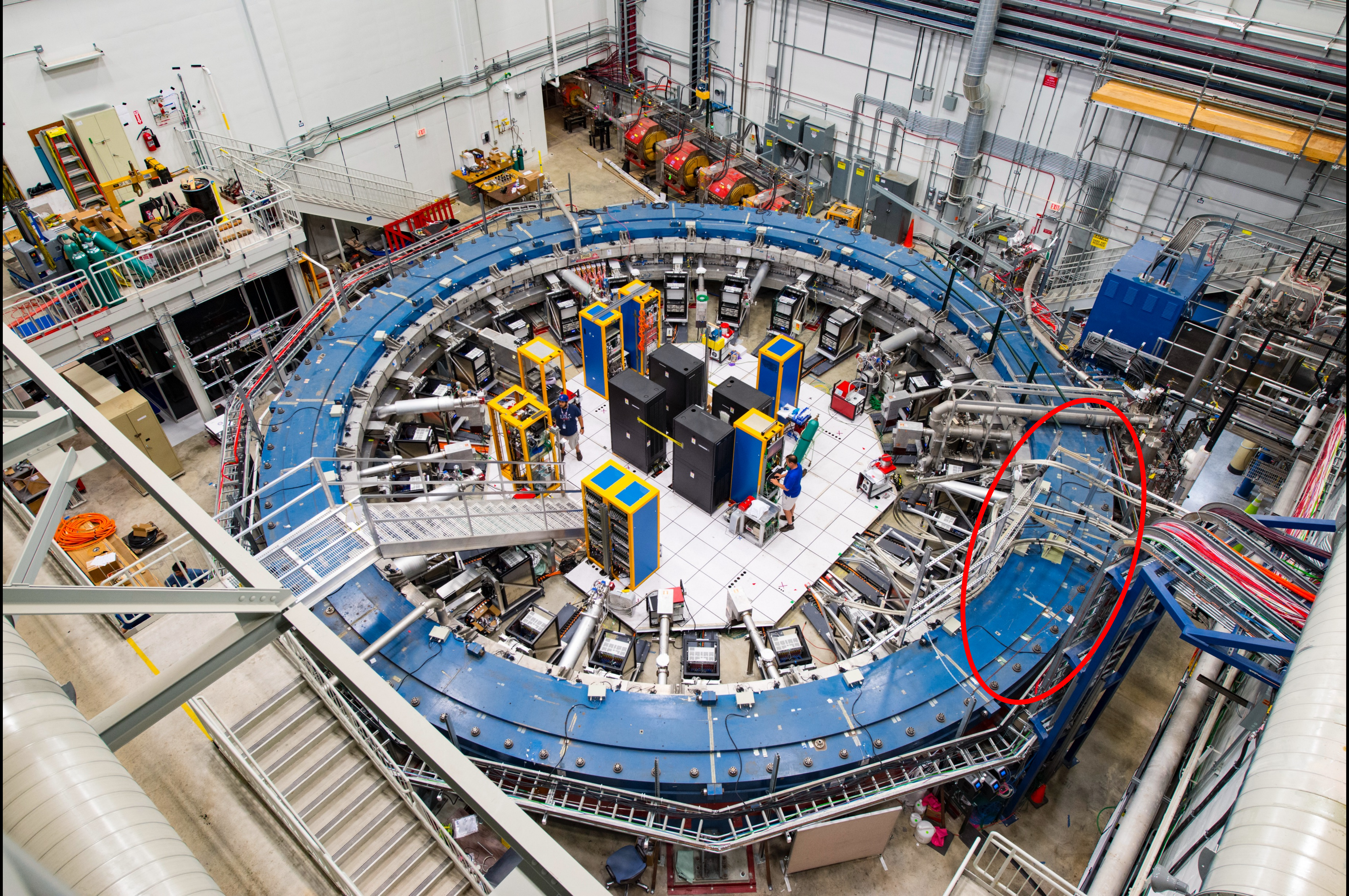
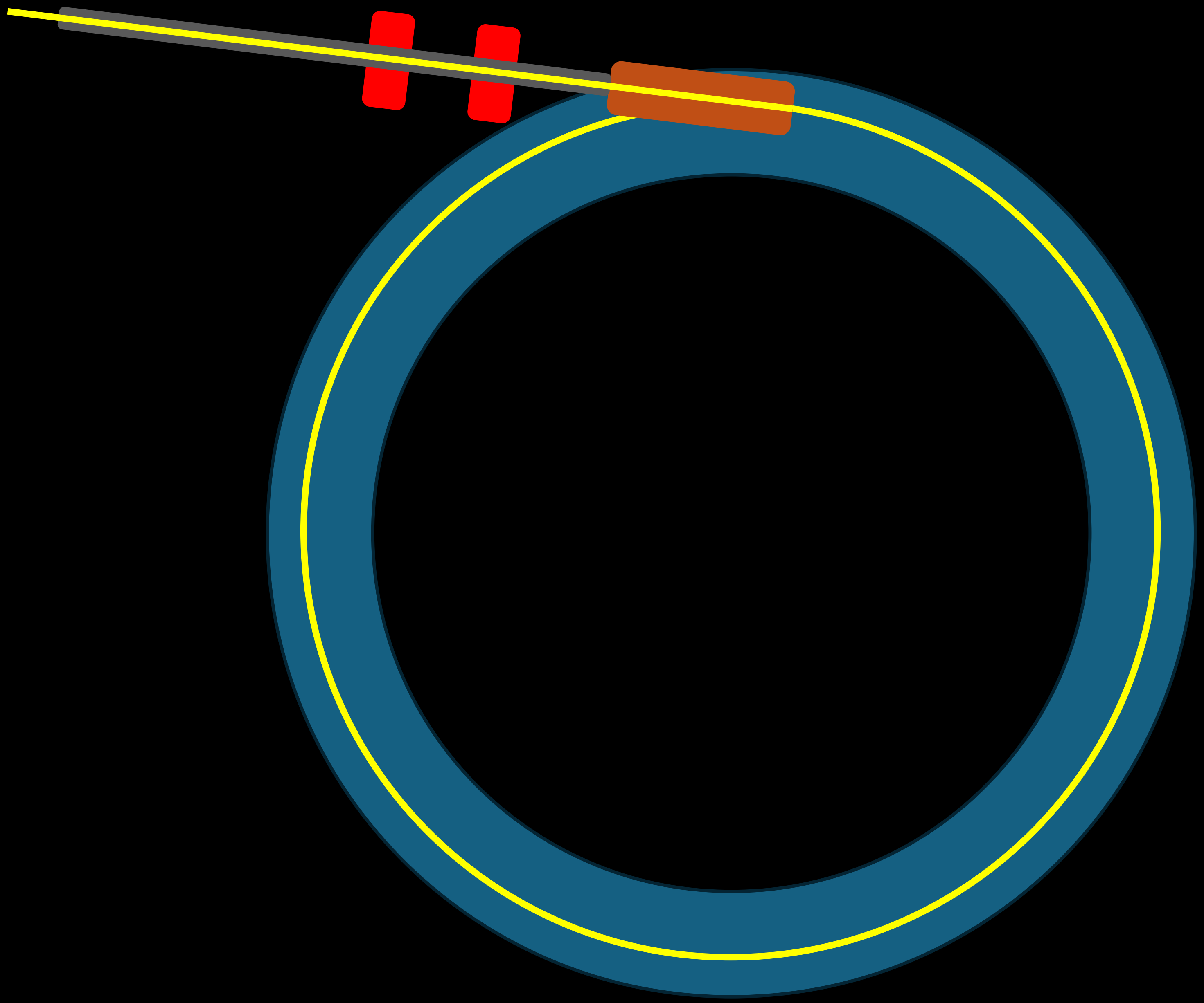


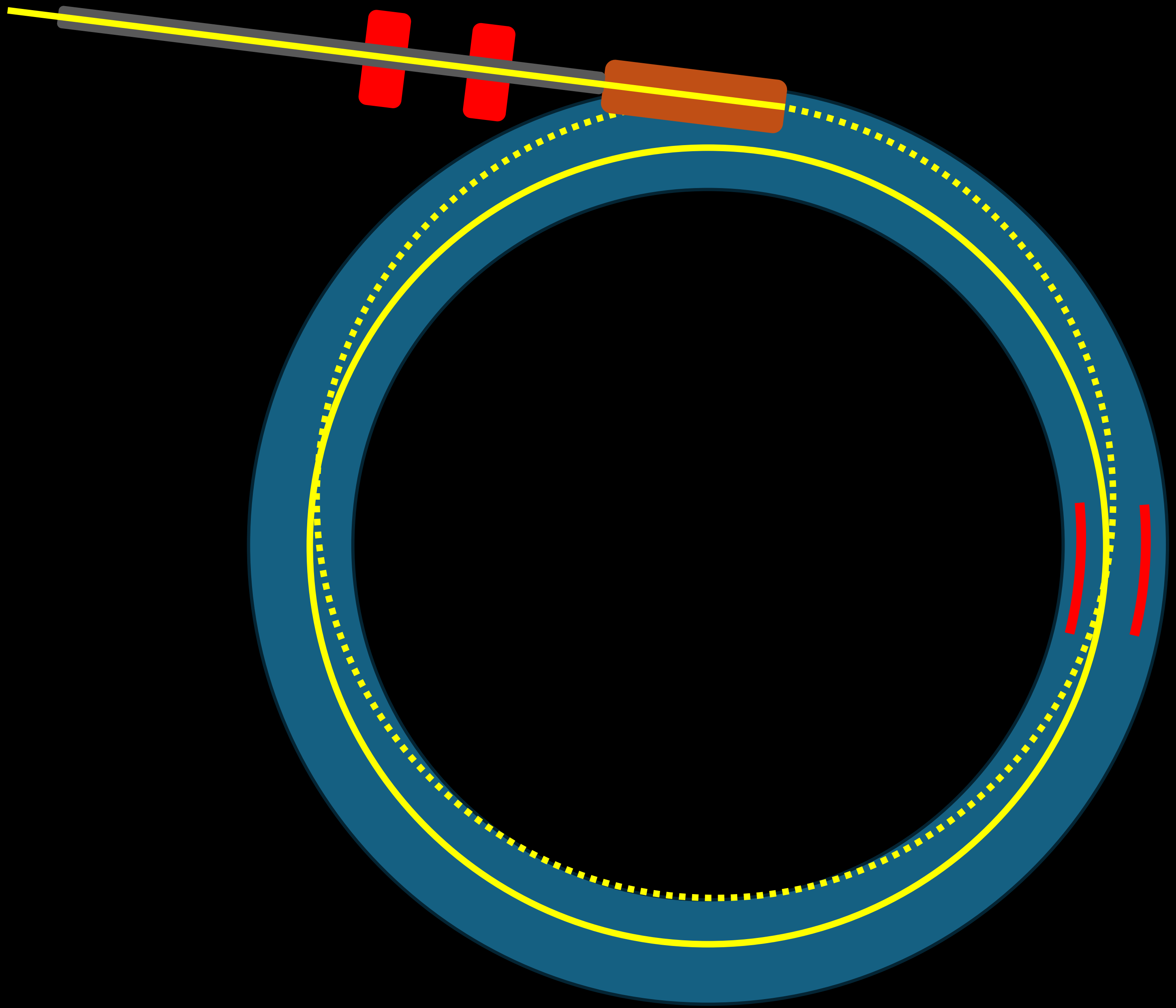


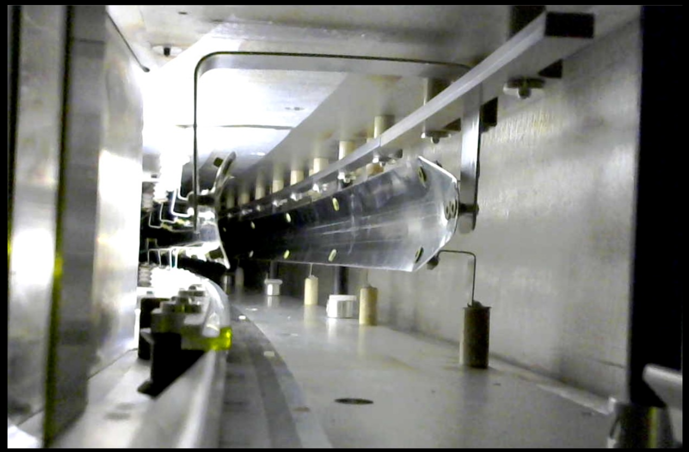


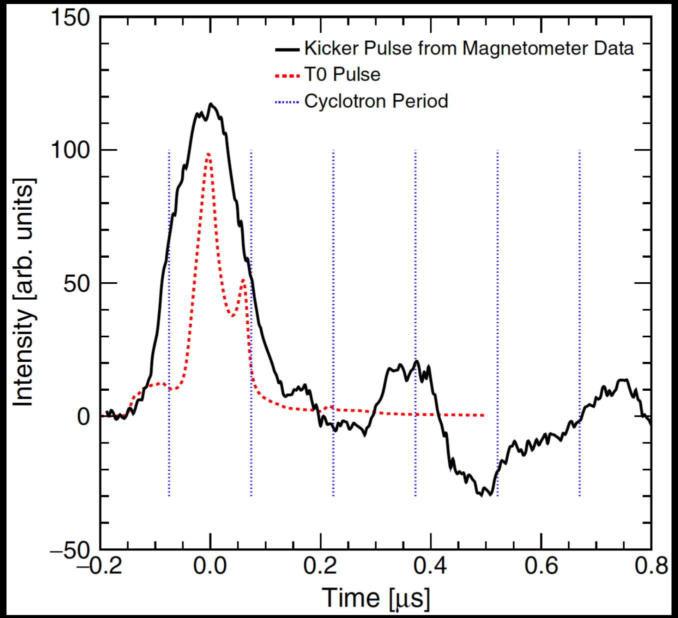


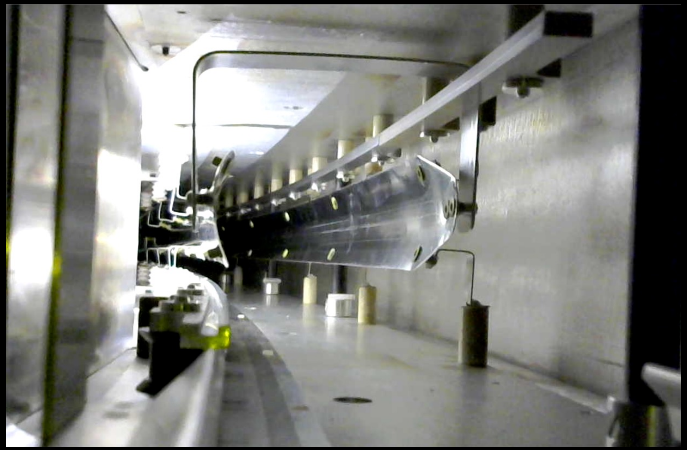


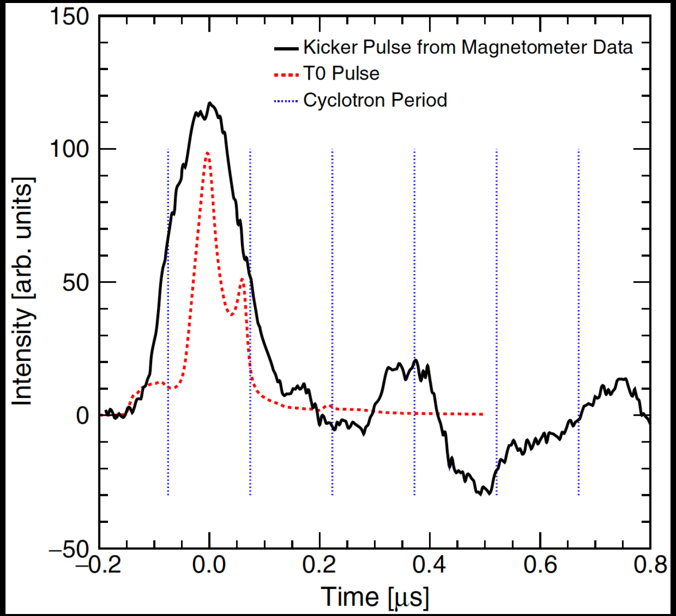






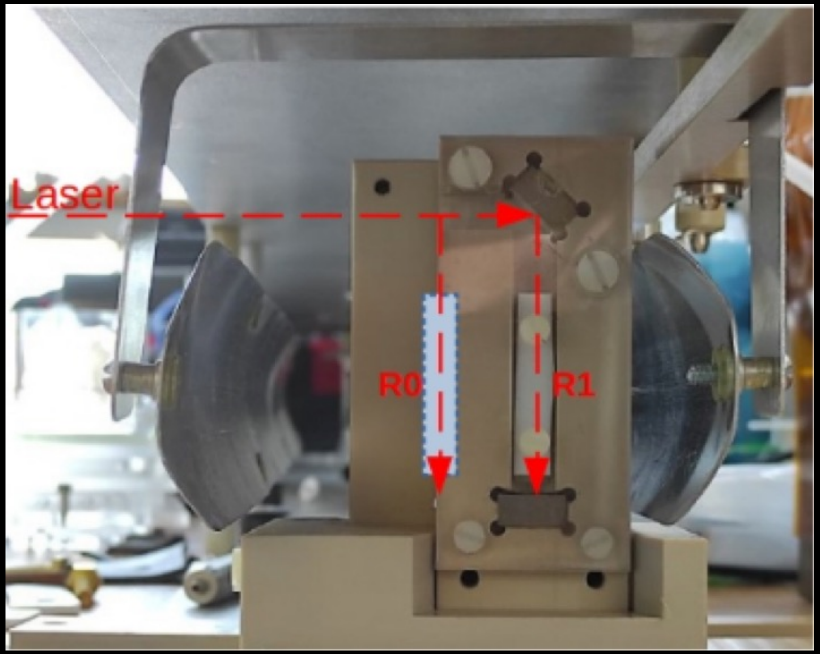

Kicker Pulse from Magnetometer Data
T0 Pulse
Cyclotron Period
Intensity [arb. units]
Time [μs]
150
100
50
0
−50
−0.2
0.0
0.2
0.4
0.6
0.8

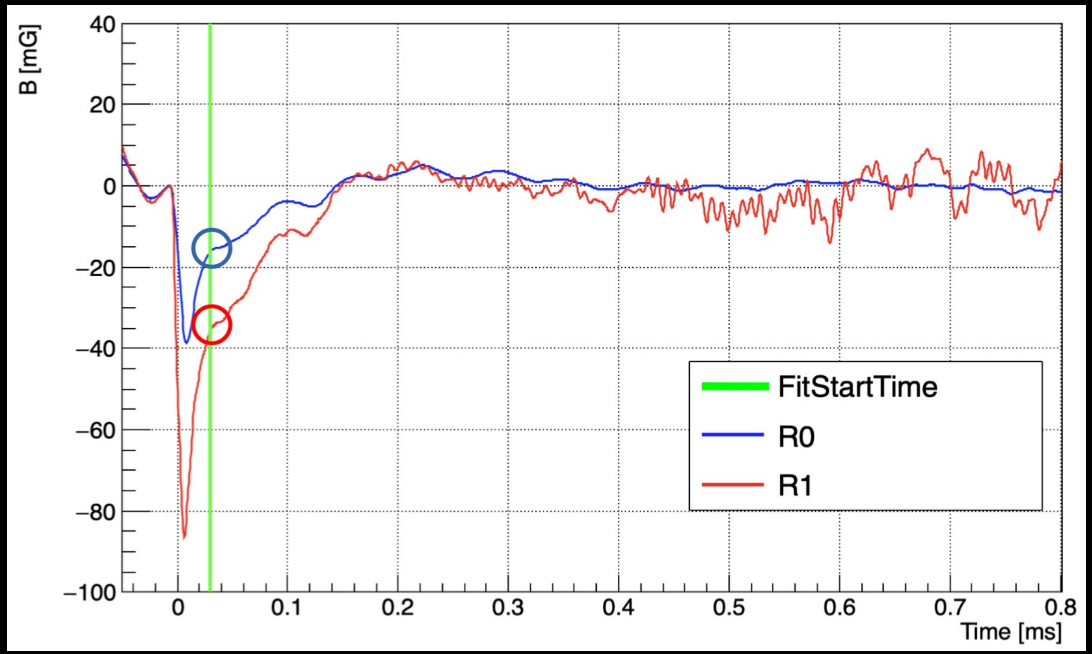


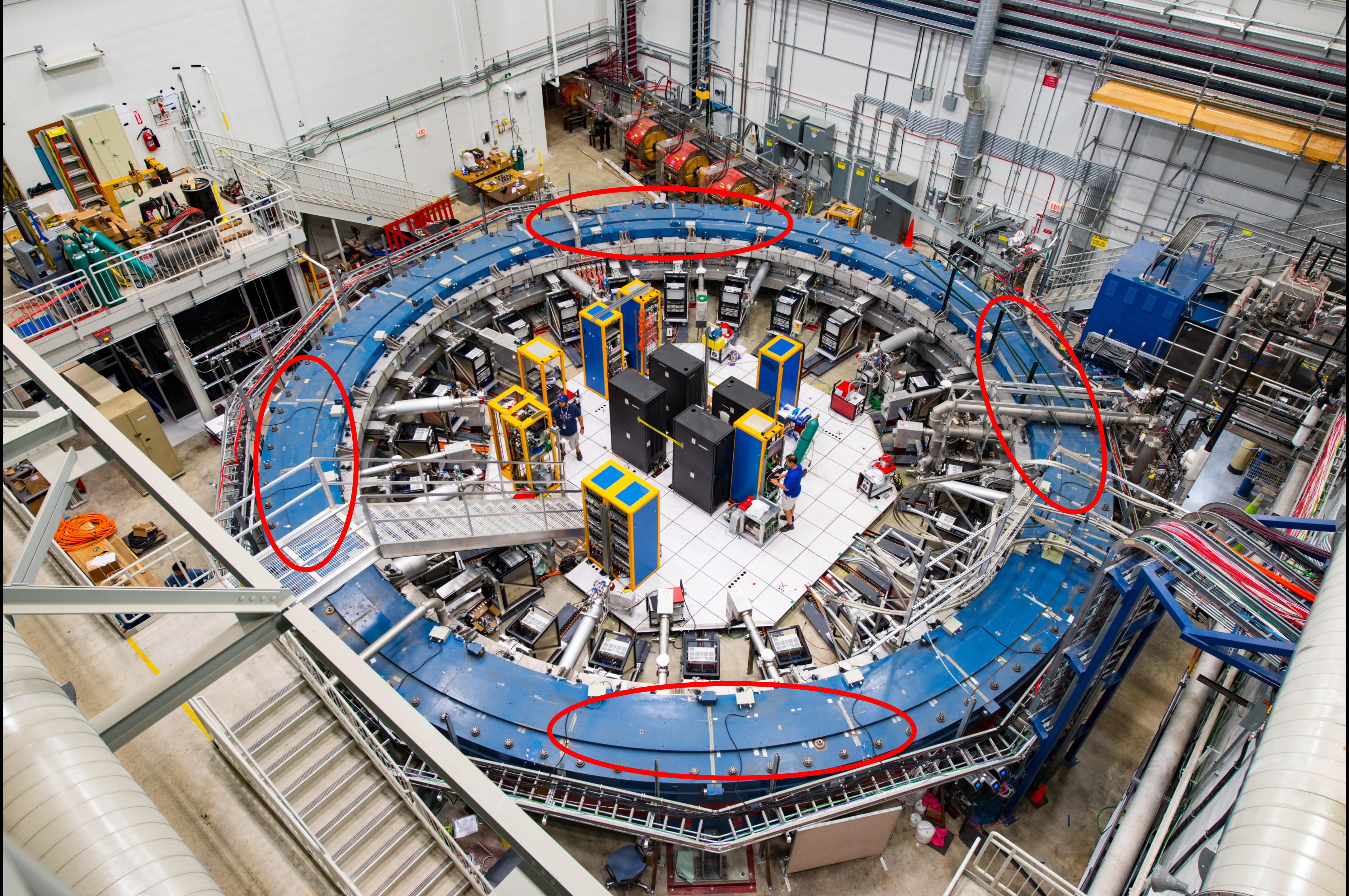

Kicker Pulse from Magnetometer Data
T0 Pulse
Cyclotron Period
Intensity [arb. units]
Time [μs]
150
100
50
0
−50
−0.2
0.0
0.2
0.4
0.6
0.8

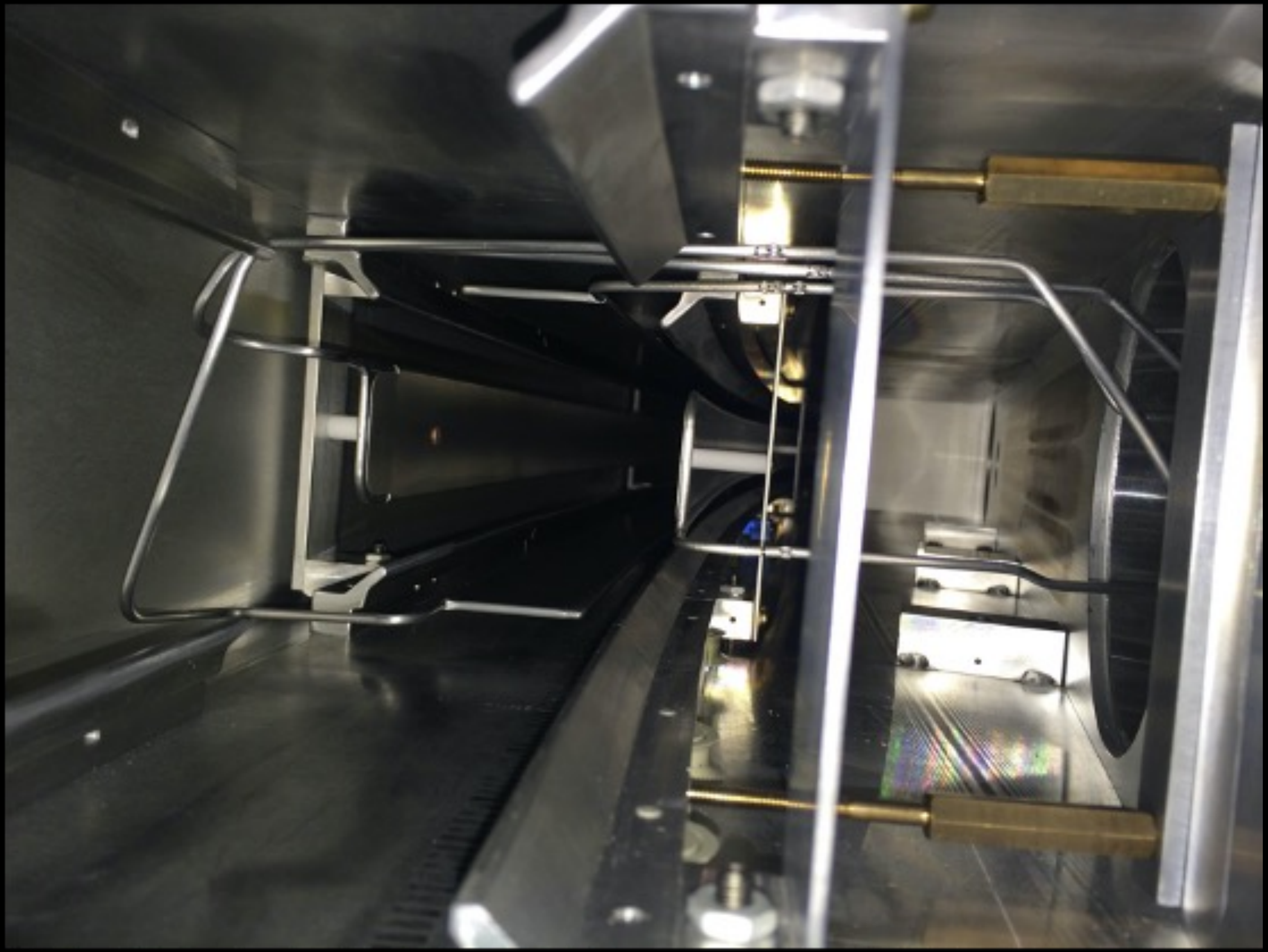
Magnetometer Analysis

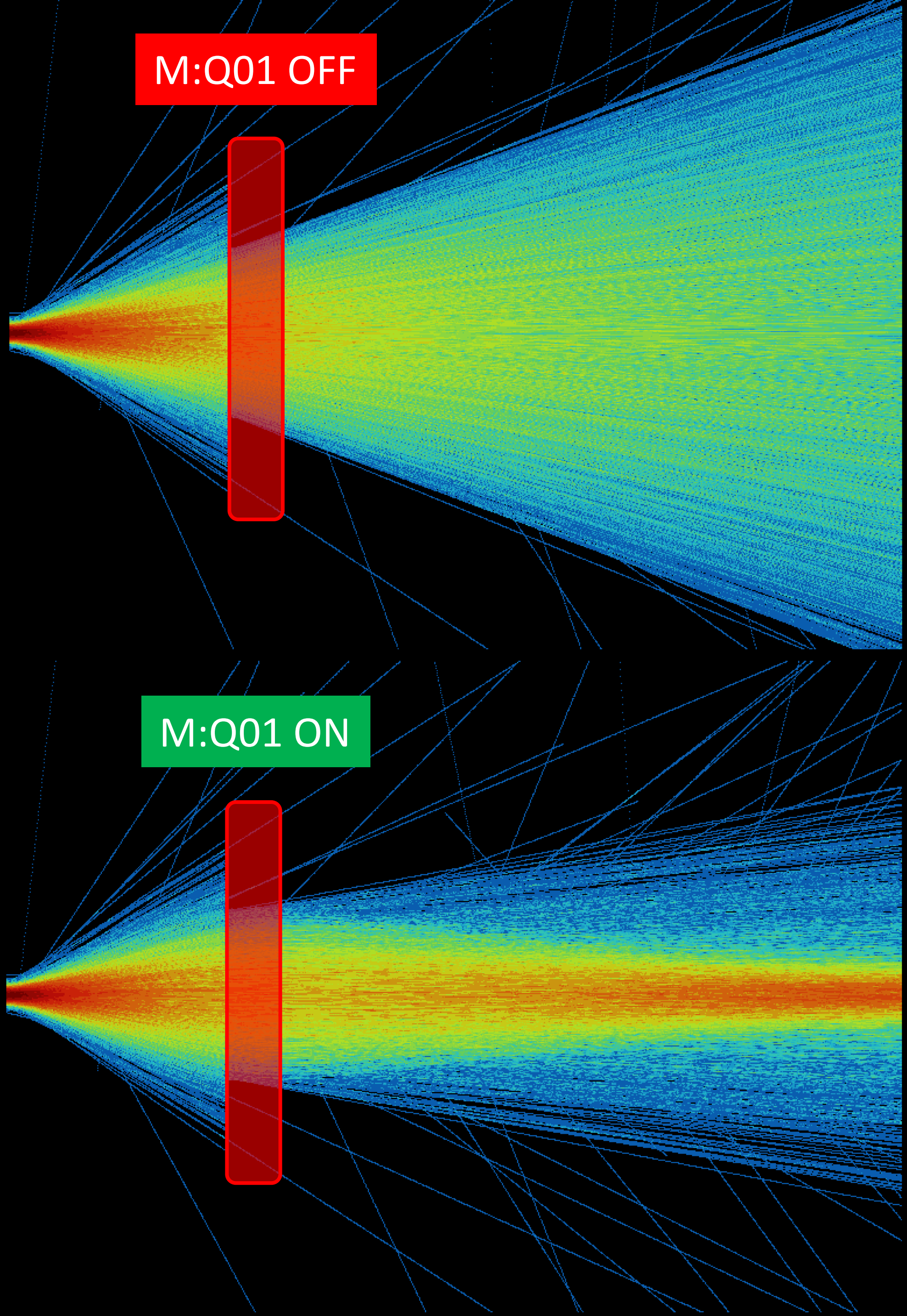
- Kickers show a transient in the measurement window that can bias the ω_a measurement
- A Faraday Effect magnetometer built by the INFN team used to precisely map the kickers field
- This measurement is now used to determine a correction and a systematic for the ω_a value







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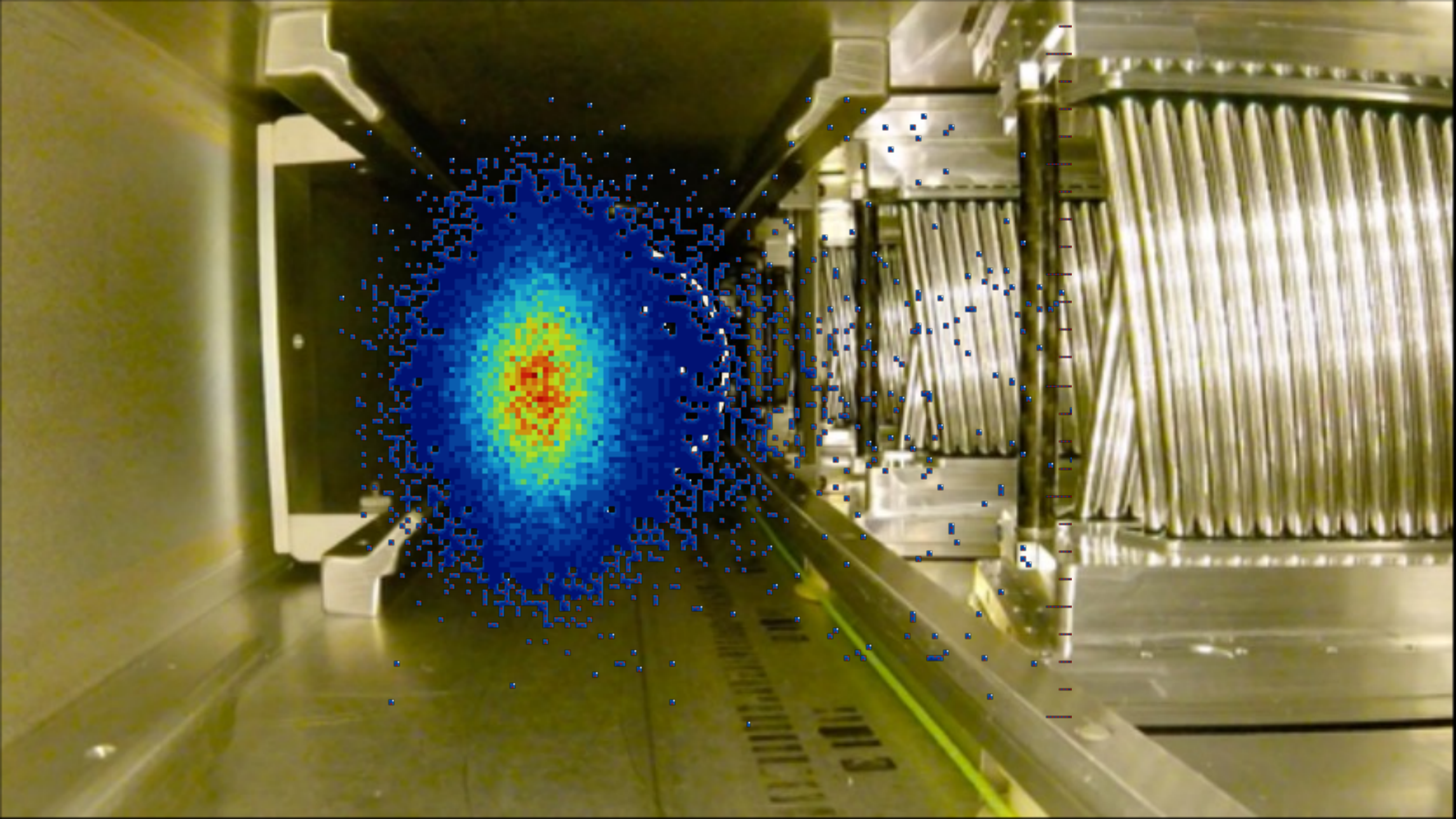
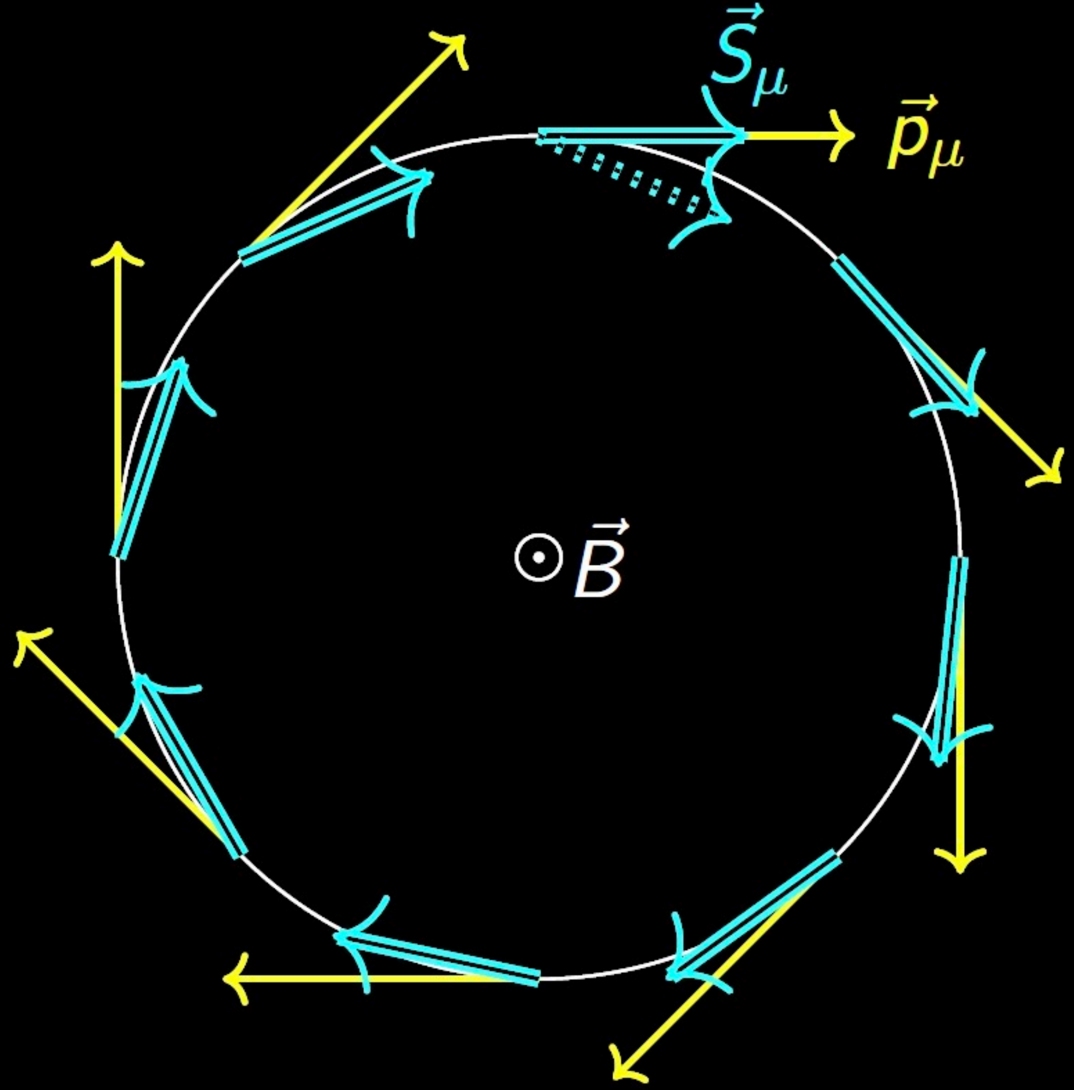
M:Q01 ON



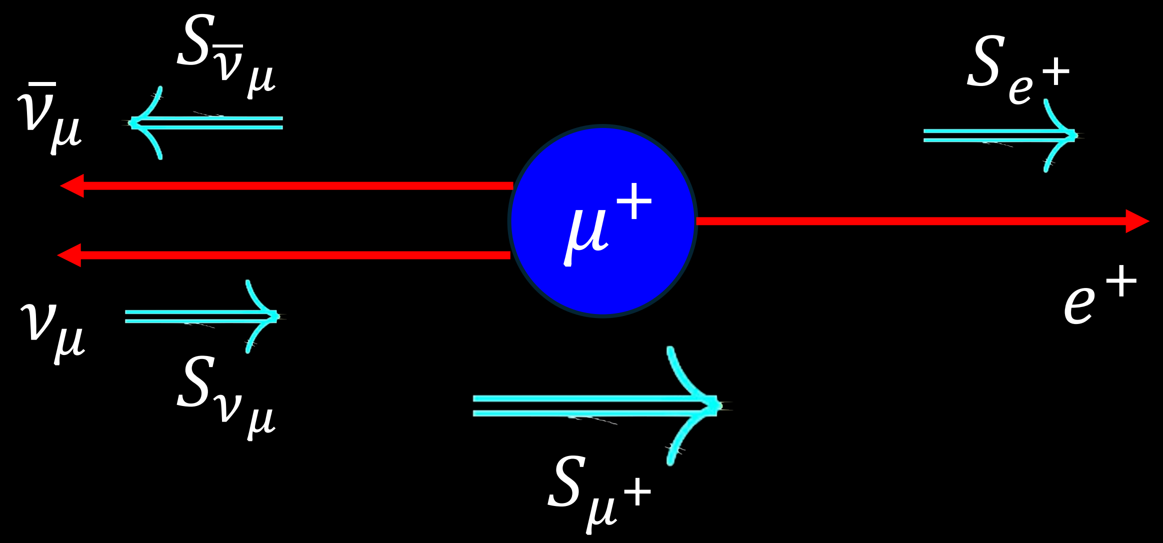
The Measurement

Three main ingredients are needed with a very high precision

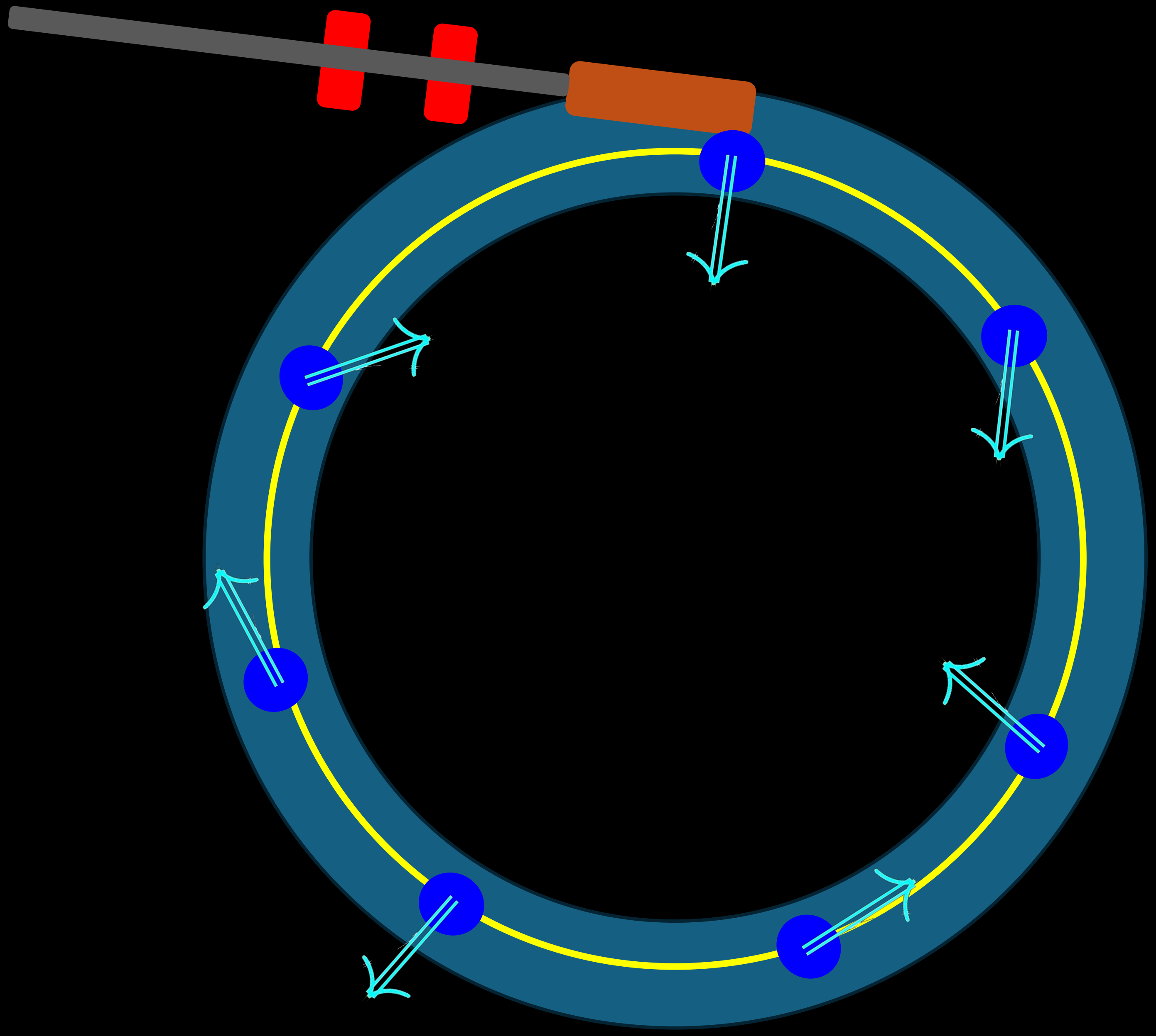


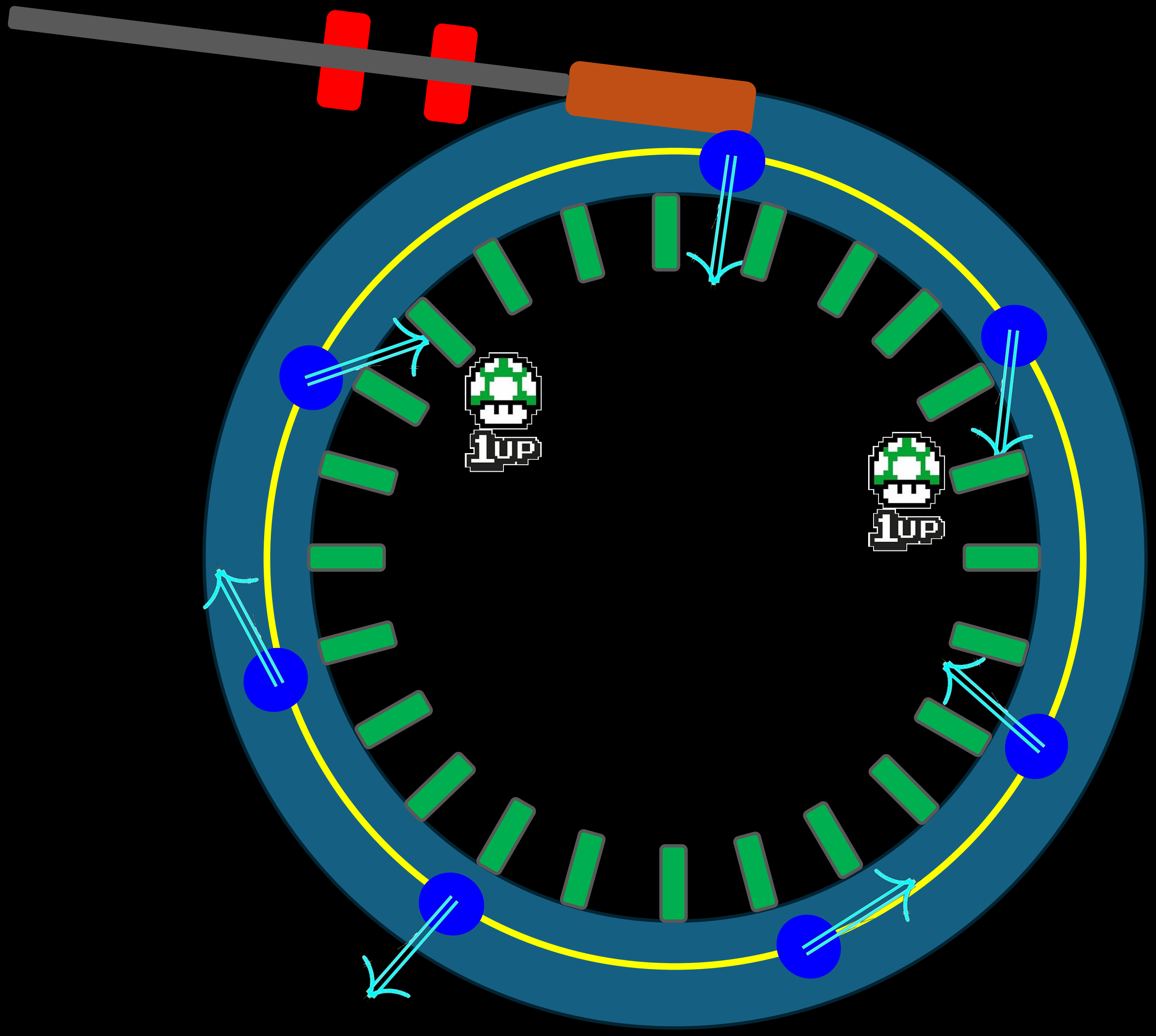
$$\omega_a = \omega_s - \omega_c = \frac{g-2}{2}\frac{e}{2m}B$$

How to measure the Polarization

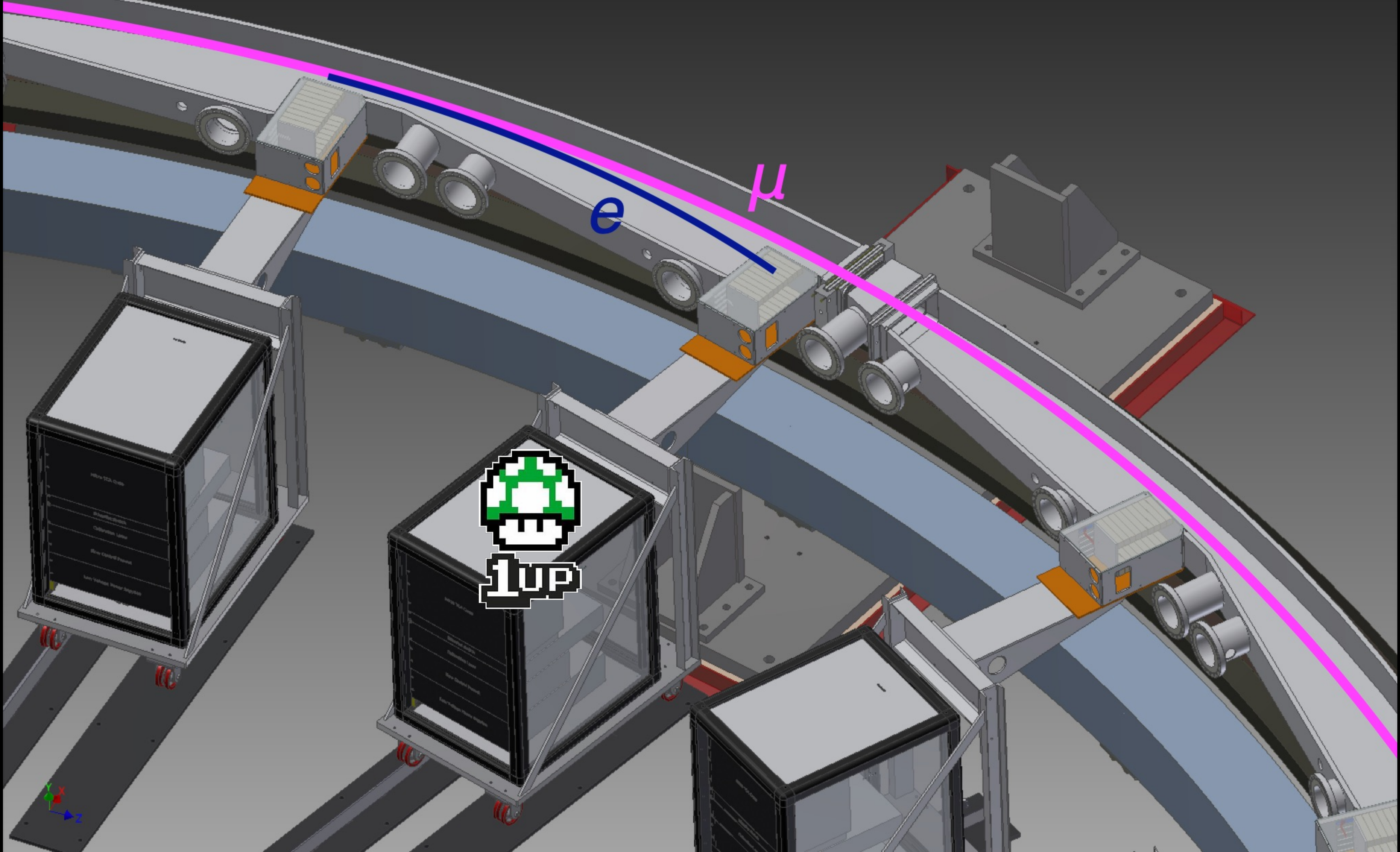


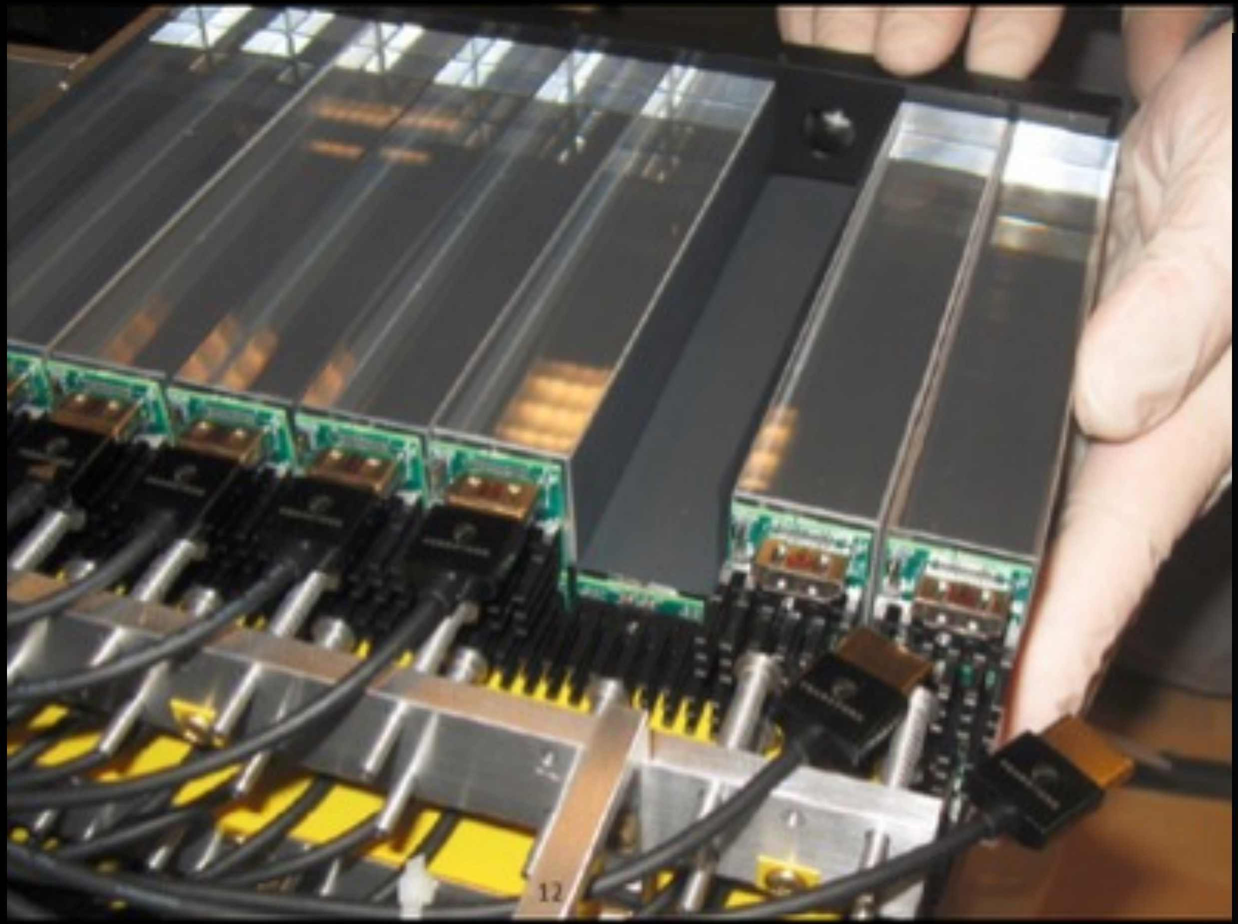
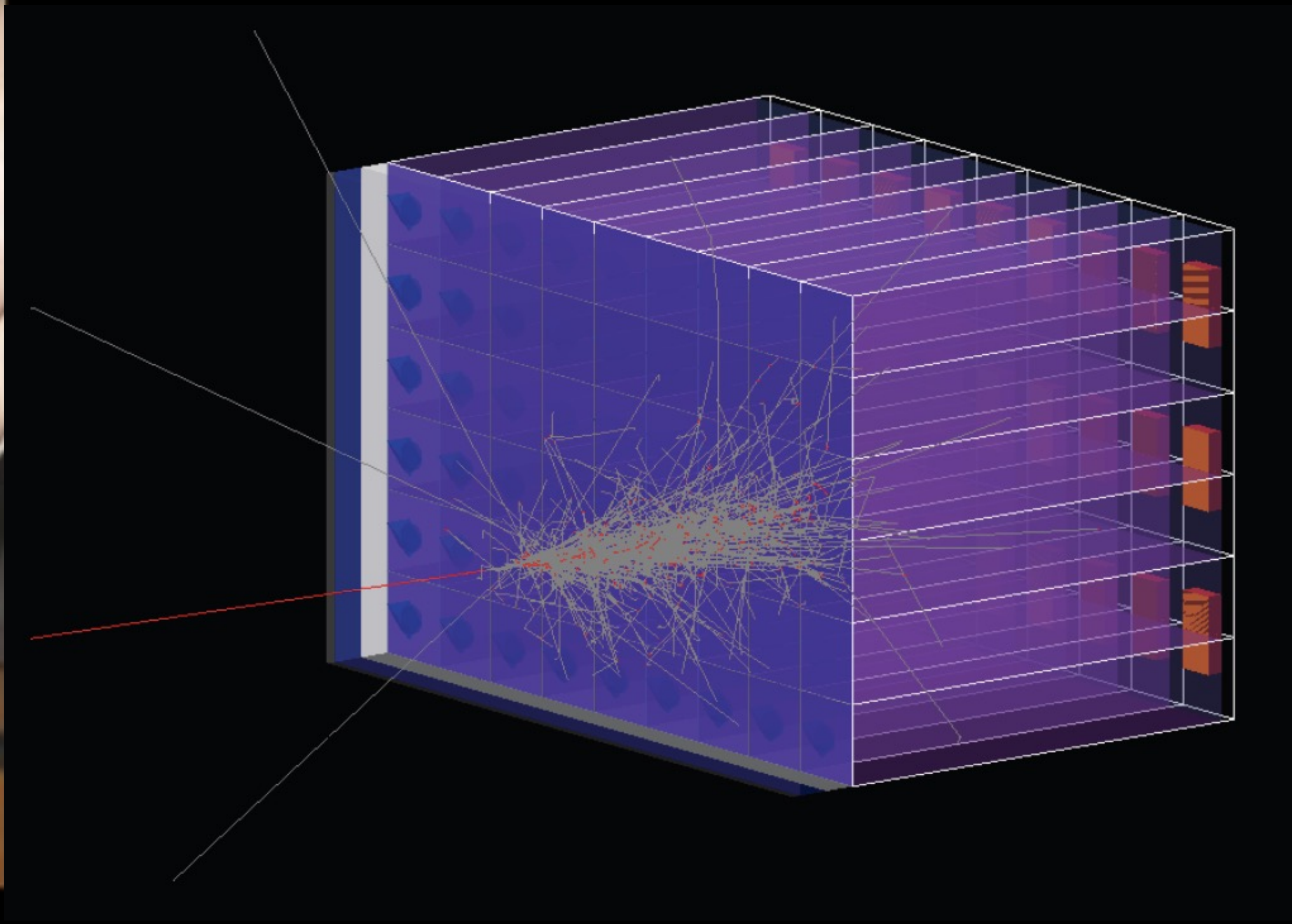
- High Momentum positrons are emitted preferentially in the muon's spin direction
- Count the number of high momentum e^+ in a fixed direction to extract ω_a

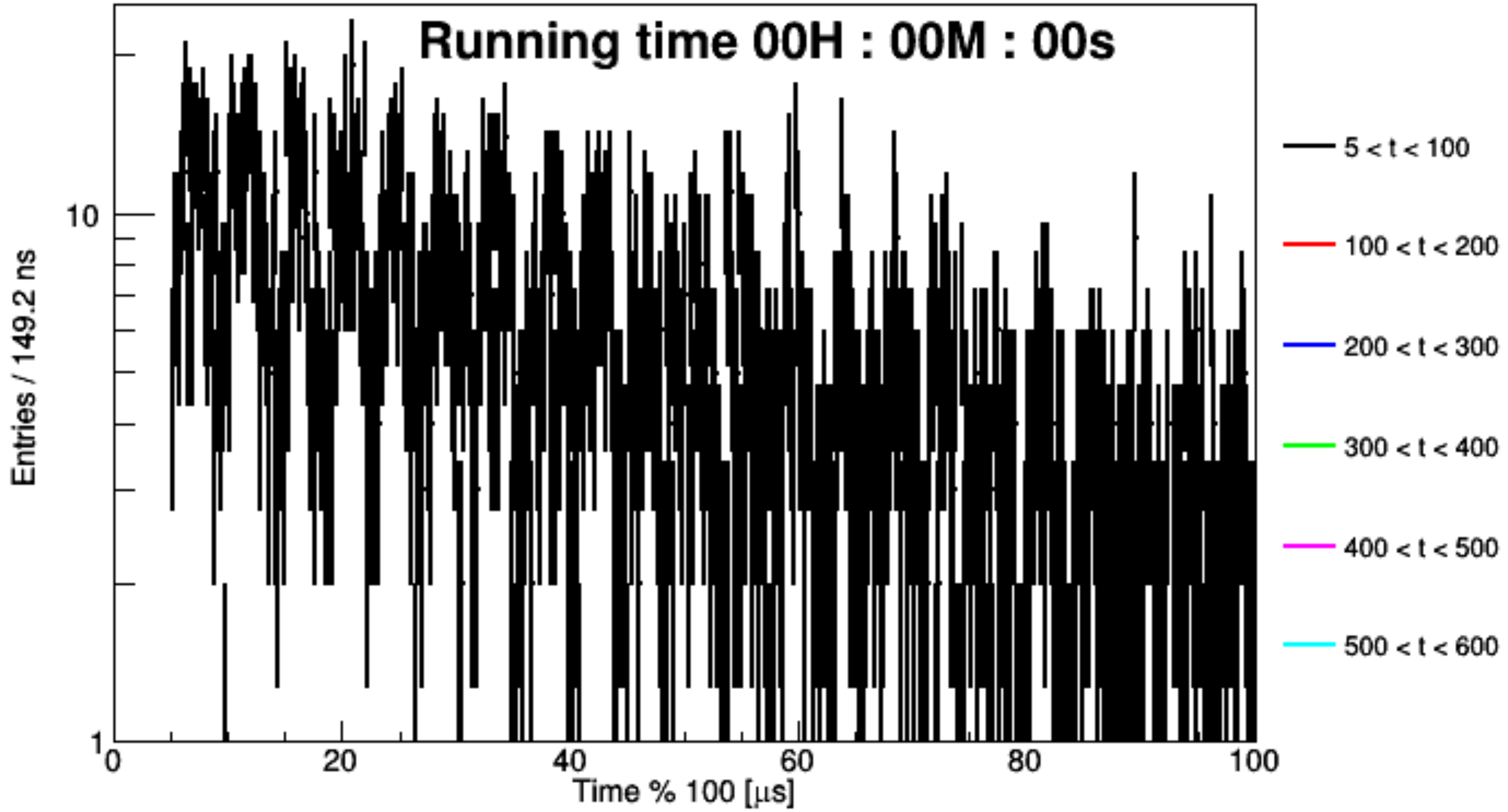



1UP
1UP

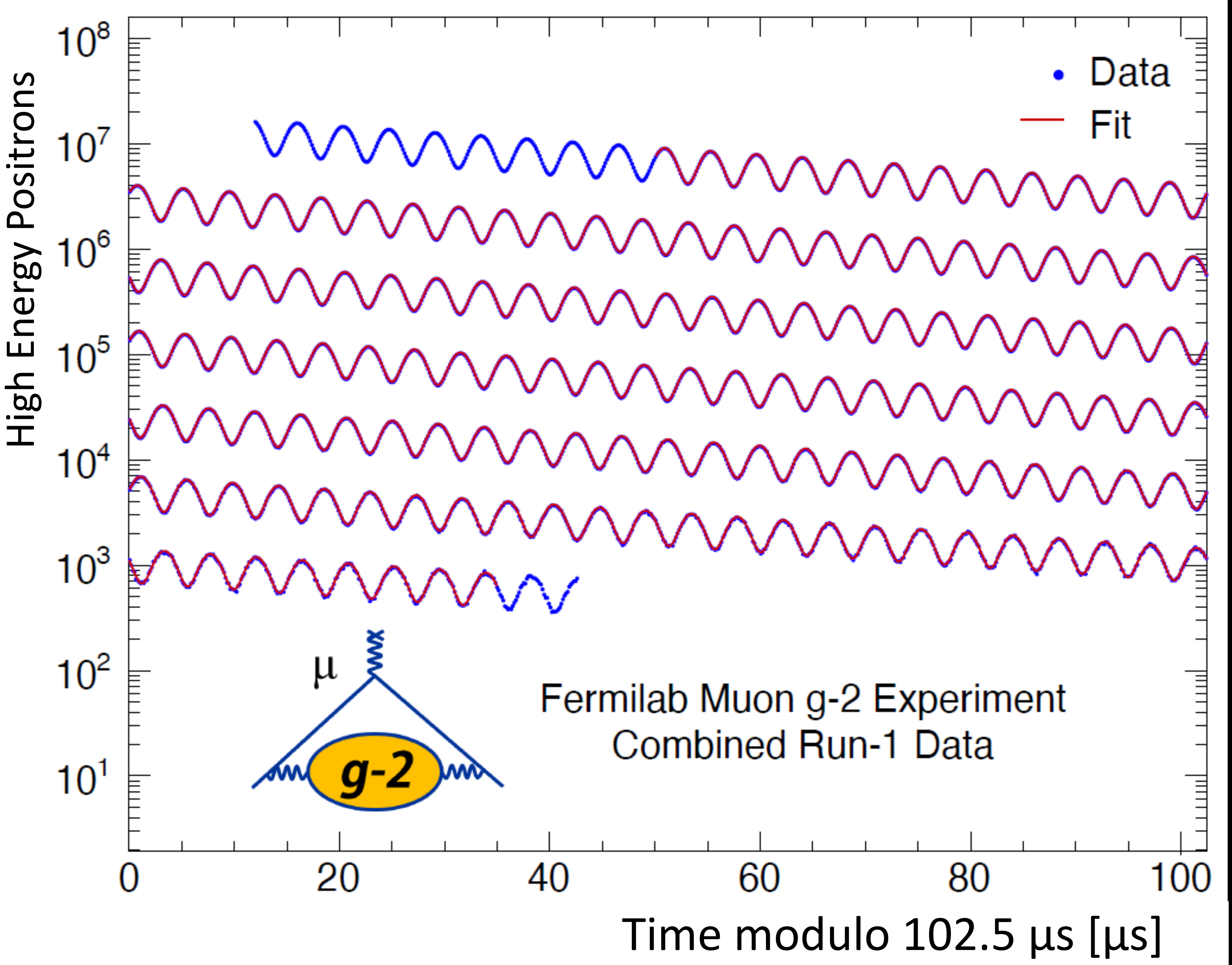

CHAMBER 10 TRACKER STATION
CALORIMETER 19
CALORIMETER 20
IRN-POL-TOP-031
DANGER
HIGH VOLTAGE


e
μ
1UP


12




Running time 00H : 00M : 00s
Entries / 149.2 ns
Time % 100 [μs]
5 < t < 100
100 < t < 200
200 < t < 300
300 < t < 400
400 < t < 500
500 < t < 600



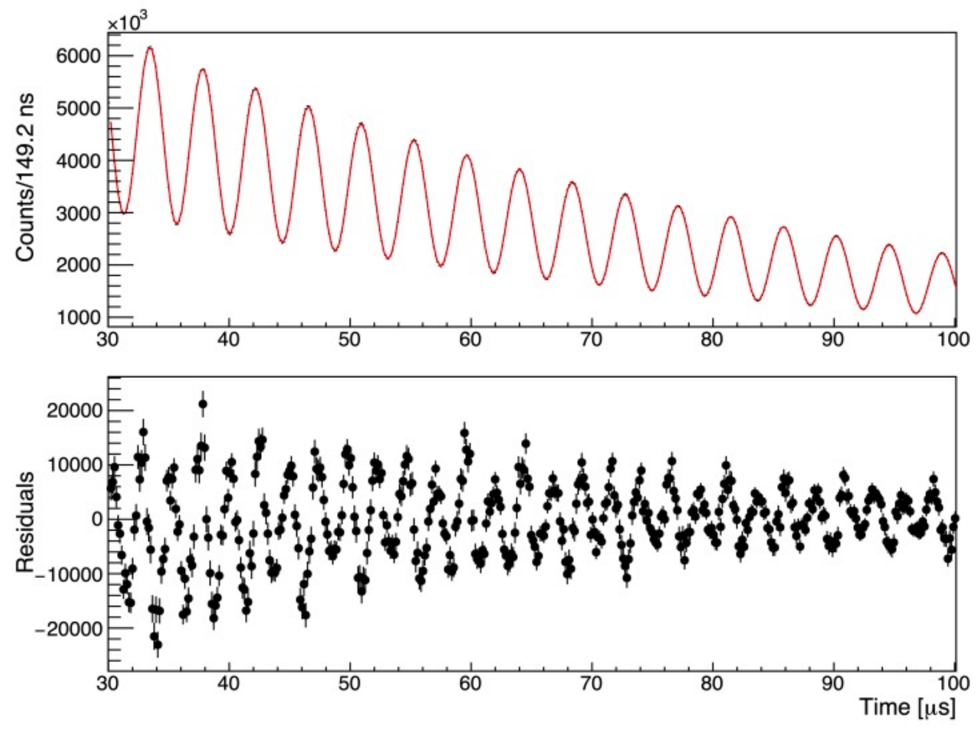
High Energy Positrons
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Data
Fit
μ
g-2
Fermilab Muon g-2 Experiment
Combined Run-1 Data
0
20
40
60
80
100
Time modulo 102.5 μs [μs]

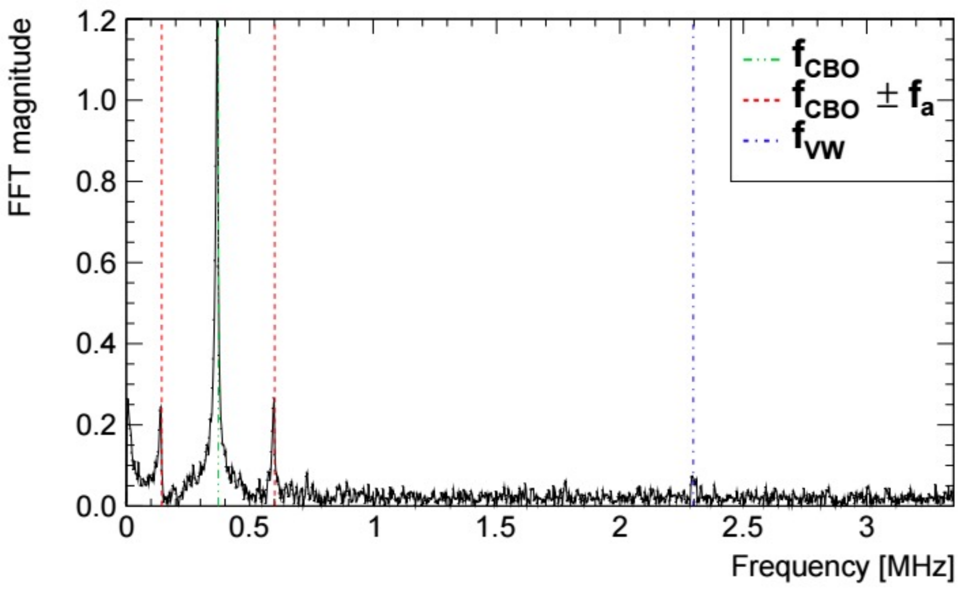
Fitting ω_a

- In principle a simple exponential fit modulated by the precession frequency variation:

$$N(t) = N_0 e^{-\frac{t}{\tau}} \cdot [1 - A\cos(\omega_a t + \varphi)]$$

- Beam Dynamics effectrs, visible in the FFT of residuals add a bias to the measured value
- Need to account for all these effects…





Fitting ω_a (for real)

$$N(t) = N_0\, e^{-\frac{t}{\gamma\tau}}\ [1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi + \phi_{BO}(t))] \cdot$$
$$\cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{\mathrm{2CBO}}(t) \cdot \Lambda(t)$$

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

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

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

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

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

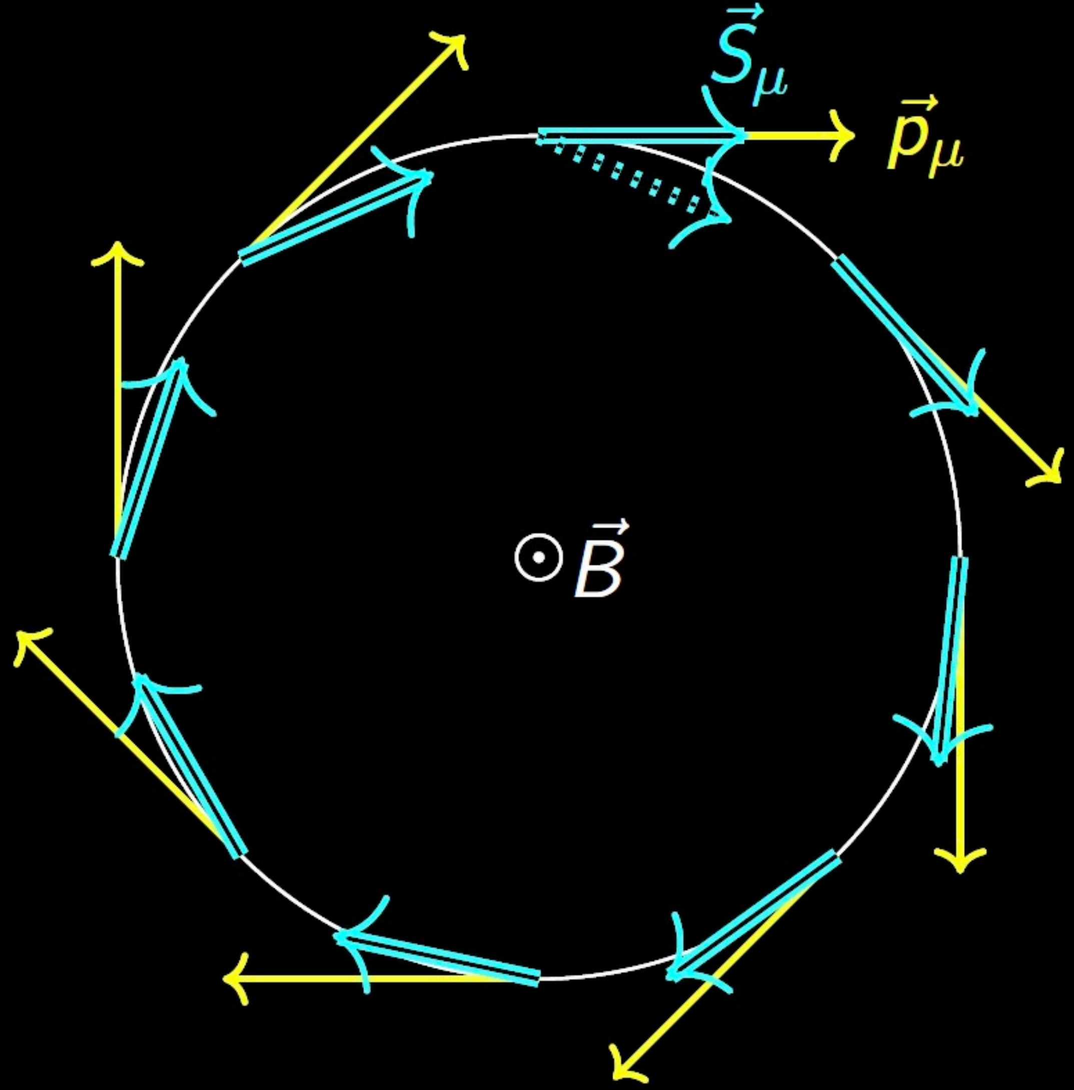
$$\phi_{\mathrm{BO}}(t) = A_\phi \cos(\omega_{\mathrm{CBO}}(t) \cdot t + \phi_\phi) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

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

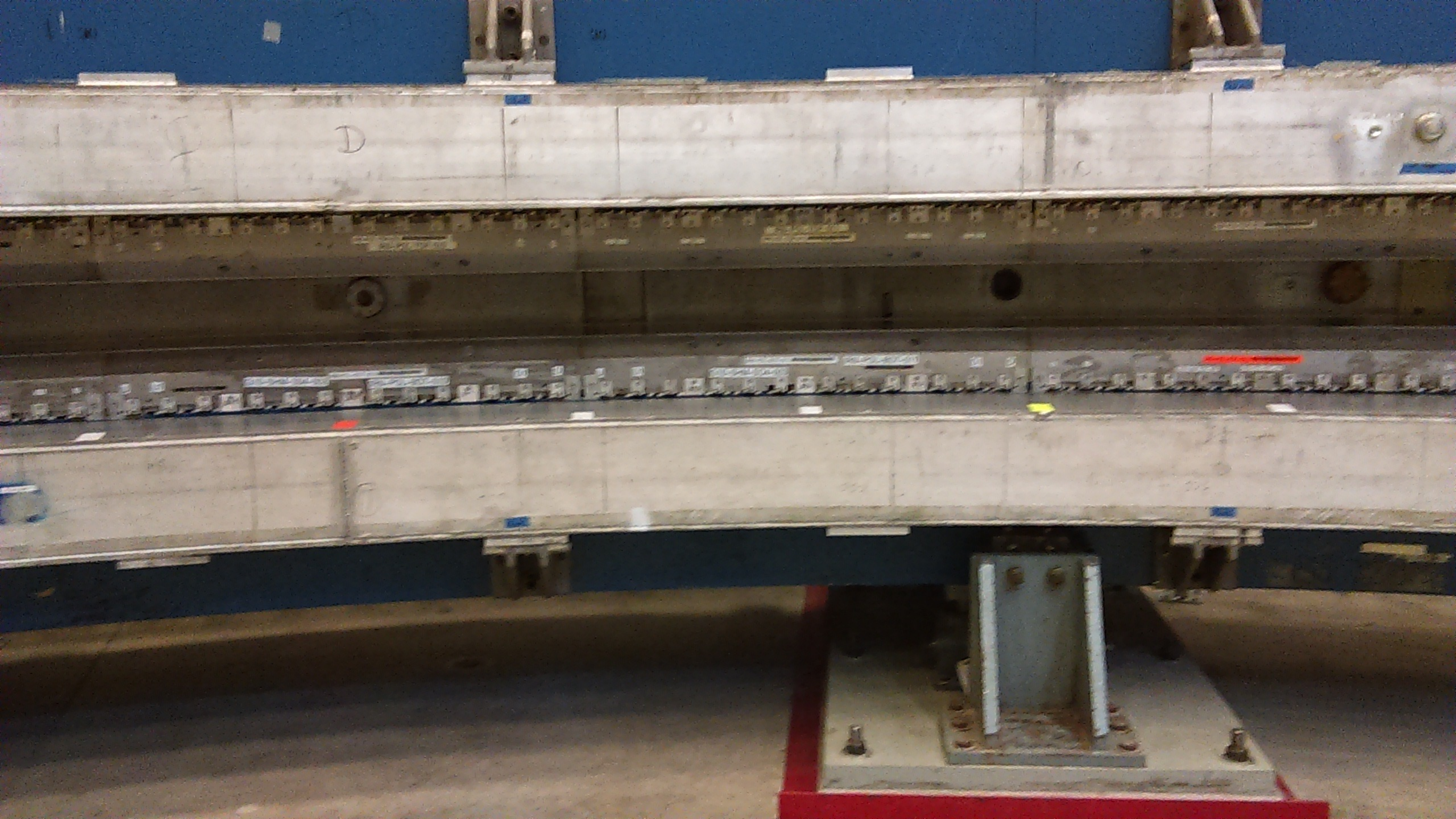
$$\omega_y(t) = F\omega_{\mathrm{CBO}}(t)\sqrt{2\omega_c/F\omega_{\mathrm{CBO}}(t) - 1}$$

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

$$\Lambda(t) = 1 - k_{LM} \int_{t_0}^{t} L(t') e^{t'/\tau}\, dt'$$

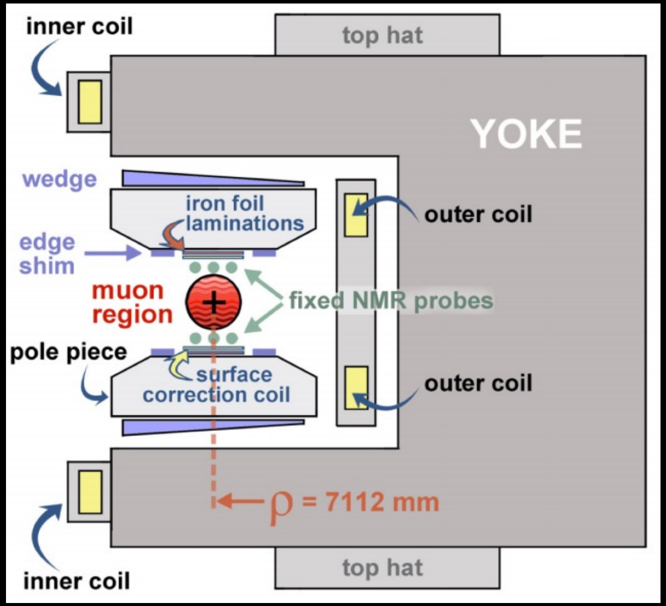


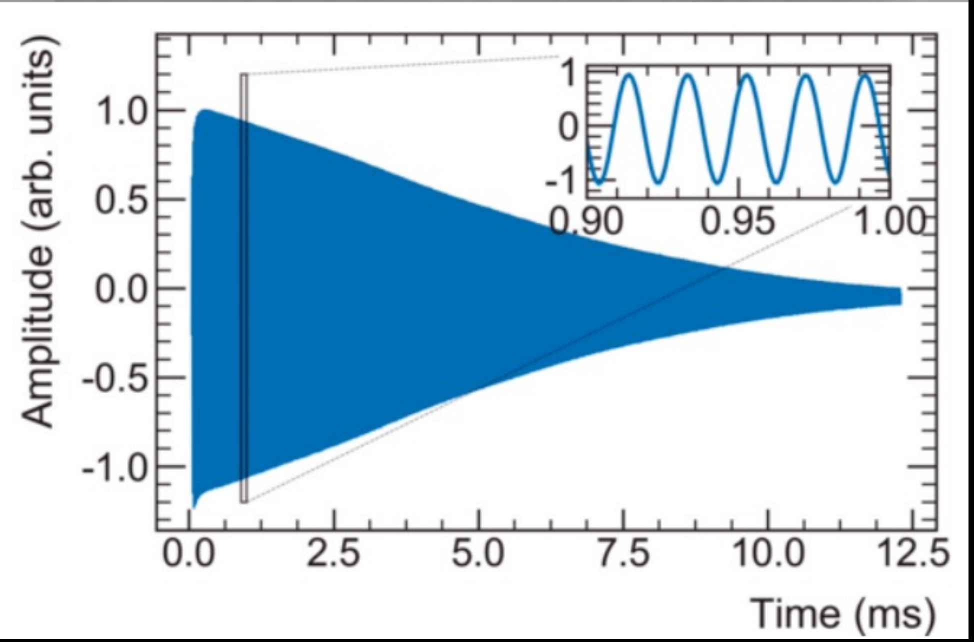
$$\omega_a = \omega_s - \omega_c = \frac{g-2}{2}\frac{e}{2m}B$$



The Magnetic Field

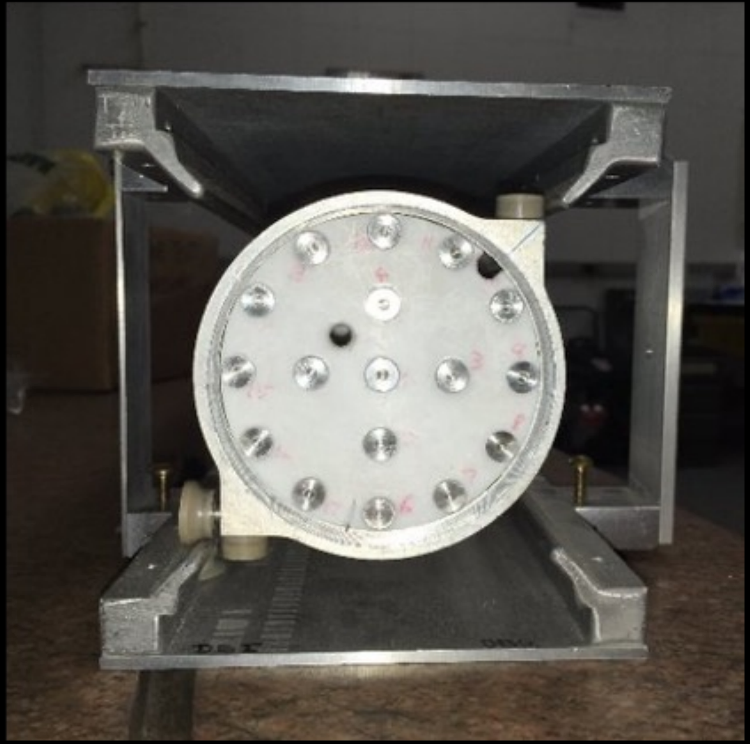
- Superconducting Magnet with 7.1m radius
- Producing 1.45 T magnetic field in the storage region
- Magnet current ~5173 A
- Provides field for bending the muons + producing the precession effect
- Highly uniform due to shimming and wedging process
- 347 NMR probes continuously monitor the field variations

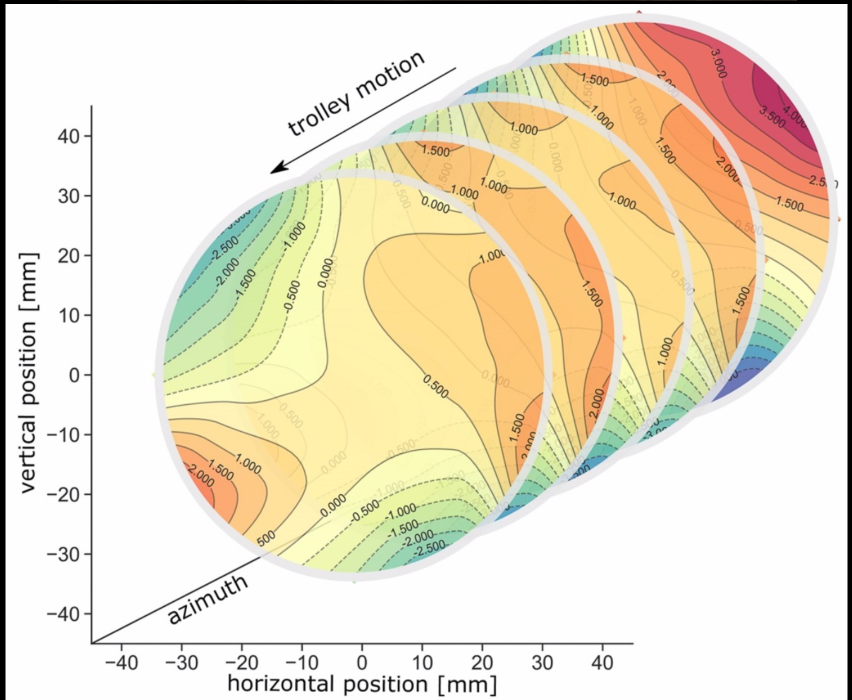




The Magnetic Field (2)

- The Trolley is equipped with 17 NMR probes
- Monitors the field INSIDE the storage region
- Runs every 2/3 days

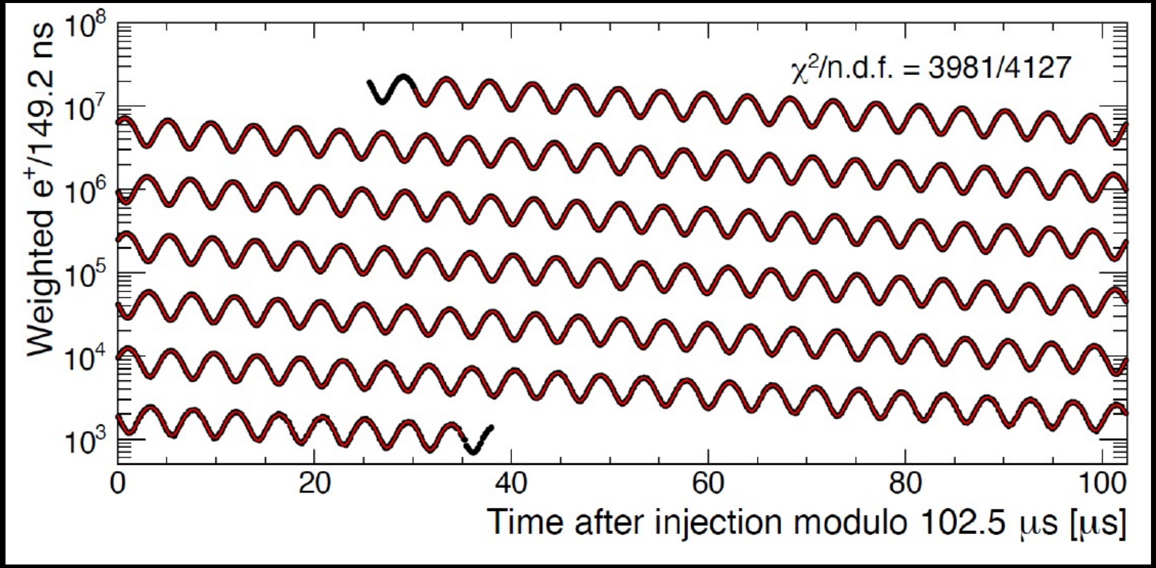




The Result

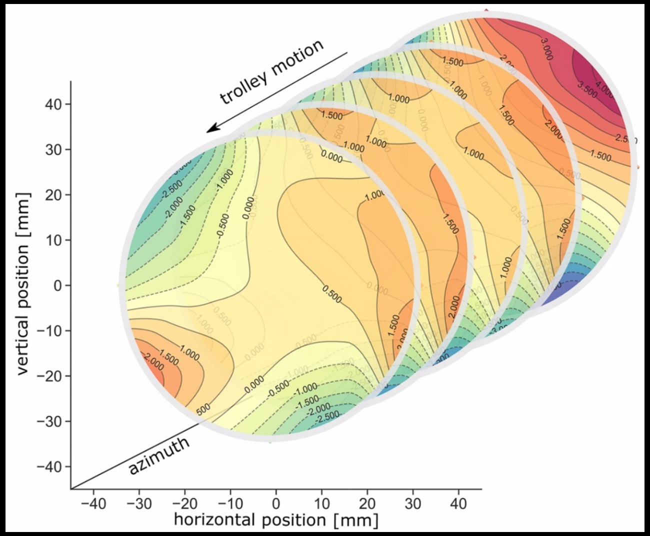
What does it mean and how it compares to theory

$a_\mu =$



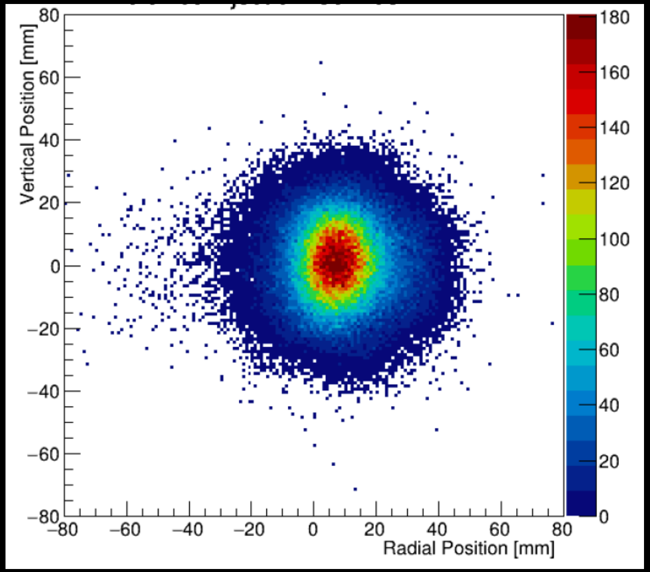
Weighted e+/149.2 ns
χ2/n.d.f. = 3981/4127
Time after injection modulo 102.5 μs [μs]

———————————————— x C.F.

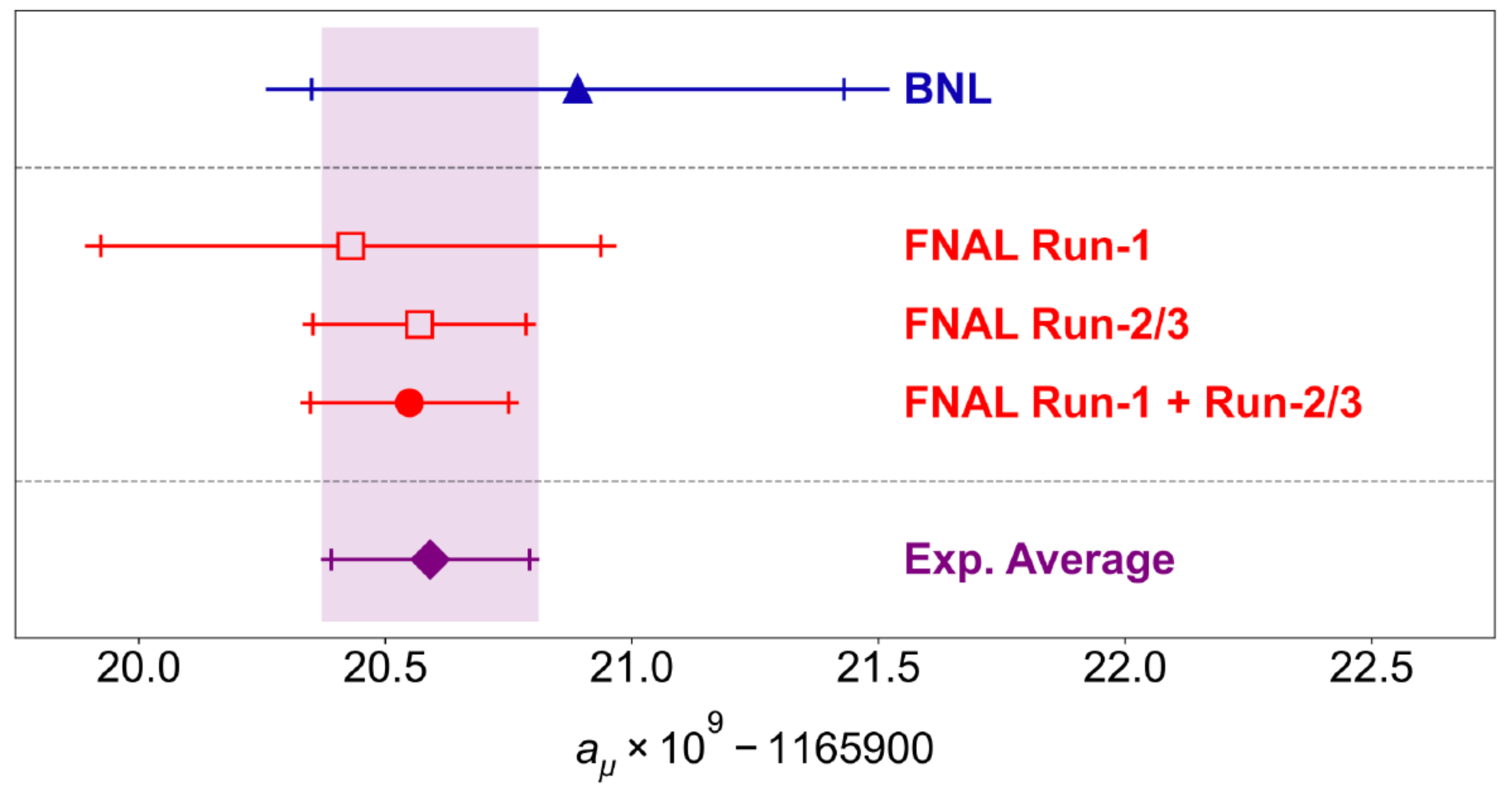


trolley motion
azimuth
vertical position [mm]
horizontal position [mm]

x

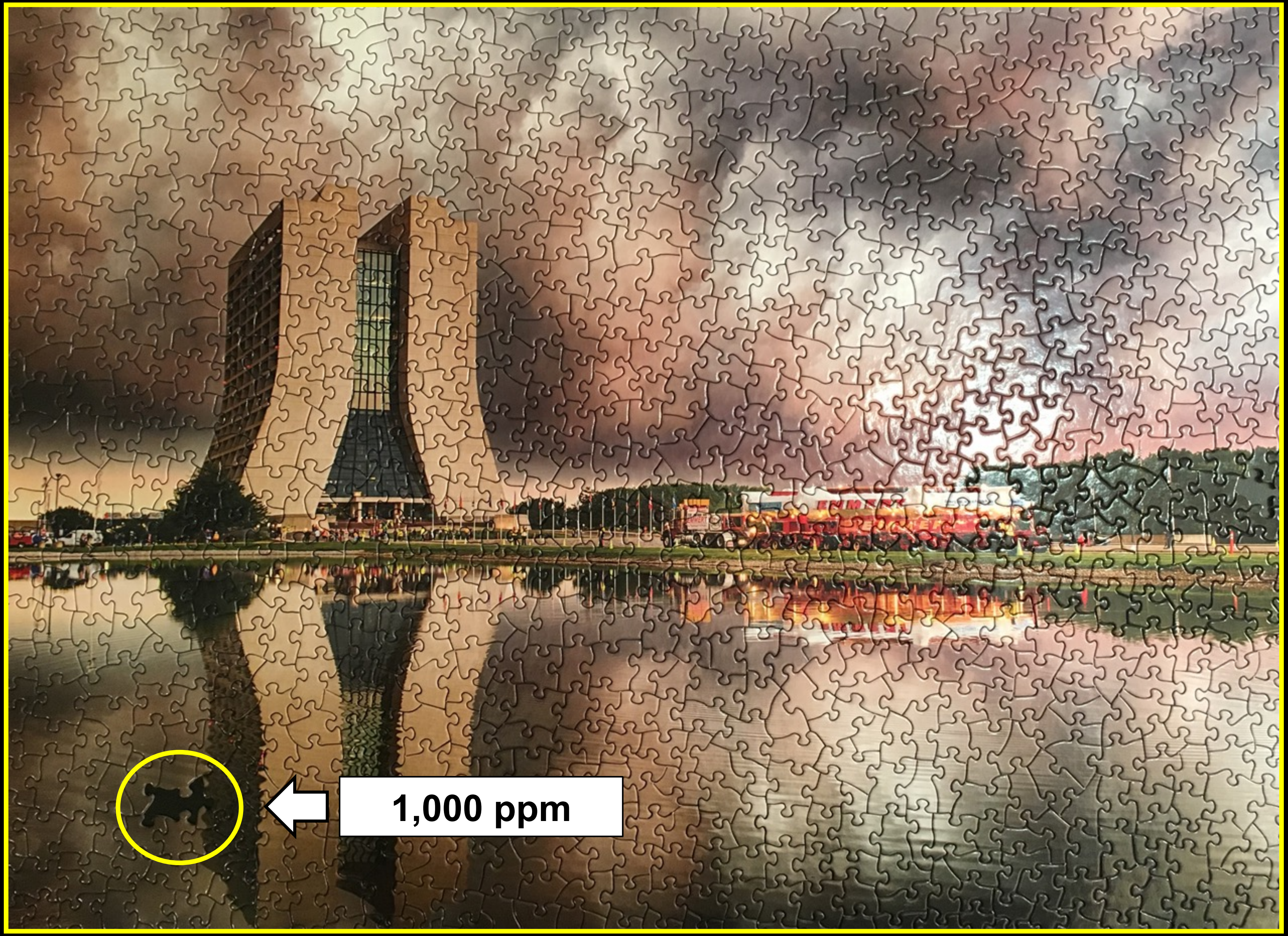


Vertical Position [mm]
Radial Position [mm]



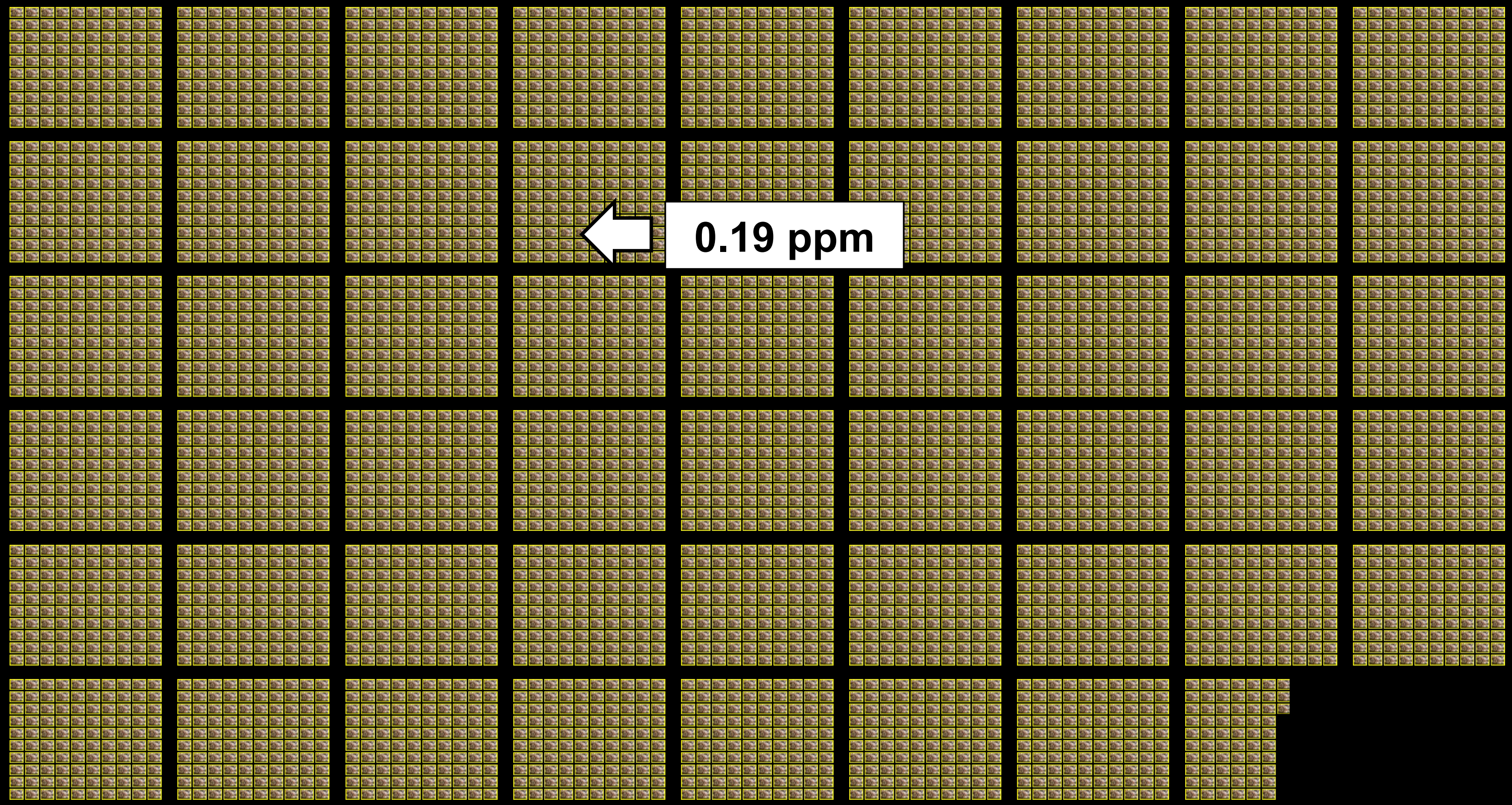
$$a_\mu^{exp} = 0.00\,116\,592\,059 \pm 0.00\,000\,000\,022\ [0.19\ ppm]$$

Un puzzle da 1000 pezzi con un pezzo mancante:

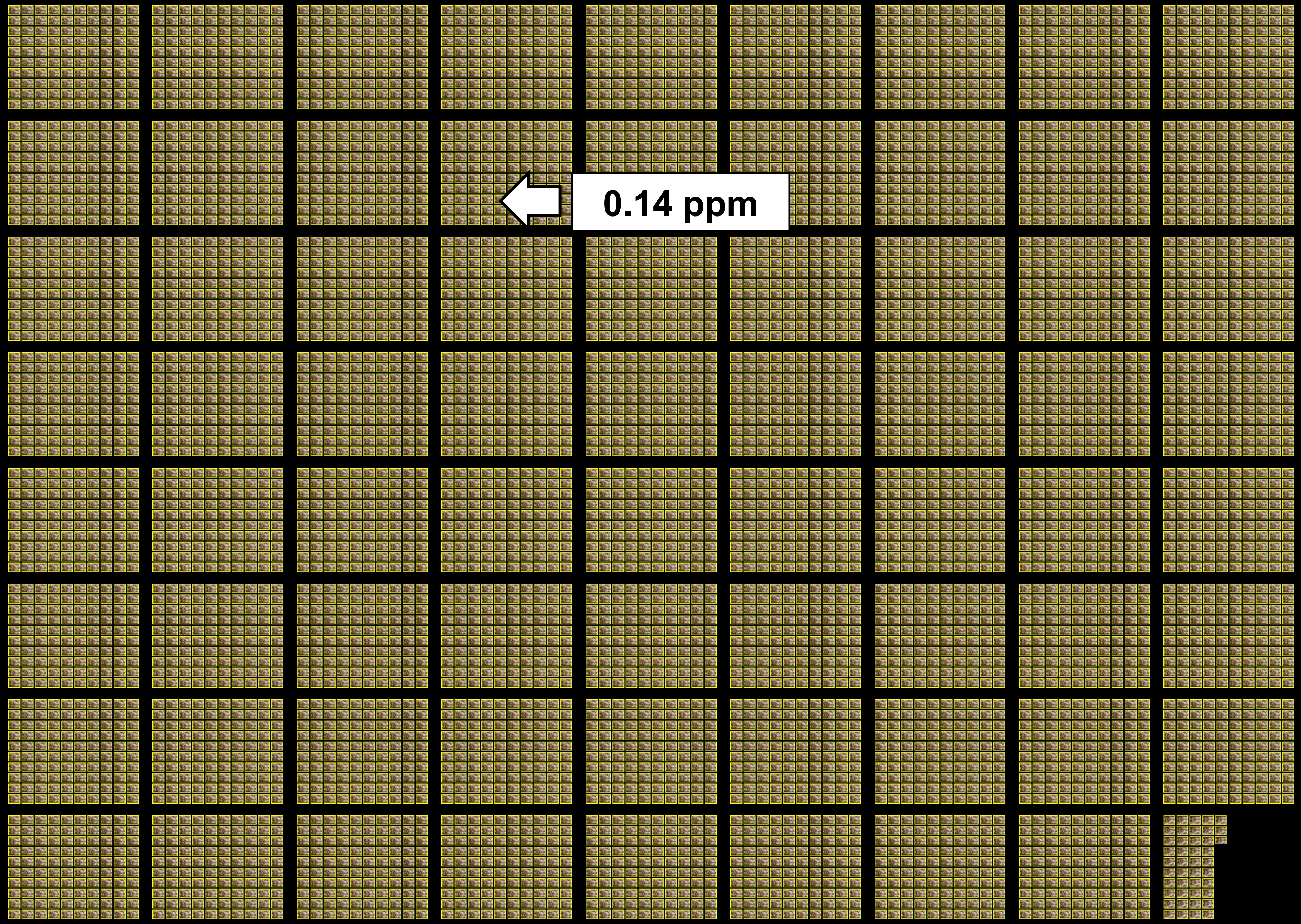


100 puzzle da 1000 pezzi con un pezzo mancante:

5263 puzzle da 1000 pezzi con un pezzo mancante:



7142 puzzle da 1000 pezzi con un pezzo mancante:

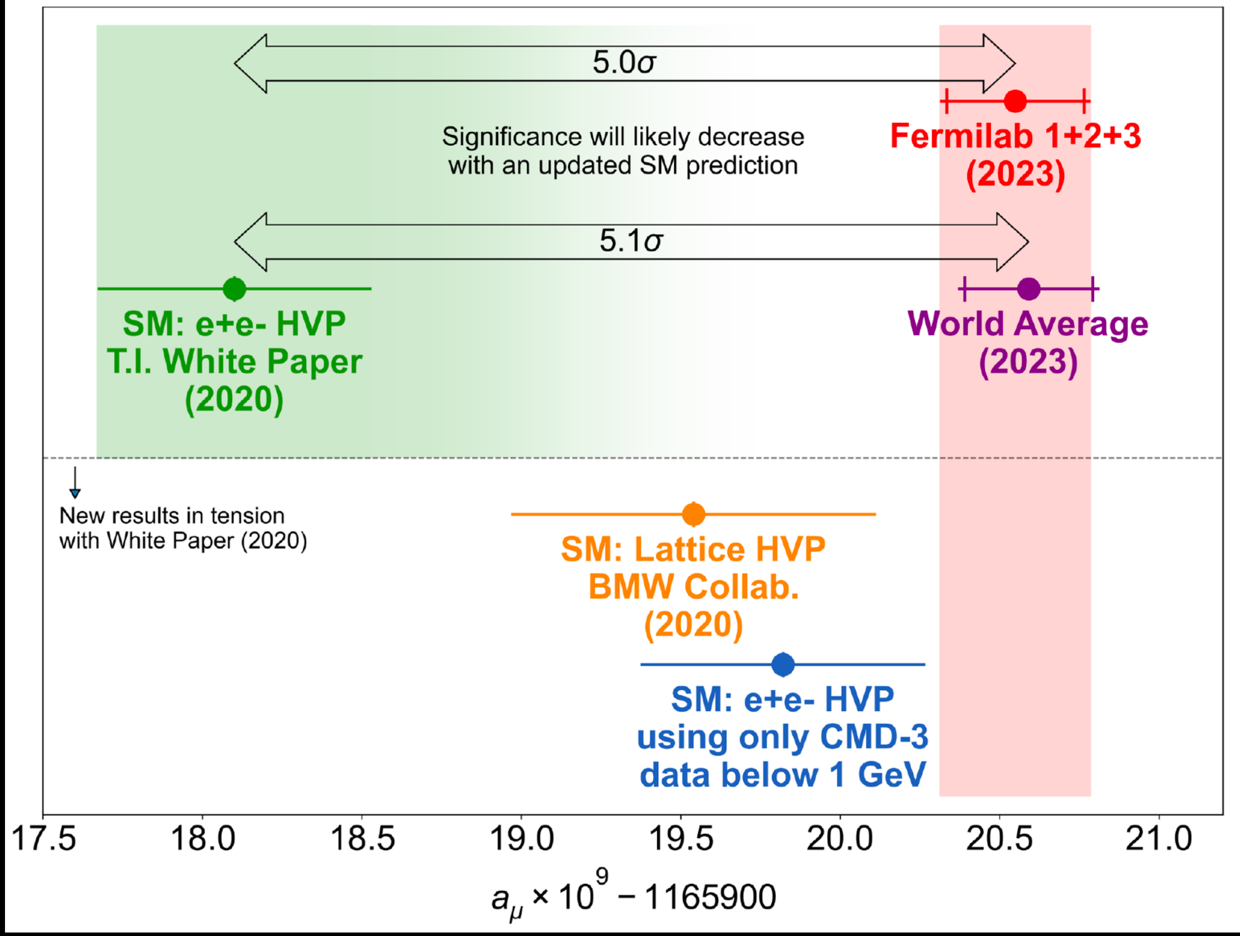


Conclusions and Future Perspectives

Ongoing analyses, Theory Puzzles

Theory Side

- Comparison with the white paper result leads to a 5.2 sigma discrepancy with the experiment
- The WP result is computed with dispersive approach and doesn’t include Lattice calculations for HVP terms
- A result from BMW (2020) using the Lattice approach shows a smaller discrepancy
- New Lattice calculations suggest an agreement with the experiment



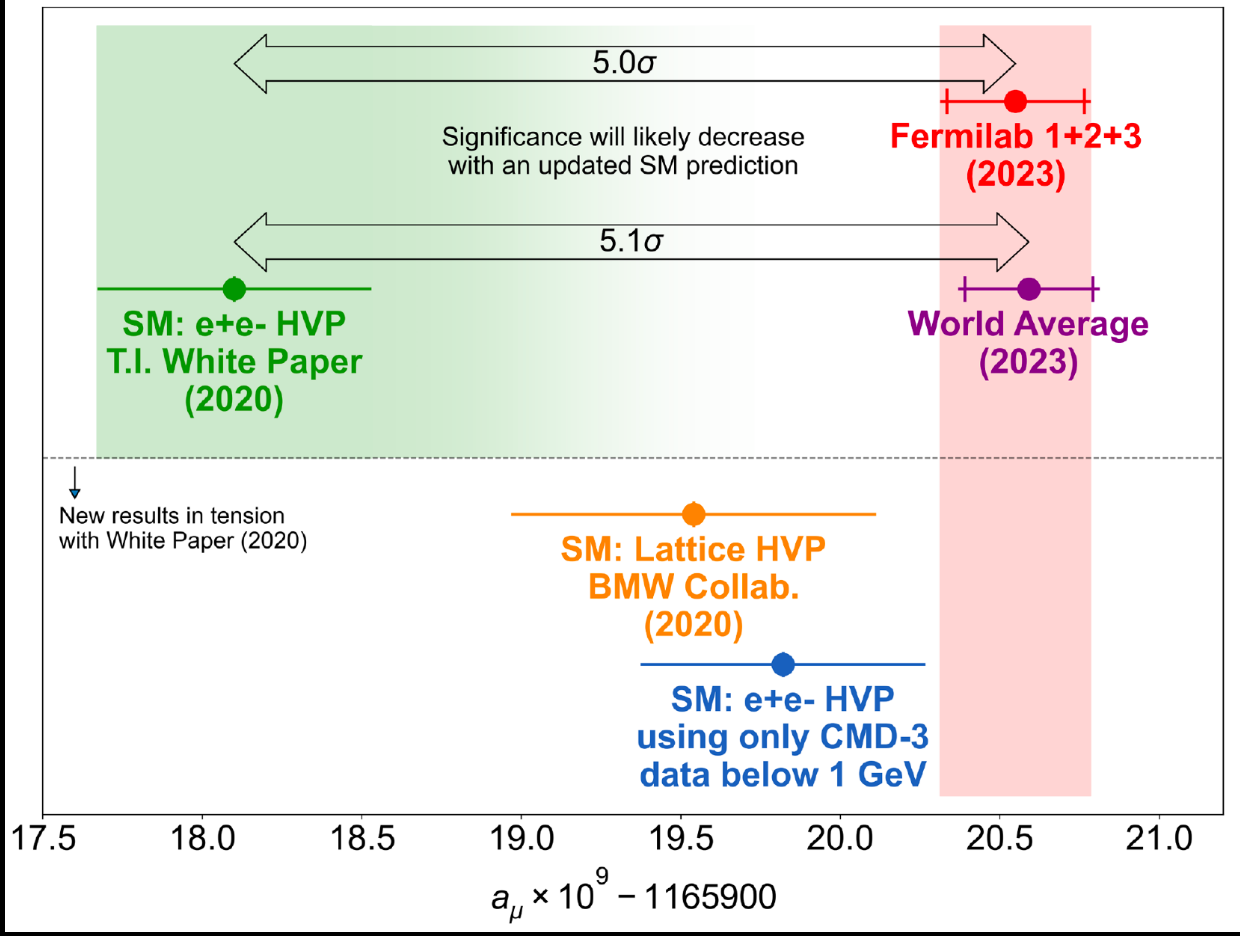
Theory Side (2)

- Dispersive approach is based on the integral

$$a_\mu^{HVP} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{+\infty}\frac{K(s)}{s}R(s)ds$$

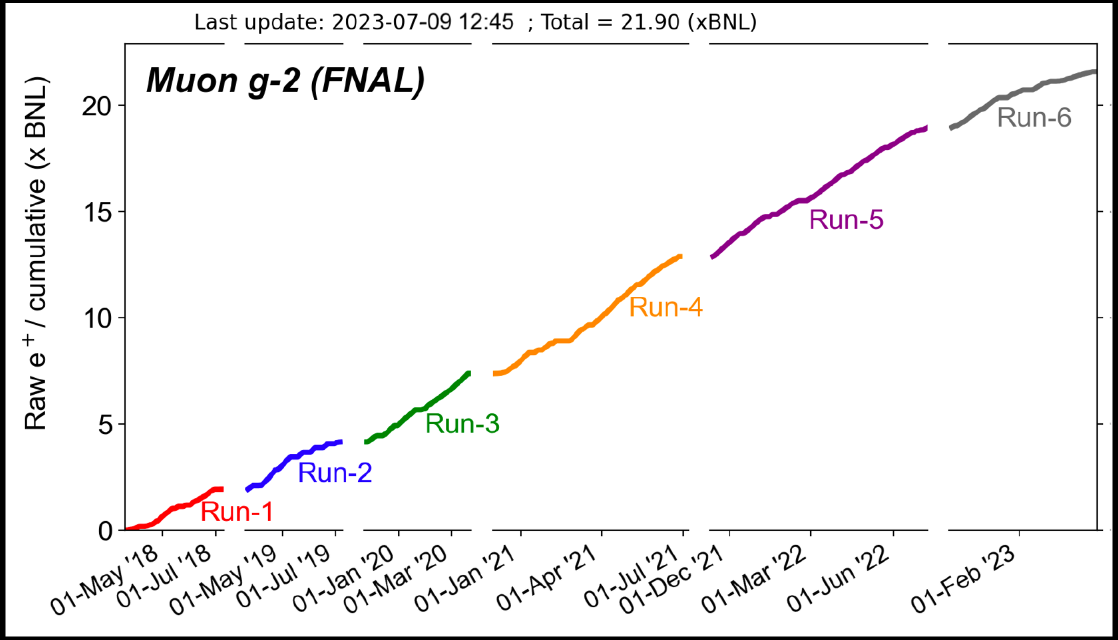
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma_{pt}(e^+e^- \to \mu^+\mu^-)}$$

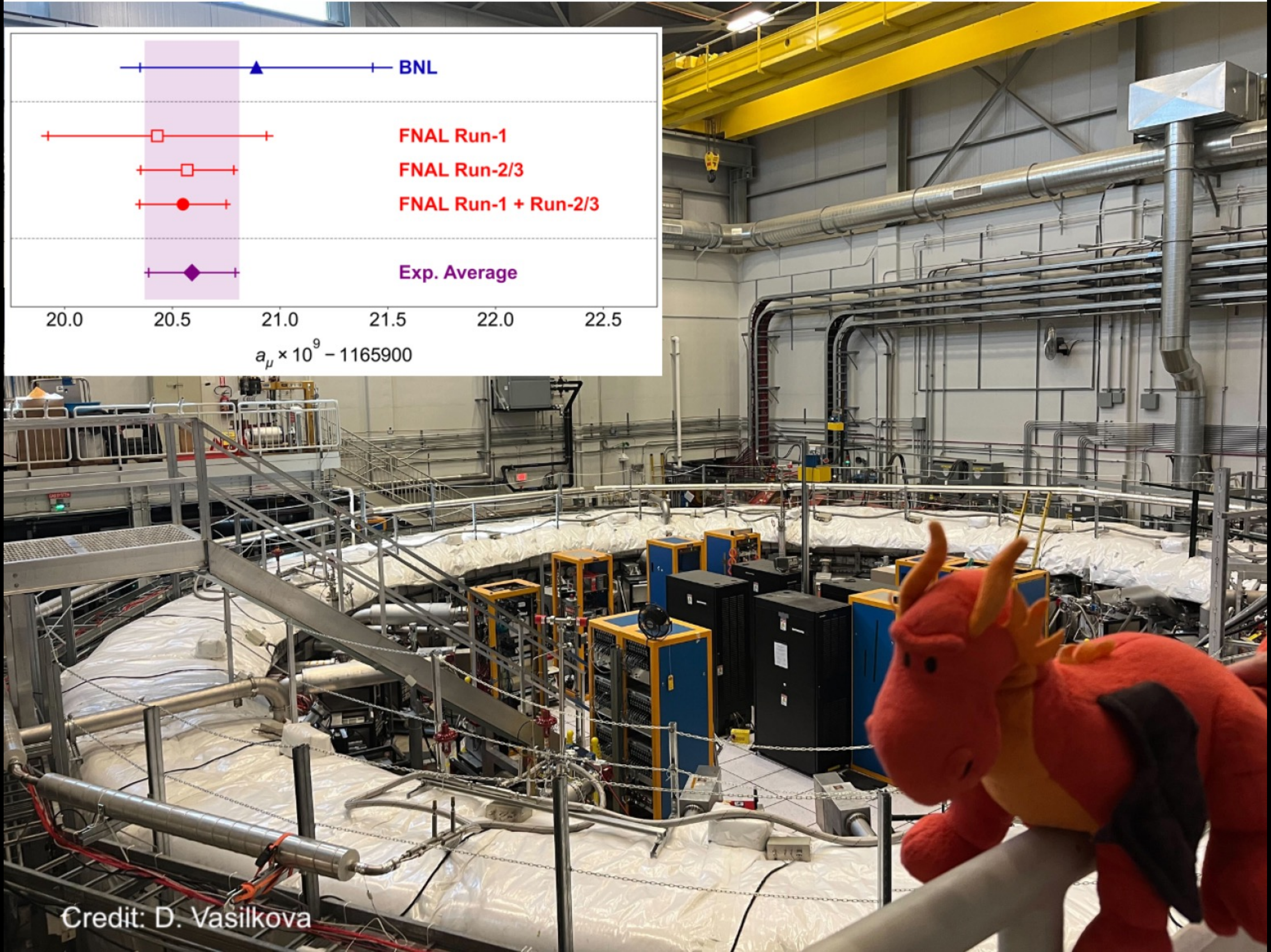
- The e^+e^- into hadrons cross section is from experiments (KLOE, BaBar etc.)
- A new result from CMD-3 (Novosibirsk) shows additional tension with the previous measurements
- A new analysis of KLOE data is undergoing to understand the reason for the discrepancies



Future results

- On the 9th of July 2023 the experiment data-taking ended
- Overall a statistical power of 21 times the BNL experiment was collected
- Run 2-3 result released on 10th of August 2023 with an uncertainty of 200 ppb
- In 2023-2024 a campaign of field measurement was conducted on the magnet
- Magnet is now at room temperature ready for decommissioning
- Run 4-5-6 are under analysis and the result is expected to be published in 2025




BNL
FNAL Run-1
FNAL Run-2/3
FNAL Run-1 + Run-2/3
Exp. Average
20.0
20.5
21.0
21.5
22.0
22.5
$a_\mu \times 10^9 - 1165900$
Credit: D. Vasilkova